A paradigm shift of focused-ion-beam machining from super-resolution to ultrahigh-throughput

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Focused-ion-beam machining occurs within a tradespace of lateral resolution (nm) and volume throughput ($\mu m^3\ hr^{-1}$). At the root of this tradespace is a power-law dependence of lateral resolution on ion-beam current, so that fine features mill slowly. This constraint limits an otherwise powerful process to directly machine complex nanostructures, yielding the conventional view of the focused ion beam as more useful for prototyping than for manufacturing. In this study, we elucidate and transform the resolution–throughput tradespace, yielding dramatic improvements of volume throughput that enable a paradigm shift.

Previous studies have used sacrificial films to mask the diffuse tail of a focused ion beam, enabling lateral super-resolution. At EIPBN 2019,[1] we introduced a chromia film to mask the beam tail, dissipate charge during milling, and super-resolve complex nanostructures in silica. However, the experimental limits of this method are unclear and lack a theoretical basis. Moreover, no previous study of this method has extended into the time domain. Presently, we report the first comprehensive investigation of the super-resolution effect, revealing that the dominant advantage is, unexpectedly, temporal. We advance our work in four ways (Figure 1a-d).

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

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

Third, we mill complex test-patterns in silica through the chromia film with a beam of gallium cations and remove the chromia by wet etching down to a newly selective interface. We measure the resulting surface topography by atomic force microscopy after each fabrication step (Figure 1c, vii-ix).

Fourth, we quantify vertical patterning 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 that exceeds a factor of 40 (Figure 1d, x-xii).

This final result of ultrahigh-throughput enables a paradigm shift of focused-ion-beam machining from prototyping to manufacturing of nanoscale devices.

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[1] A. Madison, *et al*. The 63rd International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN, Minneapolis, 2019)

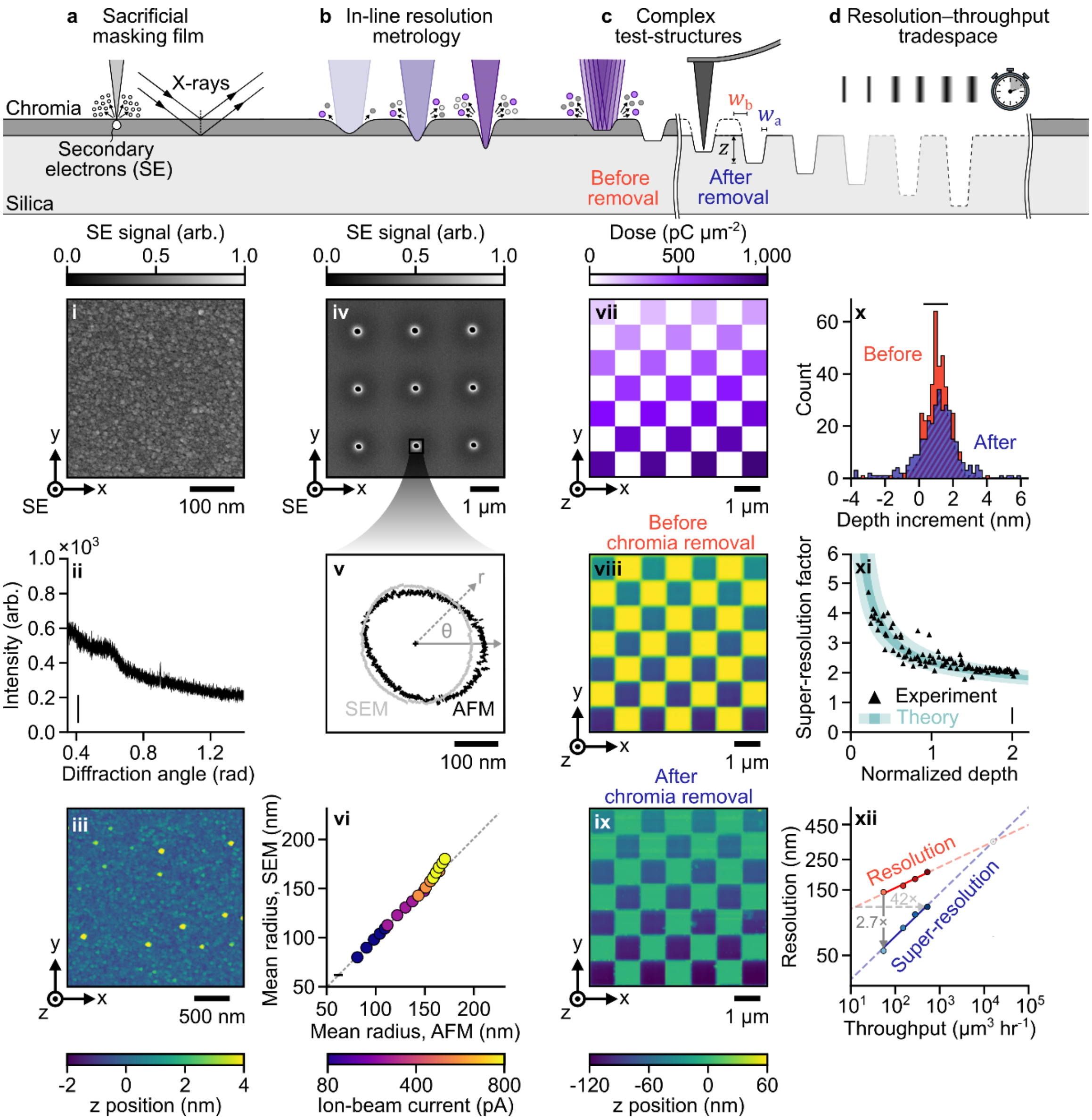

Figure 1. Overview and key results. (**a**) Characterization of chromia on silica. (**i**) Scanning electron micrograph, (**ii**) X-ray diffraction spectrum, and (**iii**) atomic force micrographs. (**b**) In-line resolution metrology. (**iv**) Scanning electron micrograph of representative pits, which test ion-beam focus. (**v**) Plots showing angular dependence of pit radius by (gray) scanning electron microscopy (SEM) and (black) atomic force microscopy (AFM). (**vi**) Plots showing correlative measurements of mean radius of pits by AFM and SEM. (**c**) Nanofabrication of complex nanostructures in silica through chromia. (**vii**) Ion-dose pattern that yields complex nanostructures (**viii**) before and (**ix**) after removal of the sacrificial chromia mask. (**d**) Study of the resolution-throughput tradespace. (**x**) Histograms showing depth increments (red) before and (blue hatch) after chromia removal. (**xi**) Plot showing lateral super-resolution factors as a function milling depth after normalization by chromia thickness. (**xii**) Plot showing resolution as a function of volume throughput for a range of ion-beam currents. Lone bars in ii, vi, x, and xi and lengths of segments in (**v**) indicate representative uncertainties of 95 % confidence intervals of respective measurements. Uncertainties in xii are smaller than data markers.