Laser-Assisted Fabrication and Multimodal Characterization of Si Microfunnel Structures

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Three-dimensional (3D) Si microfunnel arrays enable enhanced light-matter interaction for a wide range of optoelectronic and sensing applications [1]. However, scalable fabrication approaches that offer tunable geometry while providing insight into interfacial and internal structure remain limited. In this work, we demonstrate a low-cost and scalable method for fabricating Si microfunnel arrays using UV laser microdrilling followed by hydrofluoric-nitric-acetic acid (HNA) wet etching and establish a multimodal characterization framework.

UV laser microdrilled Si microhole arrays were etched in HNA using a controlled SiO_2 cap layer, converting cylindrical holes into microfunnel geometries through the coupled etching of Si and a $\approx$ 600 nm SiO_2 layer that regulates local reaction kinetics [2]. SEM imaging (***Figure 1a***), optimized using Monte Carlo electron trajectory simulations (***Figure 1b***), resolves distinct SiO_2 on Si etching behavior. A schematic (***Figure 2a***) illustrates the microhole diameter and cavity height, which scale linearly with etch time. X-ray micro-computed tomography (micro-CT) combined with 3D reconstruction was used to realize and validate the fabricated microfunnel, enabling volumetric analysis of entrance conicity, internal tapering, and depth-dependent roughness inaccessible by SEM alone (***Figure 2b***). These data reveal how etchant penetration governs funnel evolution and surface quality.

Building on this understanding, we will present a hydrophobic surface-treatment approach that removes laser-induced sidewall debris, enhances etchant penetration, and improves surface smoothness and contact angle control. The resulting microfunnel arrays support integration of functional layers for optoelectronic applications including sensors, detectors, photovoltaics, and integrated photonic platforms.

[1] E. Granizo, I. S. Kriukova, A. A. Knysh, P. M. Sokolov, P. S. Samokhvalov, and I. R. Nabiev, Nanomaterials 15, 1808 (2025).
[2] A. H. Chowdhury and H. P. Yoon, Adv. Energy Sustainability Res. 5, 2400147 (2024).

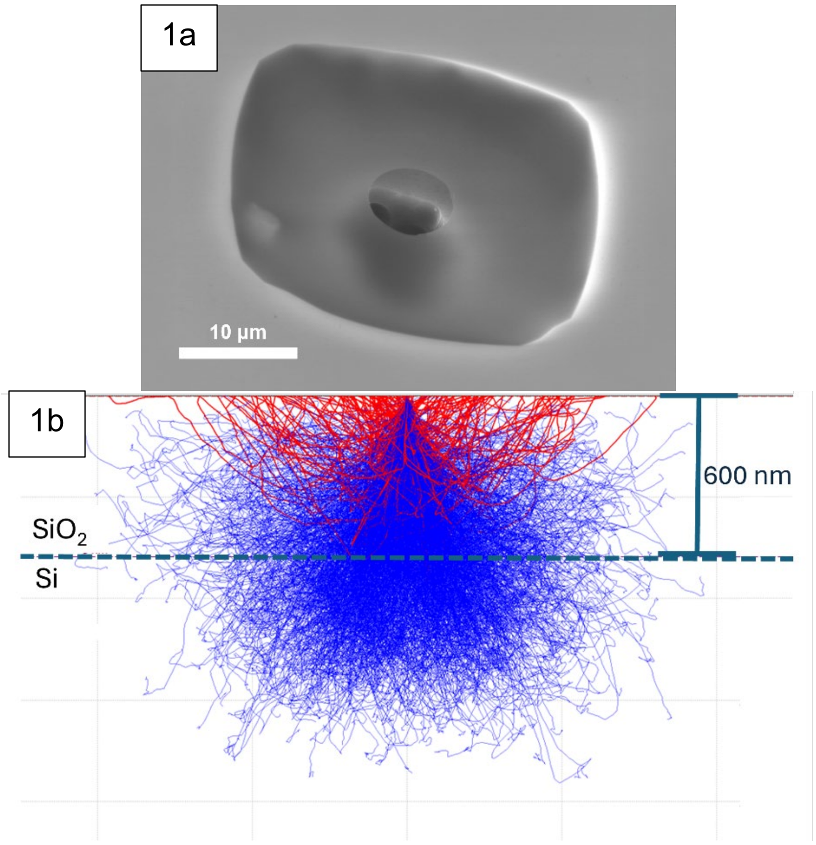

Figure 1*: (a) SEM Image of a singular microhole with a thin, translucent SiO_2 layer on top, with a centered circular hole, (b) electron trajectory simulation.*

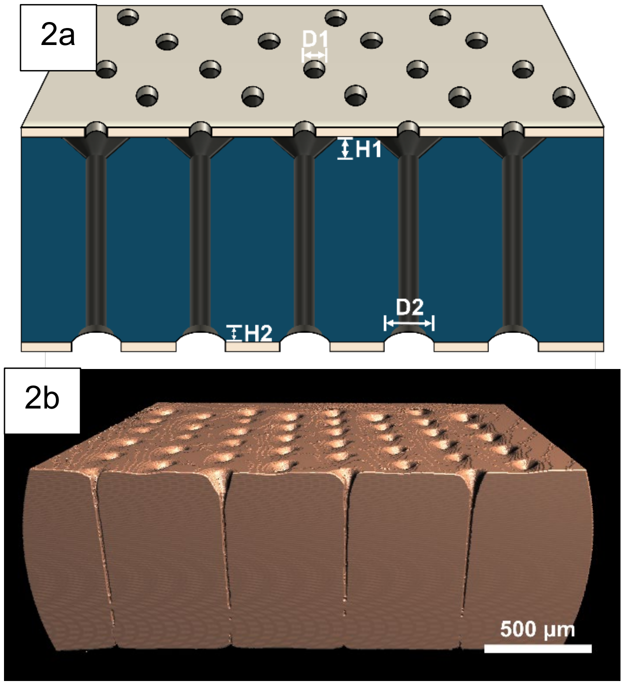

Figure 2*: (a) Schematic of conical microholes with the micrhole entrance and exit diameter (D1 and D2, respectively) and cavity height of the entrance (H1) and exit (H2), (b) 3D model of microhole array using micro-CT.*