

Fabrication of Photonic Crystals for High Temperature Applications

Joseph DeWilde
Chemical Engineering, Oregon State University

NNIN REU Site: Nanofabrication Center, University of Minnesota-Twin Cities, Minneapolis, MN

NNIN REU Principal Investigator(s): Professor Andreas Stein, Department of Chemistry, University of Minnesota-Twin Cities

NNIN REU Mentor(s): David Josephson, Department of Chemistry, University of Minnesota-Twin Cities

Contact: dewildej@onid.orst.edu, a-stein@umn.edu, josep193@umn.edu

Introduction:

Photonic crystals are materials with periodic order on an optical length scale. These materials affect the optical transmission, reflection, and thermal emission of light at specific wavelengths. Within these materials, photons with specific wavelengths cannot propagate in certain directions. Thus, photonic crystals can be used to suppress unwanted thermal emissions (i.e., unwanted heat) or to emit light in a well defined range of wavelengths [1]. For this reason, these materials could be used in more efficient thermophotovoltaic devices.

Theoretical calculations have shown that tungsten photonic crystals with a modified inverse opal structure should be able to alter thermal emission of light [2]. Tungsten photonic crystals were previously fabricated using colloidal crystal templating [3]. Tungsten was used due to its high melting point and refractive index. However, these crystals experienced grain coarsening at temperatures above 1000°C [4]. Three-dimensionally ordered macroporous (3DOM) carbon has been shown to be thermally stable at temperatures up to 2400°C. Thus, the fabrication of tungsten-coated carbon photonic crystals was investigated in hope of fabricating a thermally stable photonic crystal while

maintaining the desired photonic properties of tungsten photonic crystals.

Fabrication and Measurements:

The 3DOM carbon substrate was fabricated by infiltrating a face-centered cubic array of monodisperse poly (methylmethacrylate) (PMMA) spheres, 425 nm in diameter, with a resorcinol formaldehyde polymer resin. The PMMA spheres were then removed and the resin was carbonized by pyrolysis. The pyrolysis was performed under a nitrogen atmosphere with a ramp rate of 5°C/min up to 900°C, with a final dwell time of two hours. A scanning electron microscopy (SEM) image of the resulting carbon substrate can be seen in Figure 1. The structure possesses open windows between the pores with an average diameter of 115 ± 10 nm.

Tungsten was deposited onto the carbon substrate via a chemical vapor deposition technique. 0.2 g of tungsten hexacarbonyl precursor was placed into a flask along with a metal boat containing the carbon substrate. The flask was then treated three times by flushing with nitrogen gas followed by evacuation. The now evacuated flask was then placed into a 400°C sand bath for 20 min. Finally, the flask was cooled to room temperature. The carbon substrates underwent this deposition process three times per sample. Another photonic crystal was similarly manufactured by performing three depositions; each deposition using 0.1 g of tungsten hexacarbonyl precursor.

An SEM image of this crystal is shown in Figure 4, while Figures 2 and 3 show the crystal fabricated with 0.2 g of precursor used per deposition.

Results and Conclusions:

The fabricated photonic crystals possessed sufficient tungsten deposits at depths of about $100 \mu\text{m}$ for a 1 mm thick crystal. This depth corresponds to at least 250 layers of pores. This depth is, in principle, sufficient to exhibit the desired photonic properties.

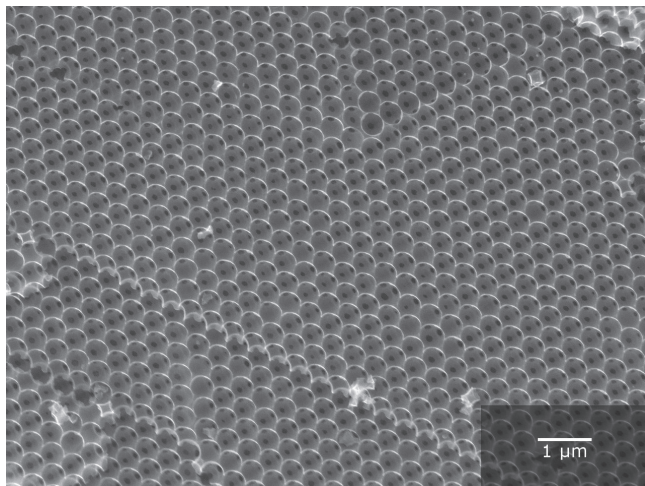


Figure 1: SEM image of a 3DOM carbon substrate. The open windows between the pores have a diameter of 115 ± 10 nm.

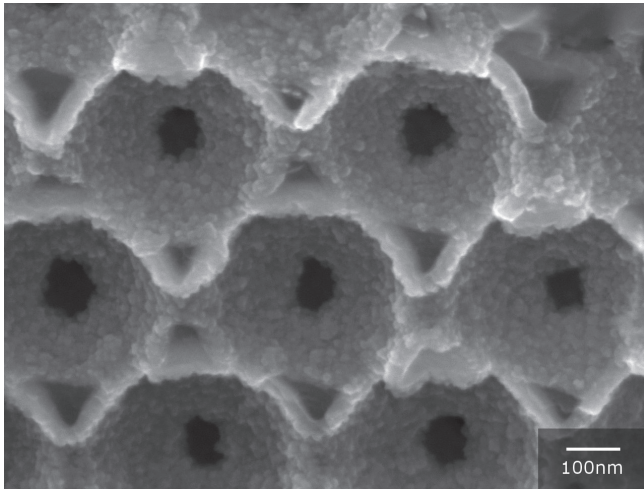


Figure 2: SEM image of tungsten-coated 3DOM carbon pores of the crystal fabricated using 0.2 g of tungsten hexacarbonyl precursor per deposition. The windows between the pores in this image have shrunk due to the tungsten deposition, possessing an average diameter 86 ± 9 nm. In addition, the roughness of the deposition and the coarse grains can be seen.

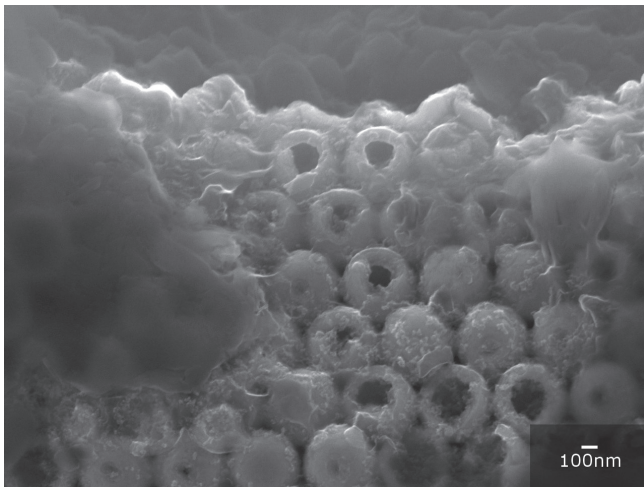
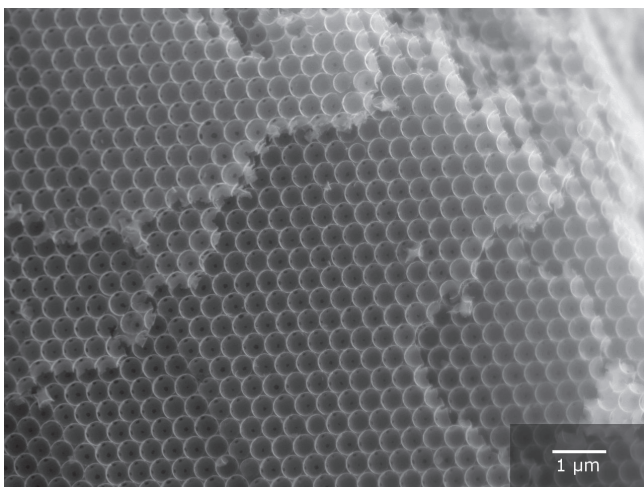


Figure 3: SEM image of tungsten-coated 3DOM carbon pores close to the surface of the crystal fabricated using 0.2 g of tungsten hexacarbonyl precursor per deposition. The pores in this image are blocked by tungsten deposits.



When 0.2 g of precursor were used, the tungsten deposits at some sites close to the surface completely blocked the pores, as shown in Figure 3. By reducing the amount of precursor to 0.1 g, windows between the pores with a diameter of 70 ± 13 nm are formed. This is seen in Figure 4. One can see in Figure 2 that the tungsten deposits constrict the windows between the pores of the photonic crystal.

Before the tungsten was deposited onto the 3DOM carbon substrate, the windows between the pores had a diameter of 115 ± 10 nm. After the tungsten deposition, the windows have been blocked by tungsten and have a reduced window diameter of 86 ± 9 nm. Pore blockages and window constrictions limit the amount of light that can interact with the photonic crystal. Additionally, the tungsten appears to have deposited in coarse grains that can cause light scattering which, in turn, can weaken the photonic properties of the crystal.

Finally, the thickness of the deposited tungsten varied with depth. This inconsistency is undesirable in photonic devices.

With some future improvements, these problems could be minimized, and this synthesis technique could hold promise for the fabrication of thermally stable photonic crystals. Current and future work will focus on increasing the pore size of the photonic crystal as well as providing a more even and disperse distribution of tungsten throughout the crystal.

References:

- [1] Denny et al., Chem. Mater. 2007, 19, 4563-4569.
- [2] Han et al, Phys. Rev. Lett. 2007, 99, 053906/1-4.
- [3] Stein et al., Chem. Mater. 2008, 20, 649-666.
- [4] Denny et al., J. Mater. Chem. 2010, 20, 1538-1545.

Figure 4: SEM image of tungsten-coated 3DOM carbon pores close to the surface of the crystal fabricated using 0.1 g of tungsten hexacarbonyl precursor per deposition. Open windows between the pores with a diameter of 70 ± 13 nm are present.