Additive Full-Wafer Fabrication of All-Inorganic Metalenses, Waveguides, and Diffractive Optics for Visible and IR Applications via Direct Nanoimprint Lithography

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ABSTRACT

Full wafer scale fabrication of high-efficiency, all-inorganic optical devices including metalenses, AR/VR waveguides, and polarization-controlled holograms is demonstrated by using additive nanoimprint lithography with nanoparticle dispersion-based inks. Approximately one-thousand 4-mm-sized metalenses are fabricated per 8-inch wafer with high optical efficiency and excellent uniformity across the wafer. The absolute and relative efficiencies of the metalenses are more than 80% and 90%, respectively, which are approximately 95% of the maximum simulated efficiencies for this specific design. The close agreement between simulated and realized efficiencies indicates that future improvements are possible, and actual efficiencies are not limited by materials or process. The fabrication of polarization-sensitive, phase/amplitude-controlled holograms demonstrates that our process is capable of replicating asymmetric nanostructures with high aspect ratios of more than 10 by direct imprinting without etching. The imprinted metalenses are free from organics due to a post-imprint calcination step and exhibit outstanding dimensional and optical stabilities, as confirmed by accelerated environmental testing (ASTM G155). Refractive index of the structures can be increased up to 2.3 using a short post-imprint atomic layer deposition process. This work opens a path for true, full-scale additive manufacturing of meta-optics.

Keywords: Additive manufacturing, nanoimprint lithography, scalability, metasurface, waveguides

1. INTRODUCTION

Remarkable progress has recently been made towards additive manufacturing of optical structures including photonic crystals and metalenses in the visible wavelengths using a TiO_2 nanoparticle (NP)-based materials and UV nanoimprint lithography (UV-NIL). Additive manufacturing approaches are fast, scalable, and cost-effective in comparison with the subtractive manufacturing methods, which are time, cost, and tool-intensive processes. The optical performance of devices fabricated using additive manufacturing platforms is improving rapidly and is now competitive or in some cases better than those fabricated using subtractive platforms. There are a few different approaches in terms of material sets used for the direct NIL-based patterning of metasurfaces that include: (1) nanoparticle-polymer composite dispersions[1], (2) sol-gel precursors[2], and (3) all-inorganic nanoparticle-based dispersions[3-4]. Moreover, there are some approaches that use NIL for patterning a hard mask followed by etching, which while employing a NIL step, retains the burdens of a subtractive process. The direct NIL-based patterning method has previously encountered some challenges, including low optical efficiency (due to low refractive index and low aspect ratio), large feature contraction, and surface roughening relative to the master mold, and oxidative instability of TiO_2 NP/polymer composites, which has raised some concerns for practical applications and reliable manufacturing.

Our direct patterning approach for all-inorganic nanoparticle-based structure is promising since it mitigates the challenges and concerns described above. For example, it was demonstrated that the high-throughput and low-cost manufacturing of metalenses can be achieved with an imprint cycle time as fast as 2 minutes per wafer.[3] The optical performance, as indicated by the absolute focusing efficiency of the metalenses, was centered at approximately 50% at 543 nm, which was the most efficient metalens patterned by NIL at that time. More recently, we demonstrated that simple post-imprint

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processes including the calcination and a few cycles of ALD can further improve the absolute focusing efficiencies of the metalenses, up to 75%, but only a few lenses achieved that efficiency and the scalability demonstration was limited to a few square inches.[4] The present study demonstrates the full-wafer fabrication of metalenses, AR/VR waveguides, and holograms showing even higher efficiencies and excellent uniformity across the wafer.

2. RESULTS AND DISCUSSION

Figure 1 shows various nanostructures fabricated by direct patterning with the UV-assisted NIL and a TiO_2 NP-based dispersion, followed by calcination at 450ºC to remove any residual organics from the structures. It is shown that our materials and process are capable of fabricating high-aspect-ratio structures (more than 10), asymmetric pillar structures, and slanted gratings.

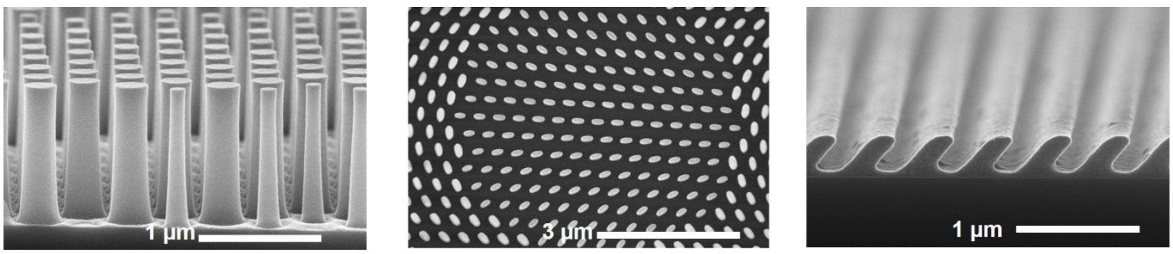

Figure 1. Various nanostructures patterned by direct NIL using TiO_2 nanoparticle-based dispersions.

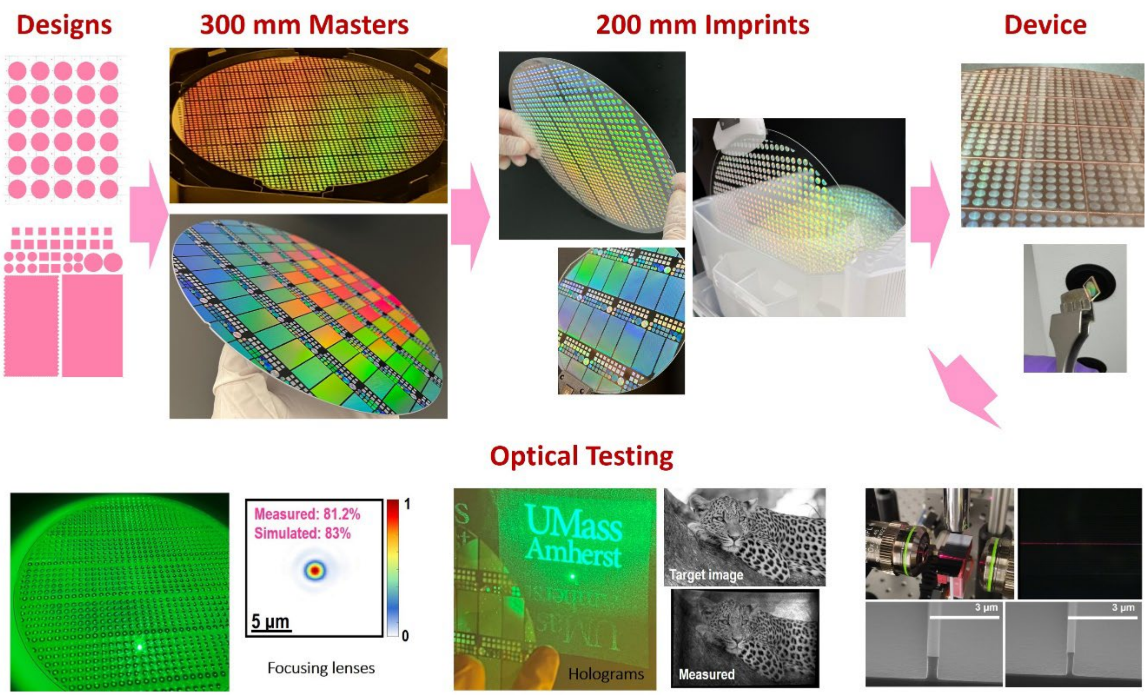

Figure 2. Complete fabrication process of NIL-based direct patterning including designing metasurfaces, mastering patterns, elastomeric stamp making, UV-assisted imprinting, mechanical dicing, and optical characterization of optical devices such as focusing metalenses, polarization-sensitive holograms, and waveguiding line patterns.

Figure 2 shows the complete process loop for successful iterations and design/process optimization to achieve high optical efficiency. It is demonstrated that approximately one thousand metalenses (lens diameter ~ 4 mm, numerical aperture ~ 0.2, design wavelength ~ 550 nm) can be fabricated per 8-inch wafer with imprint times about 5 minutes. The absolute (focused power/incident power) and relative (transmitted power/incident power) focusing efficiencies of the fabricated all-inorganic metalens devices are more than 80% and 90%, respectively, which closely matches simulated efficiencies (within 95%) of the design. We have also developed holographic devices with phase- and amplitude-controlled designs, which exhibit low speckle noise on the projected screen. AR/VR grating structures and waveguiding line structures operating in visible and infrared wavelengths have also been demonstrated.

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CONFLICT OF INTEREST DISCLOSURE

The authors declare the following competing financial interest(s): D.E.J, V.J.E, B.M., A.A., and J.J.W. have financial interest in Myrias Optics, Inc., which has licensed technology associated with imprinted optical components.

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