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Effects of Implantation and Impurity Density on Disorder of AlAs/GaAs Superlattice

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Disordering of AlAs/GaAs superlattices and degradation of the heterointerfaces have been studied. Two methods were employed for the investigation; Ion implantation of N_2 or Ar and Si doping followed by annealing. Defects introduced by N_2 or Ar implantation did not induce disordering due to enhanced Al-Ga interdiffusion. For the effect of Si doping, the doping level of 4 x 18^{18} cm^{-3} caused the diorder after 800°C, 2 h annealing, while the doping level of 1 x 10^{18} cm^{-3} did not induce the disorder under the same annealing condition. Degradation of AlAs/GaAs heterointerface doped with 7 x 10^{18} Si cm^{-3} uniformly was observed by annealing at 700°C, 2 h.

I Introduction

The superlattices and the heterojunctions of (AlGa)As system are widely used to fabricate many electronic and optoelectronic devices. These devices utilize the extraordinarily abrupt and flat heterointerfaces grown by molecular beam epitaxy or metalorganic chemical vapor deposition. For further development of these devices, investigation on the effect of processes, such as impurity diffusion, ion implantation and annealing, on the abruptness of the heterointerface is necessary. AlAs/GaAs superlattices are stable at 900 °C[1),2)] but recently it has been shown that Zn diffusion[3)] or Si implantation and subsequent annealing[4)] results in disordering and compositionally homogeneous alloy of $Al_xGa_{1-x}As$.

To explain the disordering by Zn diffusion, a modification of the usual interstitial-substitutional Zn diffusion process[3)] or As vacancy-interstitial Zn complex model[5)] has been reported. Disordering by Si implantation and subsequent annealing makes the disordering mechanism look like more complicated. In this paper we investigated the effect of ion implantation and Si impurity on disordering, separately. Firstly, the effect of ion implantation of rather inactive impurities in GaAs, such as, argon or nitrogen into AlAs/GaAs superlattice has been studied and secondly, the annealing effect of the Si-doped superlattice has been investigated.

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II Experimental

Superlattices were grown by moleclar beam epitaxy (ANELVA MBE 830) on Cr-doped semi-insulating (100) GaAs at a substrate temperature of 580° C. Prior to epitaxial growth substrates were etched by $5H_2SO_4$,$1H_2O_2$ and $1H_2O$ solution. The AlAs/GaAs superlattices were grown with thin buffer layers of 150-nm GaAs. The thickness of both AlAs and GaAs layers were 15 nm, which was estimated from the growth rate, 0.8 μm/h.

In order to produce defects of high density at appropriate depth, 80-keV N_2^+ and Ar^+ were implanted with ion flux of about 2 x $10^{12}/cm^2$ s at room temperature. The annealing condition was face to face contact with another GaAs surface in H_2 atmosphere. To observe the superlattice disordering we employed two methods, sputtering auger spectroscopy (ANELVA EMAS II) and micrograph of shallow-angle cross section. We employed ion etching instead of mechanical lapping for shallow angle cross section. Focused Ar^+ beam was irradiatd on a superlattice at an incident angle of 45 °. The sputtered hollow is curved due to spacial inhomogenity of the ion beam and the superlattice is observed as concentric circles.

The superlattice structures were profiled by monitoring Ga auger intensity (1070 eV) which has been shown to be able to resolve fine structure.[6)] The primary electron beam energy was 5 keV and the diameter on the sample was approximately 1 μm.

III Results and Discussion

3.1 Effects of Ion Implantation

Implantation of energetic ions into crystals produces atom displacement and defects. It is reported that 75-keV Ar implantation at a dose of 10^{15} cm^{-2} into GaAs forms a complete amorphous layers of 60 nm at room temperature.[7] The amorphous layer means lattice disorder but does not mean superlattice disorder. Figure 1 shows the

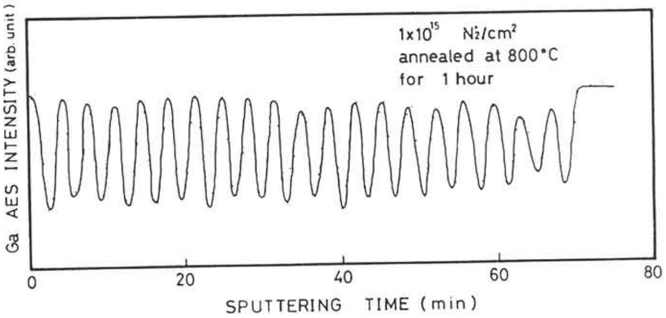

Fig.1 Ga auger profile of superlattice implanted with 80-keV, 1 x $10^{15}cm^{-2}$ N_2^+ and annealed at 800℃, 1h.

Ga auger profile of the superlattice after implantation of N_2^+ and subsequent annealing at 800 °C for 1 h. The dose was 1 x 10^{15} cm^{-2}. The implanted layer is within 100 nm from the surface considering from the fact that the projected range R_p and the range straggling ΔR_p of 80-keV N_2 in GaAs is 65 nm and 35 nm, respectively.[8] As shown in Fig. 1, there is no difference between the surface 5 to 3 layers where most of the atoms are displaced and the deeper 17 to 15 layers which are not damaged heavily. Though in the implanted sample the number of defects such as Column III and V vacancies which play an important role in Al -Ga interdiffusion may be much larger than those in the Zn-diffused or in the Si-implanted superlattices, remarkable interdiffusion was not observed in the implanted superlattice.

Figure 2 shows the Ga profiles of the sample implanted with N_2^+ at the dose of 1 x 10^{16} cm^{-2} before (a) and after (b) annealing at 875℃. The superlattice disorder which is not observed in the sample implanted with 1 x 10^{15} cm^{-2} is observed in both (a) and (b). In ion implantation, target atoms recoil on collision with incident ions. The position R_p is shown in the figure. In this superlattice, GaAs and AlAs are layered alternatively. So the actual projected range and damaged depth

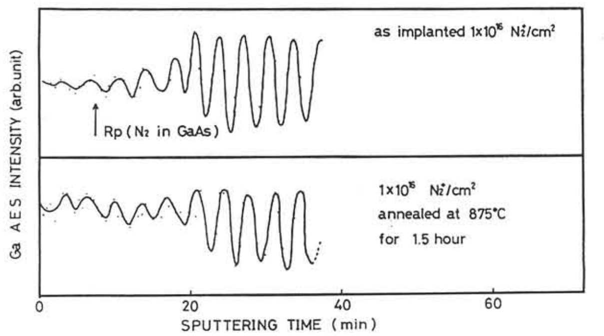

Fig.2 Ga auger profile of superlattice implanted with 80-keV, 1 x $10^{16}cm^{-2}$ N_2^+:(a) as implanted, (b) implanted and annealed at 875℃, 1.5h.

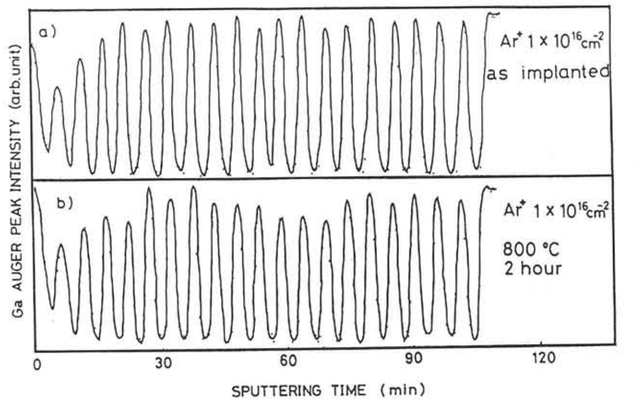

Fig.3 Ga auger profile of superlattice implanted with 80-keV Ar^+.

are deeper than 65 nm. Since implanted nitrogen forms an isoelectronic trap,[9] Ar was implanted as a more inactive impurity. Figure 3 shows the superlattice structures after implantation of Ar at the dose of 1 x 10^{16} cm^{-2}, (a) as implanted and (b) annealed at 800°C for 2 h following the implantation. There is no particular difference between (a) and (b). The disintegration of the surface 7 or 8 layers are also due to ion mixing. From these resuts it can be concluded that the enhanced interdiffusion between Al and Ga does not occur through only lattice vacancies.

3.2 The Effect of Si Concentration

In order to see the effect of impurity on the disordering excluding the effects of implantation-induced defects and impurity diffusion, 20 pairs of AlAs/GaAs layers doped with Si uniformly were grown. The doping level was 1 x 10^{19} cm^{-3} which was estimated by extraporation of net electron concentration vs reciprocal Si source temperature curve.

Figure 4 shows the Ga auger profiles in the superlattice which were annealed as follows : (a) as grown, (b) annaled at 650°C for 2 h, (c) an-

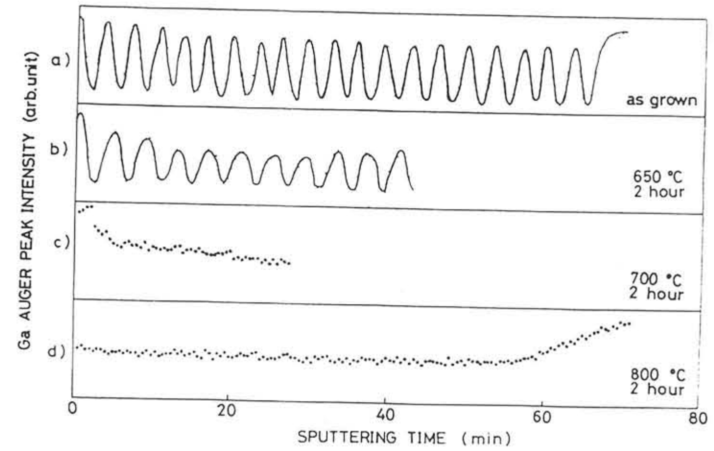

Fig.4 Ga auger profile of superlattce doped with $1 \times 10^{19} cm^{-3}$ Si under various annealing conditions.

nealed at 700°C for 2h and (d) annealed at 800 ℃ for 2h. At the annealing temperature of 650°C, the superlattice degrades slightly and becomes a superlattice of $Al_xGa_{1-x}As$ due to Al-Ga interdiffusion. The maximum and minimum x value in the superlattice are roughly estimated to be 0.18 and 0.82, respectively Assuming a constant diffusion coefficient independent on x, the diffusion profile of Al initially confined in the region $-h \leq z \leq h$ is given by $2x = \mathrm{erf}\{(h-z)/2\sqrt{Dt}\} + \mathrm{erf}\{(h+z)/2\sqrt{Dt}\}$ [10] where z is the distance measured from the center of the AlAs layer, D is diffusion coefficient and t is diffusion time. The diffusion coefficient is estimated to be $3 \times 10^{-17}\ cm^2 s^{-1}$ at 650℃ which is much larger than that in undoped superlattice, $6 \times 10^{-18}\ cm^2 s^{-1}$ at 870℃[1] or 5×10^{-21} at 800℃.[2] After 700℃ annealing the superlattice disappears except surface Ga peak. At the annealing temperature of 800°C it disappears completely. Since the doping profile is uniform, net diffusion of Si is very little in contrast to disordering by Zn diffusion although local back and forth migration of Si exsists probably.

In order to know the doping level which promotes the Al-Ga interdiffusion, a superlattice which consists of layers with different doping levels was grown. Neighboring five pairs of AlAs /GaAs layers have the same doping level and they are separated by undoped five pairs of AlAs/GaAs layers. The doping levels are, from the bottom to the top, $1 \times 10^{19}\ cm^{-3}$, $7 \times 10^{18}\ cm^{-3}$, $4 \times 10^{18}\ cm^{-3}$ and $1 \times 10^{18}\ cm^{-3}$. After annealing at 800℃ for 2 h, the sample was ion etched to make a shallow angle cross section as stated above.

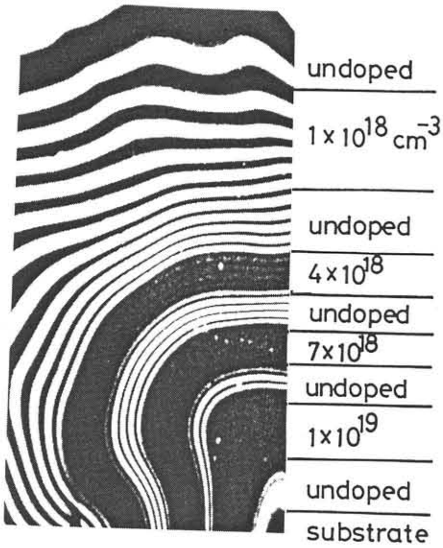

Fig.5 Superlattice disorder at different Si doping levels, annealed at 800°C, 2h. Shallow angle cross section by focused Ar beam magnifies the superlattice more than 1000. Because of the distorted Ar beam, the lines do not show concentric circles.

Figure 5 shows the superlattice structure observed by SEM. This is a quarter of a crater etched by focused Ar^+ beam. The bright lines are AlAs layers and the dark lines are GaAs layers. Because the focused Ar^+ beam was distorted, the lines do not show concentric circles. The disordering can be observed at the doping level of $4 \times 10^{18}\ cm^{-3}$, though the superlattice is not disordered completely. Above the doping level of $7 \times 10^{18}\ cm^{-3}$, the superlattice disappears completely and the neighboring undoped layers are also affected by diffused Si.

The doping level where the disordering can be observed is close to the maximum free carrier concentration, $6 \times 10^{18}\ cm^{-3}$.[11] With increasing doping level above this value, a decrease in free carrier concentration and mobility has been observed, which suggests the formation of defects such as Si precipitation[11] or increased acceptor site Si.[12] For the disordering due to Zn diffusion it has been pointed out that interstitial Zn plays an important role.[3],[5] There is possibility of the existence of the interstitial Si although the rapid thermal processing experiment has suggested for Si diffusion in GaAs that nearest-neighbor Si pair moves substitutionally by exchanging sites with either Ga or As vacancy.[13]

The disordering mechanism by Si is not clear yet but it is probable that above the doping level of approximately 5 x 10^{18} cm^{-3} there is particular change in Si position in the crystal. For understanding of the disordering mechanism, the effects of other impurities should be studied.

In order to see the degradation of the AlAs-GaAs heterointerface by Si doping, a sample of four AlAs layers (~50 nm each) sandwitchecd with thick GaAs layers (~200 ~300 nm each) was grown. Three layers of AlAs/GaAs superlattice were also grown on the substrate. Four doping levels, 1 x 10^{18} cm^{-3}, 4 x 10^{18} cm^{-3}, 7 x 10^{18} cm^{-3} and 1 x 10^{19} cm^{-3} were examined as shown in Fig. 6. A whole AlAs layer and half of GaAs layers on both sides were doped on the same level as shown in the figure. Figure 6 shows the Ga auger profiles, from top to bottom, as grown, annealed at 700°C,

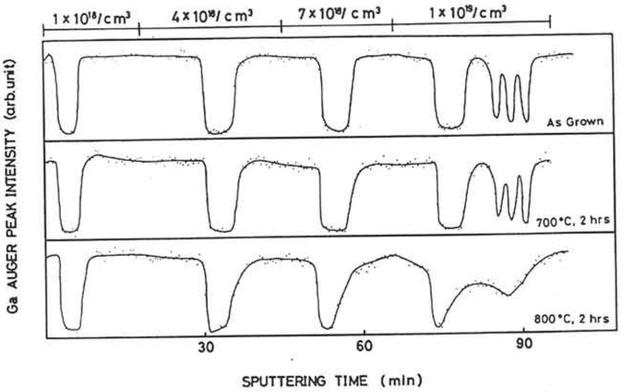

Fig.6 Ga auger profiles which shows interdiffusion of Ga and Al under different annealng conditions. Ga depressing layers correspond to AlAs layers. Doping levels of each layer are indicated on top of the figure.

2h and annealed at 800°C, 2h. The asymetric profiles is probably due to difference of the sputtering rate between Ga and Al. After 700°C,2h annealing the degradation of the interface is clearly observed at the doping level of 7 x 10^{18} cm^{-3}. Since estimation of Al-Ga diffusion coefficient is rather difficult because of the asymmetric profile, the diffusion coefficient at the Si doping level of 7 x $10^{18}cm^{-3}$is in between 2 x $10^{-17}cm^2s^{-1}$ and 1 x 10^{-16} cm^2s^{-1}, at 800°C.

In summary, disordering of AlAs/GaAs superlattice was studied by N_2^+ and Ar^+ implantation and Si doping. N_2^+ and Ar^+ implantation did not induce the enhanced interdiffusion of Al and Ga up to the dose of 1 x 10^{16} cm^{-2} while disorder due to ion mixing was observed. For the effect of Si impurity, the doping level of 4 x 10^{18} cm^{-3} caused superlattice disorder for 800°C 2hr annealing. This doping level agrees with the maximum free carrier concentration above which the doped Si is not entirely incorporated in Ga site. Degradation of AlAs/GaAs heterointerface doped with 7 x 10^{18} cm^{-3} Si uniformly was observed by annealing at 700 ℃, 2h.

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