DTU Library

Design and All-In-One Etch of Silicon Metalens for Near-Infrared Focusing

Lu, Bingrui; Hansen, Søren Engelberth; Weis, Thor August Schimmell; Giri, Rakshyakar; Arregui Bravo, Guillermo; Stobbe, Søren

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Design and All-In-One Etch of Silicon Metalens for Near-Infrared Focusing

Bingrui Lu [a], Søren Engelberth Hansen [a], Thor August Schimmell Weis [a], Rakshyakar Giri [a], Guillermo Arregui [a], Søren Stobbe [a]

[a] DTU Electro, Department of Electrical and Photonics Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.
e-mail: binlu@dtu.dk, ssto@dtu.dk

Metalenses play an important role in the new generation of micro- and nano-optical systems. A metalens consists of a series of precisely engineered subwavelength nanostructures arranged on a flat surface to manipulate light properties such as amplitude and phase [1]. Because of their small footprint, planar geometry, and excellent optical performance, metalenses show great potential in applications from sensing, imaging, and communication to astronomy, quantum photonics, and virtual/augmented reality [1]. For applications that require high efficiency and low energy consumption, interests have shifted from plasmonic metalenses to all-dielectric ones in pursuit of lower absorption and scattering losses of dielectric material compared to metal. The development of dielectric metalenses poses a number of new nanofabrication challenges, such as material quality, substrate compatibility, and fabrication techniques together with fabrication tolerances. In our work, a metalens with an array of Si pillars in various diameters placed in a hexagonal lattice is designed for near-infrared (NIR) light focusing with the center wavelength of 1550 nm. The choice of silicon guarantees material quality and substrate compatibility thanks to the technologies from today's mature silicon industry. Meanwhile, a specially designed silicon deep-etching process developed in our cleanroom is optimized to obtain high-quality fabrication with precise control of the nanostructure geometries [2].

The hexagonal unit cell of the metalens contains Si pillars with a diameter of D and height of H, coated with an anti-reflective oxide layer as shown in Fig 1a and b. The nanopillars function by delaying the phase of an optical wavefront relative to other pillars of different diameters, which allows for arbitrary phase profiles to be generated if the relative phase difference spans 2π. Through iterative design space exploration in Fig 1 c and d, the lattice period of 450 nm, the height of 1.5 μm, and the pillar diameters from 140 nm to 356 nm are found to provide the required 2π phase span and sufficient feature sizes for fabrication. For a 330 μm wide metalens with a 110 μm beam waist of collimated Gaussian input, the focal lengths are simulated to be 884 μm, 806 μm, and 730 μm, respectively, for the wavelengths 1410 nm, 1550 nm, and 1690 nm.

For the high-precision fabrication of the silicon nanopillars, a simplified procedure of All-In-One etch is developed where the wet processes of lift-off and metal mask removal are avoided. An etching mask layer is deposited on the silicon substrate before a state-of-the-art high-resolution JEOL JBX-9500 FSZ E-Beam system is used to pattern 50 nm of CSAR resist. Before the exposure, a proximity effect correction (PEC) software, Beamfox Proximity, analyzes the pattern design and adjusts local exposure dosages to achieve the intended outcome of circular patterns in the correct dimensions. To avoid structural damage from the surface tension and other mechanical impacts of wet chemistry processing steps, a highly directional plasma dry etching process developed in DTU's cleanroom called CORE (Clear, Oxidize, Remove, and Etch) is optimized. It replaces the common fluorocarbon inhibitor in the Bosch deep etching with oxygen, making it a greener process for the environment. The nanopatterns are transferred from the resist to the etching mask, and then into the silicon substrate to form high-aspect-ratio pillars. Before the final step of anti-reflective oxide growth, the resist and the etching mask are both removed directly after the silicon CORE process in the same chamber.

The silicon metalens can be placed directly on top of other photonic circuits or components to form a 3D integrated system. The fabrication process developed in this work is fully compatible with the current silicon industry but with a greener execution. The metalens will be an essential component in the integration of optoelectronic circuits [3-5]. Further measurements and applications of the metalens will be presented.

[1] W. T. Chen et al., Nat. Rev. Mater. 5 (2020), 604–620.
[2] V. T. H. Nguyen et al., J. Vac. Sci. Technol. A 38 (2020), 053002.
[3] M. Albrechtsen et al., Nat Commun 13 (2022), 6281.
[4] S. E. Hansen et al., Opt. Express 31 (2023), 17424-17436.
[5] B. V. Lahijani et al., arXiv:2204.14257 [physics.optics].

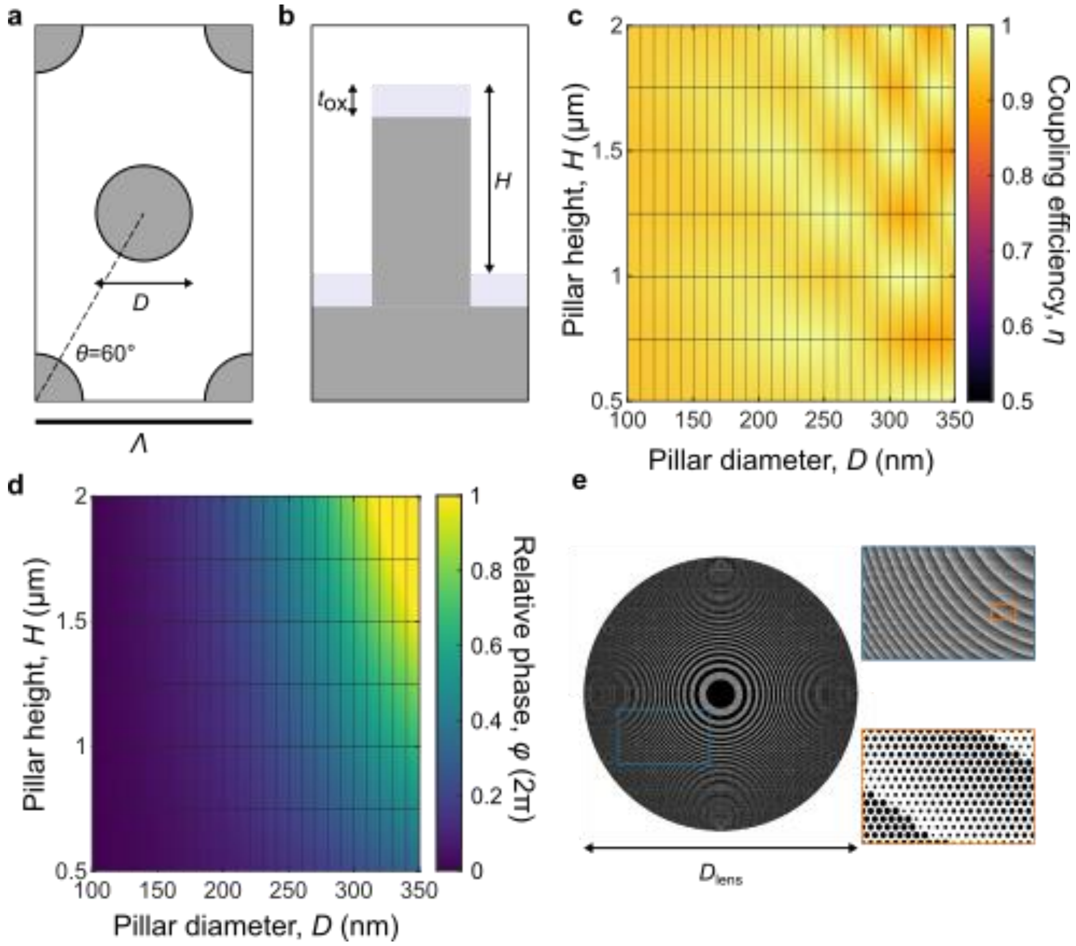

Figure 1. The design of the Si metalens. **a**, The hexagonal unit cell. **b**, Sideview of silicon pillars with height, H, and an oxide anti-reflection coating with thickness, t_{ox}. **c**, The coupling efficiency for different pillar diameters and heights.**d**, Design space of the relative phase compared to the smallest pillar diameter. **e**, The full metalens with a diameter of 330 μm.

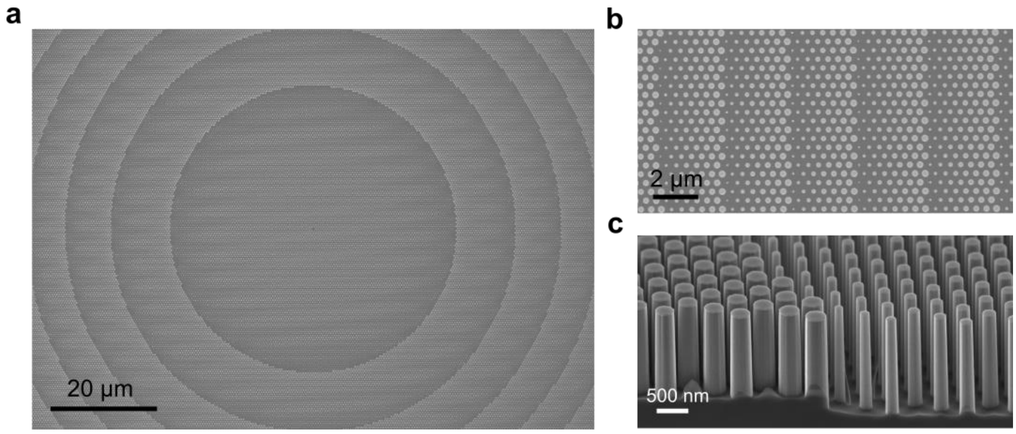

Figure 2. Scanning electron micrographs of fabricated silicon metalens. **a-b**, Topview images. **c**, tilted view.