Computation of optical field intensity in nitride based superlattice nanostructures for temperature range (300-370 K)

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Detailed analysis of near and far field intensity distribution in Gallium nitride superlattice structure has been carried out through the general solutions of wave equation and effective index has been deduced using effective index method to explore optical confinement and optical field. To obtain the better optical confinement in Superlattice structure, the physical and structural parameters like thickness of wells and barriers, wavelength, Aluminum mole composition of barrier and temperature have been optimized. The analysis of far field intensity is carried out as a function of wavelength and aluminum mole fraction in the temperature range of 300 to 370 K. It is deduced from our analysis that the Aluminum mole fraction in the barrier region strongly influences near field, far field divergence and the optical confinement.

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1. Introduction

Quantum well and superlattice structures are ultra fine-layered media capable of confining electrons and quasi-particles with quantized energy levels. Electronic transitions between sets of discrete energy levels and bands have long been employed to generate and detect electromagnetic radiation for various frequencies. The recent advancement of nanofabrication technology and characterization techniques has revitalized the applications of Superlattice and Multiple Quantum Well structures [1, 2]. These structures provide large optical gain, low threshold current density and better confinement because of its very high recombination efficiency.

The development of low threshold current semiconductor injection lasers is essential for the realization of efficient optoelectronics integrated circuits. Recently, enormous progress found in the electronics market, in which nano and micro-technologies are significantly used in high power and high frequency devices. In optical communication systems, the III-V nitride materials have a great importance due to their large band gap. The group-III nitride semiconductor alloys AlN–GaN–InN are recognized as an important materials system for the optoelectronic devices in the spectral range from infrared to ultraviolet. A compact ultraviolet light source has a wide variety of applications [3- 13]. The recent developments in the field of GaN-based optoelectronic devices have stimulated several experimental and theoretical studies on GaN/AlGaN Superlattice. Despite of the large number of reports on the fabrication of nitride-based devices, there has been a small number of theoretical investigations of near and far field intensities and their temperature and wavelength dependence on superlattice nanostructures.

Optical properties of Superlattice structure have attracted a great deal of interest recently [14]. Fig. 1 shows the planner structure of the superlattice structure and the far field distribution of the light. The refractive index is dependent on the composition of the semiconductor alloys, temperature and the wavelength of the light. The light confinement of this quantum structure is found at the centre of the total device length. The confinement is possible due to the band gap discontinuity between the well and barrier region. The required optimization has been carried out with the help of Maxwell's and wave equations.

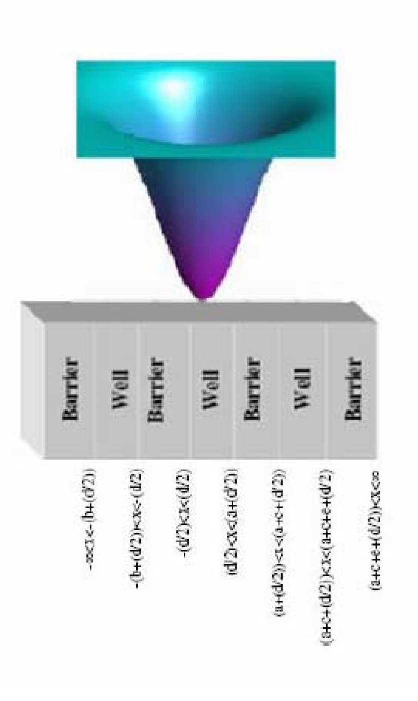


Fig. 1. Superlattice structure.

The quantum phenomena of electronic energy levels, electron wave function behavior and electron confinement in these quantum structures [15-18] of ultra thin semiconductor layers allows to study the quantum phenomena. Recently, we have carried out the analysis of wave function intensity, eigen energy and transmission coefficients in GaN/AlGaN superlattice nanostructure [21] using Transfer Matrix Method (TMM). The effect of change in Aluminum mole fraction in AlxGa1−xN barrier region has been considered through variable effective mass. The behavior of wave function intensity has been studied for superlattice structure by changing the barrier width.

There is great scope for the analysis and optimization of the physical parameters to improve the performance and characteristics of the quantum structure laser diodes. Present work explores the phenomena of optical confinement and field intensity behavior in superlattice nanostructure for three numbers of wells. The complex quantum structure laser diodes are capable of working at elevated operating temperatures, which is very significant characteristic of III group nitride based materials. We have reported here analysis of near and far field intensities for GaN based superlattice structure for the temperature range 300-370 K.

The main objective of the paper is to optimize the Superlattice structure for the better optical confinement. We have carried out the optimization of structural and physical parameters to obtain the near and far field intensities. The paper is organized as follows: second part of this paper describes the necessary mathematical analysis for the optimization of field intensities. The most significant results are discussed in third section following which are concluding remarks.

2. Physical equations

The quantum confinement has been obtained in superlattice nanostructures due to ultra thin layers of well region. However, optical field is very imperative to be optimized for the higher modal gain in superlattice nanostructures. To obtain the optical confinement in the narrow well region it is necessary to sandwich it in between the thick barrier regions. The GaN/AlGaN based Superlattice structure has been analyzed by assuming the plane wave and from Maxwell's equations (1), we can get a scalar wave equation for each ith layer as follows:

$$\frac{\partial^2}{\partial x^2}\varphi_i + \left(k_0^2\varepsilon_i + \gamma^2\right)\varphi_i = 0 \qquad (1)$$

Where, φ_i is Ey for TE mode at ith layer, γ is the modal propagation constant and k_0^2 is $\omega^2\mu_0\varepsilon_0$.

For solving the Maxwell equation, the used boundary conditions are φ_i and $\partial\varphi_i/\partial x$ must be continuous over different layers and the arbitrary constants have been obtained by using the normalization condition. The general solutions of the Maxwell equation for triple quantum well Superlattice structure are as follows:

$$\left.\begin{array}{ll}
\psi_1 = A_1 \exp k(x+g+b+(d/2)) & -\infty < x < -(b+(d/2)) \\
\psi_2 = A_2 \cos q(x+b+(d/2)) + A_3 \sin q(x+b+(d/2)) & -(b+(d/2)) < x < -(d/2) \\
\psi_3 = A_4 \cos k(x+(d/2)) + A_5 \sin k(x+(d/2)) & -(d/2) < x < (d/2) \\
\psi_4 = A_6 \cos q(x-(d/2)) + A_7 \sin q(x-(d/2)) & (d/2) < x < (a+(d/2)) \\
\psi_5 = A_8 \cos k(x-a-(d/2)) + A_9 \sin k(x-a-(d/2)) & \\
 & (a+(d/2)) < x < (a+c+d/2)) \\
\psi_6 = A_{10} \cos q(x-a-c-(d/2)) + A_{11} \sin q(x-a-c-(d/2)) & \\
 & (a+c+(d/2)) < x < (a+c+e+d/2))
\end{array}\right\}$$

$$\psi_7 = A_{12} \exp k(x-a-c-e-f-(d/2)) \qquad (a+c+e+d/2)) < x < \infty$$

$$(2)$$

Where q and k are the wave numbers for core region and the cladding region respectively and they satisfy the following conditions that relate with propagation constant along x direction:

$$\left.\begin{array}{l}
k = k_0\sqrt{N^2 - n_c^2} \\
q = k_0\sqrt{n_f^2 - N^2}
\end{array}\right\}$$

$$(3)$$

Here, N is the effective index, n_f is the refractive index of the quantum well region and n_c is the refractive region of the surrounding region of the quantum well. A_1, A_2 …A_{12} are the arbitrary constant of the well and barrier region. The Eigen value equation using arbitrary constant for calculating the effective index is

$$-\tan(q * c) = (A_{10} * k + A_{11} * q)/(A_{10} * q - A_{11} * k) \tag{4}$$

The far field intensity has been computed by taking the Fourier transform of near field ψ(x). The far field intensity can be deduced from the following relation.

$$I(\theta) = I_0\left(\frac{\cos^2\theta}{\left|k_0\cos\theta + \beta^2\right|}\left|\psi_x(k_0\sin\theta)\right|^2\right) \tag{5}$$

Here, θ is the angle made by the emitted photons at the end face of the quantum well laser diode. I_0 is the near field intensity of the structure.

$$\begin{aligned}&\varepsilon_r(E,x,T) = C(x,T) + \frac{A(x,T)}{E_g^{1.5}(x,T)} * \frac{2-\sqrt{1+y}-\sqrt{1-y}}{y^2}\\&y = [E + i\Gamma(x,T)]/E_g(x,T)\\&n = \sqrt{\varepsilon_r}\end{aligned} \tag{6}$$

Here, ε_r is dielectric function which depends on temperature, mole fraction and wavelength, E is the photon energy, n is refractive index.

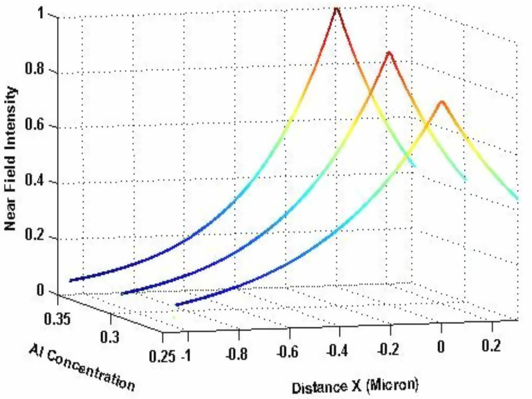
$$\begin{aligned}&C(x,T) = 2.49227*10^{-3}T - 1.80*10^{-6}T^2 - (0.74 + 4.61*10^{-3}T - 5.33*10^{-6}T^2)x\\&A(x,T) = [79.30 - 8.37*10^{-2}T + 6.73*10^{-5}T^2 + (1899 + 0.13T - 1.76*10^{-4}T^2)x + 37.51x^2]eV^{1.5}\\&\Gamma(x,T) = [-8.69 + 4.13*10^{-2}T + (24824 - 0.19T)x^2]*10^{-3}eV\end{aligned} \tag{7}$$

At this juncture, C(x,T) , A(x,T), Eg(x,T) and Γ(x,t) are the simple analytical functions of combination of concentration and temperature. The above equations show the effect of the material parameters; wavelength, mole fraction and the temperature on the refractive index. [19, 20]

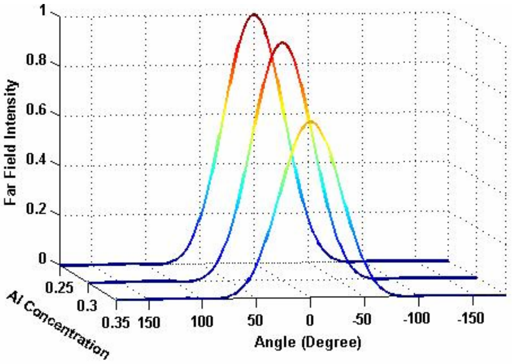
3. Results and discussion

The Superlattice structure is having a lower threshold current and better efficiency than the heterostructure. Here, we have carried out analysis of field intensity as a function of Aluminum composition in the barrier and wavelength in the temperature range of 300 to 370 K. Initially, effective index of the superlattice structure has been deduced through the effective index method using Eigen value equations. Near field solutions to the wave equations has been obtained for the fundamental mode. Far field intensity has been deduced from the near field and studied to estimate the divergence angle.

The near field intensity shows the sharp confinement at the centre region. Refractive index of well and barrier regions was considered to be 2.3189 and 2.2287 respectively. Near field shows spatial intensity distribution of the emitted light near the wave-guide end face. One of the important parameter is the Far field intensity, which is highly useful for the coupling efficiency and shows the angular intensity distribution far from the end face. Aluminum mole composition of the barrier region plays vital role in confinement of the optical field. Effect of Aluminum mole fraction on the near field has been illustrated as shown in Fig. 2(a) for the 300-nanometer wavelength at 300 K. It reveals from our analysis that near field intensity shows greater confinement for Aluminum mole fraction of 0.35 due to increase in refractive index difference between well and barrier. The band gap of the AlGaN material depends upon the aluminum concentration and thus the refractive index of the material. Due to increase in aluminum composition the refractive index lowers down and the index step between core and cladding layer therefore increases. Fig. 2 (b) illustrates the far field intensity variation with the Aluminum mole fraction. Minimum spread of far field has been estimated for the higher aluminum concentration.



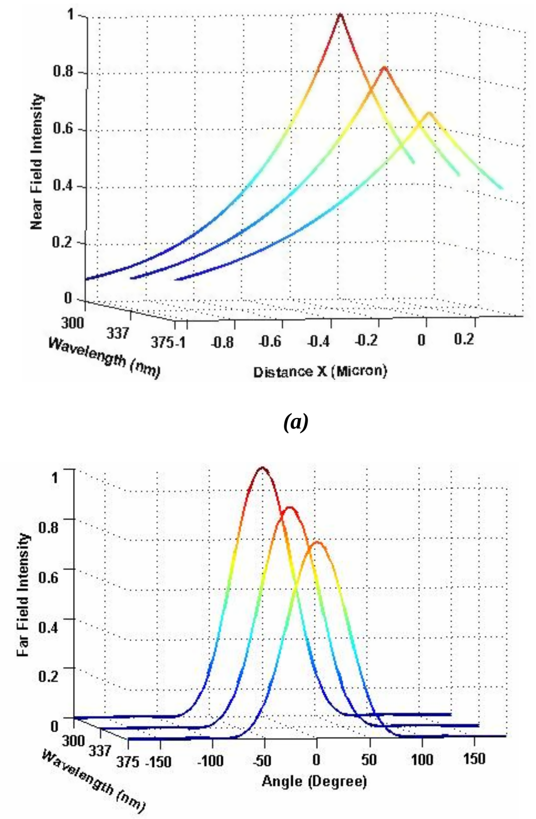
(a)



(b)

Fig. 2. (a) *Near field intensity as a function of Aluminum mole fraction;* ***2(b)*** *Far field intensity as a function of Aluminum mole fraction.*

The relative intensity changes with respect to the distance x and the optical confinement is found exactly at the centre of the total device length for near field intensity as shown in Fig. 3(a). The variation of far field intensity with angle for different values of wavelength is explored in Fig. 3 (b). It is observed due to the change in refractive index between well to the barrier layers. From our analysis the highest peak is found at the 300 nanometer wavelength for near and far field intensities. It has been attributed to the refractive index change from well to the barrier layers. The values of effective indices are deduced as 2.2296, 2.2294 and 2.2293 for the wavelengths 300, 337 and 375 nm respectively.

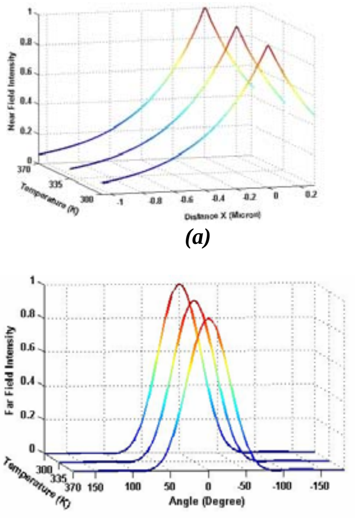


(a)

(b)

Fig. 3(a) Variation of near field intensity with wavelengths (300-375 nanometer); 3(b) Far field intensity as a function of wavelengths (300-375 nanometer).

The analysis of near and far field intensities are carried out for the 30 % Aluminum concentration and 300-nanometer wavelength. From Fig 4 (a) and (b), we observe that for the highest temperature value, spread of near and far field intensities are less as compared to the lower temperature values. As the temperature increases, carriers get energy due to the thermal excitation and number of photons is generated due to the recombination of electron hole pairs and the stimulated emission is possible. Because of the higher temperature, large number of photons is emitted very fast in less time so the spread of far field intensity is found to be less.

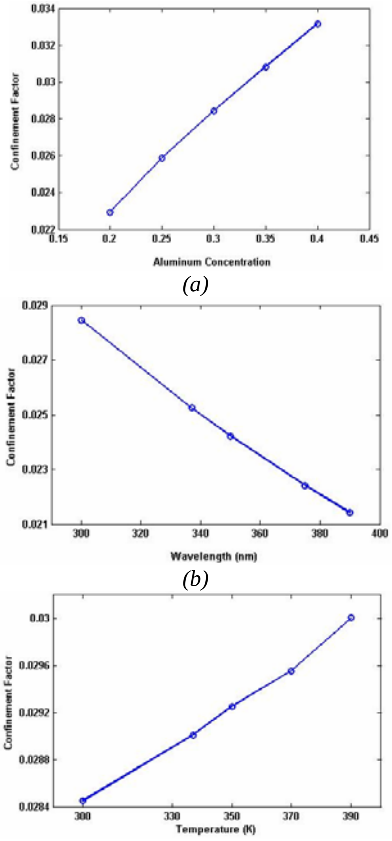


(a)

(b)

Fig. 4(a) Near field intensity as a function of temperature (300-370 K); 4(b) Far field intensity as a function of temperature (300-370 K).

Fig. 5 demonstrates the optical confinement factor as a function of wavelength, temperature and Aluminum mole fraction for the near field intensity.



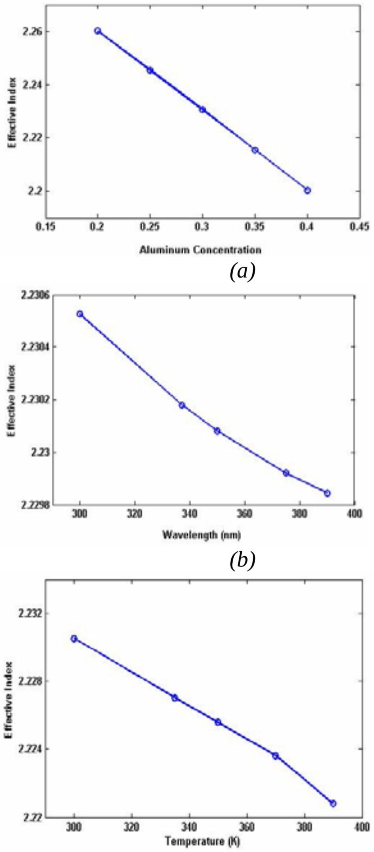
(a)

(b)

(c)

Fig. 5(a) Variation of optical confinement factor with Aluminum composition; (b) Dependence of optical confinement factor on wavelength; (c) Variation of optical confinement factor with temperature.

The confinement factor was found to be increase with temperature as well as aluminum mole fraction and decrease with the wavelength from our analysis. The optimization of structural and physical parameters is very essential for achieving proper confinement within the active region. Hence, we have obtained the variation of the effective index with the aluminum concentration, wavelength and temperature as shown in Fig. 6**.**



(a)

(b)

(c)

Fig. 6. (a)Variation of effective index with Aluminum concentration; (b) Variation of effective index with wavelength; (c) Dependence of effective index on temperature.

The decrease in effective index is found for higher values of these parameters. For the 350 wavelength, we found the effective index of 2.23045 at 300 K temperature and 30 % aluminum composition.

4. Conclusion

For the enhancing efficiency of laser diodes, quantum confinement and optical confinement are two important issues. However, quantum confinement can be controlled through the barrier height and Aluminum mole composition of the barrier. The optical confinement in such complex quantum structures is very important to enhance the modal gain. Therefore, we have carried out detailed analysis of near and far field intensities as a function of wavelength, temperature and Aluminum mole fraction. Our analysis provides useful physical insight for the optimization of complex quantum structures of Gallium nitride for better optical confinement and enhancing the efficiency of laser diodes.

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