

PROCEEDINGS OF THE SYMPOSIUM ON

**ELECTRON AND ION BEAM
SCIENCE AND TECHNOLOGY**

TENTH INTERNATIONAL CONFERENCE

Edited by

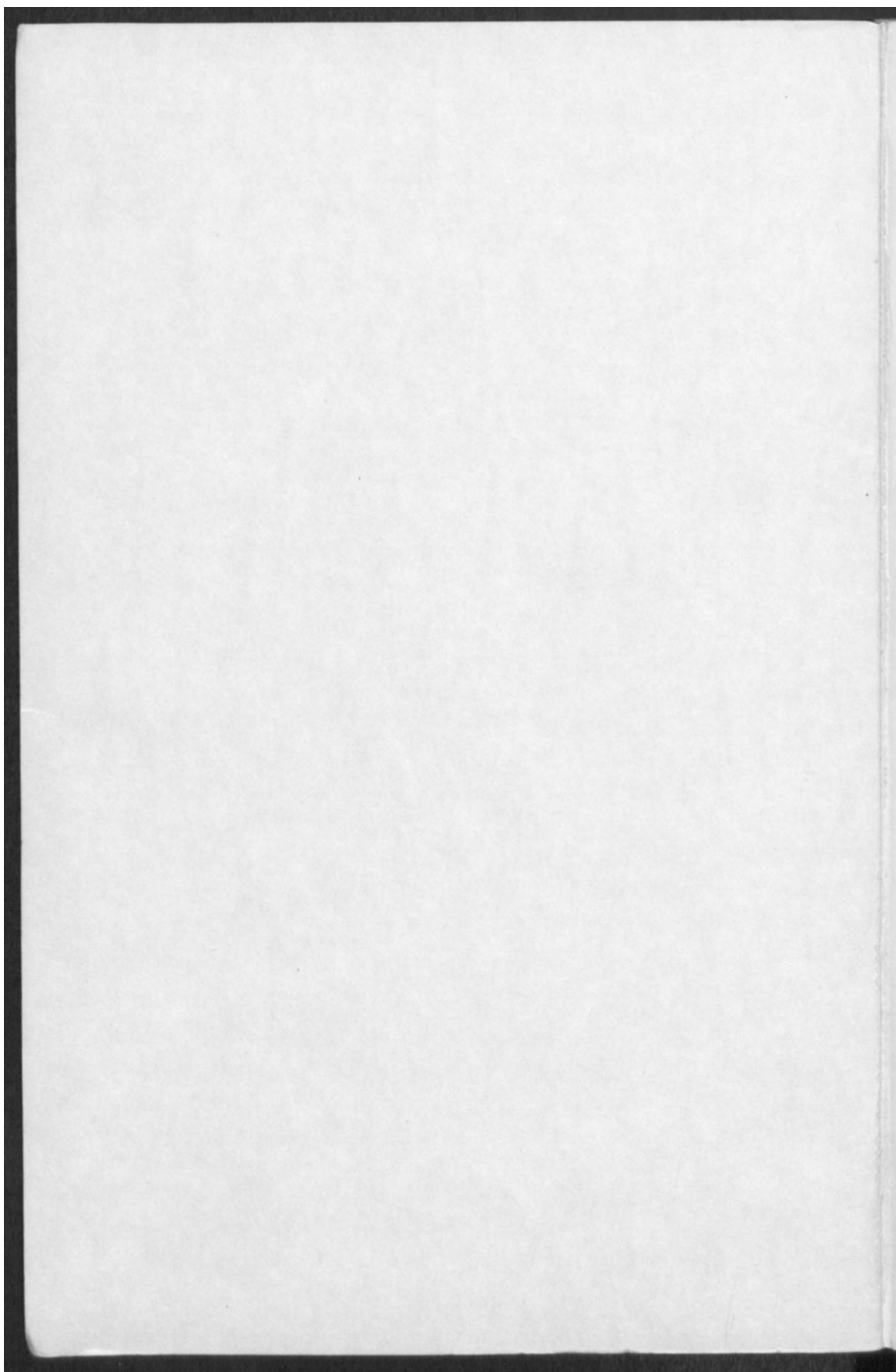
Robert Bakish
Bakish Materials Corporation
Englewood, New Jersey



*ELECTRONICS, DIELECTRICS AND INSULATION, AND
HIGH TEMPERATURE MATERIALS DIVISIONS*

Proceedings Volume 83-2

THE ELECTROCHEMICAL SOCIETY, INC., 10 South Main St., Pennington, NJ 08534-2896



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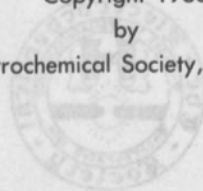
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Robert Bokish
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Englewood, New Jersey

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Library of Congress Catalog Card Number 71-120300

Printed in the United States of America

PREFACE

At the 10th and in fact final meeting of this conference 58 papers and 13 recent news papers were presented. As has always been the case with meetings past, some of the authors failed to meet the publication deadline. In order to assure timeliness of the printed record of any proceedings of a conference, including these, a publication cutoff date must be set and in this case it was September 15, 1982.

This proceedings include 48 papers. They are rearranged from the order in which they were presented at the conference. It is my hope that by presenting the papers in this order, I have prepared a reasonably coherent volume.

The papers are arranged in six sections beginning with the section on electron lithography machines and related topics. The second section contains two papers on electron beam testing. This is essentially a relatively new topic to our conference. As electron beam machines become more and more firmly entrenched in the manufacture of VLSI devices, electron beam testing will become an inseparable part of this technology. Future conferences are certain to see increased activities here. The third section contains the papers on photo resists and related topics, a continuing vital area of progress here. The fourth contains the papers dealing with proximity effects, a now regular companion in our conference. The fifth section presents the papers dealing with topics related to X-ray lithography and includes several papers on X-ray sources. The last section groups the papers dealing with ion implantation, ion optics and ion beam systems for the VLSI field. The last paper in the proceedings is the only paper outside the main thought of this volume, namely particulate beam devices and systems directed to the VLSI field.

As this is the last volume of this series, it is perhaps appropriate to reminisce briefly on the past of this conference as evidenced by the nine proceedings volumes preceeding this one.

As one goes back one sees that we began this conference by covering the complete spectrum of electron and ion beam activities. We had sections on the physics of electron and ion beams, sections on beam material interactions, sections on materials joining, sections on ion propulsion, sections on ion implantation, sections on micro analysis, sections on electron beam irradiation, and last but not least sections on micro electronics. It is this last topic as modified by two decades of progress and now referred to by VLSI that is the virtual substance of this volume. But what happened to all the other topics?

One can say that most of them are alive and well. The first, i.e. the

physics of electron and ion beams continue to be an intimate part of this volume, but they are directed to the very specific problems needing solutions to day. The beam material interactions are still part of our technology, but only very specific beam material interactions are of interest here. The other such as melting and evaporation which were usually discussed by the papers in these sessions are also established production processes. No research but most striking growth in power has been realized. For example we can see 2.5 megawatt in installations for evaporation and 9 megawatt in installations for melting capable of casting up to 100 ton steel ingots. As to materials joining we can say that electron beam welding which was the topic of many papers in the early sections is a healthy technology, serving a widest range of industries. Little if any fundamental work is in progress here, but the electron beam welder has become a most widely used and relatively common joining tool for selected applications. While interest in ion propulsion still exists, it is at a considerably low level, and many of the leaders of that technology are now working in ion beam machines for a diversity of tasks in service to the VLSI field. Ion implantation on which we had sessions in the early conferences continues to grow and is being applied to new applications. The electron micro probe like the electron beam welder has also become commonplace member of the instrumental analysis laboratory. It has had an impressive growth in capabilities and sophistication. As a matter of fact the electron and ion beams have become an inseparable part of surface analysis and have made a major contribution to problem solving in many industries.

In summary one can say that as applications matured throughout the electron and ion beam field, we find research effort falling into a level which appears proportional to anticipated rewards. For most practical purposes it can be said that research has substantially declined in most of the areas of applications referred to above. Reason being the feeling that the potential for rewards as a consequence of further research here are relatively small. Research continues unabated in the spectrum of activities that defines the VLSI field as does the apparent potential for reward here. As long as this is the case, and as long as progress effected and some partial payoff realized by those active here, we will continue to see activities and fruitful developments.

It has been a privilege and a rewarding experience to share in and be part of the development here.

R. Bakish,
Englewood, N.J.

October 19, 1982.

CONTENTS

	Page
Section One	1
An Electron Beam Microfabrication System For Lithography Below 1000 Å	
P.J. Coane, D.P. Kern, A.J. Speth and T.H.P. Chang	2
A Round Beam Exposure System With Multiple Beam Sizes	
D.P. Kern, R. Viswanathan, R.H. Naumann and T.H.P. Chang	15
A High Throughput, Direct Wafer Exposure Variable Shaped Electron Beam Lithography System	
Z. Krokar, G. Lewis, B. Piwczyk and M. Sogard	28
An Automated Control System For A High Throughput, Variable Shaped Electron Beam Lithography System	
Z. Krokar, A. Liberman, G. Lord, A. Rubin	39
A Laser-Interferometer Controlled, X,Y Air Bearing Vacuum Stage System For Direct Wafer Exposure Electron Beam Lithography	
G. Lewis and B. Pizczyk	49
Variable Spot Shaping By Means of Quadrupole Lenses	
S. Okayama, K. Shimizu and H. Kawakatsu	58
The "Swinging Objective Lens" Used In Electron Beam Exposure Machine	
Zhong-wei Chen, Jian-kun Wang and Pei-young Qiu	70
A High Speed Blanker For A 300 MHz Lithography System	
H.P. Kuo, J. Foster, W. Haase, J. Kelly, B.M. Oliver	78
A Software System For Electron Beam Lithography	
K. Saitoh and H. Morimoto	92
Multiple Electrostatic Deflectors Applied To In-Lens Deflection System For Extended Scanning Field	
E. Goto, T. Soma, M. Idesawa, T. Sasaki, T. Goto, T. Someya K. Tanaka, S. Miyauchi and G. Cogswell	103
Very High Resolution Electron Beam Lithography-Thin Films, Or Solid Substrates	
S.P. Beaumont, B. Singh and C.D.W. Wilkinson	112

High Resolution Lithography On Thin Active Semiconductor Membranes	Page
W.S. Mackie, S.P. Beaumont, C.D.W. Wilkinson and J.S. Roberts	122
Single Crystal LaB ₆ Gun For Electron Beam Lithography Tadahiro Takigawa and Isao Sasaki	135
Section Two	149
A Tripotential Method For Electron Beam Testing F.J. Hohn, D.P. Kern, P. Coane, W. Bruenger and T.H.P. Chang	150
Electron Energy Analyzer For Applications In Large Scan Field Electron Beam Testing W.H. Bruenger, F.J. Hohn, D.P. Kern, P.J. Coane and T.H.P. Chang	159
Section Three	170
Radiation Chemistry And Resist Applications Of Poly (p-Substituted Styrenes) H. Hiraoka and L.W. Welsh, Jr.	171
The Electron Beam Induced Chemistry Of Polysulfones Used As Results J. Pacansky, R. Kroeker, E. Gipstein and A. Gutierrez	179
Electron Resist Behavior Of Some Methacrylic Acid Copolymers J.H. Lai and L.T. Sheperd	185
High Resolution Negative Electron Resist: Chloromethylated Poly- η -Methylstyrene K. Sukegawa, T. Tamamura and S. Sugawara	193
A Double PMMA Resist Structure For Sub-Micron Lithography Using A Single Developer C. Dix and P. Hendy	204
Exposure Range Of Low Energy Electrons In PMMA S.A. Rishton, S.P. Beaumont and C.D.W. Wilkinson	211
Resist Heating In High Speed Electron Beam Pattern Generators H.I. Ralph, G. Duggan and R.J. Elliott	219
Decapsulation And Photoresist Stripping in Oxygen Microwave Plasmas Steven Dzioba, G. Este and H.M. Naguib	231

Practical Considerations In The Implementation Of Same-Level Mixed Lithography T.D. Berker	Page 243
Section Four	251
Proximity Effect Correction For Negative Resist In Electron Beam Lithography N. Nakayama, Y. Machida, S. Furuya, S. Yamamoto and T. Hisatsugu	252
Critical Edge Proximity Effect Corrections H.L. Berkowitz and R.L. Lux	260
Substrate Proximity Correction In Direct E-Beam Writing Peter Vettiger	269
Electron Beam Interactions In Finely Focused Beams Of Low Energy Electrons Y.W. Yau, R.F. Pease, and T.R. Groves	282
Section Five	288
Pulsed Plasma X-Ray Sources For Submicron Lithography Robert A. Gutcheck, Julius J. Muray and Melvin J. Bernstein ..	289
Aluminum Plasma X-Ray Source For Lithography Masahiro Okabe and Yoshitaka Kitamura	302
On The Use Of E.B. Guns Of The Axial Type For X-Ray Lithography S. Schiller, M. Neumann, F. Durner, W. Fahland, R. Springer and B. Steffin	315
X-Ray Mask Metallization By Multilayer Resist Lift-Off M.S. Chang	323
X-Ray Masks With High Aspect Ratio Submicron Patterns Fabricated By Using Plasma-CVD SiN _x Spacer and Membrane K. Suzuki, Y. Lida, T. Torikai and J. Matsui	333
A Step-And-Repeat X-Ray Exposure System For 0.5 μ m Pattern Replication Toa Hayasaka, Sunao Ishihara and Hiroo Kinoshita	347
Section Six	359

An Automatic System For Controlling The Ion Mass And Ion Energy In An Ion Implanter	Page
G. Ryding, T. Maymay, V. Benveniste and M. Farley	360
Beam Measurement and Dose Control In A High Current Implanter	
G. Ryding, M. Farley, M Mack, K. Steeples and V. Gillis	366
The Effect Of Implantation Of Phosphorus Into Sputtered MoSi_2 Thin Films	
T.P. Chow, C.S. Grant, W. Katz, G. Gildenblat and R.F. Reihl	372
Focussed Ion Beam Using A Triode Gun	
Masanori Komuro	385
Moving Quadrupole Lens Concept For Ion Beam Lithography	
T. Soma, E. Goto, M. Idesawa and T. Sasaki	396
Design Of An Electrostatic Ion Optical System For Ion Beam Lithography	
M. Szilagyi, H. Paik, B. Siegel	409
Fine Focused Ion Beam System Using Metal Alloy Ion Sources And Maskless Fabrication	
K. Gamo, Y. Inomoto, Y. Ochiai and S. Namba	422
Secondary Electron Images By Scanning Ion Microscope	
N. Anazawa, R. Aihara and M. Okunuki	434
Diffraction Gratings For X-Ray Fabricated By Reactive Ion-Beam Etching	
H. Aritome, K. Moriwaki and S. Namba	443
Metal-On-Polymer Masks For Ion Beam Processing	
E.L. Hu, R.E. Howard, P. Grabbe, D.M. Tennant	450
Renaissance Of Electron Beam Melting	
R. Bakish	456
Subject Index	467

ACKNOWLEDGMENT

The writer wishes to acknowledge the assistance of the conference committee members: Dr. M. Allais, Prof. M. von Ardenne, Prof. W. Barwicz, Dr. E. Bas, Dr. F. Benesowski, Dr. H. Bohlen, Dr. L.A. Fontijn, Prof. L. Habraken, Dr. C. Hayashi, Prof. A.E. Jenkins, Prof. G. Molendstedt, Dr. S. Namba, Dr. W.C. Nixon, Prof. N.A. Olshanski, Academician B. Paton, Prof. G. Slodzian and Prof. W. Smeltzer. It is also with regret that I acknowledge the untimely passing of Drs. Benesowski and Habraken; our condolences.

Special thanks are due to all conference session chairmen and co-chairmen listed here: J. Bowden, T.H.P. Chang, L. Deroose, M. Hatzakakis, F. Hohn, J. Kelly, W. Knauer, A. Neureuther, H. Pfeiffer, R.F.W. Pease, P. Rose, R. Seliger, W. Siegle, D. Spicer, L. Swanssen, C. Ting, A. Wittkower.

INTRODUCTORY REMARKS

Ladies and Gentlemen,

It gives me great pleasure to welcome you here in Montreal on the occasion of the 10th International Electron and Ion Beam Science and Technology Conference. The two decades which elapsed since the beginning of this event have been marked with tremendous progress and the practical realization and conversion to viable hardware to many ideas put forward in our earlier meetings. Electron and Ion Beam Science and Technology to day has become an integral part of the science and technology which affects our daily lives. Take the automotive, the aerospace, the defence, the metallurgical, the electronics and the computer industries, and you will see that in each and every one of them electron and ion beams have made an imprint. Our conference together with the electron, ion and photon conference which I chaired from 1960 to 1962 and with which I also was associated of later date have monitored progress here by providing in alternate years the important forums from which to air the contributions of those working here. Effective 1983 these two conferences will merge and become but one conference to meet annually. It will be referred to as the International Symposium on Electron, Ion and Photon Beam. The fusion of these two conferences was done for the benefit of the community which they served. Dr. Philip Chang of IBM Research, simply Philip to me, will tell you in a couple of minutes more about the next year event. I sincerely hope that in this, as in preceeding events, all of you will be brought up to date on the prevailing state of the art in this dynamic technology by those working in it. I also hope that the process of getting to know people in the field, your colleagues here will continue as it has for me in the two decades since I initiated this event.

Publication Editor's Note: At this point Dr. Bakish provided some procedural details for submission of papers scheduled for presentation and for inclusion in this volume.

Speaking of the Society which has hosted this event for two decades, I wish to extend my sincere thanks and those of this assembly for the 20 years of support given to this conference. I wish to close my introductory remarks with an unusually pleasant task, namely the mission to convey recognition scrolls to some of the contributors to this technology selected by our conference committee:

A.N. Broers for his contribution to Electron Lithography.

M. Hatzakis for his contribution to Photo Resist.

Hank Smith for his contribution to X-Ray Lithography.

K.H. Steigerwald for his contribution to Electron Beam Welding and Micro Machining.

S. Schiller for his contribution to High Power Electron Guns and their Applications.

and to

Professors W. Nixon, T. Everhart and S. Namba who shared the Educational Award for guiding the new generation in this technology.

May I ask the individuals to come forward and receive their awards.

And now I will turn the floor to Dr. Chang of the Steering Committee of the Electron Ion and Photon Beam Conference with which we will be merging effective 1983 and have him tell you about the 1983 event.

Philip, the floor is yours.

FUTURE MEETING PLANS FOR ELECTRON, ION & PHOTON BEAM TECHNOLOGY.

Thank you Bob.

Ladies and Gentlemen, Starting in 1983, an annual meeting on electron, ion & photon beam technology will be held under joint sponsorship of the American Vacuum Society, the IEEE and The Electrochemical Society. The meeting will be named "The International Symposium on Electron, Ion and Photon Beams" and will be organized by a Symposia Steering Committee. Proceedings of the meeting will be published in the Journal of Vacuum Science and Technology.

Meeting plans for the 1983 and 1984 Symposia have already been decided. The 1983 Symposium will be held May 30th to June 3rd, in Westin Bonaventure Hotel, Los Angeles, California with Dr. R. L. Seliger of Hughes Research Laboratory as Symposium Chairman and Mr. M. Hatzakis of IBM Research as the Program Chairman.

The 1984 Symposium will be held in the May/June period in the New York area with Mr. M. Hatzakis of IBM Research as Symposium Chairman and Mr. J. Kelly of Hewlett Packard as the Program Chairman.

Two new members of the Symposia Steering Committee were elected during the Montreal meetings to replace Prof. T. Everhart (Cornell University) and Dr. G. Varnell (Texas Instruments) who have served their terms and moved to the Advisory Committee this year. The two new members are Dr. J. Brunning of Bell Laboratory and Prof. L. Swanson of the Oregon Graduate Center. They, together with Dr. R. Bakish (Bakish Materials), Dr. T.H.P. Chang (IBM), Mr. M. Hatzakis (IBM), Dr. D.R. Herriott (Perkin Elmer), Mr. J. Kelly (Hewlett Packard), Dr. R.L. Seliger (Hughes Research), and Prof. H.I. Smith (MIT), form the current Steering Committee.

In recognition of his twenty years of service to the international electron, ion and photon beam community, an award in a form of an engraved plaque is presented to Dr. R. Bakish jointly by the Symposia

Steering Committee and The Electrochemical Society. I wish to ask Prof. T. Everhart and Dr. Streiter representing the Symposia Steering Committee and The Electrochemical Society respectively to step forward and present the award.

T.H.P. Chang
Montreal,
May 10, 1982.

J. L. COOK, D. M. WILSON, J. K. STANLEY, and T. P. CHANG

IBM Research Laboratories, Armonk, New York 10516
The authors are indebted to the IBM Research Laboratories for the use of the facilities and equipment available there. The authors are also indebted to the IBM Research Laboratories for the use of the facilities and equipment available there. The authors are also indebted to the IBM Research Laboratories for the use of the facilities and equipment available there.

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SECTION ONE

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AN ELECTRON BEAM MICROFABRICATION SYSTEM FOR LITHOGRAPHY BELOW 1000 Å

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ABSTRACT

The design criteria and performance characteristics of a Vector Scan electron beam system, modified for fabrication of structures with minimum dimensions below the hundred nanometer range, is described. The objectives are two-fold: (1) to explore the limits of electron beam lithography ; for example, beam interaction with various polymer/substrate combinations including the influence of beam energy on proximity, and (2) the fabrication of structures to determine the fundamental process and device limiting factors resulting from the scaling down of dimensions into the sub-tenth micron regime. To accomplish these objectives, two phases of system development are planned. The goal of Phase I is to achieve 200Å resolution over a scan field 100µm square. With further modifications to the electron optics, the main thrust of the second phase of development will be directed towards achieving a resolution of 40Å. Preliminary results for Phase I, which demonstrate the successful scaling down of an FET memory device mask level and the fabrication of Fresnel zone plates for applications in high resolution x-ray optics, are presented.

INTRODUCTION

Interest in the fabrication of structures with minimum dimensions in the submicron and even in the nanometer range has grown considerably over the last few years. There are several reasons for this development. First of all, there is a need to explore the limits of microfabrication itself. This involves the study of the basic processes in lithography, the interaction of radiation and substrate, of different types of materials and of ways to process these materials. Secondly, the size of these structures covers a range in which elementary processes in physics are localized such that simple structures can be used to obtain new insight into the fundamental physical properties of materials. Thirdly, there is an interest in the complex structures which will be required for feasibility studies in future generations of solid state devices. Until now, most of this work has been performed in modified scanning and scanning transmission electron microscopes. Although these instruments are very well suited for this type of work from the point of view of mechanical and electrical stability, their electron optical properties impose a severe limitation on field size. In addition, their capability of defining complex patterns is very restricted. On the other hand, most electron beam lithography systems are operating in a minimum linewidth range of one half to one micron. Their electron optical performance as well as the mechanical and electrical noise properties are designed for this application. This is at least one order of magnitude larger

than the interests of this paper. The goal of the work reported here is to develop a system which has both high resolution and flexible patterning capability.

SYSTEM DESCRIPTION

The high resolution electron beam microfabrication system is shown schematically in Fig. 1. The design is based on a Vector Scan lithography system⁽¹⁾ with modifications to significantly improve the probe forming capabilities, the noise, drift and linearity characteristics of the deflection system, to provide a vacuum environment free of contamination and to reduce the resolution limiting effects of mechanical vibration. The system can also be operated over a voltage range from 1-100kV to provide the means to investigate energy dependent beam interaction processes with lithography related materials, such as resists and other masking materials on various substrates. A view of the system is shown in Fig. 2.

The electron optical system utilizes design concepts from both scanning electron microscopes and electron beam lithography systems. It consists of (1) a probe forming system to produce a focused beam of electrons over an electron energy range of 1-100keV, (2) an electrostatic beam blanking unit⁽²⁾ designed to minimize shift in beam position during blanking, (3) a magnetic double deflection system partly immersed in the final lens and optimized for high resolution, (4) a dual channel secondary electron detector and an annular backscattered electron detector for focussing and registration purposes, and (5) a precision x-y stage driven by resonance free low inertia motors under closed loop servo control, providing 0.5 μ m positioning accuracy over ± 2 inches of travel. Accommodations for an airlock are also provided. A schematic cross-sectional view of the column is shown in Fig. 3.

The probe forming system is equipped with a single crystal LaB₆ electron gun^(3,4) which has proven its reliability in lithography systems. It is capable of generating a crossover diameter of 10 μ m with a brightness of 5×10^6 A/(cm² sr) at 25kV. Using two condenser lenses and a low aberration final lens with a working distance of 16mm, a minimum probe size of 5nm and current densities of 70 - 500 A/cm² with final beam half angles of 2.1 - 5.6 mrad can be achieved. Special attention has been paid to the design of the magnetic double deflection system^{5,6}. It is optimized for operation at 25 kV and a beam half angle of 2.1 mrad. A probe size of <10nm over a field of 100 μ m square with a placement accuracy due to electron optical distortions of <2nm is expected. The performance of the deflection system for a sequence of field sizes is summarized in Table I. The final lens has been designed to incorporate a ferrite shield for the deflection fields in order to reduce eddy currents when the system is operated in a vector scan mode.

In Figure 4 the axial field distribution for the optimized double pre-lens deflection configuration is plotted. The relative positioning of the deflection coils with respect to the bore of the final lens, as well as the placement and extent of the ferrite shielding, is schematically shown. The pattern, composed of rectangles and parallelograms as primitive shapes, is defined on a grid structure containing 16,384 addressable points on each axis. The system has capability of dose variation from shape to shape. This flexibility in shape and dose definition coupled with an inherent compatibility with the large data base of proximity corrected patterns available for all Vector-Scan lithography systems, provides the wide range of control over linewidths that is essential for fabrication of high resolution structures.

Vibration problems are an important issue for high resolution microfabrication. In those electron beam microfabrication systems with laser interferometer controlled stages for positioning the substrate, stage oscillations as small as 5nm ($\lambda/120$) can be compensated. However, beam displacements resulting from any relative movement that may occur between the electron optical column and the stage, will not be detected and eliminated by this arrangement. While the magnitude of these displacements may be tolerable for the fabrication of structures in the half micron range, this will not be the case for dimensions below 100 nm. For this reason we have incorporated a custom fabricated vibration isolation system to support the electron optical column, chamber table and vacuum components.

In order to determine the efficiency of the vibration isolation system, low frequency seismic transducers in conjunction with a real time spectrum analyzer were utilized to measure horizontal and vertical motions. The RMS velocity spectra for vertical motion in the floor and table are compared in Figure 5. The dominant floor vibration is centered around 30 Hz with a vertical displacement of 75 nm (RMS). The effectiveness of the vibration isolation system is demonstrated in the lower photograph where the amplitude has been reduced by nearly two orders of magnitude. The peak observed at 1 Hz represents the natural resonance of the total system.

Attention must also be given to the presence of resonance phenomena occurring in critical mechanical components under the stimulation of small driving forces which may, in turn, increase any relative motion existing between the electron optical column and the sample. The upper photograph in Figure 6 shows the RMS velocity spectrum for horizontal vibration in the table as measured with the seismic transducer. The spectra in the lower two photographs illustrate the vibration induced motion of the stage in the plane of the sample as measured from the back scattered electron signal produced by scanning the electron beam across a sharp edge. It was observed that a mechanical resonance occurred in the stage assembly at 55 Hz, causing 50 nm of horizontal displacement for a driving force which causes a motion of the table with an RMS amplitude of 5 nm. The introduction of moderate damping, primarily to the X axis, reduced this value by a factor of 5.

Providing a contamination free vacuum environment is also a critical requirement in high resolution work. The most familiar problem occurs as random beam displacements resulting from the electrostatic charging of organic contaminants on critically located surfaces in the electron optical column. In order to limit the introduction of organic contaminants, the column and chamber are first pumped to 10^{-6} Torr by a 450 l/sec turbomolecular pump⁽⁷⁾ which is subsequently switched off to eliminate this potential source of vibrations. The pump down time to 10^{-6} Torr is typically 15-30 minutes and is dependent on how long the system is left at atmosphere pressure. Two independent diode ion pumps⁽⁸⁾ with integral sublimators and cryowalls then maintain column and chamber at a base pressure of 2×10^{-8} Torr and 2×10^{-7} Torr, respectively.

EXPERIMENTAL RESULTS

The initial activity of this high resolution electron beam microfabrication system is to determine the fundamental process and device limiting factors resulting from the scaling down of dimensions into the regime below 1000Å. Figure 7 shows preliminary results for scaling down of the lithographic process as applied to an FET memory device. In this example, a metallization mask level has been patterned in a 1600Å thick layer of PMMA⁽⁹⁾

on bulk silicon. The pattern dimensions have been reduced by about a factor of 10 to achieve line widths of $650\text{\AA}$ without sacrificing pattern integrity. Another challenging activity is the fabrication of Fresnel zone plate lensing elements for applications in x-ray spectrometry, interferometry, holography and, in particular, high resolution x-ray microscopy. The basic principle of a Fresnel zone plate is shown in Figure 8 and consists of an array of concentric ring shaped zones which are alternately opaque and transparent. The minimum zone width determines the resolution and speed of the lensing element. The critical parameters affecting resolution are the accuracy of zone placement and the "roundness" of the zone rings. Random errors, such as localized variations in line width and edge quality only reduce the intensity which can be achieved in a focus or the image contrast, and are therefore not as important.

One specific design⁽¹⁰⁾ for x-ray optics applications is schematically illustrated in Figure 9. This x-ray lensing element is designed to be entirely self-supporting and requires a minimum zone width of $1000\text{\AA}$ with a placement accuracy of $<400\text{\AA}$. Figure 10 shows the successful fabrication of this pattern in $1600\text{\AA}$ of PMMA, on $600\text{\AA}$ of gold, on thick polyimide. The pattern is subsequently transferred into the gold layer by ion beam etching to form an x-ray lithography mask.

A second design⁽¹¹⁾ for applications in scanning transmission x-ray microscopy with soft x-rays utilizes an apodized structure to form a sub-micron spot to resolve features with dimensions $\leq 1000\text{\AA}$. Although this particular zone plate is designed to be supported by a thin silicon nitride membrane, the initial fabrication effort has been limited to bulk silicon substrates for purposes of lithography and process analysis. Results are shown in Figure 11 for a $950\text{\AA}$ minimum zone width in $1600\text{\AA}$ of PMMA on bulk silicon.

The desire to achieve higher resolution with x-ray lensing elements calls for further reduction of the minimum zone width. High resolution electron beam lithography will be the most likely candidate to meet this challenge. Progress towards the realization of a very aggressive design of a zone plate is shown in Fig. 12. The zone widths shown here are $350\text{\AA}$ which translates into a required placement accuracy of $<150\text{\AA}$.

SUMMARY

A Vector Scan electron beam microfabrication system has been modified for lithography of structures below 100 nanometers. Design parameters and operational characteristics of the system are summarized in Table II. Initial results for the Phase I application, demonstrating the successful scaling down of an FET memory device mask level and the fabrication of Fresnel zone plates for applications in high resolution x-ray optics, have been presented.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical contributions of the members of the electron beam lithography group at the IBM T.J. Watson Research Center, in particular R. Naumann for his contribution in the area of mechanical design, R. Viswanathan for his work on the analog electronics and F. Hohn for the gun design. J. Lafuente and M. Lindemann contributed the computer control software and W. Molzen was very helpful in pattern data

preparation. Many fruitful discussions with A.N. Broers and A.D. Wilson are gratefully acknowledged.

The work on x-ray zone plates was initiated by D. Sayre and R. Feder from the IBM Physical Sciences department in collaboration with J. Kirz and H. Rarback from New York State University at Stony Brook. The second project in this area represents a collaboration with N. Ceglio from Lawrence Livermore Laboratories and A. Hawryluk from MIT-Lincoln Laboratories.

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TABLE I

Beam voltage	25kV			
Energy spread	2.5eV			
Beam half angle	$2.1 \cdot 10^{-3}$ rad			
Scan Field	.1mm	.2mm	.5mm	
Spherical aberration	0.2	0.2	0.2	nm
Axial chromatic aberration	4.1	4.1	4.1	nm
Field curvature	4.0	16.1	100	nm
Astigmatism	1.3	5.1	31.9	nm
Coma	0.8	1.7	4.2	nm
Transv. chrom. aberration	1.0	2.0	5.0	nm
Total without dynamic corr.	6.0	17.6	106	nm
Total with dynamic corr.	4.3	4.9	7.7	nm
Distortion	1.3	10.2	161	nm

TABLE II

Electron Optics

Gun single crystal LaB_6
 brightness $5 \times 10^6 \text{ A}/(\text{cm}^2 \text{ sr})$
 cross over diameter $10 \mu\text{m}$

Two Condenser Lenses

Beam Limiting Aperture diameter $40 \mu\text{m} - 100 \mu\text{m}$
 beam half-angle $2.1 \times 10^{-3} - 5.4 \times 10^{-3}$

Final Lens ferrite shield
 working distance 16mm
 phase I: spot diameter $50 \text{ \AA}$
 phase II: spot diameter $5-10 \text{ \AA}$

Magnetic Deflection aberrations $< 10^{-4} \times$ field size
 for $200 \mu\text{m}$ field

Mechanical System

Table full air suspension, self leveling, resonant frequencies
 $< 1 \text{ Hz}$ horizontal and vertical

X-Y Stage Yosemite stage, ± 2 inches travel, motor driven,
 closed loop, $0.5 \mu\text{m}/\text{step}$

Vacuum System oil-free, 2×10^{-8} Torr column, 2×10^{-7} Torr chamber,
 turbomolecular pump for roughing, ion pumps
 for column and chamber

Electronics

Pattern Generator Vector Scan type, Series/1 driven (with link to Host
 system data base), compatible with other Vector Scan
 systems, proximity effect correction capability

Raster Generator

Detectors annular solid state backscattered electron detector,
 scintillator secondary electron detector

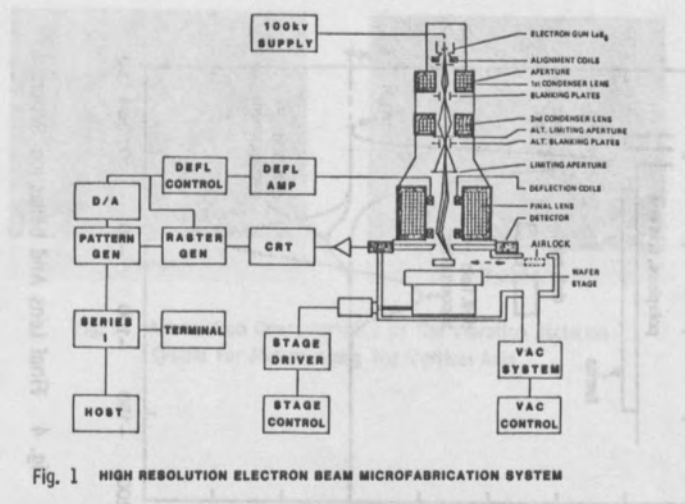


Fig. 1 HIGH RESOLUTION ELECTRON BEAM MICROFABRICATION SYSTEM

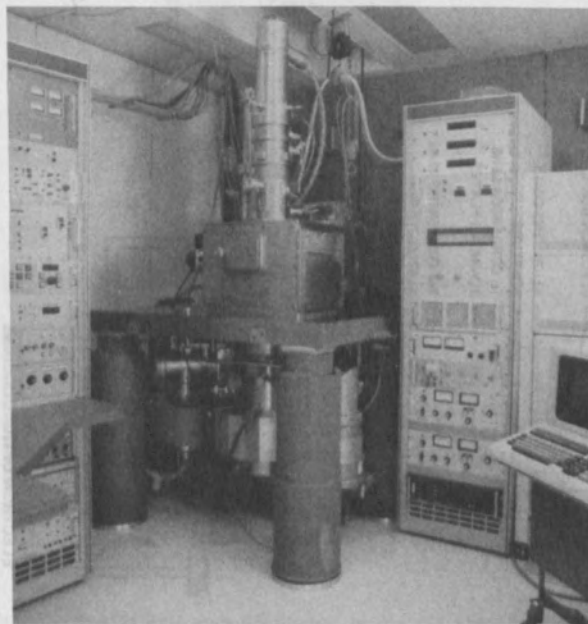


Fig. 2 General View Of The System

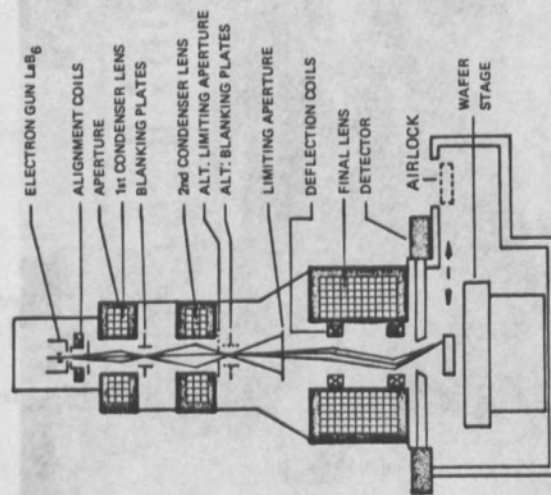


Fig. 3 SCHEMATIC CROSS-SECTION OF THE ELECTRON OPTICAL COLUMN

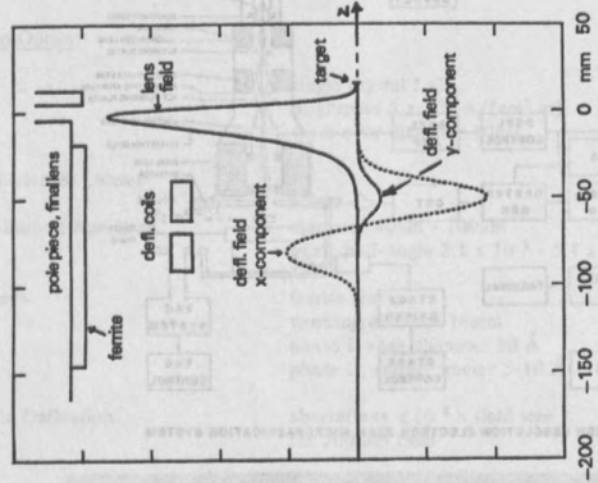


Fig. 4 Final Lens And Deflection System

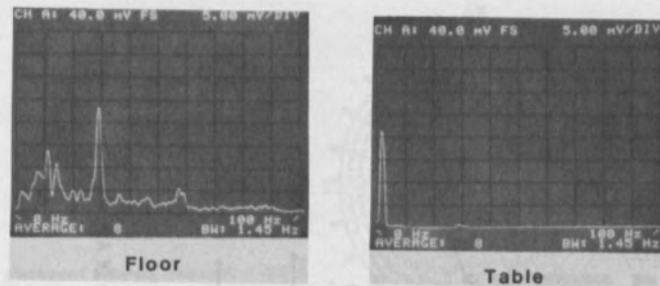


Fig. 5 Attenuation Characteristics Of The Vibration Isolation System For Motion Along The Vertical Axis

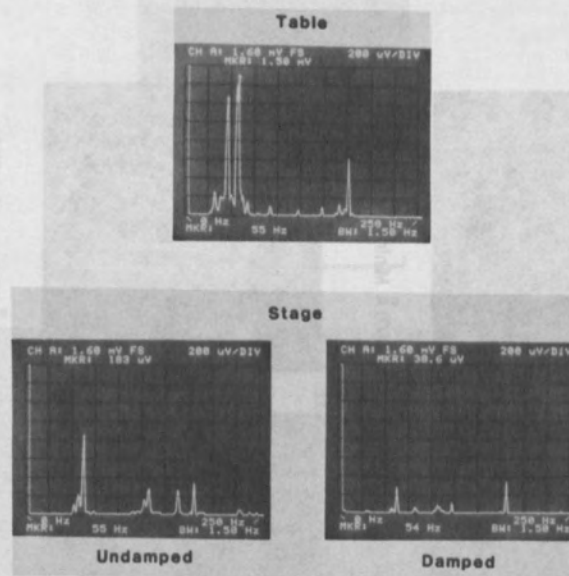
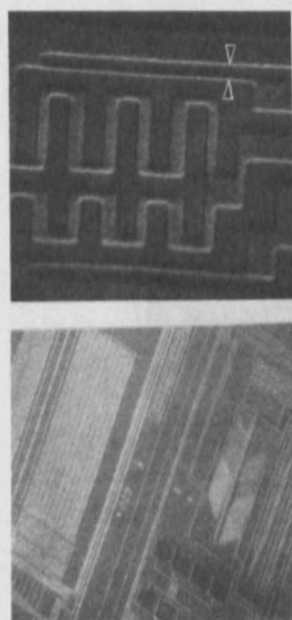
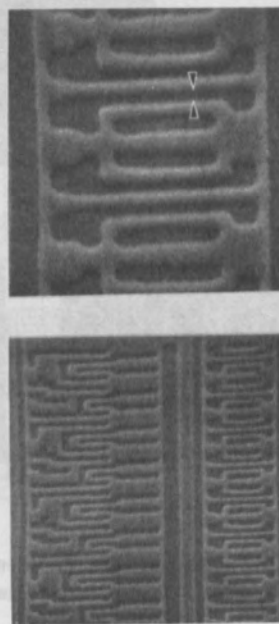


Fig. 6 Vibration Resonance Phenomena In The X-Y Stage Causing An Increased Relative Motion Between Sample And Electron Beam



1000 Å Minimum Line Width



650 Å Minimum Line Width

Fig. 7 SCALING DOWN OF MEMORY DEVICE DIMENSIONS

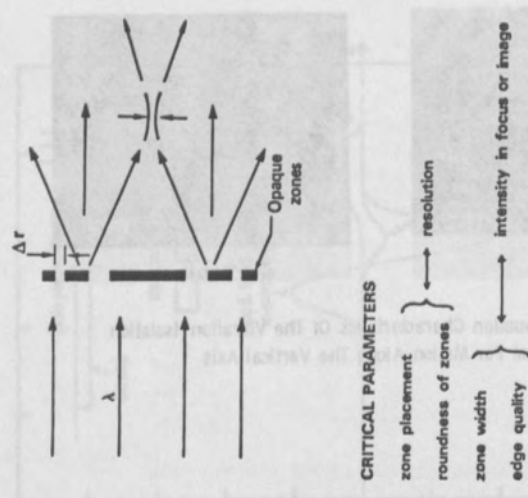


Fig. 8 Principle Of A Fresnel Zone Plate

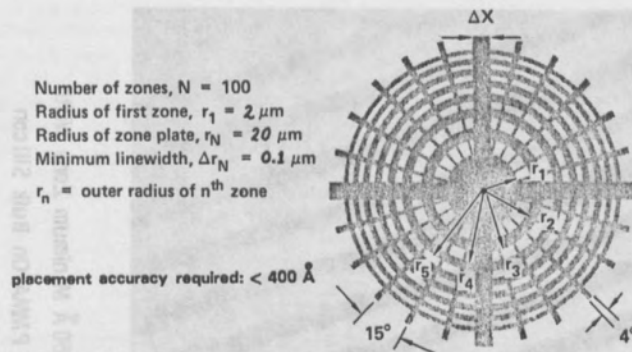
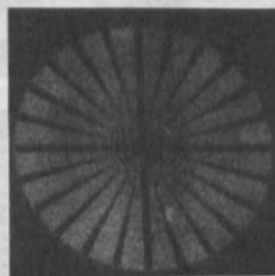
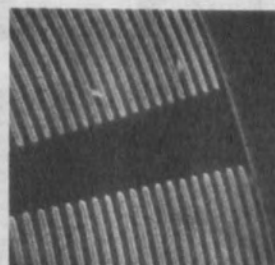
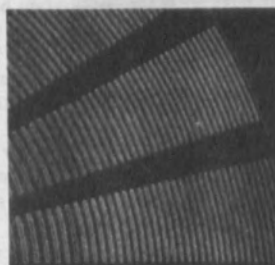


Fig. 9.

Shaded regions are to be exposed by E-beam lithography



40 μm



1000 $\text{\AA}$

Fig. 10 X-RAY ZONE PLATE FABRICATION
 PMMA On Thick Polyimide

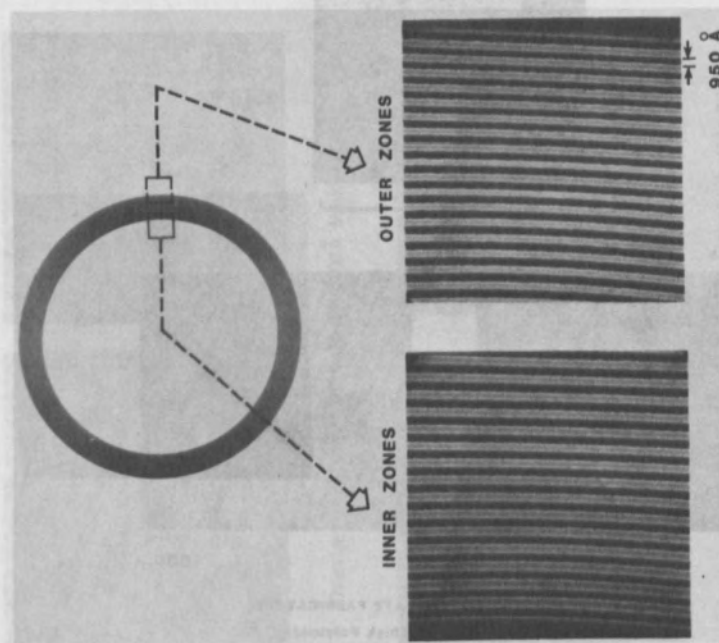


Fig. 11 X-Ray Zone Plate Fabrication
PMMA On Bulk Silicon

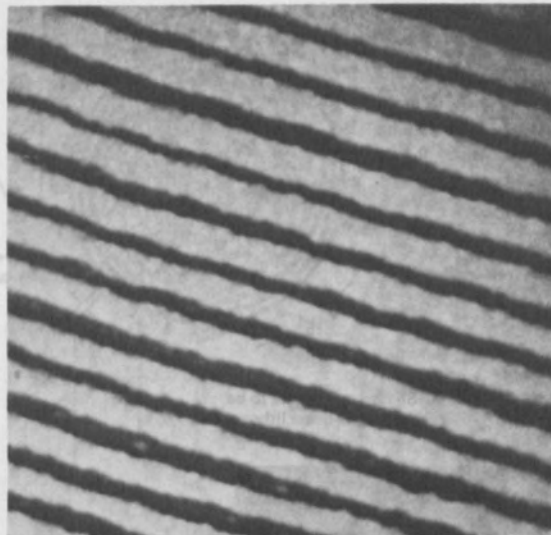


Fig. 12 350 Å Minimum Zone Width
PMMA On Bulk Silicon

A ROUND BEAM EXPOSURE SYSTEM WITH MULTIPLE BEAM SIZES

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ABSTRACT

Electron beam exposure systems can be divided into two classes: round beam systems and shaped beam systems. Round beam systems use a fixed spot size which is generally a fraction of the minimum pattern dimension. This ensures good pattern definition but can limit the writing speed. Shaped beam systems use variable beam sizes and shapes to improve throughput but can experience edge resolution problems, in particular for large variations in beam size. This paper describes a round beam system with the capability of switching at high speed between different beam sizes by selecting different beam defining apertures. With this system the edges of a pattern can be exposed with a small spot size and low current, and the interior of a pattern is filled with a large spot size at high current. Thus the high resolution for pattern definition is preserved while an increase in writing speed by a factor of at least 3 to 5 can be achieved for typical pattern. The design of the system and results of initial tests are reported.

1. INTRODUCTION

The majority of electron beam lithography systems available today use a focused round beam scanned under computer control to expose any pattern. The high resolution capability of the probe forming systems, mechanical and electrical stability that allows the accurate placement of several thousand resolution elements per linear dimension of the writing field, the precise registration and overlay capability together with the flexibility of the computer controlled pattern generation make these systems very versatile tools (1,2). Since the size of the beam is generally a fraction of the smallest pattern dimension (typically 1/4 of the smallest line width), a large number of image points has to be exposed one at time (see Fig. 1a), which limits the exposure speed and thus the throughput of such a system. Consequently these systems are mainly used for mask generation as well as for research and development.

In order to overcome this limitation variable shaped beam systems have been developed (3-6). They use typically rectangular spots of variable size, so that the shape considered in Fig. 1 could be exposed in three steps, as indicated in Fig. 1b. The improvement in exposure speed is evident. There are, however, difficulties associated with this technique, in particular the accurate joining of shapes, a dependence of the beam profile on the shape size and the ability to write arbitrary geometrical pattern.

In order to increase the exposure speed of a round beam system while preserving its accuracy, resolution, and flexibility, a round beam system with multiple beam sizes and corresponding beam currents has been proposed (1). As indicated in Fig. 1c for three beam sizes, the basic idea is to use the same small beam to define the edge of each shape, and then, depending on the size of the shape, the interior is filled with a medium or large beam or a combination of them. At constant stepping rate the increase in exposure speed is obvious, while edge definition and shape joining as well as the ability to write arbitrary pattern should not be affected at all. In addition there are possibilities to trade off accuracy with exposure speed wherever possible, by using only the larger beams.

II. GENERATION OF MULTIPLE BEAM SIZES

Variable beam sizes and currents in a round beam system can principally be achieved by changing the overall demagnification in the probe forming system. An exposure scheme as indicated in Fig. 1c, however, requires the capability to switch beam size and current between well defined values at sufficiently high speed as not to add overhead time. The initial objective is a switching time $< 1 \mu\text{sec}$. This does not seem feasible with the normally used magnetic lenses.

Therefore, we have designed a unit where different beams are obtained by selecting different beam limiting apertures without any change in the imaging conditions of the electron optical column. This arrangement is shown in Fig. 2. With 4 sets of identical deflection plates the beam can be shifted parallel to the optical axis to the location of any one of the holes on the multiple aperture stage, and then it can be returned to and directed back along the optical axis. The first beam defining aperture corresponds in size to the largest of the multiple apertures and determines the spacing necessary between holes. In the present set up we are using a $200 \mu\text{m}$ hole in the center and a $50 \mu\text{m}$ and $100 \mu\text{m}$ hole at a distance of $250 \mu\text{m}$ on either side. A voltage of ± 50 Volts from a common source is applied to the plates for switching a 25 keV beam. Additional small potentials ΔV_1 and ΔV_2 applied to the bottom 2 sets of plates and switched with the main switching potential V allow the correction of misalignments. The present switching time amounts to $1.5 \mu\text{sec}$ with a realistic goal of less than $.5 \mu\text{sec}$. Fig. 3 is a photograph of the actual unit mounted on a column spacer.

There are several options how this unit can be used in an electron optical column. We implemented it in our Vector Scan system so that the multiple apertures are close to the position where normally the final beam limiting aperture is located. This is indicated in Fig. 4. Another possibility, of course, would be to image the apertures on the wafer, by putting the unit between first and second condenser lens, for instance. In our implementation we expect in first order a change in beam current proportional to the area of the aperture holes and that is exactly what we found. Fig. 5 shows that the beam current is changing by a factor of 4 each time when switching from the $50 \mu\text{m}$ aperture to the $100 \mu\text{m}$ and to the $200 \mu\text{m}$ aperture. The spot size, on the other hand, should vary only in second order, mainly due to aberrations. We measured the effective spot size by analyzing the edge slope of the backscattered signal obtained from line scans across $1000 \text{ \AA}$ thick gold lines on silicon. The spot diameter was defined as the distance between the 10 % and 90 % intensity marks at the slope. The relative change in spot area when switching apertures is shown in Fig. 5. It obviously does not change proportional to the beam current, but we will see from test exposures, that the size of the large beam is compatible with $.5 \mu\text{m}$ beam steps. Another

way of affecting the spot size is to excite the auxiliary coil normally used for dynamic focussing of the beam, but now for defocussing in accordance with the aperture selection. An example for a certain excitation is also given in Fig. 5.

The beam was also found to show a characteristic astigmatism when one of the off axis apertures was selected. This is due to the simple geometry of the present deflectors below the multiple aperture stage. But this astigmatism adjustment is well within the correction range of the stigmator normally used in the system and can be switched for each aperture selection.

III. TEST EXPOSURES

For the purpose of exposure tests using this hardware, shapes are partitioned into sleeves of specified but variable size and the remaining interior. In the example shown in Fig. 6 we looked at squares of $12\text{ }\mu\text{m}$ side length. They are exposed using the large beam with a step size of $3/4\text{ }\mu\text{m}$ in the center and the small beam with a step size of $3/16\text{ }\mu\text{m}$ for the sleeves. The exposure is done on high contrast resist which is, by purpose, only partially developed, so that the individual exposure steps with the large beam are visible. In order to get consistently accurate beam placement independent of the aperture selection, any residual misalignment has been detected in a registration like process and the necessary beam offsets for correction are switched simultaneously with the beam size. Fig. 7 shows a section of this pattern, but now almost fully developed. It is obvious that already one sleeve with the small beam basically eliminates the raggedness of the edge due to the large steps with the large beam in the center.

The set of shapes in Fig. 8 is part of another test pattern. We use this example to estimate the improvement in writing speed which is obtainable with the proposed exposure concept. The upper part is exposed with the large beam and only 1 sleeve with the small beam. This case requires only $1/8$ of the number of exposure steps which would be needed by using only the small beam. If 2 sleeves with the small beam are exposed, the number of exposure steps is reduced by a factor of 5 (center), while even 4 sleeves still give a 3 fold reduction of the number of exposure steps (bottom).

In Fig. 9 pattern details with $1\text{ }\mu\text{m}$ minimum dimensions are shown. They were exposed with $1/8\text{ }\mu\text{m}$ step size with the small beam and $1/2\text{ }\mu\text{m}$ step size with the large beam. The top picture was taken from a pattern exposed only with the small beam whereas the bottom pattern was exposed with the large beam and only one sleeve with the small beam. No deterioration in pattern quality could be detected when using the new concept. Fig. 10 finally shows a section of a circuit pattern with $1.5\text{ }\mu\text{m}$ minimum dimensions, exposed under the same conditions as the bottom pattern in Fig. 9.

In order to get a more realistic test of the exposure concept, an actual integrated circuit pattern was exposed. Fig. 10 shows two sections from this pattern with $1.5\text{ }\mu\text{m}$ minimum dimensions and exposed with the large beam on $1/2\text{ }\mu\text{m}$ steps and one sleeve with the small beam. Timing experiments showed a reduction of writing time by a factor of 4 if pattern generator overheads due to the nonoptimized experimental set up are neglected. Although the proximity effect correction has not been used for the pattern exposed so far, the algorithm available for our Vector Scan systems is fully compatible with the new exposure concept.

SUMMARY

We have shown the feasibility of a new exposure concept to increase the throughput of a round beam vector scan system without loss in resolution, accuracy and flexibility. Beams of different size and current are used to expose the pattern. The edges of shapes are defined with a small beam and low current, while the interior of the shapes is filled with a large beam and high current. The change in beam size and current is achieved by selecting different apertures. Test exposures have been performed using a large beam and a small beam with a current ratio of 16. No deterioration in edge quality due to the large beam steps with the large beam can be achieved with 1 or 2 passes around the edge of the shapes with the small beam. Timing experiments with realistic circuit pattern indicated that a reduction of exposure times by a factor of 3 to 5 can be expected.

ACKNOWLEDGEMENT

The technical assistance of H.E. Luhn in the assembly of the electron optical components is gratefully acknowledged.

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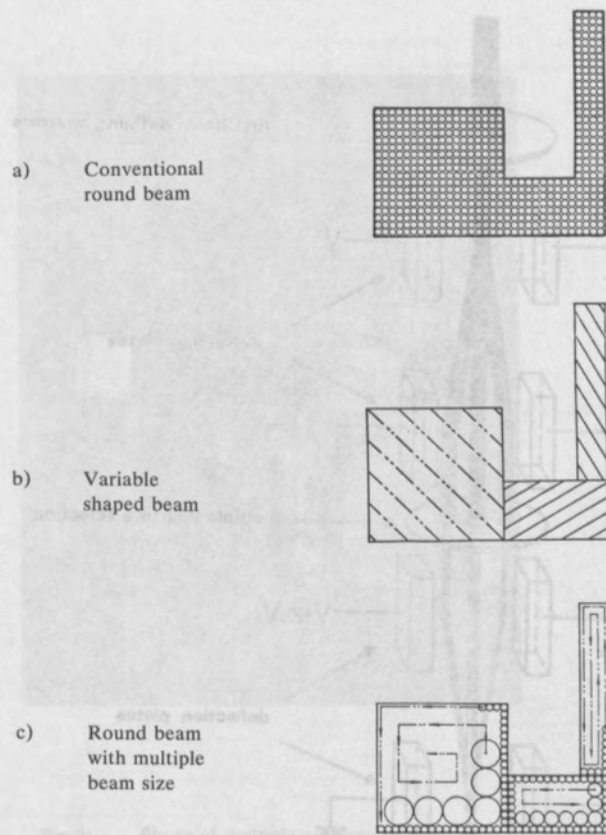


Fig 1: Exposure methods in electron beam lithography

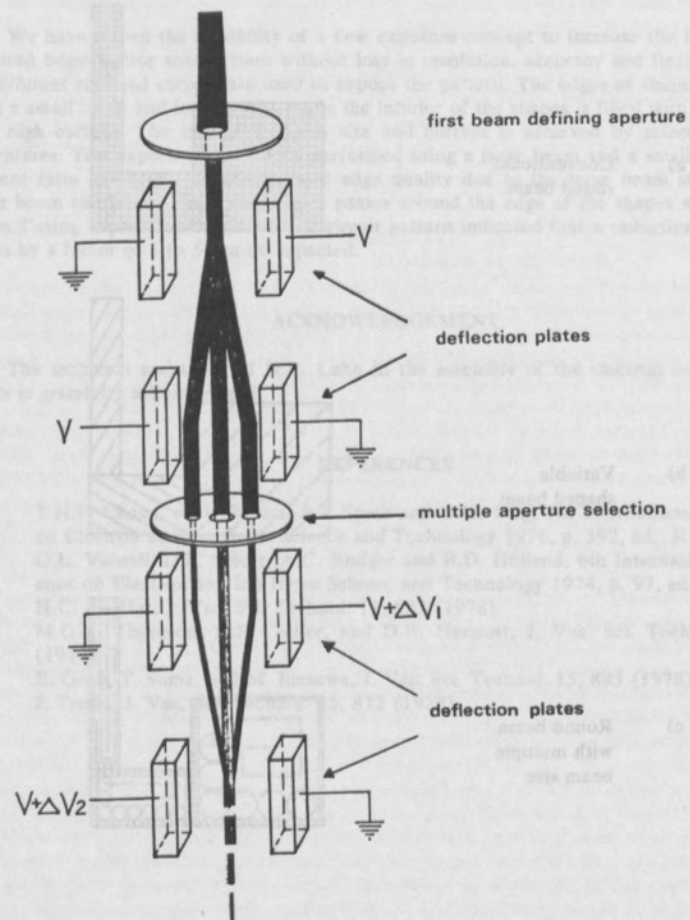


Fig 2: Multiple aperture selector

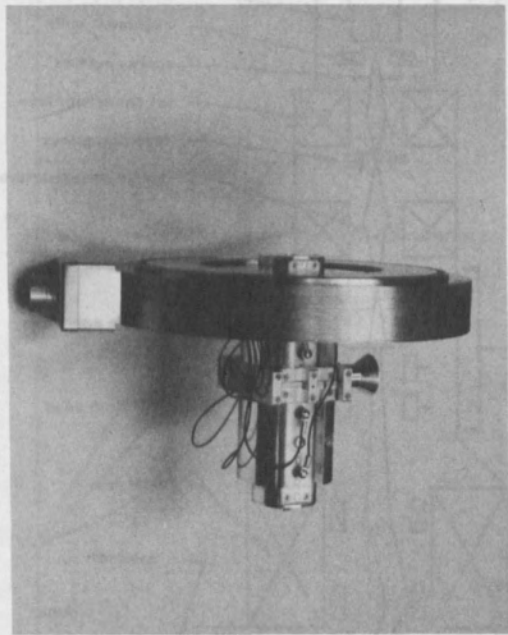


Fig 3: Photo of multiple aperture selector unit

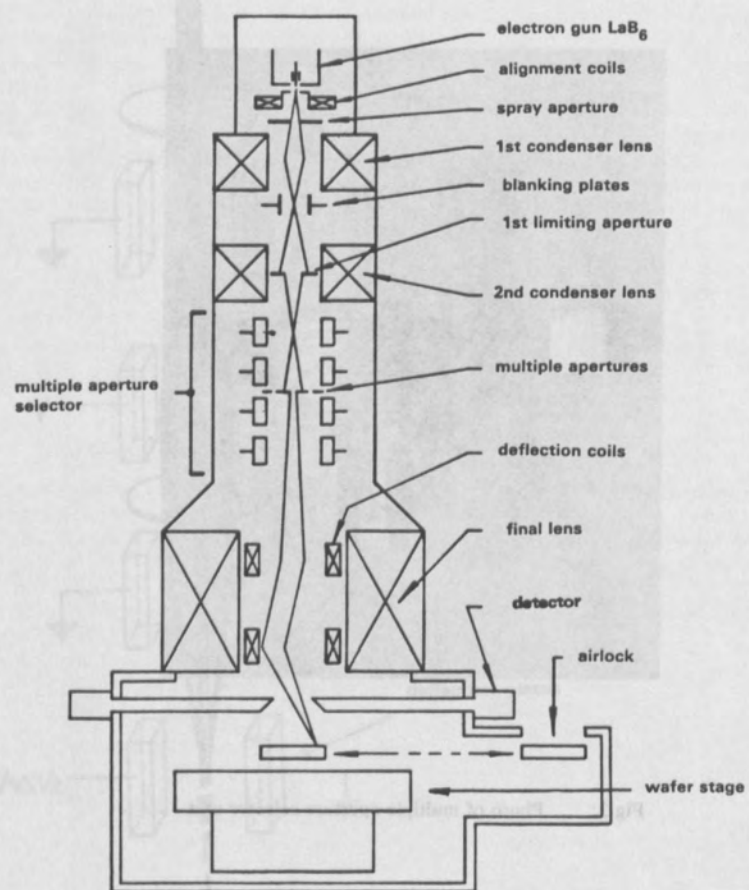


Fig 4: Schematical cross-section of the electron optical column

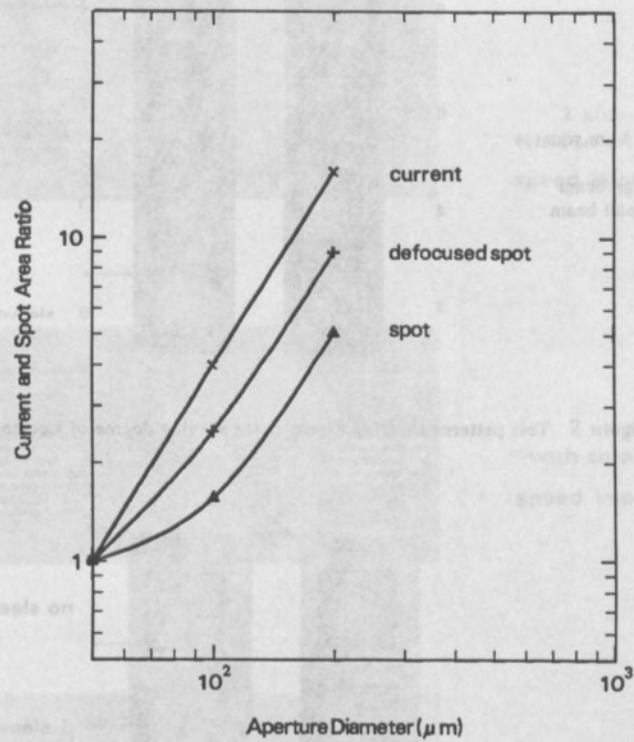


Fig 5: Relative change of beam current and spot area versus aperture diameter

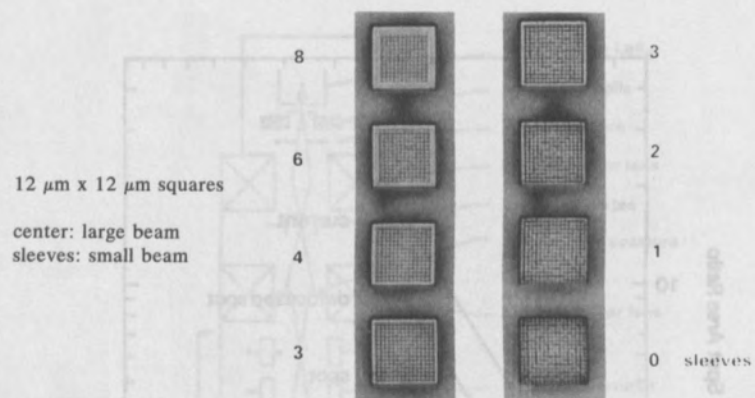


Fig 6: Test patterns showing exposure for varying degree of sleeving

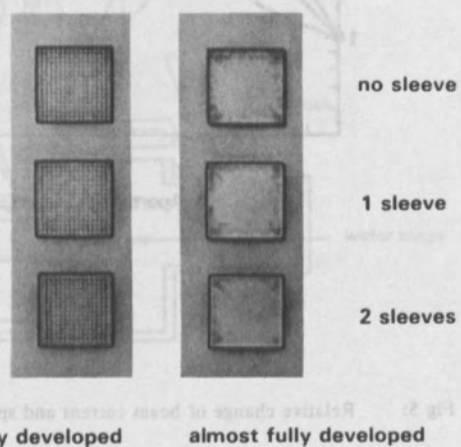
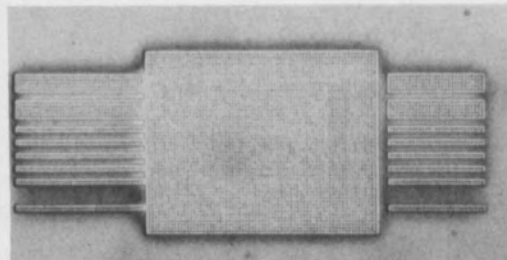
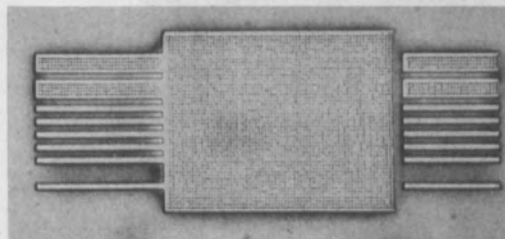


Fig 7: Test exposures showing effects of sleeving on edge quality



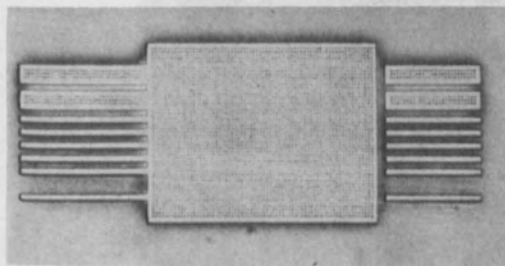
1 sleeve
with small beam
speed improvement: 8

10 μm



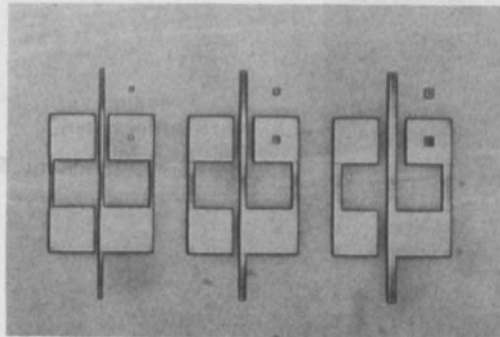
2 sleeves
with small beam
speed improvement: 5

10 μm



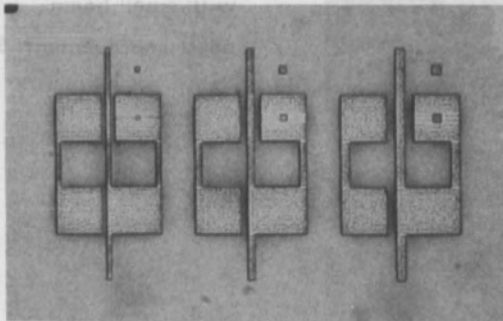
4 sleeves
with small beam
speed improvement: 3

Fig 8: Typical test pattern with $1.5\mu\text{m}$ minimum feature size.
Also shown are the speed improvements for different sleeving
using multiple beam sizes.



only small beam

5 μm



large beam +
1 sleeve with small beam

Fig 9: Test pattern with 1 μm minimum feature size

THEORY OF HIGH THROUGHPUT, DIRECT WRITE ELECTRON BEAM LITHOGRAPHY
 VARIABLE SHAPED ELECTRON BEAM LITHOGRAPHY SYSTEM
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 Abstract: A high-throughput, direct write electron beam lithography system is described. The system is capable of producing patterns with a resolution of 0.5 μm and a throughput of 100 cm^2/hour . The system consists of a high-voltage electron gun, a deflection system, and a maskless exposure head. The deflection system is a magnetic deflection system that allows for a large field of view and high deflection rates. The exposure head is a variable shaped electron beam that can be focused to a spot size of 0.5 μm . The system is capable of producing patterns with a resolution of 0.5 μm and a throughput of 100 cm^2/hour .

1. Introduction
 A high-throughput, direct write electron beam lithography system is described. The system is capable of producing patterns with a resolution of 0.5 μm and a throughput of 100 cm^2/hour . The system consists of a high-voltage electron gun, a deflection system, and a maskless exposure head. The deflection system is a magnetic deflection system that allows for a large field of view and high deflection rates. The exposure head is a variable shaped electron beam that can be focused to a spot size of 0.5 μm . The system is capable of producing patterns with a resolution of 0.5 μm and a throughput of 100 cm^2/hour .

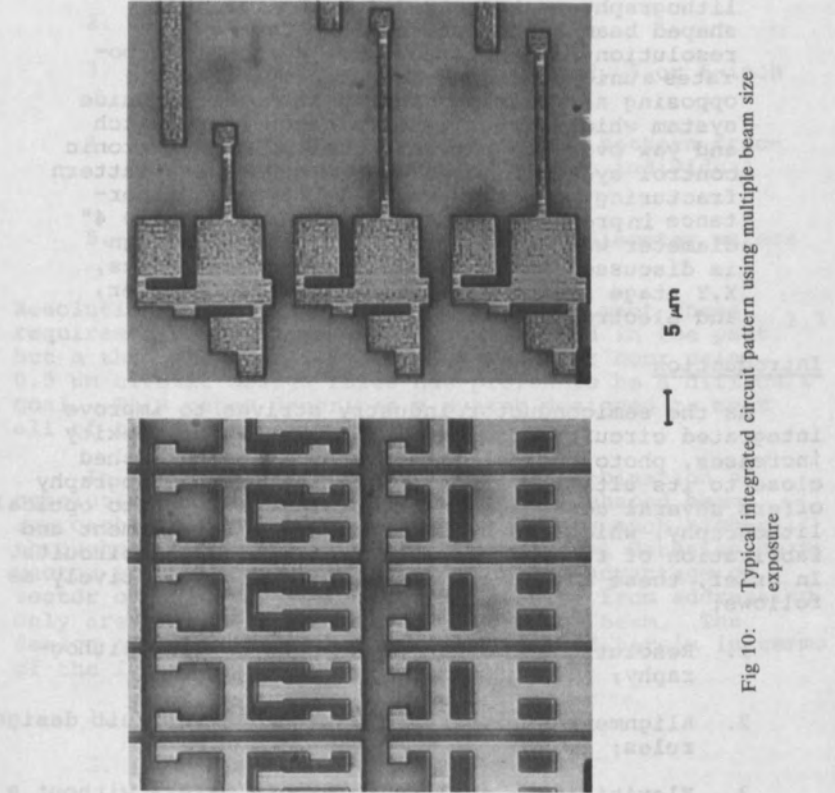


Fig 10: Typical integrated circuit pattern using multiple beam size exposure

2. System Description
 The system is a high-throughput, direct write electron beam lithography system. It consists of a high-voltage electron gun, a deflection system, and a maskless exposure head. The deflection system is a magnetic deflection system that allows for a large field of view and high deflection rates. The exposure head is a variable shaped electron beam that can be focused to a spot size of 0.5 μm . The system is capable of producing patterns with a resolution of 0.5 μm and a throughput of 100 cm^2/hour .

A HIGH THROUGHPUT, DIRECT WAFER EXPOSURE
VARIABLE SHAPED ELECTRON BEAM LITHOGRAPHY SYSTEM
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A high-throughput, direct write electron beam lithography system utilizing the variable, shaped beam architecture to achieve 0.5 μm resolution is discussed. The system incorporates a unique stage design employing dual, opposing air bearings and an air bearing guide system which virtually eliminates stage pitch and yaw over its entire travel. The electronic control system incorporates a high-speed pattern fracturing processor which is of prime importance in providing system throughput of 5-10 4" diameter wafers per hour. The system design is discussed in terms of its electron optics, X,Y stage system and automatic wafer handler, and electronic controls.

Introduction

As the semiconductor industry strives to improve integrated circuit performance and circuit complexity increases, photo optical lithography is being pushed close to its ultimate limit.¹ Electron beam lithography offers several advantages, not obtainable by photo optical lithography, which can be applied in the development and fabrication of future generations of integrated circuits. In brief, these advantages can be listed qualitatively as follows:

1. Resolution - better than photo optical lithography;
2. Alignment - compatible with 0.5 μm circuit design rules;
3. Flexibility - ability to expose wafers without a physical mask, resulting in rapid turnaround for circuit development;
4. Cost reduction - inventory reduction through the ability to quickly produce limited numbers of specific parts; low volume (10^3 to 10^5) integrated circuits can be produced without the

otherwise required masks and the consequent high mask tooling costs.

In order to provide the foregoing qualitative advantages, the following primary quantitative specifications for variable shaped beam lithography systems are desired:

1. Resolution (usable lithographic linewidth) - $0.5\ \mu\text{m}$;
2. Alignment accuracy - $\pm 0.1\ \mu\text{m}$;
3. Wafer handling capability - 3, 4, 5 or 6-inch diameter wafers;
4. Proximity effect compensation - pattern fracturing and dose compensation for individual sections of geometries;
5. Throughput - 5 to 10 four-inch diameter wafers per hour.

Resolution and alignment capabilities to meet these requirements have been amply demonstrated in the past,^{2,3} but a throughput of 5 to 10 4" wafers per hour using $0.5\ \mu\text{m}$ circuit design rules has proven to be a difficult goal. This paper describes a system designed to meet all of the foregoing requirements.

In order to achieve the required combination of resolution and throughput, the variable shaped beam approach has been chosen, since it offers much higher throughput potential than the conventional Gaussian beam, vector scan systems while retaining the advantage of vector over raster scanning that results from addressing only areas to be exposed by the electron beam. The design of the 7000-EB system is described herein in terms of the following:

1. Electron optics;
2. X,Y stage subsystem;
3. Electronic controls; and
4. Initial exposure results.

Electron Optics

The electron optical column, shown in cross section in Figure 1, consists of five electromagnetic lenses and an electron gun. The latter employs a BaSr dispenser cathode having a brightness of 3×10^5 amp/str/cm², because of its exceptional positional stability, highly stable electron emission and long service life of over 2000 hours. The electron gun provides uniform illumination of a square aperture; the image of this first square aperture is projected on a second square aperture, thereby forming a variable square or rectangular electron beam as determined by electrostatic deflectors located between these two square apertures. Three more electromagnetic lenses are utilized to demagnify the image of the shaped electron beam and to enable electrostatic blanking at a beam crossover. The fifth and final lens projects the demagnified electron beam spot on the wafer surface at the target plane. A compound, hybrid deflection system is incorporated into the final projector lens. Electro-magnetic deflectors position the beam precisely on a 6.47 mm x 6.47 mm scan field. This scan field is subdivided into 64 x 64 subfields measuring 108 μ m by 108 μ m each, as shown in Figure 2.

Beam vector scanning within each subfield is accomplished by means of fast electrostatic deflectors. In contrast, beam deflection between subfields is performed electromagnetically in raster fashion. The electron spot size is variable in 263.7 Å increments to a maximum beam size of 6.72 μ m x 6.72 μ m, with a maximum beam current density of 25 Amp/cm². The electron dose can be varied by computer control of the beam dwell time in order to compensate for the proximity effect or different resist sensitivities. The projector lens and deflectors are designed for telecentric scanning over the entire scan area. Additional electrostatic deflectors are located in the column for beam alignment and stigmatism. The entire electron optical column is ion pumped with vacuum levels ranging from 10^{-7} torr in the column to 10^{-9} torr in the gun region, in order to minimize contamination and to obtain satisfactorily stable column performance for extended time periods.

X,Y Stage Subsystem

The fundamental requirements for a high-precision, production-adapted vacuum X,Y stage are reliability, accuracy, ease of serviceability, and a contamination-free

vacuum environment. Such a stage system with the following specifications has been developed for the 7000-EB:

1. Stage travel - 16.5 cm;
2. Laser interferometer metering - $\lambda/48 = 131.8 \text{ \AA}$;
3. Maximum velocity - 7.5 cm/sec;
4. Maximum stage acceleration - $\geq 0.1 \text{ g}$;
5. Work chamber operating vacuum - $\leq 5 \times 10^{-6} \text{ torr}$.

In addition, a design was sought which offers a vacuum essentially free from all hydrocarbons and other residual gas contamination detrimental to the operation of the electron optics, and which incorporates automatic wafer loading. The stage and related equipment also had to be confined to the smallest possible floor space in order to minimize the cost of required support facilities. These requirements have been met by means of a novel, differentially pumped air bearing design.

A cross section of the differentially pumped air bearing is shown in Figure 3. A composite material plate having a size of 90 cm x 90 cm and a thickness of 6 cm is supported between air bearings adjacent to its upper and lower surfaces. Most of the air pumped into these bearings escapes to atmosphere at the edge of the bearing. The small amount of air bleeding toward the central vacuum is impeded by the long, narrow ($\leq 5 \text{ }\mu\text{m}$) gap and two differential pumping regions spaced between the air bearings and the central vacuum. The air bearings and differential pumping regions are exactly duplicated above and below the moving section, or stage plate, to insure that forces are exactly balanced on both sides of the plate, thus avoiding any bending moments and preserving the plate's flatness of $0.5 \text{ }\mu\text{m}$ overall. This technique also enables the use of an aluminum composite material for the stage plate, minimizing the system's mass and drive motor power requirements. All moving parts of the stage have a combined weight of $\sim 18 \text{ kg}$ and are driven by ball screw-servomotor combinations. An acceleration of better than 0.1 g and a maximum stage velocity of 7.5 cm/sec, limited by laser interferometer electronics operating at $\lambda/48$ least count, have been achieved.

The air bearing operates at a pressure of $\sim 40 \text{ psi}$, consuming $\sim 1 \text{ m}^3$ of dry N_2 per hour. Its calculated stiffness is $7.5 \times 10^7 \text{ lb/in}$, virtually eliminating pitch

motions of the stage. The central work chamber is cryogenically pumped to a vacuum of 5×10^{-6} torr, while the differential pumping regions are evacuated using turbomolecular pumps; this combination of pumps eliminates potential hydrocarbon contamination from vacuum pumps, which might otherwise be present.

As a result of the vacuum air bearing, the required high-precision guidance and drive mechanisms can be located outside the system vacuum envelope. The central vacuum contains only a lightweight laser interferometer mirror and a wafer clamping mechanism. Since traditional rotary feedthrough or bellows seals are avoided and all motion mechanisms are readily accessible, the reliability and serviceability of the system are greatly improved as compared with conventional systems.

The mirror surfaces for the X and Y directions are fabricated from a single piece of beryllium to provide a flatness of $\lambda/10$ and an orthogonality of ± 0.5 second of arc. This mirror is suspended from the moving stage plate as shown in Figure 3, and the electron optical column is mounted at the base of the vacuum chamber; during exposure, the resist-coated surface of the wafer is oriented downward. All other laser interferometer components are mounted outside the vacuum chamber, with the air path between critical components restricted to 5mm in order to avoid the influence of barometric pressure and humidity on interferometer measurements.

The main body of the stage forms the central vacuum chamber and serves as a mounting platform for subsystems such as the electron optical column, the laser interferometer, vacuum valves, stage guides and drives, and the fully automatic wafer handling subsystem.

The wafer handling subsystem utilizes a single vacuum chamber (or load lock) connected to the central vacuum chamber; this load lock is isolated from the central vacuum and the atmosphere by two specially-designed, lubricant-free slit valves. It incorporates a two-position elevator mechanism capable of simultaneously accommodating both an exposed and an unexposed wafer; this mechanical buffering system allows exchange of an exposed wafer in the central chamber with an unexposed wafer in the load lock in approximately 30 seconds. The load lock is evacuated to $\sim 10^{-5}$ torr by means of a turbomolecular pump.

Wafers, mounted in special carriers, are transported into and out of the load lock by means of two ball screw drives located at 90° to each other, as shown in Figure 4. Outside the load lock is an elevator carrying 8 or 16 wafer carriers in a single cassette, providing for approximately one hour of operation without manual intervention.

Electronic Controls

Electronic control systems for a high throughput variable shaped electron lithography system must perform a variety of functions. The major functions are as follows:

1. High speed pattern data transfer;
2. Electron optical column calibration;
3. Stage positional control and measurement;
4. Wafer handling; and
5. Control, monitoring, and diagnostics for subsystems such as the vacuum system, air flow controls, power supplies, etc.

Specifically, major design requirements for the 7000-EB system were as follows:

1. Data rate sufficient to expose $\sim 3 \times 10^6$ beam flashes per second;
2. Settling of the main electromagnetic deflection drive amplifier within 25 μ sec to 20-bit precision;
3. Settling of the electrostatic predeflector driver within 150 nsec;
4. Beam blanking in ≤ 5 nsec.

The rapid pattern exposure potential of the variable shaped beam architecture is made possible by a high-speed circuit pattern data path and processing facility comprised of the following components: an eight or sixteen megaword solid state pattern buffer and its associated controller; a special purpose pattern fracturing (PATFRAC) processor; and the column fast analog interface. Highly compressed circuit pattern data for an entire scan area is loaded prior to exposure from the 300-megabyte system

into the pattern mass buffer via DMA; during exposure, this data is expanded and passed in parallel fashion to the column analog interface by the PATFRAC processor.

PATFRAC, a microprogrammed, ECL bit-slice processor, computes and provides the required variable aperture and fast deflection information digitally to the high-speed column interface DAC's. It is designed for a high degree of parallel processing, and operates at a clock rate of 50 MHz.

To further augment throughput while maintaining significant flexibility, the system employs a dual beam deflection system: an electromagnetic main deflector provides a 6.47 mm x 6.47 mm scan area addressed by 18-bit, 1/4 LSB DAC's; a fast electrostatic predeflector provides settling times of < 150 nsec. for deflection between adjacent exposures within a subregion, addressed by 12-bit DAC's. The total scan area is partitioned into 4096 subregions, as shown in Figure 2. The role of the main deflector, which is operated by the PDP-11/60 system control processor, is to position the beam at the center of each required subregion, settling electronically within 25 μ sec for deflection between adjacent subregions; the fast predeflector then vectors the beam within the selected subregion to expose individual geometries.

Registration between lithographic layers is accomplished by means of a fiducial mark detection system capable of using either specimen current or electron backscatter to determine the positions of registration marks on the wafer.

After local corrections for wafer position and deformation have been computed for a given pattern site, such corrections are loaded into hardware registers for automatic application to pattern coordinates supplied by the circuit data base without further software intervention, thus maintaining high processing speed.

Similarly, corrections for main deflection system nonlinearities, stored on disk during system calibration for retrieval into memory prior to exposure, are dynamically applied to pattern data by means of hardware registers, avoiding software intervention or adjustment of the pattern data base. Dynamic focus, stigmatism, and field distortion corrections are applied in an analogous manner.

The X,Y stage is metered by a laser interferometer which provides the fundamental positional information and coordinate system for stage operation. In the step-and-repeat mode, the stage is moved to each successive pattern site and allowed to mechanically settle to a $\pm 10 \mu\text{m}$ tolerance; after this tolerance has been achieved, electronic feedback is used to adjust the beam position in order to correct for remaining stage positional error or mechanical oscillations during exposure.

Responsibility for control of functionally slow subsystems such as the wafer handling and vacuum subsystems resides with an Intel 8086 microprocessor slaved to the PDP-11/60 system control processor by a specially designed transparent interface. To permit automated real-time monitoring of system parameters which are subject to relatively slow changes, a data acquisition subsystem under control of the 8086 processor is also utilized.

An overall system block diagram of the control system electronics is shown in Figure 5.

Results

Preliminary exposure results obtained from the 7000-EB system are shown in Figures 6a through 6d. These SEM micrographs of resist exposures in $0.5 \mu\text{m}$ -thick PMMA show the system's capability of beam shaping (Figure 6a), better than $0.5 \mu\text{m}$ resolution (Figure 6b), composition of complex geometries by adjacent beam exposure (Figure 6c), and subregion butting for large pattern exposures (Figure 6d).

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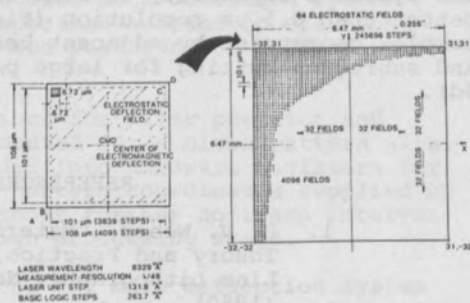
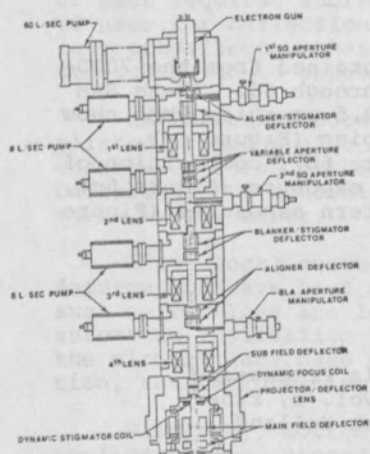


Figure 1: Variable Shaped
Beam Electron Optic Column

Figure 2: Deflection Fields

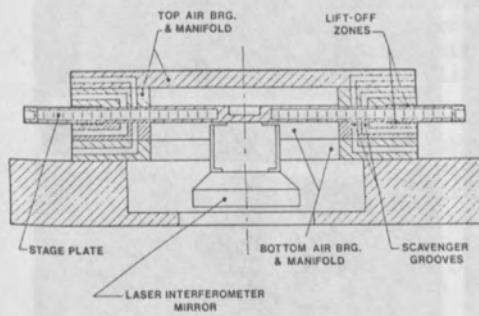


Figure 3: Cross Section of Air Bearing/Vacuum Stage

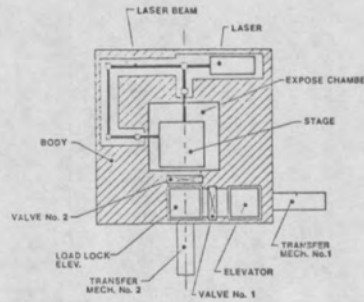


Figure 4: Stage Laser Interferometer and Load Lock Systems

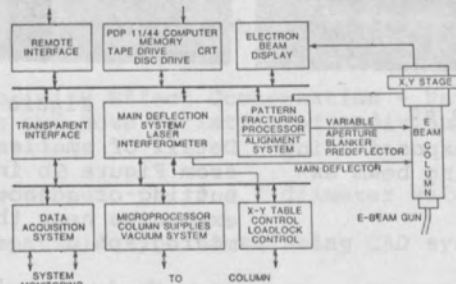


Figure 5: Block Diagram of Electronic Control System

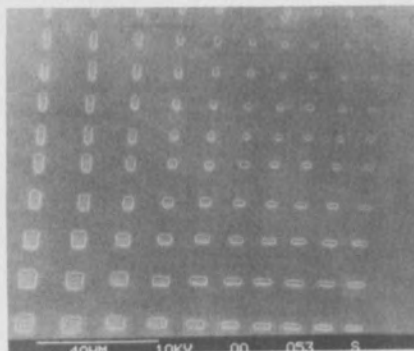


Figure 6a

Array of variable shaped beam exposures ranging from 0.3 μm to 6 μm in size.

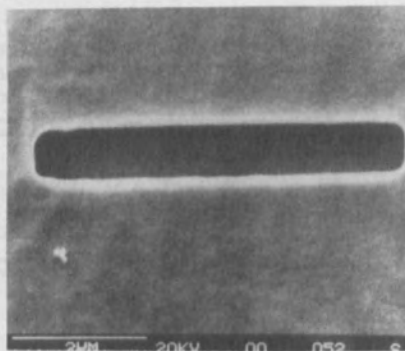


Figure 6b

Detail of single beam exposure within array in Figure 6a.

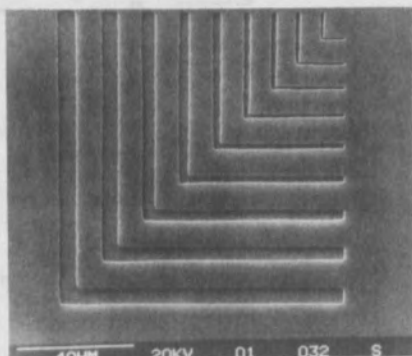


Figure 6c

L-Bar pattern exposed using multiple abutting beam exposures.

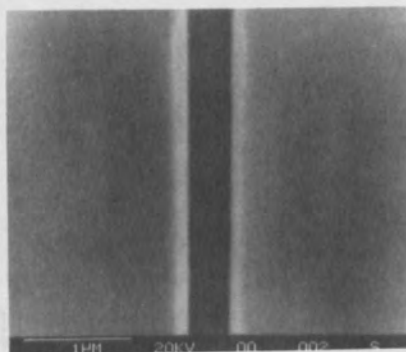


Figure 6d

Detail of smallest L-Bar from Figure 6c including butting of adjacent beam exposures near the top of micrograph.

Figure 6: SEM micrographs of shaped electron beam exposures in 0.5 μm thick PMMA resist.

AN AUTOMATED CONTROL SYSTEM FOR A HIGH THROUGHPUT,
VARIABLE SHAPED ELECTRON BEAM LITHOGRAPHY SYSTEM

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An electronic control system has been developed to meet the following requirements for production-oriented, direct write electron beam lithography: 0.5 μ m resolution, throughput of 5-10 4" diameter wafers/hour, and flexible, highly automatic operation. The system architecture partitions the workload between separate processors for high-speed data delivery and less time-critical functions. The general architecture of the system is discussed, and the electronics supporting the high-speed data delivery function are examined in detail.

Introduction

The 7000-EB direct-write, variable shaped electron beam lithography system has been developed for production use by the semiconductor industry. This paper describes the control electronics utilized in this system. The primary requirements placed on the 7000-EB system are as follows:

1. Resolution - 0.5 μ m in production;
2. Alignment - $\pm$ 0.1 μ m using prefabricated alignment marks on the wafer;
3. Wafer Handling Capability - 3, 4, 5, 6 inch diameter wafers;
4. Proximity Effect Compensation - Pattern fracturing and dose variation of individual geometry sections;
5. Throughput - 5-10 4 " diameter wafers/hour;
6. Compatibility with existing CAD systems;
7. High degree of automation - No manual controls, remote diagnostics.

Direct-write capability obviates the necessity for mask or reticle generation when a change in a circuit pattern is required; such changes are implemented by modifying the pattern data base which provides input to the lithography system. While this capability adds to the flexibility and quick turnaround ability of the lithographic system, it also enhances the importance of high system throughput. The 7000-EB system throughput of 5 to 10 4" wafers per hour was projected by computer modeling a number of advanced representative integrated circuit patterns, scaled to 0.5 μ m design rules.

Extensive display capabilities are incorporated into the system to enable the operator to assess electron beam characteristics, observe wafer fiducial marks using a scanning electron microscope (SEM) mode, and ascertain the status of the wafer or batch currently being exposed. These capabilities are supplemented by automated functions permitting sophisticated users to exercise considerable control over the system operating environment without resort to manual adjustments. Alternatively, during production, the system is capable of highly automatic operation, minimizing the requirement for a highly skilled machine operations staff.

System Architecture

In order to meet the system specifications in a cost-effective manner, a design strategy was adopted which separates the pattern data transfer path from that used by slower functions such as X,Y stage motion, control and monitoring of power supplies, data acquisition, and vacuum monitoring. This concept is illustrated by Figure 1. IC pattern data processing can be done offline; preprocessed pattern data is loaded from tape to the 300 megabyte system disk, from which it is transferred to a high-speed pattern mass memory prior to exposure.

The general system architecture is illustrated in Figure 2. The housekeeping functions, which include control and monitoring of the stage and vacuum subsystems, the automatic wafer handler, and the high voltage, lens, alignment, and stigmator power supplies, are assigned to Intel 8086 16-bit microprocessors. This leaves the DEC PDP-11/60 main computer free to exercise overall system control; to oversee pattern data delivery to the electron optical column; and to process signals from the fiducial mark detection subsystem. Despite this "division of labor" between processors, the main computer is capable

of determining the status of any subsystem controlled by the microprocessor through the transparent interface which links its DEC Unibus with the Multibus servicing the Intel microprocessor, enabling effective overall system supervision.

Within the electron optical column are three separate deflection systems: a variable aperture deflector which shapes the beam to the desired dimensions; an electromagnetic deflector which operates over the total beam scan area; and a fast, electrostatic predeflector which controls pattern writing within electromagnetically addressed subfields of the scan area. Figure 3 illustrates the dimensions of these fields. Within the scan area of 6.47 mm x 6.47 mm are 4096 electromagnetically addressed subfields. The electromagnetic deflector steps the electron beam into the center of each required subfield in raster fashion; the fast, electrostatic deflector then vectors the electron beam to each exposure position within the subfield until all necessary exposures for that subfield have been completed. Although the primary exposure area of each subfield is $101\text{ }\mu\text{m} \times 101\text{ }\mu\text{m}$, a zone of overlap between adjacent subfields is provided to simplify pattern butting; inclusion of this overlapped region brings the total subfield size to $108\text{ }\mu\text{m} \times 108\text{ }\mu\text{m}$. Electron beam size within a subfield can be adjusted by the variable aperture deflection system up to a maximum of $6.72\text{ }\mu\text{m} \times 6.72\text{ }\mu\text{m}$ in increments of $263\text{ }\text{\AA}$.

Beam deflection and size are referenced to the laser interferometer measuring system, which has a measurement resolution of $\lambda/48$ (or $132\text{ }\text{\AA}$ for a laser wavelength of $6329\text{ }\text{\AA}$). To permit this resolution, the electrostatic predeflector provides a 12-bit data range and the variable aperture deflector provides 8 bits, while the main deflector uses 20 bits to insure the precision required by the system. Main deflection scaling and gain can be adjusted independent of the pattern data base by updating gain registers to obtain the required pattern size.

Each of the five column lens supplies consists of a temperature-stabilized 16-bit DAC, driving a precision power amplifier whose output is capable of delivering up to one ampere into a column lens coil of 80 ohm resistance. The long-term stability of this amplifier has been measured at better than 50 ppm over a six month period; this degree of stability is helpful in insuring precise focusing of the electron beam by the electromagnetic lenses.

The four beam alignment supplies have 16-bit resolution, and are used to align the electron beam to the optical axis when column mechanical tolerances would otherwise cause slight misalignment. The column stigmator drivers have separate adjustments for magnitude and azimuth angle, and are controlled digitally.

The data acquisition subsystem accesses system monitoring points and stores data thus obtained in the microprocessor's memory. While this subsystem is used primarily to monitor key test points continuously during system operation, it also provides data required during calibration of beam deflection system voltages and currents.

Since the X,Y stage subsystem is described elsewhere,¹ only a brief discussion of the electronics will be presented herein. The stage's electronic driver servo is responsible for moving the stage table to within a small positional error of the center of the addressed die location. Although this error is always less than 10 μm , the beam deflection system can compensate with high accuracy for errors of up to 25 μm : a high-precision laser interferometer operating with a least count of $\lambda/48$ (132 $\text{\AA}$) monitors the stage position and provides any positional error to the main deflection system electronics, which in turn produce a compensating deflection of the beam.

Main Deflection System

A diagram showing computations performed by the main deflection system is provided in Figure 4. The X and Y coordinates of the appropriate electromagnetically addressed subfield of the total scan area are delivered to the main deflector input register file over the main computer bus. This file also contains system-specific calibration constants and wafer distortion data determined by means of the fiducial mark detection subsystem during calibration and die registration, respectively. Stage positional errors measured by the laser interferometer are directly loaded into the main deflector position error register. From these data, the system sequentially calculates correction terms for wafer position, process-induced wafer distortions, and pattern distortions arising from deflection system nonlinearity. Because of the high throughput requirement, high speed hardware is used to perform 25 real-time multiplications and 15 high-speed additions or subtractions, updating the results every microsecond. Output data delivered through the optically

isolated bus are X and Y deflections and X and Y dynamic position corrections. In addition, this bus is used to transmit data for dynamic stigmatism and focusing.

As illustrated in Figure 5, the data are decoded separately and routed to individual driver sections for digital to analog conversion. Deflection data having a 20-bit range and 16-bit dynamic position corrections are converted separately before being summed in the output driver amplifiers; this technique permits dynamic position corrections to be updated during exposure, while deflection data are updated only when the beam is blanked. Since digital to analog converters have "glitches" when major carrier bits are exercised, converting these data separately also reduces the effects of digital noise on beam deflection errors, which are further reduced by a sample and hold technique.

The deflection amplifiers are capable of continuously supplying currents of up to two amperes to the electromagnetic yoke, and settle to the required precision within 25 microseconds for adjacent subfield deflections. This accuracy of one ppm is achieved by utilizing precision, one ppm metal foil resistors and chopper-stabilized and thermally compensated low-noise amplifiers in the design of the drive amplifiers. In addition, the design includes a pole-zero cancellation of the electromagnetic deflector's inductance. Resonance in the deflection coils due to distributed capacitance occurs at a frequency well beyond the point at which the closed-loop gain crosses the open-loop response of the amplifier, insuring stable amplifier operation.

The dynamic focus and dynamic stigmator drivers, which have a maximum output current of 300 ma, both provide a 12-bit input range.

Pattern Fracturing Processor

Once the main deflector has moved the electron beam to the center of the required electromagnetically addressed subfield, the pattern fracturing processor determines beam deflections for pattern exposure within the subfield. The configuration of the pattern fracturing processor is illustrated in Figure 6.

Preprocessed pattern data are delivered in compressed form from the 300 megabyte system disk to a solid-state mass memory with a minimum of 8 million 16-bit words,

capable of expansion to 16 megawords if required. During exposure, the pattern data base resides in the mass memory and is transferred to the pattern fracturing processor on a high-speed local bus, enabling faster data delivery than would be possible using conventional direct memory access transfer from disk on the Unibus. The main computer supplies the pattern file location and length to the pattern fracturing processor, and initiates its execution.

The pattern fracturing processor considers each basic geometry within a pattern as a separate task which is fully defined by the thirteen operating registers shown in the figure. These registers, which are loaded from the mass memory as needed, provide all necessary parameters for exposing the desired geometry, such as starting and ending corners, beam size, and exposure and blanking times. Because the register values remain stable until changed, preordering of the pattern data is performed to reduce the number of words needed to define a set of pattern geometries; experience with actual pattern data has indicated that less than four words are required per geometry on the average.

The control instruction defines the processor's entry point into the writable control store, which contains routines for fracturing each supported geometric shape. Therefore, by updating the control word, the desired geometric shape and the way in which that figure should be fractured are selected. This capability permits implementation of support for a number of different shapes that are useful fracturing primitives, e.g., rectangles, triangles, and parallelograms.

The pattern fracturing processor utilizes ECL logic in order to meet its required 50 MHz clock rate. The writable control store memory discussed above has a capacity of 4096 48-bit words, expandable to 12,288, with an access time of 15 nsec. Each microinstruction restructures the operating configuration of the pattern fracturing processor during each cycle. Seven independent arithmetic and logic units perform the necessary calculations in parallel. There are also 15 different branching conditions and a number of data selections and shifts. These capabilities enable the machine to compute the desired beam size and beam location in the target plane in real time.

The computer digital data are transferred in parallel to the analog deflection electronics located near the electron optical column. Information strobed into the

column registers by the blanking pulse fully defines the X and Y electron beam size and the X and Y beam deflections within the addressed subfield. Received data are allowed to propagate through the buffered local interface to the analog deflection circuitry. After the data have been converted and the driver amplifiers have been allowed to settle, the beam is unblanked and exposure proceeds. Concurrently, new digital data are computed by the processor and delivered to the column electronics for the next exposure.

Fast Deflectors

The fast predeflector electronics, also located near the electron beam column, receive and convert deflection data from the pattern fracturing processor into voltages for the electrostatic predeflector. The resolution of the system is 12 bits for ± 5 volts output with a settling time to 0.025% of 150 to 200 nsec, depending on the step size. The fast predeflector system can correct for scale changes and rotational errors via registers in the local interface.

Beam size can be dynamically adjusted from $0.5 \mu\text{m} \times 0.5 \mu\text{m}$ up to $6.72 \mu\text{m} \times 6.72 \mu\text{m}$ by means of the variable aperture deflection system. Its output voltage ranges from zero to 22 volts; it settles in 200 nsec to 8-bit accuracy for a full-scale deflection. As with the other deflection systems, scaling of beam size can be accomplished by means of a gain correction register.

The blanker electronics switch the electron beam off and on electrostatically in less than 5nsec with driving voltages of 20 volts.

Summary

An automated system for a variable shaped spot electron beam column control has been developed for commercial application. Among the principal design concepts for this system was the separation of data paths and processing facilities for high-speed pattern data transfer from those employed for less time critical functions such as X,Y stage motion. A combination of electromagnetic and electrostatic deflection systems is utilized to deflect, form, and blank the beam. A microprogrammed pattern fracturing processor designed for highly parallel operation expands compressed circuit pattern data stored prior to exposure

in a large solid state memory; such data, including beam dimensions, pattern geometry positions, and exposure and blanking time intervals are then transmitted in digital form to column control electronics, where analog conversion and application of system-dependent corrections takes place. Both system calibration and monitoring operation are performed through the use of a high-precision data acquisition subsystem. A photo of the electronic control console incorporating all the discussed control functions with the exception of digital to analog converter and the driver amplifier section is shown in Figure 7.

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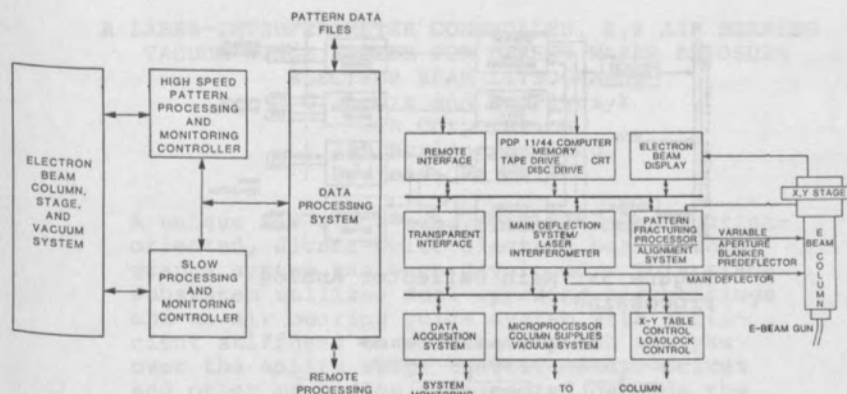


Figure 1: Partition of System Control Functions

Figure 2: System Block Diagram

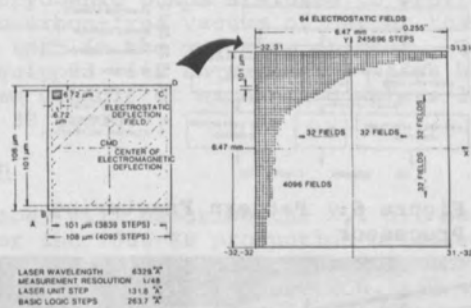


Figure 3: Deflection Fields

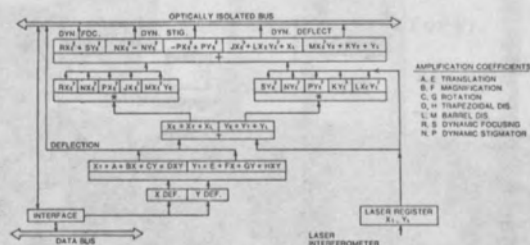


Figure 4: Main Deflector Digital Computations

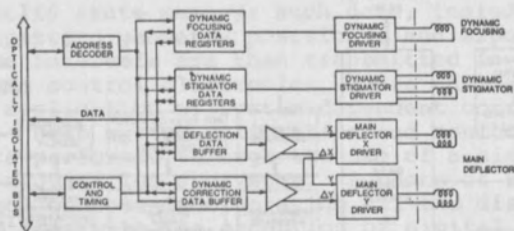


Figure 5: Main Deflector Analog Processing

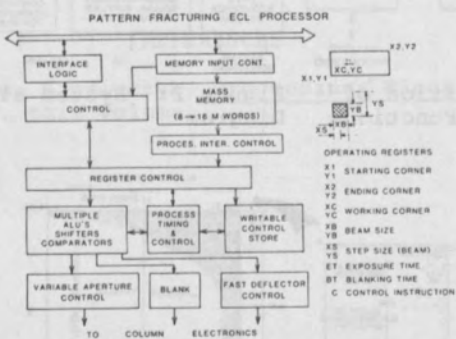


Figure 6: Pattern Fracturing Processor

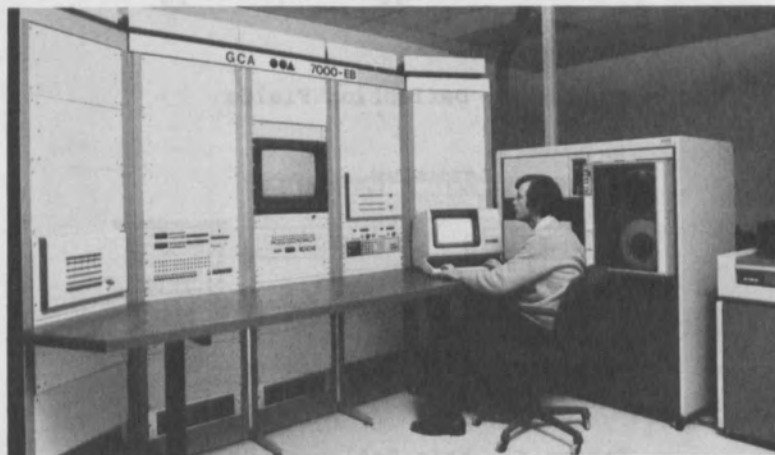


Figure 7: Photograph of Electronic Control System

A LASER-INTERFEROMETER CONTROLLED, X,Y AIR BEARING
VACUUM STAGE SYSTEM FOR DIRECT WAFER EXPOSURE
ELECTRON BEAM LITHOGRAPHY
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A unique X,Y stage subsystem for a production-oriented, direct-write electron beam lithography system has been developed. This stage subsystem utilizes dual opposing air bearings and an air bearing guide system with sufficient stiffness to eliminate pitch and yaw over the entire stage travel. Stage drives and other mechanics are located outside the system vacuum envelope for ease of service and elimination of potential lubricant contamination. A combination of turbomolecular and cryogenic pumps are used to provide a hydrocarbon-free vacuum of better than 5×10^{-6} torr in the exposure chamber. The stage is equipped with an automatic wafer handling system capable of exchanging wafers in less than 30 seconds.

Introduction

This paper will describe the X,Y air bearing stage developed for the 7000-EB production-oriented, direct-write electron beam lithography system. The combination of high throughput, $0.5 \mu\text{m}$ resolution, and high reliability required for electron beam lithography systems in future I.C. production applications places stringent requirements^{1,2} as follows on the 7000-EB's mechanical subsystems:

1. 3, 4, 5, or 6 inch diameter wafers;
2. Acceleration $\leq 0.1 \text{ g}$;
3. Settling time $\leq 0.25 \text{ sec}$;
4. Maximum velocity - 7.5 cm/sec ;
5. Maximum travel - 16.5 cm ;
6. Positional accuracy - $\pm 10 \text{ microns}$;
7. Substrate loading - 30 sec ;

8. Vacuum $< 5 \times 10^{-6}$ torr, free of hydrocarbon residual gasses;
9. Laser metering - $\lambda/48$.

Air Bearings, Stage, and Guidance Mechanisms

A cross sectional view of the X,Y air bearing stage is provided by Figure 1. The stage plate itself is sandwiched between the top and bottom air bearings, which are identical in geometry and are accurately positioned one above the other. Because of the vacuum both above and below the plate, any bending moments or stresses on the stage plate which would otherwise be present due to atmospheric pressure during operation are eliminated. Each air bearing has two differentially pumped grooves or scavengers between its liftoff areas and the central vacuum chamber. A film of nitrogen flows between the stage and the bearings on both sides. Approximately eighty percent of the gas flow is directed outward to ambient because of the short distance between the gas inlet pool and the bearing edge. Inward flowing nitrogen is impeded by the relatively long and narrow, $\leq 5 \mu\text{m}$ gap, and is pumped out through the concentric scavenger grooves. As a result, very little gas reaches the central vacuum chamber, thus allowing a pressure of better than 5×10^{-6} torr in the central chamber.

The bearings are fabricated from aluminum with an anodized surface layer. Because bearing geometry must be accurately maintained to produce the required uniform flow, pressure, travel, and leakage rate, the stages precision and long-term dimensional stability are of prime importance. Each bearing contains 24 orifice-compensated supply ports which can be adjusted to a predetermined flow rate to affect the flow and uniformity of the flying height. Each bearing is manifolded for gas supply and evacuation of the two pumpout grooves. The physical size of each bearing and manifold is approximately 60 cm square by 15 cm thick.

The stage itself is a composite structure consisting of a stage plate, a tubular transition structure, and the wafer-carrying stage. The plate is approximately 90 cm square and 6 cm thick, with a mass of only about 15 kg; this is accomplished by means of its structure: two thin plates separated by a honeycomb constructed from thin aluminum ribbon brazed together, having a density of 2.4 kg/m^3 . This design provides a modulus of elasticity equivalent to a 3.1-cm thick aluminum plate having a mass of 50 kg. Using this technique, the precision planing and

machining required for the stage plate is possible, while a low mass is maintained.

A tubular transition structure separates the laser interferometer mirror from the stage plate at the required height, and houses the clamping mechanism for holding the wafer and its carrier on the stage. The wafer-carrying stage is a beryllium block measuring approximately 23 cm square by 3.8 cm thick that has been precision machined to accept wafers in carriers for exposure, and is laser metered to provide for highly accurate determination of its position in the X and Y direction.

Figure 2 depicts stage loading versus pressure. As indicated, the pressure required for proper operation is 38-40 psi under an atmospheric load of 8500 lbs. Stage flying height vs. flow is illustrated by Figure 3. The operating point utilizes a flying height of 5 μ m at a nitrogen flow of approximately 10 scf/hr.

System stiffness vs. air bearing gap is shown in Figure 4. The stage operates at a stiffness of 7.5×10^7 lb/in. This characteristic of the air bearing film is an important parameter because it virtually eliminates pitch of the stage over its entire travel.

The precision required for the air bearing to operate successfully can be inferred from the thinness of the film ($< 5 \mu$ m) separating the moving parts. In general, the tolerances required for flatness, finish, straightness, orthogonality, and parallelism are in the micrometer or submicrometer range.

The wafer carrying stage incorporates two orthogonal reflective mirror surfaces metered using the laser beam in order to track the stage position. Wafer carriers are transported into the stage on rails which are depressed by a clamping mechanism in order to hold the carrier rigidly in the stage at the precise beam focus plane.

The X,Y servomotor and guide frame are depicted in Figure 5. Because of the stage's light weight, the motors can supply the necessary torque to accelerate the stage at $< 0.1 g$ to its maximum velocity of 7.5 cm/sec. The stage is moved from site to site by the drive system, settling in less than 250 milliseconds. Because the Y motor must drive the additional weight of the X drive and guide frame, each motor must be separately powered to move the appropriate mass, although the motors themselves are identical. The drives are directly coupled to precision

ball screws which translate the stage to any desired position. The guide bearings are preloaded to establish a stiffness of 8.0×10^6 lb/in, virtually eliminating stage yaw. Four air bearing guides are used, two for each axis as shown in Figure 5. The orthogonality of the X and Y drives and guide system is adjustable with respect to the stage mirror, and is slaved to its orthogonality, eliminating errors between the two systems. All drive motors and other mechanics are located completely outside the vacuum envelope of the exposure system, not only providing considerably enhanced ease of maintenance, but also removing a potential source of lubricant contamination for the vacuum system.

Wafers enter the system in carriers, illustrated in Figure 6, which reduce bowing by means of edge clamping. The registration surface of the carrier and the front surface of the wafer are coplanar. This is important because it establishes the focal plane between the beam and the wafer being exposed. The physical size of the carrier is always 7 inches square, making it possible to accommodate wafers up to six inches in diameter with changes required only to the individual carriers rather than to the machine configuration when wafers of different sizes are to be exposed.

The stage utilizes a Hewlett-Packard laser interferometer with its remote heads located such as to provide an air path of < 5 mm to the central vacuum chamber, eliminating dimensional errors caused by barometric or thermal changes in the system environment. The laser least count utilized is $\lambda/48$, or approximately 132 Å. As illustrated in Figure 7, the laser is completely housed in the machine base with quartz windows isolating it from the central chamber.

Automatic Wafer Handling System

The load lock system which transports the wafer from atmosphere to the exposure chamber is also depicted in Figure 7. A cassette containing wafers in individual carriers is loaded into the elevator and raised into the load position. Valve number 1 is then opened. Transfer mechanism number 1 is activated, gripping a carrier and moving it to the load lock elevator position. The carrier is released and the mechanism retracted. Valve number 1 is then closed, and the load lock chamber is evacuated. Once the vacuum has reached the required level, valve number 2 is opened, and transfer number 2 transports the carrier to stage, which is in the docked position in the

central vacuum chamber. Valve number 2 is closed, and the stage moves to the exposure position. While exposure is in progress, the process is repeated, leaving an unexposed wafer under vacuum in the load lock, ready to be exchanged with the wafer in the central chamber when exposure has been completed.

The load lock elevator is capable of accommodating two carriers simultaneously, thus allowing both an exposed and an unexposed wafer to be present. The elevator and its drive train are located in the load lock chamber and the machine base, respectively. Its three positions are obtained by a servomotor and ball screw drive which develops a velocity of 3 cm/sec and has a positional accuracy of $\pm 100 \mu\text{m}$. The moving parts of the system are in air, and a welded bellows provides the vacuum-to-air seal. A brake is coupled between the motor and ball screw for positive location of the elevator. The total travel of the elevator is 5 cm. The time required to change between adjacent locations is approximately 1 second.

The two transfer mechanisms are located external to the machine base. They are driven by servomotor-ball screw drives which develop a velocity of 10 cm/sec and provide a positional accuracy of $\pm 100 \mu\text{m}$. Their linear travel is 34 cm. Each transfer arm is equipped with a pneumatically operated clamping mechanism which has sensors to determine if a carrier is present. The arm used to transfer the wafer from the load lock chamber into the main chamber is metal bellows-isolated; a negator spring motor is used to counterbalance the atmospheric load exerted on the bellows.

The two lubricant-free, pneumatically-operated valves in the system have a travel of 4 cm. Isolation of the piston from the vacuum is accomplished by utilizing metal bellows. The valve operates by means of a wedging action which forces the Viton O-ring against the sealing surface around the port opening, which is 2 cm x 18 cm, allowing clearance for the passage of a wafer carrier. The valve operates on standard 80 psi air pressure. It is made fail-safe against loss of supply pressure by a spring load which closes it automatically should such a pressure loss occur.

The wafer cassette elevator system is housed in one of the support legs of the vibration isolation table. It can accommodate cassettes with maximum individual wafer carrier capacities of 8 or 16, sufficient for one or two

hours' operation, respectively. The elevator is driven by means of a servomotor-ball screw drive developing a velocity of 2.5 cm/sec, and providing a positional accuracy of $\pm 100 \mu\text{m}$. Loading and unloading are accomplished by means of an access door in the isolation table of the machine. Every motion of the loading system is sensed, and if the proper sequence is not maintained, the supporting electronics generate interrupts to the main computer, which takes the appropriate corrective action or stops the system pending manual intervention.

Vacuum Subsystem

The stage's vacuum system must be hydrocarbon-free to eliminate contamination of the electron optical column. The central chamber vacuum is obtained and maintained cryogenically at a pressure of better than 5×10^{-6} torr by means of a CTI Cryotorr 8 pump. The load lock is evacuated to 5×10^{-5} torr by a 550 liter/sec turbomolecular pump. This pump is backed by a mechanical pump using perfluorinated polyether as pump oil. The air bearing inner groove is evacuated by a turbomolecular pump providing a vacuum of better than 5×10^{-3} torr. The outer groove is evacuated using a mechanical pump using perfluorinated polyether as pump oil. This selection of pumps virtually eliminates the presence of contaminants in the system.

Summary

The 7000-EB laser-metered X,Y stage utilizes two opposing air bearing and air bearing guides which provide sufficient stiffness to virtually eliminate pitch and yaw; the stage plate is suspended between top and bottom air bearings by a thin film ($\leq 5 \mu\text{m}$) of nitrogen. Concentric, differentially pumped scavenger grooves permit the air bearing to be operated at an exposure chamber vacuum level of better than 5×10^{-6} torr.

A design objective which has been successfully implemented in the stage required all drive mechanics to be external to the system vacuum envelope for reliability and convenience of serviceability as well as elimination of potential contamination by lubricants. A combination of cryogenic and turbomolecular vacuum pumps is also used to eliminate potential contamination from this source.

The stage is serviced by an automatic wafer handling

system which utilizes a load lock chamber containing a mechanical buffer allowing both an exposed and an unexposed wafer to be present simultaneously; this permits exchange of wafers in less than thirty seconds. A photograph of the complete system is shown in Figure 8.

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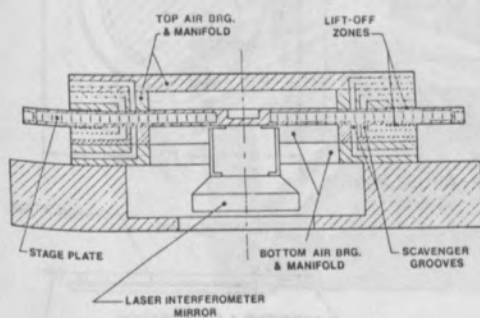


Figure 1: 7000-EB Air Bearing Vacuum Stage Cross Section

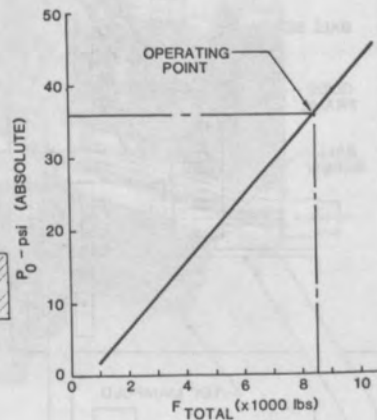


Figure 2: Stage Load vs. Air Bearing Operating Pressure

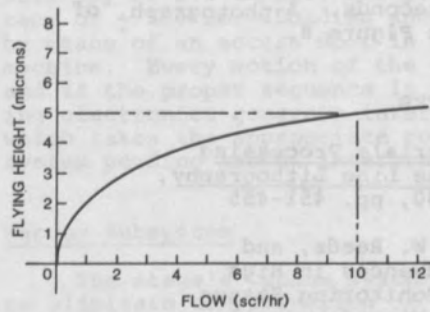


Figure 3: Stage Flying Height (Air Bearing Gap) vs. N_2 Flow Rate

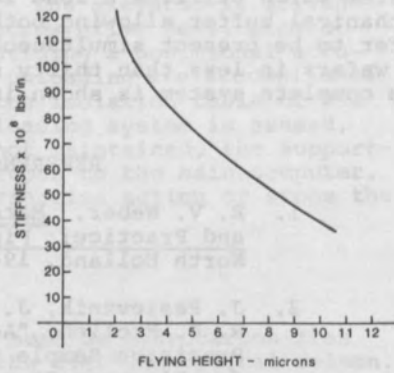


Figure 4: Stage Stiffness vs. Flying Height (Air Bearing Gap)

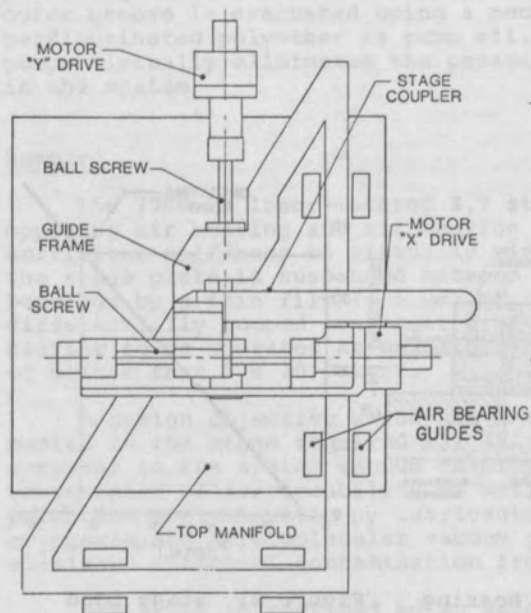


Figure 5: Stage Guide and Drive System

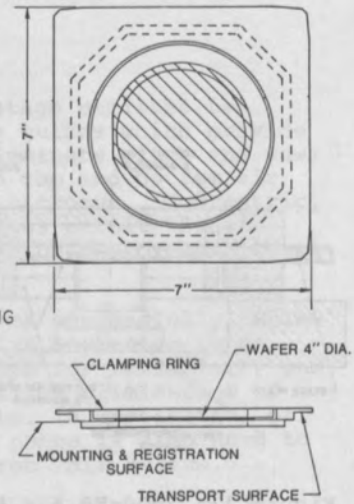


Figure 6: Wafer Carrier Configuration

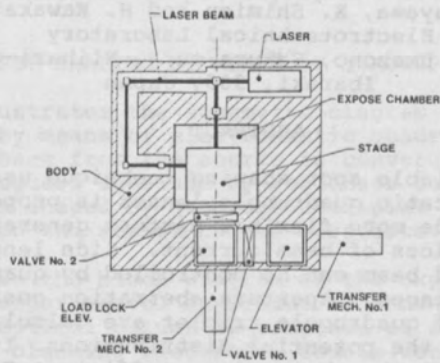


Figure 7: Laser Interferometer and Load Lock Systems

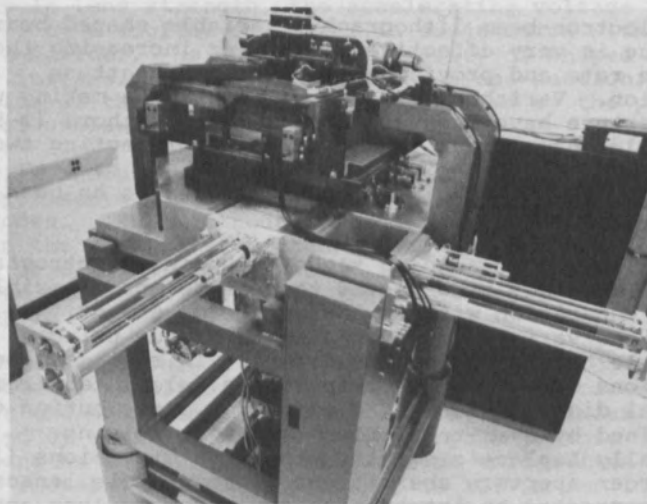


Figure 8: Photograph of Stage Mechanics

VARIABLE SPOT SHAPING BY MEANS OF QUADRUPOLE LENSES

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ABSTRACT

A variable spot shaping technique using electrostatic quadrupole lenses is proposed to provide more flexible pattern generation without loss of beam current. Side lengths of shaped beam can be controlled by quadrupole voltages. Aperture aberration coefficients of quadrupole triplet are calculated by using the potential distributions. It is clear that the aberration coefficient CA_{30} in the x-z plane (i.e. DCD-plane) is larger than any other coefficient. In the triplet, CA_{30} can be cancelled completely by new correction method.

1. INTRODUCTION

In electron-beam lithography, variable shaped beam technique is very effective method for increasing the exposure rate and providing more flexible pattern generation. Variable shaped beam techniques making use of dual aperture have been reported by many authors (1-9). A variable shaped beam is generated by projecting two superimposed beam shaping apertures. Loss of beam current by second shaping aperture increases as beam size decreases.

A variable spot shaping technique using electrostatic quadrupole lenses is expected to provide more flexible pattern generation without loss of beam current. In this report, the variable spot shaping technique using quadrupole triplet is proposed (10). Third order aperture aberrations of quadrupole triplet are calculated from the potential distribution. The potential distribution can be obtained by over-relaxation technique solving numerically Laplace's equation in three dimensions (11). Third order aperture aberrations of quadrupole lenses can be corrected by introducing the octopole lens actions. A new electrostatic lens capable of correcting third order aperture aberration is proposed. The new lens unit consists of an electrostatic quadrupole and aperture electrode. In the quadrupole triplet, aperture aberration

coefficient C_{A30} which is larger than any other coefficient can be cancelled completely by the new correction method.

2. VARIABLE SPOT SHAPING BY MEANS OF QUADRUPOLE TRIPLET

Fig. 1 illustrates the schematic diagram of variable spot shaping by means of electrostatic quadrupole triplet. The electron beam from the source is converged to illuminate a square aperture by condenser lens. The square beam is shaped by quadrupole triplet and shifted by deflector on the resist-coated substrate.

Fig. 2 shows the block diagram of the experimental system. The experimental apparatus is shown in Fig. 3. The electron optical column is composed of six parts, electron gun, blanking electrode, double condenser lenses, square aperture, electrostatic quadrupole triplet and octopole deflector.

The excitation voltages of quadrupole triplet are controlled by 3 16 bit D-A converters and 6 high voltage amplifiers. Maximum output voltage of HV Amp. is ± 1000 V with resolution of 30 mV. In order to determine the quadrupole lens strength, the accelerating voltage is measured by a digital voltmeter in conjunction with high voltage divider. As the current density of shaped beam varies inversely as increase of beam cross-section, the shot time of the shaped beam is controlled by the pulse-width of unblanking signal.

Fig. 4 shows the electrostatic quadrupole lens used in the experiments and a jig for alignment of quadrupole electrodes. The electrodes of the quadrupole lens are made in the form of truncated circular cylinders with radius of 6 mm. The mechanical length is 20 mm and the aperture radius is 5.22 mm. The total length of quadrupole triplet is 82 mm.

The variable shaped beam can be obtained by controlling the voltages supplied to the quadrupole electrodes. Fig. 5 shows the side lengths of rectangular and linear beams obtained by excitations of the quadrupole lenses. The side lengths of the shaped beam can be varied from 1 to 30 μm for rectangular beam and from 2 to 100 μm for linear beam by adjusting the voltages of the 2nd and 3rd quadrupoles within a range of ± 60 V at an accelerating voltage of 20 kV. The beam intensity distribution of the shaped beam can be obtained by using the knife edge method. Fig. 6 shows the intensity distributions for the square

beam in the x and y directions.

In Fig. 5, points A and B indicate the conditions of the minimum spot size. The quadrupole triplet can be used as probe forming lens under these conditions. Fig. 7 is a scanning electron micrograph of 1000-mesh (25.4 μm in spacing) by means of probe-forming quadrupole triplet. In this case, spot size is under 0.4 μm . Fig. 8 shows a scanning electron micrograph of an interdigital electrode pattern fabricated by a 100 μm -line beam. The line width is 0.85 μm and the spacing 3.3 μm . It shows that the smoothness of the line is far better than that of the conventional spot-beam scanning.

3. APERTURE ABERRATION OF QUADRUPOLE TRIPLET

Aperture aberration affecting the beam intensity profile of the shaped beam can be calculated by using the potential distribution obtained by over-relaxation analysis. In the quadrupole lens system, the aperture aberration in the Gaussian image plane can be expressed as follows;

$$\begin{aligned}\Delta x(z_{ix}) &= C_{A30} \alpha^3 + C_{A12} \alpha \beta^2 \\ \Delta y(z_{iy}) &= C_{A21} \alpha^2 \beta + C_{A03} \beta^3\end{aligned}\quad (1)$$

where α and β are semi-aperture angle in the image space. For quadrupole triplet, x-z and y-z planes correspond to divergent-convergent-divergent (DCD) and CDC planes, respectively.

Table 1 shows the calculated aberration coefficients of triplet. Quadrupole lens strengths represent the ratio of quadrupole voltage to accelerating voltage. z_0 is the distance between the source and the center of 1st quadrupole and z_i the working distance from the center of 3rd quadrupole. It is clear that the aberration coefficient C_{A30} in DCD-plane is larger than any other coefficient.

4. CORRECTION OF APERTURE ABERRATION

Generally in the quadrupole lens system, the correction of the aperture aberration, which is not attainable in the conventional round lens, can in theory be accomplished by combining the octopole lenses. However, quadrupole-octopole system is very difficult to use in practice. The slight misalignment in the system not only results in severe degradation of correction properties but also brings in mechanical aberrations as an extra disadvantage.

A new simplified lens possessing the function of correction of the aperture aberration is proposed. The new lens unit consists of an electrostatic quadrupole and aperture electrode. Fig. 9 illustrates a basic arrangement of the new correction lens. When the aperture electrode is aligned with the electrostatic quadrupole and a voltage is supplied thereto, an octopole field is created by the fringing effect of the quadrupole.

4.1. Potential Distribution of New Correction Lens

The potential of the new correction lens can be expressed as follows;

$$\begin{aligned}\Phi(r, \theta, z) = & \left\{ \Phi_0(z) - \frac{1}{4} \Phi_0''(z) r^2 + \frac{1}{64} \Phi_0''''(z) r^4 - \dots \right\} \\ & + \left\{ \Phi_2(z) - \frac{1}{12} \Phi_2''(z) r^2 + \dots \right\} r^2 \cos 2\theta \\ & + \left\{ \Phi_4(z) - \dots \right\} r^4 \cos 4\theta.\end{aligned}\quad (2)$$

The first term corresponds to a round lens component and the second and third terms correspond to quadrupole and octopole lens components, respectively. $\pm \Phi_2$ V are supplied to the quadrupole and Φ_0 is supplied to the aperture electrode. $\Phi_0(z)$, $\Phi_2(z)$ and $\Phi_4(z)$ of formula of (2) can be expressed as follows;

$$\begin{aligned}\Phi_0(z) &= \Phi_0 \cdot k_0(z) \\ \Phi_2(z) &= (\Phi_2 / a^2) k_2(z) \\ \Phi_4(z) &= (\Phi_0 / a^4) k_4(z)\end{aligned}\quad (3)$$

where a is the aperture radius of the quadrupole and the aperture electrode, $k_0(z)$, $k_2(z)$ and $k_4(z)$ are characteristic functions representing the potential distributions to the respective lens components.

The potential distributions of new correction lens are calculated by successive over-relaxation technique numerically solving Laplace's equation in three dimensions. The quadrupole electrodes are cylinders of radius $R = 6$ mm, mechanical length $l = 30$ mm and aperture radius $a = 5.22$ mm ($R/a \approx 1.15$). The aperture electrode is 1 mm thick and the distance between the aperture electrode and the quadrupole is 6 mm. Fig. 10 shows the calculated potential functions for the quadrupole, the octopole and the round lens components. The calculated results show that the octopole field is automatically created within the quadrupole field by supplying a voltage to the aperture electrode. Consequently, the octopole field is exactly aligned with the quadrupole.

4.2. Correction Property of Aperture Aberration of Quadrupole Triplet

In the new quadrupole correction lens, the beam trajectories can be obtained from the quadrupole and round lens potentials. The aperture aberration coefficients of formula (1) can be calculated using the particular solutions of the paraxial ray equations, the potential distributions and their derivatives. The availability of the new correction lens unit has been experimentally confirmed by using the shadow image method (12).

We consider the correction of the aberration coefficient C_{A30} of quadrupole triplet. Fig. 11 shows the correction lens system and the beam trajectories in the x-z and y-z planes. This lens system consists of three quadrupoles and one aperture electrode. The total length of the lens system is 100 mm. The spacing between 1st quadrupole and 2nd quadrupole is 30 mm and the spacing between the aperture electrode and 2nd quadrupole 5 mm. The distance between source and 1st quadrupole lens is 20 cm and the working distance is 4.9 cm. The beam trajectories show a pseudo-stigmatic operation. In this condition, increases of C_{A12} and C_{A21} induced by the correction of C_{A30} can be suppressed by making line-focus in the vicinity of the entrance of 2nd quadrupole (i.e. the position of octopole field).

Table 2 shows the variations of aberration coefficients by the excitation of the aperture electrode. The lens excitations are the ratios of the lens voltage to accelerating voltage. There are slight differences of quadrupole excitations before and after correction. This shows that the quadrupole lens actions compensate the defocusing due to the round lens action. The round lens action is very weak in this correction system. This correction method is very useful for the practical design of probe forming system with low aberration.

5. CONCLUSION

The variable spot shaping technique using the electrostatic quadrupole triplet was proposed to provide more flexible pattern generation without loss of beam current. Side lengths of shaped beam can be varied from 1 to 30 μm for rectangular beam and from 2 to 100 μm for linear beam by adjusting the voltages of 2nd and 3rd quadrupoles within a range of ± 60 V.

The aperture aberrations of the quadrupole triplet were calculated by using the potential distribution. It became clear that the aberration coefficient CA_{30} in DCD-plane is larger than any other coefficient.

A new electrostatic lens capable of correcting the aperture aberration was proposed. The advantage of this correction lens is that it is very easy to adjust the octopole component independently of the quadrupole excitation. The aberration coefficient CA_{30} of quadrupole triplet can be cancelled completely by the new correction method.

ACKNOWLEDGMENT

The authors are grateful to Dr.S.Kataoka, Electro-technical Laboratory, for his support and encouragement. The authors wish to thank K.Ogura, JEOL Co., for SEM photographs. The authors also wish to thank Messrs T.Itou and K.Kawai, JEOL Technics, for their technical assistance in producing the experimental instrument.

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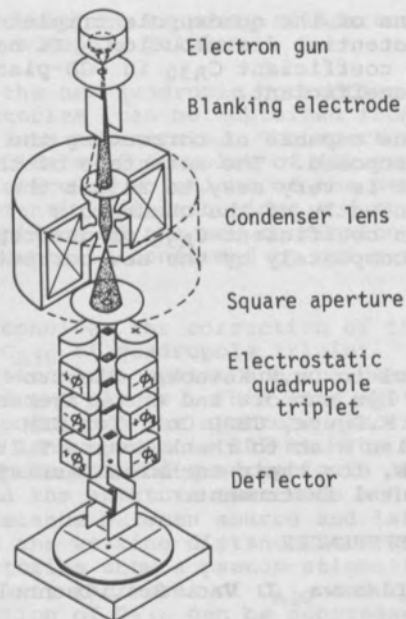


Fig. 1 Variable spot shaping by electrostatic quadrupole triplet.

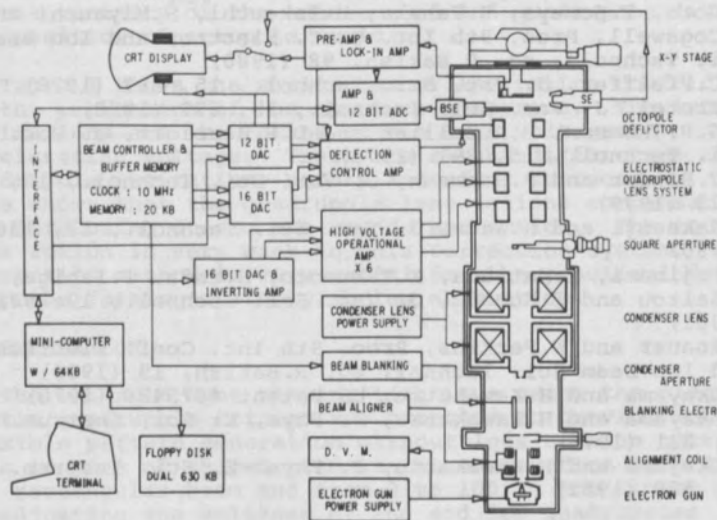


Fig. 2 Block diagram of experimental system.



Fig. 3 A general view of experimental apparatus.



Fig. 4 Electrostatic quadrupole lens and alignment jig.

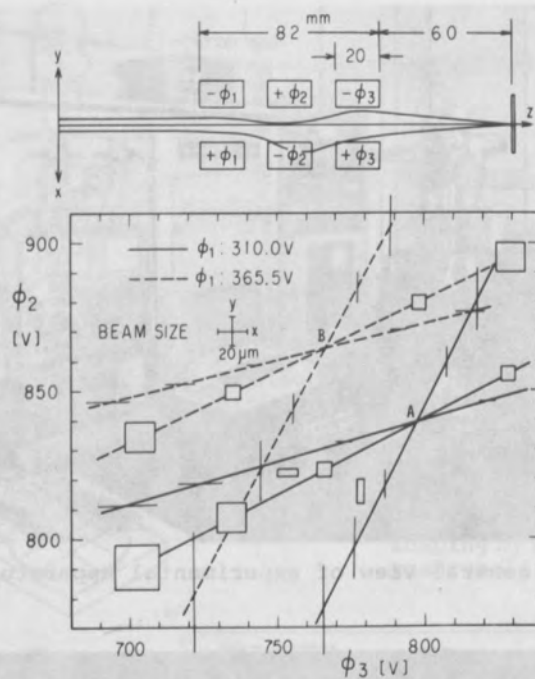


Fig. 5 Relationships between beam size and quadrupole excitations.

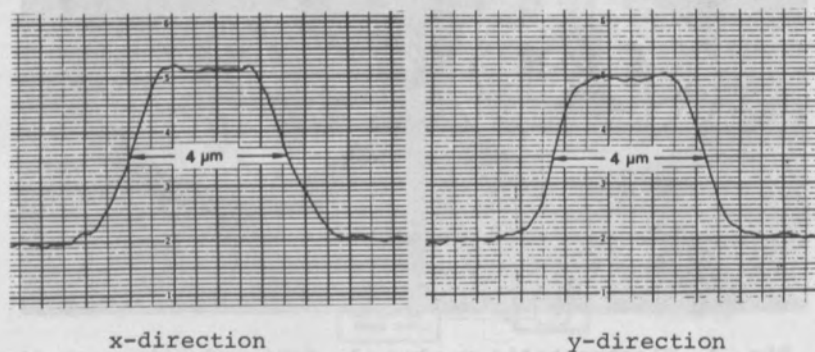


Fig. 6 Beam intensity distributions of square beam.

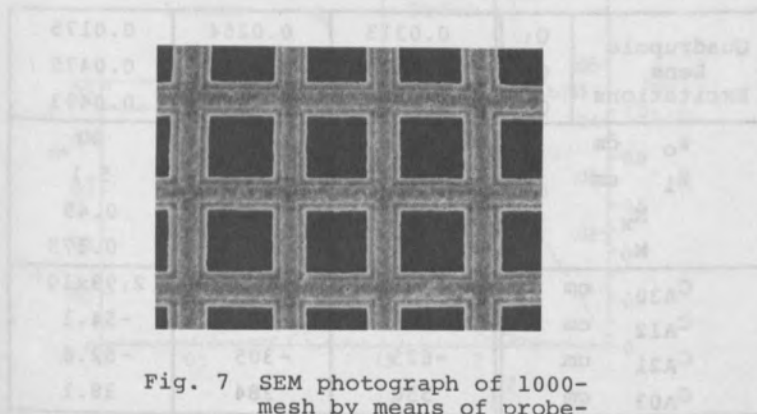


Fig. 7 SEM photograph of 1000-mesh by means of probe-forming quadrupole triplet.

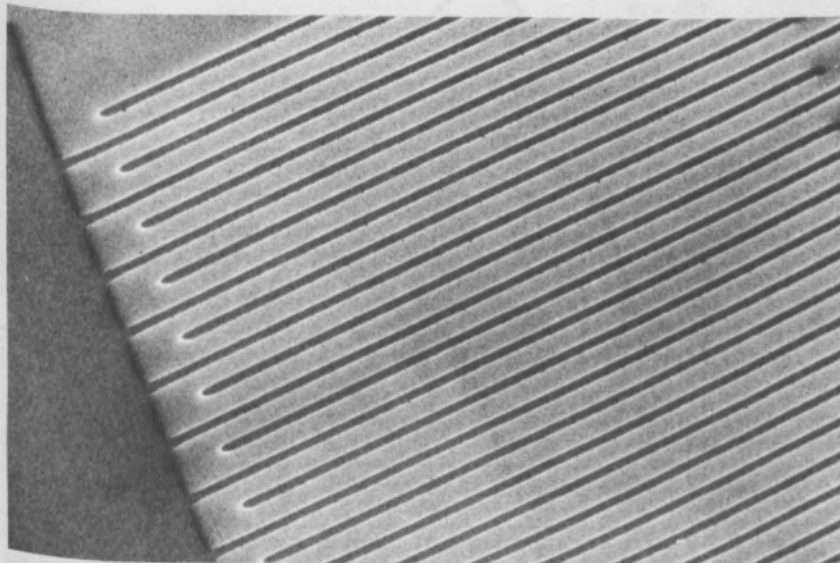


Fig. 8 SEM photograph of interdigital electrode pattern fabricated by a 100- μm line beam. 0.85 μm line-width and 3.3 μm spacing.

Quadrupole Lens Excitations	Q ₁	0.0313	0.0254	0.0175
	Q ₂	0.0490	0.0455	0.0475
	Q ₃	0.0313	0.0312	0.0493
z ₀ cm		10	20	20
z _i cm		10	7.7	5.1
M _x		1	0.48	0.49
M _y		1	0.48	0.175
C _{A30} cm		1.10×10^4	4.45×10^3	2.99×10^3
C _{A12} cm		-625	-305	-54.1
C _{A21} cm		-625	-305	-52.6
C _{A03} cm		550	284	38.1

Table 1 Calculated aperture aberration coefficients of quadrupole triplet.

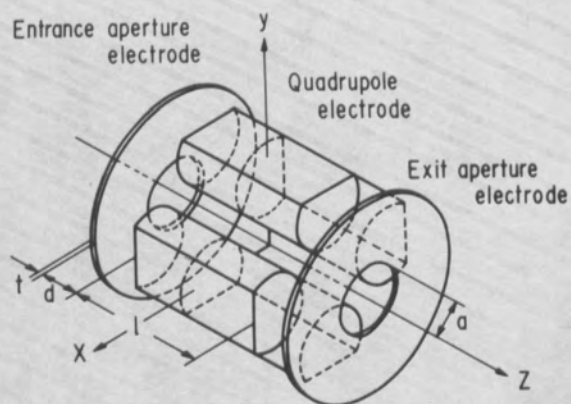


Fig. 9 Basic arrangement of the new correction lens.

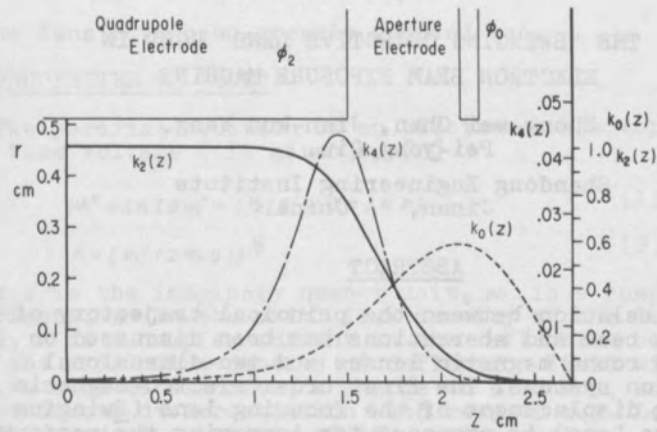


Fig. 10 Calculated potential functions of the new correction lens.

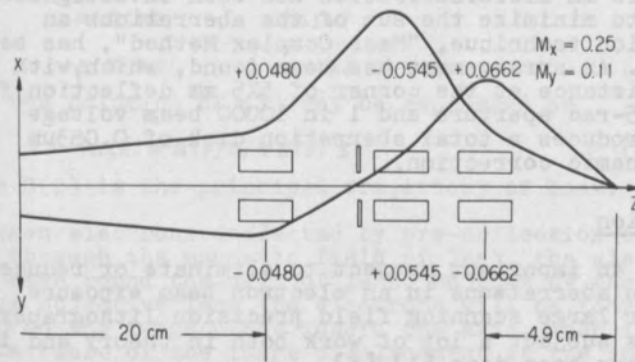


Fig. 11 Beam trajectories of quadrupole correction lens system.

Lens Excitations				Aberration Coefficients			
Q_1	Q_2	Q_3	aperture electrode	C_{A30} cm	C_{A12} cm	C_{A21} cm	C_{A03} cm
0.0480	0.0545	0.0662	0	5802	28.8	31.9	41.1
0.0480	0.0541	0.0663	-0.1127	0	54.3	57.3	40.3

Table 2 Variations of aberration coefficients before and after correction.

THE "SWINGING OBJECTIVE LENS" USED IN
ELECTRON BEAM EXPOSURE MACHINE

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ABSTRACT

The relation between the principal trajectory of electron beam and aberrations has been discussed on combined round magnetic lenses and two-dimensional deflection systems. The first order electro-magnetic swinging displacement of the focusing lens (Swinging Objective Lens) is proposed for improving the performance of electron beam scanning system. The aberrations of "SOL" is given out. The practical scanning system which may be used in microfabrication has been investigated. In order to minimize the sum of the aberrations an optimization technique, "Mass Complex Method", has been developed. An arrangement has been found, which, with 5cm working distance at the corner of 5X5 mm deflection field with 0.005-rad aperture and 1 in 10000 beam voltage ripple, produces a total aberration disk of 0.083 μ m before dynamic correction.

Introduction

It is an important subject to eliminate or reduce deflection aberrations in an electron beam exposure system for large scanning field precision lithography. About this subject a lot of work both in theory and in practice has been done [1]-[5].

The "Swinging Objective Lens" (SOL) proposed in this paper is a combined focusing lens and deflecting system, in which the optical axis of the objective lens is electro-magnetically swung synchronously with the electron-beam deflected by pre-deflection coil in first-order. In this system, the third order deflection distortion and the transvers chromatic aberration for fluctuation of voltage equals zero, and in the other third-order deflection aberrations caused by not coinciding with the first-order or "paraxial" trajectory are greatly reduced, without counting the aberrations caused by pre-deflection coil. The aberrations caused by second and third derivation of the axial flux density

of the lens have been greatly reduced too.

THE PROPERTIES OF "SOL"

The paraxial equation of an electron trajectory with beam voltage U is given by [2]

$$W_1'' - iK[BW_1' + (\frac{1}{2})B'W_1] = iKD I \quad (1)$$

$$K = [e/(2m_0 U)]^{1/2} \quad (2)$$

where i is the imaginary number unit, W_1 is a complex coordinate, B is the axial flux density of the lens field, I is a complex current in the deflection coil, D is the axial flux density of deflection field with $I=1A$, m_0 mass of electron, e charge on electron, and primes denote differentiation with respect to z . Let the independent solutions of the corresponding homogeneous equation of (1) be $a(z)$ and $b(z)$ with initial conditions

$$\begin{aligned} a(z_0) &= 0 & a'(z_0) &= 1 \\ b(z_0) &= 1 & b'(z_0) &= 0 \end{aligned} \quad (3)$$

Thus the solution of (1) may be expressed as

$$W_1(z) = a(z) S_0 + C(z) I \quad (4)$$

where $C(z)$ is the principal trajectory of beam.

When electrons deflected by pre-deflection coil pass through the magnetic field of lens, the electrons will move round the axis of lens. So that by the action of the objective lens the electrons will be focused at the point on the image plane toward the axis. Then it makes the decrease of the image displacement at the image plane. It means that electrons will pass through a longer path to get a same deflection. As the electrons move round the axis of lens, the values of $C'(z)$ and $C''(z)$ all increase. These increase the deflection aberrations. the effect of these can be seen from each geometrical aberration coefficients [2]. Especially from the parts of aberrations caused by not coinciding with the first-order trajectory it can be seen still clear. It is known that this part is the major part of the aberrations. In order to minimize this let the field of the main deflection coil is

$$D = B \cdot W_c' + \frac{1}{2} \cdot B' \cdot W_c \quad (5)$$

Thus the principal trajectory $C(Z)$ pass through the optical axis of Swinging Objective Lens which is formed by suitably complexing the field of focusing lens and the field of main deflection coil. Fig.1 shows the optical principal of Swinging Objective Lens. The optical properties of Swinging Objective Lens have been derived. The following are the expressions for the third-order geometrical aberration coefficients and the first-order chromatic aberration coefficients:

$$K_S = -\frac{1}{[\bar{a}'\alpha'^2\bar{a}']_{z_i}} \int_{z_0}^{z_i} \left\{ \bar{a}\alpha'\alpha'' + (\frac{1}{2})\bar{a}\alpha'^2\bar{a}'' + i\kappa[-(\frac{1}{8})\bar{a}''\alpha'^2\bar{a}B' - (\frac{1}{8})\bar{a}'\alpha'^2\bar{a}B' + (\frac{1}{8})\bar{a}\alpha'^2\bar{a}B' + (\frac{1}{8})\bar{a}\alpha\alpha''\bar{a}B'] \right\} dz$$

$$K_L = -\frac{1}{[\bar{a}'c\alpha'\bar{a}']_{z_i}} \int_{z_0}^{z_i} \left\{ \bar{a}c'\alpha'\alpha'' + \bar{a}\alpha'c'\bar{a}'' + i\kappa[(\frac{1}{2})\bar{a}^2\alpha'c'B' - (\frac{1}{2})\bar{a}\bar{a}'\alpha'c'B'] \right\} dz$$

$$K_R = \frac{1}{[\bar{a}'c\alpha'^2]_{z_i}} \int_{z_0}^{z_i} \left\{ -\bar{a}\alpha'c'\alpha'' + i\kappa[(\frac{1}{8})\alpha''\alpha'^2cB' - (\frac{1}{4})\bar{a}\alpha'^2cB' - (\frac{1}{4})\bar{a}\alpha\alpha''cB' + (\frac{1}{4})\bar{a}\alpha\alpha'c'B'] \right\} dz$$

$$K_A = \frac{-1}{[\bar{a}'c^2\bar{a}']_{z_i}} \int_{z_0}^{z_i} \left\{ (\frac{1}{2})\bar{a}c'^2\bar{a}'' + i\kappa[(\frac{3}{8})\bar{a}^2c'^2B' + (\frac{1}{8})\bar{a}''c'^2\bar{a}B' + (\frac{1}{8})\bar{a}'^2c'^2B' - (\frac{1}{2})\bar{a}\bar{a}'c'c'B'] \right\} dz$$

$$K_F = \frac{1}{[\bar{\alpha}' \alpha' c^2]_{z_0}} \int_{z_0}^{z_k} \left\{ -\bar{\alpha} c^2 \alpha'' + 4K[(1/8) \bar{\alpha}'' \alpha c^2 \beta' - (1/2) \bar{\alpha} \alpha' c' c \beta' - (1/8) \bar{\alpha} c^2 \alpha'' \beta' + (1/2) \bar{\alpha} \alpha c'^2 \beta'] \right\} dz$$

$$K_D = 0$$

$$K_{TV} = 0$$

$$K_{Te} = -\frac{iK}{[\bar{\alpha}' c]_{z_0}} \int_{z_0}^{z_k} \bar{\alpha} [c' \beta + (1/2) c \beta'] dz$$

$$K_{Tx} = -\frac{iK}{[\bar{\alpha}' \alpha']_{z_0}} \int_{z_0}^{z_k} \bar{\alpha} [-(1/2) \alpha' \beta - (1/4) \alpha \beta'] dz \quad (6)$$

where K_s spherical aberration, K_l coma length, K_r coma radius, K_f field curvature, K_a astigmatism, K_d distortion, K_{tv} transverse chromatic aberration for fluctuation in beam voltage, K_{te} transverse chromatic aberration for fluctuation in lens excitation, K_{tx} axial chromatic aberration.

THE APPLICATION OF "SOL"

In Fig. 2 the principal trajectory of "SOL" system is shown. Calculations show us that the deflection aberrations get markedly reduced when it is satisfied with the condition of "SOL". But because the optical axis of "SOL" is first order approximated, thus when the electron beam passed along optical axis of "SOL", the third-order aberration is existed by the effects of second-order and third-order of lens and deflectors. On the other hand the aberrations caused by the pre-deflection coil also exist. All these aberrations form the total aberrations of "SOL". In these aberrations the field curvature is still the main aberration in "SOL" system. When the electron beam revolves in opposite direction properly in a specially

arranged combined magnetic system, in a "SOL" system, the focusing of the electron beam revolving around the principal trajectory is weakened. Thus the field curvature caused by the pre-deflection coil gets partly compensated. So, in a practical system it is not necessary to make the trajectory coincide with the trajectory of "SOL". In Fig.3 the axial distribution of the deflection field required for reaching the case of "SOL" and the practical deflection field given by the improved double pre-lens deflection system is shown. From which we can see that before principle plane of lens the compensation is suitable, the principle trajectory hasn't revolved, and after the principle plane of lens the principle trajectory revolves in opposite direction. Thus, the deflection aberrations are reduced. In such a construction the field curvature is also the main aberration. In order to decrease the aberrations furthermore it is necessary to adjust the trajectory of electron beam revolving in the opposite direction properly. A new yoke structure which is easy to make has been designed for this purpose.

It is well known that the analysis of aberrations of a combined focus and deflection system is a complex nonlinear problem. The techniques described above must be incorporated in to a optimization program, so as to get a optimizational conclusion for certain object. A new developed optimization method named "Nass Complex Method" has been used for minimizing the sum of aberrations. In Fig.4 the axial distribution of the lens field and deflection field of a optimized configuration and the aberration coefficients are shown. Here the total aberration is markedly reduced. In Fig.5 the magnitude of several aberration coefficients is plotted as a function of the mutual rotation angle between the two yokes. All the aberrations has their minimum at about the same angle.

CONCLUSION

The relation between first order principle trajectory and the third-order aberration on a combined magnetic lens and deflection system has been discussed. The concept of "SOL" (Swinging Objective Lens) has been presented to minimize the deflection aberrations. It is shown that based upon the concept of "SOL", after the optimization technique, an arrangement has been

found, which, at the corners of a 5X5 mm deflection field with 0.005-rad aperture and 1 in 10000 beam voltage ripple, produce a total aberration disk of 0.083 μ m before dynamic correction. Use such a construction the dynamic correction is not necessary for a large scan field.

ACKNOWLEDGMENTS

We particularly wish to thank professor Xi-men Ji-ye of Peking University who gives us more help in preparing this paper, and the fellow workers in our laboratory for their many helpful work constantly throughout this work.

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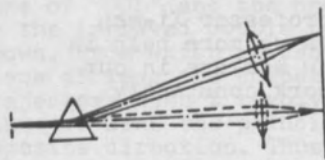


Fig.1 A schematic diagram of a Swinging Objective Lens

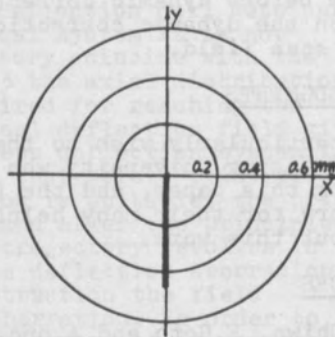
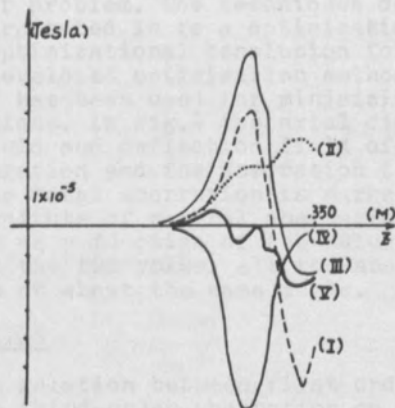


Fig.2 The principal trajectory of Swinging Objective Lens



- (I) - $C/2 \cdot B'$
- (II) - $C' \cdot B$
- (III) (I) + (II)
- (IV) D
- (V) (III) + (IV)

Fig.3 Axial distribution of the deflection field required for reaching the case of "SOL" (III), the practical deflection field given by the improved double pre-lens deflection system (IV), and the difference between (III) and (IV).

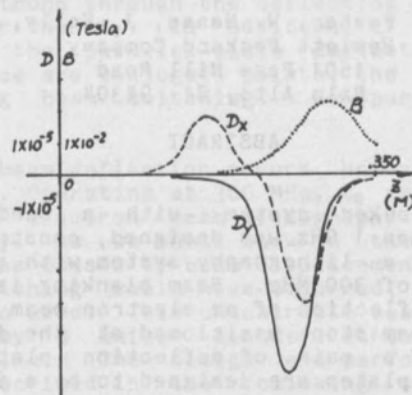


Fig.4 Axial field distribution in an optimized configuration based on "SOL". B= lens field, D_x, D_y = X- and Y- component of the deflection for unit X-deflection signal.

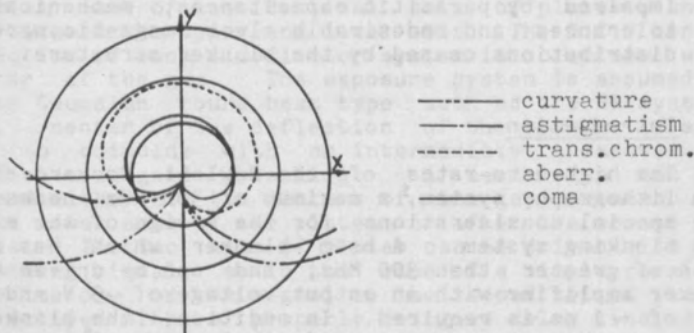


Fig.5 Magnitude of aberration coefficients as a function of the mutual rotation angle between the deflection systems for the field distribution in an optimized configuration.

A HIGH SPEED BLANKER FOR A 300 MHz LITHOGRAPHY SYSTEM

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ABSTRACT

A blanker system with a bandwidth of greater than 1 GHz was designed, constructed and tested for a lithography system with a maximum data rate of 300 MHz. Beam blanking is achieved by the deflection of an electron beam crossover onto a beam stop positioned at the deflection center of a pair of deflection plates. The deflector plates are designed to be a strip line structure with an integral delay. Spurious exposure caused by beam displacement on the wafer is minimized by conjugate blanking and by optimal choice of the length of the delay time. The optimized blanker produced a beam displacement of $< 25 \text{ \AA}$ on the wafer when a blanking voltage of 5 V was applied between the plates. Special attention was paid to ensure that the performance of the blanker is not impaired by parasitic capacitances, mechanical tolerances and undesirable electromagnetic wave distributions caused by the blanker structure.

1. Introduction

The high data rates of the Hewlett Packard electron beam lithography system,¹ a maximum of 300 MHz, necessitates some special considerations for the design of the electron beam blanking system. A beam blanker which has a bandwidth of greater than 300 MHz, and can be driven with a blanker amplifier with an output voltage of $\sim 5 \text{ V}$ and a rise time of $\sim 1 \text{ ns}$ is required. In addition, the blanker must have an attenuation ratio of at least 10^6 and beam deflection during beam switching on the targets must be smaller than one tenth of a pixel to ensure that no intolerable spurious exposures occur.

For systems with slow data rates, i.e. when the exposure time per pixel, t_e , is much longer than the rise time of the blanking signal, t_r , adequate blanking can be achieved by the deflection of the electron beam onto a beam

stop with a pair of parallel plates, assuming the transit time of the electrons through the deflection plates, t_t , is also much smaller than t_0 . In addition, if the center of deflection of the parallel-plate deflector and the wafer/mask surface are conjugate points, the beam will stay stationary during beam switching. No spurious exposures will occur.

Additional beam deflection occurs, however, when t is comparable to t_r . Operating at 300 MHz, t_0 and t_r for the Hewlett Packard electron beam lithography are 3.3 ns and 1 ns respectively. As we shall show in the next section, spurious exposures caused by beam displacement on the wafer during beam switching would have occurred, should such a blanker have been used. This undesirable beam displacement is eliminated by a unique blanker structure with an integral delay line. The design and performance of the blanker are described in the following sections. The characteristics of a simple parallel-plate blanker are also calculated and presented for comparison.

2. The Parallel-Plate Blankers

The simplest and most commonly used blanker is the simple parallel-plate blanker. More than one set of parallel plates can be used in tandem. We shall consider the special case of two identical sets of plates with a gap, G , between the upper and lower sets. The D.C. center of deflection of such a deflector system is coincident with the center of the gap. The exposure system is assumed to be of the Gaussian round beam type such as the HP system. The D.C. center of the deflection of the blanker is also assumed to coincide with an intermediate crossover to facilitate conjugate blanking. A beam stop can be positioned either at the center of the gap between the upper and lower sets of the plates or after the second set of plates. The two sets of plates can be driven with the same blanking signal, as in the case of a simple parallel plate deflector, or the signal to the second set of plates can be delayed with a properly designed delay line as in the case of a slow wave structure.

Two important considerations in designing a blanker for a lithography system are the minimization of the blanking voltage and the spurious exposures during beam switching. The minimum blanking voltage, V_B , is determined by the basic sensitivity of the deflectors and the location of the beam stop, as indicated in the following equation:

$$\left. \begin{aligned} V_B &= \frac{2\alpha}{\theta} ; \text{beam stop after the deflection} \\ &\quad \text{plates} \\ &= \frac{4\delta_0}{d} ; \text{beam stop at the center of the} \\ &\quad \text{blanker gap} \end{aligned} \right\} 1$$

where β = angle of beam deflection, mr/V
 α = semiangle of beam, mr
 δ_0 = displacement of the beam crossover
 at the center of the blanker, $\mu m/V$
 d = the diameter of the beam

Proper choice of the location of the beam stop can significantly reduce the blanking voltage. This will be clearly demonstrated later.

The spurious exposure during beam switching will not occur if the beam displacement, $M\Delta$, on the wafer/mask vanishes.

$$\Delta = \left(\delta - \frac{\theta L}{2} \right)$$

where M = the magnification of the lens(s) between the blanker and the wafer/mask
 δ = beam displacement at the exit of the blanker plates
 L = the full length of the blanker

, the apparent beam displacement, represents the displacement of a virtual source at the center of the blanker. If M is less than one tenth of a pixel, there will be negligible spurious exposure for all practical purposes.

The above mentioned quantities can be obtained by solving the equation of motion of the electrons as they traverse through the blanker:

$$\left. \begin{aligned} z &= z_0 + v_z t \\ m \frac{d^2 x}{dt^2} &= e \frac{V(t)}{D} \end{aligned} \right\} 2$$

where v_z is the velocity of an electron accelerated through a voltage difference, ϕ , and

$$v_z = \beta c$$

$$c = \text{speed of light in free space}$$

$$\beta = \frac{2\sqrt{\epsilon\phi} (1 + \epsilon\phi)}{1 + 2\epsilon\phi}$$

$$\epsilon = \frac{e}{2mc^2} = 0.978 \times 10^{-6} \quad (\text{R.M.K.S. units})$$

$$D = \text{spacing between the deflection plates.}$$

The fringing field around the ends of the deflectors are neglected.

$V(t)$ is the voltage difference between the blanker plates. To turn on the beam, the magnitude of $V(t)$ changes from V_0 , the output voltage of the blanker amplifier, to 0 at $t = 0$ with a rise time of t_r . The same voltage is applied to the lower half of the plates after a time delay t_D .

$V(t)$ can be expressed as follows:

$$V(t) = \begin{cases} \frac{1}{2} V_0 \left[1 - \operatorname{erf} \left(\frac{1.82t}{t_r} \right) \right], & -\frac{L}{2} < z < -\frac{G}{2} \\ \frac{1}{2} V_0 \left\{ 1 - \operatorname{erf} \left[\frac{1.82(t-t_D)}{t_r} \right] \right\}, & \frac{G}{2} < z < \frac{L}{2} \\ 0, & \text{elsewhere} \end{cases}$$

where L = total length of the deflector

V_0 = blanking voltage

t_D = delay time

$\operatorname{erf}(x)$ = the error function

3. Simple Parallel-Plate Blanker

The properties of a simple parallel plate blanker were calculated. This blanker is realized with $t_D = 0$ and $G = 0$ in Equation 3. Figures 1 to 3 show the angle of deflection, θ , the beam displacement at the center of the blanker, δ_0 , and the apparent beam displacement, Δ , as functions of time. The blanking pulse is assumed to propagate through the blanker plates in the direction perpendicular to the optical axis. Figure 4 and Figure 5 show Δ as a function of time for various values of the rise time of the blanking signal. The characteristics are summarized in Table I.

TABLE I. CHARACTERISTICS OF A SIMPLE PARALLEL PLATE BLANKER

Length of Plates, L	= 3.4 cm
Spacing between Plates, D	= 0.2 cm
Rise Time, t_r	= 1 ns
Angle of Deflection, θ	= 0.4 mr/V
Beam Displacement, δ_0	= 1.9 $\mu\text{m}/\text{V}$
Maximum apparent beam displacement, Δ	= 0.6 $\mu\text{m}/\text{V}$

A maximum beam displacement of 3 μm on the wafer/mask occurs with a blanking voltage of $\sim 5\text{V}$. This beam displacement is much larger than one tenth of a pixel to ensure that no spurious exposures occur.

4. An Optimized Parallel Plate Blanker

The apparent beam displacement can be minimized if a proper delay time, t , is imposed on the blanking signal feeding the lower half of the deflection plate. The optimum delay time is obtained by solving equation 1 for various values of t_D . The optimum delay time for a blanker of $L = 3.4$ cm, $D = 0.2$ cm and $G = 0.24$ cm for various values of the rise time, t_r , were calculated and are listed in Table 2.

TABLE 2

RISE TIME, ns	OPTIMUM DELAY, ns
0.1	0.27348
0.2	0.28014
0.4	0.28001
0.6	0.27965
0.8	0.27949
1.0	0.27940

5. PROPERTIES OF THE OPTIMIZED BLANKER

The properties of an optimized blanker for 20 KeV electrons will be described in this section. Table 3 lists the mechanical dimensions and electrical specifications of the optimized blanker.

TABLE 3

LENGTH	= 3.4 cm
SPACING BETWEEN PLATES	= 0.2 cm
GAP BETWEEN THE TOP AND THE BOTTOM HALVES	= 0.24 cm
OPTIMUM DELAY TIME	= 0.2794 ns
CHARACTERISTIC IMPEDANCE	= 50 ohms
RISE TIME OF BLANKING SIGNAL	= 1 ns

The apparent beam deflection, Δ , as a function of time, is shown in Figure 6. The maximum displacement is 2.5 Å/V versus the 6000 Å/V for a simple parallel-plate blanker otherwise identical physical dimensions.

Figure 7 and 8 show Δ as a function of time for various values of the blanker rise time. The apparent beam displacement is smaller than one tenth of a pixel for rise time $t_r > 0.2$ ns. For smaller values of t_r , the apparent beam displacement become larger over a time interval approximately equal to t_r . Since t_r is now much smaller than t_e , no observable spurious exposure should occur.

δ_0 as a function of the delay time was also examined, the result is shown in Figure 9. A 10% variation in the delay time results in a δ_0 of $\sim 500 \text{ \AA}$ or a beam deflection of $\sim 0.05 \text{ }\mu\text{m}$ on the wafer/mask. To avoid spurious exposures, the delay time has to be accurate to within $\sim 10 \%$ of the nominal value.

The characteristics of the optimized blanker are listed in Table 4.

TABLE 4

RISE TIME OF BLANKING SIGNAL = 1 ns
ANGLE OF DEFLECTION = 0.4 mr/V
BEAM DISPLACEMENT AT CENTER OF BLANKER = 1.9 $\mu\text{m}/\text{V}$
MAXIMUM APPARENT BEAM DEFLECTION = 2.5 $\text{\AA}/\text{V}$

In the Hewlett-Packard Lithography system, a beam stop made of gold plated silicon is positioned at the center of the blanker where a beam crossover is formed.² The diameter of the crossover is typically $< 0.1 \text{ }\mu\text{m}$ for a beam current up to 600 na. The beam semiangle is $\sim 4 \text{ mr}$. The minimum voltage required to blank the beam with an attenuation of > 10 is the voltage required to deflect the beam over a distance equal to four times the diameter of the beam. A voltage of $\sim 0.2 \text{ V}$ is thus required for the optimized blanker. The minimum voltage in practice is approximately 1 V to allow for mechanical tolerances in the construction of the blanker. If the beam stop were to be positioned beyond the blanker plates away from the crossover, the minimum voltage is the voltage required to obtain an angle of deflection equal to twice the beam semiangle, and a minimum voltage of 20 V would be required.

The physical structure of the optimized blanker was designed to be a stripline with a U shaped integral delay. The length of the "U" is chosen to obtain the optimum propagation delay shown in Table 3. The blanker plates, together with a simplified schematic of the blanker system, is shown in Figure 10. Blanking signal from the amplifier are fed into the top portion of the plates and propagated through the "U" delay and the lower half of the plates which are terminated with their characteristic impedance of $50 \text{ }\Omega$. The shape of the plate structure is trimmed as indicated in Figure 10 to maintain a constant

characteristic impedance throughout the structure. TDR measurements indicate that reflections of the blanking pulses being propagated through the structure is less than 1% anywhere along the structure.

The total blanker structure together with the mechanical support is shown in Figure 11. The mechanical structure of the system was designed to maximize the thermal stability and to minimize parasitic capacitances which can deteriorate the performance of the stripline.

6. Conclusion

The optimized blanker has been performing well with the Hewlett Packard Lithography system. Wafers/masks exposed with a 300 MHz data rate shows no observable spurious exposure. Experimental tests and theoretical calculations also indicate that the blanker design is suitable for lithographic systems with data rates up to > 1 GHz.

7. Acknowledgements

The authors would like to thank Emmett Gerrity, Joseph Kral, Ron Lackey and Steven Palermo for their help in the assembly of the blankers; Richard Mounq for the fabrication of the silicon knife edges; Tim Groves for his suggestion of the use of a knife edge at the beam crossover; Geraint Owen for his assistance in field calculation in the blanker plates; Alan Keen for assistance in testing the electrical properties of the blanker structure and Terry Miller and Rene Cook for the preparation of this manuscript. The authors would also like to express their special thanks to the model shop of HP Labs for the fabrication of the blanker structure.

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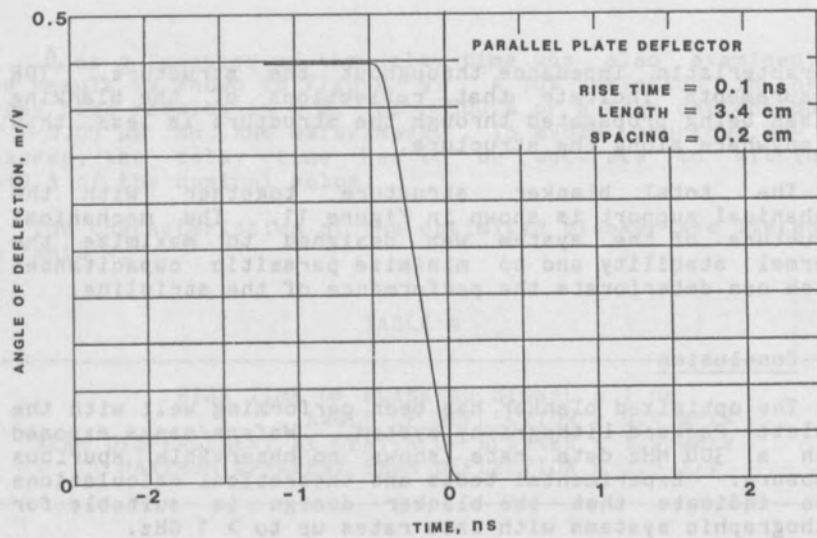


FIGURE 1

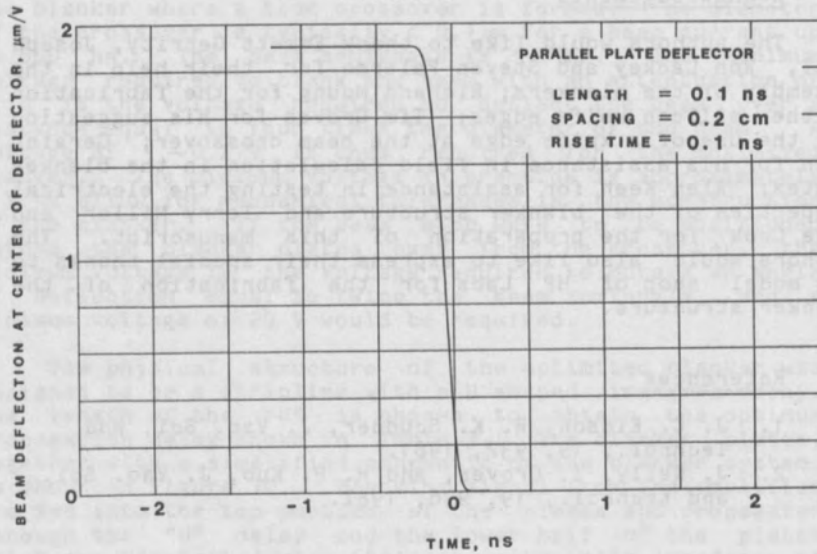


FIGURE 2

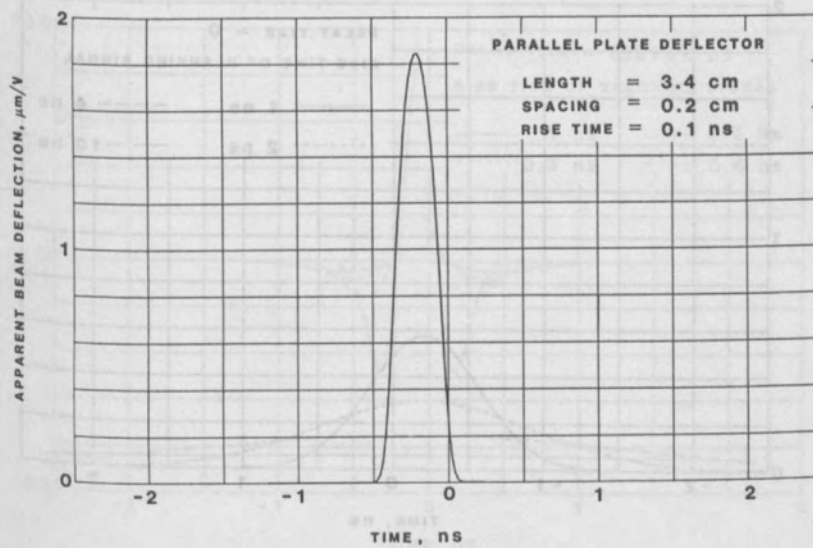


FIGURE 3

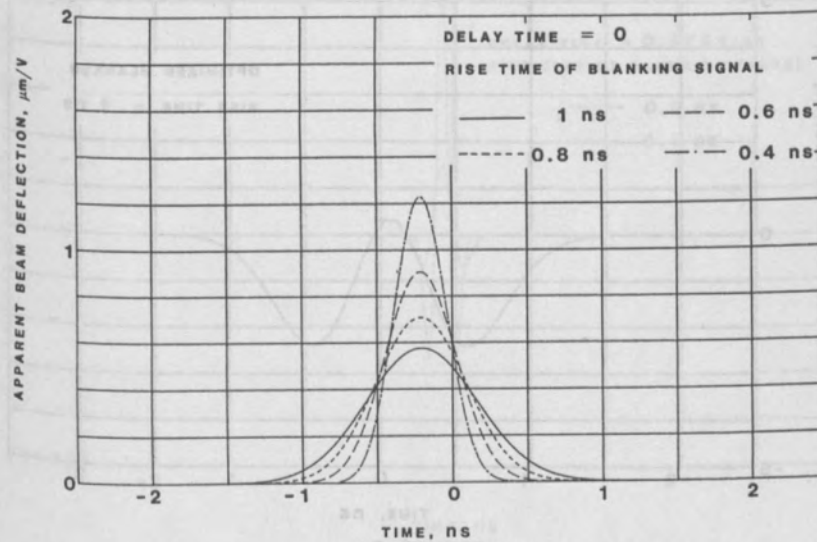


FIGURE 4

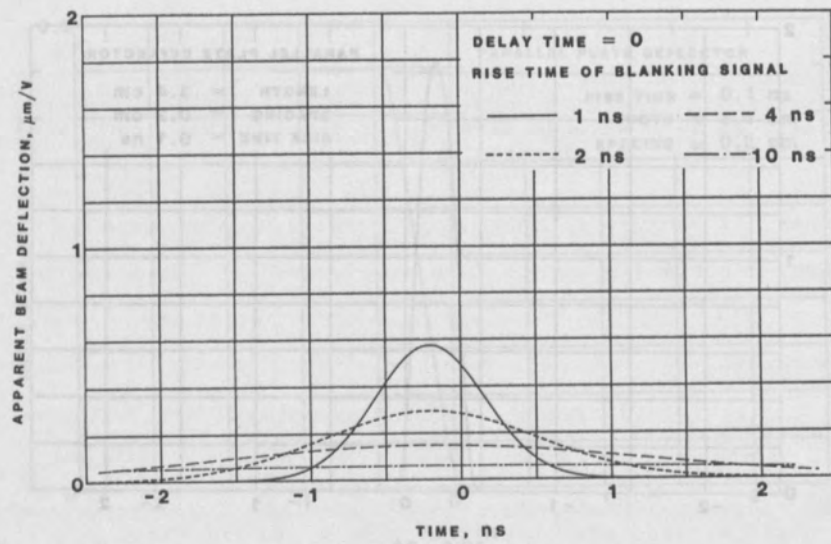


FIGURE 5

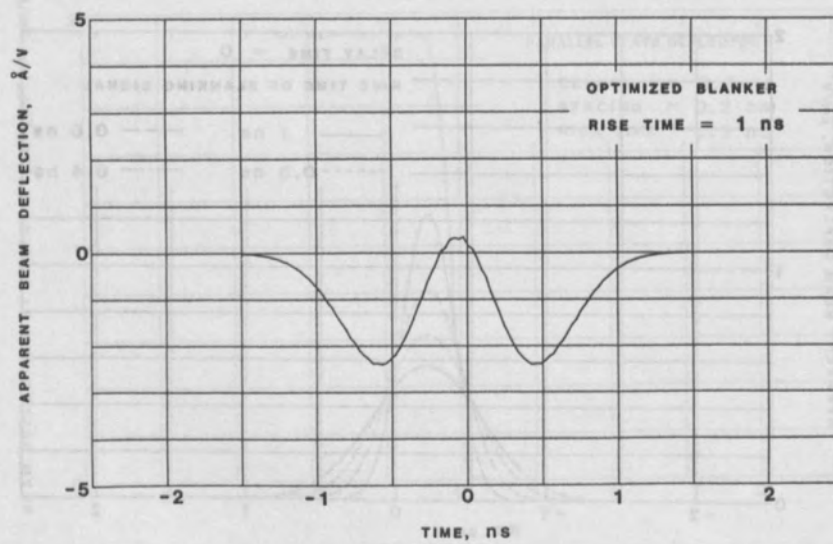


FIGURE 6

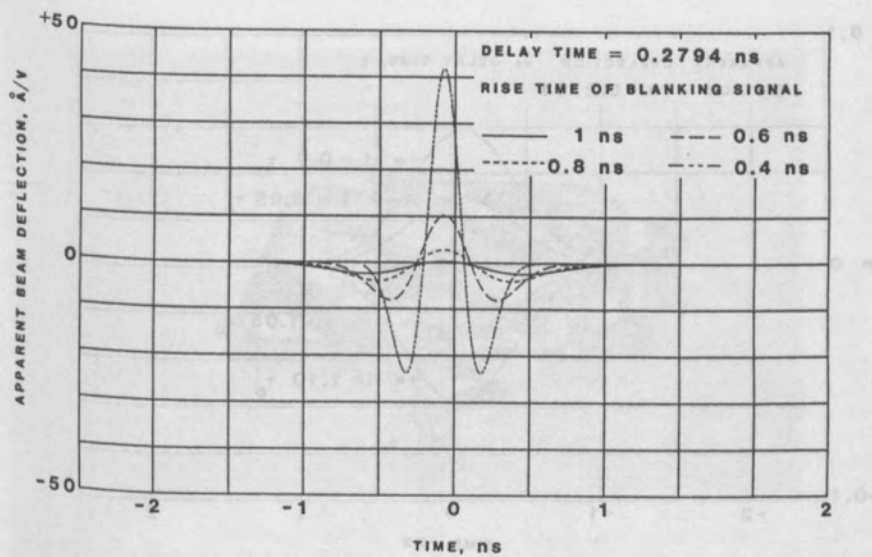


FIGURE 7

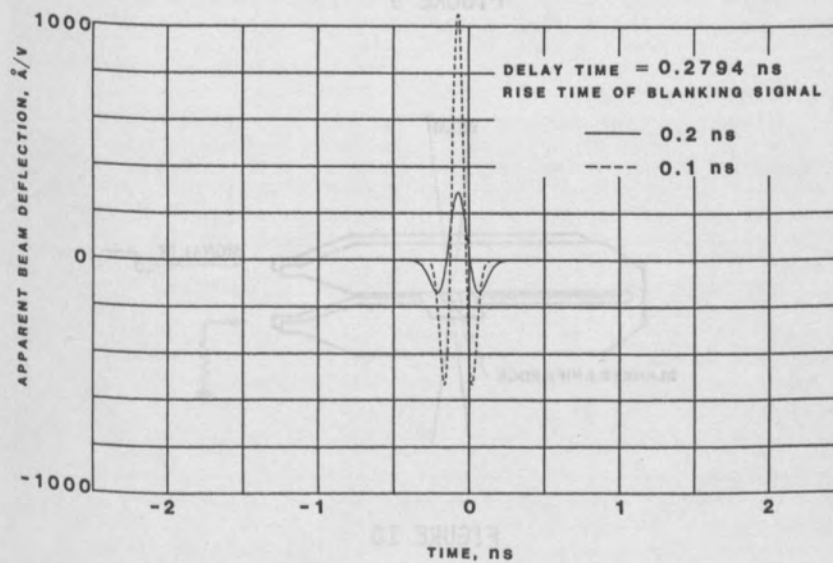


FIGURE 8

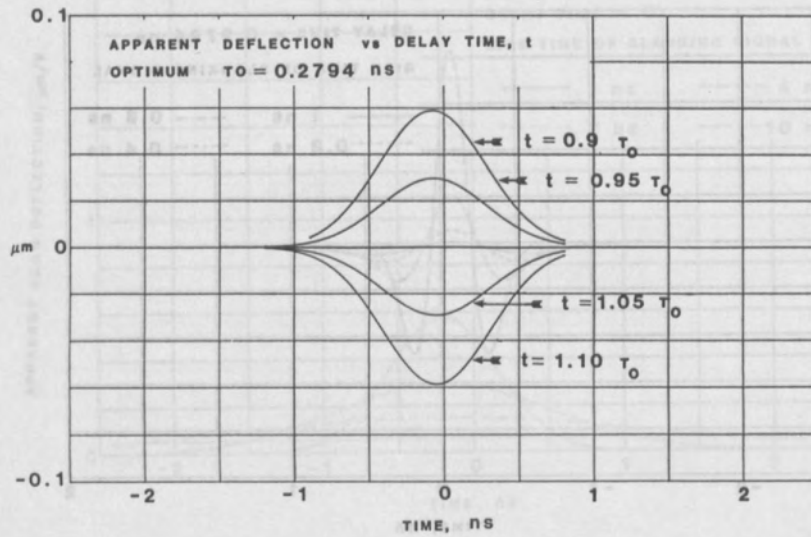


FIGURE 9

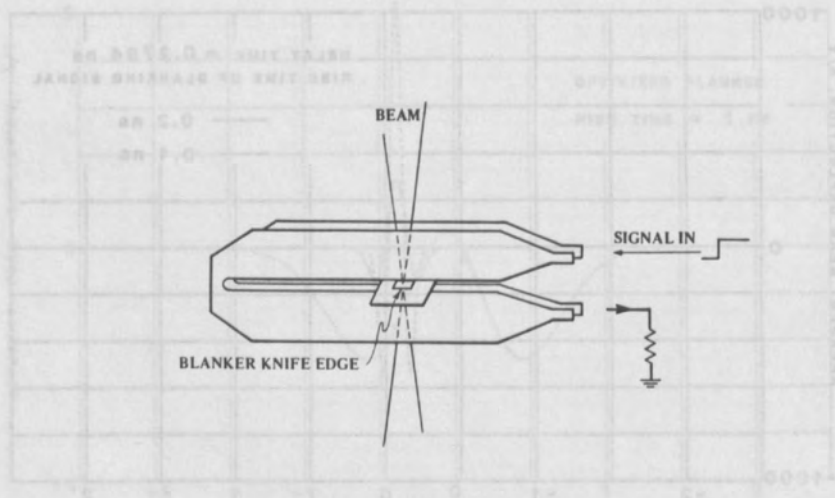


FIGURE 10

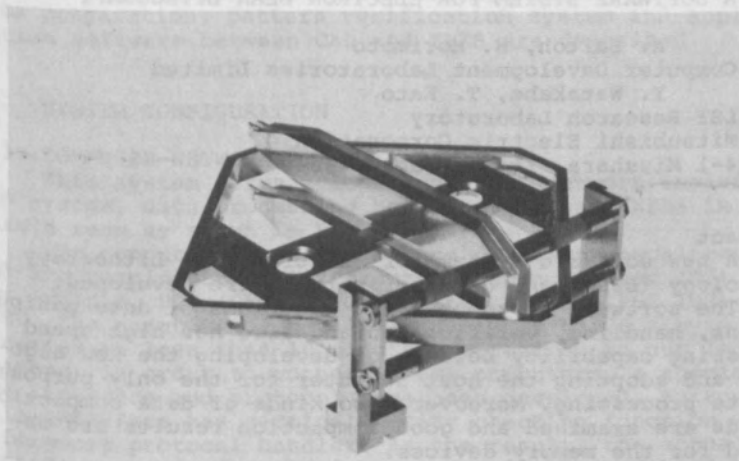


FIGURE 11

1. INTRODUCTION
Electron beam lithography technology (EBL) is one of the very important factors for VLSI device fabrication because of the high resolution down to 1 micrometer and the ultra short time. In order to realize the high performance, it is necessary to develop a system suitable for the electron beam exposure system. Recently the chip size and the volume of exposure data of VLSI have become larger, the system also has become smaller and the logic has become complicated. Consider the current devices, for instance 10K to 100K gates volume of pattern data and mask pattern size are reduced for gate as shown in Fig. 1. On the other hand, mask pattern size is developing in parallel with logic devices. Because mask size of 6" is not large, devices are required to construct a computer at a small size. It makes such large volume and mask kind of data new software system is developed and a host computer is required for data processing. Finally, full computer network, which includes CPU system and EBL, is constructed.

A SOFTWARE SYSTEM FOR ELECTRON BEAM LITHOGRAPHY

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Abstract

A new software system for Electron Beam Lithography Technology (EBLT) and computer network are developed.

The software system has the functions of data manipulations, handling, verification and also has high speed processing capability because of developing the new algorithm and adopting the host computer for the only purpose of data processing. Moreover, two kinds of data compaction methods are examined and good compaction results are obtained for the memory devices.

Concerning the computer network, the special communication interface and protocol are developed and the transfer rate of 40KB per second is achieved in data transfer from one disk to another disk.

This system enables the development of high density VLSI, such as 1M(D) RAM, in a short period.

1. INTRODUCTION

Electron Beam Lithography Technology (EBLT) is one of the very important factors for VLSI device fabrication, because of the high resolution down to 1 micrometer and the quick turn-around time. In order to realize the high performance, it is necessary to develop hardware and software suited to the Electron Beam Exposure System (EBES).

Recently the chip size and the volume of pattern data of VLSI have become larger, the pattern size has become smaller and the logic has become complicated. Considering memory devices, for instance 256K(D) RAM, a large volume of pattern data and small pattern size are required for EBLT as shown in Fig.1. On the other hand, quick turn-around time in developing is desirable for the logic devices, because many kinds of different logic devices are required to construct a computer at a same time. To handle such large volume and many kinds of data, new software system is developed and a host computer is introduced for data processing. Finally, full computer network, which includes CAD system and EBES, is constructed.

In this paper, the system configuration, pattern data preparation, pattern verification system and application software between CAD and EBES are described.

2 SYSTEM CONFIGURATION

2.1 COMPUTER NETWORK

This system forms a local computer network including CAD system, data processing host computer and EBES in shield room as shown in Fig.2.

The computers on network have different architectures and are running under different Operating System (OS), for example, PDP (DEC) in CAD system and ECLIPSE (DG) in EBES. The quantity of data is usually 10 to 20 M byte and transfer in less than 10 minutes is desired in our laboratory. In order to connect these computers, a special DMA interface and protocol have been developed. Moreover, this interface has vertical parity checking function and a firmware protocol handler. As the result, the actual transfer rate is decreased by some software overhead but retains 40 K byte/second speed in file transfer from one disk to another.

This system has several other features for convenience of use, for example, the ability to list, rename, or delete files on any disk which is connected to the system, by the command from any terminal which is connected to the system.

2.2 DATA FLOW

Pattern data (designed data), that has been finished for the LSI design, is transferred from CAD system to host computer. The data transferred to host computer is checked, modified and finally converted to EB pattern data. Host computer, which is adopted for the only purpose of pattern data processing, has capability of handle the large volume of data such as 256K and 1M(D) RAM in high speed. This system is designed so as to distribute the processing to the mini-computer functioned by relay station and/or the computers in CAD system, thus reducing the load on the host computer and avoiding some problems.

The EB pattern data is transferred to EBES through a high speed communication line and/or archived to Magnetic Tapes (MT). When the EB pattern data transfer is completed, EBES writes the patterns on the substrate. EBES (EeBES-40) is a raster type electron beam exposure system with a beam blanking rate of 40 MHz and up to 10 substrates can be automatically written under control of a previously prepared job stream (JOB QUEUE file).

3 PATTERN DATA PREPARATION

The shortening of data preparation time is a dominant factor for a quick turn around time system(1), but the processing time for VLSI becomes longer and longer, because of trends toward higher density and smaller dimensions. Thus a high speed and multi function software is desirable.

3.1 General flow of this system

At the first stage, the design data on the CAD system is converted to an intermediate Masking file (M file) by an interface program, and after performed some modifications, EB pattern data is generated by an EB formatting program which is suited to EBES.

A characteristic of this software system is the adoption of M file as an intermediate file. And the advantages of using single M file are as follows.

1) M file is a commonly used intermediate file.

All utilities are connected to single M file as is shown in Fig.3. This means that I/O of all utilities are performed only to M file and are commonly used and/or developed by all users.

2) Interface with EBES system are made easier.

There are many kinds of EBES system (raster and vector etc.) and new types are announced or under development. In general, each EBES needs its own special formatted data to be driven. When a new system is installed, developing a new formatting program for new system makes it possible to use all utilities.

3) Interface with a CAD system is made easier

For a CAD system, the same notation with EBES is adopted, that is, a new system will be introduced easily by developing only the interface program between new CAD system and M file.

4) M file is compacted

M file is a polygon base binary file which includes rectangle, trapezoid and repeat type. Compacted data means shorter data processing time.

3.2 MULTI FUNCTION OF THE SYSTEM

EBLT needs many kinds of data manipulations, for example, proximity effect correction is a special manipulation for EB data processing.

Next, some functions which comprise this system are described.

1) MERGE

Many M files are merged into one M file. Scaling, offset, rotation, mirroring and repetition are performed in merging. This utility is especially effective for memory devices which have many repetition of an identical

pattern. There is another merge utility for the merge of EB pattern data.

2) SIZING

Patterns can be enlarged or shrunk with specified volume. The OUTLINE process must be performed beforehand if correct sizing is required. Otherwise, abutting shapes will be overlapped or separated by SIZING.

3) OUTLINE

Abutting patterns can be merged outlined. At the same time, overlapping of patterns are eliminated. This function is used by the users of vector type EBES, not by raster type users, because vector type EBES exposes the overlapping patterns multiply.

4) ELIMINATE

The pattern in the specified window area is eliminated and these shapes are output to another M file or ASCII text file. With the use of the elimination utility and merging utility, pattern modification is done easily in the EB pattern data. This function is also used to correct minor digitization errors in LSI patterns.

5) OTHER UTILITY

This system has many utilities, other than mentioned above, which are already in use or under development, a proximity effect correction utility(2)(3) and a design rule checking utility (DRC) for examples. These utilities include complex and interesting algorithm, but it is beyond the scope of this paper to explain detail. So details will be published in the next paper.

4 PATTERN GENERATION USING THIS SYSTEM

4.1 JOB FILE GENERATION

Pattern layout is specified by a disk file called 'job file'. The job file is in ASCII and specifies all of the writing conditions as follows.

- a) Pattern file name to be written on the substrate.
- b) Pattern layout on the substrate.
- c) Reverse or normal tone for each pattern.
- d) Alphanumerics written on the substrate.
- e) Amount of compensation for temperature.
- f) Scale factor, and so on.

The EBES reads the information from the job file and exposes patterns in order of appearance in the job file. So the job file is regarded as an interface between EBES and its users, and it has a great influence on the performance of EBES.

The job file generation utility, which optimizes the pattern layout and writing order, is developed in order to minimize the writing time. Furthermore, this utility

automatically generates several additional patterns required by a wafer processing shop.

This utility also has a capability of interactive nested chip layout. That is, first, the software inter-relates the nested pattern layout structure. Next it expands the structure and sorts the array to optimize the chip layout. This nested chip layout capability has great advantages of pattern data volume reduction and complex chip layout.

In the case of memory devices pattern, more than 80% of the chip pattern is an iterative of one or two primitive cells. In a normal manner, these primitive patterns are expanded and no relation between them is assumed. Using the nested chip layout, the iteration pattern array is recognized as a one or two primitive patterns and reduced to less than 20% of its conventional size.

Nested chip layout also enables us to make a very complex chip layout easily. Fig.6 shows an example of a complicated chip layout and this capability realizes much flexibility needed for a design or wafer processing shop.

4.2 DATA COMPACTION

As the VLSI chip becomes complicated, the pattern data volume of the chip becomes larger. This causes a large overhead time in handling (reading, writing, calculating) the pattern data. At the same time, a large storage area (disk space) for the pattern data becomes necessary.

For this reason, it is apparent that reducing the data is very effective for EBLT. One approach is discussed above, that is, iterative pattern arrays can be reduced down to one or two elements and a nested pattern layout is used. Another approach is discussed here. This method is that, arrayed pattern in M file is interpreted and packed into EXTENDED format when it is converted to the drawing data for EBES. So the complicated job file for the purpose of reducing the pattern data volume is no longer necessary because the chip pattern is made up of one pattern file with this technique.

Both volume and the conversion time of pattern data have been reduced to 10% of the conventional method applying this technique to memory devices as shown in Fig.1.

4.3 EXAMPLPE

Fig.7 shows an example of the pattern generated by this software system. This is a DSW reticle comprising 3 VLSI memory chips. In this example, the nested chip layout technique is used in order to add test chips. Each chip is constructed with 4 subchips and EXTENDED format

is used for subchip pattern data. 5 mm wide border frame line, barcode, and fiducial marks are added automatically in job file generation. This reticle can be written within a half hour after optimization of the job file.

5 VERIFICATION SYSTEM

As is well known, verification of pattern data is very important, because errors cause severe damage to LSI production. In EBLT, it becomes a more serious problem than in conventional photo lithography techniques, because some parts of LSI pattern are constructed finally in EBLT, moreover, short checking time and precise check are needed.

A conventional pen plotter or human check are generally used for this purpose after software checking, but it takes a long time to plot even one pattern. In some cases, plotting time is longer than EBES writing time. Therefore, in order to shorten the checking time, a new verification system that aids the designer is developed. The hardware of this system is configured from color CRT, key board, joy-stick and color hard copy facility and connected to host computer as one terminal.

The software feature of this system is as follows.

- 1) Interactive checking with using zooming function.
- 2) Two kinds of display mode, fill mode and outline mode.
- 3) Multi level display capability, which enable the overlapping check.
- 4) Comparative check capability.
- 5) Location and pattern size display function.

An example is shown in Fig.8. The menu is shown at the left part and the coordinate at the top left in the figure. Verification of pattern data becomes quick and reliable with this system.

6 CONCLUSION

This paper described a computer network and software system for EBLT. However the trend of complication of LSI will continue and new EBES with more high performance will be developed in a few years. So the software will have to be developed and evaluated. Especially, new data compaction for logic LSI and the proximity effect correction software will become more important.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Dr.H.OKA, Dr.H.NAKATA and T.Kashiwaki for their encouragement.

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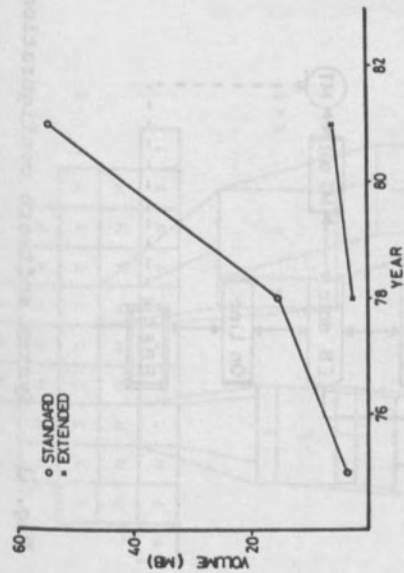


Fig. 1 Trend of the pattern data volume

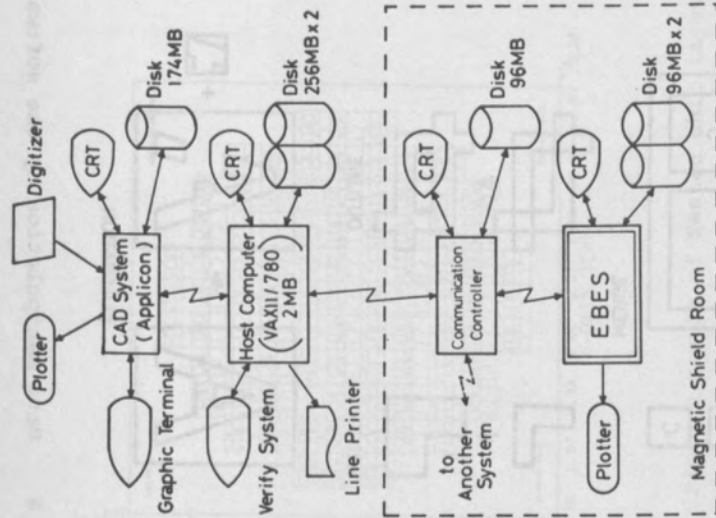


Fig. 2 System hardware configuration

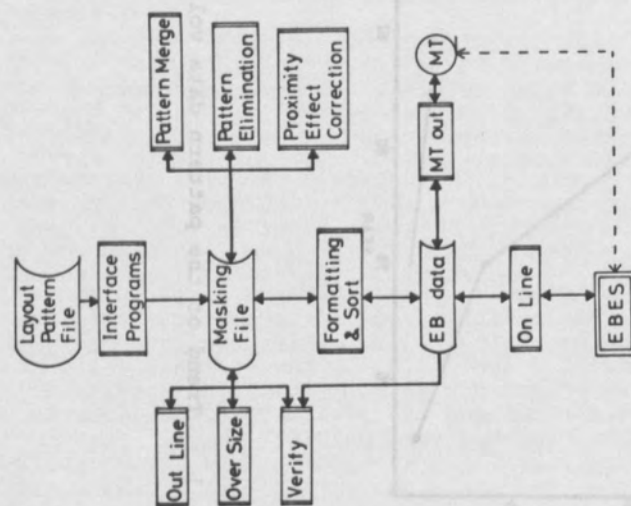


Fig. 3 System software configuration

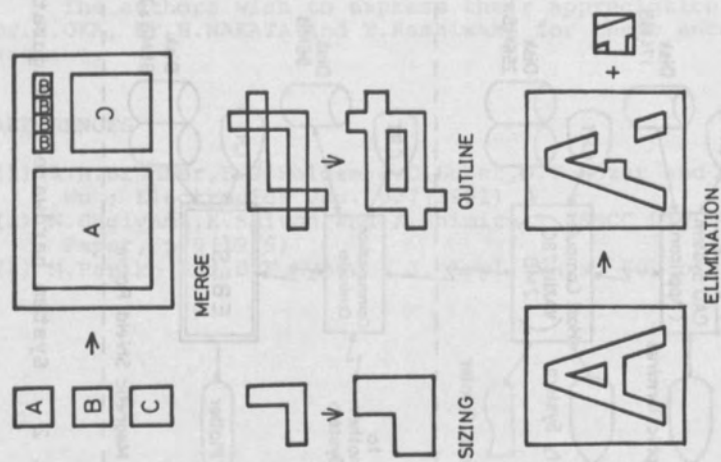


Fig. 4 Data manipulation by the software

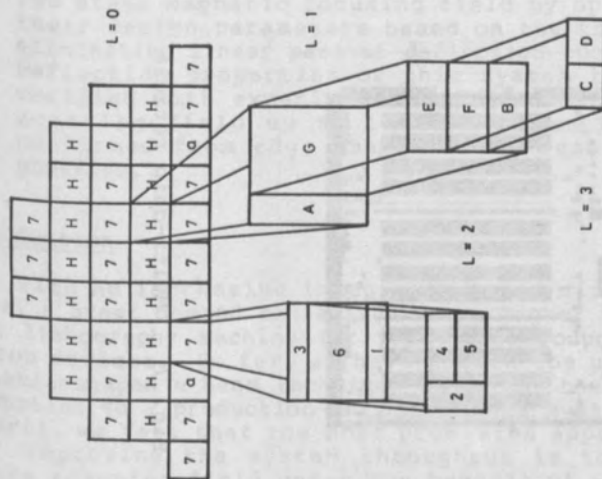


Fig. 5 Nested chip layout

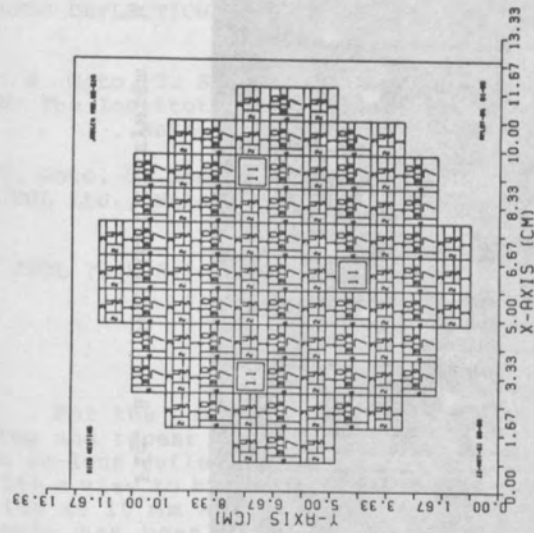


Fig. 6 Plotout result of Nested chip layout

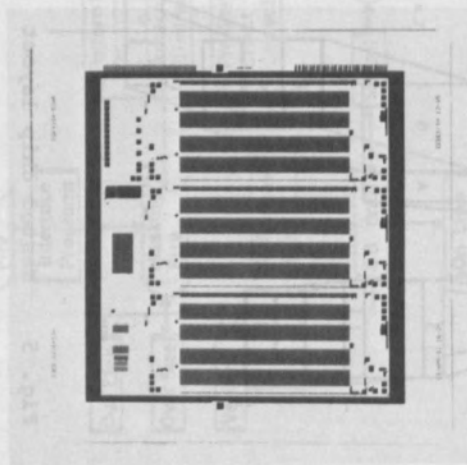


Fig. 7 Multi-chip reticle

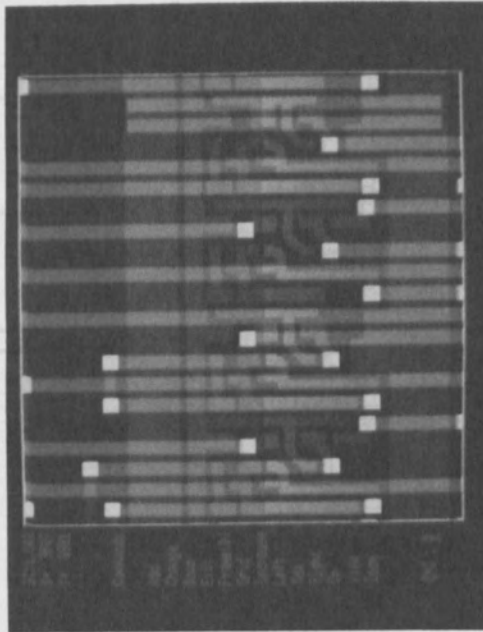


Fig. 8 Verification system

MULTIPLE ELECTROSTATIC DEFLECTORS APPLIED TO
IN-LENS DEFLECTION SYSTEM FOR EXTENDED SCANNING FIELD

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ABSTRACT

For the purpose of increasing throughput of step and repeat type e-beam lithography machines, an in-lens deflection system has been investigated with a view to extending the scanning fields to as wide as 10 mm squares. With the system, importance has been attached to reducing number of deflectors for facilitating practical operations.

A couple of electrostatic octupoles free of 3rd and 5th θ -components have been placed inside a two stage magnetic focusing field by optimizing their design parameters based on the theory for eliminating linear part of deflection aberrations. Deflection properties of this system have been verified with experiments and expandability of scanning field up to 10 mm squares has been confirmed from edge sharpness of beam current profiles.

Introduction

With an increasing integration in semiconductor devices, a great demand has arisen for a higher throughput e-beam lithography machine for practical production of sub-micron devices. So far, we have proven the usefulness of variable-shaped e-beam technique which has been successfully applied to a production-purpose e-beam system [1,2]. At present, we feel that the most promising approach to further improving the system throughput is to expand the usable scanning field under the benefit of in-lens focus deflection system.

Meanwhile, a theoretical study for such system has been propounded by the present authors at IPCR [3] concerning a practical application of the MOL (Moving Objective Lens) concept [4]. They proposed an in-lens-deflector configuration where the aberrations linear in deflection could be eliminated by use of multiple (four) electrostatic deflectors controlled in their relative strengths and rotational positions.

From the standpoint of practical design, however, it is desirable that the number of deflectors be reduced keeping inescapable aberrations within a permissible amount; thus making sure the operational stability in the system. For that reason, we are working to develop a simplified in-lens deflection system accommodating a couple of electrostatic deflectors inside a two-stage magnetic focusing lens field. The present experimental work concerns the investigation for such system, together with the theoretical approach of optimizing aberrations, carried out with a view to extending the scanning field to as wide as 10 mm square.

Theoretical Approach and Experiments

Figure 1 shows schematically the configuration of the in-lens deflection system under investigation, where two electrostatic deflectors D_1 and D_2 are arranged sequentially along a common axis which are placed in a two-stage magnetic lens field, L_1 a demagnification lens with a factor of 3 and L_2 a projection lens with a unit magnification.

According to the authors' theory [3], it is possible with this two deflector system to remove exclusively any one of the aberrations linear in deflection (linear part), e.g., coma, transverse chromatic or landing error, by the suitable choice of parameters, such as their relative intensities and rotation angle between them. Moreover, the non-linear aberrations with respect to deflection, typical with the astigmatism and the curvature of field, can be minimized by properly choosing the lengths and the positions of the deflector electrodes.

The distance between objective and image planes plays as a key parameter for deciding the property of the optical system, which directly determines the aberrations including the image blurring due to space charge effect; the excitations of magnetic lenses with given pole piece dimensions; and the maximum operation voltages of the deflectors, which is the most serious factor for putting the system into

practical use. With the present system, importance has been attached to keep the maximum voltage of deflectors within a practical value, say ± 1 kV. Finally, we have set the object-image distance to 300 mm as shown in Table 1. The distance corresponds to the value scaled up by 20 % compared with that given as an optimized parameter in the previous paper [3]. The axial distribution of the magnetic field has been calculated using the finite element method [5], the result being shown in Fig. 2. The upper lens is a conventional symmetric one which is excited with 1,600 ampere-turns. The lower lens is constructed of nine gaps of elemental lenses whose excitations can be controlled independently with a maximum ampere-turns of 300 for each. The total length and the diameter of this multi-lens construction are designed as large as 130 mm and 90 mm, respectively, to facilitate accommodation of the deflector system. The deflection field distribution along the deflector axis has been approximated by using an analytical function of hyperbolic tangent formula.

The thorough optimizations have been carried out through computer simulation to minimize the non-linear aberrations after eliminating the linear part. Following three cases of the given configuration are considered; 1) elimination of coma aberration, 2) elimination of transverse chromatic aberration, and 3) elimination of landing error. The typical design specifications used for numerical calculations are shown in Table 1. Table 2 represents the resulting aberrations for the above three cases. It should be noted from Table 2 that the residual aberrations are the largest in case 3), and on the other hand they can be kept the least in case 2). It can be emphasized, moreover, that the astigmatism and the curvature of field in case 2) have been so much reduced as to make the dynamic corrections unnecessary.

We have conducted preliminary experiments to confirm the numerical results of case (2), using the in-lens deflection column described above. The octupole electrostatic deflectors have been used which are free of 3rd and 5th θ -component fields. They are composed of eight pole electrodes over which defined potentials are distributed in the way as V_x , $(V_x + V_y)/\sqrt{2}$, V_y , $(V_y - V_x)/\sqrt{2}$, To fit the deflection field to hyperbolic tangent distribution, furthermore, grounding cylindrical electrodes having the same diameter as that of the deflector have been placed close to its top and bottom sections. The schematic of the octupole construction is illustrated in Fig. 3 together with calculated potential distribution. Figure 4 shows schematically the measuring system for carrying out the present experiments, where magnetic lenses are not illus-

trated. The electrodes of the 1st (D_1) and the 2nd (D_2) deflectors are supplied with highly stabilized potential signals through a couple of resistor networks which set the intensities and rotation angles of the deflector fields to optimized values. The intermediate deflector placed between the 1st and 2nd deflectors is just a supplementary one which is used for obtaining beam profiles. It scans a square beam over a very small range on a stage by supplying ramp signals in synchronism with a display. The system is provided with two kinds of detectors. One is of P-N junction type to be used for observing backscattered scanning images on the display and the other, consisting of a Faraday cup with a cross-wire laid over the top, is used for getting beam profiles. This cross-wire detector is fixed at the center of the stage. The stage is movable in the directions of X and Y axes by driving pulse motors. The travel distance of the stage can be measured by counting the number of pulses at a rate of $1\text{ }\mu\text{m/pulse}$ associated with the driving motors.

First, deflection sensitivity was evaluated for the in-lens system by adjusting the dimensional parameters and positions of deflectors D_1 and D_2 to optimized values; the 1st deflector (D_1) was placed close to the 1st image position just below the demagnification lens (L_1) and the 2nd deflector (D_2) nearly at the center of the projection lens (L_2).

The measurements were carried out in the following procedures. At first, backscattered electron image of the cross-wire was observed at its original position (on the optic axis) by running a fine beam over the object. Then, the electron beam was deflected in the direction of X or Y axis by acting the deflectors with definite voltages applied to their electrodes, subsequently the stage being moved along the deflection axis over to the position where the cross-wire image was coincident with a cursor on the display. The distance travelled by the stage from the origin was measured by use of the pulse counter mentioned before. Thus, deflections were evaluated precisely as functions of dynamic parameters of the deflection system. An example of the results is shown in Fig. 5. It can be recognized in the figure that the measured deflections keep to 96 % of theoretical values in a practical region and that deflection distortion is as small as 0.2 % at a deflection of 7 mm.

Square beams having side lengths of $10\text{ }\mu\text{m}$ and $3\text{ }\mu\text{m}$ were scanned over a field of up to 10 mm, and their current distribution profiles were measured by using the cross-wire detector which could be moved to deflected beam position

over the scanning area. The waveforms of the beam profiles are shown in (a), (b), (c) and (d) of Fig. 6, corresponding to the beam positions of 0 mm (at center), 3 mm, 5 mm and 7 mm deflections, respectively. Difference in edge sharpness is not discernible between the beam profiles at the center (a) and that at the corner (d) of a 10 mm square field.

Conclusion

On the basis of the theory for eliminating linear part of deflection aberrations, a simplified in-lens deflection system has been designed employing a two stage electrostatic octupole deflectors. The design parameters have been optimized to exclusively eliminate transverse chromatic aberration with minimized non-linear aberrations. Experiments for deflection properties have proven to be in good agreement with the theory, and furthermore beam profiles confirmed to keep sufficient edge sharpness over as wide scanning range as up to 10 mm. Thus, it will be concluded that the present in-lens deflection system is applicable to a higher throughput production machine, meeting the recent demand for wider scanning fields.

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Table 1 Design specification

Accel. Voltage	20 kV
Energy Spread	2 eV
Aperture Angle	5 mrad
Beam Size	10 μm sq
Scanning Field	10 mm sq
Object-Image Dist.	300 mm

Table 2 Aberration for optimized system

	case 1	case 2	case 3
<u>Image</u>			
Spherical (μm)	0.034	0.034	0.034
Axial Chr. (μm)	0.012	0.012	0.012
Trans Chr. (μm)	0.077	0.077	0.077
<u>Deflection</u>			
Coma (μm)	0.0	0.054	0.433
Field Curv. (μm)	0.155	0.003	2.398
Astigmatism (μm)	0.261	0.143	1.181
Trans Chr. (μm)	0.116	0.0	0.499
Distortion (μm)	3.422	5.97	6.18
Landing Err. (rad)	0.044	0.036	0.0
Total w/o dist. (μm)	0.336	0.175	2.755

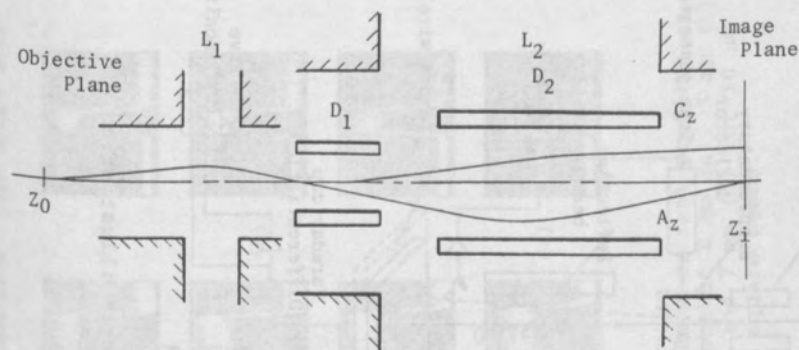


Fig. 1 Configuration of in-lens deflection system, with imaging and deflecting trajectories A_z and C_z .

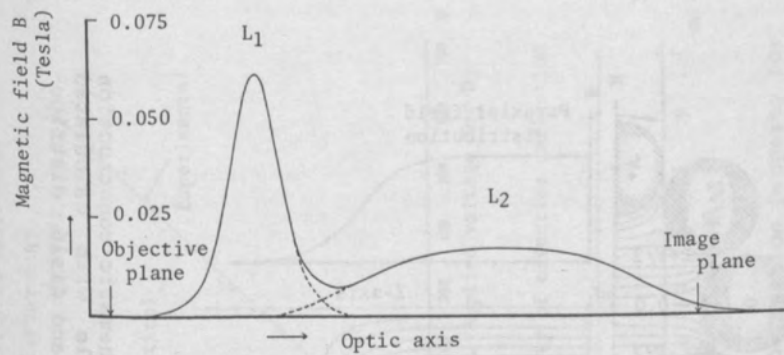


Fig. 2 Axial distribution of magnetic field for two-stage lens system.

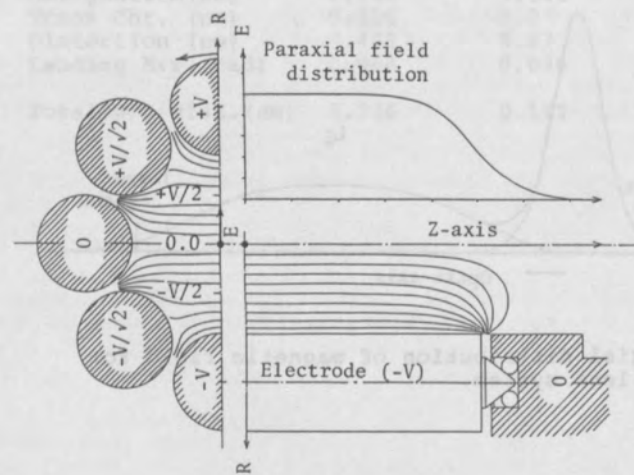


Fig. 3 Schematic construction of octupole with calculated potential and field distributions.

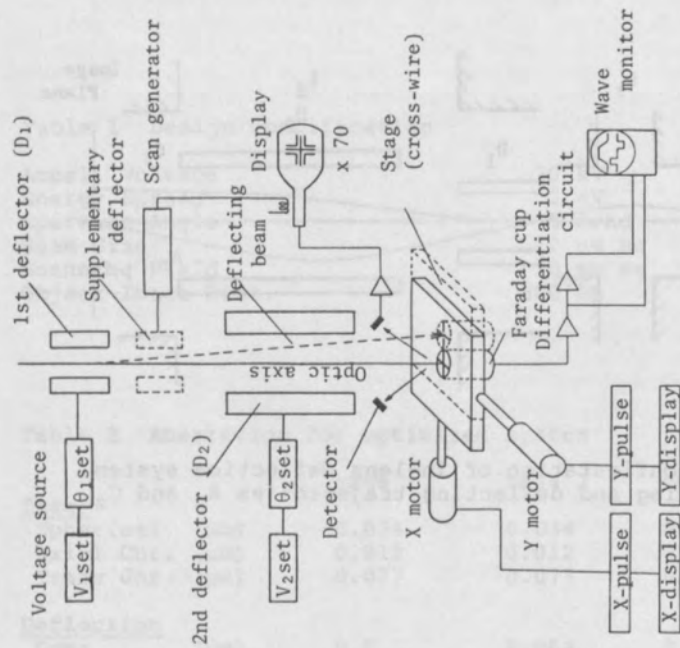


Fig. 4 Schematic illustration of measuring system.

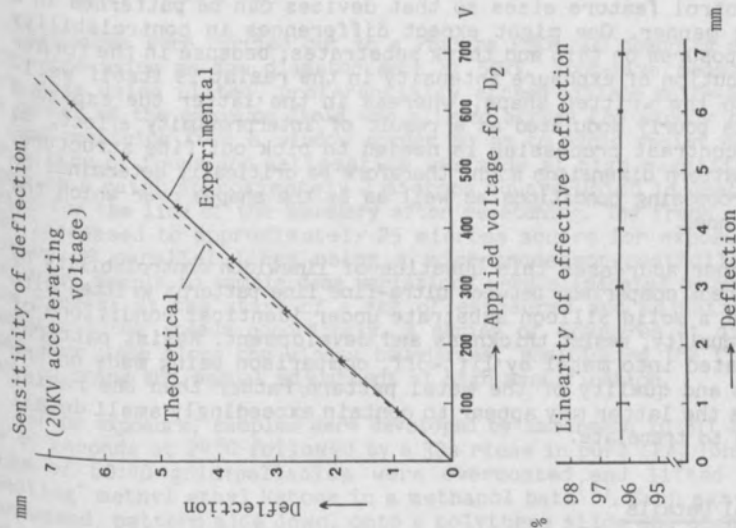


Fig. 5 Deflection property for in-lens deflection system.

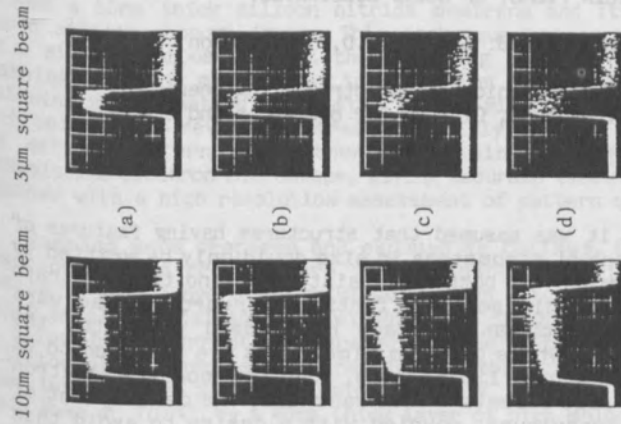


Fig. 6 Beam current profiles at deflections of 0 mm (a), 3 mm (b), 5 mm (c) and 7 mm (d) for 10 μ m and 3 μ m square beams.

VERY HIGH RESOLUTION ELECTRON BEAM LITHOGRAPHY- THIN FILMS, OR SOLID SUBSTRATES?

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Introduction

Until recently, it was assumed that structures having features of the order of a few tens of nanometres in size could only be written by electron beam lithography if both the resist layer and the substrate were thinned so as to minimise the effects of forward and backward electron scattering. Such an approach has indeed permitted the fabrication of patterns whose minimum dimensions are believed to be dictated by more fundamental limitations, such as secondary electron range and molecular size effects^(1,2). Meanwhile, the development of multi-layer resist techniques, coupled with a desire to avoid thin substrates for ease of handling, versatility and process compatibility, has advanced solid substrate e-beam lithography almost to the limits established on thin substrates^(3,4).

Now that techniques for nanostructure fabrication have been established for both thin and thick substrates, there is an increasing need to control feature sizes so that devices can be patterned in a systematic manner. One might expect differences in controlability between exposures on thin and thick substrates, because in the former the distribution of exposure intensity in the resist is itself well-confined to the written shape, whereas in the latter the exposure intensity is poorly modulated as a result of interproximity effect, so that high contrast processing is needed to pick out fine structure. Developed pattern dimensions might therefore be critically determined by dose and processing conditions as well as by the shapes over which the beam is scanned.

Our paper addresses this question of linewidth controlability by making a direct comparison between ultra-fine line patterns written with and without a solid silicon substrate under identical conditions of dose, beam quality, resist thickness and development. Resist patterns are translated into metal by lift-off, comparison being made on the dimensions and quality of the metal pattern rather than the resist stencil, as the latter may appear to contain exceedingly small detail which fails to translate.

Experimental Details

As we have found beam focus and astigmatism conditions to be critical determinants of nanostructure feature sizes, and these

variables are not easily optimised on solid substrates, it was decided to conduct our experiments by writing patterns across the boundary between a 60nm thick silicon nitride membrane and its preferentially-etched silicon support frame. This technique has been employed before for a similar purpose⁽⁵⁾, but the resulting patterns were inspected by scanning electron microscopy in reflexion mode. In our experiments, following metallisation and lift-off, the silicon substrate was etched isotropically to reveal the area originally written on solid silicon. The entire pattern could then be examined using a conventional transmission electron microscope, giving accurate linewidth measurements together with a high resolution assessment of pattern quality.

Samples were prepared and exposed as follows. 60nm thick Si_3N_4 membranes, 150 microns square, were prepared by preferential silicon etching in sodium hydroxide solution⁽⁵⁾. Each slice was divided into 5mm square samples containing four windows, one of which was later punctured to allow beam current measurement using a post-specimen current collector plate. Samples were individually spin-coated first with a 40nm thick layer of low molecular weight PMMA ($M_w=138,000$) followed, after a 20min bake at 170°C, by a 40nm thick layer of high molecular weight PMMA ($M_w=452,000$). This bi-layer system has previously been shown to give extremely efficient liftoff without loss of pitch resolution, both on thin⁽⁶⁾ and on thick⁽⁷⁾ substrates. After baking in air for 1hr, $4\mu\text{g}/\text{cm}^2$ of gold was evaporated onto the backs of the membranes as a focusing aid. Inspection of the samples using Normarski contrast showed that the resist films were of uniform thickness across the boundary between membrane and silicon frame.

Exposures were carried out in a Philips PSEM 500 scanning electron microscope using an 8nm diameter spot at 50kV. Spot-size measurements were made using tilted, preferentially etched silicon knife-edges⁽⁸⁾. The centre of the exposure field was aligned across the window boundary by dead-reckoning from a window corner so as to avoid resist exposure. Correction of focus and astigmatism was made at high magnification, exposing a patch approximately 2 microns square which is useful as a marker for the line of the boundary after re-etching. The frame size was then increased to approximately 25 microns square for exposure of a pattern of parallel lines using a microprocessor-controlled scan generator. Sample to sample dose variations were eliminated by measuring beam current at the start of a set of exposures and adjusting scan generator clock speeds accordingly. A series of exposures at different doses were made along the window boundaries, positioning the fields by dead reckoning and manual adjustment at high magnification.

After exposure, samples were developed by immersion in 3:1 IPA:MIBK for 45 seconds at 24°C followed by a 30s rinse in pure IPA. 10nm thick films of 60:40 gold:palladium were overcoated and lifted off by 'shooting' methyl ethyl ketone in a methanol bath⁽¹⁾. Each sample was then waxed, pattern side down, onto a polythene slide and etched in 5 parts 70% HNO_3 : 1 part 40% HF: 1 part glacial acetic acid with constant stirring at room temperature until the entire pattern was revealed.

through the silicon nitride film. Inspection was carried out in a JEOL JEM 100-C CTEM at 100kV.

Results

Two sets of exposures were made, one with a pattern comprising twenty lines with 1.0 micron centre-to-centre spacing and the other a much more dense pattern of 280 lines on 70nm centre-to-centre spacing. Each set consisted of eight exposures; dose was incremented by a factor of 1.10 from one exposure to the next, starting at the critical dose of 1.25×10^{-9} C/cm which just gives a reasonably continuous metal line on lift-off. Corresponding members of the two sets were given identical doses.

Fig.2 shows one member of the low line density set, exposed at a dose of $1.10E_0$. The original line of the film/solid silicon boundary can be seen clearly, the heavily exposed dot on that line being the focusing square. That part of the pattern below and to the right of the boundary was exposed on solid silicon. There is no detectable difference in linewidth between structures written on the film and those written on the solid substrate, for this and all other exposures in the dose range covered.

For much denser patterns, however, this is no longer true. Fig.3(a) and (b) shows lines written with centre-to-centre spacing of 70nm at a dose of $1.21E_0$, on thin film and solid substrate respectively. Linewidth on the thin substrate is 25nm and on the solid substrate, 35nm. We are not sure of the cause of the line-breaks seen in the thin film exposure, nor is it clear whether the poorer liftoff of the solid substrate exposure is due to rounding of the resist cross-section or not, but on the solid substrate at $1.33E_0$ liftoff is certainly no better and above $1.4E_0$ it fails altogether. Fig.4(a) shows the solid substrate exposure at $1.46E_0$, in the centre of which line detail is almost completely obliterated. Detail reappears towards the edges of the pattern (top left corner) and towards the film-solid interface (bottom right), where the contribution from backscattering is reduced. On the thin film at the same dose the grating pattern is perfect (extreme bottom right) as the higher magnification micrograph (Fig.4(b)) shows. Metal can still be lifted off from the thin substrate exposure at $1.95E_0$ shown in Fig.5(a) where the metallic strands have been prevented from lifting away by the unbroken flag of metal marking the solid substrate exposure. Note that thin film pattern quality is poor just by the boundary (see position of focusing square), presumably as a result of backscattered electrons leaving the preferentially etched edge and passing through the nitride film. Fig. 5(b) shows the thin substrate grating exposure at $1.95E_0$ away from the edge in more detail. Linewidth is approximately 30nm.

Discussion

Fig.6 shows how linewidth varies as a function of dose for both the sparse (1.0 micron pitch) and dense (70nm pitch) patterns. In the former case, solid substrate and thin film exposures lie on a common curve. This is to be expected, as the backscattered exposure due to any one line is spread over a large area so, as the pattern is widely spaced, the total backscattered contribution under any line is negligible compared with the dose given by the primary beam. Linewidth on the thin film and the thick substrate is therefore determined by the same processes in a sparse pattern, at least over the range of dose examined in this experiment.

The much greater backscattered contribution in the 70nm line pitch exposures makes linewidth control more difficult. To begin with, there is a considerable increase in linewidth at the critical dose, from 20nm for a sparse pattern to 30nm for the dense grating. As no metallic structure appears at all for a dose of $0.91E_c$, accurate dose control in the range $0.9E_c$ - $1.0E_c$ would be needed to obtain lines less than 30nm wide. Pattern quality would be extremely sensitive to beam current variations. Even above E_c linewidth increases rapidly and there is only a small range of linewidth, 30-38nm, over which control might readily be exercised before liftoff fails.

On the thin substrate, following an initial change of linewidth from 20nm in the sparse pattern to 25nm in the dense grating, the linewidth vs. dose curve approaches that for the sparse pattern and merges with it above $1.5E_c$. In the dose range $1.5E_c$ - $2.0E_c$ there is no apparent interproximity effect, linewidth being independent both of line pitch down to at least 70nm, and also of dose, simplifying feature size control.

Conclusions

We have shown, by means of a method which eliminates all extraneous sources of variation, that linewidth is more readily controlled on thin films than on thick substrates, and therefore that the use of thin substrates for nanostructure fabrication is highly advantageous. Interproximity effect and the influence of dose are much reduced, and in some cases eliminated. Solid substrate exposures, on the other hand, require very tight dose control to maintain linewidths over the whole of the limited dose range available. The details of linewidth variation on both thick and thin substrates are undergoing further investigation.

Acknowledgement

We thank John Crichton for carrying out the e-beam exposures and the Department of Natural Philosophy, Glasgow University, for TEM facilities. We acknowledge the financial support of the U.K. Science and

Engineering Research Council.

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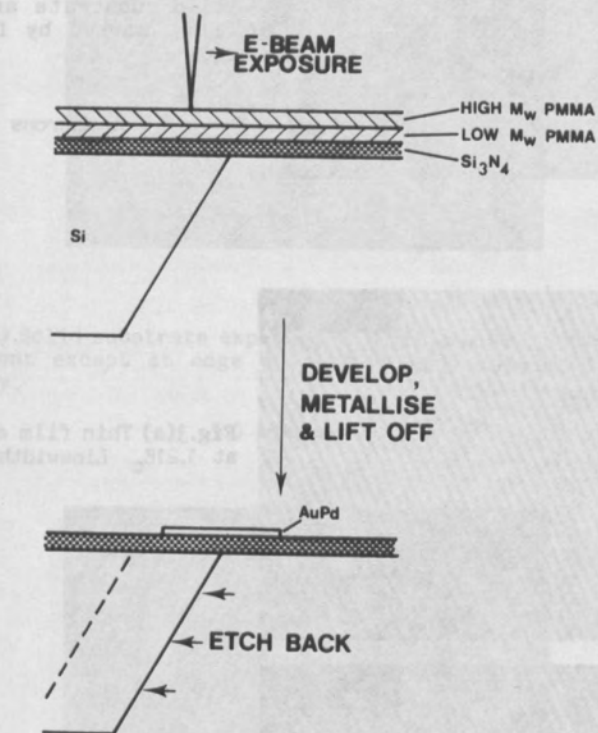


Fig.1 Schematic diagram of process steps

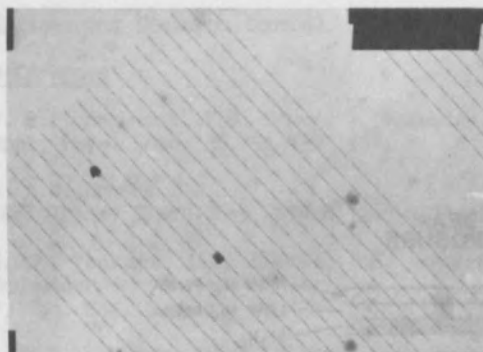


Fig.2 1.0 micron linepitch grating exposed at $1.1E_C$ across the boundary between solid substrate and thin film, marked by focusing square.

10 microns

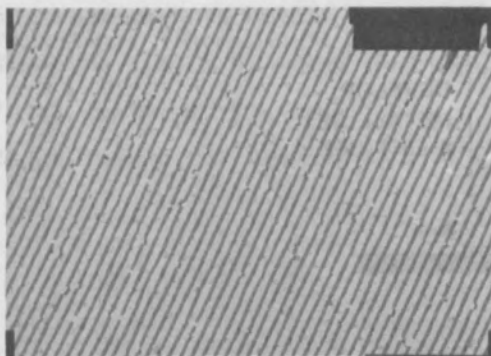


Fig.3(a) Thin film exposure at $1.21E_C$. Linewidth 26nm.

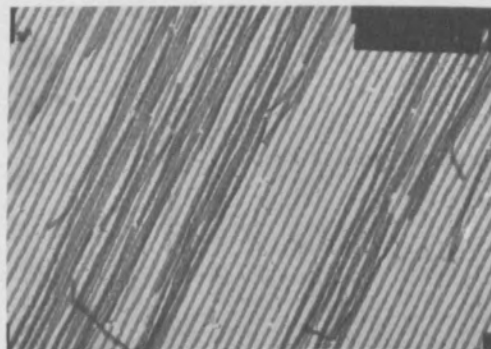


Fig.3(b) Thick substrate exposure at $1.21E_C$. Linewidth 35nm.

1.0 micron

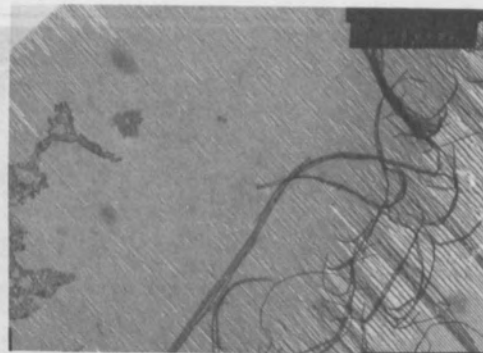


Fig.4(a) Solid substrate exposure at $1.46E_c$. Line structure is absent except at edge of pattern and close to film boundary.

5.0 microns

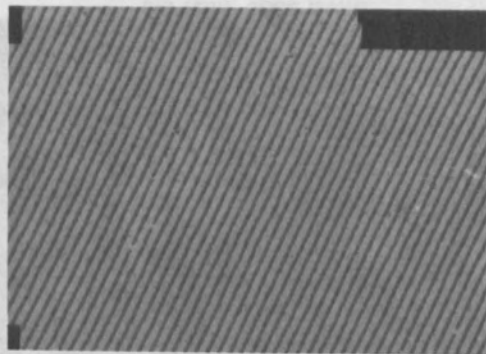


Fig.4(b) Thin substrate exposure at $1.46E_c$. Linewidth 30nm.

1.0 micron



Fig.5(a) Boundary between solid & thin substrate exposures at $1.95E_c$. Note that pattern quality is poor on thin film side of focusing square, presumably due to scattering out of the substrate.

5.0 microns

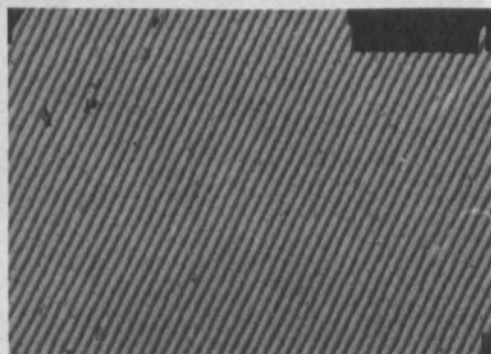


Fig.5(b) Thin substrate exposure, $1.95E_c$. Linewidth 30nm.

1.0 micron

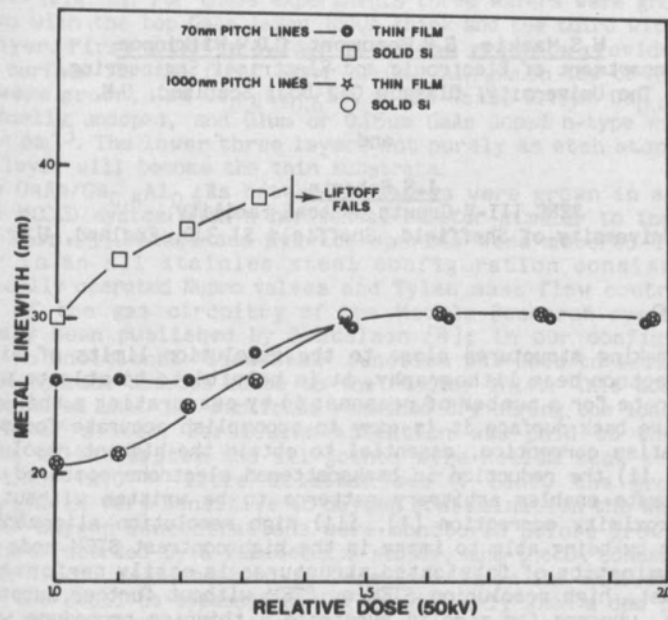


Fig.6 Graph of linewidth vs. dose for solid substrate and thin film grating exposures at 50kV on centre to centre spacings of one micron and 70nm.

High Resolution Lithography on
Thin Active Semiconductor Membranes

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Introduction

When making structures close to the resolution limits of direct writing electron beam lithography, it is helpful to be able to use a thin substrate for a number of reasons: i) by evaporating a thin gold film onto the back surface it is easy to accomplish accurate focussing and astigmatism correction, essential to obtain the highest resolution structures, ii) the reduction in backscattered electrons compared to a solid substrate enables arbitrary patterns to be written without the need for proximity correction [1], iii) high resolution alignment is made easier by being able to image in the high contrast STEM mode [2], iv) the examination of fabricated structures is easily performed in high contrast, high resolution STEM or CTEM without further substrate preparation, whereas for a solid substrate a thinning procedure would have to be performed.

In order to make the fullest use of the small geometries available using electron beam lithography in the fabrication of a GaAs MESFET it would be useful for the above reasons to be able to fabricate the device on a thin substrate of active semiconductor. We report a method of producing 500Å thick membranes of GaAs for use as thin substrates.

An outline of the method used to make the membranes is as follows: An alternating structure of $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ /GaAs/ $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ /GaAs is grown by metal-organic vapour deposition (MOCVD) on a (100) GaAs wafer. The front face is protected with wax. After thinning the wafer, the back is patterned with rectangular windows. A fast anisotropic and nonselective etch is used to etch through these openings to within 15µm of the first $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ layer. Selective etches which etch only GaAs or $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ are then used to etch successively GaAs, $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$, GaAs, $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ to leave the final GaAs layer as the thin substrate. The desired configuration is shown in Fig. 1. A window has been masked on the back of the wafer and a well etched from the back to leave the thin substrate. The ultimate device will be fabricated with the active, high resolution area on the thin substrate and the bonding pads on the solid substrate.

MOCVD Wafer Growth

The heterostructures were grown by metal-organic chemical vapour deposition (Fig. 2). For these experiments three wafers were grown, the first two with the top GaAs layer 1000Å thick and the third with a 500Å thick layer. First a 0.05µm buffer layer was grown to provide a good growing surface for the first layer of Ga_{0.4}Al_{0.6}As. On top of this four layers were grown, 1µm Ga_{0.4}Al_{0.6}As, 0.3µm GaAs, 0.15µm Ga_{0.4}Al_{0.6}As all nominally undoped, and 0.1µm or 0.05µm GaAs doped n-type with 10^{17} carriers cm⁻³. The lower three layers act purely as etch stops while the top layer will become the thin substrate.

The GaAs/Ga_{0.4}Al_{0.6}As heterostructures were grown in a Metals Research MOCVD system with a horizontal reactor similar to the design used by Bass [3]. Alkyl and hydride sources were metered into the reactor in an all stainless steel configuration consisting of pneumatically operated Nupro valves and Tylan mass flow controllers. Details of the gas circuitry of the Metals Research system have previously been published by Samuelson [4]; in our configuration however an additional "line-seal" function was used to isolate the alkyl and hydride sources close to the reactor inlet. This additional feature ensured that the manifolds remained dry during the loading and unloading of slices. Particular attention was paid to the leak-tightness of the system and all joints were Helium leak tested to better than 1×10^{-10} litre millibar sec⁻¹. Since the growth of Ga_{0.4}Al_{0.6}As is very sensitive to oxygen contamination the water and molecular oxygen concentrations were monitored before growth. Dew points were recorded by a Panametrics sensor, and the O₂ concentration by an R.I. Herresh cell, both units were located in the exhaust of the reactor, but could be bypassed during growth. Only when a dew point of -90°C (or better) and an O₂ concentration of <0.05ppm were observed was growth started. In general these conditions were realised after a purging period of 18 hours. The reactor was fitted with electronic grade trimethyl gallium and trimethyl aluminium supplied by Texas Alkyls and arsine 5% in hydrogen supplied by BOC Ltd. The latter was dried before entering the reactor using a molecular sieve module. The dopant gas for the thin active GaAs layer was 100ppm H₂S in H₂ again supplied by BOC. Prepolished undoped semi-insulating (100) substrates supplied by Metals Research were prepared for the reactor by free etching in 15:1:7 H₂SO₄:H₂O₂:H₂O reagent. Slices were rinsed several times in distilled water before a final rinse in methanol and drying under nitrogen. Immediately prior to growth slices were thermally cleaned by heating to 844°C for 15 minutes under AsH₃/H₂ (10^{-3} mole fraction). The growth conditions for these multilayer structures is summarised in the Table 1.

LAYER	GROWTH TEMP	TMG MOLE FRACTION	TMA MOLE FRACTION	AsH ₃ MOLE FRACTION	H ₂ S 100ppm MOLE FRACTION	GROWTH RATE	THICKNESS
GaAs ACTIVE	660°C	5.8×10^{-5}	-	3.1×10^{-4}	7.7×10^{-6}	2.7 $\mu\text{m/hr}$	500 Å 1000 Å
Ga _{0.4} Al _{0.6} As	820°C	5.8×10^{-5}	9.5×10^{-5}	1.1×10^{-3}	-	7.5 $\mu\text{m/hr}$	0.15 μm
GaAs	820°C	5.8×10^{-5}	-	1.1×10^{-3}	-	2.7 $\mu\text{m/hr}$	0.3 μm
Ga _{0.4} Al _{0.6} As	820°C	5.8×10^{-5}	9.5×10^{-5}	1.1×10^{-3}	-	7.5 $\mu\text{m/hr}$	1 μm
GaAs BUFFER	660°C	5.8×10^{-5}	-	3.1×10^{-4}	-	2.7 $\mu\text{m/hr}$	500 Å

Table 1.

A H₂ carrier flow of 4 litre/min and growth pressure of 1120mB was common to each deposition. A cooling period of 9 minutes was introduced between depositing the uppermost Ga_{0.4}Al_{0.6}As layer and the doped active GaAs layer. Subsequent SIMS analysis showed that during this time lapse residual TMA was purged from the reactor resulting in an abrupt transition between the two layers. Although the structure required five epitaxial deposits the resulting morphology was excellent with fewer mesa defects per square centimetre than observed on single GaAs structures of comparable thickness. In general slices were green but with different interference colours where the growth rate on the susceptor varied.

The room temperature mobility and free carrier concentration were determined by the Van der Pauw technique using tin dots alloyed under H₂. In the case of the wafer with the 500 Å thick top layer, the mobility was found to be 1388 cm²V⁻¹sec⁻¹, and the free concentration was 1×10^{17} cm⁻³. A correction for surface depletion [5] was applied to the measured carrier concentrations; however no correction was made for the conductivity of the underlying Ga_{0.4}Al_{0.6}As/GaAs structure which was nominally undoped. The Al mole fractions of the GaAlAs components of the structure were measured by x-ray double crystal diffractometry using either the [400] or assymetric [115] reflections.

Etching Procedure

The etches used during the fabrication process were as follows;

1:8:1 $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ [6]. This etches GaAs at rate of $20\mu\text{m}/\text{min}$ when freshly made, but the etch rate falls to $10\mu\text{m}/\text{min}$ as the etch cools from an initial temperature of about 45°C down to room temperature. It is anisotropic, and the etch rate is not dependant on the aluminium concentration when etching GaAlAs. This etch is used to etch wells to within $15\mu\text{m}$ of the heterostructure. Etching was always started within 1min of making up the etch.

95:5 $\text{H}_2\text{O}_2:\text{H}_2\text{O}$ [7]. This etches GaAs isotropically at a rate of $1-2\mu\text{m}/\text{min}$ but will not etch $\text{Ga}_{1-x}\text{Al}_x\text{As}$ for $x>0.3$. It was always used freshly made up, nominally at room temperature.

20% HF [7]. This etches $\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ at about $1\mu\text{m}/\text{min}$ but does not etch GaAs. A stock of the etch was diluted from 40% HF with deionised water and stored in a PTFE bottle until needed. It was used at room temperature.

The back face of the wafer has to be patterned with something that will survive exposure to all three of these etches. A good masking system was found to be $420\text{\AA}$ of gold on a thin layer of NiCr patterned by liftoff, with $1.5\mu\text{m}$ of AZ1350J spun and patterned on top of the gold.

It was desired to make membranes with a side length of between 100 and $200\mu\text{m}$. Once the size of the membrane is decided, the properties of the 1:8:1 etch determine both what the thickness of the wafer should be and what shape the opening on the back of the wafer should be. To see why this is the case, consider what happens during 1:8:1 etching of two windows with dimensions as shown in Fig. 3 defined in resist on a (100) GaAs wafer with the crystal directions also as shown. Across the (011) direction the profile will develop in the same way for both windows with a flat bottom, and sidewalls at an angle of about 52° to the vertical (Fig.4 (a)). The extent of undercut, at each side is about 0.95 times the depth etched. The width of the bottom is decreased by approximately the same amount as the depth etched. The profiles across the (011) direction, however, differ depending on the width of the mask opening. For the wide ($320\mu\text{m}$) opening the profile begins with a flat bottom and curved walls, but, as etching proceeds, the profile tends to semicircular (Fig.4 (b)). For the narrow ($20\mu\text{m}$) opening the flat bottomed phase is not seen for large etched depths and the profile is always approximately semicircular (Fig. 4 (c)). Fig. 5 (a),(b) show micrographs of the cross sections that resulted after a $350\times 80\mu\text{m}$ window in gold/resist composite was etched in 1:8:1 to a depth of $120\mu\text{m}$. The dimensions of the etched well are $595\times 300\mu\text{m}$, with the bottom being about $250\mu\text{m}$ wide.

It will be seen that the width of a membrane will be crucially influenced by the curvature at the bottom of the well before the selective etches are used. In order to keep the membrane width small,

the wafer thickness should be under 120 μ m. However, if the wafer is much thinner than 100 μ m then it becomes too fragile to handle. Wafers were thinned by hand-polishing with 5 μ m carborundum and etching with 1:8:1. Once the thickness of the wafer has been chosen, the shape of the mask opening required to give the desired membrane size is determined by the etching characteristics of the 1:8:1 etch. A mask opening of 20x200 μ m was used for membrane fabrication in these experiments.

The etch rate through a narrow opening is less than for a wide one, and this fact is used to enable the stop point of the 1:8:1 etch to be found independently of what the etch rates actually are. Fig. 6 shows part of the pattern that was used to mask the back face prior to etching. The small windows are where the membranes will be, the line of windows of decreasing width are used to determine when to stop the 1:8:1 etch. Fig. 7 shows a section through the smaller four windows in the line during 1:8:1 etching. Since the wafer is mounted on a glass slide with white wax it is easy to see which windows have etched through. Because of the dependence of etch rate on window width the windows bottom out in decreasing order of size. If the etching is stopped when the 40 μ m wide window bottoms out then all the 20 μ m wide windows will be about 10-15 μ m from the first GaAlAs layer.

After the 1:8:1 etch the wafer is removed from the glass slide by melting the wax and sliding the wafer off. The wafer is then cut up into 2x3mm chips each containing two etched wells. These are then etched in the 95:5 etch for periods of 5 minutes after each of which the samples are rinsed, dried, and checked to see if the first Ga_{0.4}Al_{0.6}As layer has been reached. At this point the well bottoms become perfectly smooth and mirror-like. The samples are then etched in 20% HF for 1min 15 sec to remove the 1 μ m thick layer of Ga_{0.4}Al_{0.6}As, then in 95:5 to remove the 0.3 μ m layer of GaAs, and finally in 20% HF to remove the 0.15 μ m layer of Ga_{0.4}Al_{0.6}As. The protecting wax is removed by rinsing in trichloroethylene. Fig. 8 is an optical micrograph of the inside of a well after the completion of etching. At the bottom is a 150x150 μ m membrane of GaAs 500 $\text{\AA}$ thick. Fig. 9 shows a 100x100 μ m membrane viewed from the top. Using a Michelson objective it was found that while the membranes themselves were flat, there was a gentle slope of 1 μ m over 20 μ m away from the edges.

Lithography

Our standard two layer PMMA resist, 400 $\text{\AA}$ of high molecular weight on top of 400 $\text{\AA}$ low molecular weight, was spun onto some membranes. A thin layer of about 100 $\text{\AA}$ of gold was evaporated onto the back of the membranes through a 400 mesh TEM grid to provide areas on which focussing could be done. Patterns were exposed at 50kV with an 80 $\text{\AA}$ spot in a Philips PSEM 500 scanning electron microscope which has been converted for lithographic use. The exposed patterns were developed in 3:1 methyl iso-butyl ketone for 30sec at 23.0 $^{\circ}$ C. 200 $\text{\AA}$ of Au/Pd was thermally evaporated from a tungsten basket onto the sample. Lift-off of the excess metal was performed using the "shooting" process [8]. Fig. 10 is a STEM micrograph of some metal lines made in this way. They are about 200 $\text{\AA}$ wide, the pitch varies from 950 $\text{\AA}$ down to 650 $\text{\AA}$. The

transmission signal through the GaAs is somewhat attenuated compared to silicon nitride of the same thickness, because of the enhanced scattering from the heavier atoms which comprise GaAs. Lift-off has not failed at the smallest pitch exposed, so it would appear that closer lines may be possible, perhaps approaching the 450Å pitch achievable with Si_3N_4 substrates, which is believed to be ultimate resolution of PMMA resist.

Conclusion

A method using selective etching of a GaAs wafer with a $\text{GaAs}/\text{Ga}_{0.4}\text{Al}_{0.6}\text{As}$ heterostructure on it has been described for producing thin membranes of active GaAs for use as thin substrates in high resolution direct writing electron beam lithography. Metal lines have been fabricated with a pitch close to the best which is possible. It will now be possible to make semiconductor devices with geometries close to the resolution limits of available resists.

Acknowledgements

This work was supported by the Science and Engineering Research Council. W.S.Mackie has a CASE studentship with the Plessey Company, Allan Clarke Research Centre, Caswell. He would like to acknowledge the support and help received from many members of staff at Caswell during the course of this work. Mr. John Crichton of the Department of Electronic and Electrical Engineering at Glasgow University provided valuable technical assistance during the course of this work.

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Figures

Fig. 1. Schematic diagram of a transistor on a thin substrate.

Fig. 2. Structure of MOCVD-grown wafer used for membrane production.

Fig. 3. Test pattern to illustrate 1:8:1 etch profiles.

Fig. 4. Cross sections through Fig. 4 test pattern as it is etched with 1:8:1;
 (a) across (01 $\bar{1}$) direction for both 320 μ m and 20 μ m wide windows,
 (b) across (011) direction for 320 μ m window,
 (c) across (011) direction for 20 μ m window.

Fig. 5. Photomicrographs of cleaved sections through a 350x80 μ m window that has been etched to a depth of 120 μ m;
 (a) across the (01 $\bar{1}$) direction,
 (b) across the (011) direction.

Fig. 6. Diagram of part of the mask used for membrane production. (Dimensions in microns)

Fig. 7. Diagram of section through sample during 1:8:1 etching, showing stopping point determination.

Fig. 8. The inside of a well after completion of etching.

Fig. 9. A 100x100 μ m GaAs membrane, 500 $\text{\AA}$ thick.

Fig. 10. STEM micrograph of 200 $\text{\AA}$ wide lines of 200 $\text{\AA}$ thick Au/Pd fabricated on a 500 $\text{\AA}$ thick GaAs substrate. Micron markers.

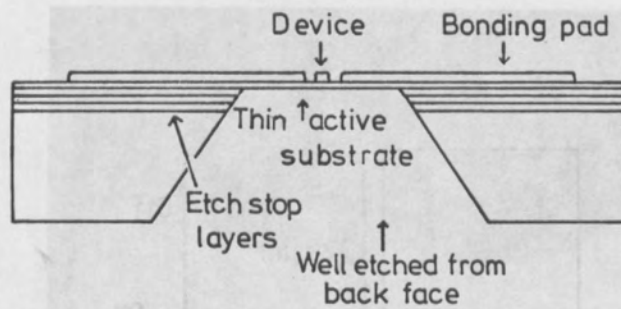


Fig. 1

GaAs	n-type	0.05 μm
Ga _{0.4} Al _{0.6} As		0.15 μm
GaAs		0.3 μm
Ga _{0.4} Al _{0.6} As		1 μm
GaAs	buffer	0.05 μm
SI substrate		400 μm

Fig. 2

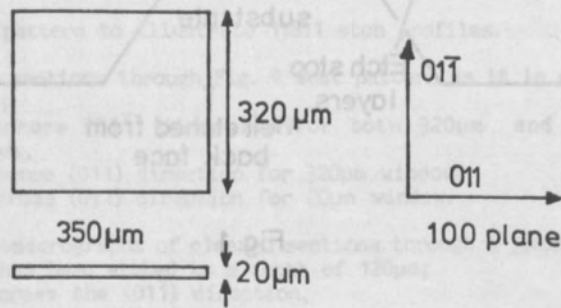


Fig. 3

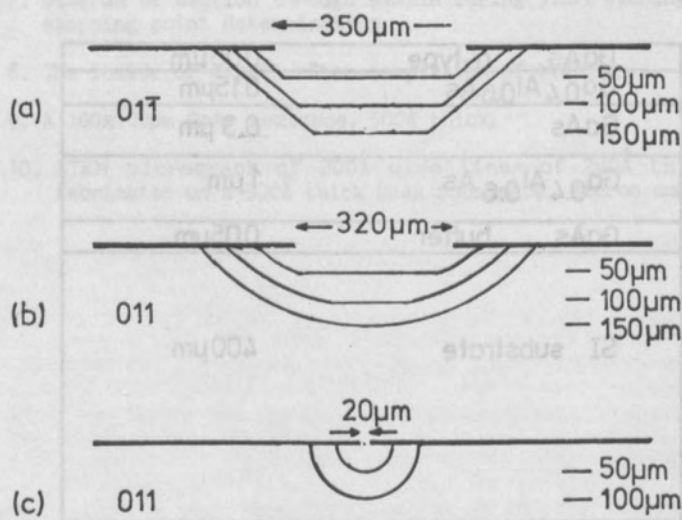


Fig. 4

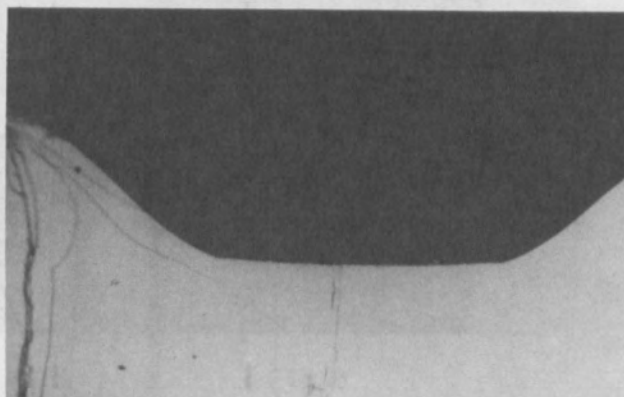


Fig. 5(a)

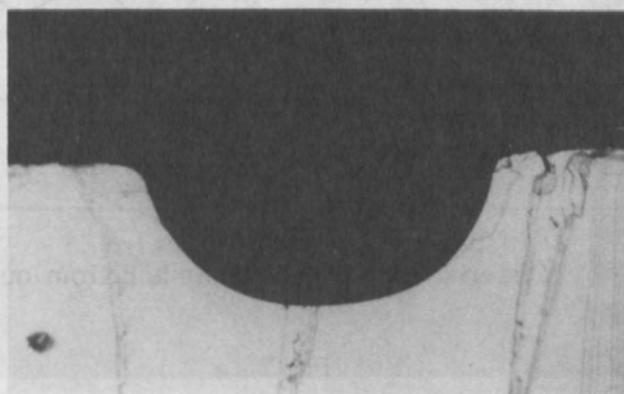


Fig. 5(b)

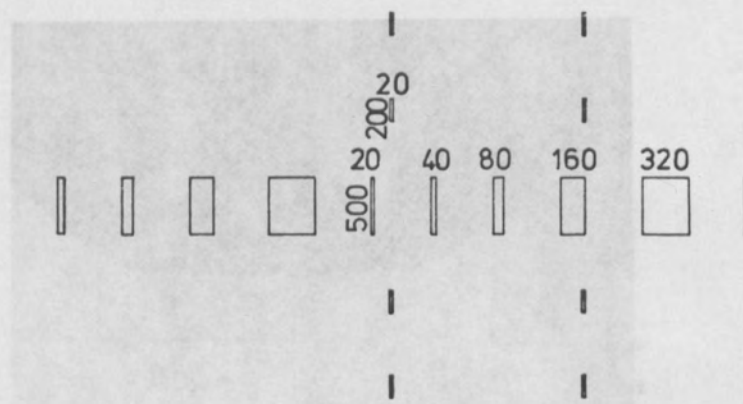


Fig. 6

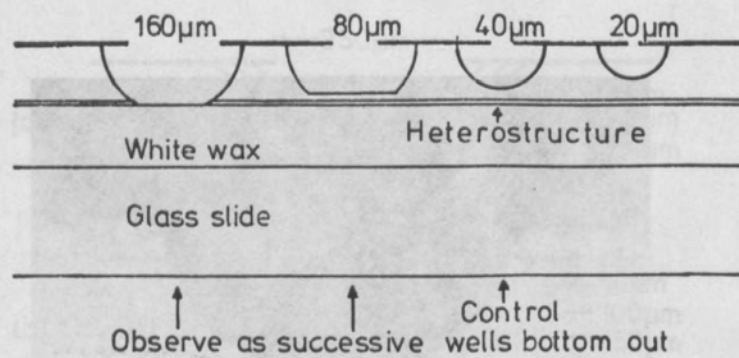


Fig. 7

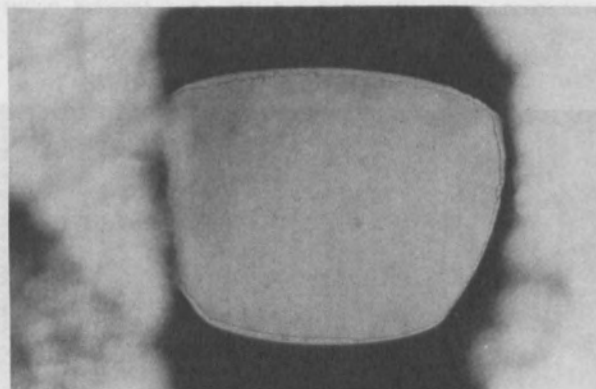


Fig. 8

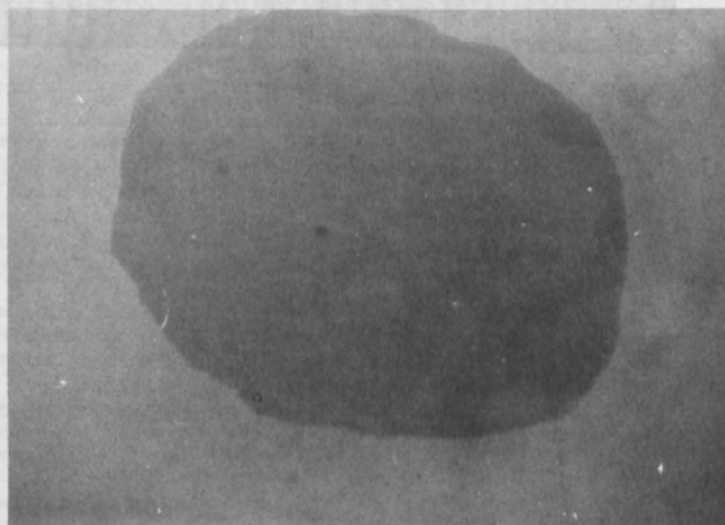


Fig. 9

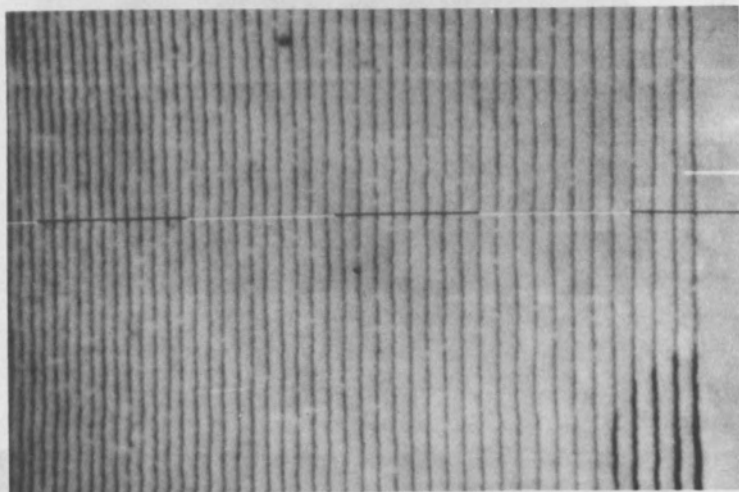


Fig. 10

Fig. 10

SINGLE CRYSTAL LaB_6 GUN FOR ELECTRON BEAM LITHOGRAPHY

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ABSTRACT

Emission characteristics of a single crystal LaB_6 cathode were studied. It was found that the $\{100\}$ and $\{130\}$ planes are emitting surfaces. The $[110]$ cathode is stable for a long period of operation, since electrons are emitted from the $\{100\}$ facet planes, which are formed on the sloping surface by preferential vaporization. Although the $[100]$ cathode has highest initial brightness, it is unstable over a long period of operation due to disappearance of the (100) plane on the cathode top. We evaluated newly designed cathodes, which have a flat surface on the cathode top. The new $[100]$ cathode with a small flat surface diameter has a high brightness and a long service life as well as an isotropic electron emission from the cathode top. This cathode can be adapted to any type of electron beam exposure system by adjusting the dimensions of the flat surface.

INTRODUCTION

Most advanced VLSI fabrication technology requires high throughput electron beam exposure systems which maintain high dosage. Moreover, long term stability and high productivity are needed, an obstacle to which is the system downtime following the replacement of the electron gun. The electron gun with a single crystal LaB_6 cathode has attracted a great deal of attention, because its high brightness and long service life satisfy these requirements.^{1~3}

Emission characteristics of the cathode strongly depend on the axial orientation and the shape of the cathode. Although conventional spherical-tipped cathodes with various tip radii have been evaluated,^{3~7} optimization of the axial orientation and the shape of the cathode for e-beam systems has not been completed as yet, and little has been reported on the stability of the cathode over a long period of operation.

The purpose of this paper is to decide the optimal axial orientation and the optimal shape of the single crystal LaB_6 cathode for e-beam systems. First, the crystallographic electron emitting surface is discussed. Second, dynamic electron emission characteristics over a long periods are interpreted based on facet plane formation caused by preferential vaporization.^{8,9} Third, correlation between emission characteristics and cathode shape is reported. Finally, a new cathode,

which has a flat surface on the cathode top, is presented and its emission characteristics are studied.¹⁰

For point e-beam systems, the [100] flat-tipped cathode with a small diameter and the [110] conventional cathode with a small dip radius are suitable. For shaped e-beam systems, the [100] flat-tipped cathode with a large flat surface diameter and the [100] conventional cathode having a large tip radius or a large cone angle are appropriate.

EXPERIMENTAL METHOD

Figure 1 shows the test system used in evaluating the electron gun. It was evacuated by ion sputtering pumps. The vacuum was higher than 3×10^{-5} Pa. The acceleration voltage was 20 kV. The magnification of the lens was about one.

The cross-over image and the emission pattern were observed on a CRT screen. The emission angle was estimated from the intensity distribution of the emission pattern. Brightness, B , was calculated from the equation

$$B = \frac{4I}{(\pi\alpha d)^2} \quad (1)$$

where α is half of the convergent angle of the beam, and equals 0.25 mrad, d is the cross-over diameter measured by the knife edge method and I is the beam current detected with a Faraday cup. The cross-over diameter was defined to be the distance between the readings corresponding to 10 % and 90 % in the electron integrated intensity distribution reflected from the knife edge. The cathode temperature was measured with an optical pyrometer through a side window attached to the gun chamber.

The cathode was mounted in a Vogel type assembly with a flat Wehnelt. Figure 2 shows a cross section of the electron gun. The distance between the cathode top and the outer Wehnelt surface was 0.20 ± 0.01 mm. The diameter of the Wehnelt aperture was 1.5 mm. The distance between the cathode and the anode was 10 mm. We evaluated the dependence of the axial orientation, tip radius and cone angle of the conventional spherical-tipped cathode on the emission characteristics. We designed a new cathode with a flat tip and evaluated its emission characteristics. Figure 3 shows SEM images of the conventional spherical-tipped cathode and the flat-tipped cathode.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

Figure 4 shows the stereographic projections, cross-over images and emission patterns for spherical tipped cathodes with a tip radius of 15 μm and a cone angle of 90° . Many investigators have been trying

to find the relationship between bright spots and specific crystallographic planes.^{5,11} Recently, Shimizu et al.¹⁴ indicated that the bright spots of the emission pattern from a clean surface at a relatively low cathode temperature, about 1320 K, correspond to the {100} and {120} planes. However, under our operating conditions where the cathode temperature is above 1700 K and the vacuum is higher than 3×10^{-5} Pa., it is inferred from this figure that bright spots correspond to the {100} and {130} planes.^{5,8} The difference of these results may be caused by different operative conditions.

Figure 5 shows brightness of these cathodes versus operation time.⁸ At the same cathode temperature, the initial brightness is highest for the [100] cathode and lowest for the [111] cathode. In order to obtain a brightness of $0.8 \sim 1.0 \times 10^6$ A/cm².sr, the [111] cathode temperature had to be set higher than those of the [100] and [110] cathodes. However, the brightness of the [100] cathode decreased remarkably after 200 ~ 300 hours of operation, in contrast to the [110] and [111] cathodes.

Figure 6 shows changes in the emission patterns and cross-over images. For the [100] cathode, the bright central region in the emission pattern and the center spot in the cross-over image, both of which correspond to the (100) plane on the cathode top, eventually disappeared. For the [110] cathode, the changes in emission pattern and cross-over image were not so clear. In the case of the [111] cathode, six bright regions were seen initially. After a long period of operation, the part of the three pairs of neighbouring bright regions merged together, resulting in three bright regions. Figures 7 and 8 shows the SEM images of the cathode top shapes¹⁵ and the corresponding line drawings, respectively. The (100) plane on the top of the [100] cathode vanished completely and the {110} and {111} planes, which have higher work functions, were formed on the sloping surface. For the [110] and [111] cathodes, {100} facet planes, which have the lowest work function, formed on the sloping surface. Initially, electrons are emitted from the regions around the {100} and {130} planes on the top and the sloping surface but after a long period of operation they are emitted from the facet planes. This is the reason why the [100] cathode is unstable, in contrast to the [110] and [111] cathode. It should be noted that the {100} planes are the important emitting surfaces, and also that electrons are emitted from the sloping surface, not from the top, of the cathode, except for the [100] cathode before facet plane formation.

Emission characteristics strongly depend upon the shape of the cathode. Figure 9 indicates the maximum brightness, cross-over diameter near the bias voltage corresponding to the maximum brightness, and half of the emission angle in the space charge limited condition versus cone angle at a cathode temperature of about 1810 K. With increasing cone angle, maximum brightness decreases and half of the emission angle increases, while cross-over diameter is roughly constant. Emission pattern and cross-over image also vary with increasing cone

angle as shown in Fig. 10. Anisotropy in emission patterns and cross-over images decreases considerably with cone angle, which is basically interpreted as being the result of electron emission from regions around the {100} and {130} planes. Figure 11 shows the relation between emission characteristics and tip radius. With increasing tip radius, the maximum brightness decreases, half of the emission angle increases and cross-over diameter becomes slightly larger.

So we can observe that, a cathode with a small tip radius and small cone angle has a high brightness as well as a sharp emission angle, while a cathode with a large tip radius and a large cone angle has a wide emission angle at the cost of brightness.

We designed the flat-tipped cathode, in order to obtain a cathode which emits electrons from its top surface and has a long service life.¹⁰ Figure 12 shows the cross-over image and emission pattern of this cathode with a 150 μm flat surface diameter. Electrons are emitted principally from the flat surface for the [100] and [130] cathodes and from the circular edge and the sloping surface for the [100] and [111] cathodes. This experimental results indicate that {100} and {130} planes are emitting surfaces. Other planes, such as {120} may also be, but this requires further investigation. Since the intensity distribution of the emission pattern of the [100] and [130] cathodes is symmetrical about the optical axis and has a Gaussian-like distribution, alignment of the electron beam along this axis is easier. Moreover, cross-over position is stable against change in bias voltage or cathode temperature, in contrast to the [110] and [111] cathodes.

When the diameter of the flat surface is reduced, the brightness increases and half of the emission angle decreases as shown in Fig. 13. The [100] and [130] cathodes with a surface diameter of approximately 50 μm and a cone angle of 90° showed an initial brightness of about $1 \times 10^6 \text{ A/cm}^2\text{-sr}$, which is almost the same initial brightness as the conventional spherical-tipped cathode with a tip radius of 15 μm . Figure 14 indicates the brightness of the [100] and [130] flat-tipped cathodes versus operation time. The [100] flat-tipped cathode is stable, because the top surface remains for a long time. The shapes of both cathodes changed with time as shown in Fig. 15. The top shape of the 50 μm [100] flat-tipped cathode changed from a circle to a square after 2700 hours of operation at about 1780 K, while the top shape of the 50 μm [130] flat-tipped cathode altered to a small triangle after 2000 hours of operation at almost the same cathode temperature. Change in the [100] cathode shape is more symmetrical, in contrast to the [130] cathode. Therefore, the [100] crystallographic orientation is the best for the flat-tipped cathode axis. The figure also suggests that the rate of change of the dimension of the [100] cathode-top is smaller than that of the [130] cathode. However, we could not confirm the rate of change of these cathode, because their operative conditions were not always just the same.

By sacrificing emission angle, the brightness of the [100] flat-tipped cathode may be made higher by using a cone angle smaller than 90° .

We considered the application of these various types of cathodes to electron beam exposure systems. For e-beam systems using a point beam, a gun with high brightness, long service life and isotropical emission is required. For this purpose, a gun using the conventional spherical-tipped cathode with a [110] axial orientation is suitable. We have evaluated over 100 [110] cathodes with a $15\text{ }\mu\text{m}$ tip radius and 90° cone angle in e-beam systems and got a performance of about $8 \times 10^5\text{ A/cm}^2\cdot\text{sr}$ for brightness and $1500 \sim 4000$ hours for service life. The [100] flat-tipped cathode with a $50\text{ }\mu\text{m}$ flat surface diameter is more effective, because of high brightness and a life almost the same as that of a [110] cathode as well as the particular feature of isotropical emission from the cathode top.

Systems using a shaped beam require a gun for which the emittance, that is the product of the emission angle and the cross-over diameter, is large and the angular intensity distribution is uniform, whereas high brightness is not so essential.^{3,4} The [100] flat-tipped cathode with a large flat surface diameter and a spherical-tipped cathode with a large tip radius or a large cone angle are appropriate for these systems. The [100] axial orientation is also considered suitable for large tip radius⁴ and large cone angle conventional cathodes, because their top surface last for a long time. For shaped e-beam systems using Köhler illumination, a beam shaping aperture has to be virtually uniformly illuminated by the divergent beam. The [100] flat-tipped cathode with a large diameter may be especially suited to this type of systems.

CONCLUSION

The optimal axial orientation and the optimal shape of the single crystal LaB_6 cathode for e-beam systems were studied. The {100} and {110} planes are excellent emitter. The [100] conventional cathode has high initial brightness, however, it is unstable due to preferential vaporization of the (100) top surface. The [110] cathode with conventional shape is stable for a considerably longer time, because electrons are emitted from the {100} facet planes which are formed on the sloping surface. The new cathode with a [100] axial orientation and a $50\text{ }\mu\text{m}$ diameter has a high brightness and a long service life as well as isotropical emission from the cathode top. For point e-beam systems, the flat-tipped cathodes with a [100] axial orientation and a small diameter flat surface or the [110] conventional cathodes with a small tip radius and/or a small cone angle are preferable. For shaped e-beam systems, the [100] flat-tipped cathodes with a large diameter or the conventional cathodes with a large tip radius or large cone angle are suitable. In conclusion, the [100] flat-tipped cathode with an appro-

prate flat surface diameter can be adapted efficiently to any type of e-beam systems.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Y. Matsumoto, Mr. S. Sano, Mr. T. Shinozaki and Mr. M. Nakasuji and Mr. K. Wada for their helpful and stimulating discussions. The authors are also grateful to Mr. H. Hagiwara in the Central Research Laboratory Denki Kagaku Kogyo Inc. for providing the single crystal LaB₆ cathodes.

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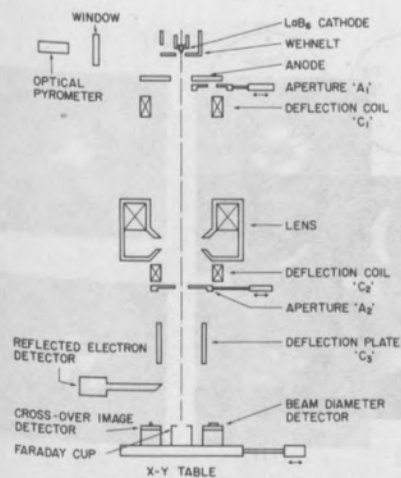


Fig.1 The test system used in evaluating the electron gun.

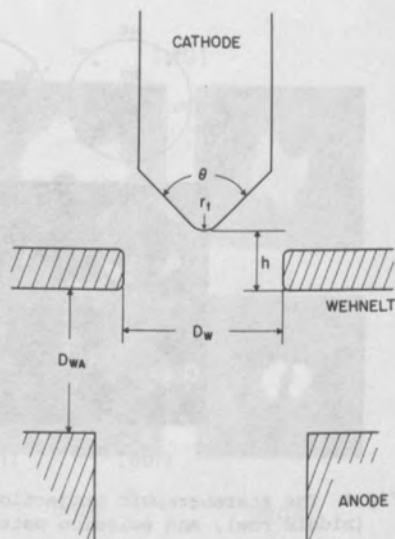
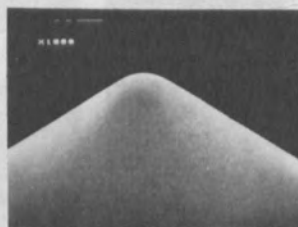
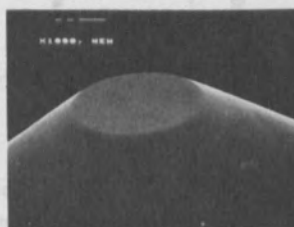


Fig.2 Cross section of the electron gun. θ represents the cone angle and r_t the tip radius of the spherical-tipped cathode. D_W indicates the diameter of the Wehnelt aperture, h the distance between the cathode top and the Wehnelt and D_{WA} the distance between the Wehnelt and the anode.



CONVENTIONAL CATHODE

30 μ m



NEW CATHODE

30 μ m

Fig.3 The SEM images of the conventional spherical-tipped cathode and the flat-tipped cathode.

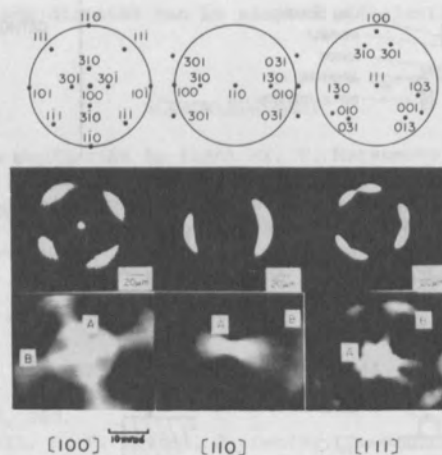


Fig.4 The stereographic projection (upper row), cross-over image (middle row), and emission pattern (lower row). Pattern A and B can be seen in the emission pattern. Circle in the stereographic projection represents 90° circle corresponding to the cone angle of the cathode.

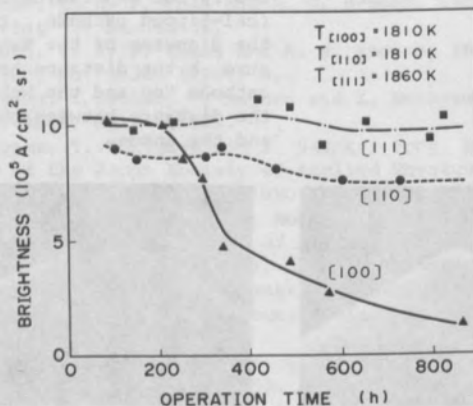


Fig.5 The brightness versus operation time for the [100], [110] and [111] spherical-tipped cathodes with a 15 μm tip radius and a 90° cone angle under the conditions of a constant cathode heating current and a constant self bias resistance corresponding to the maximum initial brightness. Initial cathode temperatures were 1810 K for the [100] and [110] cathodes and 1860 K for the [111] cathode, which were set so that the initial maximum brightness was approximately $1 \times 10^6 \text{ A/cm}^2 \cdot \text{sr}$.

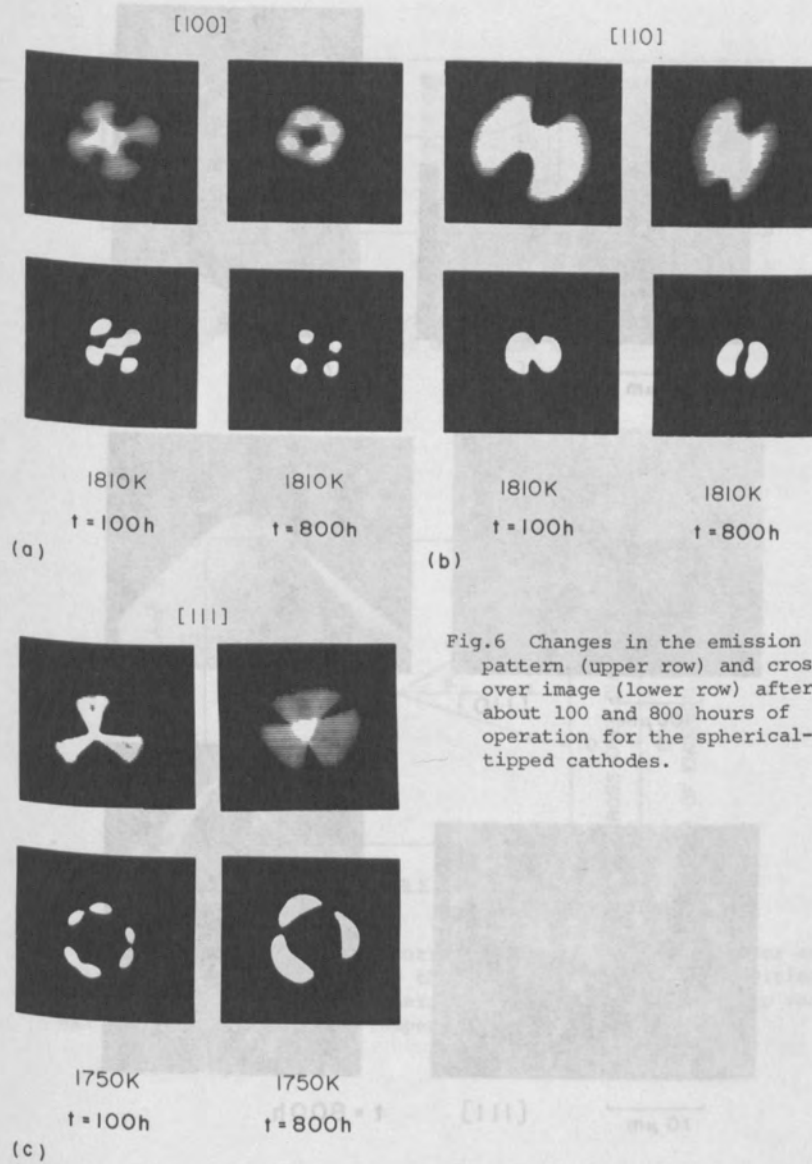


Fig.6 Changes in the emission pattern (upper row) and cross-over image (lower row) after about 100 and 800 hours of operation for the spherical-tipped cathodes.

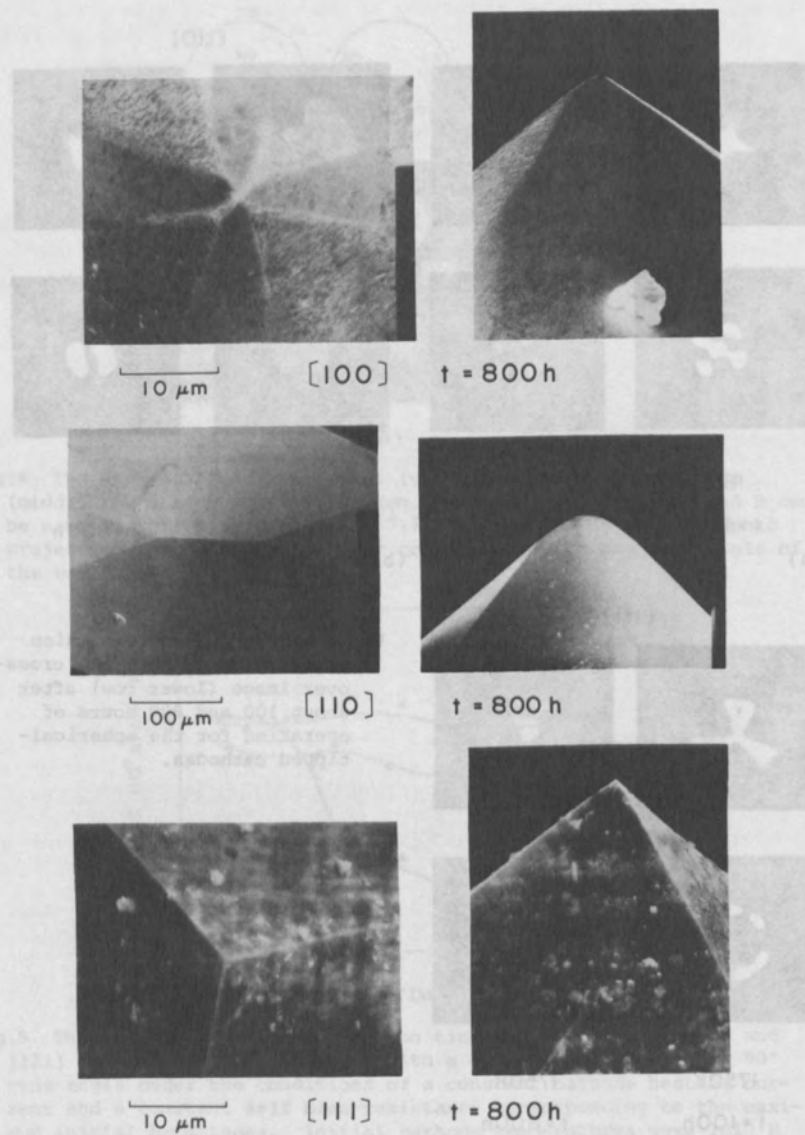


Fig.7 The SEM images of the spherical-tipped cathodes after a long period operation.

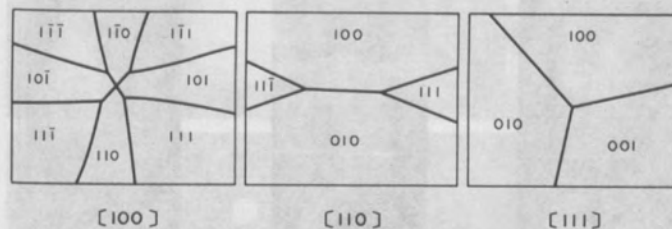


Fig.8 The line drawing of the top view of the spherical-tipped cathode after a long period of operation shown in Fig. 7

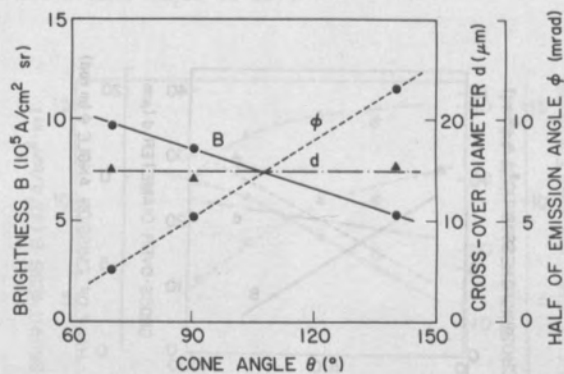


Fig.9 The maximum brightness, corresponding cross-over diameter and half of the emission angle in the space charge limited condition versus cone angle for the spherical-tipped cathode. The tip radius was 15 μ m and the cathode temperature 1810 K.

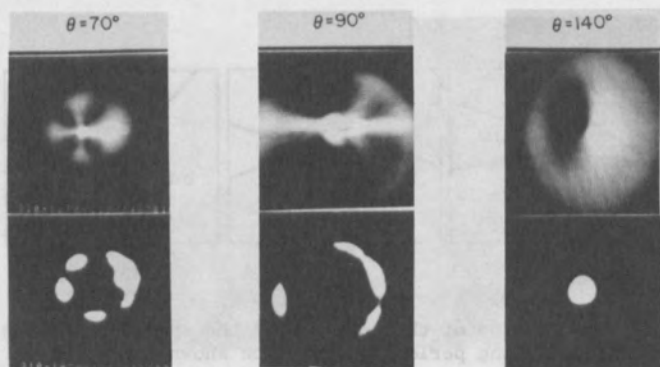


Fig.10 The emission pattern (upper row) and cross-over image (lower row) for three kinds of cone angles. The axial orientation was [130], tip radius $15 \mu\text{m}$ and cathode temperature 1810 K .

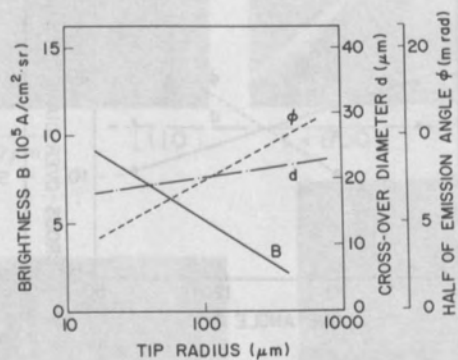
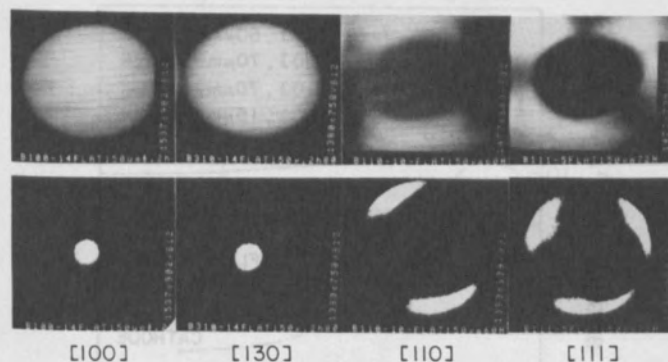


Fig.11 The maximum brightness, corresponding cross-over diameter and half of the emission angle in the space charge limited condition versus tip radius for the spherical-tipped cathode. The cone angle was 90° and cathode temperature 1810 K .



FLAT SURFACE DIAMETER 150 μm

Fig.12 The emission pattern (upper row) and cross-over image (lower row) for the flat-tipped cathodes with a flat surface diameter of 150 μm and a cone angle of 90°.

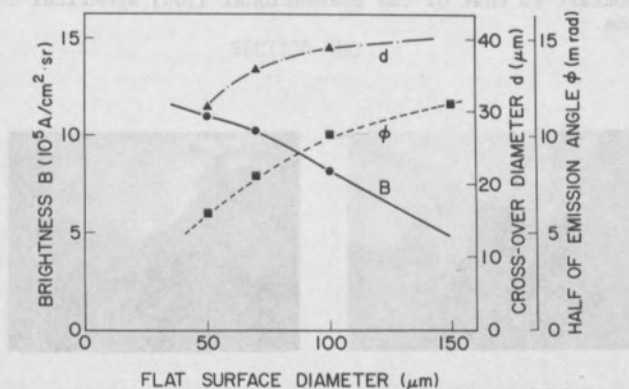


Fig.13 The maximum brightness, corresponding cross-over diameter and half of the emission angle in the space charge limited condition versus flat surface diameter. The cone angle was 90° and cathode temperature 1810 K.

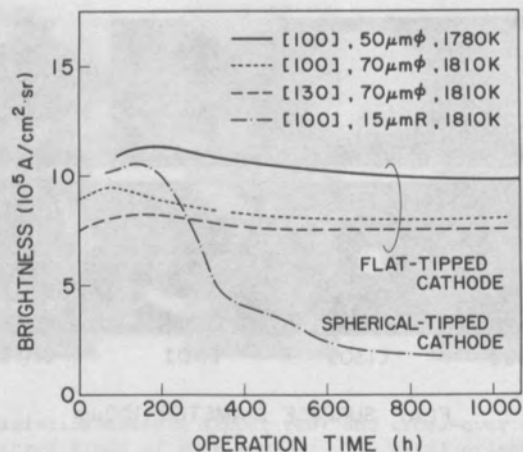
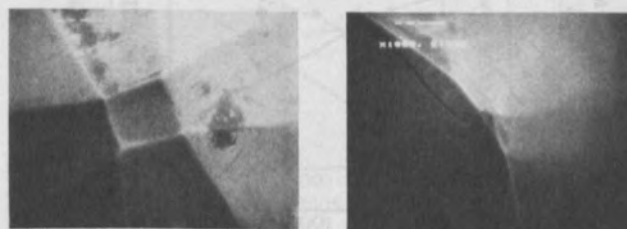


Fig.14 The brightness versus operation time for the flat-tipped cathodes. For the [100] flat-tipped cathode with a 50 μm diameter, high brightness was obtained at relatively low cathode temperature, 1780 K, and it was stable for a long time of operation, in contrast to that of the conventional [100] spherical-tipped cathode.



[100], $t=2700\text{h}$

[130], $t=2000\text{h}$

30 μm

30 μm

Fig.15 The SEM images of the flat-tipped cathode after a long period of operation. Initial flat surface diameter was 50 μm , cone angle 90° and cathode temperature about 1780 K.

A TRIPOTENTIAL METHOD FOR ELECTRON BEAM TESTING

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Abstract

A technique for contactless testing the electrical integrity of multilayer packaging modules has been developed. This technique employs electron beams on top and bottom of the sample to charge and read the electrical continuity of networks. It is based on the change of the secondary electron yield vs. the energy of the primary electrons in the low voltage range of 1-4kV. Under computer control in a vector mode operation and using a dual potential penode electron gun, top-top network charging and reading has been performed. The sample bottom is irradiated and charged by a broad "flood beam" which allows to detect the charge status on the top surface for through connections. As a result of these different charging and reading potentials a tripotential method for electron beam testing has been formulated and will be presented in conjunction with experimental results.

I. INTRODUCTION

Packaging Technology has arrived at a wiring density and complexity which begins to exceed the capability of mechanical probe testers. These packages provide the wiring network for interconnecting of chips and can take several forms such as a multilayer ceramic module consisting of 33 layers, measuring approximately 4" square by 0.2" thick to interconnect more than 100 logic chips (Fig. 1). The electrical functions of these packages are currently tested using mechanical probes (Fig. 2). Checks for defects such as opens and shorts as well as measurements of line resistance are performed. This method is rapidly reaching its practical limits due to limitations with the probes and due to the growing density and shrinking size of the contact pads to be tested. Probe testing also suffers from reliability problems due to breakage of probes and unsatisfactory electrical contacts. Also surface damage can be introduced when applying excessive probe pressure. To overcome many of these problems, a contactless testing technique as replacement of mechanical probes is desirable.⁽¹⁾

Scanning electron beams or sampling electron beams have been used to demonstrate the feasibility of noncontacting, nonloading testing of VLSI chips,^(2,3) using commercial SEM's with some modifications. Such analysis work becomes increasingly important with decreasing circuit dimensions. It is superior to mechanical probes because of higher resolution and long depth of focus, in addition to the ability to provide valuable electrical information inherent in the signal derived from the sample. Signal mechanisms such as secondary electron detection

with or without energy analysis, backscattered electron detection and probe current measurements can be applied.

Based on some of these well known electron beam testing techniques, a new approach of testing multilayer packaging modules using electron beams has been evaluated. The basic principle is to perform electrical testing using electron beams with multiple energies to introduce and read the network potentials in a floating sample. First experimental results will be presented in this paper.

Secondary electron emission - background

Insulating - or floating - sample surfaces will be exposed to the electron beam in any of these test techniques. It is therefore necessary to characterize the effect of this electron bombardment on the sample.

An incident electron will penetrate the sample surface and a.) generate secondary electrons, b.) will be backscattered, or c.) loses its kinetic energy and remains within the sample. a.) and b.) can be detected in the reflected mode, c.) results in a specimen current or changes the charge status of the sample. The ratio of escaped electrons to incident electrons determines the secondary yield. This secondary yield is strongly dependent on the energy - or potential - of the primary electrons, in particular in the low energy range between a few hundred volts and a few kV, as shown in the secondary yield vs. beam energy current in Fig. 3. From this curve it can be seen that by operating the beam at different beam potentials, a negative or positive charge or zero charge (at the x-over points) can be introduced into the floating sample. By switching the primary beam to a potential higher or lower than the x-over potential and inject the charge and then switch the primary beam back at cross-over potential, the charge status of the area can be determined. This general behavior is true for insulating and floating samples and forms the basis of a tripotential electron beam test technique which has been formulated. Further details on the secondary electron emission can be found in the literature.^(4,5)

Tripotential Test method

In order to be able to electrically test top-top network as well as top-bottom network interconnections within the sample, it is desirable to also distinguish between both. Therefore a tripotential method has been developed which is based on the dependency of the secondary electron emission yield vs. the primary electron energy, as shown in Fig. 4.⁽⁶⁾ The curves of Fig. 3 and 4 are strongly material dependent but for most materials an energy range exists for the primary electrons where the secondary electron yield is larger than unity. This range extends from the lower cross-over point at a few hundred volts to the higher cross-over point at a few kV. Any incoming electron beam of an energy not coinciding with the cross-over point will charge the sample positively or negatively. Vice versa a sample potential shifts the energy of the incoming primary electrons, generating different secondary electron yield.

The tripotential method uses three different beam potentials according to Fig. 4: V_3 for the backside charging, V_1 for the "read" or "testing," and V_2 for the top side charging. As indicated, the reading beam is kept at or near the cross-over potential of the uncharged floating sample. The detected secondary electrons generated by this beam can be used to

determine the potential being present at the network terminals. In the test procedure one end terminal of a top-top network will be charged negatively by applying a V_2 beam potential (Fig. 5). The read beam detects this charge on all other terminals indicating electrical continuity, no charge detection indicates an open. Similarly, the same signal detection method can also be used for top-bottom connections test, where the networks are charged by a bottom floodgun (7,8) at V_3 to a positive potential. The different secondary yields for the reading beam allow a distinction between top-top and top-bottom networks.

The contrast between the charged and uncharged state can be enhanced by analyzing the secondary electron energy. It is well known that almost all the secondary electrons have a kinetic energy below 10eV. Secondary electrons generated in an area which has a potential different from 0 have their energy distribution shifted by the same amount. A retarding field energy analyzer can set a threshold, below which all slow electrons are suppressed. This results in an increase in contrast between uncharged and charged areas. A detailed discussion on this effect can be found in a different paper of this issue.⁽⁹⁾

Test system - Pentode Electron Gun

The electron optical system in which the experiments were performed consists of a LaB_6 pentode type electron gun, 2 magnetic lenses, a large field deflection system and a large field secondary electron detector. The system was modified from a Vector Scan system⁽¹⁰⁾ and is capable of operating in the SEM mode as well as in the vector mode under computer control. The reading beam potential can be varied continuously between 0V to 4kV; beam currents of 2×10^{-6} A at 2kV have been achieved.

One of the new features of this test system is the pentode type electron gun. This gun allows the beam potential to be switched at high speed and it also contains a refocussing electrode which allows the cross-over to be shifted on the electron optical axis. The basic principle of the pentode gun operation is shown in Fig. 6. A standard triode gun was modified with two extra electrodes inserted between the Wehnelt and Anode. The upper electrode serves as an additional accelerating electrode, the lower one as refocussing electrode.

This set up allows two modes of beam potential operation and high speed switching between both. Switching times from one potential to the other of 100 μ s have been achieved and this can be readily improved. In the first mode this setup serves the function of a standard triode gun, both extra electrodes are held on ground potential, as indicated with the double switch in Fig. 6. If the control system flips the switches into the voltage position, the filament, bias and cathode supplies are floating at the ΔV potential, thus providing an extra accelerating potential to the electrons. For the purpose of charging the networks the cathode then is at the $V_2 = V_1 + \Delta V$ potential.

An additional stringent requirement for the test system is to keep the plane of focus for both potentials at the sample surface while switching between V_2 and V_1 without changing any of the two magnetic lenses. Two mechanisms provide the means for this requirement: a) different imaging techniques, as shown in Fig. 7, and a fine refocussing with the second electrode in the pentode as shown in Fig. 6 and Fig. 7.

For the imaging techniques the strengths of the two magnetic lenses are set such that an intermediate image of the cross-over is formed for the reading beam potential. This intermediate image then is projected onto the sample surface. No intermediate image is formed at

higher beam potentials, resulting in a telecentric electron ray imaging technique. To fine tune for refocussing the beam onto the sample surface, an additional cross-over shift on the electron optical axis is achieved by applying a potential V_f to the second electrode. This voltage is switched simultaneously with the switching of the ΔV supply.

Any field size change and image rotation due to the dual potential application has to be corrected for by some means in the system control.

Experimental results

Experiments have been carried out by using the system in two different modes of operation. First, in the computer controlled vector mode where the the beam is directed to network terminals and switched on for a pulses of variable durations. The secondary electron signal is then recorded through an analog/digital interface to the computer. Second, the SEM mode in which the system is used as a scanning electron microscope to display the sample surface and its charge status on a CRT. During the charging process, only the vector mode is used, to avoid charging of insulating areas around the terminals.

The feasibility of this testing approach on a single network pad is demonstrated in Fig. 8. An initial secondary electron signal of the uncharged pad is first detected with the inspection potential of about 1600V with the analyzer threshold set to $\sim 10V$. This is followed by increasing the beam potential to 2600V using the pentode gun and the beam switched on for a duration variable from $50\mu s$ to $125\mu s$ to inject charge on the same pad. Immediately after this, the beam potential is again returned to 1600V, and the injected charge is detected as a signal change. Fig. 8 also demonstrates that the change in signal level after charge injection is related to the charging time. It can be seen from Fig. 8 that in this particular network significant increases in signals were observed with charging timed from $5\mu s$ to $100\mu s$. Beyond $100\mu s$ the secondary electron distribution is almost completely shifted beyond the threshold and further charging only results in a small signal increase. The retention time of the charge was found to be extremely good with no noticeable changes over a few hours period.

To demonstrate the ability to test a simple network, an experiment has been conducted using a manual vector mode. This test has been performed over 5 test pads within a single chip site with pad 4 and 5 interconnected, Fig. 9. The following sequence was applied: Point 5 is first addressed with the read beam to establish the reference level for an uncharged state. Then the beam potential is switched to the higher charging voltage and pad 5 addressed again and charged for $50\mu s$. After this the beam potential is returned to its reading value and pads 1 through 5 addressed sequentially in a pulsed vector mode. The result of the test before and after charging is shown in Fig. 9. The low signal level of points 1,2,3 of about 400 mV is of the same level as point 5 before charging while points 4 and 5 show a 2-3 times higher secondary electron emission signal at about 1V. This result demonstrates that an electrical continuity exists between points 4 and 5 and no continuity to points 1,2,3. Fig. 9 also shows that an adequate increase in signal can be achieved to allow a discrimination level between opens and shorts to be readily established.

A more extensive experiment has been carried out to test multiple networks in an automated setup under computer control. The system control allows single or multiple networks to be selectively addressed with both potentials. Beam potential switching and correction for field size rotation and distortion between the two potentials are commanded by software to ensure

the correct addressing of the beam when unblanked. Fig. 10a) shows a SEM image of a charged multiple terminal network and 10b) the vector addressing in the pulsed mode. Similar to the experiment of Fig. 9 first the reference level for uncharged pads is established on the network to be charged. Automatically then the charge potential is set and the correct vector address selected. After charging for 100 μ s and switching to the read potential, all terminals of this network are tested for continuity and other networks for possible shorts. The secondary electron pulses are derived from many uncharged networks - low signal level at around 700mV, indicating opens or no shorts - and all charged terminals at about 1.6V. A suitable discrimination level can easily be set again.

The three experiments described here demonstrate the basic feasibility of this contactless electron beam testing technique for top-top networks. Additional experiments have also been conducted with a flood beam at the bottom surface to irradiate the through connections. These sets of results together demonstrated the working of the tripotential testing method.

Summary

An electron beam technique has been developed for contactless testing the electrical functions of VLSI packaging substrates. Electron optical components such as pentode electron gun, large field deflection system and large field detection system have been demonstrated to be operational. Based on the secondary electron yield vs. beam potential, a tripotential test method has been developed which allows open and shorts tests in top-top and top-bottom network interconnections. System automation under an IBM Series /1 computer was implemented and experimental results have demonstrated the basic feasibility of this testing scheme.

Acknowledgements

We would like to acknowledge the strong support by people at IBM's T. J. Watson Research Center and the helpful interaction with the IBM MLC - testing group and the Electron Beam Technology group in E. Fishkill.

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Conductor Network In Multilayer Substrate

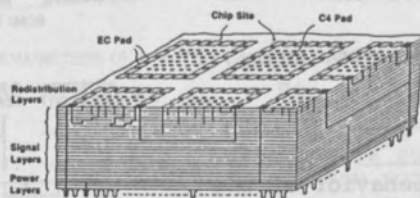


Fig. 1: Multilayer Ceramic Module with multichip interconnecting networks.

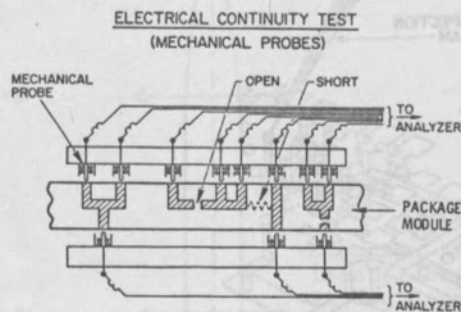


Fig. 2: Schematic of a mechanical probe tester for opens and shorts test in packaging modules.

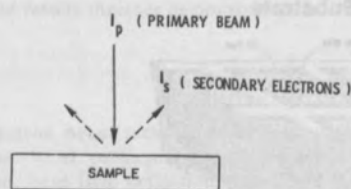
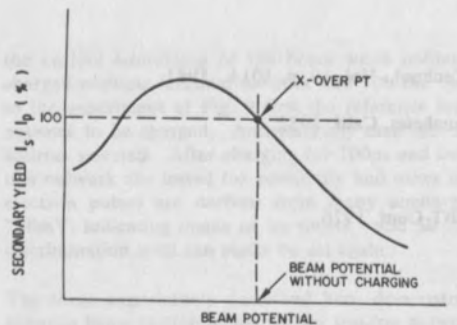


Fig. 3: Generalized behavior of the secondary electron yield vs. the primary electron energy in the low kV range.

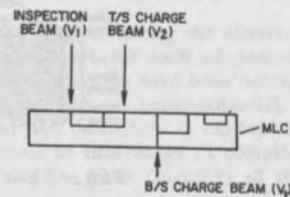
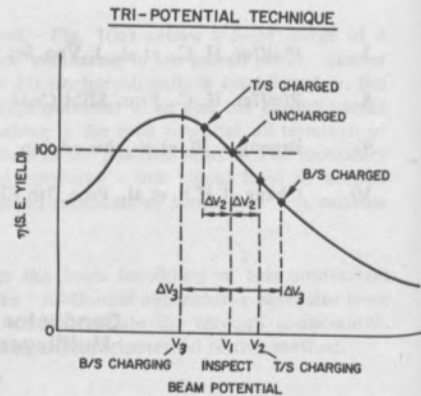


Fig. 4: Definition of beam potentials in the tri-potential technique for top-top and top-bottom network testing.

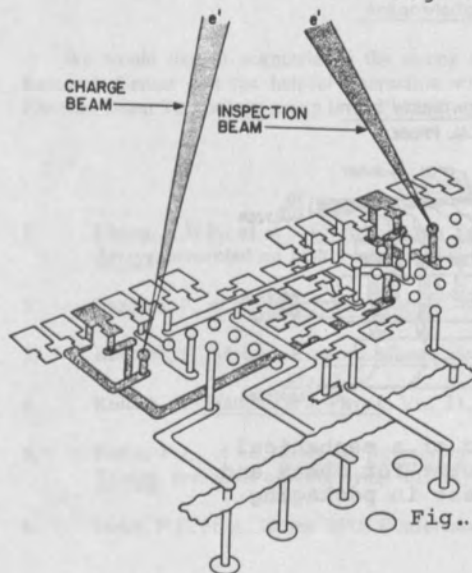
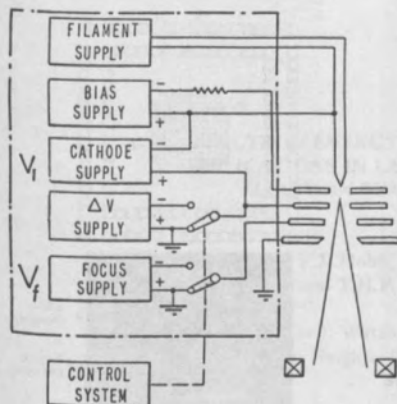


Fig. 5: Principle of dual-potential technique for top-top network testing.

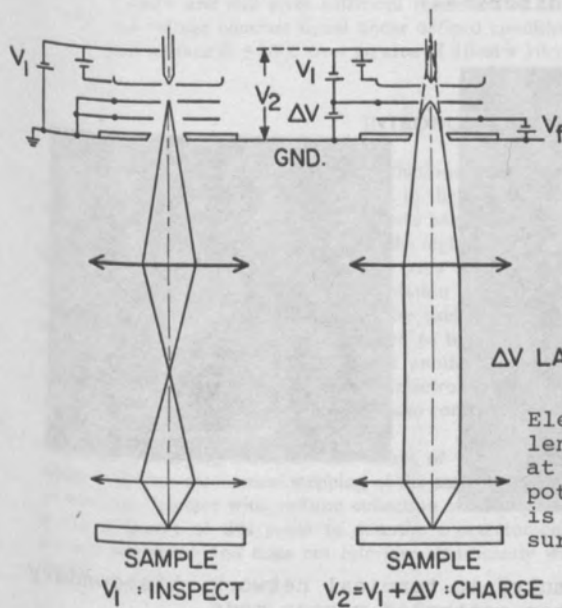


TYPICAL OPERATION PARAMETERS OF PENTODE GUN

V_1	=	-1500V	—	-2500V
ΔV	=	0V	—	-2000V
V_f	=	0V	—	-2000V

Fig. 6:

Schematics of pentode gun electronics supply for high speed beam potential switching.



ΔV LARGE

Fig. 7:

Electron rays through a two lens electron optical system at two different pentode potentials. Plane of focus is maintained on the sample surface.

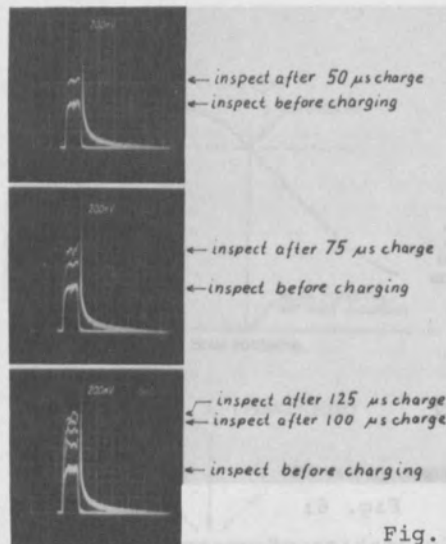


Fig. 8: Signal level change of secondary electrons for different charging times in a network when applying energy discrimination.

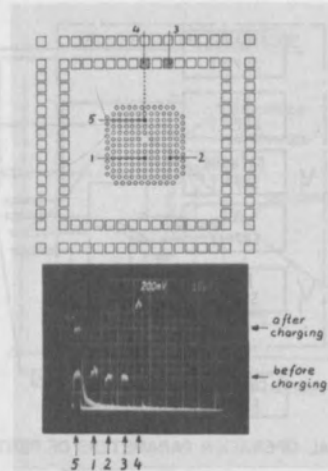


Fig. 9: Vector mode secondary electron pulses derived from a charged network 4,5 and from uncharged pads 1,2,3.

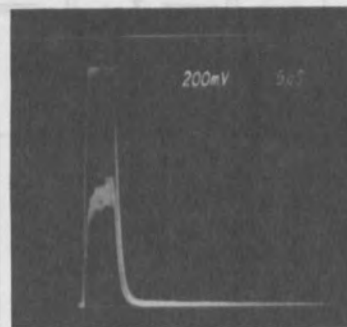
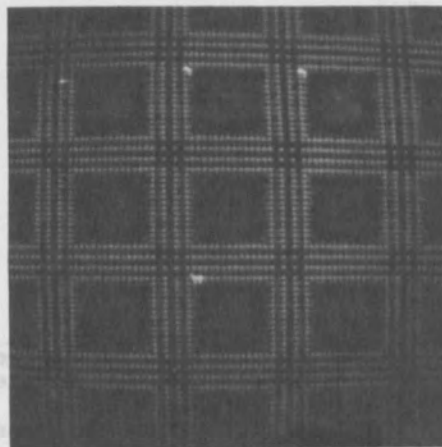


Fig. 10:

a) SEM image of a charged multiple terminal network, b) secondary electron pulse of computer controlled vector mode.

ELECTRON ENERGY ANALYZER FOR APPLICATIONS IN LARGE SCAN FIELD ELECTRON BEAM TESTING

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ABSTRACT

Electron beam testing of VLSI packaging modules by voltage contrast techniques requires electron energy analyzers with uniform collection efficiency over an area several inches wide. This has been achieved by a 4 channel retarding field energy analyzer that does not significantly interfere with the electron optical requirements at beam energies of 1-2keV and still gives sufficient resolution of 1-2eV. The uniformity of the voltage contrast signal under defined conditions of local fields on the test surface is $\pm 10\%$ over an area of 10cm x 10cm.

INTRODUCTION

Electron beam techniques for functional tests and failure analysis of integrated circuits have extensively been reported in the literature over the years (for a review see ref. (1)). More recently these techniques have also been applied to functional testing of chip interconnecting networks (2,3). The high density of contact pads on these packaging modules and the sensitivity of these pads to physical damage has made mechanical probing increasingly impractical. A solution to this problem is the use of a contactless probing technique which can be met by using a computer controlled scanning electron beam, which may be easily programmed to test any pad configuration. The test procedure, as described in more detail in another paper of this meeting (4), consists of charging one end of a network by the electron beam and sensing the presence of charge at the other end of the network by voltage contrast techniques.

Since the packaging modules with arrays of 10 x 10 chips have dimensions of 10cm x 10cm and since mechanical stepping of the sample is not considered practical at this time, an electron detector with uniform collection efficiency over this large area is required. It is the objective of this paper to describe a detector configuration that gives sufficient voltage resolution and does not interfere significantly with the electron optical requirements.

VOLTAGE CONTRAST TECHNIQUES

The surface potential of a specimen determines the impact energy of the primary electrons and also the energy of the true secondary electrons that leave the surface. Because of these two effects there are two different types of voltage contrast.

Type 1 voltage contrast uses the effect, that the energy of the primary electrons has on the number of electrons emitted from the surface. The secondary (true secondary plus backscattered) electron yield curve (Fig. 1) rises steeply at low primary energies and decreases at higher energies because faster electrons penetrate deeper into the specimen and the escape probability for secondary electrons decreases. The second unity yield point lies at 1-2keV for ceramic materials and at several keV for metals (5). Since the slope of the yield curve is very shallow, the expected voltage contrast at least for higher primary energies is very poor. The detector for type 1 voltage contrast could be very simple, for example, a flat collector plate above the specimen (2).

Type 2 voltage contrast uses the energy of the true secondaries, which have an energy distribution approximately 10 eV wide. This energy distribution is fixed relative to the potential of the emission surface. Recording this energy spectrum with various kinds of energy analyzers is the common method of measuring surface potentials with electron beams (Fig. 2).

For the functional test of packaging modules, high contrast can be expected if the energy distribution curves for charged and uncharged pads are separated from each other in the energy spectrum (Fig. 2). A retarding field analyzer, with the analyzing grid at a proper threshold voltage, will discriminate between charged and uncharged states. The retarding field analyzers generate the integral form of the energy spectrum (s-curves).

EXPERIMENTAL TEST SYSTEM

For the development of a detector usable for large area specimen, an experimental e-beam test system was set up. The electron optical column consists of a single crystal LaB_6 gun, two demagnifying lenses and a magnetic double deflection system partly inside the final lens (6,7). The deflection system was optimized within the constraints of a standard Vector Scan final lens to reduce chromatic aberrations due to the low electron energy of 1-2 keV. A large specimen chamber, with a diameter of 50 cm, provides ample space for variations in detector geometry and allows a working distance of 15 cm between final lens and specimen mounted onto a x-y table.

At a working distance of 15cm, probe currents of up to 10^{-6} amps at a resolution of $30\mu\text{m}$ over the total scan field of $10\text{cm} \times 10\text{cm}$ is obtained. This is demonstrated in Fig. 3. Field distortions are not a problem when addressing the beam to any network on the packaging module because these can be automatically compensated.

4 CHANNEL ENERGY ANALYZING DETECTOR

Retarding field analyzers have been used with two different grid configurations, hemispherical and planar (see review in (1)). Common to both techniques is that the

beam is penetrating through small apertures in the grids and that the area over which the beam can be scanned is therefore limited to about 1 mm^2 . It is impractical to scan the beam over larger areas passing through the grids, because the fields in the vicinity of biased grid bars will deflect the low energy primary electrons.

Therefore, we arranged the grids outside of the area covered by the scanning beam, as can be seen in Fig. 4. Since the distances between grids and sample are rather large, it is not possible to generate the high extraction fields on the sample surface which are normally necessary to prevent trapping of electrons in local fields. However, the structures to be tested on packaging modules are not as small as on integrated circuits, so that the problem of local field barriers causing nonlinear voltage contrast is not as severe.

In order to obtain the required uniformity of the voltage contrast signal, 4 sets of grids are arranged over the 4 corners of the sample and the signals generated by the electrons collected in these 4 channels are summed. The top of the grid housing consists of another grid which lets backscattered electrons escape without generating more secondary electrons. These would otherwise contribute to the background signal. The distance of 2.5 cm between final lens and grid housing is sufficient to avoid interaction of the slow secondary electrons with the magnetic field of the lens. This could severely affect the function of the analyzing detector.

EXPERIMENTAL RESULTS

The uniformity of the collection efficiency of the 4 channel detector was tested on a metal plate. As can be seen from Fig. 5, four channel detection is superior to single channel detection.

Figure 6 shows six complete chipsites on a multilayer ceramic module with pads connected to two different powerplanes shown as bright. Two potentials, V_1 and V_2 , were applied to these two powerplanes through pins on the backside of the module. The difference of the detector signals collected from pads at potentials V_1 and V_2 was recorded and found constant within $\pm 10\%$ through all the chipsites on the $10\text{cm} \times 10\text{cm}$ packaging module.

The energy resolution of the retarding field analyzer as demonstrated in Fig. 7 is 1.5 eV. This resolution is sufficient to discriminate between charged and uncharged states of the test pads which differ by several volts. The influence of local fields around the test pads on the collection efficiency of the secondary electrons can be seen in Fig. 8. Again 4 channel detection is superior to single channel detection.

For exact potential measurements on the test surface, the voltage contrast has to be linear. That means the integral energy distribution curves (s-curves) have to be shifted by the surface potential in a linear way. For the energy analyzing detector described here this is the case for surface potentials ranging from 0-9 volts (see Fig. 9).

SUMMARY

A 4 channel retarding field energy analyzer has been developed for electron beam testing of large area specimen. This detector has the following features:

1. The uniformity of the voltage contrast signal is $\pm 10\%$ over a test area of 10cm x 10cm.
2. The energy resolution of the energy analyzer is 1.5 eV.
3. The voltage contrast is linear in the range of specimen voltages: 0-9 volts.

This range is sufficient to discriminate between charged and uncharged testpoints and to perform the functional test of networks on packaging modules.

ACKNOWLEDGEMENT

We would like to acknowledge the support by the IBM-MLC-Testing group and the successful cooperation with the Electron Beam Technology group in East Fishkill.

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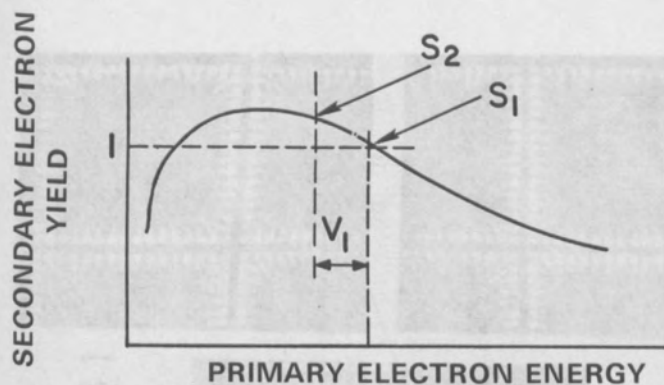


Fig. 1 Type 1 voltage contrast mechanism based on the dependence of the secondary electron yield upon primary electron energy.

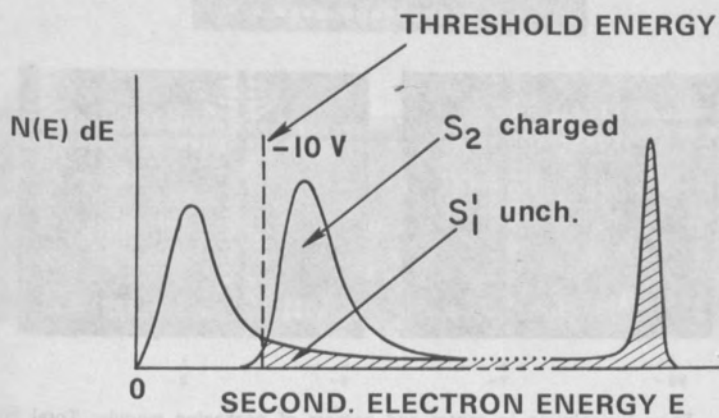


Fig. 2 Type 2 voltage contrast mechanism based on the shift of the energy spectrum of the secondary electrons by the surface potential.

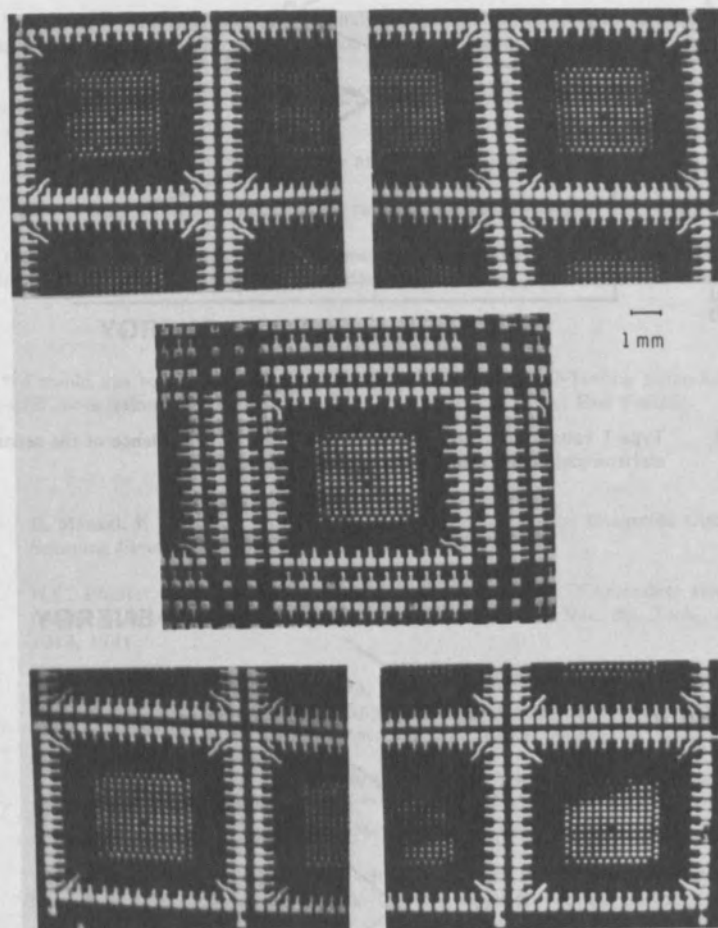


Fig. 3 Spatial resolution in center and corners of packaging module; Total Scan Field: 10cm x 10cm; Primary Electron Energy: 1.5 keV.

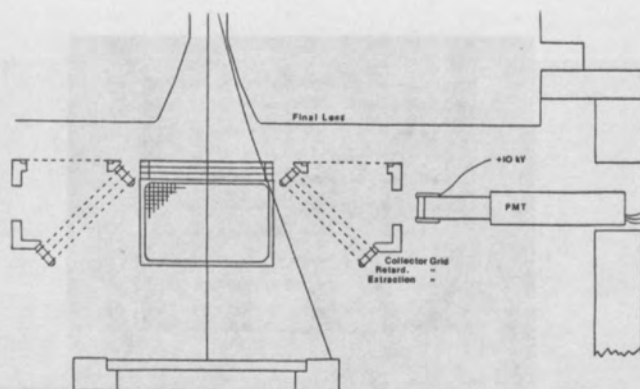


Fig. 4 4 channel retarding field energy analyzer. 2 channels are seen in cross-section, 2 channels in projection. Working distance: 15 cm; Total Scan Field 10cm x 10cm.

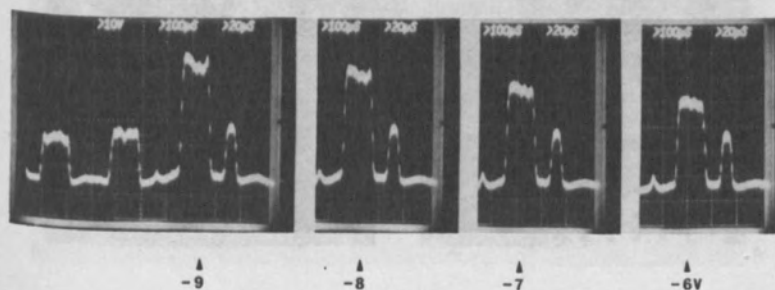


Fig. 7 Detector signal of line scan over 4 pads, with potential on 3 pads floating and potential on one pad changed in steps of 1 volt. Resulting energy resolution of retarding field energy analyzer: 1.5 eV.

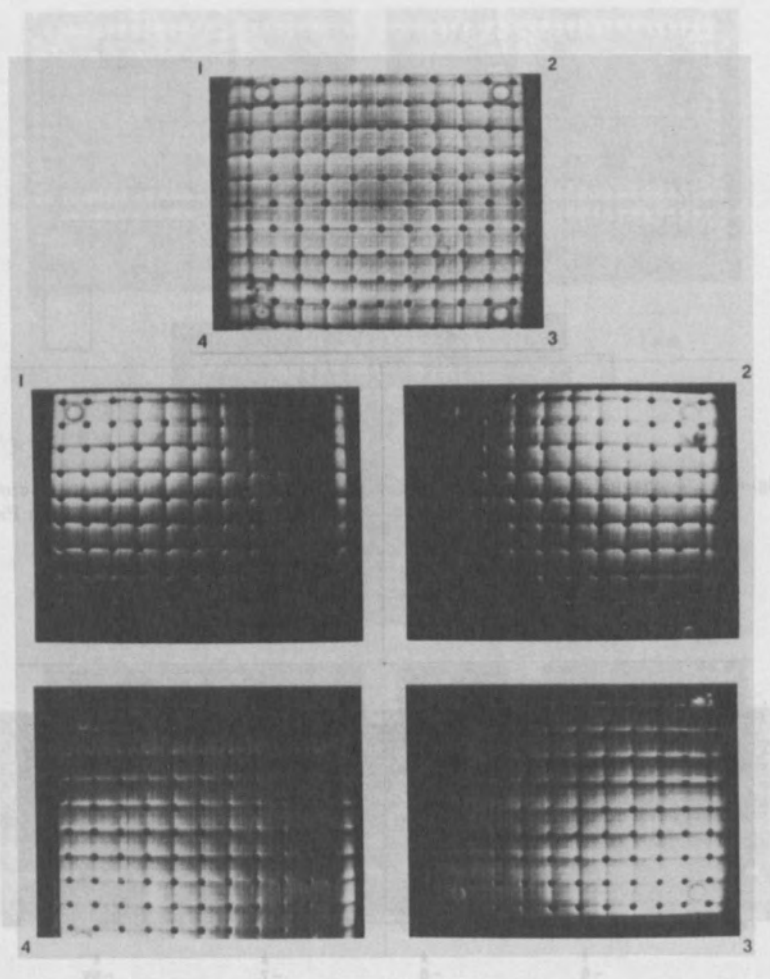


Fig. 5 Uniformity of voltage contrast signal on a metal plate 10cm x 10cm. 4 channel detection on top compared to single channel detection below.

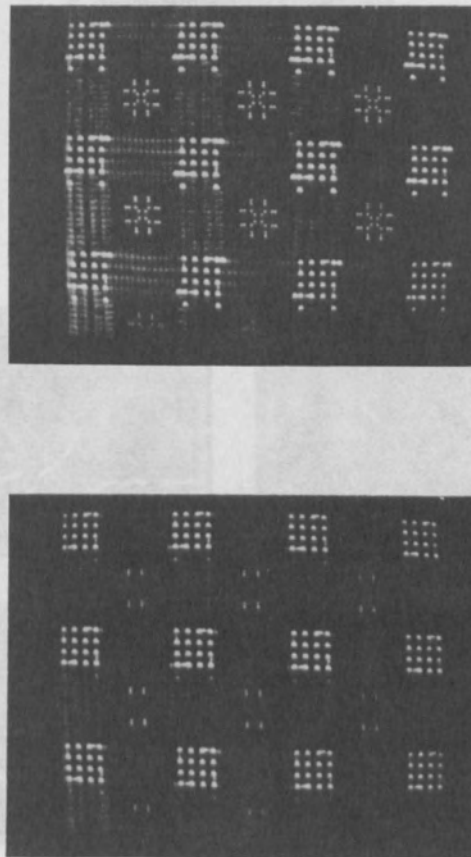


Fig. 6 Voltage contrast image of multilayer ceramic packaging module. Top: Two powerplanes with connected pads on a potential of -9 V ; Bottom: One powerplane on -9V , the other on -5V . Analyzer grid of retarding field on -8V . Potential on the rest of the pads is floating.

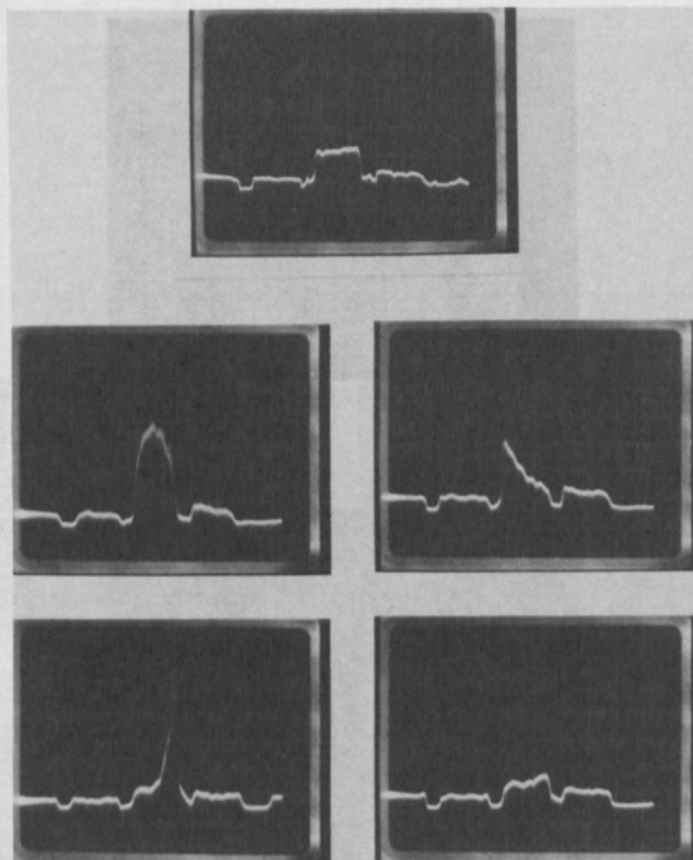


Fig. 8 Detector signal of line scan across 4 pads, Top: 4 channel detection; Below: single channel detection showing asymmetry of collection efficiency.

RADIATION CHEMISTRY AND RESIST APPLICATIONS OF POLY(p-SUBSTITUTED STYRENE)

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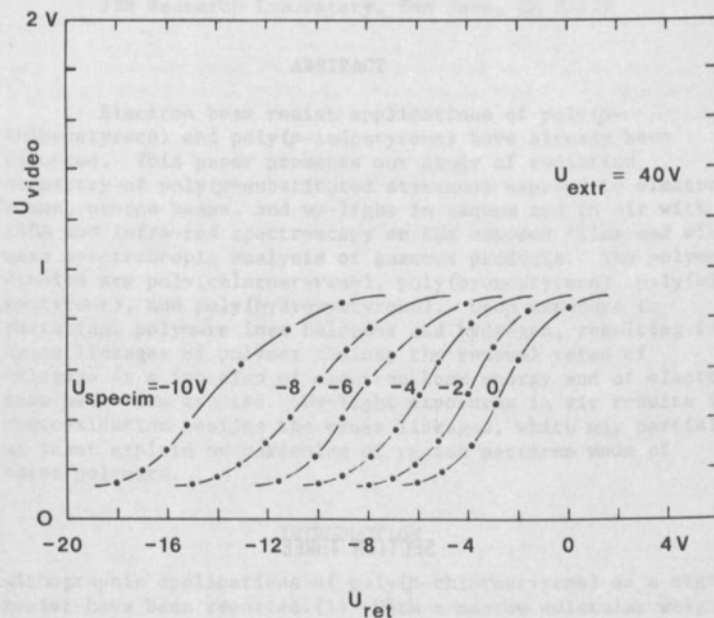


Fig. 9 Integrated energy distribution curves for different specimen potentials. Linearity range of voltage contrast: 0-9 volts.



Fig. 3. Cross-section of the ship in the 4th part. Top - 4th section, below - ship's hull in the 4th part of the ship's hull.

RADIATION CHEMISTRY AND RESIST APPLICATIONS OF POLY(*p*-SUBSTITUTED STYRENES)

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ABSTRACT

Electron beam resist applications of poly(*p*-chlorostyrene) and poly(*p*-iodostyrene) have already been reported. This paper presents our study of radiation chemistry of poly(*p*-substituted styrenes) exposed to electron beams, proton beams, and uv-light in vacuum and in air with ESCA and infra-red spectroscopy on the exposed films and with mass spectroscopic analysis of gaseous products. The polymers studied are poly(chlorostyrene), poly(bromostyrene), poly(nitrostyrene), and poly(hydroxystyrene). Upon exposure to radiation, polymers lose halogens and hydrogen, resulting in cross linkages of polymer chains; the removal rates of halogens as a function of electron beam energy and of electron dose have been studied. Uv-light exposures in air results in photooxidation besides the cross linkages, which may partially at least explain uv-hardening of resist patterns made of these polymers.

INTRODUCTION

Lithographic applications of poly(*p*-chlorostyrene) as a negative tone resist have been reported.(1) With a narrow molecular weight distribution this polymer has high electron beam sensitivity, high resolution and high aspect ratio together with strong CF_4 plasma etch resistance. Poly(*p*-iodostyrene) is also reported as an electron beam resist.(2) Poly(*p*-hydroxystyrene) and partially brominated poly(*p*-hydroxystyrene) are used as host resins in photoresists.(3),(4) Although it can be readily assumed that the cross linkage takes place through elimination of halogens under electron beam exposures, few direct evidences have ever been reported.

We wish to report here the ESCA data supporting halogen removal under uv-light, electron beam, and proton beam exposures, giving rise to cross linkings of polymer chains. In order to support the ESCA data, mass spectroscopic measurements during electron beam exposures and gaseous photoproduct analysis were carried out along with infra-red spectra of the films exposed in vacuum and in air. Extensive photooxidation together with cross linking have been found in the ESCA and infra-red spectra with these polymers irradiated in air except poly(*p*-nitrostyrene) which resulted in photo-rearrangement as a major reaction under the same condition. Cresol-formaldehyde novolac resins showed the same carbon core level signal with poly(styrenes) after

exposure to uv-light in air. We reported uv-hardening of AZ-type photoresist patterns, suggesting that indene carboxylic acid formation was contributing to this effect.(5) Photooxidized polymer surfaces, however, may contribute, at least partially, to thermal flow resistance of polymer patterns at high temperatures in addition to our originally proposed mechanism of indene carboxylic acid formation. We like to demonstrate uv-hardening of resist patterns made of poly(hydroxystyrene) with an aromatic bisazide sensitizer by photo-oxidation alone.

EXPERIMENTAL

Materials: Poly(*p*-chlorostyrene) was obtained from Aldrich Chemical Co., Poly(*p*-bromostyrene) and poly(*p*-nitrostyrene) were both from Polysciences, Inc. Poly(*p*-hydroxystyrene) and partially brominated poly(*p*-hydroxystyrene) were supplied by Maruzen Oil Co. All these polymer samples were used without further purification. Polystyrene, poly(*p*-chlorostyrene), and poly(*p*-bromostyrene) were dissolved in chlorobenzene, poly(*p*-nitrostyrene) in dimethylformamide, and poly(*p*-hydroxystyrene) in cyclopentanone. A photoresist, RD-2000N, which was made of poly(*p*-hydroxystyrene) and an aromatic bisazide, was supplied by Hitachi Chemicals.(4) The polymer films were spin-coated from these solutions onto aluminum wafers for ESCA studies, or NaCl plates for infra-red studies. The wafers with the polymer films were soft-baked at 100°C for 30 min in air prior to any subsequent experiments.

Electron Beam Exposures: The electron beam exposures were conducted with a Varian Scanning Auger electron beam gun at 0.5 to 3 KeV electron energy; doses were varied, corresponding to 30 sec to 2 min with 10 μ A electron current. With these energy range, electrons penetrate only a few thousand Angstrom or less deep into resist surfaces. Because our main tool, ESCA, can detect chemical configurations of only a few hundred Angstrom deep surfaces, we can study chemical reactions very efficiently. With higher electron energies, like 25 KeV, chemical changes we observed with 3 KeV electrons may not be observed in the same dose range, because electrons deposit energy far deeper inside polymer layers. The exposures were carried out at pressure below 10^{-6} torr at room temperature.

Proton Beam Exposures: The proton beam exposures were carried out with a Commonwealth Scientific Corp. ion beam gun at 3 KeV proton energy and 1 mA dose for 1 min under a pressure of 10^{-4} torr.

Uv-light Exposures: The uv-light exposures were conducted in air without filter or in a sealed quartz tube in vacuum with a Hanovia SH-type medium pressure mercury lamp.

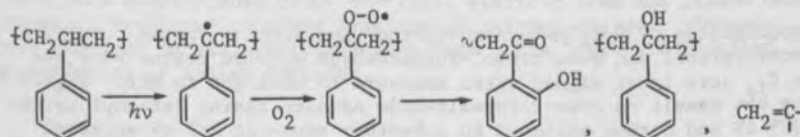
Analytical Instruments: ESCA measurements were carried out at room temperature under a vacuum better than 10^{-9} torr with a Hewett-Packard

Model 5650B ESCA spectrometer. The samples were flooded with thermal electrons during the data collections to neutralize the charge effects. Mass spectroscopic measurements were conducted during electron beam exposures with an UTI quadrupole mass analyzer. The gaseous product analysis in uv-light exposures was carried out with a Hitachi-Perkin Elmer mass spectrometer. Infra-red spectra were taken with a Perkin Elmer Model 521 spectrometer.

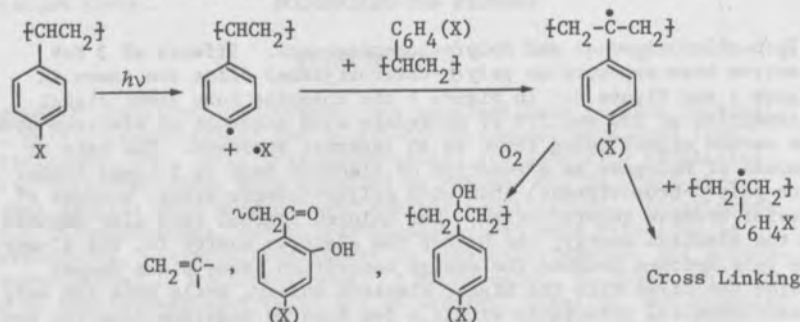
RESULTS AND DISCUSSION

Poly(p-chlorostyrene) and Poly(p-bromostyrene): Effects of 3 KeV electron beam exposure on poly(p-chlorostyrene) films are shown in Figure 1 and Figure 2. In Figure 1 the chlorine core level signal intensities at 200 and 270 eV decreases with increase of electron dose, the carbon signal being taken as an internal standard. The rate of removal of halogens as a function of electron dose is 5 times higher with poly(p-bromostyrene) than with poly(p-chlorostyrene) because of heavier bromine incorporation. The halogen removal rate also depends on the electron energy; the higher the electron energy is, the slower the rate becomes because the energy deposition takes place deeper inside the films with the higher electron energy, while ESCA can only detect chemical structures within a few hundred Angstrom from the top surfaces. With proton beams the surface damages become far more severe, as revealed in Figure 2; here the energy is deposited only on the top surfaces. The carbon core level signal after the proton beam exposure becomes broader in comparison with the one obtained after the electron beam exposure; the carbon signal with chlorine appearing at 286 eV, which is clearly seen in Figure 2a, should have completely disappeared in Figure 2b and 2c, based on the chlorine intensities in these conditions.

Poly(p-chlorostyrene) and poly(p-bromostyrene) both lose chlorine and bromine respectively upon uv-light irradiation in air or in vacuum, thereby initiating cross linkages of the polymer chains; this is shown by loss of the halogen signals in the exposed polymer films in Figure 3 on poly(p-bromostyrene), and the carbon core level signals in Figure 4 on poly(p-chlorostyrene). The uv-light exposure in vacuum resulted in disappearance of the carbon signal attached to chlorine without further complication. The uv-irradiation in air, however, resulted in the photooxidation of polymer films, as shown in Figure 4b. The similar carbon core level signal was obtained with photooxidized polystyrene. (6) Photooxidation of polystyrene has been studied extensively, and formation of ortho-hydroxy acetophenone end group is established. (7)



The new carbon core level signal at 289 eV in Figure 4b belongs to the carbonyl carbon of the acetophenone type end group, and the broad band appearing at 287 eV belongs to the carbon attached to the newly formed hydroxy group. Based on these ESCA data, the infra-red absorption band newly appearing at 1700 cm^{-1} after uv-irradiation in air and the mass spectroscopic data of HCl and hydrogen formation under electron beam and uv-light exposures in vacuum, the following scheme of the polymer reactions may be presented.

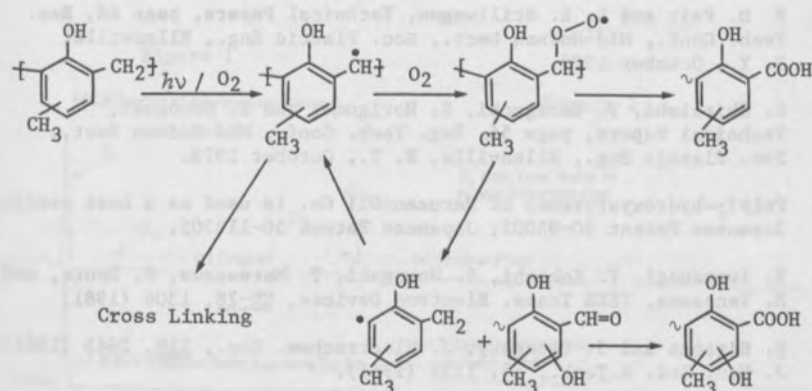


The cross linking reaction initiated by halogen elimination occurs even in air along with photooxidation accompanying the main chain scission, but it is the only reaction taking place in radiation exposures in vacuum.

Poly(p-nitrostyrene): Uv-light exposure of poly(p-nitrostyrene) in air resulted not in extensive photooxidation but in photo-rearrangement as a major reaction. This is shown by the carbon and nitrogen core level signals and the oxygen core level signal intensity after the irradiation. Figure 5 shows wide band ESCA spectra of poly(p-nitrostyrene). After uv-light exposure in air or in vacuum, a new nitrogen core level signal appears at 400 eV, 6 eV downfield shift from the original core level signal of the nitro group $-\text{NO}_2$ at 406 eV, indicating formation of neutral nitrogen group like $-\text{N}=\text{O}$ or $-\text{O}-\text{N}=\text{O}$. Under proton and electron beam exposures the elimination and the rearrangement of the nitro group take place, as shown in Figure 6c and 6d, respectively. Poly(p-nitrostyrene) yields negative tone photo- and electron beam images after development, but its pattern is not as good as the ones obtainable with para-halogen substituted polystyrenes (1), (2), although it has a mid-uv-light sensitivity.

Photooxidation of Poly(p-hydroxystyrene) and Novolac Resins: Poly(p-hydroxystyrene) and even cresol-formaldehyde novolac resins show the same C_{1s} core level signal after exposure to uv-light in air. Figure 6 shows the result on cresol-formaldehyde novolac resin; carbonyl carbon at 289 eV and carbon attached to a hydroxy group at 287 eV appeared after the exposure. Based on these and infra-red data, we propose the

following mechanism of the photooxidation of novolac resins.



The formation of acid end groups and cross linkages resulted in hardening of polymer patterns. We reported uv-hardening of AZ-type photoresists, suggesting that indene carboxylic acid formation contributed to this effect.(5) We wish to demonstrate now that without formation of indene carboxylic acid just photooxidation and accompanying cross linkages alone provide the hardening of resist patterns made of novolac resins or of polystyrenes. RD-2000N, MR-resist, made of poly(*p*-hydroxystyrene) and an aromatic bisazide sensitizer(4) was used for this purpose. Figure 7 shows the ESCA result on RD-2000N. Clearly the carbon attached to azide group disappeared after 10 min exposure to uv-light as shown in Figure 7b, which was essentially the same spectrum of unexposed poly(*p*-hydroxystyrene). After a long exposure to uv-light the polymer surfaces were covered with oxidized layers as shown in Figure 7c. For uv-hardening, such a long exposure is unnecessary. With a dose of 1 J/cm², for 1 hr exposure of our medium pressure mercury lamp, the resist thermal flow was completely prevented even at 300°C as shown in Figure 8. These results demonstrate that photooxidation alone can provide high temperature flow resistance of the polymer patterns.

In summary, we reported efficient halogen removals from para-substituted polystyrenes under uv-light, electron beam and proton beam exposures, resulting in cross linkings of polymer chains. With uv-light exposure in air, photooxidation took place, and this resulted in the hardening of resist patterns.

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THE ELECTRON BEAM INDUCED CHEMISTRY OF POLY(p-CHLOROSTYRENE) USED AS RESULTS

Figure 1

ESCA Spectra of Poly(p-chlorostyrene)

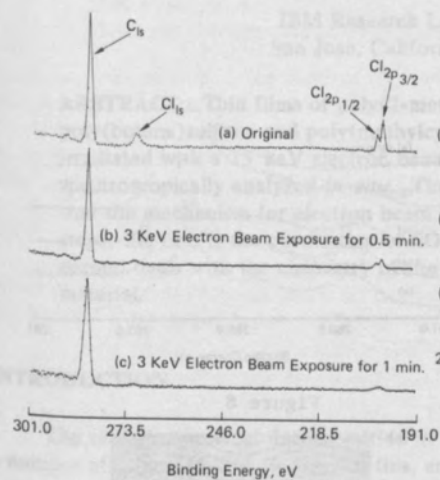


Figure 2

C_{1s} Core Level Signal of Poly(p-Chlorostyrene)

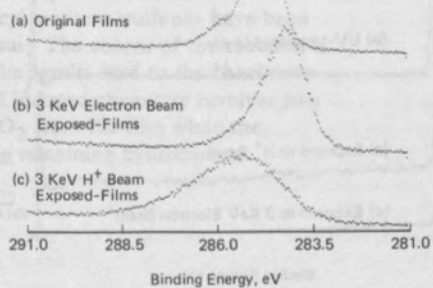


Figure 3

Poly(p-Bromostyrene)

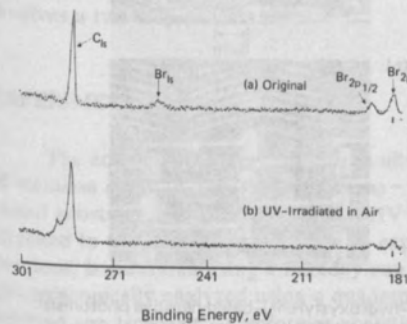


Figure 4

C_{1s} Core Level Signal of Poly(p-Chlorostyrene)

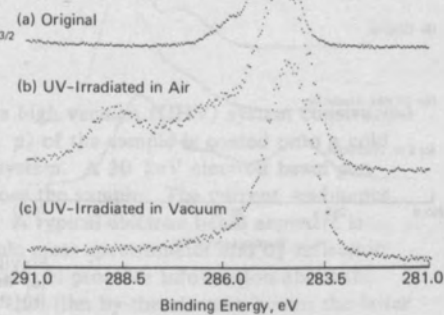


Figure 5

Wide Band ESCA Spectra of Poly(p-Nitrostyrene)

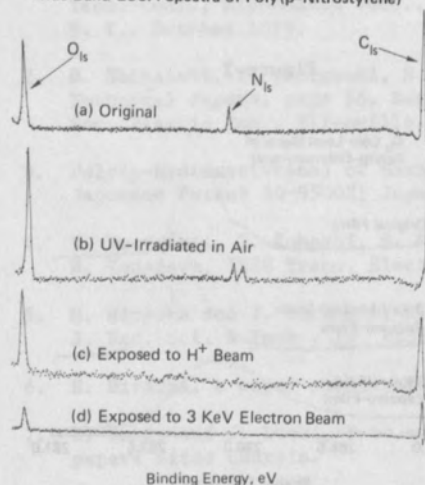


Figure 6

C_{1s} Core Level Signal of Cresol-Formaldehyde Novolac Resin

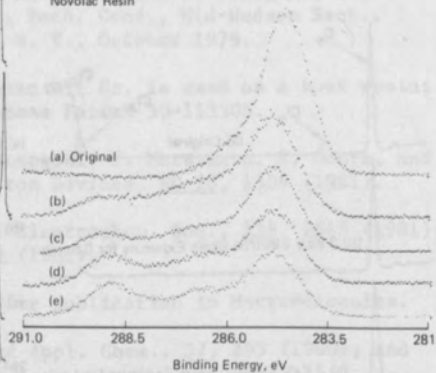


Figure 7

C_{1s} Core Level Signal

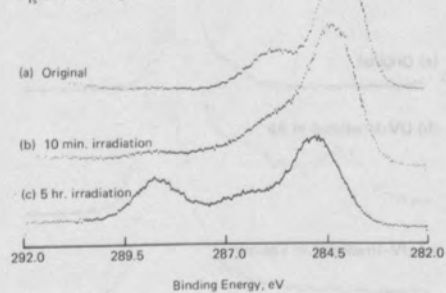
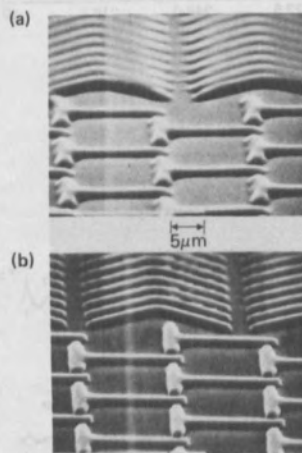


Figure 8



Poly(p-hydroxystyrene)-based negative photoresist:
(a) images heated at 300°C for 30 min.
(b) the same as (a) except 1 hr. UV-exposure in air prior to heating

THE ELECTRON BEAM INDUCED CHEMISTRY OF POLYSULFONES USED AS RESULTS

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ABSTRACT: Thin films of poly(2-methylpentene)sulfone, poly(butene)sulfone and poly(methylcyclopentene)sulfones have been irradiated with a 25 keV electron beam. The course of the reaction is spectroscopically analyzed *in situ*. The results lead to the conclusion that the mechanism for electron beam induced chemistry involves two steps; the first is the elimination of SO_2 from the film while the second deals with the chemistry of the remaining hydrocarbon material.

INTRODUCTION

The radiation induced decomposition of polysulfones has been investigated by a number of groups (1-3). Because of this, and the renewed interest of the materials in lithography, we have studied the electron beam induced mechanism for decomposition of poly(2-methylpentene)sulfone in a phenolic resin and in the pure form. In addition we have also investigated a number of other polysulfones, and report these to provide a broader perspective on the problem. These results reveal that electron beam irradiation of polysulfones, neat or mixed in phenolic resins, involves a two step process.

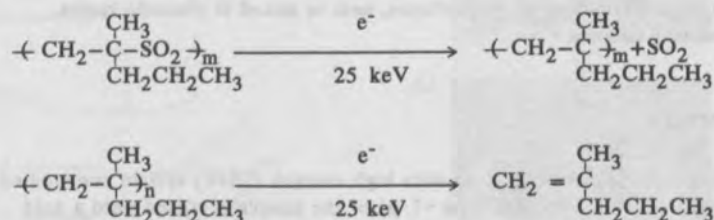
EXPERIMENTAL

The equipment (4) consists of an ultra high vacuum (UHV) system constructed of stainless steel. A thin film (thickness $\sim 1 \mu$) of the sample is coated onto a gold plated substrate and mounted in the UHV system. A 30 keV electron beam gun attached to the UHV system is used to expose the sample. The current, and hence, the dose, is measured using a Faraday cup. A typical electron beam exposure is spectroscopically analyzed using a quadrupole mass spectrometer and by reflection infrared spectroscopy. The former analytical tool provides information about the fragments, if any, that are ejected from the thin film by the electron beam; the latter provides information on the macroscopic chemical reactions induced in the bulk of the film by the electron beam.

In order to provide a quantitative comparison between the experiments reported here and others, dosimetry was performed to correlate the incident dose ($\mu\text{C}/\text{cm}^2$) with the absorbed dose (megarads). This was accomplished in two ways: first, a plastic dosimetric film (FWT-60-20, Far West Technology, Galeta, CA 93117) was calibrated by the National Bureau of Standards to provide a relationship between optical density and absorbed dose in megarads. Using this plot, it was ascertained that an incident dose of $1 \mu\text{C}/\text{cm}^2$ was equivalent to 0.39 megarads of absorbed dose. The second method involved calculating the absorbed dose using the depth-dose functions elegantly described by several authors (5); the results of this calculation ($1 \mu\text{C}/\text{cm}^2 \approx 0.44$ megarads) are in excellent agreement with the results obtained from the dosimetric film.

RESULTS AND DISCUSSION

The infrared spectrum of a $\sim 1\mu$ thick film of poly(2-methylpentene)sulfone before exposure is shown in Fig. 1. All spectra were recorded with the sample always enclosed in the UHV system. The spectrum recorded after exposure of the sulfone to a 25 keV electron beam (dose = $0.4 \mu\text{C}/\text{cm}^2$) is also shown in Fig. 1. Note that while the infrared absorptions characteristic for the sulfur-oxygen stretches at 1293 and 1114 cm^{-1} have significantly decreased, those due to the hydrocarbon portion of the system at $\sim 2900 \text{ cm}^{-1}$, remain unchanged. This is corroborated by following the mass spectrum of the volatile components ejected from the film during the irradiation. The results show that at low doses ($< 0.4 \mu\text{C}/\text{cm}^2$ or 0.16 megarads), SO_2 is primarily emitted from the film; however, at doses larger than this, the mass spectrum of 2-methylpentene is detected indicating that the electron beam is now decomposing residual polymeric hydrocarbon. The infrared spectrum at doses higher than $0.4 \mu\text{C}/\text{cm}^2$ shows that the absorptions characteristic for hydrocarbon moieties gradually disappear. In essence, the results point toward a two step mechanism, i.e.,



The best corroborative data for a two step mechanism is the loss of film thickness due to the electron beam exposure. This is summarized in Fig. 2. The thickness of the film was 1.3μ before exposure, while after exposure to $\sim 0.2 \mu\text{C}/\text{cm}^2$ about 0.9μ of the film remains. The infrared spectrum of this film was recorded before and after exposure. The ratio of absorbances at 1114 cm^{-1} (band height measurement), i.e., N/N_0 was 0.1. Consequently, although about 90% of the SO_2 was removed from the film, only 30% of the film was lost. A

30% loss in film thickness is about what is expected for loss of SO_2 since a monomeric unit for poly(2-methylpentene)sulfone consists of ~40% SO_2 by weight.

The radiation chemistry is quantified by measuring the cross section for the reaction by using the following model. A thin film on a substrate (gold in our case) is exposed with a beam of 25 keV electrons whose current is measured accurately. The number of independent molecules N that are chemically transformed in a given time t is given by the following:

$$-\frac{dN}{dt} = Q\sigma_i I_T N, \quad (2)$$

where I_T is the current in the incident plus reflected beam, σ_i is the cross section for total inelastic scattering of an electron and Q is the probability for a chemical event when an electron is inelastically scattered. In essence, the photochemical analogy of Q is the quantum yield. After rearranging Eq. (2), the following expression is obtained:

$$\int_{N_0}^N dN = -Q\sigma_i I_T \int_0^t dt, \quad (3)$$

where at $t=0$, N_0 is the initial number of molecules. After integration, the simple exponential expression which results is:

$$\frac{N}{N_0} = e^{-(Q\sigma_i)(I_T t)}. \quad (4)$$

Let $I_T t = \text{Dose}$ in units of μC (μ Coulombs)/ cm^2 and $\sigma = Q\sigma_i$, the cross section for the chemical events that lead to a decrease in a molecular species or organic functional group described by N . Thus, the cross section may be obtained using,

$$N/N_0 = e^{-\sigma D} \quad (5)$$

by measuring the changes in optical density for a particular optical absorption (to define N/N_0) as a function of incident electron beam dose. The slope of a semilog plot of N/N_0 versus D yields σ . When the dose is in units of $\mu\text{C}/\text{cm}^2$, the units of σ are $\text{cm}^2/\mu\text{C}$.

The $\ln N/N_0$ versus dose plots for variety of diazoketones, carbonates, esters, hydrocarbons, etc., have yielded straight lines from which cross sections were accurately obtained.⁶ However, for the polysulfones reported in this paper and listed in Table I, the $\ln N/N_0$ versus dose plots were all concave downward. These could be fit to the following rate law

$$\frac{dN}{dD} = -\sigma N - \lambda N^2,$$

where the incorporation of the additional term $-\lambda N^2$ is used to explain the nonexponential behavior of the polysulfone decomposition. Due to the N^2 dependence of the electron beam induced reaction, the parameter λ is a measure of the coupling of a sulfone group with neighboring sulfone groups. Thus, the first term in the rate law, σN , is for the direct decomposition of a sulfone group by electron impact, while the second involves the decomposition of neighboring sulfone

groups after a particular sulfone group has been excited or decomposed. Consequently, the rate of the reaction will be much higher at the beginning of the exposure when the number of neighboring sulfone groups and, hence, the λN^2 term, is large. In essence, this may be viewed as a cross section that becomes smaller as the reaction proceeds towards completion; consequently, the slope of the curved $\ln N/N_0$ versus dose plot extrapolated back to $D=0$, as shown in Fig. 3 for poly(2-methylpentene)sulfone, is taken as an approximate cross section for the purpose of comparing the relative sensitivities of the polysulfones listed in Table I. At this point, it is pertinent to state that as this approximate cross section becomes smaller, e.g., 0.01 for poly(methylbutene)sulfone, the curvature of the $\ln N/N_0$ versus dose plot approaches linearity.

A comparison of the cross sections listed in Table I reveals a dramatic difference between poly(2-methylpentene)sulfone and poly(butene)sulfone; the former is $9.7 \text{ cm}^2/\mu\text{C}$, while the latter is $0.01 \text{ cm}^2/\mu\text{C}$. This same order of magnitude decrease for a polysulfone with a tertiary versus a secondary substituted carbon adjacent to the sulfone moiety is also seen for poly(methylcyclopentene)sulfones where the cross section drops from 0.21 to $0.0016 \text{ cm}^2/\mu\text{C}$.

The cross sections for acyclic polysulfones are quite smaller to those for the corresponding poly(methylcyclopentene)sulfones. Presently, this is believed to be due to a competitive electron beam induced process in the cyclopentene ring.

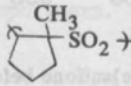
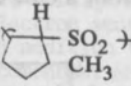
The radiation chemistry operative in the polysulfone-phenolic resin electron beam resist was modeled by preparing a mixture of 25% poly(2-methylpentene)sulfone in resin. Irradiation of thin films of the resist were followed in an identical manner as the irradiations for the neat poly(2-methylpentene)sulfone. The mechanism for the radiation chemistry of the resist was identical to that for pure polysulfone; however, the cross section for the disappearance of the polysulfone when incorporated in the resin decreased to $0.27 \text{ cm}^2/\mu\text{C}$. Presently, we can only explain this on the basis of an energy transfer from an excited polysulfone to resin. In essence, the resin protects the polysulfone from high energy radiation and, as a consequence, decreases the effectiveness of the polysulfone as an electron beam resist.

CONCLUSION

The mechanism for the electron beam induced chemistry of polysulfones, neat and in phenolic resin, consists of a two step process; the first involves the ejection of SO_2 , the second involves the transformation of the residual polymeric hydrocarbon. Measuring the cross section for the electron beam chemistry shows that when poly(2-methylpentene)sulfone is mixed in a phenolic resin, its cross section decreases by about 1/30 of that for pure poly(2-methylpentene)sulfone. Presently, we attribute this to an energy transfer process.

TABLE I

A Comparison of Approximate Cross Sections for Polysulfones

Polysulfone	Cross Section (cm ² /μC)
$\left(\text{CH}_2 - \underset{\text{CH}_2\text{CH}_2\text{CH}_3}{\overset{\text{CH}_3}{\text{C}}} - \text{SO}_2 \right)_n$	9.7
$\left(\text{CH}_2 - \underset{\text{CH}_2\text{CH}_3}{\overset{\text{H}}{\text{C}}} - \text{SO}_2 \right)_n$	0.01
	0.21
	0.0016

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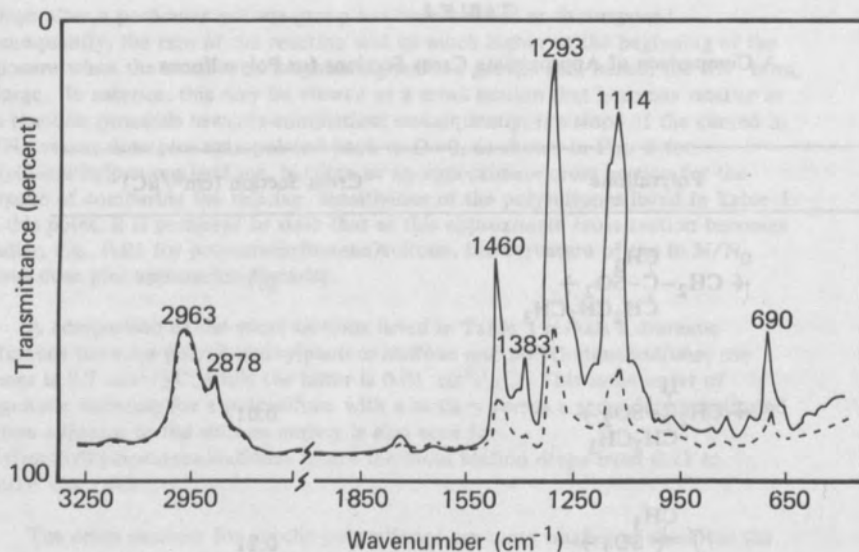


Figure 1. The infrared spectra of poly(2-methyl-1-pentene)sulfone before irradiation (—) with a 25 keV electron beam and after (-----) receiving a dose of $0.4 \mu\text{C}/\text{cm}^2$.

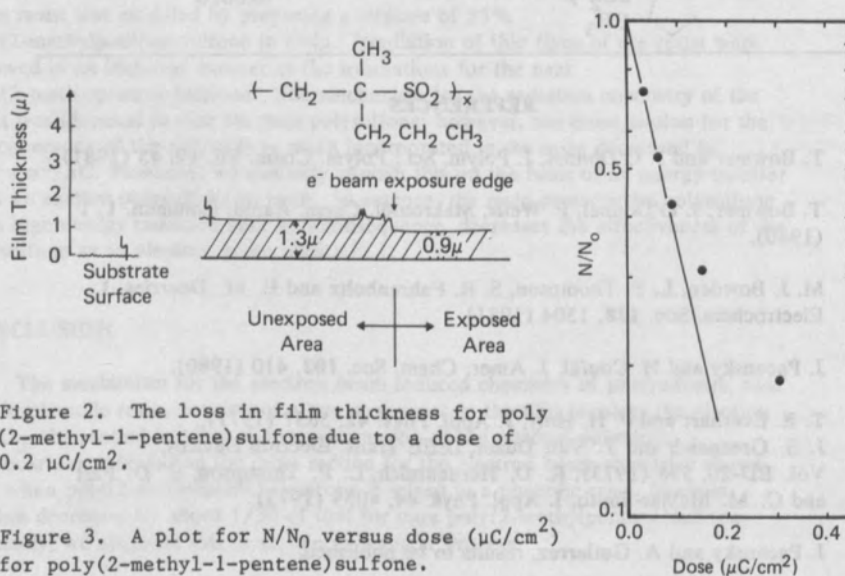


Figure 2. The loss in film thickness for poly(2-methyl-1-pentene)sulfone due to a dose of $0.2 \mu\text{C}/\text{cm}^2$.

Figure 3. A plot for N/N_0 versus dose ($\mu\text{C}/\text{cm}^2$) for poly(2-methyl-1-pentene)sulfone.

ELECTRON RESIST BEHAVIOR OF SOME
METHACRYLIC ACID COPOLYMERS

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ABSTRACT

Several copolymers of MAA/TBM and MAA/MCA were synthesized and tested as e-beam resists. Sensitivities in the 15-20 μ C/cm² range were observed. Effects of prebake temperature on resist performance were determined and thermal properties of the copolymers were investigated using DSC, TGA and FTIR techniques. It was found that intramolecular anhydride bonds are formed in MAA/TBM copolymers when heated to 200°C or above but no evidence was found of a similar process in the MAA/MCA copolymers.

INTRODUCTION

Methacrylic acid (MAA) has been previously used as a comonomer to enhance the electron sensitivity of polymethyl methacrylate (PMMA) (1, 2, 3). In addition to modifying the solubility of the polymer resists, the comonomer MAA provides reaction sites for forming anhydride structures which can improve the thermal stability (3, 4) and sensitivity of the resists.

In this paper we report results of recent work on methacrylic acid copolymer resists. In particular we report on the copolymer of MAA and t-butyl methacrylate (TBM) and of MAA and methyl α -chloroacrylate (MCA). TBM was selected because the homopolymer PTBM has been shown (5) to be a high contrast positive resist more sensitive than PMMA. MCA was selected because the homopolymer and copolymers of MCA have been shown by us and others (6, 7) as sensitive positive resists. Further, the glass transition temperature of the homopolymer PMCA is high, about 150°C.

EXPERIMENTAL

MAA/TBM Copolymers

Ten copolymers of MAA and TBM were synthesized in chlorobenzene 2-2-azo-bis-iso-butyronitrile (AIBN) as a free radical initiator. The monomer ratio in the polymerization mixture was used to control the copolymer composition. Polymerization time was varied to control the monomer conversion. Characteristics of the ten copolymers are shown in Table 1. The polymerization conditions for copolymers A(1) and A(2)

(likewise B(1) and B(2) and C(1) and C(2)) differed only in the polymerization time. The polymerization time for the (1) copolymers was longer than for the (2) copolymers.

Table 1. Characteristics of MAA/TBM Copolymers

Polymer	Composition	GPC Data		
	MAA mole %	$\bar{M}_w$	$\bar{M}_n$	$\bar{M}_w/\bar{M}_n$
Copolymer A(1)	78.2	632,000	338,000	1.87
Copolymer A(2)	80.3	507,000	359,000	1.41
Copolymer B(1)	71.4	507,000	214,000	2.37
*Copolymer B(2)	68.9	579,000	405,000	1.43
Copolymer C(1)	56.3	628,000	387,000	1.62
Copolymer C(2)	64.7	640,000	469,000	1.36
*Copolymer D	55.7	609,000	378,000	1.61
Copolymer E	41.9	509,000	303,000	1.68
*Copolymer F	36.4	385,000	182,000	2.11
Copolymer H	57.1	457,000	235,000	1.95

*Selected for e-beam exposure

MAA/MCA Copolymers

Six copolymers of MAA and MCA were synthesized in a similar manner to the MAA/TBM copolymers. Characteristics of the copolymers are shown in Table II. Since the solubility of copolymers was found to depend on the MAA content, two different solvents were used in the determination of intrinsic viscosity.

In all cases, the composition of the copolymers was determined by carbon analysis performed by Galbraith Laboratories. The molecular weight distributions were determined by gel permeation chromatography using tetrahydrofuran as the solvent and monodisperse polystyrene as standards.

E-Beam Exposure

The copolymers indicated by an asterisk (*) in Tables I and II were selected for e-beam exposure. Resist films were spin coated 1 micron thick on silicon wafers, prebaked and exposed at 20 kV in a Cambridge e-beam microfabricator. For both types of copolymer the prebake temperature was varied from 150°C to 200°C. A number of solvents and solvent mixtures were tested as developers for the resists.

These include methyl cellosolve (MCV), mixtures of MCV and keytones, acetates and alcohols, and mixtures of alcohols and acetates and toluene.

Table II. Characteristics of MAA/MCA Copolymers

Polymer	Composition	GPC Data			$(\eta)_{25^{\circ}}$
	MAA mole %	$\bar{M}_w$	$\bar{M}_n$	$\bar{M}_w/\bar{M}_n$	
Copolymer A	33.3	145,000	86,000	1.7	1.52 ^a
*Copolymer B	42.3	131,000	69,000	2.0	1.80 ^a
Copolymer C	60.9	289,000	168,000	1.7	1.27 ^a
Copolymer D	68.7	329,000	111,000	3.0	1.37 ^b
*Copolymer E	72.0	509,000	193,000	2.6	2.06 ^b
Copolymer F	81.7				2.16 ^b

a: in THF

b: in Methanol

* Selected for e-beam exposure

RESULTS AND DISCUSSION

MAA/TBM Resists

We find that the solubility and development behavior of the MAA/TBM copolymers depend significantly on the prebake temperature. When the copolymers are prebaked at the lower temperatures (150°C to 180°C) the films tend to swell or crack in most solvents. Prebaking at 200°C reduces the swelling and cracking and improves adhesion.

Of the three MAA/TBM copolymers tested, copolymer B(2), which is approximately 2:1 MAA/TBM exhibits the best sensitivity and resolution. The sensitivity is 15 μ C/cm² (with less than 10% thickness loss in the unexposed area). A typical SEM of a developed resist pattern is shown in Figure 1. The images show no sign of swelling. The resist film was prebaked at 200°C and spray developed with 1:1 mixture of MCV and methyl isobutyl ketone (MIBK). Figure 2 shows the development curve for copolymer B(2) at prebake temperatures of 160°C and 200°C.

Thermal Behavior of MAA/TBM Resists

Because of the significant effect of prebake temperature on resist properties, we further studied the thermal properties of the copolymers. Differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and infrared (IR) spectroscopy were employed.

DSC studies. Copolymers B(2) and D were studied by differential scanning calorimetry from room temperature to 300°C. Both copolymers exhibit similar thermograms; the one for copolymer B(2) is shown in Figure 3. The thermogram for unbaked copolymer shows a broad endotherm with a peak at about 230°C due to anhydride formation (the Tg of polymethacrylic acid (PMAA) is 228°C). The thermogram for the polymer prebaked at 200°C shows a smaller endotherm indicating some anhydride formation during prebake. The thermogram for the copolymer prebaked at 250°C shows no endotherm but a slight change in slope near the Tg of polymethacrylic anhydride (PMAN). Tg of PMAN is 159°C.

The DSC studies indicate that, regardless of the initial copolymer composition, a prebake of 250°C converts the copolymer to polymethacrylic anhydride. At a prebake of 200°C the copolymers are probably converted to MAA/TBM/MAN terpolymers with the degree of anhydride formation depending on the initial copolymer composition.

TGA studies. TGA thermograms of the MAA/TBM copolymers and the homopolymers are shown in Figure 4. By 250°C all polymers have significant weight loss due to the formation of polymethacrylic anhydride. Of the three copolymers tested as e-beam resists, copolymers B(2) and D had significantly more weight loss up to 200°C than did copolymer F. Initially copolymer F had the smallest proportion of MAA and thus the least anhydride formation. We attribute the improved resist performance of polymer B(2) in part to the anhydride formation (2).

IR studies. It is of interest to determine if the anhydride bonds formed in the copolymers are intramolecular or intermolecular. Fourier transform infrared (FTIR) spectroscopy was used for that purpose. Films were coated on a KCl substrate and placed in a holder with a heating element and a thermocouple. Figures 5 through 7 show the IR spectra of absorbance vs. wavenumber at several different substrate temperatures for the homopolymers PMAA and PTM and the MAA/TBM copolymer B(2). The spectra for the three polymers show the following characteristics.

1. The intensity of the broad OH absorption at 3600-2500 cm^{-1} decreases with an increase in temperature and it disappears at 250°C.
2. For the two polymers containing MAA an intense anhydride C-O-C peak at 1022 cm^{-1} appears at 200°C and increases with increasing temperature.
3. Starting at 200°C the carboxyl acid C=O peak at 1700 cm^{-1} disappears and anhydride twin peaks at 1800 and 1750 cm^{-1} emerge. Of the twin peaks, the absorption of the lower frequency peak is stronger indicating a six-membered anhydride ring formation (8). That is, the majority of the anhydride bonds are believed to be intramolecular. This supports the view that the MAA/TBM copolymers are converted to MAA/TBM/MAN terpolymers when heated to 200°C. This is consistent with the work of Moreau et al (2) who showed that 75:15:15 MMA/MAA/MAN terpolymer is more sensitive and has higher thermal stability than PMMA.

MAA/MCA Resists

As with the MAA/TBM copolymers, the resist behavior of the MAA/MCA copolymers depends on the chemical composition and the prebake temperature. However, the relationships appear to be more complex than the MAA/MCA case.

For copolymer B the sensitivity is lower and for copolymer E the sensitivity is higher when they are prebaked at 200°C as compared to when they are prebaked at 160°C or 180°C. For copolymer B the dissolution rate is significantly faster in films prebaked at 200°C than those prebaked at the lower temperatures. This indicates some thermal degradation that lowers the molecular weight.

Figure 8 shows the IR absorption spectra of MAA/MCA copolymer E at several substrate temperatures. Although the intensity of the broad OH peak decreases with an increase in temperature (indicating OH is involved in certain reactions), there are no double peaks in the frequency range 1800 to 1700 cm^{-1} which would be indicative of anhydride bonds. This is surprising in view of the fact that copolymer E contains 78 mole % of MAA.

E-beam exposures of the MAA/MCA copolymers indicate a sensitivity of 15-20 $\mu\text{C}/\text{cm}^2$ with little evidence of cracking or swelling.

SUMMARY

Several copolymers of MAA/TBM and MAA/MCA were synthesized and tested as e-beam resists. Sensitivities in the 15-20 $\mu\text{C}/\text{cm}^2$ range were observed. Effects of prebake temperature on resist performance were determined and thermal properties of the copolymers were investigated using DSC, TGA and FTIR techniques. It was found that intramolecular anhydride bonds are formed in MAA/TBM copolymers when heated to 200°C or above but no evidence was found of a similar process in the MAA/MCA copolymers.

ACKNOWLEDGEMENT

This work was supported by the U.S. Army Electronics Technology and Devices Laboratory (ERADCOM), Fort Monmouth, N.J.

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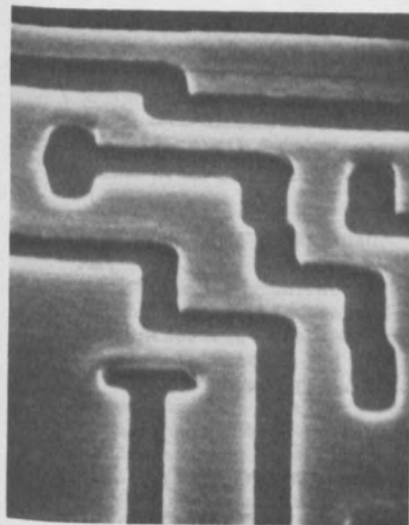


Figure 1. SEM of developed pattern in copolymer B(2).

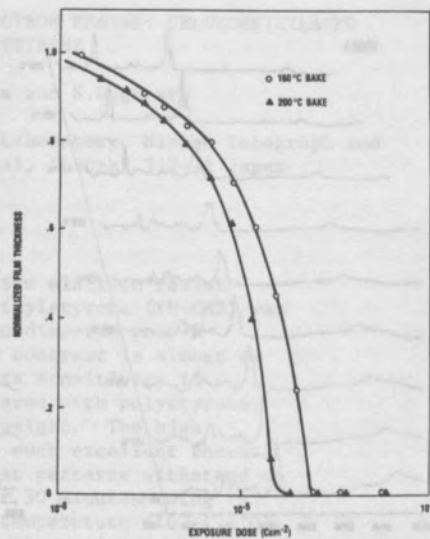


Figure 2. Development curves for copolymer B(2) in MCV/MIBK.

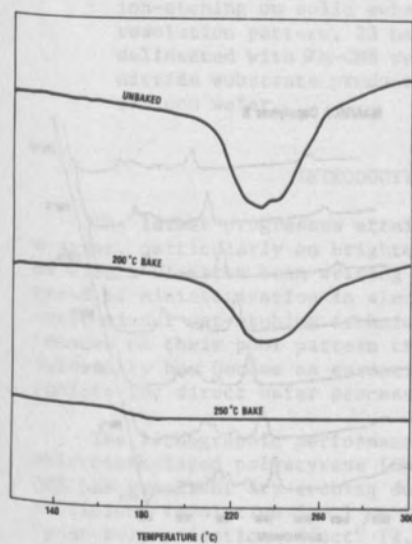


Figure 3. DSC thermogram for copolymer B(2).

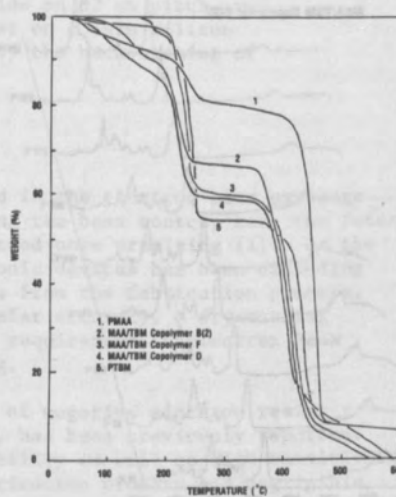


Figure 4. TGA thermograms of MAA and TBM polymers.

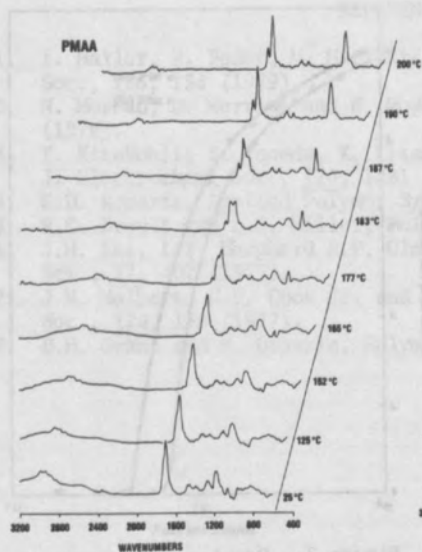


Figure 5. IR spectra of the homopolymer PMAA.

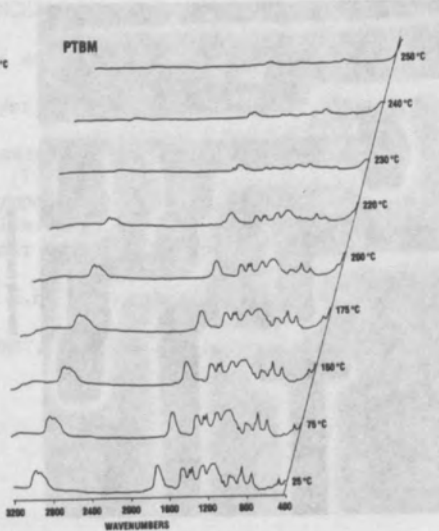


Figure 6. IR spectra of the homopolymer PTBM.

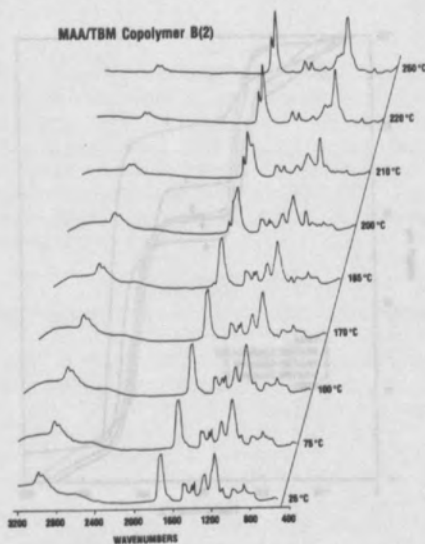


Figure 7. IR spectra of the MAA/TBM copolymer B(2).

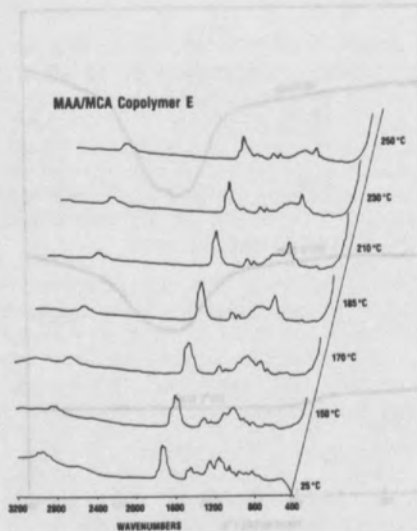


Figure 8. IR spectra of the MAA/MCA copolymer F.

HIGH RESOLUTION NEGATIVE ELECTRON RESIST: CHLOROMETHYLATED
POLY- α -METHYLSTYRENE

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ABSTRACT

A high contrast negative electron resist chloromethylated poly- α -methylstyrene (α M-CMS) was synthesized from nearly monodisperse poly- α -methylstyrene. The α M-CMS contrast is almost as high as polystyrene, but its sensitivity is enhanced by 20 times, compared with polystyrene having the same molecular weight. The high dry-etching durability and such excellent thermal stability that α M-CMS resist patterns withstand up to 200°C heat treatment for 30 minutes owing to its high glass-transition temperature (162-173°C), also ensure the utility of the resist in high resolution lithography. Submicron Au lines, as small as 0.1 μ m, were fabricated by an Ar ion-etching on solid substrate. The highest resolution pattern, 23 nm wide on 82 nm pitch, was delineated with α M-CMS resist on a thin silicon nitride substrate produced by the back-etching of silicon wafer.

INTRODUCTION

The latest progresses attained in the electron beam exposure systems, particularly on brightening the beam source, make the future of direct electron beam writing method more promising (1). As the trend of miniaturization in electronic devices has been excluding conventional wet-etching techniques from the fabrication process, because of their poor pattern transfer accuracy, a dry-etching durability has become an essential requirement in electron beam resists for direct wafer processing.

The lithographic performances of negative electron resist : chloromethylated polystyrene (CMS), has been previously reported. CMS has excellent dry-etching durability as well as high sensitivity, sufficient resolution for 1 μ m fabrication process and negligible "post polymerization effect" (2,3). Although the high contrast of CMS was achieved by the use of nearly mono-dispersed polystyrene as a starting material, for practical submicron lithography, further improvement in the resolution is necessary without losing any other

properties. Negative electron resists, where the resist reaction mainly involves the crosslink of polymer chains generally suffer from their low contrast and the swelling of exposed patterns, causing a serious loss in resolution. These problems have been overcome by refining the molecular design of resist, and a submicron negative electron resist : chloromethylated poly- α -methylstyrene (α M-CMS) (4) was developed.

Poly- α -methylstyrene (P α -MeSt) is another important aromatic polymer in the design of new electron resists because a very narrow molecular weight distribution can be obtained by a living polymerization technique. The polymer has a much higher glass transition temperature (T_g) ($\sim 170^\circ\text{C}$) than polystyrene ($\sim 100^\circ\text{C}$), and is expected to exhibit better processability in high temperature dry-etching technology. This report presents results obtained for submicron lithography with α M-CMS resist on solid substrates, and the ultimate resolution of the resist exposed on thin film substrates.

EXPERIMENTAL

α M-CMS was synthesized from living polymerized P α -MeSt with an excess of chloromethylmethylether by using tin tetrachloride as a catalyst. The chloromethylation reaction was carried out with careful control of reaction temperature and time to reduce the intermolecular crosslinking reaction, which inherently occurs as a side reaction, causing broader polydispersity. Molecular weight and its distribution were characterized by gel permeation chromatography using a Hitach model 635 GPC. The polymer T_g was measured with a Rigaku Thermoflex DSC unit.

Exposures for resist layers on solid substrates were carried out with an Elionix ESM-301 exposure system operating at 20kV. An exposure system modified from a scanning electron microscope JEOL JSM-35 was also used for exposures into resist layers on thin film substrates in its scanning transmission mode. About 50 nm thick silicon nitride films, produced by the back-etching of silicon wafer with an etchant composed of pyrocatechol, ethylenediamine, water and pyrazine (5), are used as thin film substrates. 10 nm diameter, 39 kV energy electron beam was scanned in 40-200 nm thick resist layers spin-coated on silicon wafers supporting thin film windows.

The spin-coated α M-CMS films were prebaked in a nitrogen atmosphere at 135°C for 20 to 30 minutes. The developer used was acetone, methylethylketone (MEK) or their mixtures with methanol. Methanol was used as a rinse solvent. α M-CMS film thicknesses were measured using a Talystep (Taylor-Hobson) before and after development. The contrast was calculated from the characteristic curve doses corresponding to zero and 50% thickness, as indicated in Table I. Patterns were examined using a JEOL-35 scanning electron microscope.

RESULTS AND DISCUSSION

The molecular structure of α M-CMS is shown in Fig. 1. The main polymer structure is changed from polystyrene in CMS to P α -MeSt. P α -MeSt acts as a positive electron resist, due to the methyl group at the α -position in the main chain (6). The introduction of a chloromethyl group changes the resist mode from positive to negative. The negative type behavior of α M-CMS is attributed to the higher reactivity of the chloromethyl group, compared with the degradation reactivity in the main chain (7)(8). Molecular and lithographic parameters for α M-CMS are shown in Table I with those for CMS and polystyrene. A series of α M-CMS resists were obtained in the molecular weight range of 8,300 - 188,000 with a polydispersity of 1.07 - 1.91. After chloromethylation, the molecular weight distribution remained sufficiently narrow. In order to compare sensitivity and contrast, the polymer molecular weight must be taken into account. Though the electron beam sensitivity of α M-CMS, depending on the molecular weight, is about 1/3 of that for CMS when compared with the same molecular weight, the α M-CMS contrast of 4.1 - 2.5 is much higher than that for CMS. Eventually, a considerably higher contrast is obtained in α M-CMS than in CMS, when resists having the same sensitivity are used. High T_g is another important α M-CMS advantage. Chloromethylation did not change the T_g for α M-CMS. Owing to its high T_g, 162-173°C, higher by 60-70°C than polystyrene, α M-CMS submicron patterns withstand heat treatments up to 200°C for 30 minutes without any pattern edge deformation.

The resolution of α M-CMS on solid substrates, evaluated as a well-resolved line and space width, shows strong dependences on resist thickness and molecular weight, as shown in Fig. 2. The resolution is highly dependent on resist thickness and molecular weight, and improves with decreasing resist thickness and molecular weight. A 0.8 μ m pitch pattern is resolved in a higher molecular weight resist with the sensitivity of 3.9 μ C/cm². A 0.2 μ m thick α M-CMS with a molecular weight of 19,000, whose sensitivity is 33 μ C/cm², resolved a 0.4 μ m pitch pattern. Using 0.4 μ m thick α M-CMS with this molecular weight, submicron patterns as small as 0.1 μ m can be delineated with a 0.4 μ m pitch (4).

α M-CMS resist has high dry-etching durability and excellent thermal stability due to its P α -MeSt main chain. High quality submicron pattern transfers can be achieved using dry-etching techniques. Figure 3 (a) shows complex α M-CMS patterns in various pattern sizes in a 0.4 μ m - 1.2 μ m range in 0.6 μ m thick resist. Developed resist patterns have almost the same size as designed without any proximity effect correction. With the mask of these resist patterns, silicon dioxide substrate was etched by 0.02 Torr Freon-14 gas containing 4.8% oxygen gas reactive sputter. The resist was post-baked at 220°C for 30 minutes before etching. Figure 3 (b) is a SEM photograph of silicon dioxide patterns after removing the resist. The silicon dioxide pattern sizes are slightly smaller than

those for resist patterns, indicating a little side etching effect. The etching rate ratio of 1.5 was obtained, which may be further improved by addition of hydrogen into the etching gas.(9)

Because of the side etching in the sputter by Freon-14 gas, it was difficult to reproducibly fabricate patterns as small as 0.1 μm . A higher resolution fabrication can be performed by an Ar ion etching. Figure 4 (a) shows 0.1 μm wide $\alpha\text{M-CMS}$ patterns in 0.3 μm thick resist. 0.14 μm thick Au film was ion-etched by Ar gas sputter. The etching was carried out with 0.01 Torr Ar gas pressure, and out-put of 50 W. The substrate was not particularly cooled. Au lines after removing the resist by oxygen plasma, as shown in Fig. 4 (b), does not exhibit any sign of side-etching. Figure 4 (c) is a side view of 0.1 μm wide Au lines fabricated.

The ultimate resolution of $\alpha\text{M-CMS}$ was investigated by the exposure of thin resist films on thin film substrates to minimize the resolution loss due to the scattering of incident beam, both in the resist layer and from the substrate.

Figure 5 shows the dependences of resolution on resist molecular weight and thickness. By decreasing the resist thickness and the molecular weight, very narrow lines, smaller than 0.1 μm , can be easily delineated. The highest resolution obtained is 23 nm wide lines on 82 nm pitch in 55 nm thick $\alpha\text{M-CMS}$ with a molecular weight of 6,500, which is shown in Fig. 6(a). This line width is almost the same as that made possible in high resolution positive electron resist PMMA under the same conditions (10)(11). The striking feature of the exposure on thin film substrates is that, by increasing electron dosage, wide lines with a narrow gap can be easily delineated, which are hardly obtained in negative resists on solid substrates, because of serious backscattering from the substrate and the swelling of exposed resist. Figure. 6 (b) shows 55 - 58 nm wide resist patterns separated by 32 - 35 nm gap.

This high resolution of $\alpha\text{M-CMS}$ seems to be achieved by a small extent of swelling of crosslinked polymer and small chain reaction contribution to the crosslinking reaction. As compared with polystyrene-based resists, $\alpha\text{M-CMS}$ has a higher glass-transition temperature, which is effective to prevent the resist polymer from swelling in a developer. In addition, as hydrogen atoms at the α -position of polystyrene main chain are substituted for methyl group in $\alpha\text{M-CMS}$, the chain reaction involving the hydrogen subtraction by reactive species in electron beam induced reactions is considered to be depressed.

CONCLUSION

As described above, $\alpha\text{M-CMS}$ resist has sufficient resolution for submicron electron beam lithography on solid substrates and for

nanolithography on thin film substrates. These high resolution, high dry-etching durability and high thermal stability allows applying AM-CMS resist widely in very high resolution lithography, accompanying various dry-etching techniques.

ACKNOWLEDGEMENT

The authors are greatly indebted to Mr. K.Matsuyama for his continuous encouragement. The authors are also indebted to Messrs. J.Shimada, K.Murase and O.Kogure for their valuable discussions.

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Table I. Molecular and lithographic parameters for polymers.

Materials	$\overline{M}_w$ ($\times 10^3$)	CR ^{a)} (%)	Tg (°C)	Sensitivity ^{b)} ($\mu\text{C}/\text{cm}^2$)	Contrast ^{c)} (β -value)
AM-CMS (1)	8.3	96.9	164	42	4.1
AM-CMS (2)	19	96.6	168	33	3.0
AM-CMS (3)	48	92.7	170	12.5	2.6
AM-CMS (4)	131	97.2	173	3.9	2.4
AM-CMS (5)	188	95.3	174	3	2.5
CMS (1)	14	45.8	98	15	2.2
CMS (2)	65	47.2	103	4	1.9
PSt ^{d)}	17	—	89	750	2.9

- a) CR: Chloromethylation ratio. Defined by $m/(m+n)$ in Fig. 1.
b) Evaluated as 50% residual thickness dose ($D_{0.5}$).
c) (contrast) = $\left| \log(D_{0.5}/D_0)^2 \right|^{-1}$, where D_0 is dose at zero thickness in the characteristic curve.
d) PSt: Polystyrene.

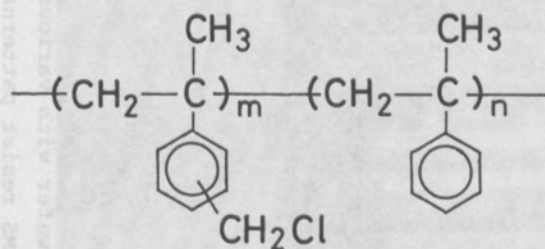


Fig. 1 Molecular structure of λ M-CMS resist.

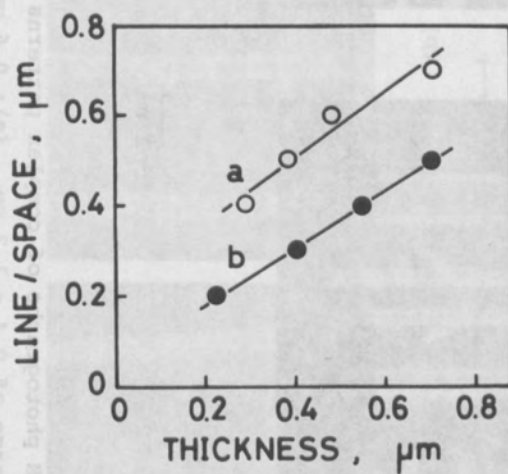


Fig. 2 Thickness dependence of λ M-CMS resolution on solid substrate. Resolution was evaluated by minimum line and space resolved. a: $\bar{M}_w$ 131,000 ($3.9 \mu\text{C}/\text{cm}^2$). b: $\bar{M}_w$ 19,000 ($33 \mu\text{C}/\text{cm}^2$).

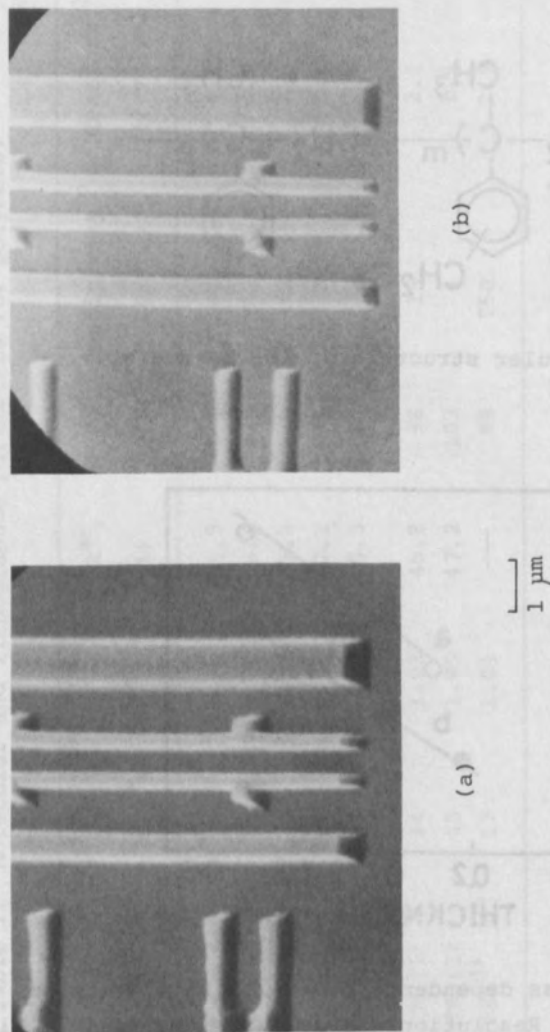


Fig. 3 SEM photographs of complex patterns on silicon wafer with various pattern sizes in a range of 0.4 - 1.2 μm . (a): 0.6 μm thick AM-CMS resist patterns on silicon dioxide developed by acetone-methanol (30:1); (b): silicon dioxide patterns after removing the resist. Etching was carried out with 0.02 Torr Freon-14 gas reactive sputter. RF power of 200 W (13.5 MHz) was used.

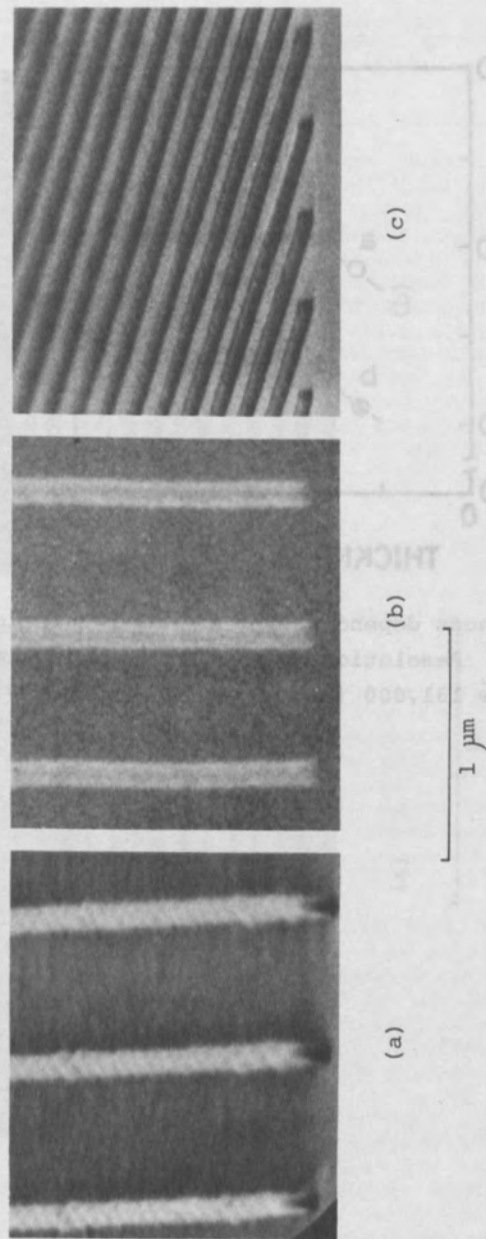


Fig. 4 SEM photograph (a) 0.1 μm wide and 0.3 μm thick Au -CMS patterns, (b) 0.1 μm wide Au lines etched with a mask of the resist patterns, (c) Side view of the Au lines. Etching was carried out with 0.01 Torr Ar gas pressure, and 50 W out-put. Substrate was not particularly cooled.

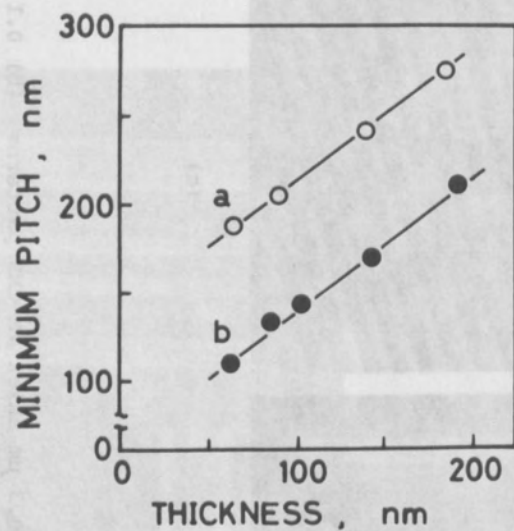


Fig. 5 Thickness dependence of λ M-CMS resolution on thin film substrate. Resolution was evaluated by minimum pitch resolved. a: $\bar{M}_w$ 131,000 ($3.9 \mu\text{C}/\text{cm}^2$). b: $\bar{M}_w$ 19,000 ($33 \mu\text{C}/\text{cm}^2$).

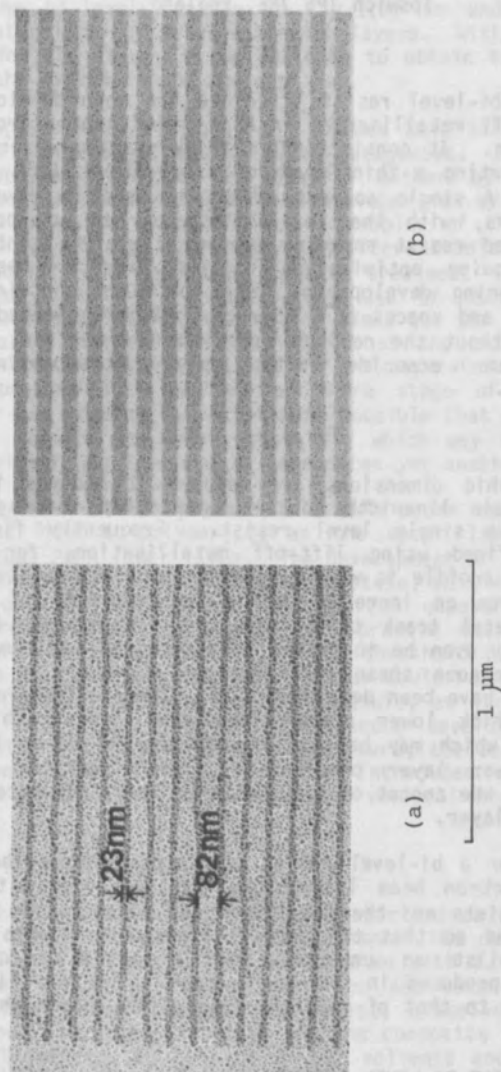


Fig. 6 TEM photograph (a) 23 nm wide λ M-CMS resist patterns on 82 nm pitch. (b): 55 - 58 nm wide λ M-CMS resist patterns separated by 32 - 35 nm gap. Initial thickness was 55 nm. Development was carried out with acetone for 10 seconds, followed by methanol rinse.

A DOUBLE PMMA RESIST STRUCTURE FOR SUB-MICRON LITHOGRAPHY USING A SINGLE DEVELOPER

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ABSTRACT

A bi-level resist structure has been developed for lift-off metallisation in high speed logic circuit fabrication. It consists of a thick spacing layer of PMMA supporting a thin layer of cross-linked PMMA copolymer. A single solvent, MIBK, is used to develop both layers, with the insolubility of the unexposed cross-linked resist ensuring precise linewidth control while allowing optimisation of the undercut resist profile during development. Metal patterns containing linewidths and spaces of $0.75\mu\text{m}$ are being fabricated on silicon without the need for proximity correction, and on gallium arsenide with only intra-proximity correction.

1. INTRODUCTION

As lithographic dimensions are reduced it becomes increasingly difficult to obtain linewidth control, good step coverage and high resolution with a single level resist. Frequently fine geometry patterns are defined using lift-off metallisation, for which the control of resist profile is vital. A reduction in the lateral circuit dimensions requires an increase in the aspect ratio of the resist profile, since metal track thicknesses are not reduced in the same proportion and may even be increased to compensate for the effects of scaling. To overcome these difficulties, a number of multi-level resist structures have been developed(1-3). These all share the common features of a thick lower planarising layer, and a thinner upper patterning layer which may be positive or negative. For lithographic purposes the lower layer provides a smooth surface, whilst its thickness reduces the amount of backscattered radiation received by the upper patterning layer.

In this paper a bi-level resist structure is described which is patterned by electron beam lithography and developed with a single solvent. The resists and the conditions for exposure and development have been selected so that the correct linewidth is obtained in the upper layer, whilst an undercut profile suitable for lift-off metallisation is produced in the lower layer. The sensitivity of the system is similar to that of a single level PMMA resist when used for lift-off.

2. CONSIDERATIONS FOR BI-LEVEL RESIST

In a single level resist the linewidth and profile are determined by the deposited energy density and the processing conditions(4,5). For lift-off processing an undercut profile is required, but the exact profile and linewidth are critically dependent upon both dose and

development. In addition it may be necessary to modify the dose and the written linewidth in order to correct for proximity effects(6). In Fig.1(a) a single level resist profile is shown schematically, and it is clear that as the linewidth is reduced and the resist thickness is increased, the sloping undercut prevents close line spacing. However, the bi-level profile in Fig.1(b) is undercut due to the differential solubility between the two layers. With careful choice of materials for the layers it is possible to obtain independent control over both the linewidth and the profile.

Although a number of bi-level schemes have been proposed, it is possible to divide them into two broad categories. Independent control of linewidth and profile is achieved either by using layers of different solubilities and a single developer, or by using two resists with mutually exclusive developers. Examples of the former category include the use of PMMA layers having different molecular weights, and hence solubility(7), and the surface treatment of AZ1350-J by a chlorobenzene soak(8). Unfortunately use of these techniques may result in an unacceptable pattern bias since the top layer continues to dissolve during the profile development of the thicker lower layer. The alternative of using two resists and separate developers, avoids the bias problem but involves an extra stage of processing using solvents or dry etching(1). Also it is possible that an interface layer may result between the two resists(9), which may not be soluble in either developer and its removal introduces yet another process stage.

The bi-level scheme presented in this paper uses a thin ($0.25\mu\text{m}$) cross-linked PMMA co-polymer(10) as the upper layer and a thicker (about $1.75\mu\text{m}$) PMMA lower layer. The development of the upper layer is non-critical since, in the cross-linked state, this resist is virtually insoluble outside the regions of electron exposure, and hence the linewidth remains constant during the profile development. In the lower layer, the energy contour at the threshold development dose is inclined so that a high contrast developer would reproduce this contour and a sloping undercut profile would result, as for the single level resist of Fig.1(a). By choosing a strong developer, MIBK, and by operating at a slightly elevated temperature, the development contrast of the lower layer is reduced. This introduces sufficient lateral dissolution of the PMMA to yield a near vertical profile in the lower layer.

3.BI-LEVEL STRUCTURE ON SILICON

The bi-level resist has been characterised on silicon substrates for use in the metallisation of short channel MOS devices and ECL gate arrays. Cleaned silicon wafers were coated with $1.75\mu\text{m}$ of a standard PMMA (mol.wt. $\sim 300\text{k}$) dissolved in xylene and baked at 160°C for 30 minutes. The second cross-linking resist, dissolved in AZ thinners, was then spun onto the substrates and the composite structure baked at 155°C for 30 minutes to both drive off solvents and fully cross-link the upper layer. The wafers were exposed in a Cambridge Instruments EBMF at 30kV and with an electron dose in the range $125\text{--}150\mu\text{Ccm}^{-2}$. Development was in MIBK at 30°C for 2 minutes, followed by a rinse in IPA for 30 seconds.

The profiles of $2\mu\text{m}$ line pairs separated by $0.75\mu\text{m}$ and $1.5\mu\text{m}$ are

shown in Fig.2. The linewidth, written without bias, remained at $2\mu\text{m}$ even at the closer separation, indicating that any inter-proximity contributions in the upper layer were negligible. However the slight difference in the profile of the central resist column indicates the presence of proximity effects nearer to the substrate. This effect was more noticeable on the higher atomic number substrate GaAs, and is discussed in the next section.

The bi-level resist has been used successfully for metal lift-off on silicon, and the process is shown by the sequence of photographs in Fig.3. The first (3a) shows the bi-level resist image of a device gate structure with minimum dimensions of $0.75\mu\text{m}$, exposed at a single dose of $150\mu\text{Ccm}^{-2}$. After coating with $0.5\mu\text{m}$ of aluminium, the effective shadowing of the top layer is clearly seen (3b), resulting in clean lift-off (3c). No proximity effects are visible at these dimensions, whereas a single level resist process requires some dose correction according to feature size to reproduce the same pattern. Considerably greater metal thicknesses could be defined using this structure, the limiting factors being the substrate topography and the collimation of the deposition source.

4. BI-LEVEL ON GaAs

The greater proportion of electrons backscattered from GaAs compared with Si causes an increase in proximity effects, with two results. Firstly, it is no longer possible to use a single dose for all shapes down to $0.75\mu\text{m}$, and intra-proximity correction is necessary for the smaller shapes. Secondly, the inter-proximity exposure of close features causes an increased undercut at the resist-substrate interface, resulting in the loss of adhesion of narrow resist filaments. Therefore, with this resist on GaAs, reliable operation is limited to dimensions of $0.75\mu\text{m}$ and above.

The bi-level structure has been used to define the source-drain and the gate metallisations for $0.75\mu\text{m}$ gate GaAs digital IC's, Fig.4. The two levels of metal are each $0.5\mu\text{m}$ thick, and the total thickness where they interconnect is $1.0\mu\text{m}$. The resist coating and development procedures were identical to those used for silicon, but the exposure for large areas was reduced to $90\mu\text{Ccm}^{-2}$, with the smallest features being written at $110\mu\text{Ccm}^{-2}$.

5. CONCLUSIONS

A bi-level resist system has been demonstrated which, although using a single developer, provides independent control of linewidth and vertical profile without the need for pattern bias. Linewidths of $0.75\mu\text{m}$ have been defined on silicon without the need for proximity correction, and on gallium arsenide with only simple intra-proximity correction.

ACKNOWLEDGEMENTS

The authors would like to thank the GaAs circuit groups for their technical assistance in the processing and metallisation of GaAs. Acknowledgement is made to the Director of Research, British Telecom, for permission to publish this paper.

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(a) Single Resist (b) Bi-level Resist

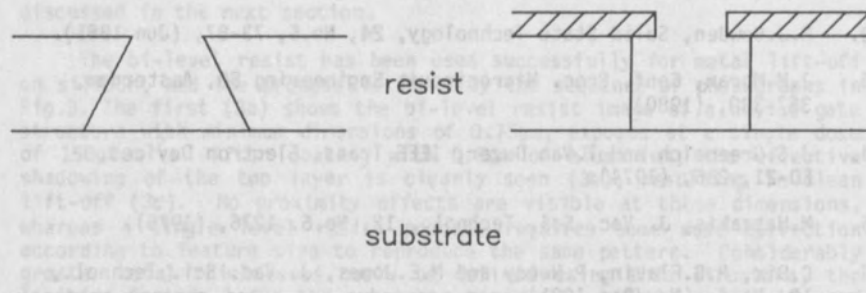


Fig.1 Resist structures for lift-off metallisation;

(a) single level and (b) bi-level.

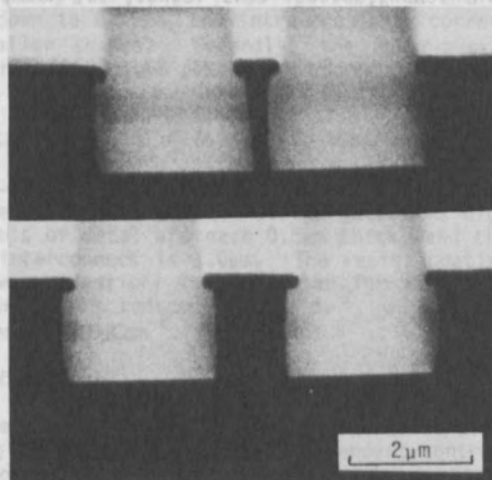
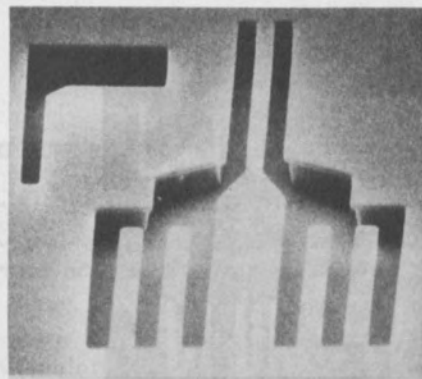
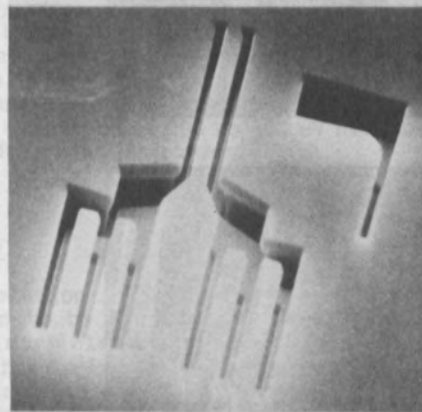


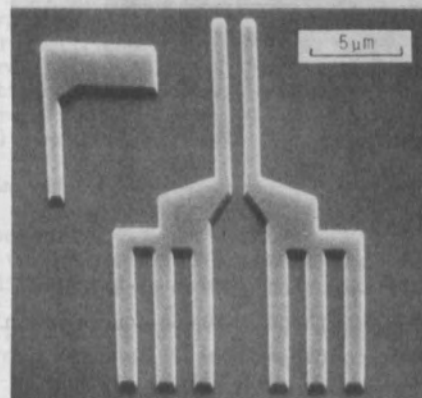
Fig.2 Pairs of $2\mu\text{m}$ wide lines separated by $0.75\mu\text{m}$ (top) and $1.5\mu\text{m}$ (bottom) in bi-level resist on silicon.



(a) bi-level resist structure showing undercut profile and freedom from proximity effects.



(b) pattern after deposition of $0.5\mu\text{m}$ of metal but before lift-off.



(c) final metal pattern after lift-off.

Fig.3 Metallisation of silicon using bi-level PMMA resist; the narrowest dimensions are $0.75\mu\text{m}$ lines and space.

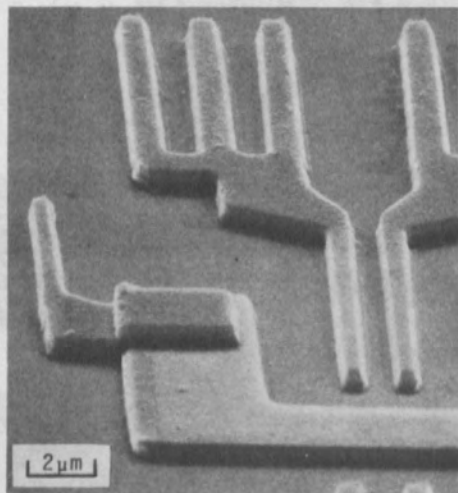
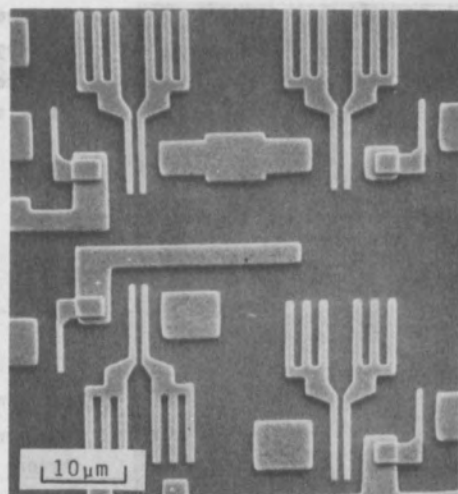


Fig.4 Two layer metallisation on gallium arsenide;
the layers are 0.5 μ m thick Ni/Au-Ge source-drain
contacts followed by 0.5 μ m thick Ti/Au gates.

EXPOSURE RANGE OF LOW ENERGY ELECTRONS IN PMMA

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Abstract

The resolution of PMMA as an electron beam resist may be limited by exposure by secondary electrons generated in the resist by the primary beam. Since relatively little is known about the range of low energy electrons in polymeric materials, a method has been developed to measure directly the exposure range in PMMA of electrons up to a few keV. We find that electrons of 200 to 300 eV have an exposure range of the order of 100 angstroms.

1. Introduction

Linewidth resolution in the electron resist poly(methyl methacrylate) has been shown to be limited to 10-20nm even under conditions of negligible primary electron scattering, i.e. thin resist films, thin substrates and high primary beam energy^(1,2). The transport of energy by secondary electrons to effect bond scissions remote from a primary beam collision centre is one possible explanation for this resolution limit. To test this hypothesis, data is needed on the number of such electrons generated, their spectral distribution and the range over which they can travel whilst retaining the ability to effect bond scission⁽³⁾. We have termed this latter factor the 'exposure range', and this paper presents a preliminary report on our measurements of the exposure range of low energy (<2.5keV) electrons in PMMA.

The technique we have employed involves exposing PMMA by a low energy electron beam through a shadow mask, developing out the degraded material and measuring the loss of thickness, which we equate to the exposure range. Our measurements are therefore directly applicable to electron beam lithography as contributions to the range from very slow, non-scissioning electrons (<5eV) is excluded. This method has been used before for energies above 400eV⁽⁴⁾. Other methods of measuring the range of slow electrons in carbonaceous material, especially those which measure gross transmission through thin films, may include non-scissioning electrons and thereby over-estimate the exposure range⁽⁵⁾.

2. Experimental Method

The apparatus used at present is shown in figures 1 and 2. An electron microscope type gun and stopped down magnetic condenser lens illuminate the lower aperture with a circular beam. The lower aperture transmits the uniform part of this beam, which is used to expose the PMMA. By mechanically scanning a 10 micron aperture below the 400 micron aperture and detecting the transmitted current it is found that the current density is constant across the aperture to within 5 percent provided that the condenser is kept significantly underfocused. This means that the current density used for each exposure can be determined easily by moving the Faraday cup under the aperture and measuring the total collected current.

The condenser may be used to control the current density, which is sufficiently stable for experiments at accelerating potentials of 100 volts and above. Below 100V, however, current stability deteriorates, so we propose to use a retarding field method for very low energy exposures. The apparatus allows us to place two 200 mesh grids beneath the lower aperture, as shown in Fig. 2. One grid is at anode potential and the second, about 0.5mm below the first, is at the required final electron potential. The sample is placed 2mm below the second grid on an X-Y movement which also carries the Faraday cup.

For the measurements above 100V presented here, the second grid is absent and the first grid serves simply as a shadow mask whose regular pattern, replicated in the PMMA after exposure and development, facilitates depth measurement by means of a Talystep profile plotter. A typical Talystep trace is shown in Fig. 4.

3. Preliminary Results

For all the results presented here the developer was 1 part methyl isobutyl ketone to 3 parts isopropyl alcohol, and the development time was 3 minutes at 21 °C. As no detectable change of depth occurs for development intervals greater than 3 minutes, we assume that in this time the solvent has removed all the degraded material that it is capable of dissolving.

Figure 5 shows developed depth as a function of charge density for an electron energy of 500 eV. The depth is seen to increase with exposure up to about 3×10^{-5} coulomb cm^{-2} . After this the depth remains fairly constant and begins to fall beyond about 10^{-4} coulomb cm^{-2} , when the polymer begins to cross-link. It is assumed that the maximum developed depth represents the maximum range over which the electrons are capable of causing bond scissions.

Figure 6 shows developed depth as a function of electron energy from 100 to 2500 eV. The charge density is constant at 5×10^{-5} coulomb cm^{-2} .

At 400 eV and above the results are seen to follow quite closely theoretical values of electron range taken from Sugiyama's tables. These were compiled using Bethe's formula with a variable number of effective atomic electrons and a variable ionisation energy, according to the incident electron energy⁽⁶⁾. In this region the developed depth increases with the 1.35 power of electron energy, as can be seen from figure 7. This value for the exponent is in close agreement with that measured by Young over the energy range 300eV-7.5keV⁽⁷⁾. The experimental results are seen to depart from the calculated ranges below 400 eV.

Exposure ranges of about 10 to 20 angstroms have been measured for 50 eV electrons. These measurements used a decelerating field and the charge density is not known.

4. Conclusion

Preliminary results for exposure ranges in PMMA of electrons from 100 to 2500 eV have been produced. These follow closely theoretical results for electron ranges in polymeric material. The range shows no sign of increasing down to 50 eV but measurements below this energy have not yet been made.

Acknowledgment

This work is supported by the Science and Engineering Research Council (U.K.). One of us (S.A.R.) wishes to thank British Telecom Research Laboratory for a CASE studentship.

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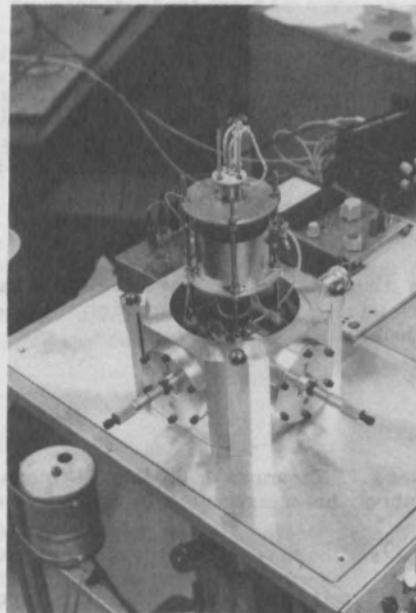
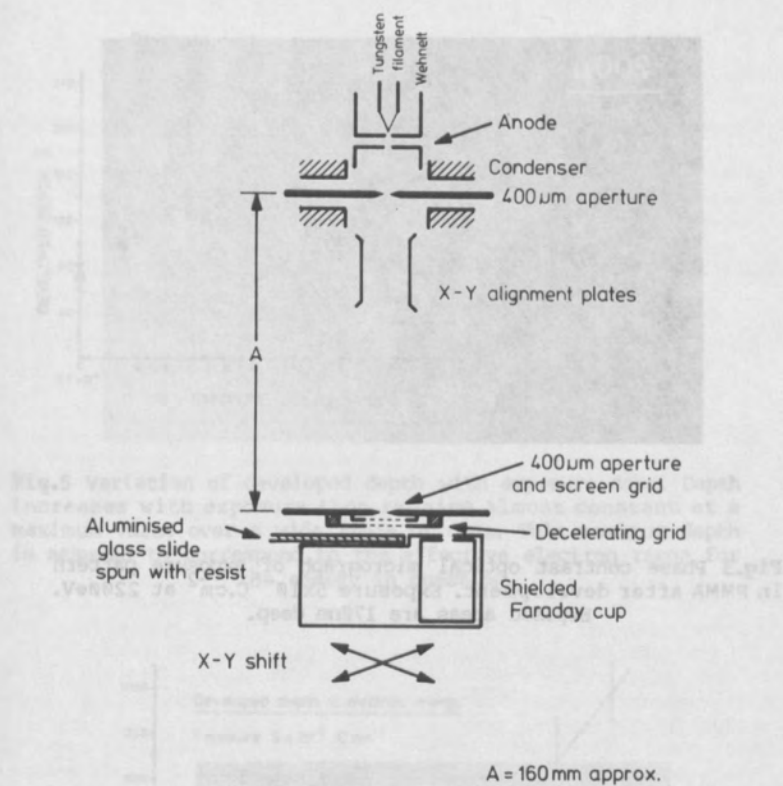


Fig.1 Low energy electron exposure system, evacuated by a
liquid nitrogen trapped oil diffusion pump.



Low energy electron exposure system.

Fig.2 Schematic diagram of apparatus showing electron-optical arrangement and current measurement system.

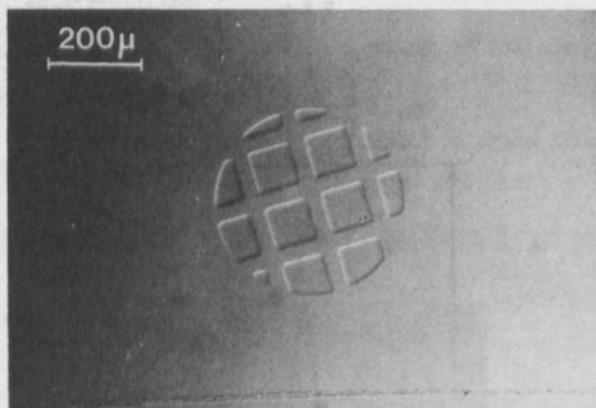
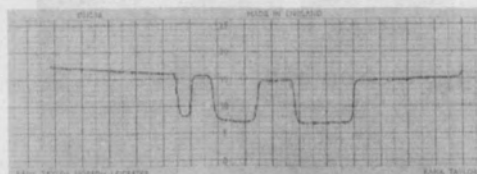


Fig.3 Phase contrast optical micrograph of exposure pattern in PMMA after development. Exposure $5 \times 10^{-5} \text{ C.cm}^2$ at 2200 eV. Exposed areas are 170 nm deep.



Resist profile

1300 eV $5 \times 10^{-5} \text{ coulomb cm}^{-2}$

Fig.4 Talystep surface profile trace of an exposed and developed area of PMMA.

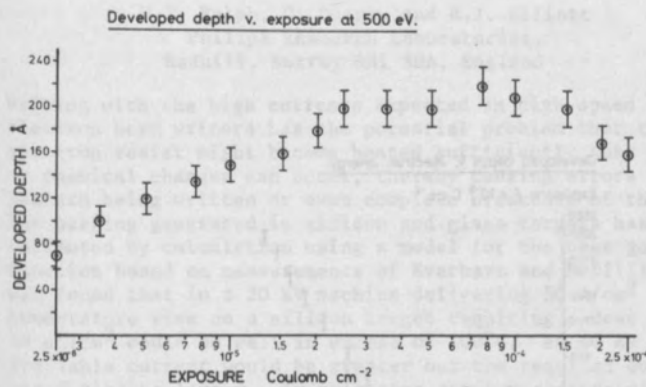


Fig.5 Variation of developed depth with exposure dose. Depth increases with exposure then remains almost constant at a maximum value over a wide range of dose. This maximum depth is assumed to correspond to the effective electron range for the energy in question.

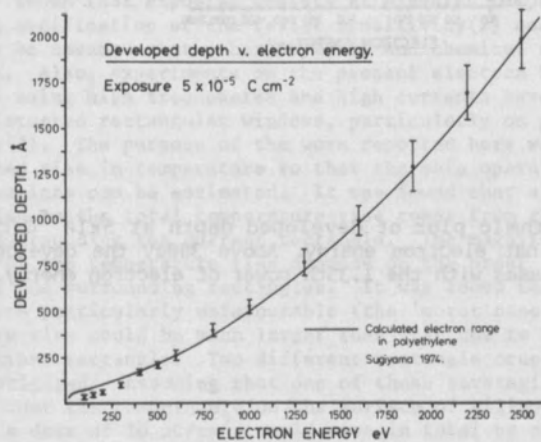


Fig.6 Variation of developed depth at constant exposure with electron energy. Measured depths correspond closely with Sugiyama's calculated electron ranges.

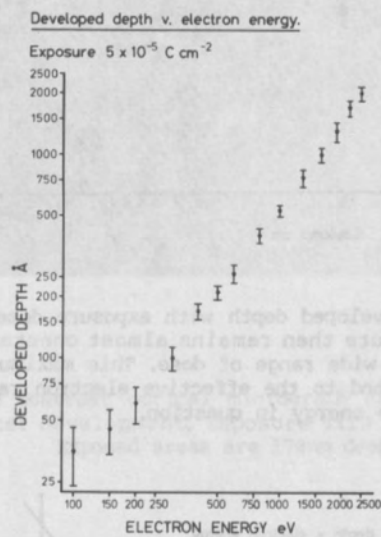


Fig.7 Logarithmic plot of developed depth at $5 \times 10^{-5} \text{ C/cm}^2$ exposure against electron energy. Above 300eV the developed depth increases with the 1.35th power of electron energy.

RESIST HEATING IN HIGH SPEED ELECTRON BEAM PATTERN GENERATORS

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Writing with the high currents expected in high speed shaped electron beam writers has the potential problem that the electron resist might become heated sufficiently that physical or chemical changes can occur, thereby causing errors in the pattern being written or even complete breakdown of the resist. The heating generated in silicon and glass targets has been estimated by calculation using a model for the heat generation function based on measurements of Everhart and Hoff(1). It was found that in a 20 kV machine delivering 50 A/cm² the temperature rise on a silicon target requiring a dose of 10 μ C/cm² could be well in excess of 100°C. At 40 kV the available current would be greater but the required dose would also be larger. In this case the temperature rise would be higher but it was found that even using a current of 130 A/cm² the temperature rises only about twice as much. Judicious choice of the order in which the individual pattern elements are written helps to minimise this temperature rise.

Using the high current, high energy beams expected in the new generation of shaped electron pattern generators to be used for lithographic purposes can give rise to large temperature rises in the resist in the regions where the resist is actually being exposed. It is already known that exposing resists at elevated temperatures results in modification of the resist sensitivity(2) and it can reasonably be assumed that other physical and chemical changes will take place. Also, experiments on the present electron beam pattern generators using high frequencies and high currents have been reported to give distorted rectangular windows, particularly on glass substrates(3). The purpose of the work reported here was to calculate the expected rise in temperature so that the safe operating conditions of such machines can be estimated. It was found that a significant contribution to the total temperature rise comes from the irradiation of areas surrounding the current rectangle. The magnitude of this component of the temperature rise depends on the order and the rapidity of writing the surrounding rectangles. It was found that if these factors were particularly unfavourable (the 'worst case'), the temperature rise could be much larger than that due to the irradiation of the current rectangle. Two different rectangle ordering strategies were investigated. Assuming that one of these strategies is used it was found that the temperature on the surface of silicon targets receiving a dose of 10 μ C/cm², could rise in total by over 100°C in a 20 kV machine capable of writing up to a 5x5 μ m square with a current density 50 A/cm². A similar machine operated at 40 kV and giving 140 A/cm² would need to deliver about twice the dose for the same resist. A temperature rise of about 300°C was calculated in this case.

The surface of a glass target under the same conditions would rise by up to another 100°C. These figures suppose that the machine is working under its highest possible current conditions. Most patterns will contain many small rectangles, resulting in an automatic reduction of the beam current and a corresponding reduction in background heating. It is indicated, however, that to realise the full high speed potential of the machine, resists with sensitivities of around 10 $\mu\text{C}/\text{cm}^2$ or better will have to be used.

Theory

The flow of heat in a normal isotropic solid is governed by the diffusion equation

$$\frac{\partial H}{\partial t} + D \nabla^2 H = S \quad (1)$$

where $H(\underline{r}, t)$ is the heat distribution function, $S(\underline{r}, t)$ is the heat source distribution and D is the thermal diffusion coefficient. The temperature T is given everywhere by

$$T(\underline{r}, t) = \frac{H(\underline{r}, t)}{c_v \rho} \quad (2)$$

where c_v is the specific heat and ρ is the material density.

For the purposes of this calculation we assume that the electron beam target is a semi-infinite block of homogeneous material. The source is distributed in some way in the material near to the surface. The existence of the surface can be accounted for inside the material by replacing the semi-infinite block by a fully infinite block and adding a second source which is the mirror image of the first in the real surface.

It has been common in calculations of this nature to assume that the source has a Gaussian distribution centred at some point below the surface. We have tried using such a source but found that the calculated temperatures depended rather strongly on the parameters that we chose for the Gaussian distribution. We assume that the reason for this was that we were calculating the temperature in the region of time and space where the source actually is and that a substantial contribution to the temperature comes from the immediate vicinity. We concluded, therefore, that we needed to know the form of the source distribution rather more accurately.

The source distribution we chose has the form

$$S(\underline{r}, t) = f V I(x, y, t) \lambda(z/R_g)/R_g \quad (3)$$

where $I(x, y, t)$ is the beam current distribution on the surface of the target. The function λ was chosen as the electron energy distribution perpendicular to the surface measured by Everhart and Hoff(1). V is the beam accelerating potential and f is a factor included to allow for the electron energy losses with back scattered electrons. Although this source is still not correct, it is easy to see that it gives the correct temperature rise at the edge of a large area, which is the most important case, and at positions far from an edge. Everhart and Hoff measured the function λ for beam energies from 5 to 25 keV and found it to be independent of beam energy over that range provided that an appropriate value for the Grün range, R_g , was used at each energy. We assumed that the function is applicable up to 40 keV and obtained the Grün range by extrapolation from the range given by Everhart and Hoff.

Using the source in equation 3, equation 1 can be solved by the Green's function method giving

$$T(\underline{r}, t) = \frac{fV}{c_v \rho R_g} \int dt' \int dx' \int dy' I(x', y', t') F\left(\frac{4D(t-t')}{R_g^2}, \frac{z}{R_g}\right) \\ \times \exp\left[-\frac{(x-x')^2}{4D(t-t')}\right] \exp\left[-\frac{(y-y')^2}{4D(t-t')}\right] / 4D(t-t') \quad (4)$$

where

$$F(\tau, \zeta) = \int d\xi \lambda(\xi) \left[\exp\{-(\zeta-\xi)^2/\tau\} + \exp\{-(\zeta+\xi)^2/\tau\} \right] / \sqrt{\pi\tau}$$

In most cases of interest the space integrals can be done analytically. For example, if a rectangle, side lengths a and b , is uniformly irradiated from time 0 to time θ we put for the current distribution

$$I(x, y, t) = Q S(x/a) S(y/b) S(t/\theta) / \theta \quad (5)$$

where S is the square function, unity for argument between zero and one and zero otherwise and Q is the total charge delivered per unit area. The temperature distribution becomes

$$T(\underline{r}, t) = \frac{f V Q}{c_v \rho R_g} \int dt \cdot \frac{S(t'/\theta)}{\theta} F\left(\frac{4D(t-t')}{R_g^2}, \frac{z}{R_g}\right) \\ \times G\left(\frac{4D(t-t')}{a^2}, \frac{x}{a}\right) G\left(\frac{4D(t-t')}{b^2}, \frac{y}{b}\right)$$

where

$$G(\tau, \zeta) = [\operatorname{erf}\{(1-\zeta)/\sqrt{\tau}\} + \operatorname{erf}\{\zeta/\sqrt{\tau}\}] / 2 \quad (6)$$

The upper integration limit t_m in equation 6 is the smaller of t and θ .

Results

The temperature rise experienced by a target being irradiated by a shaped beam was evaluated by numerical integration of the integral in equation 6. The results for the temperature rise on the surface of a glass target irradiated with a 20 kV beam is shown in Fig. 1. The point, at which the temperature is calculated, is half way along one of the edges of the square area being irradiated. The value of the quantity f has been taken as 0.9 for all the calculations. The result of a similar calculation for a silicon target is shown in Fig. 2. The highest temperature reached while the electron irradiation is actually on is indicated on each figure by the label 'irradiation off'. This highest temperature is shown for selected cases with significant parameter values in table I for glass and in table II for silicon.

The difference in behaviour between glass and silicon targets is accounted for almost entirely by the thermal conductivity of glass being two orders of magnitude smaller than that of silicon. The trends that can be derived from the tables are: on glass similar temperature rises occur for all cases; on silicon, doubling the current density approximately doubles the temperature rise, doubling the square size rather more than doubles the temperature rise and doubling the beam energy and doubling the required dose (keeping the current density fixed) approximately doubles the temperature rise.

In addition to the temperature rise calculated above, there is a 'background' temperature rise at a point due to other previously irradiated areas. The temperature rise actually experienced will depend upon not only the number of rectangles that have already been written but also on the order in which they have been written. First we find what pattern of irradiation gives the largest possible temperature rise.

The highest temperature rise at a point due to a heat source some distance away occurs at a time after the source is active proportional to the square of the distance of the source from the point. The greatest possible temperature rise at a point occurs, therefore, if the target is irradiated with a uniform dose in an inward spiral centred at that point and with just the appropriate current.

The expression for this 'worst case' is obtained substituting a current distribution

$$I(x,y,t) = Q a \delta(x^2 + y^2 - at) \quad (7)$$

into equation 4. πa is the areal rate of coverage of the target. Again, the integral over the space coordinates can be performed analytically and the time integral must be done numerically. The value of a which gave the highest temperature rise was found by trial and error. The same doses as used above were assumed but it was assumed additionally that there was only 50% coverage so that the mean dose required became $5 \mu\text{C}/\text{cm}^2$ at 20 kV and $10 \mu\text{C}/\text{cm}^2$ at 40 kV. As might be expected in the case of glass similar coverage rates of approximately $6\pi D$ gave the largest temperature rise at the centre of the spiral corresponding to $0.4 \mu\text{A}$ at 20 kV and $0.7 \mu\text{A}$ at 40 kV. The temperature $0.2 \mu\text{s}$ after the beam has been turned off is plotted in Fig. 3. In any real case the irradiation would not continue right to the centre of the spiral but would stop short at some radius. This radius is what is shown along the horizontal axis in Fig. 3.

In the case of silicon the worst coverage rate is much larger than is possible with what is a reasonable maximum available beam current. Therefore, a fixed current of $12.5 \mu\text{A}$ was used for the 20 kV calculation and $35 \mu\text{A}$ for the 40 kV calculation. The temperature rises are plotted in Fig. 4. Because the worst coverage rate was not used for the calculation, it is not immediately obvious that no pattern of irradiation could be found which would give a higher temperature rise at some point.

It is unlikely that such a pattern of exposure would be deliberately introduced but something approximating to it could easily turn up from time to time by accident. If it did, temperature rise could become higher than is acceptable in many cases. Some strategy for ordering the rectangles in each subfield is going to be needed to minimise this. We have calculated the temperature rises obtained at various points on the target surface due to irradiation of neighbouring areas assuming two different pattern element ordering strategies. The irradiated areas were account for in a continuous approximation in just the same way as in the 'worst' case described above.

Presumably, in order to reduce eddy currents all the pattern elements in a small region on a sample will have to be written together. We have assumed that the pattern elements will be written

in lanes such that all the elements in one lane will be written together and will be ordered in such a way that the beam does not jump up and down the lane very far. One possibility is to order elements according to their coordinate along the length of the lane. An approximate expression for the temperature rise in this case is obtained by substituting into equation 4, the expression for the current

$$I(x,y,t) = Q v \delta(x-vt) S(y/b) S(t/\theta) \quad (8)$$

The velocity, v , is the velocity with which the beam moves along the lane (assumed constant in this calculation). Again the integral over the space coordinates can be done analytically leaving just the time integral to be done numerically. We have calculated the background temperature rise at a point in the centre of a lane of width $50 \mu\text{m}$ with this kind of ordering. We assumed that the irradiation was terminated $1 \mu\text{m}$ before it reached the point at which the temperature rise was calculated. We assumed the same values of the parameters as for the worst case. The result is plotted for a silicon target in Fig. 5 and for a glass target in Fig. 6.

It can be seen that for the highest currents on glass, the background temperature hardly rises in the region where the beam is currently writing. This ordering could be used to minimise the background temperature rise in this case. The danger exists, however, that if a region occurs where the beam has to be stopped down, the background temperature will rise significantly.

The background heating could be eliminated if the beam was made to step large distances and return to any particular area only after it had cooled. We assume, however, that the machine will need to write all rectangles in any one region together. We have evaluated a compromise. We assumed that all the rectangles in a $50 \times 50 \mu\text{m}$ subfield were ordered in a 'uniform' way and that the subfields were ordered sequentially. This is not the same as random ordering as the latter will frequently produce close by rectangles separated in time by an amount that will cause one to give a substantial extra temperature rise to the other. Ordering to give a uniform irradiation may be hard to achieve in practice. The point where the highest temperature rise appears in a subfield is somewhere along the line running through the centres of the subfields. The temperature rises along this line are plotted in Figs. 7 and 8 for silicon and glass respectively. In all the calculations it is assumed that the point where the temperature is calculated, is at the centre of a $2 \mu\text{m}$ square within which no background irradiation is applied.

Conclusions

Drawing a conclusion from these calculations is difficult. Because of the short time constant in silicon, in general the higher the rate of input of energy from the beam, the hotter it gets. The

temperature rises in silicon under a 40 kV beam are higher than under a 20 kV beam, but they are not much higher. If resists less sensitive than has been assumed here are used and they are sensitive to 200°C rises in temperature, then the high speed pattern generator will not be able to work at high speed when writing directly on silicon at either beam energy. On the other hand, if the resists are rather more sensitive than assumed here or they are less sensitive to high temperatures, the heating of the resist is not going to be significant at either energy. It does seem that it will be necessary to use resists no less sensitive than about $10 \mu\text{C}/\text{cm}^2$ in order to take full advantage of the high speed of machine whatever accelerating potential is used.

The time constants in glass are long compared with the times taken to write a single rectangle and it increases very rapidly with increase in beam energy. This means that large rectangles being written get hot unless the writing is over quickly. It also means that there is a long temperature after-effect from the nearby rectangles that have previously been irradiated. Avoiding this is difficult. It was suggested that it might be possible to minimise this effect by ordering the rectangles so that the region currently being irradiated sweeps across the subfield moving away before the high temperature rise occurs.

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silicon

- sizes of squares -

V	I	dose	5x5	2x2	1x1
(kV)	(A/cm ²)	(μC/cm ²)	(μm)	(μm)	(μm)
20	50	10	96	34	13
20	25	10	56	18	7
40	140	20	188	63	22
40	70	20	129	35	10

Table I

Temperature on silicon under a shaped beam (in °C)

glass

- sizes of squares -

V	I	dose	5x5	2x2	1x1
(kV)	(A/cm ²)	(μC/cm ²)	(μm)	(μm)	(μm)
20	50	10	179	178	159
20	25	10	190	184	142
40	140	20	169	169	159
40	70	20	178	175	168

Table II

Temperature rise on glass under a shaped beam (in °C)

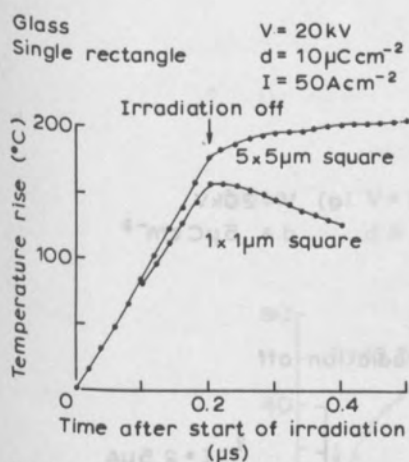


Fig.1 Temperature rise at the centre of an edge of a square irradiated on glass at 20kv.

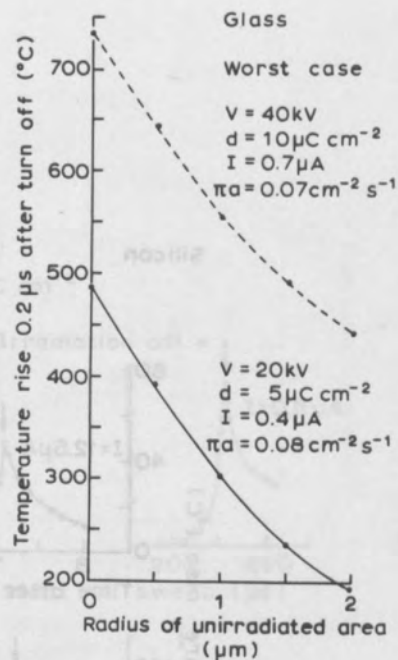


Fig. 3

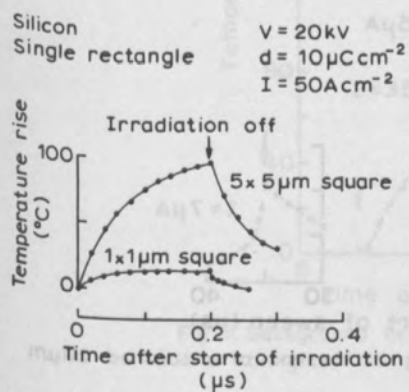


Fig.2 Temperature rise at the centre of an edge of a square irradiated on silicon at 20kv.

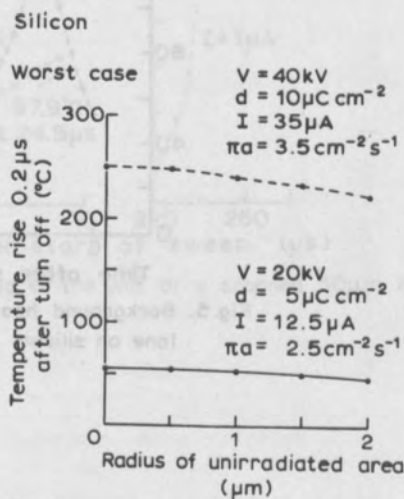
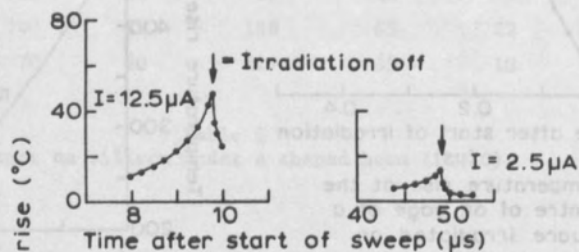


Fig. 4

Silicon

a) $V = 20\text{kv}$
 $d = 5\mu\text{C cm}^{-2}$



b) $V = 40\text{kv}$
 $d = 10\mu\text{C cm}^{-2}$

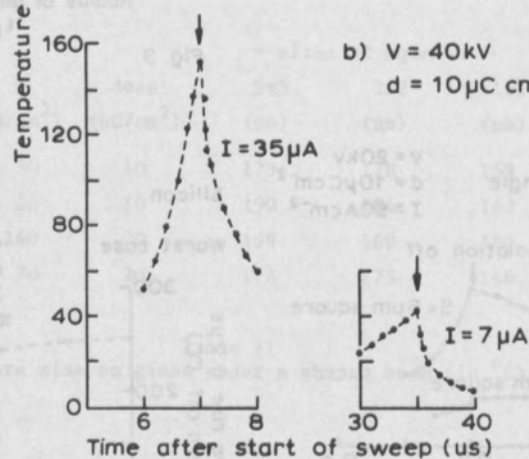


Fig.5. Background heating at the end of a scanned $50\mu\text{m}$ lane on silicon.

Glass a) $V = 20\text{ kV}$
 $d = 5\mu\text{C cm}^{-2}$

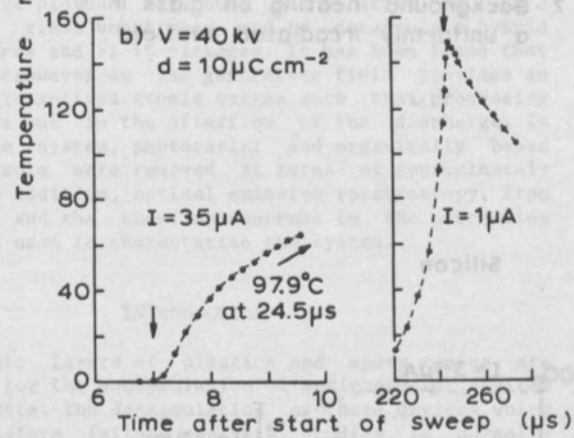
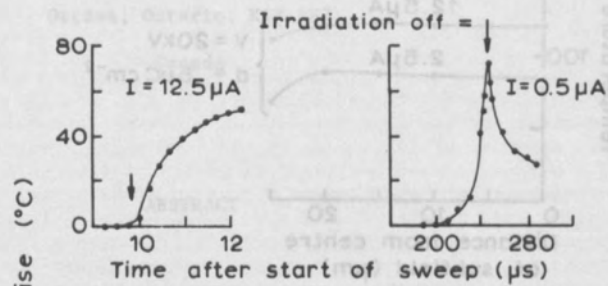


Fig.6. Background heating at the end of a scanned $50\mu\text{m}$ lane on glass.

Glass

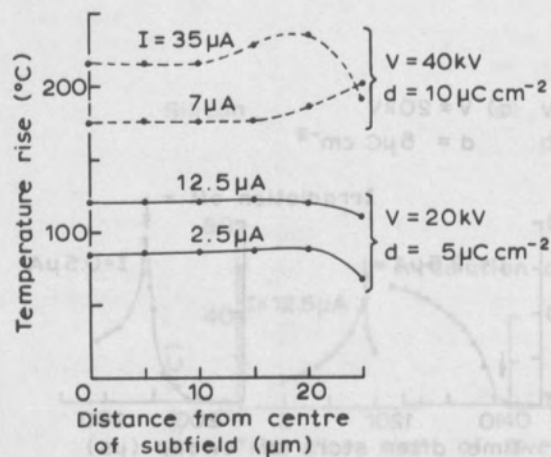


Fig. 7. Background heating on glass in a uniformly irradiated subfield.

Silicon

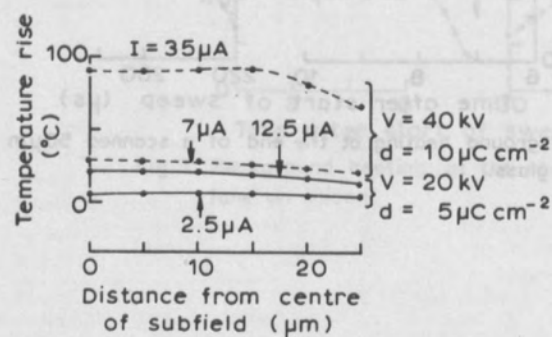


Fig. 8. Background heating on silicon in a uniformly irradiated subfield.

DECAPSULATION AND PHOTORESIST STRIPPING

in OXYGEN MICROWAVE PLASMAS

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ABSTRACT

Oxygen microwave plasmas have been used to strip AZ 1350 J photoresist on glass substrates and to decapsulate hybrid resistor networks and Si IC packages. It has been found that the use of microwaves as the generating field provides an abundance of long-lived atomic oxygen such that processing can be carried out in the afterflow of the discharge. In this downstream system, photoresist and organically based epoxy encapsulants were removed at rates of approximately $6.0 \mu\text{m}/\text{min}$. In addition, optical emission spectroscopy, from the O_2 plasma and the chemiluminescence in the processing zone, has been used to characterize the system.

INTRODUCTION

Thick organic layers of plastics and epoxy resins are commonly used for the encapsulation of semiconductor devices and microcircuits. The decapsulation of these devices which is required before failure analysis studies, is normally carried out using wet etching techniques (1-4). However, these procedures are difficult to control and may cause considerable damage to the package. The use of radiofrequency oxygen plasmas has also been reported (5) but was found to be extremely slow (e.g. several days to decapsulate plastic IC packages).

In this paper we report the use of a downstream microwave oxygen plasma technique for the removal of thick organic layers. The system provides a removal rate of up to 6 $\mu\text{m}/\text{min}$ in the afterglow of an O_2 discharge. Since processing is carried out away from the discharge zone, substrates and devices are not exposed to the plasma environment or the generating electric field. The removal process was first optimized for photoresist stripping using optical emission spectroscopy as a monitor. It was then applied to the decapsulation of hybrid resistor networks and IC packages.

EXPERIMENTS

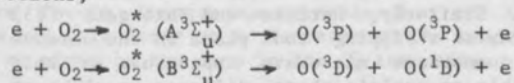
The experimental system used in the removal of organically based materials is shown in Fig. 1. The primary components of the apparatus are a microwave generator (2.45 GHz) capable of delivering up to 1000 watts, water cooled wave guides, a resonant reactor cavity, (14 mm in diameter) an evacuated etching chamber (10 cm in diameter and 20 cm in length) and an optical emission spectrometer. In addition, specimens could be heated using a resistance coil wound around the outside of the etching chamber. Substrate temperatures were measured by a thermocouple placed inside the processing chamber and adjacent to the specimen. Ultra high purity oxygen was used as the reactant gas throughout this work.

In the cases of stripping photoresist on glass substrates and decapsulation of the hybrid resistors, the samples were placed with the substrate normal to the oxygen flow. For decapsulation of Si ICs, the devices were orientated parallel to the gas flow. Although the geometrical orientation was important in terms of the stripping uniformity, no significant differences were observed in the average removal rates between the two set-ups at the same plasma-substrate distance.

Optical emission spectra were recorded from two locations for process monitoring. Spectra of the reactive plasma species were taken at the exit zone of the discharge cavity. Spectra of the organic stripping products were recorded in the etching chamber above the coated substrates. The two zones were spectroscopically independent of each other. Features in the 400-800 nm spectral range were analyzed by an 0.25 m Jarrel-Ash scanning monochromator, processed by an EMI photomultiplier tube and displayed on an X-Y recorder. No focusing optics were required to collect the light.

RESULTS AND DISCUSSION

Emission Spectra. The optical emission spectrum recorded from the oxygen plasma region is shown in Fig. 2. This spectrum was taken at the exit port of the discharge cavity, without a sample, and therefore identifies the species emanating from the plasma. The individual peaks and their corresponding wavelengths have been identified by comparison with published spectra and tables of standard spectral wavelengths (6). From the spectrum, it is evident that the afterflow is predominantly made up of atomic oxygen. Ionic and molecular oxygen are also present though in much smaller quantities. According to Bell (7), the generation of atomic oxygen in a high frequency discharge is primarily due to the dissociation of excited molecular oxygen through the following reactions;



These mechanisms would account for the abundance of atomic oxygen seen in the emission spectrum in Fig. 2.

In addition to the dissociated O_2 , a Na contaminant peak has been identified. This may be produced from the quartz cavity. Also several unidentified minor peaks were observed which may be due to contaminants from the residual vacuum. The role of these species has not been investigated in this work, however gaseous contaminants such as N_2 , H_2 and water vapor are known to enhance the yield of atomic oxygen in the plasma by providing additional dissociation mechanisms for molecular oxygen (8).

The spectrum induced by the microwave field can be compared to that reported by Griffiths and Degenkolb (9) for a radiofrequency oxygen discharge. From a comparison of the intensity ratios (Table 1) the amount of atomic oxygen in the $^5D^0$ and $^5S^0$ states observed in our microwave system is at least twice that observed in the rf system at the same applied power of 300 watts.

During the removal of organic material downstream from the discharge, chemiluminescence above the specimens revealed the band heads due to CH (431.5 nm), OH (308.6 nm) and portions of the 4th positive group of CO. The detection of these diatomic species has been observed in several previous reports (10-12) and they have been attributed to the volatile stripping products.

Effect of Microwave Power. Although absorbed power in the plasma system could be varied from 100-1000 watts, power levels in excess of 400 watts resulted in substrate heating. For this reason, the applied power was kept below 400 watts throughout the experiments.

Figure 3 shows the removal rate of AZ 1350 J resist as a function of applied power at a constant O_2 pressure of 0.3 Torr. For substrates located 10 cm from the plasma, a linear increase with power is observed and stripping rates up to 6 $\mu\text{m}/\text{min}$ were achieved. This represents an order of magnitude increase in the stripping rate when compared to conventional rf barrel systems using pure oxygen discharges (10,11). However, in comparison with other downstream systems, Wang and Gelernt (12) found that photoresist did not etch in pure oxygen plasmas and that 7% CF_4 was required to effectively strip the resist. Similarly, Horiike and Shibagaki (13) reported that no resist stripping took place in the absence of CF_4 in their downstream microwave apparatus. At this point, we are unable to explain these differences although they may, in part, be due to the materials and structure of the reactors used.

Figure 4 shows the spectral intensities of atomic oxygen (OI 436 nm, OI 543 nm, OI 533 nm and OI 615 nm) as a function of applied power. The data for the intensities from these atomic transitions were taken at the exit zone of the cavity. Also shown in Fig. 4 are the intensities due to the molecular stripping products CH, OH and CO as recorded from the chemiluminescence above the substrates.

The results in Figs. 3 and 4 are in agreement with a model proposed by Bell (7). In this model, the conversion yield of molecular to atomic oxygen is linearly dependent on the applied microwave power because the electron density increases linearly with power. Thus, at constant O_2 pressure, the flux of reactive atomic oxygen increases linearly with applied power provided the oxygen flow rate is sufficient to prevent a saturation effect. The linear increase in the etch rate is then due to the increased atomic oxygen flux.

Effect of O_2 Pressure. Oxygen pressure in the reactor cavity was varied from 0.01-10.0 Torr. At pressures less than 0.01 Torr, the discharge became weak and extended beyond the plasma cavity.

Figure 5 shows the effect of O_2 pressure on the emission intensity of the reactant OI 486 nm transition for applied power levels of 165 and 265 watts. The intensities increase

with pressure to a maximum at approximately 0.1 Torr and then fall quite rapidly. The intensity of the CO molecule used to monitor the stripping rate of resist also shows a maximum at an O₂ pressure of 0.1 Torr (Fig. 5).

In the low pressure region (<0.1 Torr) the removal of resist, hence the CO intensity, is proportional to the increase in the supply of atomic oxygen. For gas pressures greater than 0.1 Torr, the results in Fig. 5 can be interpreted as follows. Firstly, the decrease in the emission intensity of atomic oxygen is due to collisional quenching of the excited species as a result of the increase in O₂ pressure. Secondly, the increased pressure causes a decrease in the electron temperature which leads to a decrease in the energy transfer between the electrons in the plasma and the O₂ molecules. Thirdly, the increase in gas pressure favors homogeneous recombination of the atomic species and this leads to a decrease in the removal rate of resist as shown by the drop in the CO intensity.

Effect of Plasma-Substrate Distance. In the microwave system used here the distance from the plasma to the substrate was varied from 1-50 cm. Figure 6 shows the semilogarithmic plot of the removal rate of resist as a function of plasma-substrate distance. It is worth noting that for distances less than 5 cm the removal rate is enhanced due to the increase in substrate temperature as a result of the O₂ plasma and the microwave field. With the substrate located within 5 cm of the plasma and an applied power level of 350 watts, the substrate temperature rose to approximately 160°C. Since resist stripping is a thermally-activated process, the stripping rate is expected to increase exponentially.

In agreement with Collins and Robertson (14), these results show that the concentration of reactive species emanating from the discharge decay exponentially. This is expected if the survival probability is governed by atomic recombination. The stripping rate is determined by the flux of reactive species reaching the substrate. Thus the survival probability of atomic oxygen during excursion down the chamber is determined by atomic recombination.

REMOVAL OF THICK ORGANIC ENCAPSULANTS

The results presented above indicate that the oxygen microwave plasma provides a high yield of reactive atomic oxygen. Furthermore, the removal rates are one to two orders of magnitude faster than in a similar low frequency system (12). Therefore, having established the basic capability for

the removal of photoresist, decapsulation of thick ($>25\text{ }\mu\text{m}$) organic polymers on hybrid resistors and Si ICs was investigated.

In the case of hybrid resistor networks, the encapsulated substrate was exposed to the O_2 afterglow emanating from a 300 watt discharge. Decapsulation of the $10\text{ }\mu\text{m}$ thick epoxy was completed in 10 min. Figure 7 shows the laser trimmed resistor network and the underlying alumina substrate after decapsulation. The two semicircles located at the bottom of the photograph are those areas covered by the sample holder and therefore not exposed to the afterglow during the plasma decapsulation cycle.

In a second application, plastic encapsulated Si devices were placed approximately 50 cm from the discharge cavity. At this distance the device temperature did not exceed 60°C . A power level of 200 watts was used resulting in a microwave leakage field of only 2 mW/cm^2 at the location of the IC. Oxygen pressure was maintained at 0.9 Torr. Under these conditions, the particular encapsulant was removed at a rate of approximately $6\text{ }\mu\text{m/min}$. The resulting decapsulated IC is shown in Fig. 8. The organic was completely removed with no apparent damage to the bonding wires. Furthermore, subsequent electrical testing of the IC showed no significant electrical damage.

SUMMARY

We have demonstrated the capability of plasma processing in the afterflow of a dense O_2 plasma induced by 2.45 GHz microwave radiation. Optimization of the system has been achieved using optical emission spectroscopy during the removal of AZ 1350 J photoresist. This preliminary investigation demonstrated the enhanced removal rate of organic materials. Namely, stripping rates were one to two orders of magnitude faster than rates reported for rf barrel systems. Subsequently, the system was used to decapsulate Si IC packages and hybrid resistor networks. In this latter application, the time to remove thick ($>25\text{ }\mu\text{m}$) organic material was of the order 30 min which is also a significant decrease in processing time when compared to low frequency systems.

ACKNOWLEDGEMENTS

This work was supported in part by the National Research Council of Canada through its Industrial Research Assistance Program (Plasma 1100).

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TABLE 1

A comparison of the emission intensities of atomic oxygen in a radiofrequency and microwave oxygen plasma.

Intensity Ratio ^a	rf(13.56 MHz) ref. 10	mw(2.45 GHz) this work	mw/rf
OI(533.1)/OI(436.8)	0.2	0.5	2.5
OI(543.7)/OI(437.8)	0.08	0.25	3.1

a. We have assumed a constant quantum detection efficiency over the wavelength region 450-550 nm for both the rf and mw optical detection systems.

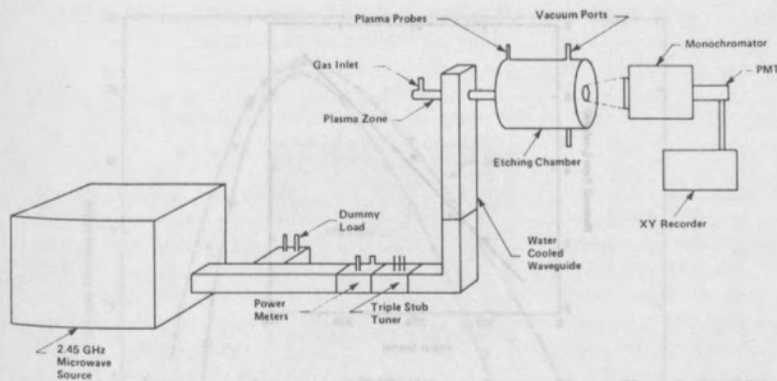


FIGURE 1. Experimental apparatus used for the removal of organic materials.

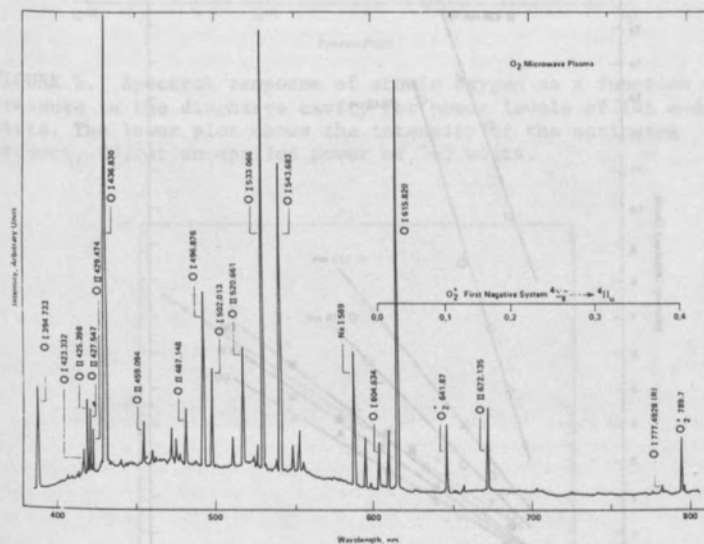


FIGURE 2. Optical emission spectrum from an ultra high purity oxygen microwave plasma in the absence of a specimen. The continuum from 400-600 nm is due to room light. Applied power was 300 watts and the O₂ gas pressure was 0.2 Torr.

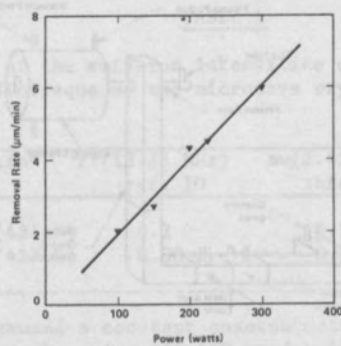


FIGURE 3. The effect of applied power on the removal rate of AZ 1350 J photoresist on glass substrates. Specimens were located 10 cm from the discharge zone.

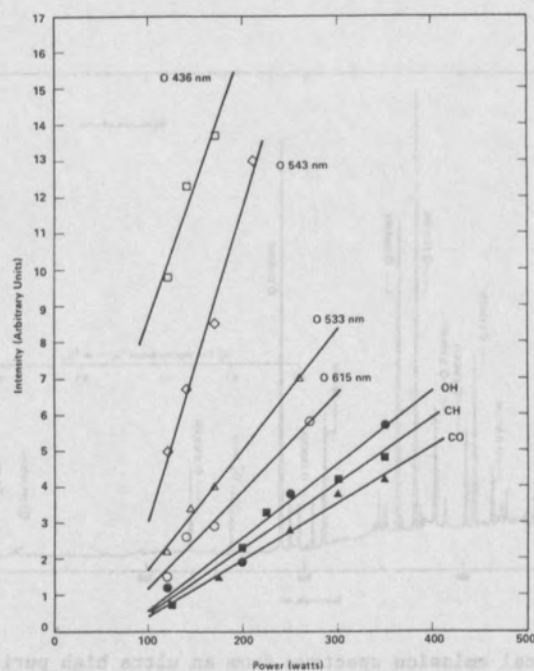


FIGURE 4. Intensity response of atomic oxygen and the diatomic stripping products OH, CH and CO as a function of applied power. The O_2 pressure was kept constant at 0.25 Torr.

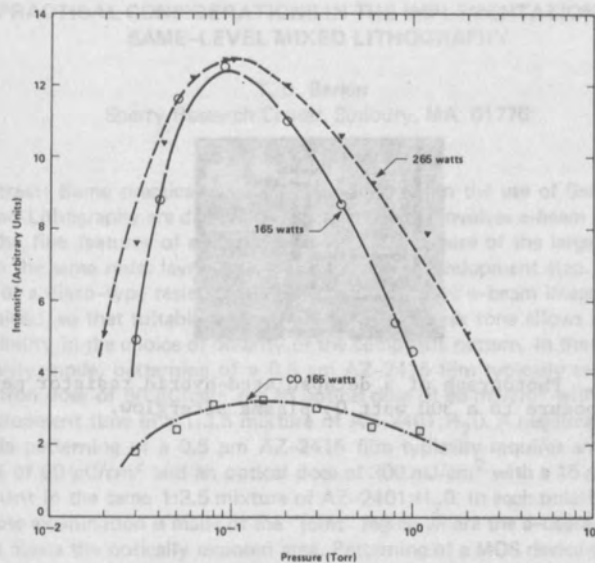


FIGURE 5. Spectral response of atomic oxygen as a function of O_2 pressure in the discharge cavity for power levels of 165 and 265 watts. The lower plot shows the intensity of the stripping product, CO, at an applied power of 165 watts.

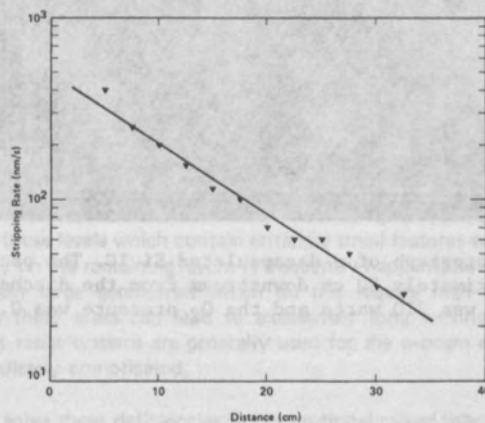


FIGURE 6. Stripping rate of photoresist on glass substrates as a function of plasma-substrate distance. The experiments were carried out at an applied power of 300 watts and an O_2 pressure of 0.1 Torr.

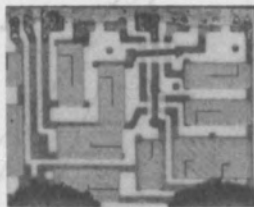


FIGURE 7. Photograph of a decapsulated hybrid resistor network after exposure to a 300 watt O_2 plasma afterglow.

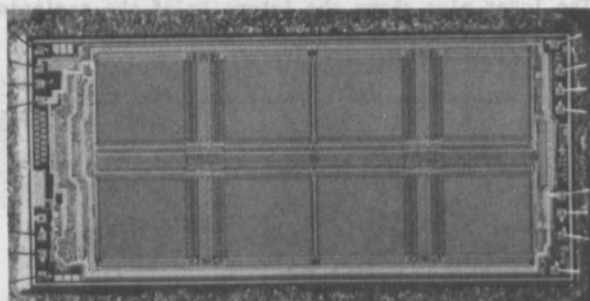


FIGURE 8. Photograph of a decapsulated Si IC. The package was located approximately 50 cm downstream from the discharge. Applied power was 210 watts and the O_2 pressure was 0.8 Torr.

PRACTICAL CONSIDERATIONS IN THE IMPLEMENTATION OF SAME-LEVEL MIXED LITHOGRAPHY

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Abstract: Some practical considerations involved in the use of Same-Level Mixed Lithography are discussed. This new process involves e-beam exposure of the fine features of a pattern and optical exposure of the large features onto the same resist layer, followed by a single development step. With the use of a diazo-type resist, either positive or negative e-beam images can be obtained, so that suitable selection of the photomask tone allows complete flexibility in the choice of polarity of the composite pattern. In the positive-polarity mode, patterning of a $0.5\text{ }\mu\text{m}$ AZ-2415 film typically requires an electron dose of $50\text{ }\mu\text{C}/\text{cm}^2$ and an optical dose of $80\text{ mJ}/\text{cm}^2$ with a 70 sec development time in a 1:3.5 mixture of AZ-2401:H₂O. A negative-polarity mode patterning of a $0.5\text{ }\mu\text{m}$ AZ-2415 film typically requires an electron dose of $60\text{ }\mu\text{C}/\text{cm}^2$ and an optical dose of $300\text{ mJ}/\text{cm}^2$ with a 15 sec development in the same 1:3.5 mixture of AZ-2401:H₂O. In each polarity mode, a close examination is made of the "joint" region where the e-beam-exposed area meets the optically exposed area. Patterning of a MOS device using this Same-Level Mixed Lithography Process in the negative-polarity mode is described. Gate lengths as small as $0.6\text{ }\mu\text{m}$ have been defined and anisotropically plasma etched into doped polysilicon. This new technique combines high resolution with high throughput on the same level while maintaining a simple process with only one coating, one development and one transfer step.

Introduction

Electron-beam lithography (EBL) is an excellent method for defining small geometries in complex semiconductor devices. However, this high resolution is accompanied by an increase in the time required to serially expose the pattern. In order to make use of the high-resolution patterning capability of EBL without totally sacrificing the higher throughput of photolithography, the exposure of an integrated circuit is sometimes done by combining optical and e-beam methods. In this "mixed lithography" approach, EBL is usually restricted to just those levels which contain critically small features while photolithography is used exclusively on the remaining levels. It frequently happens, however, that the e-beam levels also contain large geometries which do not require high-resolution patterning; serially exposing these areas can lead to excessively long writing times. Furthermore, because different resist systems are generally used for the e-beam and optical exposures, processing is needlessly complicated.

In order to solve these deficiencies in conventional mixed lithography processing, we have recently developed a new approach. This Same-Level Mixed Lithography (SLML) process¹ utilizes EBL and photolithography on the same level and in the same resist layer followed by a single-development step.

Same-Level Mixed Lithography

The Same-Level Mixed Lithography process is shown in Fig. 1. The small geometries on any given level of an integrated circuit pattern are exposed using an electron beam while the large geometries of the *same* level are defined using optical lithography. The two exposures are followed by a *single* development step which yields the complete pattern of the entire level. The imaging is done in commonly used diazo-type positive photoresists such as Shipley's AZ resists, which are sensitive to both electrons and photons. An attractive feature of these resists is that they can be processed to form either positive or negative images. The use of these resists with SLML, therefore, makes possible a very flexible lithographic process, capable of high resolution and acceptable throughput.

Water plays a key role in the imaging process in diazo-type photoresists.² Irradiation of the resist in the presence of water converts the photo-active (diazo) compound (PAC) to a carboxylic acid, and substantially enhances the solubility of the resist in a basic developer solution. Positive resist behavior results. In a water-free environment (e.g., vacuum), optical or electron exposure converts the PAC to an ester, which diminishes the subsequent development rate of the resist in the basic developer. The important point here is that the chemistry of these two processes is dominated by the availability of water during exposure and not by the radiant source.

Electron exposure in a vacuum causes not only the conversion of the PAC to an ester, which can lead to negative behavior, but also scission reactions in the Novalac resinous base of the resist which can lead to positive behavior. Diazo-type resists can therefore be processed either as positive or negative electron resists by controlling the development rate of the background areas (those regions not exposed to electrons) relative to the electron-exposed areas. Negative resist structures can be formed by exposure of the pattern with an electron beam in vacuum followed by a flood optical exposure in air to change the background into a highly soluble state.^{3,4} A short development time (typically 15 sec) is used so that the negative nature of the electron-exposed areas is preserved while the background is developed away. In the absence of a flood exposure in air, the background areas develop very slowly and a longer development time (typically 60 sec) causes the electron-induced scission reactions to dominate, resulting in a positive image. It is the *relative* development rate of the background and the electron-exposed area, as well as the total development time, that determines the tone of the image.

Positive-Polarity Exposure Mode

When a diazo-type resist is processed in a positive-polarity dual-exposure mode (Fig. 1, Path A), the resist acts as a positive electron resist and a positive photoresist. The small features of the pattern are defined with an electron beam. The large features are then optically exposed using a dark-field photomask so that the background areas receive no radiation. During development, the background develops very slowly, while the large optically exposed areas are removed rapidly. The development time is made long enough for the e-beam-exposed areas, which develop more slowly due to conversion of some PAC's to esters, to be removed and a positive composite image is obtained.

Except for the overlap areas of the pattern, each region of resist receives only one type of radiation. In the region of the overlap, exposures "add" and, under certain conditions, this can lead to a slight widening of the e-beam-generated line at the "joint" region where the electron-exposed area meets the optically-exposed area. Figure 2(a) shows an SEM micrograph of a developed resist pattern in a Shipley 3000 film of 1.2 μm initial thickness on doped polysilicon. E-beam-generated 0.7 μm lines are connected to a large optically generated pad. The electron dose was 80 $\mu\text{C}/\text{cm}^2$ with an acceleration voltage of 20 keV. The optical exposure was done with a 4:1 projection aligner and the integrated dose was 56 mJ/cm^2 . The development time was 75 sec in Microposit 300 developer.

Figure 2(b) is an enlargement of the joint region and shows clearly the standing waves on the optically exposed resist walls. The e-beam-defined area is undercut and there are no standing waves. The optical exposure is not cleanly attenuated at the photomask edge and a small amount of radiation is absorbed along the perimeters of the masked areas. This causes a slight broadening (from 0.7 μm to 0.8 μm) of the e-beam-generated line at the joint region, with the standing wave pattern extending around the corner.

Negative-Polarity Exposure Mode

When a diazo-type resist is processed in a negative-polarity dual-exposure mode (Fig. 1, Path B), the resist acts as a negative electron resist and a positive photoresist. The small features of the pattern are defined with an electron beam. The large features are now exposed using a light-field photomask with a high optical dose so that the background is changed into a highly soluble state. The background is removed very rapidly during a short development which preserves both the e-beam-exposed areas and the optically masked pads.

Figure 3 shows an SEM micrograph of a developed resist pattern in an AZ-2415 film of 0.5 μm initial thickness. E-beam-generated 0.4 μm lines are connected to a large optically generated pad. The electron dose was 50 $\mu\text{C}/\text{cm}^2$, optical dose was 222 mJ/cm^2 , and development was for 12 sec in a 1:3.5 mixture of AZ-2401:H₂O. The electron exposures have continued into the pad area. A standing wave pattern shows clearly on the optically exposed resist walls.

The electron-exposed areas also receive optical radiation. As explained earlier, the mechanisms involved in the negative electron-generated behavior and the positive optically generated behavior are different and the exposures do not "add." However, diffraction at the mask-pattern edge can lead to a variation in optical dose which affects the e-beam-defined linewidth at the overlap region.⁵ Figure 4 shows the effect of optical dose on the developed linewidth of AZ-2415 at several electron doses. The initial film thickness was 0.5 μm and the development time was 15 sec in a 1:3.5 mixture of AZ-2401:H₂O. The nominal written linewidth was 1 μm . As the optical dose increases above the minimum value which causes complete development of the background areas (170 mJ/cm^2), the linewidth decreases rapidly, then saturates at an optical dose of approximately 300 mJ/cm^2 .

If a pattern is exposed at an optical dose below the saturation value, any diffraction at the photomask edge will result in linewidth variations of the e-beam-defined areas.

Figure 5 shows this effect. Figure 5(a) is a schematic of the pattern and Fig. 5(b) is an SEM micrograph of an etched polysilicon structure after resist removal. Figure 6 shows a properly exposed pattern. There is no linewidth variation and the electron-defined gate connects smoothly to the optically defined pad.

NMOS Device Patterning

An NMOS device with a submicron gate was patterned using Same-Level Mixed Lithography. The gate level was defined using the negative-polarity exposure mode (Fig. 1, Path B) in 0.5 μm of AZ-2415 and anisotropic plasma etching of the underlying 5000 Å of doped polysilicon. An electron dose of 80 $\mu\text{C}/\text{cm}^2$, an optical dose of 300 mJ/cm^2 and a development time of 15 sec were used. The developed gate length was 0.7 μm and there was no measurable loss of linewidth during plasma etching. Figure 7(a) is an SEM micrograph of the plasma-etched structure prior to resist removal. Figure 7(b) shows the connection between the e-beam-defined gate and the optically defined pad after resist removal.

As in conventional mixed lithography, alignment to any previous patterned levels is done using e-beam registration marks. The photomask is then aligned to the present and previous levels using optical alignment marks. Any desired overlapping of the e-beam areas and optically masked areas is provided for in the design of the patterns. As can be seen in Fig. 7(a), the e-beam-defined gate extends well into the optically defined pad.

Conclusion

We have examined here the use of a new lithographic process that uses both e-beam and optical exposure of a single-resist layer. Same-Level Mixed Lithography makes use of the high-resolution patterning capability of EBL while preserving much of the throughput of photolithography. This simple process uses only one coating, one development and one transfer step. Furthermore, diazo resists hold up well under the dry etching processes which are necessary for the faithful transfer of very high resolution patterns. The ability to create both positive and negative images from one commonly used photoresist makes this an extremely flexible process that is fully compatible with existing semiconductor processing.

Same-Level Mixed Lithography was developed, in part, to address the throughput problem of EBL. There can be a significant time savings when using SLML instead of EBL; however, the exact savings depends upon the particular pattern being exposed. The time saved by not exposing the large geometries by serial exposure with the electron beam must be offset by the time spent by an extra alignment and flood exposure. The time savings and throughput increase are therefore maximized in a full-wafer optical exposure system and somewhat reduced in a wafer-stepper system. To date, we have only used SLML to fabricate discrete devices. We are now initiating a quantitative analysis of the throughput considerations of SLML through the use of specialized patterns and more complicated circuit designs.

Acknowledgements

The author wishes to thank D. D. Casey and J. A. Donahue for many helpful discussions. The aid of S. Bernacki, who coordinated the fabrication of the submicron NMOS device, is gratefully acknowledged.

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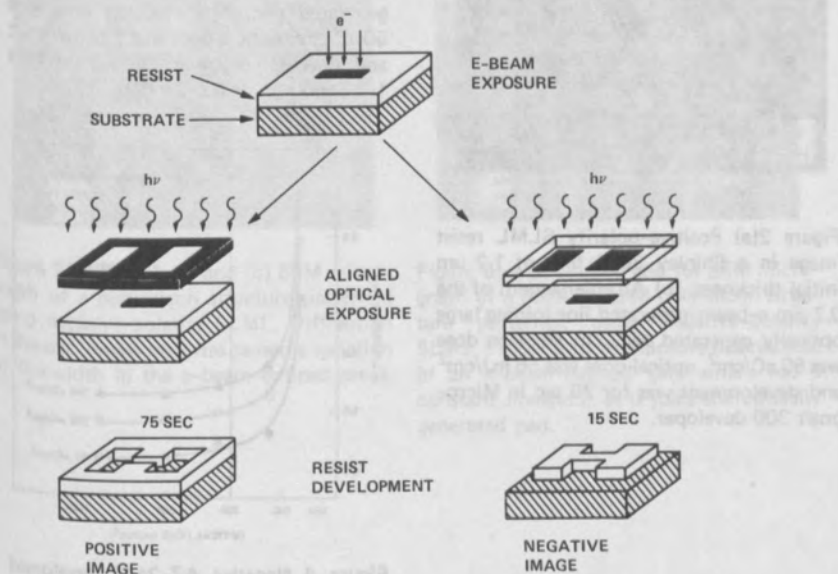


Figure 1 Same-Level Mixed Lithography (SLML). Path A uses a dark-field photomask and a long development time which results in an overall positive image. Path B uses a light-field photomask and a short development time which results in an overall negative image.

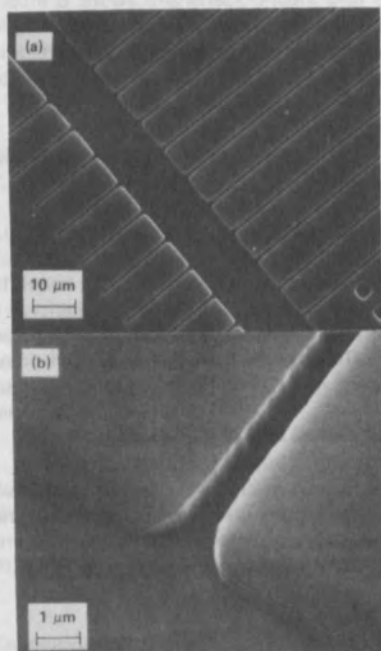


Figure 2(a) Positive-polarity SLML resist image in a Shipley 3000 film of 1.2 μm initial thickness. (b) An enlargement of the 0.7 μm e-beam-generated line joining large optically generated pad. The electron dose was 80 $\mu\text{C}/\text{cm}^2$, optical dose was 56 mJ/cm^2 and development was for 75 sec in Microposit 300 developer.

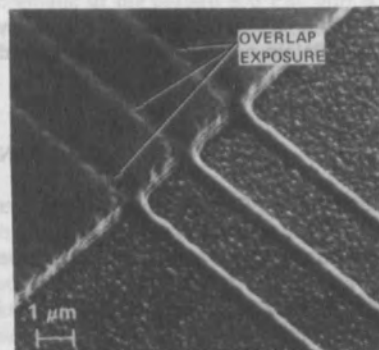


Figure 3 Negative-polarity SLML resist image in an AZ-2415 film of 0.5 μm initial thickness. The 0.4 μm e-beam-generated lines continue into the optically generated pad. The electron dose was 50 $\mu\text{C}/\text{cm}^2$; optical dose was 222 mJ/cm^2 ; and development was for 12 sec in a 1:3.5 mixture of AZ-2401: H_2O .

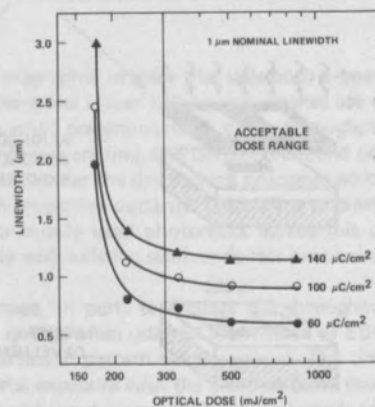


Figure 4 Negative AZ-2415 developed linewidth vs optical dose for a nominal 1 μm line. The linewidth saturates at approximately 300 mJ/cm^2 , independent of electron dose.

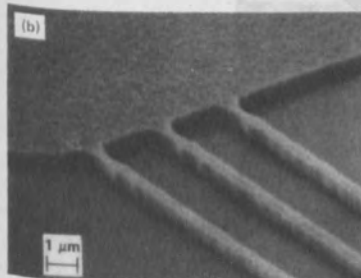
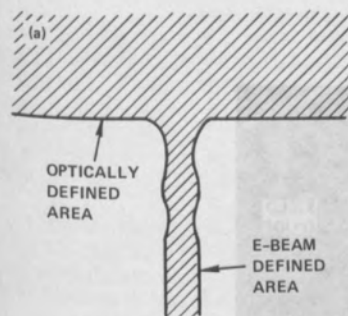


Figure 5(a) Schematic and (b) SEM micrograph of a polysilicon structure patterned using negative-polarity SLML. Diffraction at the photomask edge has caused a variation of linewidth in the e-beam-defined areas.

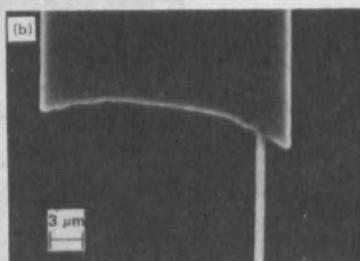
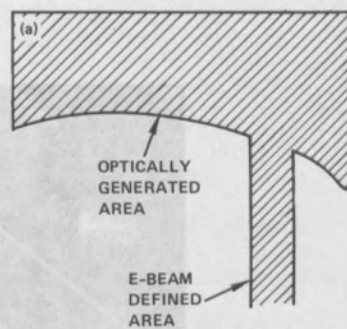


Figure 6(a) Schematic and (b) SEM micrograph of a resist-covered polysilicon structure patterned using negative-polarity SLML. Proper optical exposure has resulted in an e-beam-defined gate which has a constant linewidth as it joins the optically generated pad.

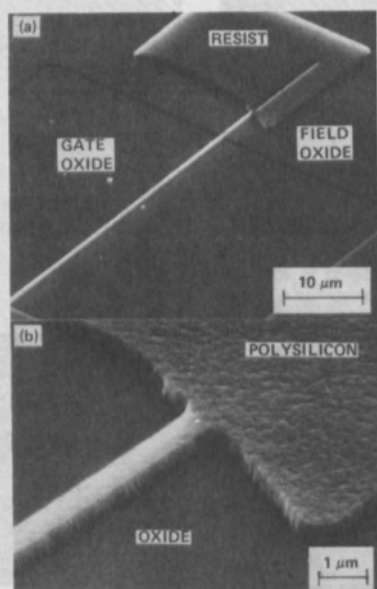


Figure 7(a) SEM micrograph of a plasma-etched polysilicon gate defined by negative-polarity SLML prior to resist removal. (b) An enlargement of the joint area after resist removal.

PROXIMITY EFFECT CORRECTION FOR NEGATIVE
RESIST IN ELECTRON BEAM LITHOGRAPHY
each structure and, accordingly, raised within itself the
the, however, it is not possible to obtain a uniform
beam. However, it is possible to obtain a uniform
exposure by using a proximity effect correction method.
This method is based on the fact that the electron dose
required for a given exposure varies with the area of the
exposed region. The electron dose required for a given
exposure is proportional to the square root of the area of
the exposed region. Therefore, the electron dose required
for a given exposure is proportional to the square root of
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is proportional to the square root of the area of the
exposed region. This method is based on the fact that the
electron dose required for a given exposure is proportional
to the square root of the area of the exposed region.

SECTION FOUR

A new proximity effect correction method for
negative resist has been developed. In this
method, a dose ratio has been introduced into the
control parameter for the negative resist. This
new method is based on the fact that the electron dose
required for a given exposure varies with the area of the
exposed region. The electron dose required for a given
exposure is proportional to the square root of the area of
the exposed region. Therefore, the electron dose required
for a given exposure is proportional to the square root of
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electron dose required for a given exposure is proportional
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1. INTRODUCTION
The proximity effect is a phenomenon which occurs in
electron beam lithography. It is caused by the fact that
the electron dose required for a given exposure varies with
the area of the exposed region. The electron dose required
for a given exposure is proportional to the square root of
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exposed region. This method is based on the fact that the
electron dose required for a given exposure is proportional
to the square root of the area of the exposed region.

Some correction techniques for the proximity effect
have been reported [1, 2]. These techniques are based on
the fact that the electron dose required for a given exposure
is proportional to the square root of the area of the
exposed region. This method is based on the fact that the
electron dose required for a given exposure is proportional
to the square root of the area of the exposed region.

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PROXIMITY EFFECT CORRECTION FOR NEGATIVE
RESIST IN ELECTRON BEAM LITHOGRAPHY

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ABSTRACT

A new proximity effect correction method for negative resist has been developed. In this method, a dose ratio has been introduced as a control parameter for the negative resist thickness after development. By using the dose ratio, both the electron dose and the size of the irradiated shape are easily determined. The dose ratio is Q/Q_0 , where Q is the electron dose which satisfies the desired resist thickness, and Q_0 is the interface gel dose. Applying this correction program to negative resist, a pattern accuracy of $\pm 0.15 \mu\text{m}$ can be achieved when the resist thickness after development is $1.1 \mu\text{m}$.

I. INTRODUCTION

There is a serious problem in electron beam lithography due to the proximity effect at less than about $1 \mu\text{m}$ dimensions. Some correction techniques for the proximity effect have been reported (1), (2). These proximity effect correction techniques can be roughly divided into two categories: one adjusts the exposure dose for each irradiated shape to obtain the desired pattern size of the resist remaining after development and the other adjusts the size of the irradiated shape.

These techniques are usually applied to positive resist, resulting in a highly accurate pattern of less than $1 \mu\text{m}$ using PMMA resist. When applied to negative resist, however, the electron dose required for linewidth cannot produce a uniform resist thickness. That is, the post-development resist of small irradiated shapes is thinner than that of large irradiated shapes. This difference in resist thickness degrades pattern quality

in the dry-etching process which follows the electron beam exposure.

To obtain uniform resist thickness, the exposure dose for each irradiated shape must be adjusted; however, the exposure dose required for uniform resist thickness results in a wider-than-desired linewidth. Therefore, proximity effect correction for negative resist needs both the exposure dose adjustment and the irradiated area adjustment for each irradiated shape.

This paper describes a new and effective correction technique which enables achievement of both a highly accurate pattern size and a uniform resist thickness after development in negative resist.

II. DOSE RATIO PARAMETER

It is necessary to determine the exposure dose and size of the irradiated area for various desired shape dimensions. To accomplish this, we studied the relationship between post-development resist thickness and the size of the irradiated area.

Figure 1 shows contrast curves of a Polydiallylorthophthalate (PDOP) negative resist (3) corresponding to various irradiated shape sizes. This graph shows that each curve has a similar slope regardless of the irradiated area. Therefore, dose ratio $\kappa = Q/Q_0$ was introduced as a new control parameter for negative resist thickness. Where Q is the exposure dose which satisfies a desired resist thickness, and Q_0 is the interface gel dose and is the minimum dose required for any detectable gel formation (4).

Table 1 lists the dose ratio κ 's at normalized thicknesses of 80% and 90% with various irradiated areas. Dose ratios at a given normalized thickness are approximately constant regardless of the size of the irradiated area. For example, using a dose ratio of 2.5, 87-90% normalized thickness over various irradiated areas was obtained. This dose ratio enables determination of both the exposure dose and irradiated area for various dimensions in the correction program.

III. CORRECTION METHOD FOR PROXIMITY EFFECT

Our correction method consists of two phases:

Phase 1

This phase is the correction of the intraproximity effect. The intraproximity effect results in a resist pattern size wider than irradiated size.

Figure 2 shows the relationship between the resist pattern size (the desired size) and the irradiated size. Where S_0 is the difference between the desired area ($2H \times 2W$) and the irradiated area; S_0 is defined as the reduction value. The irradiated area is $(2W-2S_0 \times 2H-2S_0)$. $F(R)$ is the exposure intensity distribution over the irradiated area and is given by

$$F(R) = \int_{-W+S_0}^{W-S_0} \int_{-H+S_0}^{H-S_0} f(r) dx dy \quad (1)$$

Figure 3 shows the relationship between R and r and is expressed by

$$r^2 = (R \cos \theta - x)^2 + (R \sin \theta - y)^2$$

$f(r)$ is the proximity function (5) expressed by

$$f(r) = K \left[\exp(-r^2/\beta_f^2) + \eta \cdot (\beta_f/\beta_b)^2 \cdot \exp(-r^2/\beta_b^2) \right] \quad (2)$$

Q_w is the exposure dose to obtain the desired half linewidth W . Q_0 is the interface gel dose of the irradiated area. The relationship between Q_0 , Q_w and $F(R)$ is given by

$$Q_0 \cdot F(0) = Q_w \cdot F(W) = E_0 \quad (3)$$

where E_0 is the development energy. Equation (3) is rewritten as Equation (4) using the dose ratio κ .

$$F(0)/F(W) = Q_w/Q_0 = \kappa \quad (\text{constant}) \quad (4)$$

The reduction value S_0 is obtained by Equation (4). Then the exposure dose Q_w for the desired resist thickness is calculated by Equation (5).

$$Q_w = E_0 / F(W) \quad (5)$$

Phase 2

The interproximity effect is corrected in this phase. Since the exposure dose and the irradiated area are determined without considering the effect of the exposure

intensity on the adjacent shapes when correcting the intraproximity effect, the irradiated areas are modified to take into account the effect on adjacent shapes.

The exposure dose over the irradiated area modified in phase 2 to obtain the desired thickness is almost equal to the exposure dose determined in phase 1. Therefore, the exposure dose determined in phase 1 is not modified in phase 2. Figure 4 shows the correction method of the interproximity effect. In this figure, Q_i ($i=1,2,3$) is the exposure dose. A, B, C, and D are the sampling points of shape 2. r_{1A} , r_{2A} , and r_{3A} show the distance between sampling point A and the center of each shape. S_{i0} is the reduction value determined in phase 1. S_{2A} is the reduction value at sampling point A determined in phase 2. The energy intensity at sampling point A is given by

$$Q_1 \cdot F_1(r_{1A}) + Q_2 \cdot F_2(r_{2A}) + Q_3 \cdot F_3(r_{3A}) = E_0 \quad (6)$$

$$F_i(r_{iA}) = \int_{-a_i}^{a_i} \int_{-b_i}^{b_i} f(r) \, dx \, dy \quad (i=1,2,3)$$

$$a_i = W_i - S_{i0}, \quad b_i = H_i - S_{i0} \quad (i=1,3)$$

$$a_i = W_i - S_{i0} - S_{iA}/2, \quad b_i = H_i - S_{i0} \quad (i=2)$$

Reduction value S_{2A} is obtained by solving Equation (6). The other three reduction values for shape 2 are similarly calculated. The reduction values for other shapes are calculated in the same way.

An error may be caused because all of the reduction values are determined without using simultaneous equations. Therefore, energy intensity E_j is calculated at every sampling point j ($j=1,2,3,\dots,4N$), where N is the number of shapes. Then the energy intensity error ($=E_0 - E_j$) is estimated. If the errors exceed the allowed limit, their shapes are picked up, and phase 2 is repeated until the errors fall within the allowed limit. The allowed limit is chosen by the desired pattern accuracy.

IV. EXPERIMENTAL RESULTS

This correction program was applied to delineation of 1 μm design rule integrated circuit patterns. Figure 5 shows a cross section of PDOP negative resist after development. The initial resist thickness was 1.2 μm .

In the correction, a dose ratio of 2.5 was chosen to obtain 90% normalized resist thickness. The proximity function's parameters of PDOP resist, β_f , η , and β_b are 0.46 μm , 0.86 and 2.18 μm respectively. The resist thickness after development was about 1.1 μm . A uniform resist thickness was obtained regardless of shape size. A pattern accuracy of $\pm 0.15 \mu\text{m}$ was achieved.

Using a computer that executes 1.5 million instructions per second, our correction program will compensate 10,000 shapes in about 80 seconds.

V. CONCLUSION

We have developed a new proximity effect correction method for negative resist. A new dose ratio was introduced into this method to control resist thickness. Both the electron dose and the irradiated area are easily adjusted by using the dose ratio. The desired thick resist pattern and uniform resist thickness for 1 μm design rule pattern can be obtained by using this correction program.

VI. ACKNOWLEDGMENT

Authors wish to thank Mr. Hajime Ishikawa for helpful discussions.

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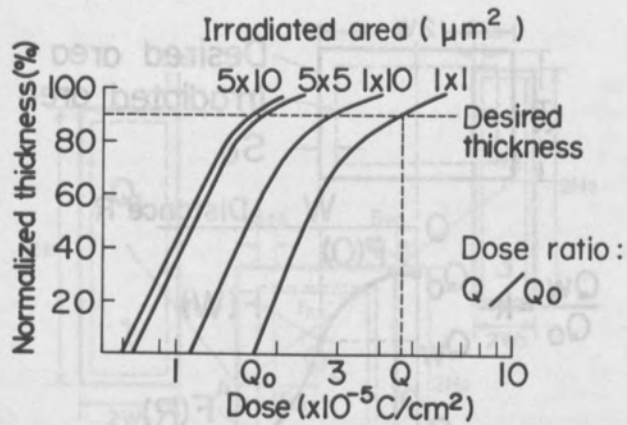


Fig. 1 Contrast curves of PDOP.
Initial resist thickness on Si: 1.2 μm ,
accelerating voltage: 20 KV,
beam current: 2nA.

Table 1 Dose ratios at normalized thickness of
80% and 90% with various irradiated areas.

Irradiated area (μm^2)	Normalized thickness	
	(80%)	(90%)
1 x 1	2.2	2.9
1 x 3	2.3	3.0
1 x 10	2.3	3.0
3 x 3	2.2	2.7
3 x 5	2.2	2.7
3 x 10	2.2	2.6
5 x 5	2.2	2.5
5 x 10	2.1	2.6

Resist: PDOP
Initial thickness: 1.2 μm

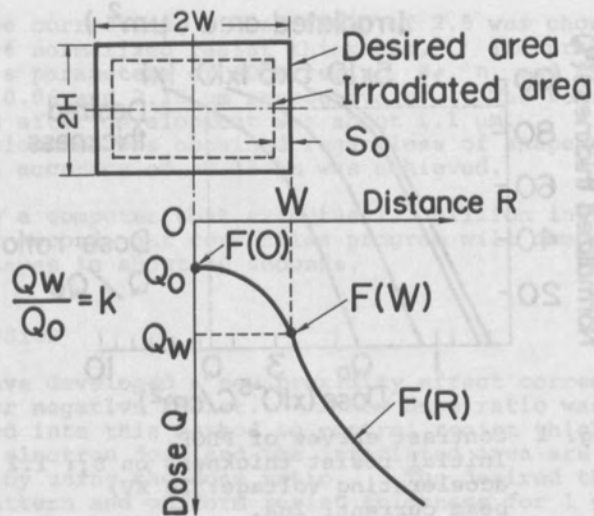


Fig. 2 Exposure intensity distribution of irradiated area.

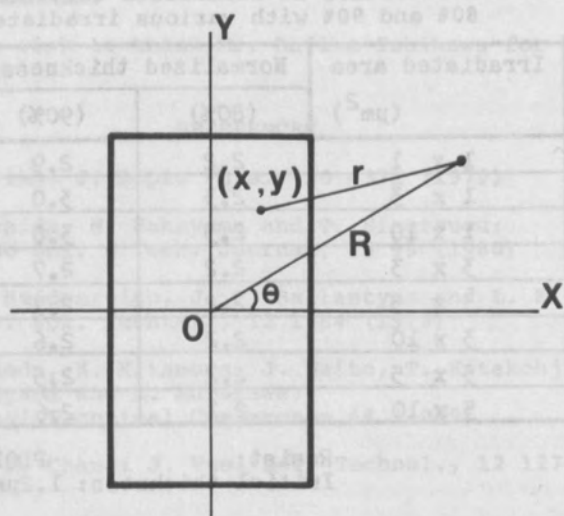


Fig. 3 Relationship between irradiated area and calculated point.

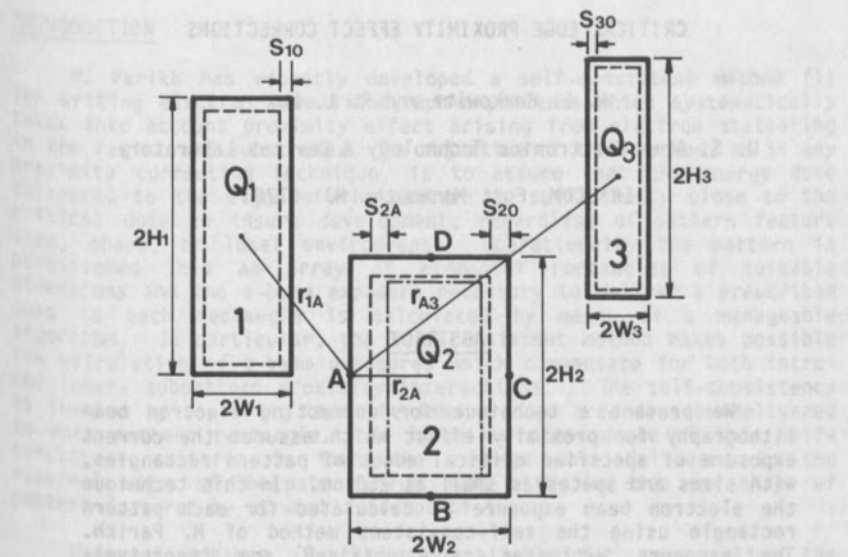


Fig. 4 Correction method of interproximity effect.

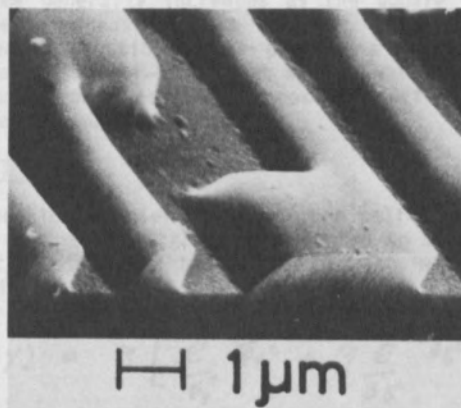


Fig. 5 Cross section of PDOP negative resist pattern.

CRITICAL EDGE PROXIMITY EFFECT CORRECTIONS

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ABSTRACT

We present a technique for correcting electron beam lithography for proximity effect which assures the correct exposure of specified critical edges of pattern rectangles, with sizes and spaces as small as 250 nm. In this technique the electron beam exposure is calculated for each pattern rectangle using the self-consistent method of M. Parikh. The exposure estimates thus obtained are iteratively improved until the dose averaged over each critical edge is equal to a specified critical dose. This is accomplished without repartitioning any pattern features solely for the purposes of proximity effect correction.



Fig. 2. Cross section of PMMA negative resist
exposed by electron beam lithography.
The pattern is a series of rectangles of varying sizes and spacings.

INTRODUCTION

M. Parikh has recently developed a self-consistent method (1) for writing electron beam lithographic patterns which systematically takes into account proximity effect arising from electron scattering in the resist and substrate. The objective of this method, as in any proximity correcting technique, is to assure that the energy dose delivered to the edges of the pattern is sufficiently close to the critical dose to insure development, regardless of pattern feature size, shape, or local environment. Operationally the pattern is partitioned into an array of elemental rectangles of suitable dimensions and the e-beam exposure necessary to deliver a prescribed dose to each rectangle is calculated by means of a manageable algorithm. In particular, the self-consistent method makes possible the calculation of e-beam exposures which compensate for both intra- and inter- subpattern proximity interactions. The self-consistency is invoked by requiring that the same average area dose be delivered to each pattern rectangle. An immediate consequence of this self-consistent criteria is that the average dose delivered to the external edges of the pattern will vary with the size and shape of pattern features by at most a factor of two.

Numerous schemes (2, 3) are available for compensating the mismatch between average dose delivered to the interior of pattern rectangles and exterior critical edges of these rectangles. These schemes all require sleeving, a process which repartitions the original pattern into a larger number of rectangles. Since the calculation time generally increases as the square of the number of rectangles, these methods increase the cost of achieving the desired proximity effect corrections. We present a novel and inexpensive extension of Parikh's self-consistent method which minimizes the need for repartitioning and results in proximity effect corrections for pattern features as small as 250 nm.

SELF-CONSISTENT METHOD

In this section a brief review of the self-consistent method is presented. We assume that the dose delivered to a point (x, y') on a lithographic resist due to a fine e-beam writing at a point (x, y) with unit exposure, is expressible as

$$D(x', y' | x, y) = \kappa \left[\frac{e^{-\frac{r^2}{\rho_f^2}}}{\rho_f^2} + \gamma \frac{e^{-\frac{r^2}{\rho_b^2}}}{\rho_b^2} \right] \quad [1]$$

where $r^2 = (x-x')^2 + (y-y')^2$

In Eq. [1] β_F and β_b are the characteristic widths for the dose distributions associated with forward scattered and back scattered electrons, respectively; n is the ratio of the integrated doses delivered by back scattered and forward scattered electrons. For convenience, k is chosen so that a properly developed, arbitrarily selected reference square, uniformly written with a unit exposure, receives a surface-averaged dose of 1. As a functional definition of the critical dose d_{crit} , we adopt the mean dose received at the periphery of the reference square. We further assume that all the patterns are comprised of rectangles which are aligned with a pair of orthogonal axes. With this limitation all results can be presented in closed form (1).

To carry through with the self-consistent method we calculate the average dose delivered to the i th rectangle, d_i , when each of the pattern rectangles is uniformly written with exposure $E(x,y) = E_j$ within the j th rectangle. Performing the indicated sums and integrals and using Eq. [1], we obtain the equation.

$$d_i S_i = \sum_j A_{ij} E_j \quad [2]$$

where S_i is the area of the i th rectangle, and the matrix element A_{ij} the symmetric double surface integral over the indicated rectangles and is given by

$$A_{ij} = \int dS_i \int dS_j D(x_i, y_i | x_j, y_j) \quad [3]$$

If all of the d_i are fixed, we have a set of linear equations in the required exposures E_j which is easily solved by either Gauss elimination or iterative methods.

In Parikh's scheme all of the d_i are set equal to the same value. Though this scheme gives adequate corrections in many cases, it does not in any way guarantee that the dose received at a particular external edge will be d_{crit} . This is true even for

isolated figures where only intra-figure proximity corrections are necessary. In figure 1 we plot the edge-averaged dose received by an isolated, 20μ m long rectangle as a function of width, when exposed according to the equal average dose criterion. We note that the narrowest rectangles are overexposed by a factor of 1.4. In fact it can be shown that the overexposure approaches a factor of 2 for a square with side much smaller than β_f . Figure 2. shows the self-consistent method recommended exposures as well the exposures required to reduce the edge-averaged dose to d_{crit} .

The values used for the proximity parameters in this and other examples are: $\beta_f = .1\mu$ m, $\beta_b = 3\mu$ m, $\eta = .8$. These values are typical for resists such as $.5\mu$ m thick PMMA with e-beam energy between 20 and 30 kev (4).

CRITICAL EDGE PROXIMITY EFFECT CORRECTIONS

We present a modified self-consistent procedure which guarantees that the edge-averaged dose at specified rectangle edges, called critical edges, will be as close to the critical dose as necessary. In this procedure the pattern to be lithographed is first partitioned into the minimum number of rectangles necessary to reflect local conditions (e.g. see figure 3). Edges whose placement are deemed critical, such as those bordering small gaps, are identified and the rectangles containing them are flagged (shown in figure 3 as dashed lines). Only one critical edge per rectangle is permitted. The pattern is then submitted for standard self-consistent proximity effect correction. The resulting exposures are used to calculate the edge-averaged dose, d^* , for each critical edge using the equation

$$d_i^* = \sum_j B_{ij} E_j \quad [4]$$

where the matrix element B_{ij} is given by

$$B_{ij} = \frac{1}{L_i} \int_{L_i} dl_i dS_j D(x_i, y_i | x_j, y_j) \quad [5]$$

Here, dS_j is a surface element in the j th rectangle and dl_i is a line element in the critical edge associated with the i th rectangle, and L_i is the length of the critical edge. The d_j of [2] are then

are determined by solving the linear system with the modified result vector.

In principle, the method is iterated until the most deviant d_i is sufficiently close to d_{crit} . In practice, we have not encountered a situation in which more than one edge correcting iteration was needed to bring d_i to within a few percent of d_{crit} .

SIMULATIONS

A demonstration proximity effect program has been written which calculates exposures for patterns containing up to 100 rectangles using the edge correcting scheme. In this section we present results calculated for the pattern shown in figure 3. Since the self-consistent technique must be used as a first step, we are able to directly compare results obtained with these two methods. Table 1 contains a complete summary of the data needed to calculate the exposures for the 11 rectangles of figure 3 as well as the exposures and edge averaged doses d^* . In this table all distances are given in μm , the exposures are referenced to that of a $10\mu m$ square (not shown), and the d^* are given in units of d_{crit} for the 6 critical edges declared (C. E. not equal to 0 in table 1). Figure 4a and 4b show the dose profile of an area encompassing rectangle 3 and sections of rectangles 1 and 4 for the self-consistent and edge-corrected methods respectively; the view is from within the 500 nm gap between rectangles 4 and 8. The inevitable rounding of corners is obvious. In figure 4a, the slight increase in dose seen as one passes into rectangle 4 indicates that the gap between rectangles 8 and 9 and rectangle 4 is narrower than it should be (in agreement with the 29% over exposure given in table 1). We note that the dose in rectangle 4 actually falls below that of rectangle 3 in figure 4b. Figures 5a and 5b display the dose profile calculated along a line segment beginning at the upper left corner of rectangle 2 and running down to the lower right corner of rectangle 4 which crosses 4 critical edges in its path. Again the differences between the dose distributions produced by the self-consistent method, figure 5a, and the edge-corrected method, figure 5b, are evident. While dose profiles can be illuminating, the bottom line for lithography is edge placement. Figure 6a and 6b display the location of the critical-dose contour nearest to the line segment atop rectangles 3, and 4 for the two techniques as before. While the overdose is nearly 30% for the self-consistent model (figure 6a), the error in placement is only 40nm. However, two such errors on either side of a 500nm gap results in an error approaching 20% in the gapwidth, more than most error budgets for proximity effect corrections will allow. The improvement

in placement for the edge-corrected critical edge of rectangle 4 is obvious from figure 6b.

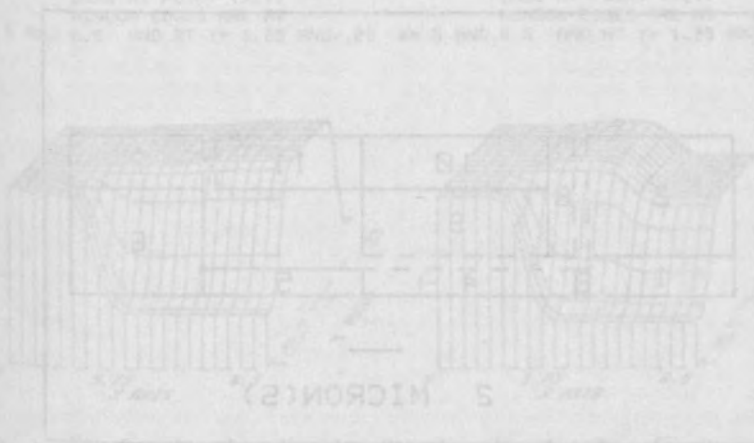
CONCLUSION

We have presented a modification to the self-consistent method for proximity effect corrections. This technique places edges which are designated as "critical" with sufficiently high precision without a need to resort to the fine tuning of rectangle boundaries.

Listings of the demonstration program can be made available by arrangement with the author.

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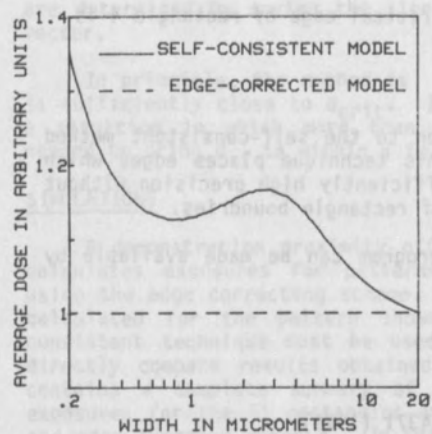


Fig. 1 Dose profiles for isolated rectangles.

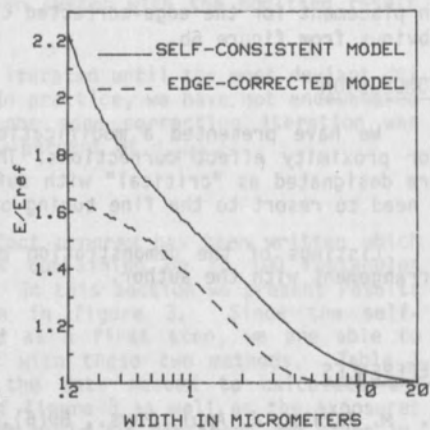


Fig. 2 Exposures calculated for isolated rectangles.

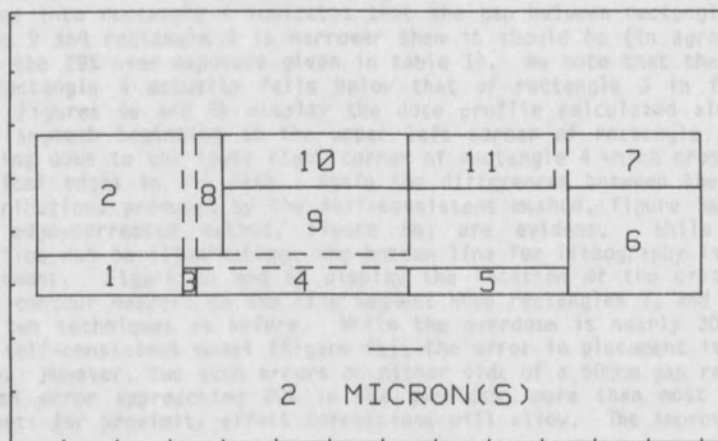


Fig. 3 Test pattern used in simulations.
The numeric labels correlate with "I" in Table 1

TABLE 1
SUMMARY OF DATA FOR PATTERN SHOW IN FIGURE 3

PATTERN DATA						RESULTS			
Bf=.1 Bb=3 Eta=.8						Self-Consistent Model		Edge-Corrected Model	
I	Xlow	Xhigh	Ylow	Yhigh	C.E.	Exp.	d*	Exp.	d*
1	0.00	5.50	0.00	1.50	0	1.13	----	1.20	----
2	0.00	5.50	1.50	6.00	2	1.05	1.30	.79	1.02
3	5.50	6.00	0.00	1.00	0	1.16	----	1.25	----
4	6.00	14.00	0.00	1.00	4	1.21	1.29	.92	1.02
5	14.00	20.00	0.00	1.00	0	1.32	----	1.34	----
6	20.00	25.00	0.00	4.00	0	1.08	----	1.10	----
7	20.00	25.00	4.00	6.00	1	1.13	1.20	.91	1.01
8	6.00	7.00	1.50	6.00	1	1.03	1.28	.77	1.01
9	7.00	14.00	1.50	4.00	3	.98	1.20	.79	.99
10	7.00	14.00	4.00	6.00	0	1.05	----	1.10	----
11	14.00	19.50	4.00	6.00	2	1.18	1.20	.97	1.01

DOSE AT POINT (X,Y) WINDOW EDGES ARE AT X= 5 AND 6.5 AND AT Y= 1.25 AND-.25 DOSE AT POINT (X,Y) WINDOW EDGES ARE AT X= 5 AND 6.5 AND AT Y= 1.25 AND-.25

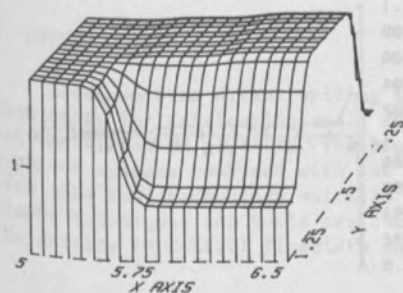


Fig. 4a Dose profile:
Self-consistent method

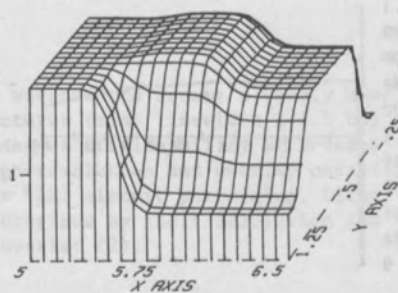


Fig. 4b Dose profile:
Edge corrected method

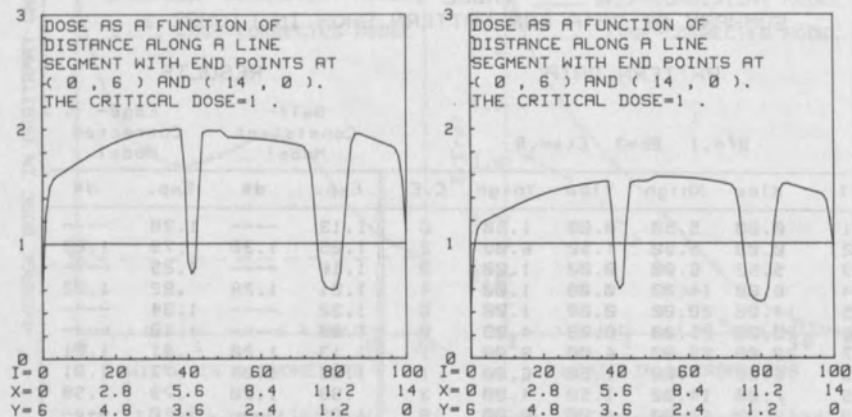


Fig. 5a Dose profile:
self-consistent method.

Fig. 5b Dose profile:
edge corrected method

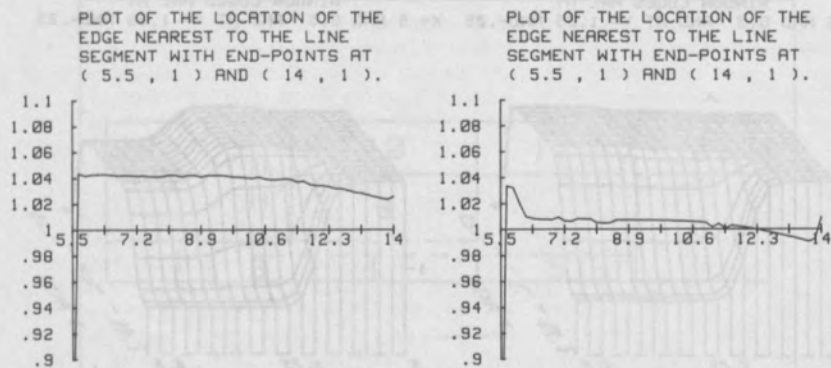


Fig. 6a Critical dose contour -
self consistent method

Fig. 6b Critical dose contour -
edge-corrected method.

SUBSTRATE PROXIMITY CORRECTION IN DIRECT E-BEAM WRITING

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ABSTRACT

The proximity effect which describes the scattering of electrons within the resist and from the substrate is one of the limiting factors in E-beam lithography. The level of backscattering from the substrate is mainly given by the atomic number of the substrate and its thickness. Linewidth and resist-profile variations are caused by different degrees of backscattering from substrates having different atomic numbers. A new approach will be described which dynamically corrects for these variations. While a pattern is being exposed, the backscattered signal is used to control the E-beam stepping rate of a vector-scan E-beam system. This feedback mechanism provides a constant exposure intensity within a shape independent of the difference in backscattering resulting from substrates with different atomic numbers and thicknesses.

Linewidth and resist-profile variations were successfully eliminated in isolated shapes exposed on top of Si, Nb and Pb. The correction technique was implemented in an IBM vector-scan E-beam system.

I. INTRODUCTION

Electron-beam direct writing has advanced to become a widely used technology for fabricating small structures (min. linewidth $\leq 1.5 \mu\text{m}$) at the VLSI level [e.g., (1)]. The high degree of flexibility of E-beam exposure systems combined with the high-resolution and overlay capabilities make this technology suitable for VLSI circuit patterning. Lithography techniques and tools are characterized by their resolution and the ability to control linewidth and overlay (2).

As minimum feature sizes are reduced, the proximity effect due to electron scattering within the resist and from the substrate sets the limits for E-beam lithography. When electrons are scattered outside the shape being exposed, they do not contribute to the dose of this particular shape (intra-shape proximity effect), whereas they may contribute to the dose received by neighboring shapes (inter-shape proximity

effect). The total energy dissipated in the resist by a given dose of primary electrons depends very much on the number of backward-scattered electrons from the substrate into the resist. The number of backscattered electrons increases with increasing atomic number and thickness of the substrate material. This nonuniform exposure and development of patterns results in variations of linewidth and spaces.

Many articles have been published on the subject of proximity effect and approaches to correct it [e.g., (3,4) and their references]. These correction techniques correct for the inter- and intra-shape proximity effects by assuming constant backscattering of electrons from the substrate. In a vector-scan E-beam system, the correction technique adjusts the exposure intensity of each shape/subshape by changing the E-beam stepping rate. The degree of adjustment is determined by numerical algorithms using certain model functions describing the electron scattering (5). The beam-stepping rate is then an integral part of the pattern data used in a computer-controlled vector-scan system.

II. LINEWIDTH VARIATIONS DUE TO DIFFERENT SUBSTRATE MATERIALS

The number of backscattered electrons into the resist is a function of the atomic number and thickness of the substrate, the beam accelerating voltage, and the resist thickness. Therefore, the above assumption is only valid if the spread of the atomic numbers of the materials used to fabricate the circuits is small. For instance, in Josephson technology, where materials with low (Si = 14), medium (Nb = 41) and high (Pb = 82) atomic numbers are used, the assumption of constant backscattering is certainly no longer valid. The influence on linewidth variations in direct E-beam writing due to substrate materials with different atomic numbers is shown in Fig. 1. It shows two-junction interferometers made in Josephson technology (6). The circuits consist of nine levels all exposed by direct E-beam writing. The materials used to pattern the levels were Si, SiO, Nb, and Pb-alloys. All levels were patterned by the lift-off technique, except the two Nb-levels, which were plasma etched. A single layer of PMMA ($\leq 1.5 \mu\text{m}$) was used as resist. The control lines (Pb-alloy) were exposed as the last level on top of a structure made of SiO, Nb, and Pb-alloys. The widths and the gaps of the control lines were designed as $2.5 \mu\text{m}$. The SEM photographs clearly show that the linewidths/gaps vary when the atomic number of the material underneath changes. The control lines become much broader on Pb-alloys (up to 30 percent) than on SiO/Nb. This is caused by the larger number of backscattered electrons on higher atomic-number materials like Pb (7). The linewidth/gap variations set the limits for the minimum gap distance between shapes.

A demonstration of the increased backscattering from materials with increasing atomic numbers is given in Fig. 2, where the backscattered signal received from a line scan across a Si/Nb/Pb structure is shown. The backscattered electrons were detected by a two-channel scintillator detector.

One approach to reduce/eliminate the influence of backscattered electrons is to use multilayer resist systems (8,9). This technique reduces the amount of backscattered electrons into the thin image-defining top layer by using a thick bottom resist layer. This layer is of low atomic number and low density; therefore, proximity effects are reduced and better linewidth control and resolution are achieved. These improvements are accomplished by a more complicated process required for the multilayer technique compared to single-layer resist.

The following describes a real-time correction technique which corrects linewidth variations within one shape caused by different atomic numbers of the substrate material. The technique has been demonstrated for single-layer resists, but it can also be used for multilayer resists.

III. REAL-TIME CORRECTION TECHNIQUE FOR LINEWIDTH VARIATIONS

The IBM vector-scan system (10) has a two-channel scintillator detector to produce backscattered signals during registration, calibration and focusing procedures. The basic idea of the new correction technique uses the backscattered signal as received from the detectors while the pattern is being exposed to control dynamically the exposure intensity of each shape. Any change in the backscattered signal at a given location will change the exposure intensity at this point by varying the beam-stepping rate proportional to the backscattered signal. Fig. 3 illustrates the basic principle of the real-time correction technique. It is assumed that the rectangle to be exposed is partially on substrate 1 and partially on substrate 2, the atomic numbers of the two substrates being different. While the rectangle is exposed, the backscattered signal adjusts the beam-stepping frequency to F1 in the areas of substrate 1, and to frequency F2 on substrate 2. Whenever the beam is deflected from one substrate material to another, the beam-stepping frequency is immediately adjusted according to the variation of the backscattered signal. Since the backscattered signal controls the beam-stepping rate, the total energy (sum of primary and backscattered) dissipated in the resist is made constant at each point to be addressed by the beam.

Fig. 4 shows the blockdiagram of the correction technique as implemented for the IBM vector-scan system. The beam-stepping controller incorporates a voltage-controlled oscillator (VCO) driven by the backscattered signal which passed a signal conditioner. In order to make the corrections reproducible, an automatic calibration feature for the range and offset of the detectors is incorporated. Before an exposure starts, the beam is deflected over a calibration mark made of two materials having a very low (e.g., Si) and a very high (e.g., Au) atomic number. The range and offset of the detectors are now automatically adjusted for a fixed minimum and maximum level of backscattering. Since the same calibration mark is always used (permanent mark on the wafer holder), the transfer function of the correction loop is made the same for each exposure which guarantees reproducible corrections. The implementation of this correction technique required only a modest amount of additional hardware (beam-stepping controller, range and offset control, and signal conditioner) to the existing IBM vector-scan system.

IV. RESULTS

Fig. 5 shows three cases of two 2.5 μm wide lines exposed and developed into PMMA on top of Si and Pb. The SEM photograph on the left shows the case with no corrections applied. The two lines on top of the 0.35 μm Pb-film are much wider than on top of the bulk Si. The center photograph shows the same patterns on the same substrates corrected according to the technique described here. In this case, a beam-stepping frequency of 1 MHz was used on Si which was automatically adjusted to 1.8 MHz on Pb. Therefore, a ratio of 1.8 for the incident electron exposure (IEE) between Si and Pb was required to fully correct the linewidth variations. The right-hand photograph demonstrates the case of overcorrection, which results in narrower lines on Pb than on Si.

The sensitivity of the IEE ratio is shown in Fig. 6. It demonstrates that an IEE ratio of 1.8 is optimum for a correction between Si (bulk) and a 0.35 μm thick Pb-film. After having determined the IEE ratio for a specific substrate configuration, the system automatically adjusts to the correct IEE ratio for any other substrate-material combinations. Fig. 7 demonstrates the ability of the technique to correct linewidth variations caused by substrate materials with low (Si), medium (Nb), and high (Pb) atomic numbers. Again, an IEE ratio of 1.8 was used for Si/Pb corrections. The photographs show that IEE ratios for Si/Nb and Nb/Pb steps were automatically adjusted to the optimum values for these combinations. They also show that 1 and 2.5 μm wide lines were successfully corrected during the same exposure with the same correction values.

No deficiencies were found in corrected patterns at substrate transitions. Hence, the control mechanism is fast enough at the beam-stepping frequencies used (up to 3 MHz). The use of higher frequencies will be evaluated.

Besides linewidth control, it is also very important that the resist profiles can be maintained on top of different substrate materials. The left-hand photograph of Fig. 8 shows the resist profile in PMMA on Si and Pb with no corrections applied. It illustrates that not only does the linewidth change, but also the resist profiles on Si and Pb are different. This may result in severe process problems if, e.g., lift-off has to be performed with such different resist profiles. The right-hand photograph shows the same shapes exposed on the same substrate but with corrections applied. It demonstrates that the correction technique is also able to maintain a required resist profile on top of different substrates.

V. SUMMARY

A new technique has been demonstrated to correct linewidth and resist-profile variations of isolated shapes caused by different atomic numbers of the substrate materials underneath the shape without deficiencies at substrate transitions. An automatic calibration system to set range and offset of the backscatter detectors to the optimum values for every exposure condition was developed. With this approach, good results for the reproducibility of linewidth corrections under different exposure conditions were achieved.

Presently used proximity-correction techniques for vector-scan E-beam systems can be combined with the substrate-correction method presented here to fully correct for proximity effects and variations in the degree of backscattering from different substrates in direct E-beam writing.

ACKNOWLEDGMENTS

The author would like to thank E. Bretscher for his contributions to the basic concept of the correction technique during the initial phase of the project, and many members of the E-beam and Josephson Groups at the IBM Research Laboratories in Rüschlikon and Yorktown Heights for stimulating discussions, in particular, D. Kern and A. Oosenbrug. Thanks are also due to P. Baechtold, T. Forster, U. Deutsch, H.P. Dietrich and D. Schlump for their technical contributions in building the hardware, and performing the exposures and wafer preparations.

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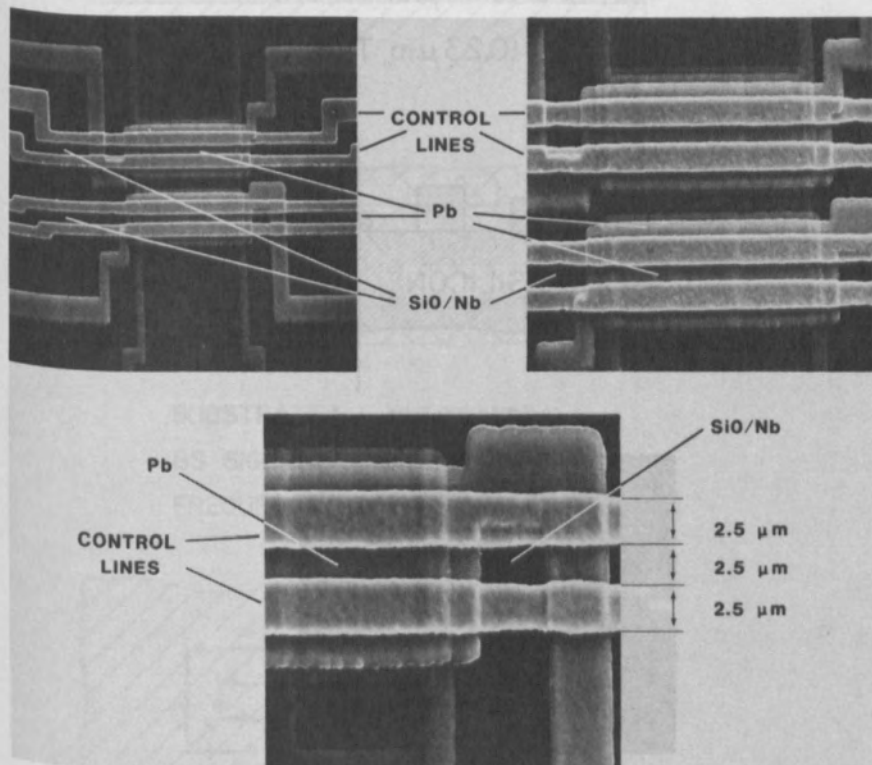


Fig. 1 Asymmetric two-junction Josephson interferometer

-  Pb ($0.55\text{ }\mu\text{m}$ THICK)
-  Pb ($0.35\text{ }\mu\text{m}$ THICK)
-  Nb ($0.23\text{ }\mu\text{m}$ THICK)

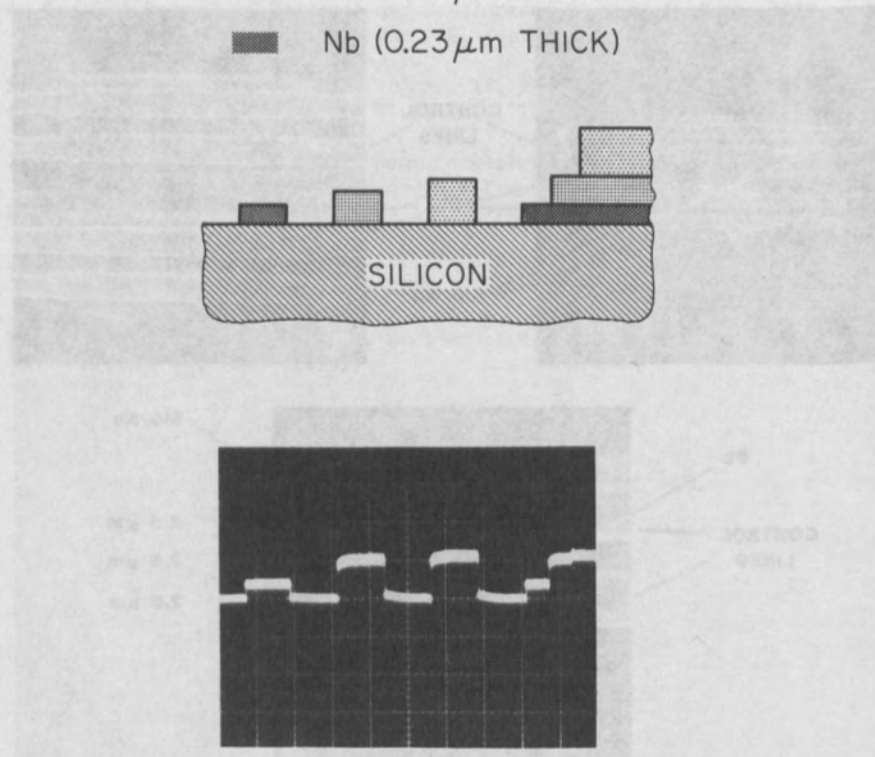


Fig. 2 Backscattered signal from a Si/Nb/Pb structure

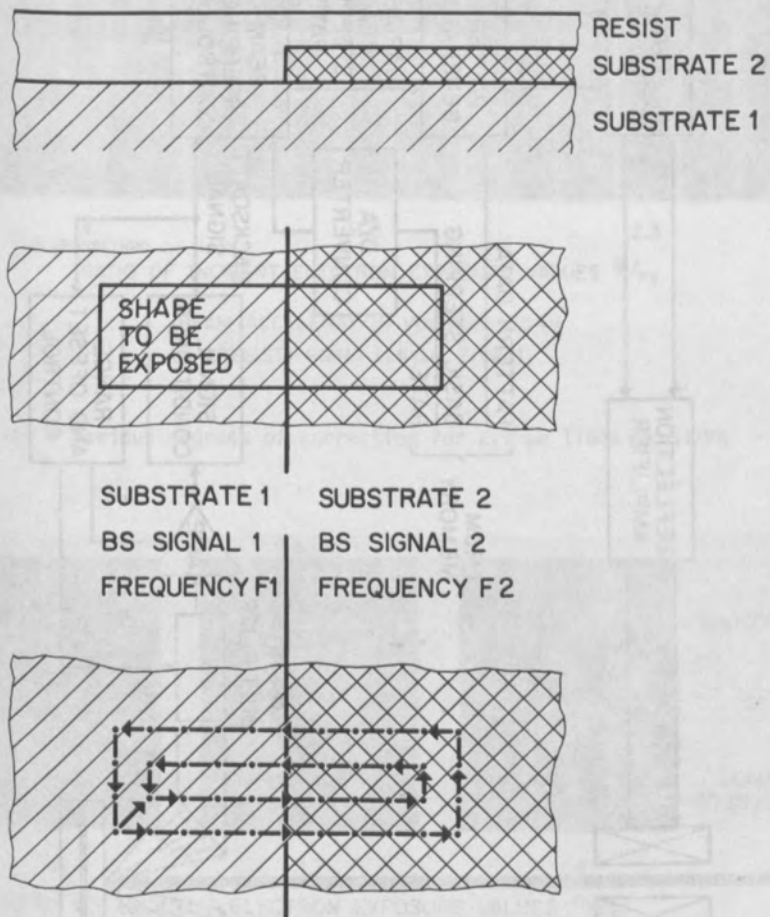


Fig. 3 Basic principle of correction technique

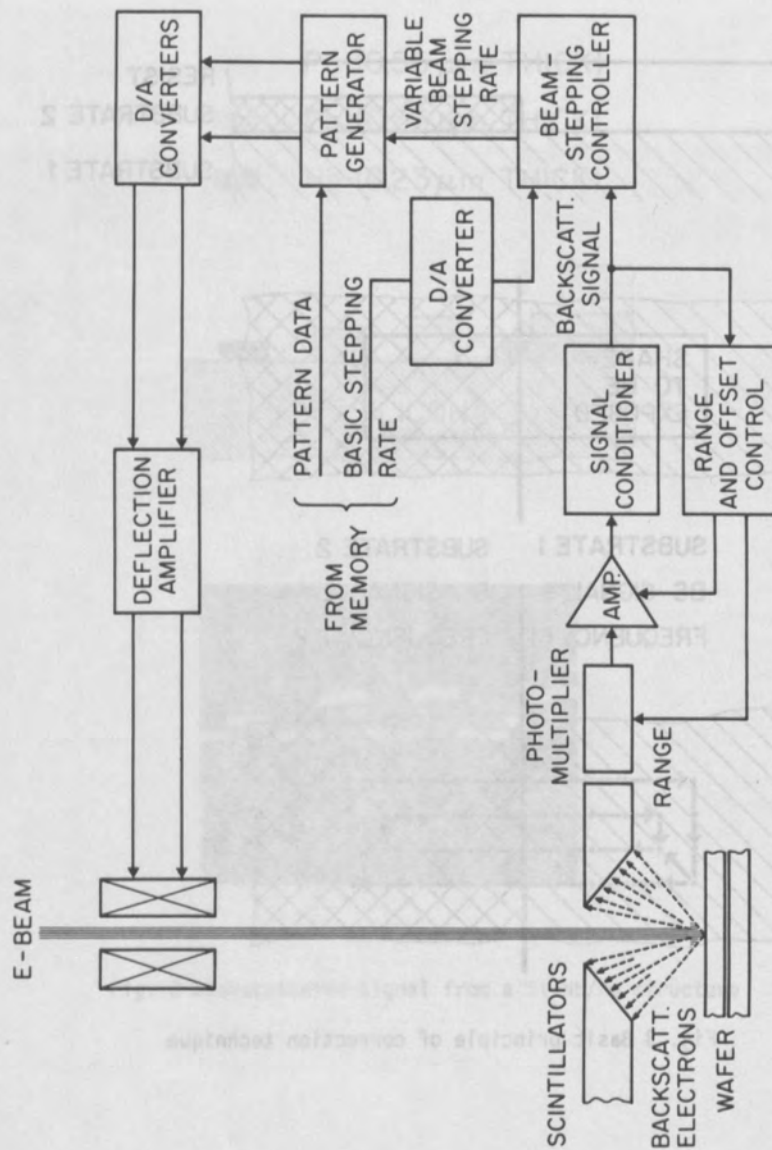


Fig. 4 Correction technique implemented for an IBM vector-scan system

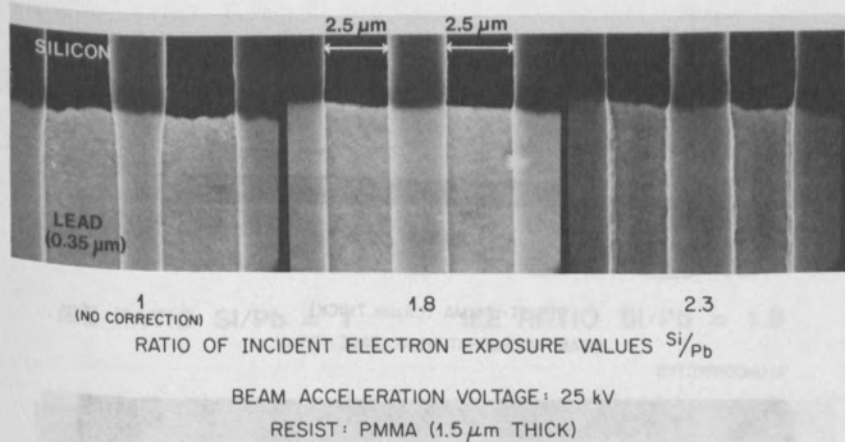


Fig. 5 Various degrees of correction for 2.5 μm lines on Si/Pb

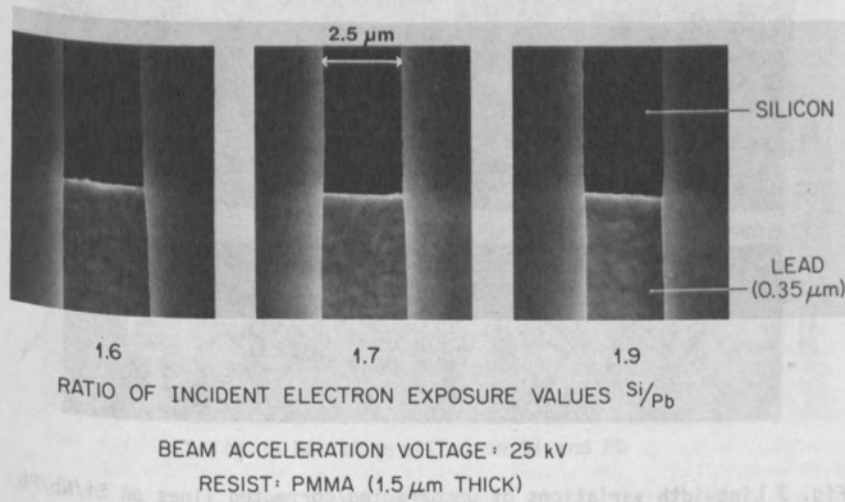


Fig. 6 Correction sensitivity for a 2.5 μm line on Si/Pb

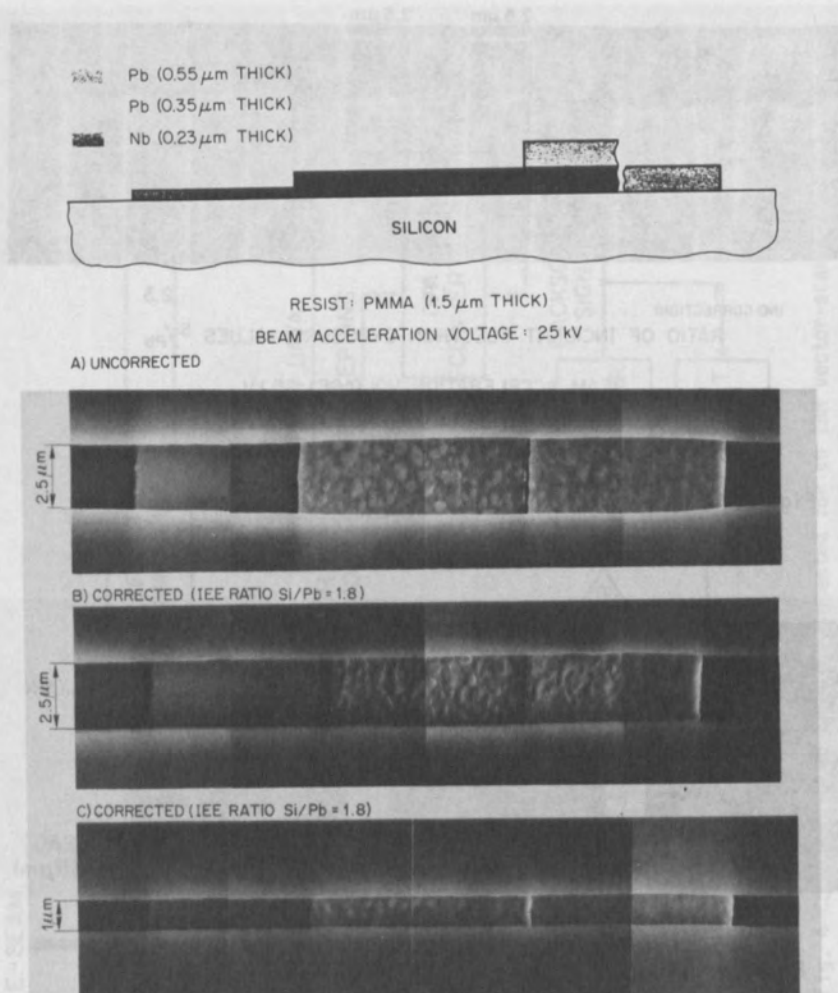


Fig. 7 Linewidth variations of uncorrected/corrected lines on Si/Nb/Pb

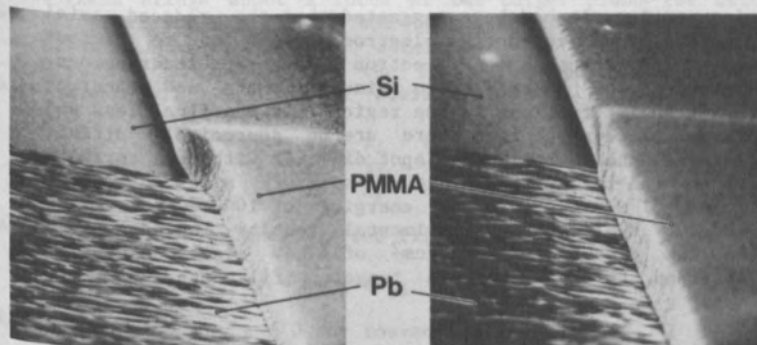
ELECTRON BEAM LITHOGRAPHY IN SINGLE-STEP
 BEAMS OF LOW ENERGY ELECTRON
 [1] and [2] have shown that the electron beam lithography process can be used to fabricate
 structures with high resolution and low cost. The authors of this paper have been working on
 the development of a new electron beam lithography process which is based on the use of
 a low energy electron beam. This process is described in this paper.

UNCORRECTED

CORRECTED

IEE RATIO Si/Pb = 1

IEE RATIO Si/Pb = 1.8



BEAM ACCELERATION VOLTAGE: 25 kV

RESIST: 1.5 μ m PMMA

Fig. 8 Resist profiles on Si and Pb

ELECTRON-ELECTRON INTERACTIONS IN FINELY FOCUSED
BEAMS OF LOW ENERGY ELECTRONS

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Abstract

Although low current beams of low energy electrons can be finely focused through the use of retarding field focusing optics, it had been suggested that the reduced axial spacing of the low energy electrons would lead to serious defocusing because of electron-electron interactions. However, the Monte-Carlo simulation of such electron-electron interactions in the region between final lens and target plane shows that there are no appreciable differences in energy spread and spot diameter with beam currents up to $5 \mu\text{A}$ transported through aperture sizes greater than 0.01 mm in radius at energies of 10 keV , 1 keV and 100 eV . Preliminary experimental results indicate that current density of 250 A/cm^2 of 1 keV electrons can be obtained by using hairpin tungsten filaments.

Introduction

Low energy ($< 5 \text{ keV}$), low current ($<< 1 \mu\text{A}$) electron beams can be finely focused by immersing the target plane in a retarding electrostatic field (Fig. 1) because the spherical and chromatic aberration coefficients C_s and C_c of the total focusing system (i.e. magnetic lens plus retarding field) are greatly reduced (1). At higher currents ($> 1 \mu\text{A}$) as needed in E-beam lithographic systems, the electron-electron interactions can become a limiting factor for the minimum probe diameter obtainable. This is true in conventional higher ($> 10 \text{ keV}$) energy electron-beam systems (2); in retarding field systems where electrons are slowed down in the region between the final lens and the target plane, the electron-electron interactions may set an even lower limit. We report here the results of the Monte-Carlo simulation of electron-electron interactions in conventional and retarding field systems. There appears to be little increased effect, and the experimental results are consistent with the conditions specified.

Monte-Carlo Simulation

A version of the program described by Groves, Hammond and Kuo (3) was modified to account for the retarding field and for image charges induced by the target plane.

A. Initialization

The simulation starts with a sample of 100 electrons distributed within the aperture area at the exit of the final magnetic lens (Fig. 2). Each electron is assigned a set of randomly generated radial coordinates (x_1, y_1) and zero initial energy spread is assumed. All the 100 electrons are directed toward an ideal geometrical point with an energy of 10 keV initially. In the conventional case, this ideal point is at the focus on the target plane; in the retarding field case, this ideal point lies beyond the target plane so that the retarding electrostatic field brings about a focus at the target plane for each beam current, final landing energy and aperture size. Every electron is also given a time t_1 which is determined by the beam current I , i.e. $0 < t_1 < 100 \cdot e/I$. And the final step of the initialization is to advance all the electrons' positions by:

$$\begin{aligned}x_1 &= x_1 + \dot{x}_1 \cdot t_1 \\y_1 &= y_1 + \dot{y}_1 \cdot t_1 \\z_1 &= z_1 + \dot{z}_1 \cdot t_1 + a t_1^2/2\end{aligned}$$

and, their velocities are modified (if necessary) by:

$$z_1 = z_1 + a t_1$$

where

$a = 0$ for conventional case

$a = \frac{e(V_2 - V_1)}{m_e}$ for retarding field case.

V_1 is the initial starting voltage

V_2 is the final target plane voltage

B. Stepping

First of all, the time of flight between the final lens plane and the target plane is divided into 100 steps of equal time T :

$$T = \frac{\ell/100}{\sqrt{\dot{x}_1^2 + \dot{y}_1^2 + \dot{z}_1^2}}$$

where ℓ is the distance between aperture and target and is 1 cm in our model. At each step, the Coulomb force and the Lorentz force between all electron pairs are calculated. Then the positions and the velocities of the electrons are updated accordingly. This process goes on until the last electron has reached the target plane. When an electron arrives at the target plane, its position and velocity are recorded.

From these recorded data, the spot diameter d , energy spread ΔE , and axial defocusing ΔZ (for conventional cases), are calculated. The spot diameter is determined such that 80% of the total current is included. In conventional cases, the minimum spot may occur at a different axial position from the focus because of electron-electron interactions. The program looks for the minimum spot diameter and its corresponding axial position by extrapolating from the positions and velocities recorded at the target plane. The energy spread is the standard deviation from the mean final energy at the target plane for both configurations.

Results (Table I)

A fixed beam current of 5 μA for different aperture sizes in the conventional arrangement was used to simulate different values of space charge parameter σ (4). As the aperture radius is decreased, the interactions become stronger; this is evident from the increase both in the energy spread and spot diameter of the electron beam. Furthermore the axial defocusing, zero at negligible interactions, reaches a maximum and then becomes negative as the electron-electron interactions are increased; this is in agreement with the classical space charge theory (4). Also shown in Table I are the two cases of retarding field configurations with final landing energies of 1 keV and 100 eV respectively. When the aperture radius is 0.1 mm or larger, the energy spread and spot diameter appear to be quite close to their conventional 10 keV counterparts. But for very small apertures, the electron-electron interactions increase considerably.

Table I Values of Energy Spread (ΔE) and Minimum Beam Diameter (d) for the Conventional and Retarding Field Configurations for a beam current of 5 μA :

RAP (cm)	ΔE (eV)	d (μm)	ΔZ (μm)	
3.0×10^{-2}	0.15	0.06	0	} CONVENTIONAL $V_1 = 10 \text{ kV}$ $V_2 = 10 \text{ kV}$
1.0×10^{-2}	0.33	0.20	+6	
3.0×10^{-3}	0.88	0.47	+73	
2.0×10^{-3}	1.20	0.69	+156	
1.0×10^{-3}	1.68	1.19	+568	
7.0×10^{-4}	2.04	1.85	+944	
6.0×10^{-4}	2.16	2.04	+1053	
5.0×10^{-4}	2.30	2.34	+866	
4.6×10^{-4}	2.36	2.46	+480	
4.0×10^{-4}	2.45	2.64	-572	
3.7×10^{-4}	2.51	2.76	-1514	
3.0×10^{-2}	0.15	0.09		} RETARDING FIELD $V_1 = 10 \text{ kV}$ $V_2 = 1 \text{ kV}$ $V_1 = 10 \text{ kV}$ $V_2 = 0.1 \text{ kV}$
1.0×10^{-2}	0.43	0.21		
3.0×10^{-3}	1.04	0.68		
3.0×10^{-2}	0.17	0.13		
1.0×10^{-2}	0.52	0.29		
3.0×10^{-3}	1.18	1.26		

Experimental Measurement

A scanning electron microscope (SEM) was modified to investigate the relation between beam diameter and beam current in conventional and in retarding field configurations. The arrangement is shown in Fig. 3. A flat aluminum slab was used as the target plane with a 1000 mesh/inch Ni grid mounted over the 2 mm diameter hole. Conventionally, the aluminum target is grounded and the cathode is at -10 kV; in retarding field mode, the target is connected to -9 kV. Underneath the mesh grid, a Faraday cup is used to collect the transmitted electrons. As the beam is scanned across the mesh, the signal rise time gives the measurement of the spot diameter and the beam current is measured. Some results are shown in Table II. Because of limitation of the SEM, contributions to the spot diameter arise mainly from the aberrations for large values of RAP and from the Gaussian diameter of the source at small values of RAP.

Table II

APERTURE RADIUS	CURRENT	SPOT DIAMETER	
RAP (cm)	I (μ A)	d (μ m)	
3×10^{-2}	5	2.3	CONVENTIONAL V ₁ =10 kV V ₂ =10 kV
3×10^{-2}	2.5	1.1	
3×10^{-2}	1	1.0	
3×10^{-2}	5	2.6	RETARDING FIELD V ₁ =10 kV V ₂ = 1 kV
3×10^{-2}	2.5	1.2	
3×10^{-2}	1	1.1	

Discussion

Dayan et al. (5) suggested that a sample size of 100 is inadequate for currents above 10 μ A at 20 kV because the sample length becomes as short as the stepping interval. We have restricted the maximum current to 5 μ A to minimize such an error. As a check on the error, three simulations were carried out with 200 electrons, the discrepancy in values of energy spread and spot diameter between 200 and 100 electrons simulation is about 10%. Furthermore, using a different set of randomly generated numbers, the variation in the results is within 5%. Further credibility to the validity of the Monte-Carlo simulation results from the agreement of values of Δz at low values of σ (i.e. serious interactions) with those determined from the classical treatment of the axial defocusing in conventional cases.

It is not immediately obvious why the electron-electron interactions are not more serious in the retarding field case. One possible

explanation is that the retardation is accompanied by an increase in convergence angle, thus reducing the interactive impulses. The experimental results are consistent with the main conclusion that the extra space charge effects in the retarding field region has only minor overall effect as predicted by Monte-Carlo calculation.

Conclusion

1. There is no significant difference in energy spread and spot diameter for the conventional ($V_1=V_2=10$ kV) and retarding field ($V_1=10$ kV, $V_2=1$ kV and 100 V) configurations for currents up to 5 μ A for the geometry shown. Hence the advantages of the previously reported low aberrations of the retarding field configuration are not offset by the electron-electron interactions in the final lens and the target plane region.
2. The Monte-Carlo space charge program predicts axial defocusing of high perveance beams in accordance with classical space charge theory.
3. Experimentally, a current density of 250A/cm² with 1 keV electrons at target plane is obtainable using tungsten hairpin filaments.

Acknowledgment

This work was supported by the Defense Advanced Research Project Agency under Contract No. MDA 903-81-C-0294.

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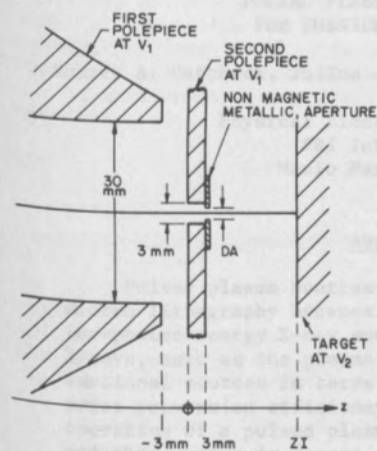


Fig. 1 Final lens region of an electron probe system. In conventional mode, $V_2 = V_1$; and in retarding field mode, $V_2 < V_1$.

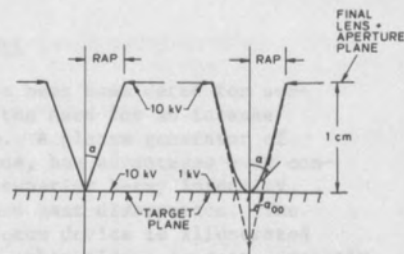


Fig. 2 Conventional and retarding field configurations simulated.

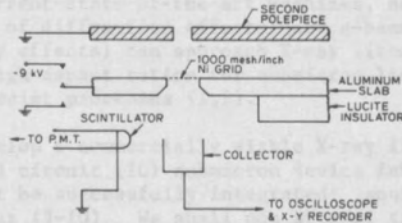


Fig. 3 Experimental arrangement for measuring beam diameter and beam current.

explanation is that the retardation is accompanied by an increase in convergence angle, thus reducing the interactive influence. The experimental results are consistent with the main conclusion that the space charge effects in the retarding field region are the same overall effect as predicted by Monte Carlo simulation.

Conclusion

1. There is no significant difference in the electron beam profile for the conventional ($V_1 = V_2 = 10$ kV) and retarding field ($V_1 = 10$ kV, $V_2 = 1$ kV) configurations for currents up to 1.0 A. The space charge effects in the retarding field region are the same overall effect as predicted by Monte Carlo simulation.
2. The Monte Carlo simulation shows that the space charge effects in the high potential region are in accordance with classical space charge theory.

Experimentally, a current density of 100 A/cm² with 1 kV electrons was obtained in the retarding field region. This is in good agreement with the Monte Carlo simulation results. The space charge effects in the retarding field region are the same overall effect as predicted by Monte Carlo simulation.

This work was supported by Advanced Research Project Agency under Contract No. NDA 503-61-2-0394.

SECTION FIVE

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PULSED PLASMA X-RAY SOURCES
FOR SUBMICRON LITHOGRAPHY

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Abstract

Pulsed plasma sources have been considered for sub-micron lithography because of the need for an intense low-photon-energy X-ray source. A plasma generator of X-rays, such as the plasma focus, has advantages over conventional sources in terms of superior X-ray intensity, power conversion efficiency, and heat dissipation. The operation of a pulsed plasma focus device is illustrated and this system is compared to other plasma sources currently available. A new rapidly pulsing device is described that has a source size less than 1 mm in diameter, an X-ray photon output (varied by choice of gas and electrode composition) that could be varied between 300 eV and 5 keV, and an output of up to 10 J/pulse. With the new sensitive X-ray resists currently being developed, replication of structure sizes down to 0.1 μm is possible in less than a minute.

Introduction

X-ray lithography offers several potential economic and technological advantages over optical, ion, or electron-beam (e-beam) lithography. For current-state-of-the-art machines, neither optical lithography (because of diffraction effects) nor e-beam lithography (because of proximity effects) can approach X-ray lithography's ability to achieve high aspect ratios for submicron line widths in single-level thick-resist processes (1,2).

In order to develop a commercially viable X-ray lithography system for integrated circuit (IC) submicron device fabrication, four equal components must be successfully integrated: source, alignment, mask, and X-ray resist (3-10). We shall not attempt to address the obstacles in implementing a complete system or present the many possible solutions for each component that are now being examined. Instead, our discussions are confined to the X-ray source: whatever the solutions eventually chosen for the other components, the source must be adaptable for use in the final system (11).

In this paper, we first briefly discuss possible X-ray sources, listing those companies or groups involved in the development of each of these types. Then we outline the operation of a typical plasma focus device (PFD), compare the operating parameters of three plasma devices now available, and show the latest exposures made by SRI International's new small-source PFD-II.

X-Ray Sources

Sources of X-rays for X-ray lithography generally fall into one of five categories:

- Electron beam--rotating anode
- Electron beam--stationary anode
- Synchrotron radiation (dedicated storage rings)
- Laser-initiated plasmas
- Electrical discharge plasmas.

Research and development efforts are being made in each of these areas, in actual source development as well as in integration of such sources into systems capable of replicating mask features. X-rays produced in the energy range between 1 and 4 keV are typically of most interest in lithography (12). In the United States, almost all of the R&D is now being funded by industry.

Electron beam--rotating anode systems have been traditionally used in past years, primarily in the area of medical diagnostics, where much higher energy spectra are desired. Recently, however, laboratories and companies have designed systems that can give emissions from the tungsten M lines at $7\text{\AA}$ (Perkin Elmer) (13), the silicon K lines at $7.1\text{\AA}$ (Matsushita Laboratories, NTT) (14-16), and the copper L lines at $13.3\text{\AA}$ (Thomson-CSF) (17). The VLSI Cooperative Laboratories in Japan has developed a six-wafer exposure system (18, 19) using a rotating source. All these systems have been able to increase the power output while retaining source sizes of 1 or 2 mm. Such systems have been used not only in the exposure of wafers (14) but also in the production of working devices (3).

The electron beam--stationary anode systems are based upon a design in which electron beams strike a conical target (such as palladium or another metal) that is cooled by a high velocity fluid. The original work on this type of continuous source began at Lawrence Livermore National Laboratory (20). The first working version was developed at Bell Laboratories (21, 22, 23), and now variations of this type of system are being developed, used, or offered for sale by Kevex (24), Eaton (24), Spire (25), Westinghouse (25), Hewlett Packard, Applied Materials and other companies.

Synchrotron radiation from dedicated storage rings is being examined by various groups as a possible source for X-rays. In the United States, researchers from IBM at Yorktown Heights will use a dedicated line at Brookhaven National Laboratory for a feasibility demonstration (2, 26, 27). A similar dedicated line will be available at BESY in Berlin, while exposures have been made at LURE in Orsay, France (by groups from LEP (28) and from Thomson-CSF) (29), and at DORIS in Hamburg, West Germany (30, 31).

Plasma sources generated by some type of laser-initiated process usable in lithography have been demonstrated or proposed by NRL (32), Avco, Mathematical Sciences Northwest, and other facilities (33, 34). These plasmas, which would use a high-intensity laser to form the plasma, are distinguished from those formed by some type of electrical discharge using a high voltage capacitor discharge. The number of companies and universities investigating this latter method is quite large, and includes U.C. at Irvine (35, 36), Marquette University, Maxwell Laboratories (37), Physics International (38, 39), Hughes Research Laboratories, Western Electric Laboratories (40), Fujitsu Laboratories (41), Hitachi, and SRI International (formerly Stanford Research Institute). The high level of interest indicated by the number of groups pursuing this research demonstrates that this type of pulsed source offers a possible solution to the X-ray lithography source problem.

Although the current direction of development of these sources has been with the goal of IC device fabrication, some of these same sources could be modified for a set of other applications, varying from biological microscopy (42)--such as single-shot still-life imaging of blood platelets using contact microscopy (43, 44)--to organic and crystal diffraction studies (45).

We can list those characteristics we view as necessary for an X-ray lithographic source:

- Sufficient flux, that is, an intensity high enough to produce 40 to 60 exposures per hour.
- Optimal X-ray photon energy, to achieve a high aspect ratio.
- High efficiency, to reduce the input energy requirements.
- Low cost, to make it competitive with the other exposure systems and affordable by smaller companies.
- Physically small system size to occupy the minimum amount of foot space in a clean room environment.
- Ease of replacement or repair.

In light of these requirements, pulsed plasma sources offer several advantages: small physical size, low capital costs, simplicity of operation, and high X-ray flux per pulse.

Plasma Focus Devices

Plasma focus devices have been studied extensively for such applications as fusion neutron production and X-ray generation for weapon simulation or structure studies (46-49). Most of the experience has been with deuterium gas, although X-rays have been produced with several other gases, including argon, krypton, and neon. Through the process of collisional excitation, these ions radiate most of the plasma energy in hydrogen- or helium-like transition lines.

A plasma focus device (PFD) produces a small volume of hot, dense plasma that is formed by pinched compression in a coaxial-electrode, pulsed-discharge device. A number of different electrode geometries can be used to produce the dense plasma (50, 51). The coaxial plasma gun has been most successful in producing intense bursts of X-rays and has received the most attention experimentally in the United States. The X-ray tube consists of two coaxial electrodes, separated at the breech end by an insulator, as shown in Figure 1. The tube is connected by fast-acting switches to a low-inductance, high-voltage capacitor bank. The electrodes are located in a vacuum chamber filled to a pressure of 0.1 to 3 torr. For X-ray production, the capacitors are charged to some operating voltage and the switch is triggered. The gas discharge initiates uniformly throughout the interelectrode region, but quickly becomes a symmetrical current sheet lying near the insulator (Figure 2). An interaction between the current and the induced magnetic field forces the plasma away from the insulator and into the axial direction. The approximate shape of the current sheet at various times is shown in Figure 3.

The moving plasma sheet ionizes the gas it encounters and sweeps it up as it moves along. When the current sheet reaches the end of the anode (interior electrode), it collapses radially to the axis. This results in the formation of a dense, hot, pinched plasma, with a radius of about 0.1 cm and lifetime of about 0.1 μ s. The plasma density and temperature depend strongly upon the initial conditions of electrode geometry, capacitor bank voltage, type of gas, and filling pressure. With the PFD source, the heat released in the focal plasma is either radiated away or transported to a large electrode area. Thus, much higher intensities are attainable than in accelerated e-beam-target sources, where target-cooling problems limit the maximum intensity achievable.

The first models of plasma focus devices, such as the one shown in Figure 4, tended to be modifications of larger machines, which had been previously constructed for very high voltage (>100 kV) or current (>1 MA) studies. With large capacitor banks, power supplies, switches and auxiliary equipment, the system typically filled a large laboratory. Newer systems, optimized for soft X-ray emissions, are now much smaller in physical size, as well as less complex in construction and operation.

Comparison of Plasma Devices

Much of the recent plasma device work has been oriented toward the replication of mask features in highly sensitive resists for lithographic applications. The gases or materials used in these systems usually produce emissions with energies in the range of 1 to 3 keV. Kuyel (40) suggests the use of argon, and Matthews (38) uses krypton. The gas jet system of Maxwell Laboratories (37) also produces 7 Å radiation. Neon produces emissions at 900 to 1000 eV (12 Å).

In calculations involving the use of neon (52, 43), it was found that the maximum line emission occurs at a plasma temperature of about 280 eV. At this temperature, a comparison of the line intensity with the intensity of recombination and bremsstrahlung continuum reveals that these latter two emissions amount to 17 percent of the total power radiated in lines near 1 keV.

The spectral output is characteristic of the gas used, and is usually highly ionized helium- and hydrogen-like transitions. Spectra produced by pulsed plasma sources have been recently shown in the literature for argon, krypton, and neon (37-39).

In a recent article (43), the authors described some single-shot systems (repetition times >2 minutes) that could be considered for use in X-ray microscopy (53). These same systems could serve for X-ray lithography. A comparison was given of the operating characteristics of five pulsed plasma sources, which included SRI's original PFD-I, a sliding spark system (54), a puffed gas (39), a gas jet (37), and an imploding wire system (55).

Recent updated versions of three of these systems have appeared; these versions can be operated at faster repetition rates and have been built specifically for X-ray lithography. In Table 1 we compare the SRI PFD-II system with systems from Physics International (38) and Maxwell Laboratories (37). No comparative data were available at this time for other systems being built for internal use by previously listed companies.

For both PIXI-10 (Physics International) and LEXI-II (Maxwell Laboratories), a puffed gas system is used, and the background pressure must be in the 10^{-5} torr range or better. In contrast, the SRI PFD-II system is a static-fill system that requires only 10^{-3} torr base pressure.

SRI's PFD-II Source

The main advantages of PFD-II are its size and its repetition rate capability. Figure 5 shows a photograph of the system, which comprises a charging capacitor, low inductance switch, and electrode/vacuum assembly. Also shown are various diagnostic detectors and pinhole

TABLE 1
PROJECTED PARAMETERS OF PULSED SOURCES

Parameter	Organization		
	SRI International	Physics International	Maxwell Laboratories
Model	PFD-II	PIXI-10	LEXIS-II
Type	Plasma focus	Gas puff	Gas jet
Energy			
In	1.5 kJ/pulse	5 kJ/pulse	13 kJ/pulse
Out	10 J/pulse (12%) 2 J/pulse (7%)	100 J/pulse (12%) 25 J/pulse (7%)	20 J/pulse (7%) 1 kJ/pulse (>20%)
Pulse length			
X-ray	20 ns	20 ns	20 ns
EUV	--	--	80 ns
Source spot size	1 mm x 5 mm	1 mm x 10 mm	1 mm x 10 mm
Repetition rate	5 Hz	1 Hz	>1/minute
Dimensions	2 ft ² (0.2 m ²)	9 ft ² (1 m ²)	24 ft ² (2.8 m ²)
Reproducibility			
Intensity	±30%	±10%	±20%
Spatial	±0.22 mm	±0.3 mm	±0.2 mm

X-ray cameras. The system has been designed to have a high repetition rate so that the variation in intensity output will be averaged over many shots. A typical exposure would take 30 seconds and thus would require about 150 pulses.

Because of the necessity of minimizing the effective footprint in a Class 100 clean room environment, the lithographic exposure system must be as small as possible, which demands that the source be correspondingly small. In order to take advantage of system hardware already developed, a source that can physically occupy the same space as optical light sources would be advantageous. This is illustrated by the attempts of Westinghouse (25) and Eaton (24) to combine commercially available wafer handlers with a stationary anode source. Eventually, a step and repeat exposure system will by necessity be used for 5-inch wafer production. To increase the throughput, very fast (high-intensity) exposures will have to be made, and a very small plasma source is the obvious solution. This is the major motivation for our reducing the PFD to its present dimensions.

Figures 6 and 7 show a freestanding nickel mask made by Polaron and the replication of this structure by the SRI PFD-II system in an FBM-110 resist-coated silicon wafer. This was accomplished by using 1 keV X-rays with a total incidence energy of 15 mJ/cm² at a repetition rate of 1 pulse per 10 seconds. The nickel mask was held in direct pressure contact with the resist. Exposures have been made both axially and radially. Further exposures will be made using other resists, including FBM-120 (10) and EK-88 (9).

The system to date has been tested only at these lower repetition rates and not at the designed rate stated in Table 1. A rapidly pulsing high-voltage power supply has been designed; when it becomes available, we plan to test the systems capabilities in the full operational mode. This testing will have to be done in conjunction with an industrial concern willing to sponsor the final phase of development of the PFD-II system.

Conclusions

The new PFD-II system recently developed by SRI International is a viable X-ray source that could be incorporated for use in an X-ray lithography system. A comparison with the other currently available sources shows that PFD-II has a smaller clean room footprint and a faster repetition rate. Using 1 keV X-rays, an exposure has been made on FBM-110 resist replicating 3 μ m features to demonstrate feasibility of the system. Further development and support are needed to examine the system's total capabilities.

Acknowledgment

Acknowledgments are given to Clay Shepherd for data acquisition efforts and to Ivor Brodie for fruitful discussions.

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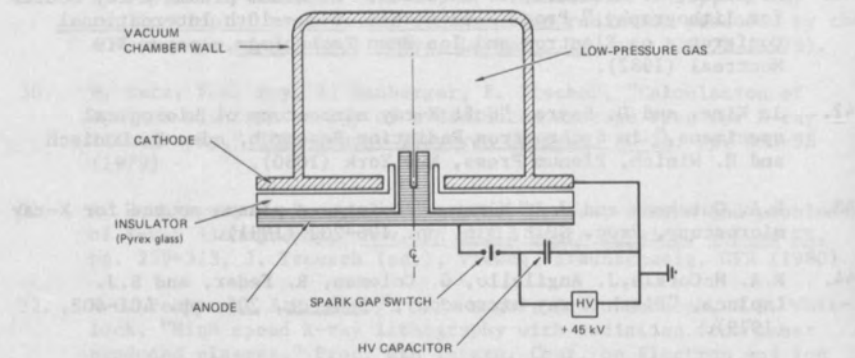


Figure 1. Electrode construction of plasma focus device.

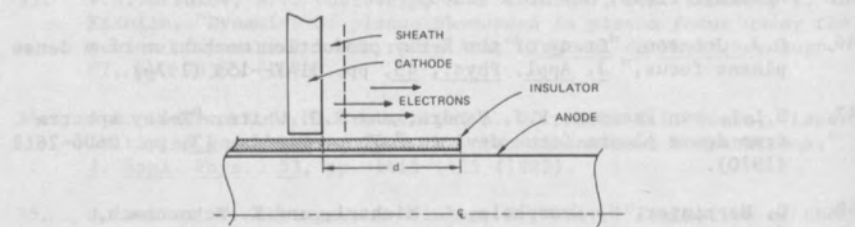


Figure 2. Initial current formation of plasma focus.

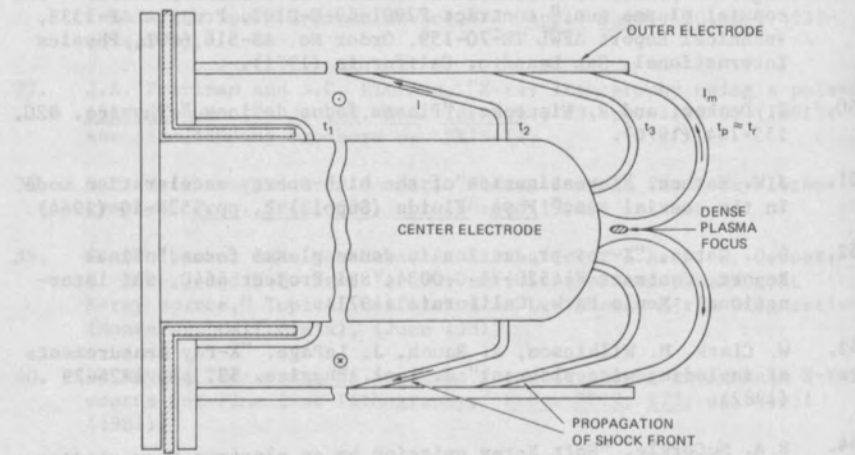


Figure 3. Current sheet propagation in coaxial plasma gun.



Figure 4. Dense plasma focus system (PFD-I) showing right half of capacitor bank, current collector ring, and switch pressurization system (on wall).

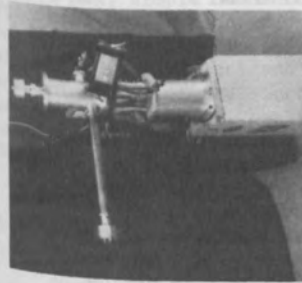


Figure 5. Newer version of plasma focus device, PFD-II, built by SRI under a VHSIC contract (USAF Aeronautical Systems Division F33615-80-C-1194).

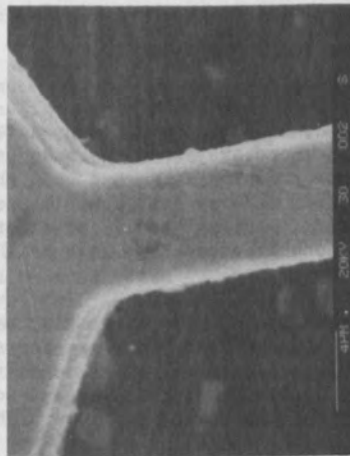


Figure 6. Polaroid nickel mask used in exposure of Figure 7.

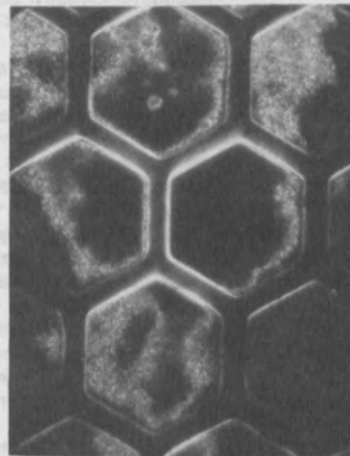


Figure 7. Replicated features of Figure 6 mask in FBM-110 resist-coated silicon wafer. X-rays of 1 keV energy were used; the incidence exposure was 15 mJ/cm².

ALUMINUM PLASMA X-RAY SOURCE FOR LITHOGRAPHY

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ABSTRACT

X-ray lithography has many advantages in submicron pattern replication, but a low-throughput problem must be overcome before it can be used practically. To increase throughput, X-ray sources with improved brightness and diameter performance are expected to be developed. As a high-brightness, small emission volume source, an aluminum plasma X-ray device has been developed. In this device, X-rays are emitted from a current pinched hot and dense aluminum plasma generated by a low inductance vacuum spark with a few kJ capacitor. With the device, a conversion efficiency of 0.2 % from electrical energy to X-rays was obtained in the wavelength range 5 to 10 Å. The brightness is $4 \text{ kW/cm}^2 \text{ sr}$ if X-ray emission rate is 1 Hz. X-ray masks were replicated to evaluate the performance of this aluminum X-ray source. Fine patterns were replicated on a PGMA resist by illuminating the mask with 40 X-ray pulses through a thin polyimide filter.

1. Introduction

X-ray lithography has many advantages in submicron pattern replication. There are, however, some problems to overcome before it can be used practically. One of the principal problems is the low throughput of X-ray lithographic systems. This is mainly because of the poor emitting power of electron beam bombardment X-ray sources conventionally used. Then high-brightness X-ray source is expected to be developed.

Recently, much research has been done on the development of high-brightness X-ray sources, and several devices have been presented as candidates of the X-ray source for lithography. A synchrotron orbital radiation (SOR) X-ray source has ideal characteristics for lithography. However, it has a high capital cost and requires a large installation space. Laser plasma sources are inefficient in converting electrical energy to the laser.

Development of plasma X-ray sources which operate by electrical discharge has begun, and various types of plasma X-ray sources for

lithography have been reported. The sliding spark device(1) for carbon plasma is a relatively long wavelength X-ray source. Gas puff devices(2,3) for Kr or Ne gas plasma are attractive sources for lithography. However, high speed gas control is required for these devices.

A new, simple aluminum plasma X-ray device has been developed. With this device, a high conversion efficiency of 0.2 % (wavelength: 5 to 10 Å) from electrical input to X-rays is obtained. The X-ray emission area is spherical and the diameter is 0.1 mm. For 1 Hz operation, the brightness of the source is 4 kW/cm².sr. To evaluate the performance of the source, replications of X-ray masks were made. Fine patterns were replicated on a PGMA resist by illuminating the mask with 40 X-ray shots through a thin polyimide filter.

2. Requirements for the X-ray source

When an X-ray mask is illuminated with a source of brightness β , the X-ray flux density ϕ is,

$$\phi = \pi\beta\alpha^2 \quad (\text{W/cm}^2) \quad (1)$$

where α is the convergence semi-angle of X-rays as seen from a point on the illuminated surface(4). The value of angle α is determined to be the lesser of those restricted by; (1) pattern edge blur from the penumbra caused by the source size, (2) pattern deviation due to mask-to-wafer distance variation, and (3) allowable minimum distance between the source and the mask as determined by the apparatus configuration and heat shield.

Requirements for the source diameter d and brightness β to replicate submicron patterns are shown in Fig.1. The X-ray flux density on the X-ray mask is assumed to be 40 mW/cm², which is the necessary power density for conventional X-ray resists(sensitivity: 20 mJ/cm²) with exposure of about 1 s through the mask membrane (X-ray transmittance: 50 %). The calculation and other assumptions are described in Appendix A. In order to decrease the possibility of the mask-to-wafer crash, distances S of more than 20 μm are necessary. As can be seen from Fig.1, source diameters d should be less than 1 mm. Necessary brightness β varies directly with $1/d^2$ to give the X-ray flux density. The brightness calculation method is described in Appendix B. As the pattern size is reduced and/or the mask-to-wafer distance increased, X-ray sources of higher-brightness and smaller spot size become necessary.

3. Al plasma X-ray source

To meet these requirements, a low inductance vacuum spark device for aluminum plasma has been developed. A schematic diagram of this

device and a photograph of the apparatus are shown in Figs.2 and 3. The apparatus has a flat or pointed cathode and anode, which are separated by 10 to 20 mm, with a metal cylinder acting as a current return from the cathode to a capacitor. The electrodes are connected to the low inductance capacitor through a coaxial transmission line. The main discharge of a few kJ from the capacitor between the electrodes is induced by a small trigger discharge.

An example of the discharge current waveform monitored with a Rogowski coil(5) is shown in Fig.4. The period of damping oscillation is 7 μ s and the maximum current is about 100 kA. By analyzing the discharge current waveform, total inductance of the system was estimated to be 40 nH.

An X-ray pinhole photograph of the plasma is shown in Fig.5. An X-ray resist PGMA, which is insensitive to visible lights, was used as a recording material. The small sphere of diameter 0.1mm is taken to be a hot, dense plasma pinched by the current. Soft X-rays of wavelength range about 5 to 10 $\text{\AA}$ by line emission and bremsstrahlung are emitted from this plasma. The outer area is a low density plasma region where ultra soft X-rays are emitted.

X-ray power dependence on the anode-cathode gap width was also investigated (see Fig.6). A PMMA resist was used to monitor the X-ray emission power. Within the width $g = 15$ mm (at 10 kV) and 20 mm (17 kV), the power was independent of the width. To prevent unstable low-voltage discharge, the width must be wide. However beyond these plateau regions, power decreased as the gap width was increased. Thus, it was found that there is an optimum anode-cathode gap width for each discharge voltage.

X-ray emission dependence on the total inductance of the system is shown in Fig.7. The inductance is controlled by the length of the transmission line from the capacitor to the X-ray emission diode. As the inductance decreases, X-ray emission increases. Inductance is a parameter for controlling discharge duration. From this tendency, it is assumed that rapid consumption of electrical energy stored in the capacitor is necessary for strong X-ray emission.

Correspondence between X-ray power and current pinch of plasma is shown in Fig.8. The current pinch is always occurred under usual apparatus conditions. However, in this experiment, to make intentionally the occurrence of the pinch unstable, capacitance of the apparatus was lowered. The occurrence of the pinch was judged from the rapid change in the discharge current waveform. In pinched case, high X-ray power was obtained. In unpinched case, however, X-ray power was very low even when the discharge voltage was increased. This shows that the occurrence of pinch is essential for X-ray emission.

The X-ray output power in the wavelength range about 5 to 10 $\text{\AA}$ is estimated to be 4 J/shot by filtering long wavelength X-rays with

thick polyimide films. Since the electrical energy stored in the capacitor is 2 kJ, the X-ray conversion efficiency is 0.2 %.

In this experiment, the period of X-ray emission was a few minutes. This much time was required because of the restricted current capacity of the high-voltage power supply. The X-ray device itself is capable of a much higher pulse rate. A charge/discharge cycle of 1 Hz is not difficult to obtain with commercial high-current H.V. power supplies. If the apparatus is operated at 1 Hz, the time-averaged brightness is $4 \text{ kW/cm}^2 \cdot \text{sr}$ because the source diameter is 0.1 mm. This brightness value is about 10 times higher than that provided by gas type devices.

4. Pattern replication

The aluminum X-ray source has been applied to expose a PGMA resist (sensitivity: 50 mJ/cm^2). A silicon wafer coated with this resist was placed 120 mm from the source. After exposure with X-rays, the resist was developed for 60 s with MIBK.

Exposure characteristics through polyimide filters of various thicknesses are shown in Fig.9. With a $2 \mu\text{m}$ filter, approx. 20 shots were necessary to have 80 % of the resist remaining. The initial thickness of the resist was $0.6 \mu\text{m}$.

To evaluate the performance of the source when applied to fine pattern lithography, X-ray mask replications were made. A polyimide film with thickness of a few μm thick was placed in front of the mask to protect it from the hot plasma and debris. The X-ray mask consisted of a $1 \mu\text{m}$ -thick membrane of polyimide and a $0.3 \mu\text{m}$ -thick Au absorber pattern. This was placed in contact with a silicon wafer coated with $0.6 \mu\text{m}$ -thick PGMA resist.

Replication patterns were obtained with 10 shots exposure. However the dosage was not adequate to make accurate patterns. As the number of shots increased, the patterns became more accurate. An SEM photograph of a bubble memory device pattern replicated with an exposure of 40 shots is shown in Fig.10. As the edge fluctuation of the mask is replicated in detail, it is concluded that high-resolution pattern replication is possible with this X-ray source.

5. Conclusion

The aluminum plasma X-ray device has the following features;

- (1) X-ray conversion efficiency is 0.2 %.

This efficiency is 20 times higher than that provided by conventional X-ray sources. Higher efficiency can be expected by better adjustment of the discharge circuit impedance to

the plasma load and faster consumption of electrical energy stored in the capacitor.

- (2) The source diameter is 0.1 mm.

High-resolution patterns are obtained with this small size source.

- (3) The source brightness is $4 \text{ kW/cm}^2 \cdot \text{sr}$ when the device is operated at a 1 Hz pulse rate.

This brightness is nearly 10 times higher than that provided by gas type devices. Electrical discharge systems which operate at 1 Hz and which store 5 to 10 times more energy than this experimental apparatus are used in gas type devices(2,7). Higher brightness X-ray sources to meet the requirements shown in Fig.1 will be obtained with these high energy discharge systems.

Appendix A

Restrictions on the semi-angles ($\alpha_1, \alpha_2, \alpha_3$) due to pattern edge blur ΔW , positional accuracy ϵ , and the minimum source-to-mask distance L_0 are as follows;

$$k \cdot S \cdot 2\alpha_1 \leq \Delta W \quad (A1)$$

$$\Delta S \cdot A \cdot \alpha_2 / d \leq \epsilon \quad (A2)$$

$$\alpha_3 \leq d / 2L_0 \quad (A3)$$

where k : degree of penumbra influence(6)

ΔS : variation in the mask-to-wafer distance

A : unit exposure area.

In order to use the X-ray flux density efficiently, the following condition must be met;

$$\alpha_1 = \text{Min}(\alpha_2, \alpha_3) \quad (A4)$$

Brightness β is calculated from Eq.(1) for a given size W , distance S , and density ϕ using angle α_1 . The source diameter d is the lesser of the diameters calculated by Eqs. (A2) and (A3). Assumptions for the estimation shown in Fig.1 are as follows;

$$\Delta W / W = 1/4, \quad \epsilon / W = 1/4$$

$$k = 1/2, \quad A = 20 \text{ mm}, \quad S = 1 \mu\text{m}$$

$$L_0 = 100 \text{ mm}$$

Appendix B

For ordinary pulse plasma X-ray sources effective power P is defined as

$$P = Q \cdot f \quad (W) \quad (B1)$$

where $Q(J)$ is the X-ray emission energy per pulse and f (Hz) is the pulse rate.

For spherical sources such as vacuum spark devices, the divergence M of the X-ray flux per unit area is

$$M = \frac{P}{4\pi \cdot (d/2)^2} \quad (W/cm^2) \quad (B2)$$

Then the brightness β of the source is as follows;

$$\begin{aligned} \beta &= M/\pi \\ &= \frac{P}{\pi^2 \cdot d^2} \quad (W/cm^2 \cdot sr) \end{aligned} \quad (B3)$$

When a cylindrical source is seen from its axis, it is regarded as series of spherical sources. If X-ray absorption in the plasma is negligible, the brightness of this source is calculated by Eq. (B3). For disc type sources, such as an EB bombardment X-ray source, the brightness β is

$$\beta = \frac{P_0}{\pi(d/2)^2} \quad (W/cm^2 \cdot sr) \quad (B4)$$

where P_0 (W/sr) is the emission power per unit solid angle. These definitions, including possible values of the brightness, are shown in Table 1.

ACKNOWLEDGEMENT

The authors wish to thank Dr.T.Inagaki for his useful discussions and encouragement.

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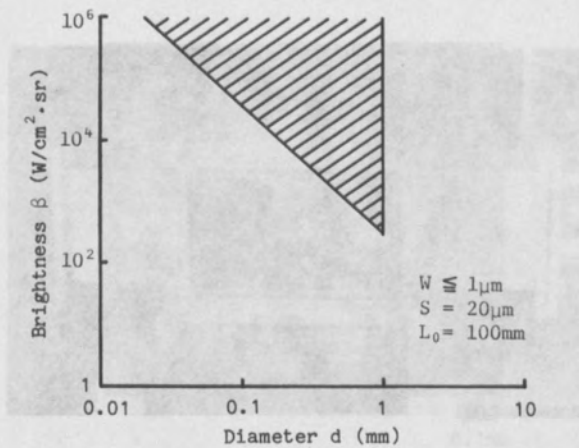


Fig.1 Required brightness and source diameter values to illuminate an X-ray mask with a flux density of 40 mW/cm²

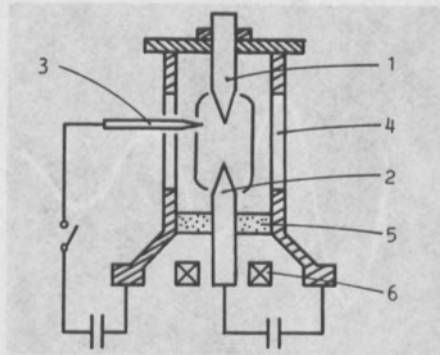


Fig.2 Schematic diagram of the apparatus
 1. Cathode 2. Anode 3. Trigger pin
 4. Window 5. Insulator 6. Rogowski coil

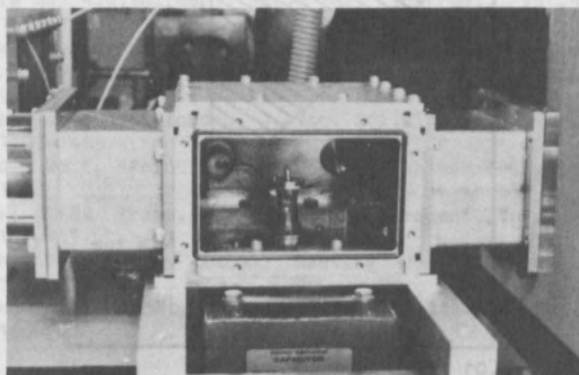


Fig.3 Photograph of an aluminum plasma X-ray source

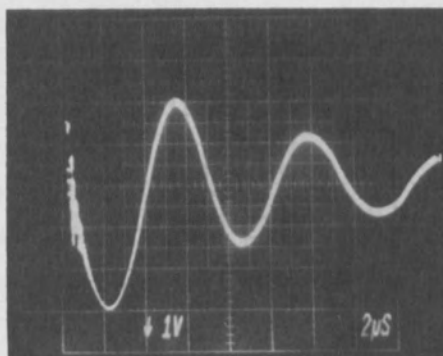


Fig.4 Discharge current characteristics for a 25 μF capacitor at 13 kV
Horizontal : 2 $\mu\text{s}/\text{div.}$ Vertical : 40 kA/div.

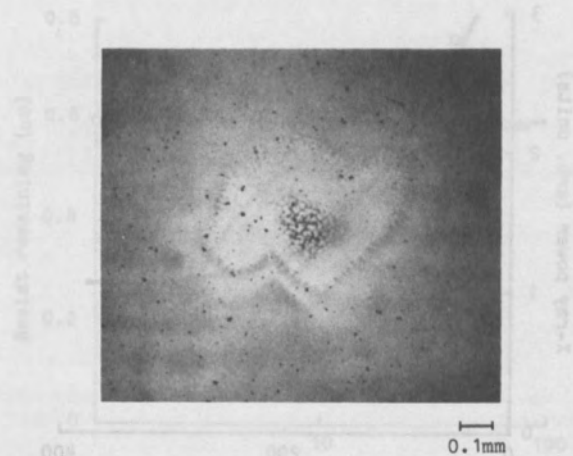


Fig.5 Pinhole photograph of the X-ray emitting plasma

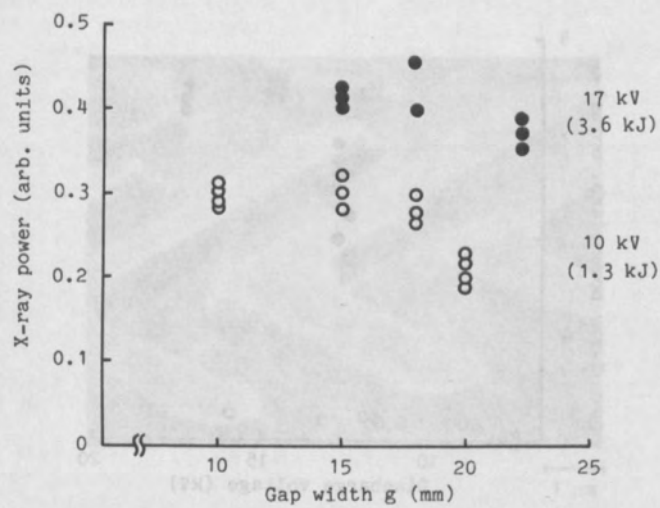


Fig.6 Relative X-ray emission power as a function of anode-cathode gap width

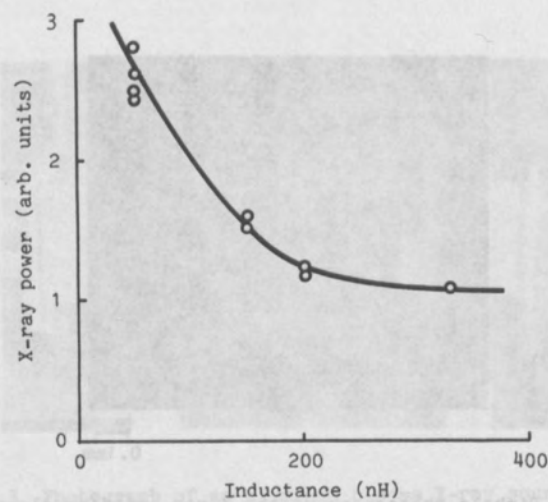


Fig.7 Relative X-ray emission power as a function of the total inductance of the apparatus

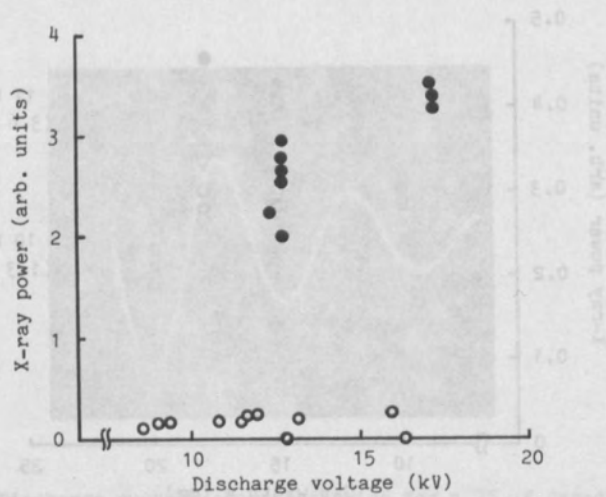


Fig.8 X-ray emission power dependence on current pinch
● : pinched ○ : unpinched

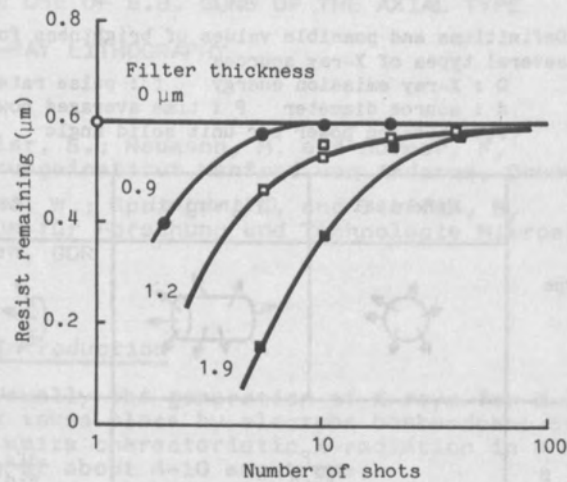


Fig.9 Exposure characteristics of PGMA resist through polyimide filters
Conditions : Exposure distance $L = 120$ mm,
Stored energy $E = 2$ kJ

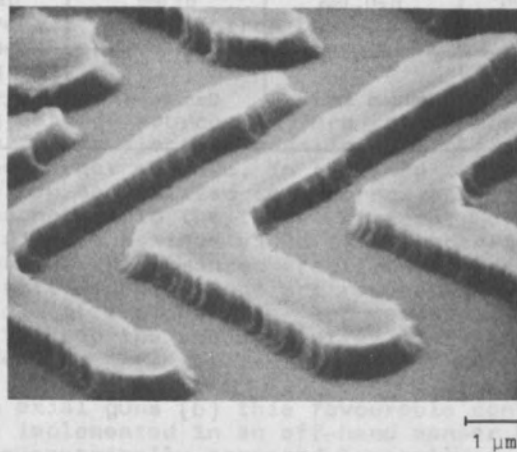
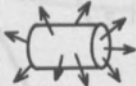


Fig.10 SEM photograph of bubble device pattern replicated on PGMA resist with 40 shots of exposure

Table 1 Definitions and possible values of brightness for several types of X-ray sources

Q : X-ray emission energy f : pulse rate
d : source diameter P : time averaged power
P₀: emission power per unit solid angle

	Spherical	Cylindrical	Disc
Source type			
Brightness β	$\frac{P}{\pi^2 \cdot d^2}$		$\frac{4P_0}{\pi \cdot d^2}$
Possible value of β (W/cm ² ·sr) Assumption	$\beta = 5 \times 10^4$ Q=50J f=1Hz d=0.1mm	$\beta = 500$ Q=50J f=1Hz d=1mm	$\beta = 20$ P ₀ =1.5W/sr d=3mm
Device	Vacuum spark	Gas type	Solid target

ON THE USE OF E.B. GUNS OF THE AXIAL TYPE
FOR X-RAY LITHOGRAPHY

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1. Introduction

Usually the generation of X-rays for X-ray lithography takes place by electron bombardment of a target which emits characteristic X-radiation in a wavelength region of about 4-10 angstroms.

For this wavelength region the preferred target materials are Pd, Rh, W(Tu), Al and Si. As the target must be intensively cooled, water-cooled rotary targets are most frequently used for beam powers above 10 kW and target materials having a rather low melting point; e.g. aluminium and silicon.

Above all, the electron beam is produced either by ring cathode sources or electron beam guns of the axial type (Fig. 1).

Ring cathode sources (A) are rather small, sturdy, and allow for an electron beam injection practically normal to the target surface. In this way the emitted X-radiation can be utilized in a narrow angular range around the normal to the target surface. Such a configuration gives a maximum yield of characteristic X-radiation whilst the unwanted fractions of bremsstrahlung and backscattered electrons are reduced to a minimum. With the aid of a backscatter suppressor it is further possible to keep the residual stray electrons off the exit window.

With axial guns (B) this favourable configuration cannot be implemented in an off-hand manner because they must be asymmetrically arranged laterally from the useful X-ray beam. This reduces the intensity of the characteristic X-radiation and, compared with a ring cathode source, results in a greater fraction of unwanted brems-

strahlung and backscattered electrons. On the other hand, however, axial guns excel in their sturdy and more reliable design, allow an enhanced degree of freedom with respect to beam shaping and guidance and, last but not least, permit the use of higher beam powers at the demanded low acceleration voltages of about 20 kV.

In our attempt to combine the advantages of axial guns and ring cathode sources we used a design (C) in which the beam generated by an axial gun is deflected directly in front of the target surface such that a beam configuration is obtained which well competes with that of a ring cathode source.

2. Description of the X-ray source

Fig. 2 gives a schematic of the X-ray source implemented in the previously described manner which bears the type designation RSQ 20/1.

Used for the purpose was a 20-kW/20-kV axial gun from the type series developed by the Manfred von Ardenne Research Institute which has been modified for application in the field of X-ray lithography. Heated by electron bombardment, its solid cathode of 6 mm diameter allows for a beam current of 1 A at an acceleration voltage of 20 kV. The cathode system is of a modified Pierce geometry. A centring system serves for focal spot alignment on the target. With the aid of a magnetic lens and a stigmator the intensity distribution in the said spot can be changed according to requirements.

The gun and the rotation axis of the target are horizontally arranged. To hit the area of the cylindrical target surface almost perpendicular the electron beam is deflected by about 90° , using a magnetic deflection system for the purpose. This system also guides the backscattered electrons in opposite direction onto a water-cooled collector. Owing to the suitable design of the pole pieces and the additional arrangement of diaphragms below the said deflection system it is ensured that practically all the backscattered electrons are removed from the useful X-ray beam.

The target has a diameter of 300 mm and rotates at a speed of 2,700 rpm. Its cylindrical sheath consists of aluminium and heat dissipation takes place via water cooling.

Arranged below the deflection system is the exit window through which the X-ray beam emerges from the vacuum of the X-ray source into the non-vacuum zone. This window consists of a convex self-supporting beryllium foil being designed to withstand the pressure difference.

The exit window is followed by a pneumatically actuated shutter the casing of which also contains a swivel-type pinhole diaphragm for taking pinhole shots of the focal spot.

We selected the size of the vacuum pumps such that a hydrocarbon-free vacuum is obtained in order to practically avoid the growth of absorbing films of decomposed hydrocarbons on the exit window.

If necessary, the X-ray source can be combined with a customary aligner. For instance, Fig. 3 depicts the combination with a modified aligner of VEB ZFT Mikroelektronik Dresden. In this case the X-ray source is suspended from a separate rack so as to avoid the transmission of vibration to the aligner.

3. Results

The efficiency of X-ray sources is characterized by the X-ray intensity attained at a defined exposure distance and by the size of the focal spot of the beam. The X-ray intensity determines the exposure time and thus the throughput in X-ray lithography whilst a small focal spot is a necessary prerequisite to obtain a high resolution in X-ray lithography.

The concurrent demand for a high X-ray intensity and a small focal spot results in a high power density in the focal spot and thus in a high thermal load of the target material. As a consequence, size and intensity distribution of the focal spot have to be chosen such that an optimized compromise is obtained between beam power and focal spot diameter. Here the great flexibility of the axial gun turned out to be very favourable. Pinhole images were used to investigate and optimize the size and intensity distribution of the focal spot.

Shown in Fig. 4 are pinhole images of the focal spot taken at different excitation and image scales of the magnetic lens. The slightly elliptic shape of the focal spot is due to the deflection aberration of the

magnetic deflection system. A suitably designed beam deflection field allows to keep this effect low so that additional excitation of the stigmator permits the adjustment of an almost circular focal spot on the target.

Clearly evident from the shots arranged side by side is the change in the focal spot caused by altered lens excitation. Apart from the size of the said spot it is especially the intensity distribution in the focal spot which can be influenced in this way. Because of the cathode geometry a poor lens excitation results in a pronounced hollow beam structure which, owing to the high power density at the fringes of the focal spot, causes thermal damage to the target surface even at a total power that is comparatively low. An excessive lens excitation, on the other hand, results in a power density peak in the centre of the focal spot. Located in-between is an optimal lens excitation at which a relatively high focal spot power may be used without causing undue damage to the target surface. In the upper row on Fig. 4 this maximum focal spot power is about 12 kW. The associated size of the focal spot amounts to approximately 3 mm.

A change in focal spot size at optimized lens excitation becomes possible only by altering the image scale. The lower row on Fig. 4 shows focal spot images for which changed pole pieces of the lens system brought about nearly twice the image scale compared with that of the upper row. Referred to optimum lens excitation this results in a maximum focal spot power of about 20 kW with spot diameters of about 6 mm.

Other parameters influencing the intensity distribution in the focal spot have been optimized, too. Special matching of the beam generating system permits to keep the focal spot practically constant over a cathode life of several 100 hours.

In the outcome of the accomplished optimization the rotary aluminium target also showed no significant reduction in X-ray intensity after some 100 operating hours at a focal spot of 20 kW beam power and a diameter of about 6 mm although the target surface exhibited a clearly visible roughness. The X-ray intensity in the region of Al-K radiation was measured with the aid of a proportional counter tube. At a beam power of 20 kW and the use of a 25-um beryllium window this intensity amounted to $5.5 \text{ mJ.cm}^{-2}.\text{min}^{-1}$ when measured at a distance of 500 mm from the focal spot. At a resist sensitivity

of 10 mJ.cm^{-2} and an additional absorption loss between beryllium window and resist of 40 % it is therefore possible to obtain exposure times of about 3 min.

The typical performance parameters of the X-ray source are again compiled in Fig. 5 to give an overall review.

4. Conclusions

It was demonstrated that an electron beam gun of axial type is a useful tool to build up a powerful X-ray source. Magnetic beam deflection permits a convenient source configuration which well competes with that of a ring cathode source. Moreover, with this type of gun it is easy to match spot size and beam power in order to obtain an optimized compromise for X-ray lithography purposes. The overall design of the source with its separate suspension rack allow for an easy arrangement with a customary contact or off-contact aligner.

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Figure 5: Typical images of the X-ray source taken at different magnifications and exposure times.

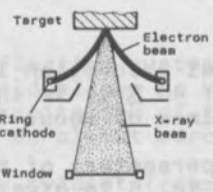
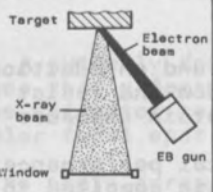
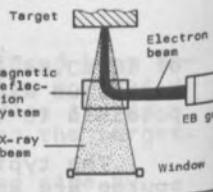
Source configuration	(A) Ring cathode source	(B) Axial gun without beam deflection	(C) Axial gun with beam deflection
Features			
Fraction of characteristic X-radiation in the useful X-ray beam	Maximal	Lower than with (A) and (C)	Maximal
Fraction of bremsstrahlung in the useful X-ray beam	Minimal	Greater than with (A) and (C)	Minimal
Fraction of stray electrons in the useful X-ray beam	Minimal	Greater than with (A) and (C)	Minimal
Attainable beam power	≈ 15 kW	≥ 20 kW	≥ 20 kW
Design	Sophisticated	Sturdy	Sturdy

Figure 1: Comparison of Various X-ray Source Configurations

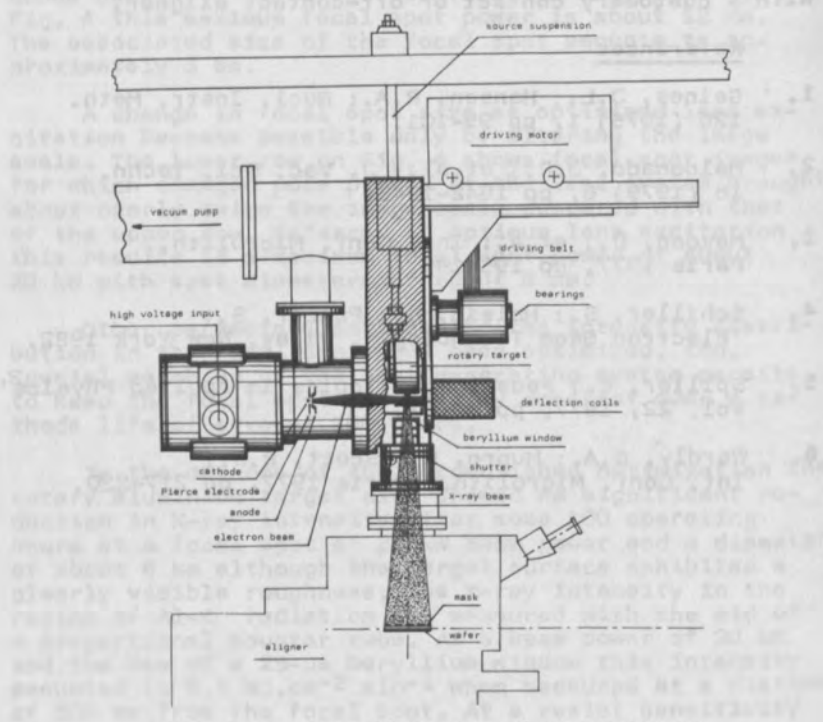


Figure 2: Overall Design of X-ray Source

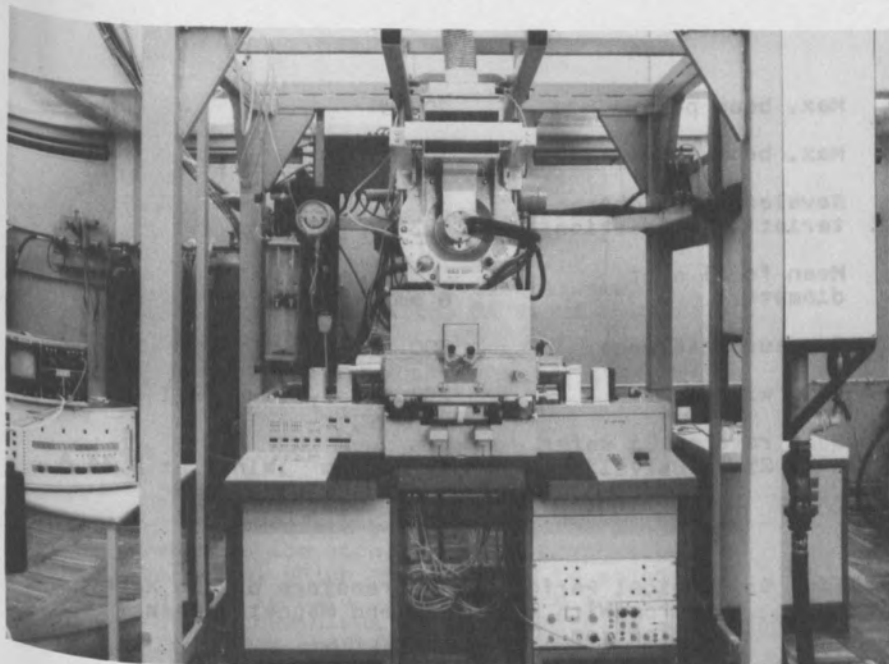


Figure 3: Combination of X-ray Source and Aligner

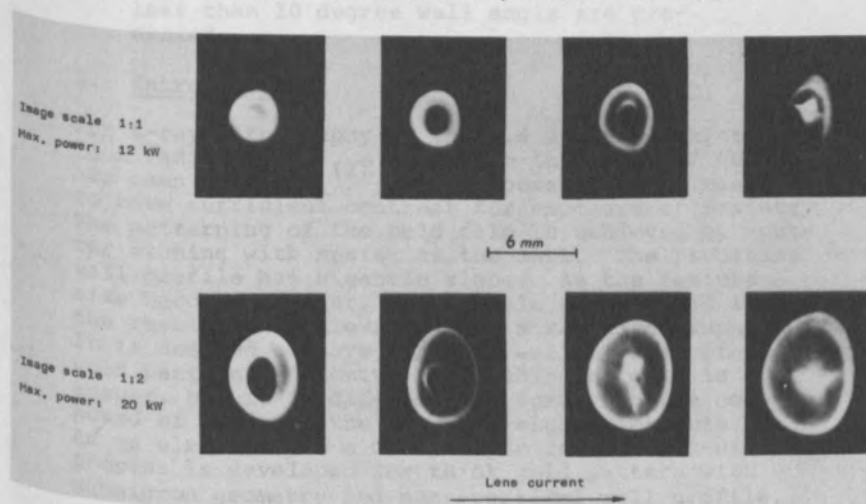


Figure 4: Pinhole Images of the Focal Spots Taken at Different Magnetic Lens Excitations for Two Image Scales

Max. beam power:	20 kW
Max. beam current:	1 A at 20 kV
Wavelength of characteristic X-radiation:	8.34 Å (Al-K)
Mean focal spot diameter:	6 mm at 20 kW
Exposure distance:	500 mm
Exit window:	25-um Beryllium foil
Dose rate on Si wafer with 25 um Beryllium:	5.5 mJ.cm ⁻² .min ⁻¹ at 8.34 Å and 20 kW beam power

Fig. 5: Typical Performance Parameters of the X-ray Source with Axial Gun and Magnetic Beam Deflection



Figure 4: Focal Spot Images of the X-ray Source Taken at Different Magnetic Lens Excitations for Two Image-Scopes

X-RAY MASK METALLIZATION BY MULTILAYER

RESIST LIFT-OFF

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Abstract

A Multilayer resist lift-off process is described in defining thick gold patterns on an x-ray mask. The process includes an intermediate pattern transfer step by reactive ion etching into a composite of polymers, which are selected to stand up to high temperature processing and to tailor themselves by dry etching to a desired edge profile suitable for metal lift-off. Results of submicron gold patterns with 0.8 micron in thickness and less than 10 degree wall angle are presented.

I. Introduction:

For x-ray lithography at the 4.4 Å characteristic Pd L radiation (1), a gold film thickness of 600 nm has been reported (2) as absorbers in x-ray masks to have sufficient contrast for exposure of resists. The patterning of the gold film is achieved by sputter etching with resist as the mask. The resultant wall profile has a gentle slope. As the feature size becomes smaller, this gentle slope would limit the resolution achievable with x-ray lithography. It is desired to have vertical wall profile of the gold pattern. Reactive ion etching of gold is an answer, but it is difficult to form volatile compound of gold for the chemical etching process. As an alternative, a multi-layer resist lift-off process is developed for thick gold pattern with submicron geometry and near-vertical wall profile.

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The desired overhangs ⁽³⁾ of the resist profile for lift-off is achieved by reactive ion etching a composite of polymers. This approach gives better dimensional and profile control than the wet development process ⁽⁴⁾ of a composite of photoresists.

II. Process:

The x-ray mask structures used in the lift-off experiments ⁽⁵⁾ are either boron nitride ⁽²⁾ or silicon carbide ⁽⁵⁾ membranes overcoated with a thin polyimide layer. Fig. 1 shows the x-ray mask metallization process by multi-layer resist lift-off. The process includes reactive ion etching and vacuum evaporation. Both are high temperature steps and the membrane structures lack the required heat-sink during these steps. In order to keep the resist polymer solvent soluble for lift-off, it is necessary to select high temperature polymers. The polymethyl methacrylate (PMMA) has relatively high glass transition temperature, but it suffers from the "necking" effect in the dry etching process. The etched line has a narrow middle section and thus limits the minimum linewidth it can lift off to above 1 micron. The exact mechanism of this phenomenon is not known at present. It might be related to the radiation sensitivity of the PMMA. The reactive ion etching of conventional photoresist baked above 150°C gives almost vertical wall profile. Therefore, it is decided to use a composite of polymers as the lift-off layer. The composite consists of a thin photoresist on top of PMMA. The dry etched profile of the composite has the overhangs with the desired undercut resulted from the "necking" effect of the PMMA layer. Typically, the PMMA thickness ranges from 0.8 to 1.6 μm . After coating, it is baked at 185°C in air for 1 hour. If necessary, it can then be blanket exposed to the deep U.V. light. This would make it easier for lift-off later on. On top of PMMA, a thin photoresist about 400 nm is coated. After baking at 90°C for 30 minutes, it is then blanket exposed to a U.V. light to remove the photosensitizers. Then, a final baking at 185°C is done for 1 hour. The composite serves as the bottom layer in the multi-layer resist approach. Throughout all the baking cycles, caution must be exercised to ramp up and down the oven temperature. The membrane ruptures very easily when there is a sudden temperature change.

The baking time given is the actual time at the desired temperature.

For the multi-layer resist approach, evaporated thin silicon film about 50 nm is used as the intermediate layer (6). The silicon film serves two purposes. In electron-beam lithography for pattern generation, the silicon film is conductive to avoid charging. Together with the thick bottom composite of polymers, the proximity effect can be minimized. The silicon film also serves as the etch mask in O_2 plasma in pattern transfer to the bottom layer, while itself is easily etched in a CF_4 plasma. In Fig. 1, there is an optional silicon film on top of the polyimide layer. It serves as an etch stop in O_2 plasma when etching is through the photoresist and PMMA composite. If it is not there, etching would continue into the polyimide layer. It may be desirable to leave the gold pattern embedded into the polyimide, if the etch depth of the polyimide can be controlled precisely.

The reactive ion etching is performed at 4 μ chamber pressure and a R.F. power density of 0.06 W/cm². The electrode spacing is set at 7.5 cm. The low pressure is necessary to achieve anisotropic etching, while the low power density is necessary to maintain low temperature during etching. For CF_4 plasma, a flow rate of 38 SCCM is used. The silicon etch rate is about 10 nm/min. The selectivity to photoresist is about 1:1. For O_2 plasma, a flow rate of 64 SCCM is used. The etch rates for photoresist and PMMA are about 35 nm/min. and 80 nm/min., respectively. The selectivity of photoresist to silicon is about 20:1. The polyimide has an etch rate of 40 nm/min.

The gold film is put down in a 10KV electron gun deposition system. A thin chromium film about 10 nm is deposited first for better adhesion of the gold film. The membrane mask is placed about 40 cm above the evaporation source. It is sufficiently far in order to have near normal incidence of gold vapor for deposition. The objective is to have near vertical wall profile for the gold pattern. The deposition rate is about 20 nm/min. It is low enough to avoid excessive heating of the membrane. Typically, 0.7 to 1.0 μ m thick

gold film is deposited.

The lift-off is done by soaking the membrane mask in acetone with a very slight agitation to enhance the removal process. Fig. 2 shows the sequence pictures of the process. The pattern optically generated has 1 μm lines and spaces. Fig. 2(a) shows the 2.0 μm thick resist profile with overhangs suitable for lift-off. Fig. 2(b) shows the gold film of 0.85 μm deposited on top of the resist pattern. Fig. 2(c) shows the gold pattern after lift-off.

III. Results:

To demonstrate the submicron capability of the lift-off process, 0.75 μm lines and spaces were optically defined with projection printing. After the pattern is developed, the dry etching process is used to transfer the pattern to the bottom composite of polymers. Fig. 3 shows the cross-sectional views of the etched profile. The total thickness of the composite is 2.0 μm with 0.4 μm photoresist and 1.6 μm PMMA. The top scanning electron micrograph is taken at 85° tilt angle, while the bottom at 90° to show the desired overhang tailored with the composite of photoresist and PMMA. Fig. 4 shows the cross-sectional views of the pattern after gold deposition, but before lift-off for several composite thicknesses. The photoresist in all three cases is fixed at 0.4 μm , while the PMMA varies at 0.8, 1.2 and 1.6 μm for (a), (b) and (c) making a total of 1.2, 1.6 and 2.0 μm , respectively. The gold thickness deposited is about 0.85 μm in all three cases. The top scanning electron micrographs are taken at 85° tilt angle while the bottom at 90°. There is plenty of room for the solvent to get into for the lift-off. Experimentally, the thickest composite shown in Fig. 4(c) was the easiest. The gold line wall profile is almost vertical. The angle is measured at about 10° from the vertical as the best case. The result is very encouraging for x-ray lithography.

For thicker gold film, the fabrication process can be repeated to build up to the desired thickness (7). If optical printing is used to generate the pattern, an absorbing dye (8) should be included in the bottom composite to suppress the reflection from

the first gold pattern. This approach will depend critically on the registration accuracy achievable. While electron-beam exposure generally gives accurate registration, a silicon interlayer is necessary to avoid charging. The present discussion is limited to dry etching into the bottom layer. The deep U.V. exposure to the bottom layer offers an alternative in the multi-layer resist lift-off process.

IV. Conclusion:

A simple lift-off technique is described for metallization on x-ray masks with thin membrane structures. The process is aimed at thick gold pattern with vertical wall profile for x-ray lithography. The technique is applicable to other solid state device fabrication.

ACKNOWLEDGMENT

Betty Belloli, Jim Kruger, Susan Ladd and Howard Nakano are gratefully acknowledged for their contributions.

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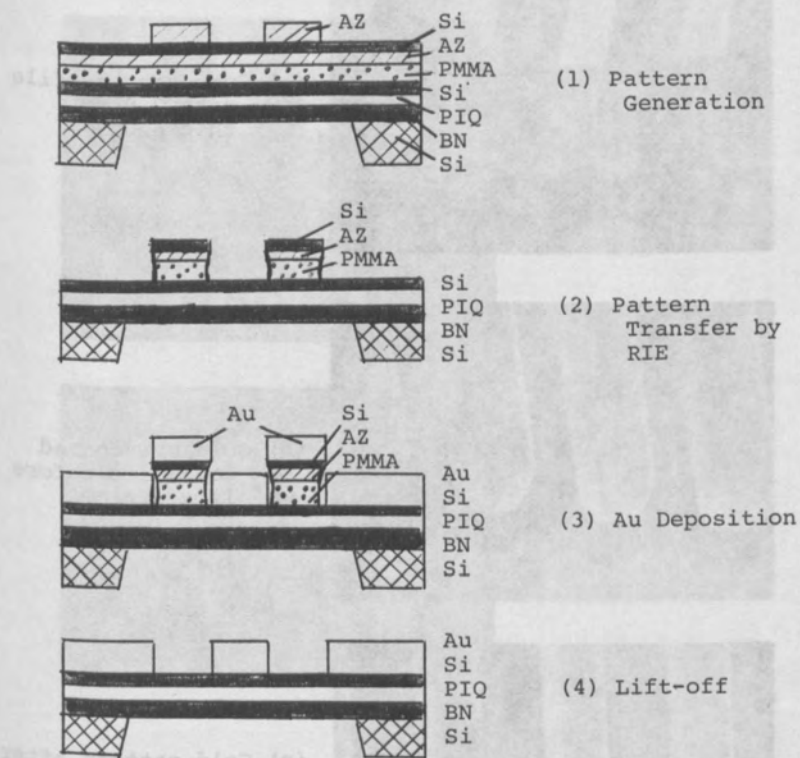
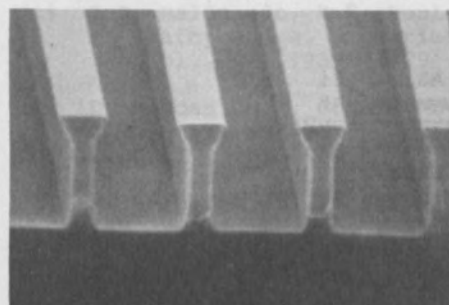
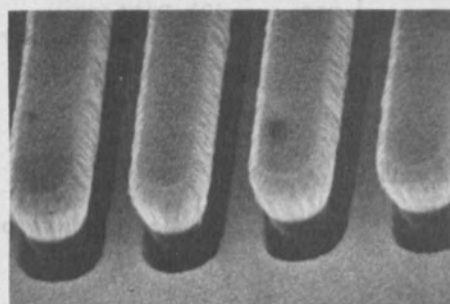


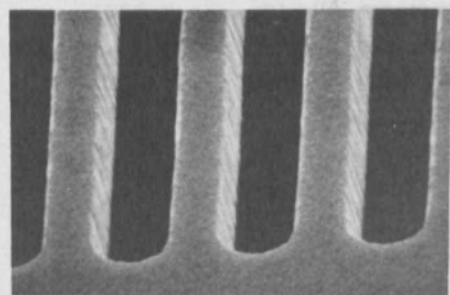
Fig. 1. Multi-layer resist lift-off process for metallization on an x-ray mask.



(a) Composite profile
with $2.0\ \mu\text{m}$
thickness



(b) Gold overcoated
composite before
lift-off

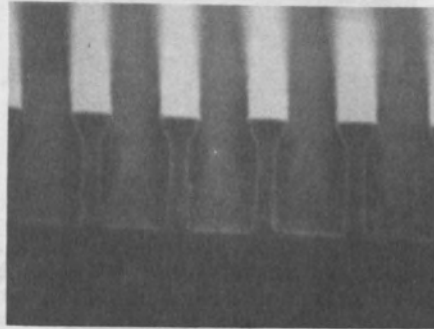


(c) Gold pattern after
lift-off

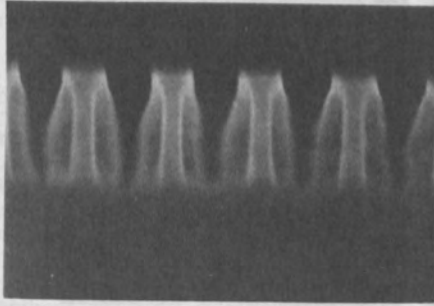
0.5U

Fig. 2. Scanning electron micrographs
showing $1\ \mu\text{m}$ lines and spaces
lift-off process. The gold film
thickness is $0.85\ \mu\text{m}$.

0.20



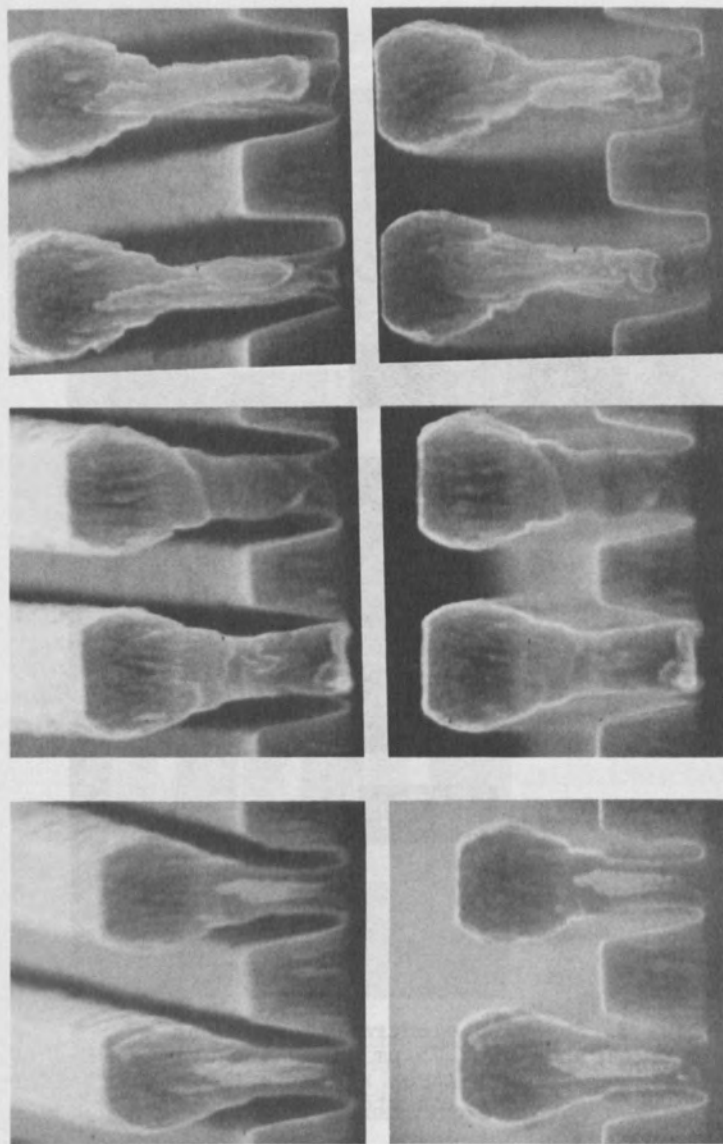
(a) 85° tilt angle



(b) 90° tilt angle

0.50

Fig. 3. Scanning electron micrographs showing 0.75 μm lines and spaces in multi-layer resist after reactive ion etching.



(a) 1.2 μm

(b) 1.6 μm

(c) 2.0 μm

Fig. 4. Scanning electron micrographs showing 0.75 μm lines and spaces with 0.85 μm thick gold deposited.

0.5 μm

X-RAY MASKS WITH HIGH ASPECT RATIO SUBMICRON
PATTERNS FABRICATED BY USING PLASMA-CVD SiN_x
SPACER AND MEMBRANE

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ABSTRACT

A simple method for fabricating x-ray masks with fine ($0.5 \mu\text{m}$ feature) and high aspect ratio (~ 2) Au patterns has been developed; the electron-beam delineated thin resist patterns are directly transferred into the rather thick SiN_x patterns (SiN_x spacer), followed by selective electroplating of Au on a single SiN_x membrane, both SiN_x spacer and membrane being prepared by plasma-enhanced chemical vapor deposition (PCVD). By applying the present method, pattern width controllability and producibility are improved.

Introduction

Preparation of ideal x-ray lithography masks with ease is one of the most significant requirements for establishing x-ray lithography technology. The x-ray lithography mask usually consists of x-ray absorber Au patterns on a transparent membrane, which is stretched over a specifically positioned frame. The Au patterns are fabricated by such a technique as selective electroplating, lift-off or ion-beam etching, using electron-beam delineated resist patterns for plating mask, lift-off base, or for ion-beam etching mask, respectively. In these methods, however, it is difficult to prepare fine and thick Au patterns that are necessary for obtaining enough contrast when exposed to principal characteristic soft x-rays, such as Si K ($7.1 \text{ \AA}$), Al K ($8.3 \text{ \AA}$), W M ($7.0 \text{ \AA}$) and Pd L ($4.4 \text{ \AA}$), because electron scattering occurs seriously in a thick resist. Besides, thick resist gives rise to serious swelling in the developer that limits the resolution, especially in case of negative resist. Thus, in order to obtain x-ray absorber patterns with high resolution, the resist should be as thin as possible. It is also required to establish a pattern transferring technique from thin resist patterns to thick Au patterns. Although a combination of metal lift-off, ion-beam etching (or reactive sputter etching) for the under-lying organic film and selective Au electroplating realize thick Au patterns with high resolution,⁽¹⁾⁽²⁾ the processes are too complicated to prepare the desired Au patterns with ease and with good line width controllability.

In the present experiment, a simple method for preparing fine ($\sim 0.5 \mu\text{m}$) and thick ($\sim 0.9 \mu\text{m}$) Au patterns has been investigated. The most remarkable point of the present method is that a plasma enhanced chemical vapor deposited (PCVD) silicon nitride (SiN_x) film is used for a selective

electroplating mask, which is reactive-sputter-etched using rather thin electron-beam delineated resist for an etching mask. Details of the above mentioned method will be described.

Preparation of the practical transparent membrane supporting x-ray absorber pattern is another point in determining a useful x-ray lithography mask. Si_3N_4 is one of the most attractive materials for the transparent membrane, because of its high transparency to both x-rays (especially Si K and Al K) and visible light, dimensional stability, smooth surface and fabrication ease. Although Si_3N_4 film deposited by pyrolytic CVD is applicable to an x-ray mask substrate⁽³⁾, it is difficult to prepare large windows with sufficient ruggedness because of high residual stress in the Si_3N_4 film. To improve membrane strength, $\text{Si}_3\text{N}_4/\text{SiO}_2/\text{Si}_3\text{N}_4$ sandwich structure⁽⁴⁾ was prepared and was found to have good properties. However, the fabrication process is too complicated for practical use. In this work, PCVD SiN_x film⁽⁵⁾ was applied to the x-ray mask substrate. (Sekimoto et al.⁽⁶⁾ reported that silicon nitride film prepared by low pressure CVD was also successfully applied to the x-ray mask substrate). Details of the PCVD SiN_x membrane mask substrate will be described later in this paper.

Mask Fabrication Steps

The x-ray lithography mask prepared in this experiment consists of 0.9 μm thick Au patterns specifically positioned on a 0.8 μm thick SiN_x membrane, which is stretched over a Si frame. The mask fabrication process is shown in Fig. 1. A Si_3N_4 film of about 0.1 μm thick is grown on a (100) Si wafer by conventional (pyrolytic) CVD. Then, it is selectively dry-etched using a photoresist mask. After resist removal, an about 0.8 μm thick PCVD SiN_x film for the transparent membrane⁽⁵⁾ is deposited on the other side of the Si wafer using reaction gases of 3 % SiH_4 (diluted by 97 % Ar gas), NH_3 and N_2 in the ANELVA PED-302 reactor. Process parameters, such as gas flow ratio, substrate temperature, pressure and rf-power are controlled to exert an appropriate tensile stress⁽⁴⁾ in the SiN_x film, ranging from about 1×10^8 dyn/cm^2 to 5×10^8 dyn/cm^2 , which will result in a flat and rugged membrane. A 50 Å thick Ti and a 200 Å thick Au as an adhesion layer and a plating base, respectively, are subsequently deposited on the SiN_x film. An about 1.2 μm thick SiN_x spacer is then deposited on the Au layer by PCVD under deposition conditions described in the next paragraph. A rather thin electron beam resist (for example, 0.3 μm thick PMMA) is then spin-coated on the SiN_x spacer, and a pattern is defined by using an electron beam lithography system. The exposed PMMA resist was developed with methyl-iso-butyl-keton/iso-propyl-alcohol=1/3 mixture for 100 sec. The SiN_x spacer is anisotropically reactive-sputter-etched with CF_4 gas plasma using the electron beam resist pattern for an etching mask. After stripping the resist in oxygen plasma, about 0.9 μm thick Au is selectively electroplated in the SiN_x opening. The SiN_x spacer and the plating base are etched away by buffed fluoric acid and by Ar ion milling, respectively. Finally, the Si substrate is selectively etched away from the bottom in a boiling 20 wt% KOH solution using the Si_3N_4 etching mask prepared in the first step. A diagram showing the completed SiN_x mask is shown in the last illustration in Fig. 1.

In the present process, including reactive-sputter-etching, sufficiently large SiN_x spacer/resist etch rate ratio is required. From this point of view, the optimum conditions for SiN_x spacer film deposition and reactive-sputter-etching have been investigated.

SiN_x Spacer Deposition

PCVD SiN_x film characteristics change variously, depending on deposition conditions.^{(5)~(8)} In this experiment, SiN_x film characteristics, especially etch rate by fluoric acid, refractive index and film density, were investigated as a function of gas flow ratio, pressure and rf power. SiN_x films were prepared in the ANELVA PED-302 reactor equipped with capacitively coupled parallel electrodes, both 200 mm in diameter. 13.56 MHz rf power was supplied into the upper electrode which is insulated from the grounded reactor chamber. The Si substrate was placed on the other grounded electrode at a point 20 mm away from the upper electrode. Reactant gases, 3 % SiH_4 (diluted by 97 % Ar), NH_3 and N_2 , are lead into the chamber via small through holes dotted all over the top electrode. The SiN_x film density was calculated from the film thickness and the wafer (2-inch diam.) weight increase measured by using ellipsometry and a balance, respectively.

Figure 2 shows refractive index, density and etch rate with 1.5 % HF of the SiN_x film as a function of NH_3/SiH_4 reactant gas flow ratio. Here, both SiH_4 and N_2 flow rates were kept constant. Substrate temperature, rf power and pressure were controlled under the conditions shown in Fig. 2. The refractive index abruptly decreased as NH_3/SiH_4 ratio increased from 1 to about 3. SiN_x films prepared under this condition are considered to be Si-rich. While refractive index was almost fixed at about 1.8 in the NH_3/SiH_4 ratio ranging from 3 to 5, the SiN_x film etch rate with 1.5 % HF increased with increasing NH_3/SiH_4 ratio. In the infrared absorption (IR) spectra measured for SiN_x films, N-H stretching bond absorption peak (3330 cm^{-1}) and Si-H stretching bond absorption peak (2150 cm^{-1}) were observed. The 3330 cm^{-1} absorption peak height for SiN_x film, prepared with $\text{NH}_3/\text{SiH}_4=5$, was twice as high as that for SiN_x prepared with $\text{NH}_3/\text{SiH}_4=1$. On the other hand, Si-H stretching bond absorption peak (2150 cm^{-1}) height was decreased with increasing NH_3/SiH_4 ratio. The above results show that the Si content in the SiN_x , which is deeply concerned with the film etch rate, decreased as NH_3/SiH_4 ratio increased from 1 to 5. Therefore, the NH_3/SiH_4 ratio, as high as 5 is suitable for the SiN_x spacer.

Refractive index, density and etch rate for the SiN_x film with 1.5 % HF is shown in Fig. 3 as a function of the total gas pressure during deposition. The total gas pressure was varied from 0.5 Torr (6.5 Pa) to 1.5 Torr (200 Pa). Both refractive index and density decreased with increasing gas pressure. From the IR spectra measurements, both N-H absorptions (3330 cm^{-1} and 1200 cm^{-1}) and Si-H absorption (2150 cm^{-1}) were found to increase with increase in the total gas pressure. These results indicate that the decrease in the refractive index and density with increasing total gas pressure were partially caused by the increase in the hydrogen content. The SiN_x etch rate by 1.5 % HF abruptly increased with the total pressure that is also, considered to be caused by the hydrogen content increase.

Figure 4 shows refractive index, density and etch rate with 1.5 % HF of the SiN_x film as an rf power function. The other conditions were kept constant, as shown in Fig. 4. In this case, there was no significant change in the IR spectra, nor in the refractive index. On the other hand, the etch rate with 1.5 % HF decreased, and the density increased with increasing rf power. This is considered to be caused by the increasing energy of the incident particles from the rf plasma with increasing rf power, that leads to higher density SiN_x films.

Typical conditions for the SiN_x spacer deposition obtained from the above results are shown in Table 1. In the IR spectrum for the SiN_x film prepared under the above conditions, considerable increases in peak height were observed, due to N-H bond absorption (3330 cm^{-1} , 1200 cm^{-1}) and Si-H bond absorption (2150 cm^{-1}). The SiN_x spacer prepared under the above conditions has fairly different characteristics from those for pyrolytic CVD Si_3N_4 or usual PCVD SiN_x . For example, refractive index (1.72) and density (2.0 g/cm^3) of SiN_x spacer are both much smaller than that of Si_3N_4 . Especially, etch rate with 1.5 % HF (2000 Å/sec) is about 1100 times higher than that of thermal SiO_2 .

Etching SiN_x Spacer

Optimum reactive-sputter-etching conditions for realizing the high aspect ratio SiN_x spacer pattern were investigated. The experiment was carried out using a cathode coupled parallel plate reactor, which consists of a 28 cm diameter polypropylene cathode to which 13.56 MHz rf power was applied. CF_4 was used for etching gas.

In Fig. 5, the reactive-sputter-etch rate for a SiN_x spacer, prepared under the conditions presented in Table 1, as well as those for PMMA (positive resist) and CMS-EX* (negative resist), are shown as a function of CF_4 pressure. Figure 5 also shows SiN_x /PMMA etch rate ratio. Both PMMA and CMS-EX are useful resists for the present process because of their high resolution. In the experimental range, SiN_x /resist etch rate ratio increased with increasing CF_4 pressure. However, in the higher pressure, pattern transferring with high fidelity is difficult because of reduction in anisotropy of etching. Therefore, in the present experiment, CF_4 gas pressure was controlled at 0.1 Torr (13.3 Pa), which was the almost maximum pressure for obtaining vertical walled SiN_x spacer patterns.

Figure 6 shows reactive-sputter-etch rate for SiN_x , PMMA and CMS-EX as a function of CF_4 flow rate. The maximum SiN_x /PMMA etch rate ratio as high as 9 was obtained at CF_4 flow rate of about 35 SCCM.

SiN_x Spacer Method Evaluation

A scanning electron micrograph of a $1\text{ }\mu\text{m}$ thick, $0.5\text{ }\mu\text{m}$ lines and spaces SiN_x spacer pattern is shown in Fig. 7. The SiN_x pattern was fabricated by

* CMS-EX is produced by Toyo Soda Manufacturing Co., Ltd. in Japan

reactive-sputter-etching in CF_4 plasma, using a $0.3\text{ }\mu\text{m}$ thick PMMA pattern for an etching mask. A vertical walled etched profile has been obtained.

Figure 8 shows a scanning electron micrograph of a $0.75\text{ }\mu\text{m}$ thick, $0.44\text{ }\mu\text{m}$ lines and spaces Au pattern which was selectively electroplated in the SiN_x spacer opening. Presenting a precise replica of a SiN_x spacer pattern, a steep profiled Au pattern with high aspect ratio has been obtained.

Figure 9 shows gap/line width ratios in $0.9\text{ }\mu\text{m}$ pitch lines and spaces PMMA resist patterns ($0.3\text{ }\mu\text{m}$ and $0.5\text{ }\mu\text{m}$ thick) as a function of electron beam dose. Gap and line width were measured at both top and bottom of the PMMA lines and spaces patterns from scanning electron micrographs of the pattern cross sections. In Fig. 9, it is shown that the pattern width controllability of electron beam lithography in $0.3\text{ }\mu\text{m}$ thick PMMA resist is better than that in $0.5\text{ }\mu\text{m}$ thick PMMA.

Figure 10 shows the bevel for a Au pattern side wall as a function of electron beam dose to the PMMA resist. The bevel was almost constant, independent with electron dose in the investigated range. Especially, in $0.3\text{ }\mu\text{m}$ thick PMMA, a bevel as steep as 87° has been constantly obtained in the dose range from about $2.8 \times 10^{-4}\text{ C/cm}^2$ to $4.5 \times 10^{-4}\text{ C/cm}^2$. The above result indicates that the electron beam resist profile, which depends on electron beam dose, does not significantly affect the Au pattern profile. The reason for this result is considered to be that the reactive-sputter-etched SiN_x spacer usually does not present the faithful replica of masking resist pattern because of excellent anisotropic etching based on high SiN_x /resist etch rate ratio.

The amount of pattern width change ($\Delta W = W_{\text{Au}} - W_g$) between gap in the PMMA pattern and Au pattern width is shown in Fig. 11 as a function of electron beam dose. Here, both W_{Au} and W_g were measured at the middle height of the $0.9\text{ }\mu\text{m}$ pitch line and space patterns. The W_{Au} was generally larger than the W_g in this experiment. When $0.5\text{ }\mu\text{m}$ thick PMMA was used, ΔW was varied with increasing dose ranging from $1.7 \times 10^{-4}\text{ C/cm}^2$ to $5.2 \times 10^{-4}\text{ C/cm}^2$, while for $0.3\text{ }\mu\text{m}$ thick PMMA, ΔW was almost constant in the above dose range. This result demonstrates the superior pattern width controllability of the SiN_x spacer method. Correction of the electron-beam exposing width, which was kept constant in the above experiment, will be effective for minimizing the ΔW .

X-Ray Mask Property

Figure 12 shows a 2-inch diameter SiN_x membrane mask. Au patterns on the back of the SiN_x membrane can be clearly seen. The SiN_x membrane ($t = 1\text{ }\mu\text{m}$) transparency to visible light, measured by using a silicon-photo-diode, was about 80 % that is high enough for the mask alignment using visible light. The SiN_x membrane also has high transparency to soft x-rays, such as $\text{Si-K}(7.1\text{ }\text{\AA})$, $\text{Al K}(8.3\text{ }\text{\AA})$ and $\text{W M}(7.0\text{ }\text{\AA})$. Si K radiation attenuation by the $1\text{ }\mu\text{m}$ thick SiN_x membrane is only about 9 %, which is a big advantage for realizing a short exposure time. $1\text{ }\mu\text{m}$ thick SiN_x membranes with large areas, up to 40 mm-diameter⁽³⁾, can be easily prepared. Warp of the mask, which is one of the most important property for the fine pattern lithography, was measured by

Fizeau interference method to be about 1 μm for a 38 mm diameter membrane, which is as small as that for $\text{Si}_3\text{N}_4/\text{SiO}_2/\text{Si}_3\text{N}_4$ sandwich structure membrane⁽¹¹⁾.

Summary

A practical method for preparing a simple structured x-ray lithography mask with high aspect ratio Au patterns has been presented. Submicron featured Au patterns with about 1 μm thickness could be easily obtained from 0.3 μm thick PMMA resist patterns by using the " SiN_x spacer method". It was shown that the present method produced steep profiled Au patterns with good line width controllability.

Although only experimental results for the " SiN_x spacer method" using positive electron beam resist (PMMA) have been described, negative resist, such as CMS-EX, is also applicable to the present process. The " SiN_x spacer method" as well as the SiN_x membrane substrate will be acceptable for practical use, such as in MOS device fabrication, because of their simplicity and productivity.

Acknowledgements

The authors would like to thank Drs. D. Shinoda, F. Saito and Y. Okuto for their continuous support.

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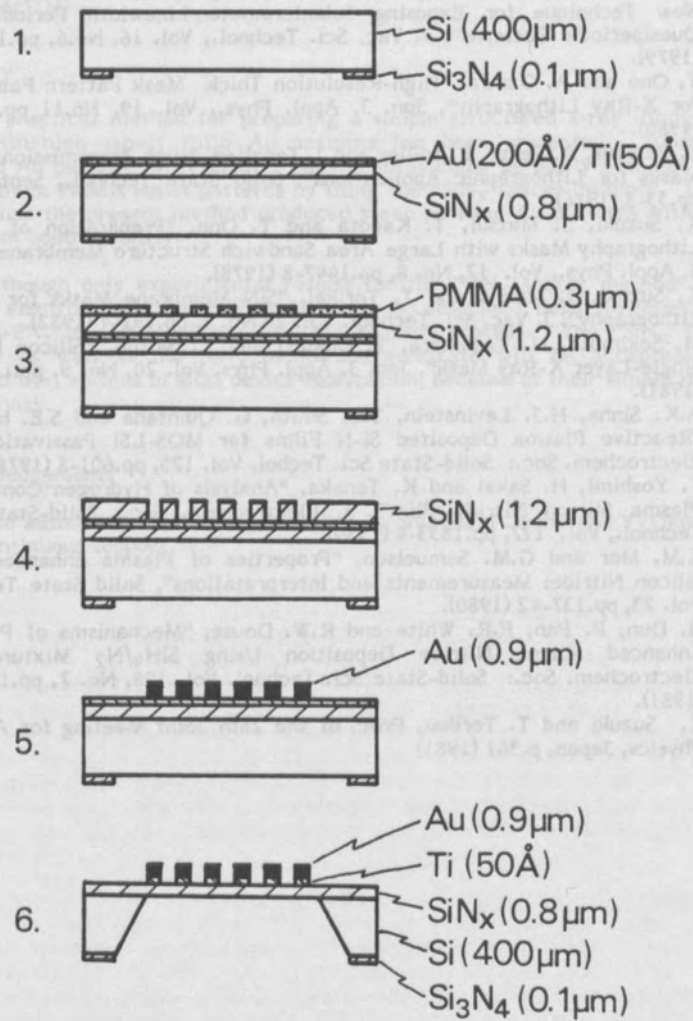


Fig. 1 X-ray mask fabrication process using SiN_x spacer.

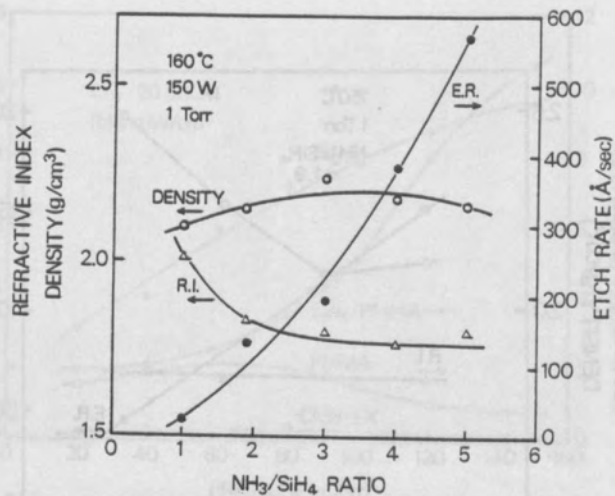


Fig. 2 Refractive index, density and etch rate with 1.5 % HF for SiN_x films vs. NH_3/SiH_4 ratio.

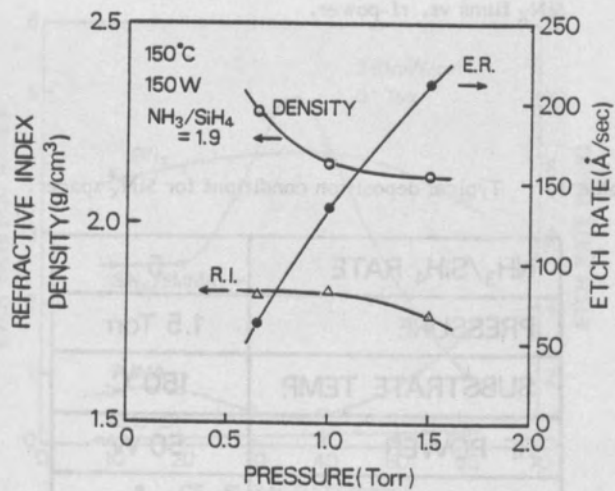


Fig. 3 Refractive index, density and etch rate with 1.5 % HF of SiN_x films vs. total gas pressure.

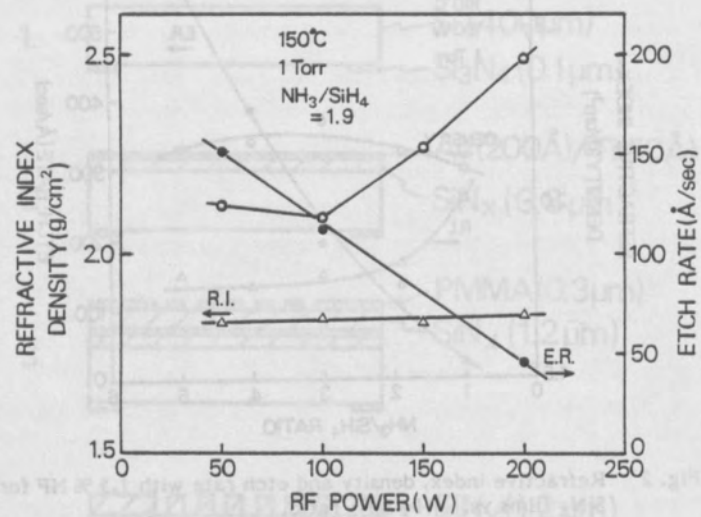


Fig. 4 Refractive index, density and etch rate with 1.5 % HF for SiN_x films vs. rf-power.

Table 1 Typical deposition conditions for SiN_x spacer.

NH ₃ /SiH ₄ RATE	5
PRESSURE	1.5 Torr
SUBSTRATE TEMP.	150 °C
RF POWER	50 W
DEPOSITION RATE	500 Å/min

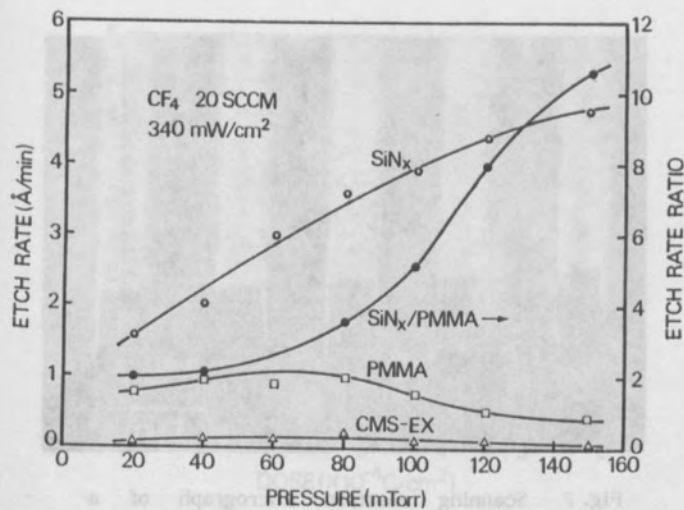


Fig. 5 Reactive-sputter-etch rate for SiN_x spacer, PMMA and CMS-EX vs. CF₄ gas pressure. SiN_x/PMMA etch rate ratio is also shown as a function of CF₄ gas pressure.

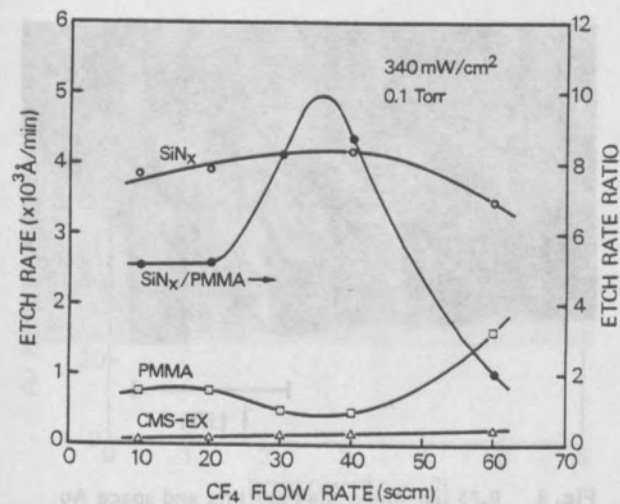


Fig. 6 Reactive-sputter-etch rate for SiN_x, PMMA and CMS-EX vs. CF₄ gas flow rate. SiN_x/PMMA etch rate ratio is also shown as a function of CF₄ gas flow rate.

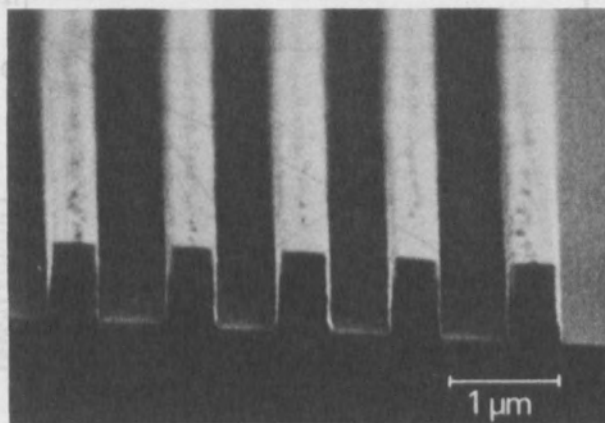


Fig. 7 Scanning electron micrograph of a reactive sputter etched SiN_x spacer pattern ($1.0\text{ }\mu\text{m}$ thick, $0.5\text{ }\mu\text{m}$ lines and spaces).

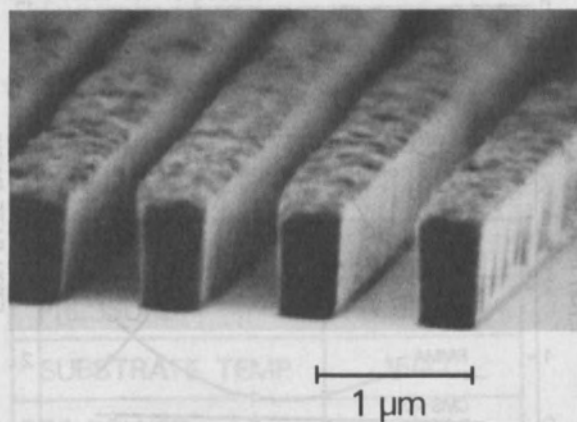


Fig. 8 $0.75\text{ }\mu\text{m}$ thick, $0.44\text{ }\mu\text{m}$ line and space Au patterns fabricated by electroplating using SiN_x spacer patterns for plating masks.

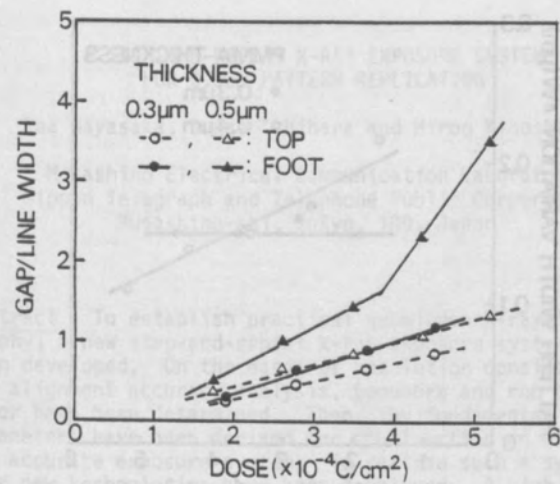


Fig. 9 Gap/line width ratios for 0.9 μm pitch line and space PMMA resist patterns vs. electron beam dose.

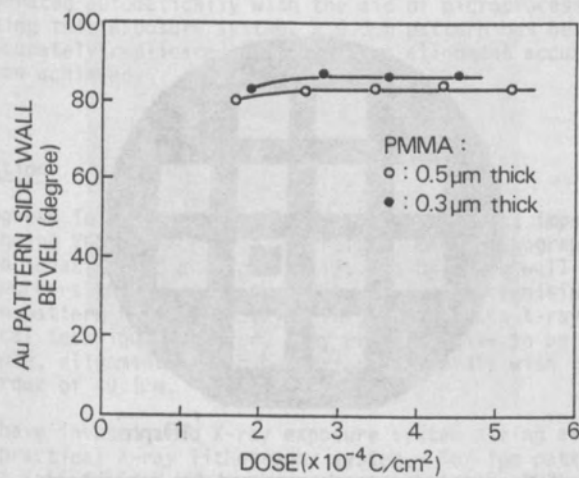


Fig.10 Bevel in 0.9 μm pitch line and space Au patterns vs. electron beam dose to the corresponding PMMA resist.

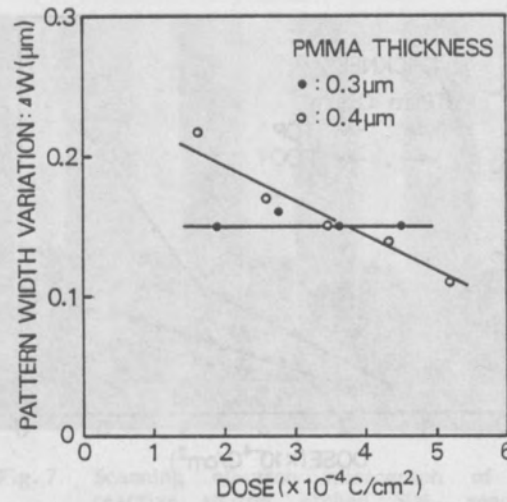


Fig.11 Pattern width variation ΔW vs. electron beam dose to the PMMA resist. Here, $\Delta W = W_{\text{Au}} - W_g$ (W_{Au} : Au pattern width, W_g : gap in the corresponding PMMA resist pattern).

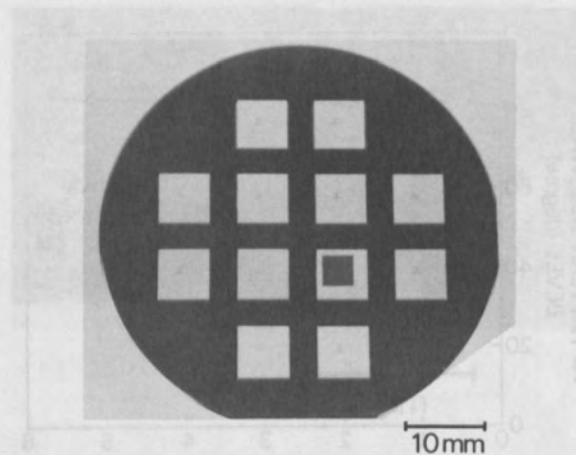


Fig.12 SiN_x membrane mask prepared for experiments using SiN_x spacer method. The mask consists of $0.9\mu\text{m}$ thick Au patterns, supported by a $0.8\mu\text{m}$ thick SiN_x membrane stretched over a Si frame. Transparent window size is 6.5mm square.

A STEP-AND-REPEAT X-RAY EXPOSURE SYSTEM FOR 0.5 μ m PATTERN REPLICATION

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Abstract To establish practical submicron X-ray lithography, a new step-and-repeat X-ray exposure system has been developed. On the basis of resolution consideration and alignment accuracy analysis, penumbra and run out error have been determined. Then, the fundamental system parameters have been derived for constructing an efficient and accurate exposure system. To realize such a system, some new technologies have been developed. A high power Si-K X-ray source brings a large X-ray flux on the wafer through a silicon nitride mask membrane. An optical mark and gap detection method is connected with a precise alignment mechanism placed on an X-Y table designed for wafer stepping. This construction enables an atmospheric environmental exposure. In addition, the exposure system can be operated automatically with the aid of microprocessors. Using this exposure system, a 0.5 μ m pattern has been accurately replicated, and a $\pm 0.1\mu$ m alignment accuracy has been achieved.

Introduction

Progress in microlithography is one of the most important subjects for advancing VLSI performance. Therefore, many lithographic techniques have been investigated and applied(1). It has been well demonstrated by many workers that X-ray lithography is a very promising method for submicron pattern replication(2). In order to make X-ray lithography a practical technique, however, many problems have to be overcome. For example, alignment has to be performed rapidly with the accuracy on the order of $\pm 0.1\mu$ m.

We have investigated X-ray exposure system aiming at building up of a practical X-ray lithography system. For 1 μ m pattern replication, a full field X-ray exposure system has already been built(3), which has been applied to the test fabrication of several devices(4). Then, we commenced the development of an X-ray exposure system for 0.5 μ m pattern replication. This paper describes the design, construction and performance obtained for developed step-and-repeat X-ray

exposure system for 0.5 μ m pattern replication.

System considerations have been carried out to realize an accurate and efficient exposure machine having 0.5 μ m resolution and corresponding alignment accuracy. Some geometrical parameters such as X-ray source spot size, source to mask distance, mask to wafer gap and exposure area size have been derived. Prior to the above mentioned derivation, optimum penumbra and run out error values were investigated and determined on the basis of resolution and alignment accuracy analysis. As a result of the above mentioned investigations, a step-and-repeat scheme has been chosen.

Efforts have been made to realize a step-and-repeat proximity aligner suitable for 0.5 μ m pattern replication. Lateral(x,y, θ) and vertical(z, α , β) alignment were required at each exposure site to satisfy high alignment accuracy. A new optical mark and gap detection method, using bifocal objectives, precise mask stage and wafer stage for adjusting relative displacement in six degrees of freedom, and an air bearing guided X-Y table for wafer stepping have been developed for the aligner.

System considerations

The required system performance is shown in Table 1. To clarify the resolution conditions, penumbra have been used as a criteria. It is possible to reduce penumbra enough to resolve 0.5 μ m pattern by increasing the source to mask distance, or by reducing gap and/or source spot size. On the other hand, it is required to reduce source to mask distance for the reduction of exposure time. From the results of resist pattern profile simulation and exposure tests, optimum penumbra for 0.5 μ m pattern replication has been found to be 0.25 μ m.

TABLE 1 REQUIRED SYSTEM PERFORMANCE

Minimum linewidth	0.5 μ m
Alignment accuracy	$\pm 0.1\mu\text{m}(2\sigma)$
Wafer size	3 and 4 inch
Maximum die size	20 $\times$ 20 mm ²

In considering alignment accuracy, mask-wafer mark alignment accuracy, run out error caused by proximity gap fluctuation, mask error and stability, and wafer distortion have to be taken into account. Wafer distortion is considered to be a function of wafer radii or exposure area size. Thus, alignment accuracy may be expressed by the root of the sum of the square of terms mentioned above. Therefore, alignment accuracy is related to the exposure area size. The smaller the exposure area size, the higher the alignment accuracy. From the viewpoint of throughput, it is desired to make the number of exposures per wafer as small as possible, since alignment time

should be taken into account. Therefore, $20 \times 20 \text{ mm}^2$ area is considered to be optimum for $0.5 \mu\text{m}$ pattern. This value means the necessity of a step-and-repeat scheme.

The mask to wafer gap has been estimated from the results of wafer flatness measurements. The optimum X-ray source spot size has been determined from the desired resolution, run out error and the maximum input power focused on an X-ray target. The optimum source to mask distance has been obtained from the relation between exposure time, penumbra, spot size, gap and the distance.

X-ray wavelength for submicron lithography has also been optimized from the standpoint of X-ray generation efficiency, absorption at the resist, mask substrate, mask absorber and source window. Si-K α radiation, suitable for the silicon nitride mask membrane, has been found to provide several advantages in a practical lithography system (5). The resultant system parameters are summarized in Table 2.

TABLE 2 SYSTEM PARAMETERS

Mask to wafer gap	$10 \mu\text{m}$
Source-mask distance	120 mm
Source spot size	3 mm diam.
Source input power	20 kW

System construction

Figure 1 illustrates the construction of the developed exposure system. The system consists of an X-ray source and an aligner, which is constructed from a wafer stepping subsystem, mark and gap alignment subsystem and an automatic control system. For operating convenience, and to make possible the use of a vacuum chuck on a mask and wafer to control their flatness, it has been decided to employ atmospheric environmental exposure. Figure 2 shows the exposure system developed.

Si-K α X-ray is generated by electron beam bombardment of a water cooled rotating anode. In order to obtain long target lifetime, a 150mm diameter and a 6000rpm rotation speed were chosen. An electron gun has the ability to provide a beam power up to 20kW with a 20kV accelerating voltage. Generated X-rays are fed through a Be window and a special shaped X-ray guide. Usually used X-ray flux at the wafer surface is about 1 mW/cm^2 .

In the alignment system, mark alignment and gap control should be carried out at each exposure site. Mark alignment accuracy and gap controllability required of the alignment system are $\pm 0.05 \mu\text{m}$ and $10 \pm 0.3 \mu\text{m}$, respectively. The alignment has to be done very quickly to keep the throughput maximum, and has to be retained during exposure to avoid changes in the permissible drift. Alignment time is desired to be shorter than 1 second per exposure.

To fulfill these requirements, a closed loop feedback alignment system was designed. Since optically transparent X-ray masks have been made available(6), the system utilizes unique bifocal optical microscopes and ITV cameras for detecting alignment marks.

Alignment system

In the aligner for the X-ray exposure system using divergent X-rays, vertical alignment(control of both mask-to wafer gap(z) and their parallelism(α, β)) is required in addition to the lateral alignment(x, y, θ). To perform these alignments, alignment marks are arranged on a mask and a wafer as shown in Fig.3. Figure 4 shows the structural outline of the alignment system. The system is a closed loop feedback system, consisting of three detecting channels, a feedback unit and a fine positioning mechanism. Each detecting channel has a microscope with bifocal objective, a distortion compensated ITV camera and a video signal processor. The positioning mechanism is a complex of mask stage and wafer stage, the latter is carried on a stepping X-Y table. Figure 5 is a photograph of the aligner itself. Relative motion of mask and wafer along the six axes shown in Fig.3 is made possible by the mechanism.

Each of the detecting channels makes the detections shown in Table 3. First, the LFP(Lower Focal Point) for each channel is set in focus with a corresponding wafer mark by moving the second objective. Second, mask marks are set in focus with the UFPs(Upper Focal Points) by varying the mask attitude(z, α, β). Since the LFPs and UFPs are located $10\mu\text{m}$ apart from each other along the optical axis, mask and wafer are set parallel with a $10\mu\text{m}$ separation. Then, lateral alignment is made by moving the wafer stage for x and y , and the mask stage for θ . Alignment error along the θ axis is calculated from the difference between X axis errors detected at channels A and B.

TABLE 3 DETECTIONS MADE AT EACH CHANNEL

	Ch. A	Ch. B	Ch. C
Wafer-LFP focusing	○	○	○
Mask-UFP focusing	○	○	○
Misalignment X	○	○	—
Misalignment Y	—	—	○

In this alignment method, the mark contrast is very important. Therefore, we form microgrooves on the wafer as a wafer mark as illustrated in Fig.6. The unetched portion(center) serves as a wafer mark. The mask marks are formed together with a mask absorber pattern. The mask marks and the wafer mark are magnified by the microscope, and their magnified images are projected onto an ITV camera. Figure 7

shows an image of mask mark and wafer mark on the ITV camera. The image is optically divided into domains I, II and III by light path converter. Domains I and III are given focus offsets of $2\mu\text{m}$ and $-2\mu\text{m}$ relative to domain II, respectively, for the static detection of focusing. The mark image is also electrically divided into mask domain and wafer domain in order that the signal processor can identify the mask mark and wafer mark. The video signal processor detects sharpness and location of mark edges and then determines i) mask(wafer) mark defocus versus the UFP (LFP) for the bifocal objectives, ii) relative displacement between mask mark and wafer mark.

Figure 8 shows typical focus detecting characteristics. Resolution is better than $0.2\mu\text{m}$ at zero crossing point. Deviation in the zero crossing point with variation in lighting intensity from 100% down to 50% is also less than $0.2\mu\text{m}$. Detecting range is about $\pm 6\mu\text{m}$.

Figure 9 shows an example of displacement detecting characteristics. Very high detecting resolution, $0.03\mu\text{m}$, has been obtained over the approximately $\pm 8\mu\text{m}$ detecting range. Due to the detection principle, excellent linearity and immunity to mark contrast are realized.

The positioning mechanism for step-and-repeat exposure system must have a positioning resolution of the order of $0.01\mu\text{m}$ over 100mm stroke. In order to fulfill conflicting requirements for high resolution and large stroke, the fine positioning mechanism has been designed to be set on an X-Y table for wafer stepping.

For fine adjusting in six degrees of freedom, fine positioning stages(mask stage and wafer stage) must have six moving axes. Each stage has been designed to have the performance as shown in Table 4.

TABLE 4 ALIGNMENT MECHANISM DESIGN VALUES

Stepping stage

Axis	Stroke	Accuracy	Stepping time
X	100 mm	$\pm 1\mu\text{m}$	0.5 sec/15 mm
Y	190 mm	$\pm 1\mu\text{m}$	0.5 sec/15 mm

Fine stages

Stage	Axis	Stroke	Resolution
Mask stage	θ	$\pm 2'$	0.15"
	Z	100 μm	0.05 μm
	α, β	$\pm 2'$	0.5"
Wafer stage	X	$\pm 20\mu\text{m}$	0.01 μm
	Y	$\pm 20\mu\text{m}$	0.01 μm

By the mask stage, vertical alignment may be performed. Lateral alignment is done by driving the wafer stage(x,y) and the mask stage(θ). The movement of these stages are performed by balancing the bending of the elasticplates with the driving force applied by the electro-magnets. Since this construction eliminates backlash and stick-slip, very high positioning resolution, $0.01\mu\text{m}$, has been achieved as shown in Fig.10.

For wafer stepping, an air bearing guided X-Y table has been developed. The X-Y table is driven by moving coil linear motors. Since there is no mechanical contact in this table system, smooth and precise movement characteristics and excellent maintainability have been realized.

System performances

Figure 11 shows an alignment signal for X axis alignment, which is performed by driving the wafer stage in the X direction. Servo alignment with almost $0.02\mu\text{m}$ stability is demonstrated. Figure 12 shows the feedback alignment procedures for wafer focusing and lateral alignment. In wafer focusing, the feedback alignment from an initial defocus of $5\mu\text{m}$ is completed in 0.3 seconds with an accuracy of $0.2\mu\text{m}$. In lateral alignment, x, y and θ alignment are executed simultaneously, and are completed in less than 0.4 seconds with an accuracy better than $0.05\mu\text{m}$. The alignment sequence is controlled by a microcomputer, and a total alignment time of 0.5 seconds is made possible by overlapping these controls.

Figure 13 shows the overlay accuracy for this system. Two different masks were used for this experiment. Therefore, these results include a mask error and a measurement error in addition to alignment error. The standard deviation in the X and Y components is less than $0.07\mu\text{m}(\sigma)$. From these data, mark alignment accuracy was estimated to be better than $\pm 0.1\mu\text{m}(2\sigma)$.

By using this system, a $0.5\mu\text{m}$ pattern has been replicated in the FBM(7) and CMS(8) resists, as shown in Fig.14. The FBM resist requires an about one minute exposure time. This corresponds to a throughput of more than 5 three-inch wafers per hour. Figure 15 shows replicated and developed $0.5\mu\text{m}$ lines and spaces patterns traversing $0.6\mu\text{m}$ thick SiO_2 steps.

Conclusion

In order to establish a practical method for $0.5\mu\text{m}$ pattern replication, a step and repeat X-ray lithography system has been designed and developed. Alignment accuracy with a less than $\pm 0.1\mu\text{m}(2\sigma)$ standard deviation have been achieved by the use of newly developed optical serve alignment system. The use of Si-K α radiation with the

FBM resist has reduced exposure time to less than one minute. A $0.5\mu\text{m}$ pattern has been replicated on SiO_2 steps.

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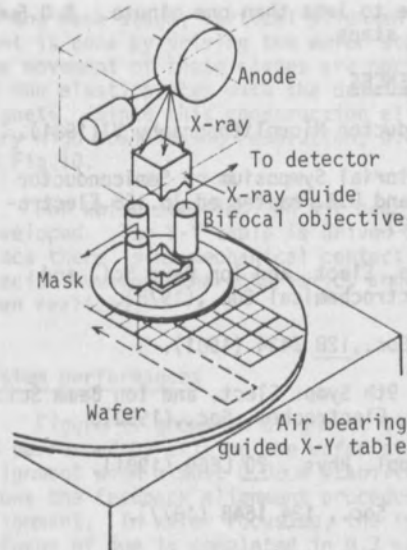


Fig. 1 Construction of the system

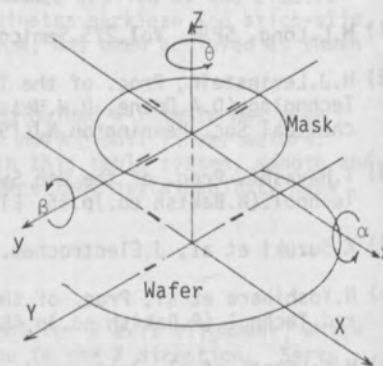


Fig. 3 Mark arrangement and co-ordinate system for aligner. Single lined marks are on the wafer and double lined marks on the mask.

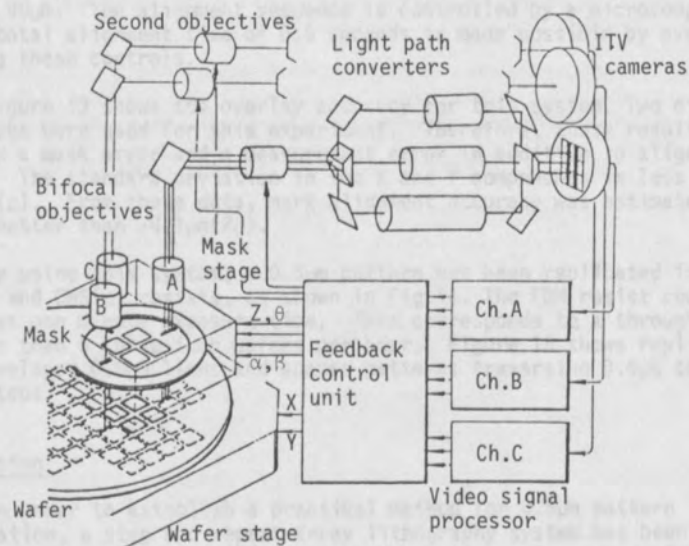


Fig. 4 Structural outline of the alignment system

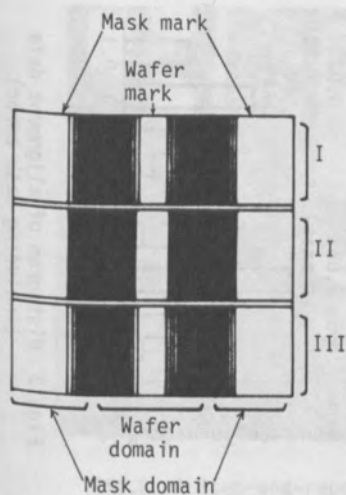


Fig. 7 Mark image on ITV camera

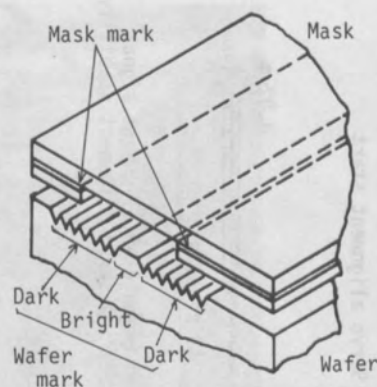


Fig. 6 Alignment mark configuration

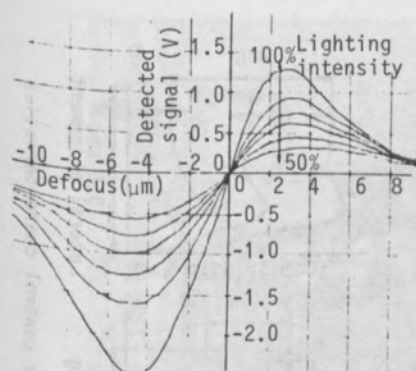


Fig. 8 Focus detection characteristics

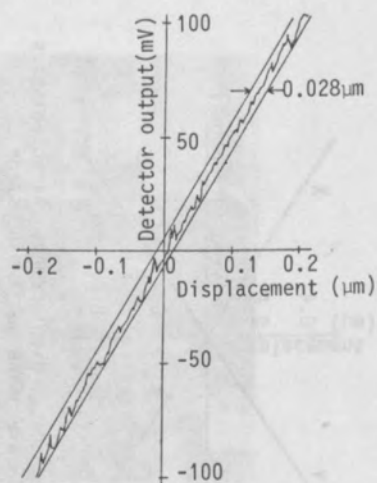


Fig. 9 Relative displacement between mask and wafer detection characteristics. The wafer was covered by SiO_2 ($0.3 \mu\text{m}$ thick) and resist.

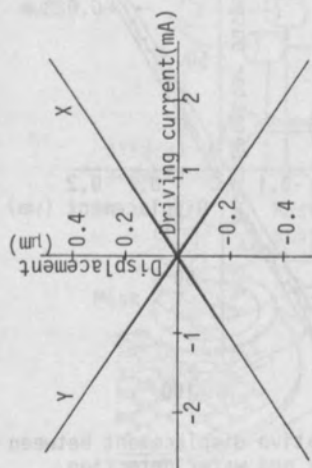


Fig. 10 Mechanical displacement characteristics of wafer fine positioning stage

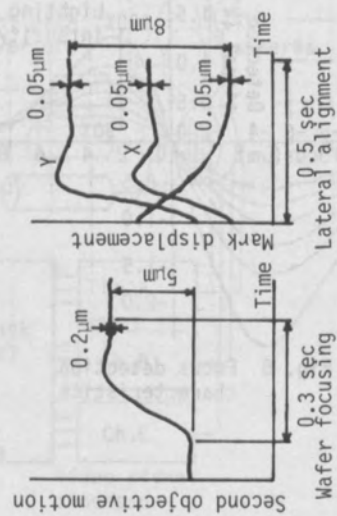


Fig. 12 Feedback control characteristics

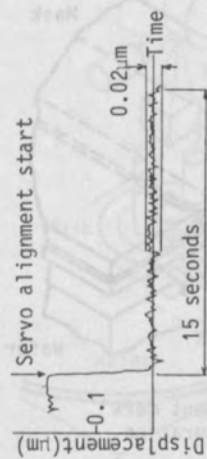


Fig. 11 An example of alignment signal showing servo alignment stability

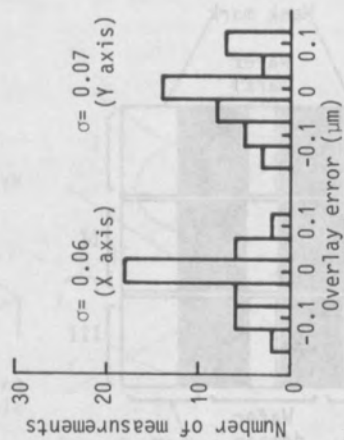


Fig. 13 Histogram of alignment data (including mask error)

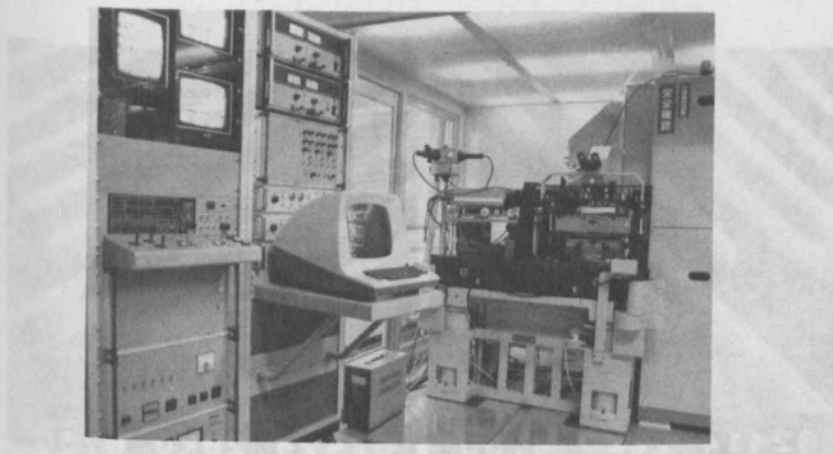


Fig.2 A Step-and-repeat X-ray exposure system.

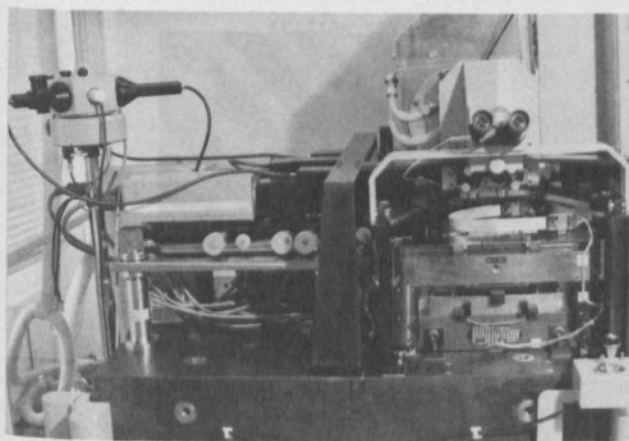


Fig.5 The alignment system for step-and-repeat exposure system.

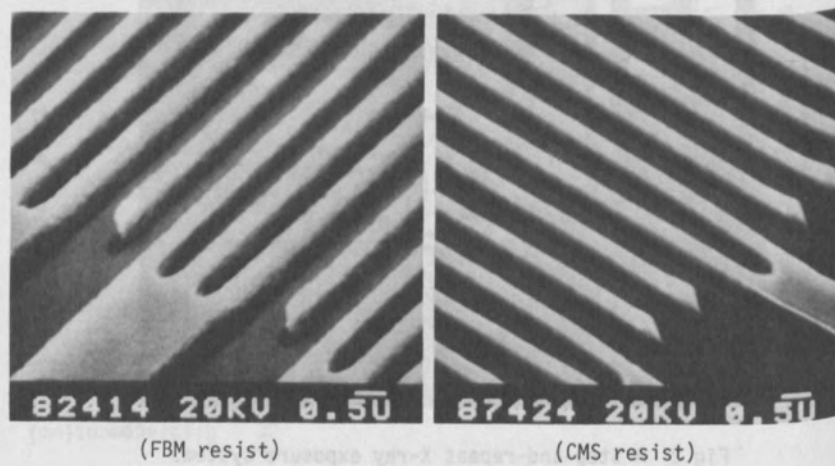


Fig.14 X-ray lithography in FBM and CMS using a step-and-repeat exposure system.

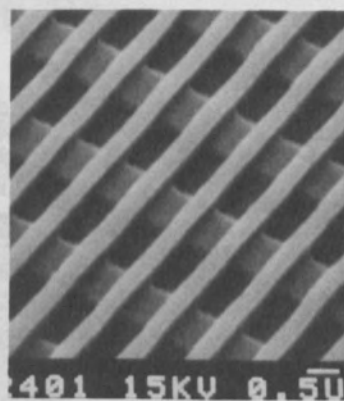


Fig.15 Replicated resist(FBM) pattern covering SiO_2 steps(0.5 μm thick).

INTRODUCTION

This report was prepared for the purpose of providing information on the status of the development of the automatic control system for the control of the reactor. The system is designed to control the reactor power level and to maintain the reactor at a constant power level. The system is designed to be able to handle any possible situation that may arise. The system is designed to be able to handle any possible situation that may arise.

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SECTION SIX

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AN AUTOMATIC SYSTEM FOR CONTROLLING THE ION MASS AND ION ENERGY IN AN ION IMPLANTER

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(FPM resist) (FPM resist)

Fig. 14 X-ray lithography in FPM and CMOS using a
step-and-repeat exposure system.

X12.500000

Semiconductor wafers can easily be destroyed in an ion implanter if the operator selects the wrong energy or ion specie. We will describe a microcomputer system which automatically controls the ion acceleration potential and tunes the analyzer system to the desired ion specie.

Communication with a supervisory computer ensures that the selected parameters are appropriate for the given wafer type or process recipe.

Fig. 15 Replicated resist(FPM) pattern
covering 500 steps(0.5μm pitch).

INTRODUCTION

Semiconductor wafers are easily destroyed in an implanter if the operator selects the wrong energy or ion specie. Unfortunately test results of the implantation process are not available until several steps later in the manufacturing cycle. Consequently incorrect implanter adjustment can persist without detection and thousands of valuable wafers can be inadvertently destroyed.

In most implanters energy and mass are selected by manual control of system power supplies. Although functional, this technique has several disadvantages as follows:

1. A slight error in ion beam energy or analyzer setting can lead to implantation with the wrong ion species. The operator is particularly vulnerable when the required ion is located close to adjacent peaks in the mass spectrum.
2. Power supplies are frequently controlled "open-loop" and there is no guarantee that the commanded set point has been achieved.
3. The system can be set up so that the ion beam current is not maximized and system throughput is degraded.
4. Mass resolution of the analyzer system is a good indicator of source conditions, power supply stability and beam quality. This information is not readily available in a manual system.
5. Direct output data concerning the energy and mass adjustments is not available for use with a process supervisory computer or data acquisition and storage system.

In this paper we describe an automatic Mass/Energy control system which avoids these drawbacks and paves the way for total automation of the implanter.(1)

METHODOLOGY AND DESCRIPTION

The ion specie is generally selected by first setting the desired ion energy and then adjusting the field strength of a sector analyzing magnet system. The deflection field is controlled by regulating the current in the excitation coils of an electromagnet. This concept can be described in the form:

$$M = f(I, E) \quad (1)$$

where M = the atomic mass of the ion
and I = the analyzing magnet current
 E = the energy of the incident ions

The automatic system to be described is shown schematically in Figure 1. The microcomputer based system generates control signals for both the high voltage power supply which accelerates the ions (0-80kV), and the power supply which generates the deflection field of the analyzer (0-150A). The output signal of the high voltage power supply is sensed directly by a precision resistive divider attached to the ion source and the output signal of the analyzer power supply is sensed directly by a precision resistor in series with the magnet coils. This approach is believed to be the most direct, error free technique for sensing these critical parameters and the least likely to fail in an industrial environment.

The control system performs the following basic functions:

1. Energy Control

The control signal for the High Voltage power supply is ramped to a value corresponding to the desired energy. The signal is then "fine-tuned" until the measured voltage is within ± 0.1 kV of the required value. The final voltage, which determines ion energy, is monitored throughout machine operation. Implantation is disabled and the operator is alerted in the event of unusual conditions such as power supply drift or instability.

2. Analyzer Magnet Control

From the selected mass and the measured energy, the processor calculates a window of magnet current within which the desired ion specie is to be found. Equation (1) is solved using second and third order correction terms accounting for loss and hysteresis phenomena of the magnet, and the magnet current is then ramped to the lower boundary of the window. Typical values of the window width are equivalent to ± 0.2 a.m.u. (atomic mass units) at mass 11 (boron) and ± 0.5 a.m.u. at mass 75 (arsenic).

3. Beam Peak Search

The controller searches for the desired ion beam by scanning the magnet current within the established window. A Faraday cup, located behind the

resolving aperture of the analyzer, provides the microcomputer with a signal of beam intensity and the magnet current is varied so as to maximize this beam signal.

4. Mass Resolution Measurement

During the peak finding routine the microcomputer stores values of beam current and atomic mass in a two-dimensional array. From this the resolution of the analyzer, R , is calculated using the following definition:

$$R = \frac{M}{\Delta M} \quad (2)$$

where M = atomic mass

and ΔM = full width at half height of the beam peak

5. Self Calibration

The microcomputer is programmed with fixed constants for solving equation (1) and the atomic mass of a given peak is generally determined within ± 0.4 a.m.u. using these values. For increased precision with a specific implanter a self calibration feature is included. Whenever mass 40 (argon) or mass 75 (arsenic) is selected, the constants are recalculated from the actual values of voltage and magnet current required to find the beam peak. These new values are used in subsequent operation of the controller and provide typical accuracies in atomic mass calculation better than ± 0.1 a.m.u. Argon and arsenic were selected for self calculation because of the simple and unambiguous spectrum produced when the ion source is operated on these materials.

6. Fine Tune

At anytime the microcomputer can be commanded to "fine-tune" the analyzer. In this mode the magnet current is adjusted slightly to each side of the beam peak and the value for maximum beam is reestablished provided it still remains within the acceptable magnet current "window".

7. Spectrum Recording

The control system can also be commanded to record ion source spectrum data. In this mode the magnet is first ramped quickly from zero to full-scale and the values of magnet current corresponding to beam peak signals are recorded in memory. The magnet current is then ramped from zero to full-scale a second time, but in this case the scan speed is reduced as each peak is traversed so that its atomic mass and intensity can be calculated and displayed.

8. Manual Controls

The control system has been designed with a manual backup feature which enables the operator to control the high voltage and magnet power supplies directly using potentiometers located behind the front panel.

This mode is provided for troubleshooting and emergency operation of the implanter in the event of computer failure.

9. Communication to Supervisory Computer

The Mass/Energy control system is in constant communication with a supervisory system (2) located in the ion implanter. Actual values of energy and mass are transmitted to the supervisory computer which compares them with previously established set point values. If the actual values do not match their corresponding set points within programmed limits, the implanter is prevented from processing wafers.

In an alternative mode of operation the supervisory computer directly "downloads" the values of ion mass and energy required for a particular implantation recipe. It then checks that the Mass/Energy control system has correctly tuned the implanter to these values.

CONCLUSION

The Mass/Energy control system described has greatly simplified and improved the reliability of implanter set-up. In conjunction with a supervisory computer the possibility of implanting wafers with the wrong energy or ion species has been virtually eliminated.

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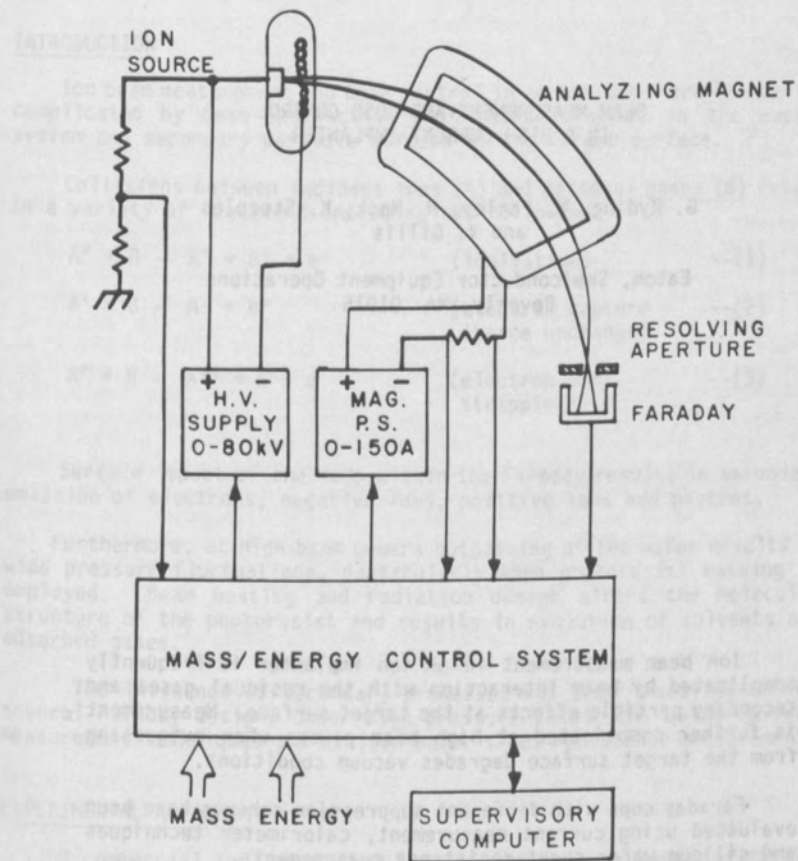


Figure 1. Mass/Energy Control System.

This mode is provided for troubleshooting and emergency operation of the implanter in the event of computer failure.

5. Communication to Supervisory Computer

The safety control system is in constant communication with a supervisory system (7) located in the ion implanter building which allows the operator to monitor the status of the implanter and to initiate various control functions. The supervisory system also provides a means for the operator to initiate various control functions.

BEAM MEASUREMENT AND DOSE CONTROL IN A HIGH CURRENT IMPLANTER

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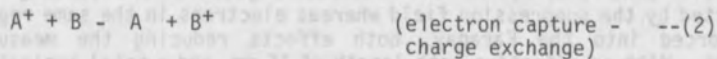
Ion beam measurement in an ion implanter is frequently complicated by beam interaction with the residual gases and secondary particle effects at the target surface. Measurement is further complicated at high beam powers when outgassing from the target surface degrades vacuum conditions.

Faraday cups with different suppression schemes have been evaluated using current measurement, calorimeter techniques and silicon wafer sheet resistance measurements.

INTRODUCTION

Ion beam measurement and dose control in an implanter are frequently complicated by beam interaction with residual gases in the vacuum system and secondary particle effects at the target surface.

Collisions between incident ions (A) and residual gases (B) result in a variety of reactions including the following:



Surface impact of the ions within the Faraday results in secondary emission of electrons, negative ions, positive ions and photons.

Furthermore, at high beam powers outgassing of the wafer results in wide pressure fluctuations, particularly when photoresist masking is employed. Beam heating and radiation damage alters the molecular structure of the photoresist and results in evolution of solvents and adsorbed gases.

The influence of secondary processes has been investigated for several Faraday designs under high pressure conditions using current measurement techniques and silicon wafer sheet resistance measurement.

EXPERIMENTAL APPROACH

A commercial implanter (1,2,3) was used to study beams of Boron, Phosphorous and Arsenic with intensities between 0.1 and 20 mA and energies between 40 and 80 KeV. The system contains two Faradays (2) for dose control and this feature was exploited to compare the different secondary suppression methods shown schematically in Figures 1-4. The Faraday currents were recorded as pressure in the target region was varied by admitting air through a fine control leak valve. Silicon wafers were also implanted under these varied conditions and the relative dose was determined from four point probe sheet resistance

measurements. Dose and anneal parameters for all species were arranged for maximum sensitivity with dose.

RESULTS AND DISCUSSION

Typical results for a 10 milliamper Arsenic beam at 60 KeV are displayed for four different Faraday schemes in Figures 1-4. Measured current is plotted as a function of target chamber pressure. In Faraday 1, the electrostatic suppression electrode is independent of the Faraday and the measured current is reduced significantly as the pressure is increased. We postulate that this results from residual gas ionization, reaction (1), and not secondary effects from the Faraday surface. Ions created in the entrance region of the Faraday are extracted by the suppression field whereas electrons in the same region are forced into the Faraday, both effects reducing the measured current. With an effective path length of 15 cm, and a total ionization cross section (4) of $\sim 2 \times 10^{15} \text{ cm}^2$ a signal reduction of 10% would be expected at a pressure of 10^{-4} torr. This is reasonably consistent with the observations.

In Faraday 2 the bias supply current is returned to the Faraday and in this case, the measured current increased as the pressure increases. This can also be explained by residual gas ionization in the region between the ground defining aperture and the suppression electrode. In this case ions are pulled into the Faraday whereas electrons are repelled thus increasing the measured current.

In Faraday 3 a double electrode configuration was developed to minimize the influence of residual gas ionization. It can be seen that the sensitivity to pressure is greatly reduced and the small attenuation at high pressures is probably a result of electron capture by the primary ions (reaction 2).

Finally, in Faraday 4 electrostatic suppression fields have been replaced by magnetic fields and similarly excellent flat response characteristics are observed. The magnetic scheme has an added advantage with intense beams which "blow-up". This delicate charge balance is easily disturbed and beam integrity is destroyed in the presence of electric fields.

Typical implantation results are shown in Figure 5 which displays sheet resistance as a function of target chamber pressure and compares Faraday 1 with Faraday 4. As expected Faraday 1 results in a higher dose at high pressures and the sheet resistance is reduced. In contrast Faraday 4 with magnetic suppression provides wafer doping which is far less sensitive to system pressure.

CONCLUSION

The use of magnetically suppressed Faradays offers significant advantages in an ion implanter. Implantation can be initiated earlier in the pump down cycle so that higher wafer throughputs are achieved. Vacuum requirements of the system can generally be relaxed and the effects of photoresist outgassing are minimal over rather broad limits.

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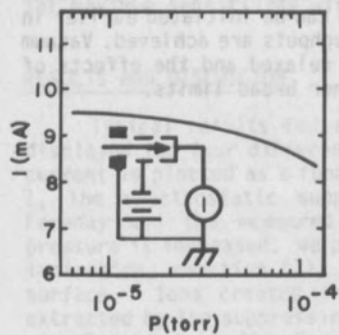


Fig. 1. Faraday 1. Current vs. Pressure for 10 mA, 60 KeV As^+ beam.

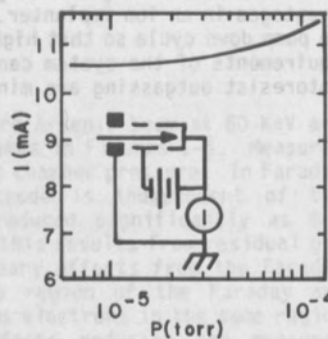


Fig. 2. Faraday 2. Current vs. Pressure for 10 mA, 60 KeV As^+ beam.

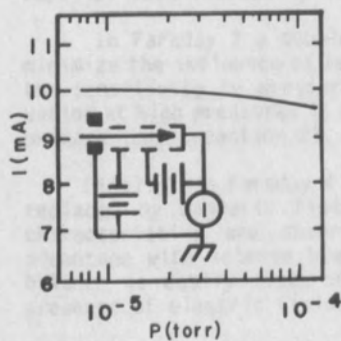


Fig. 3. Faraday 3. Current vs. Pressure for 10 mA, 60 KeV As^+ beam.

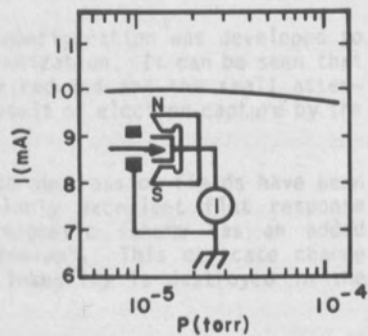


Fig. 4. Faraday 4. Current vs. Pressure for 10 mA, 60 KeV As^+ beam.

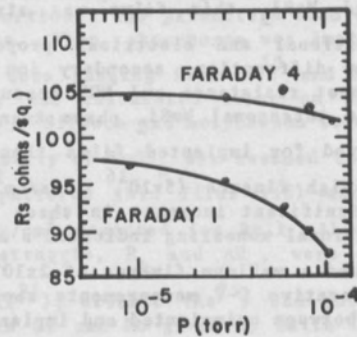


Fig. 5. Sheet Resistance as a function of Pressure for Faradays 1 and 4. 10^{15} ions cm^{-2} Arsenic at 80 KeV.

THE EFFECT OF IMPLANTATION OF PHOSPHORUS
INTO
SPUTTERED MoSi_2 THIN FILMS

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ABSTRACT

The effect of phosphorus implantation into dc-magnetron sputtered MoSi_2 thin films was studied. The structural, compositional and electrical properties were examined with X-ray diffraction, secondary ion mass spectrometry (SIMS), sheet resistance and MOS measurements. A higher hexagonal to tetragonal MoSi_2 phase transition temperature was observed for implanted films than for unimplanted ones. At high fluence (5×10^{16} ions/cm²), MoP was detected, with a significant increase in sheet resistance. Isothermal and isochronal annealing indicated a minimum temperature of 950°C and a maximum fluence of 2×10^{16} ions/cm² can be used. Comparative C-V measurements showed similar MOS characteristics between unimplanted and implanted films.

INTRODUCTION

In the course of development of a refractory and highly conductive interconnection system for very-large-scale-integrated (VLSI) circuits, several refractory metal silicides, such as MoSi_2 (1-5) and WSi_2 (6-9) and TaSi_2 (10,11), are under study as an alternative to the widely used doped polycrystalline silicon (poly-Si). These metal silicides, unlike the metals, have resistance to high temperature oxidation and to most chemicals routinely encountered during device fabrication.

Since the gate metal is often used as ion implantation mask during the source/drain doping in a self-aligned process, the effect of implantation of various group III and V ions - phosphorus, arsenic and boron - on the properties of silicide thin films needs to be studied. Also, recently, it has been reported (12,13) that doping MoSi_2 films with phosphorus can help stabilize silicide-gate threshold voltage and form low resistant and reliable contacts between silicide and silicon substrates. In that study, doped silicide films were

deposited by using a Mo/Si target in a phosphine/argon atmosphere. In this paper, the effect of phosphorus implantation on the structural, compositional and electrical characteristics of sputtered molybdenum disilicide thin films are investigated. Also, its effect on the flatband voltage and threshold stability of silicide-gate MOS capacitors was studied.

EXPERIMENTAL PROCEDURE

Molybdenum disilicide films, nominally 3000Å thick, were deposited onto oxidized silicon substrates. The sputtering was done in an MRC 603 system using dc magnetron from an alloy target of stoichiometric proportion. The parameters used were 2KW of power and 3μ of argon pressure. Then, phosphorus was implanted into the silicide films with a dose ranging from 10^{15} and 5×10^{16} ions/cm². The implantation energy was calculated using an interpolation program based on Brice (14). Silicon and molybdenum were used as interpolating points. The density of MoSi₂ was assumed to be 5.7 g/cm³, which was measured on sputtered thin films (15) and was less than the values of 5.9-6.3 g/cm³ reported for bulk silicide (16). The projected range and straggle, R_p and ΔR_p , were calculated for boron (B¹¹), phosphorus (P³¹), arsenic (As⁷⁵) and antimony (Sb¹²¹), using their range data in Si and Mo given by Smith (17). These are depicted in Figs. 1 and 2, respectively, up to 500 KeV. The corresponding values in molybdenum are also shown. The energy used was 140KeV throughout this experiment. Unimplanted samples were also included for comparison. Subsequently, a silicon dioxide (silox) layer was deposited at 350°C on top of MoSi₂ in order to prevent outdiffusion of phosphorus ions during the high temperature annealing steps. Also, it protects the silicide from oxidation by any trace of oxygen in the annealing ambient. The wafers were annealed in nitrogen between 900-1000°C for times up to 1 hr. The oxide layer was later removed with buffered HF. Sheet resistance was measured using a four-point probe before and after implantation as well as after annealing and removal of the oxide cap.

MOS capacitors were made on (100), n-type, phosphorus-doped wafers. Various thicknesses (<2000Å) of oxide were grown at 1000°C in dry oxygen. The 3000Å-thick silicide films were then sputtered. Half of the samples were implanted with phosphorus at 5×10^{15} ions/cm² and 50KeV while the rest were not implanted. The silicide films were then patterned into 20-mil-diameter dots with photoresist and etched

in a planar plasma etcher with NF_3 (18,19). A 5000Å-thick oxide layer was then deposited in a low pressure system and subsequently the samples were annealed at 900°C for 1 hr. Another patterning step defined the contact holes and buffered HF was used to etch the oxide. Aluminum was then put on both sides of the wafers. The front side was patterned and etched in $\text{H}_3\text{PO}_4/\text{HNO}_3$ solution. A final annealing step in H_2 at 400°C finished the process.

STRUCTURE AND COMPOSITION

X-ray diffraction measurements were made with a Siemens D500 automated powder diffractometer. After deposition or ion implantation, the silicide films were essentially amorphous. The X-ray diffraction pattern only showed a small and broad peak around 2θ of 41.6°, corresponding to the (111) peak of the hexagonal and low temperature phase of MoSi_2 . This confirms that during ion implantation, little recrystallization took place. However, annealing these films at high temperatures resulted in significant structural changes, as shown in Figs. 3 and 4. Fig. 3 shows the major diffraction peaks for the silicide films which are (a) unimplanted, and implanted with (b) 10^{15} , (c) 2×10^{16} and (d) 5×10^{16} phosphorus ions/cm². These films were then annealed at 900°C for 1 hour. The unimplanted film had tetragonal MoSi_2 (t- MoSi_2) as the major phase, with small traces of hexagonal MoSi_2 (h- MoSi_2) and Mo_2C or carbon-stabilized, hexagonal Mo_5Si_3 ($\text{Mo}_5\text{Si}_3(\text{C})$) phases. For the film implanted with 10^{15} ions/cm², h- MoSi_2 appeared as a significant minor phase (Fig. 3(b)). When the implantation dosage exceeded 2×10^{16} ions/cm², major structural difference can be observed. h- MoSi_2 became the major phase, with t- MoSi_2 as a minor, though significant, phase. Also, for the most heavily implanted (5×10^{16} ions/cm²) case, MoP was detected in significant amounts. Furthermore, Mo_2C or $\text{Mo}_5\text{Si}_3(\text{C})$ was no longer detectable, inferring that it was a contaminant from the sputtering target and not a product of the implantation process.

In Fig. 4, the diffraction peaks for films implanted with the same fluences but were then annealed at 1000°C for 1 hr. are shown. The unimplanted film had the same features as the 900°C case, with the (110)-oriented, t- MoSi_2 as the major phase (Fig. 4(a)).

Little change was seen for the 10^{15} ions/cm² implanted film, except the amount of h-MoSi₂ decreasing to trace level (Fig. 4(a) vs. Fig. 4(b)). On the other hand, for the two heavily implanted samples, the predominant phase was changed from h-MoSi₂ into t-MoSi₂. Also, the t-MoSi₂ appears to be more randomly oriented than the undoped or lightly doped films. Moreover, MoP was again observed for the film implanted with 5×10^{16} ions/cm² case but not the one with 2×10^{16} ions/cm².

There are several interesting observations that can be made from the diffraction data just described. Firstly, the presence of phosphorus in the silicide apparently increases the hexagonal to tetragonal MoSi₂ phase transition temperature. For the undoped film, it has been shown to be $\sim 800^\circ\text{C}$ (20). This is also confirmed by our present data for the undoped film which, after annealed at 900°C for 1 hr., had mostly t-MoSi₂ phase. For the silicide film implanted with 10^{15} /cm², the transition was almost completed at 900°C . But increasing the dosage to over 2×10^{16} ions/cm² has made the transformation take place between 900 and 1000°C . Secondly, the main contaminant observed here is Mo₂C or Mo₅Si₃(C). Mo₂C has a face-centered cubic structure and a bulk resistivity of $65 \mu\Omega\text{-cm}$ at 300K (21). Hexagonal Mo₅Si₃, similar to its niobium counterpart (22), has only been found in the presence of carbon (23) but its resistivity has not been reported. Thirdly, while no molybdenum/phosphorous compound was detected at low dosage, MoP was detected at a dosage of 5×10^{16} ions/cm². The occurrence of this compound has been mentioned previously in a phosphorus-ion-induced silicide formation study (24). Molybdenum phosphide has a bulk resistivity of $0.9 \text{m}\Omega\text{-cm}$ at 300°K (25), several orders of magnitude higher than that of the silicide.

Fig. 5 shows the depth profiles of various ions obtained from SIMS for the unimplanted sample and two as-implanted samples. Specifically, the ions are molybdenum ($^{96}\text{Mo}^+$), silicon ($^{28}\text{Si}^{++}$), phosphorus ($^{31}\text{P}^+$), carbon ($^{12}\text{C}^+$) and argon ($^{40}\text{Ar}^+$). Molybdenum and silicon are the main constituents and their intensity ratio is fairly constant throughout the film. The presence of carbon further confirms the X-ray data earlier. It was probably incorporated during the high temperature metallurgical step in the alloy target fabrication. On the other hand, argon was entrapped in the film during sputtering since it was used as the sputtering gas. The presence of argon and carbon in alloy-sputtered silicide films has also been observed in the case of NbSi₂ (22). Fig. 5(a) is for the unimplanted

film whereas the profiles for silicide films implanted with phosphorus fluence of $1 \times 10^{15}/\text{cm}^2$ and $5 \times 10^{16}/\text{cm}^2$ are shown in Fig. 5(b) and (c) respectively. For all three films, high intensity of mass 31 in the surface oxide film is not attributed to phosphorus ions. Instead, it is probably due to molecules such as SiH. At a dose of $1 \times 10^{15}/\text{cm}^2$, the phosphorus ions were just detectable (compare Fig. 5(a) with 5(b)). Also, the peak of the phosphorus ions can be seen very close to the middle of the silicide films, as simulated.

The peak intensity of phosphorus ions (mass 31) in the silicide is correlated with the peak phosphorus concentration as calculated from the dosage and projected straggle, as shown in Fig. 6. A linear relationship is observed for dosage at or above 5×10^{15} ions/ cm^2 .

The high temperature annealing did not significantly change the relative percentage of molybdenum, silicon and argon but redistributed phosphorus and carbon. Only the profiles for the unimplanted sample and the sample implanted with 5×10^{16} ions/ cm^2 , after annealing at 900°C , are shown in Figs. 7(a) and (b), respectively. Though the level of phosphorus became fairly uniform within the film, it accumulated at the outer interface. Also, the saturation level apparently depended on the implantation dosage. Fast outdiffusion of phosphorus through WSi_2 has also been observed (26). The distribution of carbon is even more interesting. Initially, it was uniform but, after annealing it became localized or clustered, particularly for the implanted samples. Since Mo_2C or $\text{Mo}_5\text{Si}_3(\text{C})$ was detected after annealing, the variation of the carbon ions is probably related to the nucleation of these carbide phases. Finally, there is no distinguishing difference between films annealed at 900 and 1000°C .

RESISTIVITY

Electrical properties of these silicide films were characterized with of sheet resistance measurements. As illustrated in Fig. 8, sheet resistance was studied as a function of annealing temperature for various films annealed for 1 hour in nitrogen. The as-implanted films all had sheet resistance of approximately $30\Omega/\text{square}$. In general, the sheet resistance decreased with increasing temperature up to 950°C . Beyond that, the variation of sheet resistance with temperature was small. However, the sheet resistance of the sample implanted with 5×10^{16} ions/ cm^2 was approximately twice that of the rest. Specifically, the sheet resistance of the most heavily implanted sample dropped from $33\Omega/\text{square}$ to $7\Omega/\text{square}$ after 1 hr. at 950°C while the rest from $28\text{--}31\Omega/\text{square}$ to $3.8\text{--}4.5\Omega/\text{square}$. After 1

hr. at 1000°C, the sheet resistance was essentially the same in either case as those annealed at 950°C.

In the case of isothermal annealing, the sheet resistance was measured as a function of annealing time up to 1 hr. at 1000°C for various dosage, as shown in Fig. 9. Generally, the sheet resistance dropped off abruptly during the first 15 min of annealing. Thereafter, the change of sheet resistance with time was small. In particular, the unimplanted film and the films implanted up to 2×10^{16} ions/cm² all decreased their sheet resistance from 26-33Ω/square to 3.3-5.5Ω/square after 15 min at 1000°C. After one hour of annealing, the sheet resistance was between 4 and 4.8Ω/square. On the other hand, in the case of implantation with 5×10^{16} ions/cm², a sheet resistance of 7.5Ω/square was obtained after 15 min, leveling off only to 7Ω/square after 1 hr.

To understand the annealing characteristics of these silicide films, the structural data obtained from X-ray diffraction are correlated with the sheet resistance measurements. After implantation, even at the heaviest fluence used here, the films were essentially amorphous, as reflected in the fairly high sheet resistance (26-33Ω/square). This indicates little heating occurred in this step. After annealing at 900°C for 1 hr., the unimplanted sample was recrystallized into mostly (110)-oriented t-MoSi₂ and hence the decrease in sheet resistance to 5.8Ω/square. The silicide film which was implanted with 10^{15} ions/cm² also had (110)-oriented t-MoSi₂ as the predominant phase. In this case, the higher resistance measured (10Ω/square) can be attributed to the presence of h-MoSi₂. When the silicide films were implanted with over 2×10^{16} ions/cm² and annealed at 900°C for 1 hr., they contained mostly h-MoSi₂ and also t-MoSi₂. Hence, still higher sheet resistance (31-35Ω/square) was measured. In the case of 5×10^{16} ions/cm², MoP, which has resistivity several orders of magnitude higher than that of the silicide, also contributed to the higher resistance here.

When the annealing temperature was increased to 1000°C, the undoped showed little change in diffraction pattern or sheet resistance. The disappearance of h-MoSi₂ in the film implanted with 10^{15} ions/cm² resulted in decreased sheet resistance (from 10 to 4Ω/square). The annealing behavior for the films implanted with 2×10^{16} and 5×10^{16} ions/cm² differed in that, despite h-MoSi₂ was transformed into t-MoSi₂ in both cases, the presence of MoP in the

latter but not the former resulted in a nearly two-fold increase in sheet resistance (7 vs 4 Ω /square). In this way, one can see the effect of implantation of phosphorus on the structure and resistivity of these films.

MOS PROPERTIES

To investigate the effect of these properties on device characteristics, MOS capacitors were fabricated and tested. The work function, threshold voltage stability and breakdown voltage were studied with comparative C-V measurements. The flatband voltages determined from C-V measurements are shown in Figs. 10(a) and (b), for the unimplanted and implanted samples respectively. Since extrapolation of the flatband voltage to zero oxide thickness from least-square-fitting yields ϕ_{MS} values of 0.67 and 0.57eV, the work functions are hence 4.93 and 4.83eV, respectively. The corresponding surface state densities calculated from the slope of the V_{FB} vs t_{ox} dependence were 1.26×10^{11} and 1.24×10^{11} /cm². Also, temperature-bias stress measurements, performed with +10V at 200°C for 15 min on these devices resulted in negligible flatband voltage shift, indicating threshold voltage stability. Furthermore, breakdown voltage measurements also yielded similar results for these two types of devices.

For the case of 400Å-thick oxide, the breakdown field distributions are shown in Figs. 11(a) and (b), for unimplanted and implanted gates, respectively. On the average, the breakdown field of ~7MV/cm was observed. Based on these results, the implanted silicide film, in the case of implantation fluence of 5×10^{15} ions/cm², showed little difference in MOS properties when compared with the unimplanted ones.

SUMMARY

The effect of phosphorus implantation into molybdenum disilicide thin films has been studied. The structural, compositional and electrical properties of these films were investigated with X-ray diffraction, secondary ion mass spectrometry and sheet resistance measurements. Implanted films showed a higher hexagonal to tetragonal MoSi₂ phase transition temperature than the unimplanted one.

Also, at high fluence (5×10^{16} ions/cm²), MoP was detected, with in a sheet resistance value twice that of the unimplanted or lightly implanted films. Isothermal and isochronal annealing indicated a minimum temperature of 950°C and a maximum fluence of 2×10^{16} ions/cm² can be used. Comparative C-V measurements showed similar MOS characteristics between the unimplanted and implanted silicide films.

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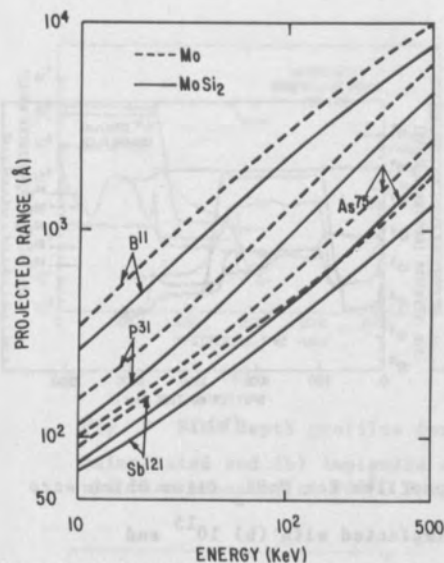


Fig. 1 Calculated projected range of B^{11} , P^{31} , As^{75} and Sb^{121} in Mo and $MoSi_2$.

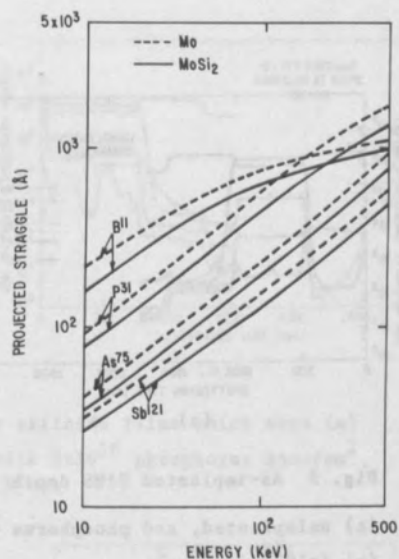


Fig. 2 Calculated projected straggle of B^{11} , P^{31} , As^{75} and Sb^{121} in Mo and $MoSi_2$.

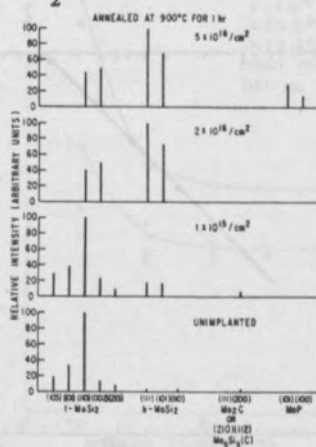


Fig. 3 Major X-ray diffraction peaks for various MoSi₂ films after implantation and annealing at 900°C for 1 hr.

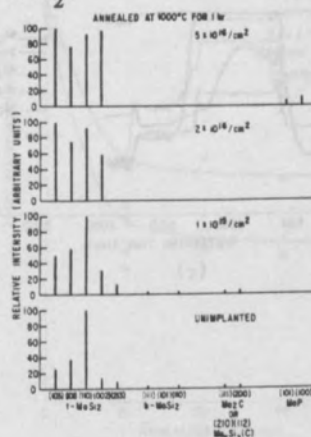


Fig. 4 Major X-ray diffraction peaks for various MoSi₂ films after implantation and annealing at 1000°C for 1 hr.

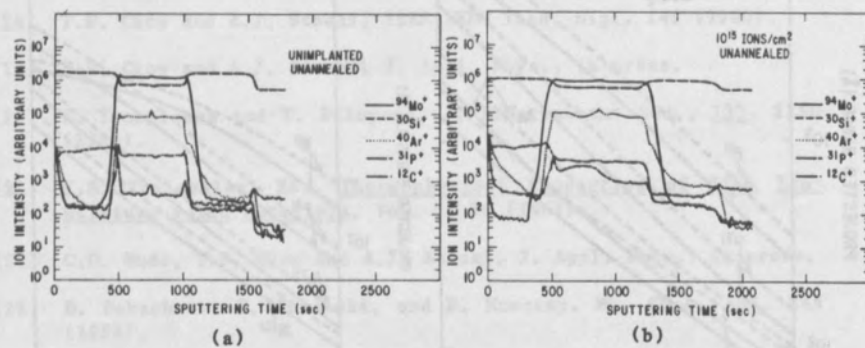


Fig. 5 As-implanted SIMS depth profiles for MoSi_2 films which were (a) unimplanted, and phosphorus implanted with (b) 10^{15} and (c) 5×10^{16} ions/cm².

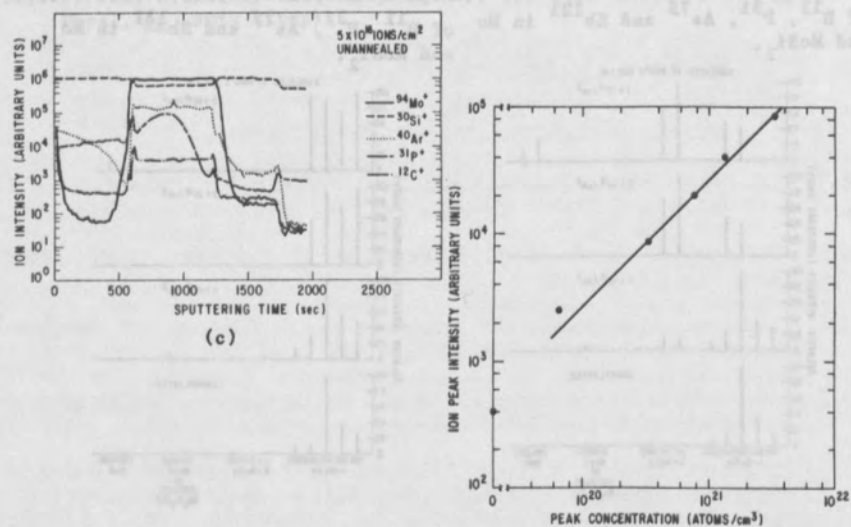


Fig. 6 Mass 31 ion peak intensity as a function of calculated peak concentration of implanted phosphorus.

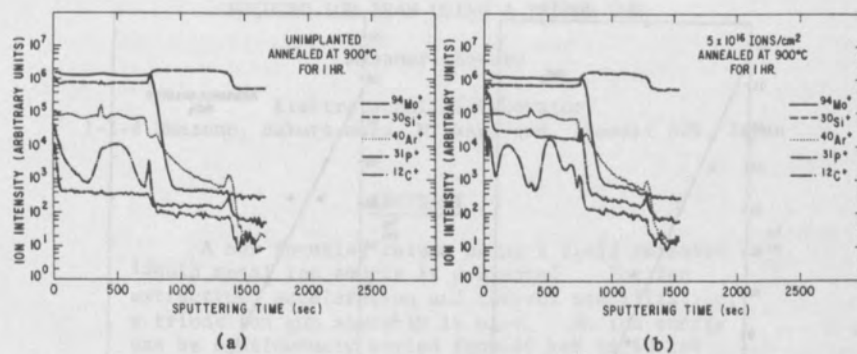


Fig. 7 SIMS depth profiles for silicide films which were (a) unimplanted and (b) implanted with 5×10^{16} phosphorus ions/cm², and then annealed at 900°C for 1 hr.

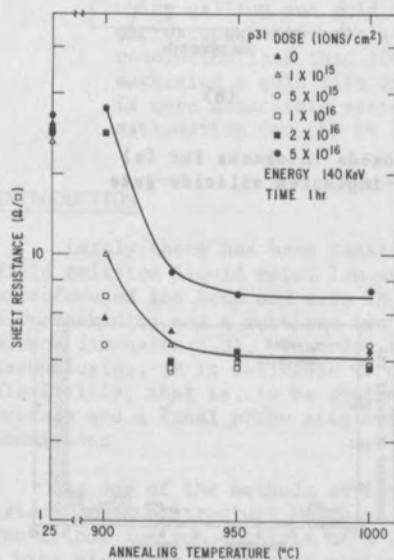


Fig. 8 Sheet resistance as a function of annealing temperature for various silicide films annealed for 1 hr.

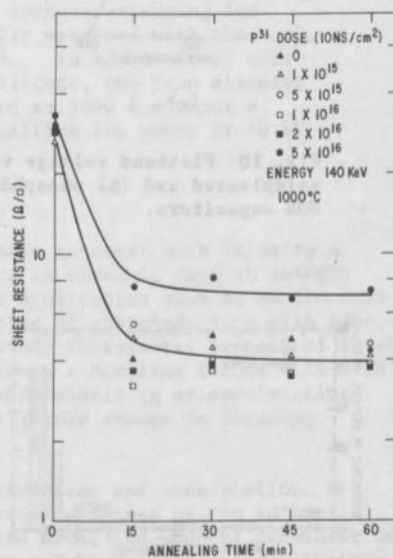
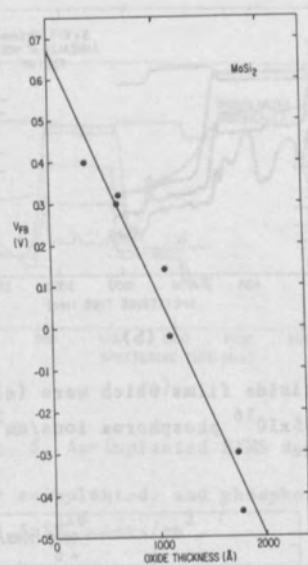
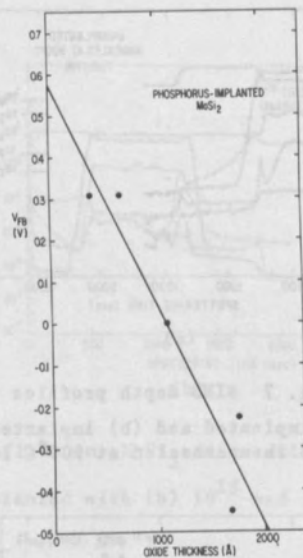


Fig. 9 Sheet resistance as a function of annealing time at 1000°C for silicide films implanted with various dosage of phosphorus.

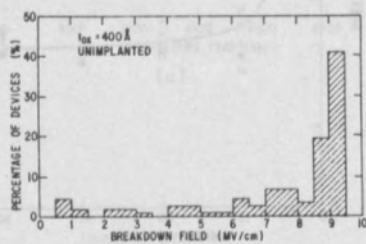


(a)

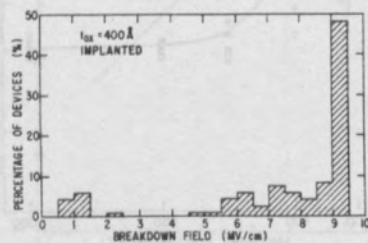


(b)

Fig. 10 Flatband voltage vs. oxide thickness for (a) unimplanted and (b) phosphorus-implanted silicide-gate MOS capacitors.



(a)



(b)

Fig. 11 Gate oxide breakdown field distribution for (a) unimplanted and (b) phosphorus-implanted silicide-gate MOS capacitors.

FOCUSED ION BEAM USING A TRIODE GUN

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ABSTRACT

A new focusing column using a field emission liquid metal ion source is presented. For ion extraction, acceleration and current stabilization, a triode ion gun assembly is used. An ion energy can be continuously varied from 20 keV to 50 keV with a small deviation (~ 5 mm) of the virtual crossover point. At the same time, the value of an angular intensity at 50 kV increases by about twice compared with the value ($35 \mu\text{A}/\text{sr}$ at $10 \mu\text{A}$ gallium ion current) at 20 kV. The accelerated ions are focused down on a target by one einzel lens. By using gallium and gold ion sources, scanning ion microscope images are readily obtained with the resolution less than $1000 \text{ \AA}$. In addition, by micro-machining a gold film on silicone, the beam diameter is more accurately estimated as $1000 \text{ \AA}$ without a astigmatism for the 55 pA gallium ion probe at 50 kV.

INTRODUCTION

Lately there has been considerable interest both in using a field emission liquid metal ion source in order to form an intense microfocused ion beam and also in its application such as an ion beam micromachining and a maskless ion doping of semiconductors with sub-micron dimension(1-3). In order to study fundamental aspects of these technologies, it is desirable to develop a focusing column with high flexibility, that is, to be controllable widely in an accelerating voltage and a final probe size with a little change in focusing conditions.

As one of the methods of ion extraction and acceleration, a triode ion gun structure has been already proposed by the authors(4). The triode ion gun consists of a liquid metal ion source, a cathode and a bias electrode which acts similar to a Wehnelt of a triode electron gun. From our preliminary results, it has been shown that the emission current can be adjusted by a lower voltage applied to the bias electrode than the extraction voltage (typically $4\sim 8 \text{ kV}$) in the usual diode structure and that a stability of the emission current can be considerably improved by feedback to the bias voltage of the current

fluctuation.

In this work, the features of the focused ion beam column using the triode ion gun with a maximum accelerating voltage of 50 kV are presented and some results obtained by use of the submicron ion probes of Ga and Au are demonstrated.

ION OPTICAL COLUMN

Figure 1 shows a schematic diagram of the optical column developed here. In the triode ion gun used here, the ion emitter apex locates at about 1.8 cm apart from the cathode and the ions can be accelerated up to 50 kV in this space. In order to realize an high stable ion emission for a long periode, the total emission current is detected at the cathode and stabilized by feedback to the bias voltage applied between the emitter and the bias electrode. Detailed characteristics of this ion gun are described in next section.

An electrostatic einzel lens has been used, because the variation of a focal point with the change in the accelerating voltage can be minimized by means of applying the divided accelerating voltage to the inner electrode of the lens, and because the wide space can be obtained between the ion gun and the lens in order to attach the beam blanking electrode and the movable objective aperture. The distance between the emitter and the principal plane of the lens is about 7.5 cm. The lens is usually excited so that the magnification becomes 0.9. In this lens excitation, the spherical and chromatic aberration coefficients are calculated as 1800 cm and 40 cm, respectively. Since the objective aperture size limiting a lens acceptance half angle mainly rules the final probe diameter, four different apertures can be supported on the holder and selected from outside vacuum. Two parallel plate deflectors are designed so that an astigmatism by deflection is less than 200 Å at 50 kV. Therefore, the maximum scanned area at 50 kV is restricted to about 450 μm square. At present, the deflection signals are applied from a double ramp wave generator and only simple patterns such as a grating can be delineated on a target.

In Fig.2 an external view of the present column is shown. The triode electron gun assembly of the electron microscope is used for the triode ion gun. Thus, all the sections floated on the high voltage can be equipped in vacuum. The column is evacuated by 4 inches oil diffusion pump with a liquid N₂ trap and the vacuum is within 2×10^{-7} Torr. By use of the detector usually used in scanning electron microscope, scanning ion microscope images can be displayed by detecting secondary electrons generated with ion bombardment. Thus, the optical axis can be mechanically adjusted by both the movements of the ion emitter to the cathode aperture and of the illumination column to the lens axis, observing the scanning ion microscope image.

CHARACTERISTICS OF THE TRIODE GUN

In the triode ion gun, the electric field at the emitter apex generated by the accelerating voltage is controlled by the bias voltage and the geometrical configurations such as a protrusion length and an aperture diameter of the bias electrode. The experimental dependence of the accelerating voltage required to extract a Ga ion current of 5 μA on the bias voltage is shown in Fig.3 for two values of the protrusion length H , where the bias cap with the aperture diameter of 3.2 mm is used. Since the shielding effect by the bias cap is strengthened with the decrease in the protrusion length, the slope of the linear relation increases for the small value of H . Accordingly, by choosing the electrode geometry appropriately, the accelerating voltage in the range of 20 kV and 50 kV can be changed with the bias voltage of +0.6 kV to -2.6 kV.

In addition to this main property of the triode gun, some effects caused by focusing action in the acceleration space can be considered. The illustration of Fig.4 shows the ion trajectories expected for different accelerating voltage. In the case of higher voltage denoted by V_2 , many ions will be converged and pass through the cathode aperture compared with the case of lower voltage denoted by V_1 . Then the increase in angular intensity should be observed with the increase in the accelerating voltage. At the same time, the shift of the virtual crossover point, denoted by Δa in the figure, will occur.

The relationship between the accelerating voltage V_a and Δa can be determined from the measurement of the lens excitation (the ratio of the voltage applied to the lens to V_a) at which the scanning ion microscope image is in focus. The result is presented in Fig.5, where the value of Δa is the increment from the value at 12 kV obtained by removing the bias cap. Such a shift causes a defocusing of the image which can be smoothly readjusted by the fine focusing power supply as shown in Fig.1. On the other hand, the defocusing is not observed with the change in the emission current of 2 to 20 μA at a fixed accelerating voltage, probably because the change in the bias voltage required to vary the current is considerably small compared with the accelerating voltage.

Figure 6 shows a dependence of the angular intensity on the accelerating voltage for some values of the emission current I_t for the Ga and the Au ion sources. As expected from the beam trajectories, the angular intensity increases linearly. Since the source brightness increases proportionally to the accelerating voltage, the crossover diameter at 50 kV becomes 0.8 times compared with that at 12 kV, neglecting an aberration in the acceleration space on the virtual image. Therefore, the ultimate probe diameter expected in this column is the same order as the crossover size at 12 kV which is probably a few hundreds angstrom(1).

EXPERIMENTAL RESULTS BY FOCUSED BEAMS

Scanning ion micrographs of the surface of Ni 1000 mesh/inch are shown in Fig.7, where a) the Ga and b) the Au ion sources are operated under the conditions of the 30 kV accelerating voltage and the 0.47mrad acceptance half angle. Moreover, both pictures are taken with the same magnification. As gold at the elevated temperature significantly vaporizes, the working temperature is always checked by use of a spot thermometer. However, a high voltage over 40 kV could not be applied stably to the ion gun because of generation of discharge. From our previous report(5), the energy spread is 12 eV for the Au at 2 μ A and for the Ga at 5 μ A for the working temperature of $\sim 200^\circ\text{C}$. Then the expected probe diameters are calculated as 750 $\text{\AA}$ for both the Ga and the Au ion beams, which is corresponding to the image resolution less than 1000 $\text{\AA}$ evaluated in both pictures. In addition, we should note that the vertical edge of the image obtained by the Au ion beam is not well defined in comparison with that by the Ga.

Pictures in Fig.8 show also scanning ion micrographs of the Ni mesh obtained by the Ga ion beam under the conditions of the 30 kV accelerating voltage and 94 μ rad acceptance half angle. Under these conditions, the chromatic aberration disc is calculated as 150 $\text{\AA}$, but the image resolution estimated from Fig.8 b) is about 200 $\text{\AA}$. When we assume that the image resolution is about one half of the real probe diameter(6), the virtual crossover diameter of this source is estimated as $\sim 400 \text{\AA}$ which is the reasonable value in comparison with the result of the 380 $\text{\AA}$ width line delineation reported by Seliger et al). In Fig.8 b), it is also seen that the vertical edge is not well defined with the magnitude of a few hundreds angstrom. At present, it is not understood whether such a phenomenon is caused by a fluctuation of the probe current, by the change in the position of the ion probe, or by other effects. However, since the degree of the indefiniteness is different in the cases of the Ga and the Au ion beam, this problem seems to be essential in forming a probe less than 1000 $\text{\AA}$ by use of the liquid metal source and the optical column with the magnification of unity.

In order to determine the probe diameter more exactly, 1300 $\text{\AA}$ thickness gold films on silicone substrate are prepared and micro-machined by the ion beam. Figure 9 shows scanning electron microscope images of the gold film machined by 50 kV Ga ion probes. The Ga source is operated under the conditions of the 5 μ A emission current and the temperature less than 300°C . The vertical wide lines are delineated by the ion current of 3 nA (3.8 mrad acceptance half angle) and with a scanning time of 57 sec/mm. The line width is estimated as 0.7 μm . On reduction of the objective aperture size by 1/8, the probe current decreases to 55 pA and about 90 lines in a 40 μm square are delineated with the scanning time of 300 sec/mm. Then the total exposure time is 18 minutes. As seen in these photos, the lines of 1000 $\text{\AA}$ width is clearly sputter-etched without any astigmatism and with a fluctuation of line width less than a few hundreds angstrom. Figure 10 is scanning

electron micrographs showing cross sections of the grooves presented in Fig.9. Figure 10 a) is for the 0.7 μm wide line and the profile shows an asymmetrical feature. This is due to the asymmetrical distribution of the probe current density which is probably caused by the misalignment of the objective aperture position to the optical axis. On the other hand, the profile of the 1000 Å wide line is very sharp and shows the symmetrical aspect, but the detailed dimension is estimated as 1200 Å at the surface and 600 Å at the bottom. Therefore the probe diameter defined as the full width at half maximum is less than 1000 Å.

SUMMARY

It was shown that the present optical column based on the triode ion gun structure was easy to control the accelerating voltage, the emission current and the final probe diameter, and also the ion gun could be readily assembled and exchanged. The ion probe with the order of 1000 Å in diameter was stably obtained by use of both the Ga and the Au ion sources, though for the Au the accelerating voltage over 40 kV could not be stably applied to the ion gun. Moreover, a remarkable astigmatism could not be recognized in forming the ion probe with 1000 Å diameter. Further high resolution pattern delineation will be attained by some improvements such as a stability of the high voltage.

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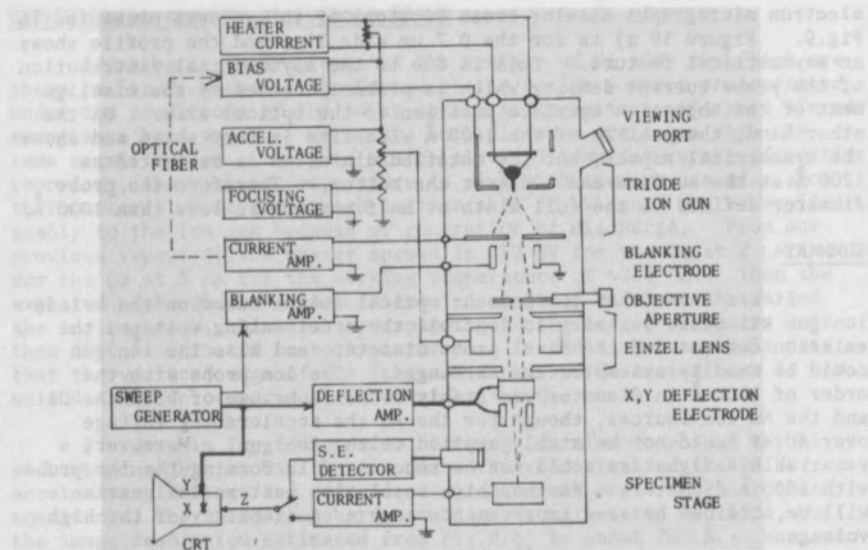


Fig.1 Schematic diagram of the focused ion beam apparatus using the triode ion gun.

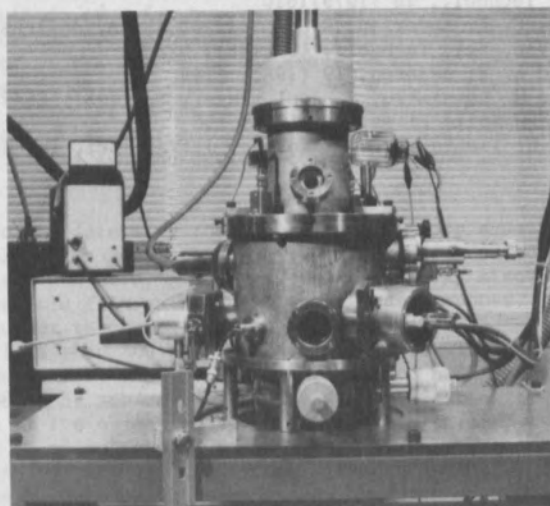


Fig.2 External view of the ion optical column.

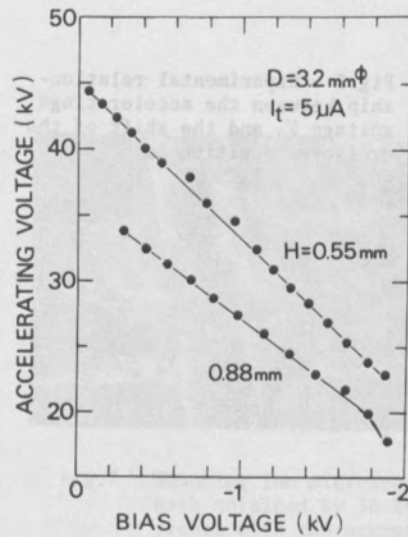


Fig.3 Characteristics of the triode ion gun, where the dependence of the accelerating voltage required to extract a gallium ion current of 5 μ A is presented for two values of the length H protruded from the bias electrode with an aperture of 3.2mm.

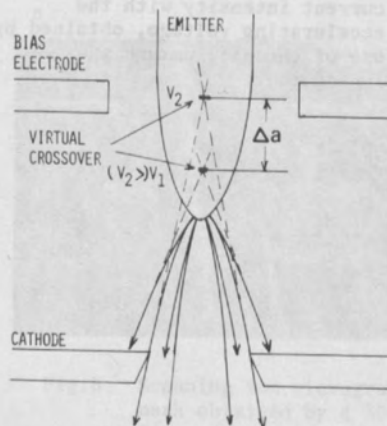


Fig.4 Schematic of the ion trajectories in the acceleration space, where V_1 and V_2 are the accelerating voltage ($V_2 > V_1$) and Δa the shift of the crossover position.

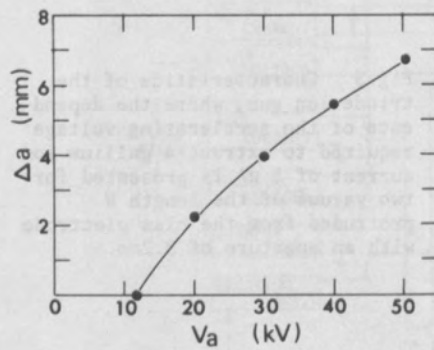


Fig.5 Experimental relationship between the accelerating voltage V_a and the shift of the crossover position Δa .

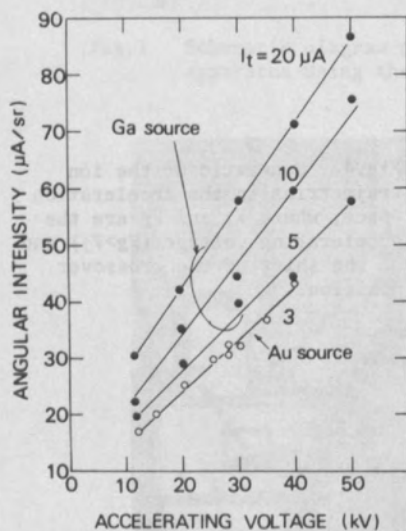


Fig.6 Variations of the angular current intensity with the accelerating voltage, obtained by use of the gallium and the gold ion source.

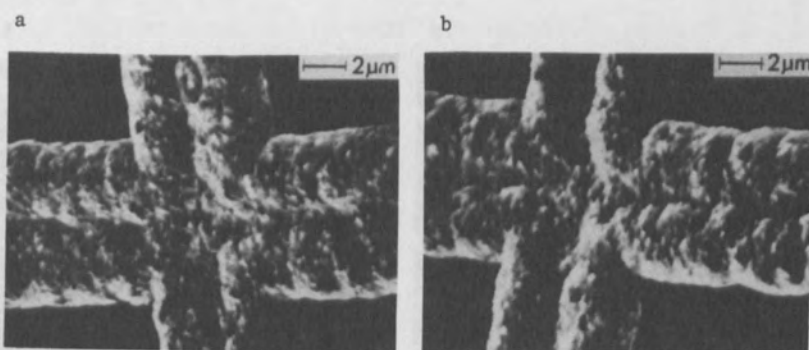


Fig.7 Scanning ion microscope images of the surface of nickel mesh obtained by 30 kV gallium (a) and gold (b) ion probes with the acceptance half angle of 0.47 mrad, where the probe current is 28 pA for the gallium and 21 pA for the gold.

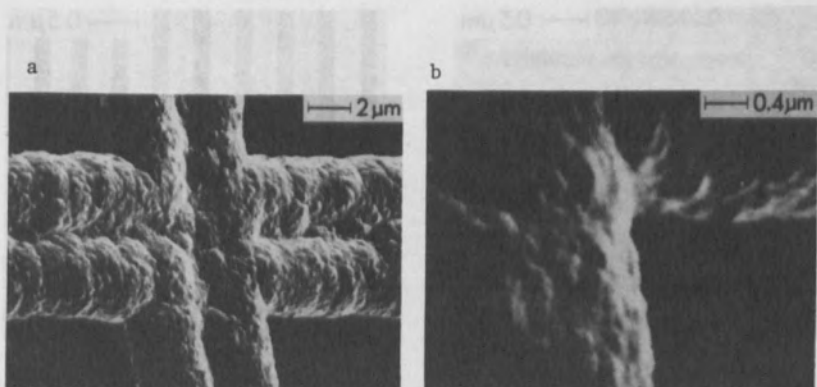


Fig.8 Scanning ion micrographs of the surface of the nickel mesh obtained by a 30 kV gallium ion probe with the 94 μrad acceptance half angle, where the calculated aberration disc is 150 Å.

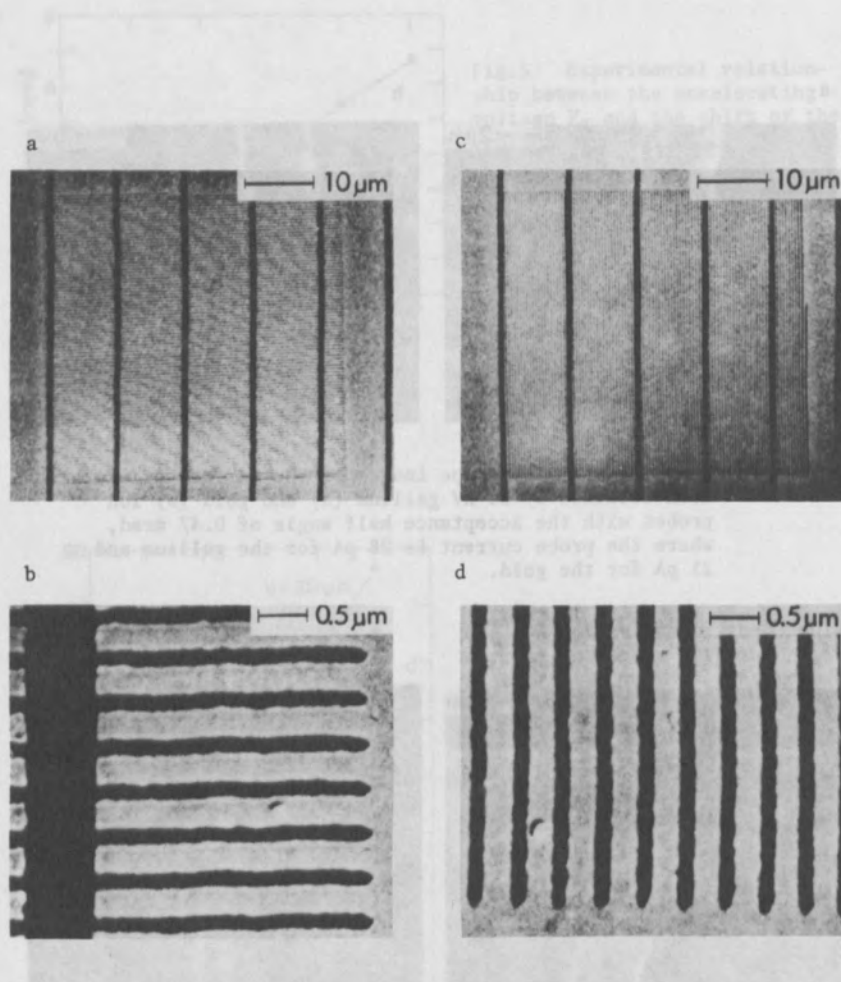


Fig.9 Scanning electron micrographs of a 1300 Å thickness gold film on silicon substrate machined by 50 kV gallium ion probes. Vertical lines estimated as 0.7 μm width are etched with the 3 nA probe current and narrow lines estimated as 1000 Å width with the 55 pA probe current.

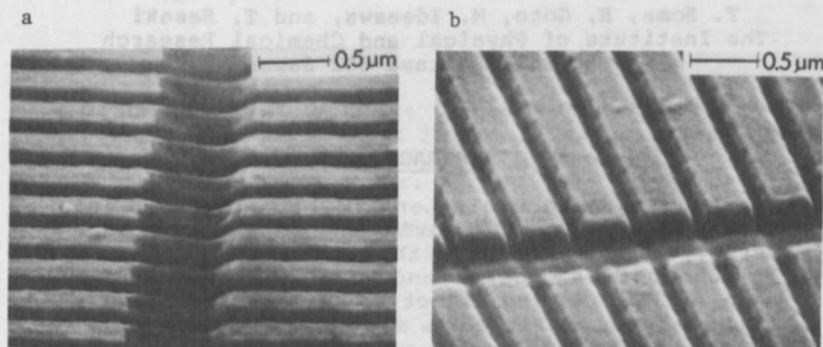


Fig.10 Scanning electron micrographs showing the cross sections of a) 0.7 μm wide line and b) 1000 $\text{\AA}$ wide line in the gold film machined by 50 kV gallium ion.

MOVING QUADRUPOLE LENS CONCEPT FOR ION BEAM LITHOGRAPHY

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ABSTRACT

Moving Quadrupole Lens (MQL) concept is introduced as a means of moving its lens axis transversely in synchronism with the deflection signal. The theoretical background is given as an extension of MOL (Moving Objective Lens) and the merit of MQL focus deflection system is discussed against that consisting of separate quadrupole lenses and deflectors. Also the practical problem are considered for physical realization of the MQL focus deflection system with the aim of applying it to high energy ion beam lithography system.

Introduction

Five years ago, at the 14th Symposium on Electron, Ion and Photon Beam Technology, held in Palo Alto, California, we introduced a mathematical formulation of MOL (Moving Objective Lens) concept, gave some theoretical consideration concerning the elimination of deflective aberrations, and derived the aberration formulas for the system of mixed focus and deflection field [1].

Since then, we believe, this concept has had considerable influence on the development of high performance electron beam focus deflection system, especially for the shaped beam, used in the exposure system for micro-fabrication [2]-[10]. Here, we introduce a new concept, MQL or Moving Quadrupole Lens concept, which, we hope, will be useful for development of high performance focus deflection system for high energy charged particle beam as well as electron beam.

MQL concept like the MOL concept, provides a means of moving quadrupole lens, transversely to its optical axis, in synchronism with the deflection signal. The theoretical background will be given as an extension of MOL and the merit of MQL focus deflection system is discussed against

that consisting of separate quadrupole lenses and deflectors. Also the physical interpretation will be given to each term of MQL, which will be useful for physical realization of MQL system.

MOL Concept

Since the MQL concept is an extension of the MOL concept, and the MOL concept is not necessarily well understood among people concerned, the presentation of the MOL concept seems to be in order.

It is well known that the axially symmetric lens field can be represented as

$$\phi_F(w, \bar{w}, z) = \sum_{k=0}^{\infty} (-1)^k \frac{(w \bar{w})^k}{4 (k!)^2} \phi_F^{(2k)}(z) \quad (1)$$

where w is the complex notation of the x-y coordinate as $w = x + iy$, $\bar{w}$ its complex conjugate, z the lens axis coordinate, and $\phi_F(z)$ the axial potential function (Fig. 1). The MOL concept can be formulated as a two dimensional Taylor expansion, in a plane perpendicular to its optical axis, of an axially symmetric lens field. The MOL potential ϕ_{MOL} is defined as the expansion of eq. (1) with respect to w and $\bar{w}$ with increment W and $\bar{W}$, respectively, which are the amount of shift in two dimension or the complex deflection parameters, and ϕ_{MOL} is written as

$$\begin{aligned} \phi_{MOL}(w, \bar{w}, W, \bar{W}, z) &= \phi_F(w + W, \bar{w} + \bar{W}, z) \\ &= \sum_{k=0}^{\infty} \frac{1}{k!} \left(W \frac{\partial}{\partial w} + \bar{W} \frac{\partial}{\partial \bar{w}} \right)^k \phi_F \end{aligned} \quad (2)$$

Expanding eq. (2) up to $k = 3$, we obtain, using the function,

$$\phi_{MOL}(w, \bar{w}, W, \bar{W}, z) = \sum_{k=0}^{\infty} (-1)^k \frac{(W \bar{W})^k}{4 k! (k+n)!} \phi_F^{(2k)}(z) \quad (3)$$

the following formula,

$$\phi_{\text{MOL}} = + F_0(w, \bar{w}, \phi_F(z)) \quad (4)$$

$$+ \frac{1}{2} (W\bar{w} + \bar{W}w) F_1(w, \bar{w}, -\frac{1}{2} \phi_F^{(2)}(z)) \quad (5)$$

$$+ \frac{1}{2} (W^2\bar{w} + \bar{W}^2w) F_2(w, \bar{w}, -\frac{1}{32} \phi_F^{(4)}(z)) \quad (6)$$

$$+ \frac{1}{2} (W\bar{W} + \bar{W}W) F_0(w, \bar{w}, -\frac{1}{4} \phi_F^{(2)}(z)) \quad (7)$$

$$+ \frac{1}{2} (W^3\bar{w} + \bar{W}^3w) F_3(w, \bar{w}, -\frac{1}{1152} \phi_F^{(6)}(z)) \quad (8)$$

$$+ \frac{1}{2} (W^2\bar{W} + \bar{W}^2W) F_1(w, \bar{w}, -\frac{1}{16} \phi_F^{(4)}(z)) \quad (9)$$

In deriving the above formula, the recurrence relations

$$\begin{aligned} \frac{\partial}{\partial w} w^n F(w, \bar{w}, f(z)) &= n w^{n-1} F(w, \bar{w}, f(z)) \\ &= w^{n-1} F(w, \bar{w}, n f(z)) \end{aligned} \quad (10)$$

$$\frac{\partial}{\partial \bar{w}} w^n F(w, \bar{w}, f(z)) = n w^n F(w, \bar{w}, f(z))$$

$$= w \frac{n+1}{n+1} F_{n+1}(w, \bar{w}, - \frac{1}{4(n+1)} \frac{(2)}{n} f_n(z)) \quad (11)$$

and their complex conjugate forms are useful, which can easily be derived from eq. (3) by applying rules of differentiations. Since the term

$$\frac{n}{n} w F_n(w, \bar{w}, f_n(z)) \quad (12)$$

represents the potential for 2n-tuple pole field with $f_n(z)$ as its axial function, the terms in the above equation

$$\frac{n}{n} w \frac{n}{n} F_n(w, \bar{w}, f_n(z)) \quad (13)$$

are shown to describe the dynamic 2n-tuple field, dynamic in the sense that its intensity varied as the deflection parameter. Since the phase angle associated with W is α and that of w is θ , the real part of this term or the real potential function can be shown to vary as $\cos n(\theta - \alpha)$, that is, it is the potential function obtained from eq. (12) rotated by α around z-axis and multiplied by $|W|$. This rotation by α can be realized by mixing two component field, one is that for $W = 1$, the other is that obtained by rotating it by $\pi/2n$, the mixing ratio being determined by the ratio of real and imaginary part of W . Thus the eq. (13) is a compact way of describing two dimensional dynamic 2n-tuple field realized by two component driving field. For example, for $n = 1$, it represents a two dimensional deflection system consisting of two sets of cosine distributed deflectors of the same design arranged with axes of deflection aligned with x and y coordinate axis, respectively (Fig. 2).

Equation (4) is the potential for the original axially symmetric lens field; eq. (5) is the potential for the dipole field with its axial function of $-1/2 \phi_F^{(2)}(z)$, angular dependence of $\cos(\theta - \alpha)$ and its intensity varied linearly as the amount of shift; eq. (6) is the potential for the quadrupole lens field with its axial function $1/32 \phi_F^{(4)}(z)$, angular dependence of $\cos 2(\theta - \alpha)$, and intensity varied as $|W|^2$ or the square of the amount of shift, it

should be noted that this field corresponds to the dynamic stigmator in ordinary deflection system; eq. (7) is the potential for axially symmetric lens field with its axial function of $-1/4 \phi_F^{(2)}(z)$, intensity varied as the square of the amount of shift, this corresponds to the dynamic focus in ordinary deflection system; eq. (8) is the higher order term and can be neglected for third order discussion; eq. (9) is the potential for dipole field with its axial function of $1/16 \phi_F^{(4)}(z)$, angular dependence of $\cos(\theta - \alpha)$, and intensity varied as the third order of the shift amount, this field corresponds to the dynamic distortion correction field in ordinary deflection system; these are depicted in Fig. 3. Although eq. (5) and (9) are both dipole field, they can not be the same deflector because the axial distribution is different.

It should be noted that, although in the above discussion, the axial functions $f_n(z)$ are the derivatives of a given function $\phi_F(z)$, it can, in general, be an independent functions, further it can be generalized to be the complex functions having two independent components as

$$\dot{f}_n(z) = f_n(z) \exp(-i \beta_n(z)) \quad (14)$$

both amplitude $f_n(z)$ and phase $\beta_n(z)$ are functions of z . If $\beta_n(z)$ is constant it represents, for $m = 1$, for example, the angle of fixing or the rotational position of the deflector with respect to x -axis. For general $\beta_n(z)$, it can be modeled as a stack of thin deflectors, each having different intensity and rotational position, as shown in Fig. 4. It should also be noted that the axial functions in eqs. (5)-(9), since they are the derivative of a given function $\phi_F(z)$, they are all overlapping, that is, we consider the system with overlapping component fields.

Equations (4)-(9) represent the potential for shifted lens field correct up to the third order, it is possible to correct third order aberrations by adding correction fields to each of the above axial functions [1]. It is up to the designer of the system whether each axial function be considered as a whole or as the sum of shifted lens and the correction to it.

Next we consider how the deflection aberrations can be eliminated in the MOL system. Figure 5 shows schematically how the deflective coma and the transverse chromatic aberration can be eliminated. It consists of parallel shifter consisting of two sets of deflectors, DM and DS, each deflects the beam in the same amount but opposite in direc-

tion, followed by a lens MOL, which is shifted transversely by the same amount of shifted beam, so that the beam enters the lens at the center; thus it is clear that no deflective coma appears. Since the direction of the shifted beam remains unchanged regardless of the energy of the incident beam, it focuses at the same point if the target plane is coincident with the focal plane; so the transverse chromatic aberration can also be eliminated by this configuration without using dynamic correctors.

Next let us consider the deflective astigmatism and the distortion aberrations. It can be shown that these aberrations are made up of two components; one derived from the lens field and the other derived from the deflector field. It can be shown that these are canceled out, if you consider overlapped lens and deflection field and take appropriate axial function for lens and deflector. It is well known that the dynamic stigmator is needed to correct astigmatism if lens and deflector field are considered separately.

Figure 6 is taken from Pfeiffer's paper, VAL (Variable Axis Lens) is his terminology for MOL. They showed experimentally the feasibility of the MOL concept and applied it to a practical electron beam exposure system for micro-fabrication [9]. Although there are some discrepancy between his formulation and ours, they are on the same line.

Formulation of MQL

In the same way as above MQL can be formulated by the Taylor expansion of quadrupole lens field [11]. Let ϕ_Q be the potential for a quadrupole lens field of a given axial function ϕ_Q as

$$\phi_Q(w, \bar{w}, z) = \frac{1}{2} (w^2 + \bar{w}^2) F_Q(w, \bar{w}, \phi_Q(z)) \quad (15)$$

where F_2 is given in eq. (3) with $n = 2$. The MQL potential ϕ_{MQL} is defined by the following formula

$$\begin{aligned} \phi_{MQL}(w, \bar{w}, W, \bar{W}, z) &= \phi_Q(w + W, \bar{w} + \bar{W}, z) \\ &= \sum_{k=0}^{\infty} \frac{1}{k!} \left(W \frac{\partial}{\partial w} + \bar{W} \frac{\partial}{\partial \bar{w}} \right)^k \phi_Q \end{aligned} \quad (16)$$

Expanding eq. (16) up to $k = 3$, we obtain

$$\phi_{\text{MQL}} = \frac{1}{2} (w^2 + \bar{w}^2) F(w, \bar{w}, \phi(z)) \quad (17)$$

$$+ \frac{1}{2} (Ww + \bar{W}\bar{w}) F(w, \bar{w}, 2\phi(z)) \quad (18)$$

$$+ \frac{1}{2} (W\bar{w} + \bar{W}w) F(w, \bar{w}, -\frac{1}{12}\phi(z)) \quad (19)$$

$$+ \frac{1}{2} (W^2 + \bar{W}^2) F(w, \bar{w}, \phi(z)) \quad (20)$$

$$+ \frac{1}{2} (W\bar{W}w + \bar{W}\bar{W}\bar{w}) F(w, \bar{w}, -\frac{1}{4}\phi(z)) \quad (21)$$

$$+ \frac{1}{2} (W^2\bar{w} + \bar{W}^2w) F(w, \bar{w}, -\frac{1}{384}\phi(z)) \quad (22)$$

$$+ \frac{1}{2} (W\bar{W}w + \bar{W}\bar{W}\bar{w}) F(w, \bar{w}, -\frac{1}{4}\phi(z)) \quad (23)$$

$$+ \frac{1}{2} (W^3\bar{w} + \bar{W}^3w) F(w, \bar{w}, -\frac{1}{12}\phi(z)) \quad (24)$$

$$+ \frac{1}{2} (W^2\bar{W}w + \bar{W}^2W\bar{w}) F(w, \bar{w}, -\frac{1}{96}\phi(z)) \quad (25)$$

$$+ \frac{1}{2} (W^3\bar{w} + \bar{W}^3w) F(w, \bar{w}, -\frac{1}{23043}\phi(z)) \quad (26)$$

If we consider aberrations up to the third order, the terms having up to the fourth order in $w, \bar{w}, W, \bar{W}$, or eqs. (17), (18), (19), (20), (21), (23) and (24) need be retained.

To generalize the MQL concept, the axial functions in eqs. (18)-(26), although they are the derivative of a given function $\phi_0(z)$ in the above formulation, can be considered as independent complex functions each having two independent components as well, and the similar discussion about the dynamic correction can be made as given for MOL.

Table 1 shows the angular dependence, the order of W , and the axial function of each term of MQL, which constitute the background for physical realization. Consider the first line corresponding to eq. (18), as an example, this is a dipole field with axial function of $2\phi_0(z)$, angular dependence of $\cos(\theta + \alpha)$, meaning the dipole field should be rotated in opposite direction to that of W . It is known to the author that misalignment in static stigmator can be corrected by mixing the dipole field of appropriate direction and intensity with the original quadrupole field [12]; this can be considered as a static version of MQL taking into account of eq. (18). Detailed account of other terms of MQL and the aberration formulas will be given elsewhere.

Conclusion

MQL concept is introduced as an extension of MOL concept, it may have such applications as electronic adjustment or alignment for stigmator as used in the electron microscope; scanning system using quadrupole lens for focusing; scanning and shaping system for shaped beam scheme by quadrupole lens [13].

Acknowledgment

The authors would like to acknowledge members of the EBX group of Japan Electron Optics Laboratory Ltd., T. Goto and T. Someya, to name a few, for their valuable comments and suggestions.

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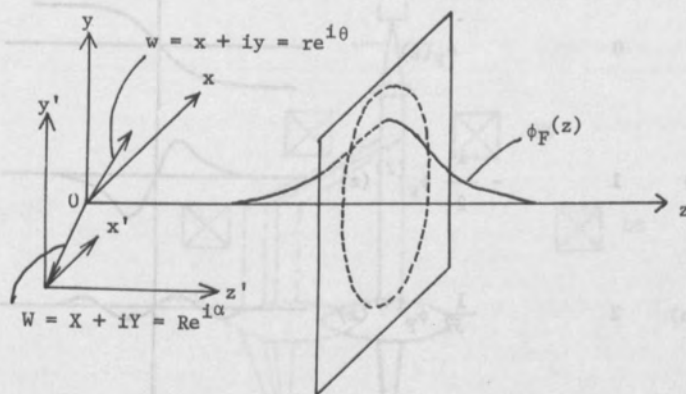


Fig. 1 Coordinate system

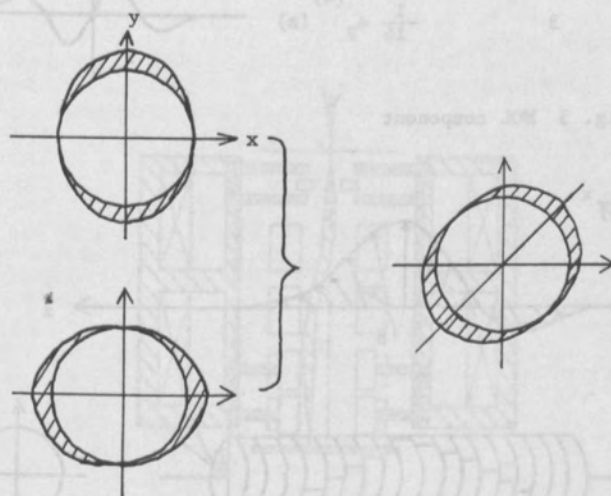


Fig. 2 Rotation of deflection field by adding two component fields

Angular depend Order of W Axial funct.

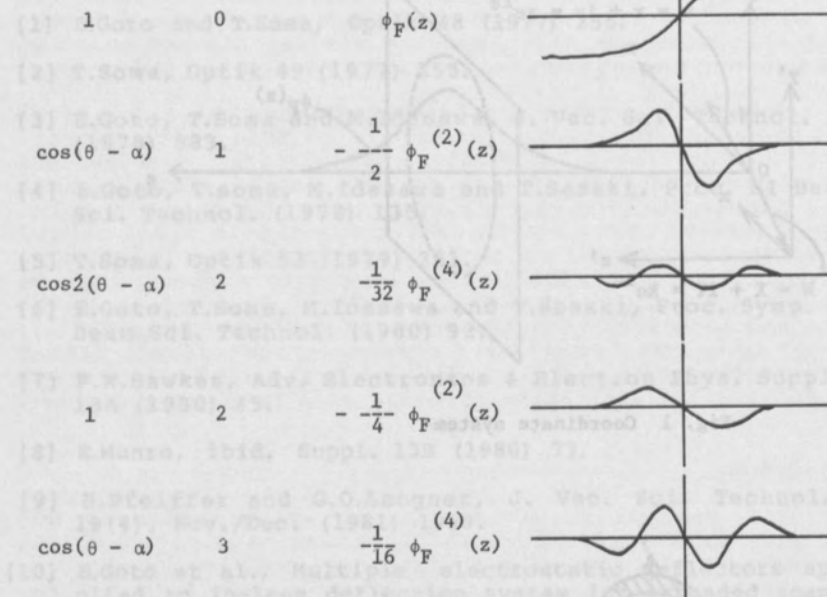


Fig. 3 MOL component

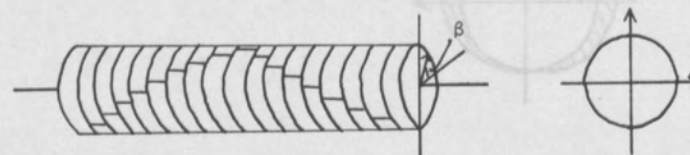
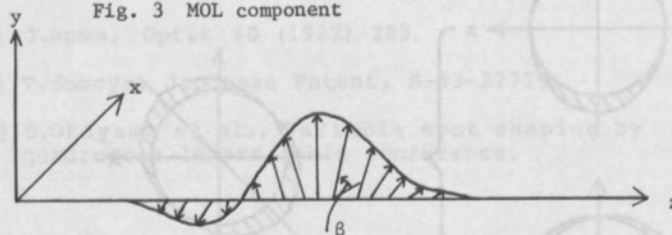


Fig. 4 Distributed deflector

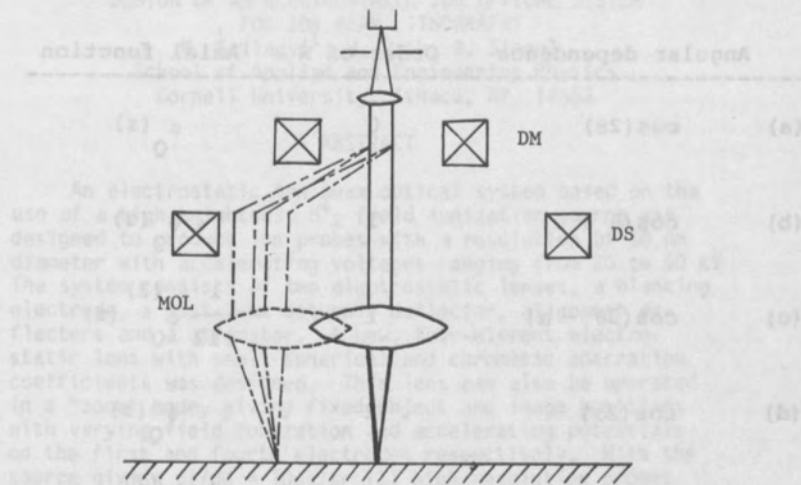


Fig. 5 Schematic MOL system

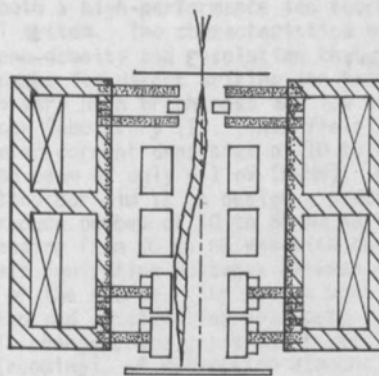


Fig. 6 Variable Axis Lens (VAL) concept (Pfeiffer)

Table 1 MQL components

	Angular dependence	Order of W	Axial function
(a)	$\cos(2\theta)$	0	$\phi_Q(z)$
(b)	$\cos(\theta + \alpha)$	1	$2 \phi_Q(z)$
(c)	$\cos(3\theta - \alpha)$	1	$-\frac{1}{12} \phi_Q^{(2)}(z)$
(d)	$\cos(2\alpha)$	2	$\phi_Q(z)$
(e)	$\cos(2\theta)$	2	$-\frac{1}{4} \phi_Q^{(2)}(z)$
(f)	$\cos(\theta + \alpha)$	3	$-\frac{1}{4} \phi_Q^{(2)}(z)$
(g)	$\cos(\theta - 3\alpha)$	3	$-\frac{1}{12} \phi_Q^{(2)}(z)$

DESIGN OF AN ELECTROSTATIC ION OPTICAL SYSTEM
FOR ION BEAM LITHOGRAPHY

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ABSTRACT

An electrostatic ion beam optical system based on the use of a high brightness H_2^+ field ionization source was designed to produce ion probes with a resolution of 10 nm diameter with accelerating voltages ranging from 20 to 60 kV. The system consists of two electrostatic lenses, a blanking electrode, a post-lens octupole deflector, alignment deflectors and a stigmator. A new, four-element electrostatic lens with small spherical and chromatic aberration coefficients was designed. This lens can also be operated in a "zoom" mode, giving fixed object and image positions with varying field ionization and accelerating potentials on the first and fourth electrodes respectively. With the source giving $dI/d\Omega = 10 \mu A/sr$ (1) high resolution probes with current densities $> 100 \text{ amp/cm}^2$ can be scanned over 10^4 beam diameters.

1. INTRODUCTION

To produce high resolution probes for ion beam lithography it is necessary to have both a high-performance ion source and a high-quality ion optical system. The characteristics of the ion source determine the current density and resolution that can be realized in the focussed beam probe for direct writing ion beam lithography. An H_2^+ ion source with very high brightness and low energy spread has been developed in our laboratory (1). This field ion source produces H_2^+ beams with angular current densities of 10 to $20 \mu A/sr$ with an energy spread in the beam of only $\approx 1 \text{ eV}$ (FWHM). Based on these source characteristics our aim is to design a practical ion beam system that will produce probes of 10 to 50 nm in diameter accelerated to energies ranging from 20 to 60 keV with current densities $> 100 \text{ A/cm}^2$ and field ionization voltages between -6 and -10 kV with respect to the tip of the source. The system must be flexible in both field ionization and accelerating voltages: if either condition of these voltages is changed, the position of the ion probe spot should not change (zooming). A deflection element should be able to scan the probe over 10^4 beam diameters.

The ions of the beam must be focussed by an electrostatic ion optical system since in the electrostatic lenses the refraction is

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independent of the charge-to-mass ratio. Electrostatic lenses are widely covered in the literature (2-5) and it is well known that generally their aberrations are much higher than those of magnetic lenses that are used to focus electron beams. Therefore, the resolution of the ion probe is severely aberration limited, and it is necessary to use an ion optical system with the minimum possible aberrations.

The system we have designed consists of two electrostatic lenses, a rapid blanking electrode with small deflection voltages held near ground potential and situated at a crossover between the two lenses. A post-lens octupole deflector is used to scan the probe (Fig. 1) lens. There are alignment deflectors and a stigmator between the objective and the projector. The objective lens focusses the virtual point object (5-10 Å in diameter as observed in FIM mode) to a crossover between the two lenses. This crossover is imaged by the projector lens to the target and deflected by the octupole deflector. The image distance must be long enough to accommodate the octupole deflectors and the collectors for secondary electron read-out.

The source size is very small, so actual limiting probe dimensions are determined by the aberrations of the probe forming system. As the field ionization voltage V_1 (6-10 keV) is only a fraction of the accelerating potential V_4 (20-60 kV) the value of the convergence half angle of the beam after the first lens (α_1) is much smaller than its initial value (α_0) at the source. This effect is enhanced if the first lens is used at a relatively high magnification M because

$$\alpha_1 = \frac{\alpha_0}{M} \sqrt{\frac{V_1}{V_4}}$$

The optical properties of the first lens will thus be more critical than the projector lens which can operate with a much smaller acceptance angle.

2. THE OBJECTIVE LENS

The first electrode of this lens is at the same potential as the field ionization electrode of the source: this element is a thin flat electrode with a small aperture in it to pass the beam. (It has been shown (6) that thick first electrodes tend to increase spherical aberration.) The acceptance angle is defined by a separate variable aperture between the source and the first electrode. The final electrode of the lens is at ground potential. Therefore, the positive potential of the tip defines the actual acceleration energy (20-60 keV). Since we want to operate our system to produce probes with resolution in both nanometer and submicron ranges, the lens should have both small spherical and chromatic aberrations. At low values of α_0 the lens is totally chromatic aberration limited but at larger

angular apertures spherical aberration becomes the dominant factor and rapidly limits the magnitude of the acceptance angle and therefore the beam current density that can be realized in the focussed probe.

A typical value for the coefficient of spherical aberration of the best available electrostatic einzel lenses related to the focal length (7) is $C_{s0}/f_0 = 2.5$. The coefficient of chromatic aberration can be as low as $C_{c0}/f_0 = 0.5$ but unfortunately these two data do not come together: if the chromatic aberration is low the spherical is high (8) and vice versa.² It has been suggested (5) that the optical properties can be improved by using composite lenses of four or more elements. For our purposes it was also necessary to use four-element lenses because of the requirement of flexibility in both field ionization and accelerating voltages (V_1 and V_4 , respectively). An additional constraint follows from the fact that at high beam energies no focussing electrode can have a voltage much higher than the accelerating potential. This constraint rules out most of the traditional approaches utilizing very high ratios of subsequent potentials. Moreover, the gap sizes between the electrodes must be large enough to prevent electrical breakdown, so the lens performance cannot be improved by simply scaling down all the dimensions.

Even with so many constraints the number of parameters is still very high (shapes and sizes of the electrodes, their relative positions and the voltages on the two middle electrodes). A very large number of different combinations were investigated using the available methods of computer aided design. The field distributions were determined by the use of a program developed in our laboratory (9) based on the charge density method (10). Ray tracing and calculations of the optical characteristics and aberration coefficients were carried out using an adaptation of Munro's program (11).³

Simple asymmetric three-element lenses were investigated first. A small cylindrical electrode inside the second electrode was later introduced to reduce both aberration coefficients simultaneously. A typical pair of the spherical and chromatic aberration curves is shown in Fig. 2. The dependence of the aberration coefficients on the length L_3 of the additional electrode is shown for the geometrical arrangement that was chosen on the basis of an extensive computer analysis (see Fig. 1). All geometrical dimensions are expressed in units of the aperture D of the second electrode on the object side. For the case shown in Fig. 2 the diameter of the additional electrode is $D_3 = 1.5 D$. As we can see, it was possible to choose an

² f_0 , C_{s0} and C_{c0} refer to the object space. The aberration coefficients are for the infinite magnification case (object at the focal point).

³The influence of the finite aperture in electrode V_1 was neglected and object space was considered as equipotential.

arrangement such that the minima of the two aberration curves almost exactly coincide with each other. At the "best" value of L_3/D we have $C_{s0}/f_0 = 2.79$ and $C_{c0}/f_0 = 0.72$. For comparison it is interesting to remark that if we remove the additional electrode the coefficient of spherical aberration becomes slightly lower, ($C_{s0}/f_0 = 2.65$) but the coefficient of chromatic aberration will be three times worse ($C_{c0}/f_0 = 2.13$). A clear advantage of the four-electrode lens is that both coefficients can be kept low simultaneously.

A further improvement was possible by changing the position and diameter of the additional electrode. Let us choose $D_3 = D$ and $L_3 = 0.75 D$. (The entrance plane of the new electrode is situated at a distance D from the first electrode.) For this arrangement the aberration coefficients are as low as $C_{s0}/f_0 = 2.08$ and $C_{c0}/f_0 = 0.62$. The electrode potentials related to the potential of the final electrode are $V_1 = 0.2$, $V_2 = 0.0$, $V_3 = 1.5$ and $V_4 = 1$, respectively. The potentials are expressed here in electron optical units which is a convenient way of taking care of the limits. The ratio of the accelerating voltage to tip voltage, V_4/V_0 , was taken equal to unity. The voltage on the first electrode V_1 is set by the required field ionization voltage. There are then two free parameters (V_2 and V_3) though neither of them should be much less than zero or higher than 1.5 to allow operation in a practical voltage range. Actually, the final electrode is at ground potential and the tip of the source is held at the positive potential corresponding to the energy of acceleration (20-60 keV). The actual voltages are shown in Fig. 1 for an accelerating voltage of 30 kV ($V_4/V_1 = 5$).

These values of the aberration coefficients are very satisfactory, indeed. Our asymmetric four-element lens realizes a significant improvement in both spherical and chromatic aberration figures. If we choose the unit as $D = 4$ mm, the focal lengths have values of 5.3 mm and 11.8 mm on the object and image sides, respectively. The coordinates of the corresponding focal points are -0.2 mm and 7.7 mm where the origin is at the first electrode V_1 . The imaging properties of the lens are sensitive to the object position. Table I gives the image position, magnification, and aberration disk for different object positions between -0.10 cm and -3.0 cm and initial acceptance angles of $\alpha_0 = 1, 2$, and 5 mrad. As one can see, a total axial aberration disk of 100 Å can be achieved with this lens even at the relatively high value of $\alpha_0 = 5$ mrad where spherical aberration begins to play an important role in addition to the chromatic aberration. The aberration figure remains low over a wide range of magnification, an important factor in designing the projector lens because this magnification will define the acceptance angle to the projector. At $\alpha_0 = 2$ mrad the aberration disk can be made as small as 31 Å; with $\alpha_0 = 1$ mrad the smallest value is 15 Å.

In order to keep the acceptance angle reasonably low at the

projector lens, the magnification of the first lens must be at least $M_1 = 2$ to $3\times$. As shown in Table I, this condition can be satisfied for relatively small values (2-3 mm) of the object distance Z_0 . However, adapting the first lens to the H_2^+ ion source with the emitter tip and cathode at cryogenic temperatures introduces limits on the minimum object distance. (Other ion sources such as the liquid metal ion source may not have this limitation.) For the H_2^+ source the distance must be large enough to allow the placement of a cathode cap for differential pumping, a radiation shield and a variable aperture to define the acceptance angle. Therefore, the real, low magnification aberration coefficients related to Z_0 can serve as figures of merit of the lens (6) in this case. It means, that the lens must be operated at a longer than optimum value of the object distance which implies a lower than optimum value of the magnification. In order to minimize these undesirable effects, the lens was scaled up in all geometrical dimensions by a factor of 1.5. Though this inevitably leads to the increase of the aberration figure by the same factor, the object distance need not be moved very far from the optimum value so a higher magnification can be utilized and the overall performance will not deteriorate too much. In order to find the best compromise, a thorough investigation of the lens performance was carried out for the same value of $V_4/V_1 = 5$ and different values of the potentials V_2 and V_3 . Fig. 3 shows the dependence of the crossover image distance, magnification and total aberration figures for $\alpha_0 = 1, 2$, and 5 mrad on the value of V_2 for fixed values of $Z_0 = -6$ mm and $V_3 = 1.5$. The dependence of the same quantities on V_3 for the same value of Z_0 and $V_2 = 0.1$ is shown in Fig. 4. The dependence on V_2 of the aberration coefficients related to the focal length for the infinite magnification case is given in Fig. 5 for two values of V_3 (1.25 and 1.5). In the same figure the axial positions of the object space focal point, Z_f , are also shown as functions of V_2 . In order to achieve a given object distance, a higher absolute value of Z_f is desirable. At the same time, moving the focal point farther from the first electrode causes an abrupt increase in the spherical aberration coefficient. The problem is even more evident if the aberration figures are compared. The V_2 dependences for $Z_0 = -8$ mm and $V_3 = 1.5$ are shown in Fig. 6. As we wanted a relatively high magnification and the lowest possible aberration figure simultaneously, a compromise was needed. As a result of this compromise $V_2 = 0.2$ and $V_3 = 1.5$ were chosen for the scaled-up system ($D=6$ mm). The imaging characteristics as a function of the object distance are shown in Table II. As we can see, even at $Z_0 = -8$ mm we still have a magnification $M = 2.06$ and the aberration disk for $\alpha_0 = 2$ mrad is $72 \text{ \AA}$.

An additional feature of the four-element lens is its flexibility in both the final accelerating voltage V_4 and the field ionization voltage V_1 . The lens can be operated in a "zoom" mode, i.e., fixed positions for the object (virtual source) and the crossover image where a fixed blanking aperture must be placed while V_1 and V_4

can be set at different desired values of field ionization voltage and accelerating voltage. We have investigated the zooming conditions for different values of the object distance. Zooming can be achieved in many different ways. In order to have a clear picture, the ratio $V_3/V_1 = 7.5$ was fixed and values of V_2/V_1 at which zooming occurred were investigated for different values of V_4/V_1 . As the voltage between the tip and the field ionization electrode varies between 6 and 10 kV while the value of the acceleration voltage desired is between 20 and 60 kV, V_4/V_1 has a range between 2 and 10. The results are given in Fig. 8. If we allow an unlimited range for the variables, the curves form closed loops [as in reference (5)] but we have included only those parts of the curves that are within practical voltage limits and correspond to reasonably low aberration figures. The aberration disks for the curve with $Z_0 = -8$ mm, $Z_1 = 5.07$, are between 56 Å and 72 Å for $\alpha_0 = 2$ mrad.

3. THE PROJECTOR LENS

The projector lens focusses the blanking aperture on the work-piece. If the first lens is used at a high enough magnification, the projector lens does not increase the axial aberration figure appreciably since the angular divergence of the beam from the crossover is very small. The axial aberration figure can even be reduced further if a suitably chosen demagnifying projector lens is utilized. However, as we wish to investigate patterning in resists with a wide range of probe diameters (from 10 nm up into the submicron range) with post lens deflection scanning the probe over 10^4 beam diameters, it is necessary to have long working distances for the larger probe diameters to minimize deflection aberrations. Since the working distance increases with the magnification, a compromise is needed again. The aim of the design is to find a lens which would give only small contributions to the axial aberrations even at higher than unit magnification and would provide reasonably long working distances.

The first electrode of the projector lens is a continuation of the last electrode of the first lens and held at ground potential V_4 . The last electrode of the projector lens should be at the same potential as the work stage, and thus must also be at ground potential. The projector lens is therefore an einzel lens. At least two more electrodes are needed to provide the necessary flexibility and lens performance to obtain good imaging over a range of accelerating voltages and different working distances. In principle, any four-element asymmetric einzel lens would do the job, but in order to meet the criteria desired over a wide range, many different options were investigated. Since a CAD program that allows rapid interactive calculations of the optical properties of lenses with equidiameter lenses was available (13), we started with a lens consisting of four equidiameter cylinders and equal gaps between them. The optical properties of this lens are very good. If we combine them with the first lens described above (Table I) excellent performance can be

achieved in both probe size (overall axial aberration figure) and current density. With the object at $Z_0 = -2$ mm, the axial probe size can be as small as 22 Å with a corresponding current density of more than 800 A/cm². However, there is a serious limitation with this lens: we were not able to achieve a working distance longer than 2-3 cm. Therefore, a systematic search was carried out to find a lens with low aberrations and longer working distance. We proceeded again with finding a good three-electrode lens first and then introducing additional electrodes. As an einzel lens can never have as good optical properties as a well designed totally asymmetric lens, it was very difficult to find a lens with both small spherical and small chromatic aberrations given the practical limitations. To obtain adequate beam currents for high current densities in larger probes ($\approx 0.1 \mu\text{m}$), the acceptance angle, α_0 , must be increased. But then spherical aberration dominates and smaller values of C_s are required. The lens finally decided upon is shown in the schematic given in Fig. 1. It is a symmetric 5-electrode einzel lens with two different voltages V_5 and V_6 on its three central electrodes. This lens has the best performance if we are interested in a wide range (10-100 nm) diameter probe sizes. The working distance of this lens can be varied between 3 and 10 cm. Naturally, the longer working distance gives higher magnification and larger aberration figures. For a 3 cm working distance the magnification is almost exactly one, for the 10 cm working distance its value is 2.2x. The dependence is very close to linear. In the following, the results will be given for the 3 cm working distance case with the understanding that a higher value can easily be obtained by sacrificing some of the good axial aberration features while gaining in the deflection aberrations. The spherical, chromatic and total aberration disks of the projector lens are plotted as functions of the incident acceptance angle, α_1 , in Fig. 8.

4. THE OCTUPOLE DEFLECTOR

An octupole deflector (12) is used in dipole regime to deflect the ion probe over 10^4 beam diameters. Our aim is to produce deflection aberrations (distortion, curvature of field, coma, astigmatism, deflection chromatic aberration) small enough to achieve the desired probe resolution. It is also required that the deflector should be placed at the ground potential region. For this purpose a modified version of the program described in reference (13) was used. This program requires an analytical function as its input. Therefore, the axial field distribution of the projector lens calculated by the charge density method was simulated by a series of 9th order polynomials. The deflection aberrations were then calculated in the usual way (13).

A single element post-lens deflector was found to be adequate for our purposes. The deflector was placed at the plane where the axial potential becomes constant (8 mm, i.e., approximately one

diameter from the last gap in the electrodes). This is equivalent to using as large a working distance as possible. The deflection distance is proportional to the applied deflection voltage, the working distance and the length of the deflector (we chose $L_{\text{defl}} = 12$ mm) and it is inversely proportional to the radius of the deflector. The different deflection aberrations are plotted versus the deflection distance in Fig. 9 for the case of $\alpha_0 = 2.3$ mrad⁴ and a 3 cm working distance. As we can see, the dominant deflection aberration at deflection distances $< \pm 0.2$ mm is the deflection (transverse) chromatic aberration. At this value of α_0 the spot size is around 10 nm and a deflection distance of ± 0.1 mm corresponds to $\sim 20,000$ beam diameters. For larger diameter probes the work-piece can be positioned at larger working distances in order to minimize deflection aberrations. The transverse chromatic aberration still remains the dominant factor.

5. CONCLUSION

An electrostatic ion optical system for application in an ion beam lithography system was designed to produce ion probes of 10 to 50 nm in diameter with accelerating voltages ranging from 20 to 60 kV. The system consists of two electrostatic lenses, a blanking electrode between the two lenses, a post-lens octupole deflector, alignment deflectors and a stigmator. The objective lens focuses the virtual point object of this lens to a crossover at the blanking aperture between the two lenses. The crossover is imaged by the projector lens to the target and deflected by the octupole deflector. (Fig. 1).

Satisfactory operation of this system can be achieved with the first lens with a magnification $M = 2.06$ and focusing the object placed at -8 mm from the first electrode to a crossover at 5.07 cm from the first electrode. This regime was achieved by choosing $V_2 = 0.2$ (see Fig. 6 and Table II). The corresponding aberration disk is 71.6 Å for $\alpha_0 = 2$ mrad for a field ionization voltage of -6 kV and an accelerating potential of 30 kV.

Combining these data with those of the second lens (Fig. 8) and of the octupole deflector (Fig. 9) we arrive at the total aberration disk (probe diameter) shown in Fig. 10 vs. the initial acceptance half angle, α_0 , for the axial beam (undeflected beam) and for two different values of the deflection distance $DD = \pm 0.1$ mm and 0.2 mm. The small but finite value of the source diameter (5 Å) is taken into account. The contribution of the deflection aberrations are almost constant over these small deflections because the deflection

⁴With the first lens magnification of $M_1 = 2.06$ and the beam accelerated from a field ionization energy of 6 keV to a final energy of 30 keV the incident acceptance half-angle of the projector, $\alpha_1 = 0.5$ mrad.

aberrations are dominated by the transverse chromatic aberration which does not depend on the acceptance angle.

The current density curves are shown in Fig. 11 as functions of α_0 . For small values of α_0 when the beam is totally chromatic aberration limited, the current density should approach limiting saturation value. However, because the source size is finite, the current density actually decreases at very small values of α_0 and has a maximum at a certain optimum value of the initial acceptance half angle. The larger the deflection distance (DD) the flatter the current density dependence on α_0 . With a deflection, DD = ± 0.1 mm, a square field of 0.2×0.2 mm can be realized. From Fig. 11, the maximum current density will be realized with an acceptance half-angle, $\alpha_0 = 2.5$ mrad to give a beam current of 0.2 na and a probe diameter of < 150 Å. Thus, a current density of 110 amp/cm^2 will be obtained with beam deflected almost 10^4 beam diameters. An angular current density of $10 \mu\text{A/sr}$ and an energy width of the ion beam of 1 eV is taken for the source.

ACKNOWLEDGMENT

This work was supported by DARPA through ONR Grant N00014-80-C-0587.

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TABLE I

OBJECT PLANE	IMAGE PLANE	MAGNIFICATION	DISK DIAMETER D_1 (Å)		
Z_0 (cm)	Z_1 (cm)	M	$\alpha_0 = 1$ mrad	$\alpha_0 = 2$ mrad	$\alpha_0 = 5$ mrad
-3.00	0.98	0.177	53.4	270.8	4021.0
-2.00	1.08	0.267	32.1	106.2	1374.0
-1.00	1.40	0.541	18.9	41.1	279.5
-0.90	1.48	0.603	17.9	38.1	229.6
-0.80	1.57	0.681	17.0	35.5	188.0
-0.70	1.69	0.782	16.2	33.4	154.4
-0.60	1.85	0.918	15.7	32.0	128.5
-0.50	2.08	1.111	15.4	31.2	110.3
-0.40	2.43	1.407	15.8	31.8	100.4
-0.30	3.03	1.919	17.3	34.8	101.3
-0.20	4.33	3.015	22.1	44.4	123.3
-0.10	9.06	7.030	43.2	86.5	237.7

ION OPTICAL PROPERTIES OF THE FIRST LENS FOR
 $D = 4$ mm, $V_1 = 0.2$, $V_2 = 0.0$, $V_3 = 1.5$, $V_4 = 1.0$

TABLE II

OBJECT PLANE	IMAGE PLANE	MAGNIFICATION	DISK DIAMETER D_1 (Å)		
Z_0 (cm)	Z_1 (cm)	M	$\alpha_0 = 1$ mrad	$\alpha_0 = 2$ mrad	$\alpha_0 = 5$ mrad
-3.00	1.92	0.311	48.2	195.7	2756.0
-2.00	2.27	0.506	34.9	91.8	978.6
-1.00	3.81	1.363	31.1	63.9	280.1
-0.90	4.31	1.641	32.6	66.4	260.8
-0.80	5.07	2.061	35.3	71.6	254.5
-0.70	6.34	2.770	40.7	82.1	268.4
-0/60	8.96	4.224	52.9	106.4	325.4
-0.50	17.35	8.889	94.3	189.4	553.3

ION OPTICAL PROPERTIES OF THE FIRST LENS FOR
 $D = 6$ mm AND POTENTIALS $V_1 = 0.2$, $V_2 = 0.2$,
 $V_3 = 1.5$, $V_4 = 1.0$

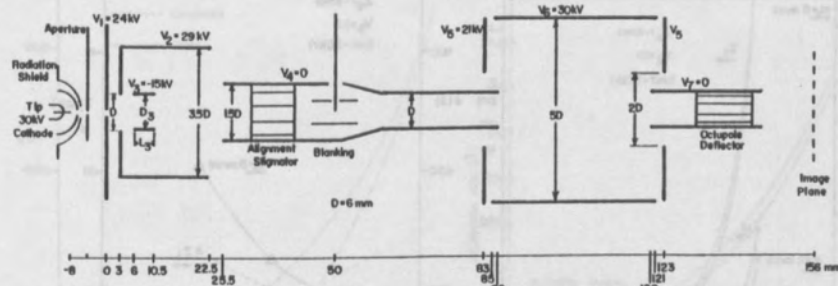


Fig. 1. The schematic of the ion optical system (voltages for 30 keV accelerator).

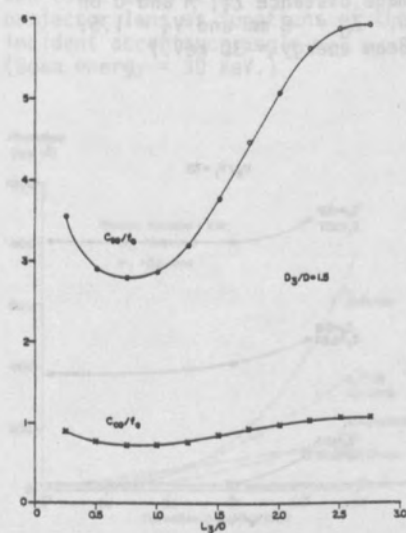


Fig. 2. Spherical and Chromatic aberration coefficients as functions of length of additional electrode, L_3 .

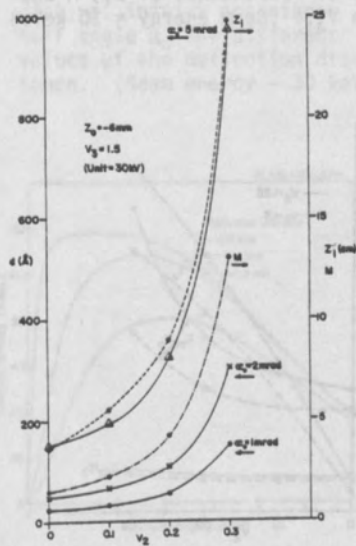


Fig. 3. Dependence of cross-over image distance, Z_i , magnification, M , and aberration figures, d on V_2 . (Beam energy = 30 keV.)

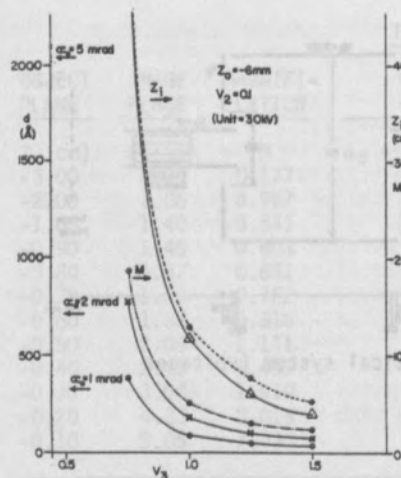


Fig. 4. Dependence of Z_1 , M and d on V_3 . (Beam energy = 30 keV.)

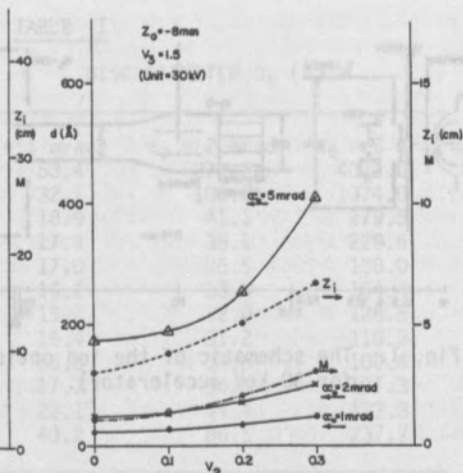


Fig. 6. Dependence of crossover image distance Z_1 , M and d on V_2 . $Z_0 = -8$ mm and $V_3 = 1.5$. (Beam energy = 30 keV.)

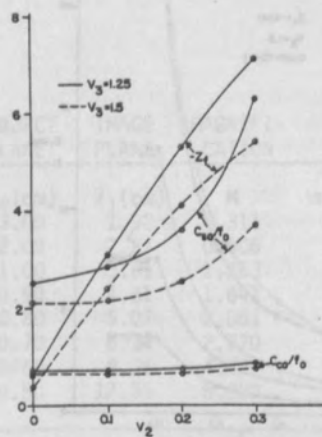


Fig. 5. Dependence of C_{50} , C_{co} and position of focal point, Z_f on V_2 .

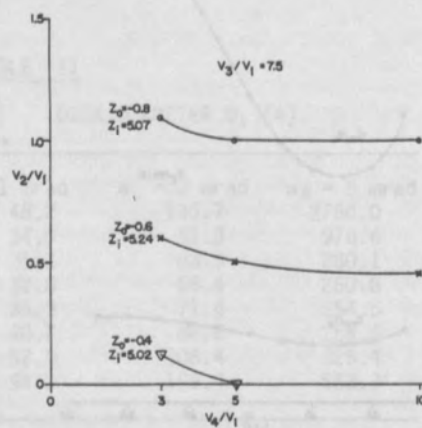


Fig. 7. Zooming curves: dependence of V_2/V_1 on V_4/V_1 for different pairs of fixed object (Z_0) and image (Z_1) distances.

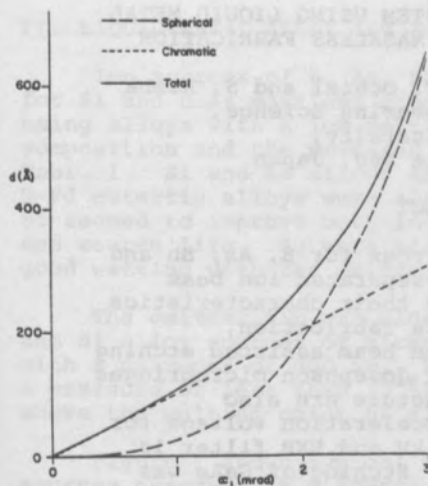


Fig. 8. The spherical, chromatic and total aberration disks of the projector lens as functions of the incident acceptance angle α_i . (Beam energy = 30 keV.)

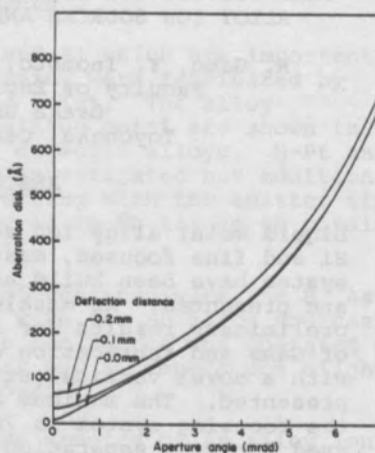


Fig. 10. Total aberration disk vs. initial acceptance half angle α_0 for different values of the deflection distance. (Beam energy = 30 keV.)

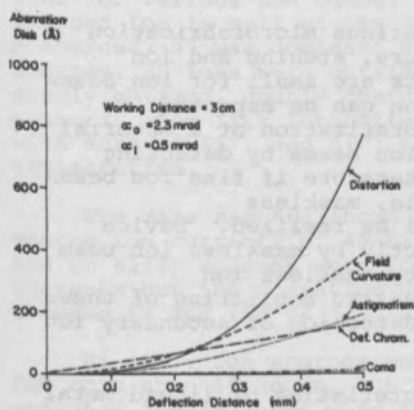


Fig. 9. Deflection aberrations vs. deflection distance for $\alpha_0 = 2.3$ mrad, $\alpha_i = 0.5$ mrad, working distance = 3 cm. (Beam energy = 30 keV.)

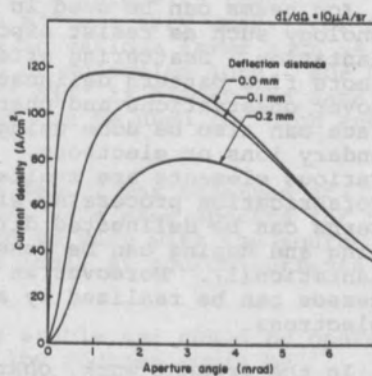


Fig. 11. Current density vs. initial acceptance half angle α_0 for different values of the deflection distance. (Beam energy = 30 keV.)

FINE FOCUSED ION BEAM SYSTEM USING LIQUID METAL
ALLOY ION SOURCES AND MASKLESS FABRICATION

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ABSTRACT

Liquid metal alloy ion sources for B, As, Sb and Si and fine focused, mass-separated ion beam system have been build and their characteristics are presented. As maskless fabrication, preliminary results for ion beam assisted etching of GaAs and fabrication of Josephson microbridges with a novel vertical structure are also presented. The maximum acceleration voltage for the focusing system is 70 kV and EXB filter is used for mass separation. Etching of GaAs was performed by 40 keV Ar bombardment in chlorine atmosphere and it was found that the etching rate was $\sim 5 \mu\text{m}\cdot\text{min}^{-1}\cdot\text{mA}^{-1}\cdot\text{cm}^2$ at a current density of $\sim 2 \mu\text{A}/\text{cm}^2$.

I. INTRODUCTION

Ion beams can be used in various microfabrication technology such as resist exposure, etching and ion implantation. Scattering effects are small for ion beams and more fine pattern delineation can be expected. Moreover observations and characterization of a material surface can also be done using ion beams by detecting secondary ions or electrons. Therefore if fine ion beams of various elements are available, maskless microfabrication processing will be realized. Device patterns can be delineated directly by maskless ion beam etching and doping can be done by maskless ion implantation(1). Moreover an in-situ monitoring of these processes can be realized by a detection of secondary ion or electrons.

In the present work, characteristics of liquid metal alloy ion sources and fine focused ion beam system using the liquid metal alloy ion sources are presented. For maskless fabrication, preliminary results of ion beam assisted etching and fabrication of Josephson microbridges with a novel vertical structure are described.

II. LIQUID METAL ALLOY ION SOURCES

Ion sources of B, As, Sb and Si which are important for Si and GaAs maskless processing were fabricated by using alloys with a low melting point. The alloy composition and the measured melting point are shown in Tabl. 1. Si and As alloys are eutectic alloys. B-Pt and B-Pd eutectic alloys were also investigated but addition of Ni seemed to improve both in wetting with the emitter tip and source life. Au were added in Sb-Pb alloys to obtain good wetting with the emitter tip.

The emitter tip was made of tungsten wire for B, As and Si alloy sources or nickel wire for Sb alloy sources with a diameter of 300 μm . The ion source was operated at a pressure of less than 10^{-6} Torr and a temperature slightly above the melting point of alloys.

Figure 1 shows typical mass spectra of As alloy ion sources observed at a source current of 40 A and by using a 15° sector magnet. Current intensity of As^{++} is about 3 times more intense than current intensity of As^+ . This is advantageous for high energy implantation because beam energy of As^{++} is two times the acceleration voltage.

Tab. 2 shows alloy composition and fraction of atom flux for various ion beams, that is, fraction of doubly charged ion is half of its current intensity fraction. For B sources, B^+ was dominant and B^{++} was very weak. For Sb sources, Sb ions were obtained in various forms such as singly charged, doubly charged or molecular ions. For Si sources, atom flux intensity of Si^{++} is almost the same with that of Si^+ , and Si^{++} beam can be used for high energy implantation.

The mass spectra shown in Tab. 2 was observed at source ion currents of 40-50 μA . The mass spectra for Si and Sb alloy sources were found to vary with the source currents but the variation was small at source currents between 10 and 150 μA (2,3).

Si alloy ion sources were stable and could be operated for more than 60 hours. Sb alloy sources could be operated for 25 hours when the emitter temperature was carefully kept slightly above the melting point. B and As alloy sources had a life of 3-10 hours.

III. FOCUSED ION BEAM SYSTEM

Our fine focused ion beam systems are consisted of two

symmetric einzel lenses and a 15 cm long EXB mass separator. Figs. 2 and 3 shows the block diagram and a photograph of the focused ion beam system. The distance between the extractor electrode and the center of the objective lens is 6.1 cm and the distance between the target and the center of the projector lens is 6 cm.

The structure of the einzel lens is similar to that designed by Hanszen and Lauer(4), and optical characteristics of the lens were calculated by a finite element method(5). The spherical and chromatic aberrations (C_s , C_c) for the objective and the projector lenses are 1300 cm and 15.5 cm, respectively and the overall magnification M is ~ 0.90 which slightly varies with the acceleration voltage.

The calculated beam spot size d for the present focusing column, which is given by

$$(d)^2 = M^2[\rho^2 + (\frac{1}{2}C_s\alpha^3)^2 + (C_c\frac{\Delta E}{V}\alpha)^2] + [\frac{1}{2}C_{sp}(\frac{\alpha}{M})^3]^2 + (C_{cp}\frac{\Delta E}{V}\frac{\alpha}{M})^2$$

is shown in Fig. 4 as a function of the beam acceptance half angle α . In the calculation, the source size ρ and an energy spread (FWHM) of an ion beam ΔE is assumed to 30 nm and 10 eV, respectively.

The EXB mass separator distorts a beam spot and induce an elliptical spot due to the energy spread of the beam. The dotted line in Fig. 4 shows a calculated length of the major axis for a beam energy of 70 keV. In the calculation, the mass resolution $\delta m/m$ is assumed to be 0.1, that is, ^{10}B and ^{11}B can be separated. It is clear from Fig. 4 that a distortion due to an EXB filter is rather small. It is also found that the second order aberration is negligibly small.

Fig. 5 shows examples of secondary electron images of 50 μm Cu mesh and 25 μm Al wire coated with a conducting paste, observed by the present mass-separated focusing system. The probe ions are Si^{++} or Au^+ ions accelerated at 50 kV. The resolution obtained is $\sim 1 \mu\text{m}$ in Figs. 5a and b and $\sim 0.5 \mu\text{m}$ in Fig. 5c.

As shown in the next section, a 1 μm diameter hole was formed in a Si_3N_4 membrane. Therefore, this and the observed secondary electron image resolution indicate that a focused, mass-separated ion beam of a diameter of $\leq 1 \mu\text{m}$ is formed by the present system. This spot size is ~ 5 times larger than the calculated value. This is due to a

fluctuation in power source and misalignment of optical elements.

IV. MASKLESS FABRICATION

a) Ion Beam Assisted Etching and Others

For maskless etching, there are several promising techniques including ion beam assisted etching(6,7) and these are shown in Tab. 3. Ion beam etching relies on physical sputter effect and etching rate is low. The etching rate of Si and GaAs by 500 eV Ar ion was 60 and 260 $\text{\AA} \cdot \text{min}^{-1} \cdot \text{cm}^{-2} \cdot \text{mA}^{-1}$ or 1.6×10^{-16} and $7 \times 10^{-16} \text{ cm}^2/\text{ion}$.

Maskless direct pattern fabrication by ion beam sputter etching can be done for any material even with a low sputter yield because etching selectivity between a mask and the material induce no limitation in the case of maskless fabrication. However, the speed is very low.

In order to increase etching speed, use of chemical effect is effective. Ion beam assisted etching, radiation enhanced etching and beam modification technique of chemical properties are promising methods. As preliminary experiments, etching of GaAs by 60 keV Ar ions in Cl_2 atmosphere ($\sim 10^{-3}$ – 10^{-2} Torr) was performed and ~ 200 times higher etching rate than the sputter etching was observed as shown in Tab. 3. This process is attractive because it requires no development process after ion bombardment.

Radiation enhanced etching provides still higher etching rate. This etching technique utilizes facts that chemical properties in radiation damaged region change from that in undamaged region and etching rate is enhanced. For this technique, the etch depth is limited by an ion range and a wet etching process is necessary. However ion dose required to get enhancement is ~ 2 orders of magnitude lower than ion beam assisted etching. For Si, the dose is 10^{14} – $10^{15}/\text{cm}^2$ for Ar or other ions with a similar mass(8). This dose can be decreased to less than $10^{14}/\text{cm}^2$ if ion bombardment is done at low temperature, eq., at liquid nitrogen temperature. The etching rate for Si corresponds to 2×10^{-11} – $10^{-12} \text{ \AA} \cdot \text{cm}^2/\text{ion}$ at a dose of 10^{14} – $10^{15}/\text{cm}^2$ as shown in Table 3, if ion range or damaged depth is assumed to be $0.2 \text{ }\mu\text{m}$.

Etching by beam modification of chemical properties is also an interesting technique. It has been observed that etching rate of Cr films ($200 \text{ \AA}/\text{min}$) by CCl_4 plasma etching can be reduced to 100 to 0 by Sb implantation at a dose of 1×10^{15} to $1 \times 10^{16}/\text{cm}^2$ (9). This fact also provides several

orders of magnitude higher etching rate than sputter etching.

Modification of chemical properties by ion beam mixing also seems to provide very high rate etching or other direct pattern fabrication method, because the necessary dose is a few times 10^{15} ions/cm² (10).

The last three methods mentioned above require development process after ion bombardment but still have an advantage over a conventional method in the point that no resist process is necessary.

b) Fabrication of Microbridges

As applications of maskless process, fabrication of microbridges with a novel vertical structure has been performed. The bridges, as shown in Fig. 6(c), have a three dimensional structure which connects two Nb planes separated by a thin insulating film through a small pinhole in the insulator and have many advantages over conventional bridges (11).

Fabrication processes using conventional technique and maskless technique are compared in Figs. 6a and b. The process using focused ion beam is not only simple but also reliable and controllable because in-situ monitoring is easily be performed. Fig. 7 shows an example of a hole in a Si₃N₄ membrane formed by 50 keV Au⁺ beam. The process can be monitored by measuring a current at a sample holder as shown in Fig. 8. At an initial stage, all Au⁺ ions are stopped in Si₃N₄ film and no current is detected at the sample holder. When a hole is formed, sharp rise of the current is observed because Au⁺ ions reach the sample holder through the opening in the Si₃N₄ membrane.

The bridges fabricated by the maskless process showed promising Josephson effect and details of their characteristics will be published elsewhere.

SUMMARY

It was shown that using liquid metal alloy ion sources, various focused ion beam can be obtained. From the present study on fabrication of Josephson microbridges, it was also shown that in-situ monitoring is easy for maskless process and consequently the process is more reliable over conventional techniques. Etching is most time-consuming process and development of techniques with a high etching rate is desired. For this purpose, there are several possibilities including an ion beam assisted

etching technique.

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Tab. 1 The alloy composition and a melting point.

Atomic composition (at.%)			Melting point (°C)
B 60	Ni 13	Pt 27	800
As 28	Pt 72		597
Sb 50	Au 8	Pb 42	300
Si 31	Au 69		370

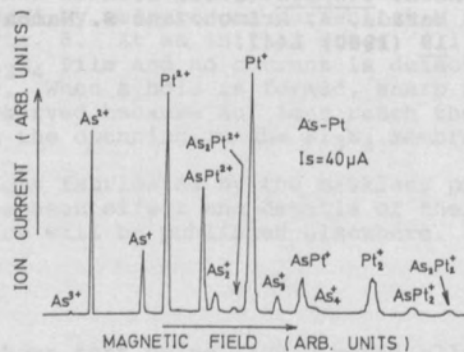


Fig. 1 Mass spectra of a As alloy ion source.

Tab. 2 Alloy composition and atom flux fraction of alloy ion sources.

material composition (at.%)			atom flux fraction (%)								
B	Ni	Pt	$10B^+$	$11B^+$	B^{2+}	Ni^+	Ni^{2+}	Ni_2^+	Pt^+	Pt^{2+}	Pt_2^+
60	13	27	8.1	33.0	0.5	10.6	4.8	3.7	24.2	12.3	2.9
Sb	Pb	Au	Sb^+	Sb^{2+}	Sb_2^+	Sb_3^+	Sb_3^{2+}	Sb_5^{4+}	$Au^+ + Pb^+$	$Au^{2+} + Pb^{2+}$	
50	42	8	6.8	0.9	7.3	5.5	0.7	2.4	49.7	8.4	
			$Au_2^+ + Pb_2^+$	$Au_3^+ + Pb_3^+$	$AuSb^+ + PbSb^+$	$AuSb_2^+ + PbSb_2^+$					
			3.7	3.1	5.7	5.8					
As	Pt		As^+	As^{2+}	As^{3+}	As_2^+	As_3^+	As_4^+	Pt^+	Pt^{2+}	Pt_2^+
28	72		6.8	10.1	0.1	4.1	4.9	1.7	26.3	12.1	7.8
			$AsPt^{2+}$	As_2Pt^{2+}	$AsPt_2^+$	$As_2Pt_2^+$					
			0.6	13.8	0.6	1.9					
Si	Au		Si^+	Si^{2+}	Si_2^+	Au^+	Au^{2+}	$AuSi^+$			
31	69		12.2	12.0	1.9	60.9	2.9	10.1			

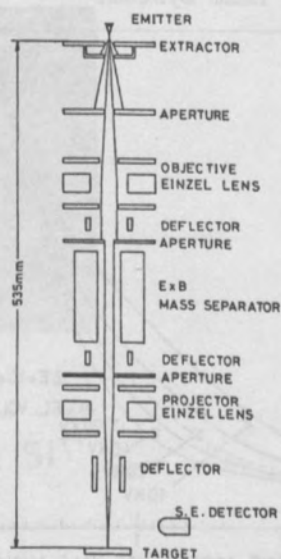


Fig 2 Block diagram of a mass-separated, focused ion beam system.

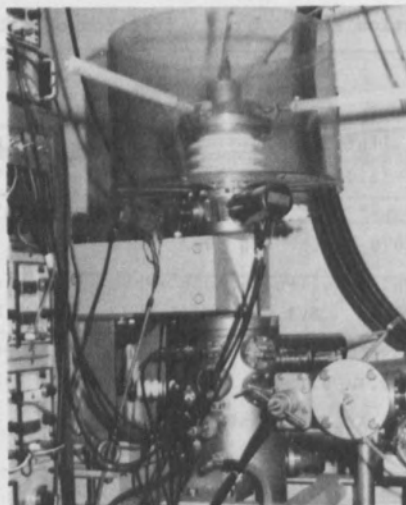


Fig. 3 Photograph of a mass-separated, focused ion beam system.

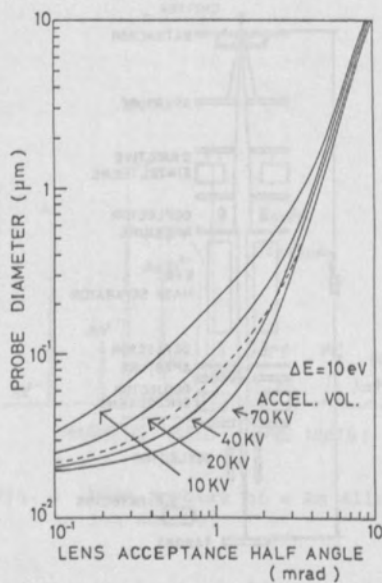
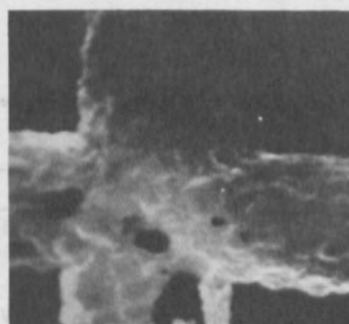


Fig. 4 Probe beam diameter as a function of the beam acceptance half angle at various beam energy.



(a)

50kV 200pA Si^{++}



(b)

50kV 280pA Au^+

→ 10μm



(c)

50kV 100pA Si^{++}

→ 10μm

Fig. 5 Secondary electron imate of 50μm Cu mesh (a), (b) and 25μm Al wire stained by conducting paste (c).

Tab. 3 Etching rate or ion dose required for various direct pattern fabrication techniques.

method	etching rate or dose
ion beam etching	60(Si), 260(GaAs) $\text{\AA} \cdot \text{min}^{-1} \cdot \text{cm}^2 \cdot \text{mA}^{-1}$ ($5 \times 10^{-16} \text{\AA} \cdot \text{cm}^2 / \text{ion}$)
ion beam assisted etching	60kV Ar, $5 \text{ \AA} \cdot \text{min}^{-1} \cdot \text{cm}^2 \cdot \text{mA}^{-1}$ ($1 \times 10^{-13} \text{\AA} \cdot \text{cm}^2 / \text{ion}$)
radiation enhanced etching	$N_D = 10^{14} - 10^{15} / \text{cm}^2$, $t \leq 0.2 \text{ \AA}$ ($2 \times 10^{-11} - 10^{-12} \text{\AA} \cdot \text{cm}^2 / \text{ion}$)
beam modification	$N_D = 10^{15} - 10^{16} / \text{cm}^2$

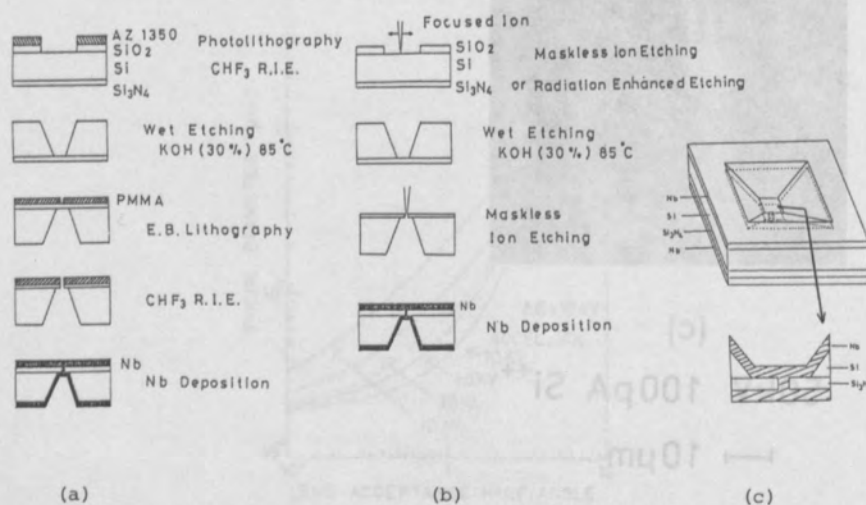


Fig. 6 Conventional (a) and maskless (b) fabrication process of Josephson.

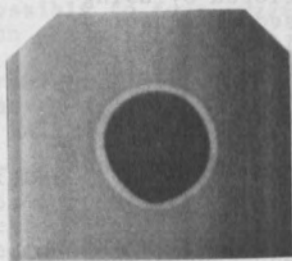


Fig. 7 A pinhole formed in 950 Å thick Si₃N₄ membrane.

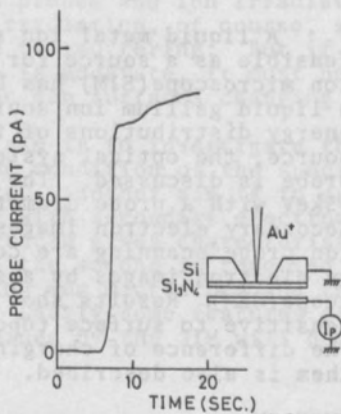


Fig. 8 Current variation during drilling.

SECONDARY ELECTRON IMAGES BY SCANNING ION MICROSCOPE

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A liquid metal ion source is shown to be feasible as a source for microscopy. A scanning ion microscope(SIM) has been developed by using a liquid gallium ion source. Based on measured energy distributions of the liquid metal ion source, the optical system for forming the ion probe is discussed. The ion probe used is Ga^+ of 35keV with a probe diameter of less than $0.1\mu\text{m}$. Secondary electron images obtained by the gallium ion probe scanning are compared with the secondary electron images by a scanning electron microscope(SEM). Results show that SIM images are more sensitive to surface topography than SEM images. The difference of charging-up phenomena between them is also described.

INTRODUCTION

A liquid metal ion source is becoming an important technique in semiconductor technology. With respect to this kind of ion sources V.E.Krohn(1) investigated ion generations of fusible metals, and J.F.Mahoney(2) examined alkali metals including cesium. In 1979, using a 55keV gallium ion source R.L.Seliger(3) showed the possibility of submicron fabrication for semiconductor industry.

Very high brightness of the liquid metal ion source(4) enables applications not only to fabrication but also to microscopic image formation (5). Although microscopic imaging with ion beams is partly used as the technique of scanning ion massanalyzers (6), the attainable probe size is limited in a few micron range by the limited brightness of the conventional ion source (e.g. duoplasmatron). The recent developments of the liquid metal ion source which can provide a high resolution probe through its small virtual source size and high intensity, drastically changed the situation.

On the other hand, the energy spread of the liquid metal ion source is considerably large due to its fundamental property of emission process (7). Besides, available ion species for the liquid metal ion source are limited to metals having low melting point and low vapor pressure. These limitations might restrict the applicability of the ion source.

Phenomena induced by ion irradiation are sputtering, secondary ion emission, photon emission and secondary

electron emission. To detect these phenomena will provide various kinds of images, each of which is expected to give us useful information of specimen surfaces. In the present work secondary electron imaging was employed in order to examine the performance of ion probes and ion irradiation effects. In the case of ion irradiation, of course, specimen surfaces suffer damage due to sputtering. But if the change of the specimen surface is moderate, it must be possible to form images of specimen surfaces changing under ion irradiation.

In the present work, our aim is to investigate the probe size limitation under the condition of the specific energy spread of the ion source. Another aim is to apply a gallium ion probe to imaging with secondary electrons.

The first part of this article gives characteristics of the gallium ion source. In the second is reported the ion optical system of a scanning ion microscope and the performance of the ion probe. Lastly some features of secondary electron images obtained by the SIM will be described.

SCANNING ION MICROSCOPE

Gallium ion source An ion analyzing system has been constructed in order to investigate the emission properties of ion sources. In the system energy distributions are measured by a 90deg. deflection electrostatic energy analyzer (EA), of which the radius of trajectory is 5cm and the energy resolution is less than 1eV. Mass spectra are measured by a quadrupole mass analyzer (QM) with a mass resolution of 300.

For ion emission of liquid metals the operation at about 5kV is necessary. On the other hand, since the QM cannot measure at a beam energy of more than several tens of eV, the beam energy must be reduced down between the ion gun and the QM. In a retarding column, the beam is decelerated to 250eV at the EA and eventually becomes of an average energy of 50eV at the entrance aperture of the QM. The system can be operated at 2×10^{-10} Torr after 300°C baking.

An emitter of the ion source consists of a needle and a reservoir which reserves the liquid metal and prevents the liquid metal from dropping due to the stress of high electrostatic force. The liquid metal is heated by a filament supporting the emitter. In the case of a gallium emitter, the reservoir temperature was kept at about 600°C. The emitter was dipped in advance into a gallium crucible to prepare it for a steady current in another vacuum chamber. Figure 1 shows a measured mass spectrum (a) and energy distributions (b) of the gallium emitter.

Two peaks of Fig.1(a) are isotopes of gallium: $^{69}\text{Ga}^+$ and $^{71}\text{Ga}^+$. In the range of emission currents from $5\mu\text{A}$ to $40\mu\text{A}$, multicharged ions and cluster ions were not detected in the measurement.

Fixing the window of the QM at mass units of 69 and 71, energy distributions were measured by EA scanning. The left side of Fig.1(b) shows energy distributions of the isotopes at an emission current of $5\mu\text{A}$, and the right those at $20\mu\text{A}$. The origin of abscissa (0eV) is arbitrary. No difference was observed among FWHMs of the energy distributions of both isotopes. Raising the energy resolution of the EA, the energy distributions of $^{69}\text{Ga}^+$ were measured. Figure 2 shows the change of the energy distributions at emission currents from $2.5\mu\text{A}$ to $40\mu\text{A}$. The following experiments were done in the emission current range from $5\mu\text{A}$ to $10\mu\text{A}$, so that the energy spread of the ion source can be estimated to be 10eV to 15eV. This value of energy spread is almost ten times that of tungsten cathode electron sources, and results in deteriorating the ion probe quality.

Optical system A schematic diagram of the SIM is shown in Fig.3. Gallium ions emitting from the needle type emitter, pass through a single lens system (an objective lens) and focus onto a specimen surface. Ion-induced secondary electrons are collected by a detector which is kept at a positive high voltage. The objective lens (OL) is of symmetrical einzel type. Calculated spherical and chromatical aberration coefficients are 900cm and 10cm, respectively, with the working distance of 1cm. The performance of the OL is assessed from these values and shown in Fig.4. The abscissa is the semiangle (θ) of irradiation cone and the ordinate the ion probe radius (r_p) on the right and the probe current (I_p) on the left, where r_p is simply estimated by

$$r_p = \sqrt{(C_s \theta^3 / 4)^2 + (C_c \eta \theta)^2},$$

with $\eta = \Delta E / E$ because the contribution of the Gaussian image of the source is so much smaller than r_p as to be neglected we put 10eV and 35keV into ΔE and E , respectively. The probe current was obtained from the measured angular intensity.

ION-INDUCED SECONDARY ELECTRON IMAGES

The secondary electron images were obtained by the gallium ion beam operating at 35keV. The size of the ion probe used was less than $0.1\mu\text{m}$ in diameter with a probe current of 20pA . Figure 5 shows a comparison of the secondary electron images obtained by the SIM and SEM.

The specimen is a EPROM commercially available. The surface of the EPROM was directly examined through the window broken open. The surface of the specimen to be directly observed is, therefore, a silicon oxide layer. The bottom left of the figure is the SIM image at 35kV and others the SEM images at 30kV, 15kV and 5kV. The micrograph of SIM was taken with an exposure time of 200 seconds after the SEM observation(*). The SEM image at 5kV is of poor quality due to charging-up. On the image at 30kV, on the other hand, topographic contrast of the specimen surface appears to be depressed, deteriorating the observation of topographic details. Regarding topography of the surface, even though the SEM image at 15kV is the best among the SEM images, the SIM image is better than the SEM image, particularly in contrast.

Compared SEM and SIM images at high magnification, SEM images would, matter of course, show more detailed structure. The magnification of Fig.5 does not allow for discussion on the difference of resolutions between SEM and SIM. It should, therefore, be noted that the better quality of SIM images primarily owes to the better contrast in the present case.

One of the advantages for SIM practical applications is its insensitivity for charging-up. As shown in the figure one can hardly see charging-up effects on the SIM image, regardless of an insulating material sample. This trend of insensitivity for charging-up was also observed on comparison of images of biological specimen.

The SIM is, of course, not completely free from charging-up and actually the charging-up effect can often be observed at higher magnification. However, it is worthy to note that the SIM is substantially not desirable for such a very high magnification observation that charging-up is observable, because erosion of the specimen surface due to ion-induced sputtering incurs drastic changes of the surface topograph.

Another example of SIM images is shown in Fig.6 (SIM 1-2-3). The specimen is an alloy of Si-Al-B. In the figure SEM image (SEI) is also shown. All of them were the same area. The SIM images follow the sequence of events (1+2+3). While small scratches and stains on the surface are observed in every SIM images, they cannot be found in the SEM image. To explain this feature one may speculate that ion-induced secondary electrons are generated in a very shallow surface region. This enables the SIM to observe fine scratches and stains even though the resolution of SIM is not so good as that of SEM.

*) R.Levi-Setti showed that charging-up on the SEM image is much reduced in the case of SEM observation after gallium ion irradiation.

Looking at the cracks across the Fe-Al grain, those in the BEI are most visible, followed by the SEI next. In the SIM image, however, one can hardly see those cracks except the biggest one across the center of the grain, whereas the resolution of the SIM is good enough for observing them. To confirm this we prepared a specific sample of Al-Zn, on which Pt-Pd alloy film of 150Å thick was evaporated. The secondary electron image of this sample by SIM and SEM are shown in Fig.7. In the SEM image we can clearly see the eutectic structure of the substrate whereas any such structure can no more be observed in the SIM image. The dark area in the SIM image is due to a stain on the sample. This result suggests that contribution of backscattered electrons should be taken into account, in the contrast formation of SEM images in this case. In the SIM image, on the other hand, the secondary electrons generated are free from such a backscattering effect, leading to more surface sensitive observation capability.

Under ion irradiation the specimen surface should change with elapsed time. Such a change can be observed through the change of the contrast as seen in Fig.6. The contrast of Fe-Al rich grain varies from bright to dark against Si rich region with increase of irradiation dose (1→2→3). The contrast change like this was also observed on the Al-Zn alloy sample. Figure 8 shows non coating Al-Zn surface changing with increase of irradiation dose. During observation this area of the specimen surface is continuously irradiated with the gallium ion beam of 0.1nA in probe current and 0.2µm in probe diameter. The exposure time for photographing was 3 minutes. On the first one of the serial images, one can find a weak contrast of eutectic structure, which is the reverse of that after long irradiation (photo 3, 25min.).

On the image of 25min. the topographic contrast enhancement is observed because the surface topograph has changed due to ion beam etching.

To understand the contrast formation in the SIM images we should take into account surface etching, implantation of gallium ions and vacuum condition, particularly, oxygen partial pressure which causes the formation of surface oxide layers. However, since the vacuum pressure in the specimen chamber of the SIM is at the order of 10^{-5} Torr with oil diffusion pumping, detailed discussion cannot be allowed regarding such a shallow surface region as contributes to the contrast of SIM images.

CONCLUSION

Using the newly developed scanning ion microscope, it has been found that the gallium ion probe can produce seco-

ndary electron images with enough brightness and resolution. It should be noted that the secondary electron images of SIM are more sensitive to the surface topograph than SEM images. The former was shown to include no information of deeper region than ion penetration depth. It has been also found that the SIM enables us to observe insulating material surfaces without any marked deterioration due to charging-up. These results suggest that the SIM is becoming a useful tool for surface observation.

ACKNOWLEDGEMENTS

The authors are grateful to Professor Ryuichi Shimizu for helpful discussions.

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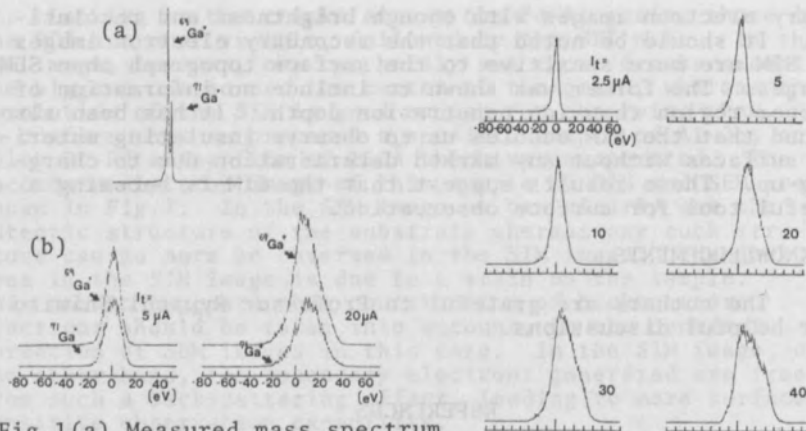


Fig.1(a) Measured mass spectrum of the gallium emitter. (b) Energy distributions of the gallium emitter.

Fig.2 The change of energy distribution of gallium emitter with the change of emission currents from $2.5 \mu\text{A}$ to $40 \mu\text{A}$.

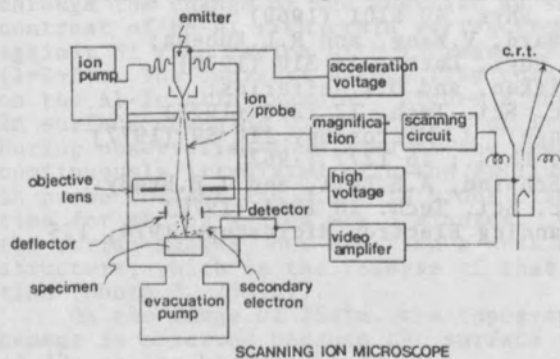


Fig.3 Schematic diagram of the scanning ion microscope.

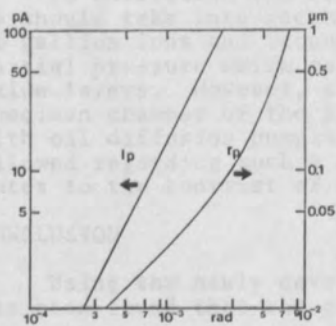


Fig.4 Calculated probe radius (right) and probe current(left) vs the semiangle of irradiation cone. The probe current was obtained from the measured angular intensity.

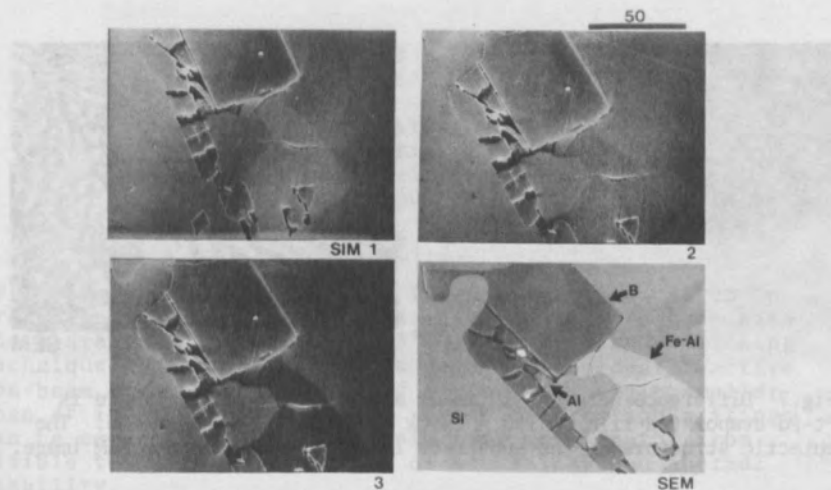


Fig.5 Comparison of the secondary electron image of SIM (bottom left) and those of SEM. The specimen is the surface of EPROM.

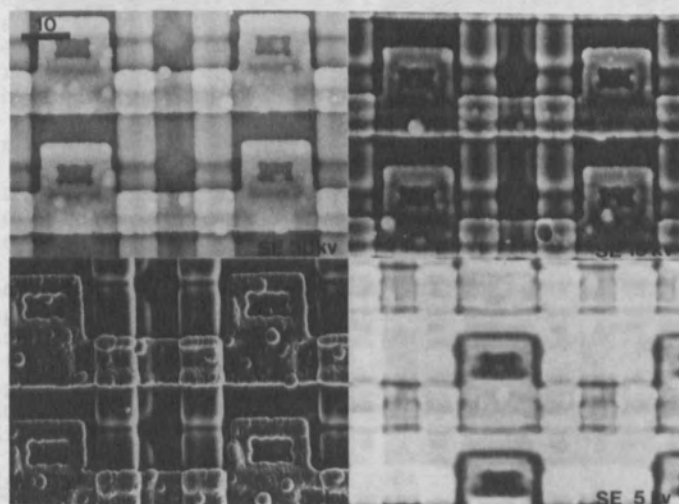


Fig.6 Comparison of the composition contrast between SIM images and SEM image (bottom right). The SIM images follows the sequence of exposures (1+2+3). The specimen is the alloy of Si-Al-B.

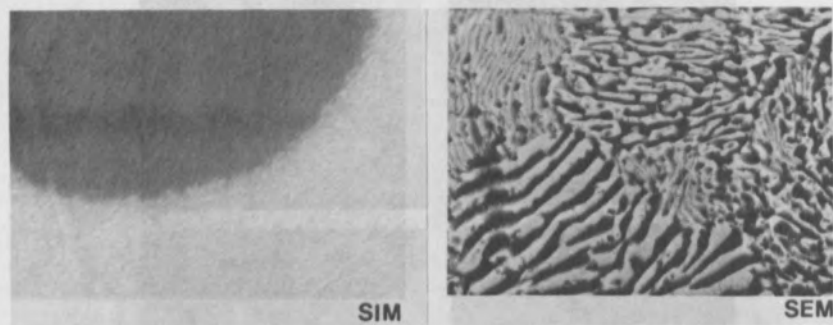


Fig.7 Difference between SIM image and SEM image. The sample is Pt-Pd evaporated film of 150 Å thick on Al-Zn alloy substrate. The eutectic structure of the substrate is not observed on the SIM image.

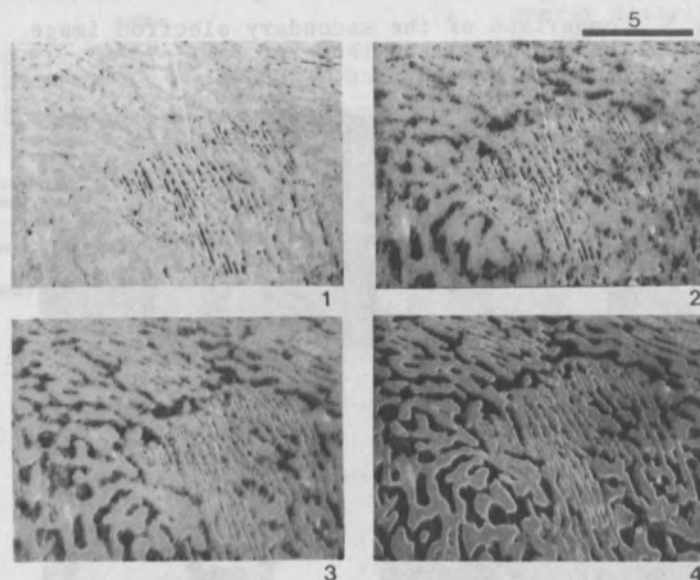


Fig.8 SIM images of non-coating Al-Zn surface changing with increase of ion irradiation dose. The surface was continuously irradiated with gallium ion probe of 0.1nA and 0.2μm in diameter.

DIFFRACTION GRATINGS FOR X-RAY FABRICATED BY REACTIVE ION-BEAM ETCHING

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ABSTRACT

CF_4 reactive ion beam etching is successfully applied to produce blazed SiO_2 and Si gratings for spectroscopy with the blaze angle between $27^\circ \sim 3^\circ$. A new two-stage etching technique combining inclined and normal incident reactive ion-beam etching was developed for a blaze angle smaller than 4° in Si single crystal. These diffraction gratings can be expected to be very useful for wavelengths from visible to soft x-ray because of mechanical and thermal stability.

INTRODUCTION

SiO_2 is a suitable and a useful grating material for wavelengths from optical to soft x-ray region. The Ar ion-beam etching technique, successfully employed to produce PMMA blazed gratings(1), is not applied to produce SiO_2 gratings, because the etching rate of SiO_2 is lower than that of AZ1350, the mask material for ion etching (Table 1). Recently, SiO_2 blazed grating is reported using Ti as mask material(2).

In this paper, it is shown that reactive ion-beam etching is successfully employed as means to produce blazed diffraction gratings of SiO_2 , in which holographically-formed AZ1350 gratings are used as mask patterns for the inclined beam(3). The blaze angle can be controlled by varying the incident angle of the ion beam. But it is difficult to produce gratings with a blaze angle less than 4° by this method. Next, it is shown that a new two-stage etching technique has been developed to fabricate Si diffraction gratings with very small blaze angles down to 1° , which are useful in a soft x-ray region.

FABRICATION OF SiO_2 BLAZED GRATINGS

A schematic diagram of the ion-beam-etching apparatus is shown in Fig. 1. The stage can be tilted to select an appropriate angle. In Table 1 are shown the etching rates of SiO_2 , AZ1350 and Si for CF_4 and Ar at a normal incident ions. The accelerating voltage of ions was 500 V and the

the ion current density was 0.4 mA/cm^2 . Although the etching rate of SiO_2 by an Ar ion beam is lower than that of AZ1350, it is higher than that of AZ1350 in the case of CF_4 reactive ion beam.

Figure 2 shows a fabrication process of SiO_2 blazed gratings. Gratings on SiO_2 substrates were made holographically by using a He-Cd laser ($3250 \text{ \AA}$).

Figure 3 shows a SEM photograph of a profile of the reactive ion-beam-etched holographic gratings with a period of $1.06 \text{ \mu m}$ and a blaze angle of 8° . The substrate consists of SiO_2 only in this case. Blaze angles between 4° to 27° were obtained when the tilt angle of the incident ion beam was varied from 85° to 60° . These results are shown in Fig. 4. The relation between the blaze angle θ and the beam tilt angle ϕ is given by the following equation(4):

$$\frac{V_s(\phi + \theta_s)}{\sin \theta_s} = \frac{V_m(\theta_p) \cos(\alpha + \phi)}{\cos \phi \sin(\alpha + \theta)}$$

where $V_s(\beta)$ and $V_m(\beta)$ are the etching rate of the substrate and the resist at a beam tilt angle β , respectively, α the facet angle of resist patterns and $\theta = \phi - \theta_p$, θ_p the angle of maximum etching rate of the resist. The calculated relation between the blaze angle θ and the beam tilt angle ϕ is shown using the facet angle of resist patterns: 45° . The agreement between the experimental and the calculated results is well. The diffraction efficiency of the Al coated SiO_2 grating shown in Fig. 3 was measured by a non-polarized light in the wavelength region between $2000 \text{ \AA}$ and $5000 \text{ \AA}$ as shown in Fig. 5. The efficiency at a blaze angle ($2920 \text{ \AA}$) was a high value of 90 %.

FABRICATION OF Si BLAZED GRATINGS

As described above, gratings with a blaze angle between 4° and 27° could be obtained. But it was difficult to produce gratings with a blaze angle smaller than 4° due to the divergence of the beam. To produce gratings with a blaze angle smaller than 4° , a new two-stage technique was developed.

Figure 6 shows a schematic process to produce diffraction gratings with a small blaze angle. Si blazed gratings were fabricated using the SiO_2 gratings as the etching masks which were obtained by the inclined reactive ion-beam etching technique. The original grating-patterns

were formed by means of a holographic exposure in AZ1350 resist whose thickness was 0.13 μm . CF_4 reactive ion-beam etching was employed to fabricate SiO_2 and Si gratings with an ion-beam etching apparatus shown in Fig. 1.

Figure 7(a) shows a SEM photograph of the SiO_2 grating with a blaze angle of 20° on a Si substrate. Next, Si blazed gratings were fabricated using the SiO_2 grating as the etching mask with CF_4 reactive ion-beam etching at normal incidence. Figure 7(b) shows a SEM photograph of the Si grating with a blaze angle of $3^\circ \pm 1^\circ$. A very small blaze angle has been achieved which was difficult to fabricate by a technique so far available. The blaze angle of the Si grating can be calculated to be 3.9° by the following equation:

$$\theta_m = \sin^{-1} \left(\frac{V_2(0)}{V_1(\theta_s)} \right) \cdot \sin \theta_s$$

where θ_s and θ_m are blaze angles of SiO_2 and Si, respectively, $V_1(\beta)$ and $V_2(\beta)$ are the etching rate of SiO_2 and Si at a tilt angle of β , respectively. The etching rates of SiO_2 and Si for the present conditions are 35 and 7 nm/min, respectively. The experimental value in Si agreed well with the calculated one. A blaze angle less than 1° can be obtained by the present technique. As a blaze angle of 1° corresponds to a blaze wavelength of 290 $\text{\AA}$ for a grating period of 830 nm, these gratings can be expected to be useful in soft x-ray region.

CONCLUSION

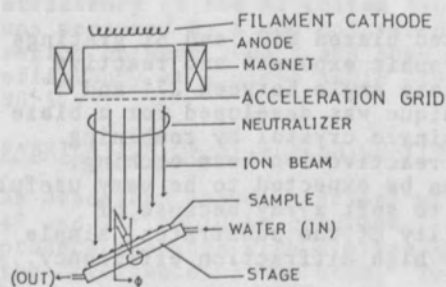
We have successfully fabricated blazed SiO_2 and Si gratings for spectroscopy using holographic exposure and reactive ion-beam etching, with the blaze angle between 27° and 3° . A new two-stage etching technique was developed for a blaze angle smaller than 4° in Si single crystal by combining inclined and normal incident reactive ion-beam etching. These diffraction gratings can be expected to be very useful for wavelengths from visible to soft x-ray because of mechanical and thermal stability of the substrates, simple fabrication process and their high diffraction efficiency.

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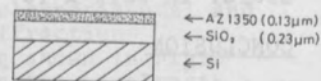
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Table 1. Etching rates of various materials for CF_4 and Ar at normal incidence (500 V, 0.4 mA).

GAS	MATERIAL		
	SiO_2 (nm/min)	AZ1350 (nm/min)	Si (nm/min)
CF_4	36	12	7
Ar	6	18	6



(1) resist coating



(2) holographic exposure
(He-Cd laser $\lambda = 3250 \text{ \AA}$)



(3) CF_4 reactive ion etching



Fig. 1. Schematic diagram of the ion-beam etching apparatus. Fig. 2. Fabrication process of SiO_2 blazed grating.

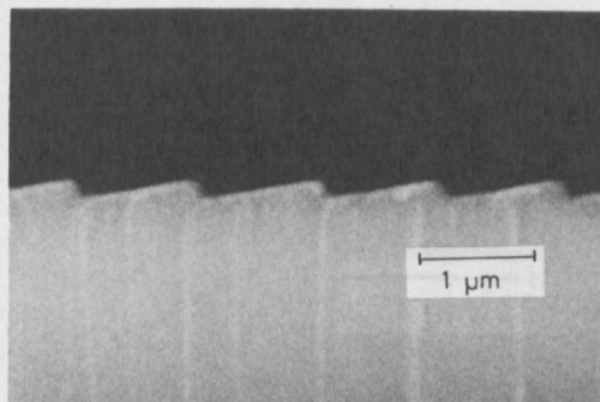


Fig. 3. SEM photograph of a SiO_2 blazed grating. The grating period is $1.06 \mu\text{m}$.

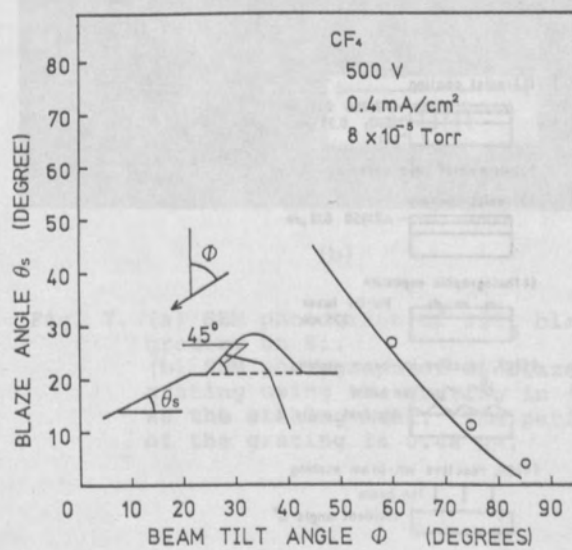


Fig. 4. Blaze angle as a function of the beam tilt angle.

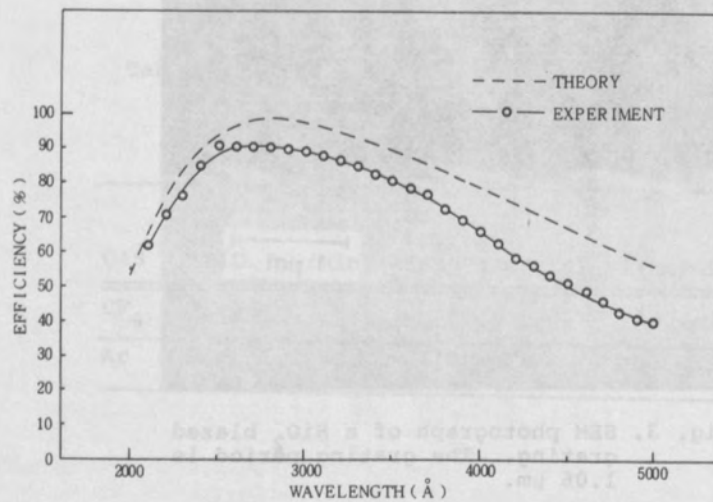


Fig. 5. Diffraction efficiency vs. wavelength

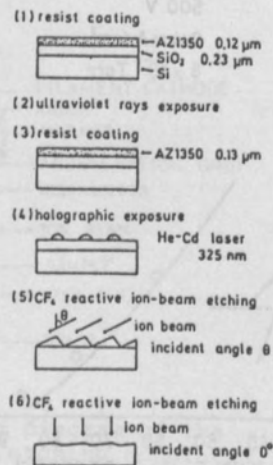
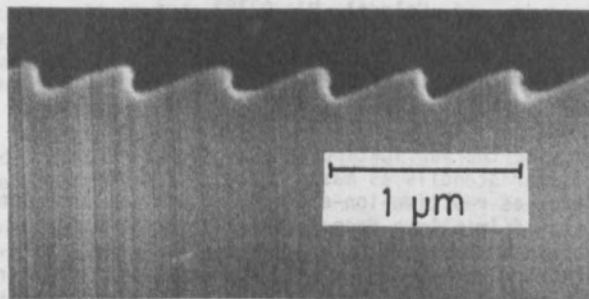
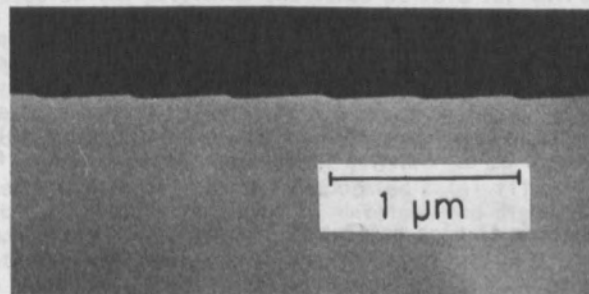


Fig. 6. A schematic process to produce gratings with a small blaze angle.



(a)



(b)

Fig. 7. (a) SEM photograph of SiO_2 blazed grating on Si.
 (b) SEM photograph of Si blazed grating using the grating in (a) as the etching mask. The period of the grating is $0.48 \mu\text{m}$.

METAL-ON-POLYMER MASKS FOR ION BEAM PROCESSING
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ABSTRACT

We describe the fabrication and use of multilayer metal-on-polymer stencils as masks for directed ion-beam processes such as reactive-ion-etching and ion implantation. The thin metal film allows deep features to be transferred into the substrate during etching, or acts as a high contrast mask during ion implantation. The underlying polymer allows the clean removal of the stencil in organic solvents which do not attack the substrate. When combined with e-beam lithography, the method is capable of extremely high resolution. We show examples of submicron features transferred into Si and GaAs using these masks.

Processes using directed beams of ions (e.g., reactive ion etching, ion beam lithography, ion implantation) are integral parts of current semiconductor device fabrication. These techniques have become increasingly important as more stringent requirements are set on reduced device dimensions, linewidth accuracy and alignment tolerance. Pattern stencils to be used in ion processing should meet the following criteria:

- a. replication of high resolution features
- b. durability
- c. easy removal without damage to the substrate

We have designed multilevel, metal-on-polymer (MOP) masks that satisfy the above requirements. E-beam patterned MOPs have been used as masks for transferring ~200 nm features into GaAs and Si substrates by reactive ion etching. MOP stencils incorporating Au metal have been successfully used as masks for selective area proton bombardment of InGaAs as well as for As implants into silicon. In all cases, the stencils were cleanly and easily removed after use without damage to the underlying substrate.

Though typical polymer resists are easily applied, patterned and removed without damage to the substrate they mask, they are often unsatisfactory for use as high resolution masks. For ion etching applications, the relatively high etching or sputtering rate of the polymers makes it difficult to obtain etched structures having high aspect ratios. For ion implantation, the low ion stopping power of

polymers necessitates very high aspect ratio masks for submicron features. Both of these problems can be eliminated by replacing the polymer masks with thin metal layers. Fine-grained films of NiCr alloys have etch rates between 10 and 100 times slower than semiconductors such as Si or GaAs.⁽¹⁾ High density metals such as Au have stopping powers for high energy ions at least 10 times larger than polymers and are in this respect much better than SiO₂ as masks for ion implantation. Difficulty may arise in removing metal masks that have been deposited directly on the substrate, without damaging the substrate itself. The MOP technique we describe combines the resolution and durability of the metal film masks with the easy removal of the polymer stencils.

We describe here the process sequence for the fabrication of an optical and e-beam metal-on-polymer mask. In both cases, the initial layer spun on is polyimide, a high glass temperature (320°C) polymer.⁽²⁾ This is useful in maintaining pattern integrity, and ensuring clean resist removal under processing conditions of high local heating (for example, due to high local incident ion flux). In the case of the optical MOP, the polyimide was spun on to a thickness of 0.3 μm and baked at 160°C for one hour. 1.3 μm of positive photoresist, AZ1350J⁽³⁾ was spun atop of the polyimide and baked at 70°C for thirty minutes. Since the solvents of the polyimide and AZ1350J are dissimilar, there is no need of an intermediate layer to prevent interdiffusion of the two resists. The resist is exposed in the desired pattern, and an undercut profile developed in the upper layer optical resist using a chlorobenzene hardening process.⁽⁴⁾ A blanket exposure is given to the resist and a metal film thermally evaporated through the openings in the upper resist layer. The undercut profile of the optical resist facilitates clean liftoff of the evaporated metal film. Liftoff is achieved by soaking the sample in AZ developer to dissolve the fully exposed upper layer of resist, leaving the underlying polyimide intact. The MOP stencil is completed by reactive ion etching in an oxygen plasma to transfer the resist pattern into the polyimide layer. The use of RIE here allows control of the profile of the lower layer polymer and maintains the resolution of the original pattern.

The top of Figure 1 is an SEM micrograph of a MOP stencil atop a GaAs substrate. The stencil is comprised of ~60 nm Ni(Cr) on 0.3 μm polyimide. The substrate was subsequently etched in a mixture of CCl₂F₂, argon and oxygen⁽⁵⁾ and the resulting etched feature with the MOP mask remaining is shown in the lower left portion of Figure 1. Note that the MOP stencil remains in excellent condition after etching the GaAs to a total depth of approximately 1 μm . The final micrograph of Figure 1 shows the clean GaAs structure after removal of the MOP stencil.

We are interested in using the e-beam patterned MOPs to produce lateral features much finer than those obtained with the optical MOPs. Accordingly, the total thickness of the resist stencil must be thinner

to avoid unreasonably high aspect ratios that would prevent the achievement of good liftoff metal patterns. For these stencils, the initial layer of polyimide was spun on to a thickness of $\sim 0.2 \mu\text{m}$, and then baked at 200°C for one hour. The "upper layer" resist in this case is actually a high resolution e-beam bilevel resist that has been previously described.⁽⁶⁾ The bilevel comprised approximately 100 nm of polymethylmethacrylate (PMMA) atop 200 nm of a copolymer of methylmethacrylate and methacrylic acid (P(MMA-coMAA)). The e-beam patterns were written at 30 keV using a SEM; an undercut pattern was developed into the bilevel using a 3:7 solution of cellosolve:methanol. A 5 nm layer of Cr and a 30 nm layer of Ni(Cr) were evaporated through the stencil, the unwanted portions of the mask were then lifted off by immersion in acetone, and the stencil completed, as for the optical MOP, by RIE in O_2 . Figures 2 and 3 show fine structures etched into Si and GaAs substrates, respectively, using the e-beam MOPs as masks. The Si patterns were formed by RIE in CF_3Br at 30 mTorr pressure and 400 V bias, and the GaAs patterns were etched in a $\text{CCl}_2\text{F}_2/\text{Cl}_2$ gas mixture at 5 mTorr pressure and 150 V bias voltage.

Figure 4 shows an optically patterned MOP used as a mask for ion implantation. The three scanning electron micrographs illustrate the major processing step used to form the MOP implant mask. The top micrograph shows the undercut resist profile with the evaporated metal films (Cr/Au/Cr) cleanly broken across the edge. The thin top layer of Cr is used to prevent sputtering of the Au mask. The middle micrograph shows the metal pattern on the thin polyimide layer. The bottom micrograph shows the completed MOP profile after reactive ion etching the polyimide in the exposed areas.

The MOP structures form easily applied and easily removed implantation masks that are useful for a wide variety of material substrates. The control of the stencil profile, achieved using RIE, allows potentially greater control of the implantation profile. By using a thin, highly absorbing gold film atop of a fairly thin resist layer the total thickness of the implantation mask can be kept thin enough to allow fine lateral features without having the aspect ratio of the mask so large that it (e.g.) promotes excess ion scattering.

Metal films offer greatly improved contrast over polymer films for application to processes like ion implantation and reactive ion etching. Metal-on-polymer masks combine these features with the ease of removal of polymer layers. High-aspect-ratio etching and high contrast masking for ion implantation have been demonstrated using this process.

We wish to thank J. M. Moran for supplying the polyimide used in this study.

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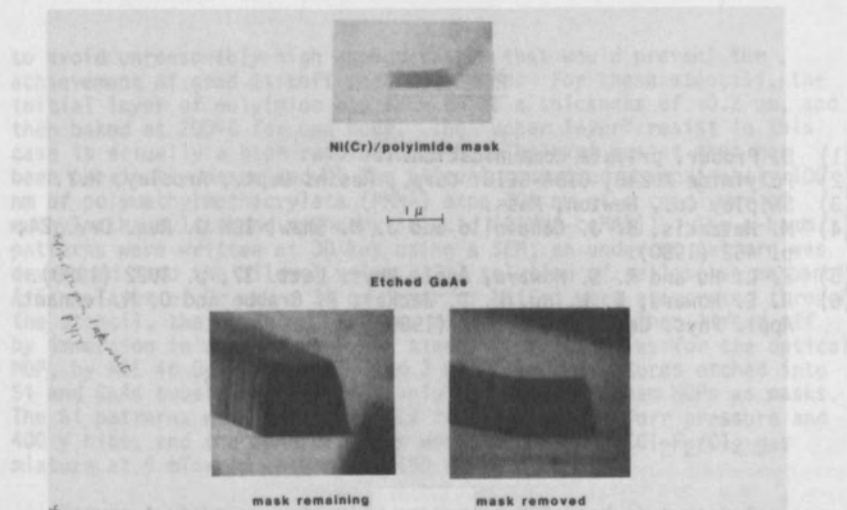


Fig. 1a: MOP stencil on GaAs substrate; 1b: Etched GaAs pedestal with MOP mask in place; 1c: Etched pedestal after removal of MOP mask.

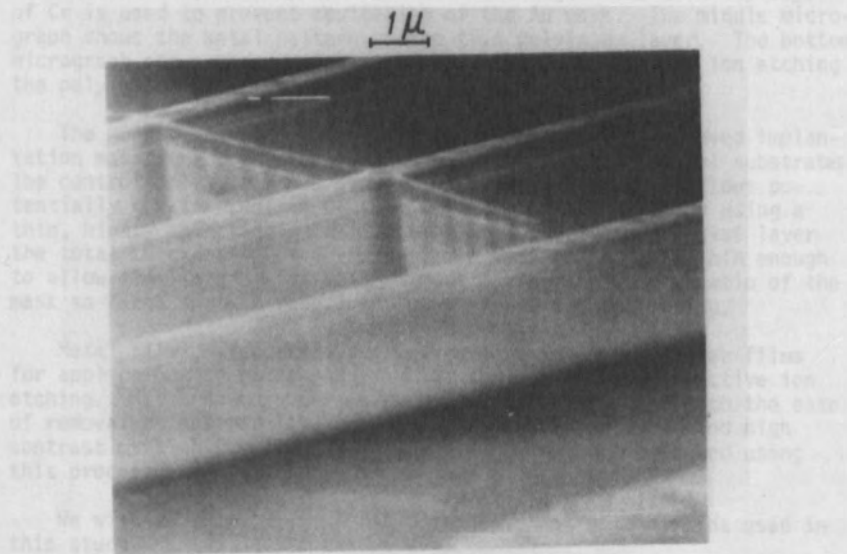


Fig. 2: Patterns etched in silicon using RIE in CF_3Br plasma through an e-beam defined MOP mask.

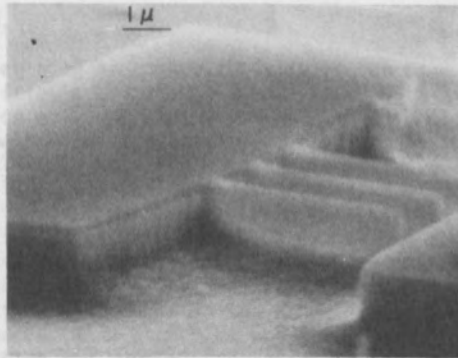


Fig. 3: Patterns etched in GaAs using RIE in a $\text{CCl}_2\text{F}_2/\text{Ar}/\text{O}_2$ plasma through an e-beam defined MOP mask.

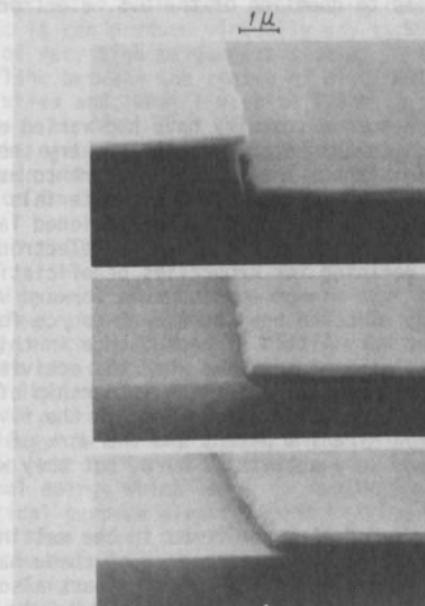


Fig. 4: Steps in formation of (Cr/Au/Cr)-on-polyimide MOP mask for ion implantation; 4a: Undercut resist profile with evaporated metal broken cleanly across resist edge; 4b: Metal pattern on polyimide layer; 4c: Completed MOP stencil, after RIE of polyimide.

RENAISSANCE OF ELECTRON BEAM MELTING

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ABSTRACT

A brief review of factors governing electron beam melting technology introduces the topic. It is followed by the substance of the process and recent equipment developments. The article concludes by a review of the factors which lead to doubling of the U.S. electron beam melting power by the end of 1982.

INTRODUCTION

The energy crisis and resources scarcity have had varied effects on different technologies. In the metallurgical industry the increased cost of energy and materials has lead to much effort to assure that the best possible properties are extracted from the materials it produces. These two factors, together with others to be mentioned later, prevailing at this time have refocussed attention on the electron beam as a source for melting and refining for properties beneficiation. A 1907 patent by M. von Pirani¹⁾, a man of considerable forward vision, is the recorded begining of the electron beam as a heat source for melting and refining of metals. But very little of consequence in this field actually took place until the mid-fifties when the activities of the Temescal Metallurgical Corporation under the leadership of Hugh Smith placed the technology in the public eye again. In the five decades which elapsed between von Pirani's patent and the work of Smith's²⁾ and his associates, there were activities here, but they were of no real consequence.

Temescal pioneered the use of electron beams in the melting and refining of the refractory metals, and a major part of these have been essentially so processed ever since. These early years also saw National Research Corporation and Alloyd Corporation in the U.S.A., the Institute M. von Ardenne-LEW team in East Germany, Degussa, Heraeus in West Germany and Four Cyclop in France also enter this market. To day only two companies of the original group remain active in this field, the von Ardenne-LEW team and Heraeus now Leybold Heraeus. Of recent date however, we have a newcommer here, it is North Hill Enterprises of

Albany, Oregon.

The Temescal beginning of consequential electron beam melting activities of the late fifties culminated a decade later with 3 megawatt hybrid vacuum induction electron beam melting furnace to process ferritic steels.³⁾ Steel processing has always been the real challenge for those in the electron beam field because only entry in ferrous metals processing could permit true explosive growth for electron beam melting and refining if and when it comes. The life of this hybrid installation was relative short with a combination of the technical problems with the transverse guns which powered the system and problems with the coupled with the induction furnace. In fact problems in either module lead to production shut downs in the whole installation resulting in essentially unacceptable economics and leading to its untimely demise. At about that time the von Ardenne Institute-LEW partnership of East Germany, build a 1.7 megawatt electron beam furnace for the steel works in Freital⁴⁾, also specifically aimed at steel processing. This furnace though much modified and now operating only at 1.2 megawatt of power has remained in operation to this very day, and has been responsible for generation of much steel processing technology. In fact it is claimed that it can produce virtually any type of alloy steel with the exception of very high manganese steels. I believe it has been the important link between the zenith of electron beam melting reached at the late sixties and, what I wish to refer to as, the renaissance of the technology to day. This renaissance is also affecting in a most positive way the electron beam melting and refining of reactive and refractory metals which has been a viable economic process here since its introduction in the late fifties.

WHY ELECTRON BEAMS?

Before proceeding any further it is appropriate to review briefly the substance of electron beam heating and the one phase of metals processing technology which it defines. That is electron beam melting and refining. There are of course other thermal electron beam applications, but I will not discuss them here. The thermal energy generated by the electron beam is a product of an energy conversion process in which the kinetic energy of the highly accelerated beam forming electrons is converted to heat on impact with the work piece. This conversion produces thermal energy which leads to heating, melting and evaporation. For most practical purpose electron beam heating has no upper temperature limit. It thus makes possible the melting of virtually any material and the maintaining in cold wall crucible molten metal pools in vacuum for any length of time. This permits the removal of gasses and the selective evaporation of impurities in accordance to their vapor pressures and specific evaporation rates as seen in Fig. 1 and Fig. 2. This cardinal to purification aspect in fact can also present a problem when one needs to manufacture alloys containing high volatility constituents and special attention must be given to this point. The recent availability of electron guns capable of stable operations pressures

up to 10^{-2} has simplified the production of such alloys. Electron beams can advantageously be used for refining of refractory metals reduced by aluminum as they are capable of economically removing the surplus aluminum left from the reduction. A cross section of a typical example of an advanced gun is seen in Fig. 3.

Electron beam melting can handle a wide variety of feed configurations covering the gamut from a diversity of ingot shapes through scrap of various dimensions including particulate and granular feeds. Within the limits of the power available one can control independently the energy needed for melting and that for refining. This permits versatility when one wishes to process in the same furnace both very high purity materials and melt at very high rates. Circular and rectangular cross section ingots can readily be produced as can ingots weighing up to 100 tons. The nature of electron beam heating permits unusual flexibility in controls.

WHY RENAISSANCE?

I referred as renaissance of the technology the recent refocussing on the electron beam as a desirable heat source for melting and refining. It is a result of the coexistence of needs which can be served best by the advances in vacuum technology and the technology of electron beam generation equipment achieved in the last decade. Advances in beam control electronics including the incorporation of microprocessors to program the beam path and extent of residence time at a particular site have also been invaluable here.

Let me consider the needs first: The energy crisis and its repercussions in raw material supplies which began with the oil embargo of 1973 is still with us. It warrants increased attention to both energy and materials conservation despite the apparent glut and disarray of prices prevailing at time of this presentation as consequence of our recession.

Electron beam heating is a most efficient mean for electrical energy conversion. This makes its utilization for melting and refining a wise selection at time when concern about energy prevails through electron beam melting is certainly not the most energy conservative process. The energy distribution for an electron beam power for melting is shown in Fig. 4.

Electron beams however, offer processing with outstanding flexibility making possible perhaps the most outstanding property beneficence for a given energy investment. Energy recovery from the cooling waters in recirculating systems could further improve the user's energy economics in special cases.

The prevailing recession has momentarily relieved pressure from all conservation moves. I believe however that this is but a temporary

state of affairs and in no way should it cause a reversal in commitment of many to conserve resources. This being the case electron beam processing of some alloys which has produced in these very alloys properties⁵⁾ equivalent to alloys with considerably higher alloy content will have to increase in importance. It is my opinion that additional work to establish precisely the economics here is long overdue and urgently needed. In fact I think that such studies should be initiated immediately and believe that those who generate the first results here will be handsomely rewarded.

Concerns with environmental pollution have always been intimately associated with the metal processing industry. It can be unequivocally stated that the electron beam is the cleanest efficient heat source available to the metals processing industry to day. Building of large electron beam melting plants is not likely to present the plant builder with the pollution problems associated with alternate metal melting techniques. Permit for the construction of a 2.4 megawatt furnace in the North East was obtained in two months. Obtaining permit for a comparable capacity furnace powered by a less sophisticated heat source would have taken possibly up to a year, and there would have been no certainty of approval.

The next factor to contribute to the renaissance of electron beam melting and refining is the expansion of the market for materials which have been traditionally so processed. Here reference of course is made to the refractory and reactive metals. As a consequence of this trend we are seeing for the first time and lead by the Titanium industry the construction of multi megawatt electron beam melting and refining installations.

Another important factor which is exerting influence here also is the new requirement of those making directionally solidified or single crystal components for jet engines and stationary turbines. These manufacturing entities require alloys free from metallic inclusions. This objective appears impossible to meet with alternate technologies.

It is known that super alloys to day have an ever increasing content of reactive and or refractory metals known for their ease of oxidation and inclusion formation. It is also known that melting in refractories lined crucibles always increases the content of non metallics. Electron beam remelting offers truly outstanding capabilities in non metallics reduction and removal. Here one will use a melting throff with option for bottom pouring permitting the skimming off of ceramics or oxides which float and coalesce on the surface of the melts. Some of the oxides also decompose with their metallic content dissolving in the molten pool.

As this paper is being presented the leading producers of alloys for the field and those producing jet engines and turbines are working with electron beam remelting. One can mention here at least Special Metals,

Howmet, Pratt & Whitney and General Electric as active in this field. The outcome of these studies could be either the across the board adoption of electron beam remelt as a quality control tool for jet engine materials, or it could lead to a requirement that all these alloys be electron beam remelted. The answer should be forthcoming within the next 6 to 12 months.

Electron beam furnaces with special design features offer some exciting but less than well known options to the processor of virtually all metals advantageously processed with electron beams. Reference here is made to the ability to produce hollow tube drawing stock by using cold mandrills in conjunction with the habitual in electron beam melting cold wall mold.

Again with suitable designed cold plates one can cast directly a diversity of sandwich materials ingots permitting variation in both the individual components of the sandwich and the relative thickness of these components.

With the steadily increasing competition in the lower grade steels market from the less developed nations perhaps the last bastion to guarantee survival of advanced technology countries steel industries is through taking the initiative in broader use of advanced technologies. Electron beam in steel processing appear to be one such avenue.

Accrued experience apparently indicates economic viability of electron beam technology in special steel melting in the Eastern Countries where furnaces to cast up to 20 tons have been operational for some time. A furnace to cast 30 ton steel ingots will be going on stream this summer and the two largest electron beam furnaces in the world are in construction here. They will be powered by eight 1.2 megawatt guns and will have the capability to cast 100 ton ingots. The layout of guns for these furnaces is shown in Fig. 5.

The major technological advances in the performance characteristics brought about by the differentially pumped high power axial electron guns lead originally to their implantation in the Eastern Countries. The further advances which have taken place in the last five years which among other have included gas focussing and made possible large tonnage ingots is the ability to maintain with no interruption power for 100 hours even at the full 1200 KW rated power for all guns powering an installation. Fig. 6 shows data on the statistical studies for cathode lifetime on such guns. This increase in reliability has also become an important new factor to be considered not only in evaluation of the economic viability of the electron guns as a potential source for large scale specialty steel processing, but also for powering large installations in general.

SUMMARY

In summary then the renaissance of electron beam applications for mel-

ting and refining appears to be soundly based on a series of world developments and industry requirements. These are met by the progress in vacuum technology on one hand and electron beam generating system capabilities and control electronics on the other. By the end of 1982 this renaissance will have doubled the electron beam melting and refining capacity of the U.S.A.

Information on the performance on the two largest 9.6 megawatt electron beam steel melting and refining installations to go on stream in the near future in the USSR on one hand and on the two 2.4 megawatt installations for the processing of reactive metals which go on stream in the U.S. later this year are eagerly awaited. These results will have far reaching consequences to the future of this technology including its possible adoption by the steel industry.

Prior to the prevailing renaissance both in the East and the West there was much reservation when considering electron beam heating as a reliable heat source for truly large scale melting and refining installations. While this concern has been laid to rest by the thirteen years of experience at Freital, the long range trend is not clear. Look at Fig. 7 which shows a 100 KW transverse gun of yesterday and a 1200 KW gun, the best technology to day has to offer, and draw your own conclusion. To me at least after more than two decades of involvement it appears highly probable that results from performances of the furnaces now in construction will be the foundation of the next phase, the real growth phase of electron beam technology which those involved here have been looking for for years. If this is indeed to happen, the economics of these U.S.A. and out world will have to be drastically better than they are at this moment.

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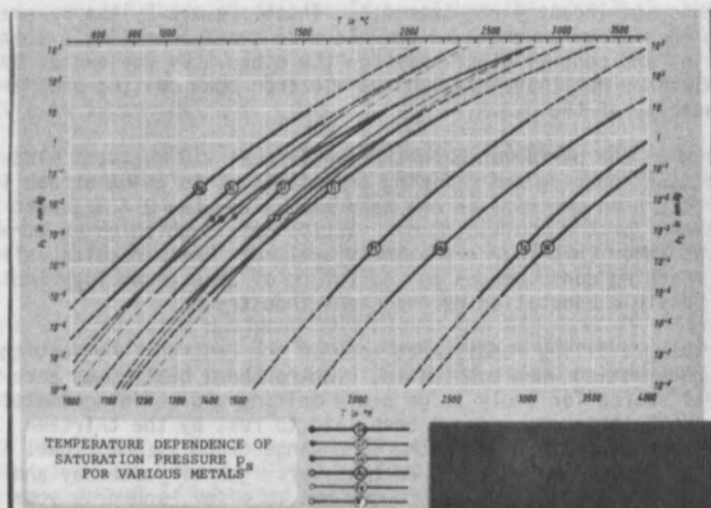


FIG. 3.
Typical Cross Section
of Advanced Gun.

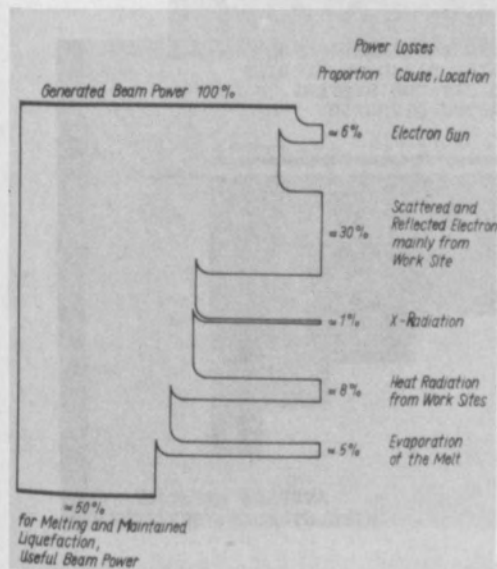
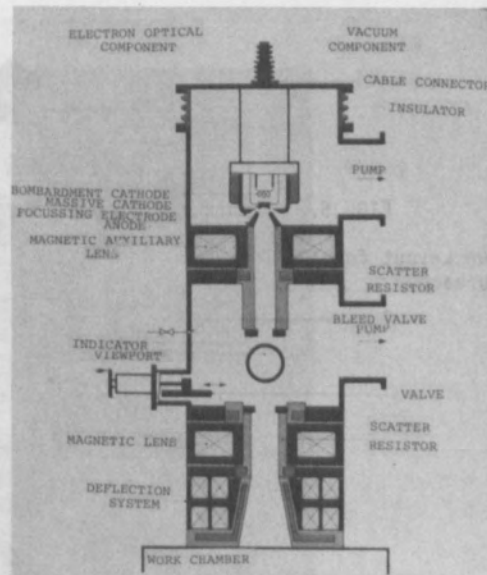


FIG. 4.
Electron Beam Power
Distribution.

FIG. 5.
Gun Layout for 100 Ton
Furnace.

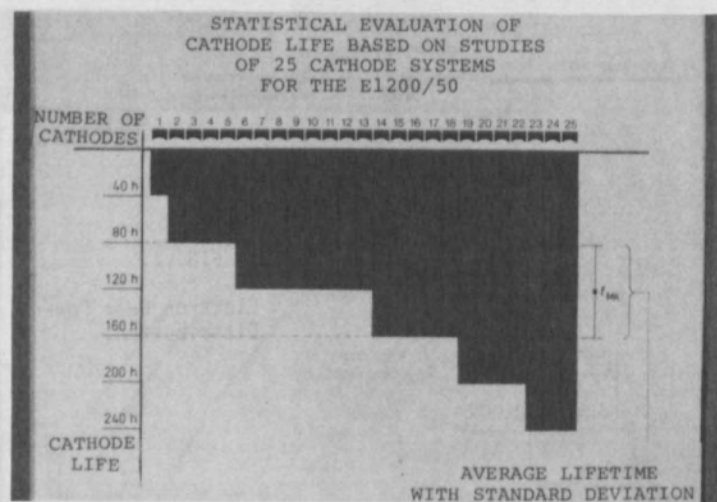
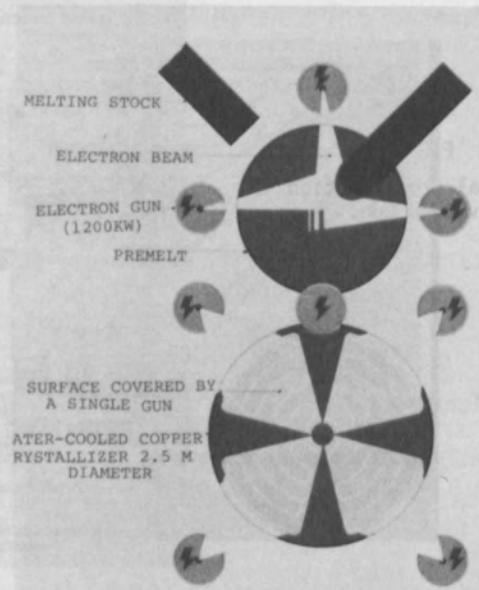


FIG. 6.

Aberrations
 coefficient
 chromatic
 deflection
 limiter in
 spherical
 Acceptance
 Air Bearing
 guides E.V.
 Alignment
 accuracy
 Angular surge
 Anesthetics
 Apparatus
 Application
 Aspect ratio
 Axial pattern
 Axial
 defocusing
 function
 gun, 315
 Axially symmetrical



FIG. 7.

Electron Guns of Yesterday and To-Day.

Beam
 blasting, 33
 profiles, 107
 size change, 18
 beam-steering
 Bifocal object
 Bit level resist, 334, 335
 Blanking, 410, 411, 416
 Blazed grating, 443, 444
 Brightness, 138
 Characteristic function, 61, 62
 Charging-up, 417
 Chromatic (aberration), 410, 412
 Chloroacetylated poly-*n*-methylstyrene, 192
 Closed-loop feedback alignment, 350
 Coarse rotation, 371
 Composition, 374
 Control
 controlled vector mode, 163
 network, 93
 conjugate blurring, 30

FIG. 2.
Our Layout for 2
Furnace.



FIG. 3.

INDEX

- Aberrations
 - coefficients (SOL), 72
 - chromatic, 410
 - deflection, 411
 - linear in deflection, 104
 - spherical, 410
- Acceptance angle, 410, 411
- Air Bearing, 49, 50
 - guided X-Y table, 352
- Alignment, 28
 - accuracy, 348
- Angular current, 417
- Annealing, 377
- Aperature aberration, 60
- Application (SOL), 73
- Aspect ratio, 338
- Au pattern, 337
- Axial
 - defocusing, 284
 - function (potential), 397
 - guns, 315
- Axially symmetric lens, 397
- Beam
 - blanking, 33
 - profiles, 107
 - size change, 18
- Beam-stepping rate control, 271
- Bifocal objectives, 350
- Bi level resist, 204, 205
- Blanking, 410, 411, 416
- Blazed grating, 443, 444
- Brightness, 136
- Characteristic function, 61, 62
- Charging-up, 437
- Chromatic (aberration), 410, 412
- Chloremethylated poly- α -methylstyrene, 193
- Closed loop feedback alignment, 350
- Complex notation, 397
- Composition, 374
- Computer
 - controlled vector mode, 153
 - network, 93
- Conjugate blanking, 80

- Contactless testing, 154
- Control, 361
- Copolymers, 186
- Correction
 - lens, 61
 - program, 256
- Cost reduction, 28
- Crossover, 410
- Cross-wire detector, 106
- Current
 - density, 417, 418
 - pinch, 304
- Data
 - acquisition, 42
 - compaction, 96
 - flow, 93
 - manipulation, 231, 232, 236
- Deflection
 - aberration, 400, 411, 416
 - accuracy, 3
 - coma, 406
 - distortion, 106
- Deflectors, 410, 411, 415
- Diago-type photoresist, 415
- Diameter, 138
- Diffraction grating, 444
- Directional solidification, 459
- Direct wafer exposure (EBL), 49
- Direct writing capability, 40
- Dynamic
 - correctors, 400
 - 2n-tuple field, 399
- Electron beam
 - exposure, 179, 186
 - exposure system, 139
 - heating, 457
 - induced chemistry, 179
 - lithography, 2, 15, 112, 243, 252
 - lithography technology, 92
 - lithography throughput, 246
 - melting, 456
 - testing, 150, 159
- Einzel lenses, 411, 412, 414, 415
- Electrocal discharge, 302
- Electron
 - optical column, 3
 - optics, 30
- Electronic controls, 33

Electrostatic
 in lens deflection system, 103
 lenses, 409
 predeflector, 34
 Emission characteristics, 135
 Emitting surface, 138
 Encapsulation, 231
 Energy
 accelerating, 409, 412
 analysis, 160
 field ionization, 412, 413
 intensity, 255
 spread, 284, 409
 Equation of motion of electrons, 80
 Exposure scheme for electron beam lithography, 15
 Exposure time, 348
 Facet plane, 137
 Faraday, 367
 Fast Deflectors, 45
 Field ion source, 413, 422
 Finite element method, 105
 Flat-tipped cathode, 136
 Flexibility, 28
 Focus deflection system, 397
 Focussed ion beam, 413, 422
 system, 424
 GaAs, 450, 451, 452
 Gallium
 ion beam, 388, 390
 probe, 434, 438
 Gap size, 411
 Gas puff, 293
 Glass, 219, 223
 Gold ion beam, 387, 388
 Guidance mechanism, 50
 Heating, 219
 Hetero structure, 127
 High resolution, 2
 lithography, 122
 High speed electron beam
 blanker, 78
 lithography system, 78
 High voltage, 219
 H₂⁺ ion beams, 409, 413
 Hyperbolic tangent distribution, 105
 Implantation, 36, 367

Incident electron exposure ratio, 272
 Infrared spectron, 179, 180
 Integral delay line, 83
 Interdigital electrode pattern, 60
 Interactive checking, 97
 Interaproximity
 correction, 204
 effect, 115, 254
 Ion beam
 assisted etching, 425
 processing, 450
 Ion
 etching, 196
 induced secondary electron image, 436
 IR spectra, 188
 JOB file, 95
 Large area detector, 161
 Large scann field, 159
 Laser, 291
 Laser interferometer, 32, 35, 41, 49
 Lift-off, 326, 327
 Linear beam, 59
 Linear voltage contrast, 162
 Lines and spaces pattern (0.5 μ m), 352
 Linewidth
 correction, 273
 variation, 270
 Liquid metal
 alloy ion source, 423
 ion source, 423
 Lithography, 126, 333
 Low energy electrons exposure, 211
 MAA/MCA resist, 189
 MAA/TBM resist, 187
 Magnetic, 368
 Magnification, 413
 Manostucture fabrication, 112, 115
 Maskless fabrication, 422, 425
 Masks, 334, 450
 Mass, 363
 Membrane, 334
 Metal organic vapor deposition, 122, 123
 Methacrylic acid, 185
 M file, 94
 Microbridges, 426
 Microcomputer, 362
 Microwave plasma, 234

Microwave power, 234
 Minimized footprint, 299
 Mixed lithography, 243
 Monte-Carlo, 18
 initialization, 283
 simulation, 283
 stepping, 283
 Mo₂C, 375
 MoP, 377
 MOP metal on polymer, 450, 451
 MoSi₂, 372
 MOS properties, 378
 Moving objective lens, (MOL), 396
 Moving quadrupole Lens (MOL), 396
 Multi-lens construction, 105
 Multiple aperture selector, 16
 Multiple beam size, 16
 Multi-layer resist, 327

 Negative electron resist, 193
 Negative resist, 253
 Nested chip layout, 96
 NIMOS device patterning, 246
 Non-linear aberrations, 105

 Objective lens, 409
 Octopole field, 62
 Open/shut test, 154
 Optical emission spectra, 233, 323
 Optimized parallel-plate blander, 82

 Pattern
 fracturing processor, 43, 44
 quality, 17
 replication (0.5 μ m), 347
 Pentode electron gun, 152
 Perveance, 286
 Phase transition temperature, 375
 Phosphorus implantation, 372
 Phosphorus redistribution, 376
 Photoresist stripping, 231, 232
 Plane (100), 137
 Plasma
 density, 292
 focus, 292
 X-ray source, 302
 PMMA, 204, 205, 311, 443, 452
 exposure, 211, 212
 Polyamide, 451
 Poly (p-bromostyrene), 172, 173

Poly
 (p-chlorestyrene), 172, 173
 (p-hydroxystyrene), 172, 173
 (p-nitrostyrene), 172, 174
 (p-substitute styrenes), 171
 Polysulphones, 179, 183
 Potential, 397
 Potentials
 accelerating, 414
 field ionization, 414
 lens, 412
 Probe
 diameters, 414, 417
 Testing, 150
 Production-purpose e-beam system, 103
 Projected
 range, 372
 straggle, 373
 Projector lens, 414
 Proximity effect, 269
 compensation, 29, 39
 correction, 260, 263
 program, 264
 Pseudo-stigmatic operation, 62

 Quadrupole
 lens, 397
 triplet, 59

 Radiation chemistry, 171, 181
 Reactive
 ion beam etching, 443, 444, 445
 ion etching, 323
 plasma, 232
 sputter, 194
 sputter etch, 336
 Real time correction technique, 271
 Reduction of exposure time, 18
 Refractive index, 335
 Refractory metals, 460
 Replication, 305
 Resist, 336
 application, 171
 profile control, 272
 profile correction, 273
 Resolution, 28, 29, 409
 Retarding field, 282
 analyzer, 161
 Rotating anode, 290

Sample charging, 152
 Scaling down of structures, 5
 Scanning ion microscope (SIM) 388, 434, 437, 438, 439
 Secondary electron emission, 151
 Self consistent method, 261
 SEM, 1,3,4,6
 mode, 153
 Semi-angle, 306
 Semiconductor membranes, 122
 Shaped beam, 139, 397, 403
 Sheet resistance, 376
 Si-K α X-ray, 349
 Silicon, 219, 223
 Silicide work function, 378
 Simple parallel-plate blander, 81
 Single crystal LaB₆ cathode, 135
 Six degrees of freedom, 351
 Sizing, 95
 Slow wave structure, 79
 SOL
 aberration coefficients, 72
 applications, 73
 swinging objective lens, 70
 Source diameter, 303
 Source of brightness, 303, 307
 Space charge theory, 286
 Spacer, 335
 Spectrum, 293, 363
 Spot diameter, 284
 Square beam, 106
 Static detection of focussing, 351
 Stationary anode, 290
 Stigmator, 403, 409
 Stripeline deflector, 83
 Structure, 374
 Submicron pattern, 194
 Substrate backscattering, 270
 Substrate proximity correction, 269
 Suppression, 368
 Surface depletion, 124
 Synchrotron radiation, 291

 Taylor expansion, 398
 T-butyl methacrylate, 185
 Temperature rise, 222
 Thermograms, 188
 Thin film substance, 195
 Throughput, 29
 Topographic contrast, 438
 Transverse chromatic aberration 400

Tripode ion gun, 385, 386, 387, 389
 Tripotential test method, 151,
 Two-stage magnetic focussing lens field, 104

Vacuum system, 4

Variable

axis lens (VAL), 401
 shaped beam, 58
 shaped EBL thography, 39
 shaped e-beam technique, 103
 shaped lithography, 28
 spot shaping, 58

Verification system, 97

Very high resolution EBL, 112

Vibration, 4

VLSI, 92

Voltage contrast, 160

Wafer handling system, 52

Warp, 338

Wider scanning field, 107

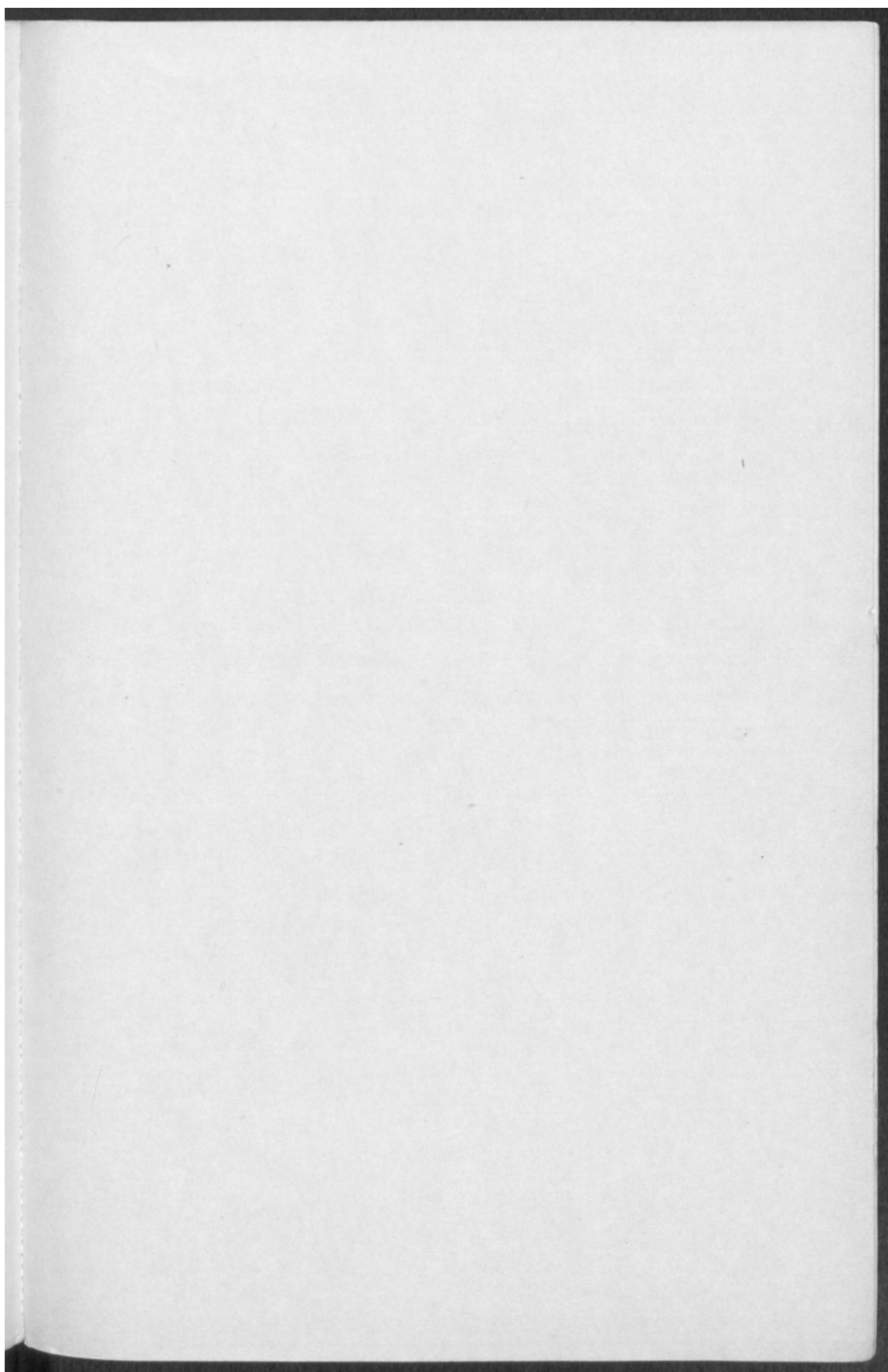
Working distance, 414, 415

Writing speed, 17

X-ray, 333, 443

emission, 304
 exposure system, 347
 flux density, 306
 lithography, 289, 302, 315, 327
 mask, 305, 323, 324, 327
 source, 289, 316, 317, 319
 source efficiency, 317
 zone plate, 5

Zooming, 410



Tripode ion gun, 385, 386, 387, 388
Tributential test method, 151
Two-stage magnetic focusing lens field, 145

Vacuum system, 4

Variable

axis lens (VAL), 301
shaped beam, 58
shaped C.T. lithography, 38
shaped x-beam technique, 103
shaped lithography, 28
spot shaping, 58

Verification system, 97

Very high resolution C.T., 117

Vibration, 4

VLSI, 92

Voltage contrast, 160

Wafer handling system, 52

Warp, 333

Wide scanning field, 107

Working distance, 414, 415

Writing speed, 17

X-ray, 333, 343

emission, 304

exposure system, 347

flux density, 306

lithography, 205, 302, 315, 327

mask, 205, 301, 324, 327

source, 209, 310, 317, 319

source efficiency, 317

zone plate, 5

Zooming, 410

