Silver-coated silicon pillar photonic crystals: Enhancement of a photonic band gap

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For a two-dimensional lattice of Si pillars it is shown both experimentally and theoretically that a photonic band gap for the light polarized perpendicular to pillars can be strongly enhanced by means of a silver coating of the pillars. A sizable omnidirectional photonic band gap is demonstrated for both square and triangular lattice of silver-coated Si pillars in the near-infrared and visible spectral range. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1541948]

Photonic crystals (PCs) are structures with a periodically modulated refractive index.[1] They have recently triggered a lot of interest in connection with their numerous potential technological applications ranging from antenna substrates to photonic integrated circuits (see Ref. 2 and references therein). PC performance is determined by frequency gaps forbidden for the propagation of the electromagnetic waves, the so-called photonic band gaps (PBGs). When the refractive index modulation increases, the range of the angles of incidence displaying PBG becomes wider and at a sufficiently strong refractive index modulation, a PC can exhibit PBG for all angles of incidence, the so-called omnidirectional PBG.

Usually, only nonmetallic materials are used for the fabrication of PCs operating in the spectral range of a material transparency. However, it has recently been shown theoretically in both two[3] and three dimensions[4,5] (2D and 3D, respectively) that metals can strongly improve PBG properties of a PC without significant losses in the gap region.[3–5] Experiments in this field, especially in the near infrared and visible, remain behind theory. PBG properties of the 3D metallo-dielectric PCs made of silver-coated dielectric spheres[5] and chrome spheres[6] have only been experimentally studied in the GHz spectral range. For approximately the same spectral range, an interesting 2D PC consisting of both dielectric and metal cylinders was demonstrated.[7] Only very recently, a 3D metallo-dielectric PC has been studied at infrared wavelengths[8] PBG properties of 2D metallo-dielectric PCs have not yet been examined in the infrared and shorter wavelengths. A 2D PC is suitable for the application in on-chip devices, and therefore study of PBG properties of such a 2D PC is of great practical value.

The goal of the present work is to construct a 2D metallo-dielectric PC and to study its PBG properties. Our main idea is to use a regular 2D lattice of Si nanopillars as a template for the preparation of a metallo-dielectric 2D PC slab. Si pillars are coated with silver and the transmission and reflection spectra of PC of so-prepared Si@Ag pillars are studied.

Recently, a 2D PC slab of Si pillars sandwiched between two cladding Ag layers has been fabricated and its photonic properties have been studied.[9,10] This system displays high transmittance for the light polarized perpendicular to the pillars (TE mode), but the light polarized parallel to the pillars (TM mode) is quite lossy because of the strong surface plasmon absorption of the Ag claddings. Therefore, in the following we only concentrate on the TE mode. However, for a 2D PC of Si pillars, a TE mode PBG is too narrow, practical value of this PC being doubtful. Nevertheless, as shown in this work, an enhancement of a PBG for the TE mode due to the Ag coating of pillars renders this system useful for applications.

The method of preparation of a regular 2D lattice of Si nanopillars has been reported in Ref. 11. Si pillars were prepared using the self-formed etching mask method combined with the electron beam lithography. In this work, Si pillars have been coated with Ag using a sputtering technique. In Fig. 1(a), the scanning electron micrograph (SEM) of the square lattice (period $a \sim 500$ nm) of Si pillars (diameter of pillar $2r(\mathrm{Si}) \sim 50$ nm) is shown. The same lattice after silver coating (diameter of pillar with coating $2r(\mathrm{Si+Ag}) \sim 150$ nm) is shown in Fig. 1(b).

In Fig. 2(a), calculated (layer Korringa–Kohn–Rostoker method, see Ref. 12) transmission spectra of the square lattice ($a = 500$ nm) of silver-coated Si pillars are shown as a function of the silver coating thickness. The TE-polarized light was propagated in the [0,1] lattice direction, with the lattice consisting of 40 rows of pillars. Our numerical simulation has been performed for infinitely long cylinders. Experimental values of the dielectric constant of both Ag and Si[13] have been used in the calculation. Keeping the radius of Si pillars fixed to $r(\mathrm{Si})/a = 0.05$, we varied $r(\mathrm{Si+Ag})/a$. Figure 2(a) shows that PBG broadens dramatically with increasing $r(\mathrm{Si+Ag})/a$. In addition to the PBG transmittance dip, a strong and sharp absorption band appears at 1.5–1.7 eV in the spectrum of the 2D PC of Si@Ag pillars. This band is associated with the surface plasmon of Si@Ag pillars.

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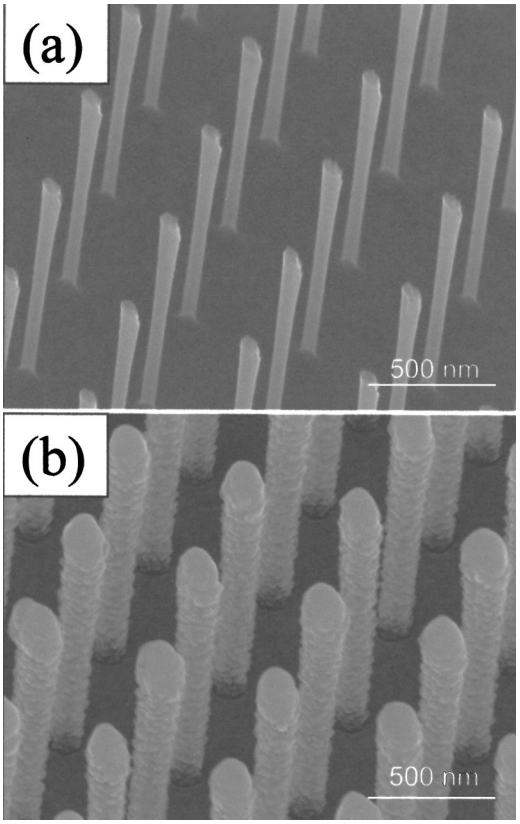

FIG. 1. Scanning electron microscope (SEM) image of the square lattice of Si pillars with diameter of 50 nm and period of 500 nm before Ag coating (a) and after Ag coating (b), the diameter of Si@Ag pillars being ~150 nm.

Measurements of the transmission and reflection spectra of our Si@Ag pillar lattices were made using a microoptical technique similar to those for Si pillar lattices. Details of the spectra measurement are described in Refs. 9, 10 (transmission) and Refs. 9, 14 (reflection). Renishaw Ramascope

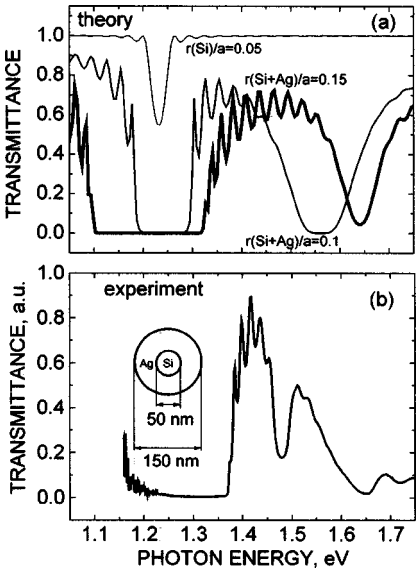

FIG. 2. (a) Calculated transmittance spectra of the square lattice ([0,1] or Γ-X direction) of Si pillars with $a=500$ nm and $r(\mathrm{Si})/a=0.05$: Si pillars–thin line, Si@Ag pillars with $r(\mathrm{Si+Ag})/a=0.1$–intermediate line and Si@Ag pillars with $r(\mathrm{Si+Ag})/a=0.15$–bold line. Cylinders were assumed infinitely long in the calculation. (b) Experimental transmittance spectra of the square lattice of Si pillars with $a\sim500$ nm, $r(\mathrm{Si})/a=0.05$ and $r(\mathrm{Si+Ag})/a=0.15$.

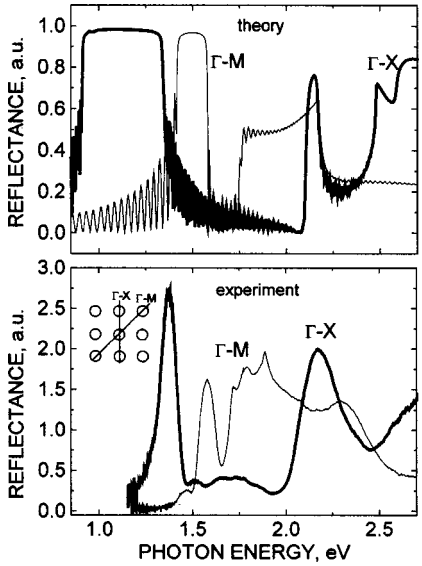

FIG. 3. Calculated (top) and experimental (bottom) reflectance spectra of the square lattice of Si@Ag pillars with $a=500$ nm, $r(\mathrm{Si})/a=0.05$ and $r(\mathrm{Si+Ag})/a=0.25$ for the Γ-X and Γ-M lattice directions for normal incidence of light on the PC faces.

equipped with microscope, charged coupled device camera, and single monochromator was used. Samples for reflection spectra measurement for both square and triangular lattices consisted of 200 rows of pillars with 200 pillars in each row. Samples for the transmission spectra measurement consisted of the 40 rows of pillars with 200 pillars in each row.

For the transmission spectra measurement, pillar lattice was sandwiched between two silver layers as in Refs. 9, 10. In Fig. 2(b), the transmission spectrum of Si@Ag pillar lattice for the TE polarization and the [0,1] lattice direction is shown. In good agreement with theoretical calculations, 2D PC of Si@Ag pillars displays quite broad PBG. The experimental spectrum displays plasmon bands as well as a theoretical one. Some discrepancies in position of the PBG and plasmon features in experimental spectrum compared to the theoretical one can be explained by the finite height of pillars ($\sim1.1\ \mu$m).

For potential applications of 2D pillar PC slabs, it is important to obtain an omnidirectional PBG (o-PBG) for the TE mode. It is easy to show that an o-PBG can be obtained for both square and triangular lattices of the Si@Ag pillars. In Fig. 3, theoretical and experimental reflection spectra of the square lattice of Si@Ag pillars ($a=500$ nm; $r(\mathrm{Si})/a=0.05$; $r(\mathrm{Si+Ag})/a=0.25$) for two different lattice directions are shown. As one can see, there is an overlap of the reflection PBG bands for different directions in the range of 2 eV. This is a clear indication of the existence of an o-PBG (the second PBG). Although agreement between theory and experiment in Fig. 3 is good, one can notice that, instead of the broad reflection band in the range of 1.0–1.3 eV, experimental spectrum for the Γ-X direction displays a sharp band corresponding to the high-energy edge of the theoretical band. The reason for this is the finite height of pillars, reflection for the wavelengths comparable and longer than the height of the pillars being strongly decreased.

In Fig. 4, the theoretical and experimental reflection spectra are shown for the triangular lattice of Si@Ag pillars. The result is similar to that for the square lattice. There is an

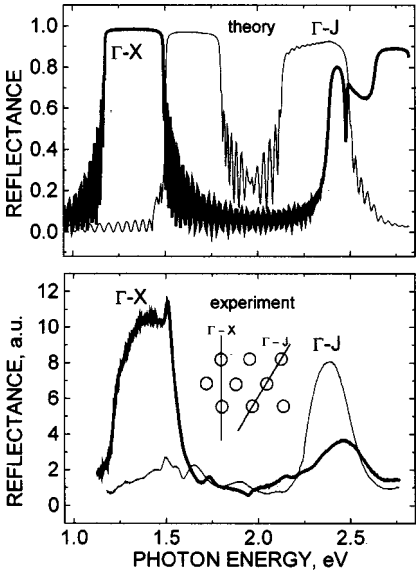

FIG. 4. Calculated (top) and experimental (bottom) reflectance spectra of the triangular lattice of Si@Ag pillars with $a=500$ nm, $r(\mathrm{Si})/a=0.09$ and $r(\mathrm{Si+Ag})/a=0.18$ for the Γ-X and Γ-J lattice directions for normal incidence of light on the PC faces.

overlap of the reflection PBG bands for different directions in the range of 2.5 eV indicating the existence of an o-PBG. For both triangular and square lattices, reflection in the o-PBG range is less than 1.0 because of the Ag absorption. Optimization of the lattice and pillar parameters can minimize the absorption of these PCs.

It is especially important to obtain an o-PBG for the telecommunication wavelength of 1550 nm. Although we did no experiments in this spectral range, our calculations show that o-PBG with up to $\sim 20\%$ relative width (PBG width to midgap frequency ratio) can be opened for the triangular lattice of Si@Ag pillars. In Fig. 5, relative PBG widths of the triangular lattices with fixed $r(\mathrm{Si+Ag})=1100$ nm and varying ratios $r(\mathrm{Si+Ag})/a$ and $r(\mathrm{Si})/a$ are shown. Obviously, o-PBG width of 20% is almost independent of $r(\mathrm{Si})/a$ at rather small values of $r(\mathrm{Si})/a$. However, even small changes in $r(\mathrm{Si+Ag})/a$ can decrease the o-PBG width.

To summarize, we have demonstrated the 2D metallo-

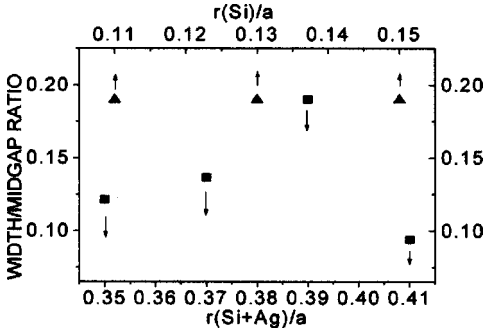

FIG. 5. Relative PBG width of the triangular lattice of Si@Ag with $r(\mathrm{Si+Ag})=1100$ nm. Triangles are for $r(\mathrm{Si+Ag})/a=0.39$ and different values of $r(\mathrm{Si})/a$. Squares are for fixed $r(\mathrm{Si})/a=0.13$ and varied $r(\mathrm{Si+Ag})/a$.

dielectric PC for the near-infrared and visible spectral range. We have prepared Ag-coated Si pillar lattices and demonstrated enhancement of PBG due to the Ag coating of the pillars. Omnidirectional second order PBGs for the TE mode for both square and triangular lattices of pillars were obtained.

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