Nanofabrication and Characterization of Quasicrystal Metasurfaces using Shadow-Sphere Lithography

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Abstract:

The fabrication and screening processes of quasicrystalline metasurfaces have been optimized to reduce the time and the cost using shadow-sphere lithography (SSL) and template-directed self-assembly. Characterization of these quasicrystals has revealed sharp peaks in reflectance, as well as features as small as 20 nm. The parallel configuration of the these quasicrystals allows for hundreds to be fabricated and characterized within hours — much faster than they could be simulated.

Introduction:

Aperiodic and quasiperiodic metasurfaces have great potential for application to ultrasensitive biosensing, but their development has been slowed by difficulties in; i) fabricating them over large areas, and ii) simulating their optical properties computationally. To address these challenges in nanophotonics, the Whitesides lab has recently developed a method for high-throughput fabrication and screening of quasicrystalline metasurfaces using template-directed self-assembly combined with shadow-sphere lithography (SSL). In this project, we focused on optimization of the self-assembly process and on the quasicrystal fabrication and characterization. The speed, versatility of the patterns, and reproducibility of the fabrication process allow for a remarkably quicker and cheaper method for fabrication.

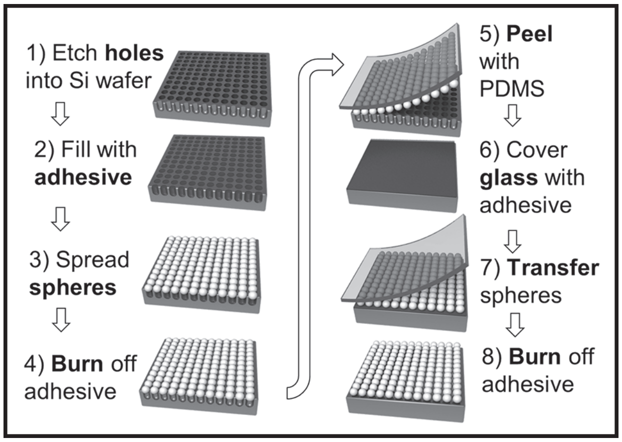

Figure 1: Diagram of the templated self-assembly process [1]. This template shows an arbitrary square pattern.

Method:

Templated Self-Assembly. Templated self-assembly reduces the time of fabrication from weeks for a single to a few hours for hundreds. The silicon template was created by first direct writing a pattern into a mask. The image on the mask was a 6 × 13 array of different quasicrystals, with changing incremental spacing between the holes and different rotational orientations. This image, a single 3.5 × 7 mm rectangle, was then projected five times smaller using an i-line stepper onto a 76.2 cm photoresist-covered silicon wafer 77 times, until the wafer was covered. The spheres were assembled into the holes of the wafer and then transferred to a glass slide using PDMS. This process is more clearly laid out in Figure 1. The spheres retain the pattern initially etched into the silicon. The template is then reusable 10-20 times, allowing for thousands of quasicrystals to be created using a single wafer.

Shadow-Sphere Lithography. Shadow-sphere lithography (SSL) combines techniques from shadow lithography and nanosphere lithography, optimizing both to obtain the finest features. To fabricate, the substrate was placed on a custom-made stage at anywhere between a 45°-70° angle to the horizontal inside an electron-beam evaporator. Using electron beam physical vapor deposition (EBPVD), a thin film of titanium and then gold was deposited onto

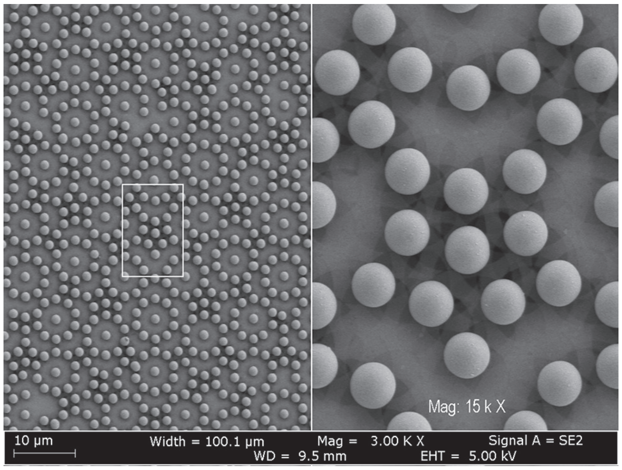

Figure 2: Spheres assembled in a Penrose tiling pattern on the left. On the right is a 5× magnified image of one of the central features with the shadow patterns in between.

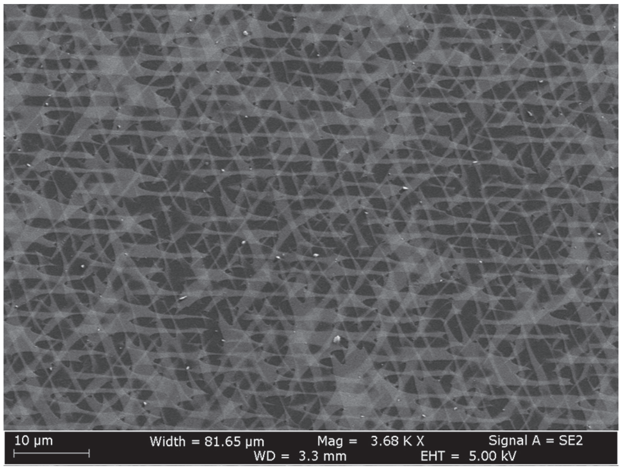

Figure 3: The shadow patterns after the spheres have been removed of a Penrose tiling pattern. The lighter gray is the deposited gold with features smaller than 100 nm.

the stage, which was suspended upside down inside the vacuum chamber. The sample was then rotated while maintaining the original tilt from the horizontal for each deposition of titanium, and then repeated for gold. The spheres were then removed using a simple piece of tape, leaving the shadow patterns — the places where the spheres blocked — behind. Figure 2 shows the spheres and the shadow patterns between them. Figure 3 shows the shadow patterns after the spheres have been removed.

Results:

Using scanning electron microscopy (SEM), it was possible to measure the width of the features on the metasurfaces. Each sample was also characterized using Fourier transform infrared spectroscopy (FTIR). Ideally, the thinner the lines, the sharper the peak in reflectance at certain mid-IR wavelength values. The desired result for sharp peaks was obtained as can be seen in Figure 4, although not as sharply defined as expected. The difference in spacing led to a sharper peak for the patterns with more densely packed spheres, where the shadow patterns were finer.

Conclusions and Future Work:

We provided proof-of-concept for the fabrication of metasurfaces. Templated self-assembly is possible and allows for a rapid, low-cost method of patterning spheres for the fabrication of quasicrystals, with minimal defects. Mechanizing this process could lead to an almost 100% transfer rate of the spheres. Shadow-sphere lithography creates fine features with replicable accuracy and allows for quasicrystals to be created in parallel. This drastically decreases the time and money required to fabricate and characterize these metasurfaces. Trends can be seen in changing the spacing of the spheres and the rotational orientation in an array of quasicrystals; however, more in-depth analysis needs to be conducted.

Acknowledgements:

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References:

[1] Nemiroski, A., et al., Engineering shadows to fabricate optical metasurfaces, ACS Nano, 8(11): 11061-70, 2014.

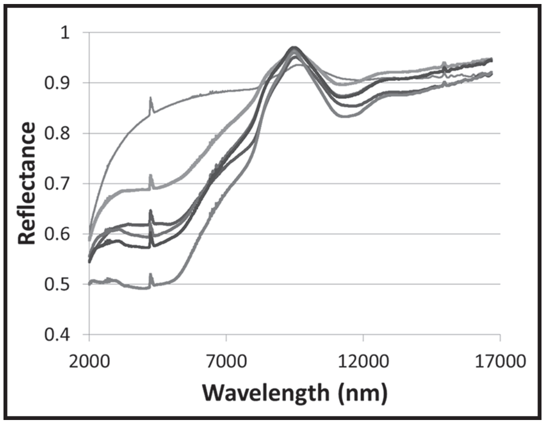

Figure 4: Graph of reflectance from an FTIR scan from 2-17 µm of one column, as spacing increases. The highest line is the background reflectance of the substrate. The lowest line belongs to the most densely packed pattern of spheres. A sharp peak is visible around 10 µm.