# Beryllium implantation induced deep level defects in *p*-type 6H–silicon carbide

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Beryllium implantation into *p*-type 6H–SiC and subsequent thermal annealing have been performed. The deep level defects induced by this beryllium-implantation process have been investigated using deep level transient spectroscopy. Four deep levels labeled BEP1, BEP2, BEP3, and BEP4 were detected in the temperature range 100–500 K. The prominent hole trap BEP1 with an energy level at $E_V+0.41$ eV agrees well with the acceptor level of beryllium determined by Hall effect measurements. The remaining hole traps with energy levels at $E_V+0.60$ eV, $E_V+0.76$ eV, and $E_V+0.88$ eV, respectively, are proposed to be beryllium-implantation induced defects or complexes. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1542687]

Silicon carbide (SiC) is a promising material for high-frequency, high-temperature, and high power electronic devices.[1,2] Being a relatively light group IIA element, beryllium (Be) is expected to induce less damage during implantation as compared to aluminum (Al) or boron (B). Furthermore, Be can be implanted to greater depths and could be useful for fabricating thick *p*-type layers in SiC. Recently, SiC diodes were made from Be implantation and a better forward characteristics was obtained in comparison with those produced by Al and B implantation.[3] Be is a doubly charged acceptor in SiC and, from Hall measurements, the acceptor levels were determined to be $E_V+0.42$ eV and $E_V+0.60$ eV in 6H–SiC.[4] On the other hand, Be in *p*-type SiC also acts as a donor when residing on an interstitial lattice site thus becoming a compensation center.[5]

Deep level transient spectroscopy (DLTS) has been employed to study the Be-implantation induced deep level defects in SiC materials.[6–9] Our previous DLTS study of Be-implanted *n*-type 6H–SiC revealed five Be-implantation induced deep levels, namely BE1–BE5 at $E_C-0.34$ eV, $E_C-0.44$ eV, $E_C-0.53$ eV, $E_V+0.64$ eV, and $E_V+0.73$ eV, respectively.[6,7] Recently, two deep acceptor states $Be_1$ at $E_V+0.535$ eV and $Be_2$ at $E_V+0.925$ eV were observed on Be-implanted *p*-type 4H–SiC by using the DLTS technique.[8] Further, DLTS study taken on *p*-type 4H–SiC implanted with radioisotope $^7$Be revealed two dominant hole traps labeled A at $E_V+0.735$ eV and B at $E_V+1.065$ eV, respectively. The deep level B was shown to be related to one Be atom or a defect complex containing one Be atom.[9]

In this work, we have investigated the deep levels in Be-implanted *p*-type 6H–SiC using DLTS.[4] The *p*-type 6H-SiC samples used in the present study were 5-$\mu$m-thick Al-doped (0001) oriented epilayers grown on $p^+$–type 6H–SiC substrate purchased from CREE Research Inc. The Al acceptor concentrations were $\sim 1\times10^{16}\,\mathrm{cm}^{-3}$ and $\sim 1\times10^{18}\,\mathrm{cm}^{-3}$ in the epilayer and the substrate, respectively. At room temperature and also at 500 °C, 50–470 keV Be was implanted to form a box-shaped profile with Be concentration of about $1\times10^{18}\,\mathrm{cm}^{-3}$. Using a rapid thermal annealing system, samples were annealed in flowing argon at 1600 °C for 30 s in order to repair the implantation induced damage and electrically activate the dopant. These samples were then immersed in 10% hydrofluoric acid solution to remove the oxide layer, and then rinsed in boiling acetone, ethanol, and deionized water. Large area ohmic contacts were fabricated by Al deposition on the back side of the samples followed by 5 min 900 °C annealing in flowing nitrogen gas. Schottky barrier diodes (SBD's) were prepared by depositing gold dots of 0.6 mm diameter onto the Be-implanted side of the samples.

With the DLTS system described in Ref. 10, measurements were carried out by applying a reverse bias of $V_r=-6$ V to the SBD and using a 1 ms forward filling pulse of $V_p=6$ V. The energy levels and the capture-cross sections of the defects were determined from the Arrhenius plots of the thermal emission rates, whereas the trap concentrations were obtained from the peak heights of the DLTS signal using the procedure described in Ref. 11.

The DLTS spectra taken for the 1600 °C annealed Be room-temperature implanted *p*-type sample are shown in Fig. 1 for two rate window settings (6.82 ms and 54.56 ms). Four peaks from majority carrier (hole) traps BEP1, BEP2, BEP3, and BEP4 respectively, were observed in the 6.82 ms rate window spectrum between 100 and 500 K. DLTS measurements of a SBD contacted on unimplanted Al-doped *p*-type 6H–SiC as control sample were also performed. The spectrum is also shown in Fig. 1 (dotted line) and none of the traps (BEP1–BEP4) is present in this unimplanted sample

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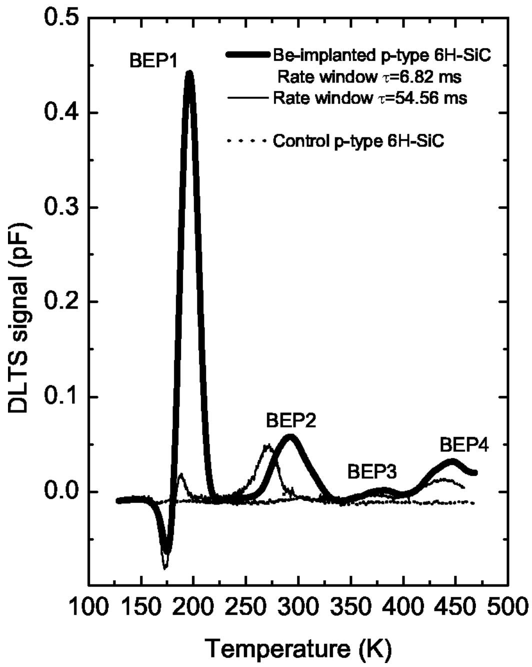


FIG. 1. DLTS spectra taken for the Be-implanted *p*-type 6H–SiC and unimplanted control sample which has been annealed at 1600 °C for 30 s. The measurements were performed with different rate windows $\tau = 6.82$ ms and 54.56 ms, respectively.

indicating that these traps are indeed induced by Be implantation. The parameters of the above deep level defects were derived by the Arrhenius evaluation technique assuming a temperature independent capture-cross section. Energy levels $E_T$, capture-cross section $\sigma_p$, and concentrations $N_T$ of the defects determined as stated earlier are summarized in Table I.

It may be noted from Fig. 1 that using the longer rate window (54.56 ms), the BEP1 peak is both reduced in size and shifted to lower temperature. However, during the experiment, it was noted that the capacitance of the SBD junction decreased by about 90% in the range 200 to 160 K. This dramatic decrease of SBD capacitance is due to the freeze out of carriers into the ‘‘shallow’’ Al acceptors (which are located around 0.21–0.23 eV above the valence band).[12] To demonstrate the carrier freeze out of the present Be implanted samples, a thermally stimulated capacitance (TSCAP) measurement was made on the SBD using a reverse bias of $V_r = -6$ V and an initial forward filling pulse of $V_p = 6$ V. The resulting spectrum for the temperature range of 100–450 K is shown in Fig. 2. For the purpose of comparison, the TSCAP of an unimplanted Al-doped *p*-type 6H–SiC is also shown. The carrier freeze out of the Be-implanted and the control samples is clearly seen to be the same for both samples in the sharp fall in capacitance in the temperature range 160–200 K with only the data above 200 K being higher for the Be-implanted sample as a result of implantation induced deep acceptors. It is seen from Fig. 1 that the BEP1 peak, which occurs at around 200 K, is being strongly influenced by carrier freeze out, which causes the observed negative peak artifact. It is believed that this negative peak is produced by the effect that the large series resistance has on the measurement of capacitance. For the longer rate window

TABLE I. Energy levels $E_T$, capture cross section $\sigma_p$, and concentration $N_T$ of the deep level traps determined using DLTS data of the Be-implanted *p*-type 6H–SiC.

| | $E_T$(eV) | $\sigma_p$(cm$^2$) | $N_T$(cm$^{-3}$) |
|---|---|---|---|
| BEP1 | $E_V+0.41$ | $\sim 10^{-13}$ | $4-10\times 10^{14}$ |
| BEP2 | $E_V+0.60$ | $\sim 10^{-15}$ | $1-6\times 10^{13}$ |
| BEP3 | $E_V+0.76$ | $\sim 10^{-16}$ | $1-3\times 10^{13}$ |
| BEP4 | $E_V+0.88$ | $\sim 10^{-17}$ | $2-6\times 10^{13}$ |

setting, BEP1 is almost totally obscured by this carrier freeze-out phenomenon, which has also been reported for B-implanted Al-doped *p*-type 6H–SiC in which the DLTS peak due to the B acceptor level ($E_V + 0.35$ eV) was severely reduced in magnitude through carrier freeze out.[13]

In the present study, the trap BEP1 ($E_V + 0.41$ eV) has activation energy agreeing well with the first Be acceptor levels as determined from Hall measurements. Furthermore, as shown in the TSCAP data of Fig. 2, the capacitance of the Be-implanted SBD increases above the control experiment in the temperature range in which the BEP1 peak is observed suggesting that the thermal ionization of this level supplies free holes. In summary, these results suggest that the BEP1 deep level is due to the Be impurity acting as an acceptor.

It is interesting to note that one of the double Be acceptor levels ($E_V + 0.42$ eV) detected by Hall measurement[4] was not observed in the previous Be-implanted SiC DLTS spectra.[8,9] One cause of this discrepancy is possibly the different annealing condition/period used, and the fast Be diffusion in SiC. The shape of the as-implanted Be profile was found to change considerably after annealing above 1300°C even for a time period as short as 1 min.[6,7,14] However, another plausible explanation is related to the freeze out of the

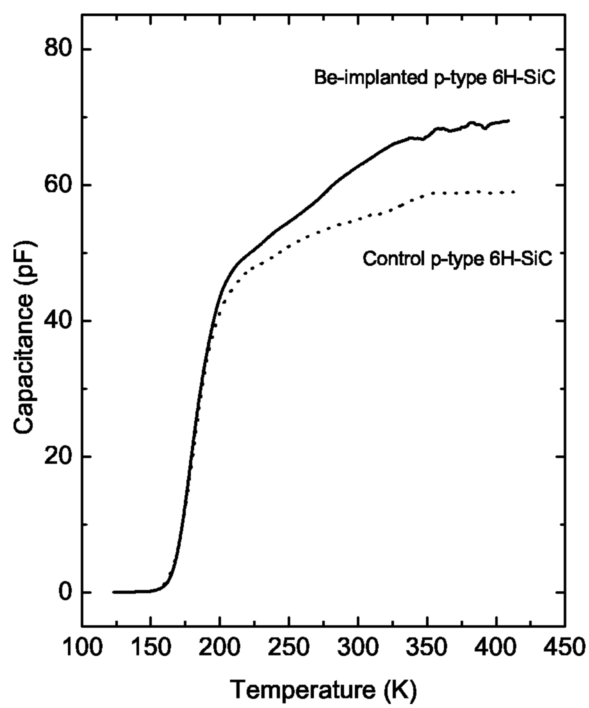


FIG. 2. TSCAP measurements for Be-implanted *p*-type 6H–SiC and unimplanted control samples at a reverse bias $V_r = -6$ V with a forward filling pulse $V_p = 6$ V.

shallow Al acceptors,[9] which as discussed herein, takes place below 200 K. If the rate window time constant employed is too large such that the peak of the deep level appears below 200 K, the freeze out of the carrier would strongly inhibit the DLTS peak in a similar fashion to the BEP1 peak distortion found in the present work.

The activation energy of BEP2 ($E_V + 0.60\,\mathrm{eV}$) is identical to that reported from the Hall measurements of Maslakovets *et al.*[4] in Be-diffused 6H–SiC which was attributed to the second ionization of the double Be acceptor. It is noted from Fig. 1, however, that the BEP2 peak height is about one order of magnitude lower than that of BEP1. Even accounting for differences in depletion region width between BEP1 and BEP2, this factor would seem untenable if the observed BEP2 peak were really originating from a second ionization level of the double Be acceptor center. Thus, while we associate this deep level with the second level as seen in the Hall measurements, we believe that its origin could lie in some alternative Be-related defect rather than the second ionization level of the Be acceptor. It is also noted that the activation energy of BEP2 is also close to the deep level $Be_1$ ($E_V + 0.535 - 0.585\,\mathrm{eV}$) observed in the DLTS study of Be-implanted 4H–SiC, the origin of which is still uncertain.[8]

As stated earlier, very limited DLTS studies have been reported on Be-implanted SiC. Krieger *et al.*[8] implanted Be into *p*-type 4H–SiC and found two deep acceptor states $Be_1$ and $Be_2$ located at $E_V + 0.535\,\mathrm{eV}$ and $E_V + 0.925\,\mathrm{eV}$, respectively. Further, two hole traps labeled A ($E_V + 0.735\,\mathrm{eV}$) and B ($E_V + 1.065\,\mathrm{eV}$), were observed in 4H–SiC implanted with radioisotope $^7$Be in which the hole trap B was shown to be related to a Be atom or a defect complex containing one Be atom by the radiotracer DLTS technique.[9] Though these studies were performed on 4H–SiC, the activation energies of the deep levels can be directly compared in the present 6H–SiC study because the valence band edges of 4H– and 6H–SiC are energetically aligned.[9,15–17] Referenced to the present work, the BEP3 peak (at $E_V + 0.76\,\mathrm{eV}$) is found to be relatively weak and smeared. This deep level has an energy level close to some previously observed deep traps induced by electron irradiation or Be implantation. A deep level labeled H2 at $E_V + 0.78\,\mathrm{eV}$ was identified in electron irradiated *p*-type 6H–SiC.[18] However, H2 was found to anneal out at about 350 °C and, thus, the correlation between the present BEP3 and the H2 traps seems unlikely as in the present study the sample was annealed to 1600 °C. The energy level of BEP3 is also close to hole traps seen by others in Be-implanted SiC. For example, a hole trap labeled BE5 was located at $E_V + 0.73\,\mathrm{eV}$ (6H–SiC)[6] and another labeled A has been reported in 4H–SiC at $E_V + 0.735\,\mathrm{eV}$.[9] It is, thus, suggested that the present BEP3 deep level is the same hole trap as seen in these other works. This being the case, there is some evidence that this deep level is not to be related to the Be dopant but that it is likely attributed to the residual impurity B-related *D* center.[9]

The deep hole trap BEP4 ($E_V + 0.88\,\mathrm{eV}$) has an activation energy close to those of $Be_2$ ($E_V + 0.925\,\mathrm{eV}$)[8] observed in Be-implanted *p*-type 4H–SiC and the deep level labeled B ($E_V + 1.065\,\mathrm{eV}$) in radioactive isotope $^7$Be-implanted *p*-type 4H–SiC.[9] In the latter study, it was proposed that the $Be_2$ observed in Ref. 8 was the same deep level as the deep trap B. Moreover, it was clearly shown that this level was related to a defect (or a defect complex) containing one Be atom. These results were consistent with the electron paramagnetic resonance (EPR) study of Be diffused 6H–SiC, in which the Be diffusion induced Be-related complex behaved as a deep level in the band gap of SiC.[19] The activation energy of the BEP4 does, however, fall outside experimental error to those reported for deep levels $Be_2$ or B. This could be due to the difference in polytype, the annealing process, or the crystal stress in the studied SiC samples. Clearly, further work is required to study factors affecting the energy of this deep level.

In conclusion, *p*-type 6H–SiC materials with Be implantation and postimplantation annealing have been studied. DLTS measurements have revealed four deep hole traps BEP1–BEP4. The BEP1 level at $E_V + 0.41\,\mathrm{eV}$ is consistent with the ionization level of the Be acceptor observed in Hall measurements.[4] BEP2 is suggested to be associated with a Be-related defect, while BEP3 and BEP4 are proposed to be Be-implantation induced deep level defects or complexes.

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