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Control of As Precipitation in Low Temperature GaAs by Electronic and Isoelectronic Delta Doping

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A systematically study of electronic (Si and Be) and isoelectronic (In and Al) delta-doping effect on the formation of arsenic precipitates in GaAs grown by molecular beam epitaxy (MBE) at low substrate temperature are presented. Both electronic dopant Si and isoelectronic dopant In are capable to accumulate As precipitates in post-growth annealed samples. Precipitate As is depleted from the regions doped with Be or Al. The results suggest that the electronic property of impurity don't have a direct correlation with the As precipitation process. The effect of doping concentration is reported also.

1. TEXT

Molecular-beam-epitaxy (MBE) growth of GaAs and AlGaAs at low substrate temperature (LT's) have recently attracted much attention[1-5], due to its unique electronic[6] and optical[7] properties. Unlike GaAs grown at ~600 ^{o}C, growth at low temperature (200~300 ^{o}C) is very nonstoichiometric with up to 1.5 at. % excess arsenic in the material[8].Upno post-growth annealing, excess As precipitate into clusters and change the resistance of the LT-GaAs to a high resistivity state. Therefore, tailoring As precipitate size and density through the precipitate coarsening process is quite useful in controlling the electronic and optical properties of the LT materials. Effects due to delta doping in LT-GaAs have been reported[11] to result in two-dimensional array of precipitates. In this work, we propose a systematic study of the electronic impurity (Si and Be) and isoelectronic impurity (In and Al) delta-doped structures in LT-GaAs.

The layer structures were grown in a Varian Gen II MBE system under arsenic rich condition. The GaAs and $Al_{0.25}Ga_{0.75}As$ growth rate were 1 μm/hr. Following the native oxide desorption at 580 ^{o}C, a 0.3 μm GaAs buffer layer was first deposited at 600 ^{o}C to smooth the surface. Growth was then interrupted and the substrate temperature was rampped down to 230 ^{o}C. Two low temperature structures were grown. Sample A contains two delta-doped regions which are separated by 50 nm $Al_{0.25}Ga_{0.75}As$. The first region contains five Si delta-doped layers with spacing of 50 nm GaAs. The Si sheet densities are 2, 4, 8, 12 and 16× 10^{12} cm^{-2} ,respectively. The second region contains five Be delta-doped layers with the same sheet densities as Si. Sample B contains two delta-doped regions which are separated by 50 nm GaAs. These two regions contain four Al and five In delta-doped layers with spacing of 50 nm GaAs respectively. Just before the delta-doped layer growth, As shutters was closed to reduce the background pressure. Open only the Al (In) shutter during delta doping growth, which resulted in Al sheet density of 1.25, 2.5, 5.0, and 6.25×10^{14} cm^{-2} (1.06, 2.06, 4.13, 5.19 and 6.25×10^{14} cm^{-2} for In). After growth the samples were cleaved into pieces and annealing in furnace for 10 min. at 600, 700, 800 and 900 $^{\circ}$C respectively in forming gas and a GaAs wafer proximity.

Figure 1 is the bright-field TEM images of Si delta-doped region annealed at 600 ^{o}C for 10 min. The TEM image shows a high concentration of arsenic precipitates in all the low temperature grown regions. Between the delta-doped layers, the As precipitate concentration is estimated to be 1.8×10^{17} cm^{-3}. This value agrees generally with the result reported by early investigators[9]. An increase in number density of As precipitates with doping concentrations and the formation of precipitate accumulation lines are observed. The position of precipitate accumulation planes are coincided with Si delta-doped layers. The dependent of relative As line density on Si doping concentration is shown in Fig. 2 . The As line density decreases with decreasing Si doping concentration and reduces to the background value for the lowest concentration which is almost indistinguishable form the

TEM image. Uniform distribution of As precipitates (not shown) indicates that Be delta-doping, even with the same concentration as Si, has no obvious effect on the formation of As precipitate during 600 ^{o}C annealing. While annealing temperature raised to 800 ^{o}C, as shown in Figure 3, there exist precipitate depletion zones around the position of Be delta doping and accumulation zones between the doped layers. The precipitate size is estimated to be 10 nm, which is smaller than that in Si doped region (14 nm).

Figure 4 shows the bright-field TEM image of In delta-doped region in sample B annealed at 600 ^{o}C for 10 min. As precipitate density is estimated to be 2.4×10^{17} cm^{-3} in the undoped region. This result is compatible with that in sample A. Formation of precipitate accumulation planes in In delta-doped layers is clearly observed. Size of precipitate on the accumulation zone is about two times than those in undoped region. Dependence of the relative As precipitate line density on In doping concentration is shown in Fig. 5. With the same tendency of Si delta-doped structure, the line density decreases with decreasing In doping concentration and the precipitate accumulation effect is disappear for the lowest concentration. Both electronic dopant Si and isoelectronic dopant In can accumulate As precipitates, as indicated from a comparison of Fig. 4 with Fig. 1. Nevertheless, in order to get the same precipitate accumulation efficiency In sheet doping concentration must be about an order of magnitude larger than Si.

In the Al delta-doped region of sample B annealed at 600 ^{o}C for 10 min., as shown in Fig. 6, the As precipitate are depleted and form the precipitate depletion planes of width about 4 nm. The precipitate depletion position are coincided with Al delta-doped layers. For high doping concentrations, the depletion planes are easily observed. But for the lowest concentration it become indistinguishable which is comparable with In delta-doped case as discussed above. Compared with Be delta-doped structure, both electronic dopant Be and isoelectronic dopant Al are capable of depleting As precipitate during post-growth annealing. However, the precipitate depletion efficiency is difficult to be compared due to the different doping concentration used in this work.

The preference for As precipitate formed in Si doped LT-GaAs and depleted in Be doped region has been reported [10,11]. There are several plausible explanation suggested. From the point of charge state of As interstitial, Melloch et al.[11] though that the positive As interstitial will be attracted by the negatively charged As precipitate in n-type (Si) doped material and repelled by the positively charged As precipitate in p-type (Be) doped material. Kavanagh[12] suggested that it is resulted form a difference in the precipitate/matrix interfacial energy between doped and undoped LT-material. This model had been proposed by Mahalingam[13] to explain the precipitate accumulation zone and precipitate depletion zone in LT GaAs/AlGaAs heterostructure. In this work, As precipitate is observed to accumulated in Si (electronic) and In (isoelectronic) delta-doped layers while depleted in Be (electronic) and Al (isoelectronic) delta-doped layers. In LT-GaAs Fermi-level is observed to be pinned midgap, regardless of doping, by the very large concentration of deep-level traps. So, it suggest that the electronic property of impurity may not have a direct correlation with the As precipitation process if the precipitation is dominant by the same mechanism in all the four cases studied in this work. Up to now, there is no strong data suggests the precipitate/matrix interfacial energy difference between doped and undoped LT-GaAs, but it is acceptable to make such assumption. The precipitate/matrix interfacial energy is assumed largest for Al (Be) doped LT-GaAs and lowest for Si (In) doped LT-GaAs compared with undoped LT-GaAs. During post-growth annealing, excess As diffuse from undoped regions toward Si and In doped layers while deplete from Al and Be doped layers to undoped region. Further studies are necessary to clarify this assumption.

We have systematically studied the electronic (Si and Be) and isoelectronic (In and Al) delta-doping effect on the formation of arsenic precipitates in GaAs grown at low substrate temperature by MBE. Upon post-growth annealing, As precipitates form preferentially in Si and In delta-doped layers while deplete in Al and Be doped planes. This result suggests that the electronic property of impurity don't have a direct correlation with the As precipitation process. The ability to control the As precipitates in LT materials would lead to many useful application. This work has been supported by the National Science Council, Republic of China, under contract NSC-82-0404-E009-239.

2. FIGURES

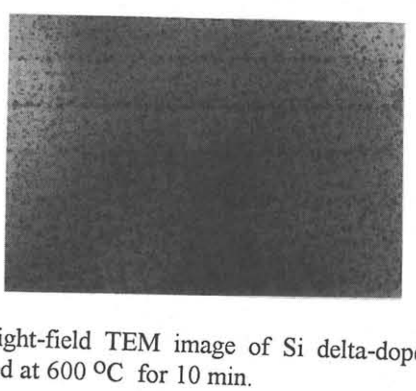

Fig. 1 Bright-field TEM image of Si delta-doped region annealed at 600 ^{o}C for 10 min.

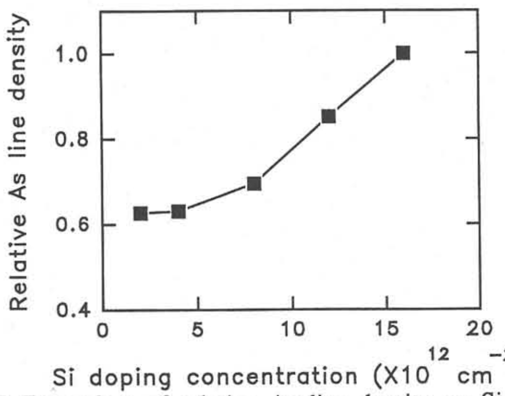

Fig. 2 Dependent of relative As line density on Si sheet doping concentration for sample A annealed at 600 °C

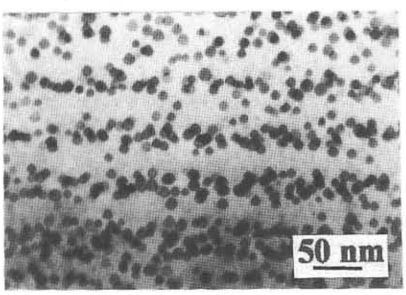

Fig. 3 Bright-field TEM image of Be delta-doped region annealed at 800 °C for 10 min.

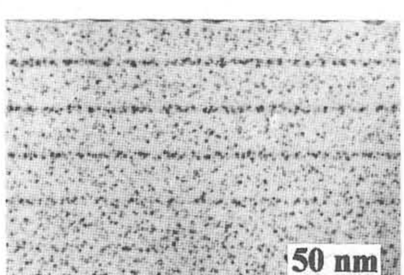

Fig. 4 Bright-field TEM image of In delta-doped region of sample B annealed at 600 °C for 10 min.

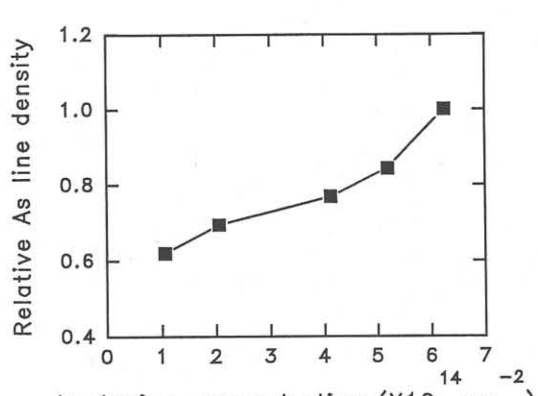

Fig. 5 Dependent of relative As line density on In sheet doping concentration for sample B annealed at 600 °C for 10 min.

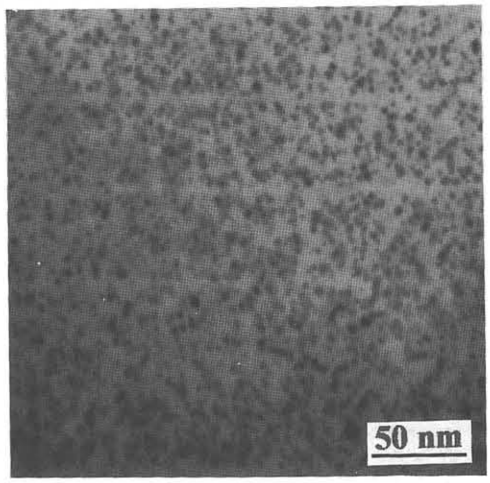

Fig. 6 Bright-field TEM image of Al delta-doped region of sample B annealed at 600 °C for 10 min.

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