Reduction of Be out-diffusion from heavily doped GaAs:Be layers by pseudomorphic $In_xGa_{1-x}As$ barrier layers

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The effectiveness of suppressing Be out-diffusion from a Be-doped GaAs layer by strained InGaAs layers using secondary ion mass spectroscopy has been evaluated. The experimental structures consist of an 800 Å Be-doped ($\sim 1\times10^{19}$ cm^{-3}) GaAs layer sandwiched between 80 Å $In_xGa_{1-x}As$ ($x=0,0.1,0.25$) layers. The samples were subjected to rapid thermal annealing (RTA) at 750 °C for 6 min. It is clearly observed that Be diffusion beyond the InGaAs layers is the fastest for the structure with $x=0$ and the slowest for the structure with $x=0.25$.

Beryllium (Be) is widely used as the base dopant in heterojunction bipolar transistors (HBTs) grown by molecular beam epitaxy (MBE). To optimize the microwave performance of the device, the base thickness is usually limited to less than 0.1 μm and thus the base doping concentration has to be very high ($\geqslant 1\times10^{19}$ cm^{-3}). It is well known that for HBTs with very high Be doping concentration in the base, Be atoms can diffuse into the emitter region during MBE growth[1–3] and during high current-stress operation.[4] This can significantly degrade device performance. The dc current gain of HBTs with abrupt emitter-base junctions is particularly sensitive to Be diffusion. We have examined the diffusion characteristics of Be dopant species in layers of GaAs with thin pseudomorphic InGaAs barrier or guard layers on top and bottom. It is seen that Be diffusion can be suppressed to a large extent in the presence of the pseudomorphic layers.

We have recently studied the propagation of point defects (vacancies, intentional and unintentional impurities, etc.) in semiconductor heterostructures both theoretically and experimentally.[5] Our model, based on linear elasticity theory,[6,7] shows that defects originating in lattice-matched regions can be prevented from entering, or can be trapped by, a pseudomorphic layer, depending on the sign of the strain induced by the defect and the strain in the pseudomorphic layer. We have verified this model experimentally by photoluminescence measurements on specially designed GaAs/AlGaAs quantum well structures. In the present study we have performed secondary ion mass spectroscopy (SIMS) measurements to examine the effectiveness of thin pseudomorphic InGaAs layers in controlling Be out-diffusion from a heavily doped GaAs layer.

The experimental samples are GaAs-based heterostructures grown by MBE, as shown in Fig. 1. They consist of an 800 Å Be-doped ($\approx 1\times10^{19}$ cm^{-3}) GaAs layer sandwiched between 80 Å $In_xGa_{1-x}As$ ($x=0,0.1,0.25$) layers. The trilayered structures are embedded in bulk $Al_{0.4}Ga_{0.6}As$ in which thin GaAs layers are added periodically to mark the thickness for accurate determination of the Be doping profile. A 100 Å GaAs cap layer was finally grown to prevent oxidation of the top AlGaAs layer. The intended role of the $In_xGa_{1-x}As$ layers is to inhibit Be diffusion. The entire heterostructure is grown at a substrate temperature of 600 °C, except the $In_xGa_{1-x}As$ layers, which are grown at 520 °C. The samples are then subjected to rapid thermal annealing (RTA) at 750 °C for 6 min. SIMS measurements were made on the as-grown and annealed samples to determine the extent of Be diffusion. The resolution of these measurements is believed to be about 15 Å.

Shown in Fig. 2 are SIMS data of the In, Al, and Be profiles in an as-grown sample with strained $In_{0.25}Ga_{0.75}As$ layers. The notches in the Al profile indicate the positions of the thin GaAs layers. The periodicity of the notches in all the samples are exactly the same, indicating identical growth rates and layer thicknesses. The Be profiles in different samples can thus be compared directly. Figure 3(a) shows an enlarged Be doping profile measured in the as-grown samples. It can be clearly seen that the Be profile in the structure without strained InGaAs layers ($x=0$) is slightly broader than that in the structures with the strained layers. The shoulder on the left-hand side of the Be profiles, which corresponds to the leading edge of the growing layer, is believed to be due to segregation effects.[1] It is well known that during MBE growth of Be-doped GaAs, Be atoms tend to ride on the growing surface, resulting in asymmetric Be profiles. It is interesting to note that, with the addition of the strained InGaAs layers, Be segregation during MBE growth is suppressed. There are therefore two clearly identifiable effects of the presence of the strained layer. The first is a reduction of surface riding of Be atoms; the second and greater effect is the reduction of Be out-diffusion. The widths of the Be profiles measured at a Be concentration of 10^{17}

100 Å GaAs
50 Å-GaAs / 450 Å $Al_{0.3}Ga_{0.7}As$ (4 prd)
80 Å $In_xGa_{1-x}As$
800 Å Be: GaAs (8x10^{18} cm^{-3})
80 Å $In_xGa_{1-x}As$
50 Å-GaAs / 450 Å $Al_{0.3}Ga_{0.7}As$ (4 prd)
1000 Å GaAs
S. I. GaAs Substrate

FIG. 1. GaAs-based heterostructures for Be diffusion measurements.

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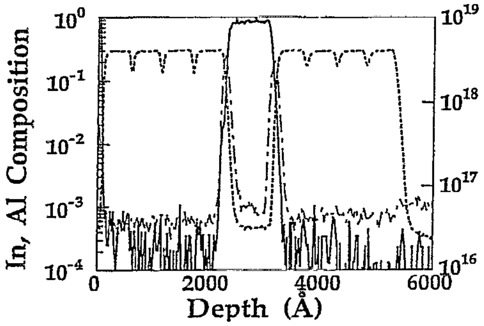


FIG. 2. Secondary ion mass spectroscopy data of the In, Al, and Be profiles in an as-grown sample with strained $In_{0.25}Ga_{0.75}As$ layers.

cm^{-3} are 1130, 1080, and 1060 Å for $x=0$, 0.1, and 0.25, respectively. After RTA at 750 °C for 6 min, the Be profiles are significantly broadened, as can be seen in Fig. 3(b). The width of the Be profile measured at a Be concentration of 10^{17} cm^{-3} are 1860, 1590, and 1460 Å for $x=0$, 0.1, and 0.25, respectively. It is clear that the width of the entire Be concentration profile is reduced with increasing strain in the InGaAs layers. These results indicate that strained $In_xGa_{1-x}As$ layers can indeed inhibit the diffusion of Be into the AlGaAs/GaAs superlattice regions. The surface riding of Be atoms, which may be due to an enhancement of the Be-to-cation bond strength, is currently being investigated. In this letter we focus on the aspect of out-diffusion of Be atoms.

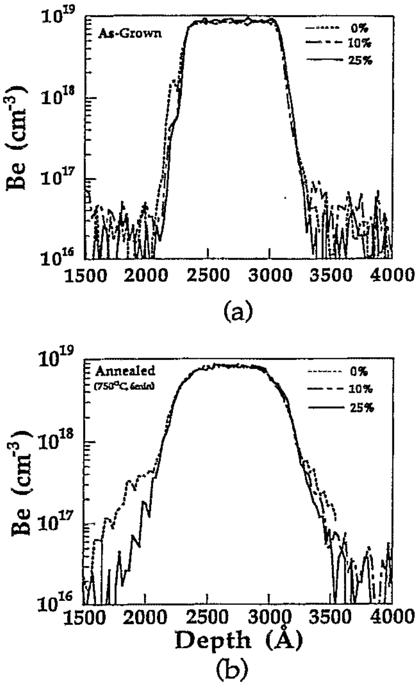
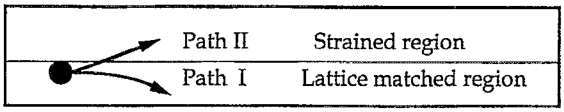


FIG. 3. An enlarged Be profile measured before (a) and after (b) rapid thermal annealing at 750 °C for 6 min.



Strain in the pseudomorphic layer	Strain induced by defect	Preferred path
Compressive ($\varepsilon<0$)	Compressive ($\delta\varepsilon<0$)	I
Compressive ($\varepsilon<0$)	Tensile ($\delta\varepsilon>0$)	II
Tensile ($\varepsilon>0$)	Compressive ($\delta\varepsilon<0$)	II
Tensile ($\varepsilon>0$)	Tensile ($\delta\varepsilon>0$)	I

FIG. 4. The preferred path of defect propagation.

The reduction in the out-diffusion of Be can be explained by a model of defect propagation described by us recently.[5] For the sake of clarity, the essential elements are reiterated. The process that is considered in this model involves a defect outside the pseudomorphic layer in a lattice-matched region gradually penetrating into the pseudomorphic layer, as schematically shown in Fig. 4. Defect propagation will involve straining the chemical bonds and distorting them, thereby introducing local strain. The defect will prefer to follow a path where the force required to start the distortion, $\partial E/\partial(a_0\epsilon)$ (E is the energy, ϵ is the strain, and a_0 is the lattice constant) is the least. It can be shown that the force needed to produce an excess distortion $\Delta\epsilon_{xx}$ in a lattice-matched region of a (100)-oriented crystal is

$$\frac{\partial \delta E_{II}}{a_0 \partial \delta \epsilon_{xx}} = a_0^2 c_{11} \delta \epsilon_{xx} \tag{1}$$

and the force required to produce the distortion in a pseudomorphic layer is

$$\frac{\delta E_I}{a_0 \delta \epsilon_{xx}} = a_0^2 (c_{11}\epsilon_{xx} + c_{12}\epsilon_{yy}), \tag{2}$$

where c_{11} and c_{12} are the elastic constants. The preferred path of defect propagation is determined by Eqs. (1) and (2) and the signs of $\delta\epsilon_{xx}$, ϵ_{xx}, and ϵ_{yy}, and is summarized in Fig. 4. This model suggests that defects originating in lattice-matched regions can be prevented from entering, or can be trapped by, a pseudomorphic layer, depending on the signs of the strain induced by the defect and the strain in the pseudomorphic layer. In either case a defect, which could be an impurity atom, will be prevented from propagating across a pseudomorphic layer and entering the lattice-matched region on the other side of the strained layer.

In conclusion, we have shown that strained InGaAs layers can slow down the diffusion of Be from a heavily doped GaAs layer. The results are relevant to the design and performance of high-frequency HBTs. We are currently conducting experiments on GaAs/AlGaAs HBTs grown by MBE and having InGaAs barrier layers on either side of the Be-doped base layer.

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