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Effects of Sacrificial Oxidation on Characterization of Defects in High-Purity Semi-Insulating 4H-SiC by Discharge Current Transient Spectroscopy

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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), 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. The reverse current consists of the reverse current through the balk and the surface leakage current of the diode. It is elucidated that the sacrificial oxidation could dramatically reduce the surface currents of diodes in the case of high-purity semi-insulating 4H-SiC, suggesting that the densities and emission rates of traps in the bulk of the SiC can be determined from the transient reverse current.

Introduction

We have investigated X-ray detectors operating at room temperature using semi-insulating SiC. Semi-insulating semiconductors are essential for next-generation semiconductor devices. However, there are electrically active intrinsic defects (i.e., traps) in these semiconductors. Because these traps behave as generation centers in the depletion region of the diode and produce a generation current in the reverse-biased diode, they degrade the performance of X-ray detectors. To determine the possibility of semi-insulating SiC being used as a portable X-ray detector operating at room temperature, it is necessary to investigate these traps.

Although transient capacitance methods, e.g., deep level transient spectroscopy (DLTS) [1], are powerful methods to characterize traps in low-resistivity semiconductors, they are not feasible in semi-insulating semiconductors because the measured capacitance of the diode fabricated using semi-insulating semiconductors is determined by the thickness of the diode, not by the depletion region of the junction [2,3]. Thermally stimulated current (TSC) [4] is suitable for characterizing traps in semi-insulating semiconductors. However, it is difficult to analyze experimental TSC data when traps with similar emission rates are included in the semiconductor. Moreover, because the effect of pyroelectric currents and the temperature dependence of the steady-state leakage current must be considered in the TSC analysis, an isothermal measurement is more suitable for characterizing traps than is TSC.

Without any assumptions regarding traps, 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), and has applied it to high-purity semi-insulating SiC [5,6]. However, these transient currents consisted of currents not only in the bulk, but also on the surface of the diode. The surface leakage current results mainly from surface defects formed by mechanical and chemical polishing of SiC surfaces. To remove those surface defects, the SiC surfaces including the defects are oxidized, and then the oxidized layers are etched using HF, which is referred to as sacrificial oxidation.

In this study, we report on our investigation of the effects of sacrificial oxidation on the characterization of high-purity semi-insulating 4H-SiC

Discharge Current Transient Spectroscopy

DCTS can determine the densities and emission rates of defects in a semi-insulating semiconductor from the transient reverse current $I_{\mathrm{dis}}(t)$ of a Schottky barrier diode at a constant temperature [7,8]. In DCTS, the following evaluation function is defined using the experimental $I_{\mathrm{dis}}(t)$:

$$D(t, e_{\mathrm{ref}}) \equiv \frac{t}{qS}\left[I_{\mathrm{dis}}(t) - I_{\mathrm{S}}(V_{\mathrm{R}})\right]\exp(-e_{\mathrm{ref}}t + 1) \,, \tag{1}$$

where $I_{\mathrm{S}}(V_R)$ 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 [9]. From the time ($t_{\mathrm{peak}i}$) and value ($D(t_{\mathrm{peak}i}, e_{\mathrm{ref}})$) of each peak, we can accurately determine the emission rate ($e_{\mathrm{t}i}$) and sheet density ($N_{\mathrm{t}i}$) of the corresponding defect as:

$$e_{\mathrm{t}i} = \frac{1}{t_{\mathrm{peak}i}} - e_{\mathrm{ref}} \tag{2}$$

and

$$N_{\mathrm{t}i} = \frac{D(t_{\mathrm{peak}i}, e_{\mathrm{ref}})}{1 - e_{\mathrm{ref}}t_{\mathrm{peak}i}} \,, \tag{3}$$

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

Experiment

A 0.3713-mm-thick high-purity semi-insulating 4H-SiC wafer was purchased from Cree Inc., and was cut to a size of 5 mm × 5 mm. The diode without sacrificial oxidation was fabricated as follows: Ni electrodes with a radius of 1.25 mm were evaporated onto both sides of the chip. Since thermal treatment was not carried out, the diodes work as a back-to-back diode. After the current-voltage ($I - V$) characteristics and transient current were measured, the diode with sacrificial oxidation was fabricated. After the Ni electrodes were removed using HCl, each side of the chip surface was oxidized in an O_2 atmosphere at 1273 K for 2 hours. After the sacrificial oxide layer on the chip was removed using HF, Ni electrodes with the same radius were evaporated onto both sides of the chip.

The $I - V$ characteristics of the diodes were measured from 0 to -100 V using a Keithley 236 source-measure unit (SMU236). We waited for 30 s, referred to as the delay time, to measure the reverse current at each bias after the bias was changed by -1 V [6]. After the bias voltage was rapidly changed from 0 V to –100 V, $I_{\mathrm{dis}}(t)$ was measured at V_{R} of -100 V at 393 K. The densities and emission rates of traps in semi-insulating 4H-SiC were determined by DCTS.

Results and Discussion

Figure 1 shows the $I - V$ characteristics obtained devices fabricate on surfaces with and without sacrificial oxidation, denoted by open circles and solid diamonds, respectively. The leakage currents at -100 V were -122.9 and -15.8 pA without and with sacrificial oxidation, respectively. It is clear from Fig. 1 that the sacrificial oxidation could dramatically reduce the current proportional to the bias in the diode without sacrificial oxidation, which might be a surface current.

Figure 2 shows the transient reverse current obtained devices fabricate on surfaces with and without sacrificial oxidation, denoted by open circles and solid diamonds, respectively. The transient reverse currents at 1000 s, which are assumed to be $I_{\mathrm{S}}(V_{\mathrm{R}})$, were -115.5 and -26.0 pA without and with sacrificial oxidation, respectively. Since $I_{\mathrm{S}}(V_{\mathrm{R}})$ was reduced by sacrificial oxidation, we can measure $I_{\mathrm{dis}}(t)$ due to the emission of traps in the bulk over a wide time range.

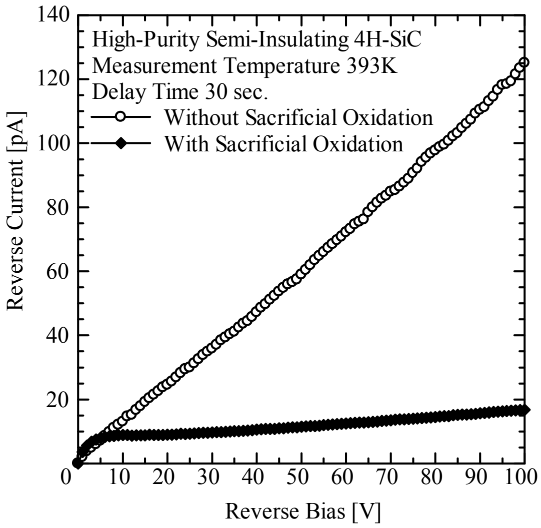

Fig. 1. $I-V$ characteristics for devices fabricated on surfaces with and without sacrificial oxidation.

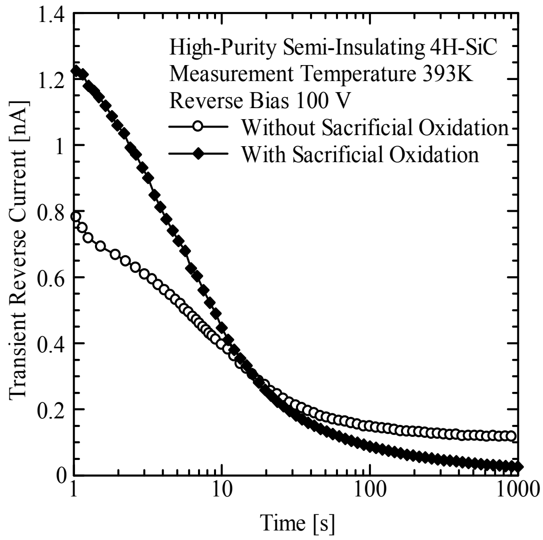

Fig. 2. Transient reverse current for devices fabricated on surfaces with and without sacrificial oxidation.

Figure 3 shows the DCTS signal with $e_{\mathrm{ref}} = 0$ s^{-1}, denoted by the solid line. One peak and one shoulder appear in the figure. From Eqs. (2) and (3), e_{t1} and N_{t1} of the corresponding trap (Trap1) are determined as 5.24 × 10^{-3} s^{-1} and 2.21 × 10^{12} cm^{-2}, respectively. In the figure, the broken line represents the signal simulated with the obtained values using

$$D_{\mathrm{t}i}\left(t, e_{\mathrm{ref}}\right) = N_{\mathrm{t}i} e_{\mathrm{t}i} t \exp\left[-\left(e_{\mathrm{t}i} + e_{\mathrm{ref}}\right)t + 1\right]. \tag{4}$$

It is clear from Eqs. (3) and (4) that the peak value of the component of the DCTS signal corresponding to each trap can be changed by e_{ref}. Figure 4 shows the DCTS signal with $e_{\mathrm{ref}} = 0.02$ s^{-1}, denoted by the solid line. The peak in Fig. 4 corresponds to the shoulder in Fig. 3. Using Eqs. (2) and (3), e_{t2} and N_{t2} of the corresponding trap (Trap2) are determined as 9.20 × 10^{-2} s^{-1} and 1.46 × 10^{12} cm^{-2}, respectively. In the figure, the broken line represents the signal simulated with the obtained values using Eq. (4). Since the measured signal is larger than the broken line for times < 10 s, the DCTS signal is considered to be affected by other traps. Figure 5 shows the DCTS signal with $e_{\mathrm{ref}} = 0.126$ s^{-1}, denoted by the solid line. Using Eqs. (2) and (3), e_{t3} and N_{t3} of the corresponding trap (Trap3) are determined as 1.27 × 10^{-1} s^{-1} and 1.29 × 10^{12} cm^{-2}, respectively. In the figure, the broken line represents the signal simulated with the obtained values using Eq. (4). Since the broken

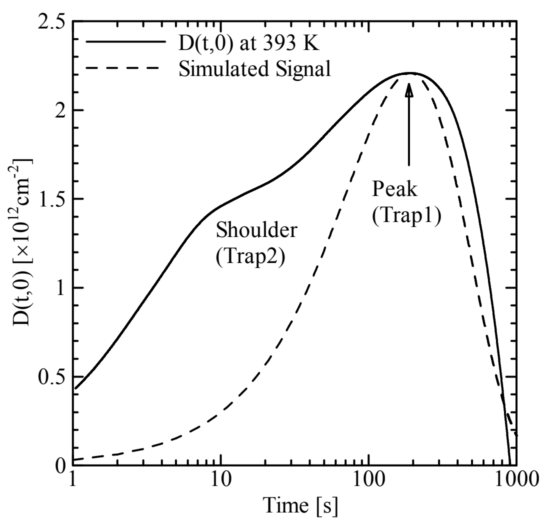

Fig. 3. DCTS signal with $e_{\mathrm{ref}} = 0$ s^{-1}.

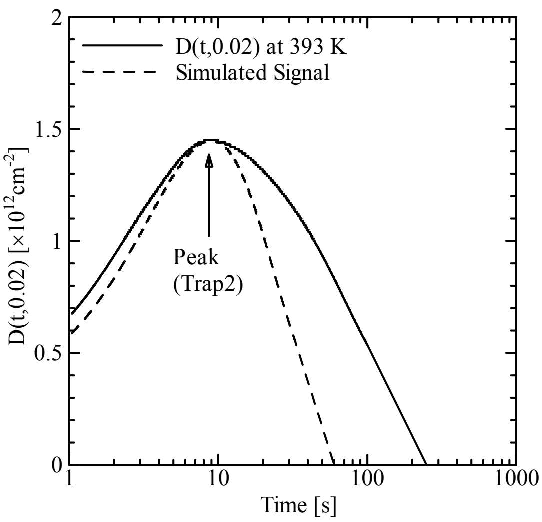

Fig. 4. DCTS signal with $e_{\mathrm{ref}} = 0.02$ s^{-1}.

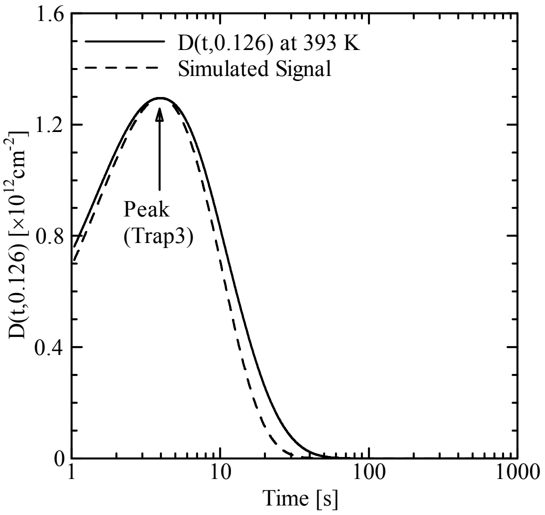

Fig. 5. DCTS signal with $e_{\text{ref}} = 0.126\ \text{s}^{-1}$.

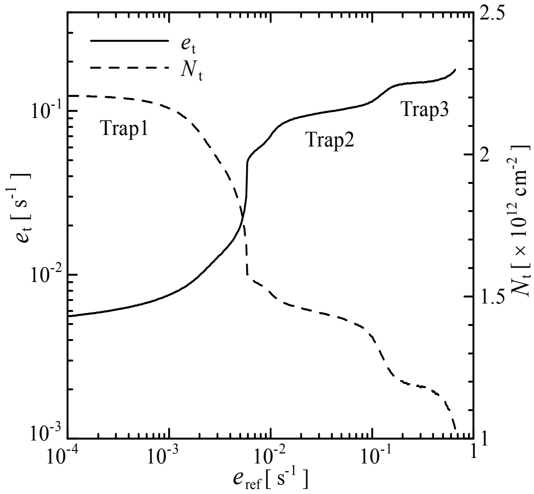

Fig. 6. The e_{ref} dependence of $e_{\text{t}i}$ and $N_{\text{t}i}$ determined from the maximum of the DCTS signal.

line is fitted with the solid line, the DCTS signal is considered to be affected by other traps with comparable emission rates. Judging from these results, at least three types of traps are included in the high-purity semi-insulating 4H-SiC.

Figure 6 shows the e_{ref} dependence of $e_{\text{t}i}$ (solid line) or $N_{\text{t}i}$ (broken line) determined from the maximum of the DCTS signal calculated using each e_{ref}. In this analysis [7], the e_{ref} range of almost constant e_{t} and N_{t} corresponds to a trap with a discrete energy level. At least three discrete values of e_{t} or N_{t} clearly appear in the figure, and are close to the obtained values in Figs. 3-5.

Summary

It is elucidated that sacrificial oxidation could dramatically reduce the surface currents of diodes in high-purity semi-insulating 4H-SiC, suggesting that the densities and emission rates of traps in the bulk of the SiC can be determined from the transient reverse current. We applied DCTS to determine those properties of traps, and moreover could characterize three types of traps with comparable emission rates.

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