Scalable Fabrication of High Performance, All-Inorganic Metalenses, Waveguides and Diffractive Optics via Nanoimprint Lithography

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Planar metalenses, waveguides, and diffractive optics are enabling for augmented reality (AR), light field displays, compact precision imaging and 3D sensors. All rely on high refractive index (RI) contrast for performance and efficiency. Waveguide gratings for AR require high refractive index to achieve large fields of view. Metalenses are diffractive optical elements in a sub-micron form factor comprised of high aspect ratio, high refractive index posts that direct light to the focal spot. Pillar shape, symmetry and positioning provide additional design control over polarization, amplitude or phase. Current approaches to all-inorganic metalens fabrication require time, materials, and cost intensive subtractive fabrication on semiconductor process platforms. For example, metalenses operating in the infrared for 3D sensors can be fabricated out of silicon, employ small device footprints, and are entering commercialization via subtractive processing. Visible wavelength devices, however, cannot be fabricated out of silicon and require high refractive index transparent materials such as TiO_2 that are much more difficult to etch. Moreover visible wavelength devices that deliver images to the user often require large device areas, such as for waveguides for smart glasses, presenting additional economic challenges for subtractive processing. Additive fabrication via nanoimprint lithography (NIL) in which devices are printed using stamps replicated from a master offers an efficient, cost-effective alternative manufacturing pathway for planar optics.[1-3] In our work, we fabricate all inorganic, high refractive index optics via NIL with TiO_2 nanoparticle dispersion inks. The all inorganic components offer better performance and superior mechanical and optical stability relative to devices produced via NIL using polymer/nanoparticle composites.

Recently we reported the rapid fabrication of visible wavelength 400 um diameter metalenses with numerical apertures of 0.2 and focusing efficiencies of greater that 50% using NIL with 2 minutes of process time per imprint.[2] Here we extend that work and demonstrate the fabrication of lenses with absolute efficiencies of greater than 75% (more than 90% of the design efficiency) using large area masters suitable for full-wafer fabrication. We employ atomic layer deposition (ALD) as a post-imprint treatment that enables tuning of the refractive index from 1.9 to 2.2 using a small number of cycles (less than 20), which improves lens efficiency.[3] Moreover the ability to tune the RI of the imprinted optics to match that of the substrates removes concerns about the thickness of the residual layer in the device, resolving an issue for the use of NIL in some applications. Additional cycles of ALD can futher be used to precisely tune feature dimensions and feature spacings within the device to optimize performance and to offset shrinkage relative to the master. We further demonstrate the excellent optical and material stabilities of the all-inorganic imprinted optics.

[1] Beaulieu, M. R.; Hendricks, N. R.; Watkins, J. J., "Large-Area Printing of Optical Gratings and 3D Photonic Crystals Using Solution-Processable Nanoparticle/Polymer Composites" ACS Photonics 2014, 1 (9), 799-805.

[2] Einck, V.J.; Torfeh, M; McClung, A; Jung, DE; Mansouree, M; Arbabi, A; Watkins, JJ. "Scalable Nanoimprint Lithography Process for Manufacturing Visible Metasurfaces Composed of High Aspect Ratio TiO 2 Meta-Atoms" ACS Photonics 2021, 8 (8), 2400–2409.

[3] Jung, DE; Howell, IR; Einck, VJ; Arisoy, F.D.; Verrastro, L.D.; McClung, A; Arbabi, A; Watkins, JJ "Refractive Index Tuning of All-Inorganic TiO2 Nanocrystal-Based Films and High Aspect Ratio Nanostructures Using Atomic Layer Deposition: Implications for High-Throughput Fabrication of Metalenses" ACS Applied Nanomaterials, 2023, 6, 3, 2009–2019

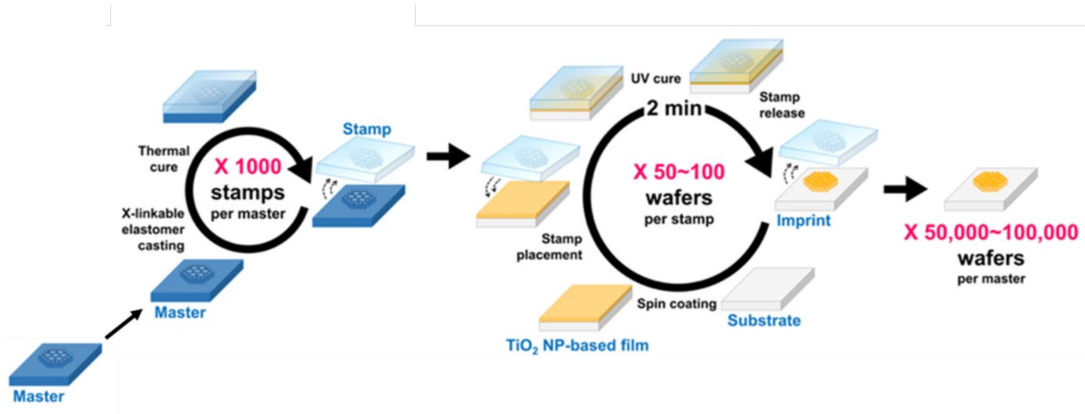

Figure 1. Schematic of planar optics fabrication using nanoimprint lithography.[2]

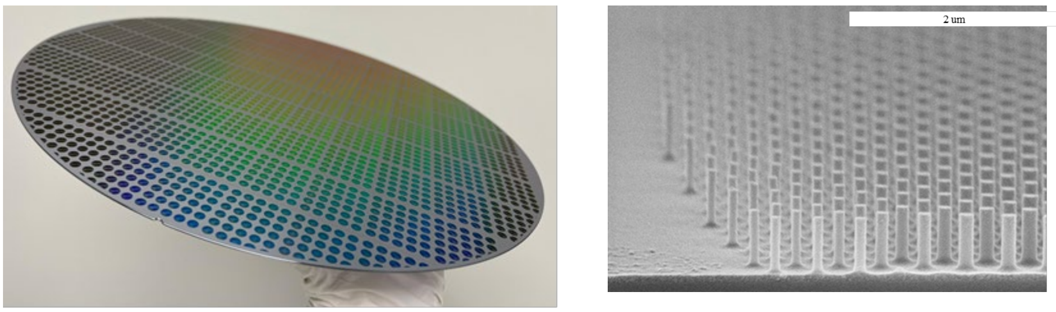

Figure 2. Full wafer master for metalens fabrication via NIL (left). Printed metalens (right).

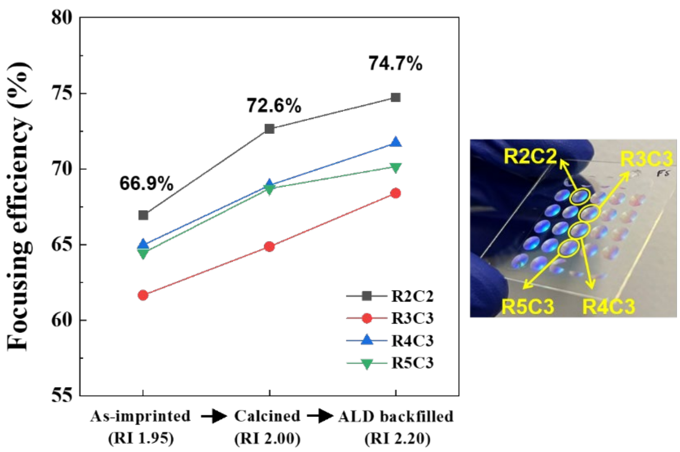

Figure 3. Lens efficiencies for imprinted lenses priot to and after post-processing using ALD.[3]