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# Effect of strain on the interdiffusion of InGaAs/GaAs heterostructures

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The results of interdiffusion experiments on two multiple quantum well heterostructures of InGaAs/GaAs are presented. The two samples each had four quantum wells with indium concentrations, in order from the surface, of 5%, 15%, 20%, and 10%. The two samples also had different barrier layer thicknesses to allow any strain or depth dependence of the diffusion to be observed. No effect of strain or depth on the diffusion was observed. © 1999 American Institute of Physics.

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## I. INTRODUCTION

The presence of strain in quantum well heterostructures has been used in semiconductor devices for a number of years, and its role on the thermal stability of such heterostructures has been widely discussed. There is as yet, however, no consensus as to whether the presence of strain enhances diffusion or not. In 1989, Iyer and LeGoues<sup>1</sup> reported that strain enhanced the diffusion of Si-SiGe heterostructures whilst two years later in the same system Höllander *et al.*<sup>2</sup> found that strain had only a minor effect. For the III-V semiconductors, Gillin and co-workers<sup>3-5</sup> studied the InGaAs/GaAs system in detail and found no detectable effect of strain and in 1994 published an analysis showing that strain should not affect diffusion as the elastic strain energy is too small.<sup>6</sup> However, the following year Ryu *et al.*<sup>7</sup> showed results for InGaAs/GaAs which suggested that strain does affect the diffusion in this system and reanalyzed some of the data of Gillin *et al.*<sup>3</sup> to show that it was consistent with their model.

While we feel that for the Si-Ge system there is still insufficient data to state categorically whether strain does or does not affect the diffusion, we report in this article the results which show that there is no strain effect in the diffusion of InGaAs/GaAs, and discuss possible reasons for the effects noted by Ryu *et al.*<sup>7</sup>

## II. EXPERIMENTAL METHOD

For this work, two molecular beam epitaxy (MBE)-grown multiple quantum well (MQW) samples of InGaAs/GaAs were used. Each sample consisted of four quantum wells each of 10 nm width but with indium concentrations between 5% and 20%. A schematic of the two samples is given in Fig. 1. The different indium concentrations in the well were placed in the order used so that any effects such as enhanced diffusion caused by the surface or substrate would not be confused with a strain effect. Similarly, the structures were grown with different barrier thicknesses in order to look for any depth effects, which may be caused by the interdiffusion of vacancies from the surface.

Following growth the samples were capped on both the front and back surface with 30 nm of plasma enhanced chemical vapor deposition (PECVD)-grown silicon nitride ( $n=2.1$ ) deposited at a temperature of 300 °C. This encapsulant has been shown to be equivalent to a high arsenic overpressure environment during annealing<sup>8</sup> and results in virtually no injection of point defects from the surface. Following encapsulation, the samples were cleaved in to 5 mm by 5 mm squares for annealing. Annealing was performed in a double-graphite strip heater where the sample is placed between two resistively heated strips in a helium ambient. The temperature measurement and control were performed with an Accufiber optical thermometry system. A linear ramp to temperature was used with ramp times of 15 s. The system was calibrated against the melting points of zinc, aluminium, silver, and gold and was found to be accurate to  $\pm 1$  °C over the temperature range of 400–1100 °C. Photoluminescence at 80 K was excited using the 514 nm line from an argon ion laser and dispersed in a 1 m spectrometer and detected using a LN2 cooled germanium detector. Details of the analysis used to obtain diffusion lengths from the photoluminescence data are given in Refs. 3–5.

## III. RESULTS AND DISCUSSION

Samples were repeatedly annealed at temperatures from 900 to 1050 °C for times between 10 and 120 s. After annealing, the photoluminescence was recorded to obtain the diffusion length before the sample was returned to the furnace for another anneal. Total anneal times for the different temperatures were 420, 300, 120, and 60 s for the anneal temperatures of 900, 950, 1000, and 1050 °C, respectively. The diffusion length data at each anneal temperature were plotted as diffusion length squared against anneal time and for each quantum well in each sample, this produced a straight line, see, for example, Fig. 2. This proves that the diffusion coefficient is constant. The gradient of these lines gives the diffusion coefficient for intermixing.

Table I gives the diffusion coefficients for sample I for each of the four quantum wells, the errors quoted in this table are those given from a least-squares fit to each data set and ignore the effects of systematic errors, such as the ramp phase, which will be discussed later. From the data presented in Table I, it can be seen that there is no systematic variation

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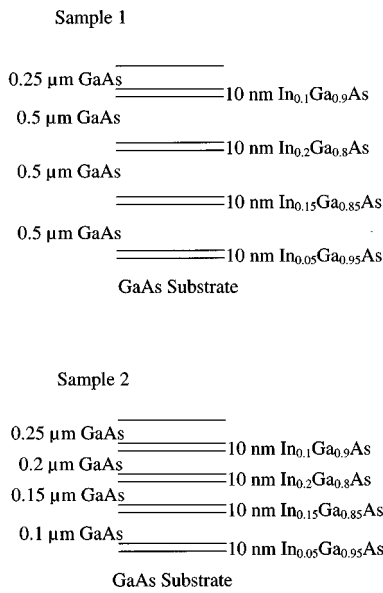


FIG. 1. Schematic diagram of the two structures used in these experiments.

in diffusion coefficient with the indium concentration and hence with the strain in the quantum well. If one looks at the data presented in Table I in depth order, rather than in order of strain, the 900 °C data show what could be a slight decrease in diffusion coefficient with depth, however, none of the other anneal temperatures show anything other than random variations between the different quantum wells. This point is further emphasized by an experiment where we took a piece of sample I and sample II and annealed them together, face-to-face, so that there would be no possibility of variations in anneal temperature, ramp rate, etc. As the quantum wells in each sample were at different depths, we hoped to see any evidence for a depth dependence more clearly. The results of these experiments, performed at 900 and 1000 °C, are presented in Fig. 3 as diffusion coefficient against depth. As can be seen from Fig. 3, there is no strong effect of depth but it is very noticeable that there are distinct variations between the samples, with there being three to four times greater average diffusion coefficient in sample II compared with sample I. This is despite the care that was taken to ensure that the two samples experienced identical process conditions. This is an effect that we have seen in other experiments where we have looked at samples which were grown on wafers taken from next to each other in the boule, with quantum wells grown together in a single growth run and processed together as in these experiments. These variations in diffusion coefficient are almost identical be-

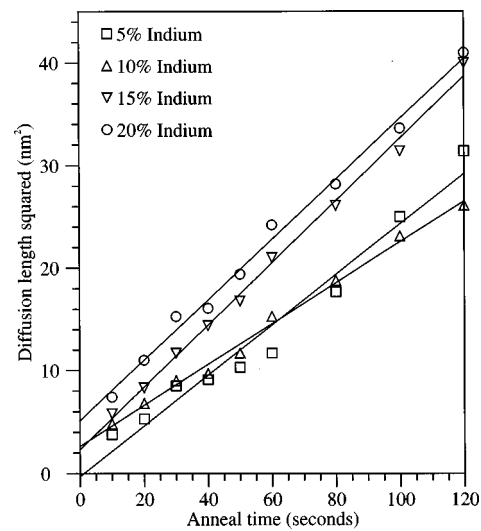


FIG. 2. Graph of the diffusion length squared data against anneal time for the four quantum wells in sample I for an anneal temperature of 1000 °C.

tween the samples, independent of anneal temperature, and thus reflect real variations in the samples rather than experimental uncertainty. This lack of a depth dependence on the diffusion coefficient is in contradiction to some of our earlier experiments.<sup>3</sup> In that work, we saw a small decrease in the diffusion coefficient as the depth of the quantum well from the surface increased. Those results were put down to the indiffusion of group III vacancies caused by the diffusion of gallium into the encapsulant. The encapsulant used in these experiments has a higher refractive index and is known to contain less oxygen than those used previously, it is this change, we believe, that has reduced the surface effect to an immeasurable level.

Given that these experiments show that there is no systematic variation in the diffusion coefficient with the strain in the quantum well, strains vary from 0.36% for the 5% indium well to 1.4% for the 20% indium well, it is necessary to address the analysis of Ryu *et al.*<sup>7</sup> which appear to show a strain effect in this material. In their work, Ryu *et al.*<sup>7</sup> grew a sample with two quantum wells, widths 60 and 120 Å, of In<sub>0.2</sub>Ga<sub>0.8</sub>As in GaAs barriers and annealed it in a furnace for times between 1.5 and 10 h, it appears from this article that each anneal was performed on a separate sample although this is not explicitly stated. Using the photoluminescence from the quantum wells and a standard Fick's law approach, identical to that used here, they produce data which show an apparent increase in diffusivity for short anneal times which reduces as annealing progresses. It is this which they use as

TABLE I. Diffusion coefficients for the four quantum wells in sample I at the various anneal temperatures used.

Anneal temperature (°C)	Diffusion coefficient $\times 10^{-16}$ (cm <sup>2</sup> /s)			
	In <sub>0.05</sub> Ga <sub>0.95</sub> As	In <sub>0.1</sub> Ga <sub>0.9</sub> As	In <sub>0.15</sub> Ga <sub>0.85</sub> As	In <sub>0.2</sub> Ga <sub>0.8</sub> As
900	0.47 ± 0.01	0.30 ± 0.01	0.40 ± 0.02	0.42 ± 0.01
950	1.2 ± 0.1	1.4 ± 0.1	2.0 ± 0.1	2.2 ± 0.1
1000	6.2 ± 0.4	5.0 ± 0.2	7.6 ± 0.3	7.4 ± 0.2
1050	53 ± 5	58 ± 7	70 ± 8	82 ± 9

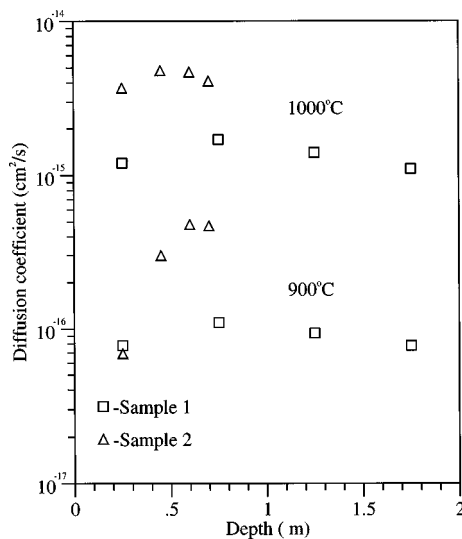


FIG. 3. Measured diffusion coefficients for both samples I and II for anneal temperatures of 900 and 1000 °C plotted as a function of the depth of the quantum well from the surface.

the basis for the strain enhanced model and they go on to use this model to reanalyze some data from Gillin *et al.*<sup>3</sup> to show that it is consistent. However, an analysis of their original data using the Fick's law model does show a remarkably good fit to straight line behaviour, although this straight line does not give a zero diffusion length for zero anneal times. This behavior is identical to that which we have observed in most diffusion experiments on semiconductors, both strained and unstrained. As this nonzero intercept on the diffusion length, squared against anneal time plot appears to be present in all experiments regardless of the presence of strain, it is reasonable to look for an explanation which is experiment dependant rather than sample dependant.

The most obvious cause of systematic error in diffusion experiments is the treatment of the ramp time of the sample during annealing. This extra annealing is normally ignored in most analysis. This is partly because for conventional furnaces, it is exceptionally difficult to know how long the sample takes to reach the furnace temperature. With the double-graphite strip heater, we have used throughout these experiments the sample, which has a low thermal mass, is placed between the strips which are heated rapidly with an electric current. By embedding a small diameter thermocouple into a dummy sample, we have been able to measure the response of the sample to the strips. We have found that the sample temperature follows a virtually identical anneal excursion to the strips, although there is an approximately one to two second delay between the sample temperature and the outside surface of the strips. As the ramp rate is controlled, using optical thermometry, to give a linear ramp, and as we know the activation energy for the diffusion process<sup>4</sup> we can easily calculate the effect this extra ramp phase will have on our samples. Obviously, if an experiment is performed using a single sample which is always given an identical anneal, the effect of the ramp phase will be identical for each anneal and it will have the effect of pushing the diffusion length squared against time plot up, keeping the fit lin-

ear but giving a positive intercept. It should be noted that in this case there is no error introduced into the determination of the diffusion coefficient. This is exactly the behavior observed in the data of Gillin *et al.*<sup>3</sup> which Ryu *et al.*<sup>7</sup> reanalyzed. If, on the other hand, a number of samples are used such that one sample receives a single anneal of 1 h, while another sample receives a single anneal of 10 h, then the samples which have the shorter anneal times see a bigger effect of the ramp phase. This will have the effect of creating data which appear to have a decreasing diffusion coefficient as annealing proceeds. A similar effect although not nearly as severe would be seen if a single sample were repetitively annealed but with the anneal time increasing with each anneal; this scenario is often used to follow the diffusion to large diffusion lengths while still collecting large amounts of data for smaller diffusion lengths.

Finally, we need to address the mechanism through which Ryu *et al.*<sup>7</sup> proposed that the strain enhanced the diffusion, changes in the vacancy creation rate due to strain. This theory is based on the work of Antonelli and Bernholc<sup>9</sup> who calculated that in Si:Ge there is a change in the vacancy energy in the presence of hydrostatic strain, however, Antonelli and Bernholc<sup>9</sup> also calculate the vacancy energy under biaxial strain, such as found in these samples, and they found that there was no change. While, this alone would count against the theory that compressive strain enhances diffusion, there is another more important consideration, all of this assumes that the vacancy concentrations are in thermal equilibrium and that such changes in formation energy will be significant. Recent work by Khreis *et al.*<sup>10</sup> showed that in InGaAs/GaAs, in particular, and probably in all III-V materials, the vacancy concentration in the material is independent of temperature with a value of  $\sim 10^{17} \text{ cm}^{-3}$ . Thus as the vacancy concentrations are nonequilibrium the proposed method of strain enhanced interdiffusion is not possible.

#### IV. CONCLUSIONS

The results of diffusion experiments on InGaAs/GaAs MQWs with wells of different indium concentrations are presented. The results show that the presence of strain in the quantum well has no effect upon the diffusion coefficient for intermixing. We also show that the effect of the ramp time during annealing can produce systematic errors in the determination of the diffusion length but that by correctly performing an experiment to follow the diffusion as a function of time these errors will not produce an error in the diffusion coefficient.

Furthermore, recent published data which show that vacancy concentrations in III-V materials are at nonequilibrium values remove the mechanism through which any strain enhancement was believed to act.

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