Deep level traps in the extended tail region of boron-implanted *n*-type 6H–SiC

M. Gong,[a] C. V. Reddy, C. D. Beling, and S. Fung
Department of Physics, The University of Hong Kong, Hong Kong

G. Brauer, H. Wirth, and W. Skorupa
Institut fur Ionenstrahlphysik und Materialforschung, Forschungszentrum Rossendorf, Postfach 510119, D-01314 Dresden, Germany

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Deep traps in the boron extended tail region of ion implanted 6H–SiC *pn* junctions formed during annealing have been studied using deep level transient spectroscopy. Dramatically high concentrations of $\sim 10^{16}$ cm^{-3} of the *D* center have been observed through the unusual appearance of minority peaks in the majority carrier spectra. No evidence is found for any shallow boron acceptor in this region, but an induced hole trap I_h at $E_V + 0.46$ eV is found under cold implantation conditions. These results support the picture of the extended tail, rich in boron-vacancy complexes such as the *D* center, which forms as a result of vacancy enhanced indiffusion. The dominance of the electrically active *D* center in the depletion layer of the technologically important SiC *pn* junction diode suggests the need for further research in this area. © *1998 American Institute of Physics.* [S0003-6951(98)04021-2]

Boron implantation is one of the established methods to produce buried p^+ doping profiles in SiC substrates, but it is always associated with the creation of unwanted radiation damage. In order to remove the radiation damage induced by the implantation, and to electrically activate the boron acceptor, samples are usually annealed at high temperature. A number of studies have recently been reported on the defects produced in as ion-implanted and annealed SiC.[1–8] In particular, secondary ion mass spectroscopy (SIMS) studies have revealed a significant in-diffusion of boron atoms during postimplantation annealing[5,6] while for Al implanted SiC only out-diffusion has been observed.[5,8] In the case of boron, the long 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.[5,8] As this tail has a concentration equivalent to that of the donor in the substrate and overlaps the *n*-side depletion layer of the *pn* junction formed by the implantation, knowledge about boron compensation and deep levels in this region becomes very important for device design and manufacture. The main aim of the present work was to study the residual deep level defects in the diffusion tail region of the boron-implanted *pn* junction using deep level transient spectroscopy (DLTS).

The SiC material used in the experiment was obtained from CREE Research Inc. The wafers were *n*-type 6H–SiC(0001) having a basic nitrogen dopant concentration of 1×10^{18} cm^{-3} with a chemical vapor deposition (CVD) grown epilayer of 10 μm thickness and a 1.3×10^{16} cm^{-3} nitrogen dopant concentration. Multiple energy implantations (160, 115, and 80 keV at doses 5.7×10^{14}, 3.6×10^{14}, and 3.0×10^{14} cm^{-2}, respectively) of boron ions were carried out to form a buried rectangular doping profile in the length range 200–400 nm. Four samples were implanted at different substrate temperatures of 20, 200, 400, and 600 °C, respectively. After ion implantation, all samples were annealed at 1700 °C for 10 min in order to remove the radiation damage induced by the implantation, and to electrically activate the boron acceptor. This was followed by a reactive ion etching to bring the boron-implanted region to the surface. A typical SIMS profile showing the concentration of boron as a function of the depth is given in Fig. 1. A long boron tail due to the in-diffusion during the annealing is observed, which is similar to that observed by Rao *et al.*[5] and Pensl *et al.*[6]

A 200 nm nickel layer was evaporated onto the rough *n* side and aluminum on the implanted front surface (*p* side) of the wafers in a vacuum of 1×10^{-6} Pa. This was followed by annealing at 950 °C for 3 min in an argon gas atmosphere in order to make ohmic contacts to both *p*- and *n*-type re-

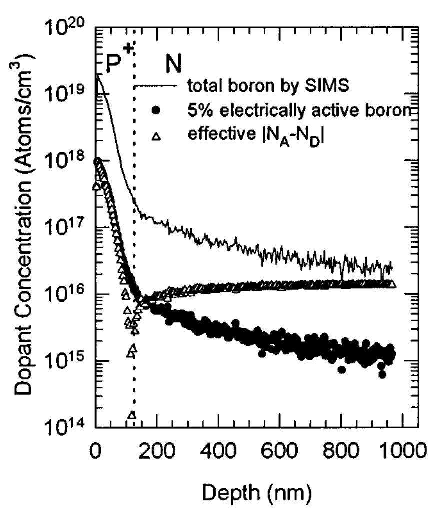

FIG. 1. Dopant concentration depth profile for 400 °C B-implanted *n*-type 6H–SiC *pn* diode after 1700 °C 10 min annealing.

[a]Electronic mail: mgong@hkusub.hku.hk

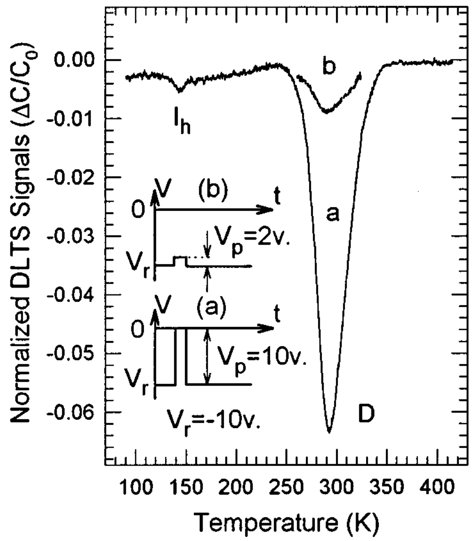

FIG. 2. Normalized DLTS spectra under various forward filling pulse heights V_p for 400 °C B-implanted n-type 6H–SiC.

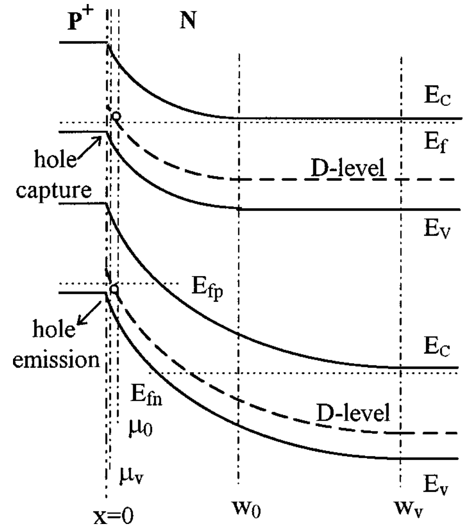

FIG. 3. Band diagram showing hole emission and capture region on the n-side half of a pn diode under zero and reverse bias conditions.

gions. Current–voltage ($I-V$) characteristics revealed a pn junction diode that switched on at a forward bias of ~2 V with a reverse leakage current at 10 V reverse bias of less than 0.5 μA. At 77 K, the rectifying nature of the pn diodes still prevailed with a similar switch on bias. However, carrier freeze-out in the p-type layer, as seen in Hall effect measurements,[8] caused a high series resistance in the boron layer and a less than ideal forward characteristic which reached only 2 mA at 10 V. The capacitance–voltage ($C-V$) characterization gave an average donor concentration N_D in the depletion layer of 1.5×10^{16} cm^{-3}, which agreed well with the manufacturer's value. This confirmed that good p^+n junction structures were indeed being formed. Using a 5% electrical yield of implanted boron,[1] an approximate profile of effective electrical dopant concentration (N_A-N_D) can be obtained. This is shown with triangular symbols in Fig. 1, together with the delimitation of p^+ and n regions at a depth of ~100 nm. From Fig. 1, it is clearly seen that the depletion region, which extends at least 450 nm into the n region, as calculated from the known band gap and dopant concentration, must overlap the boron tail where the concentration is at least 10^{16} cm^{-3}.

A typical normalized DLTS spectrum of the 400 °C B-implanted sample is shown in Fig. 2(a). It is of interest to note that this spectrum corresponds to a trap filling pulse of zero bias ($|V_p|=|V_r|$), under which conditions no majority carrier (electron) traps are observed in any of the four samples. Such traps, if present, would be expected to yield positive going DLTS signal peaks. Instead, two minority (hole) carrier traps, labeled "D" and "I_h" (induced hole trap), were observed as negative going peaks in the samples. The intensity of the D level remained nearly constant in all the samples, while the peak height of I_h was reduced with increasing substrate temperature T_s and disappeared in the 600 °C sample. The activation energies of the traps are found to be $E_V+0.65$ and $E_V+0.46$ eV for D and I_h, respectively, with the capture cross section of the D trap being about 5×10^{-14} cm^2. To check that the D and I_h levels were introduced by implantation, we carried out a control test on a Au-Schottky contacted unimplanted n-epilayer, but these levels were not observed.

The anomalous appearance of a reversed signal in a majority DLTS spectrum without minority carrier injection has been well explained by Meijer *et al.*[9] Such peaks are unexpected in that if hole emission occurred from D and I_h centers in the p-type region, then the increased negative ionized acceptor charge in this region would lead to a positive going DLTS signal. The negative going peaks are caused by minority carrier capture and emission within the minority free carrier tail as it extends into and recedes out of the majority carrier region.[9] The emission from the n-type region can be explained with reference to the energy band diagram shown in Fig. 3, which shows an abrupt p^+n junction at $x=0$. This type of band bending is expected for our system at all temperatures, seeing that the negative and positive ionizations of the boron layer ($x<0$) and nitrogen doped layers ($x>0$) result from the charge transfer on Fermi-level adjustment. That this is so is confirmed by the continued rectifying nature of the $I-V$ characteristics down to 77 K. It can be seen from Fig. 3 that the hole Fermi energy E_{fp} intersects the hole trap energy at a position μ_v closer to the junction under reverse bias than the respective position under zero μ_0. The holes trapped in the region $\mu_0-\mu_v$ are emitted under reverse bias, decreasing the net positive charge in this region and giving rise to a decreasing capacitance transient which results in a negative minority DLTS peak.

The observed energy position and capture cross section of the D level agree well with the reported values of the well known D center,[1,10,11] which has been observed in B-implanted or B-doped CVD grown SiC. Indeed, electron paramagnetic resonance (EPR) measurements associate the D center with a boron-vacancy complex.[12] This is consistent with the fact that both the D level in our samples and the D center as seen by others[1,10,11] exist in the boron-rich region and are thermally stable. All these features lead us to believe that the deep level $E_V+0.65$ eV is the D center. The other deep hole trap observed in the experiment is I_h. Although only formed in the low substrate temperature B-implanted samples, this defect is also thermally stable once formed. At this stage, without additional information available, we cannot be sure whether or not it is boron related. We can, however, be sure that this defect is not the shallow substitutional boron level as seen by Suttrop *et al.*[1] at $E_V+0.3$ eV, because not only is the energy markedly different but this defect forms only at low temperature.

According to Fig. 3, minority trap peaks could always be found in a majority spectrum because a free-carrier tail always exists. In normal cases, however, a minority signal scarcely appears unless either the minority carriers are purposely injected $|V_p|>|V_r|$ or the filling pulse height approaches the flatband voltage $|V_p|\approx|V_r|$.[13] In our experiment, minority signals were dramatically high, for example, $(\Delta C/C_0)_{D\ \mathrm{level}}=0.064$, and were even detected under the measurement condition of $V_p=2$ V and $V_r=-10$ V (see Figs. 2(a) and 2(b). It is well known that the normalized DLTS peak height is given by[14]

$$\frac{\Delta C}{C_0}=\frac{N_T}{2N_D}, \tag{1}$$

with a measurement condition of $|V_p|=|V_r|$ and an assumption that all the deep traps in the depletion region width (w_v)take part in the transient process. This holds approximately correct for a majority trap (with an even distribution). From Fig. 3, however, it is clear that only hole traps in the region of $(\mu_0-\mu_v)$ make a contribution to the minority trap capacitance transient. Thus, Eq. (1) should be modified according to

$$\frac{\Delta C}{C_0}\approx\frac{N_T}{2N_D}\,\frac{\mu_0-\mu_v}{w_v}, \tag{2}$$

where, μ_0 and μ_v, are defined as the edges of the minority carrier (hole) tail under zero and reverse bias V, respectively. As $(\mu_0-\mu_v)$ is relatively small, a large concentration of N_T is needed to make an observable minority trap signal. In the general case, we have $N_T <$ or $\ll N_D$, so that the peak is very weak and minority carriers should be injected to strengthen the signal,[9,13] in which case the term $(\mu_0-\mu_v)$is replaced with the hole (minority carrier) diffusion length.

In our experiment, the amplitude of the minority D-center peak $(\Delta C/C_0)$ is as high as 0.064, which is greater than the height of the same minority peak $(\Delta C/C_0=0.056)$ seen by Saddow *et al.*[11] with an epitaxially grown junction. It is significant that their measurement differed from ours in that a 5.5 mA minority carrier injection was required to enhance the D-center signal. The strong signal seen under our essentially zero injection condition indicates that the concentration of the D level at $E_V+0.65$ eV is much larger in the region of $(\mu_0-\mu_v)$ close to the junction as compared to the epitaxial case. As the width of minority free carrier tail is strongly dependent on the position of the quasi-Fermi level E_{fp} and the deep level concerned, and the energy band bending as well,[9] it is difficult to calculate an accurate value of the D-center concentration. The small width of the hole emission region compared to the depletion layer width would, however, suggest a D-center concentration of at least $\sim 10^{16}\ \mathrm{cm}^{-3}$. It is of interest to note that the observation of peak I_h suggests that the defect responsible for this level is also present in some abundance close to low temperature implantation formed junctions.

While both boron atoms and D centers are observed in the *pn* junction region, no evidence for the shallow boron acceptor is found. The B level, considered as the shallow acceptor, was reported by Suttrop *et al.*[1] In their B-implanted p-type 6H–SiC Schottky contacted samples, the concentrations of the B-acceptor and D center were almost the same. This means that the proportion of the shallow boron (substitutional acceptor) to the deep boron (D center) in the implantation region (which would be the dominant source of signal in Ref. 1) is quite different from that found in the extended tail region of our samples, where the D center dominates.

Recent research has shown that the extended tail is formed as a result of damage-enhanced in-diffusion.[5,6,8] It has been pointed out, in the earlier work on boron diffusion in SiC,[15] that the acceptor-defect complex plays a decisive role and the most mobile boron-associated complex is the boron-vacancy pair. This implies that the presence of implantation induced vacancies causes the boron atoms to diffuse rapidly. That vacancies should be present behind the implantation region is not something predicted by TRIM calculations, but is nevertheless experimentally observed using positron annihilation spectroscopy, divacancies at ppm concentrations having been observed by Brauer *et al.*[7] This vacancy enhanced B diffusivity model affords a natural explanation of why it is more favorable for a boron atom to form a D center or other boron-vacancy complexes rather than an isolated substitutional boron acceptor.

In conclusion, our experiment demonstrates that the boron diffusion tail overlaps the depletion layer in an annealed implanted p^+n junction and this tail appears rich in the D center, thus strengthening the assignment of this center of a boron-vacancy complex. Since the D center may play an important role from the viewpoint of device engineering, the present study indicates that further studies on the properties of defects in the diffusion tail region will be necessary.

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