ALUMINUM AND ELECTRON-IRRADIATION INDUCED DEEP-LEVELS IN N-TYPE AND P-TYPE 6H-SIC

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ABSTRACT

Two deep levels, located at E_V+0.26eV and E_C-0.44eV, in Al-implanted n-type samples and one at E_V+0.48eV in p-type samples have been observed by the deep level transient spectroscopy. The level of E_V+0.26eV is identified as the shallower aluminum-acceptor. The 1.7 MeV electron-irradiation, used as a probe to distinguish the implantation induced deep-levels, induces at least six electron traps in the n-SiC and one hole-trap in the p-type material. The peak positions of these deep-levels in DLTS spectra are quite different from those induced by Al-implantation. This result suggests that various damages are formed after heavy ion (Al) and light particle (e^-) irradiation.

INTRODUCTION

Ion-implantation is one of the established methods to produce buried doping profiles in SiC substrates. However, it is always associated with the creation of unwanted radiation damage even after a high temperature (1700°C) annealing.[1-4] Secondary Ion Mass Spectroscopy (SIMS) studies have revealed a significant in-diffusion of boron atoms during post implantation annealing while only out-diffusion of aluminum atoms have been observed.[1-4] In the case of boron-implantation, a long boron-tail that extends into the n-type substrate epilayer has a high concentration of about $\sim 10^{17}cm^{-3}$ and is attributed to an enhanced in-diffusion mechanism.[1,3] Our previous work has revealed that the boron tail , with a total concentration larger than that of donor in the substrate, overlaps the depletion region of the pn junction formed by boron-implantation and is D-center dominant.[4] The existence of a high concentration defect region overlapping the depletion layer is probably harmful for devices.

In this work, Al-implantation induced defects in n- and p-type 6H-SiC are studied, because aluminum doping not only is one of the most important acceptor dopant but also has a quite different distribution from that of boron. The deep level transient spectroscopy (DLTS) experimental results of electron-irradiation introduced deep centers also are also presented in this work for helping us to distinguish whether the defects are ion-related or not. The detailed properties of the defects induced by electron irradiation is being reported in another publication.[5]

EXPERIMENTS AND RESULTS

The SiC material used in the experiment was obtained from Cree Research Inc. The wafers were n- and p-type 6H-SiC(0001) with a chemical vapor deposition grown epilayer of

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10μm thickness. The donor concentration in n-type epilayer is 7×10^{15} cm^{-3} which was grown on 5×10^{18} cm^{-3} nitrogen doped substrate and the Al acceptor concentrations in the p-type epilayer and substrate are 1.1×10^{16} and 4.5×10^{18} cm^{-3} respectively. Aluminum implantations were carried out with various energies so as to form a box implantation profile. A set of such implantations was performed at different substrate temperatures from 20°C to 1200°C. The final mean concentration of the dopant was 7×10^{19} cm^{-3} as obtained by TRIM code simulation and confirmed by SIMS. After Al-Multiple energy implantations of Al-ions were carried out to form a buried rectangular doping profile. Samples were maintained at different temperatures from room temperature to 1200°C during ion implantation. After ion implantation, all samples were annealed at 1700°C for 10 minutes in order to remove the radiation damage induced by the implantation, and to electrically activate the aluminum acceptors. Reactive ion etching was used to bring the Al-implanted region to the surface and to reduce the leakage current through the edge of the samples.

Nickel layer was evaporated onto the n-side and aluminum on the p-side surfaces the samples including Al-implanted p^+n, p^+p and un-implanted n- and p-type control wafers. This was followed by annealing at 950°C in order to make Ohmic contacts to both p and n-type sides. Au- SiC(p) Schottky contacts were made on the Al-implanted p-type and un-implanted materials for electron irradiation. 1.7 MeV electron irradiation was carried out with a final dose of 1.1×10^{15} e/cm^2.

The DLTS experimental results of the Al-implanted n-6H-SiC are presented in Fig. 1. Two strong deep level peaks (labelled as A_k and I_D respectively) can be clearly seen within the temperature range from 80K to 400K. One is due to majority carrier (electron) trapping and the other is due to minority trapping (hole). All the samples, with different substrate temperature (T_S) during implantation, have the same DLTS spectra except the amplitude of the signals. On the other hand in the Al-implanted p-type materials, only one deep-level (labelled as A_{IH}) was observed in the samples with a lower substrate temperature <400°C as shown in figure 2.

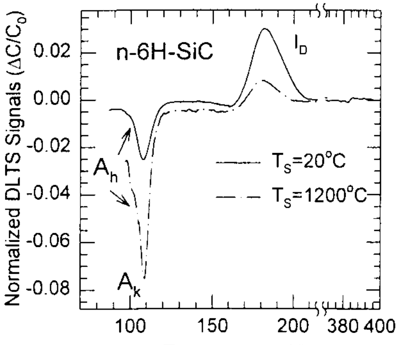

Fig. 1. Typical normalized DLTS spectra of 20°C and 1200°C Al-implanted n-type 6H-SiC p^+n samples.

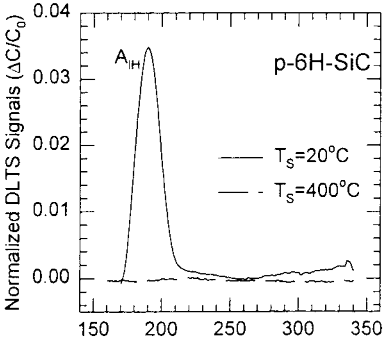

Fig. 2. Typical normalized DLTS spectra of 20°C and 400°C Al-implanted p-type 6H-SiC Schottky diode samples.

No DLTS signal was observed in un-implanted n- and p-type materials. However, at least six deep levels in n-type and one in p-type SiC appeared in the DLTS spectra, which are labelled as E_1, E_2, ... E_6 and E_H, respectively, as shown in figure 3. The positions of the above deep levels in the band-gap are determined by the Arrhenius plots as shown in Fig.4 and in Table I.

DISCUSSIONS

It is noticed that neither of these peaks appears in the B-implanted n-type 6H-SiC samples.[4] The negative signal, which is labelled as A_k in figure 1, appears without the condition of minority carrier (hole) injection very much like the D-center in boron-implanted SiC.[4] These indicate that this signal is from the free hole tail region of the n-side depletion layer, and the defect has a higher concentration compared to that of the shallow donor in that region. The result also implies an Al-related involvement for this defect since it exists only and always in Al-implanted samples. It is possible that the Al-related defects are in the n-side of the p^+n structure because a small Al-doping tail extends into the n-side. The position of this level, located at E_V+0.26eV, being so close to the Al-acceptor level at 0.23~0.28eV above the valence band measured by photoluminescence (PL),[6] in p-type SiC, strongly suggests that it is a shallow Al-acceptor. In particular, there is always a small shoulder (A_h) on the low-temperature side of the A_k peak in all the DLTS spectra as shown in Fig.1. This phenomenon probably supports the observation of PL,[6] namely, the Al-atoms occupy both h (hexagonal) and k (cubic) lattice sites. According to Ikeda's results,[6] the aluminum atom with a shallower level is at the h-site and the deeper level one is at the k-site. The amplitude of A_k, in our work, is larger than that of A_h, which also agrees with the result of photoluminescence[6].

As previously mentioned our samples showed an Al-implantation induced deep level donor signal at E_C-0.44eV, which we label as I_D (induced electron trap). The observation of this single level is to be compared with the work of Troffer et al.[3] who find at least six different

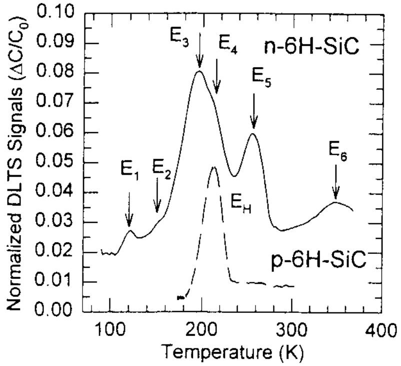

Fig. 3. Typical normalized DLTS spectra of e^-irradiated n-type and p-type 6H-SiC Schottky diade samples.

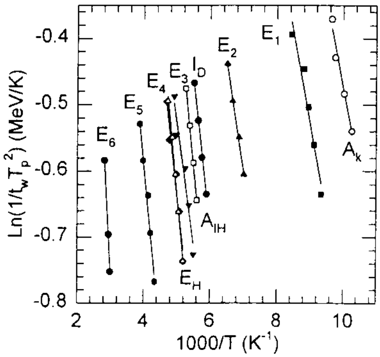

Fig. 4. Arrhenius plots of electron and hole emission rates ($e_{n,h}$) as a function of 1000/T, for deep levels corresponding to electron-traps (solid symbols) and hole -traps (closed).

Table I. Deep-levels induced by Al and electron-irradiation in this work

Sample	Deep-level	Sample	Deep-level
Al-implanted n-6H-SiC	A_k: E_V+0.261eV I_D: E_C-0.442eV	1.7MeV e^--irradiated n-6H-SiC	E_1: E_C-0.271eV E_2: E_C-0319eV
Al-implanted p-6H-SiC	A_{IH}: E_V+0.485eV		E_3: E_C-0.358eV E_4: E_C-0.439eV
1.7MeV e^--irradiated p-6H-SiC	E_H: E_V+0.525eV		E_5: E_C-0.502eV E_6: E_C-0.938eV

Al-induced deep levels (labelled ID_3, ID_4, ID_8 ID_9 RD_1 and RD_2 in fig. 7 ref. 3) in both 4H and 6H-SiC, using DLTS. It is not clear whether the I_D level we see corresponds to one of the levels seen by Troffer et al. Their ID_9 peak has a very similar energy. Irrespective of whether this is so or not, in comparing the spectra of Troffer with ours, one may arrive at an important conclusion, namely, that various damages with different distributions have been introduced during implantation. Specifically, it seems that I_D is abundant in the deeper tail region beyond the implantation and is relatively dilute near the surface. In the work of ref. 3, a Schottky contacted sample was employed thus yielding information only on defect centers within the near surface implantation region.[3] This phenomenon is similar to that observed by us for boron-implanted n-6H-SiC, where none of the implantation induced donor levels were found in the post-implantation range.[4] The presence of a different spectrum of induced defects close to the surface and deeper into the implantation range is most likely to be a consequence of the various selective properties of surface defect gettering and damage enhanced diffusion.

Unlike the Al-implanted n-type materials, only one implantation induced hole trap (A_{IH}: E_V+0.48eV) was observed in the p-type 6H-SiC samples, whose implantation procedures were carried out at a substrate temperature of lower than 400°C as shown in Fig. 2. Compared with the spectrum of 20°C Al-implanted sample in figure 1, a weak down-going signal, which appears near 190K as A_{IH} does, can be found but not in 1200°C Al-implanted one's. This phenomenon is similar to the induced deep hole-trap (at E_V+0.46eV) in B-implanted SiC, which appeared only in the lower temperature implantation samples and was labelled as I_h in our previous work.[4] However, they are not the same defect because of the different capture cross sections. It is interesting to note that both of these two defects were formed only in the low-temperature implantation procedures but they can withstand a very high temperature (1700°C) annealing. A possible structure of the defects is a complex of the implanted ion (B or Al) and an originally existing defect (or impurity) "X". Some characteristics of this original defect are that it can dissolve during the hot –implantation while the new complex Al-X (or B-X at a different energy position) has a very stable structure once it was formed and that it is non-active for DLTS measurement.

Electron-irradiation introduces a large defect family, at least six deep level defects in n-type SiC and one in p-type as shown in Fig. 3. As the positions of these deep levels are quite different from those induced by Al-implantation, one can understand that the deep levels I_D and A_{IH} in this work are indeed not simple vacancy or divacancy. It can be noticed that these defects did not appear in the boron implanted n-type[4] and p-type SiC[2,3]. It means that they are aluminum-related.

CONCLUSIONS

Aluminum and electron irradiation induced deep level defects have been studied using deep level transient spectroscopy. The shallow aluminum acceptors A_k and A_h, which occupy the cubic (k) and hexagonal (h) lattice sites respectively, have been identified. In addition to the shallow acceptors, there are two implantation-induced deep level damages one in n-type material and one in p-type, both of which are thermally stable. As the defect A_{IH} can only be formed in the low-temperature implantation procedure, it should have a different structure from that of the defect I_D in n-SiC. The 1.7 MeV electron-irradiation induces at least six electron traps in n-SiC and one hole-trap in p-type one. These various deep-levels in DLTS spectra present a large defect family. In order to reveal the properties of these defects, further work is needed.

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