Mechanical Engineering Dissertation Defense

Flexible Porous Catalytic Stamps for Conformal Electrochemical Nanoimprinting of Inorganic Semiconductors: A Mechanical Perspective

School for Engineering of Matter, Transport and Energy

Emmanuel Dasinor
Advisor: Bruno Azeredo

Abstract

Optical metasurfaces for hyperspectral imaging, co-packaged optoelectronic interconnects, and near-eye augmented reality/virtual reality waveguides demand patterning routes for transparent, near-IR materials that achieve sub-100 nm resolution with controlled three-dimensional geometry over wafer-scale and often curved substrates. Metal-assisted chemical imprinting (Mac-Imprint) directly addresses this need by etching only where a catalytic stamp achieves intimate contact with a semiconductor substrate. This renders mechanics the determinant of fidelity and enabling curvature-aware pattern transfer suited for silicon-photonics gratings, waveguide in/out couplers, dispersion-critical metasurfaces, etc. This dissertation develops a mechanics-first framework for Au-coated polyvinylidene fluoride (PVDF) /polyimide laminate stamps under pneumatic actuation and delivers four contributions. First, a full finite-element model of the Mac-Imprint electrochemical cell (laminate, O-ring clamp, frictional/adhesive contact) is established to predict large-deflection kinematics, interfacial tractions, and failure precursors. Second, the model is experimentally validated without fitted parameters via (i) non-contact measurements of freestanding center-point deflection versus pressure and (ii) digital image correlation of biaxial in-plane strain at first contact, reproducing both within <4% deviation, establishing quantitative confidence in the forward fields. Third, the validated forward mechanics reveals a repeatable imprint error structure, a global pitch distortion superposed on a smooth, low-order spatial gradient, arising from the bending-to-membrane transition and clamp tractions, while also localizing stress concentrations that bound stamp durability (yield/delamination/Au-film fracture). Lastly, these liabilities are converted into controls through a deterministic, adjoint-free inverse posed as least-squares period matching on the lattice neighbor graph. Two closed-form updates; (i) a global pitch correction that removes the mean drift and (ii) a neighbor-wise geometric projection that flattens the gradient, solve separably per iteration with a single finite-element call. Evaluating chords in the local tangent plane handles optical curvature without special cases. Implemented as a lightweight, Computer-Aided Design-integrated pre-export step, the method restores uniform period on planar wafers and plano-convex lenses while maintaining intimate contact and avoiding interfacial failure, enabling period-faithful masters for nanoimprint lithography and substrate conformal imprint lithography replication in the targeted photonics applications.

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