Optics of CMOS compatible 3D photonic band gap crystals

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Abstract

We study optical properties of CMOS-compatible 3D silicon inverse woodpile photonic crystals in the near-infrared. Spectrally overlapping reflectivity peaks for both polarizations and many directions form the experimental signature of a photonic band gap with a relative bandwidth up to 16%.

1. Introduction

Photonic crystals are metamaterials that offer an unprecedented range of applications [1]. The fundamental tailoring of the photonic density of states in photonic band gap crystals serves to control emission of light [2,3] and has the potential to trap photons in tiny cavities [4]. Applications realized with photonic crystals include lasers [5], light emitting diodes [6], and solar cells [7]. Three-dimensional (3D) photonic crystals with a diamond-like symmetry are particularly interesting since they have broad 3D photonic band gaps [8]. Of particular appeal are so-called inverse woodpile photonic crystals [8], because of their conceptual ease of fabrication and robustness to imperfections [9].

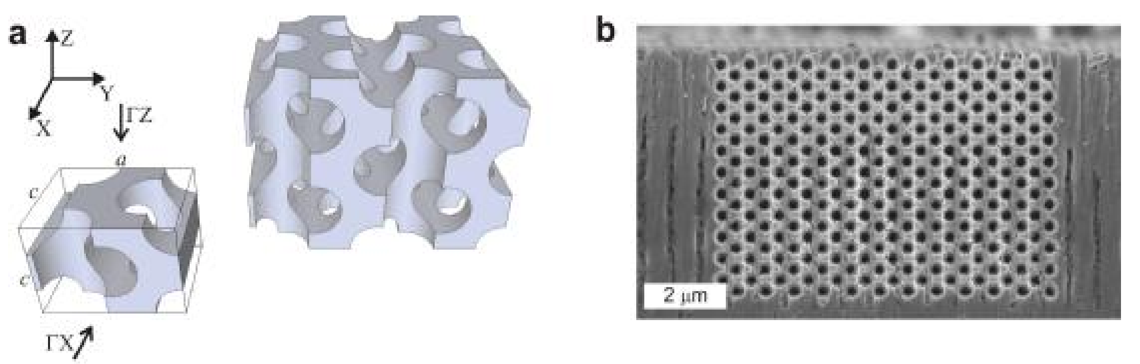

Fig. 1: Structure of silicon inverse woodpile 3D photonic band gap crystals. (a) Schematic representation of the orthorhombic unit cell of a cubic inverse woodpile photonic crystal (left) and a crystal consisting of eight unit cells (right). The structure consists of two identical sets of pores running in two orthogonal sides in the ΓX and ΓZ directions of reciprocal space. (b) Scanning electron microscope image viewed from the ΓX-direction of a cubic inverse woodpile crystal with lattice parameters a = 693 nm, and c = 488 nm ($a/c = \sqrt{2}$) and pore radii r = 145 nm. The crystal is surrounded at left and at right by a 2D crystal.

It is an outstanding challenge to experimentally demonstrate a photonic band gap. Inside the photonic band gap the density of optical states equals zero, which can be investigated via spontaneous emission, see e.g. Ref. [2,3]. To date, such experiments have not yet been performed due to the limited availability of suitable detection methods. An experimental signature for a photonic band gap is obtained if one can demonstrate that stopbands are position-independent and overlap for different directions and orthogonal polarizations. To the best of our knowledge, such a detailed analysis of 3D photonic band gap crystals has not yet been reported.

2. Experimental methods

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Fig. 1(a) shows the orthorhombic unit cell of an inverse woodpile photonic crystal (left) together with a crystal consisting of eight unit cells (right). The structure consists of two identical sets of pores with radius *r* running in two orthogonal directions, where each set has a centered-rectangular lattice with sides *a* and *c*. When $a/c = \sqrt{2}$, the inverse woodpile photonic crystals is cubic with a broad band gap with a relative width up to 25.4% [9]. We have fabricated many inverse woodpile photonic crystals in single-crystal silicon using a newly developed CMOS compatible method, see Refs. [9,10]. Fig. 1(b) shows a scanning electron microscope (SEM) image of one of these crystals.

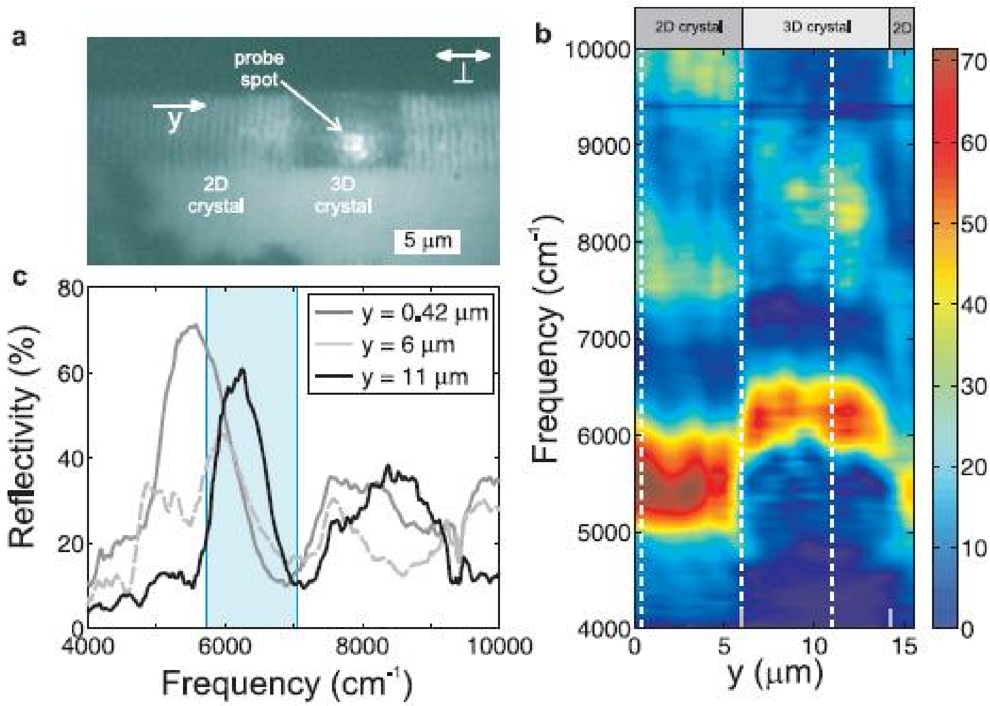

Fig. 2. Position- and frequency-resolved reflectivity for a Si inverse woodpile photonic crystal. (a) Microscope picture of the crystal placed in the setup. The bright spot near the center of the crystal is reflected focused light. (b) Reflectivity as a function of y-position of the spot on the photonic crystal surface. The scan starts on the two-dimensional crystal (y = 0 μm), continues over the inverse woodpile photonic crystal ($6 < y < 14$ μm) and on the two-dimensional crystal. Grey lines on the abcissa indicate the boundaries of the crystal. The white dashed lines indicate positions for spectra shown in (c). (c) Select reflectivity spectra taken at the y-coordinates given by the white dashed lines in (b). The calculated stop gap in the ΓX-direction is marked by the blue bar [12].

To study the crystal's optical properties we performed reflectivity experiments. Light from a supercontinuum white light source (Fianium) is polarized and focused on the crystal with a reflecting objective to avoid dispersion (Ealing). The numerical aperture NA=0.65 of the objective results in an angle-average over 0.44π sr solid angle in air. The diameter of the focused beam is estimated to be 1 μm from experiments on micropillars [11]. Reflected light is collected by the same objective, and the spectrum is resolved using Fourier transform infrared spectroscopy (BioRad FTS-6000).

3. Experimental signature of a broad 3D band gap

Fig. 2 shows the position-dependent reflectivity along the ΓX-direction for polarized light. Fig. 2(a) shows an optical microscope image of the inverse woodpile photonic crystal (dark square) taken during the reflectivity scan, viewed as in Fig. 1(b). The bright spot centered on the photonic crystal is the focal spot of the white light source.

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Fig. 2(b) shows a contour-plot of the measured reflectivity as a function of position. A broad reflectivity peak is observed for the inverse woodpile crystal between 5600 and 6900 cm^{-1} with a high reflectivity of 60%. The representative spectrum is shown in Fig. 2(c). This distinct peak is observed in the same frequency range over the entire 3D crystal surface. The stopband corresponds to the stopgap in the ΓX-direction (blue bar in Fig. 2(c)), which is part of the 3D photonic band gap. The maximum reflectivity is likely limited by surface roughness that scatters light in directions not collected by the objective. The finite thickness of the crystals could also reduce the reflectivity.

We have studied the position-dependent reflectivity spectra for two orthogonal crystal surfaces and two orthogonal polarizations, by taking scans similar to the one shown in Fig. 2. A broad reflectivity peak appears for both directions and polarizations with maxima up to 67%. The stopbands overlap between 5900 and 6900 cm^{-1}, corresponding to a relative bandwidth of 16%. This position-independent overlapping stopband for orthogonal polarizations and crystal directions is an experimental signature for the photonic band gap, with a relative bandwidth up to 16% [12].

In our experiments we have collected spectra over 0.44 π sr solid angle in air. We have measured the reflectivity from two orthogonal crystal surfaces and we observe intense peaks. Therefore, it is most likely that the observed stopbands extend over 0.88 π sr solid angle. By invoking crystal symmetry, our observations correspond to stopbands up to 1.76 π sr solid angle of the inverse woodpile photonic crystal, in other words nearly half of all accessible directions.

4. Conclusions and outlook

We have studied the polarization-dependent reflectivity of 3D silicon inverse woodpile photonic crystals. We observe a position-independent stopband overlapping for orthogonal polarizations and many directions. This is the experimental signature of a broad 3D photonic band gap, which is supported by calculated bandstructures. For good measure, the observed signature of the band gap is no experimental proof yet, since we cannot yet exclude unlikely possibilities of closed or shifted stopbands in certain directions. A true experimental observation of a band gap entails studies where the density of optical states is probed via the emission rate of quantum dots. Indeed, ongoing studies in our group reveal strongly inhibited emission in the frequency range of the band gap.

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