Investigation of Optical Gain of Type-I and Type-II Nano Hetrostructure

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Abstract: ***This paper deals the investigation of optical gain characteristics of a single quantum well of material composition $InGa_{0.76}N_{0.24}$ (Type-I) sandwiched between the barriers of material composition GaN. The structure is grown on GaN substrate and $In_{0.53}$ $Ga_{0.47}As$ (Type_II) sandwiched between the barriers of material composition $GaAs_{0.51}Sb_{0.49}$. The structure is grown on InP substrate. Apart from optical gain, we have also investigate energy band structure along with valance and conduction band envelope functions and the comparative picture of the two hetrostructures (Type-I and Type-II) within two polarization i.e. Transverse electric(TE) and Transverse Magnetic(TM). The behavior of quasi Fermi levels for the valance and conduction band has also been investigated. For optical gain simulation, the hetrostructure has been modeled with the help of six band k.p method. The 6×6 diagonalized K.p Hamilton has been solved to evaluate the light and heavy hole energies. For the injected carrier density of $15\times10^{12}/cm^2$, the optimized optical gain is found ~ 30320.21/cm at wavelength 0.93 µm and ~ 12327.21/cm at wavelength 1.85µm for Type-I and Type-II hetrostructures respectively.***

Keywords: Optical Gain, Type-I and Type-II, TE and TM mode, Hetrostructures

1. Introduction

In the area of Optoelectronics, semiconductor hetrostructures play an important role. Since two decades, the III- V semiconductors based quantum well hetrostructure have been widely used for lasing applications [1].Lasing hetrostructures offer the improved performance in the terms of long wavelength, High intense beam output and switching speed. Due to minimal inter-modal delay effects and minimal losses, hetrostructures semiconductors are very important for optoelectronic device applications [2-3]. For obtaining lasing, quantum well structure is most effective approaches. However, high carrier density is required for homogeneous quantum wells, to invert their population before any stimulated emission process. In this paper we investigate the Optical Gain of Type-I hetrostructure InGaN/GaN and Type-II hetrostructure InGaAs/GaAsSb which is capable of better carrier and optical confinement. P.A.alvi et al. have calculated the optimized optical gain with in TE mode 9000/cm at corresponding lasing wavelength of 1.95µm under very high pressure [4]. The modal gain and optical losses have been studied within TE and TM modes by Rashmi Yadav et al. She also reported that maximum gain is achieved at the lasing wavelength 1.40 µm and 1.25 µm in TE and TM mode respectively [6]. In Recent Research, H.K Nirmal have studied that the various lasing characteristics like refective index, differential gain and antiguiding factor in relation with the photonic energy with in TE and TM mode [7]. Emanuele et al. reported that Deep-UV optical gain in AlGaN-Based Graded index separate confinement hetrostructure. He designed a graded Index laser double hetrostructure with AlGaN in active region to enhance the optical confinement of hetrostructures [8]. In [9] Wei Guo have reported that stimulated emission and optical gain for 250 nm emission from an AlGaN hetrostructure. Hongping Zhao et al. analyzed that improved gain media self consistently for Type-II InGaN hetrostructure [10-11].

2. Device Structure

The proposed model have a Two hetrostructures i.e Type-I hetrostructure InGaN/GaN and Type –II hetrostructure InGaAs/GaAsSb. For Type-I InGaN/GaN hetrostrusture, single quantum well of width 4nm of ternary compound InGaN sandwiched between the barrier layer of GaN of 6nm. The whole hetrostructure has been grown on the substrate of binary compound GaN. For Type-II InGaAs/GaAsSb hetrostrusture, single quantum well of width 4nm of ternary compound InGaN sandwitched between the barrier layer of GaAsSb of 2nm. The whole hetrostructure has been grown on the substrate of binary compound InP. Optical gain or material gain is the important properties of lasing hetrostructures which is explained in different polarizarion mode. InGaAs/GaAsSb 'W' type lasers on substrate has been investigated in [13]. Chia-Hao Chang et al. investigated the optical gain for InGaAs/GaAsSb quantum well hetrostructure [14-16]. Recently, Balie Chen et al. have reported the optimized wave function overlap and transition wavelength for InGaAs/GaAsSb type-II quantum well hetrostructure [17]. For the calculation of discrete energy levels within the conduction band, the single band effective mass equation can be used as

$$-\frac{h^2}{2m_c^*}\nabla^2\Psi + V_c\Psi = E_c\Psi \qquad (1)$$

where Ψ is the envelope function h is plank's constant, m_c^* conduction effective mass, V_c potential of conduction band, E_c is conduction band electron energy level. For calculation of discrete energy levels (i.e. conduction electron and light and heavy hole levels) within the quantum well hetrostructure we have used 6×6 Hamilton matrix.

$$H_{6\times6}(k) = \begin{pmatrix} H^+_{3\times3} & 0 \\ 0 & H^-_{3\times3} \end{pmatrix} \qquad (2)$$

where $H^+_{3\times3}$ and $H^-_{3\times3}$ can be expanded as (2) with $\cup$ = + or – represents upper and lower blocks.

$$H^{U}_{3\times 3} = -\begin{pmatrix} P+Q-V_h(Z) & R(k)\pm iS(k) & \sqrt{2}R(k)\pm\dfrac{i}{\sqrt{2}}S(k) \\ R(k)\pm iS(k) & P-Q-V_h(Z) & \sqrt{2}Q\pm i\sqrt{\dfrac{3}{2}}S(k) \\ \sqrt{2}R(k)\pm\dfrac{i}{\sqrt{2}}S(k) & \sqrt{2}Q\mp i\sqrt{\dfrac{3}{2}}S(k) & P+\Delta_{so}-V_h(Z) \end{pmatrix} \qquad (3)$$

In (2) $V_h(Z)$ represents the unstrained valence band edge, Δ_{so} represents the spin-orbit split-off energy. Also $P = P(k)+P(\varepsilon)$ and $Q = Q(k)+Q(\varepsilon)$ is expanded in equations (4) and (5), also, S(k) and R(k) are expanded in equation (6)

$$P(k)=\left(\frac{\hbar^2}{2m}\right)\gamma_1\left(k_t^2+k_z^2\right) \qquad (4a)$$

$$P(\varepsilon)=-a_v\left(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}\right) \qquad (4b)$$

$$Q(k)=\left(\frac{\hbar^2}{2m}\right)\gamma_2\left(k_t^2-2k_z^2\right) \qquad (5a)$$

$$Q(\varepsilon)=-\frac{b}{2}\left(\varepsilon_{xx}+\varepsilon_{yy}-2\varepsilon_{zz}\right) \qquad (5b)$$

$$S(k)=\left(\frac{\hbar^2}{2m}\right)\sqrt{3}\left(\frac{\gamma_2+\gamma_3}{2}\right)k_t^2 \qquad (6a)$$

$$R(k)=\left(\frac{\hbar^2}{2m}\right)2\sqrt{3}\gamma_3k_tk_z \qquad (6b)$$

For quantum well structures optical gain coefficient can be written as

$$G(E)=\frac{q^2M_B^2}{E\varepsilon_0m_0^2chn_{eff}W}\sum_{i,j}\int_{E_g}^{E_{gb}}m_{r,ij}C_{ij}A_{ij}(f_c-f_v)L(E-E')dE \qquad (7)$$

Where E is the optical energy, q is the electron charge, n_{eff} the effective refractive index of the laser structure, w the width of the quantum well, i and j the conduction band and valance band quantum numbers, C_{ij} is the spatial overlap factor, $€_0$ permitivity, MB^2 bulk momentum.

3. Results and Discussion

Fig 1and fig 2 shows the wavefunction waveform for the Type-I and Type-II hetrostructure respectively which shows the expected conduction and valance band alignment. To know the valance subbands energy level six band hamilton is used.

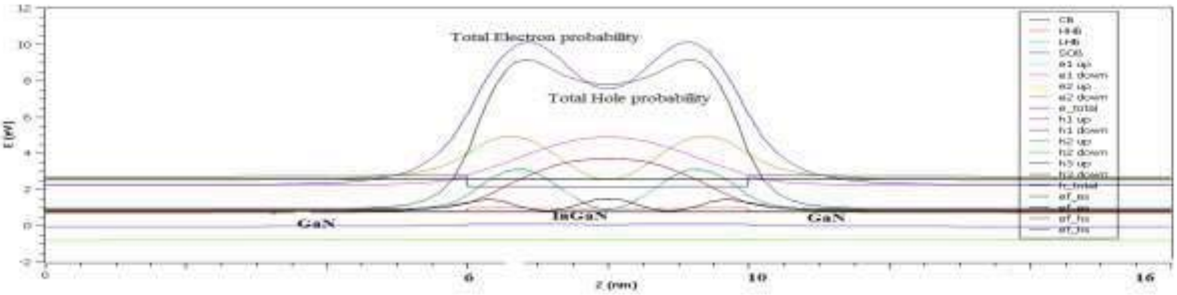

Figure 1: Wavefunction waveform for Type-I hetrostructure InGaN/GaN

From the figure 1 it is clear that electron confinement at the quantum well is good as compared to hole confinement for type-I hetrostructure.

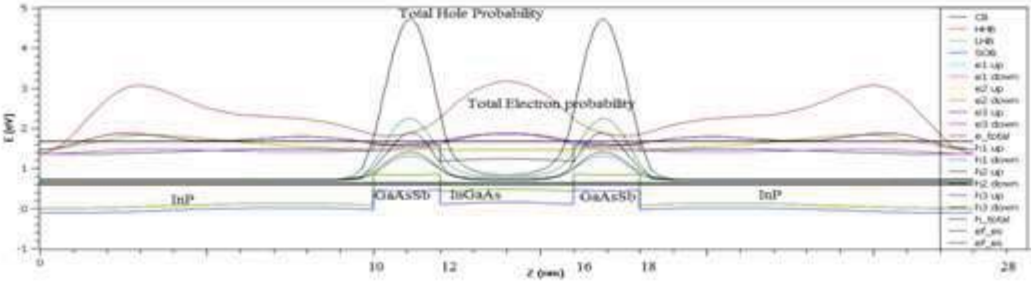

Figure 2: Wavefunction waveform for Type-II hetrostructure InGaAs/GaAsSb

But figure 2 shows the hole confinement at quantum well is good as compared to electron confinement for type-II hetrostructure.

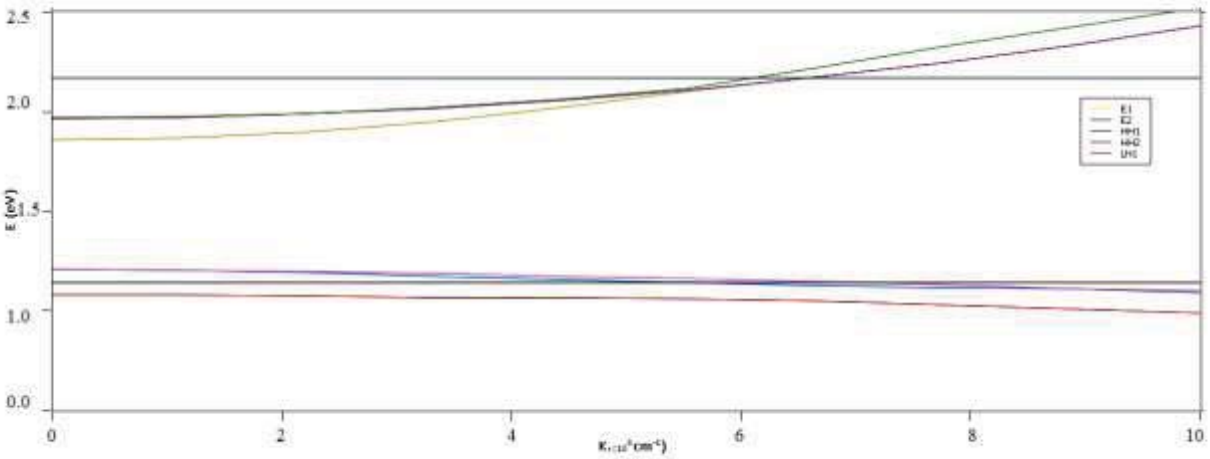

Figure 3: Conduction and valance band dispersion profiles for Type-I hetrostructure InGaN/GaN at 300K

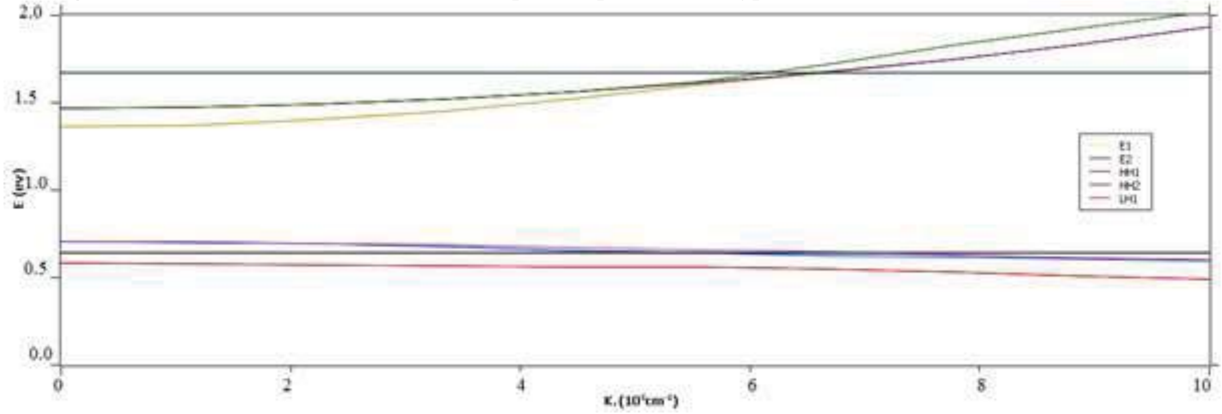

Figure 4: Conduction and valance band dispersion profiles for Type-II hetrostructure InGaAs/GaAsSb at 300K

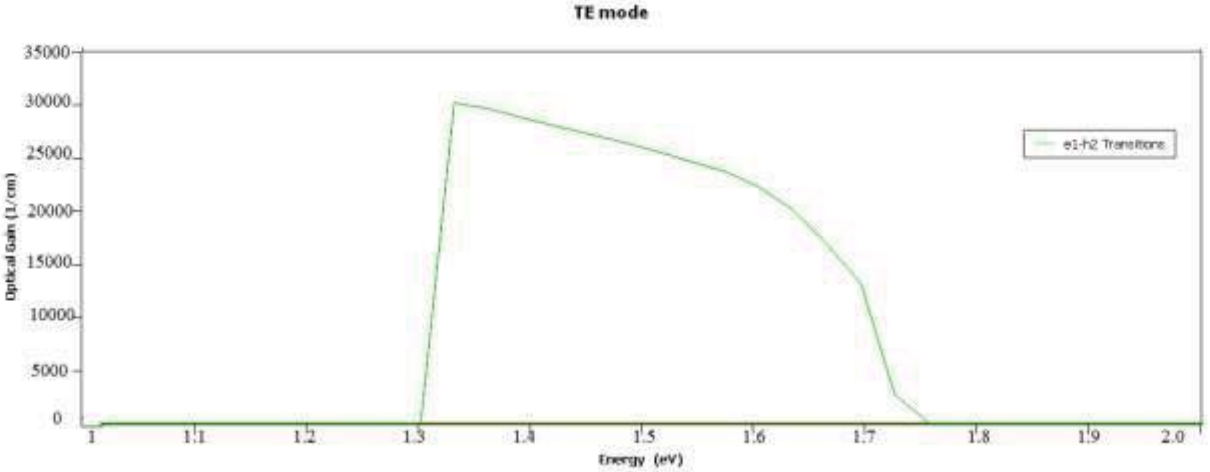

Figure 5: Optical gain as a function of photon energy for Type-I hetrostructure InGaN/GaN at 300K

In TE mode for Type-I hetrostructure $InGa_{0.76}N_{0.24}$ the optical gain is found for e1-h1 transition is ~ 4.961/cm (not shown in waveform)at corresponding lasing wavelength 0.775µm, for e1-h2 transition is 30320.21 at corresponding lasing wavelength 0.93µm. By observation it is found that the optical gain is negligible in e1-h1 transition as compared to e1-h2 transition.

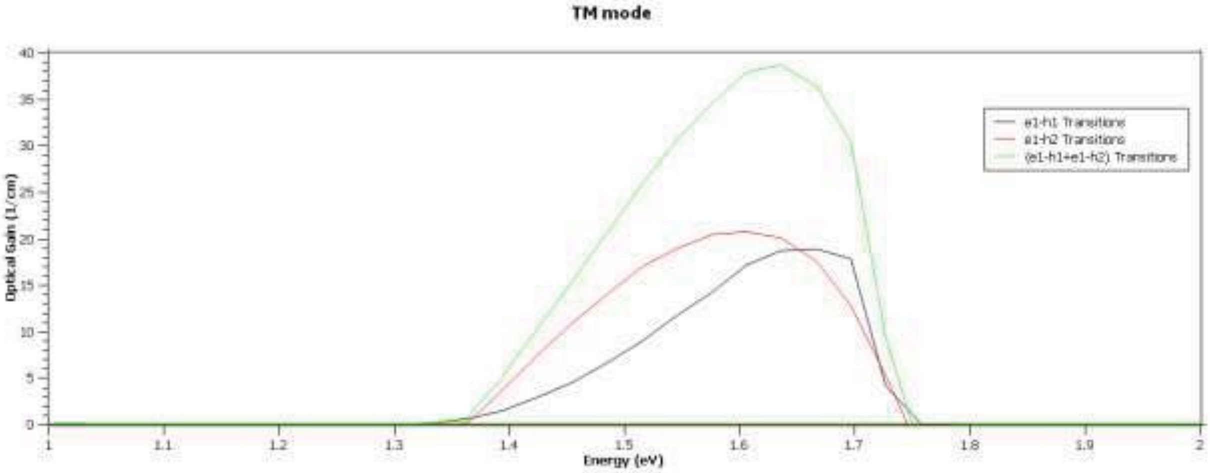

Figure 6: Optical gain as a function of photon energy for Type-I hetrostructure InGaN/GaN at 300K

From figure 6 it is observed that the optical gain for Type-I InGaN/GaN hetrostructures in TM mode is ~18.8933/cm at corresponding lasing wavelength 0.74 µm for e1-h1 transition and ~20.6839/cm at lasing wavelength 0.77µm for e1-h2 transition. The total (e1-h1+e1-h2) optical gain is~38.6765/cm at corresponding wavelength 0.76µm.By observation it is clear that the maximum optical gain is found in TE mode for Type-I InGaN/GaN hetrostructure.

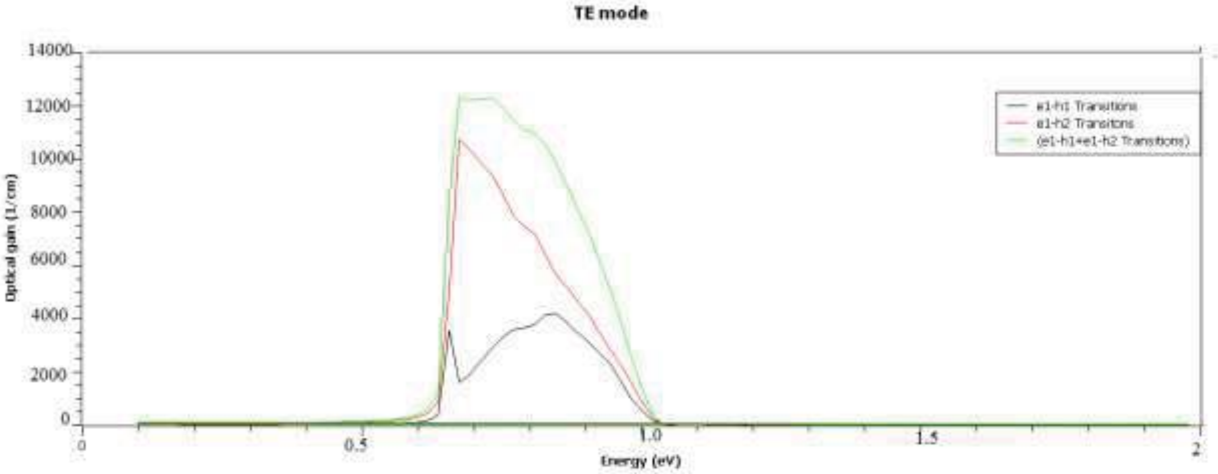

Figure 7: Optical gain as a function of photon energy for Type-II hetrostructure InGaAs/GaAsSb at 300K

For Type-II hetrostructure InGaAs/GaAsSb the optical gain is found ~ 4193.308/cm at corresponding wavelength 1.47 µm (e1-h1transition) and ~ 10741.74/cm at corresponding wavelength 1.85 µ m (e1-h2 transition). The total optical gain is ~ 12327.2/cm at corresponding wavelength 1.85 µm (e1-h1+e1-h2 transition). From the figure it is concluded that the optical gain is less for e1-h1 transition as compared to e1-h2 transition.

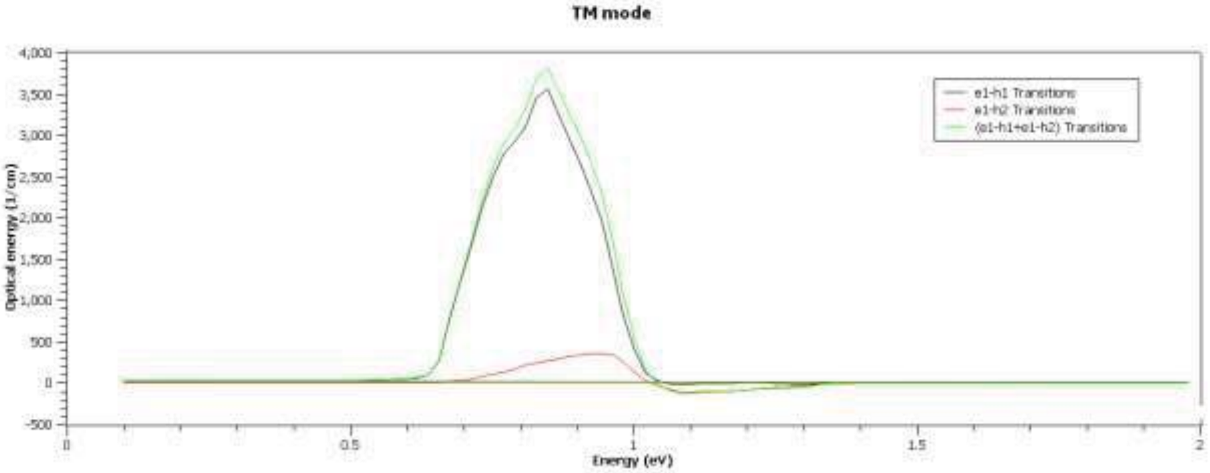

Figure 8: Optical gain as a function of photon energy for Type-II hetrostructure InGaAs/GaAsSb at 300K

For e1-h1 transition (Type-II hetrostructure InGaAs/GaAsSb) optical gain is found ~ 3555.16/cm at corresponding lasing wavelength 1.47 µm and for e1-h2 transition the optical gain is ~ 347.10/cm at corresponding lasing wavelength 1.34 µm. The total optical gain is found ~ 3819.18/cm at corresponding lasing wavelength 1.47 µm. From figure 7 it is clear that the maximum optical gain is achieved for e1-h1 transition. In TE mode type-II hetrostructure the maximum optical gain is found for e1-h2 transition where as in TM mode type-II hetrostructure the maximum optical gain is found for e1-h1 transition which is the just reverse case from the TE mode.

4. Conclusions

We have investigated that Optical Gain of the two hetrostructures i.e. Type-I and Type-II hetrostructures. For the type-1 hetrostructure maximum optical gain is found ~ 30320.21/cm at photonic energy 1.333eV within TE mode Where as in Type-II hetrostructure maximum optical gain is found ~ 12327.21/cm at photonic energy 0.675eV with in TE mode. On the behalf of comparative study of both the Type-I and Type-II hetrostructures, it is suggested that Type-I hetrostructures is better than type-II hetrostructure due to its maximum optical gain.

By the investigation of both hetrostructures Type-I and Type-II we found that maximum optical gain is obtained in Type-I hetrostructure within TE mode.

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