Silicon Metasurfaces for Magneto-Optics

CNF Project Number: 2472-16

Principal Investigator(s): Gennady Shvets

User(s): Daniil Shilkin, Maxim Shcherbakov, 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), Air Force Office of Scientific Research, and National Science Foundation (NSF)

Contact: gs656@cornell.edu, ds2232@cornell.edu, mrs356@cornell.edu, mb2583@cornell.edu, shilkin.daniil@physics.msu.ru

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

Primary CNF Tools Used: JEOL 9500, Zeiss Ultra SEM, Oxford Cobra ICP Etcher, Oxford PECVD, SC4500 Evaporator, CHA Evaporator

Abstract:

E-beam lithography is applied to fabricate arrays of optically resonant silicon disks followed by covering them with a nickel film to be used in magneto-optical measurements.

Summary of Research:

Electron-beam lithography is often applied to produce semiconductor optical metasurfaces with a typical feature size of 100 nm or below [1,2]. Below are the results of applying this technique to fabricate dense arrays of optically resonant amorphous silicon (α-Si) disks on a glass substrate followed by covering the structure with a thin nickel film to be used in magneto-optical measurements [3]. The pattern presented three 0.5 × 0.5 mm^2 arrays with a constant period of 400 nm and the varied diameter of the disks (Figure 1). The desired height of the disks was 135 nm, and the desired nickel thickness was 5 nm. The resist was hydrogen silsesquioxane (HSQ). Fused silica glasses with a thickness of 0.5 mm were used as substrates.

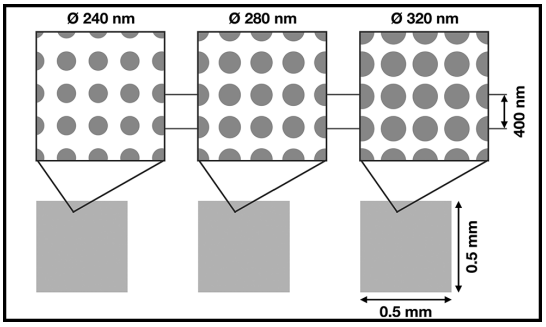

Figure 1: Scheme of the pattern.

The substrates were covered by α-Si using the Oxford plasma enhanced chemical vapor deposition (PECVD) system. The parameters were fixed at the following values: temperature 200°C, microwave power 10 W, pressure 1 Torr, SiH_4/Ar 25/475 sccm. The deposition rate, measured close to the substrate center, was found to depend on the substrate dimensions and varied from 10.6 nm/min (for 1-inch circles) to 11.6 nm/min (for 10 × 10 mm^2 squares). For the desired samples, 135 nm thick films were fabricated. The film thicknesses were measured by FilMetrics F50-EXR using the dispersion data obtained by the Woollam spectroscopic ellipsometer.

The fabricated α-Si films were covered with the resist layer by spin coating. The standard procedure resulted in a non-uniform deposition of the film: the profile of the vacuum holder appeared on the resist layer. This was overcome by placing an aluminum disk on the chuck and fixing the substrates with a Kapton® tape.

The e-beam exposure was performed using JEOL 9500. The files were prepared by standard methods including the proximity effect correction. In every session, the pattern was exposed with a number of different base doses. The other varied parameters included the beam current and the shot spacing, the resist thickness, the baking temperature and time, the choice of the charge dissipative layer, the choice of the developer, and the developing time. These parameters are discussed below.

After the pattern development, samples were etched using Oxford Cobra HBr etcher with the parameters fixed at the following values: HBr/Ar 20/7 sccm, RIE/ICP 30/1500 W, pressure 11 mTorr. The etching rate of 178 ± 2 nm/min was measured using 400-nm-thick films by etching for different times.

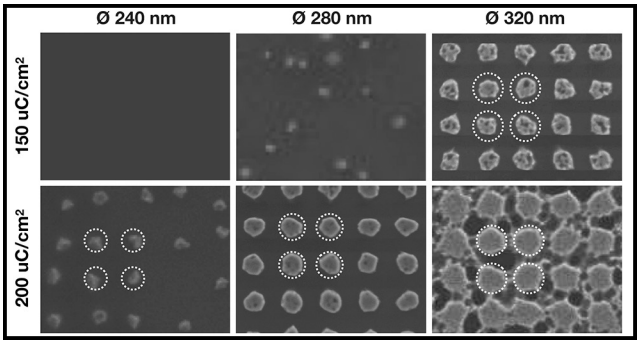

Figure 2: SEM of one the first fabricated samples. Circles indicate the diameter set in the pattern.

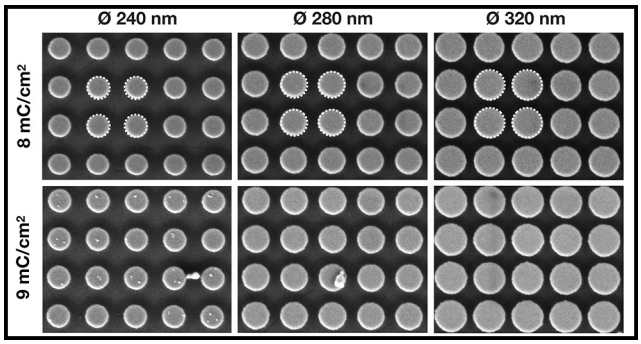

Figure 3: SEM of the last fabricated sample. Circles indicate the diameter set in the pattern.

For samples with the silicon thickness of 135 nm, the etching time of 50 s provided full etching outside of the mask with no cut-off. The presence of the resist residue on top of the disks was not desired, but not critical for our purpose.

The resulting structures were covered by a 5 nm nickel film using the SC4500 odd-hour evaporator. The thermal source was used with the deposition rate set to 0.5-1.0 Å/s.

Figure 2 shows scanning electron microscope (SEM) images of one of the first samples that was fabricated as follows. The 6% HSQ solution was spin coated at 3000 rpm for 60 s with the lid opened. The resist was baked at 170°C for 2 min and covered with DisCharge by spin coating at 3000 rpm for 60 s. The beam current was 1 nA; the shot spacing was 6.5 nm. The pattern was developed in 300 MIF for 2 min, rinsed in water and blow dried. The SEM images were obtained after plasma etching for 43 s and spin coating DisCharge. The fabricated disks appeared to exhibit irregular shapes with either dimensions reduced (at low doses) or disks merged (at higher doses). The optimal dose was found to depend on the diameter of the disks.

These issues were solved as follows. First, the shapes were found to be smoother when a gold film is used instead of the DisCharge. The gold was deposited after the resist baking using CHA thermal evaporator with the deposition rate set to 1.0 Å/s. Second, the use of the 'salty' developer instead of MIF 300 significantly increased the contrast of the resulted pattern. Finally, using a thinner (30 nm) resist provided the best correspondence between the set and the obtained disk diameters.

Figure 3 shows SEM images of the last sample that was fabricated as follows. The 2% HSQ solution was spin coated at 4000 rpm for 60 s with the lid closed. The resist was baked at 115°C for 70 s and covered with a 13 nm gold film. The beam current was 20 nA; the shot spacing was 5 nm. Directly after the exposure, the gold was removed by wet etching for 30 s in gold etch, the sample was rinsed in water and put into 'salty' developer for 1 min, then rinsed in water, rinsed in isopropyl alcohol (IPA), and blow dried by nitrogen. The SEM images were obtained after plasma etching for 50 s and nickel film deposition. The fabricated disks have a smooth circular shape with the dimensions very close to the set values at a single optimal dose for all of the diameters (the size variations are less than SEM accuracy).

The established metasurface fabrication approach is scalable; thereby promising versatile platforms for ultrathin optical devices poised to find use in free-space and integrated photonics.

Acknowledgements:

This work was supported by the Office of Naval Research (ONR) under Grant No. N00014-17.1-2161, by the Air Force Office of Scientific Research (FA-9550-16-1-0069 and FA9550-16-1.0013), and by the Cornell Center for Materials Research with funding from the NSF MRSEC program (DMR-1719875).

References:

[1] Z. Dong, et al. Nano Letters 17(12), p.7620-7628 (2017).

[2] A. Martins, et al. Optics Express 26(8), p.9573-9583 (2018).

[3] M.G. Barsukova, et al. ACS Photonics 4(10), p.2390-2395 (2017).