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Enhanced damage accumulation in carbon implanted silicon

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The accumulation of damage in Si implanted with $^{12}C^+$ was investigated experimentally using aligned Rutherford backscattering analysis. The damage profiles in Si implanted with $^{12}C^+$ or $^{11}B^+$ at 50 keV to the same doses and dose rate were compared. It was found that the damage accumulates at a noticeably higher rate by $^{12}C^+$ implantation than by $^{11}B^+$, especially for doses $>2\times10^{15}$ cm^{-2}. In order to explain our results we suggest that self-interstitial Si atoms are captured by the implanted C atoms, forming complex defects which are stable at room temperature.

The ion implantation is presently a routine doping process in silicon integrated circuit technology. It is well known that ion implantation introduces radiation damage, which may be detrimental to the electronic device performance. Partial annealing of the damage occurs concomitantly with the implantation process and this phenomenon is called dynamic annealing. The dynamic annealing is known to be more pronounced for light mass ion implantation, low dose rate, and heated substrates. The extent of this *in situ* annealing determines the final as-implanted damage concentration and consequently strongly influences the choice of the post-implantation annealing regime, required for efficient damage repairing.

In the present investigation, the as-implant damage concentration in $^{12}C^+$ implanted Si is compared with that by $^{11}B^+$. Since the masses of these ions are nearly equal, almost similar collision cascade properties and primary defect production rates are expected to occur when their energy and dose rate are identical. However, in contrast to this prediction, the actual damage profiles due to $^{11}B^+$ and $^{12}C^+$ implants at an energy of 50 keV, performed to the same doses, differ significantly particularly for doses in excess to 1×10^{15} cm^{-2}. For example, the damage concentration level after $^{12}C^+$ implantation to a dose 4×10^{15} cm^{-2} results about ten times higher than that of $^{11}B^+$. This seems to indicate that the dynamic annealing is strongly influenced by the chemical nature of carbon.

Besides oxygen, carbon is the most widely discussed impurity in Si and it is known to affect many different phenomena in the crystal.[1–5] Recent investigations demonstrated that by C^+ implantation it is possible to reduce the transient enhanced diffusion[6] and prevent dislocation formation in Si coimplanted with B^+.[7] In addition, the electrical activation of implanted B is significantly influenced by a C^+ coimplantation such that the reverse annealing phenomenon can be suppressed.[8] All these mentioned facts may be explained assuming that C atoms trap self-interstitial Si atoms (Si_I) during the ion implantation and the subsequent annealing process.[2,3]

In the present study, we have investigated the as-implanted damage profiles produced by $^{11}B^+$ and $^{12}C^+$ implantations in n-type (100) oriented silicon wafers with resistivity of 4–11 Ω cm. All the implantations were performed at an energy of 50 keV, at a dose rate of 0.4 μA/cm^2 with $^{11}B^+$ to the doses of 1 and 4×10^{15} cm^{-2} or $^{12}C^+$ to doses ranging rom 2×10^{14} to 5×10^{15} cm^{-2}. The substrates were tilted by 7° with respect to the beam incidence direction to minimize the ion channeling. The defect profiles were analyzed by Rutherford backscattering spectrometry (RBS) with a 760 keV He^{++} beam aligned with the ⟨100⟩ crystal direction. The overall energy resolution of the RBS analysis was of 14 keV. The as-implanted damage was obtained using an iterative procedure to calculate the dechanneling background.[9] In order to minimize room-temperature annealing effects, all the implanted samples were stored in liquid-nitrogen while waiting for the RBS analysis.

Figure 1 presents the damage depth profiles in samples implanted with $^{11}B^+$ or $^{12}C^+$ to the doses of 1×10^{15} cm^{-2} [Fig. 1(a)] and 4×10^{15} cm^{-2} [Fig. 1(b)]. For the lower dose, the damage profile due to the $^{11}B^+$ and $^{12}C^+$ implantations are almost similar, with concentration levels at the profile

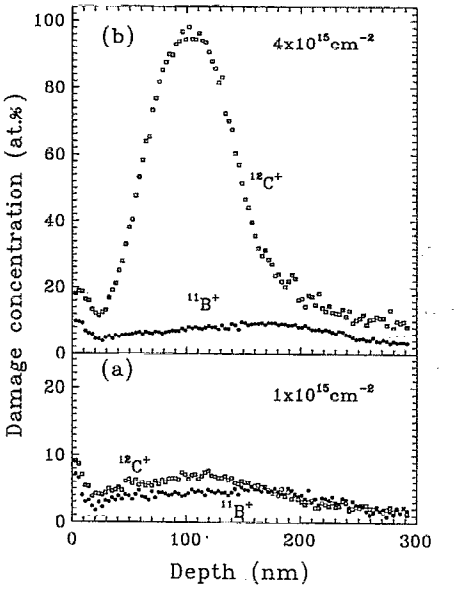

FIG. 1. Depth profiles of the damage created by $^{11}B^+$ and $^{12}C^+$ implanted Si at RT with energy of 50 keV and doses of 1×10^{15} cm^{-2} (a) and 4×10^{15} cm^{-2} (b).

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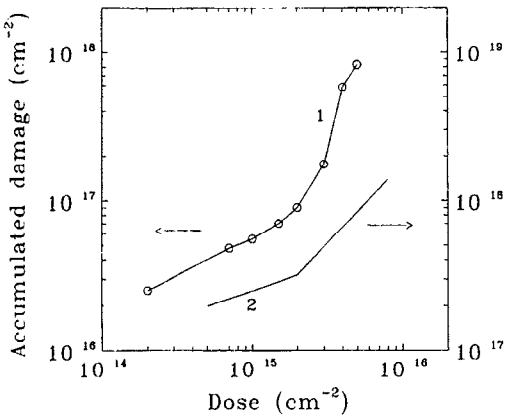

FIG. 2. Accumulated damage as function of the implanted $^{12}C^+$ dose at 50 keV (curve 1) and at 200 keV (Eisen and Welch) (curve 2).

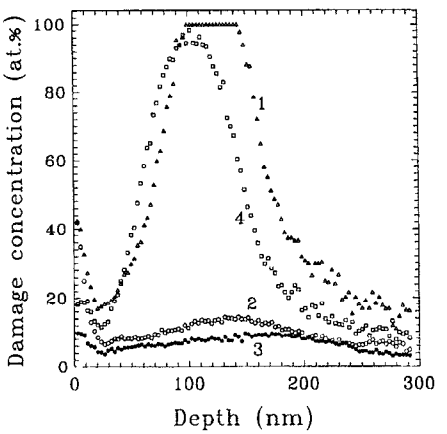

FIG. 3. Damage concentration depth profiles in Si samples implanted to doses of 4×10^{15} cm^{-2} and energy of 50 keV of $^{12}C^+$ at 100 °C followed by $^{11}B^+$ at RT (curve 1); $^{12}C^+$ at 100 °C (curve 2), $^{11}B^+$ at RT (curve 3) and $^{12}C^+$ at RT (curve 4).

peak of 5% and 7%, respectively. The increasing of the $^{11}B^+$ dose by a factor of 4 resulted in an increase of a factor of 2 in the accumulated damage. However, for the case of $^{12}C^+$ the same increasing of the dose leaded to a fourteen times increase of the damage concentration level at the profile peak.

The accumulated damage by $^{12}C^+$ implantation at 50 keV was studied for doses ranging from 2×10^{14} to 5×10^{15} cm^{-2}. The accumulated damage is considered here as the depth integral of the damage concentration profile. Figure 2 compares the accumulated damage versus the implanted $^{12}C^+$ dose from the present work with those extracted from the article by Eisen and Welch,[10] regarding a 200 keV $^{12}C^+$ implanted at a dose rate of 0.6 μA/cm^2.

It is interesting to note that for doses $<2\times10^{15}$ cm^{-2} independently of the energy the accumulated damage increases with the square root of the dose (Φ). For the dose range $>2\times10^{15}$ cm^{-2}, while the data of Eisen and Welch[10] indicate that the accumulated damage dependents linearly with Φ, our data vary with Φ^n ($2<n<3$).

The enhanced damage accumulation for $^{12}C^+$ doses above 2×10^{15} cm^{-2} can be explained considering that the dynamic annealing becomes strongly reduced when C concentration in the Si sample exceeds the $\approx2\times10^{20}$ cm^{-3} (the concentration at the profile peak for a $^{12}C^+$ implantation at 50 keV and dose of 3×10^{15} cm^{-2}). Such enhancement of damage accumulation was not observed by Eisen and Welch,[10] probably because for their implanted doses at energy of 200 keV the C concentrations are below 2×10^{20} cm^{-3}.

The above results may be explained assuming that C atoms capture Si_I atoms produced in the collision cascades. The accumulation of trapped Si_I atoms in the neighborhood of the C atoms would form complex defect precipitates within the Si matrix. By increasing the C^+ dose, either the concentration of precipitates or their sizes should increase. Hence, enhancement of damage accumulation and reduction of the dynamic annealing take place.

Further evidence that the presence of a high C concentration influences the dynamic annealing in Si is shown in Fig. 3, for the case of samples implanted first with $^{12}C^+$ (at 100 °C) and subsequently with $^{11}B^+$ (at RT) to equal doses of 4×10^{15} cm^{-2} (curve 1). The damage profile of as-implanted $^{12}C^+$ (curve 2) reveals that the accumulated damage during this hot implant is below the 15% level. During the subsequent $^{11}B^+$ implantation accumulated damage formed a buried amorphous layer with thickness of 50 nm, centered at the depth of 125 nm. For comparison the damage profiles due to a single RT implantation at a dose of 4×10^{15} cm^{-2} with $^{11}B^+$ (curve 3) and $^{12}C^+$ (curve 4) were included.

In summary, we have demonstrated that the dynamic annealing during the implantation of light ions, like $^{12}C^+$ or $^{11}B^+$, is noticeably reduced when the Si contains C in concentration $>2\times10^{20}$ cm^{-3}. It is suggested that the implanted C atoms create trapping centers for Si_I atoms, generated in the collision cascades. The precipitation of Si_I at the trapping centers forms complex defect structures which are stable at room temperature.

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