Beam Exposure Strategies matter – System Complexity and Application Space Trade-offs

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Beam Lithography (in form of laser beam or electron beam lithography) is one of the key technologies in micro- and nanofabrication, used in device- and process development, in special production and in volume production for mask making. Although the technological advances in the last four decades led to highly specialized and sophisticated tools, we should keep in mind that fundamentally the technology is a printing process.

Similar to printing in the macro-world, the printed images are composed of simple pixels or more complex shapes (such as rectangles and triangles), and these basic shapes are positioned in the image either by rastering the image (raster scan), or by directly moving to the areas to be exposed (vector scan). Various beam architectures with combinations of raster and vector have been proposed and implemented for mask fabrication and direct-write.

These scanning and shaping strategies lead to four fundamentally different system architectures (see figure 1). Each one is beneficial for a particular application space, as each one of these beam shaping and beam scanning strategies comes with particular benefits and drawbacks. Raster scan exhibits better positional accuracy (errors are repeatable and therefore correctable) while in parallel the coupling of print resolution (spot size) to throughput and exposure latitude limits its scalability. Gray Beam strategies mitigates this to some degree by de-coupling the address grid from the spot size, but the limiting effect on exposure latitude remains. Beam Shaping (in form of variable shaped beam) decouples blur from the exposed area and thereby enables higher exposure latitude at faster area printing rates.

Three of these architectures are used in today's systems, two in mask making (being successful for different reasons), and one in R&D and special production applications. Mask making was long dominated by raster scan tools using Gaussian beams and is still using this architecture for trailing technology nodes and lower-end large area masks, whereas today's advanced mask making is dominated by vector scan variable shaped beam tools (VSB), with a potential comeback of raster scan tools in the form of Multi-beam. The third potential mask making architecture that combines raster scan with beam shaping[1] didn't go beyond the pilot phase because of a less favorable scalability compared to Multi-beam.

In contrast, the most basic and popular architecture for R&D applications remains the vector scan Gaussian beam with pixel-by-pixel and shape-by-shape composition of the required image. This is highly flexible and adequate in low-throughput or low pattern density applications, particularly for non-Manhattan layouts (e.g. photonic and other curved structures). We will present a top-down / bottom-up analysis on fundamental benefits and drawbacks of beam shaping and beam scanning strategies, and discuss the rationale why in the macro world raster-scan based systems are dominating (e.g. monitors, office printers). This analysis is based on factors such as the write time vs. resolution tradeoff (e.g. theoretical limits such as the space charge effect[2], or practical limitations such as Tennant's law[3]), susceptibility to statistical and systematic errors, exposure latitude, data processing bandwidth and potential for distributed processing, and overall system complexity. Multi-beam approaches as well as cell projection technology (CP) fits well within this framework and will be discussed herein.

Some error sources (such as noise, beam settling, drift, heating, charging) require tight control of the exposure in form of application specific field positioning and/or field order, multi-pass and also a control of the exposure order within the field. The randomness of these error sources and other limiting factors (such as pattern density, resist thickness, topography, substrate material variations, etc.) are the reason why in the nano-lithography world there is no "one size fits all" printing process – each application requires a different optimization. In addition, intelligent fracture and filling strategies (such as curved fracturing) have a significant impact on exposure quality and speed for the various tool architectures, and will move from R&D, prototyping and special production to volume production where Internet of Things (IoT) applications drive an integration of non-CMOS devices (curved layouts) with standard CMOS layouts. From a design flow point of view, this will i) change the CMOS paradigm that each design vertex is design intent, and ii) drive new resolution enhancement techniques, since the quality metrics is not just "getting the correct CD", but also to get smooth edges, controlled circularity or ellipticity, or controlled sharp corners. Since curves have an arbitrary (design tool dependent) digitization, better ways of defining "design intent" are needed.

Understanding the fundamental architectural tradeoffs and their inherent error sources provides an explanation of successes and failures of the past within the different application spaces, and concludes the elements necessary for a successful lithography system along with its required data flows.

Shape / Scan	**Raster**	**Vector**
Gauss	Raster Gaussian (Mask Making)	Vector Scan, Gaussian Fill (R&D, Special Production)
Shaped	Raster Shaped Beam (not in use)	Variable Shaped Beam (Mask Making, Special Production)

Figure 1. Raster / Vector Scanning and Gauss / Shaped Beams lead to four fundamentally different system architectures

[1] S.Rishton et al., Raster Shaped Beam Pattern Generation, JVST B 17(6), p. 2927 – 2931 (1999)

[2] J.A. Liddle, et al., "Space-charge effects in projection electron-beam lithography: Results from the SCALPEL proof-of-lithography system", JVST B 19(2), p. 476 (2001).

[3] Donald M. Tennant, Chapter 4, "Limits of Conventional Lithography", in Nanotechnology, Gregory Timp Ed., Springer (1999) p. 164.