Effect of interdiffusion on the subbands in an $In_{0.65}Gs_{0.35}As/GaAs$ multiple-quantum well structure on GaAs Substrate at 1.55μm operation wavelength

M.C.Y. CHAN*, E. HERBERT LI* and K.S. CHAN**

* Department of Electrical & Electronic Engineering, University of Hong Kong, Pokfulam Road, Hong Kong.

** Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong.

ABSTRACT

Analysis of high indium concentration in interdiffused $In_{0.65}Gs_{0.35}As/GaAs$ multiple quantum well (MQW) structure on GaAs Substrate is being studied. This material can achieve operating wavelengths around 1.5μm for applications in fiber optics communications. The large lattice mismatch problem (over 4.5% in this study) can be solved by using a linearly-graded InGaAs buffer layer for reducing any dislocation between the adjacent layers. Interdiffusion in the MQW structure can modify the composition profile in order to tailor the optical absorption and refraction properties. Results show that this system can have promising device performance operates at around 1.55μm and which base on the more matured and reliable GaAs technology.

INTRODUCTION

For optoelectronic device application, the majority of semiconductor material are based on III-V compounds, and in particular the InP- and GaAs- based ones. Interest applications for fiber optics communications have their lowest loss at 1.55μm. Because of the well-developed GaAs-based device technology, the fabrication of optical devices on GaAs substrate is most suitable for telecommunication applications. In this paper, a high indium concentration of InGaAs layers in interdiffused InGaAs/GaAs multiple quantum well (MQW) growth on GaAs substrate is investigated. This may be realized at bandedge of around 1.5μm operation wavelength with applications in optical modulation. The optical modulation is due to the Quantum-Confined Stark Effect (QCSE) [1], which is unique to quantum structure, and which describes the change in the confined energy levels and in the absorption properties of QW structure when the electric field is applied across the structure. Interdiffusion of constituent atoms across the well and barrier interfaces [2] can provide the possibility of continuous modification of the material bandgap [3] in QW structure which can be controlled by the disordering process parameters [4]. This process is produced by using post-growth thermal annealing [5] to induce the solid-state interdiffusion of In and Ga atoms through the InGaAs/GaAs QW heterointerfaces [6]. The optical properties of QW, such as absorption [7] and refractive index [8], can be modified by the process of interdiffusion so that it provides the ability to tune the operating wavelength.

MODEL FORMULATION

Theoretical study on these materials is presented here to characterize the properties of subbands and the effect of electro-absorption. The material used in this study consists of 8.5 periods 90Å/40Å of $In_{0.65}Gs_{0.35}As/GaAs$ multi-layers structure which is shown in Fig.1. First, a 500Å n-type GaAs buffer layer is grown on n^+-GaAs substrate. A linearly graded InGaAs buffer with 20% per μm varying grading rate is following by n-type GaAs buffers. The final indium

Mat. Res. Soc. Symp. Proc. Vol. 417 © 1996 Materials Research Society

composition of the buffer is 50%. On top of the buffers, the MQW structure is grown, and followed by 5000Å of p-type InGaAs.

In epitaxial growth, the problem of lattice mismatch is due to a barrier-layer with different lattice constants of well-layer. This is generally accommodated by a combination of coherent strain and misfit dislocations. A lattice misfit parameter is defined as $\varepsilon = |a_w - a_b|/a_w$, where a_w and a_b are the lattice constant of well and barrier respectively. The critical thickness (h_c) for pseudomorphic epitaxy is derived by considering the thickness dependence of the strain energy and dislocation energy, and by minimizing the total energy. The critical thickness is obtained by [9]

$$h_c = \frac{b(1-\gamma\cos^2\Theta_{db})[\ln(\frac{h_c}{b})+1]}{8\pi(1+\gamma)f\cos\lambda} \qquad (1)$$

where γ is Poisson's ratio, Θ_{ab} is the angle between the dislocation line and its Burgers vector, and λ is the angle between the slip direction and that line in the interface plane which is normal to the line of intersection between the slip plane and the interface.

For growth direction z along <001>, the lattice-mismatch in coherently strained pseudomorphic InGaAs/GaAs MQW results in a biaxial compressive strain (perpendicular to the growth direction) in the well. This will increase the energy gap between the conduction band and both the degenerate valence bands and the spin-orbit split off band. A uniaxial component of strain (parallel to the growth direction) will lifts the degeneracy of the heavy hole and light hole bands at the Brillouin zone center, with the heavy hole band moving towards the conduction band edge and the light hole band moving further away from the conduction band edge. The equations of the strain QW is given by [10] $\varepsilon_{xx}=\varepsilon_{yy}=|a_w-a_b|/a_w=\varepsilon$, $\varepsilon_{zz}=-2\varepsilon(C_{12}/C_{11})$, $\varepsilon_{xy}=\varepsilon_{yz}=\varepsilon_{zx}=0$. The hydrostatic- and shear-components of the strain are $\delta E_{hy}=-2a\varepsilon(C_{11}-C_{12})/C_{11}$ and $\delta E_{sh}=-2b\varepsilon(C_{11}+2C_{12})/C_{11}$, respectively, where a, b are deformation potentials, C_{11} and C_{12} are the elastic constants.

The interdiffusion process is to consider post-growth thermal induced interdiffusion of the two excess alloy species through all the heterointerface in the MQW structure under stoichiometric conditions. The disordering of structure is considering the interdiffusion of the gallium from the barrier region into the wells, along with the out-diffusion of indium from the wells into the barriers. The interdiffusion is modeled here by using Fick's law with an equal and constant interdiffusion coefficient for the two interdiffusion species [11]. The extent of interdiffusion process is characterized by a diffusion length L_d which is defined here as $L_d = \sqrt{Dt}$, where D is the diffusion coefficient and t is the annealing time. The superposition principle is assumed for all of the layers considered in the structure, which includes the MQW core layers and the cladding layers. The In composition profile $\chi(z)$ as a function of L_d is given by:

$$x(z) = \frac{x_0}{2}\sum_{i=1}^{N}\left[erf(\frac{z-a_i}{2L_d}) - erf(\frac{z-b_i}{2L_d})\right], \qquad (2)$$

where χ_0 is the as-grown In concentration in the well; N is the number of well; erf( ) denotes the error function; $z \geq 0$ is the growth axis of the MQW layers where the MQW structure is positioned on the positive side; a_i and b_i are the left and right interface positions respectively of the i^{th} as-grown well within the MQW core, those are shown in Fig.2.

The diffused In composition profile defined by Eq.(2) is added to obtain the interdiffused MQW parameters. The MQW subband edge at the zone-centre of Γ_b-valley symmetry can be calculated separately for electrons and holes, using the Ben-Daniel and Duke model [12] using

the Schrödinger equation, which is solved numerically using a finite difference method for the energy eigenvalues. The other standard methods of calculation for the MQW eigenstates are tight-binding [13] and transmission tunneling [14]. The former method takes into account the presumption of some well-to-well coupling with an approximate coupling strength of the ground states which introduces inaccuracy in case of strong coupling. It also ignores coupling of the upper states. The later model becomes inaccurate in thick multi-layered structures and inapplicable in the case of thick barriers. The valence subband dispersion for the mixing between heavy- and light-holes states are considered here using an effective Hamiltonian approach [15] in order to calculate the absorption coefficient accurately. This approach is based on the analogous application of the tip method to the subbands.

The interband transitions are considered here without the electron-hole coulomb interaction. the linear absorption coefficient $\alpha(\omega)$ may be determined in terms of the imaginary part of the dielectric function $\varepsilon_2(\omega)$ using the relation: [16]

$$\alpha(w) = \frac{w\varepsilon_2(w)}{c_0 n_R(w)}, \qquad (3)$$

where $n_R(\omega)$ and c_o are the refractive index of the MQW and the velocity of light in vacuum respectively. The incident electromagnetic radiation is assumed to propagate parallel to the x-y plane (perpendicular to z-axis) of the QW layer, therefore α and ε_2 are anisotropic with polarization (TE and TM) [17]. ε_2, which is based on the direct interband transitions around the absorption edge in the Γ-valley, is expressed as:

$$\varepsilon_2^{TE,TM}(w) = \frac{e^2 M_b^2 \wp}{\pi\varepsilon_o m_o^2 w^2 L_z} \sum_{l,l'} \int dk \left|\langle \Psi_{Cl} | \Psi_{Vl'} \rangle\right|^2 L(E_{Cl}(k_{//}) - E_{Vl'}(k_{//}) - \hbar w), \quad (4)$$

where ε_0 is the permittivity of free space; ε and m_0 are the electron charge and rest mass respectively; $M_b^2 = m_0^2 P^2 / 3\hbar$ and P is given by Kane's model; L is the Lorentzian broadening factor with half-width-half-maximum Γ_b; the summation in the above equation is over all the subband and mini-subband bound and continuum states in both bands; and $\wp$ is the polarization factor at the band-edge where $\wp^{TE}$=3/2 (HH), 1/2 (LH) and $\wp^{TM}$ = 0 (HH), 2 (LH).

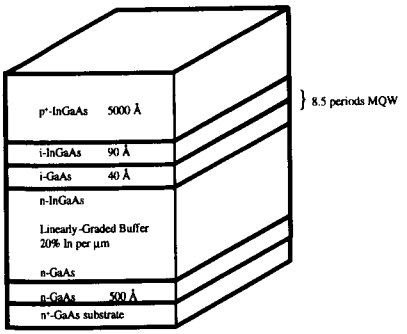


Fig.1 Schematic diagram of InGaAs/GaAs MQW structure.

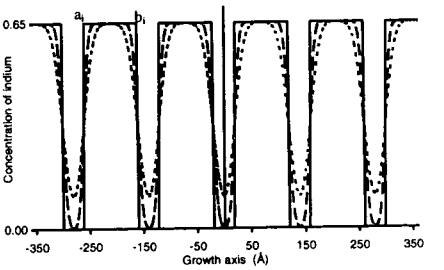


Fig.2 Profiles of indium composition for L_d=0 (——), 5 (– – –) and 10Å (- - -), only 6 wells and 5 barriers are shown.

RESULTS AND DISCUSSIONS

In the numerical analysis of the model described in above section, the MQW structure consisted of 8 wells and 9 barriers in the core region of InGaAs/GaAs material system. In this study, the effect of stark shift on the MQW is based on the change of interband optical transitions by varying the electric field, and the effect of interdiffusion is mainly based on the modification the confinement profile by varying the interdiffusion length.

Fig.3 shows the stark shift energy ΔE for the band-edge optical transition with applied electric field up to 100kV/cm, for various values of L_d. It can be seen that the stark shift increase in magnitude with increasing strength of the applied field in all cases. It is noticed that the stark shift in the diffused MQW is generally smaller than the as-grown MQW. As the L_d is larger, the stark shift will reduce. However, at the field of 20kV/cm, the stark shift of L_d=5Å is larger than other cases.

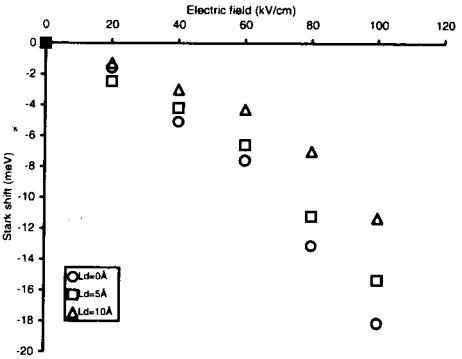
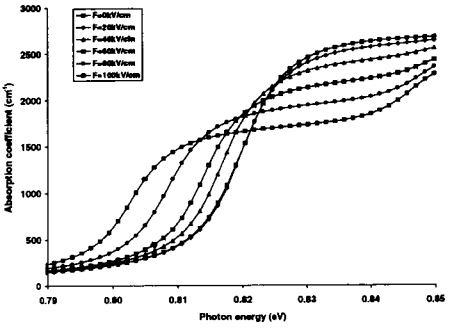


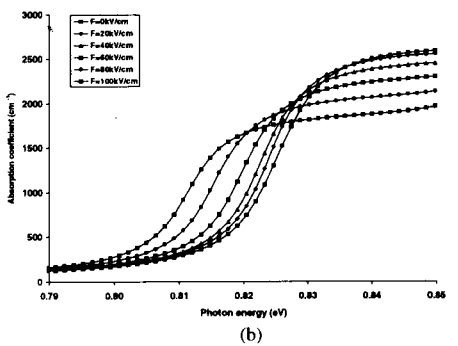
Fig.3 Quantum Confined Stark shift with applied electric field for an InGaAs/GaAs MQW, for various values of interdiffusion length L_d.

The room temperature absorption coefficient spectra for TE polarization for an as-grown MQW and for the disordered MQW with Ld=5 and 10Å are shown in fig.4a-c, for various values of the applied electric field. It is shown that in both cases the values of absorption coefficient edge decreases with increasing the applied field and the as-grown MQW has a higher absorption edge at all field than does the diffused MQW, especially L_d=10Å. The field pull apart the wavefunctions of electron and hole thereby reducing the overlapping between their wavefunctions. It is seen that drop in absorption coefficient at bandedge is smaller for the largest value of interdiffusion length. In the disordered MQW the electron and hole wavefunctions are less strongly confined and show a large penetration out of the wells. Also, It is intend to show here that variation of the diffused MQW enables the stark shift and absorption edge to be modified in different way from that achieved by well width variation only.

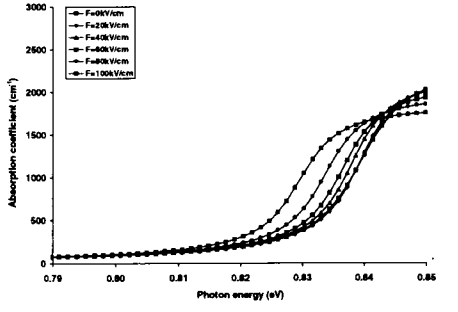
Fig.5a-c show the change in the TE polarization absorption coefficient due to the application of an electric field, for wavelength around the fundamental absorption edge, for L_d=0Å, 5Å and 10Å, respectively. The change in electroabsorption is defined as $\Delta\alpha=\alpha(F)-\alpha(F=0)$. It can be seen that a maximum value of $\Delta\alpha$ results near the respective fundamental absorption edge in all case. A shifting of the fundamental absorption edge is from 0.808eV to around 0.833eV. This range is near 1.5μm the best operating wavelength for optic fiber. The magnitude of change in absorption is about 1000cm^{-1} in L_d=0Å and 5Å, 800cm^{-1} in 10Å. This



(a)

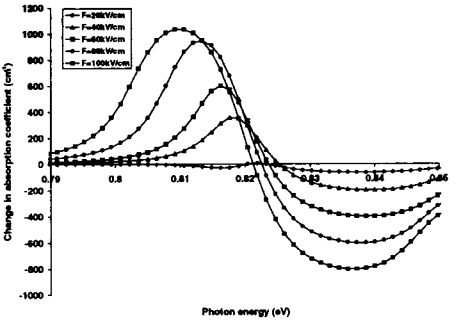


(b)

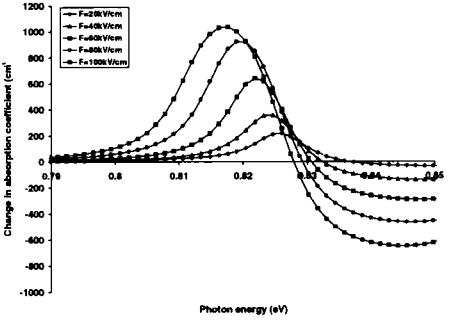


(c)

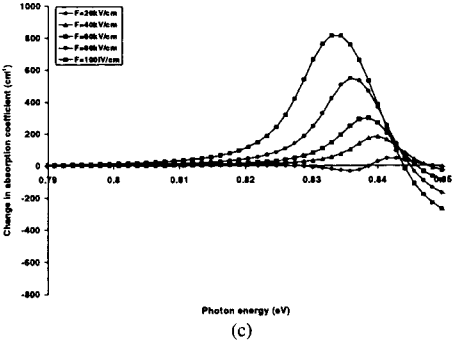
Fig4. Absorption coefficient spectra for TE polarization for an InGaAs/GaAs MQW ,for various values of applied field up to 100kV/cm, for (a) L_d=0Å, (b) L_d=5 Å, and (c) L_d=10Å.



(a)



(b)



(c)

Fig.5 Change in absorption coefficient for TE polarization with applied field for an InGaAs/GaAs MQW, for various values of applied field up to 100kV/cm, for (a) L_d=0Å, (b) L_d=5Å, and (c) L_d=10Å.

material system can be considered as a candidate for amplitude modulators which relies on change in the absorption coefficient due to an applied electric field. Since the optical absorption coefficient changes vary rapidly near the bandedge, this effect can be used to produce high efficient intensity modulation.

CONCLUSIONS

In this paper the effect of stark shift and interdiffusion in optical absorption on 65% indium concentration in InGaAs/GaAs MQW structure have been presented. The change in absorption coefficient at bandedge is observed in all case for the applied electric field. Although the effect of diffused MQW can be achieved to adjust the operating wavelength, the magnitude of absorption change and stark shift are also reduced. However, the drawback can be accepted. The overall results show an enhancement of the electroabsorption effect for the diffused MQW type material. This can have very useful applications in optical communication system, which operates at 1.55μm, base on more matured and reliable GaAs technology.

ACKNOWLEDGMENTS

This work is supported in parts by HKU-CRCG grant and City University of Hong Kong Strategic Research Grant.

REFERENCES

1. D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard, W.Wiegmann, T.H.Wood, and C.A.Burrus, Phys.Rev.Lett. **53**, 2173 (1984)
2. F.Iikawa, P.Motisuke, J.A.Brum, M.A.Sacilott, A.P.Roth, and R.A.Masut, J.Cryst. Growth **93**, 336 (1988)
3. M.D.Camras, N.Holonyak, Jr., R.D.Burnham, W.Streifer, D.R.Scifres, T.L.Paoli, and C.Lindstrom, J.Appl.Phys. **54**, 5637 (1983)
4. M.T.Furtado, M.S.S.Loural, E.A.Sato, and M.A.Sacilotti, Semicon. Sci Technol. **7**, 744 (1992)
5. D.G.Deppe and N.Holonyal, Jr., J.Appl. Phys. **64**, R93 (1988)
6. E.H.Li, J.Micallef, and B.L.Weiss, Jpn.J.Appl.Phys. **31**, L7 (1992)
7. J.Micallef, E.H.Li, and B.L.Weiss, Superlattices and Microstructure **13**, 125 (1993)
8. J.Micallef, E.H.Li, and B.L.Weiss, J.Appl. Phys. **62**, 3164 (1993)
9. J.W.Matthews and A.E.Blakeslee, J.Cryst.Growth **27**, 118 (1974)
10. H.Asai and K.Oe, J.Appl.Phys. **54**, 2052 (1983)
11. J.Crank, The Mathematics of Diffusion, 2nd edition, Oxford University, Oxford, 1975, pp.15
12. D.J.Ben Daniel and C.B.Duke, Phys.Rev. **152**, 638 (1966)
13. G.Bastard, Acta Electron. **25**, 147 (1983)
14. J.D.Ralston, S.O'Brien, G.W.Wicks, and L.F.Eastman, Appl.Phys.Lett. **52**, 1511 (1988)
15. K.S.Chan, J.Phys.C, Solid State Phys. **19**, L125 (1986)
16. F.Bassani and G.P.Parravicini, Electronic States and Optical Transitions in Solids, Pergamon, Oxford, 1975, pp.154
17. J.S.Weiner, D.S.Chemla, D.A.B.Miller, H.A.Haus, A.C.Gossard, W.Weigmann, and C.A.Burrus, Appl.Phys.Lett. **47**, 664 (1985)