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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 \( \text{EH}_{6/7} \) center \((E_g \sim 1.55 \text{ eV})\) is the dominant midgap level as observed in DLTS spectra for \( n \)-type epilayers. The activation energy of \( \text{EH}_{6/7} \) center is unchanged regardless of applied electric field, indicating that the charge state of the \( \text{EH}_{6/7} \) center may be neutral after electron emission [acceptor-like \((0/0)\) 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 semisolating substrates.

In high-quality \( n \)-type 4H–SiC epilayers, \( Z_{1/2} \) \((E_g \sim 0.65 \text{ eV})\)\(^{3}\) and \( \text{EH}_{6/7} \) \((E_g \sim 1.55 \text{ eV})\)\(^{4}\) 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 \( \text{EH}_{6/7} \) 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 \( \text{EH}_{6/7} \) 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: \( 2 \times 10^{14}–2 \times 10^{15} \text{ cm}^{-3} \)) 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 \( \mu \text{m/h} \), 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 \( \mu \text{m} \).

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 \( 20 \mu \text{m} \), 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 \( \text{EH}_{6/7} \) 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

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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. 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. The activation energy obtained from the Arrhenius plot was almost unchanged irrespective of applied electric field.

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

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

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