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INTERSUBBAND OPTICAL GAIN SPECTRA IN COMPRESSIVELY STRAINED InGaAs/GaInP QUANTUM WELL

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ABSTRACT

In this paper, the theoretical analyses of the optical intersubband transitions in strained InGaAs/GaInP quantum well are investigated. A simplified method of the treatment of the compressive strain effects incorporation for the wavefunction and thus the intersubband dipole matrix is discussed. The effects of Gallium mole fraction, quantum well width and compressive strained on the band properties, intersubband transitions and optical absorption/gain spectra are shown to be pronounced. Thus this present investigation could become a good guild for tuning the optoelectronic properties of many quantum devices utilizing intersubband electronics in their various technological applications.

Keywords: InGaAs/GaInP quantum well, strain effects, intersubband transition and absorption/gain spectra.

INTRODUCTION

Intersubband electronic optical transitions in semiconductor quantum well structures have become an important subject of interest to many researchers due to their potential for device applications such as optical detections, light-emitting devices and solar cell devices [1-5]. The intersubband based devices realized from heterostructures of very thin epitaxial layers of group III-V semiconductors as key components of many optoelectronic devices [2, 5]. This is owing to their increased strength of electro-optical interactions by confining carriers to small [6]. Therefore, electronic quantum devices such as lasers, photodetectors, modulators and switches are developed based on the theory of quantum well systems [7]. InGaAs based heterostructures are among the most widely studied semiconductor devices. The application of InGaAs in optical fiber telecommunication is of great importance because of its high- speed as well as high sensitivity when used as a photodetector in the photon wavelength range of $1.1 \sim 1.7 \mu m$. They also have faster time response, higher external quantum efficiency (EQE) as well as lower dark current for the same sensor area when compared to germanium (Ge) based heterostructures [8-10]. Recently, several research studies have been carried out to compare the external quantum efficiency (EQE) of metamorphically grown InGaAs bulk subcell on Ge Substrates by Spectrolab. The result shows that the bulk material shows higher EQE values than those of quantum wells in the 880 – 900nm region while the quantum wells have higher EQE values in the

$400 - 600\, nm$ range [11]. A while ago, quantum well, superlattice and bound-to–continuum active region designs were reported to function at room temperature pulsed operation [12]. It was also discovered that the threshold current and emission efficiency of conventional InGaAs/InP lasers on InP substrates strongly depend on operating temperature [13]. By varying the ratio of InAs and GaAs in $In_{1-x}Ga_xAs$ active region, the optical and mechanical properties can be tuned [14]. InGaAs based quantum well devices are mostly grown on (001) InP substrates with compositions matching the lattice parameter of $In_{0.53}Ga_{0.47}As$ to ensure a zero mechanical strain. However, InGaAs lattice parameter increases linearly with the concentration of InAs in the alloy [14]. During solidification from a solution containing GaAs and InAs, the liquid-solid phase diagram shows that GaAs are taken up at a much higher rate than InAs depleting the solution of GaAs [10]. In InGaAs based heterostructures, the adoption of GaInP as the upper and lower claddings is usually preferred over AlGaAs. This is majorly because of the fact that GaInP is an Al-free semiconductor material which is relatively insensitive to impurities, such as oxygen and carbon, during material growth processes [15].

In this present paper, we theoretically analyse the intersubband transition and gain/absorption spectra of device structure having InGaAs quantum well active region embedded by GaInP barriers compressively strained to InP and GaP. The effects of these substrates on the first two heavy-hole valence bands are compared and discussed. This paper is therefore organized as follows: In section 2, the theoretical approaches to obtaining band properties, transition energies and optical absorption/gain spectra are discussed. Results and discussions are given in section 3. Finally, a summary is presented in section 4.

THEORETICAL CONSIDERATION

In our analysis, we consider an intersubband transition in the heavy-hole band emanating from compressive strain. The first two subband state $n_{12} = 1{,}2$ interacting with photon energy governed by the Schrodinger wave equation. For the case of finite quantum well approximation, the well-known solution of the confinement energies in the subband applies [16-18].

$$\alpha = \frac{m_b K}{m_w} tan \frac{K L_w}{2} \qquad (1)$$

Where $K = \sqrt{2m_w E_n/\hbar}$ and $\alpha = \sqrt{2m_b(V_0 - E_n)/\hbar}$ are the components of the well and barrier wavenumbers. The effective masses of the well and barriers are denoted m_w and m_b while V_0 is the band offset. It is possible to approximate the wavefunction of the fine quantum well by the infinite quantum well model as described in the ref. [18]

$$\phi_n(z) = \sqrt{\frac{2}{L_{eff}}} \sin \frac{n\pi}{L_{eff}} z \qquad (2)$$

Here, z is the position, L_{eff} is the so-called effective quantum well width which can be obtained from the confinement energy of the infinite well approximation for the lowest energy state $n = 1$.

$$E_1 = \frac{\hbar^2 \pi^2}{2 m_e L_{eff}^2} \qquad (3)$$

In the equation above, the energy E_1 is the lowest energy obtained by solving the transcendental equation (1). Considering the occupation of carriers, the optical absorption or gain due to the band-band transition reflects the rule [19-20]

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$$\alpha(\hbar\omega) = \frac{\pi\omega}{n_r c\varepsilon_0}\frac{2}{\Omega}\sum_{k_t}[\hat{e}.\mu_{12}]^2\,\delta(E_b - E_a - \hbar\omega)(F_a - F_b) \tag{4}$$

Where Ω is the volume, n_r is the refractive index of the InGaAs quantum well active region. The variables F_a and F_b represent the Fermi factors given by the Fermi Dirac distribution. The delta function appearing in equation (4) accounts for the spectral broadening and can be represented by the well-known Lorentzian lineshape [21]

$$\delta(E_b - E_a - \hbar\omega) \sim \frac{\Gamma/\pi}{(E_b - E_a - \hbar\omega)^2 + (\Gamma)^2} \tag{5}$$

In equation (4), $\hat{e}.\mu_{12}$ represents the transition dipole matrix element of the transitions from state $n = 1$ to $n = 2$ being considered. Under this current approximation, the dipole moment is obtained from the normalised envelope wave function along the quantum well growth direction z, which is due to the heavy hole excitation by the light beam [18]

$$\mu_{12} = \int_{-L_{eff}/2}^{L_{eff}/2} \phi_2(z)\, z\phi_1(z)dz \tag{6}$$

In the limit of little mixing of the valence band light and heavy holes due to strain, the intersubband transition is expected to follow the usual intersubband selection rule which permits transverse magnetic (TM) polarization [22].

RESULTS AND DISCUSSIONS

In this study, we considered only the valence heavy-hole transitions in the first two subband state $n_{12} = 1,2$. All the band parameter inputs were obtained from ref. [18] and are presented in Table 1. The resulting ternaries for the well and barrier are interpolated using the Vegards law [16].

Tab. 1: Band parameters of binary InAs, GaAs, InP and GaP semiconductors.

Binary	E_g(eV)	$m_e(m_0)$	γ_1	γ_2	a_0(Å)	n_r
InAs	0.3600	0.0260	20.0000	8.5000	6.0583	3.5000
GaAs	1.4200	0.0670	6.9800	2.0600	5.6532	3.1900
InP	1.3440	0.0795	5.0800	1.6000	5.8697	-
GaP	2.8860	0.1300	4.0500	0.4900	5.4505	-

The compressively strained InGaAs/GaInP on two different substrates GaP and InP are investigated.

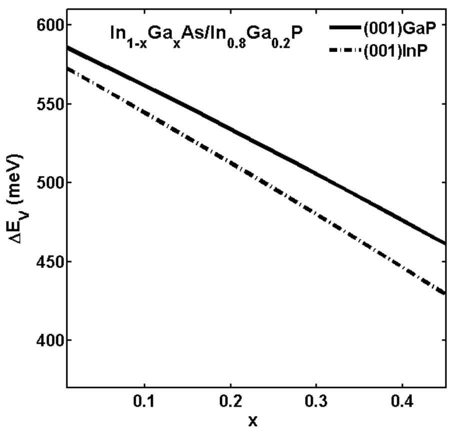

Fig. 1: (a) Heavy hole valence band offset ΔE_v(eV) against Ga mole fraction x.

Figure 1 and figure 2 show the valence heavy hole band offset ΔE_v(eV) and the band gap energy changes of band gap ΔE_g (eV) calculated for InGaAs/GaInP quantum well using the substrates GaP and InP.

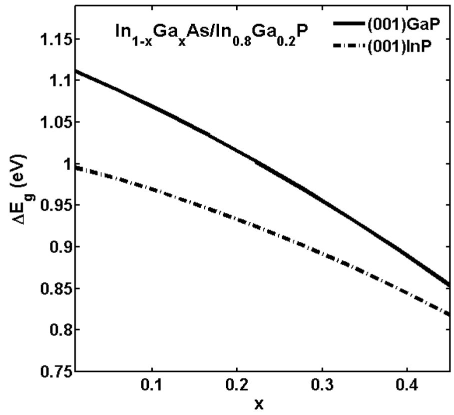

Fig. 2: Change in heavy hole bandgap ΔE_g(eV) against Ga mole fraction x.

The plots show tremendous changes in the band gaps of the InGaAs and InGaP epilayers strained to GaP and InP substrates. Within the range of the Ga mole fraction $0 \leq x \leq 50\%$ in the InGaAs active region using 20% Ga mole fraction in GaInP barriers, the changes in the bandgap are found to be decreasing with Ga composition. This is also found to have a similar trend for the heavy hole band offset ΔE_v. This is because the effects of this compressive strain become higher as the Ga mole fraction increases. The plots of the carrier confinement energies of the heavy holes are depicted in the figure.

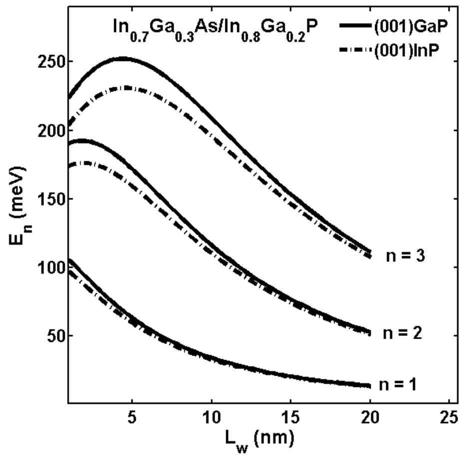

Fig. 3: Heavy hole E_n(meV) against quantum well width L_w (nm).

The energy states of the InGaAs/GaInP quantum well as a function of the active region well width, L_w is depicted in figure 3 for the quantum states $n = 1,2,3$, for different quantum states. It can be seen that the results show that, the energy states, E_1, E_2, E_3 decrease with increasing quantum well width (L_w). In all the quantum states $n = 1,2,3$, the eigenstates for the quantum well structure formed on GaP substrate are lower than the quantum well structure formed on InP substrate.

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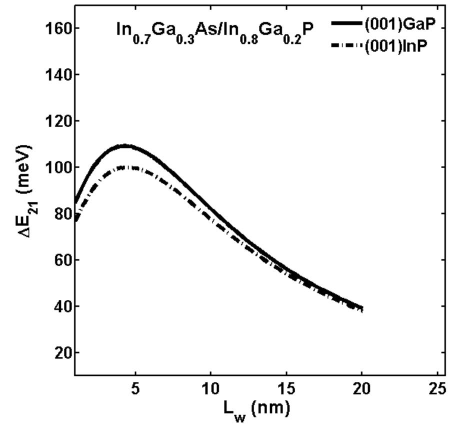

Fig. 4: Transition energy of E_{21}(meV) against quantum well width $L_w(nm)$.

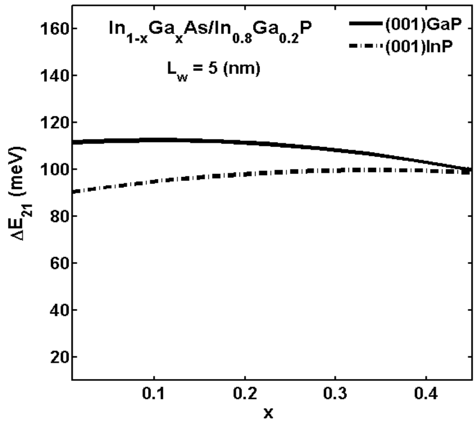

Fig. 5: Transition energy of E_{21}(meV) against Ga composition x

We calculated the transition energies of InGaAs/GaInP for the various well widths and Ga mole fraction of the InGaAs active region. The plots of the transition energies E_{21}(meV) as a function of quantum well width L_w and Ga mole fraction (x) are shown in Figures 4 and 5 respectively. The results show that the transition energy drops as the well width becomes larger. This shows that better electronic and optical properties of InGaAs/GaInP quantum well can be obtained when the well width is relatively small. It is seen that the transition energy of the InGaAs/GaInP quantum well is higher when GaP substrate is used. This trend is similar in all the three quantum states $n = 1,2,3$ for the Ga mole fraction $x = 0.3$ considered in Figure 5.

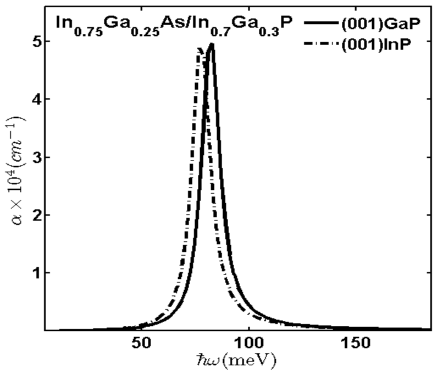

Fig. 6: Optical absorption spectra $\alpha(\omega)$ against photon energy $\hbar\omega$.

The effect of different substrates on the optical properties of the InGaAs/GaInP quantum well can be appreciated more on the calculated result of the optical absorption spectra in Figure 6. The absorption peak of InGaAs/GaInP quantum well using GaP as a substrate is higher than that using InP as a substrate. Such a strain effect can be used in tuning the optoelectronic properties of quantum wells for intersubband electronic device applications [22].

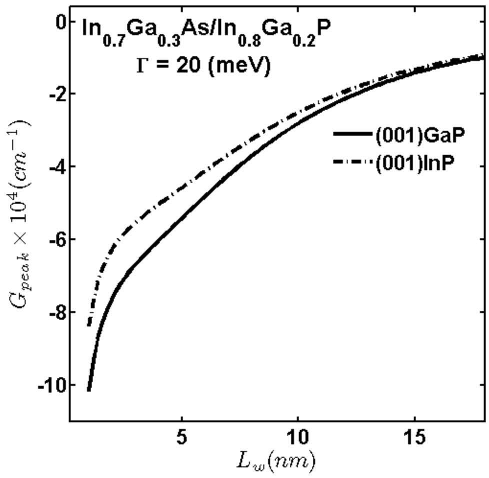

Fig. 7: Peak gain α_{peak} against quantum well width $L_w(nm)$.

The peak absorption is calculated from the absorption spectra of InGaAs/GaInP at the photon energy $\hbar\omega = \Delta E_{12}$. Also, the optical gain spectra of the InGaAs/GaInP quantum well were calculated from the optical absorption peak as $G_{peak} = -\alpha_{peak}$ [21]. The plot of the peak gain against quantum well width L_w is depicted in Figure 7. The result shows that the peak gain increases as the quantum well width increases. From equation 4, it can be deduced that the peak absorption /gain is dependent on the injection carrier density [23]. Therefore, there are more possibilities for a radiative recombination which will lead to the improvement of the optical gain [23].

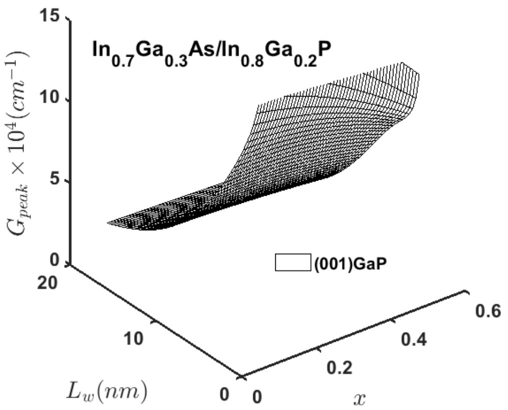

Fig. 8: 3D mesh of the α_{peak} against Ga mole fraction, x and quantum well width L_w for (001) GaP.

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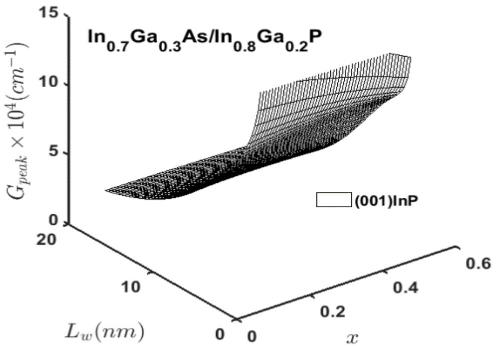

Fig.9: 3D mesh of the α_{peak} against Ga mole fraction, x and quantum well width L_w for (001) InP substrates.

Figure 7 shows a plot of the peak absorption as a function of the well width. From the result, it can be seen that the peak absorption increases non-linearly as the well width increases. This trend corresponds to the investigation as reported in ref. [24]. Figure 8 and figure 9 show the 3D surface plot for the dependence of the peak gain G_{peak} on the Ga mole fraction, x of the InGaAs active region and its quantum well width L_w for GaP and InP substrate respectively. The 3D plot shows clearly how G_{peak} changes versus the Ga mole fraction x and the quantum well width L_w. The G_{peak} monotonically increases as L_w increases just as the Ga mole fraction x of the InGaAs quantum well active region.

CONCLUSION

This research paper theoretically investigated the intersubband optical transitions in strained InGaAs/GaInP quantum well nanostructure. The effects of the active region mole fraction x and the well width on the band offsets, confinement energies, transition energies and optical absorption/gain spectra were studied. A simple mathematical treatment was adopted to obtain approximations for the wavefunction and subsequently the intersubband dipole matrix due to the modifications by strain presented. The underlying physical mechanisms of strain-induced tuning of the optical spectra of InGaAs/GaInP quantum well nanostructure on different substrate GaP and InP on the (001) substrate orientation were discussed. It is observed that the confinement and transition energies, bandgap, the resulting valence heavy hole band energy, and energy state of quantum well are all dependent on the alloy mole fraction, x of the quantum well material $In_{1-x}Ga_xAs$. In summary, based on a simple theoretical analysis, it can be shown that the intersubband optoelectronic properties of InGaN/GaInP quantum well can be tuned by varying the mole fraction of the Ga in InGaAs quantum well active region, the L_w quantum well width and the straining substrate.

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