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# High-temperature characteristics of SiC Schottky barrier diodes related to physical phenomena

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**Abstract:** This paper experimentally studies the temperature dependencies of current–voltage (I–V) and capacitance–voltage (C–V) characteristics of SiC power devices, and discusses the relationships between physical phenomena and the measured characteristics in SiC. Two SiC Schottky barrier diodes (SBD) with different specifications were studied for temperatures ranging from 25 to 450°C. Their I–V characteristics show that SBDs indeed function as rectifiers at extremely high temperatures, but forward conduction and reverse blocking performance significantly deteriorates when the temperature exceeds 200°C. C–V characteristics show diffusion potential reduction with temperature, and p–n junction characteristics were found for the junction barrier Schottky structure.

**Keywords:** temperature characteristics, SiC, Schottky barrier diode, device structure

**Classification:** Electron devices

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## 1 Introduction

Wide bandgap semiconductor devices have attracted attention for potentially overcoming the performance limitations of semiconductor devices, which result from the material properties of conventional semiconductor Si [1]. SiC in particular has been seen as an ideal semiconductor material for high voltage power devices, due to its high critical breakdown electric field and large thermal conductivity [2, 3]. We have focused on the high temperature operational capabilities of SiC devices, and studied the switching behavior of SiC Schottky barrier diodes (SBD) and JFETs under extremely high ambient temperature [4, 5, 6]. We have also clarified the junction capacitance–reverse bias voltage (C–V) characteristics of SiC devices for the entire rated voltage range, and related these to the device structure and process parameters [7, 8].

This paper advances these studies, and discusses the temperature dependency of current–voltage (I–V) and C–V characteristics of SiC devices, from 25 to 450°C, then relates these characteristics to physical phenomena in SiC. Two types of SiC SBDs are studied: SBD1 has 600 V, 6 A ratings (SDP06S60, Infineon, 1.4 × 1.4 mm), and SBD2 has 600 V, 4 A ratings (CPWR-0600S004, Cree, 1.39 × 1.39 mm). SBD2 has a junction barrier Schottky (JBS) structure [9], and the characteristics induced by the JBS structure are precisely investigated.

Section 2 discusses the temperature dependency of forward conduction and reverse blocking I–V characteristics. Section 3 discusses the temperature dependency of C–V characteristics. Section 4 presents the conclusion.

## 2 Temperature dependency of I–V characteristics

### 2.1 Forward conduction characteristics

The temperature dependencies of forward conduction I–V characteristics were measured. The device was placed in a temperature controlled chamber filled with air, and the temperature was varied from 25 to 450°C in 25°C


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steps. The I–V characteristics were measured with a Tektronix 371B curve tracer and heat resistive wire while maintaining Kelvin connection.

Fig. 1 (a) and (b) shows the measured result at temperatures of 25, 150, 300, and 450°C, for SBD1 and SBD2. The characteristic curves of both devices exhibit a shallower slope and smaller ramp-up voltage as the temperature increases. The effective series resistances in the SBDs are extracted from the high current region of the I–V characteristics, as shown in Fig. 1 (c).

When the temperature dependency of the series resistance $R$ is approximated by Eq. (1), the coefficient $n$ for the respective devices becomes:

$$R = R_0 \left( \frac{T}{T_0} \right)^n . \tag{1}$$

Here, $T$ is the absolute temperature, and $R_0$ is the resistance at reference temperature $T_0$.

The series resistance of SBD1 is approximated by $n = 1.66$ for temperatures higher than 200°C and by $n = 0.17$ for temperatures lower than 100°C. The series resistance of SBD2 is approximated by $n = 2.12$ for temperatures higher than 200°C, and $n = 0.69$ for temperatures lower than 100°C. This clearly shows the characteristic change from the low (around room) temperature to high temperature region for both devices, and that a single $n$ value cannot approximate the series resistance over the entire temperature range. It can be interpreted that the acoustic phonon scattering and intervalley scattering dominate the resistance characteristics in the high temperature region, and impurity scattering affects the characteristics in the low temperature region. But, another important factor is incomplete ionization of donors at room temperature, due to the relatively deep donor levels in SiC. This affects the low temperature characteristics. Conventionally, acoustic phonon scattering and intervalley scattering dominate the resistance characteristics for Si devices. Therefore, these results indicate characteristics specific to SiC

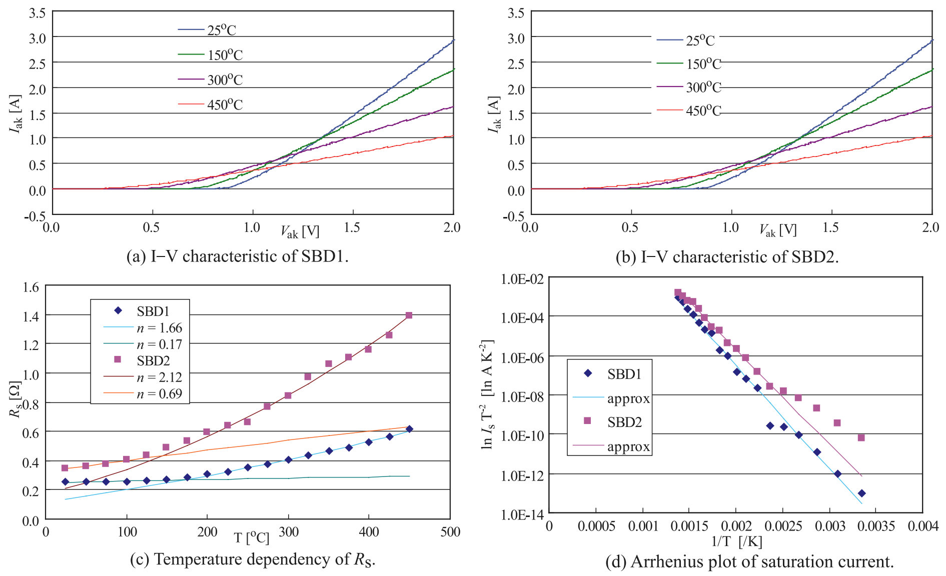


**Fig. 1.** Temperature dependency of forward conduction characteristics of SiC SBDs.

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SBDs.

The saturation current of SBDs, $I_{\mathrm{S}}$, which is expressed by Eq. (2), is extracted from the data in the low current region. The barrier height, $\phi_{\mathrm{B}}$, is extracted from an Arrhenius plot of saturation current in Fig. 1 (d).

$$I_{\mathrm{s}} = A^{*}T^{2}e^{-\frac{q}{kT}\phi_{\mathrm{B}}}. \tag{2}$$

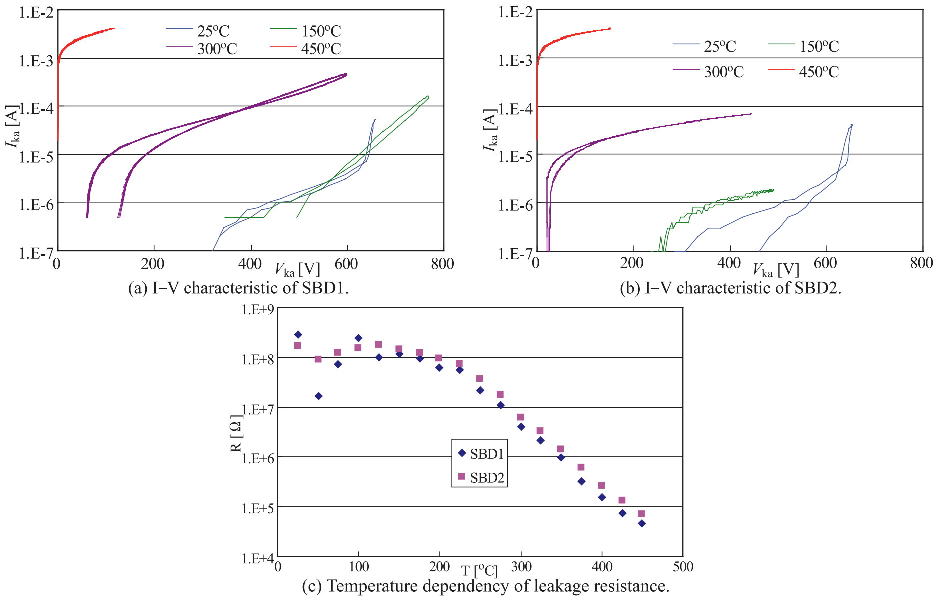
Here, $A^{*}$ is the effective Richardson constant, $q$ is the unit charge, and $k$ is the Boltzmann constant.

SBD1 and SBD2 show $\phi_{\mathrm{B}} = 0.96$ and $0.88\,\mathrm{eV}$, respectively. The barrier heights are considered as reasonable for a SiC SBD, which is estimated from the bandgap of SiC and the work function of Schottky metal Ti. The smaller barrier height in SBD2 may attribute to the difference in the fabricated process.

## 2.2 Reverse blocking characteristics

The reverse leakage current and temperature dependency of SiC SBDs were evaluated with the same measurement setup as in the last subsection. The measured I–V characteristics for SBD1 and SBD2 are shown in Fig. 2 (a) and (b), respectively. Both SBDs have breakdown voltages higher than 600 V at room temperature with avalanche characteristics. The results also show that the leakage current at blocking condition increases with temperature. The temperature dependency of the leakage resistance of SiC SBD at blocking condition is shown in Fig. 2 (c). For temperatures below 200°C, the leakage resistance for both devices is greater than 10 MΩ; however, the leakage resistance diminishes significantly with temperature in the high temperature region (> 200°C).

The temperature dependency of I–V characteristics for forward conduction and reverse blocking demonstrate that the studied SiC SBDs can func-



(a) I–V characteristic of SBD1. (b) I–V characteristic of SBD2. (c) Temperature dependency of leakage resistance.

**Fig. 2.** Temperature dependency of reverse blocking characteristics of SiC SBDs.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tion as diodes at high temperature. Conduction and blocking performance, however, deteriorate significantly when the temperature increases into the high temperature region (> 200°C).

## 3 Temperature dependency of C–V characteristics

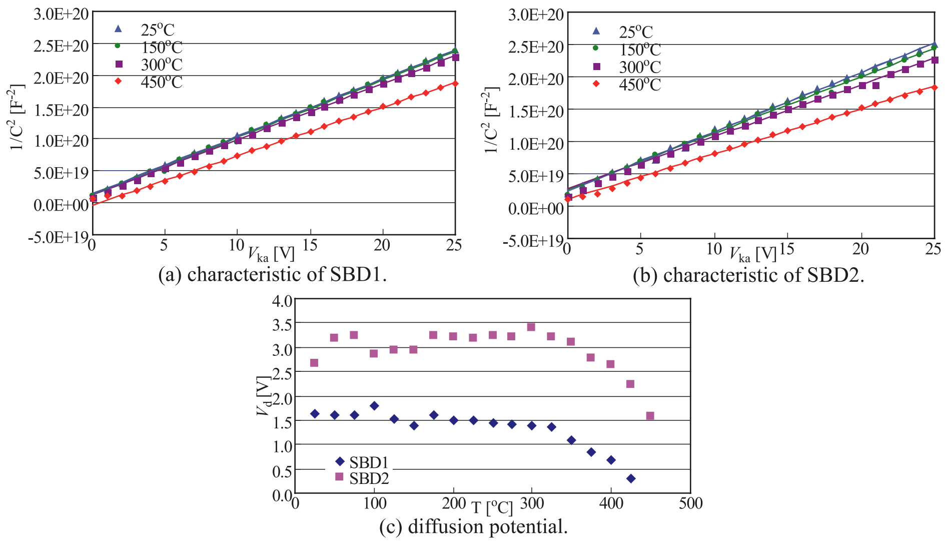
The C–V characteristics of SiC SBDs and their temperature dependencies are evaluated in this section. The measurement setup presented in a reference [7] was used for the measurement. Fig. 3 shows the measured results for four temperature parameters for SBD1 and SBD2. They show that the junction capacitance for the same bias voltage increases with a rise in temperature.

The relation between the differential capacitance, induced by the depletion region in the drift layer, and the bias voltage condition can be expressed as in Eq. (3) [10].

$$\frac{1}{C^2} = \frac{2\,(V - V_\mathrm{d})}{S^2 \varepsilon_0 \varepsilon_\mathrm{s} q N_\mathrm{d}}. \tag{3}$$

Here, $V$ is the reverse bias voltage, $V_\mathrm{d}$ is the diffusion potential, $N_\mathrm{d}$ is the net donor concentration, $S$ is the area of the active region, and $\varepsilon_0$ and $\varepsilon_\mathrm{S}$ are the permittivity of vacuum and the relative permittivity.

The diffusion potential and the net donor concentration are extracted from the intercept and gradient of the $\frac{1}{C^2}$–V plot shown in Fig. 3 (a) and (b), respectively. The temperature dependency of the extracted $V_\mathrm{d}$ is shown in Fig. 3 (c). Fig. 3 (c) shows that SBD1 and SBD2 have diffusion potentials of approximately 1.5 and 3.0 V for a low temperature condition. Both values are higher than the barrier height extracted from the Arrhenius plot of saturation current in the last section. The difference between diffusion potential and barrier height is especially large for SBD2, which may be due to its device structure. That is, SBD2 implements a JBS structure, and the expansion of depletion region, which originates from an implanted p$^+$ well, introduces



(a) characteristic of SBD1.
(b) characteristic of SBD2.
(c) diffusion potential.

**Fig. 3.** Temperature dependency of C–V characteristics of SiC SBDs.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p–n junction characteristics in the diffusion potential. The diffusion potential shows temperature dependency, and decreases with a rise in temperature, as shown in Fig. 3 (c).

## 4 Conclusion

This paper measured I–V and C–V characteristics for two types of SiC SBD, and characterized their temperature dependency. The device parameters were also extracted from the characterized results, and their temperature dependencies were associated with the physical phenomenon occurring in the devices.

The SiC SBDs maintained their rectification properties and operated as diodes under extremely high temperatures. The static performance degradation becomes severe when the temperature exceeds 200°C. The performance degradation of the majority carrier device at high temperature is unavoidable, but the temperature at which noticeable characteristic changes occur can be managed by optimizing the device geometry size and process parameters.

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