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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 (V_C), which has been extensively studied by electron paramagnetic resonance. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1886904]

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.[1] For several-kilovolt application, bipolar devices are superior to unipolar devices in terms of on-resistance owing to the effect of conductivity modulation.[2] Deep levels, especially midgap levels, act as an efficient carrier generation and recombination center, being a possible lifetime killer. Therefore, it is essential to understand the properties and origins of midgap levels for developing SiC bipolar devices. Control of deep levels is also a key issue to realize high-purity semi-insulating substrates.

In high-quality *n*-type 4H–SiC epilayers, $Z_{1/2}$ ($E_c - 0.65$ eV)[3] and $EH_{6/7}$ ($E_c - 1.55$ eV)[4] 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.[5] Since the $EH_{6/7}$ center is located at midgap and has a large capture cross section (σ), 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.[6] 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: 2×10^{14}–2×10^{15} cm^{-3}) grown by chimney-type hot-wall chemical vapor deposition (CVD).[7] 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.[8] Schottky metals were thermally evaporated onto surface 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 1.8×10^{15} 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 4.9×10^{13} 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} cm^{-3} range. The activation energy and capture cross section (σ) were determined to be 1.55 eV and 1×10^{-14} cm^2 from the Arrhenius plot of emission time constant, assuming a

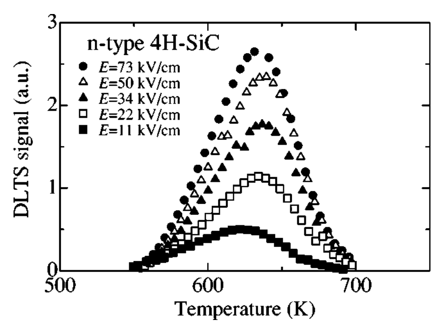

FIG. 1. High-temperature DLTS spectra for a Ni/4H–SiC (*n*-type) Schottky structure under various electric fields.

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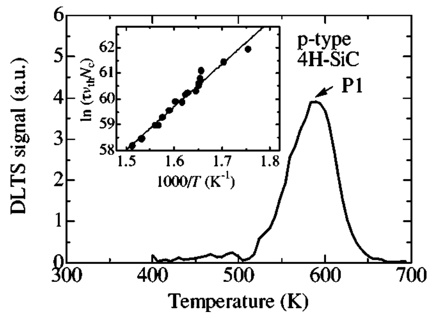

FIG. 2. High-temperature DLTS spectrum measured on a Ti/4H–SiC (p-type) Schottky structure. Inset: Arrhenius plot of emission time constant.

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: 3×10^{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 8×10^{-15} cm^2 from the Arrhenius plot (shown in the inset). To our knowledge, this is a midgap level first observed in p-type SiC. The concentration of trap P1 for this particular sample was 4.1×10^{12} cm^{-3}. Although the observed DLTS peak may consist of a few overlapping peaks ascribed to different centers, it is difficult to resolve in the present DLTS system.

The dependence of emission-time constant (τ) on electric field for the trap P1 is shown in Fig. 3. The applied electric field was changed by changing pulse voltage from 0 to 9.5 V under a constant reverse bias of 10 V. As shown in Fig. 3, the emission time constant was almost constant regardless of electric field, indicating the absence of Poole–

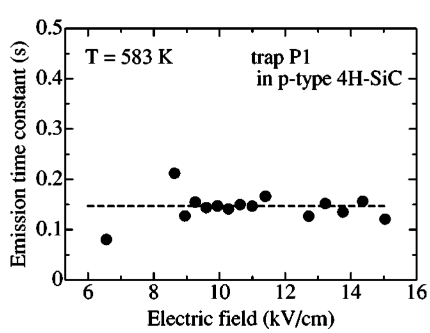

FIG. 3. Relation between emission time constant (τ) and electric field for the trap P1 shown in Fig. 2.

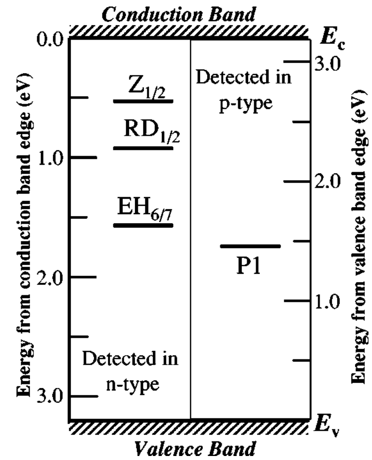

FIG. 4. Overview of ground states of deep levels detected in both n- and p-type 4H–SiC epilayers.

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 EI5 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 EI5 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 EI5 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 1×10^{-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 liner 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 electrons.[15] 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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