Chemical Assisted Etching with Ne^+ & He^+ Ion Microscope: –Preliminary Study of Nanomachining Properties with O_2 and XeF_2

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Introduction:

Since 2009, Intel Corporation PDebug development and the Zeiss Microscopy applications development teams have been collaboratively studying the properties of Neon Gas Field Ion Source (GFIS) beams for microscopy and nanomachining applications. More recently, this research has expanded to include analyzing the benefits of introducing gas assisted etch chemistries during Ne^+ and He^+ nanomachining in bulk substrates. The work presented in this talk was carried out at Zeiss Microscopy, LLC in Peabody MA, and at NIST in Gaithersburg, MD.

Background:

Researchers around the world have demonstrated unique machining capabilities of He^+ GFIS in thin films for nano-electronic and nano-photonic device fabrication. For example, recent results from Pickard et. al., demonstrated 5 nm spacing for plasmonic devices machined in Au films [1] and Sidorkin, et. al., have demonstrate patterning of 6 nm dots in hydrogen silsesquioxane (HSQ) films using Helium Ion Microscope (HIM) [2]. He^+ ions however does not exhibit the necessary machining (sputtering) capabilities in bulk films, such as SiO_2, Si, and Cu commonly used in semiconductors. Furthermore, He^+ beam also has a relatively high substrate interaction volume, making it a poorer candidate for some machining applications requiring machining in close proximity to a transistors channel region [3]. It was these limitations of He^+ GFIS that led to the investigation and subsequent development of Ne^+ GFIS. Neon, similar to helium, has the uniquely high ionization energy relative to potential source contaminants, such as CO_2, N_2, and H_2O. The table in Fig. 1 shows comparison of the ionization energies for several noble gasses and other common contaminant gasses. Neon, relative to other noble gas options, has an ionization energy that is 5 to 7 eV higher than common impurity gasses that could migrate into the source region and cause damages to the source tip. High ionization energy is an important property for a GFIS to ensure a stable source and emission [4].

Ionization Energy (eV)		
He	24.6	Good GFIS Candidates
Ne	21.6	
Ar	15.8	Poor GFIS Candidates
Kr	14	
Xe	12.1	
O	13.7	Commom Impurities
N	14.5	
CO_2	13.8	
N_2	14.5	

***Figure 1**: Ionization Table for Noble gasses and common impurities.*

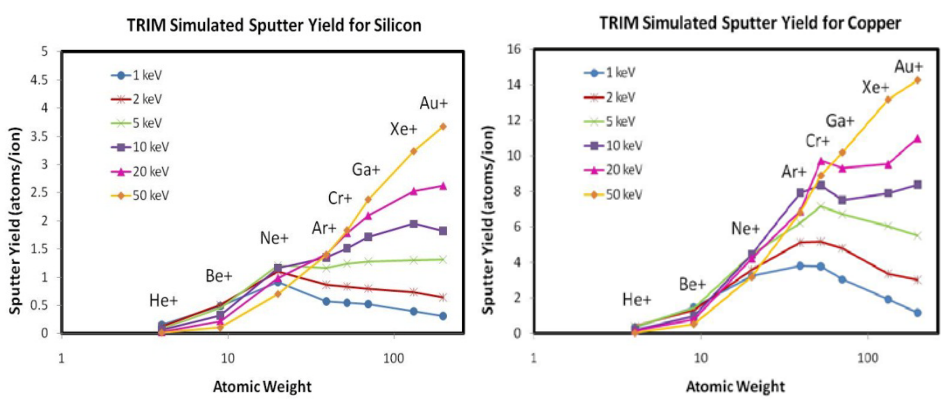

Figure 2: *Simulated sputter yield of silicon and copper using 1, 2, 5, 10, 20, and 50 keV He^+, Be^+, Ne^+, Ar^+, Cr^+, Ga^+, Xe^+, and Au^+ at 0 degree incident angle. The sputter yield is plotted against atomic weight of the incident ion species.*

Sputter yield is another key attribute required for ion beam machining in bulk materials. In Fig. 2, SRIM [5] Si and Cu sputter yield simulations are shown for ions of different mass for energies of 1 keV to 50 keV. For lighter ions (e.g. He^+ and Be^+) the sputter yield is negligible and decreases with increase in beam energies; whereas, for the heavier ions (20 to 60 AMU) the sputter yield increases with increasing beam energies peaking out at ~ 60 keV, which is well above the energies typically used for FIB applications. Although Ar, Kr, and Xe have very favorable sputter yield and material interaction properties, their ionization threshold is too closely matched with impurity gasses, making them higher risk for source contamination. In these energy ranges, Neon sputter rate is ~50X higher than helium for bulk semiconductor materials such as Cu, Si, and SiO_2 and is about 2.5X lower sputter rate than gallium LMIS.

In addition to the relatively high sputter yield, neon GFIS has also demonstrate resolution on the order of 1- 2 nm for (35-65 edge resolution technique) [6]. Resolution is also a critical attribute for nanomachining on semiconductors devices, which have minimum features size of less than 20 nm, with scaling to sub 10 nm by 2015 [7].

Empirical Study Results of GFIS Chemical Assisted Etching

In previously published work, He^+ and Ne^+ GFIS have demonstrated novel machining capabilities in thin films and bulks substrates respectively. For Ne^+ GFIS, work published by Intel and Carl Zeiss has demonstrated sputtered vias as small as 25 nm in diameter in SiO_2 and Cu bulk substrate material [8]. Although 25 nm FIB machined vias are certainly an impressive result, straight sputtering of vias have a number of draw backs, such as re-deposition due to non-volatilized sputtered byproducts, limited selective removal of one film over another, and potential for excessive sub-surface damage due to high doses required to remove materials. Additionally, residual non-volatilized byproducts within the machined via can cause subsurface material mixing, making it difficult to identify the transition from one film to another. Identifying the transition between one film to another is paramount for successful circuit modification where failing to identify an endpoint could result in under etching which would result in poor connections or shorts to other signals in the device. For these reasons, ion beam induced chemical assisted etching is an absolute requirement for via machining and signal cutting.

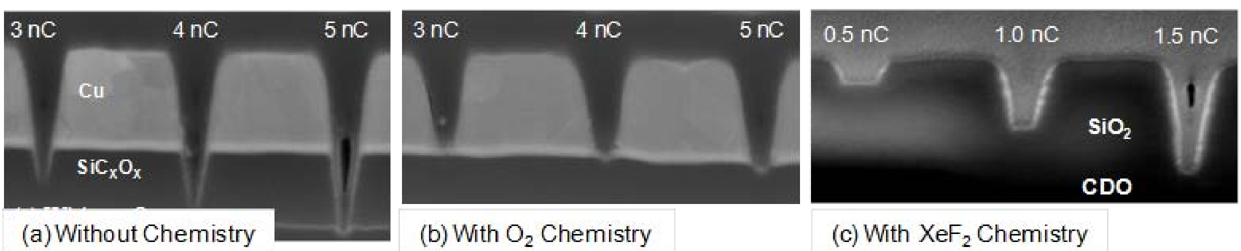

Figure 3: *Cross sectional comparison of 10 kV Ne^+ machined vias: (a) sputtered via in a Cu film; (b) via in a Cu with O_2 etch chemistry; (c) via in SiO_2 film with XeF_2 chemistry.*

Two chemistries typically used with Ga^+ FIBs to increase and retard etch rates in dielectric films are XeF_2 and O_2 (or H_2O) respectively. In Fig. 3 (a) and (b), results comparing Cu film machining over SiC dielectric film are show with and without the presence of an oxidizing chemistry (O_2). Note, when the O_2 chemistry is present during the Ne^+ FIB via machining, the etch terminates at the copper to SiC interface – demonstrating that O_2 chemistry is effectively retarding the etch of the dielectric layer below the Cu. In Fig. 3 (c), Ne^+ FIB via machining is shown in SiO_2 film for doses ranging from 0.5 to 1.5 nC, demonstrating an approximately 2.5X enhancement factor in removal rate over sputter vias. Although this enhancement factor is lower than expected (due to low XeF_2 partial pressure available in the gas delivery system used), it demonstrates the basic principle that the material removal rate can be increased by XeF_2, or decreased in the case of O_2 chemistry. In this paper we will discuss the evolution of the development of the neon GFIS, present empirical results for GFIS nanomachining attributes, and present recent data on He^+ and Ne^+ gas assisted etching with XeF_2, O_2, and H_2O.

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