Large area Si-FIB patterning of SiO2 hard mask on 3D crystallographic nanostructures

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Accurate nano-patterning of highly topographic surfaces is of utmost importance in the efforts to fully employ the 3rd dimension in top-down fabricated nanosystems. Focused ion beam (FIB) patterning is a possible approach, however maintaining the integrity of the nanostructure around the modified volume is a challenge. Here we report about the use of a Si-ion beam from a vertical FIB to selectively open a silicon dioxide hard mask on top of silicon nano "wedges", well aligned over fairly large areas (1 x 1 cm^2). This resistless approach enables straightforward alignment on existing structures and relative high resolution patterning on top of 3D nanostructures.

Silicon nano wedges were fabricated wafer scale on <100> silicon wafers by combining interference lithography on a silicon nitride mask layer with anisotropic silicon etching and local oxidation of the silicon (LOCOS) [1]. The hard mask stack deposited/grown on top of the wedges consisted of 1.5 nm chemically grown SiO_2, 22 nm LPCVD amorphous silicon (a-Si) and 8nm thermally grown SiO_2. The Si-FIB employed is emitted from a AuGeSi Liquid Metal Alloy Ion Source (LMAIS) with a downstream Wien filter on a VELION FIB-SEM system [2]. The top-down FIB on a laser interferometer stage enables accurate sample positioning at nm precision with respect to the ion beam which ensured stable and reliable functionalization of the nano wedge apex over cm long distances.

A dose test for an 8nm thick SiO_2 mask on top of silicon wedges resulted in an optimized range of 60 – 80 µ C/cm^2 at 4.5 pA beam current and 70 keV Si^{++} beam energy (fig. 1) The Si^{++} beam at the right kinetic energy/dose settings modifies the silicon oxide such that the etch rate in HF is significantly increased [3], (fig. 2, 3). To demonstrate selective masking, a Si^{++} beam modified SiO_2 8 nm masking layer was selectively etched in HF and the opened areas used to locally etch the silicon nanostructures underneath in TMAH (fig. 3). The successful etching of the silicon suggests that the mask layer stack used including the a-Si stop layer, properly protected the underlying monocrystalline silicon from being modified by the potential impact of the ion beam.

[1] Berenschot et al., Self-Aligned Crystallographic Multiplication of Nanoscale Silicon Wedges for High-Density Fabrication of 3D Nanodevices, ACS Appl.Nano Mat. 10, 15847 (2022).
[2] L. Bischoff, P. Mazarov, L. Bruchhaus, J. Gierak, Liquid metal alloy ion sources - An alternative for focused ion beam technology, Appl. Phys. Rev. 3, 021101 (2016).
[3] T. Sadoh, H. Eguchi, A. Kenjo, M. Miyao, Etching characteristics of SiO2 irradiated with focused ion beam, Nuclear Instruments and Methods in Physics Research B 206 478–481 (2003)

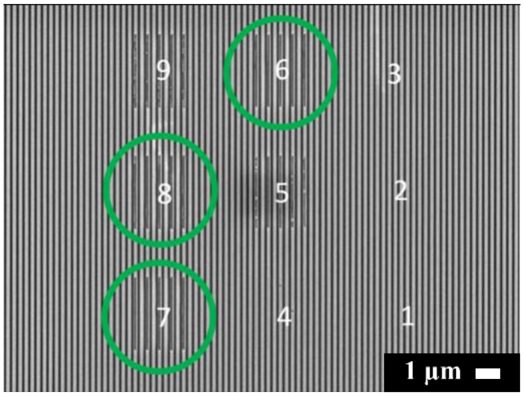

Figure 1: Dose increasing in equal steps from (1) 10 $\mu c/cm^2$ to (9) 90 $\mu c/cm^2$. The green circled dose regions are in the optimal range.

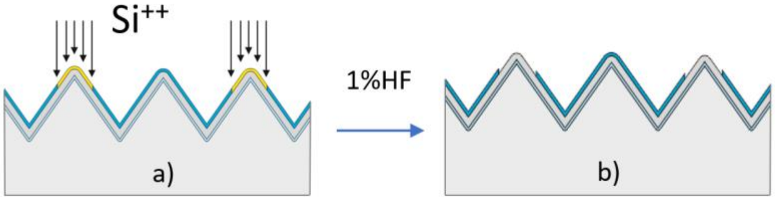

Figure 2: Si^{++} beam modified regions (yellow) have 1% HF etchrate ~ 13.7 - 24.0 nm/min, based on a reduced etch time between 20 and 35 s to arrive from a) to b), down from ~90 s for unmodified SiO_2.

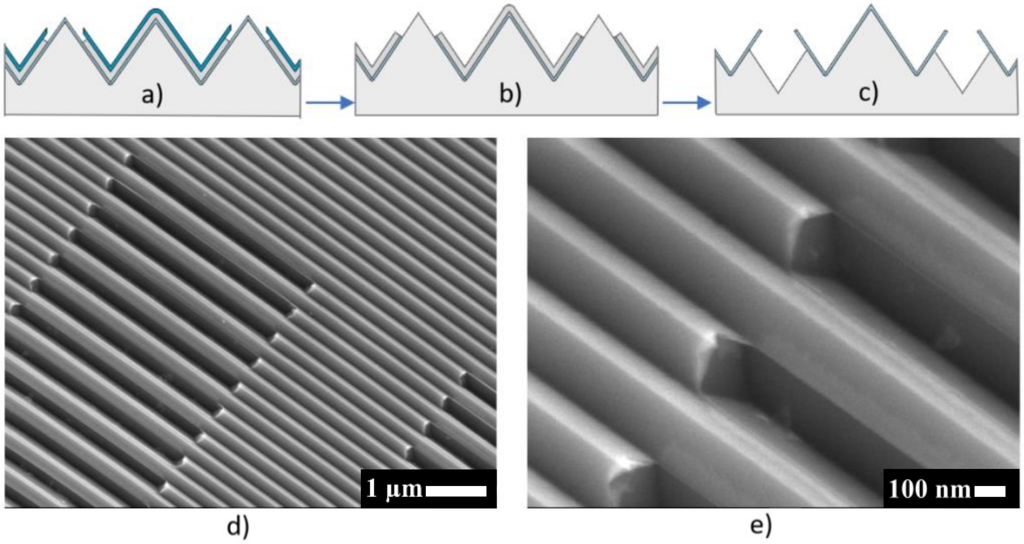

Figure 3: a) TMAH etching of 22nm a-Si, b) 1%HF 1.5 nm SiO_2 etching, c) TMAH etching of monocrystalline Si, d)-e) SEM images of fabricated structures.