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Phys. Status Solidi RRL **7**, No. 7, 481–484 (2013) / **DOI** 10.1002/pssr.201307151

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Surface Tamm states in a photonic crystal slab with asymmetric termination

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Received 10 April 2013, revised 29 April 2013, accepted 30 May 2013
Published online 6 June 2013

Keywords macroporous silicon, electrochemical etching, photonic crystals, surface Tamm states

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The reflection and transmission spectra of a finite thickness 2D photonic crystal slab (PCS) based on macroporous silicon are investigated. Periodic photonic crystal region is separated from air by homogeneous silicon interfacial layers. These interfacial layers at the silicon/air boundary being defects of the photonic crystal lattice, define the properties of surface Tamm states in the photonic stop-bands (PSBs). It is demonstrated experimentally and theoretically that the reflection spectra of a structure with different thicknesses of the interfacial layers on both sides of the PCS depend on the illuminated side. At the same time, the transmission spectra are identical for both light directions in agreement with the reciprocity principle. Analysis shows that the dependence of the reflection spectrum on the side of light entrance is due to scattering losses in the real structure.

1 Introduction A specific feature of photonic crystal (PC) structures with a limited number of periods, fabricated by simultaneous electrochemical etching of macropores and trenches in silicon [1], is the presence of an unstructured silicon layer at the interface with air. Under certain conditions, this interfacial layer can give rise to localized surface states of the Tamm type [2–6], and strongly affects the optical characteristics of a structure. In particular, the reflection and transmission spectra for light incident onto the PCS in the direction perpendicular to the pore axis may have resonance states in the photonic stop-bands (PSBs) [1, 4]. In the absence of scattering losses, the magnitude of surface states in both reflection and transmission spectra is small, being only due to the finite thickness of the PC. In the presence of losses, the amplitude of dips in reflection spectra grows substantially. The surface states in a symmetric PC structure with equal interfacial layers were analyzed in [4]. It was found that the spectral position of such resonance states depends on the thickness of the interfacial layer. Calculation of the electromagnetic field distribution in the near-field zone at the surface-mode frequency indicated a surface standing wave near the outer row of pores.

The goal of the present study was to examine the optical characteristics of an asymmetric PCS structure having interfacial layers of different thicknesses.

2 Samples and methods Figure 1 shows the structure under study, constituted by 5 rows of pores "cut out" in the Γ–K direction of the triangular lattice of macroporous silicon. The lattice period is $a = 3.75$ µm, and the pore filling ratio of the pore radius r to the period, $r/a = 0.43$. The interfacial layers are characterized by the distance from the centers of the outer row of pores to the edge of the structure (see Fig. 1b). These distances are $w_1 = 2.57$ µm $= 0.685a$ and $w_2 = 2.07$ µm $= 0.552a$. The structures were fabricated by joint electrochemical etching of deep macropores and trenches in n-Si (100) under backside illumination of the wafer. A more detailed description of the fabrication technique can be found in [1, 7, 8].

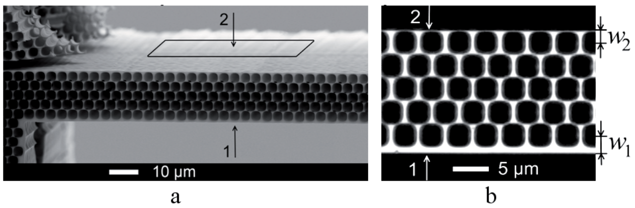

Figure 1 a) Scanning electron microscopy (SEM) and b) optical microscopy images of PCS. The interfacial layer thicknesses are w_1 on side 1 and w_2 on side 2.

Polarization dependences of the reflection coefficient R and transmission coefficient T of the PCS were measured at a spectral resolution of 8 cm^{-1} with a Digilab FTS 6000 Fourier spectrometer equipped with a UMA 500 IR microscope. Light polarized along (TM polarization) or across (TE polarization) the pore axis was focused onto the side wall of a structure in the form of a 50 × 50 μm^2 square (Fig. 1a). The incident light formed a cone with an axis normal to the illuminated surfaces. The cone is composed of inclined beams within the range 10°–30°. The experiment was performed so that the structure was illuminated on either side 1 or side 2. The spectral dependences were calculated by the Fourier modal method in the scattering matrix form [9, 10]. The losses for the Rayleigh scattering of light on inner pore surfaces were accounted for, as it was done in [11], by introduction of a complex refractive index for silicon, $n_{\mathrm{Si}} = 3.42 + ki$. To simplify the simulation procedure, we used a fixed value of the incident angle θ, varied in XZ plane under the fitting. Two other parameters were varied in the fitting: namely $r/a = 0.42$–0.44 and $k = 0$–0.05.

3 Experimental results Figure 2 shows experimental and calculated reflection and transmission spectra for TE- and TM-polarized light for a PCS illuminated from sides 1 and 2. Let us consider first TE polarization. It can be seen in Fig. 2a, b that if light enters from side 1, the first TE photonic stop band shows a single resonant reflection dip at a frequency $\nu = 1050$ cm^{-1}. If light enters from side 2, there are no dips in the PSB. In fitting, the best agreement with the experiment was obtained for both light incidence directions at $r/a = 0.43$, $k = 0.025$, and $\theta = 15°$. It can be seen in Fig. 2c, d that, irrespective of the side from which light enters the structure, the experimental transmission spectra remain the same (the difference is on the level of measurement noise). The calculated transmission spectra are shown in the same plot and are also practically identical for both directions of light incidence. The peaks in the transmission spectra corresponding to surface modes have an exceedingly small amplitude. To show these modes, we additionally presented the calculated transmission spectrum on the logarithmic scale (Fig. 2d).

4 Calculations As already noted, the existence of surface states is due to the homogeneous interfacial silicon layers with thicknesses $w_{1,2}$ on outer boundaries of the structure. Let us analyze the origin of the resonances in the reflection spectra for the case $k = 0$ (Fig. 3a–d). In the lossless case, the amplitude of the surface dips is very small. In order to emphasize these small dips, we present the calculated reflection spectra as –log (1 – R). The latter coincides with extinction if there are no losses and diffraction ($T + R = 1$), Ext = –log T = –log (1 – R). It can be seen in Fig. 3a that, at $w_{1,2} = 0$, there are no dips inside the PSB. If a layer with a thickness $w_1 = 0.552a$ is introduced on one of the sides, a resonance at 1260 cm^{-1} appears at the band edge (Fig. 3b); for a thicker interfacial layer $w_1 = 0.685a$, the resonance shifts closer to the middle of the PSB at 1050 cm^{-1} (Fig. 3c). Noteworthy is the change on the short-wavelength edge of the PSB. For the asymmetric structure with two interfacial layers of different thicknesses (Fig. 3d), only a single resonance related to the thicker layer is observed within the first PSB. The dip owing to the thin interfacial layer is not observed, which is presumably due to an increase in the total thickness of the PSB and to a

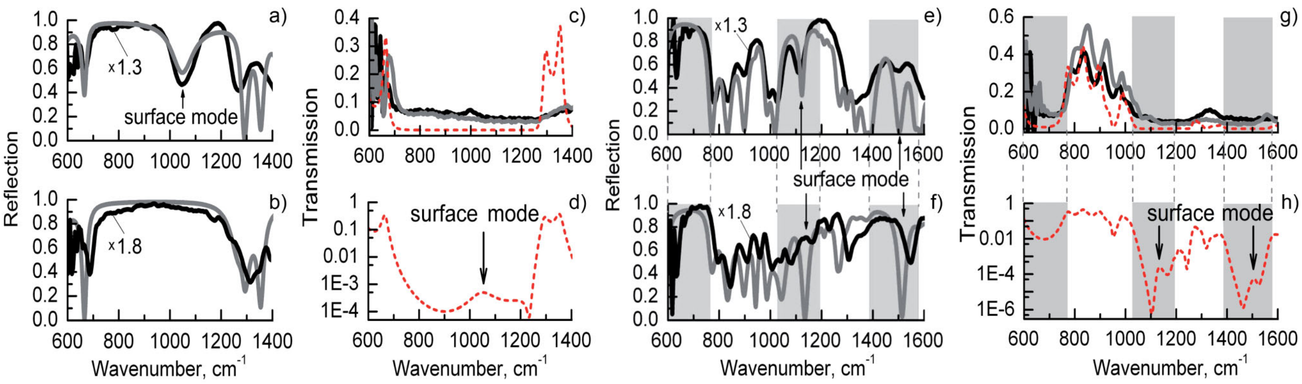

Figure 2 Reflection spectra for TE (a, b) and TM (e, f) polarized light: experimental (black line) and calculated (grey line) for illumination from sides (a, e) 1 and (b, f) 2. The experimental reflection spectra are multiplied by factors indicated in the figure. Transmission spectra for TE (c, d) and TM (g, h) polarized light: (c, g) experimental for illumination from side 1 (black line), from side 2 (grey line) and calculated (red dotted line), the same for both sides; (d, h) calculated transmission plotted on a logarithmic scale. Grey areas show the PBS regions.

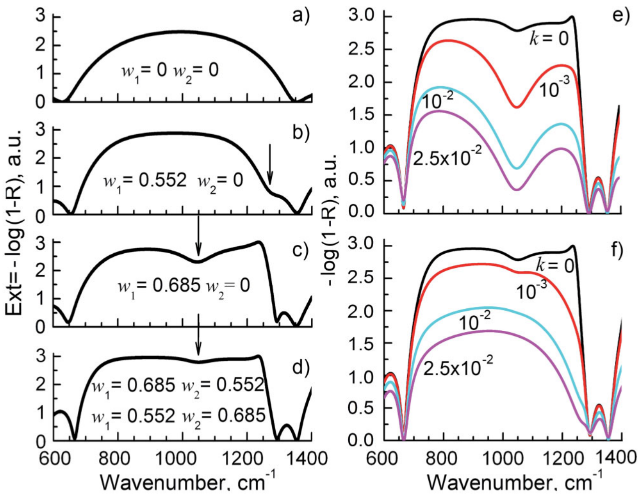

Figure 3 Calculated extinction spectra for TE polarization (light is incident on the side of the variable interface layer w_1): (a–d) for the lossless case $k = 0$ of structures with different $w_{1,2}$ (in the graphs indicated in units of a); spectra of structures with $w_{1,2}$ shown in (d) at various $k \neq 0$ for illumination from side (e) 1 and (f) 2. Calculation parameters: $n_{Si} = 3.42$, $r/a = 0.43$, $\theta = 15°$.

transformation of the short-wavelength edge of the stop-band.

It is worth noting that the reflection spectra in Fig. 3d, calculated without taking into account the scattering ($k = 0$), are identical and independent of the side of light incidence. Consequently, the reason for the difference between the reflection spectra taken at side 1 and side 2 are the light losses accounted for by the parameter k.

Let us consider the effect of k on the magnitude of reflection dips under illumination from different sides of the structure, see Fig. 3e, f. Compared with the lossless structure in Fig. 3a–d, in the case of $k \neq 0$ the plotted quantity $-\log(1 - R)$ does not coincide now with extinction $\text{Ext} = -\log(1 - R - A)$, where $A \neq 0$ is the absorption (losses) coefficient. As can be seen from Fig. 3e, f, the magnitude of the dip at 1050 cm^{-1} grows with the increase of k for light incident on side 1 (Fig. 3e) and decreases under illumination of side 2 (Fig. 3f). Thus, with increasing losses the effect of the surface mode created by the input interfacial layer becomes stronger, and that of the mode associated with the output layer, weaker, to the point of its complete vanishing.

In TM polarization, the interfacial layers $w_{1,2}$ give rise to surface states in the second and third PSBs, rather than in the first one. For example, a layer with thickness $w_1 = 0.552a$ leads to the appearance of two dips; at $\nu = 1140$ cm^{-1} in the second PSB and at $\nu = 1510$ cm^{-1} in the third PSB, and a layer with thickness $w_1 = 0.685a$ gives rise to dips at $\nu = 1125$ cm^{-1} and 1505 cm^{-1} in the second and third stop-bands, respectively. Indeed, the position of the surface modes in the reflection spectra in Fig. 2e, f depends on the illuminated side of the structure. That is, as also in the case of the TE polarization, the mode associated with the input interfacial layer appears in the reflection spectra. The transmission spectra for the case of TM polarization are also nearly identical, irrespective of the side of light entrance (Fig. 2g, h).

5 Discussion The PC layer well reflects light in the PSB range, but, because the PC is finite, the transmission T is not zero, even though being very small. Light is mostly reflected, and the reflection coefficient becomes highly sensitive to the thickness of the interfacial layer. In the absence of absorption (scattering), the direction of light incidence does not affect the reflection and transmission spectra, i.e. $R_1 = R_2$ and $T_1 = T_2$. At $k \neq 0$, the transmission spectra remain identical, $T_1 = T_2$, whereas the reflection spectra become different, $R_1 \neq R_2$. This behavior of the reflection and transmission spectra is fully confirmed experimentally and can be explained in terms of the reciprocity principle [12]. It follows from the reciprocity principle that transmission of light through any optical structure remains unchanged when the light source and detector are swapped. In terms of the reciprocity principle, the measuring of the transmission spectra of the PCS from its different sides means the swap of the source and the detector. This explains the identity of the two experimentally measured transmission spectra. In measuring the reflection spectra on the different sides of the PCS, the source and detector are not swapped and, therefore, the conditions of the classical reciprocity principle are not fulfilled. It means that reflections from two sides may not be the same. If there are no losses, the equality between transmissions leads to the equality between reflections in accordance with the energy conservation law. As soon as the Rayleigh scattering is taken into account (which we describe in the simulations as $k \neq 0$), part of energy, A, is “absorbed”, and the resonant excitation of the surface mode magnifies the absorption at the resonance. Under illumination from side 1, $R_1 = 1 - T - A_1$, and under that from side 2, $R_2 = 1 - T - A_2$. A similar process occurs for the TM polarization, with modes moving in frequency within the second and third bands as the illuminated side is changed from 1 to 2. At scattering losses evaluated for our structure by $k = 0.025$, the reflection in the PSB range is insensitive to the signal from the backside of the structure constituted by 5 rows of pores because the amplitude of light reflected from there is too small. This light has no effect on the structure of the electromagnetic field and interference of beams in the input interfacial layer, being responsible for the appearance of resonant reflection dips. Apparently, the decrease in the light attenuation due to the weaker scattering intensity or lower number of PCS periods must lead to a lesser difference between the spectra obtained in reflection from different sides of the structure. Because the surface layers and, consequently, the surface modes as well, are different for the two sides of the PCS, then $A_1 \neq A_2$. So, at equal T it leads us to the conclusion of the inequality of R_1 and R_2.

The above discussion is supported by the calculated electromagnetic field distributions through the slab. Details

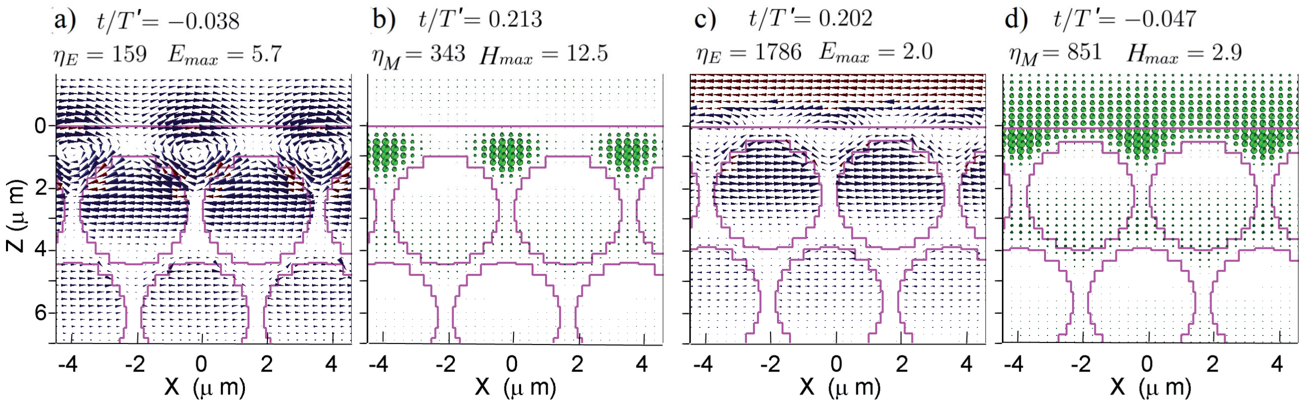

Figure 4 Calculated spatial distributions of the electric (blue and brown cones in (a, c)) and magnetic (green circles in (b, d)) fields in the slab for normal incidence of TE polarized light for illumination from side (a, b) 1 and (c, d) 2. The length of the cones (circles area) is proportional to the field strength at the central point of each cone (circle). Cones specify the corresponding electric field direction by their orientation. Fields are shown for an incoming frequency $a/\lambda = 0.402$ corresponding to the dip in the PSB for $w_1 = 0.685a$.

of the calculation can be found in [13]. Figure 4 shows the upper two rows of the slab near sides 1 and 2.

If the sample is illuminated from side 1, then the electric field is located mostly in subsurface region and takes the shape of vortices situated between the upper pores. The maxima of the magnetic fields are in the centres of these vortices. The time difference between the shown patterns when the electric (Fig. 4a, c) and magnetic (Fig. 4b, d) fields become maximal is approximately a quarter of the oscillation period, $t \approx 0.25T'$. The ratio between maximal and minimal electric (magnetic) field energies over the period of electromagnetic oscillations, η_E (η_M), exceeds unity by several orders of magnitude. These facts indicate that the electric and magnetic fields from Fig. 4a, b represent the standing wave of the surface mode. In the case of light incidence from side 2, the electromagnetic field is also located in the subsurface region. This is not surprising since the frequency is inside the photonic stop band and the propagation of light inside the structure is suppressed. At the same time, the vortices of electric field are less pronounced. Furthermore, the maximal values of electric and magnetic fields (E_{max} and H_{max}) over the light oscillation period are several times lower than those in the case of the illumination from side 1. Hence, the surface mode near side 2 does not appear under illumination from side 2.

Asymmetric structures of various type in connection with "violation" of the reciprocity principle have been previously studied in a number of experimental [14–17] and theoretical [18, 19] works. It can be seen that our results are in a complete agreement with the general reciprocity relations. The difference of reflections corresponds to the broken spatial symmetry ($w_1 \neq w_2$) combined with nonzero absorption (scattering) and does not contradict the reciprocity principle.

6 Conclusions It follows from the above analysis that, at zero losses, the reflection spectra of a PCS with asymmetric boundaries are the same and independent of the side of light incidence. If, however, there are losses related to scattering or absorption of light within the structure, then the surface modes due to the input interfacial layer start to prevail in reflection spectra even at small values of k. The experimental reflection spectra of the structure under study show modes associated with only the interfacial layer on the illuminated side, with those related to the back-side interfacial layer hardly appearing. At the same time, the transmission spectra are independent of the direction of light incidence. These spectra are always the same, both with and without losses.

Acknowledgements The study was financially supported by the Russian Foundation for Basic Research (projects nos. 09-02-00782 and 12-02-00795) and a grant for leading scientific schools no. HSh-3008.2012.2. S.D. and A.B. acknowledge financial support from IRCSET and Trinity College Dublin.

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