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Antireflection and Enhanced Absorption in Tapered Silicon Photonic Crystals

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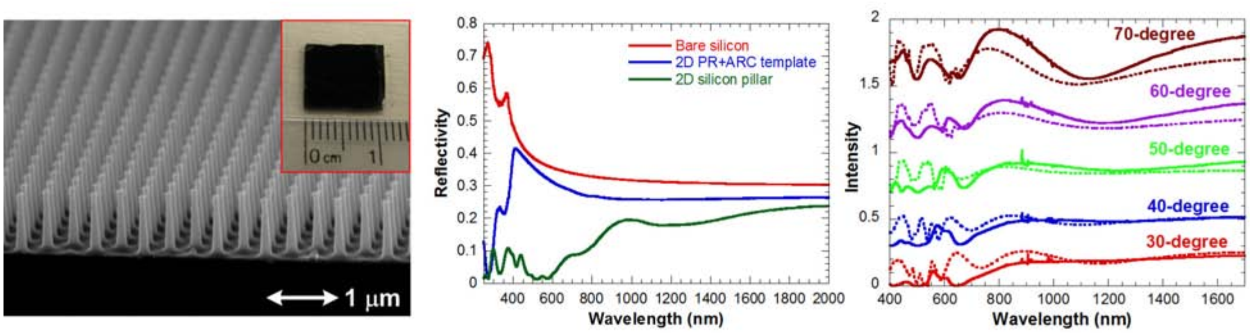
Abstract: Tapered silicon photonic crystals provide a broad and wide-angle antireflective window and strong optical resonances for enhanced absorption for TE- and TM-polarized light, respectively, showing the potential for improving the performance of photovoltaic devices.

OCIS codes: (050.5298) Photonic crystals; (160.4760) Optical properties ; (220.4241) Nanostructure fabrication

1. Introduction

Two-dimensional photonic crystals (2D PhCs) have been extensively studied as the building blocks to realize functional devices for optical networking, image display, bio-medical sensing, and photovoltaic applications. Recently, as an emerging field, disordered nanopillar arrays are used to improve the efficiency of solar cells through its reduced optical reflection, enhanced absorption and enhanced carrier collection efficiency [1, 2]. Tapering of nanopillars could further improve the antireflection and enhanced absorption properties [2, 3]. To our best knowledge, the effects of the photonic bandgap (PBG) property of 2D PhCs on the reduced optical reflection and/or enhanced absorption are rarely discussed in the literature. In our previous work, we developed a technique for directly transferring holographically generated photoresist/antireflection coating (PR/ARC) patterns into silicon by using a novel single-step deep reactive ion etching (SDRIE) technique to realize 2D silicon photonic crystals with a high aspect ratio, good uniformity and a tapered sidewall profile without scalloping [3]. However, the optical property of such structures was not resolved yet. In this work, we characterize the resultant PhC samples by using a spectrophotometer and an angle-variable spectroscopic ellipsometer. Reflection spectra of this PhC structure under different incident angles and polarizations are measured for observing its antireflection and optical resonant effect. Optical resonance is mainly due to the existence of PBG inside this material. A spectroscopic ellipsometer is also used for further verifying this unique PBG phenomenon. We also analyze the PhC structure with rigorous coupled-wave analysis (RCWA) method, taking the dispersion and absorption of materials into account, for comparison with the experimental data. It is found that such resonance will enhance the absorption inside the silicon PhC structure, thus increasing the efficiency as applying this structure for solar energy conversion.

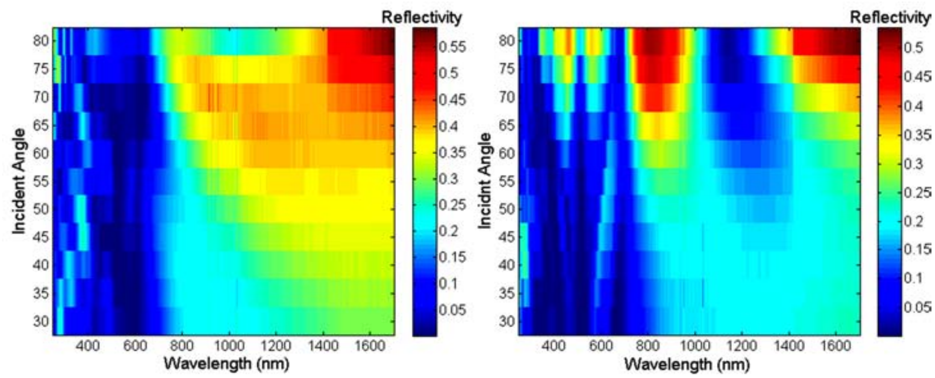


(a) (b) (c)

Figure 1 (a) SEM picture and photograph of resultant silicon photonic crystal sample (b) Measured optical reflection spectrum of bare silicon, 2D PR/ARC templates on silicon, and tapered silicon PhCs with 8-degree incidence (c) Measured (solid) and calculated (dash) reflection spectra at different incident angles along the ΓM-direction of hexagonal silicon PhCs for TM-polarization. The curves are offset for clarity.

2. Sample preparation

2D periodic templates with a hexagonal lattice of elliptical geometry are realized using the holographic lithography with a double exposure and a 60-degree rotation of samples over a large area. The purpose of using the hexagonal lattice is to obtain a broader PBG area; even though its geometry is elliptical. With an optimized process procedure, we have shown that the width of the resultant patterns can be adjusted and fine tuned by controlling the total exposure energy and development time [4]. We developed a SDRIE process with a controlled mixture of Ar/SF6/C4F8 gas to attain smooth and controllable sidewalls while simultaneously keeping the advantages of high etching rate (~222 nm/min) and high mask selectivity (~85:1). Polymer deposition for protecting lateral sidewalls and deep silicon etching proceed simultaneously in SDRIE process. The slope of etched sidewall profile can be easily controlled by engineering the composition of gas mixture [3]. A tall 800 nm silicon photonic crystal with a positive slope (+65 nm/ m) of sidewall profile, smooth sidewalls, an averaged ellipticity of 1.6228, and a filling factor (radius-to-period ratio) of 0.146 is realized as shown in Figure 1(a). The resultant PhC sample is highly uniform over the entire sample area, around 1 cm^2. The size of PhC patterns is limited by the exposed area of the holographic setup.



(a) (b)

Figure 2 Measured reflection spectra of tapered silicon photonic crystals along ΓM-direction under different incident angles for (a) TE- and (b) TM-polarization

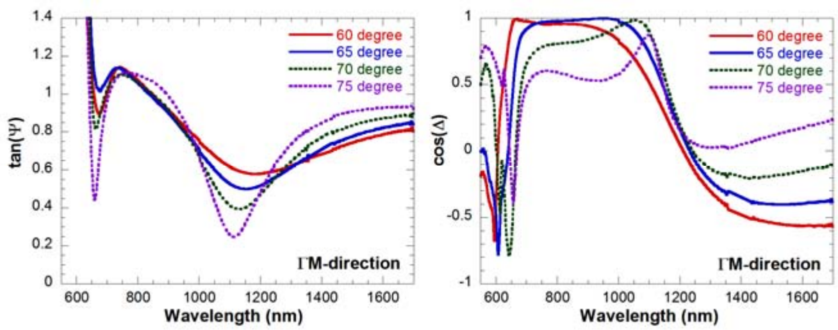
3. Optical characterization

Figure 1(b) shows the close-to-normal (8-degree) incident optical reflection spectra of bare silicon, 2D PR/ARC templates on silicon, and tapered silicon photonic crystals that are measured by using a spectrophotometer. Lower reflectivity of 2D PR/ARC templates is due to its lower effective index which serves as a buffer layer between air and silicon substrate. Dips at around 365 nm of wavelength as well as in the ultraviolet (UV) region are due to the absorption characteristic of the ARC. For the tapered silicon photonic crystal, lower reflectivity is due to its deeper sub-wavelength structure and gradually changed effective index between air and silicon. Slight optical resonant effect can be seen at the wavelengths of 1200 nm, 550 nm and UV region. By combining those effects, the overall reflectivity of this nanostructure is below 10% in the entire UV-to-visible region and is only around 2% in the wavelengths between 500 nm and 600 nm. It is believed that the TM resonance in this structure is mainly due to the existence of PBG which causes dips in the angular reflection spectra. In order to verify this effect, the PBG location is calculated by solving the Maxwell equation with rigorous coupled-wave analysis (RCWA) method, taking both dispersion and absorption of materials into account. The geometry of the silicon PhCs for RCWA simulation is set according to the real structure as shown in Figure 1(a) except the slope of sidewalls which is set to be vertical in the simulation model. Figure 1(c) compares the measured and calculated reflection spectra under different incident angles and polarizations along the ΓM-direction of the hexagonal silicon PhCs for TM-polarization. The curves are offset for clarity. Similar behavior is found along the other symmetric points of this structure. From the dips in the measured angular reflection spectra, the PBGs locate at the wavelengths around 650 nm and 1100 nm. There is a good agreement between the experimental and calculated spectra, although measured reflection spectra show weaker and much complex resonances. We believe that this is due to the tapered sidewall of the real structure which reduces the resonant effect.

Figure 2 shows the measured reflection spectra of tapered silicon photonic crystals along ΓM-direction under different incident angles. Optical characteristics of silicon PhCs are totally different than that of bare silicon. For TM-polarization, antireflective effect and slight optical resonance happen for smaller incident angles. However, the resonance becomes stronger for larger incident angles since now more light can see the periodicity of this structure, as shown in Figure 2(b). Similar resonance phenomenon is found along all symmetric points of this PhC structure.

The resonance will help to trap the light inside the PhC structure and thus enhance the absorption. Contrary to the strong resonance for the TM-incidence, only slight resonance is found for TE-incidence, as shown in Figure 2(a). This is partially due to the lack of full PBG for TE-polarized light in this tapered nanopillar structure. On the other hand, this tapered silicon PhC structure with a gradually changed effective index now serves as a good buffer layer between air and silicon substrate for the TE-polarized light, resulting in a broad and angular-insensitive antireflective window between 400 and 700 nm of wavelength. The measured reflectivity at 40- and 70-degree of incident angles in this antireflective window is below 1% and 3%, respectively. As compared to the high reflectivity of bare silicon (around 45% and 70% at 40- and 70-degree of incident angle) for the same polarization, this material will be able to transmit more TE-polarized light into the silicon in both normal and angled incidence.

Spectral ellipsometry is also used for further verifying this unique PBG phenomenon. The measured ellipsometry parameters along the ΓM symmetry direction of hexagonal silicon PhCs under different incident angles are shown in Figure 3. Parameters tan( ) and cos(Δ) represent the reflection ratio between the TM and TE polarizations and the phase difference through the material-light interaction, respectively. For oblique incidence, the reflection of different polarized light would manifest differently in their corresponding spectra. Theoretically, the reflection caused by the TM photonic bandgap would appear as a dip and a steep slope in the tan( ) and cos(Δ) spectrum, respectively. We indeed find similar phenomenon at the wavelengths of 650 nm and 1100 nm along the symmetry points, verifying the existence of full TM PBGs inside the PhCs.



(a) (b)

Figure 3 Measured spectra of PBG ellipsometry parameters (a) tan( ) and (b) cos(Δ) along ΓM symmetry direction of the hexagonal silicon PhCs under different incident angles

3. Conclusions

Reflection spectra of this PhC structure under different incident angles and polarizations are measured for observing its optical characteristics. Strong optical resonances for TM-mode are found in this structure, which is mainly due to the existence of full PBGs inside the material. This PBG phenomenon is further verified by the spectroscopic ellipsometry. Such strong resonance will greatly enhance the optical absorption inside silicon PhCs. On the contrary, with a gradually changed effective index, this structure serves as a good buffer layer for the TE-polarized light between air and silicon, resulting in a broad and angle-insensitive antireflective window in the visible region. With the help of both antireflective and absorption-enhanced characteristics in this structure, we believe that this PhC material can be used for various applications, including but not limited to the enhancement on the conversion efficiency of photovoltaic devices.

4. References

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