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Enhanced Field Induced Optical Absorption in Graded Coupled Quantum Wells

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Coupled quantum wells have been known to display unique Stark shifts. In this paper, a scheme, whereby the potential profile of the coupled quantum well structure is slightly inclined, is proposed for lowering the electric field required for complete well decoupling. Numerical calculations of the absorption spectra of the graded coupled quantum wells under an electric field confirm the above effect. Moreover, room temperature absorption current spectra of the p-i-n diode samples fabricated show good agreement with the calculated results.

1. INTRODUCTION

Quantum wells coupled via a thin separating barrier have been shown to display unique Stark shifts, which are much different from that of isolated quantum wells.[1)] It is possible to decouple both quantum well structures for electrons and holes and hence localise the particles in the respective wells by the application of an electric field, resulting in large changes of the optical coefficient.[2)] However, the electric field necessary for the decoupling of the strongly coupled quantum wells is too high.

In this paper, we propose a new scheme, whereby the potential profile of the coupled quantum well structure is slightly inclined for lowering the electric field required for complete well decoupling. Numerical calculations of the absorption spectra and room temperature absorption current spectroscopy of samples of graded coupled quantum wells fabricated will be presented.

2. DESIGN OF GRADED COUPLED QUANTUM WELLS

The potential profile of any quantum well structure can be inclined by either an applied electric field, or by a varying material composition. In a structurally pre-biased quantum well, it is noted that the

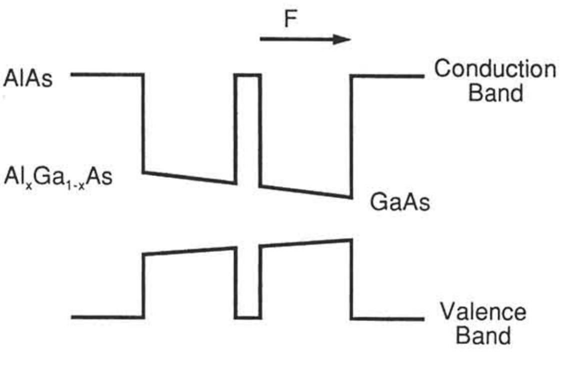

FIGURE 1
Schematic potential profile of a structurally pre-biased graded coupled quantum well.

inclination of the conduction band is in the opposite direction to the valence band. Since the Stark shift achievable in a quantum well system is proportional to the effective mass of the particle involved,[3)] the case whereby the applied electric field further increases the inclination of the valence band is expected to bring about a larger Stark shift of the fundamental absorption peak in an isolated single quantum well.[4)]

In the graded coupled quantum well structure, the energy bands are varied continuously across the whole structure, as shown in Fig. 1, to enhance the field induced decoupling effect. However, the direction of the electric field to be applied for achieving the above

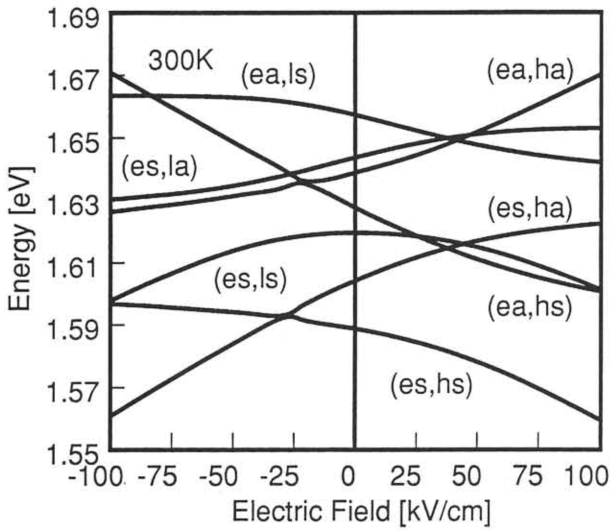

FIGURE 2
Electric field dependence of the transition energies of an AlGaAs/AlAs graded coupled quantum well structure with the aluminium content varied linearly from 0 to 0.05 across the entire structure.

enhancement is not apparent at first glance.

Numerical calculations of the eigen energy levels, wave functions and absorption spectra of the graded coupled quantum wells under an electric field have been made, using the tunnelling resonance model and variational computations.[5] Figure 2 shows the electric field dependence of the transition energies of an AlGaAs/AlAs graded coupled quantum well structure with the aluminium content varied linearly from 0 to 0.05 across the entire structure. The well width and the separating AlAs barrier thickness are 17 monolayers (ML, 1ML=2.83Å) and 2ML respectively. The electric field is positive if it is applied in the direction as to further increase the inclination of the valence band. It is clear that enhancement of the decoupling effect, via the merging of the electron symmetric-heavy hole antisymmetric (es,ha) and electron antisymmetric-heavy hole symmetric (ea,hs) transitions, only occurs when the electric field further increases the inclination of the valence band.

The effect of the degree of inclination of the energy bands in the graded coupled quantum well structures is next examined. Figure 3 shows the dependence of the decoupling electric field and maximum absorption coefficient achievable upon complete decoupling

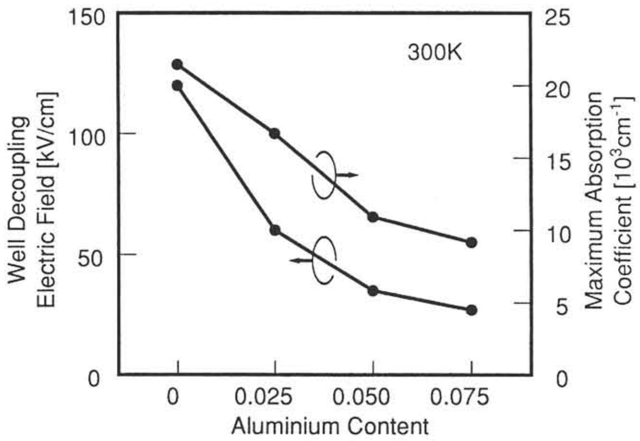

FIGURE 3
Dependence of decoupling electric field and maximum absorption coefficient achievable upon complete decoupling on the aluminium content at the extreme end of the potential profile.

on the aluminium content x at the extreme end of the potential profile shown in Fig. 1. The physical dimensions of the structure is the same as that mentioned above. It can be seen that a larger inclination of the energy bands results in a lower electric field necessary for complete well decoupling. However, too sharp an inclination results in decoupling at lower oscillator strengths since the squared overlap integrals of the electron and heavy hole wave functions vary more slowly with the electric field.

3. OPTICAL ABSORPTION SPECTRA

The calculated room temperature absorption coefficient spectra of the graded coupled quantum well structure under various electric fields is shown in Fig. 4. The aluminium content of the structure is varied linearly from 0 to 0.05 for the system and the well width and separating AlAs barrier thickness are 17ML and 2ML respectively.

As in the case of the normal strongly coupled quantum well structure, only transition peaks of identical symmetries are observable at zero electric field. With an increase in the electric field, the electron symmetric-heavy hole antisymmetric and electron antisymmetric-heavy hole symmetric absorption peaks appear and merge into a strong single peak at wavelength 768nm and field 40kV/cm. This corresponds to

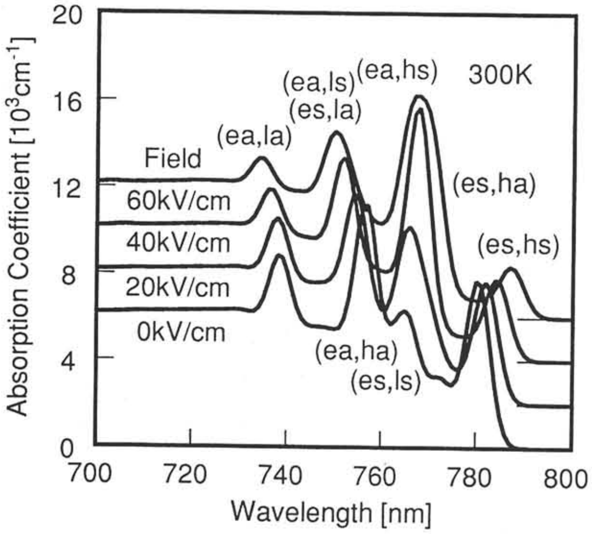

FIGURE 4
Calculated room temperature absorption spectra of the graded coupled quantum well. The notation (ei,jk) represents a transition between the electron i (s for symmetric, a for antisymmetric) and j (h for heavy, l for light) hole k (s for symmetric, a for antisymmetric) modes.

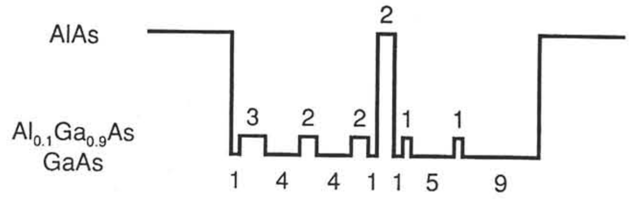

FIGURE 5
Schematic potential profile of the equivalent graded coupled quantum well structure, where the thickness of the embedded ultrathin $Al_{0.1}Ga_{0.9}As$ layers in the entire 36 monolayer structure is varied to simulate the ideal case. The integers in the figure indicate the thickness of each layer in monolayers.

an absorption coefficient variation of 7160cm^{-1} with respect to the zero field state, and compares favourably with the necessary well decoupling electric field of 120kV/cm and maximum absorption coefficient variation of 5710 cm^{-1} at the same field of 40kV/cm with respect to the zero field state in a normal strongly coupled quantum well structure of GaAs with the same physical dimensions.

4. SAMPLE FABRICATION

Actual fabrication of the graded coupled quantum well structure by molecular beam epitaxy (MBE) is difficult since the aluminium content must be varied rapidly and continuously across just 36ML. Moreover, a slight fluctuation in the aluminium flux could easily upset the profile of the entire structure. Consequently, the equivalent graded coupled quantum well structure shown in Fig. 5, whereby alternating ultrathin GaAs and AlGaAs layers of variable widths are used to simulate the varying aluminium content, has been employed in place of the ideal structure for fabrication by the operation of the Knudsen-cell shutters in the MBE system. The calculated absorption spectra of the equivalent structure is shown in Fig. 6 and

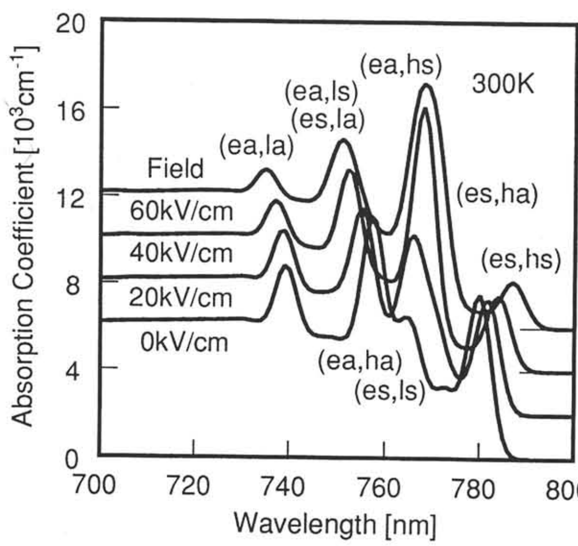

FIGURE 6
Calculated room temperature absorption spectra of the equivalent graded coupled quantum well.

it matches that of the ideal structure in Fig. 4 very well.

To examine the enhanced electroabsorption effect, fifteen sets of the equivalent graded coupled quantum well structure are embedded in the intrinsic region of a p-i-n diode. Figure 7 shows the room temperature absorption current spectra obtained at various reverse biases. It can be noticed that an absorption peak at 774nm suddenly appears at a bias of -2.25V, when compared with the spectra of bias 0V, -1V and -2V. The peak clearly distinguishes itself with a bias of -2.5V and above. This is in fairly good agreement with the calculation results.

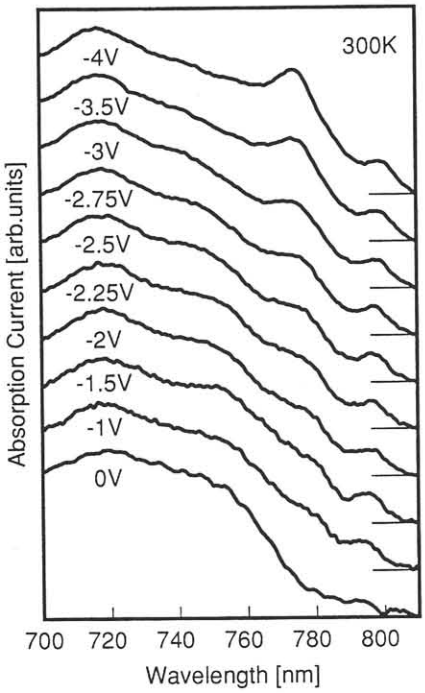

FIGURE 7
Room temperature absorption current spectra of the equivalent graded coupled quantum well structure at various transverse driving voltages.

5. CONCLUSIONS

A novel coupled quantum well structure, whereby the potential profile is slightly inclined, is proposed for lowering the electric field required for complete well decoupling. The aluminium compositional profile is set such that the inclination of the energy bands vary continuously across the whole structure and the electric field is applied in the direction as to further increase the inclination of the valence band. Numerical simulation of the absorption spectra at various electric fields reveals a strong dependence of the decoupling electric field on the built-in structural potential inclination. Room temperature absorption current spectra of the p-i-n diode samples fabricated with the equivalent graded coupled quantum wells in the intrinsic region have shown good agreement with the calculated results. Consequently, it can be concluded that in the graded coupled quantum well structure, large absorption coefficient variations occur at a much lower electric field, pointing out the possibility of high speed optical modulation with low driving voltages.

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REFERENCES

1. S.R.Andrews, C.M.Murray, R.A.Davies and T.M. Kerr; Phys. Rev. B **37** (1988) 8198.
2. K.Tada, Y.C.Chan and T.Ishikawa; Paper of Technical Group on Opt. and Quantum Electron., Institute of Electronics, Information and Communication Engineers OQE89-102 (1989) 37.
3. G.Bastard, E.E.Mendez, L.L.Chang and L.Esaki; Phys. Rev. B **28** (1983) 3241.
4. K.Nishi and T.Hiroshima; Appl. Phys. Lett. **51** (1987) 320.
5. T. Ishikawa and K. Tada; Jpn. J. Appl. Phys. **28** (1989) L1982.