Materials Science & Engineering Doctoral Defense

Metal-Assisted Electrochemical Nanoimprinting: Delivering Resolution and Throughput via Engineered Stamps

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Abstract

Recent advancements in the field of light wavefront engineering rely on complex 3D metasurfaces composed of sub-wavelength structures which, for the near infrared range, are challenging to manufacture using contemporary scalable micro- and nanomachining solutions. To address this demand, a novel parallel micromachining method, called metal-assisted electrochemical nanoimprinting (Mac-Imprint) was developed. Mac-Imprint relies on the catalysis of silicon wet etching by a gold-coated stamp enabled by mass-transport of the reactants to achieve high pattern transfer fidelity. This was realized by (i) using nanoporous catalyst to promote microscale etching solution diffusion and (ii) semiconductor substrate pre-patterning with millimeter-scale pillars to provide etching solution storage. However, both of these approaches obstruct scaling of the process in terms of (i) surface roughness and resolution, and (ii) areal footprint of the fabricated structures. To address the first limitation, this dissertation explores fundamental mechanisms underlying the resolution limit of Mac-Imprint and correlates it to the Debye length (~0.9 nm). By synthesizing nanoporous catalytic stamps with pore size less than 10 nm, the sidewall roughness of Mac-Imprinted patterns is reduced to levels comparable to plasma-based micromachining. This major improvement allows for the implementation of Mac-Imprint to fabricate Si rib waveguides with limited levels of light scattering on its sidewall. To address the second limitation, this dissertation focuses on the management of the etching solution storage by developing engineered stamps composed of highly porous polymers coated in gold. In a plate-to-plate configuration, such stamps allow for the uniform patterning of chip-scale Si substrates with hierarchical 3D antireflective and antifouling patterns. The development of a Mac-Imprint system capable of conformal patterning onto non-flat substrates becomes possible due to the flexible and stretchable nature of gold-coated porous polymer stamps. Understanding of their mechanical behavior during conformal contact allows for the first implementation of Mac-Imprint to directly micromachine 3D hierarchical patterns onto plano-convex Si lenses, paving the way towards scalable fabrication of multifunctional 3D metasurfaces for applications in advanced optics.

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