Tuning of one-dimensional Si/SiO$_2$ photonic crystals at the wavelength of 1.54 μm

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Abstract

We simulate the tuning of reflectance of a one-dimensional photonic crystal (PC) by means of charge injection. The PC is constituted from highly doped silicon layers alternating with silicon oxide layers. The wavelength of the light is assumed to be the important communications wavelength of 1.54 μm. A realistic simulation shows that sensitive tuning, and switching as well, can be achieved for an impurity density $\sim 10^{19}$/cm^3 even for superlattices only a few periods long. The reflectance results are satisfactorily interpreted in terms of photonic band structure calculations.

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Photonic crystals (PCs) by now constitute a mature field, with numerous applications. One of these is in *tuning*, namely the optical response of the PC is altered by means of some external agent. Such control of the response – for instance reflectance or spontaneous emission – includes the special case of *switching* it on and off. The large number of papers published on the subject of tuning of PCs may be classified as follows. (1) Producing *structural changes* in the PC, without changing the material properties of the ingredients [1]. This has been achieved by miscellaneous methods such as using mechanical stress, a piezoelectric material subjected to an electric field, insertion of diodes, and the tip of an atomic force microscope. (2) A second method of control is obtained by the incorporation of a *ferroelectric or a ferromagnetic substance* within the PC; an applied electric or magnetic field, respectively, will then alter the photonic band structure and, consequently, the response [2]. (3) Further, two papers exploit the *thermo-optic effect* to tune wave propagation in PC waveguides and channel-drop devices [3]. (4) Infiltration of the PC with a *liquid crystal* – remarkably sensitive to temperature changes, pressure, and applied electric or magnetic fields – is a much favoured approach [4]. (5) In continuation, illumination by an *intense laser beam* can produce small (non-linear) changes in the refractive index of a constitutive material of the PC. Here advantage is taken of the electro-optic or the photorefractive effects in order to tune diverse PC structures [5]. (6) The last category of tuning considered – and the one that concerns us in this communication – is based on the creation of *electron–hole pairs* in a semiconducting constituent of the PC. This can be accomplished either by heating the semiconductor (T-tuning) or by charge injection (N-tuning) [6–17].

T-tuning is the most effective for narrow-gap semiconductors, such as InSb, that give rise to large densities of free electrons — excited thermally from the valence band to the conduction band. This was shown to lead to dramatic changes in the photonic band structure of InSb cylinders in a square lattice [6]. Similar results were obtained in Ref. [7], and the possibility of controlling the direction of wave propagation in a Y-shaped, two-dimensional (2D) PC waveguide was proposed [8]. Recently, simulations of T-tuning in 1D [9] and 2D [10] PCs were also performed. And the tuning of pulses traversing 1D and 2D PCs with defects was reported in Refs. [11] and [12], respectively. Moreover, T-tuning of InAs quantum dots in a PC

cavity can enhance or suppress their rate of spontaneous emission [13].

As for N-tuning, the charge injection may be realized either by means of optical excitation or by forward biasing a p–n junction. The latter technique is based on free carrier injection into the intrinsic region of a forward biased p–i–n device [18]. Faster carrier density changes are achieved by embedding a metal–oxide–semiconductor structure in optical devices [19]. Theoretical investigations, mostly on strongly doped n-Si PCs, were carried out for 2D photonic band structure [6], for simulation of CW transmission in 1D [9] and 2D [10] PCs and for transmission of pulses in 1D [11] and 2D [12] PCs with defects. Recently it was also shown that the rate of spontaneous emission of an atom (modeled by a dipole), embedded in a superlattice, can be substantially altered by N-tuning [14]. On the experimental side, optical excitation was preferred, achieving ultrafast tuning in 2D PCs [15]. Guided modes in PC waveguides were also tuned [16] and it was demonstrated that a nanocavity in a PC can be optically controlled [17].

In this communication we show that sensitive N-tuning can be achieved in a simple configuration, with technologically important and readily processable materials, and at an important infrared wavelength. The configuration is a 1D PC or superlattice; the materials are silicon and silicon oxide, and the wavelength is 1.54 μm — widely employed in optical communications (relying on Er-doped optical fiber amplifiers). We have already demonstrated that tuning of the spontaneous emission is feasible for just such a system at the same wavelength [14].

In what follows we simulate reflectance measurements, for a n-Si/SiO$_2$ superlattice, as a function of the donor impurity concentration in the Si layers. This concentration, N, is our tuning agent and it is assumed to be high, $N \sim 10^{19}$/cm^3 — which is necessary for achieving sensitive tuning with the wavelength fixed at $\lambda_0 = 1.54$ μm. Although such high concentrations could be expected to be destructive for a device based on these ideas, we will demonstrate that a judicious choice of the parameters can minimize undesirable absorption. We use the plasma model for a realistic description of the n-Si dielectric constant:

$$\frac{\epsilon(\omega)}{\epsilon_\infty} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i/\tau_e)} - \frac{\omega_{ph}^2}{\omega(\omega + i/\tau_h)}. \tag{1}$$

Here, ϵ_∞ is the high-frequency dielectric constant, $\tau_{e,h}$ are the electron and hole scattering times, and $\omega_{pe,h} = (4\pi n_{e,h}^2 e^2/m_{e,h}\epsilon_\infty)^{1/2}$ are their plasma frequencies. The densities of the electrons n_e in the conduction band and of the (effective) holes n_h in the valence band are related to the impurity concentration N by $n_{e,h} = (n_i^2 + N^2/4)^{1/2} \pm N/2$. Because the intrinsic concentration n_i is very small in comparison to N, actually $n_e \simeq N$ and $n_h \simeq n_i^2/N$. See Ref. [9] for the numerical values of the parameters.

Usually, the period of the superlattice d is chosen to be comparable to the operational wavelength λ_0. If we take $d = 0.73$ μm, with the Si layers occupying a fraction $f = 0.5$, Fig. 1 is obtained for the reflectance. Note that, for $n = 50$
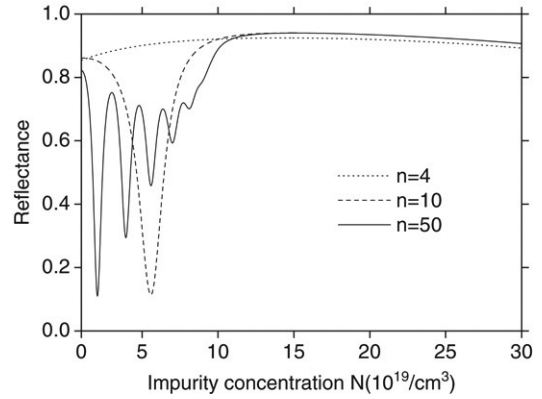

Fig. 1. Reflectance for a one-dimensional photonic crystal of Si and SiO$_2$ layers. The silicon layers are strongly doped and we show how the reflectance is tuned by varying the impurity concentration. 4, 10, and 50 periods in the length of the superlattice are considered. The period is $d = 0.73$ μm.

periods, the $R(N)$ curve is initially very steep, with a 70% decrease of the reflectance, which surely is a desirable tuning characteristic. Moreover, if we eliminate the absorption (by substituting $\tau_{e,h} = \infty$ in Eq. (1)) the resulting figure is indistinguishable on this scale. On the downside, however, the response is qualitatively dependent on the number of periods. This aspect can be remedied by selecting a much larger period, $d = 7$ μm; Fig. 2. A steep response is seen for N $\simeq 5 \times 10^{19}$/cm^3, which is not very sensitive to either the number of periods or to absorption (bottom panel; in the top panel the absorption has been "turned off"). By changing N from 4.14 to 5.74×10^{19}/cm^3, *switching* is also possible, for the reflectance drops from a high value (0.8 for $n = 10$) to zero. For greater values of the concentration, though, the reflectance is strongly impacted by dissipation, so that the regime $N > 6 \times 10^{19}$/cm^3 is unsuitable for tuning.

The three almost vertical lines in Fig. 2(a), at $N \simeq 5$, 23 and 31×10^{19}/cm^3, have the appearance of band edges that are characteristic of $R(\omega)$ plots. To convince ourselves that they are, indeed, band edges – although in the $R(N)$ representation (with ω as a parameter) – let us look at two different renditions of the photonic band structure in Fig. 3. Here, for the unlimited PC, the frequency ω is plotted as a function of the Bloch wave vector k (N being a parameter) in part (a) and as function of the impurity density N (now with k as the parameter) in part (b). The heavy horizontal line represents the frequency $\omega_0 = 2\pi c/\lambda_0$. As Fig. 3(a) clearly shows, this line lies completely in the band gap for $N \lesssim 3 \times 10^{19}$/cm^3 — between the curves "3" above and below the ω_0 line. For this reason, in this range of N the light must be completely reflected in the ideal, absorptionless and infinite superlattice — as is suggested by Fig. 2(a). For $N = 5 \times 10^{19}$/cm^3 the lower curve "5" already intersects the ω_0 line, thus making optical modes available for propagation. Fig. 3(b) confirms this reasoning and, moreover, the left edge ($k = \pi/d$) of the central band crosses the line ω_0 at the precise value of the transition from the low-N stop-band to a pass-band — at $N = 4.9 \times 10^{19}$/cm^3. For greater N values Fabry–Perot oscillations of the reflectance are
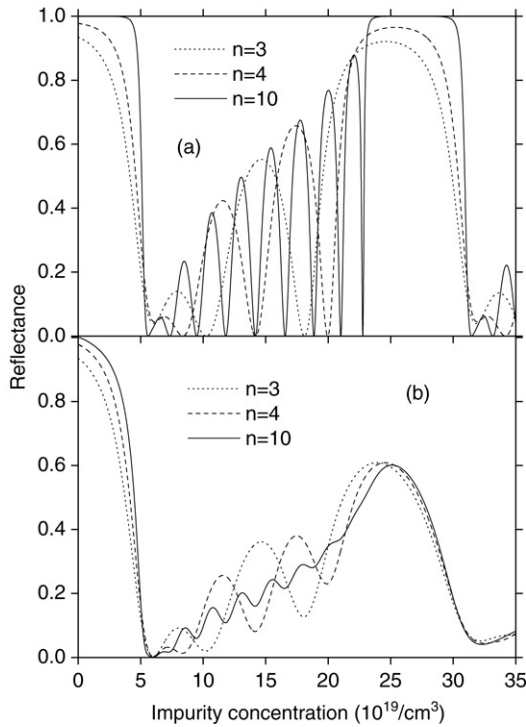
Fig. 2. As in Fig. 1 for a period $d = 7$ μm, now considering superlattices three, four, and ten periods long. Absorption has been turned off in (a) and turned on in (b). Note that the band edge at $N \simeq 5 \times 10^{19}/\mathrm{cm}^3$ is appropriate for tuning.
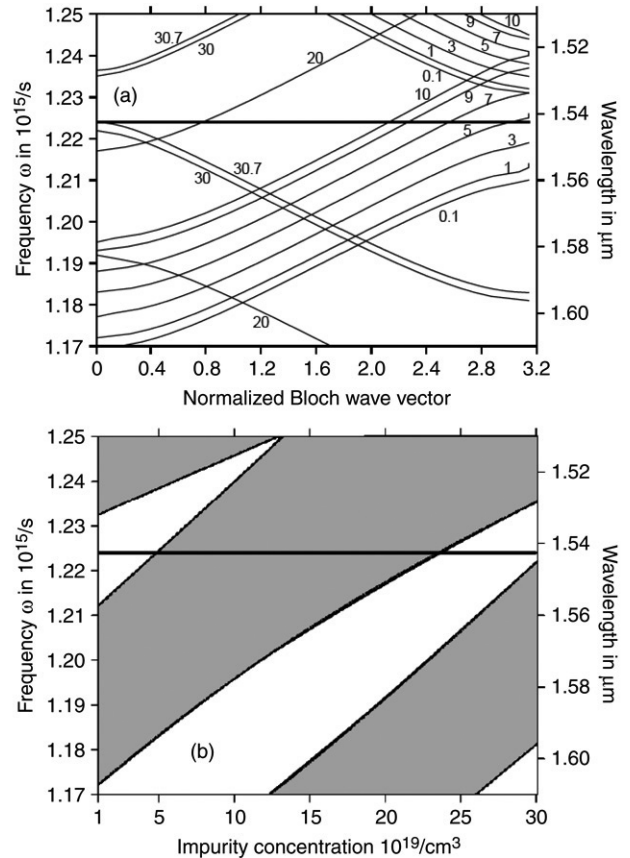

Fig. 3. Band structure for the (infinite) photonic crystal considered in Fig. 2(a). The frequency (wavelength) is plotted on the left (right) side axis as function of the normalized Bloch vector kd (with N as parameter) in part (a) and vice versa in part (b). In (a), the numbers next to each line are the values of N in $10^{19}/\mathrm{cm}^3$. The horizontal lines mark the frequency corresponding to the wavelength of 1.54 μm.

apparent in Fig. 2(a) and, in a damped form, also in Fig. 2(b). Entirely similar considerations are applicable to the band edge at $N \simeq 31 \times 10^{19}/\mathrm{cm}^3$ in Fig. 2(a). And a glance at the lower curve "30.7" in Fig. 3(a) reveals that it is just tangent to the ω_0 line — which fixes the band edge at $30.7 \times 10^{19}/\mathrm{cm}^3$. As for the band edge at $N \simeq 23 \times 10^{19}/\mathrm{cm}^3$ in Fig. 2(a), we note that in Fig. 3(a) the curve "20" crosses the ω_0 line, while this line lies between the curves "30", namely in a band gap. The precise position of the band edge is given by the intersection, in Fig. 3(b), of the right side edge of the central band (for $k = 0$) with the ω_0 line — $N = 23.6 \times 10^{19}/\mathrm{cm}^3$.

Why is the first stop-band, at $N \lesssim 5 \times 10^{19}/\mathrm{cm}^3$, quite insensitive to absorption, while the second stop-band, centered at about $27 \times 10^{19}/\mathrm{cm}^3$, suffers strong attenuation? This is readily explained by the fact that, as N increases, so does the scattering of the free electrons from the impurities. Mathematically, this scattering manifests itself in smaller collision times $\tau_{e,h}$ in Eq. (1).

We have thus shown that both tuning and switching of the reflectance is possible in a Si/SiO_2 one-dimensional photonic crystal at the technologically important wavelength of 1.54 μm. This could be accomplished by either optical or electrical charge injection, varying the impurity density at $N \sim 10^{19}/\mathrm{cm}^3$, even with a small number of PC periods. In the case of electrical tuning a unit cell of four Si layers – p-type, intrinsic, n-type, and oxide – could be advantageous. The first three layers would form a p–i–n diode and would serve to modify the carrier concentration, while the oxide layer would

increase the dielectric contrast. Such tuning of the reflectance in photonic crystals could have a positive impact on silicon optical devices such as waveguides, modulators, and laser cavities.

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