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Determination of Intrinsic Defects in High-Purity Semi-Insulating 4H-SiC by Discharge Current Transient Spectroscopy

Hideharu Matsuura[a], Miyuki Takahashi, Yoshitaka Kagawa, Shoichi Tano and Takayuki Miyake

Department of Electronic Engineering and Computer Science, Osaka-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan

[a]matsuura@isc.osakac.ac.jp

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Abstract. To determine the energy levels of intrinsic defects in high-purity semi-insulating 4H-SiC, we apply discharge current transient spectroscopy (DCTS) that is a graphical peak analysis method based on the transient reverse current of a Schottky barrier diode, because transient capacitance methods such as deep level transient spectroscopy and isothermal capacitance transient spectroscopy are feasible only in low-resistivity semiconductors. Seven intrinsic defects are detected in the high-purity semi-insulating 4H-SiC. From the temperature dependence of the emission rate of each intrinsic defect, its activation energy is approximately determined.

Introduction

We have investigated X-ray detectors operating at room or elevated temperatures using high-purity semi-insulating SiC [1,2]. For making use of semi-insulating semiconductors as an active layer in electronic devices as well as a substrate for lateral power microwave devices, the properties of intrinsic defects in them should be investigated in detail because they strongly affect the electric properties of the devices.

Although powerful methods to characterize electrically active defects in low-resistivity semiconductors are transient capacitance methods, e.g., deep level transient spectroscopy (DLTS) [3] and isothermal capacitance transient spectroscopy [4], the methods are not feasible in semi-insulating semiconductors. Thermally stimulated current (TSC) [5] is suitable for characterizing them in semi-insulating semiconductors. However, it is difficult to analyze the experimental TSC data when defects with close emission rates are included in the semiconductor. Moreover, because the influence of the pyroelectric currents and the temperature dependence of the steady-state leakage current should be considered in the analysis, an isothermal measurement is more suitable for characterizing them than TSC.

A graphical peak analysis method using the isothermally measured transient current (DCTS: discharge current transient spectroscopy) [6] can be applied to high-purity semi-insulating 4H-SiC, besides SiN_X films [7-8], $Pb(Zr,Ti)O_3$ films [6], and high-resistivity Si pin diodes [9].

In this study, we report on our investigation of intrinsic defects in high-purity semi-insulating 4H-SiC using DCTS.

Discharge Current Transient Spectroscopy

DCTS can determine the densities and emission rates of defects in a semi-insulating semiconductor from the transient reverse current $i(t)$ of a Schottky barrier diode at a constant temperature. In DCTS [6-9], the following evaluation function is defined using the experimental $i(t)$;

$$D(t,e_{\mathrm{ref}}) \equiv t[i(t)-i_{\mathrm{s}}]\frac{\exp(-e_{\mathrm{ref}}t+1)}{qS} \quad , \tag{1}$$

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where i_s is the steady-state leakage current at a reverse bias voltage (V_R), q is the electron charge, S is the electrode area, and e_{ref} is the peak-shift parameter [6]. From the time (t_{peaki}) and value (D_{peaki}) of each peak, we can accurately determine the emission rate (e_{ti}) and sheet density (N_{ti}) of the corresponding defect as

$$e_{ti} = \frac{1}{t_{peaki}} - e_{ref} \tag{2}$$

and

$$N_{ti} = \frac{D_{peaki}}{1 - e_{ref} t_{peaki}} \quad , \tag{3}$$

because the DCTS signal is theoretically given by [6-9]

$$D(t, e_{ref}) = \sum_i N_{ti}\, e_{ti}\, t \exp[-(e_{ti} + e_{ref})\, t + 1] \quad . \tag{4}$$

The application software for DCTS (for the Windows operating system) can be downloaded for free at our Web site (http://www.osakac.ac.jp/labs/matsuura/).

Experiment

A 0.37-mm-thick high-purity semi-insulating 4H-SiC wafer was purchased from Cree Inc., and Ni electrodes with a radius of 1.25 mm were evaporated onto both sides of the sample. The current-voltage characteristics and transient reverse current were measured using a Keithley 236 source-measure unit. This diode behaved as a back-to-back diode [1]. The $i(t)$ for V_R of –100 V was measured after a bias voltage was rapidly changed from 0 V to –100 V at a constant temperature. The temperature range of the measurement was from 303 to 373 K. The densities and emission rates of intrinsic defects in the semi-insulating 4H-SiC were determined by DCTS. The details of the sample preparation, the behavior of contacts, and the measurement setup were described in [1], [2], and [6].Results and Discussion

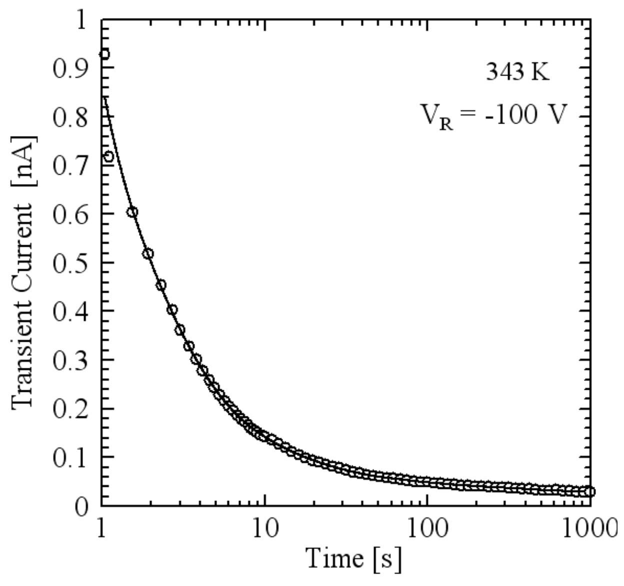

Fig 1. Transient current at 343 K.

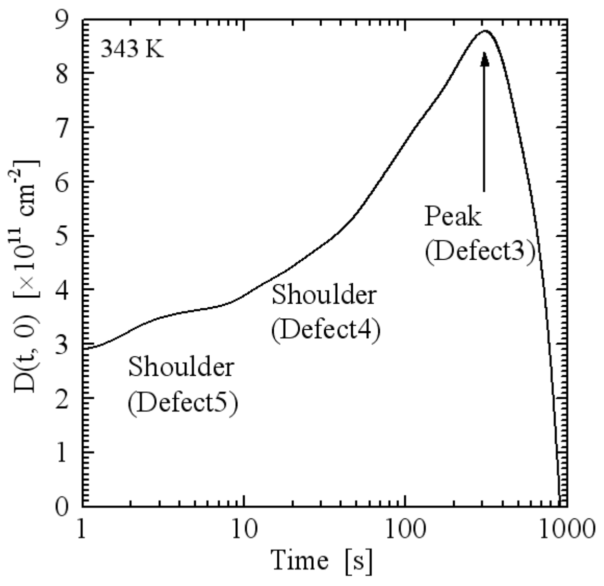

Fig. 2. DCTS signal with $e_{ref} = 0$ s^{-1} at 343 K.

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Figure 1 shows the $i(t)$ at –100 V at 343 K. In the figure, circles represent the experimental data, and the solid line was calculated by interpolating $i(t)$ with a cubic smoothing natural spline function.

Figure 2 shows the DCTS signal with $e_{\mathrm{ref}} = 0$ s^{-1}. One peak and two shoulders appeared in the figure. From the peak of the DCTS signal, the sheet density and emission rate of the corresponding defect, referred to as Defect3, were determined as 8.7×10^{11} cm^{-2} and 3.3×10^{-3} s^{-1}, respectively. It is clear from Eq. 3 that the peak value (i.e., $D_{\mathrm{peak}i}$) of the component of DCTS signal corresponding to each defect can be changed by e_{ref}. Figure 3 shows the DCTS signals with e_{ref} of 0.01 and 0.05 s^{-1}, denoted by the solid and broken lines, respectively. The peaks in Fig. 3 correspond to the shoulders in Fig. 2. Using Eq. 2, the emission rates of defects, referred to as Defect4 and Defect5, were determined from the peak times in Fig. 3, as 4.1×10^{-2} and 3.1×10^{-1} s^{-1}, respectively. Although the DCTS signals with various e_{ref} were calculated, any peaks corresponding to other defects were not detected. Therefore, the transient reverse current at 343 K was produced mainly by three types of defects (i.e., Defect3, Defect4, Defect5).

Figure 4 shows the DCTS signal with $e_{\mathrm{ref}} = 0$ s^{-1} at 353 K, where there are two peaks and two shoulders. In the same way as illustrated for the DCTS signal at 343 K, the emission rates of four defects (Defect2, Defect3, Defect4, Defect5) were determined.

Finally, the $N_{\mathrm{t}i}$ and $e_{\mathrm{t}i}$ of seven types of defects were determined by DCTS in the temperature range between 303 and 373 K. When the diode is considered to be fully depleted at V_{R}, the densities of defects can be calculated as $N_{\mathrm{t}i}$ divided by the thickness of the wafer. Under the assumption, the densities of defects in the SiC were between 10^{12} and 10^{13} cm^{-3}.

The relationship between $e_{\mathrm{t}i}$ and T is given by [4,9]

$$e_{\mathrm{t}i} \propto T^2 \exp\left(-\frac{\Delta E_i}{kT}\right) , \tag{5}$$

where ΔE_i is the activation energy for the i th defect, which is the energy level measured from the valence band maximum (E_{V}) for p-type or the conduction band minimum (E_{C}) for n-type. From the

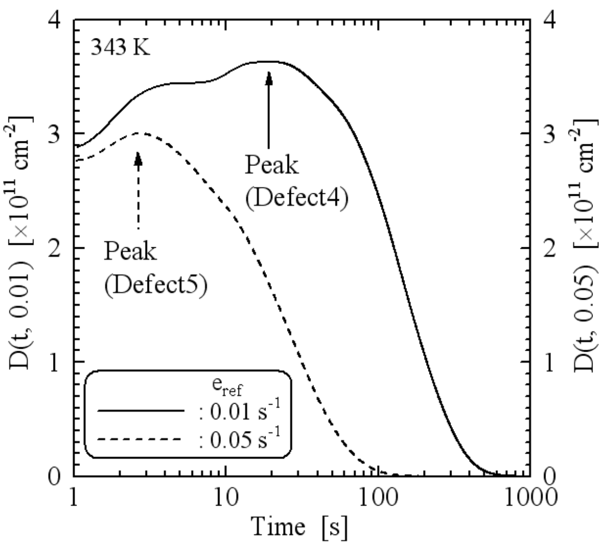

Fig. 3. DCTS signals with e_{ref} of 0.01 and 0.05 s^{-1} at 343 K.

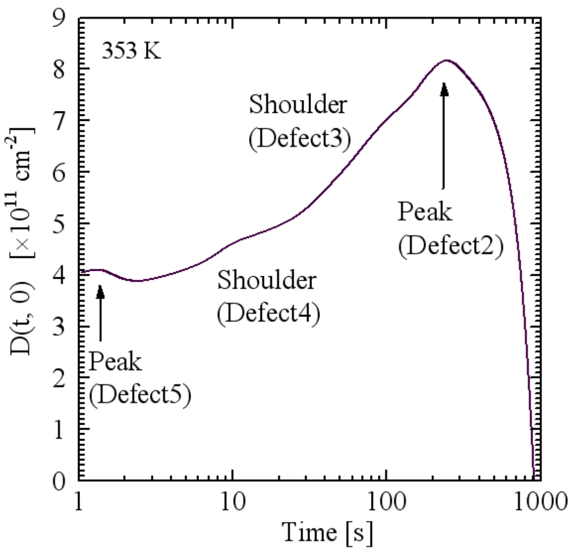

Fig. 4. DCTS signal with $e_{\mathrm{ref}} = 0$ s^{-1} at 353 K.

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relationship between e_{ti}/T^2 and T shown in Fig. 5, the energy levels for Defect2, Defect3, Defect4, Defect5, and Defect6 were approximately determined as 1.8, 1.9, 1.6, 1.1, and 0.87 eV, respectively. The precise determination of the energy levels is in progress.

It is difficult to characterize electrically active deep levels in semi-insulating 4H-SiC. According to DLTS studies on deep levels in low-resistivity 4H-SiC epilayers irradiated with high-energy electrons [10,11], the energy levels of intrinsic defects were 0.65 and 1.55 eV below E_C, and 0.49, 0.79, 0.84, 1.27, and 1.44 eV above E_V. According to literature [12], the (0/+), (-/0) and (--/-) levels of Si vacancies were reported to be 0.31 eV above E_V, 1.98 and 1.31 eV below E_C, respectively, while the (0/++) level of C vacancies was 1.53 eV above E_V because of the negative-U behavior. The investigation of origins of intrinsic defects detected by DCTS is in progress.

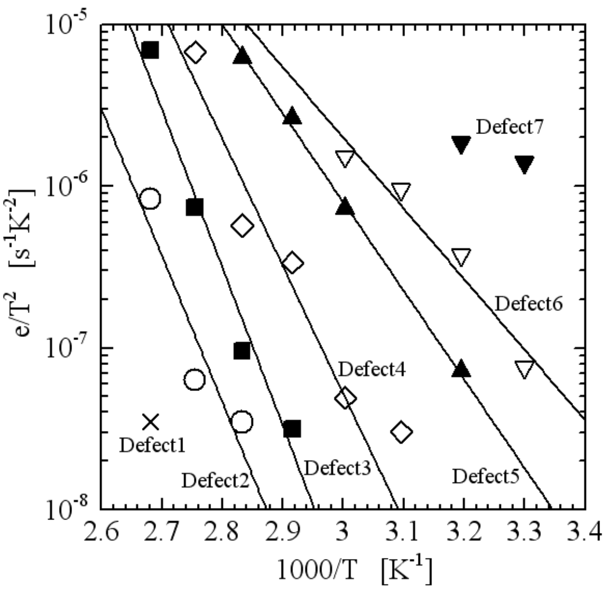

Fig. 5. Temperature dependence of emission rate.

Summary

It was elucidated that DCTS is applicable to semi-insulating semiconductors. DCTS could determine the densities and emission rates of intrinsic defects in high-purity semi-insulating 4H-SiC. From the temperature dependence of the emission rate of each intrinsic defect, its energy level could be approximately determined.

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