Fast Turn-around Time, Layer-by-Layer Fabrication of 3D Photonic Crystals

Leo T. Varghese, Li Fan, Yi Xuan, Lin Zhao and Minghao Qi

School of Electrical and Computer Engineering, and Birck Nanotechnology Center
Purdue University, West Lafayette, IN 47907, USA

The ability to manipulate and direct the flow of light in a small volume is of great interest. Three-dimensional (3D) photonic crystals (PhCs) have advantages over their 2D slab counterparts for their robustness to fabrication imperfections and unique capabilities such as confining light in air. However, the limiting factor is their difficulty in fabrication: despite years of development, there has not been a fast, robust and cost-effective fabrication route for 3D PhCs that have low quantities of uncontrollable defects, yet simultaneously allowing designed cavities and waveguides to be introduced at desired locations.

Here we propose and demonstrate the proof-of-concept on a fast-turnaround process to fabricate a so-called "woodpile" 3D PhC (Fig. 1f). We first construct a scaffold from hydrogensilsesquioxane (HSQ), an e-beam resist, and then refill the scaffold with high-index materials such as silicon or TiO_2 through chemical vapor deposition or atomic layer deposition. While the process of refilling was similar to the self-assembly approach, our structure, patterned with e-beam lithography in HSQ, will not suffer from uncontrollable defects and grain boundaries. Moreover, intentional defects could be programmed to create optical cavities.

The process flow of making this woodpile scaffold is shown in Fig. 1. A silicon wafer is first spin coated with HSQ and logs are written using the Leica VB6 UHR-EWF EBL system. To fill the trenches, the sample is spun coated with SU8 and is then placed in vacuum to ensure complete filling of HSQ trenches. We found that without the assistance of vacuum, it is difficult to completely fill the trenches. After hard baking, the resist is then planarized by using CF_4/Ar reactive ion etching (RIE). The dry etching conditions are carefully optimized to etch down the SU8 resist in a consistent fashion to planarize the HSQ logs and the SU8 logs. HSQ is once again spun onto the wafer and the 2nd layer of logs is written, aligned perpendicular to the 1st layer. The processes of SU8 filling and planarization are then repeated to build up the layers.

Figure 2 shows the 1st layer of HSQ and SU8 logs after planarization. As can be seen, the surface is smooth and the whole process could be repeated to form multiple periods. After the desirable number of periods has been achieved, SU8 resist can be removed by piranha or O_2 plasma. Fig. 3a shows our 2-layer scaffold of HSQ where the SU8 was removed via piranha, showing the quality of the planarization and the robustness of the process.

The HSQ woodpile scaffold can sustain high temperatures and thus can be easily refilled with various materials, including amorphous/poly-silicon, titanium dioxide and indium phosphide, in the interstitial space by chemical vapor deposition or atomic layer deposition. This is an advantage over organic based scaffolds which do not normally sustain high temperatures. With a dip in dilute hydrofluoric acid to remove the HSQ scaffold (Fig. 3b), we can obtain a complete 3-D PhC to target wavelengths spanning from the visible to the infrared. The ease of fabrication and fast turn-around time of this 3-D PhC compared to other lay-by-layer techniques offer the possibility to scale up and to realize such a structure for cost and time effective production.

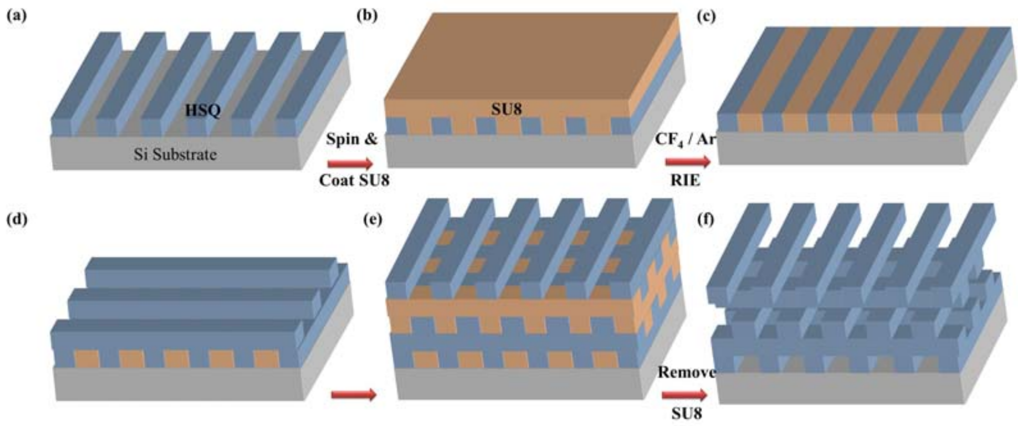

Fig. 1: Schematic of woodpile process flow: (a) HSQ logs patterned by EBL; (b) SU8 spun and filled; (c) Planarization of HSQ and SU8; (d) HSQ logs patterned perpendicular to the bottom layer using EBL; (e) Multiple layers of SU8 and HSQ woodpile structure formed by repeating (a), (b), (c) and (d); (f) final HSQ woodpile scaffold.

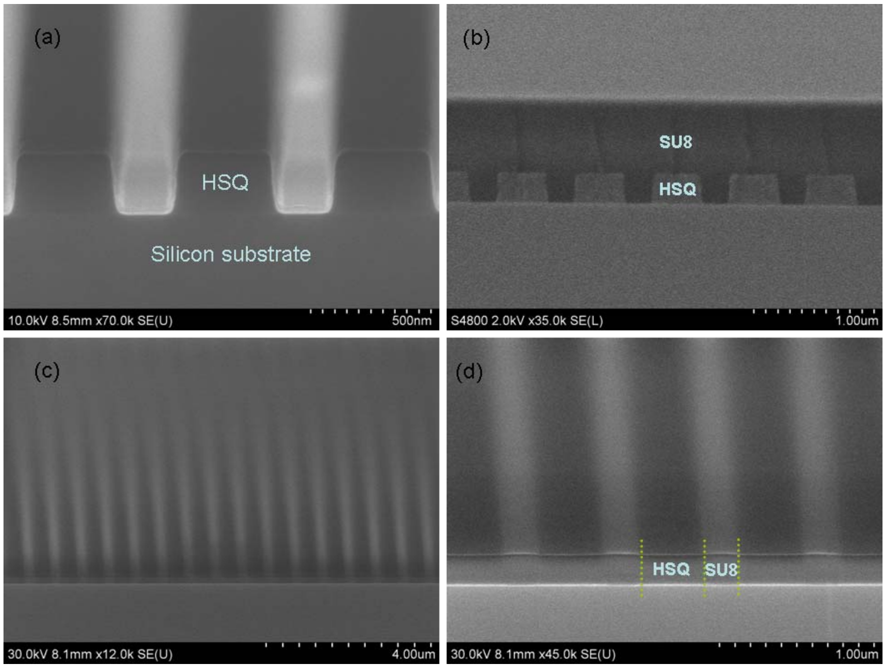

Fig. 2: SEM pictures of the first layer woodpile structure: (a) HSQ logs of 410nm with a period of 650nm; (b) SU8 resist completely filling the trenches; (c) and (d) Planarized 1st layer woodpile of HSQ and SU8 logs.

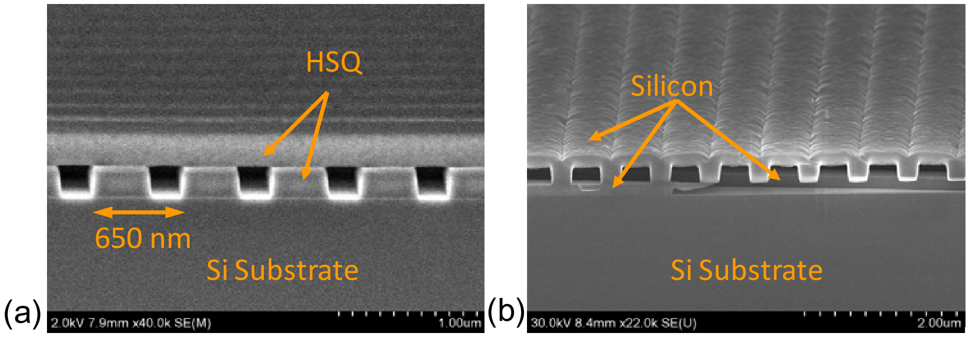

Fig. 3: (a) Cross-sectional SEM micrograph of the 2 layer HSQ scaffold with the first layer SU-8 removed. The 2nd layer HSQ sticks well with the first layer to survive the removal of SU-8 in piranha cleaning, and there is no visible sagging of the 2nd layer HSQ, showing high quality in planarization of the 1st layer. (b) The structure in (a) is refilled with Si at 650 °C and the HSQ is consequently removed by HF dip.