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Mechanism for enhancement of electrical activation of silicon in GaAs by aluminum co-implantation

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A pronounced enhancement in the electrical activation of implanted Si in GaAs is demonstrated by co-implantation of Al. The maximum enhancement (×2) occurs when the Si distribution is shallow, there is a separation between the Si and Al distributions with the Al being deeper, the Si and Al are implanted at doses of <1×10^{13} \text{cm}^{-2}, and subsequent annealing of the co-implanted GaAs is performed under capless or proximity cap conditions. A model considering gettering of the oxygen present in the bulk Czochralski-grown GaAs to the implanted Al is invoked to explain the observed activation enhancement.

Only a fraction of implanted n dopants is electrically active in GaAs even after the most optimized annealing. Co-implantation of n dopants which occupy Ga sites (e.g., Si) with a column V element (e.g., P) and those which occupy As sites with column III impurity (e.g., Ga) has been reported to enhance the dopant activation in GaAs. It was previously shown that Al co-implantation with n dopants followed by capless rapid thermal annealing (RTA) enhances the electrical activation of these dopants in GaAs. The maximum carrier enhancement due to Al co-implantation occurs at n-dopant doses typically used for n channels in GaAs metal-semiconductor field-effect-transistors (MESFETs) (i.e., <1×10^{13} \text{cm}^{-2}).

The effect of Al co-implantation (at 160 keV) on the Si activation and on Hall mobility in the Al dose range of 1.5×10^{11}-4.5×10^{13} \text{cm}^{-2} has been discussed earlier. The Si activation increases initially with the Al dose and the maximum carrier enhancement occurs at an Al dose of 4.5×10^{12} \text{cm}^{-2}. The Si activation and carrier mobility begin to deteriorate at higher Al doses. At an Al dose of 4.5×10^{13} \text{cm}^{-2} the Si was mostly deactivated, which is in agreement with the published data of Farley and Streetman.

In this letter the activation enhancement of implanted Si has been studied systematically as a function of Al$^+$ energy. Due to lack of space the electrical data from only those Al doses is included which resulted in the maximum carrier enhancement. It is shown that the position of the Al profile with respect to the implanted Si profile determines where the electrical activation enhancement occurs spatially in the Si implanted region. Control experiments with dual Al and O implant indicate that Al can strongly getter oxygen present in the implanted GaAs substrate. The role of oxygen gettering in electrical activation enhancement is further confirmed with a Mg co-implant since like Al, Mg also has a strong bond with O. A phenomenological model which explains the observed activation behavior is proposed.

Semi-insulating CZ grown LEC (100) GaAs wafers were either implanted with $^{29}$Si$^+$ only (30 keV, 6.0×10^{12} \text{cm}^{-2}) (control sample) or were dual implanted with Al$^+$ at energies of 30 (sample A), 160 (sample B), and 450 keV (sample C) with doses of 1.5, 4.5, and 10×10^{12} \text{cm}^{-2}, respectively.

The implanted wafers subsequently underwent RTA with either a Si-proximity cap or with a conventional plasma enhanced chemical vapor deposited (PECVD) Si$_3$N$_6$ cap. The Si-proximity RTA will be referred to as capless RTA from here on in the text. The electrical characterization of the annealed samples was performed by CV and Hall measurements. Atomic profiles of Si, Al, and O on a selected number of samples were obtained by secondary ion mass spectrometry (SIMS).

Figure 1 shows atomic profiles of Si and Al from samples B and C after capless RTA at 850 °C for 10 s (the as-implanted and annealed profiles of Al and Si were indistinguishable from each other).

Carrier concentration profiles (CV) of the control sample and those of samples C after capless RTA at 850 °C/10 s are shown in Fig. 2 [curves (i)-(iv)], respectively. In sample A where the Al and Si depth profile are spatially coincident the Si activation is enhanced primarily in the tail region [compare curves (i) and (ii)]. However, the Si activation remains practically unaffected in the peak region in sample A. When the Al profiles were deeper than...
should further enhance the dopant activation.

The effect of an oxygen gettering occurs due to its strong chemical affinity for Al. The oxygen migration towards the implanted Al is probably facilitated by the cumulative damage created by the dopant and Al implants. Since O is known to act as a deep double electron trap and the Mg+ implanted sample (1.5 × 10^12 cm^-2 at 160 keV) underwent capless RTA at 850 °C/10 s was submitted to a capless RTA at 850 °C/10 s prior to the Si implantation. After the Si+ implantation a second cap was used to improve SIMS sensitivity for oxygen detection. The effect of the Al is expected to be most pronounced at doses where the proportion of the background oxygen relative to implanted dose is significant, i.e., in the low dose regime ( < 1 × 10^13 cm^-2).
FIG. 4. Carrier concentration profiles (CV) from a sample implanted only with Si (control sample) and from a sample co-implanted with Mg ($1.5 \times 10^{12}$ cm$^{-2}$ at 160 keV) after capless RTA at 850°C for 10 s.

Profiles are deep the O is gettered away from the peak region of the Si profile, resulting in higher electrical activation there.

It is believed that the deterioration of the Si activation in the capped annealed samples is related to the H diffusion from the cap during the anneal. Perhaps the H from the cap decreases the O gettering efficiency of the Al due to Al—H interaction.

It is conceivable that point defects are also playing an important role in determining the Si activation in co-implanted samples. However, the observed activation enhancement can be directly correlated with the O movement.

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