Proportional 3D grayscale lithography and plasma etching of fused silica

G. Malvicini, C. J. Thalakkottoor, H. Schift
Paul Scherrer Institute, Laboratory for Nano and Quantum Technologies, 5232 Villigen PSI, Switzerland
giulia.malvicini@psi.ch

Three-dimensional (3D) micro-structures in fused silica are essential for micro-optical and microfluidic devices, but their fabrication remains challenging due to the need for precise depth control, profile fidelity, and optical-grade surface quality. In inductively coupled plasma reactive ion etching (ICP-RIE) pattern transfer, grayscale-defined resist profiles are particularly sensitive to resist-to-substrate selectivity, fluorocarbon passivation dynamics, and surface roughening mechanisms such as micromasking. This work establishes a quantitatively controlled grayscale direct-write lithography (DWL) to ICP-RIE process that enables proportional (near-unity selectivity) transfer of continuous 3D topographies into fused silica while maintaining nanometre-scale intrinsic surface roughness.

Grayscale exposure was performed using a Heidelberg DWL66+ system (405 nm) to encode continuous height profiles through dose modulation in a positive-tone DNQ–novolak resist (ma-P 1225G, 5–6 µm thickness). Contrast-curve calibration and design optimization were applied to minimize depth steps and produce smooth resist gradients. Pattern transfer was carried out using a $CHF_3/CF_4/O_2$ plasma chemistry. Gas flows were systematically varied within CHF_3 = 20–40 sccm, CF_4 = 3–10 sccm, and O_2 = 3–8 sccm.

A stable process window yielding resist-to-silica selectivity close to unity ($S \approx 0.9–1.0$) was identified, enabling direct 1:1 depth transfer of grayscale resist profiles into fused silica at an etch rate of approximately 70 nm/min for total etch times of ~60 min. The selectivity exhibited a non-linear dependence on the CHF_3/CF_4 ratio, reflecting the balance between fluorine availability and surface passivation, with oxygen acting as a tuning parameter for suppressing excessive polymer accumulation and reducing selectivity. Confocal profilometry confirmed high profile fidelity across representative 3D geometries (Fig. 1), while atomic force microscopy (AFM) measurements revealed intrinsic surface roughness of approximately 3 nm RMS in micromasking-free regions (Fig. 2). Larger-scale roughness ($Rq \approx 10–50$ nm) was dominated by micromasking effects linked to chamber conditions. To accelerate exploration of the gas-chemistry space, a machine-learning-based optimization approach was introduced, providing selectivity and etch-rate predictions from experimental data. This tool shows strong potential for guiding the development of etching recipes for DNQ–novolak-based resists with varying thicknesses. These results demonstrate a reproducible and scalable grayscale process chain for fabricating continuous 3D fused-silica microstructures with precise depth control and low optical scattering, directly relevant to micro-optics and microfluidic applications.

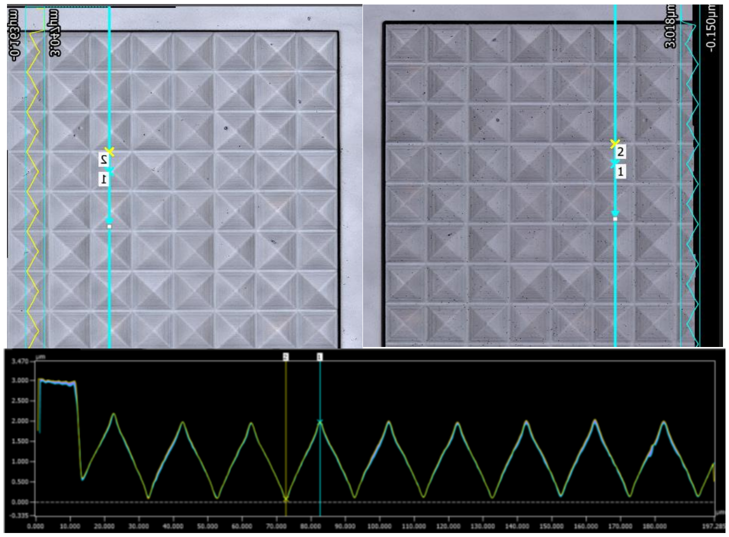

Figure 1: Comparison (c) between the ma-P1225 profile (a) and etched fused silica profile (b). The profile overlap shows the successful proportional pattern transfer, and achievement of selectivity 1:1.

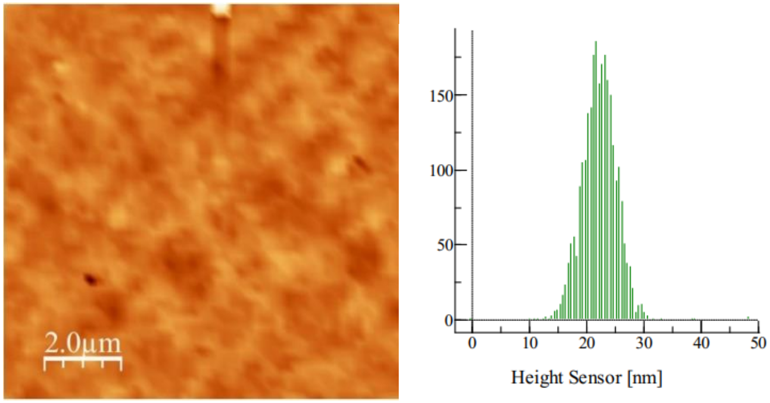

Figure 2: AFM roughness measurement in etched fused silica: micromasking – free region. Scan size: 10 × 10 µm². RMS roughness = 3 nm.