Visible-Light Metasurfaces Based on Silicon-Rich Silicon Nitride

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Principal Investigator(s): Gennady Shvets

User(s): Melissa Bosch

Affiliation(s): School of Applied and Engineering Physics, Department of Physics; Cornell University

Primary Source(s) of Research Funding: Office of Naval Research (ONR), National Science Foundation (NSF)

Contact: gs656@cornell.edu, mb2583@cornell.edu

Website: http://shvets.aep.cornell.edu

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Abstract:

Optical metasurfaces, consisting of planar arrangements of lithographically-defined subwavelength scatterers, offer a highly compact and scalable alternative to conventional freespace refractive optical elements. We report on the fabrication 500 nm thick silicon-rich silicon nitride (SRN) metasurfaces exhibiting tunable optical resonances, fit for various photonic applications requiring visible light modulation. For example, we integrate SRN-metasurfaces with liquid crystals (LCs) to demonstrate voltage-controlled zoom lenses operating at red/green/blue (RGB) wavelengths. Their scalability, ultrathin-profile, and CMOS-compatibility renders SRN-metalenses uniquely poised to benefit RGB imaging technologies such as augmented reality and depth perception devices.

Summary of Research:

I. Silicon-Rich Silicon Nitride (SRN) Metasurfaces. Metasurfaces have drawn considerable interest over the past decade owing to their widespread potential applications. Semiconductor and dielectric metasurfaces are especially promising platforms for efficient light modulation owing to their low Ohmic losses and support of localized Mie-type resonance modes which are spectrally-sensitive to the permittivity of the media adjacent to the metasurface array [1]. Typically, metasurfaces working at visible wavelengths are composed of GaP or TiO_2, requiring costly and time-consuming deposition processes (i.e., metal-organic chemical vapor deposition and atomic layer deposition) [2,3]. Our project focuses on the PECVD-based fabrication of SiN_x metasurfaces with sub-100 nm feature sizes and moderate (1:4) aspect ratios. Our ellipsometric characterization of PECVD-deposited SiN_x thin films shows flexible control over the films' refractive index and extinction coefficient through variations in the SiH_4:NH_3 gas ratio (Figure 1). Several gas ratios yield SRN films exhibiting low extinction coefficients and acceptable refractive indices at RGB wavelengths: fit for use as the constituent material of visible-light metasurfaces. A scanning electron microscope (SEM) image of a representative SRN metasurface is shown in Figure 2, consisting of an array of rectangular SRN resonators on a silica substrate, where the spacing between neighboring resonators governs the bandwidth of the optical resonance. The SRN devices are fabricated using plasma-enhanced chemical vapor deposition (Oxford PECVD) of SRN onto a fused silica substrate; HSQ 6% spin-coat, baking, and e-beam exposure at 7.5 mC/cm^2 (JEOL 9500FS); development in TMAH/NaCl (0.25/0.7N) salty solution; and pattern transfer to the SRN layer through reactive ion etching (Oxford 100). The fabricated samples were characterized with a scanning electron microscope (Zeiss Ultra), showing good accuracy of geometric dimensions.

II. Tunable-Focus Lens Using a Liquid-Crystal-Embedded SRN-Metasurface. In one application, we utilize PECVD SRN films to create a SRN-metalens behaving as a visible-light lens with voltage-actuated zoom. Metalenses with tunable focal lengths offer many advantages to contemporary vision and imaging systems; however, most metalenses have static focal lengths after fabrication. Our previous work used amorphous silicon metasurfaces infiltrated with liquid crystals (LCs) to demonstrate a varifocal metalens with voltage-actuated focal length in the infrared [2].

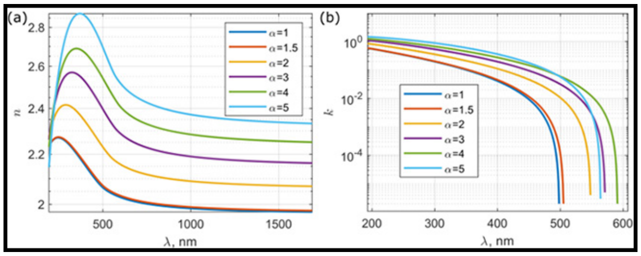

Figure 1: (a) Refractive index n and (b) extinction coefficient k of PECVD-deposited SRN films as a function of the SiH_4:NH_3 gas ratio α and wavelength λ.

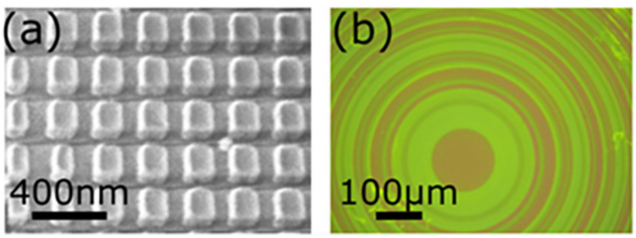

Figure 2: (a) A scanning electron microscopy (SEM) image of a representative SRN-metasurface, consisting of a periodic array of rectangular SRN pillars on a silica substrate. (b) Optical microscope image of the fabricated 1.5-mm-diameter spherical SRN-metalens. The different colors of the concentric rings of the metalens correspond to unique metasurface pillar geometries.

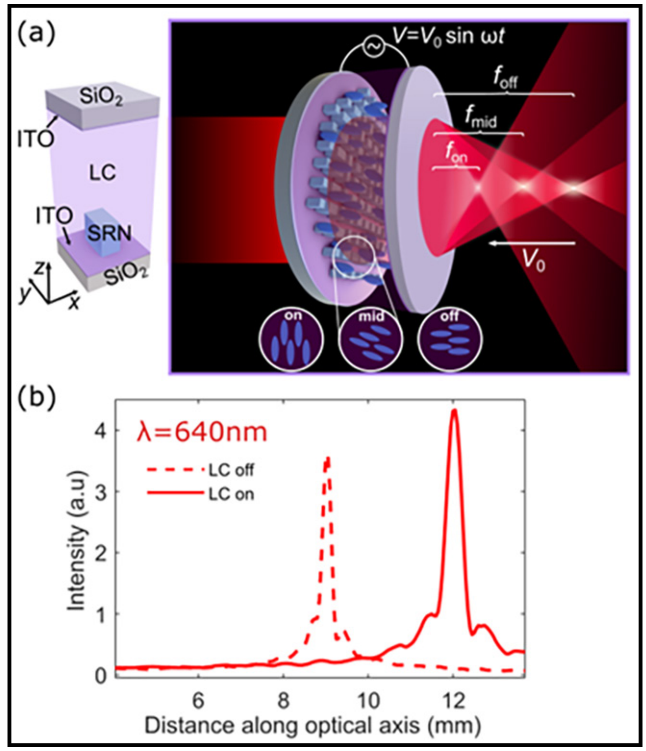

Figure 3: Left: The metasurface unit cell, consisting of a rectangular SRN meta-atom embedded in a LC and sandwiched between two transparent conducting indium-tin-oxide (ITO)-coated silica plates. Right: An AC voltage applied across electrodes modulates the LC molecule orientation and resulting focal length of the metalens. (b) Simulated intensity of transmitted light along the optical axis of the SRN-metalens for λ = 640 nm. The lens acts as a converging lens with a 9 mm focal length in the absence of an external electric field (dashed red line) and a 11 mm focal length in the presence of an external electric field (solid red line).

We merge this design strategy with SRN thin film engineering to design and fabricate SRN-based resonant LC-metalenses (Figure 2b) that enables switchable-focus at visible wavelengths. The metasurface unit cell is a rectangular SRN pillar embedded in a nematic LC and sandwiched between two conductive plates, as shown in Figure 3a. The local phase response of the SRN meta-atoms are modulated by means of the field-dependent LC, resulting in continuous and reversible modulations of the metalens focal length. In one design for red light meta-atom geometries are optimized to impart phase shifts that approximate the ideal focusing phase profile for a converging lens with focal distance $f = f_{off}$ in the LC "off" state, while simultaneously engineered to impart the phase profile of a converging lens with $f = f_{on}$ in the LC "on" state. To validate the approach, we fabricated a 1.5-mm-diameter spherical metalens that facilitates voltage-actuated switching between two distinct focal distances of f_{off} = 9 mm and f_{on} = 11 mm at a wavelength of 640 nm. Our simulations at predict high-contrast switching between focal spots in response to the "off"-to-"on" permittivity modulation of the LC, as shown in Figure 3b.

References:

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