An Unconventional Tradespace of Focused-Ion-Beam Machining

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INTRODUCTION

Nanoelectronic manufacturing involves a broad variety of fabrication processes for making products of different value. At the state of the art, focused-ion-beam machining is commercially viable only for modifying select devices of high value, such as editing circuits[1,2] and repairing photomasks.[3,4] Beyond the nanoelectronic domain, however, this machining process has diverse applications, due to its ability to directly pattern complex nanostructures without serial lithography. In all of its applications, focused-ion-beam machining occurs within a fundamental tradespace of lateral resolution and volume throughput. A power-law dependence of lateral resolution on ion-beam current defines the conventional tradespace, such that fine features take much longer to mill than coarse features. This intrinsic constraint results in the conventional view of focused-ion-beam machining as slow and costly.

Previous studies[5,6] have used sacrificial films to mask the diffuse periphery of a focused ion beam, mitigating defects at the pattern edge and enabling a form of lateral super-resolution. However, it is unclear if a sacrificial mask presents any fundamental advantage for improving lateral resolution, in comparison to simply reducing ion-beam current. To answer this open question, we investigate the resolution–throughput tradespace of focused-ion-beam machining. We discover that a sacrificial mask enables patterning to occur with the lateral resolution of a low value of ion-beam current, and the volume throughput of a high value of ion-beam current. The throughput advantage could extend to two to three orders of magnitude, so that the principal benefit of the super-resolution effect is in the temporal domain, rather than the spatial domain. An advantage of this magnitude would be surprising, and the effect could be comparable to other nanofabrication processes that were disruptive to the conventional state of the art in their times, such as chemical amplification of resist materials,[7,8] and stepper systems for optical lithography.[9,10] To better understand this unconventional tradespace and surprising advantage, we summarize the first comprehensive and systematic study of this topic,[11] integrating four concepts for the most widely available type of electron–ion beam system with a gallium source.

RESULTS

Sacrificial Masking Film

First, we deposit a sacrificial film of chromia, Cr_2O_3, onto substrates of silica, SiO_2, and apply scanning electron microscopy, X-ray diffraction, and atomic force microscopy to characterize the mask. The measurement results show that the chromia mask dissipates charge under irradiation of an electron beam, is primarily amorphous, and has nanometer roughness, respectively (Figure 1a, i-ii).

In-Line Resolution Metrology

Second, we develop a novel method for in-line metrology of ion-beam resolution by scanning electron microscopy within an electron–ion beam system (Figure 1b, iii-iv). The method enables reproducible focus of the ion beam and provides an initial characterization of effective patterning resolution.

Complex Test-Structures

Third, we mill complex test-structures in silica through the chromia film with a beam of gallium cations and sacrifice the chromia by wet etching down to an interface with a new selectivity. We measure the resulting surface topography by atomic force microscopy after each fabrication step, extracting milling depths and edge widths from parametric models of surface profiles and propagating uncertainty through Monte-Carlo simulation (Figure 1c, v-vi).

Resolution–Throughput Tradespace

Fourth, we quantify vertical resolution of approximately 1 nm and lateral super-resolution factors that range from approximately two to six, which we also predict theoretically without adjustable parameters. We find an improvement of volume throughput for equivalent resolution that exceeds a factor of 40 with minimal extrapolation and in potential excess of a factor of 500 for our lowest value of ion-beam current (Figure 1d, vii-viii, Table 1).

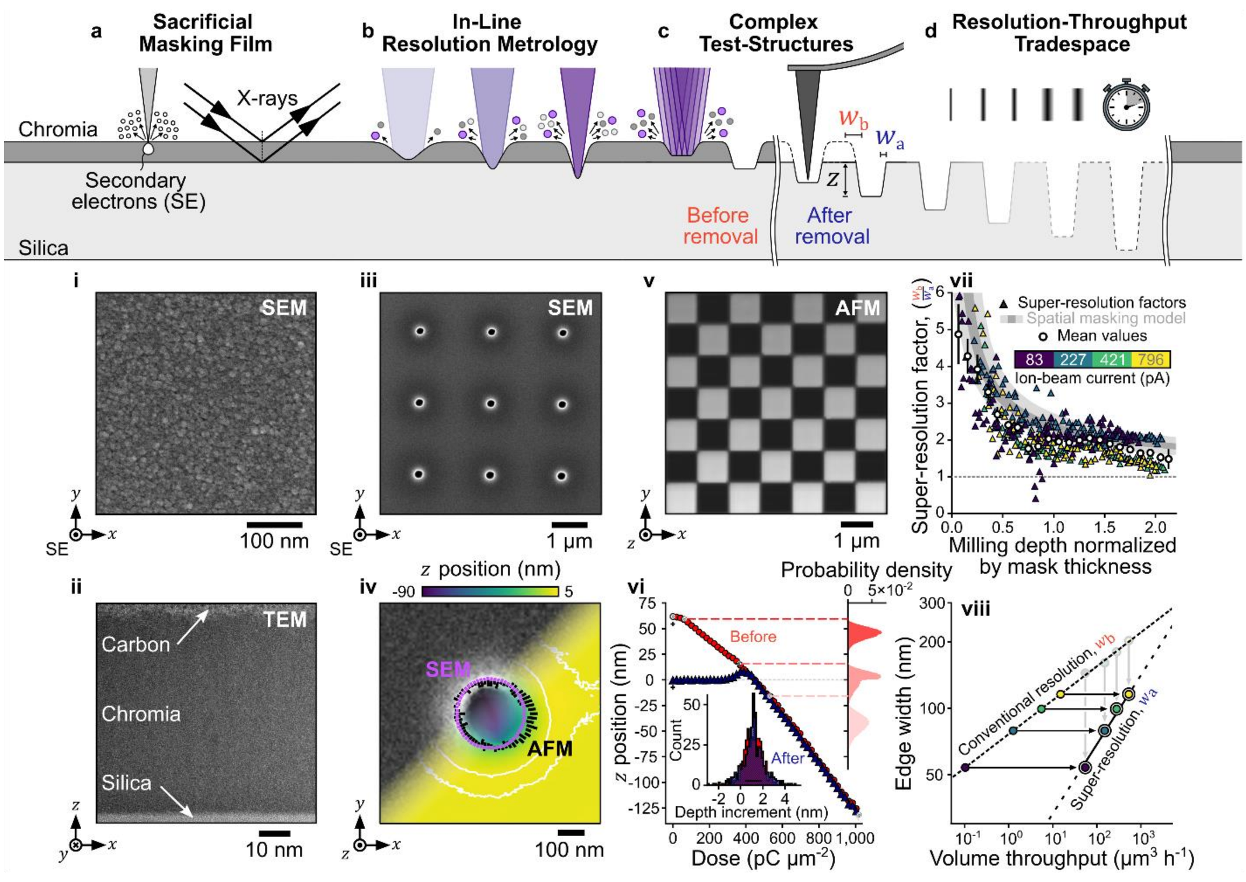

FIGURE 1. Experimental Overview and Key Results. (**a**) Sacrificial masking film. (**i**) Scanning electron micrograph (SEM) and (**ii**) transmission electron micrograph (TEM) showing the film. (**b**) In-line resolution metrology. (**iii**) Scanning electron micrograph and (**iv**) atomic force micrograph (AFM) showing structures to test lateral resolution. (**c**) Complex test-structures. (**v**) Atomic force micrograph showing structure to test vertical response and (**vi**) corresponding plot showing vertical response as a function of ion dose. (**d**) Resolution-throughput tradespace. (**vii**) Plot showing super-resolution factor, which we calculate as the ratio of edge width before and after removal of the mask, as a function of milling depth. (**viii**) Plot showing edge width as a function of volume throughput. Bars and crosses are 95 % coverage intervals. Uncertainties in (viii) are smaller than the data markers.

TABLE 1. Lateral Resolution and Volume Throughput

	Before Removal of Mask		After Removal of Mask		Factor of Improvement	
Ion-Beam Current (pA)	**Lateral Resolution (nm)**	**Volume Throughput ($\mu m^3\ h^{-1}$)**	**Lateral Resolution (nm)**	**Volume Throughput ($\mu m^3\ h^{-1}$)**	**Lateral Resolution (–)**	**Volume Throughput (–)**
83 ± 1	144.4 ± 0.2	54.5 ± 0.2	53.9 ± 0.4	0.10 ± 0.02	2.678 ± 0.016	528 ± 28
227 ± 1	160.7 ± 0.2	151.0 ± 0.2	79.2 ± 0.2	1.25 ± 0.04	2.029 ± 0.006	119 ± 4
421 ± 3	180.1 ± 0.2	280.7 ± 0.2	99.3 ± 0.6	5.52 ± 0.22	1.814 ±0.010	51 ± 3
796 ± 4	202.5 ± 0.2	529.8 ± 0.4	112.9 ± 0.2	12.72 ± 0.22	1.794 ± 0.004	42 ± 2

Uncertainties are 95 % coverage intervals. Insignificant figures are present to avoid significant rounding errors.

CONCLUSION

In this abstract, we summarize several advances to the state of the art of focused-ion-beam machining.[11] New theory enables engineering design of a sacrificial masking process, which was previously empirical, allowing its prediction and optimization for device fabrication. Theoretical predictions generally agree with experimental results, quantifying the extent to which a mask can improve the tradespace of lateral resolution and volume throughput. The improvement is so large as to be potentially analogous to the gain mechanism of chemical amplification of resist materials, in which effective thresholding improves contrast in photolithography, or increases in sensitivity improve areal throughput of electron-beam lithography.[8] These results suggest that sacrificial masking could enable not only ultrarapid prototyping of complex devices, which is relevant for research and development, but also commercial manufacturing of device arrays that would conventionally require hundreds to thousands of hours of machine time. This transformation is potentially similar to the deviation of stepper systems away from the limiting trend of a power law between lateral resolution and areal throughput for diverse lithography processes.[10] Future work might optimize this unconventional tradespace, not only in the domain of nanoelectronic manufacturing, but also for producing microscopy standards,[12] diffractive optics,[13] electromagnetic metasurfaces,[14] and nanofluidic molds.[15]

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KEYWORDS

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