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# Combined Effects of High-Energy Si, Zn and Ga Ion Implantation and Annealing on the Reduction of Threading Dislocations in GaAs on Si

Masao Tamura and Tohru Saitoh

Optoelectronics Technology Research Laboratory,

5-5 Tohkodai, Tsukuba, Ibaraki 300-26

MeV energy Si, Zn and Ga ion implantation and post-growth annealing have been adapted to eliminate threading dislocations in 3 μm-thick GaAs on Si. Si implantation is most effective for reducing threading dislocations in the near-surface region where excess vacancies are created by implantation, suggesting that dislocations disappear by absorbing vacancies. However, no reduction effect of dislocations is observed in the case of Zn implantation. Ga implantation shows an intermediate effect between Si and Zn results. Such different effects on dislocation behavior are attributed to different movement of these impurities during annealing.

## 1. INTRODUCTION

A large lattice mismatch (4.1 %) and a large difference in the linear thermal expansion coefficients (factor of 2.5) between GaAs and Si results in the formation of heteroepitaxial GaAs layers with significant interfacial strain and high-density structural defects. In this matter, the generation of threading dislocations in grown GaAs films is the most serious problem in the case of application to minority carrier devices. To date, considerable efforts have been made to reduce the generation of threading dislocations. However, the dislocations still remain on the order of $10^6$ /cm$^2$~$10^7$ /cm$^2$ in GaAs. In this study, we adapted high-energy ion implantation and annealing to 3 μm-thick GaAs films on Si in order to reduce the density of threading dislocations.

There are two main motivations for using high-energy ion implantation. The first is due to a fact that there are distinct vacancy-rich and interstitial-rich regions in implanted layers[1] as shown in Fig. 1: a vacancy excess exists in the region shallower than the projected range ($R_p$) depth and an interstitial excess in the region deeper than $R_p$. Therefore, we can expect interactions between vacancies and threading dislocations in the surface region during annealing, presumably resulting in the disappearance of dislocations by absorbing vacancies in this region. The second is due to a fact that ion implantation-induced damage shows a high gettering efficiency for pre-existing impurities in the substrate. It is very interesting whether or not such a gettering phenomenon is also effective for pre-existing high-density defects. Moreover, it is anticipated that a high-concentration of buried impurities has a strong influence on the behavior of dislocations during annealing[2-4].

## 2. EXPERIMENTS

A 3 μm-thick GaAs film was grown at 600 °C on Si (001) wafers tilted toward [110] by 3° from [001] by the MBE method. The samples after growth were implanted at room temperature with $1\times10^{15}$ cm$^{-2}$/1.7 MeV and $5\times10^{15}$ cm$^{-2}$ /2 MeV Si, $5\times10^{15}$ cm$^{-2}$/3 MeV Zn, and $1\times10^{15}$ cm$^{-2}$/2.7 MeV and $5\times10^{15}$ cm$^{-2}$/3 MeV Ga ions. These implantation energies were chosen to have $R_p$ depths between 1.5 an 2 μm in the GaAs film. The samples were then variously annealed by either the rapid thermal annealing or the furnace annealing system in face-to-face contact

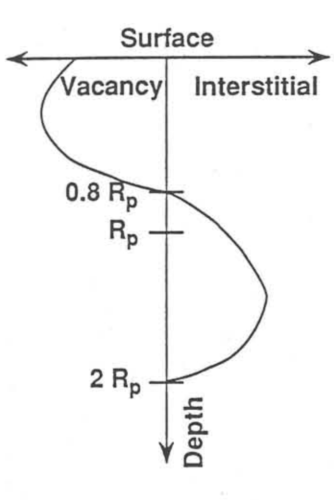


Fig. 1 Schematic drawing of distribution of point defects in the substrate introduced by ion implantation.

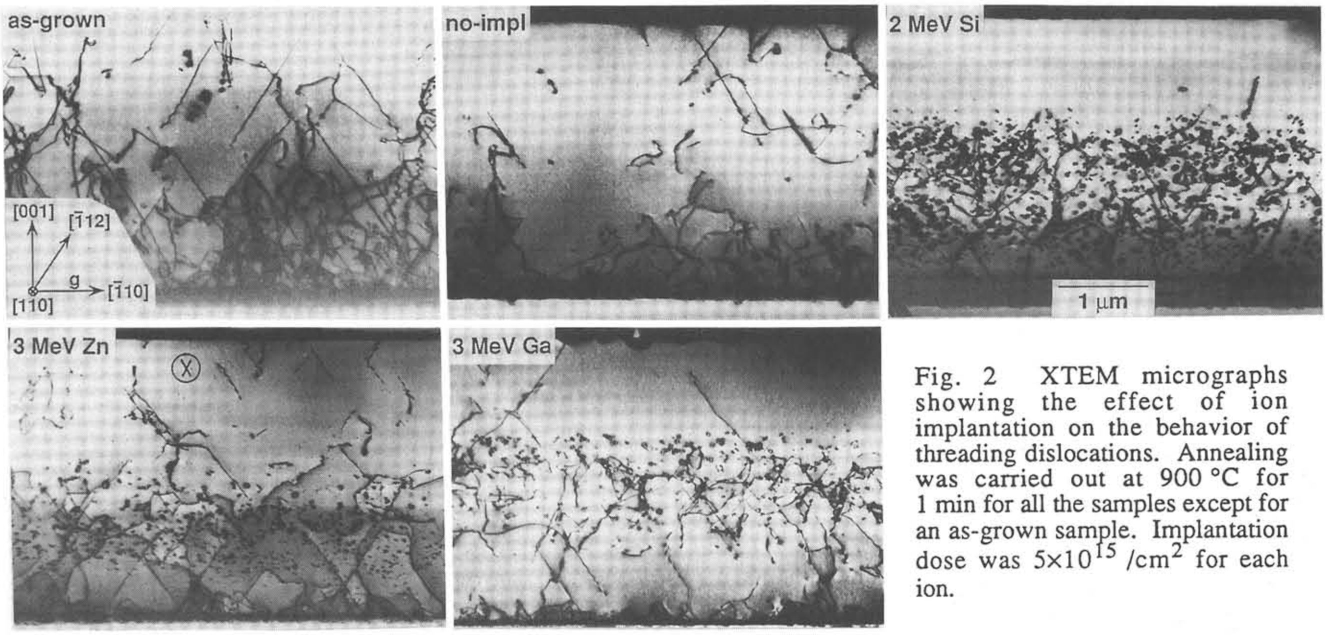


Fig. 2 XTEM micrographs showing the effect of ion implantation on the behavior of threading dislocations. Annealing was carried out at 900 °C for 1 min for all the samples except for an as-grown sample. Implantation dose was $5\times10^{15}$ /cm$^2$ for each ion.

with another GaAs wafer in an $N_2$ ambient. Conventional and high-resolution cross-sectional TEM (XTEM), and SIMS were used to investigate defect structures and impurity profiles, respectively.

## 3. RESULTS and DISCUSSION

Figure 2 compares the effect of ion species on the behavior of dislocations after annealing, particularly in the surface region together with the results of as-grown and no-implanted samples for comparison. We note that a high-density of dislocation loops was generated in implanted regions below 1 μm from the surface in every implanted sample. Only an annealing treatment without implantation effectively reduced dislocations by activating the slipping system of dislocations, although considerable parts of dislocations still remained in the surface region. On the other hand, it can be recognized from the figure that Si implantation is most effective for suppressing threading dislocations in the upper region among Si, Zi and Ga implantation results. In Zn implantation, the density of dislocations in upper region is almost the same as that in the no-implantation case. This result is a strong contrast to a reducing phenomenon of dislocations in GaAs on Si by Zn diffusion[2]. Ga implantation had an intermediate effect on dislocation suppression between Si and Zn results. This order of ion species on dislocation suppression effect was independent of annealing and implantation conditions.

Concerning defect creation in the as-implanted state, we checked whether such damage as amorphous clusters and/or point-defect clusters are left in the near-surface region through which the ions have passed. One typical example of an XTEM micrograph which was taken from the region denoted by X in Zn implantation in Fig. 2, is shown in Fig. 3. As can be seen from the micrograph, we confirmed that no above-mentioned defects remain in this region.

The different effects of Si, Zn and Ga ions on the dislocation behavior in Fig. 2 is attributed to a different movement of such impurities during annealing. Figure 4 shows depth profiles of Si and Zn before and after annealing at 900 °C for 1 min measured by SIMS. In the case of Si, the annealing-induced diffusion is very small, as can be recognized in Fig 4 (a). Compared to this, Zn showed a rapid diffusion toward the surface side (Fig. 4 (b)). Such fast diffusion of Zn has a strong correlation with inhibiting the disappearance of dislocations in the surface region in Fig. 2. Created vacancies by implantation will be consumed during Zn diffusion. The diffusion behavior of Ga is in the meddle between Si and Zn.

We mention two remarkable phenomena of the interaction between dislocations and implantation-introduced impurities, and between dislocations and implantation-induced defects, as

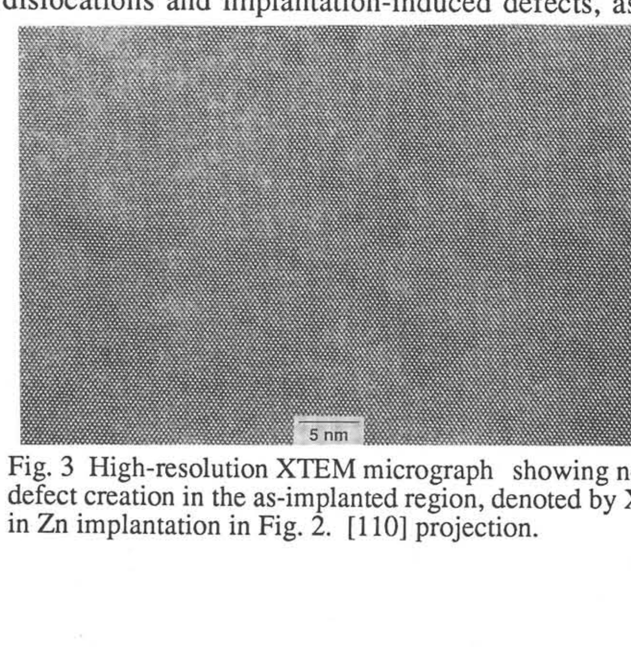


Fig. 3 High-resolution XTEM micrograph showing no defect creation in the as-implanted region, denoted by X in Zn implantation in Fig. 2. [110] projection.

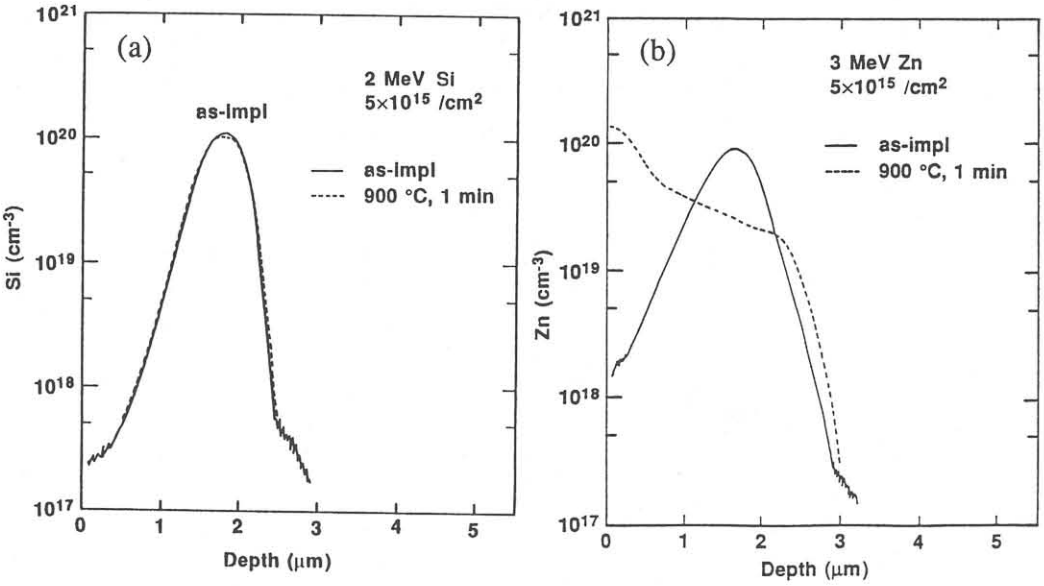


Fig. 4 Depth profiles of Si (a) and Zn (b) before and after annealing at 900 °C for 1 min. Implantation conditions are indicated in the figure.

shown for Si implantation results in Fig. 5. One feature is bending of dislocations along the [$\bar{1}$10] direction (Fig. 5 (a)). This shows that some forces act on dislocations around here, resulting in a change in the moving directions of dislocations during the annealing process. This position almost coincides with the high-concentration region ($>10^{19}$ /cm$^3$) of implanted Si, where Si diffusion little occurred even by annealing. Therefore, such a highly Si-doped region is considered to have induced a bending force on the dislocations[3,4].

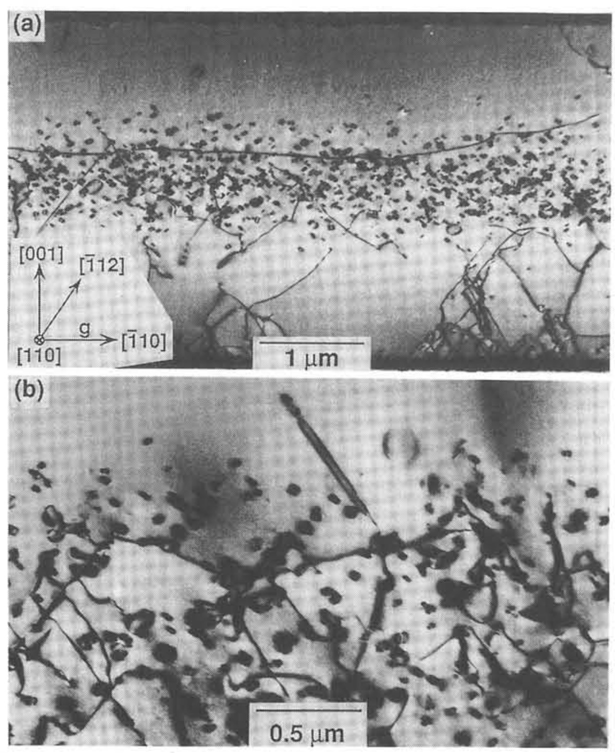


Fig. 5 XTEM micrographs showing the interaction between dislocations and implanted layers for Si implantation results. (a) A sample was annealed at 800 °C for 30 min after implantation at 1.7 MeV with a $5\times10^{15}$ /cm$^2$ dose. (b) A sample was annealed at 1000 °C for 1 min after implantation at 2 MeV with a $5\times10^{15}$ /cm$^2$ dose.

Another phenomenon is the interaction between dislocations and dislocation loops in the implanted region (Fig. 5 (b)). It is observed in the micrograph taht loops lie on dislocations lines, and that dislocation lines are terminated at the loops, suggesting a strong interaction between defects during the loop formation stage while annealing.

## 4. CONCLUSION

In order to eliminate threading dislocations in MBE grown 3 μm-thick GaAs films on Si, MeV energy Si, Zn and Ga ion implantation combined with post-growth annealing was adapted into the above mentioned samples. Si implantation showed the most effective result for elimination of dislocations in the near-surface region in a GaAs film. However, no appreciable reduction effect of dislocations was realized by both Ga and Zn implantation. These adverse effects of impurities on the behavior of dislocations were caused by the movement of implanted impurities during annealing. Si little diffused during annealing at high temperatures such as 900 and 1000 °C, while Zn showed a rapid diffusion toward the surface side. From these results, elimination of dislocations by adapting high-energy implantation and annealing was considered to be resulted from dislocation climb by absorbing vacancies introduced by implantation.

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