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Optical characterisation of 2D macroporous silicon photonic crystals with bandgaps around 3.5 and 1.3 μm

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Abstract

Transmission measurements were performed on thin 2D silicon photonic crystals (PCs) with 1–4 crystal rows in order to investigate the effect of a finite structure and to obtain an estimate of the crystal thickness necessary to minimize crosstalk between adjacent waveguides. For wavelengths deep within the H-bandgap a strong exponential decay revealing an attenuation constant of 10 dB per crystal row was measured. For opto-electronic applications, the lattice constant of macroporous Si was successfully downscaled from a pitch of 1.5 to 0.5 μm. Reflection measurements performed at these structures show good agreement with corresponding bandstructure calculations exhibiting a complete bandgap around $\lambda = 1.3$ μm. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the last years photonic crystals (PCs) have gained considerable interest due to their possibility to “mold the flow of light”. [2] Light travelling in the plane of periodicity with a frequency within the photonic bandgap is totally reflected by an infinitely extended *bulk* crystal and the electromagnetic field penetrating into the PC is exponentially damped. Since PC devices will contain small, finite crystals, it is necessary to investigate the properties of finite crystals and their relation to the properties of infinite crystals. For a thin slab of a PC the light will no longer be totally reflected but a certain amount of it is transmitted. As thin crystals no longer have long-range periodicity, it is not possible to describe their properties with band structure calculations. Instead, one must rely on transmission or reflection calculations, which indicate that transmission within the bandgap decreases logarithmically with an increase in crystal thickness.

Besides interesting physical properties, PCs possess a considerable potential for opto-electronic applications. The incorporation of linearly extended defects leads to localised photonic states in the bandgap. Light can be guided through these waveguides allowing high integration densities for opto-electronic components. However, coupling

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phenomena have to be understood for the defect design to determine the minimum distance between two waveguides.

Macroporous Si is an ideal system to study the properties of 2D PC due to its high aspect ratio and perfect surface finish. Moreover, the pore diameter can be tuned independently from the lattice constant allowing to measure the whole gap map [2,3]. In the past, the lattice constant of macropores has been constantly reduced from 8 μm [4] to recently 680 nm [5]. In this letter, for the first time, we present structures with a lattice constant of 500 nm exhibiting a complete bandgap around 1.3 μm.

2. Transmission of finite photonic crystals

The fabrication process of macroporous silicon uses a photo-electrochemical etch process [6]. For the transmission measurements on thin slabs, pores with a radius $r = 0.45$ μm and a depth of 100 μm were etched arranged in a triangular lattice with a pitch of $a = 1.5$ μm. After the pore formation the pore radius was widened to $r = 0.68$ μm by subsequent thermal oxidation and wet etching. In order to measure the transmission of light travelling through thin slabs of the 2D PC, bars with varying thicknesses were fabricated. Applying a special microstructuring technique [7] bars containing 1–4 crystal rows have been prepared [8].

Transmission measurements were performed using a pulsed laser setup [8]. The laser source was tuneable within a wavelength range of $3 < \lambda < 5$ μm with a bandwidth of 150 nm, suitable for the analysis of the bandgap for H-polarisation (3.1 μm $< \lambda < 5.5$ μm). Transmission was measured parallel to the Γ–K direction for H-polarisation, i.e., H-field parallel to the pore axis (Fig. 1(a)). For comparison calculations of the transmittance using the Sakoda approach [9,10] were performed and a very good agreement with the experimental results can be observed. Plotting the transmittance on a logarithmic scale against the penetrated crystal thickness, a linear relationship is observed (Fig. 1(b)). This reveals an exponential decay of the transmission with increasing crystal thickness as expected from the case of bulk PC. From the slope a decay constant of about 10 dB per crystal row can be derived for wavelengths deep within the gap ($\lambda = 3.5$ μm). In summary the bandgap of the bulk crystal is already perceptible for one crystal row. This can be ascribed to the strong refractive index contrast between the air pores and the silicon pore walls as well as by the high perfection of the investigated structures. For integrated defect structures, a minimum distance of about 6–8 crystal rows should be considered to avoid crosstalk between neighbouring waveguides.

3. Photonic bandgap around $\lambda = 1.3$ μm

To obtain bandgaps around $\lambda = 1.3$ μm a downscaling of the above described triangular pore lattice is necessary. Therefore the pitch was adjusted to $a = 0.5$ μm. The pores fabricated had a radius $r = 0.18$ μm and a depth of 100 μm.

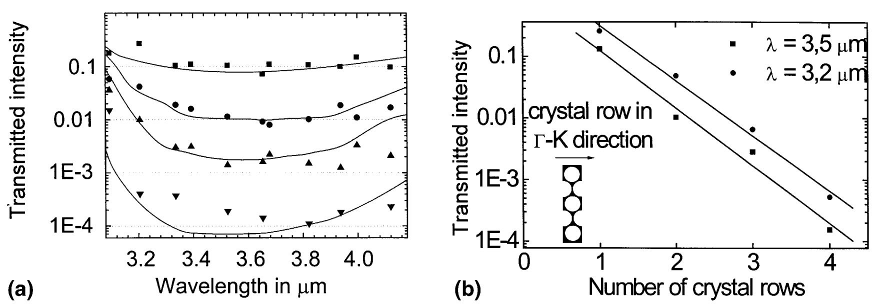

Fig. 1. (a) Measured and calculated transmission for wavelengths within the H-bandgap. Points: Measurements for 1(■), 2(●), 3(▲) and 4(▼) crystal rows, Lines: calculations. (b) Measured transmission as a function of slab thickness for two wavelengths within the bandgap.

During the process they were widened to $r = 0.215$ μm since a complete bandgap opens up at ratios $r/a > 0.4$. To investigate the 2D-bandgaps in the near IR reflection measurements were performed. For this purpose the samples were cleaved along the Γ–K direction to gain access to the side walls of the pores and to get a clean-cut interface. For the reflection measurements an IR microscope equipped with a polarizer and a mirror objective with an opening angle of 30° was used similar to [11]. The spectra were detected by a FTIR-spectrometer containing a tungsten lamp, CaF_2-beamsplitter and a MCT-detector. The reflection for E- and H-polarisation was measured along the Γ–M direction using a gold mirror with a nominal reflectivity of 98% as reference. The resulting sample spectra are shown in Fig. 2. Due to the relatively wide opening angle the measured signal comprises contributions ranging from normal incidence reflection up to 30° off-axis and off-plane incidence reflections. The first-order bandgap investigated here weakly depends on the direction of incidence [11]. Therefore bandstructure calculations performed along the wavevector path Γ–M–K–Γ can still be employed as a good approximation for the interpretation of the reflection spectra. They were computed for $r/a = 0.425$ using 967 plane waves. The shaded spectral ranges represent theoretically expected regions of high reflectivity. They mainly coincide with the bandgaps along the Γ–M direction. However, it has to be considered that total reflection can also appear for bands which cannot be excited by the incoming plane wave because of symmetry reasons [11]. They are drawn as thin lines in the bandstructure (Fig. 2). Fig. 2 reveals good agreement between theoretical predicted ranges of total reflection and experimentally determined high reflectivity regions. Finally from the calculated bandstructure a complete bandgap for E- and H-polarisation can be derived for the spectral range from 1.22 to 1.3 μm, thus incorporating the wavelengths of the second telecommunication window.

4. Conclusion and outlook

Transmission measurements of thin 2D PCs with 1–4 rows revealed a logarithmic decay of 10 dB per crystal row deep within the photonic bandgap. We therefore conclude that thin crystals with only a few rows accurately exhibit the photonic bandgap ascribed to infinite crystals. It can be concluded that a distance of 6–8 crystal rows should be sufficient to suppress crosstalk behaviour of neighbouring waveguide modes in the PC. The described structure was successfully downscaled and fabricated with a pitch of 0.5 μm exhibiting a complete photonic bandgap in the near IR around 1.3 μm. Since this is already close to the absorption limit of silicon, further downscaling of

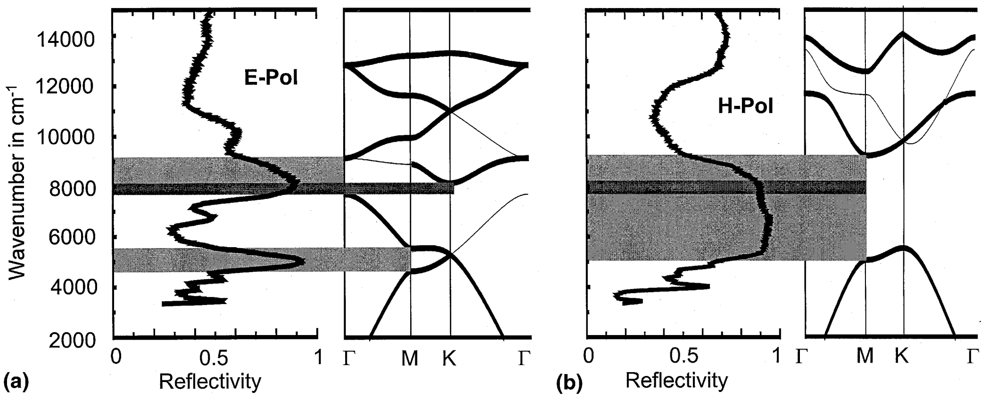

Fig. 2. Measured reflectivity for Γ–M direction and comparison with bandstructure: (a) E-Polarization, (b) H-Polarization. Grey shaded ranges correspond to regions of high reflectivity. Dark shaded range shows the complete bandgap around 8000 cm^{-1} (= 1.25 μm).

the macroporous silicon structure should not be of practical interest. The presented new structures contain several waveguides with distances of 2–7 crystal rows. This will enable us in future to investigate coupling phenomena directly and to verify the presented model for thin slabs.

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