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ELECTRO- ABSORPTION AND REFRACTION AT 1.5μm IN InGaAs/AlGaAs SUPERLATTICE GROWTH ON GaAs SUBSTRATE

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Abstract - High indium concentration $In_{0.65}Ga_{0.35}As/Al_{0.33}Ga_{0.67}As$ superlattices on GaAs substrates are useful for modulators and optical communication applications. This is due to the lowest loss 1.55μm optimum wavelength for operation of fiber optic system. The optical parameters such as absorption coefficient and change in refractive index with applied electric field are investigated.

I. INTRODUCTION

For optoelectronic device application, the majority of semiconductor materials 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. The materials of choice are usually InP-based lattice-matched compounds. Because of well-developed GaAs-based device technology, the fabrication of optical devices on GaAs substrate is most suitable for telecommunication applications. This may be realized at a bandedge of around 1.55μm by InGaAs/AlGaAs strain superlattice on GaAs substrate with applications in optical modulators and phase modulators. The operating wavelength of 1.55μm requires a 65% of indium concentration of InGaAs. The large difference of lattice constant between the well and barrier is created. A recent report shows that the use of a linearly graded buffer in these materials was successfully fabricated without any dislocation between the adjacent layers[1].

II. THEORY

Theoretical study on these materials is presented here to characterize the effect of electro-absorption and the change of refractive index at room temperature. The superlattice used in this study consists of 10 periods 70Å-30Å $In_{0.65}Ga_{0.35}As/Al_{0.33}Ga_{0.67}As$ multi-layers structure, shown in Fig.1. First, a 500Å n-type GaAs buffer layer is grown on n^+-type GaAs substrate. A linearly graded InGaAs buffer with 15% per μm varying grading rate is following by n-type GaAs buffers. The final indium composition of the buffers is 50% which will reduce the dislocation between the superlattice structure. On top of the buffers, the superlattice structure is grown, and followed by 5000Å of p-type $In_{0.45}Ga_{0.55}As$.

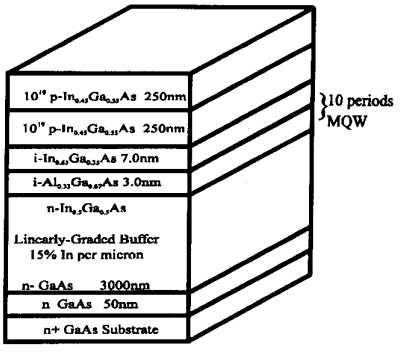

Fig.1 Schematic diagram of InGaAs/AlGaAs superlattice structures.

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 $f = |a_w - a_b| / a_w$, 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[2]

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

where γ is Poisson's ratio, Θ_{db} 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

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plane which is normal to the line of intersection between the slip plane and the interface. For growth on (100) substrate, $b=a/\sqrt{2}$ and $\Theta_{db}=\lambda=60°$. In the case of a multiple quantum well structure or superlattice, strain is often absorbed within both the well material and the barrier material. By using a linearly compositional graded buffer, the excess stress due to the large lattice misfit is fully relaxed. The distribution of strain between well-layer and barrier-layer can be balanced. We can ensure that there will be no net accumulation of excess stress in the superlattice. That is, optimum buffer composition appears to minimize the strain in the InGaAs wells without exceeding a critical thickness due to strain for an individual barrier layer or due to cumulative strain from the MQW structure. The critical thickness of $In_xGa_{1-x}As$ on $Al_{0.33}Ga_{0.67}As$ with and without indium concentration from 50% to 65% is plotted in Fig.2. From the graph, the critical thickness of $In_{0.65}Ga_{0.35}As$ layers on $Al_{0.33}Ga_{0.67}As$ layer with 50% indium linearly graded buffer is below 80Å.

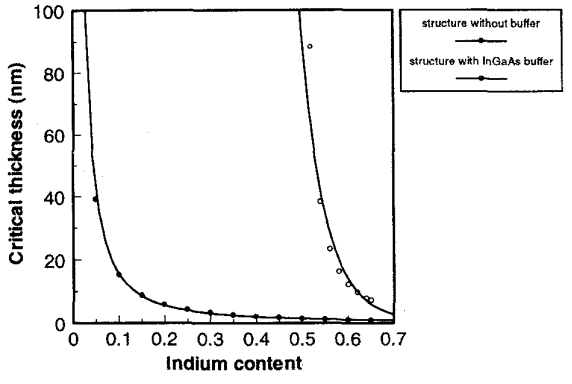

Fig.2 Critical thickness of InGaAs/AlGaAs with InGaAs linearly graded buffer with 50% Indium.

A superlattice[3] is a periodic series of QW's separated by two distinct materials A (called well) and materials B (called barrier). For a sufficient thin barrier, the QW's are strongly coupled by the resonant process. The resonant coupling of the QW's causes the original QW discrete energy level to broaden into minibands (ΔE) of width for electron and heavy hole. The application of electric field across a superlattice breaks the energy degeneracy of tunneling-coupled well, and the minibands formed by the original coupling will be removed. Since the miniband is centered at the non-degenerate energy level, a blue shift[4] of the absorption spectrum is expected. Moreover, the transition energy of superlattice is smaller than the individual uncoupled quantum well by $(1/2)\cdot\Delta E$. Carriers are delocalized and the superlattice structure exhibits to some extent a three-dimensional behavior. When there is an applied electric field (F) across the superlattice. Carriers tend to localize and the structure recovers a two-dimensional behavior. The energy levels of adjacent quantum wells will be misaligned by qFd, where q is electron charge and d is the superlattice period. This is very unlike the quantum-confined Stark Effect. The superlattice absorption spectrum could be viewed as the sum of absorption steps corresponding to transitions connecting holes and electrons localized in well separated by n periods and occurring at energies $E_{QW}+nqFd$ ($n = 0, \pm1, \pm2, ...$), where E_{QW} is the fundamental transition energy associated to the isolated quantum well. The corresponding oscillator strengths are related to the overlap between hole and electron wavefunctions. At the high field limit regime, where $qFd = \Delta E$[5], all the oblique transitions, except those connecting adjacent well, will vanish since the overlap of wavefunctions centered in adjacent wells decrease rapidly, due to the drastic decrease of tunnel probability. As the field is further increased, the system behaves as a series of uncoupled quantum wells. The blue shift and amplitude of optical absorption tend to saturate, and a hint of red shift is finally observed. The effect of red shift corresponds to the combination of the usual intrawell effect known as the quantum confined Stark Effect due to the field-induced deformation of the quantum-well potential.

III. RESULTS AND DISCUSSION

In the numerical analysis of the model described in above sections, all the material parameters are taking at room temperature as shown in Table.1.

Table 1
Material parameters of InGaAs and AlGaAs at room temperature

	$In_xGa_{1-x}As$	$Al_{0.33}Ga_{0.67}As$
Lattice constant(Å)	5.6533+0.405x	5.6559
Bandgap energy(eV)	$1.424-1.501x+0.436x^2$	1.88
Conduction band offset(%)	78	22

The band structure model in the calculation is determined by tight-binding approach with valence band-mixing. We have also analyzed the optical absorption of the structure. The result of the calculation for F=0kV/cm and 100kV/cm is shown in Fig.3. The absorption edge without applied electric field is located at 1.54μm with the magnitude of $7500cm^{-1}$. When a field of 100kV/cm is applied, the edge will red shift to 1.55μm with $7000cm^{-1}$ magnitude.

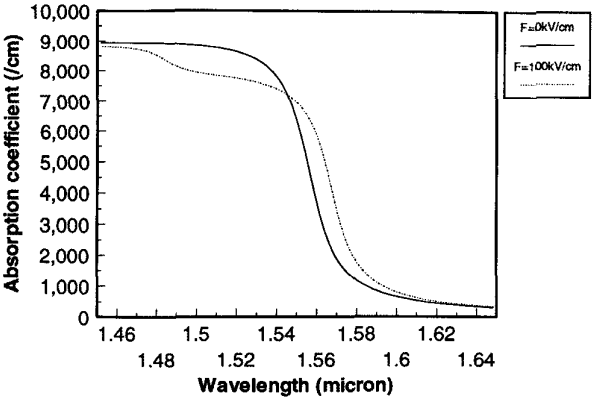

Fig.3 The TE polarized absorption coefficient of InGaAs/AlGaAs for the values of electric field, F=0kV/cm and F=100kV/cm.

In this model, we observed that the blue shift of absorption peak is quite small within a high field limit regime. The change of optical absorption is also small. In order to have a large change of optical absorption for application to optical modulator, we apply a high electric field large than the high field limit. The change of absorption coefficient spectrum is shown in Fig.4. The result shows that the magnitude of optical absorption change is about 2300cm^{-1} at 1.565μm which can be used as amplitude modulators.

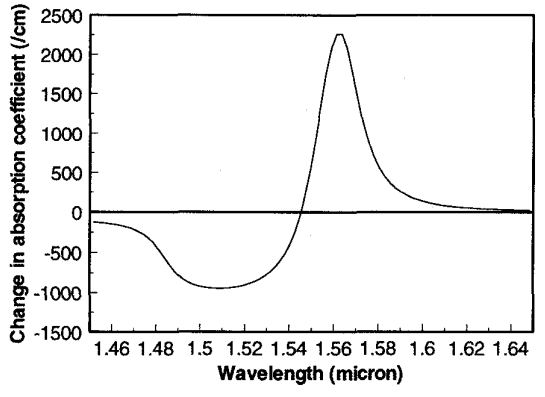

Fig.4 The TE polarized electroabsorption spectrum, change in absorption coefficient, α(F=100kV/cm)-α(F=0kV/cm).

The amplitude optical modulation relies on changes in the absorption coefficient due to an applied electric field. This effect involves the shifting of the bandedge of absorption spectrum to lower energies with the applied field. Since the optical absorption coefficient changes very rapidly near the bandedge, this effect can be used to produce high efficient intensity modulation. Assuming an ideal situation, the intensity modulation can be expressed in terms of an on-off coefficient (R) given by

$$R=\exp(\Gamma\Delta\alpha L), \qquad (2)$$

where Γ is the overlap between the quantum well layer and an optical mode of the waveguide which is taken to be 0.01[6], and L is the interaction length of the modulator. We take a 100μm long as a modulation length. The spectrum of on-off coefficient is shown in Fig.5. It can be seen that the maximum value of on-off coefficient is about 1.26 at the wavelength of 1.565μm.

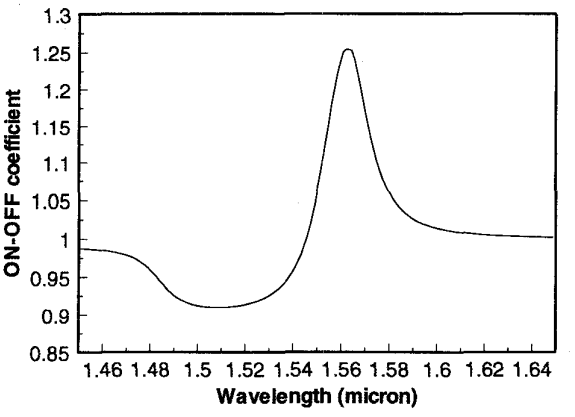

Fig.5 The spectrum of on-off coefficient

We have also calculated the change in refractive index. The relationship between the electric field induced refractive index change Δn and the absorption coefficient change Δα is given by the Kramers-Krönig Transformation[7]:

$$\Delta n(E,F)=\frac{c\hbar}{\pi}P\int_0^{\infty}\frac{\Delta\alpha(E',F)}{E'^2-E^2}dE' \qquad (3)$$

where P stands for the principal cauchy integral, Δα(E',F)=α(E',F)-α(E',0), α(E',F) is the absorption coefficient at electric field F and optical energy E', the unit of α and E are cm^{-1} and eV, respectively and $c\hbar/\pi$ is equal to 6.28×10^{-6}. The spectrum of the change in refractive index is shown in Fig.6. A dispersion of refractive index change of 0.035 was obtained with peaks at 1.55μm(min.) and 1.57(max.) which can be used for phase modulations.

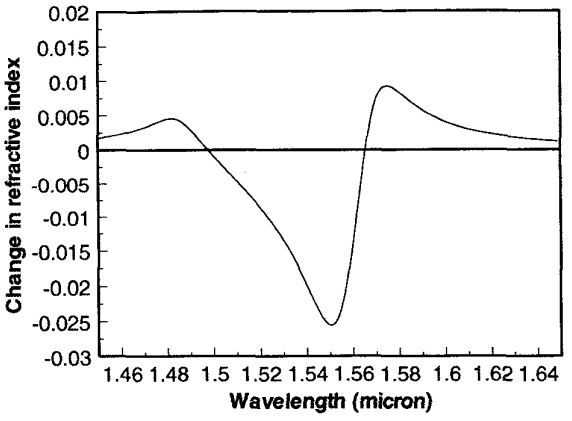

Fig.6 Change in refractive index due to electroabsorption spectrum in Fig.4

The phase modulation due to $\Delta\alpha$ can be calculated by considering an ideal situation for the phase difference per unit length,

$$\Delta\phi = \frac{2\pi\Delta n}{\lambda}, \qquad (4)$$

in a waveguide-modulator type of structure. The unit of eqn.4 is radian/μm. The phase difference of waveguide-modulator type in the range of 1.45μm-1.65μm is shown in Fig.7. It should be noted that the values obtained may only be used as an indicator. A confinement factor of 0.0025 per quantum well has not been taken into consideration.

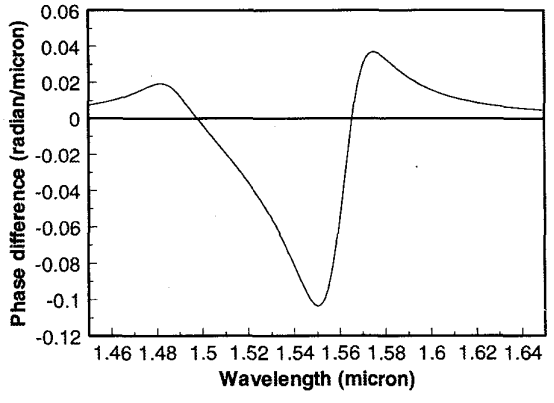

Fig.7 The phase difference in a waveguide modulator type.

IV. CONCLUSION

In this paper we have presented theoretical results of the room temperature change in absorption coefficient and refractive index due to an applied field with 65% indium concentration in InGaAs/AlGaAs superlattice. The results show an enhancement of the electroabsorption effect for the superlattice type material. This can have very useful applications in optical communication system, which operates at 1.55μm, based on the more matured and reliable GaAs technology.

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