STUDY THE FILTERING PROCESS IN ONE DIMENSIONAL PHOTONIC CRYSTAL WITH AND WITHOUT DEFECT SEMICONDUCTORS

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ABSTRACT
In this paper, we theoretically investigate the effect of the doping concentration on the properties of one dimensional semiconductor photonic band structures. Our numerical method is based on the transfer matrix method. The numerical results show that the photonic band gaps in is sensitive to the changes in the doping concentration. In addition, the width of the gap of is less sensitive to the change in the doping concentration. Our structures could be of technical use in optical electronics for semiconductor applications. We have designed the first case is (SiO2/GaAs)N photonic crystal (PC) without defect layers and the second case are (SiO2/n-Ge/GaAs)N and (SiO2/GaAs)ND(SiO2/GaAs)N photonic crystals with defect layers. The numerical results show that the number of photonic band gaps (PBG) in the second case (PC with defect layer) is greater than that in the first case (PC without defect layer).

KEYWORDS: *photonic crystal, doping density, transfer matrix method, semiconductor materials*

I. INTRODUCTION

The goal of introduce the photonic crystal is to control the optical properties of materials. The pioneering works in the field of photonic crystal (PC_s) are happen by Yablonovitch and John [1-3]. In 1987, Eli Yablonvitch give the idea to form artificial periodic structures depend on the permittivity, in order to control the propagation of the light and the theory of a photonic band gap (PBG) materials was born. Photonic crystals (PC_s) are periodic layered structures and can be classified as one, two or three dimensional PC_s. The existence of PBG is the most fundamental property for PC_s. The PBG in a PC is like to the electronic band gap in a solid as there is analogy between the structural periodicity of a PC and the periodic arrangement of the atomic potential [4]. The existence of wide band gaps (PBG_s) in PC_s has different applications such as optical switches, optical filters, wave guides and resonance cavities [5-9].

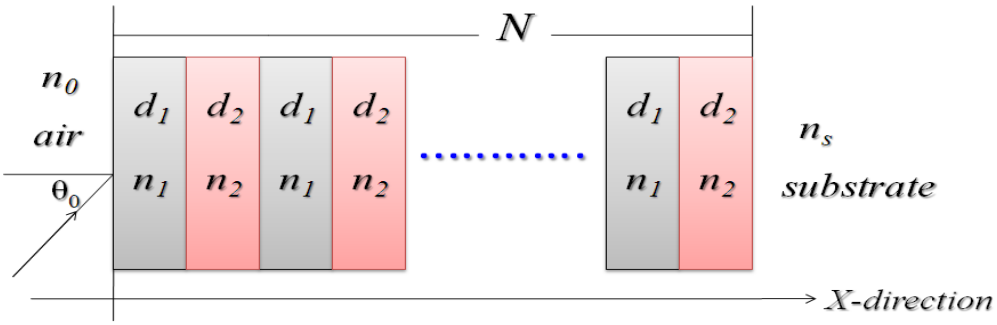
In recent years, optical filters based on PC_s, which have a feature of tunable PBG are more important in communication. There are many ways to make a filter tunable. The PBG can be tuned by means of some external agents. If the defect material is a ferroelectric, the tuning in PBG achieved by the external electric field and it is referred to as E-tuning [10,11]. Another filter is called M-tuning which use of magnetic field to tune the optical properties in a photonic crystal [12-15]. We can make a temperature-tuning filter by using superconducting defect because of the temperature-dependent London penetration length in the superconducting materials [16-23]. Temperature Tunable filter is also obtained by using liquid crystal as a defect layer [24, 25]. In the present study, we consider a semiconductor medium as one dimensional photonic crystal, since the dielectric property of semiconductor depends not only on temperature but also on wavelength. In addition we have tuning for narrow band filter by using a semiconductor as a defect layer. So if we use the defect materials in a photonic crystal like intrinsic semiconductor as one of the layer, it is becomes T-tuning because the dielectric constant of it is a function of intrinsic carrier density which is a strong function of temperature [26, 27]. PC_s infiltrated with intrinsic semiconductor such as InSb are M-tuning devices [28-30]. In addition to the pervious filters, we found another filter which PC_s containing extrinsic

semiconductor like as n-Si, n-Ge and n-InSb, where the dielectric constant of it is dependent on the carrier concentration [31-35]. This case, known as the N-tuning (N is the carrier concentration) [36] which is important and affect on the semiconductor optoelectronics.

The aim of the present work is to investigate and analyzed the photonic band gap in N-tuning filter. We used the pure photonic crystal of $(SiO_2/GaAs)^N$ and the defect photonic crystals of both forms $(SiO_2/n\text{-}Ge/GaAs)^N$ and $(SiO_2/GaAs)^N D(SiO_2/GaAs)^N$ where n-Ge is n-type semiconductor with doping donor impurity. We choose n-Ge because it is more available extrinsic semiconductor as n-Si. The dielectric of extrinsic semiconductor is dependent on the carrier concentration (donor density). We study and analyzed the transmission of electromagnetic wave in visible and near infrared region. The calculation shows that the position of PBG can be changed by changing the carrier concentration (doping density). The analysis of this work was calculated by using of the transfer matrix method TMM [37].

In this paper we have investigated the transmission as a function of carrier concentration (concentration donor impurity). We found that by increasing the concentration carrier, the PBG will be shifted towards the shorter wave length. Also the transmission will be shifted by the variation of some variables such as doping density, the defect thickness, and the angle of incidence for both TE and TM waves.

II. BASIC EQUATION



Figure(1):- Schematic diagram of 1D-binary structure; the thicknesses of its constituent materials are denoted by d_1 and d_2, respectively, and the corresponding refractive indices are separately indicated by n_0, n_1, n_2, and n_s, where n_0 is the refractive index of the air and n_s is the refractive index of substrate.

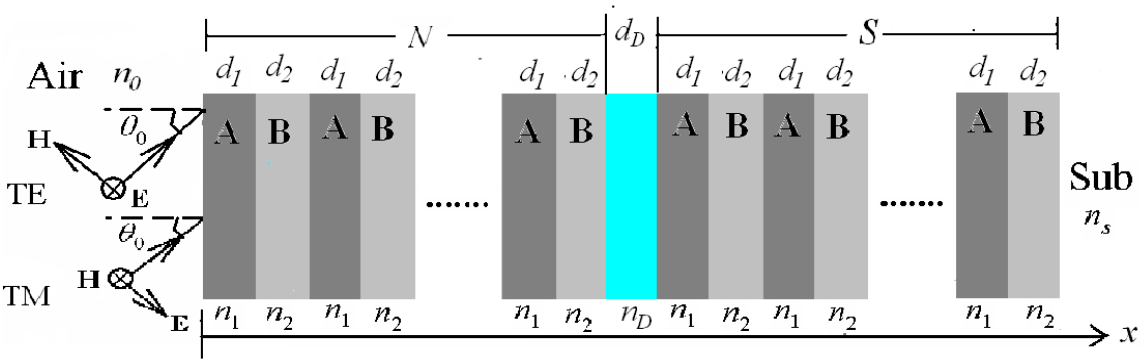


Figure (2):- Schematic diagram of 1D-ternary structure in the form $(LH)^N D(LH)^S$, in which the thicknesses of the three constituent layers are denoted by d_1, d_2, and d_d. The corresponding refractive indices are separately indicated by n_o, n_1, n_2, n_d, and n_s, where n_o=1 is taken for free space and n_s is for the substrate and defect layer in the middle of the two periodic.

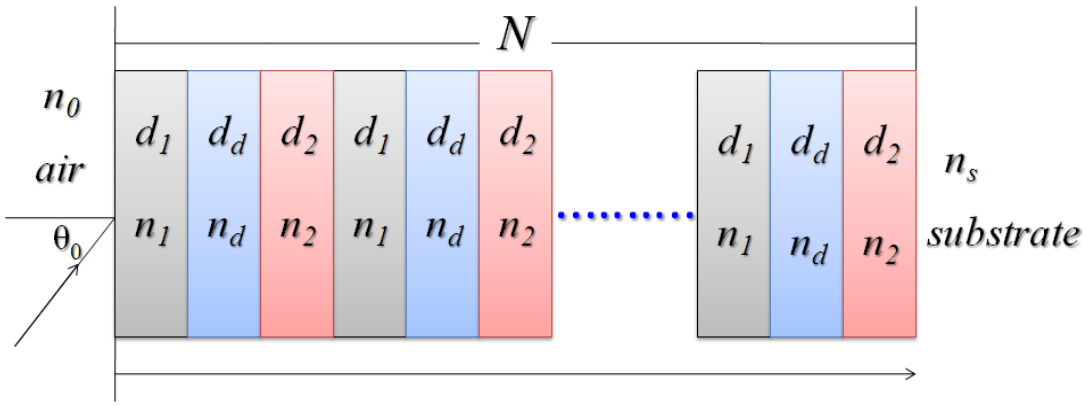


Figure (3):- Schematic diagram of 1D-ternary structure in the form $(LDH)^N$, in which the thicknesses of the three constituent layers are denoted by d_1, d_2, and d_d. The corresponding refractive indices are separately indicated by n_o, n_1, n_2, n_d, and n_s, where n_o=1 is taken for free space and n_s is for the substrate.

Plasma of free electrons in conduction bands and free holes in the valence bands are represented the semiconductor layers. The densities of free electrons and free holes are given as a function of the donor density N_d by [38],

$$n_{e,h} = \sqrt{{n_i}^2 + \frac{{N_d}^2}{4}} \pm \frac{N_d}{2}, \quad (1)$$

Where the intrinsic density n_i is small in comparison to N_d. The plasma frequency of electrons and holes ($\omega_{pe,h}$) are given by;

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

Where ε_∞ is high- frequency dielectric constant, M_e is the effective mass of electron and M_h is the conductivity effective mass for holes which can be obtained from the effective masses of the light (M_{lh}) and heavy holes (M_{hh}), as follows:

$M_h = M_{hh}(1+ r^{3/2}) / (r+r^{3/2})$ and

$r = M_{hh} / M_{lh}$. (3)

The plasma model for the dielectric function takes into account that the absorption can be described by [39, 40];

$$\varepsilon_D(\omega) = \varepsilon_\infty\left(1 - \frac{{\omega_{pe}}^2}{\omega^2 - j\frac{\omega}{\tau_e}} - \frac{{\omega_{ph}}^2}{\omega^2 - j\frac{\omega}{\tau_h}}\right) \quad (4)$$

Where τ_e and τ_h are the scattering times which is given by

$$\tau_{e,h} = M_{e,h}\,\mu_{e,h}/e. \quad (5)$$

Where μ_e, μ_h are the carrier mobility for electrons and holes which are given by;

$$\mu_e = 92 + \frac{1268}{1+\left(\frac{N_d}{1.3\times10^{17}}\right)^{0.91}} \quad \text{and} \quad (6)$$

$$\mu_h = 54.3 + \frac{406.9}{1+\left(\frac{N_d}{2.35\times10^{17}}\right)^{0.88}}$$

From these equations we can obtain the dielectric constant of n-Ge. So the refractive index of n-Ge (n_D) can be given by $n_D = \sqrt{\varepsilon_D}$ .In figure 1, 2, 3 the thicknesses of L, H and D are denoted by d_1, d_2 and d_D respectively. The reflectance and the transmittance can be calculated by TMM to analyze the filtering properties. According to TMM, the transmittance T and the reflectance R can be determined by:

$$R = |r|^2 = \left|\frac{M_{21}}{M_{11}}\right|^2 \quad \text{and}$$

$$T = |t|^2 = \left|\frac{1}{M_{11}}\right|^2. \tag{8}$$

Where r and t are the reflection coefficient and the transmission coefficient, and M_{11}, M_{21} are the two matrix elements of the following total system matrix.
For binary structure, we have:-

$$M(a) = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} \cos\beta_1 & \frac{-i}{p_1}\sin\beta_1 \\ -i\,p_1\sin\beta_1 & \cos\beta_1 \end{pmatrix} \begin{pmatrix} \cos\beta_2 & \frac{-i}{p_2}\sin\beta_2 \\ -i\,p_2\sin\beta_2 & \cos\beta_2 \end{pmatrix} \tag{9}$$

Where $a=(d_1+d_2)$ is the lattice constant. The elements m_{11}, m_{12}, m_{21} *and* m_{22} were computed to take the following form:-

$$m_{11} = \cos\beta_1 \cos\beta_2 - \frac{p_2}{p_1}\sin\beta_1 \sin\beta_2 \tag{10-a}$$

$$m_{12} = \frac{-i}{p_1}\sin\beta_1 \cos\beta_2 - \frac{i}{p_2}\cos\beta_1 \sin\beta_2 \tag{10-b}$$

$$m_{21} = -i\,p_1\sin\beta_1 \cos\beta_2 - i\,p_2\cos\beta_1 \sin\beta_2 \tag{10-c}$$

$$m_{22} = \cos\beta_1 \cos\beta_2 - \frac{p_1}{p_2}\sin\beta_1 \sin\beta_2 \tag{10-d}$$

Where:-

$$\beta_1 = \frac{2\pi\, d_1}{\lambda} n_1 \cos\theta_1 \quad , \quad \beta_2 = \frac{2\pi\, d_2}{\lambda} n_2 \cos\theta_2 \tag{11}$$

$$p_1 = n_1 \cos\theta_1 \quad , \quad p_2 = n_2 \cos\theta_2 \tag{12}$$

For TE wave,
and

$$p_1 = \frac{\cos\theta_1}{n_1} \quad \textit{and} \quad p_2 = \frac{\cos\theta_2}{n_2} \tag{13}$$

For TM wave.

For a system of N periods the total characteristic matrix $M(Na)$ can be obtained by using the same expressions which used in equation (10), then the reflection coefficient (*r*) and the transmission coefficient (*t*), can be obtained as follows:-

$$r = \frac{\left(M_{11} + M_{12} f_s\right) f_0 - \left(M_{21} + M_{22} f_s\right)}{(M_{11} + M_{12} f_s) f_0 + (M_{21} + M_{22} f_s)} \qquad (14-a)$$

$$t = \frac{2 f_0}{(M_{11} + M_{12} f_s) f_0 + (M_{21} + M_{22} f_s)} \qquad (14-b)$$

The expressions for f_0 and f_s are defined as follows:-

$$f_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}} n_0 \cos\theta_0 \qquad \text{and} \qquad f_1 = \sqrt{\frac{\varepsilon_0}{\mu_0}} n_s \cos\theta_s \qquad (15)$$

Finally the reflectance and the transmittance are given by;

$$R = \left| r^2 \right| \quad , \quad T = \frac{f_s}{f_0} \left| t^2 \right| \qquad (16)$$

For ternary structure, we have:-

$$M(a) = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} =$$

$$\begin{pmatrix} \cos\beta_1 & \frac{-i}{p_1}\sin\beta_1 \\ -i\, p_1 \sin\beta_1 & \cos\beta_1 \end{pmatrix} \begin{pmatrix} \cos\beta_d & \frac{-i}{p_d}\sin\beta_d \\ -i\, p_d \sin\beta_d & \cos\beta_d \end{pmatrix} \begin{pmatrix} \cos\beta_2 & \frac{-i}{p_2}\sin\beta_2 \\ -i\, p_2 \sin\beta_2 & \cos\beta_2 \end{pmatrix} \qquad (17)$$

Where $M(a)$ is the matrix for one period and $a = (d_1 + d_d + d_2)$ is the lattice constant.

The elements m_{11}, m_{12}, m_{21} *and* m_{22} were computed from the reference

III. NUMERICAL RESULTS AND DISCUSSION

The parameters of the material for the defect layer, n-Ge, in our calculation are $n_i = 2.12\times10^{13}$ cm^{-3}, $\varepsilon_\infty = 16.0$, $M_e = 0.12\ M_0$, $M_{hh} = 0.28\ M_0$, $M_{lh} = 0.044\ M_0$. Where $M_0 = 9.1\times10^{-31}$ Kg is the mass of free electron [41, 42]. The refractive index for SiO_2 is $n_1 = 1.45$ [43] and the refractive index for GaAs $n_2=3.3$ [44]. All parameters are calculated at room temperature 300^0K.

3.1. Transmission spectra in pure and defect photonic crystal

We will study the comparison between two structures; the first one is PC without defect layer, $(LH)^N$, and the second one is PC with defect layer;s designed $(LH)^N D(LH)^N$ and $(LDH)^N$. In figures 4a and 5a, we plot the transmission spectra for photonic crystal without defect layer which has a structure as $(SiO_2/GaAs)^N$ where the thickness of SiO_2 , d_1=350 nm, the thickness of GaAs, d_2= 150 nm, and the number of periods, N=10. Also we plot a transmission spectra for the defect 1D photonic crystal in which the defect layer is n-Ge with thickness, d_D=250 nm is sandwiched between SiO_2 and GaAs in

this formula $(SiO_2/GaAs)^N$ D $(SiO_2/GaAs)^N$ and when we put the defect layer as a ternary layer with the form $(SiO_2/D/GaAs)^N$. We can observe in figure (4-a) within visible spectra there is a PBG in the left and right edges with the structure without defect layer in PCs. The left PBG is located below λ_H=419.64 nm and the right PBG is located above λ_L=614.29 nm, respectively. When we used the defect layer, n-Ge in the middle with the doping density $N_d = 1\times10^{17}$ cm^{-3} and defect thickness d_D=250 nm. Figure (4-b) show that the PBG realize a transmission narrow band filter and two transmission peaks at wavelengths, λ=414.29 nm and λ=625 nm are obtained. The value of transmittance at this wavelength is small and the left PBG is located below λ_H=417.86 nm and the right PBG is above λ_L=610.71 nm. We have designed new structure in figure (4-c), $(SiO_2/ D/GaAs)^N$, and we have observed within the visible spectra many PBGs at different positions.

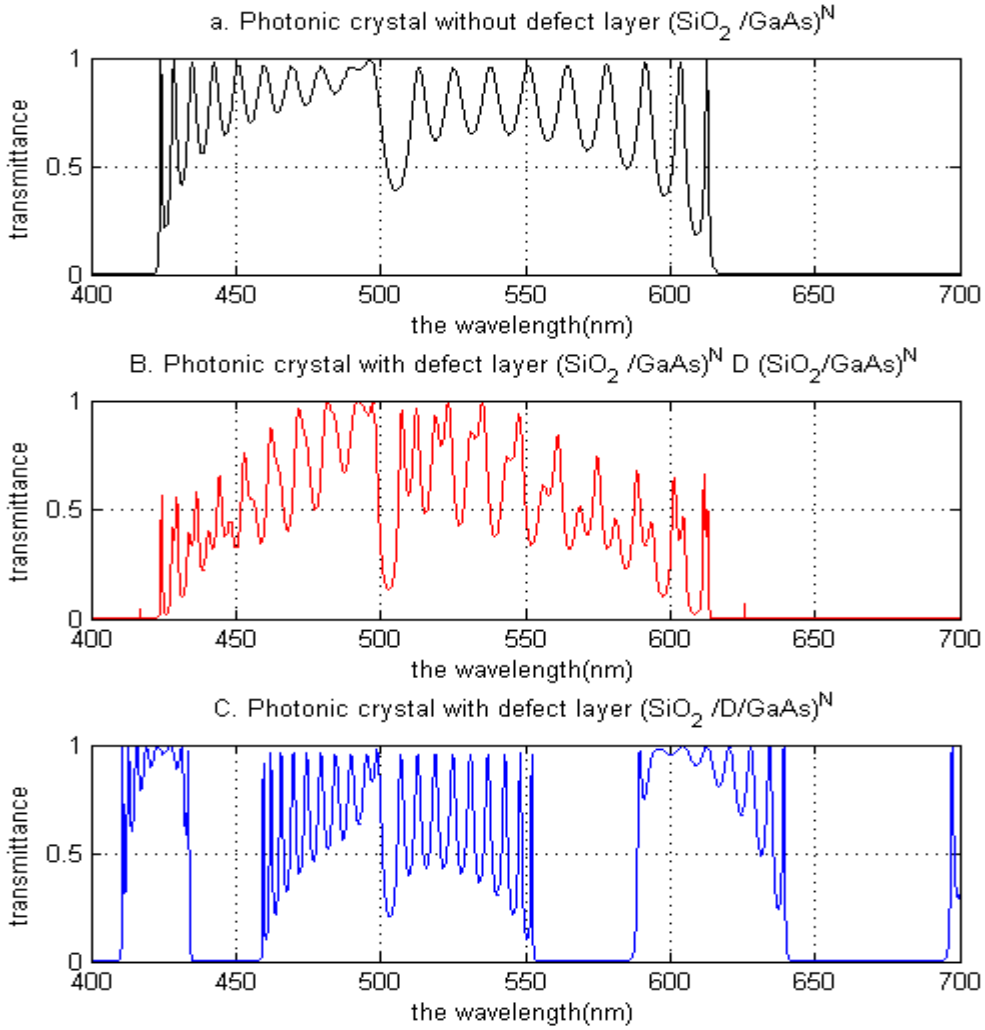


Figure (4):- Transmission spectra for 1D binary SiO_2 /GaAs PBG structure for d_1= 350 nm,d_2 =150 nm and photonic crystal with defect layer n-Ge is d_D=250 nm in visible region.

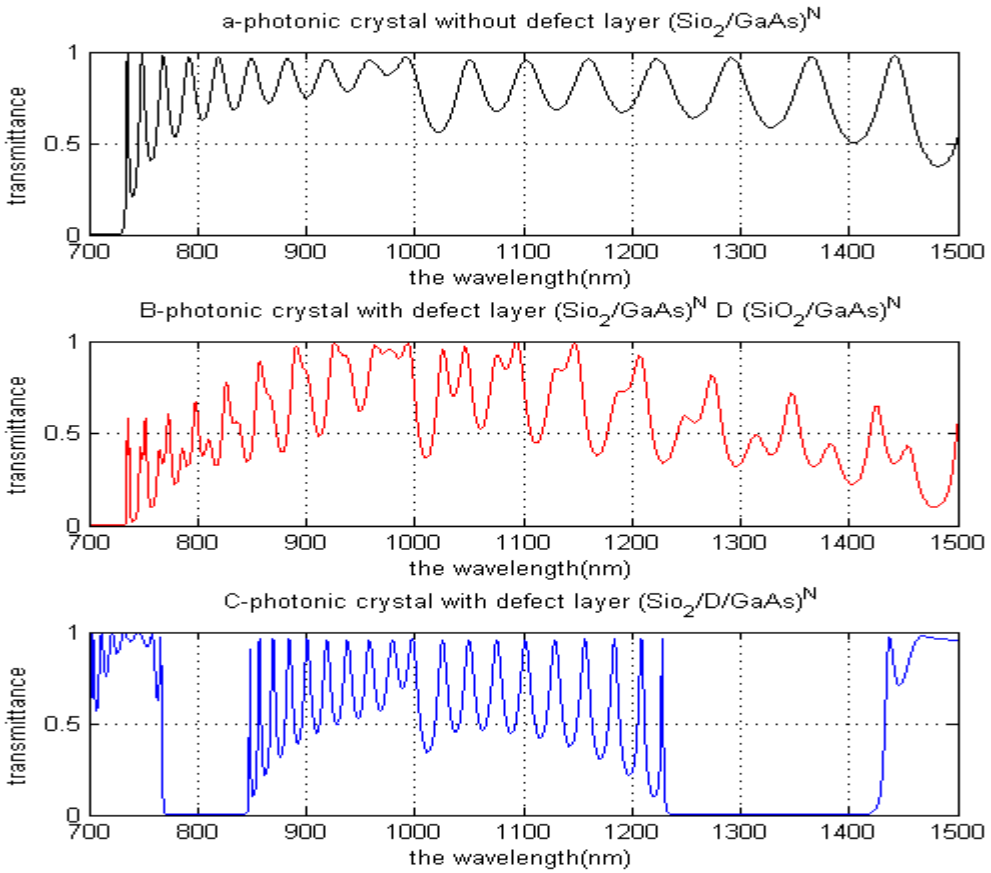


Figure (5):- Transmission spectra for 1D binary SiO_2 /GaAs PBG structure for d_1= 350 nm and d_2 =150 nm and photonic crystal with defect layer n-Ge considering d_D=250 nm in infrared region.

We have designed a new filter within near far infrared range in figure (5) by using one dimensional photonic crystal with and without defect layer. PC structure without defect layer within near infrared (NIR) observed in (figure (5-a) and PC structure with defect layer observed in (figure (5-b)). We have observed in figures (5-a) and (5-b), there is no PBG within NIR range (750-1500), just the intensity of the transmission beaks is decreased with the defect layer in figure (5-a). We can observe something is different in figure (5-c) where is the PC structure is $(SiO_2/ D/GaAs)^N$. We can obtained two PBGs within NIR range; one of them is located between (770-845 nm) and the second one is wider than the first between (1230-1420nm).

3.2. Transmission peaks as a function of Doping density in n-Ge:-

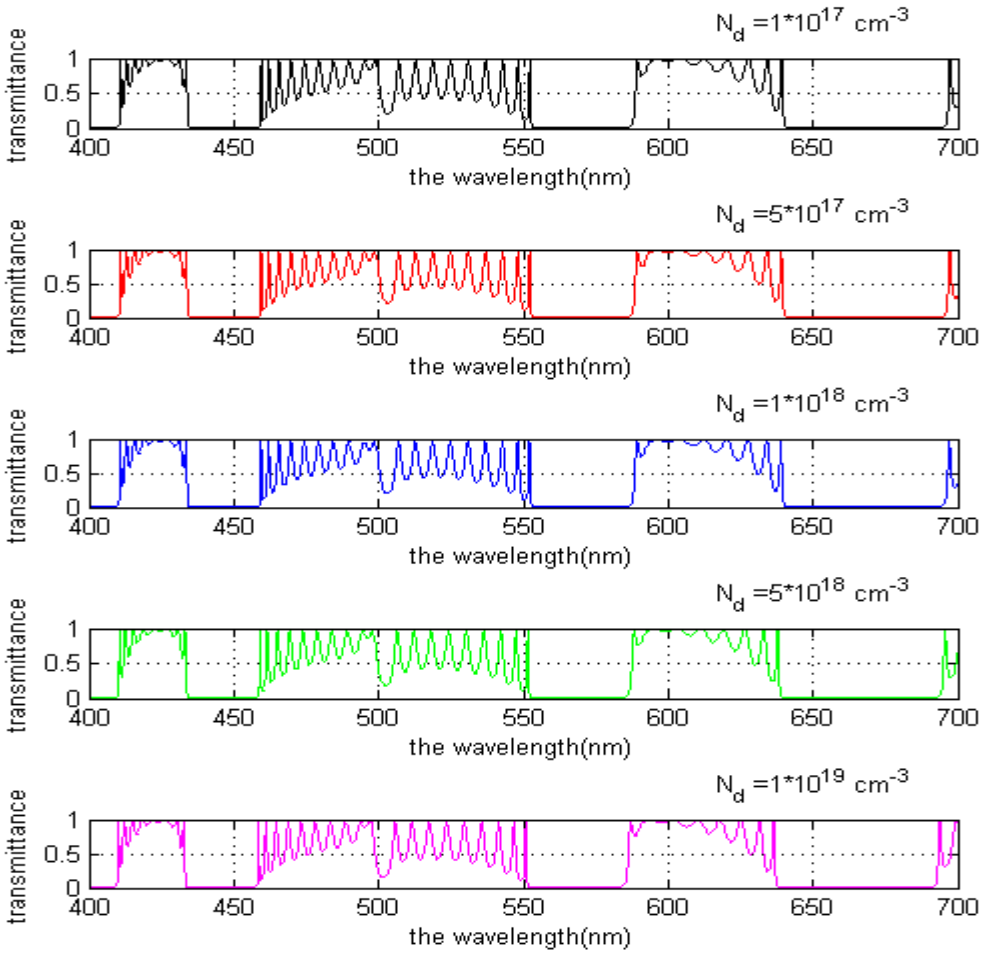


Figure (6a):- Transmission spectra for the defect 1D PCs at normal incidence, in visible region spectra ,with different doping densities N_d =1×10^{17}, 5×10^{17}, 1×10^{18}, 5×10^{18}, and 1×10^{19}cm^{-3} respectively, considering the thickness of defect layer n-Ge is d_D=250 nm.

Now we studying the filter properties by using the following structure $(SiO_2/D/GaAs)^N$. In this structure there are a number of PBGs in visible and infrared region and the shifting occurs in the PBG because of the change of the doping density in n-Ge at the same thickness. In figure (6a), we plot the transmittance spectra for different donor densities of the defect layer N_d =1×10^{17}, 5×10^{17}, 1×10^{18}, 5×10^{18}, and 1×10^{19} cm^{-3} respectively, and d_D=250 nm. This figure shows that, four PBG are obtained and as the doping density increases, the filtering process is changeable where the PBG is shifted to short wavelength (blue shifted). At N_d=1×10^{17} cm^{-3}; the first PBG is located below λ_H= 405.357nm and at high doping density N_d=1×10^{19}cm^{-3}; the first PBG is located below λ_H=407.143 nm. The final PBG is located between (λ_L= 637.5nm- λ_H =691.71nm). There are also many blue shifted PBGs at N_d=1×10^{17} cm^{-3} in figure 6b and located between (λ_L= 775nm- λ_H =840nm), the other PBG with a wider bandwidth between ((λ_L= 1222.5nm- λ_H =1420nm). Also figure 6b show that, two PBGs; the first PBG at N_d=1×10^{19}cm^{-3} is located between (λ_L= 765nm- λ_H =830nm) and the second PBG is wider than the first PBG and located in (λ_L= 1220nm- λ_H =1385nm) .

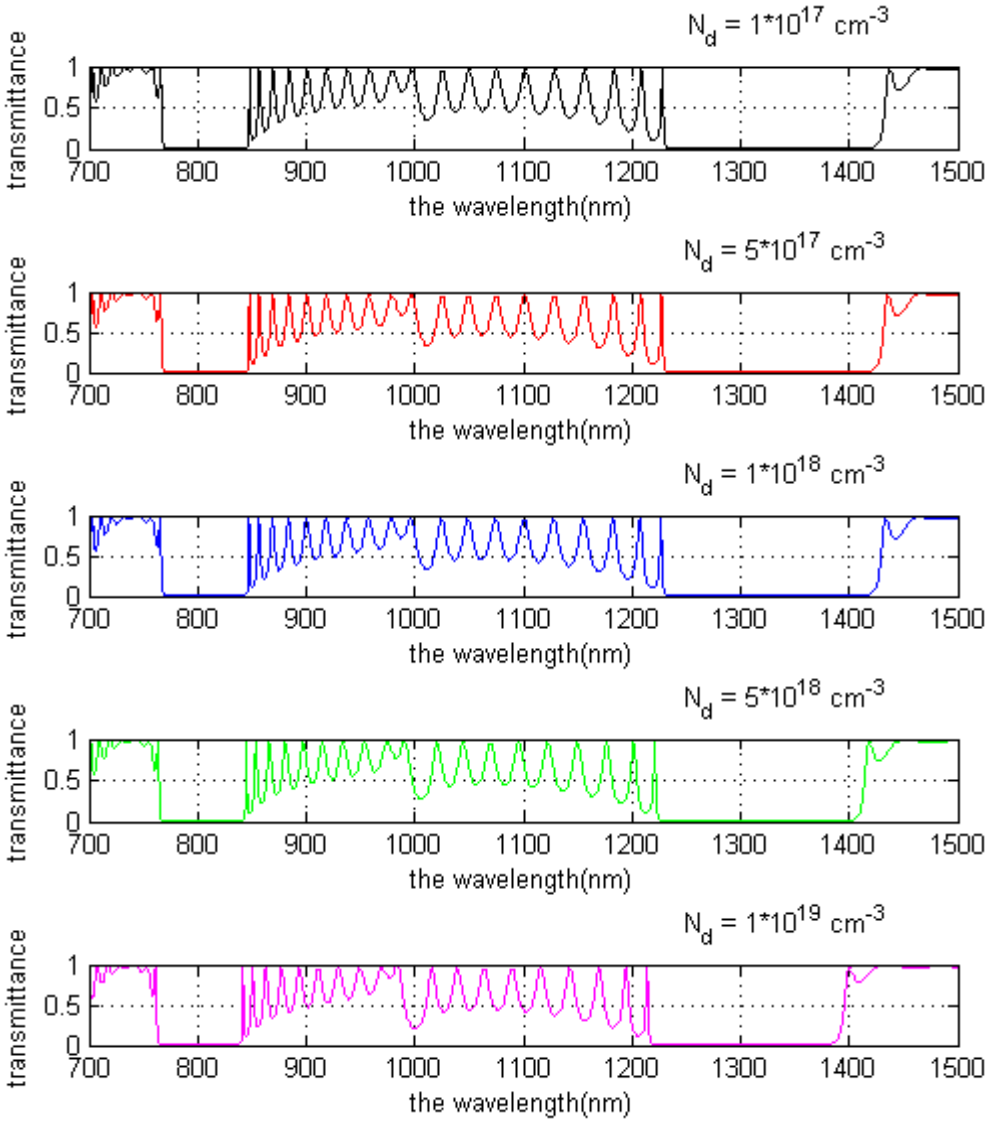


Figure (6b):- Transmission spectra for the defect 1D PC_s with normal incidence in near infrared spectra at different doping densities N_d =1×10^{17}, 5×10^{17}, 1×10^{18}, 5×10^{18}, and 1×10^{19}cm^{-3} respectively, considering the thickness of defect layer n-Ge is d_D=250 nm.

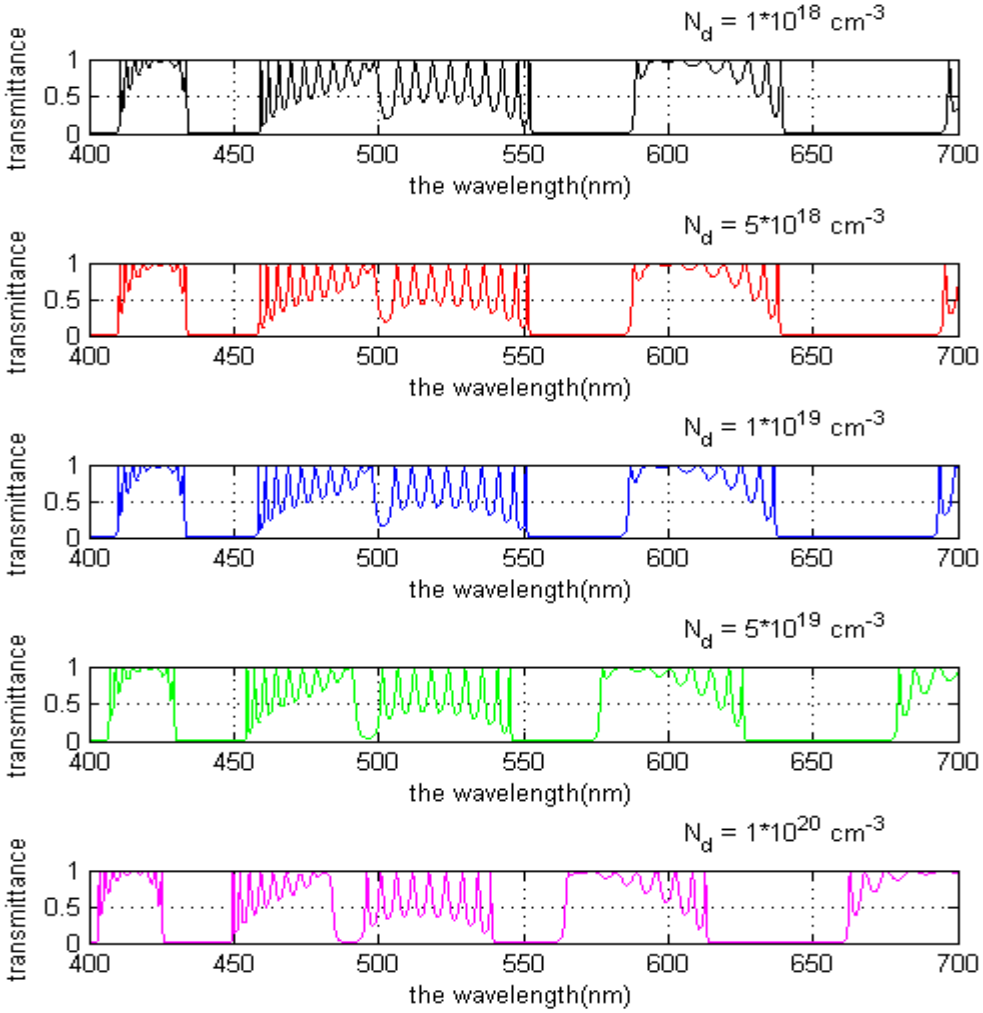


Figure (7a):- Transmission spectra for the defect 1D PC_s with normal incidence, in visible region spectra, at different doping densities N_d =1×10^{18}, 5×10^{18}, 1×10^{19}, 5×10^{19}, and 1×10^{20}cm^{-3} respectively, considering the thickness of defect layer n-Ge is d_D=250 nm.

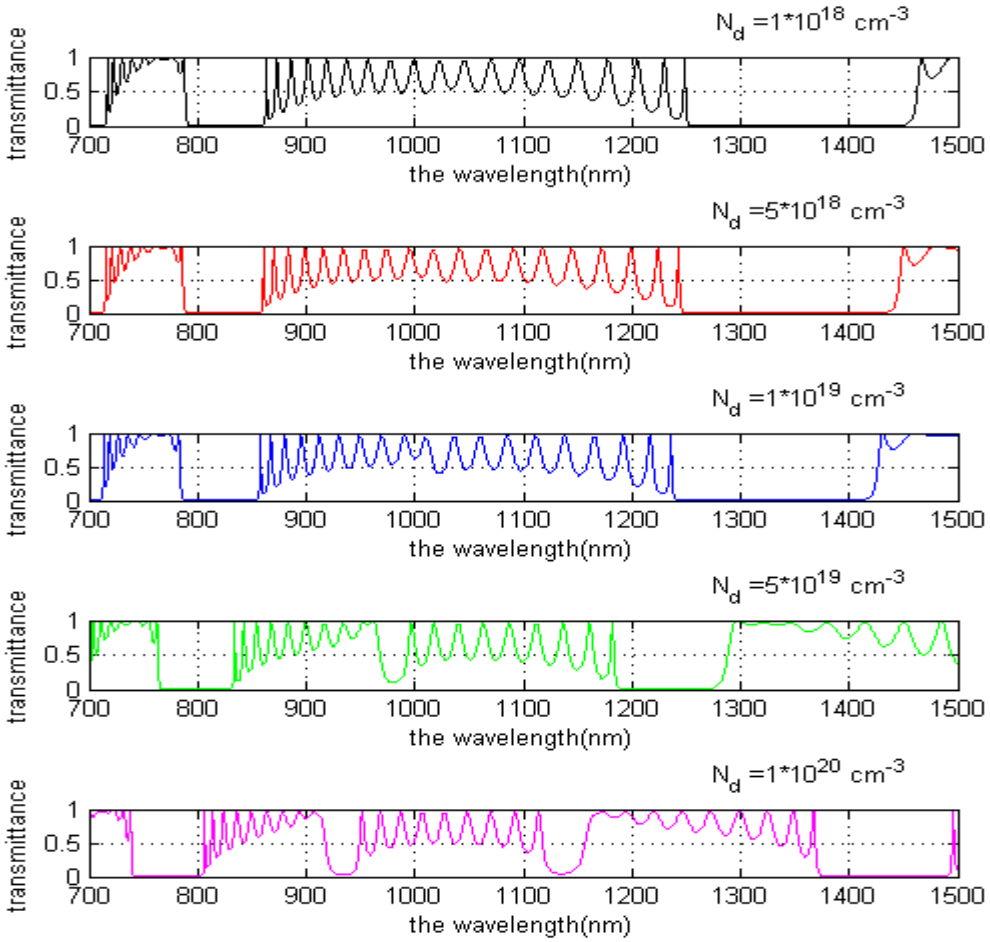


Figure (7b):- Transmission spectra for the defect 1D PC_s with normal incidence in near infrared spectra with different doping densities N_d =1×10^{18}, 5×10^{18}, 1×10^{19}, 5×10^{19}, and 1×10^{20}cm^{-3} respectively, considering the thickness of defect layer n-Ge is d_D=250 nm.

A similar blue shifted in figures (7a, 7b), is also seen but the shift is very large than that in figures (6a, 6b), and we found that as the doping density increases to N_d =1×10^{20}cm^{-3}, the number of PBG is increases also. The width of the new PBG is small and the width of the first PBG decreases as the doping density increase until disappears. From (6a, 6b, 7a, 7b) we can make the changeable filter because the position of PBG can be shifted by the changing of doping density, this in visible and near infrared spectra. The defect D can be taken different types of semiconductors such as n-Si, n-InSb or n-GaAs, this different types leads to different filters.

IV. CONCLUSION

We have been investigated theoretically the filtering properties for a defect photonic crystal structure in visible and near infrared spectra for $(SiO_2/n\text{-}Ge/GaAs)^N$. We show that, the transmission can be shifted by the variation of some variables such as doping density, the defect thickness, and the angle of incidence for both TE and TM waves. By using the defect n-Ge, we have found that the photonic band gap is blue shifted when the doping density increases in visible region. Also by increasing the concentration of the defect layer, the number of the PBG increases. A filter with multiple channels (multiple PBG) can be used in the optical communications.

V. FUTURE WORK

Photonic crystals are attracted to all authors in recent years. In the future work we will design different one dimensional photonic crystal as a sensor and a good filter. Also in the suture we will obtained our study in two dimensional photonic crystals as well as the photonic crystals in biology.

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