Fabrication of nm-rough 3D ellipsoidal X-ray focusing optics via grayscale lithography and selective thermal reflow

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Reflective X-ray and EUV optics require surface roughness well below 1 nm RMS to suppress scattering losses at wavelengths ranging from a few picometers to several nanometers. Achieving such ultra-smooth surfaces on 3D geometries, such as ellipsoidal focusing optics, remains a major fabrication challenge. While grayscale laser direct-write lithography (DWL) enables large-area, continuous 3D topographies, its ultimate performance is limited by resist material properties, exposure discretization, and surface replication fidelity.

In this work, we present a systematic roughness investigation of 3D optical surfaces, focusing on both wide linear slopes and ellipsoidal profiles fabricated by grayscale DWL (Fig. 1). Linear slopes were first used as a reference geometry, allowing direct atomic force microscopy (AFM) measurements even on deep structures patterned in resist and replicated in PMMA. On these structures, RMS roughness values of 5.2 nm in resist, 4.7 nm in GMN PS90 (Optool) replicas, and 1.3 nm in PMMA after selective thermal smoothing were measured over a surface area of 10×10 μm^2, establishing a quantitative baseline for process-induced roughness reduction. The fabrication workflow is shown in Figure 2.

For ellipsoidal structures, direct AFM characterization of the concave resist surface was not feasible. Instead, roughness was assessed on convex replicas obtained by transferring the resist pattern into GMN PS90, enabling AFM access to the optical surface. A second replication step into GMN PS90 and then PMMA produced convex ellipsoids suitable for AFM before and after locally selective thermal smoothing (TASTE) [1]. RMS roughness values of 5.7 nm for GMN PS90 and 1.8 nm for PMMA after reflow were obtained on ellipsoidal geometries, demonstrating consistent smoothing trends across the two 3D shapes.

AFM measurements reveal distinct roughness regimes for resist, GMN PS90, and PMMA, and demonstrate that material transfer combined with controlled thermal reflow can significantly reduce local roughness while preserving the global freeform geometry. Together, these results establish a fabrication and metrology workflow for grayscale-fabricated optics. By combining optimized exposure strategies, multi-step replication, and material-specific smoothing, we outline viable pathways toward sub-nanometer roughness on complex 3D surfaces, relevant for EUV and soft X-ray focusing applications.

[1] Schleunitz, *et al.* *Nano Convergence* 1, 7 (2014)

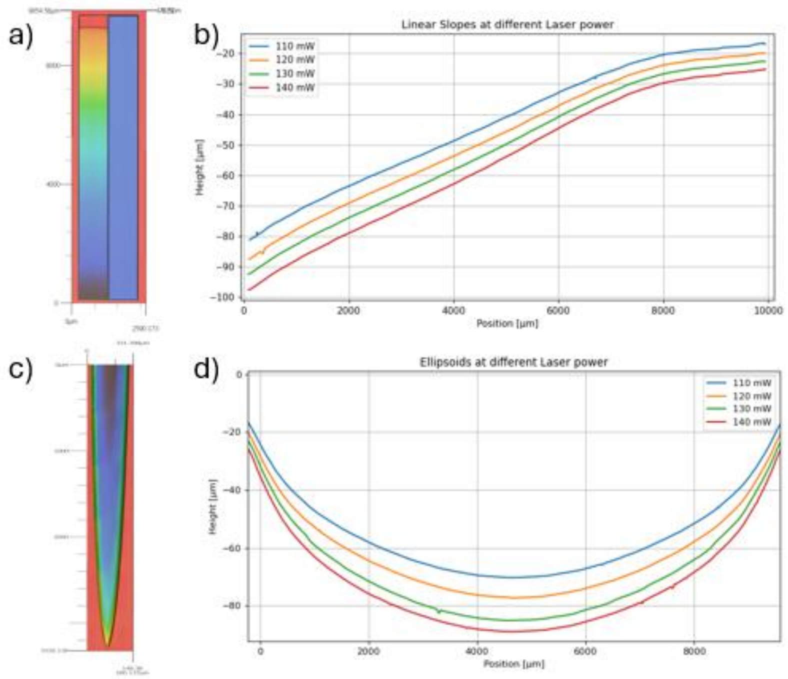

Figure 1. Linear slopes (a, b) and ellipsoidal structures (c, d) fabricated in mr-P 22G XP (micro resist technology): 3D surface renderings and corresponding 2D profiles obtained at different exposure powers. For the ellipsoids, only the terminal region of the 3D surface is shown for improved visualization.

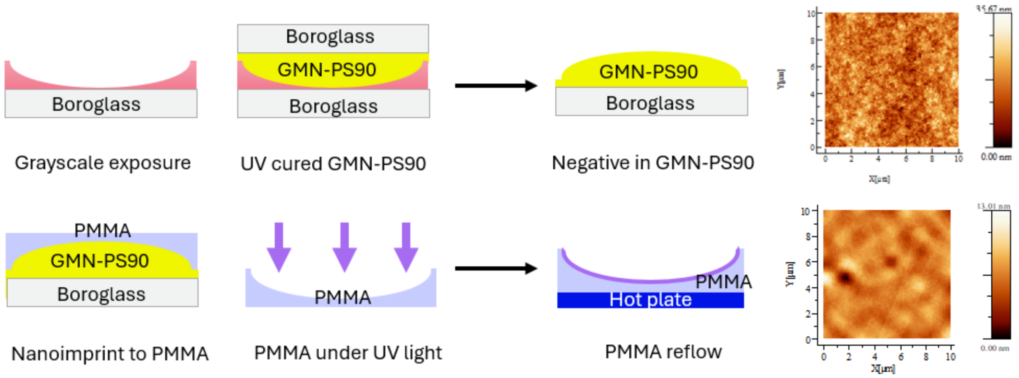

Figure 2. Schematic of the fabrication and replication workflow for ellipsoidal structures. The ellipsoidal geometry is first generated by grayscale lithography and replicated into GMN-PS90. The RMS roughness of the convex GMN-PS90 surface, measured by AFM over a 10×10 µm² area, is 5.7 nm. The GMN-PS90 replica is then used as a master to imprint the structure into PMMA, followed by a selective thermal reflow process. After reflow, the ellipsoidal surface in PMMA exhibits a final RMS roughness of 1.8 nm.