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Kyoto University
Midgap levels in both $n$- and $p$-type 4H–SiC epilayers investigated by deep level transient spectroscopy

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Midgap levels in $n$- and $p$-type 4H–SiC epilayers have been investigated by deep level transient spectroscopy (DLTS). The EH$_{6/7}$ center ($E_c$−1.55 eV) is the dominant midgap level as observed in DLTS spectra for $n$-type epilayers. The activation energy of EH$_{6/7}$ center is unchanged regardless of applied electric field, indicating that the charge state of the EH$_{6/7}$ center may be neutral after electron emission [acceptor-like (0/−) trap]. In $p$-type epilayers, a deep level located at 1.49 eV above the valence band edge has been detected. The lack of Poole–Frenkel effect in emission time constant from this deep level suggests that this level is donor-like (+/0). From the energy level and charge state, this defect center may originate from a single carbon vacancy ($\text{V}_C$), which has been extensively studied by electron paramagnetic resonance. © 2005 American Institute of Physics. DOI: 10.1063/1.1886904

Midgap levels in both $n$- and $p$-type 4H–SiC epilayers were investigated by DLTS in the wide temperature range (90–830 K) on Schottky structures (Ni for $n$-type and Ti for $p$-type epilayers). In these measurements, the capacitance was measured periodically in a period width, in which the transient is to be measured and then developed into Fourier series. Schottky metals were thermally evaporated onto surfaces of the samples, and ohmic contacts were formed with Ag paste on the back side. The diameter of Schottky contacts was 800–1500 μm.

Figure 1 shows the DLTS spectra with a period width of 0.05 s in the temperature range from 550 to 700 K obtained from a Ni/SiC ($n$-type) Schottky structure for various electric field. The net donor concentration and thickness of the sample used in the measurements were $1.8 \times 10^{15} \text{ cm}^{-3}$ and 20 μm, respectively. The electric field was changed by changing the pulse voltage from 0 to −40 V under a constant reverse bias of −50 V. The DLTS spectra were dominated by one peak at 630 K, the trap concentration of which is $4.9 \times 10^{13} \text{ cm}^{-3}$. Note that the authors selected this sample with a relatively high trap concentration to obtain a high signal-to-noise ratio in DLTS, the typical concentration of EH$_{6/7}$ center in as-grown epilayers is in the $10^{11}$–$10^{12} \text{ cm}^{-3}$ range. The activation energy and capture cross section ($\sigma$) were determined to be 1.55 eV and $1 \times 10^{-14} \text{ cm}^2$ from the Arrhenius plot of emission time constant, assuming a linear dependence of the capture cross section on the applied electric field, which has been extensively studied by electron paramagnetic resonance.

Silicon carbide (SiC) is a promising material for realizing high-power devices owing to superior properties such as wide band gap, high breakdown field and high thermal conductivity. High-voltage (300–600 V) Schottky barrier diodes are now on the market. In addition, several field effect transistors (FETs) have been investigated for unipolar switching devices. For several-kilovolt application, bipolar devices are superior to unipolar devices in terms of on-resistance owing to the effect of conductivity modulation. Deep levels, especially midgap levels, act as an efficient carrier generation and recombination center. Many of their features, however, still remain unknown especially for the EH$_{6/7}$ center.

In high-quality $n$-type 4H–SiC epilayers, $Z_{1/2}$ ($E_c−0.65 \text{ eV}$) and EH$_{6/7}$ ($E_c−1.55 \text{ eV}$) centers are two major deep levels (electron traps). Through deep level transient spectroscopy (DLTS) under light illumination, the $Z_{1/2}$ center has been revealed to be a negative U center. Since the EH$_{6/7}$ center is located at midgap and has a large capture cross section ($\sigma$), this center is a candidate for a dominant carrier generation and recombination center. Many of their features, however, still remain unknown especially for the EH$_{6/7}$ center, because very high temperature is required to detect it. The origins of these defect centers are also an open question. Further, very little information is available about deep levels in the lower half of band gap of SiC. In this work, the authors have investigated deep levels in both $n$- and $p$-type 4H–SiC epilayers. By DLTS measurements at high temperature on $p$-type epilayers, a midgap level has been detected. The charge states of midgap levels in both $n$- and $p$-type epilayers have been estimated by double-correlated DLTS (DDLTS) measurements.

Samples used in this study were $n$- and $p$-type 4H–SiC(0001) epilayers (doping level: $2 \times 10^{14}$–$2 \times 10^{15} \text{ cm}^{-3}$) grown by chimney-type hot-wall chemical vapor deposition (CVD). The growth temperature and growth rate were 1750 or 1800 °C and 12–20 μm/h, respectively. Deep levels in both $n$- and $p$-type epilayers were investigated by DLTS in the wide temperature range (90–830 K) on Schottky structures (Ni for $n$-type and Ti for $p$-type epilayers). In these measurements, the capacitance was measured periodically in a period width, in which the transient is to be measured and then developed into Fourier series. Schottky metals were thermally evaporated onto surfaces of the samples, and ohmic contacts were formed with Ag paste on the back side. The diameter of Schottky contacts was 800–1500 μm.

FIG. 1. High-temperature DLTS spectra for a Ni/4H–SiC ($n$-type) Schottky structure under various electric fields.
temperature-independent capture cross section, indicating that the trap is the \( EH_{6/7} \) center.\(^4\) From Fig. 1, the peak temperature was almost unchanged irrespective of applied electric field. The activation energy obtained from the Arrhenius plot was also almost constant for different electric field (not shown). Since these results suggest the absence of Poole–Frenkel effect,\(^9\) \( EH_{6/7} \) center might have a neutral charge state after electron emission, being an acceptor-like (0/−) trap in \( n \)-type \( 4H \)-SiC. Although a small shift of peak temperature was observed at the lowest electric field (11 kV/cm), this shift is in the opposite direction to that expected from the Poole–Frenkel effect.

The DLTS spectrum measured for a Ti/\( 4H \)-SiC (\( p \)-type) Schottky structure is shown in Fig. 2. The employed period width was very long, 1.0 s, to detect midgap levels at relatively low temperature. Deep levels were probed from the valence band edge to midgap by using a high-purity (the net acceptor concentration: \( 3 \times 10^{14} \) cm\(^{-3} \)) \( p \)-type epilayer. Titanium was employed for Schottky contact, because titanium has higher barrier height than nickel for \( p \)-type SiC. As shown in Fig. 2, a DLTS peak (labeled P1) was observed at 590 K. The trap P1 was revealed to have an activation energy of 1.49 eV and a capture cross section of \( 1 \times 10^{-14} \) cm\(^2\).\(^{10} \) From our knowledge, this is a midgap level first observed in \( p \)-type \( 4H \)-SiC, respectively. The trap P1 located at 1.49 eV above the valence band edge is the major deep level. No other traps will not exist in the deeper energy region up to \( E_v + 1.7 \) eV from DLTS measurements up to 700 K. Thus, it can be concluded that the \( EH_{6/7} \) (0/−) and P1 (+/0) are the dominant midgap level in \( n \)- and \( p \)-type \( 4H \)-SiC, respectively. The trap P1 may be attributed to a single \( V_C \), as described previously. Although the origin of \( EH_{6/7} \) center is still unknown, several experimental correlations have been reported. Storasta \( et \) al. have performed low-energy electron irradiation experiments, by which only carbon atoms are displaced.\(^6\) They observed the linear increase in \( EH_{6/7} \) concentration when increasing the electron fluence. We found that the formation of \( EH_{6/7} \) center can be suppressed under C-rich growth condition during CVD.\(^{13} \) Thermal annealing experiments showed that the \( EH_{6/7} \) center is stable up to a high temperature of 1600 °C.\(^{14} \) From these results, it may be reasonable that the \( EH_{6/7} \) center is a \( V_C \)-related defect, as Storasta \( et \) al. have also suggested.\(^6\)

More recently, Umeda \( et \) al. have made photoexcited EPR measurements on \( n \)-type \( 4H \)-SiC irradiated with high-energy Frenkel effect. This result suggests that the trap P1 may be in a neutral charge state after hole emission [donor-like (+/0) in \( p \)-type \( 4H \)-SiC].

In electron paramagnetic resonance (EPR) study of \( p \)-type \( 4H \)-SiC,\(^{10,11} \) the microscopic structure of the E15 center, one of major EPR-active centers, has been identified as an isolated carbon vacancy \( (V_C) \).\(^{12} \) From photo-EPR, Son \( et \) al. have revealed that the E15 center is donor-like (+/0), and the level is located at 1.47 eV above the valence band edge.\(^{10} \) This defect center can be detected even after high-temperature annealing at 1600 °C.\(^{11} \) Based on the similarity in energy level, charge state, and thermal stability, we suggest that the trap P1 observed in DLTS and the E15 center observed in EPR can be ascribed to the same origin, a single \( V_C \).

Figure 4 illustrates an overview of ground states of deep levels detected in both \( n \)- and \( p \)-type \( 4H \)-SiC epilayers. In \( n \)-type \( 4H \)-SiC epilayers, the \( Z_{1/2} \) and \( EH_{6/7} \) centers are dominant deep levels, and the RD\(_{1/2} \) located at \( E_c - 0.9 \) eV (Ref. 3) is occasionally observed. High-temperature DLTS analyses on \( 4H \)-SiC up to 830 K revealed that the \( EH_{6/7} \) center \((E_c - 1.55 \) eV) is the deepest level observed, and any other traps should not exist up to 1.9 eV, assuming a capture cross section of \( 1 \times 10^{-14} \) cm\(^2\). In \( p \)-type \( 4H \)-SiC epilayers, the trap P1 located at 1.49 eV above the valence band edge is the major deep level. No other traps will not exist in the deeper energy region up to \( E_v + 1.7 \) eV from DLTS measurements up to 700 K. Thus, it can be concluded that the \( EH_{6/7} \) (0/−) and P1 (+/0) are the dominant midgap level in \( n \)- and \( p \)-type \( 4H \)-SiC, respectively. The trap P1 may be attributed to a single \( V_C \), as described previously. Although the origin of \( EH_{6/7} \) center is still unknown, several experimental correlations have been reported. Storasta \( et \) al. have performed low-energy electron irradiation experiments, by which only carbon atoms are displaced.\(^6\) They observed the linear increase in \( EH_{6/7} \) concentration when increasing the electron fluence. We found that the formation of \( EH_{6/7} \) center can be suppressed under C-rich growth condition during CVD.\(^{13} \) Thermal annealing experiments showed that the \( EH_{6/7} \) center is stable up to a high temperature of 1600 °C.\(^{14} \) From these results, it may be reasonable that the \( EH_{6/7} \) center is a \( V_C \)-related defect, as Storasta \( et \) al. have also suggested.\(^6\)

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electrons. They suggested that a single $V_C$ is negatively charged in $n$-type 4H–SiC, and its acceptor level (0/−) should be located in the energy range of 1.1–1.8 eV below the conduction band edge. Therefore, the speculation that the EH$_{6/7}$ center is the acceptor level of $V_C$ may not cause severe contradiction, although more careful investigations are required to make a conclusive remark.

In summary, midgap levels in both $n$- and $p$-type 4H–SiC epilayers were investigated by DLTS. DDLTS study for as-grown $n$-type epilayers revealed that the EH$_{6/7}$ center, located at $E_c - 1.55$ eV, is acceptor-like (0/−). In $p$-type 4H–SiC epilayers, a midgap level (P1) located at $E_v + 1.49$ eV was detected. This level is donor-like (+/0), and may be ascribed to a single $V_C$, which has been extensively studied by EPR. No other levels deeper than EH$_{6/7}$ and P1 were observed in high-temperature DLTS on $n$- and $p$-type 4H–SiC epilayers, respectively.

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