A deep level transient spectroscopy study of electron irradiation induced deep levels in *p*-type 6H–SiC

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1.7 MeV electron irradiation-induced deep levels in *p*-type 6H–SiC have been studied using deep level transient spectroscopy. Two deep hole traps are observed, which are located at $E_V+0.55$ eV and $E_V+0.78$ eV. They have been identified as two different defects because they have different thermal behaviors. These defects at $E_V+0.55$ eV and $E_V+0.78$ eV are annealed out at 500–200 °C, respectively, and are different from the main defects $E1/E2$, $Z1/Z2$ observed in electron irradiated *n*-type 6H–SiC. This indicates that new defects have been formed in *p*-type 6H–SiC during electron irradiation. © *1999 American Institute of Physics.* [S0021-8979(99)05010-0]

I. INTRODUCTION

Ion implantation has widely been employed to realize selective area doping in SiC device processing. Recent research results have revealed that various defects exist even after a 1700 °C post implantation annealing.[1–3] Therefore, it is important to understand the properties of radiation-induced defects. High-energy electron irradiation is widely used to study the defects in semiconductors since it is a controllable method to introduce intrinsic defects and complex centers. In past years, some results were obtained for electron irradiated defects in 6H–SiC using different methods.[4–11] The properties of the defects in *p*-type materials are important since *n*-channel metal–oxide–semiconductor-type devices have been widely used. However, very few studies have been made on *p*-type 6H–SiC and only some discrepant results were reported. Several new near-infrared lines were measured in the electron irradiated *p*-type 6H–SiC after 750 °C annealing using photoluminescence.[7] Electron spin resonance measurement, however, revealed the existence of five electron irradiation-induced deep centers that can be annealed off in the temperature region from 150 to 700 °C.[8] On the other hand, no positron trap was observed using positron annihilation spectroscopy measurements.[9,10] In the present work, we report the experimental results of electron irradiation-induced deep levels in *p*-type 6H–SiC using deep level transient spectroscopy (DLTS)—an electrical method. The annealing behavior of the induced deep centers is also discussed.

II. EXPERIMENT AND RESULTS

The starting material in this work was 6H–SiC *p*-type 6H–SiC(0001) with an epilayer of 10 μm thickness from Cree Research Inc. The aluminum acceptor concentrations were 9.0×10^{15} and 6.6×10^{18} cm^3 in the epilayer and the substrate, respectively. Aluminum was deposited on the backside of the wafers in vacuum following a 950 °C metallization process in nitrogen gas for ohmic contact. 1.7 MeV electrons, which can penetrate the wafer thus producing damage throughout the epilayer,[12] with doses of 2.26×10^{14} and 1.13×10^{15} e/cm^2 were applied using a Van de Graaff accelerator. After the irradiation, Au/SiC Schottky barrier diodes were fabricated by depositing high purity gold. Current–voltage and capacitance–voltage meters were employed to monitor the quality of the samples. DLTS measurements were carried out using a 6 V reverse bias and a 6 V forward filling pulse. The DLTS system has been described elsewhere.[13]

Typical DLTS spectra of the electron irradiated *p*-type 6H–SiC are presented in Fig. 1. Two deep levels, named as *H*1 and *H*2, respectively, were observed in the temperature region of 180–400 K. Both deep levels are induced by electron irradiation since they are electron dose dependent and increase linearly with electron dose. Their positions in the band gap are 0.55 and 0.78 eV above the valence band, respectively, which are calculated from the Arrhenius plots (Fig. 2). From the intercepts of the Arrhenius plots, the capture cross sections are calculated to be 1.23×10^{-11} cm^2 for *H*1 and 1.35×10^{-14} cm^2 for *H*2. The effective mass of the hole used in the calculation is $0.25m_0$.[14] The generation rates of *H*1 and *H*2 are approximately 0.008 and 0.012 cm^{-1}, respectively.

III. DISCUSSIONS

To the best of our knowledge, only limited experimental results on particles irradiated *p*-type (aluminum-doped) 6H–SiC using DLTS technique have been reported.[15–17] A deep level, having an ionization energy of 0.49 eV (close to our present result of 0.55 eV) was observed in the nitrogen-implanted *p*-type 6H–SiC.[15] However, this deep level center could withstand 1100 °C heat treatment. In the 5.5 MeV alpha particle irradiated *p*-type 6H–SiC, two similar deep levels, located at $E_V+0.56$ eV and $E_V+0.69$ eV, were observed.[16] Although these two levels existed in the starting

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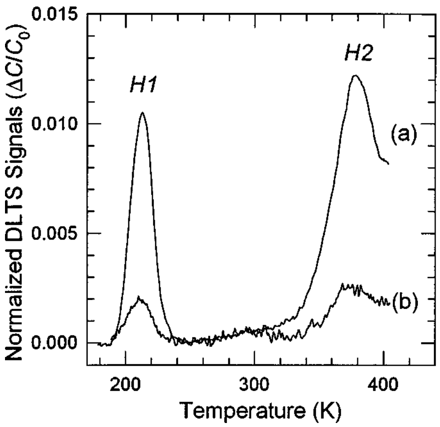

FIG. 1. Typical normalized DLTS spectra of electron irradiated *p*-type 6H–SiC with various electron doses, (a) 1.13×10^{15} e/cm^2 and (b) 2.26×10^{14} e/cm^2. The rate window used in the experiment for these spectra is 6.82 ms.

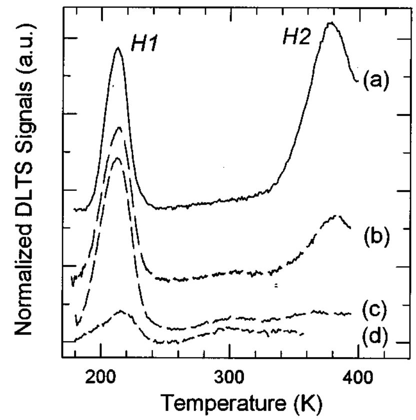

FIG. 3. DLTS spectra of electron irradiated *p*-type 6H–SiC before and after annealing. (a) Before annealing, (b) 200 °C annealing, (c) 300 °C annealing, and (d) 500 °C annealing.

material, they were still considered as irradiation damage related defects by the authors since their concentrations indeed increased after α-particle irradiation. The DLTS peak of the level $E_V+0.56$ eV, in Rybicki's experiment,[16] appeared at the temperature of 280 K in the DLTS spectrum with a rate window of 21.5 ms as seen in Fig. 1 in Ref. 16. In the present work, however, the DLTS peak of $E_V+0.55$ eV is situated at 210 K in the spectrum with a rate window of 6.82 ms. This means that these are unlikely to be the same deep center, because if they were, the DLTS peak of $E_V+0.55$ eV in our experiment would be located at a higher temperature position.

The position of the deeper level ($E_V+0.69$ eV), observed by Rybicki, seems to be different from that in our observation. On comparing the DLTS spectra before and after α-particle irradiation in Figs. 1 and 2 of Ref. 16, we can see that the position of the level ($E_V+0.69$ eV) changed from 380 to 390 K after irradiation. In fact, one can also see that a shoulder exists on the lower temperature side of the DLTS peak ($E_V+0.69$ eV) after irradiation. Although, Rybicki did not distinguish this difference, we believe that the two peaks, which were considered as the same deep level, are not the same. We think that the latter one is very likely to be a new deep level introduced by the irradiation and the former one may well be the shoulder of the latter. The dominant deep level situated at 390 K in the DLTS spectrum after irradiation in Ref. 16 may have a position deeper than the reported 0.69 eV in which case the level in question would be closer to the value of *H*2 in our work. Thus this deep level induced by the α-particle irradiation is very probably the same as defect *H*2 observed in this experiment. It has been noticed that the capture cross section of this level in Ref. 16 is 1.34×10^{-16} cm^2, which is about two orders smaller than that of *H*2 (1.35×10^{-14} cm^2). This discrepancy may be due to the different methods for estimating the values of the capture cross sections. It has been found that the capture cross section measured by changing the filling pulse width is sometimes smaller than that calculated as this work.[11]

In order to understand the thermal properties of the defects observed in the present work, 5 min isochronal annealing was carried out in nitrogen gas. Figure 3 gives the DLTS spectra of the samples before and after annealing, and Fig. 4 shows the concentrations of *H*1 and *H*2 as a function of the annealing temperature. The defect *H*1 was annealed out at the temperature of 250 °C, while *H*2 was thermally stable up

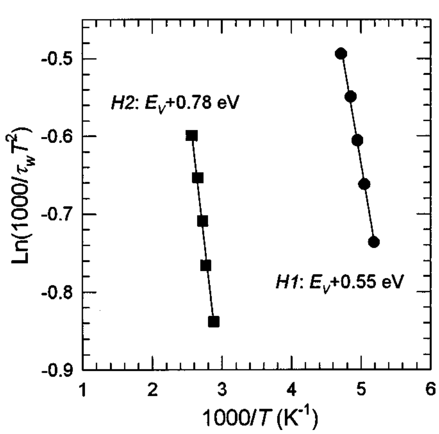

FIG. 2. Arrhenius plots of hole emission rates of electron irradiation-induced deep levels in *p*-type 6H–SiC as a function of 1000/*T*. Here τ_w is the rat window.

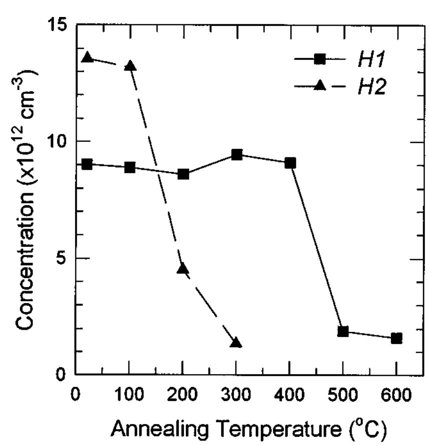

FIG. 4. Concentration of the electron irradiation-induced deep levels in *p*-type 6H–SiC as a function of 5 min isochronal annealing temperature.

to 500 °C. It is clear that the two defects $H1$ and $H2$, have different thermal behaviors. Namely, they are not the same defect.

In the previous studies of electron irradiated *n*-type SiC, a number of deep levels were observed using DLTS.[5,6,11] The main deep centers were $E1/E2$ and $Z1/Z2$, which could withstand a high temperature ($>$1000 °C) annealing.[5,6] In this work on *p*-type material, however, the deep centers $H1$ and $H2$ can be annealed out at 500 and 250 °C, respectively. This indicates that the defects $H1$ and $H2$ are different from $E1/E2$ and $Z1/Z2$ in *n*-type 6H–SiC. We recall that if the defects $H1$ and $H2$ that were not observed in *n*-type SiC did exist in *n*-type material then they would only introduce deep levels in the lower half of the band gap and act as hole traps. Another possible model of the defect $H1$ or $H2$ is a complex center of vacancy and impurity (aluminum in this work). To distinguish between these two cases, the employment of boron doped *p*-type material would be necessary. Unfortunately, boron doped *p*-type SiC material is not yet commercially available.

In electron irradiated *n*-type 6H–SiC, the deep levels, such as $E1/E2$, $E3/E4$, and $Z1/Z2$, usually appear in pairs.[5,6,11] This was believed to be due to the inequivalent lattice sites (two cubic *k* sites and one hexagonal *h* site in 6H–SiC), which have the same nearest neighbors but different next nearest neighbors. According to this model, any vacancy or substitutional impurity related defect should belong to either the *k* site or the *h* site. Therefore, it is reasonable to expect that any irradiation-induced defect should appear in a paired form with concentration ratio of 2:1.[5] For some defects, however, the variation due to the inequivalent lattice sites may be too small to be observed, as for the well-known *D* center (vacancy-boron complex),[1,2] the deep level $E_C-1.25$ eV ($E7$) in Ref. 11 and the level $E_C-0.51$ eV in Ref. 4. From Fig. 1, it can be seen that no small DLTS peak exists as a shoulder of $H1$. However, on the higher temperature side of deep level $H2$ a shoulder exists. Just like the experiment done by Rybicki,[16] the highest measurement temperature of our DLTS system is around 400 K; it is difficult to known if there was a smaller peak on the higher temperature side. Therefore, it cannot be sure that the shoulder is always accompanying with the defect $H2$ and having a fixed concentration ratio. As the defects $H1$ and $H2$ are not as thermally stable as $E1/E2$ and $Z1/Z2$, they probably are some kind of defect complex of vacancy and interstitial impurity. By using DLTS technique only, it is difficult to obtain further information about their structures.

IV. CONCLUSIONS

In conclusion, two deep centers have been observed in 1.7 MeV electron irradiated *p*-type 6H–SiC in the temperature region of 180–400 K using deep level transient spectroscopy. The deep level at $E_V+0.55$ eV with an estimated capture cross section of 1.23×10^{-11} cm^2 can be annealed off at 500 °C, while another one at $E_V+0.78$ eV having a capture cross section of 1.35×10^{-14} cm^2 dissociates at the temperature of 250 °C. Their different thermal behaviors make it possible to identify these as two different defects. To understand the structures of these defects, further work is necessary. In particular, measurements on electron irradiated boron-doped SiC will be helpful.

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