Transmission Characterization of Drilled Alternating-Layer Three-Dimensional Photonic Crystals

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ABSTRACT

We propose a new three-dimensional photonic crystal structure or drilled alternating-layer photonic crystal (DALPC), which can be fabricated by a combination of the deposition of alternating layers of dielectric films and one-time dry etching. Our band calculation predicts that the DALPC has a photonic band gap (PBG) in all directions. We fabricated a Si/SiO_2 DALPC by electron beam lithography, bias sputtering, and fluoride-gas electron cyclotron resonance etching. We measured the light transmission of the DALPC sample in both the in-plane and vertical directions. We observed a transmission minimum around the 1.4-μm-wavelength for all measured directions and TE/TM polarizations, which demonstrated a potential of the DALPC as a three-dimensional PBG material.

INTRODUCTION

Photonic crystals (PC) [1] are now the subject of considerable attention. To pursue a full PBG or a very high Q-value, the PC structure should be three-dimensional (3D). It is relatively easy to construct the self-assembly-based 3D PCs [2,3], but it is very difficult to introduce structural modulations such as a defect to realize device functions. By contrast, device functions can be readily introduced into a lithography-based 3D structure, in which all the PC elements are defined artificially. However, the lithography-based 3D structures reported to date [4-7] require a very complicated fabrication process that needs a large number of alignment processes or sophisticated micromachining, thus making it unrealistic for use in producing commercially viable PCs.

We have proposed a novel three-dimensional photonic crystal, or drilled alternating-layer photonic crystal (DALPC), which can have a full PBG [8,9]. Our DALPC is based on a two-dimensional alternating layer structure and can be deposited by rf-bias sputtering. The automatic shaping effect that occurs in bias sputtering (autocloning) was discovered and developed by Kawakami and co-workers to fabricate 3D PCs [10,11]. We added a nanolithography to the autocloning-based alternating-layer structure to realize a full PBG by creating connectivity in the vertical direction. The main DALPC fabrication processes, namely two-time fine-line lithography, one sequential sputtering deposition, and one-time drilling by dry etching, are based on very mature technologies with few process steps. So the DALPC structure should be highly controllable and easy to fabricate.

In this paper we report the fabrication of a Si/SiO_2 DALPC focusing on the optical communication wavelength (1.5 μm) and measurement of its transmission characteristics.
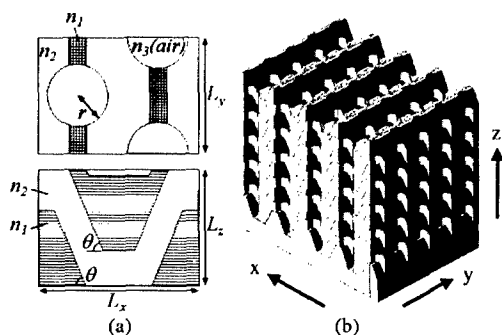
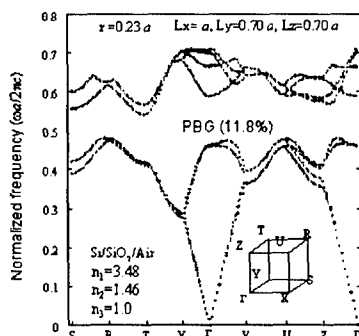**Figure 1.** Schematic depiction of a DALPC.

Figure 2. Photonic band structure of a DALPC obtained from a band calculation by the plane wave expansion method.

DRILLED ALTERNATING LAYER PHOTONIC CRYSTALS

Figure 1 shows a schematic depiction of a DALPC. A DALPC is composed of alternating layers (refractive index: n_1 and n_2) and cylindrical holes (index: n_3) drilled through the entire structure. The corrugated alternating layers can be formed by autocloning. This structure is equivalent to a diamond structure, which can have a full PBG. Figure 2 shows the photonic band structure of a DALPC based on a band calculation obtained by the plane wave expansion method [8]. We considered a Si/SiO$_2$/air DALPC (n_1, n_2, n_3=3.48, 1.46, 1.0) and set the lattice constant at ($x/y/z = 0.7/0.5/0.5$ μm) to give a PBG wavelength of 1.5 μm. As a result, we obtained a PC with a large gap/midgap ratio of 11.8% , which is large enough to enable us to realize various PC-based devices.

EXPERIMENTAL DETAILS

We fabricated a Si/SiO$_2$/air DALPC in which the lattice constant was ($x/y/z = 0.7/0.5/0.3$ μm). The fabrication methods and technologies we used here were the same as those employed in previous report [9]. We used electron beam lithography to form grooves for autocloning the upper PC structure and to make masks for use when drilling air holes. We suppressed the alignment error of the holes we drilled in the alternating-layer structure to as little as 50 nm. The grooves were fabricated on a Si substrate with a thick surface thermal oxide cladding layer (1 μm) and then 4 periods of alternating layers of Si (0.16 μm) /SiO$_2$ (0.15 μm) were deposited by bias sputtering under autocloning conditions. After that we drilled air holes by means of electron cyclotron resonance plasma etching with a CF$_4$-SF$_6$ gas mixture[12], which is suitable for a Si/SiO$_2$ system. We used a Ni mask and minimum substrate bias voltage in the drilling because very we needed a high aspect ratio for the air holes (diameter: ~300 nm, depth : ~1.5 μm) .

We measured the light transmission characteristics of a DALPC sample in the in-plane direction as follows. A flat alternating-layer multilayer was formed around the DALPC so we removed most of it by dry-etching leaving 10 μm-wide mesas that acted as index guiding waveguides. We prepared two input and output waveguides for every DALPC sample. We prepared samples for two directions (Γ-X and

Γ-Y) and with transmission lengths of 2, 5, and 10 periods. To measure the transmission spectrum, we used a wavelength tunable laser as a light source and a tapered-hemispherical-end optical fiber to allow coupling with the waveguides on the sample from a cleaved facet. We detected the output light using a multimode fiber with a large spot size. To obtain the polarization characteristics, we undertook measurements using both TE-polarized and TM-polarized single-mode light as the input light.

We also measured the light transmission characteristics in the vertical direction by preparing large-area (500 x 500 μm) DALPC samples. We used the same experimental setup that we used for the in-plane direction measurement. The light was incident from the rear of the substrate and detected at the top of the DALPC. Here TE polarization means that the electric vector was parallel to Γ-Y and TM polarization means the magnetic vector was parallel to Γ-Y.

RESULTS AND DISCUSSION

Figure 3 shows scanning electron microscope images of a DALPC sample fabricated in this study. Figure 3(a) shows a bird's eye view of the sample, which demonstrates almost exact alignment between holes and autocloning-based structure. Figure 3(b) shows a cross-section of the sample. It is obvious that the drilling reached the bottom of the PC, where the depth was about 1.5 μm. This was very important because with samples where the drilling did not reach the bottom there was no clear structure related to PBG in the in-plane transmittance. However, figure 3(b) also demonstrates the air-holes were far from their ideal cylindrical shape. Especially, the undercut of the top Si layer seemed to be very serious, which was probably caused by reflected radicals at the edge of the Ni mask. We modified etching conditions from those of previous report [9] to drill deeper by increasing the selectivity of Ni to the alternate layers. The undercut seemed to increase as the Ni selectivity increased. Figure 3(b) also shows that the autocloning of the corrugated alternating-layer structure was successfully accomplished
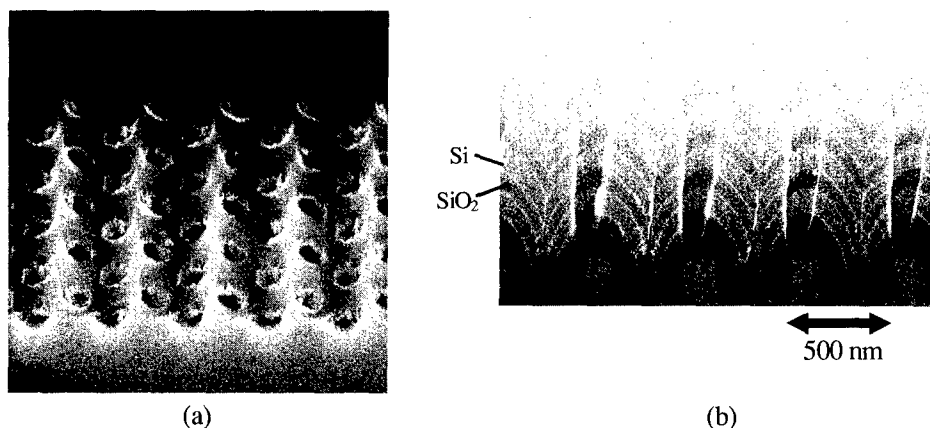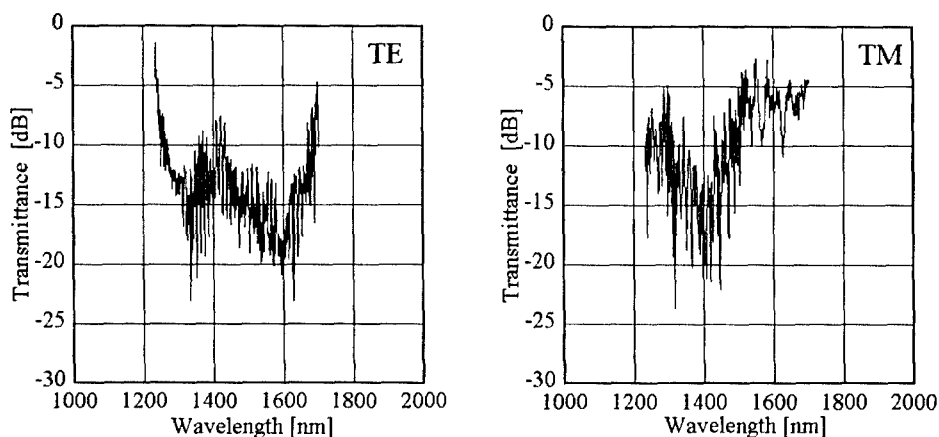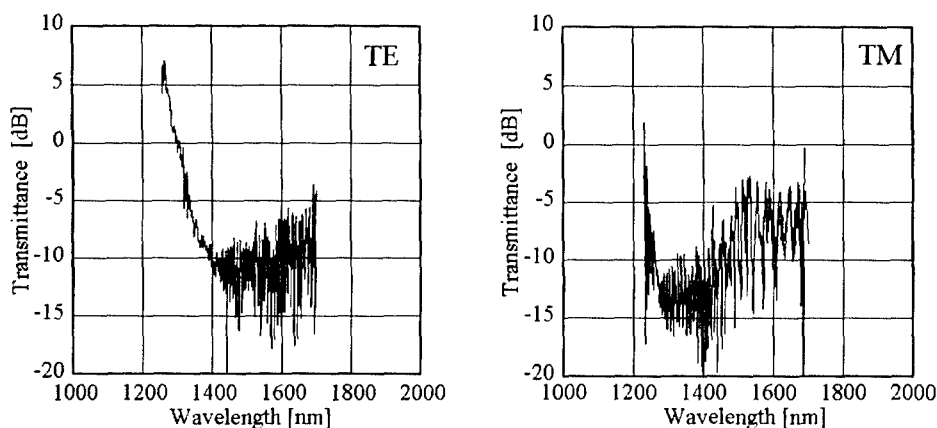

Si

SiO₂

500 nm

(a)   (b)

Figure 3. Scanning electron microscope images of a DALPC sample fabricated in this study. (a) A bird's eye view. (b) A cross-section.

Figure 4. Transmittance of DALPC samples in in-plane directions. The transmission length of the sample was 5 periods.

Figure 4 shows in-plane light transmission spectra of the DALPC at a transmission length of 5 periods. We observed a wide (1.3-1.7 μm) transmission attenuation band for TE polarization in both the Γ-X and Γ-Y directions, where the maximum transmission loss was as large as 20 dB. We also observed an attenuation band for TM polarization although it was somewhat small, which suggested that a full PBG was not achieved in the sample. The attenuation band was considerably wider than what we estimated from the band calculation. When the transmission length was 2 periods the spectra were qualitatively similar but the attenuation band somewhat unclear compared with that of 5 pairs. When the length was 10 pairs the output light was so weak that we could not obtain reliable transmission spectra due to the
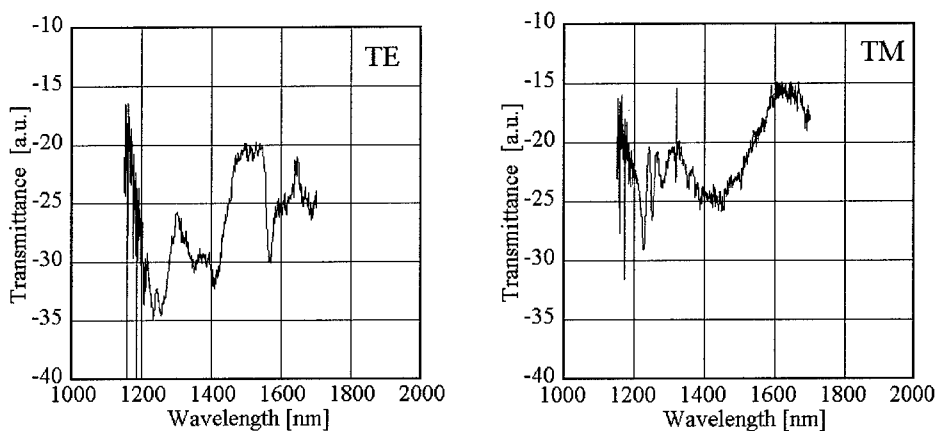
Figure 5. Vertical transmittance of the DALPC sample.

detection limit of our measurement system. Figure 5 shows vertical transmission spectra of a DALPC. Several dips were observed for both TE and TM polarization, although the origin was unclear.

Here it is noted that there was a transmission minimum about a wavelength of 1.4 μm for all directions and polarizations. The correspondence of the transmission minimum in all the measured spectra strongly suggests that a full PBG may open at around 1.4 μm. This roughly corresponds to the PBG center we have calculated for this structure. There was no strong attenuation in the in-plane TE spectra of samples with no drilling . By contrast, in samples with air holes (the same as those of the DALPC sample) drilled into a flat alternating-layer, although the in-plane TE transmission spectra exhibited a attenuation band in the same way as the DALPC sample, there was no clear attenuation in the TM spectra. So we believe the correspondence of the transmission minimum in all the measured spectra to be an inherent characteristic of the DALPC structure. The imperfect PBG, the abnormally wide attenuation band, and the coexistence of plural dips in a transmittance were mainly due to the imperfect ion of air holes which were far from an ideal cylindrical shape. So we are currently examining ways of drilling deeper without causing any deterioration in the air hole shape.

CONCLUSION

We have fabricated Si/SiO_2 DALPCs that were designed to have a full PBG at 1.5 μm and have reported their transmission characteristics in detail for the first time. We found a transmittance minimum at about 1.4 μm in all directions and polarizations measured. This is a very important achievement, despite the fact that the measured sample did not have a full PBG, because it shows the possibility that a realizable DALPC can have a full PBG. We believe that after finding a way to control the shape of the drilling and optimizing the alternating-layer structure formed by autocloning we will be able to obtain a DALPC sample with a large full PBG.

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