All-Inorganic Diffractive Optics, Lightguides and Metalenses using Nanoimprint Lithography and High Refractive Index Nanoparticle Inks

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Diffractive optics, light guide gratings and metalenses (flat lenses) are of significant interest for emerging DoD and commercial applications including virtual and augmented reality (AR/VR) devices, precision imaging and compact, aberration free optical systems. While great strides have been made in the design and feasibility demonstrations for these devices, significant challenges remain for their high-throughput, cost effective manufacturing. We describe a rapid, reliable and scaleable additive manufacturing process for "printing" these components using a variation of nanoimprint lithography (NIL) and crystalline metal oxide nanoparticle-based inks.

Metalenses are ultrathin planar (flat) lenses comprising periodic high aspect ratio and high refractive index nanofeatures that efficiently diffract light. Despite the compact metalens form factor with heights less than a micron, their performance can match and even exceed that of bulkier refractive components. In addition to making lenses more compact and lightweight, metalenses possess more degrees of freedom than traditional optical elements, and can be designed to achieve a desired amplitude, phase, or polarization distributions by tuning size, shape, pitch and material properties. High refractive index (RI) transparent metal oxides such as titania are the materials of choice for practical metalenses as they are optically and mechanically stable and their high refractive index enables the use of nanofeatures with achievable aspect ratios. These materials properties are also sought after for diffractive optics and waveguide gratings, particularly for use in VR headsets, AR glasses, head-up displays, and other optical applications.

Current approaches to all-inorganic metalens fabrication are subtractive in nature and comprise a lengthy sequence of time and materials intensive steps, including many cycles of atomic layer deposition (ALD), electron beam lithography, and reactive ion etching that in all require 10s of hours and must be repeated for each wafer. Here, we report a one-step additive manufacturing process to fabricate metalenses, diffractive optics, and waveguide gratings for visible wavelengths within minutes. Nanostructures with aspect ratios larger than eight and critical dimensions smaller than 60 nm were produced using NIL and a titanium dioxide nanocrystal-based imprint material, resulting in inorganic structures exhibiting a refractive index of n=1.9. RI can be increased to 2.1, when desired, by post processing. The NIL approach requires a silicon master for the desired optical elements, which is fabricated once via subtractive processing. 100s to 1000s of polymer replications of the silicon master can then be created by casting and curing crosslinked siloxane films on the master. Each of those siloxane replicas can then be used as stamps for the additive imprint process for the fabrication of many optical wafers containing arrays of lenses. In this way, the cost of the master fabricated by subtractive processing is amortized over 10,000s to 100,000s of optical wafers instead of being used for the fabrication of each wafer.

As a demonstration, we fabricated metalenses with numerical apertures of 0.2 and focusing efficiencies over 50%. Manufacturability of 400 um diameter lens arrays over large areas was assessed by performing 15 manual imprints in 30 minutes (2 minutes of process time per imprint) with a single stamp. We have used such stamps for greater than 30 imprints while preserving lens quality, paving the way for high-throughput low-cost manufacturing. Metalenses with a diameters of 4 mm, diffractive gratings and lightguides were similarly fabricated.

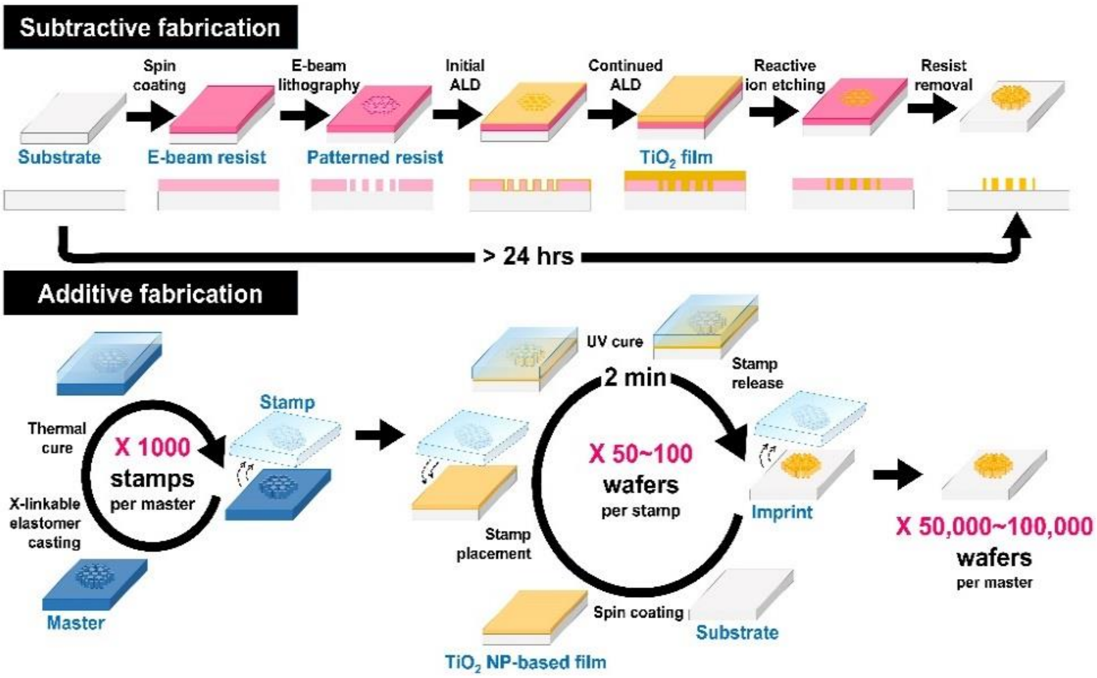

Figure 1. Comparison of subtractive and additive schemes for TiO_2 metalens fabrication.[1]

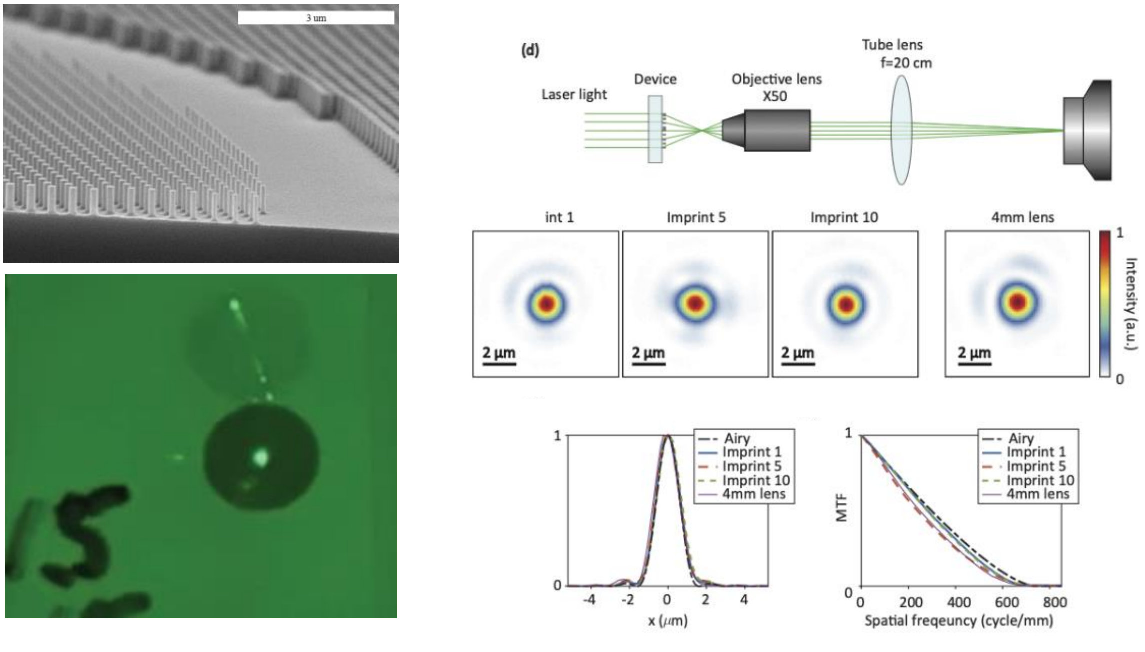

Figure 2. Characterization of 400 um and 4 mm diameter metalenses with focal lengths of 980 µm and numerical apertures (NA) of 0.2 tested at 543 nm. SEM image of printed metalens (top left). Optical image showing printed lens focusing green light (bottom left). Schematic for measuring lens efficiency (top right). Focal spot images for imprints 1, 5 and 10 of a 400 diameter um lens and a 4-mm diameter lens. Scale bar, 2 µm. (f) Line cuts of centers of focal spots shown in (d). The focal spot of an ideal metalens (Airy function) is also presented. (g) On-axis modulation transfer functions (MTF) for different imprints. The ideal MTF is also shown for comparison.[1]

1. Einck, V. J.; Torfeh, M.; McClung, A.; Jung, D. E.; Mansouree, M.; Arbabi, A.; Watkins, J. J. *ACS Photonics* **2021**, *8*, 2400-2409.