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Gallium implantation induced deep levels in *n*-type 6H–SIC

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Two Ga-acceptor levels, located at $E_V+0.31$ eV and $E_V+0.37$ eV, respectively, have been observed in the gallium implantation manufactured p^+n diodes using deep level transient spectroscopy. The behavior of the implanted gallium is very similar to that of implanted aluminum, except that the positions of the introduced levels are different. This result strongly supports the recent model, which was used to explain the discrepant results between boron and aluminum implantation induced deep levels. Besides the two acceptor levels, a thermally stable electron trap is also observed and has been tentatively attributed to a Ga-related complex. © *1999 American Institute of Physics.* [S0021-8979(99)01201-3]

I. INTRODUCTION

Because the diffusion coefficients of most dopants in SiC are negligible at the temperatures lower than 1800 °C, the development of ion implantation for SiC for device technology is of great importance. The research that has so far been carried out on boron- and aluminum-implanted SiC, by means of secondary ion mass spectroscopy (SIMS) and deep level transient spectroscopy (DLTS), has revealed that the implantation-induced defects have different redistribution behavior during the post-annealing procedure.[1–3] For this reason, different DLTS spectra were observed in boron- and aluminum-implanted *n*-type 6H–SiC.[2,3]

Implantation of SiC with gallium has not been extensively used to form a *pn* junction diode because an earlier experiment indicated that a lower critical dose of 1.8×10^{14} cm^{-2} was required for recrystallization of the implanted layer.[4] The only experiment that has so far yielded the ionization energies of the gallium acceptor in SiC has been a photoluminescence (PL) work.[5] The purpose of the present study is to understand if gallium has the same electrical properties, such as the induced deep levels, as aluminum in SiC since both have a similar redistribution behavior[1,6] and to present more evidences which may support our recently proposed model explaining the results of DLTS measurement of the boron- and aluminum-implanted *n*-type 6H–SiC.[2,3]

II. EXPERIMENT

The SiC material used in this work was *n*-type 6H–SiC(0001) with an epilayer of 10 μm thickness obtained from CREE Research Inc. The nitrogen donor concentrations were 7×10^{15} and 5×10^{18} cm^{-3} in the epilayer and the substrate, respectively. Gallium implantation was carried out at 600 °C with energies of 480 and 960 keV so as to form a box implantation profile with a final mean dopant concentration of about 1×10^{19} cm^{-3}. This p^+n junction structure was confirmed by SIMS, and was found to be of similar form to that found for boron and aluminum profiles in our previous works.[2,3] After ion implantation, the sample was annealed at 1700 °C for 10 min in order to reduce the implantation damage and to electrically activate the Ga acceptors. Reactive ion etching was used to remove the low gallium concentration surface region and to reduce the leakage current through the edge of the samples for the DLTS measurement. Nickel and aluminum were deposited on *n*- and *p*-type sides, respectively, following a 950 °C metallization process to form Ohmic contacts. The quality of the diode sample was assessed by means of the capacitance–voltage and the current–voltage characteristics.

The DLTS system, which was used in this work, have been presented elsewhere.[7] The measurements were carried out by applying a reverse bias of $V_r=-6$ V with a forward filling pulse of $V_p=6$ V. Under this condition, only majority carriers (electrons in the *n*-type region and holes in the *p*-type region) were injected into the depletion regions during the filling time. Therefore, if there is any negative signal appearing in the DLTS spectra, it must originate from a minority carrier trap, which comes from the minority carrier tail region.[2]

III. RESULTS AND DISCUSSION

In Fig. 1, typical DLTS spectra of this work are presented, in which the plot A is the Ga-implanted sample and the plot B is the unimplanted control sample. It is clearly seen that two minority and one majority carrier traps (deep levels) have been observed in the Ga-implanted sample, while there is no sign of deep level in the control sample. The three deep levels are labelled as G_k, G_h, and I_G, respectively. The positions of G_k and G_h in the band gap were $E_V+0.37$ eV and $E_V+0.31$ eV as determined by the Arrhenius analysis shown in Fig. 2. As the signal of the majority trap I_G is relatively weak and partially overlaps the signal

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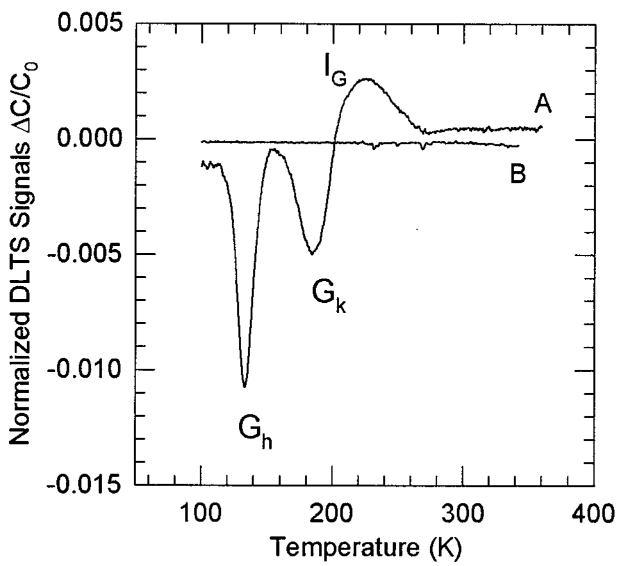

FIG. 1. Typical DLTS spectra without minority carrier (hole) injection for (A) 600 °C Ga-implanted, and (B) unimplaned *n*-type 6H–SiC, with a window rate of 6.82 ms.

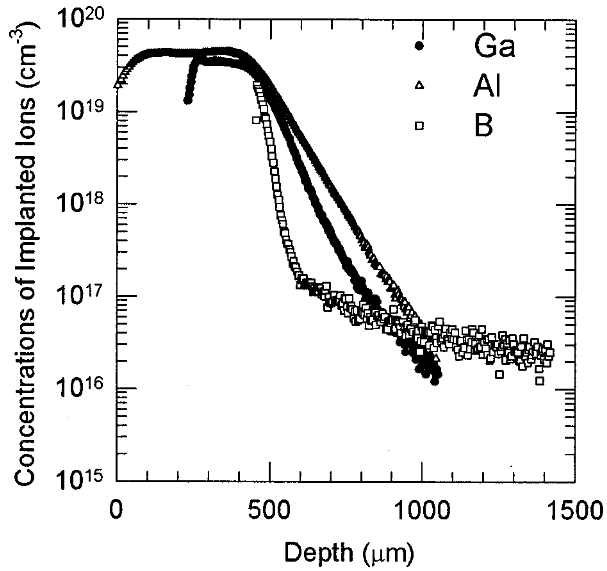

FIG. 3. Concentration depth profiles of the implanted Ga, Al, and B atoms from SIMS.

G_k, especially when the window rate is decreased, it is difficult to give a reliable value of the position of this level. Because of the same reason, the value of G_k: $E_V+0.37$ eV may have a larger error.

The positions of the observed deep level signals are different from those in B- and Al-implanted *n*-6H–SiC samples,[2,3] giving reason to believe that all the three deep levels have some connection to the implanted gallium atom. To the best of our knowledge, there has not been any report of Ga-related level measured by an electrical method. The only report is a result of PL, which has shown two Ga-acceptor levels, situated at $E_V+0.333$ eV and $E_V+0.317$ eV, that are probably connected with atoms occupying *k* (cubic) and *h* (hexagonal) lattice sites, respectively.[5] Compared to the PL result, the deep levels of $E_V+0.37$ eV and $E_V+0.31$ eV in this work, can be considered as the same defects. Namely, the $E_V+0.37$ eV level corresponds to the *k*-site gallium atom and $E_V+0.31$ eV to the *h*-site one. Since the concentration of the *k*-site Ga is larger than that of the *h*-site one, the subscript of G_k and G_h defined earlier may need to be exchanged. It has to be pointed out that the positions of the two acceptors in the spectrum are neither as close as those of *k*- and *h*-site aluminum measured by DLTS[3] nor those of *k*- and *h*-site boron by the admittance spectroscopy.[8] The possible reasons for this are still unclear.

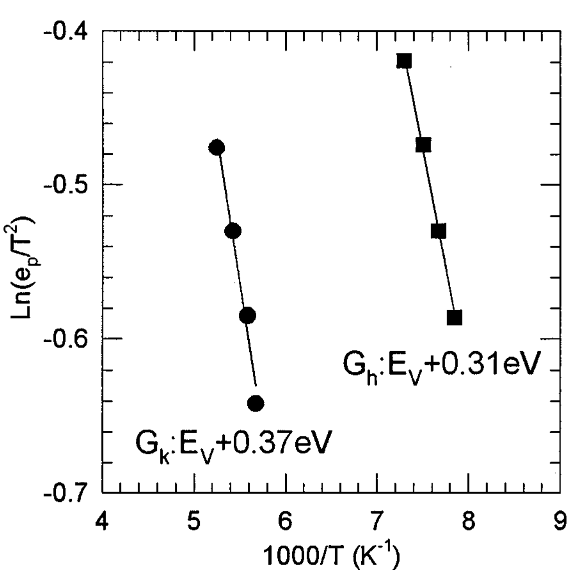

FIG. 2. Arrhenius plots of hole emission rates as a function of 1000/T, for deep levels corresponding to minority carrier peaks, G_k and G_h.

Figure 3 presents the concentration distributions of boron, aluminum, and gallium atoms measured by SIMS after post-annealing at 1700 °C for 10 min. Since the projection ranges of the implantations and the etched thickness of these samples are different, we have, for purposes of comparison, chosen the positions of the far knee of the plateau region as the reference point and have shifted the profiles so as to make this point coincident as shown in Fig. 3. The resulting comparison shows clearly that the implanted aluminum and gallium atoms have a similar shape of profile, while a deeply extended tail is seen for the case of boron. After the whole implantation procedures, p^+ layers were formed. The position of the p^+n junction occurs where the concentration of electrically active atoms of the implanted elements is equal to that of donor in the substrate. The end region of the implantation layer thus extends into the *n*-type side of the diode sample, causing the deep-level defects in this region to be observed as either positive (electron-trap) or negative (hole-trap) signals, as described in our previous work.[2]

Comparing the DLTS spectra with the SIMS results of the samples implanted with various elements, an interesting correlation is noted. Namely, if the samples have similar implantation profiles as in aluminum and gallium then the respective DLTS spectra are similar, but if the profile looks different as in the case of boron then the corresponding DLTS spectrum is expected to be different. For the B-implanted samples, the end region of the redistributed boron profile is a deeply extended tail, caused by damage-enhanced in-diffusion, so that the dominant defect in this region is the boron-vacancy pair (D center).[2] On the other hand, no enhanced in-diffusion of either aluminum or gallium atoms has been observed after implantation procedures. As a result, instead of D-center-like defect, two shallow Ga-acceptor levels in this work (Al-acceptor levels in previous work[3]) appear in the DLTS spectrum. This indicates that there is no obvious interaction between the Si-site impurity and the adjacent C-site vacancy, which is the structure of the D center ($B_{\mathrm{Si}}-V_{\mathrm{C}}$),[9] during post-annealing so that the gallium or aluminum atoms mainly exist at substitutional lattice sites as shallow acceptors and there is no enhanced in-diffusion. Therefore, the DLTS spectrum of the Ga-implanted sample is similar to that of Al-implanted one, except that the positions of the deep levels differ.[3]

Besides the two Ga acceptors, an electron trap (the positive signal) I_G was observed as shown in Fig. 1. This deep level center is an implantation induced defect since it does not appear in the control sample. It can be seen that a deep electron trap I_d (induced donor trap), situated at $E_C - 0.44$ eV, was also observed in the Al-implanted n-type 6H–SiC.[3] In that work, we pointed out that the deep level I_d was possibly a non-Al-related defect since the distributions of the defects in the Al-implanted layer were different from those in B-implanted layer. Generally, if I_d were a primary radiation damage defect, one would expect the same DLTS peak to appear in the spectrum of Ga-implanted samples. However, the peak positions of these two deep levels (I_d and I_G) in the DLTS spectra are quite different, with the peak I_G occurring at ~230 K while that of I_d at ~165 K with the same window rate. It is thus believed that I_G and I_d are indeed ion-related defects—being some kind of complex of implantation damage with either Ga or Al atom. Just like the defect I_d,[3] I_G is also thermally stable and can even withstand an annealing of 1700 °C.

IV. CONCLUSION

In conclusion, two gallium-acceptor levels have been observed in the Ga-implanted p^+n junction sample using deep level transient spectroscopy. As far as we know, this is the first time these acceptor levels have been seen by an electrical method. The energy levels in the band gap are $E_V + 0.31$ eV and $E_V + 0.37$ eV, respectively, which agree with the PL result that shows the same levels. In addition, an implantation induced electron trap exists even after a 1700 °C annealing. A remarkable similarity of both the SIMS profiles of the implanted atoms and the DLTS spectra (with one positive and two negative signals) has been observed between the gallium- and aluminum-implanted samples. This result strongly supports the suggestion that various crystal damages occur with different spatial redistributions.

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