Materials Science Forum Vols. 600-603 (2009) pp. 393-396
online at http://www.scientific.net

Characterization of Traps in Semi-Insulating 4H-SiC by Discharge Current Transient Spectroscopy

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Keywords: SiC, semi-insulating semiconductor, transient current, characterization of traps

Abstract. In order to characterize traps in semi-insulating 4H-SiC that is regarded as an attractive semiconductor for X-ray detectors, we apply discharge current transient spectroscopy (DCTS) that is a graphical peak analysis method based on the transient reverse current of a diode. We have found at least three types of traps whose emission rates at 373 K are 4.9×10^{-3}, 8.3×10^{-3} and 8.0×10^{-2} s^{-1}. Since it is difficult to characterize traps in semi-insulating semiconductors by transient capacitance methods, it is demonstrated that DCTS is a powerful method for determining the densities and emission rates of traps in semi-insulating semiconductors.

Introduction

Li-doped Si Schottky barrier diodes and SDD (silicon drift detector) have been developed for use in X-ray energy spectroscopy. In order to form a wide depletion region in a diodes, a high reverse bias (e.g., -100V) is applied to the diode. Since the resistivities of high-purity Si is not enough to reduce the reverse current of the diode at room temperature to 1 nA, highly resistive SiC has been investigated. However, deep defects in semiconductors degrade the performance of X-ray detectors. When the high reverse bias is suddenly applied from 0 V, moreover, a transistor reverse current due to these defects flow, which breaks the junction field-effect transistor connected to the detector. Recently SiC has been highly purified, and its resistivity is much higher than 10^6 Ωcm. Compared with V-doped semi-insulating 4H-SiC, deep defects in high-purity semi-insulating 4H-SiC are considered to be much lower. In order to research a possibility of high-purity SiC being used as a portable X-ray detector operating at room temperature, therefore, it is necessary to investigate deep defects related to the transient current.

There are transient capacitance methods to determine the densities and energy levels of defects (i.e., traps), for example, deep level transient spectroscopy (DLTS) [1] and isothermal capacitance transient spectroscopy (ICTS) [2] for low-resistivity semiconductors, and the heterojunction-monitored capacitance (HMC) method [3] for high-resistivity semiconductors. In the case of applying the transient capacitance methods to metal-insulator-semiconductor diodes, traps at the insulator-semiconductor interface can mainly be investigated [4]. In the case of a semi-insulating semiconductor diode, on the other hand, the measured capacitance is a capacitance determined by the thickness of the diode, not determined by the depletion region of the junction. This is because the dielectric relaxation time becomes large due to its high resistivity [3], indicating that it is difficult to determine the densities and energy levels of traps in semi-insulating semiconductors and insulators by transient capacitance methods.

Thermally stimulated current (TSC) is suitable for evaluating the densities and emission rates of traps with one thermionic emission rate or with completely different thermionic emission rates in semi-insulating semiconductors and insulators [5]. However, it is difficult to fit a TSC simulation to the experimental TSC data in the case of the diode including traps with close emission rates. Moreover, since the influence of the pyroelectric currents and the temperature dependence of the steady-state leakage currents must be considered when the measurement temperature increases continuously, an isothermal measurement is more suitable for evaluating the densities and emission rates of traps than TSC.

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Although the densities and emission rates of traps can be obtained by fitting a simulation to the transient current at a constant temperature, one should assume the number of trap species before the curve-fitting procedure, indicating that the densities and emission rates strongly depend on the assumed number of trap species. Moreover, in the curve-fitting procedure, the too many curve-fitting parameters (i.e., densities and emission rates) should be changed simultaneously, suggesting that the obtained values should be less reliable.

Without any assumption of the number of trap species, on the other hand, one of the authors has proposed a graphical peak analysis method to determine the densities and emission rates using the isothermally measured transient current, referred to as discharge current transient spectroscopy (DCTS) [6-8], and has applied it to SiN_x films [6], $Pb(Zr, Ti)O_3$ films [7], and high-resistivity Si pin diodes [8]. From each peak of the DCTS signal, the density and emission rate of the corresponding trap can be determined accurately.

In this study, we report on our investigation of a possibility of DCTS determining traps in semi-insulating 4H-SiC.

Discharge Current Transient Spectroscopy

Let us consider the transient reverse current $I_{\mathrm{TR}}(t)$ of a diode after a reverse bias (V_{R}) is suddenly applied from 0 V ($t = 0$ s), which is theoretically expressed as

$$I_{\mathrm{TR}}(t) = -qS\sum_{i} N_{\mathrm{t}i} e_{\mathrm{t}i} \exp(-e_{\mathrm{t}i}t) + I_1(V_{\mathrm{R}})\,. \tag{1}$$

where $I_1(V_{\mathrm{R}})$ is the steady-state leakage current at V_{R}, q is the electron charge, S is the electrode area, and $N_{\mathrm{t}i}$ and $e_{\mathrm{t}i}$ are the density per unit area and emission rate of the ith trap, respectively.

The signal of DCTS is defined as [7]

$$D(t, e_{\mathrm{ref}}) \equiv \frac{t}{qS}\left[I_{\mathrm{TR}}(t) - I_1(V_R)\right]\exp(-e_{\mathrm{ref}}t + 1)\,, \tag{2}$$

where we can shift the peak discharge time of the DCTS signal by changing the parameter (e_{ref}). Substituting $I_{\mathrm{TR}}(t)$ in Eq. (1) for $I_{\mathrm{TR}}(t)$ in Eq. (2) yields

$$D(t, e_{\mathrm{ref}}) = \sum_{i=1} N_{\mathrm{t}i} e_{\mathrm{t}i} t \exp\left[-(e_{\mathrm{t}i} + e_{\mathrm{ref}})t + 1\right]. \tag{3}$$

The peak value of the DCTS signal is

$$D(t_{\mathrm{peak}i}, e_{\mathrm{ref}}) = N_{\mathrm{t}i}\left(1 - e_{\mathrm{ref}} t_{\mathrm{peak}i}\right). \tag{4}$$

at

$$t_{\mathrm{peak}i} = \frac{1}{e_{\mathrm{t}i} + e_{\mathrm{ref}}}\,. \tag{5}$$

Using $t_{\mathrm{peak}i}$ and $D(t_{\mathrm{peak}i}, e_{\mathrm{ref}})$, the values of $N_{\mathrm{t}i}$ and $e_{\mathrm{t}i}$ can be determined as

$$N_{\mathrm{t}i} = \frac{D(t_{\mathrm{peak}i}, e_{\mathrm{ref}})}{(1 - e_{\mathrm{ref}} t_{\mathrm{peak}i})}\,. \tag{6}$$

and

$$e_{\mathrm{t}i} = \frac{1}{t_{\mathrm{peak}i}} - e_{\mathrm{ref}}\,. \tag{7}$$

respectively. When more than one trap with close emission rates exist in a semi-insulating SiC, the DCTS signal became broader and each peak cannot be distinguished. In this case, from the maximum of the DCTS signal when e_{ref} is changed continuously, the density and emission rate of each trap can be determined [7].

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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. $I_{TR}(t)$ was measured at –100 V at 373 K. The densities and emission rates of traps in semi-insulating 4H-SiC were determined by the DCTS method.

Results and Discussion

The current-voltage characteristics of the semi-insulating 4H-SiC diode showed the characteristics of a back-to-back diode. Figure 1 shows $I_{TR}(t)$ at –100 V at 373 K in the diode. The DCTS signal was calculated using Eq. (2) with $e_{ref} = 0$ s^{-1} and $I_1(-100) = 1.24$ pA, and denoted by the solid curve in Fig. 2. The maximum time and value are 216 s and 1.69×10^{11} cm^{-2}, respectively. From Eqs. (6) and (7), N_{t1} and e_{t1} of the corresponding trap (Trap1) are determined to be 4.61×10^{-3} s^{-1} and 1.69×10^{11} cm^{-2}, respectively. In the figure, the broken curve represents the signal simulated with the obtained values using

$$D(t, e_{ref}) = N_{t1} e_{t1} t \exp[-(e_{t1} + e_{ref})t + 1]. \quad (8)$$

Since the solid curve is larger than the broken curve at < 100 s, the DCTS signal is considered to be affected by other traps.

In order to evaluate other traps, e_{ref} was chanced. The solid curve in Fig. 3 represents the DCTS signal with $e_{ref} = 0.002$ s^{-1}. The maximum time and value are 107 s and 1.23×10^{11} cm^{-2}, respectively. From Eqs. (6) and (7), N_{t2} and e_{t2} of the corresponding trap (Trap2) are determined to be 7.29×10^{-3} s^{-1} and 1.57×10^{11} cm^{-2}, respectively. In the figure, the broken curve represents the signal simulated with the obtained values. Since the solid curve is much broader than the broken curve, the DCTS signal is considered to be affected by other traps with close emission rates

Figure 4 shows the DCTS signal (solid curve) with $e_{ref} = 0.2$ s^{-1}. The maximum time and value are 3.58 s and 1.29×10^{10} cm^{-2}, respectively. From Eqs. (6) and (7), N_{t3} and

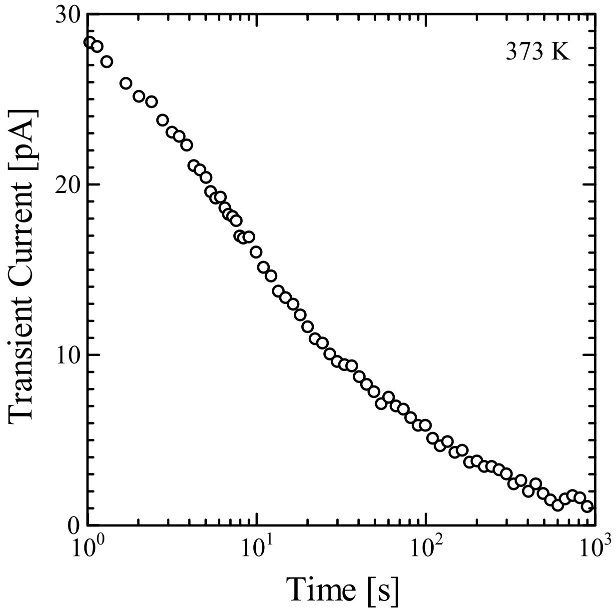

Fig. 1. The transient reverse current of semi-insulating 4H-SiC.

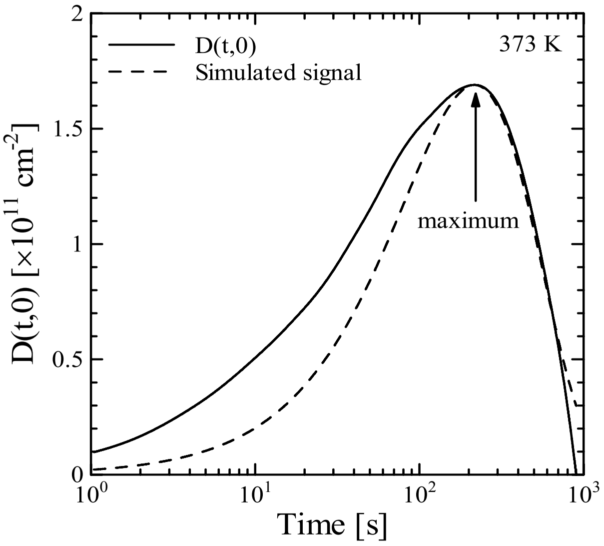

Fig. 2. DCTS signals with $e_{ref} = 0$ s^{-1}.

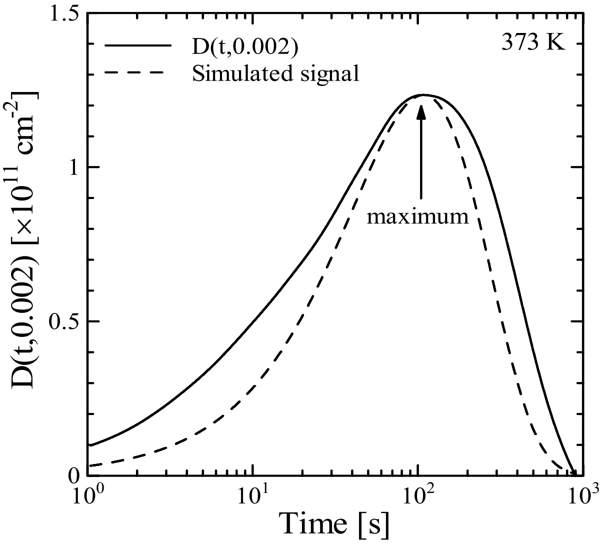

Fig. 3. DCTS signals with $e_{ref} = 0.002$ s^{-1}.

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e_{t3} of the corresponding trap (Trap3) are determined to be 7.86×10^{-2} s^{-1} and 4.56×10^{10} cm^{-2}, respectively. In the figure, the broken curve represents the signal simulated with the obtained values. Judging from these results, at least three types of traps are included in the semi-insulating 4H-SiC.

Figure 5 shows the e_{ref} dependence of N_t (broken line) or e_t (solid line) determined from the maximum of the DCTS signal. At least three discrete values of e_t or N_t clearly appear in the figure. Moreover, the e_{ref} range of the almost constant N_t clearly corresponds one to one to the e_{ref} range of the almost constant e_t. Therefore, it is found that DCTS can distinguish among three types of traps (Trap1, Trap2 and Trap3) with close emission rates by changing e_{ref}. From the average of the almost constant N_t and e_t, N_t and e_t of each trap are determined; e_{t1} and N_{t1} are 4.9×10^{-3} s^{-1} and 1.7×10^{11} cm^{-2}, respectively, and e_{t2} and N_{t2} are 8.3×10^{-3} s^{-1} and 1.5×10^{11} cm^{-2}, respectively, and e_{t3} and N_{t3} are 8.0×10^{-2} s^{-1} and 4.5×10^{10} cm^{-2}, respectively.

Conclusion

From the transient reverse current of the metal/semi-insulating 4H-SiC/metal diode, the densities and emission rates of three types of traps in the semi-insulating 4H-SiC could be determined by the transient current method (i.e., DCTS).

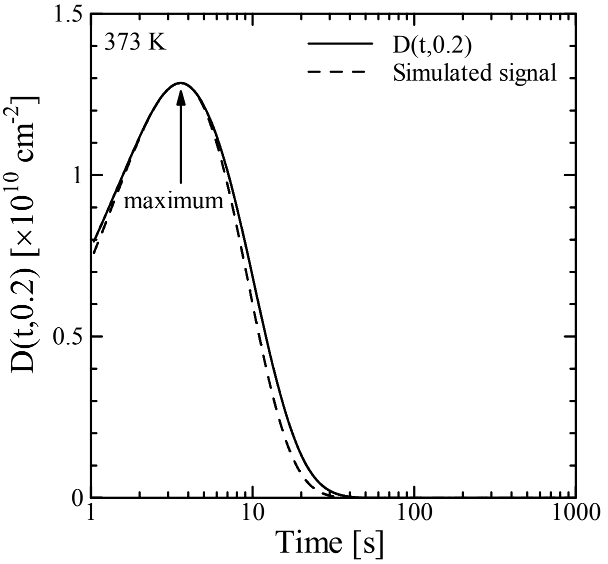

Fig. 4. DCTS signals with $e_{ref} = 0.2$ s^{-1}.

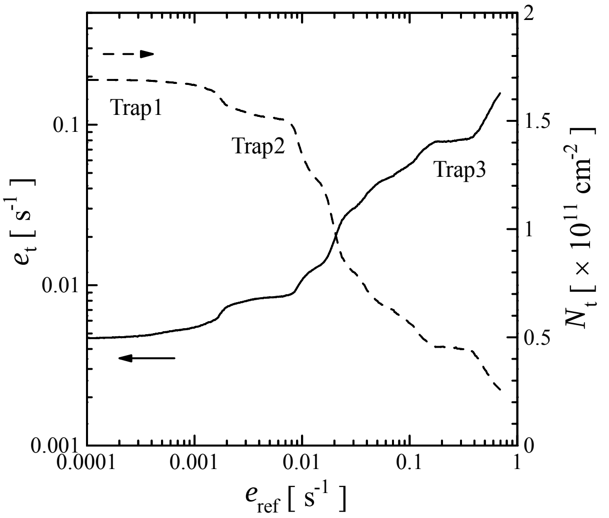

Fig. 5. The e_{ref} dependence of N_{ti} or e_{ti} determined from the DCTS signal.

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