On the Fabrication and Performance of a Diamond Metalens for Imaging Quantum Emitters

R. Grote and G. Lopez
Singh Center for Nanotechnology, Quattrone Nanofabrication Facility
University of Pennsylvania, Philadelphia, PA 19104

Solid-state quantum emitters have emerged as robust single-photon sources and addressable spins key components in rapidly developing quantum technologies for broadband magnetometry, biological sensing, and quantum information science. Performance in these applications, be it magnetometer sensitivity or quantum key encryption error-rate, is limited by the number of photons detected. However, efficient collection of a quantum emitter's photoluminescence (PL) is challenging as its atomic scale necessitates diffraction-limited imaging with nanometer-precision alignment, oftentimes at cryogenic temperatures. In this work, we explain the process modeling, the fabrication and ultimately the device performance of a diamond metalens. Using empirical data, the effective blur and microloading effects of the FOX-16 electron beam negative resist (Dow Corning) process were used to model the resulting exposure latitude across varying pattern densities from an array of tower patterns (Fig. 1). Exposures were performed on an Elionix ELS-7500EX running at a 20MHz fixed clock using 1 nA beam current and a 5 nm beam step size (shot pitch). We demonstrate how implementing a process modeling technique for a negative resist[1] can help to target the process window needed to obtain the desired pattern and shape fidelity in one iteration (Fig. 2). Using the FOX-16 as a hardmask, a pattern transfer into diamond was performed using a dry etch process. As a result of our metalens, we are able image an individual quantum emitter, an isolated nitrogen-vacancy (NV) center in diamond, using a dielectric metalens composed of subwavelength pillars etched into the diamond's surface (Fig. 3). The metalens eliminates the need for an objective by operating as a high-transmission-efficiency immersion lens with a numerical aperture (NA) greater than 1.0. This design provides a scalable approach for fiber-coupling solid-state quantum emitters that will enable the development of deployable quantum devices.

[1] J. R. Bickford, G. G. Lopez, N. Belic and U. Hofmann, J. Vac. Sci. Technol., B 32, 06F511 (2014).

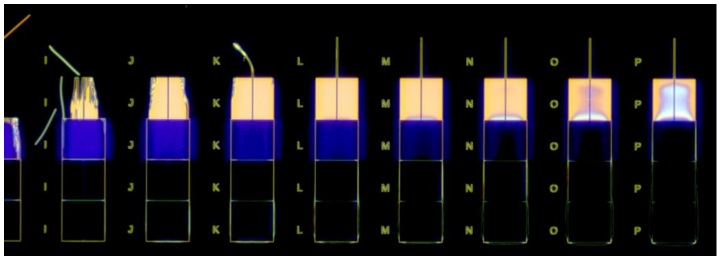

Figure 1: Optical Image of Calibration Pattern: FOX-16 process was calibrated by extracting the exposure latitudes of the tower patterns above.

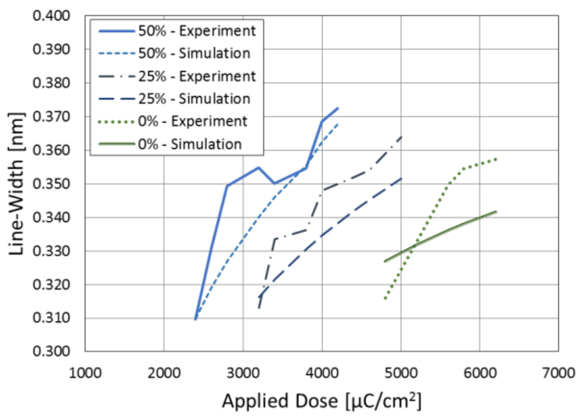

Figure 2: Exposure Latitude: The exposure latitudes of the 50%, 25% and 0% pattern densities are shown with their simulation. Fitting parameters were an FWHM effective blur of 67 nm with microloading loading values of 75%, 92%, and 100% for 0%, 25%, and 50% pattern density respectively. The loading values are relative development rates to the 50% pattern density.

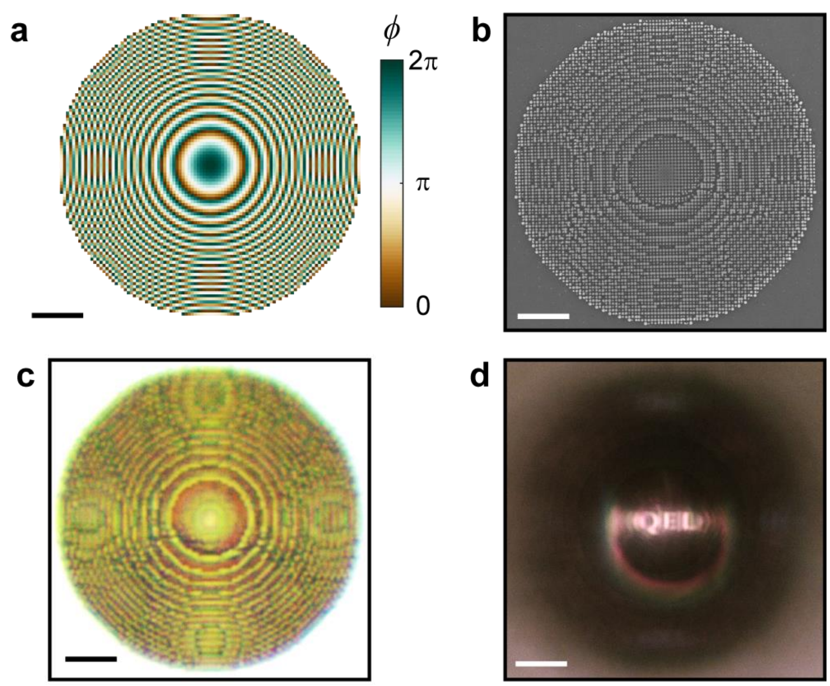

Figure 3: Metalens Design and Fabrication. Top-down images of (a) the Fresnel phase profile used for the design; (b) SEM image of pillar map; (c) bright-field reflection optical micrograph of the metalens surface; and (d) image of a macroscopic chromium shadow mask with the letters QEL formed through the metalens in a bright-field transmission microscope. All scale bars are in microns.