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Attenuation of optical transmission within the band gap of thin two-dimensional macroporous silicon photonic crystals

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The transmissivity within the photonic band gap of two-dimensional photonic crystals of macroporous silicon is reported as a function of crystal thickness. Measurements were carried out for crystals of nominally 1, 2, 3, and 4 crystal layers using a commercial parametric source, with a wavelength tunable from 3 to 5 μm. For wavelengths well within the 3–5 μm photonic band gap, attenuation of approximately 10 dB/crystal layer is obtained, in agreement with calculations based on plane wave expansion methods. For these materials, one should be able to achieve photonic crystal functionality in many applications with very small crystal volumes. © *1999 American Institute of Physics.* [S0003-6951(99)01046-3]

Dielectric structures with periodicities of their dielectric constant on a wavelength scale and with sufficiently high dielectric contrast are capable of exhibiting a complete photonic band gap (PBG).[1,2] This fact has generated a great deal of interest in the past decade and many applications of photonic crystals have been proposed. In order to create novel devices that take advantage of the properties of photonic crystals predicted in Refs. 3–9, precise experimental studies of linear wave propagation in photonic crystals are indispensable. Of further importance are studies that make the connection between the well known properties of infinite photonic crystals and the properties of finite sized crystals used in practical situations.[10–15]

In this letter we investigate, experimentally and theoretically, the transmissivity of a two-dimensional triangular lattice of air cylinders in silicon[16,17] with a lattice pitch of 1.5 μm. In particular, we study the dependence of the transmissivity within the photonic band gap on the number of photonic crystal layers for very thin crystals. We find that the transmissivity is attenuated by approximately 10 dB per photonic crystal layer within the photonic band gap.

The crystals were fabricated in macroporous silicon, which is a type of porous silicon that has been extensively studied during this decade.[18] Macroporous silicon has emerged as an ideal material for the detailed optical characterization of two-dimensional photonic crystals. Its fabrication is based on standard semiconductor processes, allowing one to achieve high geometric accuracies and large ordered arrays of pores with high aspect ratios. Details of the macropore formation process were described in Refs. 16, 17, 19, and 20. Briefly, macropores with pore radii from 0.1 to 10 μm can be formed in moderately doped (100) oriented n-type silicon wafers when anodized in an aqueous hydrofluoric acid solution and illuminated from the wafer backside. If applied to a polished silicon wafer, the pore arrangement becomes random. We created pore nuclei arranged in a two-dimensional (2D) triangular lattice with lattice pitch $a = 1.5$ μm by lithography and alkaline etching. During the pore growth, the macropores inherited the triangular order of the nuclei to form cylindrical pores of radius $r = 0.45$ μm and a typical length of 100 μm (see Fig. 1). After the pore formation, the pore radius was widened using oxidation and wet chemical etching to produce pores of radius $r = 0.68$ μm.

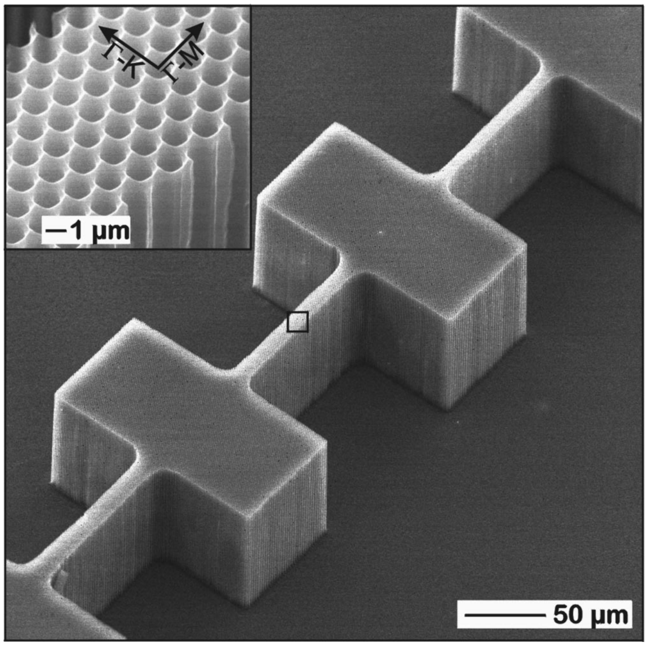

FIG. 1. Scanning electron microscope image of a bar of macroporous silicon, the width of which is periodically altered. The inset is an enlarged view (15×) of the narrower part marked with a square.

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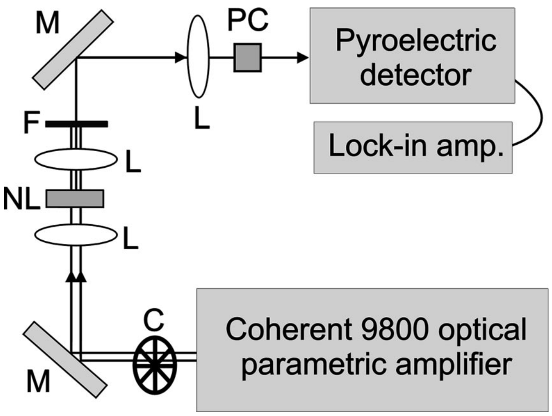

FIG. 2. Simplified schematic of apparatus used to produce tunable, spatially coherent mid-IR light. C=optical chopper; F=long wavelength pass filter; L=lens; M=mirror; NL= AgGaS$_2$ nonlinear crystal; PC=photonic crystal sample.

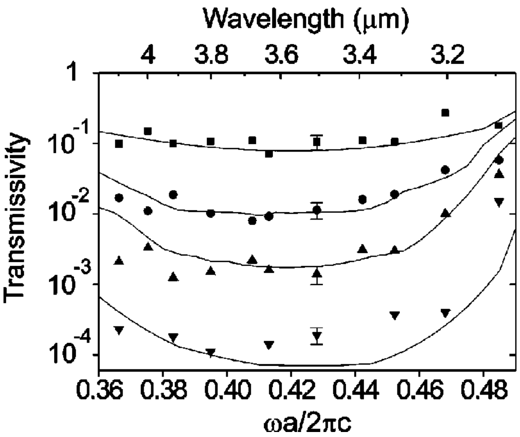

FIG. 3. Measured and calculated transmissivity as a function of frequency within the photonic band gap for samples with small numbers of crystal layers. Solid lines: calculated transmissivity, with 1, 2, 3, and 4 crystal layers. Points: measured transmissivity, with 0.89 ± 0.04 (■), 1.8 ± 0.1 (●), 2.9 ± 0.1 (▲), and 4.2 ± 0.2 (▼) crystal layers.

With the help of the microstructuring technique described in Ref. 21, we created high aspect ratio, well-defined bars of macroporous silicon which allow the coupling of light propagating perpendicular to the pore axes (Fig. 1). The width of the bar has been periodically altered via the phototechnique used in the microstructuring process. The narrow areas consist of distinct numbers of crystal layers, whereas the wide sections provide mechanical stability. The region within the square consists of six crystal layers along the $\Gamma-K$ direction of the triangular lattice. The structures, which possess a height of 100 μm, are fixed on a silicon substrate.

In order to probe the transmissivity of these narrow regions of varying thickness, we required a tunable, spatially coherent source of mid-IR light. This was achieved using difference frequency generation[22] (see Fig. 2). A coherent 9800 optical parametric amplifier was used to produce two tunable near-IR beams through a nonlinear down conversion process. After achieving spatial and temporal overlap of the beams, they were focused onto a 1 mm thick AgGaS$_2$ crystal, which produced light with a frequency equal to the difference of the frequencies of the two incident beams via a second down conversion process. The resulting light was tunable with a wavelength range of $3<\lambda<5$ μm and had a typical bandwidth of approximately 150 nm. The mid-IR beam consisted of approximately 200 fs pulses at a repetition rate of 250 kHz, with an average power of 5 mW (the short pulse width is only relevant in that it allows for substantial down conversion efficiency). After the pump beams were filtered out, the mid-IR light was focused onto the photonic crystal sample using a ZnSe lens with a focal length of 19 mm, producing a spot size of approximately 20 μm. The transmitted light was measured using a pyroelectric detector and a lock-in amplifier with an optical chopper and the transmissivity was obtained by normalizing this to the incident power.

We investigated the dependence of transmissivity on the number of crystal layers for samples with approximately 1,2,3, and 4 crystal layers, oriented in the $\Gamma-K$ direction. A crystal layer for the $\Gamma-K$ direction was defined as the rectangular area within the infinite crystal containing one row of pores. A measure of the number of crystal layers was obtained by counting the number of crystal layers across the sample and performing a weighted average using the Gaussian spatial profile of the focused beam. Using this method the crystal thicknesses were determined to be 0.89 ± 0.04,1.8 ± 0.1,2.9 ± 0.1, and 4.2 ± 0.2 crystal layers. The source was tuned within the **H**-polarization band gap, which spanned approximately $3.1<\lambda<5.5$ μm. The results of the transmissivity measurements are shown in Fig. 3.

Calculations of the transmissivity were made using the method of Sakoda.[10] This method is an extension of the plane wave method for band structure calculation and allows the transmissivity through a finite slab of a 2D photonic crystal to be calculated. In order to account for the spectral bandwidth of the mid-IR pulses used in the experiment and the nonuniform slab thickness, we have convoluted the calculated transmission data with a respective spectral window function and averaged over crystals with slightly different thicknesses. This removes most of the sharp resonances predicted by Ref. 10, leaving behind a relatively smooth spectrum within the photonic band gap. At this point we want to stress that the calculation of the photonic band structure alone is insufficient to provide a qualitative explanation of the measured transmission spectra. The boundary conditions for a finite-sized photonic crystal can lead to gaps in the transmission spectra, even though eigenmodes are present in the spectrum of the infinite crystal. This may occur as a result of the symmetry mismatch between the external plane wave and the eigenmode of the crystal[23] or Fabry–Perot resonances within the crystal.[10]

The results of the transmissivity calculations are shown along with the experimental data in Fig. 3, and show reasonable agreement. Deep within the photonic band gap, the transmissivity drops by about 10 dB per crystal layer, exhibiting an approximate exponential decrease as expected for an evanescently decaying field. We observe a maximum attenuation of 40 dB for only four crystal layers, i.e., 99.99% of the incident light is being attenuated by only 6 μm of photonic crystal (approximately 73% of which is air). The disagreement at the high-frequency band edge is ascribed to the fact that the parameter r/a for the sample could not be measured precisely and had an error of ±0.005. We note that random thickness fluctuations occur along the samples, as well as the periodic thickness fluctuations inherent to the photonic crystal geometry. However, the random scattering caused by these fluctuations cannot alone explain the overall trend in the results as it would lead to a thickness-independent upward shift in the transmissivity that is not reflected in the data. Furthermore, absorption processes do not play a significant role since for our sample, with a doping level $<10^{17}$ cm^{-3}, the free carrier absorption depth in the 3–5 μm wavelength range is of the order of centimeters (much longer than the sample thickness) and interband two-photon absorption cannot occur. Similar transmissivity results are expected for the **E** polarization band gap, although the attenuation per row would likely be less since the band gap is not as wide as for the **H** polarization case. We note that even though the concepts of Brillouin zone and band gap are not applicable due to the loss of discrete translational symmetry, these thin crystals exhibit some of the main features of the infinite crystal.

In summary, we have fabricated high aspect ratio, well-defined bars of macroporous silicon photonic crystals and performed transmission measurements and calculations for very thin crystals with 1–4 layers. The attenuation per layer was found to be approximately 10 dB and the agreement between theory and experiment was good. These results clearly demonstrate that very small volumes of macroporous silicon photonic crystals can be used for practical applications such as waveguides or filters, and for quantum optics experiments.

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