

## NEAR INFRARED FILTERING PROPERTIES IN PHOTONIC CRYSTAL CONTAINING EXTRINSIC AND DISPERSIVE SEMICONDUCTOR DEFECT

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**Abstract**—In this work, near infrared filtering properties in a transmission narrowband filter are theoretically investigated. The filter is a defective photonic crystal of  $(LH)^N D(HL)^N$ , where  $N$  is the stack number,  $L$  is  $\text{SiO}_2$ ,  $H$  is  $\text{InP}$ , and defect layer  $D$  is an extrinsic semiconductor of  $n$ -type silicon ( $n$ -Si). It is found that there are multiple transmission peaks within the photonic band gap (PBG) as the defect thickness increases. The filtering position can be changed by varying the doping density in  $n$ -Si. That is, the peak (channel) wavelength is blue-shifted when the doping density increases. In the angle-dependent filtering property, the channel wavelength is also blue-shifted as the angle of incidence increases for both TE and TM waves. These filtering properties are of technical use in the applications of semiconductor optoelectronics.

### 1. INTRODUCTION

Photonic crystals (PCs) are periodic layered structures and can be classified as one-, two-, or three-dimensional. PCs can possess frequency regions in which the propagation of electromagnetic waves is forbidden. Such regions are called the photonic band gaps (PBGs) analogous to the electronic band gaps (EBGs) in solids. With the existence of PBGs, engineering PBGs to realize certain photonic devices has attracted much attention in the optical and photonic communities. For a simple one-dimensional (1D) PC, a popular application is to design narrowband transmission filters. Such a filter

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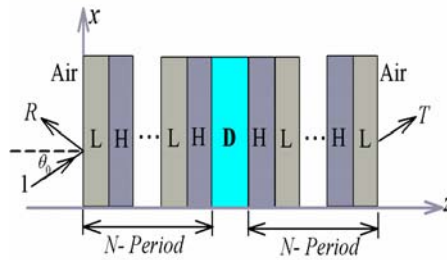
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with a structure of  $(\text{LH})^N/\text{D}/(\text{HL})^N$  or  $(\text{LH})^N/\text{D}/(\text{LH})^N$  is referred to as a multilayer Fabry-Perot resonator (FPR) [1]. Filters are used as a wavelength (frequency) selective device which is of particular importance in optical electronics and communications.

PC-based optical filters, which have a feature of tuning, are more practical and interesting to the community in recent years. Depending on the tuning agent, there are several ways to make a filter tunable. We can make a temperature-tuning filter by using liquid-crystal as a defect layer [2–4]. Temperature-tunable filter is also obtainable with a superconducting defect [5–10]. If the defect material is a ferroelectric, then the tuning can be achieved by the external electric field (or applied bias voltage) [11]. Filters that are tuned by the magnetic field are also available thus far [12, 13]. It should be noted that, in reality, once the crystal is made, there is not variation in the crystal structure in terms of temperature, electric field or magnetic field as mentioned in the above references. Thus, a filter with tunable feature can be achieved only by the defect material whose permittivity or permeability is a function of temperature, electric field or magnetic field.

In addition to the above-mentioned tuning, there is another tuning for the narrowband filter, i.e., use of semiconducting material as a defect layer. For the intrinsic semiconductors, tuning can be made by the variation of intrinsic carrier density which is a strong function of the temperature. For the extrinsic semiconductors, tuning is obtained by changing the doping density. Photonic structures containing extrinsic semiconductors such as  $n$ -Si,  $n$ -Ge, and  $n$ -InSb have been reported recently [14–19].

The purpose of this paper is to investigate the filtering properties for  $\text{SiO}_2/\text{InP}$  photonic crystal containing a defect of  $n$ -Si. PC made of  $\text{SiO}_2/\text{InP}$  bilayers has been fabricated and its defective structure for narrowband filter design is reported recently [20, 21]. This filter is designed to operate at near infrared (NIR) wavelength. In this work, based on the use of  $\text{SiO}_2/\text{InP}$ -PC, we would like to make a detailed analysis on the filtering properties in a narrowband transmission filter by adding a defect layer of  $n$ -Si. We choose  $n$ -Si because it is a strongly dispersive extrinsic semiconductor. Its dielectric function is strongly dependent on the doping density. It will be seen that the position of transmission peak can be changed by the doping density. Thus, by varying the doping density, the proposed structure can be used as an alternative for the design of a tunable filter called an  $N$ -tuning filter [16]. Our analysis is made by the transmittance which can be calculated by making use of the transfer matrix method (TMM) [22]. The TMM has been widely used in the analysis of electromagnetic wave properties in 1D PCs [23–27]. We shall show how the transmission peak



**Figure 1.** A one-dimensional filter structure,  $(LH)^N/D/(HL)^N$ , where  $L = \text{SiO}_2$ ,  $H = \text{InP}$  are the low-, high-index layers, respectively, and the center  $D = n\text{-Si}$  is the defect layer. The optical wave with a unit power impinges obliquely at  $z = 0$ , and  $R, T$  represent reflectance and transmittance, respectively.

(channel wavelength) will be shifted by the variation of doping density, the defect thickness, and the angle of incidence for both TE and TM waves.

## 2. BASIC EQUATIONS

In the analysis that follows, we shall use the calculated transmittance for a one-dimensional defective photonic crystal shown in Figure 1 to study the filtering properties. Here,  $n\text{-Si}$  is used for the defect layer. Since, the tunable feature arises from the use of  $n\text{-Si}$ , it is necessary to first describe its dielectric function. For an  $n\text{-Si}$  semiconductor, the dielectric function including the absorption can be described by the plasma model, namely [15]

$$\epsilon_D(\omega) = \epsilon_\infty \left( 1 - \frac{\omega_{pe}^2}{\omega^2 - j\frac{\omega}{\tau_e}} - \frac{\omega_{ph}^2}{\omega^2 - j\frac{\omega}{\tau_h}} \right), \quad (1)$$

where  $\epsilon_\infty$  is the high-frequency dielectric constant, and  $\tau_e$  and  $\tau_h$  are the electron and hole scattering times related to the carrier mobilities  $\mu_{e,h}$  by

$$\tau_{e,h} = \frac{m_{e,h}\mu_{e,h}}{e}, \quad (2)$$

where  $\mu_{e,h}$  is expressed as,

$$\mu_e = 92 + \frac{1268}{1 + \left(\frac{N_d}{1.3 \times 10^{17}}\right)^{0.91}}, \quad \mu_h = 54.3 + \frac{406.9}{1 + \left(\frac{N_d}{2.35 \times 10^{17}}\right)^{0.88}}, \quad (3)$$

where  $N_d$  is the donor density (in unit of  $\text{cm}^{-3}$ ), and the electron and hole plasma frequencies are given by

$$\omega_{pe,h} = \left( \frac{n_{e,h} e^2}{m_{e,h} \varepsilon_\infty \varepsilon_0} \right)^{1/2}. \quad (4)$$

Here,  $m_e$  is the effective mass of electron and  $m_h$  is the effective mass of hole which can be determined by the effective masses of the light ( $m_{lh}$ ) and heavy ( $m_{hh}$ ) holes,

$$m_h = m_{hh} \frac{1 + r^{3/2}}{r + r^{3/2}}, \quad (5)$$

where  $r = m_{hh}/m_{lh}$ ,  $n_{e,h}$  are the densities of electron and hole given by

$$n_{e,h} = \sqrt{n_i^2 + \frac{N_d^2}{4}} \pm \frac{N_d}{2}, \quad (6)$$

where  $n_i$  is the intrinsic density and  $N$  the donor density. The refractive index of  $n$ -Si is  $n_D = \sqrt{\varepsilon_D}$ . It is worth mentioning that the doping-dependent mobilities in Equation (3) are suited at 300 K [28]. These two relationships are accurately empirical and widely applied to compute the carrier mobilities for the doped Si. In addition, Equation (5) arises from the fact that Si is a multiple-valley semiconductor, leading to the different effective masses for holes in distinct bands.

To analyze the filtering properties, we shall capitalize on the transmittance spectrum for the structure in Figure 1, in which the thicknesses of  $L$ ,  $H$ , and  $D$  are denoted by  $d_L$ ,  $d_H$ , and  $d_D$ , respectively. The transmittance and reflectance can be calculated through the use of the transfer matrix method (TMM) [22]. According to TMM, transmittance  $T$  and reflectance  $R$  are determined by the following expressions,

$$R = |r|^2 = \left| \frac{M_{21}}{M_{11}} \right|^2, \quad T = |t|^2 = \left| \frac{1}{M_{11}} \right|^2, \quad (7)$$

where  $r$  and  $t$  are the reflection coefficient and transmission coefficient, and  $M_{11}$ ,  $M_{21}$  are the two matrix elements of the following total system matrix

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} (D_L P_L D_L^{-1} D_H P_H D_H^{-1})^N (D_D P_D D_D^{-1}) (D_H P_H D_H^{-1} D_L P_L D_L^{-1})^N D_0. \quad (8)$$

Here,  $P_i$  ( $i = L, H$ , and  $D$ ) is the propagation matrix in layer  $i$  given by

$$P_i = \begin{pmatrix} \exp(jk_i d_i) & 0 \\ 0 & \exp(-jk_i d_i) \end{pmatrix}, \quad (9)$$

where  $k_i = \omega n_i / c$  is the wave number in layer  $i$ , and  $D_q$  ( $q = 0, L, H$ , and  $D$ ) is the dynamical matrix in medium  $q$  which is dependent on the polarization of the incident wave, i.e.,

$$D_q = \begin{pmatrix} 1 & 1 \\ n_q \cos \theta_q & -n_q \cos \theta_q \end{pmatrix} \quad (\text{TE wave}), \quad (10)$$

$$D_q = \begin{pmatrix} \cos \theta_q & \cos \theta_q \\ n_q & -n_q \end{pmatrix} \quad (\text{TM wave}), \quad (11)$$

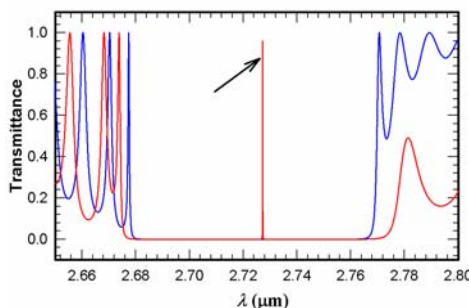
where  $q = 0$  is for the air with  $\epsilon_0 = 1$ .

### 3. NUMERICAL RESULTS AND DISCUSSION

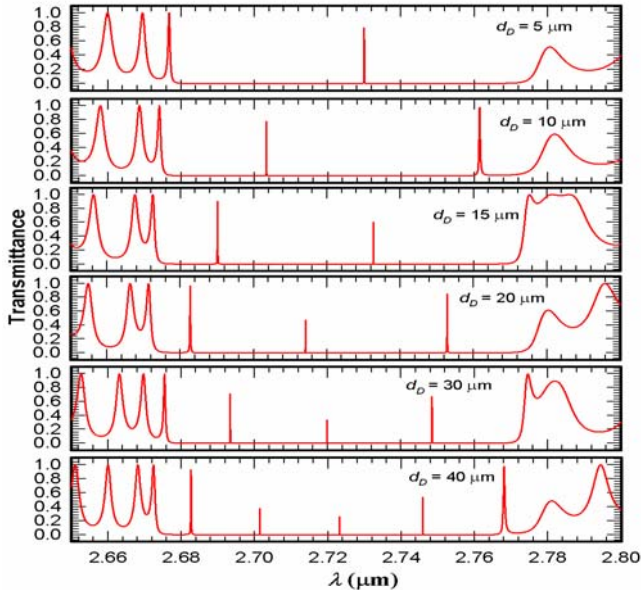
The material parameters for the defect layer,  $n$ -Si, in our calculation are  $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ ,  $\epsilon_\infty = 11.7$ ,  $m_e = 0.26m_0$ ,  $m_{hh} = 0.49m_0$ , and  $m_{lh} = 0.16m_0$ , where  $m_0 = 9.1 \times 10^{-31} \text{ kg}$  is the mass of free electron [15]. The low-index dielectric is  $\text{SiO}_2$  with  $n_L = 1.45$  and the high-index one is  $\text{InP}$  with  $n_H = 3.52$  [21].

#### 3.1. Transmission Peaks as a Function of Thickness in $n$ -Si

Let us first investigate how the transmission peaks vary as a function of the defect thickness of  $n$ -Si. In Figure 2, we plot the transmittance spectrum (blue color) for the ideal PC of  $(\text{LH})^N$ , where thicknesses



**Figure 2.** Calculated normal-incidence transmittance spectra for ideal PC of  $(\text{LH})^N$  (blue) and defective PC (red). Here, the thickness of  $n$ -Si is  $d_D = 1 \text{ mm}$  and the doping density is  $N_d = 1 \times 10^{17} \text{ cm}^{-3}$  are used in our calculation.



**Figure 3.** Normal-incidence transmittance spectra for the defective PC with different defect thicknesses of  $d_D = 5, 10, 15, 20, 30, 40 \mu\text{m}$ , respectively. The doping density is fixed at  $N_d = 1 \times 10^{17} \text{cm}^{-3}$ .

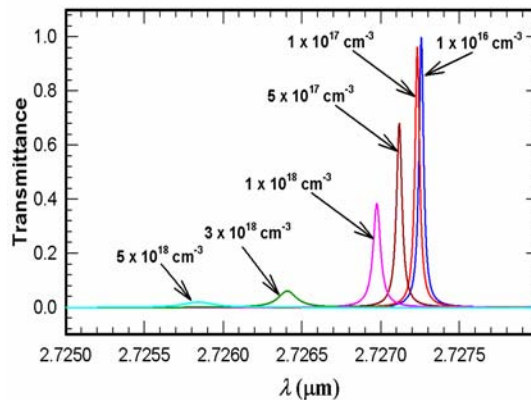
$d_L = 4.54 \mu\text{m}$ ,  $d_H = 1.22 \mu\text{m}$ , and  $N = 20$  are used. It can be seen that, at NIR, there is a PBG with left and right band edges at  $\lambda_L = 2.6786 \mu\text{m}$  and  $\lambda_H = 2.7647 \mu\text{m}$ , respectively. Our goal is to engineer this PBG to realize a transmission narrowband filter based on the addition of defect layer. When the  $n$ -Si is placed in the middle as a defect layer, there appears a transmission peak (indicated by the arrow) at  $\lambda_p = 2.7272 \mu\text{m}$  with a peak height of  $T = 0.9598$ . Here, the doping density is  $N_d = 1 \times 10^{17} \text{cm}^{-3}$  and defect thickness  $d_D = 1 \mu\text{m}$  are taken. The peak position locates in the vicinity of the gap center of PC of  $(\text{LH})^N$ .

Figure 3 shows how the number of transmission peaks changes as the defect thickness increases. It can be seen that there is a single transmission peak when  $d_D$  is smaller than  $10 \mu\text{m}$ . At  $d_D = 10$  and  $15 \mu\text{m}$ , there are two peaks within the PBG in Figure 2. At  $d_D = 20$  and  $30 \mu\text{m}$ , three peaks are generated. As  $d_D$  is increased up to  $40 \mu\text{m}$ , five peaks can be obtained. This means that a multichannel filter can be achieved by increasing the thickness of the defect layer, which is consistent with the result reported by Ghosh et al. [21]. A filter with multiple channels is of technical use in a wavelength division

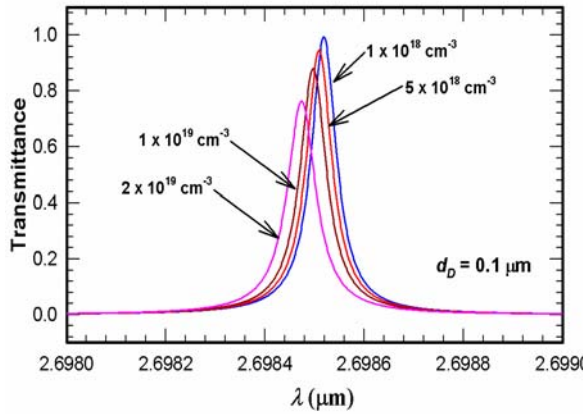
multiplexing (WDM) application which is of important in optical communications.

### 3.2. Transmission Peaks as a Function of Doping Density in *n*-Si

We now study the shifting feature in such a filter structure. The shifting comes from the variation of the doping density in *n*-Si. With the same thicknesses for SiO<sub>2</sub> and InP. In Figure 4, we plot the transmittance spectra at  $d_D = 1 \mu\text{m}$  for different donor densities of  $N_d = 1 \times 10^{16}$ ,  $1 \times 10^{17}$ ,  $5 \times 10^{17}$ ,  $1 \times 10^{18}$ ,  $3 \times 10^{18}$ , and  $5 \times 10^{18} \text{ cm}^{-3}$ . It can be seen that the filtering is changeable since the peak wavelength  $\lambda_p$  is blue-shifted as the doping density increases. At a density of  $1 \times 10^{16} \text{ cm}^{-3}$ , a nearly total transmission can be attained because of near unity peak height. In addition to the blue-shift, the peak shape is also broadened along with a lowering in the peak height. At high density of  $5 \times 10^{18} \text{ cm}^{-3}$ , the peak height is greatly suppressed and negligibly small. In order to remain the filtering feature at higher doping density, the thickness  $d_D$  of *n*-Si is required to be thinner. This result is illustrated in Figure 5, in which  $d_D$  has been reduced to  $0.1 \mu\text{m}$  from  $1 \mu\text{m}$ . For thinner defect, the transmission peak is high enough to maintain the filter requirement even at a highly doped defect of *n*-Si. In addition, a similar blue-shift in Figure 4 is also seen and the extent of shift is smaller than that in Figure 5.



**Figure 4.** Normal-incidence transmittance spectra for the defective PC with different doping densities  $N_d = 1 \times 10^{16}$ ,  $1 \times 10^{17}$ ,  $5 \times 10^{17}$ ,  $1 \times 10^{18}$ ,  $3 \times 10^{18}$ , and  $5 \times 10^{18} \text{ cm}^{-3}$ , respectively. The thickness of *n*-Si is fixed at  $d_D = 1 \mu\text{m}$ .



**Figure 5.** Normal-incidence transmittance spectra for the defective PC with different doping densities  $N_d = 1 \times 10^{18}$ ,  $5 \times 10^{18}$ ,  $1 \times 10^{19}$ , and  $2 \times 10^{19} \text{ cm}^{-3}$ , respectively. The thickness of  $n$ -Si is fixed at  $d_D = 0.1 \mu\text{m}$ .

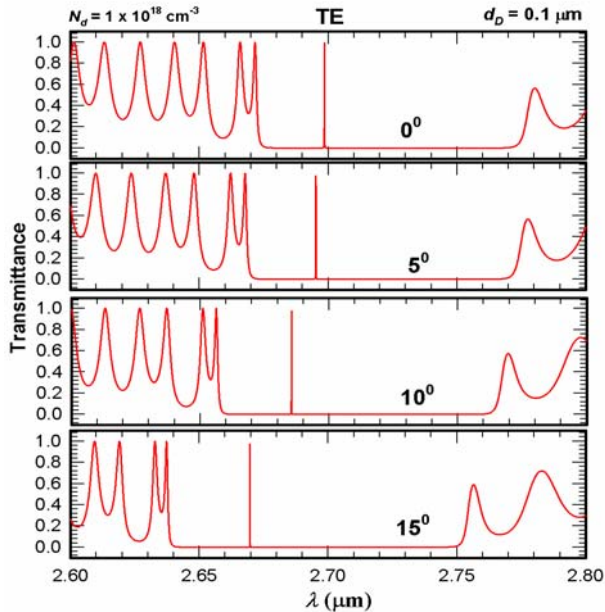
### 3.3. Transmission Peaks as a Function of Angle of Incidence

We have so far investigated the filtering properties in the case of normal incidence. We now turn our attention to the angular dependence of filtering for this filter structure. To investigate the angle-dependent properties, the results of two polarizations, TE and TM, for the incident wave will be given. In Figure 6, transmittance spectra at different angles of incidence,  $\theta_0 = 0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$ , respectively, are shown for the TE wave at  $d_D = 0.1 \mu\text{m}$  and  $N_d = 1 \times 10^{18} \text{ cm}^{-3}$ . Some features are of note. First, the transmission peak is blue-shifted as the angle increases. The PBG structure also is blue-shifted. And the size of PBG is enhanced when the angle is increased. For TM wave, all these three features are also found and thus are not replotted here.

### 3.4. Modified Structure for Multichannel Filters

The considered structure shown in Figure 1 can be modified to achieve a multichannel filter. This can be done by the structure with coupled defects, namely,  $(\text{LH})^N/(\text{LHLD})^M\text{LHL}/(\text{HL})^N$  [29]. In this structure, multiple channels are generated within the PBG and the channel number is equal to  $M$ , the number of coupled defects. Thus, using  $n$ -Si as a defect layer of  $D$  in this modified structure, we can make the filter changeable because the peak positions can be shifted by the variation of doping density. Shifting features are expected to be similar





**Figure 6.** TE-wave transmittance spectra for the defective PC with a doping densities  $N_d = 1 \times 10^{18} \text{ cm}^{-3}$  and thickness  $d_D = 0.1 \mu\text{m}$  for different angles of incidence,  $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$ , respectively.

to those described previously. Besides, the defect layer  $D$  can also be chosen to be other semiconductor like  $n\text{-Ge}$  or  $n\text{-InSb}$  such that the shifting in multichannel filter is achieved.

#### 4. CONCLUSION

The filtering properties for a defective PC operating in NIR region have been analyzed in this work. With a defect of  $n\text{-Si}$ , which is a dispersive and absorptive medium, we have found that the channel wavelength is shown to be blue-shifted when the doping density increases. At a moderate doping density, the filtering can be obtained at a thicker defect layer, whereas a thinner defect is required for a highly doped  $n\text{-Si}$ . In the angular dependence, it is found that the channel wavelength is also blue-shifted as a function of angle of incidence for both TE and TM waves. By increasing the defect thickness, it is possible to obtain a multichannel filter. A filter with features of multiple channels and of shifting is of particular use in the optical communications.

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