# THERMAL STABILITY STUDY OF OXYGEN IMPLANTED AlGaAs/GaAs SINGLE QUANTUM WELL STRUCTURES USING PHOTOREFLECTANCE

P J Hughes, E H Li* and B L Weiss
Department of Electronic & Electrical Engineering
University of Surrey, Guildford, SURREY GU2 5XH, UK

H E Jackson
Department of Physics, University of Cincinnati
Cincinnati, OHIO, 45220-0011, USA

J S Roberts
Department of Electronic & Electrical Engineering
University of Sheffield, Sheffield, S1 3JD, UK

**Abstract**

The effects of interdiffusion on the band structure of two $Al_xGa_{1-x}As/GaAs$ single quantum well (SQW) structures were studied using room temperature photoreflectance. Rapid thermal annealing of the SQW structures at temperatures of 800°C, 900°C and 1000°C for times up to 180 seconds resulted in limited interdiffusion. Low dose ($10^{14}$ $cm^{-2}$) oxygen implantation reduced the thermal stability of these structures where the extent of the interdiffusion was found to be greater for the implanted samples for identical annealing conditions.

**Introduction**

The optical properties of quantum well (QW) structures have been the focus of much attention for many years for the development of novel optical devices[1]. Tailoring their properties has been achieved through the modification of the confinement profile of the QW structure using controlled interdiffusion across the well/barrier interface[2]. This interdiffusion of the QW results in a modification of the subband structure, and thus the bandgap and optical properties, of the as-grown QW (AGSQW). Thermal annealing of $Al_xGa_{1-x}As/GaAs$ AGSQW structures results in the interdiffusion of Ga atoms from the well layer and Al atoms from the barrier layers across the well/barrier interface to produce a graded compositional profile.

* permannent address is Department of Electrical engineering, University of Hong Kong, Hong Kong



Mat. Res. Soc. Symp. Proc. Vol. 354 © 1995 Materials Research Society

However, it has been shown that the rate of interdiffusion may be enhanced significantly through the introduction of specific impurities, such as oxygen[3], or vacancies[4] using ion implantation or surface $SiO_2$ layers respectively, followed by annealing to remove the implantation damage. Ion implantation is particularly useful for the introduction of the required impurities at selected locations due to the high degree of control in both spatial and depth dimensions, making it the desired process for the implementation of interdiffusion for the fabrication of devices. In addition, studies of GaAs and AlGaAs materials have shown that the presence of oxygen atoms result in the formation of highly resistive materials due to the reduction of free carrier levels in the sample[5] which has been used for the electrical isolation of devices such as heterostructures lasers[6].

As transition energies of the QW depend upon the shape of the confinement profile, the Al-Ga interdiffusion can be measured optically by monitoring the systematic 'blue' shift of the QW transition energies as a function of the annealing temperature and time. Photoreflectance[7] (PR) is an optical technique which detects all the transitions in a QW structure is therefore well suited for the study of interdiffusion in QW structures.

**Experimental Method**

The two AGSQW structures investigated here were grown by metal-organic vapour phase epitaxy (MOVPE) on (100) semi-insulating GaAs substrate. Both structures have nominal $Al_xGa_{1-x}As$ barrier layer thicknesses of 1000Å above and below the well and are terminated with a 50Å cap. The GaAs QW thickness, $L_z$, for these two structures were 57Å and 108Å, as measured from the ground state transition energies using both photoluminesence[8] and PR[8], with nominal mole fraction barrier compositions of x = 0.2 and 0.3 respectively. For reference, these structures will be referred to by the notation $x/L_z$(Å): 0.3/100 and 0.2/50. All layers were undoped, although evidence of residual p-type doping due to background carbon acceptor concentrations were found using phase sensitive PR[9].

The PR system which is used here is a standard arrangement and has been described elsewhere[10]. Thermal annealing was achieved using a double graphite strip rapid thermal annealing system (RTA), where the structures were placed in a chamber between graphite strips which were resistively heated. For these experiments, three rapid anneal cycles at fixed anneal temperatures of 800°C ,900°C and 1000°C for anneal times of 10, 60, 120 and 180 seconds were used. The implantation of oxygen into the AGSQW structures was carried out at room temperature using 150 keV oxygen ions at an ion dose of $1 \times 10^{14}$ $cm^{-2}$. The ion energy was determined using SUSPRE[11] to place the peak of the implanted oxygen profile at the centre of the well layer while the peak of the implantation induced damage occurred at a depth of 260Å. The samples were annealed to remove the implantation induced damage and to activate the oxygen ions.

**Results and Discussion**

The AGSQW structures studied here formed part of a detailed room temperature PR study of the band structure of GaAs/$Al_xGa_{1-x}As$ SQW structures[8]. The PR spectra for both structures exhibited strong Franz-Keldysh oscillations (FKO) near both the GaAs substrate and $Al_xGa_{1-x}As$ barrier energies, which were found to originate from strong built-in dc electric fields at the barrier/substrate interface[10]. The spectra were fitted using a lineshape model which included expressions for the FKO and several Third Derivative Functional Forms (TDFFs) to determine the PR transition features.

The results obtained from the lineshape modelling together with the theoretical modelling of the structures are summarised in Fig. 1 where the QW transitions[8], which were investigated in this study, have been identified. For reference, the transitions between electron to heavy-hole and light-hole are abbreviated by $H_{mn}$ and $L_{mn}$ respectively, where m and n are the subband indices of the conduction and valence bands respectively.

Annealing both samples at 800°C for up to 180 seconds showed no significant energy shifts for either $H_{11}$ or $L_{11}$ transitions of sample 0.2/50[8], at 1.497 eV and 1.520 eV respectively, or the $H_{22}$ and $H_{33}$ transitions of sample 0.3/100[8], centred at 1.541 eV and 1.696 eV respectively, demonstrating the thermal stability of the AGSQW structures at 800°C upto 180 seconds.

The PR spectra of sample 0.2/50 annealed at 800°C, 900°C and 1000°C for 180 seconds for the $H_{11}$ and $L_{11}$ transitions are shown in Fig. 2(a). The spectra show that both transitions experienced significant 'blue' shifts and that the $H_{11}$ - $L_{11}$ splitting decreased with increasing annealing temperature and time after annealing at 900°C and 1000°C. This is seen in the PR spectra shown of Fig. 2(a) where the transition become less well resolved as the interdiffusion proceeds. The behaviour of these two transitions is attributed to changes in the subband SQW structure due to Al diffusing into the centre of the well, thereby increasing the bandgap of the interdiffused QW. The effects of interdiffusion on higher order transitions was studied using the $H_{22}$ and $H_{33}$ transitions of sample 0.3/100. The PR spectra of the interdiffused samples over the three different temperatures for 180 seconds in the energy range 1.5 eV to 1.8 eV, which includes these transitions of the QW, are shown in Fig. 2(b). Due to the structural differences of these samples, the ground states are located deeper in the QW for sample 0.3/100 which has a larger value of $L_z$ and a greater barrier Al concentration than the 0.2/50 sample, as shown in Fig. 1. At these energies the FKO component, which can be described as an exponentially decaying oscillation above the band-edge energy 1.421 eV[10], is stronger than that of the QW transition and thus dominates the PR spectrum and in most cases this situation was maintained as the sample was annealed.

In contrast, the higher order transitions lie at energies which are far above the FKO region of the PR spectrum. With increasing RTA temperatures and times, the higher order transitions are also 'blue' shifted with the $H_{22}$ experiencing a greater shift in energy than the $H_{33}$ transition, see Fig. 2(b). The behaviour of these two higher order transitions indicates that some transitions, such as the $H_{33}$, are less sensitive to the changing shape of the confinement profile with interdiffusion than are other transitions,

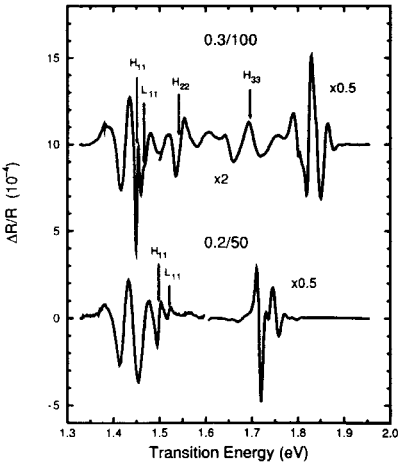


Figure. 1 Normalised change in reflectance ΔR/R versus probe beam energy for both AGSQW structures showing the QW transitions under investigation.

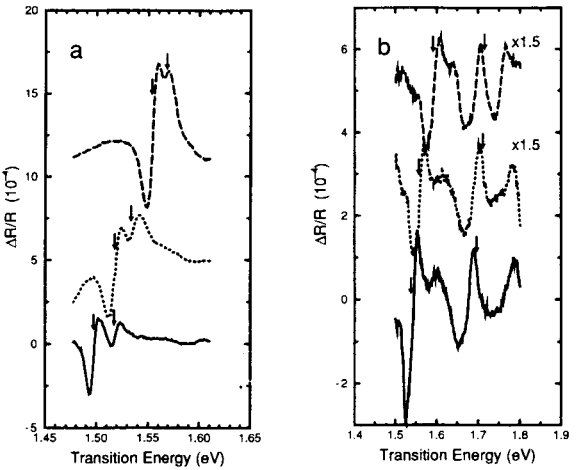


Figure 2. PR spectra of the interdiffused SQW structures for (a) 0.2/50 and (b) 0.3/100 showing the 'blue'shift in energy of the QW transitions as a function of annealing temperature; 800°C (———); 900°C ( - - - - - - ); 1000°C ( — — — ) for an anneal time of 180 seconds.

such as the $H_{22}$. The changing shape of the well as the interdiffusion proceeds can be seen in Fig. 2(b) where the higher order transitions have broadened with increasing anneal temperature which reduces the overlap between the electron and hole wavefunctions. This spectral broadening is attributed to fluctuations in the effective well width resulting from roughness at the well/barrier interface caused by Al-Ga interdiffusion.

The effects of oxygen implantation and subsequent annealing conditions were studied using sample 0.3/100. The spectra of the as-implanted preannealed AGSQW showed no PR features which indicated the presence of a high level of implantation induced damage. Annealing at 800°C produced no PR features due to the QW transitions while annealing at 900°C showed a significant recovery of these transitions which improved gradually with increasing annealing time due the gradual removal of the implantation damage. However, the sensitive nature of the PR intensity to implant damage resulted in a factor of five reduction of the intensity of the QW transitions in the implanted samples when compared to the unimplanted samples. This reduction in PR signal can be explained by the influence of oxygen implant damage which creates a large number of non-radiative recombination sites which reduce the lifetimes of carriers. Energy shifts for the higher order transitions were found to be greater in the implanted samples indicating a greater level of interdiffusion had occurred. The extent of oxygen induced interdiffusion can be seen in Fig. 3 where the $\Delta R$ spectra for the unimplanted and implanted samples at 1000°C for 120 seconds are shown. From the spectra, a greater shift of the higher order $H_{22}$ and $H_{33}$ transitions was found. It is interesting to note that although the intensity of the PR signal is reduced, oxygen implantation does not adversely affect the PR lineshape ie. no spectral broadening of the QW transitions were observed. The enhancement of the interdiffusion using implantation suggests that implanting low dose oxygen into the QW creates a large number of defects and hence vacancies which on anneal accelerate the interdiffusion of Al and Ga atoms across the QW interfaces. This accelerated interdiffusion however is a strong function of the post implant annealing conditions.

**Conclusions**

It has been shown here that PR is a useful technique to study the effects of interdiffusion on the band structure of QW structures by monitoring the behaviour of all of the QW transitions. For the annealing conditions used here only moderate interdiffusion occurred. The oxygen implanted samples were found to have a lower thermal stability, i.e. a greater energy shift than in the unimplanted samples, which indicates the presence of more extensive interdiffusion. This result demonstrates that the role of oxygen implantation is potentially very promising for future device fabrication.

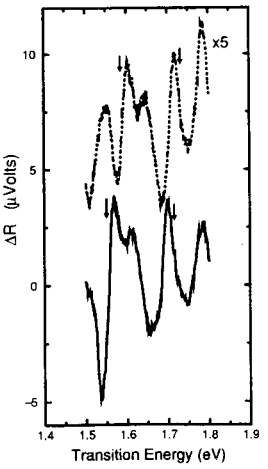


Figure 3. PR spectra for sample 0.3/100 for both the unimplanted ( ——— ) and oxygen implanted (- - - - - -) samples at an anneal temperature of 900°C for 120 seconds.

**Acknowledgements**

The authors acknowledge the financial support of the UK Science and Engineering Research Council, NATO, UPGC-RGC grant of Hong Kong and the staff of the D R Chick Laboratory for assistance with the ion implantation.

**References**

1. H Okamoto, Jap J Appl Phys, **26**, 315, 1987
2. M Ghisoni et al., Mat Res Soc Symp Proc, **262**, 823, 1993
3. B L Weiss, I V Bradley, N J Whitehead and J S Roberts, J Appl Phys, 71, 5715, 1992
4. E S Koteles et al, Opt & Quantum Elect, **23**, S779, 1991
5. G B Stringfellow and G Hom, Appl. Phys. Lett. **34**, 794, 1979
6. R P Bryan et al., Appl Phys **55**, 94, 1989
7. O J Glembocki, Proc SPIE, **1286**, 2, 1990
8. P J Hughes, T J C Hosea and B L Weiss, submitted to J Appl Phys
9. P J Hughes, B L Weiss, T J C Hosea, submittd to J Appl Phys
10. P J Hughes, B L Weiss, submitted to Appl Phys Lett
11. SUSPRE is a computer code developed by R P Webb, University of Surrey for VG IONEX