Anomalous Effects of Lamp Annealing in Modulation-Doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ and Si-Implanted $In_{0.53}Ga_{0.47}As$

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***Abstract*—The effects of pulsed halogen-lamp annealing on modulation-doped $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructures and Si-implanted $In_{0.53}Ga_{0.47}As$ have been studied to determine the suitability of this process in the fabrication of high-performance field-effect transistors. Implantation and annealing of these materials are necessary for contact and self-aligned gate formation. Mobilities as high as 7400 $cm^2/V \cdot s$ are measured at 300 K in undoped molecular-beam epitaxy InGaAs implanted with 8×10^{12} cm^{-2} $^{29}Si^+$ and lamp annealed at 700°C for 5 s. Anomalous overactivations (up to 120 percent) are observed in these layers when silox encapsulation is used during annealing, but the effect is absent for GaAs proximity capping. Sharp decreases in sheet-electron concentration and mobility occur in the normal modulation-doped structures for annealing temperatures >750°C, while this trend is much smaller in the inverted structures. Arsenic loss from the InAlAs doping layer is attributed as the main mechanism for this behavior, which makes the inverted structure more suitable for device processing. Depth profiling in the modulation-doped structures indicates that there may be serious pinchoff problems in these devices when annealed at higher temperatures due to outdiffusion of impurities from the InP substrate. Values of interdiffusion coefficients at the InGaAs/InAlAs heterointerfaces, being reported for the first time, are almost three orders higher than those measured in the GaAs/AlAs systems.**

I. Introduction

$In_{0.53}Ga_{0.47}As$ and $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ modulation-doped (MD) heterostructures have demonstrated their usefulness for high-speed field-effect transistors [1]–[4]. Ion implantation and rapid thermal annealing [5], [6] for n^+ contact-layer formation can lead to better device performance through the reduction of contact resistance with alloyed or nonalloyed [7] ohmic contacts and self-aligned gate formation with refractory metal gates [8]. It has been recently reported that the degradation of the electrical characteristics of GaAs/AlGaAs MD heterostructures is much smaller by rapid thermal annealing than by conventional furnace annealing [9], [10]. In this paper, we report the results of a systematic study of rapid thermal annealing of InGaAs/InAlAs MD heterostructures and Si-implanted InGaAs grown by molecular-beam epitaxy (MBE).

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II. Implantation and Annealing

Undoped InGaAs layers, 1.5–3.0 μm thick, were grown by MBE on (100) InP : Fe substrates. The layers have net donor concentrations of 5×10^{15} cm^{-3} and room-temperature mobilities of 9000–10 000 $cm^2/V \cdot s$. $^{29}Si^+$ was implanted at room temperature in a nonchanneling direction at an energy of 100 keV and with a dose of 8×10^{12} or 3×10^{13} cm^{-2}. The implanted samples were annealed in a Heatpulse 210T halogen-lamp annealing station in an ultrapure N_2 or Ar ambient. The annealing time was kept fixed at 5 s, while the temperature was varied in the range of 700–850°C as measured by a chromel-alumel thermocouple contacted to a monitor Si wafer. Either 2000-Å chemical-vapor-deposited silox or a polished GaAs proximity wafer was used as encapsulation during annealing to minimize As loss from the surface.

Normal and inverted InGaAs/InAlAs MD heterostructures, as shown in Fig. 1, were grown by MBE. The room- and low-temperature mobilities are 10 000 and 37 000 $cm^2/V \cdot s$, respectively, for a sheet-carrier concentration of 1.5×10^{12} cm^{-2} in the normal structure and are 9700 and 31 000 $cm^2/V \cdot s$, respectively, for a sheet-carrier concentration of 1.7×10^{12} cm^{-2} in the inverted structure. The net electron concentration in the Si-doped InAlAs layer is $(2–3) \times 10^{18}$ cm^{-3}. An undoped multi-quantum well with 10 periods of 100-Å InGaAs and 100-Å InAlAs was grown between the InP substrate and the undoped InAlAs buffer layer to minimize and control the outdiffusion of impurities from the substrate during growth as well as during lamp annealing [11]. The normal and inverted structures were sequentially grown on different pieces of the same InP : Fe wafer. The MD samples were annealed in a flowing Ar ambient with a GaAs proximity wafer. Either In or Ni/Ge/Au/Ni/Au contacts were made on the four corners of clover-leaf samples for Hall measurements and alloyed for 2 min at 400–450°C in forming gas ambient.

NORMAL STRUCTURE

UNDOPED	InGaAs	50 Å
Si-DOPED	InAlAs	250 Å
UNDOPED	InAlAs	80 Å
2-DEG.→ UNDOPED	InGaAs	0.2 μm
UNDOPED	InAlAs	0.2 μm
UNDOPED	InGaAs/InAlAs MQW	0.2 μm
S. I.	InP	SUB.

(a)

INVERTED STRUCTURE

UNDOPED	InGaAs	50 Å
UNDOPED	InAlAs	350 Å
UNDOPED	InGaAs	300 Å
UNDOPED	InAlAs	60 Å
Si-DOPED	InAlAs	120 Å
UNDOPED	InAlAs	0.4 μm
UNDOPED	InGaAs/InAlAs MQW	0.2 μm
S. I.	InP	SUB.

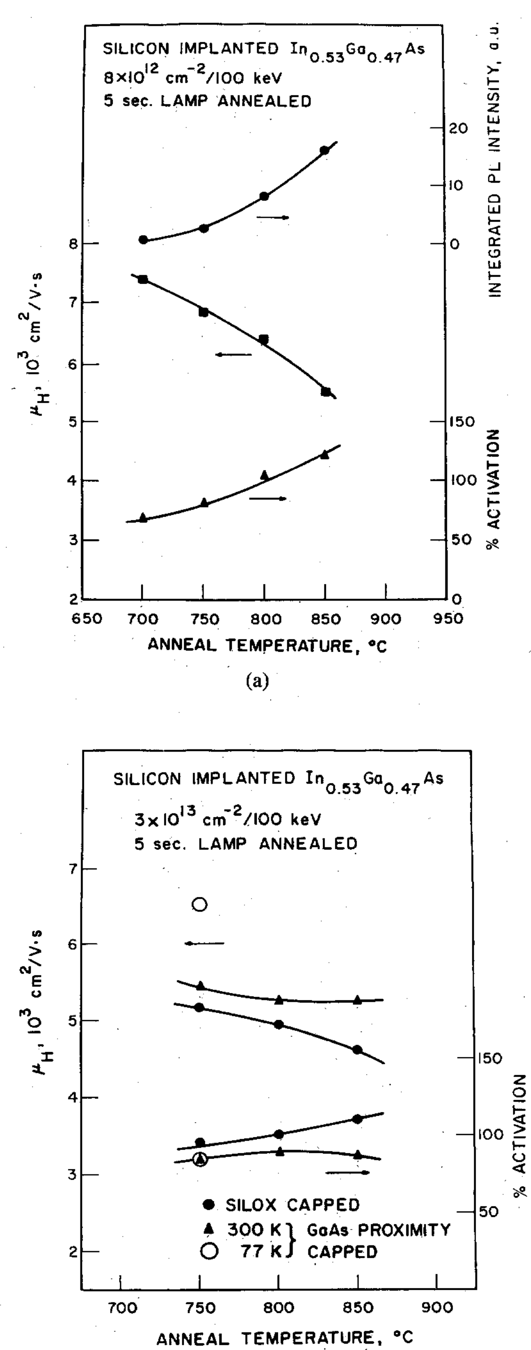
(b)

Fig. 1. Schematics of (a) normal and (b) inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ modulation-doped heterostructures used for lamp-annealing studies.

III. Results and Discussions

A. Implanted and Annealed InGaAs

Implanted and annealed InGaAs samples were characterized by Hall and low-temperature photoluminescence (PL) measurements. The results are illustrated in Fig. 2(a) and (b). Surface decomposition was not observed in the silox-capped samples, while a slight surface As loss was evident in the proximity-capped samples at annealing temperatures of 850°C and higher. From Fig. 2(a), it is apparent that the integrated PL intensity follows the activation, which is similar to our observations in GaAs [12]. A sheet mobility of 7400 $cm^2/V \cdot s$ was measured in the sample implanted with 8×10^{12} cm^{-2} Si^+ and annealed at 700°C for 5 s. The Hall mobility increases slightly and the activation remains almost invariant at 77 K, which indicates negligible freeze out at low temperatures. The measured activation in the silox-capped samples exceeds 100 percent for annealing temperatures greater than 800°C. Overactivation was more strongly observed in samples implanted with a lower dose. Annealing at 850°C yielded an activation of 120 percent. The effects of unintentional doping in the InGaAs epitaxial layers were taken into account with a two-carrier model of the Hall effect [13] to derive activations from measured sheet-carrier concentrations. Similar overactivations were observed at high annealing temperatures for Si-implanted InAlAs [14].



(b)

Fig. 2. Integrated photoluminescence intensity, Hall mobility, and dopant activation as a function of anneal temperature in Si-implanted and lamp-annealed $In_{0.53}Ga_{0.47}As$ for an implant dose of (a) 8×10^{12} cm^{-2}, and (b) 3×10^{13} cm^{-2}.

To understand this phenomenon, the electron concentration in samples implanted with a dose of 3×10^{13} cm^{-2} and annealed at 800°C were profiled by successive layer removal and Hall measurement. Fig. 3 depicts these profiles for silox- and proximity-capped samples. It is observed that the profile in the proximity-capped sample is in reasonable agreement with the calculated LSS profile, while the silox-capped sample exhibits a high electron concentration near the surface. The proximity-capped

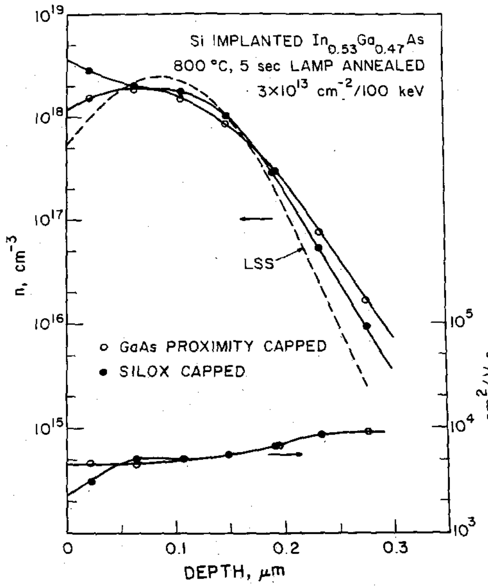
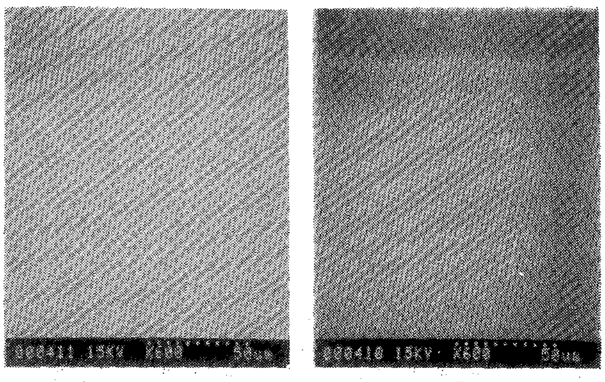
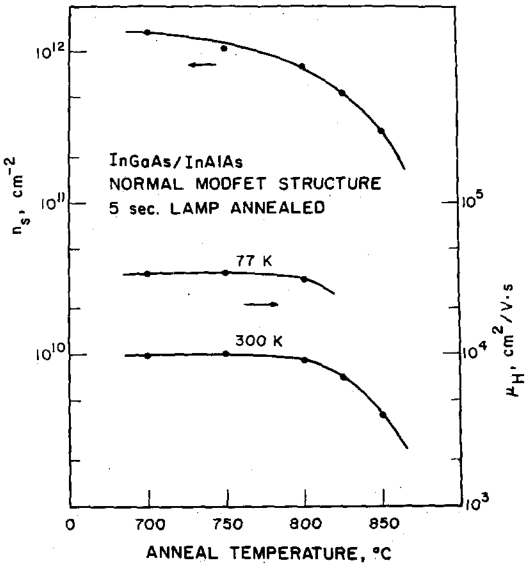


Fig. 3. Measured depth profiles of electron concentration and mobility in Si implanted and lamp-annealed $In_{0.53}Ga_{0.47}As$ using silox and proximity capping during annealing. The calculated LSS profile is also shown for comparison.

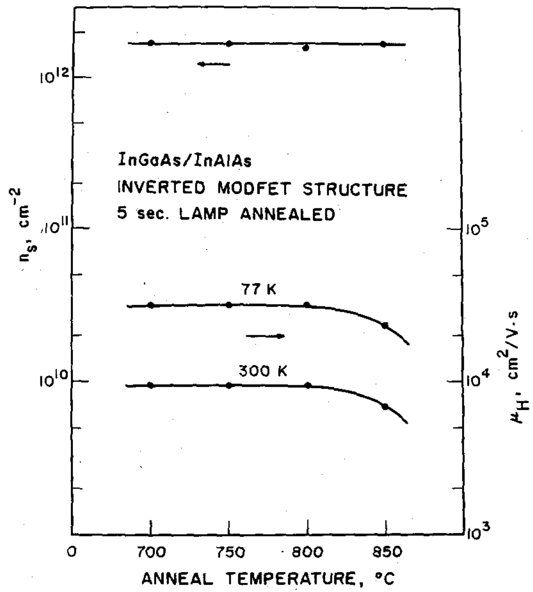


(a) (b)

Fig. 4. SEM photomicrographs showing surface morphology of inverted InGaAs/InAlAs modulation-doped heterostructures after 5-s lamp annealing at (a) 750°C and (b) 850°C.



(a)



(b)

Fig. 5. Measured variation of sheet electron concentration and mobility with lamp annealing temperature in (a) normal, and (b) inverted InGaAs/InAlAs modulation-doped heterostructures.

samples did not exhibit overactivation even with visible surface decomposition due to As loss. In view of these results we think that the observed overactivation in silox-capped samples arise from donor-like defects induced by strains due to the difference in thermal expansion between the silox capping layer and the substrate. This strain is smaller in the proximity-capped samples. Another possibility is the creation of donor-like centers by group III vacancies. Further work is necessary to clarify these anomalous phenomena.

B. Lamp-Annealed InGaAs/InAlAs Heterostructures

Use of GaAs proximity capping prevented anomalous surface effects discussed in the previous section. The surface morphology of rapid thermal-annealed InGaAs/InAlAs samples is shown in Fig. 4(a) and (b). At an annealing temperature higher than 820°C there is visible surface decomposition due to As loss in both structures. Excess Ga in the surface layers was observed by energy-dispersive X-ray measurements. The effects of annealing temperatures on the electrical characteristics of normal and inverted InGaAs/InAlAs MD structures are shown in Fig. 5(a) and (b). The ohmic contacts to the normal MD structure annealed at temperatures higher than 820°C were unstable at 77 K. Both the mobility μ and sheet-carrier concentrations n_s at 300 and 77 K decrease for high annealing temperatures in both types of structures, but the decrease is larger in the normal structure. It should be stressed that the high electron mobility was maintained for the inverted MD structure even after annealing at

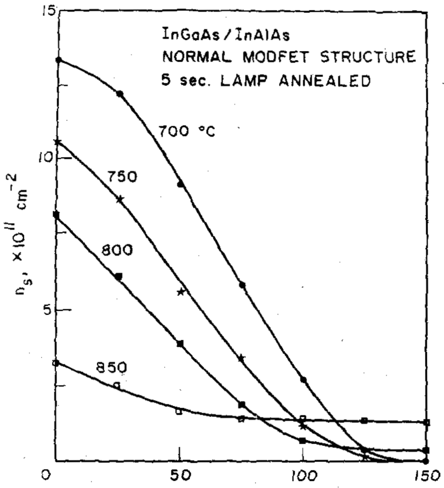


Fig. 6. Variation of sheet electron concentration with etching distance in InGaAs/InAlAs modulation-doped heterostructures lamp annealed at different temperatures.

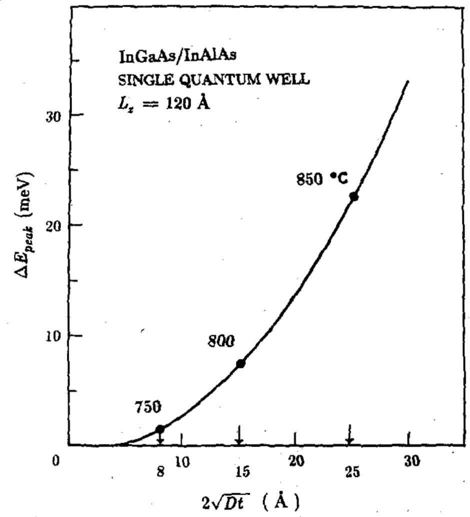


Fig. 7. Calculated energy shift of main PL peak as a function of $2\sqrt{Dt}$. D is the interdiffusion coefficient and t is the annealing time. Measured energy shifts at different annealing temperatures for 5-s annealing time are shown with the calculated curve.

800°C. Sheet carrier concentrations are almost identical at 300 and 77 K in both structures, which imply full depletion in the InAlAs doping layer.

The mechanisms that might be responsible for the decrease of μ and n_s are: 1) diffusion of Si from the n^+ InAlAs layer to the channel region; 2) compensation in the n^+ InAlAs layer due to As loss from the surface; 3) outdiffusion of impurities from the substrate into the surface region; and 4) compositional disordering of the heterointerface by atomic interdiffusion [15], [16]. Si diffusion can be eliminated as a significant mechanism since n_s decreases at high annealing temperatures in both structures and, in fact, the inverted structure with a thinner InAlAs space layer shows a smaller change of n_s.

Surface-related phenomena will affect the normal structure more severely since 1) the distance between the surface and the InGaAs channel in this structure is much smaller than that in the inverted structure, and 2) the doping layer that provides electrons to the 2-DEG channel is between the surface and the InGaAs channel. Moreover, the use of a very thin (50-Å) undoped InGaAs top layer and a fully depleted InAlAs doping layer makes the normal structure used in our experiments very sensitive to surface effects.

Successive layer removal and Hall measurements were made with normal structures annealed at different temperatures. Fig. 6 shows the dependence of the sheet-carrier concentration at 300 K on total etched depth. Samples annealed at a higher temperature exhibit a smaller rate of decrease of n_s, which might imply reduced effective doping of the n^+ InAlAs layer. Visible and invisible As loss near the surface might leave a large density of vacancies and traps and reduce the effective doping of the n^+ InAlAs layers. Compensation in Si-doped MBE GaAs layers due to As loss from the surface has been recently demonstrated by photoluminescence measurements [10]. Samples annealed at 800 and 850°C have residual sheet-carrier concentrations of 4×10^{10} and 1.3×10^{11} cm^{-2}, respectively, after etching of the n^+ InAlAs layers. Upon further etching these residual concentrations remained constant and were found to result from unintentional doping in the InGaAs/InAlAs superlattice layer between the substrate and the undoped InAlAs buffer. These results indicate the outdiffusion and gettering [11] of impurities from the substrate into the superlattice during high-temperature annealing. It has been reported that impurities including Si and S outdiffuse from InP:Fe substrates into InGaAs layers grown on them by MBE [17]. When the residual carrier concentrations due to impurity outdiffusion from the substrate are taken into account, n_s in the normal structure decreases more rapidly than that shown in Fig. 5(a) for high annealing temperatures. It should be noted that the observed residual carrier concentrations could lead to difficulties in pinchoff in these devices.

The effects of impurity outdiffusion from the substrate on μ and n_s in the 2-DEG channel would be approximately the same for both structures, since they were grown on the same substrate under identical conditions. We have studied the effects of group III atom interdiffusion in InAlAs/InGaAs quantum-well structures that were lamped annealed under identical conditions. The InGaAs wells were 120 Å thick. The annealing time was kept fixed at 5 s while the temperature was varied from 700 to 850°C. The low-temperature (77 K) photoluminescence peak was recorded in each case. It was observed that the spectral peak position moved to higher energies with increase of annealing temperature. We interpret this behavior as being indicative of Al-Ga interdiffusion across the interface. We have modeled this trend by taking into account error-function diffusion and solving the Schrodinger equation for the wells of nonuniform thickness. the results of this simulation are shown in Fig. 7. The interdiffusion coefficients

D at different temperatures are obtained by fitting the simulated data. Values of $D \sim 10^{-16} - 10^{-15}$ cm^2/s are obtained for the anneal temperature range 750–850°C, which are much higher than values reported earlier for GaAs/AlAs and GaAs/$Al_xGa_{1-x}As$ structures [15], [16], [18]. We think that the added presence of In in our material and defects at the hetero-interfaces may enhance the diffusion rates. From X-ray diffraction measurements we estimate the residual mismatch (with respect to InP) in $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ to be $\sim 10^{-5}$ and 10^{-4}, respectively, which are very small. The thermal expansion coefficients in the alloys, however, at the annealing temperature are different, and this may affect the diffusion process. We have also estimated the effects of atomic interdiffusion at the heterointerface on n_s, using the model of Grinberg and Shur [19] for a graded interface. Similar to the results obtained by these authors for GaAs/AlGaAs, we observe a slight increase of n_s with increase in the degree of grading. Observed variations of μ and n_s for both structures with annealing temperatures exclude substrate outdiffusion and atomic interdiffusion as being responsible for the decrease of μ and n_s. We conclude that compensation due to As loss in the InAlAs doping layer is the dominant mechanism responsible for this decrease in rapid thermal annealed InGaAs/InAlAs MD heterostructures.

IV. Conclusion

It is demonstrated that rapid thermal annealing produces high activation in Si-implanted InGaAs and maintains a high electron mobility in InGaAs/InAlAs MD heterostructures. Anomalous overactivation was observed in Si-implanted InGaAs annealed with silox capping. The reasons for this behavior are not fully understood and some probable causes, based on our data, are discussed. The degradation of the electrical characteristics of InGaAs/InAlAs modulation-doped heterostructures annealed at high temperatures is attributed to compensation resulting from As loss at the surface. A thicker InGaAs capping layer and n^+ InAlAs doping layer and an increased separation of the 2-DEG from the surface would reduce the decrease of μ and n_s in rapid thermal annealed MD structures. It is therefore apparent that inverted or pulse-doped normal structures will be more suitable for high-performance modulation-doped field-effect transistors fabricated with rapid thermal annealing. The atomic interdiffusion coefficients at the InGaAs/InAlAs heterointerface were determined from measurements on lamp-annealed quantum well structures. Values of D are $\sim 10^{-15}$–10^{-16} cm^2/s in the annealing temperature range of 750–850°C, which are approximately three orders higher than those obtained for GaAs/AlAs heterostructures. Finally, it should be stressed that the outdiffusion of impurities from InP substrates after high-temperature annealing could lead to difficulties in pinchoff in the field-effect transistors, which usually employ alloyed ohmic source and drain contacts with large penetration depth of the metals.

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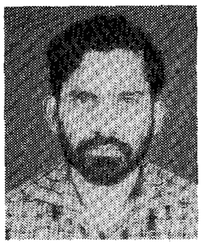

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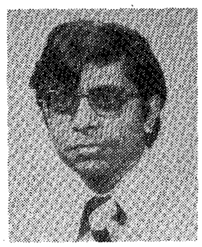

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