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Electrical characterization of defects in heavy-ion implanted n-type Ge

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Abstract

Deep-level transient spectroscopy was used to investigate the electrically active defects introduced in n-type Ge during heavy-ion implantation of 160 keV ions. Various noble heavy-ions were used for implantation and the main defects introduced were found to be electron traps with energy levels at $E_C - 0.09$ eV, $E_C - 0.15$ eV and $E_C - 0.30$ eV. Another defect with a level at $E_C - 0.38$ eV, shown to be the E-center (V–Sb defect), is also present in a very low concentration. The main defects in heavy-ion implanted Ge are different from those introduced by MeV electron irradiation, where the main defect is the E-center. Since electron irradiation introduces mainly point defects, this indicates that heavy-ion implantation introduces defects of a more extended nature, such as vacancy and/or interstitial clusters and their combinations with impurities or foreign species in the Ge. We have also demonstrated that these defects are not species related.

Article Outline

1. Introduction

The low effective mass of holes in Ge has opened up the possibility of using Ge in ultra fast complimentary metal–oxide–semiconductor devices [1]. There is renewed interest in the properties of defects in Ge because defects ultimately determine the performance of devices. In recent studies, the properties of the defects introduced during high-energy gamma, electron and proton irradiation of Ge were reported [2], [3], [4], [5] and [6]. The defects introduced during electron beam deposition of Pt Schottky contacts on n-Ge, where particles heavier than electrons create the defects, have also been characterised [7]. Little data are available regarding the electronic properties of defects introduced during the implantation of Ge with heavier ions, such as dopants. Implantation by heavy-ions is typically encountered during doping as well as pre-doping amorphization [10]. These implantations will introduce, among others, extended defects (e.g. clusters) that have different electronic and annealing characteristics compared to those of the well-studied point defects introduced during electron irradiation. The effect of indium implantation has been studied and the formation of these extended defects reported [10].

In general, irradiation and implantation induced defects will influence device performance, but neither the nature of heavy-ion implantation induced defects nor their influence on devices has yet been established for Ge. Depending on the application, these defects may either be beneficial for or detrimental to optimum device functioning. For example, for Si it has been shown that the defects introduced during high-energy electron and proton irradiation increase the switching speed of devices [9].

In this study, we report on the electronic properties of defects introduced in n-type Ge using several different noble heavy-ions for implantation. The noble-ions are chemically inert and provide a large range of ion sizes and masses that can be used to study implantation damage of other ions with a similar size or mass.

We show here that all the heavy-ion implantation introduces three prominent electron traps in Ge similar to that observed for In [8]. In order to investigate if the foreign species have any effect on the defects observed, we also implanted Ge samples with 160 keV Ge-ions.

2. Experimental

To study the implantation related defects, we have used bulk-grown, (1 1 1) oriented, n-type material doped with Sb to a level of (2–3) × 10^{15} cm^{-3}. Before metallization and implantation, the samples were first decreased and subsequently etched in a mixture of H_2O_2:H_2O (1:5, 30% H_2O_2) for 1 min. Immediately after cleaning and drying, they were inserted into a vacuum chamber where AuSb (0.6% Sb) was resistively deposited on their back surfaces for ohmic contacts. The samples were then annealed at 350 °C in Ar for 10 min to minimize the contact resistivity of the ohmic contacts. Thereafter the front sides of the samples were implanted at room temperature with 160 keV ions at an angle of 0° to a fluence of 2 × 10^{11} cm^{-2}. Before Schottky contact deposition, the samples were chemically cleaned again as described above. Palladium contacts, 0.6 mm diameter and 200 nm thick, were then resistively deposited on the implanted side of the Ge through a mechanical mask [7]. Deep-level transient spectroscopy (DLTS) was used to study the defects introduced in the Ge after implantation.

3. Results and discussion

In curves (a) and (b) of Fig. 1, we depict the DLTS spectra for an In-implanted and electron irradiated sample, respectively [8]. Note that, although not shown, the unimplanted Ge did not contain any defects in detectable concentrations [7]. Curves (c), (d), (e), (f) and (g) show the spectra obtained for noble-ion implantation of He, Ne, Ar, Kr and Xe, respectively. The most significant electron traps indicated are $E_{0.09}$, $E_{0.15}$ and $E_{0.30}$ with levels at $E_C - 0.09$ eV, $E_C - 0.15$ eV and $E_C - 0.30$ eV, respectively. The defect signatures in Fig. 2 indicate that the $E_{0.30}$ defect is virtually the same for all the different implanted ions. The apparent capture cross section for this defect was found to be 1.1 × 10^{-13} cm^{-2}. Although the level of $E_{0.30}$ is very close to that found for the divacancy after electron irradiation $E_C - 0.29$ eV [2], the divacancy anneals out at 150 °C whereas $E_{0.30}$ is still present after annealing at 200 °C [8]. This also suggests that this defect is of a more extended nature. The defect signatures for the $E_{0.09}$ and $E_{0.15}$ defects do not align completely, indicating that they may not be exactly the same defect. The energy levels for these two defects were found to be $E_C - 0.09 \pm 0.005$ eV and $E_C - 0.15 \pm 0.005$ eV, respectively. It has been observed (not shown here) that the $E_{0.09}$ defect exhibits emission rate dependence on biasing, which is characteristic of field enhanced emission possibly due to the Poole–Frenkel effect. This can possibly explain the different apparent capture cross sections observed for the various ion implantations because implantation with the different ions results in a slightly different free carrier concentrations for each of these samples. The apparent capture cross section for the $E_{0.09}$ defect varies between 7.6×10^{-14} and 1.2×10^{-13} cm^{-2} and that of the $E_{0.15}$ defect from 8.6×10^{-15} to 1.8×10^{-14} cm^{-2}.

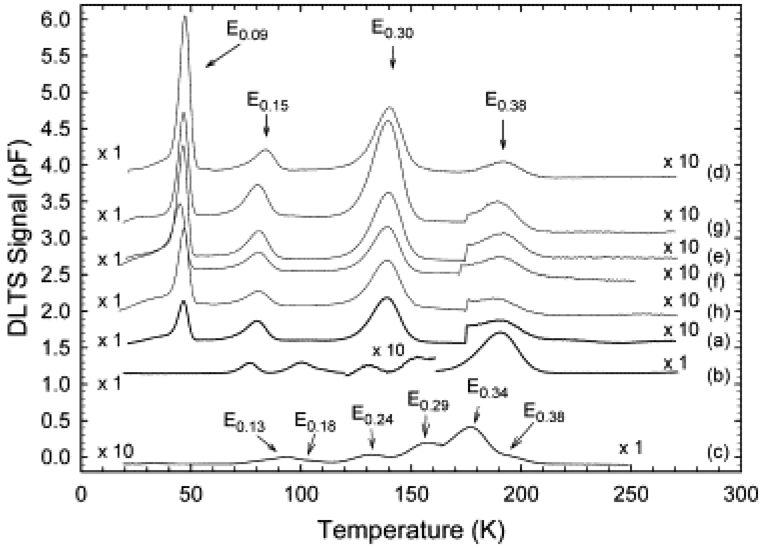

Fig. 1. DLTS spectra of 160 keV heavy-ion implanted Ge: In **[8]** (curve(a)), He (curve (c)), Ne (curve (d)), Ar (curve (e)), Kr (curve (f)), Xe (curve (g)), Ge (curve(h)), high-energy electron irradiated Ge **[8]** (curve (b)). These spectra were recorded using a rate window of 80 s^{-1} at a quiescent reverse bias of −2 V with a filling pulse, V_p, of 1.8 V superimposed on the reverse bias.

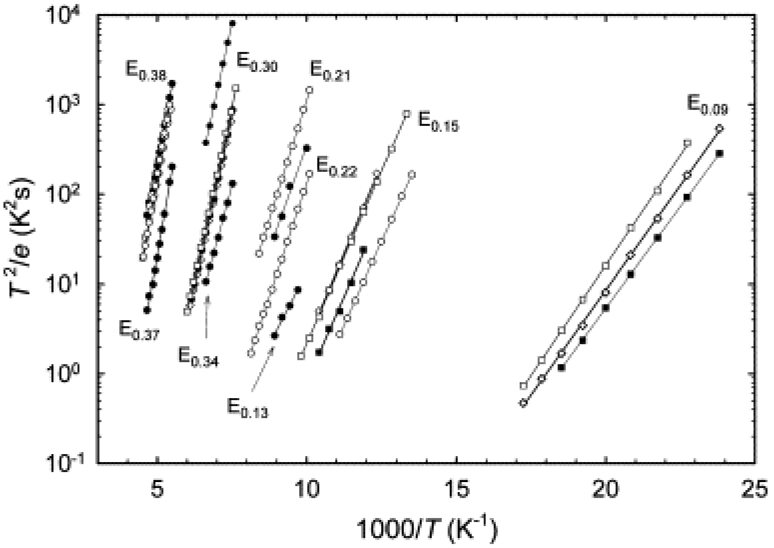

Fig. 2. Arrhenius plots for defects in heavy-ion implanted Ge: He (●), Ar (□), Xe (◇), In (■), and MeV electron irradiated Ge (○). All data were acquired using the recording conditions defined in the caption of **Fig. 1**.

A defect, $E_{0.38}$, in a much lower concentration, is also indicated at around 190 K. Note that from Fig. 1 and the Arrhenius plots in Fig. 2, the only defect that is clearly introduced both during MeV electron irradiation and implantation is $E_{0.38}$ and it is only introduced in a low concentration in the implanted Ge. $E_{0.38}$ has been identified as the (- -/-) charge state of the E-center (V–Sb) in Sb-doped Ge [2], [3] and [8]. This implies that single vacancies are only produced in small quantities during implantation with heavy-ions, otherwise the $E_{0.38}$ concentration would have been much higher. This is understandable because heavy-ions deposit much more energy per unit length than electrons, thereby increasing the probability of the formation of defects larger than the single vacancy that is required for the formation of the E-center.

Note that the spectrum obtained for the He-implanted Ge (curve (c)) does not share the same features as the other heavy-ion implanted spectra. Comparing it to the electron irradiated spectrum (curve (b)), we see that the two small peaks at about 130 and 150 K are similar to the defects $E_{0.21}$ and $E_{0.22}$ [8]. However, we found that these two defects have levels $E_C - 0.24$ eV and $E_C - 0.29$ eV which are different than the $E_{0.21}$ and $E_{0.22}$ found for electron irradiated Ge. Also note the $E_{0.18}$ and $E_{0.13}$ defects indicated with levels $E_C - 0.18$ eV and $E_C - 0.13$ eV and capture cross sections 3.1×10^{-15} and

6.9×10^{-16} cm^{-2}, respectively. The $E_{0.38}$ defect is also observed, closely spaced to another defect, labelled $E_{0.34}$. The defects associated with these peaks have energy levels $E_C - 0.37$ eV and $E_C - 0.34$ eV and apparent capture cross section of 4.6×10^{-14} and 1.8×10^{-14} cm^{-2}, respectively. It is therefore clear that the He-ions, which have a much lower mass compared to the other heavy-ions implanted, do not create the same structural defects in Ge. The defects that are created are present in very low concentrations and do not correspond to the three prominent defects introduced by implantation of heavier ions. As above, this is the result of the very different energy deposited per unit length for He-ions compared to heavier ions.

Finally, we deduce from Fig. 1 and Fig. 2 that the three main implantation induced defects do not correspond to any of the defects introduced during electron irradiation. This implies that the $E_{0.09}$, $E_{0.15}$ and $E_{0.30}$ defects have a different physical structure than the defects introduced during electron irradiation. We speculate that they are related to higher order vacancy complexes, larger than the divacancy, or interstitial clusters, formed when an ion creates multiple point defects in the same physical environment that interact to become clusters.

In order to investigate the effect of lattice damage without introducing foreign species, we also investigated the implantation damage introduced by implanting Ge-ions into the Ge substrate. The DLTS spectrum recorded for a Ge-implanted sample is shown in curve (h) of Fig. 1. It is clear that Ge introduce the same main three electron traps, as well as the E-center in small concentrations. The DLTS signatures of the Ge implantation induced defects coincided well with those of the other heavy-ion defects (not shown in Fig. 2 for clarity). The electronic properties of these defects therefore do not depend on the implanted ion and we can thus conclude that they are simply physically different, possibly larger than the divacancy, introduced during ballistic collisions, and independent of the implanted ions.

4. Conclusion

We have investigated, using conventional DLTS, the defects introduced during heavy-ion implantation of n-type Ge. Our results reveal that the main defects introduced have energy levels at $E_C - 0.09$ eV, $E_C - 0.15$ eV and $E_C - 0.30$ eV. Low concentrations of the

V–Sb complex, or E-center, with an energy level at $E_C - 0.38$ eV, were also found to be introduced during implantation.

We have also demonstrated that the main defects are different from the point defects introduced by electron irradiation because the two sets of defects have very different electronic properties. By comparing the DLTS spectra of the heavy-ion implanted Ge (except for He), we could establish that these defects are observed for all implantations, including Ge implantation, and are therefore not species related. Since we have shown that these defects are not the same as the point defects introduced by electron irradiation, we propose that they are related to vacancy or interstitial clusters of various sizes, but larger than the divacancy.

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