SiC Schottky Barrier Diodes

Outline:

This application note describes the differences in physical properties between silicon carbide (SiC), a wide-bandgap semiconductor, and silicon (Si), which are materials of power semiconductor devices. It also discusses the high withstand voltage of SiC Schottky barrier diodes (SBDs) and why the JBS and MPS structures help improve leakage and surge current that are problems of SBDs.

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1. SiC power devices

Silicon carbide (SiC) comprises silicon (Si) and carbon (C) atoms. Each atom is surrounded by four different atoms in the form of a regular tetrahedron. SiC is a compound semiconductor with the densest tetrahedral arrangement. SiC has many crystalline structures called polytypes that exhibit different physical properties because of periodic differences in the overlap of tetrahedrons.

Compared to silicon, SiC has a wider energy gap where no electron states can exist (called a bandgap) between the valence band (i.e., an energy band filled with valence electrons) and the conduction band (i.e., an empty energy band in which electrons can be present). A wide bandgap provides a strong chemical bond among atoms and therefore a high electric breakdown field. SiC has an electric breakdown field roughly ten times that of silicon. Because of a strong atomic bond, SiC has greater lattice vibration and consequently conducts energy more easily than silicon. Therefore, SiC is a semiconductor material with good thermal conduction. The polytypes of SiC include 4H-SiC and 6H-SiC that are hexagonal crystal structures and 3C-SiC that is a cubic crystal structure. Table 1-1 compares the physical properties of silicon and other semiconductor materials. 4H-SiC is commonly used as a semiconductor material because it provides a better balance among electron mobility, dielectric breakdown strength, saturation velocity, and other physical properties than other polytypes of SiC.

Table 1-1 Physical properties of typical semiconductor materials

Property	Unit	Si	4H-SiC	6H-SiC	3C-SiC	GaN	GaAs	Diamond
Bandgap	eV	1.12	3.26	3.02	2.23	3.39	1.43	5.47
Electron mobility μ_e	cm^2/Vs	1400	1000/1200	450/100	1000	900	8500	2200
Hole mobility μ_h		600	120	100	50	150	400	1600
Electric breakdown field E_c	V/cm	3.0×10^5	2.8×10^6	3.0×10^6	1.5×10^6	3.3×10^6	4.0×10^5	1.0×10^7
Thermal conductivity λ	W/cmK	1.5	4.9	4.9	4.9	2.0	0.5	20
Saturated electron drift velocity V_{sat}	cm/s	1.0×10^7	2.2×10^7	1.9×10^7	2.7×10^7	2.7×10^7	2.0×10^7	2.7×10^7
Relative dielectric constant ε		11.8	9.7/10.2	9.7/10.2	9.7	9.0	12.8	5.5

As shown in Table 1-2, the resistance of the drift region accounts for a large percentage of the on-resistance per area of high-voltage power devices. To reduce on-resistance, it is necessary to either increase the dopant concentration in the drift region or reduce its thickness. However, the dopant concentration is inversely proportional to the withstand voltage. In the case of silicon with low breakdown strength, it is impossible to further increase the dopant concentration without compromising the withstand voltage. It is also difficult to reduce the thickness of the drift region of a silicon device because the expansion of the depletion region could cause punch-through (between drain and source) when a reverse bias is applied across the drain and source. SiC power devices with breakthrough performance have been appearing lately because the dielectric breakdown strength of 4H-SiC is nearly ten times that of silicon as shown in Table 1-1. For example, the withstand voltage of a MOSFET can be simply expressed as:

Withstand voltage = maximum electric breakdown field × depletion region thickness ÷ 2

(The assumption is a triangular electric field distribution.)

This equation indicates that because of a higher electric breakdown field than that of silicon, SiC makes it possible to increase the dopant concentration in the drift region and thereby reduce its thickness to obtain the same withstand voltage. Electron and hole mobilities (μ) characterize how quickly an electric field can accelerate the velocity of an electron or a hole (velocity = mobility (μ) × electric field (E)). A higher mobility (μ) means that an electric current flows more easily, resulting in lower resistance. The maximum velocity attainable is called the saturation velocity.

Table 1-2 Simulated on-resistances of a double-diffused Si MOSFET

Withstand Voltage	600V	1000V
R_{ch}	1%	0.3%
R_{JFET}	18%	14%
R_{drift}	81%	86%
R_{sub}	0.1%	0.03%
TTL	100%	100%

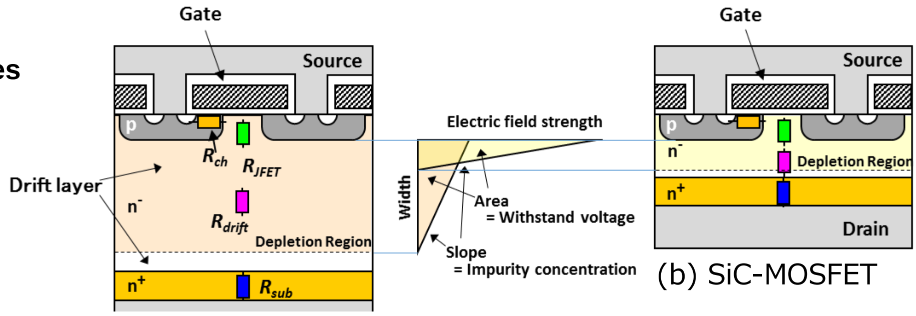

Figure 1-1 Structure of a double-diffused MOSFET

In addition, the high thermal conductivity (λ) of SiC makes it ideal as a material for high-power semiconductor devices.

SiC makes it possible to create high-voltage power devices with unprecedentedly low on-resistance thanks to a heavily doped thin drift region as shown in Figure 1-1 (b).

2. SiC Schottky barrier diodes (SBDs)

For example, high-voltage diodes are used in power factor correction (PFC) circuits for power supplies and as freewheel diodes in inverter circuits. High AC power is applied to switch on and off these circuits repeatedly. Table 2-1 shows the electrical characteristics and features of high-voltage diodes.

Table 2-1 Comparison of the characteristics of high-voltage diodes

Electrical characteristic and symbol **(Improvement direction)**	**Effect on circuits**	**Si material**		**SiC material**	
		FRD	**SBD**	**SBD**	**SBD (Improved JBS structure)**
Withstand voltage, V_R (High)	Voltage surge during switching	★★★★*	★	★★★★★	★★★★★
Leakage current, IR (Low)	Thermal runaway	★★	★	★★★	★★★★
Forward Voltage, VF (Low)	Considerable effect on efficiency	★★★	★★★★★	★★★	★★★
Reverse recovery time, t_{rr} (Low)	Considerable effect on efficiency	★	★★★★★	★★★★★	★★★★★
Surge Current, I_{FSM} (Large)	Inrush current when switching on	★★★★★	★	★	★★★

A larger number of ★ indicates better. * FRD: Fast recovery diode

Nowadays, there is demand for increasing the efficiency, suppressing the noise, and reducing the size of power supplies. To reduce the size of power supplies, they are operated at increasingly high frequency, causing switching loss to constitute an increasingly large percentage of overall power loss. Switching loss is reduced by using various circuit design techniques, such as soft switching that makes a circuit less susceptible to the effect of reverse recovery charge (Q_{rr}), a major contributing factor for switching loss.

As is commonly known, Q_{rr} is caused by residual minority carriers that occur when a pn junction diode transitions from the “on” to “off” state. For this reason, it is ideal for this application because SBDs that use Schottky barriers generated by semiconductor-metal junctions rather than pn junctions do not have minority carriers. However, high-voltage SBDs cannot be fabricated using silicon.

SBDs have other drawbacks. An SBD has a possibility of thermal runaway because of a larger leakage current than that of a pn junction diode, low surge current capability, and no margin against surge current (inrush current) during the turn-on of a power supply circuit.

The use of SiC, a wide-bandgap semiconductor, provides a solution to the withstand voltage problem. In addition, a new SBD structure solves the leakage and surge current problems. The following sections describe these benefits of SiC SBDs.

Figure 2-1 compares the turn-off waveforms of a silicon FRD and a SiC SBD with the same withstand voltage on the same circuit.

In principle, SiC SBDs have no reverse recovery charge (Q_{rr}) due to minority carriers. Although a small reverse recovery current flows because of metal-semiconductor junction capacitance and the pn junction of the JBS or MPS structure described later, the SiC SBD exhibits very low reverse recovery charge, which is the very characteristic of SBDs.

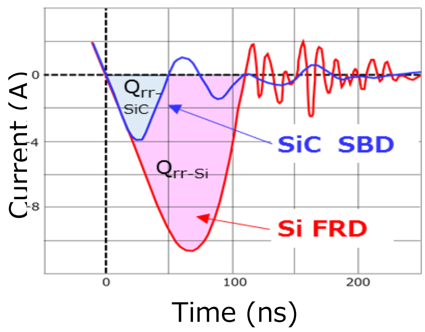

Figure 2-1 Turn-off waveform comparison between silicon and SiC SBDs

2.1. Increasing the withstand voltage using SiC

When an SBD with a typical structure is reverse-biased, the depletion region extends into the Si as shown in Figure 2-2 (a). The area of the triangle formed by the electric breakdown field and the depletion region thickness represents the withstand voltage of an SBD. The depletion region thickness is inversely proportional to the dopant concentration. Increasing the dopant concentration helps reduce the resistance of silicon and therefore the forward voltage (V_F) of the SBD, but at the expense of withstand voltage (i.e., triangle area).

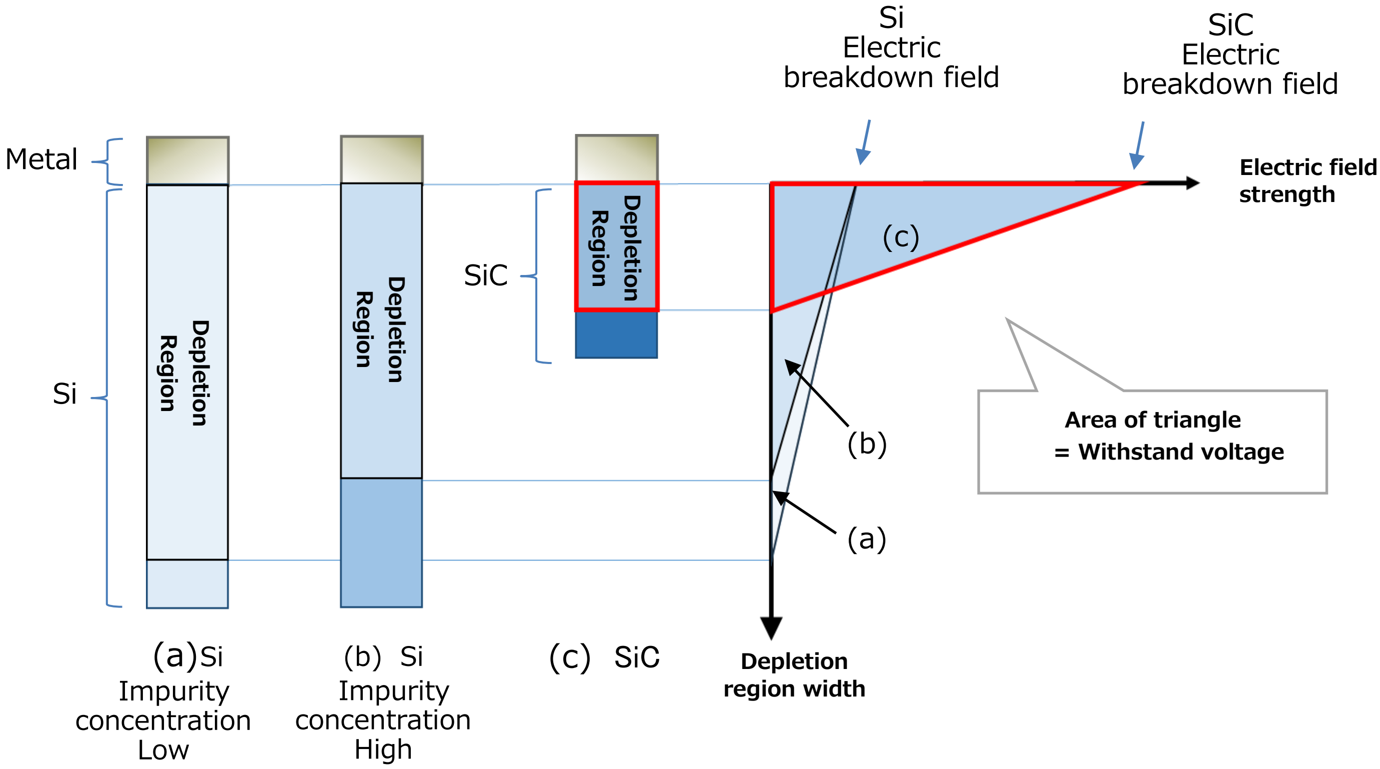

Figure 2-2 Relationship between withstand voltage and depletion region in SBD

The electric breakdown field of SiC is nearly 10 times as high as that of silicon. As shown in Figure 2-2 (c), it is therefore possible to increase the withstand voltage (i.e., triangle area) of a SiC SBD even if it is heavily doped to reduce the thickness of the depletion region.

Heavy doping also makes it possible to reduce the thickness of the SBD chip because of the reduced extension of the depletion region. When an SBD is forward-biased, the resistance across the thickness direction can be considered as series resistance. Therefore, reducing the chip thickness helps reduce the forward voltage of an SBD.

2.2. Junction Barrier Schottky (JBS) structure to reduce leakage current

An SBD is formed by the junction of a semiconductor with a metal. It acts as a diode because of a difference in the work function between a semiconductor and a metal. Because the molecular structure may be discontinuous at the semiconductor-metal interface, irregularities on the surface, crystal defects, or other anomalies may occur. The current called leakage current (I_r) flows when a high electric field is applied across a semiconductor-metal interface with many crystal defects.

In SBDs with a conventional structure, the depletion region extends into the semiconductor side as shown in Figure 2-3, causing the electric field produced by electric charge (or electrons) to be the strongest at the semiconductor-metal interface.

In contrast, in a JBS diode, the depletion region extends between p and n^- regions that are partially buried below the semiconductor surface. When the reverse bias voltage increases, p-type depletion regions punch through each other and the position of the maximum electric field moves directly under the p region. This reduces the electric field on the surface that has a high probability of defects, thereby reducing leakage current.

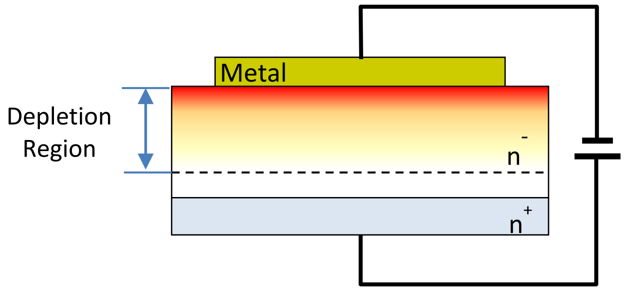

Figure 2-3 Depletion region and maximum electric field in a SBD with a conventional structure

The color depth of the n^- layer indicates the strength of the electric field

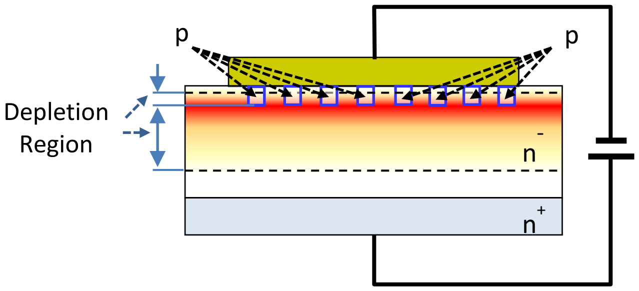

Figure 2-4 Depletion region and maximum electric field in a JBS diode

2.3. Improved JBS structure to increase the surge current capability

When a conventional SBD is forward-biased, current flows through the following path: metal → Schottky barrier → n^- layer → n^+ layer . The n^- layer has relatively large resistance because of low dopant concentration. Therefore, the I_F - V_F curve of this SBD looks like the one shown in Figure 2-5.

Applications of this SBD include PFC circuits, which must be guaranteed to operate at high current because they are instantaneously exposed to large current during the turn-on and turn-off of a power supply as well as during load variations. In that event, SBDs with an I_F - V_F curve like the one shown in Figure 2-6 might be overheated more than expected.

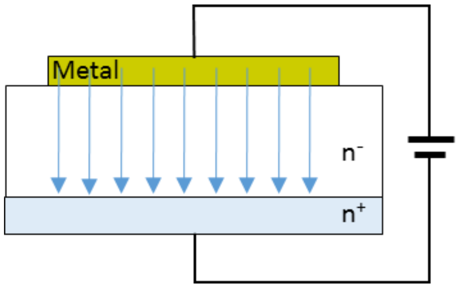

Figure 2-5 Current flow through a conventional SBD

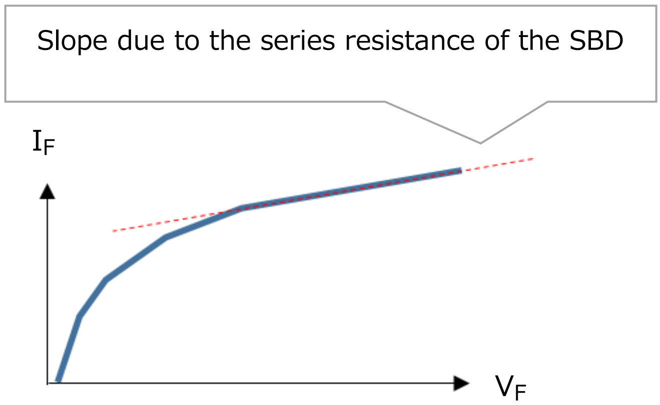

Figure 2-6 I_F-V_F curve of a conventional SBD

To address this problem, Toshiba has developed new SBDs with an improved JBS structure incorporating the concept of the Merged PiN Schottky (MPS) structure.

The MPS structure has p^+ regions buried in the n^- region of an SBD as shown in Figure 2-7 Shaded Area. (Toshiba's MPS structure has larger p^+ regions with higher dopant concentration in place of some of the p regions of the conventional JBS structure.) One of the p^+ regions and the n^- region form a pn junction diode, which turns on when large current (surge current) flows. This increases the current-carrying capability of the SBD, thereby reducing a rise in forward voltage even at high current and increasing the maximum allowable surge current. The MPS structure is characterized by the p^+–n^-–n^+ configuration below the anode electrode. At low current, the n^- region typically has high resistance. However, when this SBD is forward-biased, holes and electrons flow into the n^- region from the p and n regions respectively while maintaining electroneutrality. At this time, both holes and electrons exist in the n^- region with high concentration (Figure 2-8). Consequently, the n^- region acts like a heavily doped region, particularly at high current, exhibiting very low resistance (conductivity modulation).

As a result, this SBD has an I_F-V_F curve as shown in Figure 2-9, with low V_F in the high-current region.

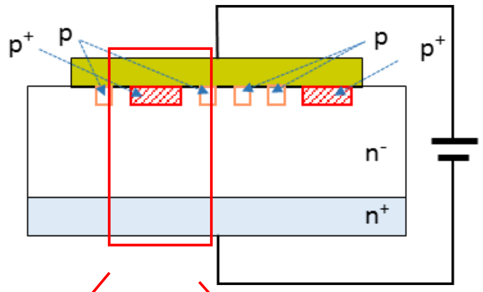

Figure 2-7 SBD with an improved JBS structure

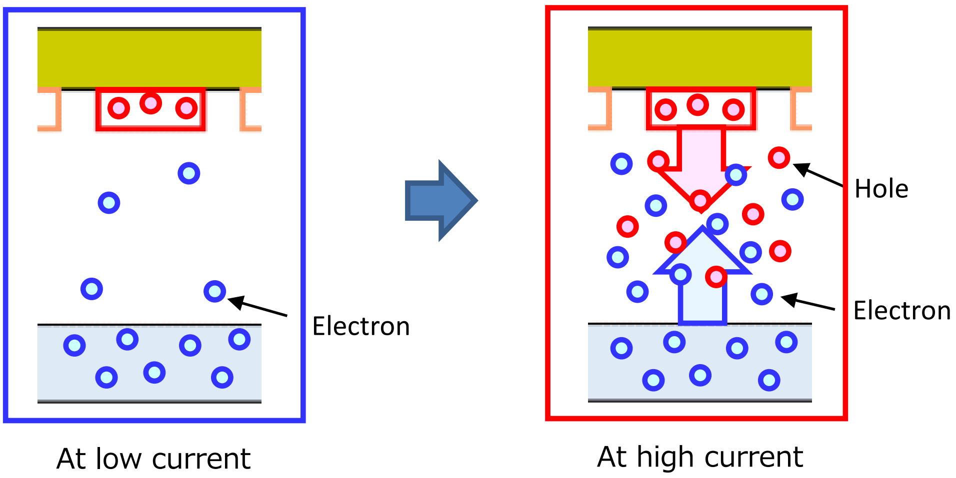

Figure 2-8 Conductivity modulation

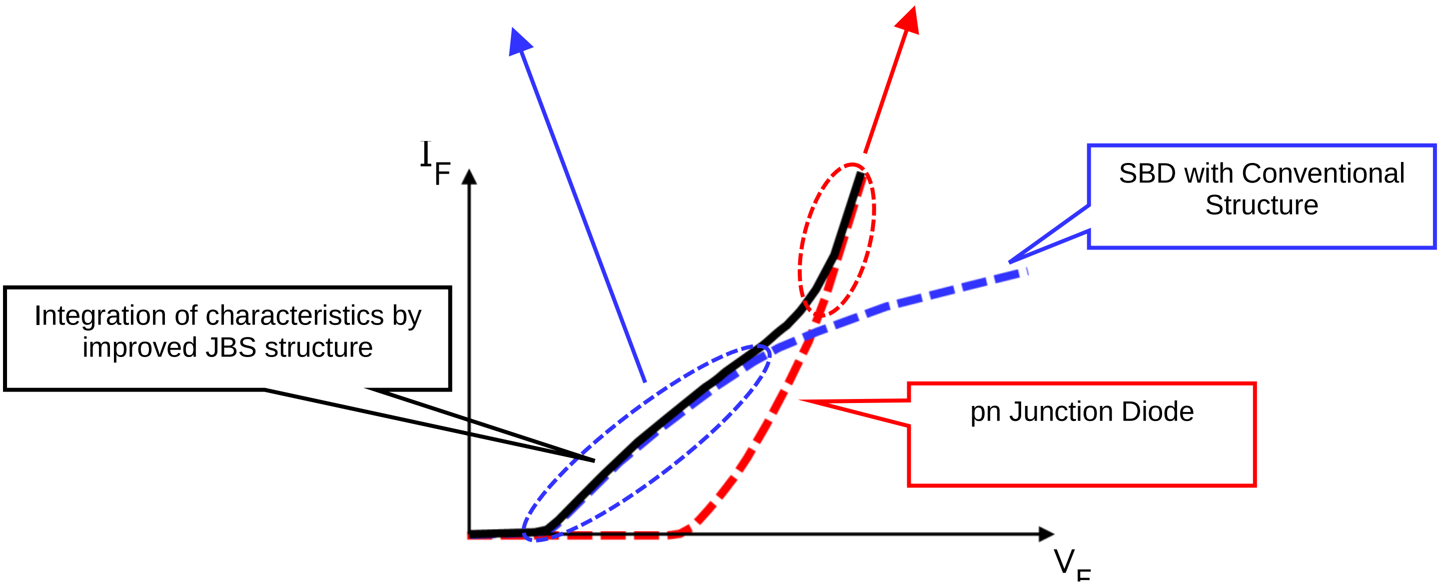

Figure 2-9 I_F-V_F curve

2.4. Temperature characteristics of the SiC SBD

Figure 2-10 shows examples of I_F-V_F curves of a SiC SBD at different temperatures.

As is the case with a typical Si SBD (Figure 2-11), in the low-I_F region, the forward voltage (V_F) of a SiC SBD at a given current decreases as temperature rises. However, in the high-I_F region, the forward current (I_F) at a given forward voltage decreases as temperature rises.

This phenomenon occurs because the resistance of a semiconductor changes owing to the heat generated.

The following two factors contribute to the changes in the resistance of a semiconductor:

1. Excitation of donor electrons to the conduction band (a decrease in resistance)
2. Diffusion of electrons caused by lattice vibration (an increase in resistance)

Because of a strong interatomic bond, wide-bandgap semiconductors such as SiC are affected more by lattice vibration than silicon. In addition, donors are less likely to be excited in SiC than in silicon owing to a wide bandgap. Therefore, in the low-current region, excitation has a significant impact on the resistance of a semiconductor, and diffusion is considered to have more influence as current increases. Consequently, a SiC SBD exhibits I_F-V_F curves as shown in Figure 2-11. This phenomenon in which the temperature coefficient reverses at high current also occurs in a silicon diode at high current exceeding the rated current (average forward current or forward DC current).

Therefore, when connected in parallel, silicon diodes are susceptible to a positive feedback effect because of a reduction in resistance caused by the thermal excitation of donor electrons, leading to thermal runaway. In contrast, SiC SBDs have negative feedback in the high-I_F region because of an increase in resistance caused by the diffusion of electrons. By using this region, SiC SBDs can be connected in parallel relatively easily as long as care is exercised as to forward current.

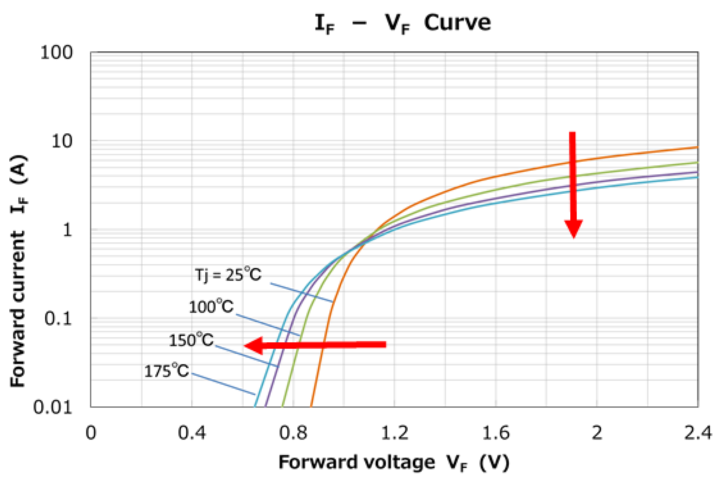

Figure 2-10 Example of temperature characteristics of a SiC SBD

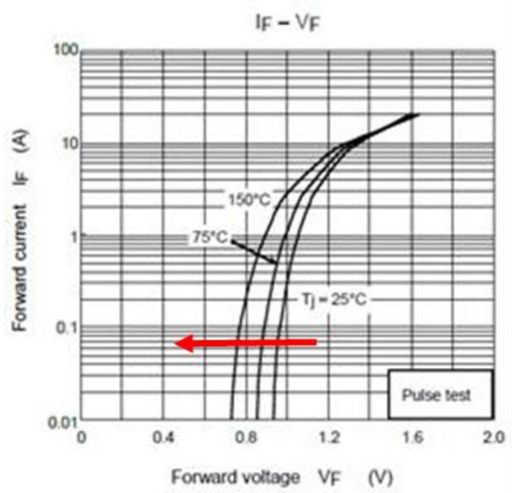

Figure 2-11 Example of temperature characteristics of a Si SBD

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