Journal of Electron Devices, Vol. 17, 2013, pp. 1400-1405

Journal of Electron Devices
www.jeldev.org

NOVEL BAND-PASS FILTER DESIGN USING PHOTONIC MULTIPLE QUANTUM WELL STRUCTURE WITH p-POLARIZED INCIDENT WAVE AT 1550 nm

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Received 31-12-2012, online 8-01-2013

ABSTRACT
Transmittance of one-dimensional photonic multiple quantum well structure is numerically computed using transfer matrix technique for normal and oblique incidence of p-polarized electromagnetic wave. Dimensional configuration and material composition of the structure is varied to observe the modulation in filter bandwidth at 1550 nm for optical communication purpose. $Al_xGa_{1-x}N/GaN$ composition is chosen as unit block of the periodic organization, with $Al_xGa_{1-x}N$ layer as the barrier and GaN as well of the 11-layer structure. Refractive index of $Al_xGa_{1-x}N$ is considered as a function of mole fraction and operating wavelength following Adachi's model. Material having lower refractive index possesses greater width in lateral dimension compared to that of the material having higher refractive index. Variation of incident angle of p-polarized wave along with suitable choice of slab thicknesses and Al mole fraction makes it efficient band-pass filter at desired frequency region.
Keywords: Photonic Multiple Quantum Well, Transmittance, Transfer Matrix Technique, p-polarization, Band-Pass Filter

I. INTRODUCTION

Photonic crystal is a multilayer periodic arrangement where propagation of electromagnetic wave along quantized direction is governed by thicknesses and refractive indices of the materials. This is a revolutionary building block for the next generation optical communication due to its inherent characteristics of restricting e.m wave of certain wavelength and simultaneously allowing other spectra. This arises by virtue of the concept of photonic bandgap; may be exhibited in one, two or three dimensions. Among them, 1D photonic crystal structures, having advantage of theoretically analyzing optical characteristics near accurately along with lack of confinement in other two spatial dimensions; are already exercised to construct LASER [1], LED [2], waveguide [3], switch [4]. Photonic crystal fibers are developed on this concept, and has already been used in optical communication [5], optical nonlinearity [6], integrated photonics [7], sensing [8], high power technology [9], quantum information science [10] etc. Experimental characteristic validation of these novel devices are well-supported by the advancement in microelectronics technology.

Jiang [11] established the fact that quantized states are available in photonic crystal due to photonic confinement, and transmission property can be explained by resonant tunneling. Xu [12] fabricated and characterized 1D photonic MQW structures using porous Si, and reflectance spectra are analyzed at lower wavelength region. Chen [13] calculated transmission coefficient by plane-wave expansion method. Kalchmair [14] developed infrared photodetector using $Al_{0.3}Ga_{0.7}As/GaAs$ material for 2D confined PC slab. Xu [15] again fabricated 1D photonic crystal using nanoporous Si, and characterized in visible spectra. Researchers also showed that these MQW structures can be used in photonic integrated circuits [16]. Ming [17] calculated the effect of thicknesses of different slabs on transmission property, and also effects of the coupling between resonance photonic states. It is recently established that incorporation of metamaterial

modifies the optical filter property [18] of 1D PC structure. Effect of refractive index of materials on transmission spectra [19] for designing multi-narrow channel band filter was analyzed by transfer matrix technique. For modeling HBT at lower wavelength region, GaAs/AlGaAs material composition based PBG structure is theoretically considered [20]. Optical transmission was also studied using negative refractive index material [21] at higher frequency.
In the present paper, transmittivity of photonic multiple quantum well (PMQW) structure is characterized for normal and oblique incidence of p-polarized e.m wave at 1550 nm for different layer dimensions and material compositions to analyze the width of pass-band of the proposed band-pass filter. Material properties are considered as function of composition and operating wavelength to make the computation more realistic. The study will help the designers to design the photonic filter as required for applications in the domain of optical communication.

II. MATHEMATICAL MODELING

Consider the smallest unit of 1D photonic crystal structure comprising of GaAs/$A_{lx}Ga_{1-x}As$ material composition where forward and backward propagating waves are given by-

$$a_2 = t_{21}a_1 + r_{12}b_2 \qquad (1.1)$$

$$b_1 = t_{12}b_2 + r_{21}a_1 \qquad (1.2)$$

where r_{ij} and t_{ij} are reflectivity and transmissivity in passing from layer *i* to layer *j*. They are related to the refractive indices of the materials following Fresnel's equation as

$$r_{ij} = -r_{ji} = \frac{n_i - n_j}{n_i + n_j} \qquad (2.1)$$

and

$$t_{ij} = t_{ji} = 2\frac{\sqrt{n_i n_j}}{n_i + n_j}. \qquad (2.2)$$

Eq. 2.1 and Eq. 2.2 are valid for normal incidence of input wave. The reflectivities *r* and transmissivities *t* are coupled by the relation

$$r^2 + t^2 = 1. \qquad (3)$$

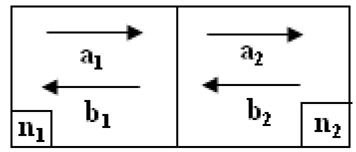

Fig 1: Schematic picture of forward and backward waves in smallest unit of 1D photonic crystal

For p-polarized incident wave at angle θ_1, interface reflectivities are given by

$$r_{12} = -r_{21} = \frac{n_1\cos(\theta_2) - n_2\cos(\theta_1)}{n_1\cos(\theta_2) + n_2\cos(\theta_1)}. \qquad (4)$$

From the wave equations, transfer matrix corresponding to the interface can be obtained as

$$M^T{}_{1,2} = \frac{1}{t}\begin{pmatrix} 1 & r_{21,12} \\ r_{21,12} & 1 \end{pmatrix}. \qquad (5)$$

Considering the phase factor of the field propagating through uniform medium, propagation matrix is given as

$$P_{1,2} = \begin{pmatrix} \exp[jk_{1,2}d_{1,2} & r_0 \\ 0 & -\exp[jk_{1,2}d_{1,2}] \end{pmatrix}. \qquad (6)$$

where d_i is the propagation length in i^{th} layer, and k_i is the wavevector in that layer. Thus, transfer matrix for the elementary cell is

$$M = M^T{}_1 P_1 M^T{}_2 P_2. \qquad (7)$$

For a perfectly periodic medium composed of N such elementary cells, the total transfer matrix for such a structure is

$$M_{tot} = M_N\ . \qquad (8)$$

Transmission coefficient is given by

$$T = \frac{1}{M_{11}{}^2(tot)}. \qquad (9)$$

III. RESULTS AND DISCUSSION

Using equation (9) derived earlier, transmittivity of the 1D photonic crystal structure is computed as function of operating wavelength centered at 1550 nm. In Fig 2, transmittance is obtained by varying material composition of the barrier layer ($Al_xGa_{1-x}N$) for normal incidence of p-polarized wave. It is observed that with higher Al mole fraction, bandgap increases, which effectively decrease the refractive index. This causes the sharp fall of transmission at lower wavelength, and hence the passband shifts at the left w.r.t centered wavelength. It may also be concluded that with slight variation in Al percentage, the filter property improves due to sharp reduction of transmittivity. The simulation is carried out for specified dimension of the well and barrier widths.

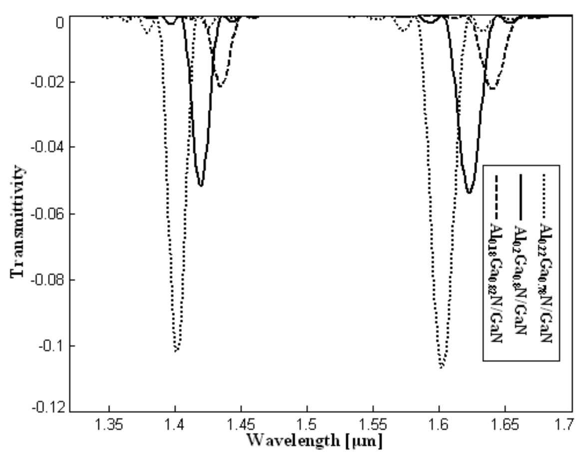

Fig 2: Transmittivity vs wavelength of em wave for normal incidence with constant layer dimensions and different material compositions

By varying width of barrier and well regions independently, it is observed that the bandwidth of the filter changes around the central wavelength. If barrier width of the structure is increased up to a critical value, passband width decreases, which results in a narrow band filter. This is plotted in Fig 3a. Higher dimension of barrier than the critical magnitude results opposite change in filter bandwidth. But by increasing the width of well, passband width monotonically decreases; as shown in Fig 3b. This is due to the fact that by increasing thickness of the either of the dielectric slab, periodicity increases, which affects the elementary cell matrix following Eq (7). Hence the transfer matrix for the structure is affected, which causes the reduction of wave at the output along the quantized direction with increase of wavelength. This initiates the early fall of transmittance. Hence bandwidth of the filter decreases.

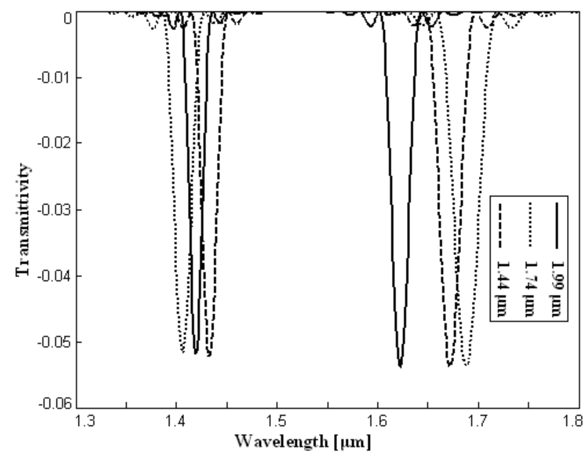

Fig 3a: Transmittivity vs wavelength of em wave for normal incidence for $Al_{0.2}Ga_{0.8}N/GaN$ composition and constant well width but different barrier width

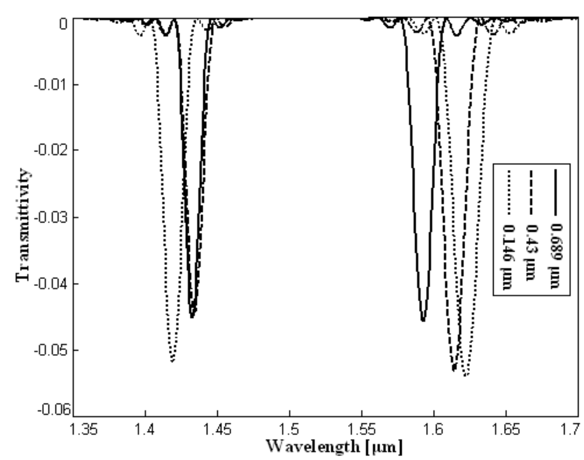

Fig 3b: Transmittivity vs wavelength of em wave for normal incidence for $Al_{0.2}Ga_{0.8}N/GaN$ composition and constant barrier width but different well width

Due to oblique incidence, propagating wave has to traverse longer distance than the case of normal incidence, and hence Brillouin zone will be quenched to a smaller wave-vector range. As a result, photonic bandgap will shift towards smaller frequencies i.e., larger wavelengths. So the bandwidth of the filter will shift towards higher wavelength region. This is plotted in Fig 4a. With gradual increase of incidence angle, the filter bandwidth shifts towards right of the central wavelength due to the shift of photonic bandgap. This is plotted in Fig 4b with the fact that the structure is unable to exhibit complete bandgap, i.e., there does not exist any arbitrary wavelength for which both TE and TM wave will exhibit bandgap. But the simulation is restricted to the lower incidence angles, as in the limiting case; there is no possibility of existing photonic bandgap.

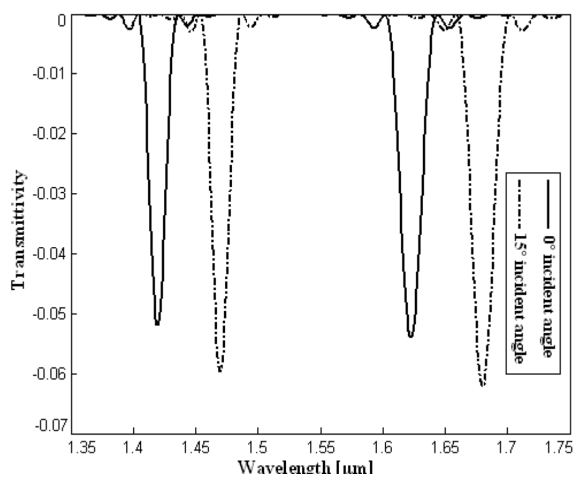

Fig 4a: Comparative study of transmittivity vs. wavelength of em wave for normal and oblique incidence with constant barrier and well widths and $Al_{0.2}Ga_{0.8}N/GaN$ composition

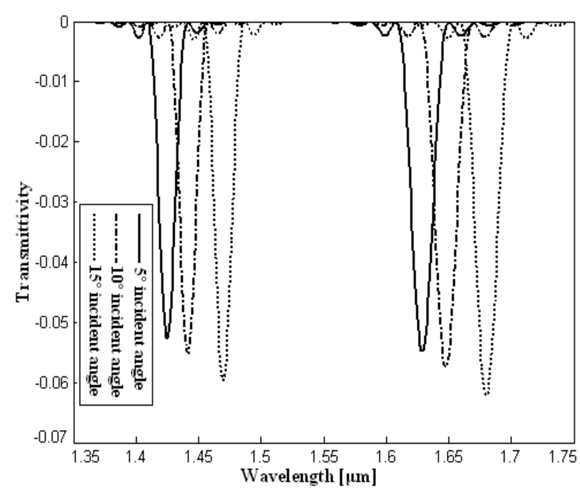

Fig 4b: Transmittivity vs. wavelength of em wave for different oblique incidence angle with constant barrier and well widths and $Al_{0.2}Ga_{0.8}N/GaN$ composition

By changing material composition of the barrier layer with oblique incidence, the nature of shift of the band-pass filter remains same with a variation in the magnitude of transmittivity only. This is shown in Fig 5. This is because due to the oblique incidence, the dispersion curve is restricted, and the bandgap becomes "incomplete" one, so signal decreases more at some particular frequency values.

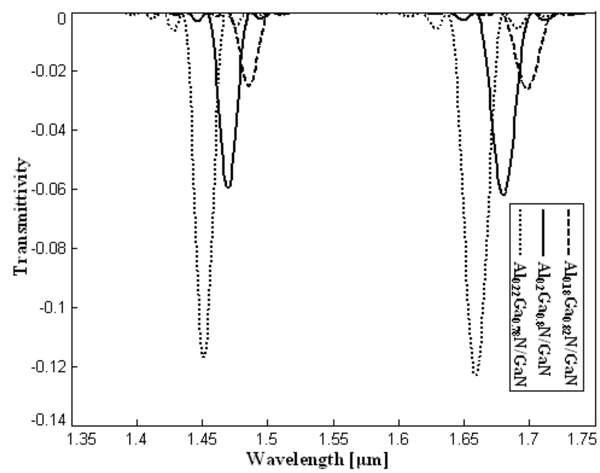

Fig 5: Transmittivity vs wavelength of em wave for 15° oblique incidence for constant layer dimensions and different material compositions

By varying width of the either layer independently for oblique incidence, two distinct changes may be observed compared to the case of normal incidence. The width of filter increases for a particular dimension when oblique incidence of the wave is considered, which is due to the same physical effect discussed earlier. Also the magnitude of transmittance becomes smaller at particular frequencies, may be observed from Fig 6(a) and Fig 6(b). So it provides better characteristics from the point of view of filter design.

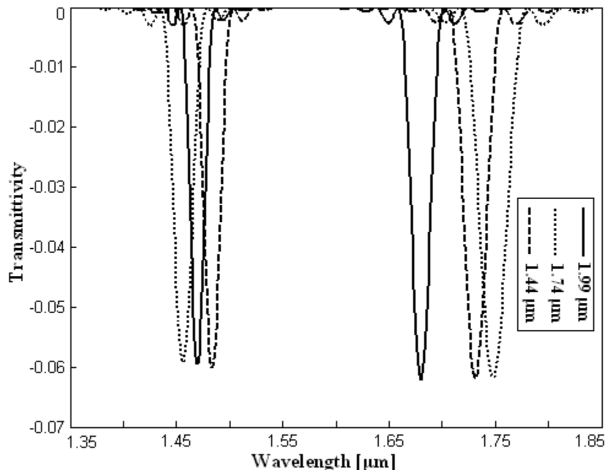

Fig 6a: Transmittivity vs wavelength of em wave for 15° oblique incidence for $Al_{0.2}Ga_{0.8}N$/GaN composition and constant well width but different barrier width

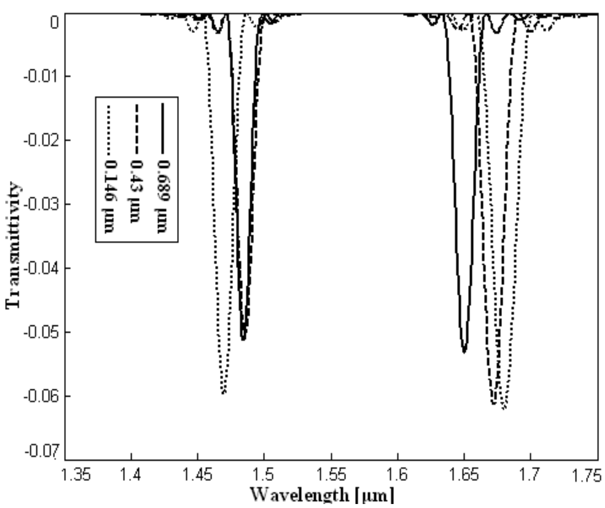

Fig 6b: Transmittivity vs wavelength of em wave for 15° oblique incidence for $Al_{0.2}Ga_{0.8}N$/GaN composition and constant barrier width but different well width

IV. CONCLUSION

In summary, transmittivity of one-dimensional photonic multiple quantum well structure is computed for different slab thicknesses and barrier material compositions. Normal and oblique incidence of p-polarized electromagnetic wave is considered on the structure with 1550 nm wavelength. Dependence of passband spectrum on dimension of the materials as well as on the Al mole fraction gives the potential advantage of tuning the filter bandwidth. Also variation of incident angle modifies the filter property due to formation of incomplete photonic bandgap. Parameters for the simulation are chosen in such a way that centre wavelength of the proposed bandpass filter is always surrounded by two photonic bandgaps; which makes it a better candidate for optical communication.

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