3D Photonic Crystals Fabricated Through Direct Laser Writing

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Abstract:

We developed a procedure for fabricating woodpile photonic crystals which involved writing structures into AZ P4210 positive photoresist and a subsequent gold electroplating process.

Introduction:

A photonic crystal is a periodic structure in which the period is on the order of the wavelength. In a three-dimensional (3D) photonic crystal, a 3D photonic band gap is possible. A band gap is the range of frequencies in which light cannot penetrate the crystal regardless of incident angle and polarization. Defects can be engineered in the structures for which light at band gap frequencies can be guided or confined within the crystal, in principle, without loss [1]. Photonic crystals with designed defects enable new types of optical integrated circuits, the analog of electrical integrated circuits. Routing signals optically can eliminate performance problems caused by nanowire capacitance and signal crosstalk in nanoscale electrical signal processing systems [1].

Our photonic crystal fabrication process included direct laser writing, in which 800 nm laser pulses with durations less than 100 femtoseconds were tightly focused in order to expose a photosensitive sample [2]. Each focused pulse had a power density of 400GW/cm^2, which was enough for two photon nonlinear absorption process. Direct laser writing was capable of fabricating 3D structures into photoresist and feature sizes were controlled by modulating the output power. Our setup employed a shutter and a PI Nanocube 3D piezo translation stage, both of which were computer controlled through a Labview program (see Figure 1).

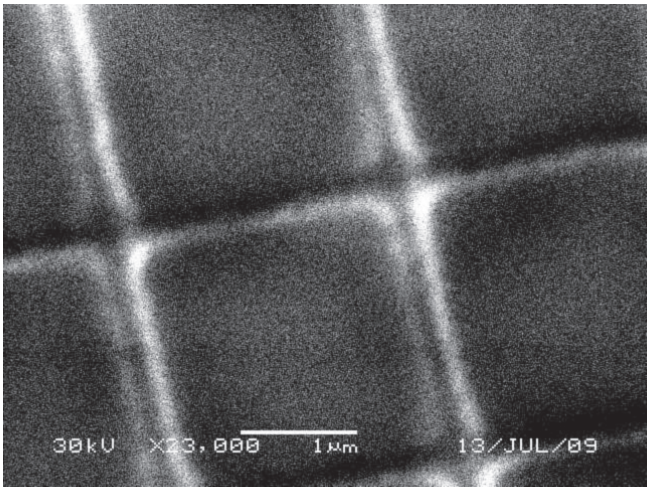

Figure 2: A grid sample written with 100 μW of output power, stage velocity of 0.1 mm/s.

Experimental Procedure and Results:

Sample Preparation. The first step of sample preparation was to use a three boat thermal evaporator to deposit a 50 nm layer of titanium followed by a 50 nm layer of gold onto a glass microscope coverslip. The gold served as the seed layer necessary for a subsequent electroplating process, and the titanium layer was necessary for adhesion of the gold to the substrate. The final sample preparation step was to spin-coat a layer of AZ P4210 positive photoresist onto the substrate.

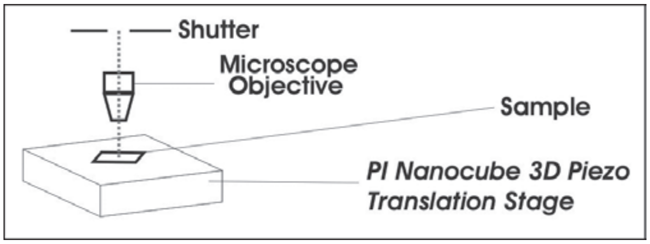

Figure 1: Direct laser writing setup.

Determining the Writing Power. Since we desired to create the smallest features possible, the output power that resulted in the smallest feature in the photoresist was the optimal writing power. Test structures to determine this were written into a 2 μm layer of photoresist at output powers ranging 50-200 μW with a stage velocity of 0.1 mm/s. When attempting to measure the feature size of these test samples, however, we encountered a problem: the gold seed layer had a lower modification threshold than the AZ P4210 photoresist, and under an optical microscope, modified gold and properly exposed photoresist were indistinguishable. A sample written with 100 μW of output power exhibited only seed layer

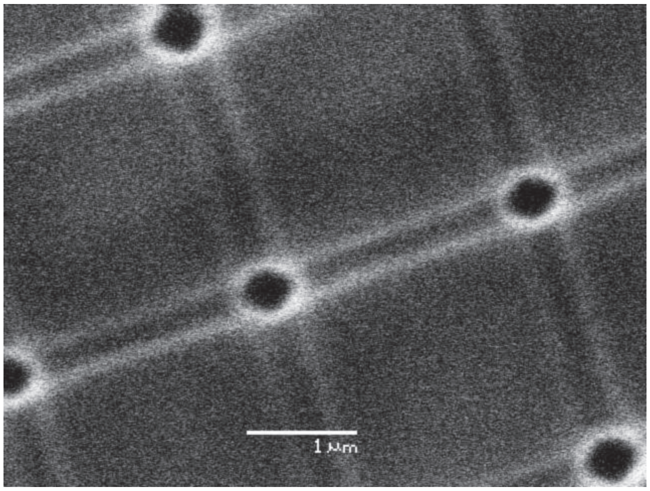

Figure 3: A grid sample written with 125 μW of output power, stage velocity of 0.1 mm/s.

modifications, as seen in Figure 2. When the output power was increased to 125 μW, dark holes appeared in the sample (Figure 3). These holes were locations where the photoresist was developed away because of a double exposure dose due to the crossing of written lines. The visible lines in the image were seed layer modifications, not developed photoresist, whereas a properly written structure would be lines of developed photoresist.

To eliminate the visibility of seed layer modifications, we sputtered a thin gold layer onto the sample surface. After applying the gold coating, only the locations where the photoresist was developed away were visible in the SEM. To fix the underexposure without increasing feature size we reduced the velocity of the PI stage, which increased the exposure dose of the material. When the stage velocity was reduced to 0.025 mm/s, 75 μW of output power yielded proper exposure and a desired feature size of 100-300 nm (see Figure 4).

Gold Electroplating Process. Infiltrating the written structures with gold was the final step of our fabrication process. 6 μm tall test structures were electroplated for different time durations and 1 mA of current.

Only 150 nm filling occurred for durations under five minutes, and overfilling occurred after a duration of 30 minutes. Thus, the time it took to fill a 6 μm tall structure was between 5 and 30 minutes. Once this time was determined, it could be used to extrapolate the filling times for taller structures.

Conclusion:

We developed a procedure using a direct laser writing system to fabricate gold woodpile photonic crystals through two-photon absorption in photoresist and a subsequent electroplating process. We prepared substrates by evaporating gold and titanium, then spin-coating a layer of positive photoresist. We determined the writing power and stage velocity that yielded a desired 100-300 nm feature size. Finally, we investigated the electroplating process and determined that it takes between 5 and 30 minutes to fill a 6 μm structure.

Future Work:

Further investigation into the correct time parameters of the electroplating process is necessary. Once correct time parameters are established, the woodpile photonic crystal structures written into the photoresist can be infiltrated with gold. The resulting gold woodpile photonic crystals are expected to have 3D photonic band gaps. Defects can then be engineered in the crystals to pursue applications such as optical circuitry.

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References:

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[2] M. Deubel et al. (2006). 3D–2D–3D photonic crystal heterostructures fabricated by direct laser writing. Optics Letters, 31, 805-807.

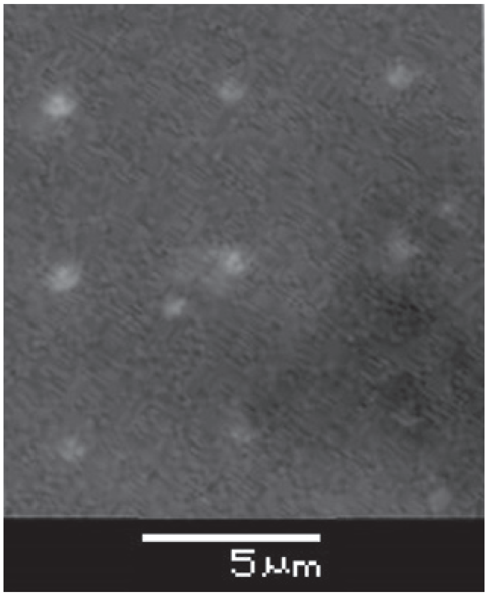

Figure 4: A sample of holes with diameter 100-300 nm, written with 75 μW of output power, stage velocity of .025 mm/s.