

# Impurity-induced layer disordering of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ heterostructures

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Impurity-induced layer disordering of  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructures grown by molecular beam epitaxy has been observed by Auger electron spectroscopy depth profiling. We find that  $\text{Si}^+$  ion implantation to concentrations greater than  $2 \times 10^{19}$  atoms  $\text{cm}^{-3}$  enhances the intermixing of Ga and Al in these heterostructures at an annealing temperature of 1075 K. However, the relatively high temperature which is required to activate the interdiffusion of Ga and Al in the region of high Si concentration is sufficient to induce In diffusion in regions of lower Si concentration. Zinc diffusion is found to completely intermix the Ga and Al in the heterolayers at temperatures as low as 825 K, which is below the temperature at which significant In diffusion occurs in undoped regions.

The ternary semiconductor alloys  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  and  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ , which are lattice matched to InP, have recently found application in the fabrication of optoelectronic devices operating in the 1.3–1.6  $\mu\text{m}$  spectral region. The thermal processing of these ternary alloy systems can be complicated by the fact that the interdiffusion of the group III metals cannot necessarily be described by a single effective diffusion coefficient.<sup>1</sup> Gradients in the elemental chemical potentials which provide the driving force for diffusion can originate from causes other than simple concentration gradients.<sup>1,2</sup> We recently have demonstrated that, for annealing at 1085 K, the interdiffusion at an  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  interface is dominated by Ga and In diffusion which leads to the development of strong modulations of the originally nearly constant In concentration profile.<sup>3</sup> We attribute this effect to the disparity between the mobility of Ga and Al in the ternary alloys which leads to the establishment of a gradient in the In chemical potential on annealing.

Recently, the technique of impurity-induced layer disordering (IILD) has been demonstrated to be effective in increasing the intermixing of Ga and Al at GaAs/AlAs, GaAs/GaAlAs, and  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  interfaces.<sup>4–8</sup> If it is possible to modify the relative mobilities of the group III metals, then it should be possible to affect the evolution of the concentration profiles at the ternary heterointerfaces during annealing. Therefore, we have investigated the effect of  $\text{Si}^+$  ion implantation and Zn diffusion on mixing in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructures in order to assess the effect of impurities on the relative mobilities of the group III metals, and to test the hypothesis that it is the disparity between the Ga and Al mobilities that leads to In diffusion at  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterointerfaces.

The heterostructures used in these experiments were

grown by molecular beam epitaxy (MBE) on InP substrates with an intervening 400 nm buffer layer of  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ . One structure, used for the  $\text{Si}^+$  implantation experiments, consisted of a superlattice of 20 periods of alternating layers of 12.0 nm of  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  and 15.0 nm of  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ . A similar structure consisting of 15 periods of alternating 10.0 nm layers was used in the Zn diffusion experiments. Except for Zn diffusion, the samples were annealed in a "pill box" with GaAs caps in flowing  $\text{H}_2$ , and the compositional depth profiles were measured by Auger sputter depth profiling as described previously.<sup>3</sup> The  $\text{Si}^+$  was implanted at 200 keV, and the Si distribution was measured by secondary-ion mass spectrometry (SIMS) depth profiling.<sup>9</sup> Zinc diffusion was carried out at 825 K in an evacuated ampoule containing  $\text{Zn}_3\text{As}_2$ .

The depth profiles of the as-grown heterostructures exhibited abrupt interfaces with flattened tops and bottoms in the Ga and Al concentrations indicating that the resolution of the depth profiling experiment was able to resolve the structure of the superlattice. The In concentration exhibited a weak modulation throughout the 20-period superlattice in the as-grown sample indicating that the intended  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layers were slightly In rich relative to the  $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  layers. After annealing the as-grown heterostructure at 1075 K for 1 h, the modulation of the Ga profile decreased, the Al profile showed a lesser decrease in modulation amplitude, and the In profile became more strongly modulated. These results are consistent with the model for Ga and In interdiffusion presented previously.<sup>3</sup>

Figure 1 shows the compositional depth profile of a superlattice that has been ion implanted with  $\text{Si}^+$  at a dose of  $5 \times 10^{14}$   $\text{cm}^{-2}$ . This implant produced a peak Si concentration of  $2.5 \times 10^{19}$  atoms  $\text{cm}^{-3}$  at a depth of 150 nm as shown by the SIMS depth profile (Fig. 2). This Si profile is similar to that predicted by the LSS theory for the implantation of 200 keV  $\text{Si}^+$  into GaAs.<sup>10</sup> The effect of the Si implantation was to induce some uniform mixing of the Ga and Al in the

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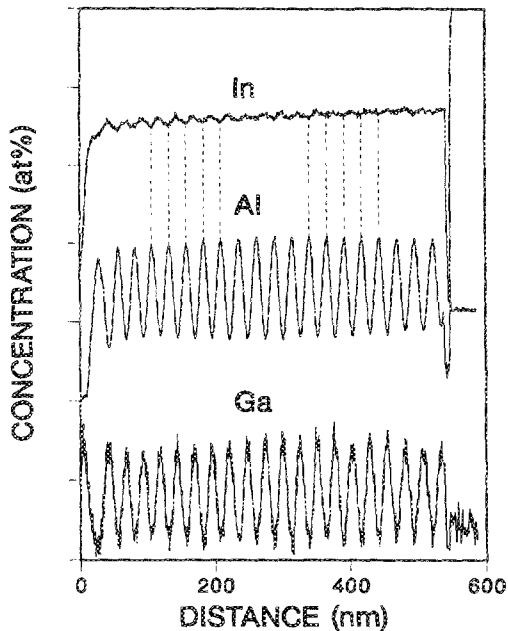


FIG. 1. Concentration profiles of the group III metals in a 20-period  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructure after  $\text{Si}^+$  ion implantation to a dose of  $5 \times 10^{14} \text{ cm}^{-2}$ . One vertical division equals 20 at. %. The curves have been arbitrarily offset for clarity, and the vertical dashed lines emphasize the phase relationship of the In and Al profiles.

superlattice as evidenced by a rounding of the Ga and Al concentration profiles relative to the as-grown material. A weak modulation of the In profile persists, and it is out of phase with the Al profile as is indicated by the dashed lines in Fig. 1.

Figure 3 shows the depth profile of a Si-implanted su-

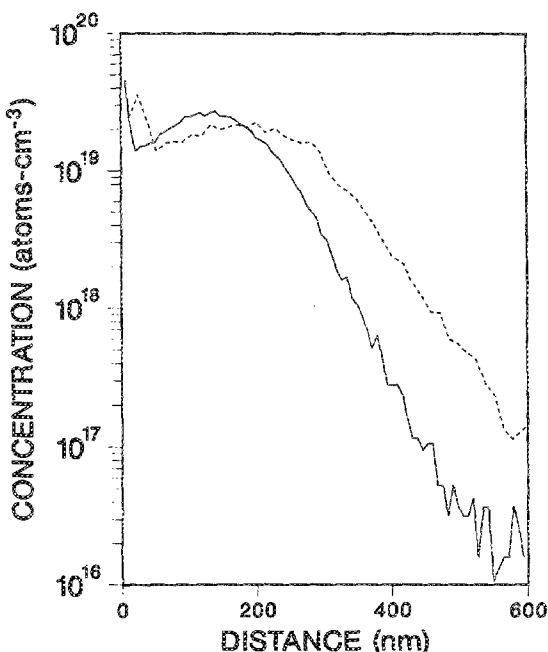


FIG. 2. Si concentration profiles resulting from the 200 keV,  $5 \times 10^{14} \text{ cm}^{-2}$   $\text{Si}^+$  ion implant into a 20-period  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructure: the solid line is the as-implanted profile, the dashed line is the profile after annealing for 1 h at 1075 K.

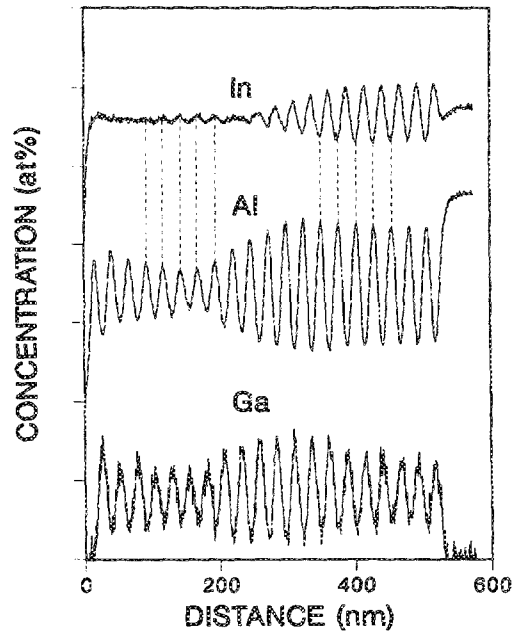


FIG. 3. Concentration profiles of the group III metals in the ion-implanted heterostructure of Fig. 1 after annealing for 1 h at 1075 K. Legend as in Fig. 1.

perlattice that has been annealed for 1 h at 1075 K. In this sample the interdiffusion of Ga and Al is enhanced in the region of the peak of the Si concentration, and the In concentration has not become modulated in the region of Ga/Al intermixing. If the mobility of the Al is increased to be equal to that of the Ga, then the Al and Ga will rapidly interdiffuse, driven by their concentration gradients, and this will inhibit the establishment of an In chemical potential gradient. Si is known to be effective in enhancing the Ga/Al intermixing at concentrations above  $3 \times 10^{18} \text{ atoms cm}^{-3}$  in GaAs/GaAlAs.<sup>6</sup> A similar threshold effect can be seen in Fig. 3 where beyond 225 nm into superlattice, where the Si concentration is less than  $2 \times 10^{19} \text{ atoms cm}^{-3}$  (as seen in the dashed curve in Fig. 2), the In has diffused into the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  regions, and the Ga and Al have not intermixed. Careful examination of the In profile in Fig. 3 reveals that in the region of Si-induced IILD the small oscillations of In concentration are in phase with the Al concentration oscillations while beyond 225 nm the In and Al oscillations remain out of phase. The phase reversal in the region of high Si concentration suggests that in this region the Al may be more mobile than the Ga. This result would be consistent with interstitial diffusion of group III metals. In the case of interstitial diffusion one might expect the smaller  $\text{Al}^{3+}$  ion (ionic radius 0.57 Å) to diffuse more rapidly than the larger  $\text{Ga}^{3+}$  ion (ionic radius 0.62 Å). However, the mechanism of Si-induced IILD is not certain, and this result may also be consistent with other proposed mechanisms.

An identical 20-period superlattice sample was implanted with a  $\text{Si}^+$  dose of  $5 \times 10^{12} \text{ cm}^{-2}$ , resulting in a peak Si concentration of  $2.5 \times 10^{17} \text{ atoms cm}^{-3}$ . This lightly implanted sample did not exhibit Ga/Al intermixing, and the In concentration developed a uniform modulation on annealing confirming the presence of a concentration thresh-

old for Si-induced IILD in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ . Also the Zn-induced IILD experiment of Kawamura *et al.* was repeated on the 15-period superlattice.<sup>7</sup> Our results confirm the results of Ref. 7, and we observe complete intermixing of the Ga and Al and no modulation of the In profile after Zn diffusion at 825 K for 1 h.

These results support the hypothesis that it is the difference in mobility between the Ga and the Al that leads to the establishment of a chemical potential gradient for In diffusion in annealed  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterointerfaces. When the Al mobility is increased either by doping with more than  $2 \times 10^{19}$  atoms  $\text{cm}^{-3}$  of Si or by Zn diffusion, the Ga and Al interdiffuse and the In concentration remains relatively constant. Under the same conditions of time and temperature, the interdiffusion of the In and Ga is still taking place in regions implanted with less than  $2 \times 10^{19}$  atoms  $\text{cm}^{-3}$  Si. This result suggests that difficulties may be encountered when attempting to use  $\text{Si}^+$  implant-induced IILD to define lateral confinement structures in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructures by Ga and Al interdiffusion. The concurrent interdiffusion of Ga and In in the undoped regions at higher temperatures has the potential to affect device properties in these heterostructures. It remains to be ascertained whether some combination of Si concentration and thermal cycle can be found which enhances Ga/Al intermixing while not leading to significant Ga/In intermixing in the unimplanted regions. However, it is clear that Zn diffusion can lead to IILD at temperatures low enough to suppress In/Ga interdiffusion

and thus may be the method of choice for defining lateral confinement structures in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$  heterostructures.

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<sup>9</sup>The SIMS depth profiles were measured by Charles Evans and Associates, Redwood City, CA using a  $\text{Cs}^+$  primary ion beam and negative ion detection.

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