Tunable Semiconductor Metasurfaces for Active Lensing

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Primary CNF Tools Used: JEOL 9500, Zeiss Ultra SEM, Oxford Cobra ICP etcher, Oxford PECVD

Abstract:

Optically thin metamaterials, or metasurfaces, provide strong modulations to spatial and spectral properties of light. We engineer metasurfaces based on high index low-loss semiconductors, which exhibit narrowband and/or tunable optical resonances for near-infrared photonic applications. We report on the design, fabrication, and characterization of resonant silicon metasurfaces and thermally-tunable germanium metasurfaces to demonstrate active lensing. By virtue of their scalability and compactness, semiconductor metasurfaces present a promising alternative to traditional optical elements.

Summary of Research:

Silicon Metasurfaces. Semiconductor resonators, such as germanium and silicon, are attractive candidates for efficient metadevices owing to their high refractive index, infrared transparency, and support of strong localized Mie-type resonance modes [1,2].

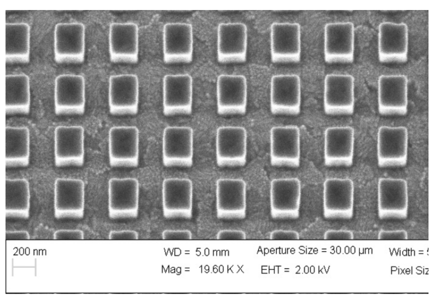

Figure 1: SEM of a typical α-Si-based near-IR resonant metasurface on a SiO_2/ITO substrate.

Our project focuses on the design and fabrication of resonant amorphous silicon (α-Si) meta-surfaces with sub-50 nm feature sizes, suitable for various applications where compact and efficient light modulation is needed. An example of a typical α-Si metasurface under study is shown in Figure 1, consisting of an array of rectangular α-Si patches on a fused silica substrate, with the gap between adjacent resonators governing the *Q*-factor of the optical resonance.

In one application, we employ α-Si metasurfaces towards the design and fabrication of a metalens with tunable focus. Metalenses with tunable functionalities are critical to the miniaturization of vision and imaging technologies such as spatial light modulators and adaptive optics; however, most metalenses have static functionalities preset by their geometries. By selecting three constituent resonator geometries that impart phase shifts in increments of 2π/3, the spatial phase profile for a converging metalens is achieved. To enable tunability, the meta-atoms are designed to have a locally-adjustable optical phase response dependent on the permittivity of the surrounding media, and the lens is encapsulated in a liquid crystal (LC) cell, which offers an absolute shift up to 0.7 in the in-plane permittivity upon application of an external electric field.

For metasurface fabrication, amorphous silicon (α-Si) films are deposited onto ITO-covered fused silica substrates using plasma-enhanced chemical vapor deposition (Oxford PECVD), and film surface is treated with SurPass 3000 adhesion promoter. HSQ 6% was spun and baked to form a 100 nm thick layer over the α-Si, coated with DisCharge anti-charging layer, e-beam exposed at a dose of 250 µC/cm^2 (JEOL 9500FS), and developed in MIF 300 solution for 120 s. The pattern was transferred to the α-Si layer using reactive ion etch (Oxford Cobra). The resulting samples were characterized with a scanning electron microscope (Zeiss Ultra). The project is currently in the LC encapsulation stage. Our simulations predict a focal spot position shift from +8 mm to -8 mm in response to the maximum permittivity modulation of the LC, as shown in Figure 2.

Germanium Metasurfaces. Next, we utilize the large thermo-optic coefficient of germanium (Ge) [3] to demonstrate a resonant Ge-based metalens, which can be controlled by heat. The metalens building blocks are high aspect-ratio anisotropic double-pillar Ge meta-

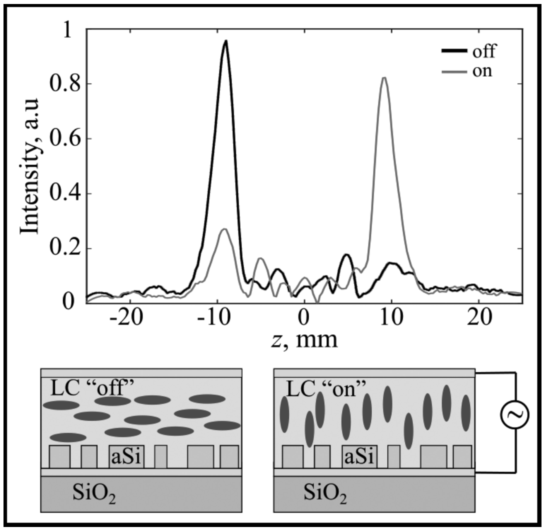

Figure 2: Top, simulated intensity of light transmitted through the α-Si metalens, plotted along the optical axis of the lens. The lens acts as a converging lens with +8 mm focus in the absence of an external electric field (black line) and acts as a diverging lens with a -8 mm focus in the presence of an external electric field (light gray line). Bottom, schematic of an α-Si metalens design.

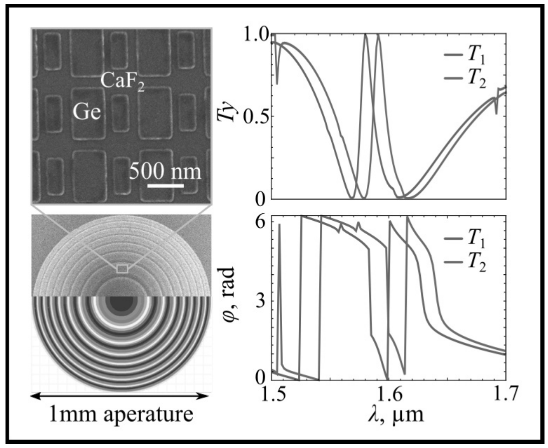

Figure 3: Top Left, zoomed-in SEM of one of the fabricated metalens phase steps. Bottom Left, an SEM of the fabricated 8-step spherical metalens. The lower half of the lens is color-coded according to its eight phase steps. Right, simulated temperature-dependent transmission and phase spectra for one of the meta-atom geometries (zone 8).

atoms, as shown in Figure 3. Such structures support high quality-factor resonances which can be excited by one of the principal linear polarizations of an incident light and whose spectral positions can be widely tuned by heating the metasurface [4]. The meta-atom geometries are selected to impart the required hyperbolic phase profile for a spherical lens, while simultaneously optimized to exhibit high efficiency contrast with thermal tuning. The selection therefore enables control over the intensity of the focused light. Representative transmission and phase spectra of the meta-atoms are presented in Figure 2. We verify the tunable metalens concept experimentally by fabricating and characterizing a Ge metasurface patterned on a quartz substrate. The device fabrication consisted of seven steps: e-beam evaporation of 630 nm of Ge (CVC SC4500); standard PMMA spin-coat, baking, and e-beam exposure at 1000 μC/cm^2 (JEOL 9500FS); development in MIBK:IPA 1:3; e-beam evaporation of a 30 nm chrome (Cr) mask; liftoff in room-temperature sonicated acetone for 20 min; pattern transfer to the Ge layer through HBr reactive ion etching (Oxford Cobra); and removal of residual Cr mask with argon ion milling (AJA Ion Mill).

Figure 3 presents an SEM image of one of the meta-atom geometries of fabricated metalens. The experimental focal spot tuning is shown in Figure 4; by increasing the temperature of the fabricated metasurface, a continuous intensity modulation of the focal spot of the metalens is demonstrated, with up to 55% intensity modulation achieved by increasing the temperature from 25-125°C.

References:

[1] Soref, Richard. "Mid-infrared photonics in silicon and germanium." Nature photonics 4.8 (2010): 495.

[2] Frey, Bradley J., Douglas B. Leviton, and Timothy J. Madison. "Temperature-dependent refractive index of silicon and germanium." Optomechanical technologies for Astronomy. Vol. 6273. International Society for Optics and Photonics, 2006.

[3] Bosch, M., Shcherbakov, M. R., Fan, Z., and Shvets, G. (2019). Polarization states synthesizer based on a thermo-optic dielectric metasurface. Journal of Applied Physics, 126(7), 073102.

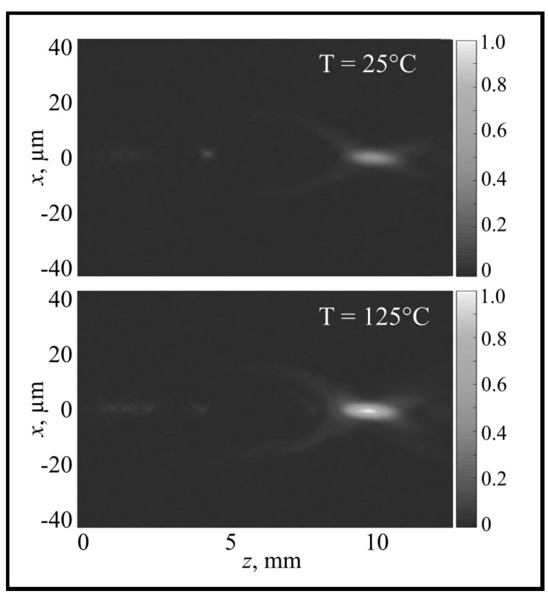

Figure 4: Experimental temperature-dependent focal spot profiles of the metalens. Top, focusing profile of the metalens at a temperature of 25°C. Bottom, focusing profile of the metalens at a temperature of 125°C.