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Post-implantation defects instability under 1 MeV electron irradiation in GaAs

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Abstract The influence of 1 MeV electron irradiation on the stability of post-implantation defects in GaAs has been investigated. The n-type GaAs wafers of <100> orientation were implanted with 150 keV As^+ ions below the amorphization threshold at RT using the implantation dose of 2×10^{13} ions cm^{-2} at a constant flux of 0.1 μA cm^{-2}. Then the implanted samples were irradiated with a scanned beam of 1 MeV electrons from a Van de Graaff accelerator in a dose range $(0.5–5.0)\times10^{17}$ cm^{-2} at 320 K. RBS and channeling spectroscopy of 1.7 MeV $^4He^+$ ions were used to determine the depth distribution of defect concentration before and after 1 MeV irradiations. New results of an "oscillatory" behaviour of the damage level as a function of 1 MeV electron fluence are presented.

Key words electron annealing • GaAs • implantation

Introduction

One of the main drawbacks of ion implantation into semiconductor crystals is generation of lattice damage which deteriorates their physical parameters. Therefore, it is necessary to remove post-implantation defects in order to activate the implanted impurities and to obtain the desired electrical activity of the crystal. The removal of damage and the recrystallization of the implanted layer can be achieved by various treatments such as conventional long term furnace annealing at elevated temperatures or some transient annealing techniques using pulsed or scanned electron [1, 5, 6, 11, 13], light or laser beams [10]. There have been many annealing studies using these techniques in relation to III-V semiconducting compounds and in particular to GaAs, reporting satisfying recovery of post-implantation damage or electrical activity. The influence of ionization on stability and transformation processes of simple and complex defects in semiconductors has been the subject of studies in many papers [3, 7–9, 12].

In our previous work [13] we reported the results of the influence of 300 keV electron irradiation on GaAs single crystals implanted with 150 keV As^+ at RT. The results revealed a distinct increase of post-implantation damage level – the effect opposite to defect annealing.

The aim of the present work was to determine how the post-implantation defects in GaAs evolve at different depths below the surface and how such evolution depends upon the fluence of 1 MeV electron irradiation.

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Experiment

All samples were prepared from melt grown (Czochralski) single crystals of n-type GaAs with 10^{17} cm^{-3} Te, provided by the Institute of Electronic Materials, Warsaw. The thickness of the GaAs wafers was in the range 300–400 μm. Each wafer was treated by mechanical lapping from one side and mechanical and chemical polishing from the other side being exposed to implantation. The samples 2" in diameter were implanted with 150 keV As$^+$ ions to a dose of 2×10^{13} cm^{-2} to create a disorder level below the amorphization threshold. A constant flux of 0.1 μA cm^{-2} of As$^+$ ions was employed for implantation at RT. The ion beam was scanned electrostatically to assure uniformity of ion implantation over the sample area. To avoid axial channeling all samples were implanted in a misoriented direction of 7^0 tilt angle between the surface normal and the ion beam. Then, the implanted samples of 5×5 mm^2 dimensions were irradiated at the same 7^0 angle with a scanned beam of 1 MeV electrons from a Van de Graaff electron accelerator in a dose range (0.5–5.0) $\times10^{17}$ cm^{-2}, in a 3×10^{-6} Torr vacuum. The electron beam intensity of 1 μA cm^{-2} was used to maintain the samples at constant temperature not exceeding 320 K. A colloidal silver glue was used to fix the samples at a 7^0 angle to a copper plate which in turn was mounted on a water-cooled brass holder. Copper-constantan thermocouples were attached to the sample – copper joint. The post-implantation damage distributions, before and after electron irradiation, were measured by RBS-c random and channeling spectra (axial <100> spectra) of 1.7 MeV ^{4}He$^+$ ions using the classical relation by Chu et al. [4]. The damage distributions related to both Ga and As peaks in the RBS spectra were calculated using the "Defect" computer program, see ref. [13]. The RBS measurements were performed at the Forschungszentrum Rossendorf, Germany.

Results and discussion

Fig. 1(a–c) shows a series of <100> aligned channeling spectra of GaAs samples implanted with 150 keV As$^+$ ions to a dose 2×10^{13} cm^{-2} for selected 1 MeV electron fluences. This behaviour is better seen in Fig. 2(a–b) which presents the damage depth distributions (damage profiles) as extracted from the <100> channeling spectra given in Fig. 1(a–c). In order to show more clearly the behaviour of damage profiles under 1 MeV electron irradiation Fig. 3 presents the damage fluctuations in three selected depths of the damage distributions, namely for 0, 20 and 50 nm (curves a, b, and c, respectively) from the surface of a sample. The curve a) represents damage level variations at the surface, but the curves b) and c) – show these variations at the maximum and at the slopes of the damage profiles. An "oscillatory" behaviour of the damage at these selected depths under increasing electron fluence is very well seen. These variations occur in the whole range of electron fluences.

In the case of the subsurface defect concentration (curve a), the damage level increases with the first three electron fluences and then runs oscillating to some asymptotic value of about 50% of total amorphization, much higher than the initial, as implanted level, of about 28%. The other two curves b) and c), representing damage level variations at 20 and 50 nm, show at the onset a decrease of damage followed by damped oscillations.

It is worth to notice that the damage levels of curves b) and c) for the maximum electron fluence 5.0×10^{17} cm^{-2} amount to 21% and 13%, and are lower than their initial as – implanted values – 32% and 17%, respectively. Apart from the oscillatory behaviour, this decrease indicates that defect annihilation processes take place at these depths, decreasing the defect concentration to some asymptotic values.

Using pulsed electron beam annealing of Si$^+$ and Cr$^+$ implanted GaAs Alberts et al. [4] found a significant increase of a damage peak which occurred after several peaks decreasing from the amorphization level. The authors argue that this effect is probably related to a disrupted surface structure being a result of transient surface melting, which takes place above 0.7 Jcm^{-2} energy density of the electron beam pulses, and subsequent regrowth of the implanted layer. In our case, the appearence of damage level oscillations at three various sample depths shows a repeated increase and decrease of damage. Since the crystalline GaAs can hardly be amorphized by a single dose of 0.5×10^{17} cm^{-2} of 1 MeV electrons at RT, we have a heavily damaged layer as can be inferred from the RBS-c measurements. The reason of great differences between Albert's [1] and our results depends very likely on the experimental conditions, i.e. amorphization and partial damage of the implanted layer,

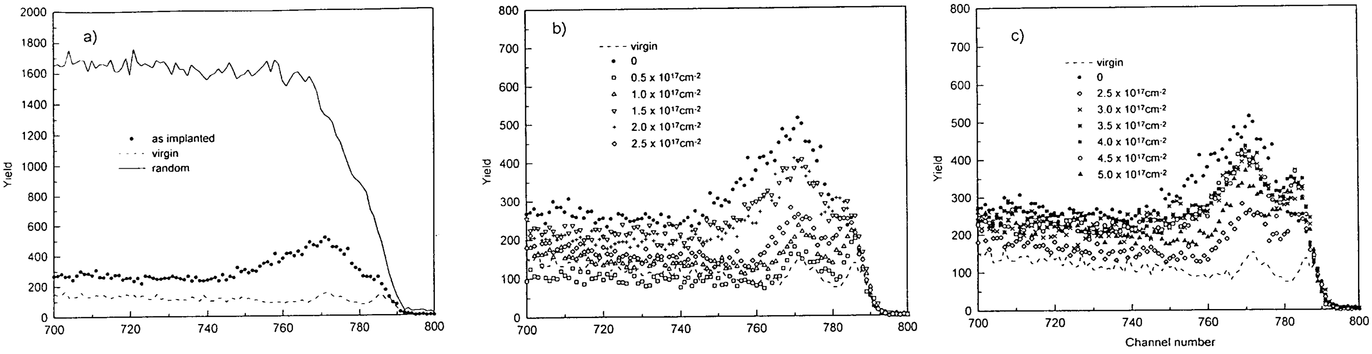

Fig. 1. Evolution of <100> aligned ion channeling spectra of GaAs implanted with 150 keV As$^+$ ions to a dose 2×10^{13} cm^{-2}: a) as implanted, b)–c) after 1 MeV electron irradiation with varying fluences.

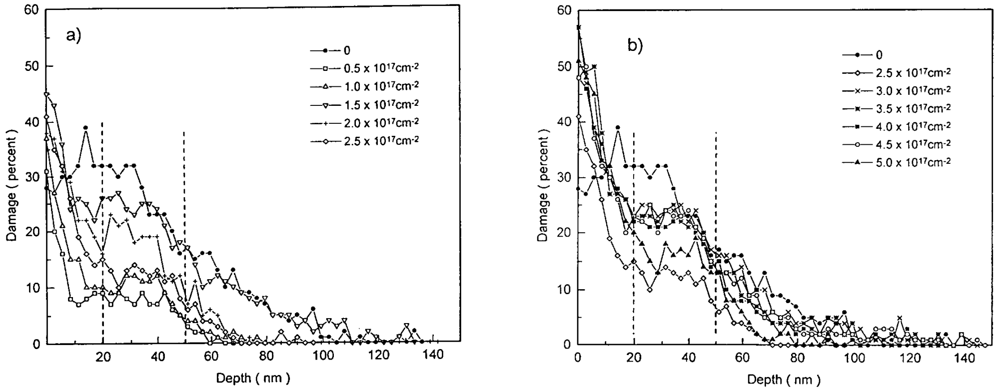

Fig. 2(a–b). Depth distributions of damage as extracted from the channeling spectra presented in Fig. 1(a–c) for different 1 MeV electron fluences.

low (pulsed) and high (scanned) electron energy irradiations and different implanted ions of Si, Cr, and As, respectively. TEM investigations on weakly damaged GaAs layers by Wesch et al. [14] indicate that in these layers defect structures consisting of point defects, point defect clusters and amorphous zones exist. High resolution electron microscopy studies on individual displacement cascades by Bench et al. [2] provides strong proof that the damage within the core of isolated cascades is amorphous. It is evident that in the implanted layer these various defect structures are not uniformly distributed along the path of ions.

Assuming a similar distribution of post-implantation defect structures in our weakly damaged samples, transformation processes of defects should proceed in a different way, leading to the observed damage level behaviour at various subsurface regions of the implanted layer.

The present results support our view from the previous paper [13] on the processes responsible for the increase of defect concentration under electron irradiation. The charge state of defects is changed in the field of ionization and modifies the energy barrier for their migration. At least a part of them out-diffusing from the damaged zones and migrating through the sample will make stable associations with the intrinsic or impurity atoms in the crystal, increasing in this way defect concentration [13].

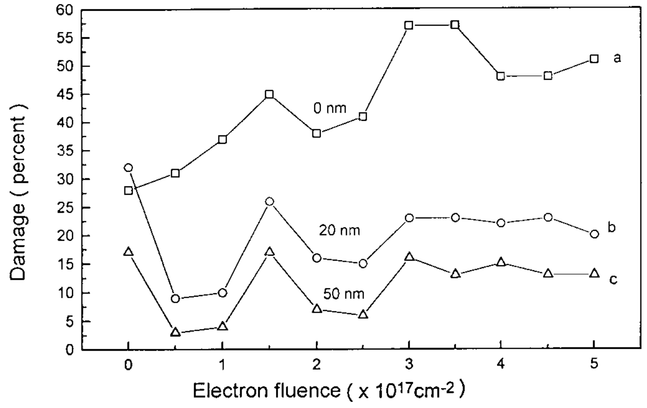

Fig. 3. Damage level fluctuations at 0, 20 and 50 nm from the surface of the sample as a function of 1 MeV electron fluences.

The participation of Frenkel pairs created by 1 MeV electrons in the transformation processes should be rejected because their concentration is several orders of magnitude lower than the concentration of defects introduced by implantation.

Conclusions

It has been shown using RBS-c spectroscopy of 1.7 MeV $^4He^+$ ions that 1 MeV electron irradiation of GaAs implanted with 150 keV As^+ ions at RT induces damped oscillations in the damage level. The increase of defect concentration appearing during oscillations confirms the results obtained in our previous paper [13]. This effect can be attributed to ionization induced alteration of a defect charge state and to the enhanced out-diffusion of simple defects from the damaged zones making then associations with other defects in a crystal. The asymptotic value of ionization induced damage oscillations indicates that some of the radiation-produced defects are stable under ionizing radiation. Further investigations are necessary to explain in more detail the oscillating behaviour of a damage level taking place in the implanted GaAs under electron irradiation, especially at lower electron energy, close or below the energy threshold for atomic displacement.

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