

High Temperature Power Electronics – Application Issues of SiC devices

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ABSTRACT

High temperature operation capability of power devices enhances performance of the system especially in the automotive industry where weight and volume are critical factors. SiC devices are capable of operating at higher voltages, higher frequencies, and higher junction temperatures, which result in significant reduction in weight and size of the power converter and an increase in efficiency. In this paper, thermal behavior of SiC devices in a buck converter configuration and characterization of several SiC devices will be presented.

I. INTRODUCTION

Research efforts of many material scientists and engineers have made silicon carbide (SiC) material based devices a better prospect than what it was a decade ago. The theoretical advantages that SiC material offer are being realized by using prototype or experimental devices in many different applications. High temperature operation capability of power devices can enhance performance of the system especially in the automotive industry where the weight and volume are critical factors. SiC devices are capable of operating at higher voltages, higher frequencies, and higher junction temperatures, which result in significant reduction in weight and size of the power converter and an increase in efficiency. Research efforts on SiC device applications at ORNL and the University of Tennessee focus on high temperature testing of SiC devices in a wide temperature range to study the high temperature behavior of the devices. Also, thermal behavioral models developed from the test data are being used in high power converter simulation studies for hybrid electric vehicle applications.

First, the characterization of the SiC devices (Schottky diodes, JFETs) will be presented. Then the thermal behavior of SiC devices in a buck converter configuration will be presented. Four different buck converters were developed with Si IGBTs, Si pn diodes, SiC JFETs, and SiC Schottky

diodes for endurance tests. The devices in the converters were operated at different voltage and current levels and at different frequencies in order to subject them to thermal stress and study their behavior. The results and analysis of the test data will be presented in the following sections.

II. SiC SCHOTTKY DIODE

Presently, SiC Schottky diodes are the most mature and the only commercially marketed SiC devices available. These diodes are commercially available up to 1200V/20A or 600V/20A. The following section presents static and dynamic characteristics of a 600V, 10 A Schottky diode, which was used in the applications to be presented in the later sections.

A. Static Characteristics

After extensive testing, I - V characteristics of a 600 V, 10 A diode were obtained at different temperatures in the -50°C to 175°C ambient temperature range (Fig. 1). Considering the piece-wise linear (PWL) model of a diode, which includes a fixed voltage drop, V_D and a series resistance, R_D ; the diode I - V curves can be approximated with the following equation:

$$V_d = V_D + R_D \cdot I_d \quad (1)$$

where V_d and I_d are the diode forward voltage and current, and V_D and R_D are the diode PWL model parameters.

Fig. 2 shows R_D and V_D values of a 600 V/10 A SiC Schottky diode with respect to temperature. As seen in these figures, V_D

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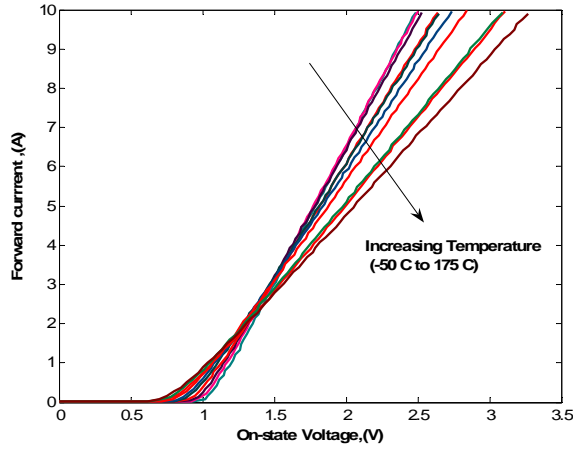


Fig. 1. Experimental I-V curves of a 10A SiC Schottky diode.

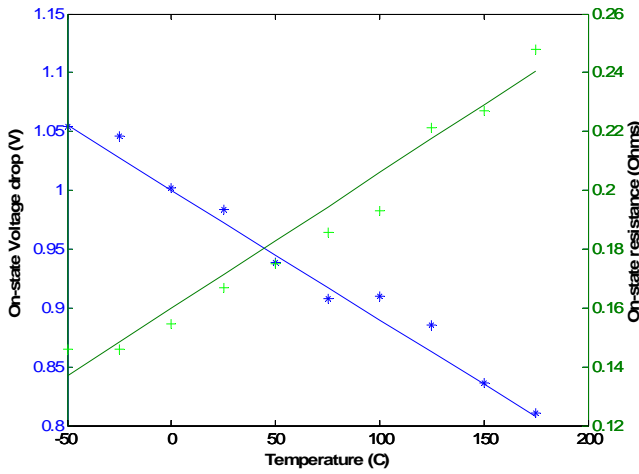


Fig. 2. R_D and V_D obtained from the experimental data.

decreases with temperature and R_D increases with temperature.

Increase in R_D is a sign of the positive temperature coefficient that the SiC Schottky diodes have, which implies that these devices can be paralleled easily. Equations below show the temperature dependence of the SiC Schottky diode PWL model parameters.

$$V_D = -0.001 \cdot T + 1 \quad (2)$$

$$R_D = 0.00046 \cdot T + 0.16 \quad (3)$$

where T is the temperature in $^{\circ}\text{C}$.

B. Dynamic Characteristics

The SiC Schottky diode was also tested in a chopper circuit to observe its dynamic properties. The chopper was switched at 1 kHz with a 40% duty cycle. The reverse recovery current waveforms obtained are shown in Fig. 3. Note that theoretically, Schottky diodes do not display reverse recovery phenomenon. The reverse recovery is because of the diode capacitance. The reverse recovery current of a SiC

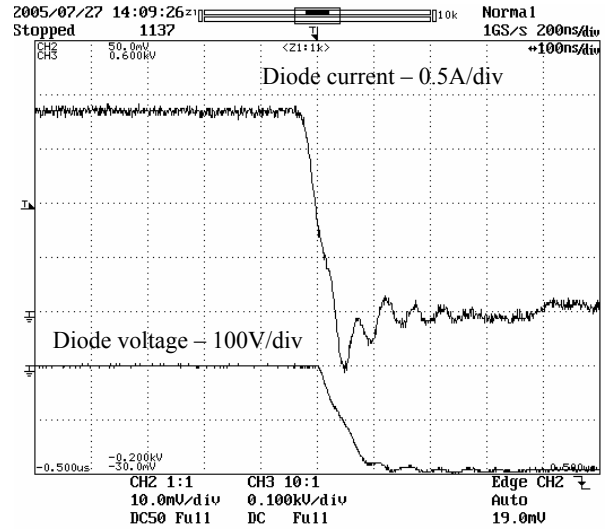


Fig. 3. Reverse recovery waveforms of the 600 V/ 10 A SiC Schottky diode.

Schottky diode does not change much with forward current and also with change in temperatures [1]. This phenomenon reduces the losses of the main power switch and hence results in improved system performance. The effect of this reverse recovery on the main power switch will be illustrated in the buck converter test results.

III. SiC VJFET

A. Static Characteristics

A JFET has several advantages compared with MOSFET devices. A JFET has higher switching speed and is free from the gate oxide interface problems unlike the MOSFET [2-4]. A SiC vertical junction field effect transistor (VJFET) is typically a normally-on device and conducts even though there is no gate voltage applied. A negative gate voltage has to be applied for it to stop conduction. A normally-on device is not desirable for power electronics since it requires additional protection circuitry to prevent a dc bus short if the gate signals fail. This normally-on feature also demands special gate drive designs. Also, new device designs are being developed to make it a normally-off device [5-7].

The SiC VJFET, unlike the Si JFET, can be used in high-voltage, high-power applications because of its vertical structure and the intrinsic properties of SiC. A normally-on SiC VJFET rated at 1200 V and 2 A was tested to study the high temperature behavior of the device. The forward characteristics of this device at different temperatures are shown in Fig. 4. The on-resistance of the VJFET increases from 0.36 Ω at -50°C to 1.4 Ω at 175°C as shown in Fig. 5. The values of the on-resistance are high; however, this device is a low current rated device, and it is one of the first of its

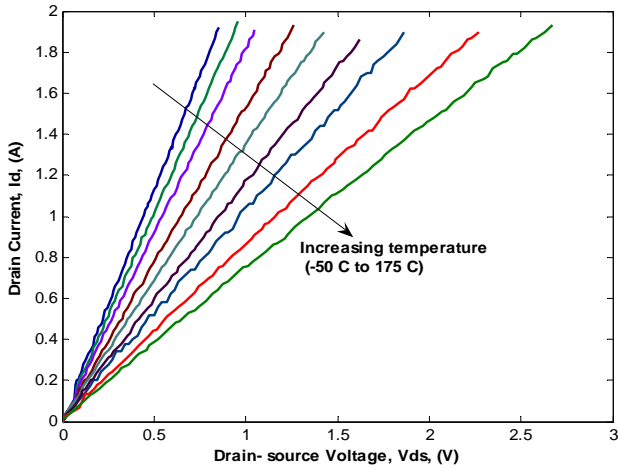


Fig. 4. i - v characteristics of SiC VJFET at different temperatures.

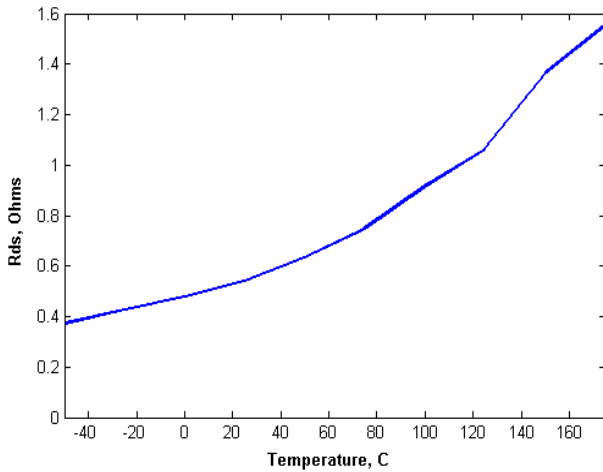


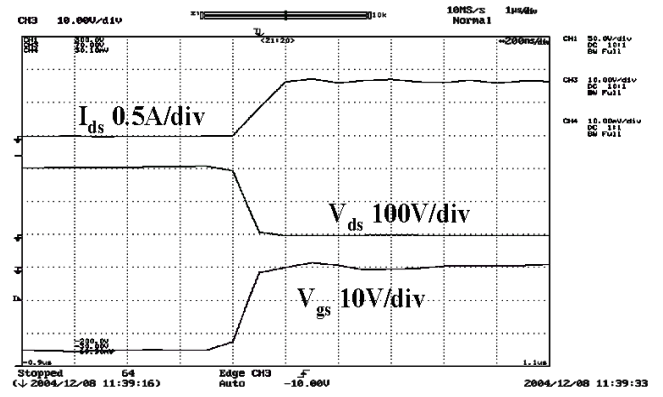
Fig. 5. On-resistance of SiC VJFET at different temperatures.

kind. It is expected that as the technology matures, lower on-resistance will be possible.

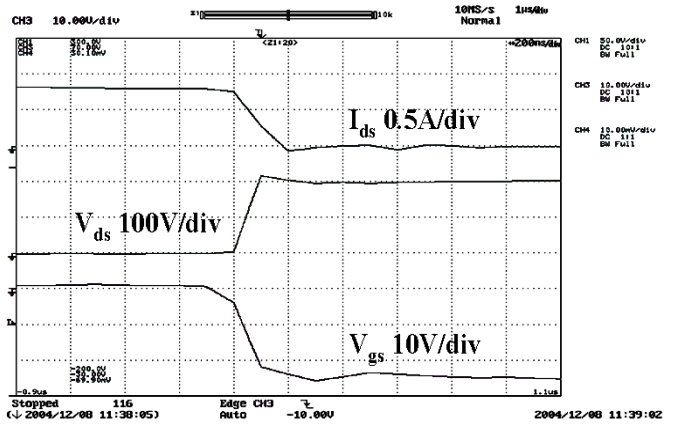
As seen in Figs. 4 and 5, SiC VJFETs have a positive temperature coefficient, which means that, like SiC Schottky diodes, their conduction losses will be higher at higher temperatures. Positive temperature coefficient makes it easier to parallel these devices and reduce the overall on-resistance.

B. Dynamic characteristics

SiC VJFETs are normally-on devices and they can only be turned off by applying a negative voltage that is higher than what a typical Si power device requires. Based on the pinch-off characteristics, a gate drive was designed to determine the dynamic characteristics of the VJFET [8].



(a)



(b)

Fig. 6. The gate and switching waveforms of the SiC VJFET.

When SiC VJFETs are operated at high frequencies, they need high peak gate currents to charge and discharge the gate capacitances faster. A 250 kHz operation was achieved with a series gate resistance of 5.4 Ω and a peak gate current of 0.38 A.

The gate voltage and the switching waveforms of the VJFET are shown in Fig. 6. The device has a turn-off delay $t_{d,off}$ of 40 ns, fall time t_f of 80 ns, turn-on delay $t_{d,on}$ of 20ns, and rise time t_r of 100 ns.

IV. BUCK CONVERTER ENDURANCE TESTS

The specifications of the devices and components used in the converters are shown in Table 1, and the circuit topology is shown in Fig. 7. The Si and SiC devices were selected with close ratings. The static, dynamic, and gate characteristics of the SiC devices used in these converters were presented in the previous section.

Thermocouples were attached to the cases of these devices to monitor their thermal responses. All the devices except the SiC VJFETs and the SiC diode with the Si VJFET devices were attached to a heat sink.

Table 1. Specifications of the devices and components used in the buck converters

SiC JFET	1200 V, 2 A
SiC Schottky diode	600 V, 10 A
Si IGBT	1200 V, 11 A
Si pn diode	600 V, 10A
Inductor	1.2 mH
Thermocouple	type T

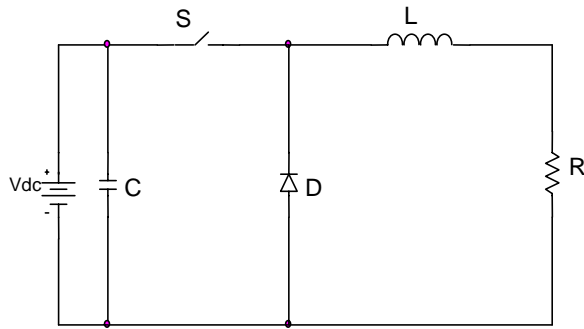


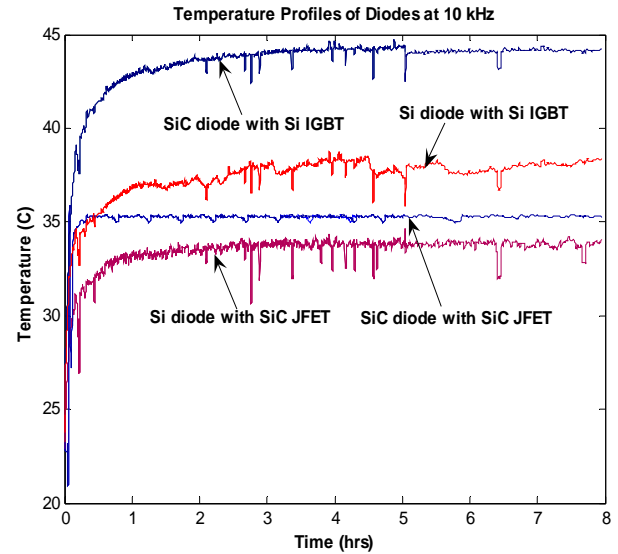
Fig. 7. The buck converter topology.

The buck converters were fed from a single dc supply and the operating current was limited to a maximum of 2 A because of the SiC JFET current rating. They were operated continuously for 7.5 hours every day for 6 months. During this time, their operation was closely observed and their case temperature data were recorded.

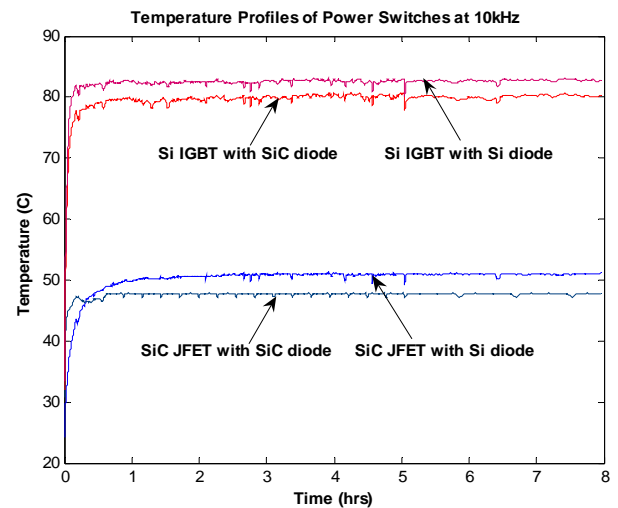
The temperature profiles of each device recorded for 7.5 hours are shown in Fig. 8. These profiles show that the SiC diodes were operating at higher temperatures than the Si diodes with the same power switches. It should be noted that the SiC diode with the SiC VJFET is operated without a heat sink but the Si diode with SiC VJFET had a heat sink. However, the Si and SiC diodes with the Si IGBTs were operated with heat sinks and still the SiC diode has higher operating temperature. A static characteristic comparison indicates that the on-state resistances of the SiC diodes are much higher than those of the Si pn diodes, and hence they have higher conduction losses [8]. A previous ORNL simulation study [9] has shown that the conduction losses of these SiC Schottky diodes dominate at lower switching frequencies, up to 20 kHz, and they are much higher than those of the Si pn diodes. This experimental study confirms the results of the simulation study.

SiC VJFETs, without heat sinks, operate at much lower temperatures than Si IGBTs, which indicates that the SiC devices have lower losses than the Si IGBTs. It can be seen from the figure that there is a difference of 30°C in the operating temperature. The comparison of the static characteristics of the SiC JFET and the Si IGBT is shown in Fig. 9. It can be seen from Fig. 9 that the conduction losses of the Si IGBT are much higher than the SiC VJFET and hence

the difference in the operating temperature. Note that the Si IGBT and the SiC JFET with the SiC diodes operate at lower temperatures than the ones with the Si pn diodes. This is again because of the better reverse-recovery characteristics of the SiC Schottky diodes incur lower currents in the gated devices.



(a) Diodes.



(b) Switches.

Fig. 8. Temperature profile for 10-kHz operation of buck converter.

Figs. 10 and 11 show all the temperature profiles of power switches and diodes plotted together for different frequencies. Fig. 12 shows that the operating temperatures of the SiC diodes do not change much with an increase in

switching frequency because the switching losses of SiC Schottky diodes are significantly lower than those of the Si pn diodes. However, the Si diodes have higher switching losses, and hence their operating temperatures get higher as the frequency increases.

that the SiC diodes have less effect on the main power switch because of the negligible reverse-recovery losses. Even though the temperatures of the Si IGBT in the all-Si converter increase as the switching frequency increases, the Si pn diode compared with the SiC Schottky diode still operates at a slightly lower temperature.

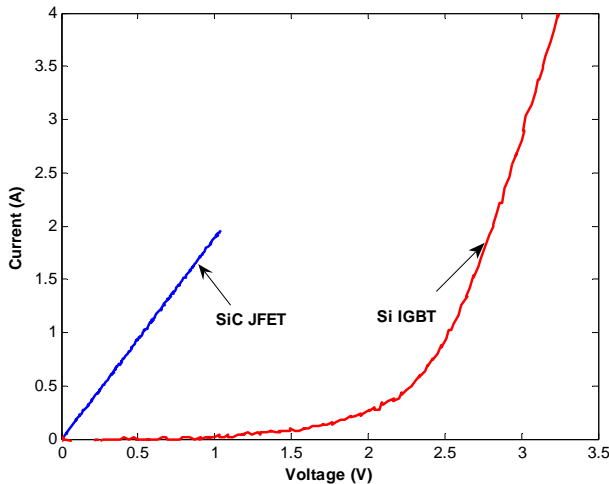


Fig. 9. Comparison of static characteristics for Si IGBT and SiC JFET.

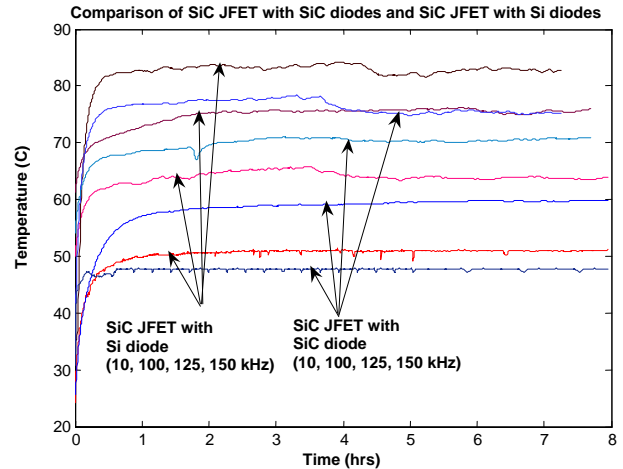


Fig. 11. Temperature profile of SiC VJFETs at different operating frequencies.

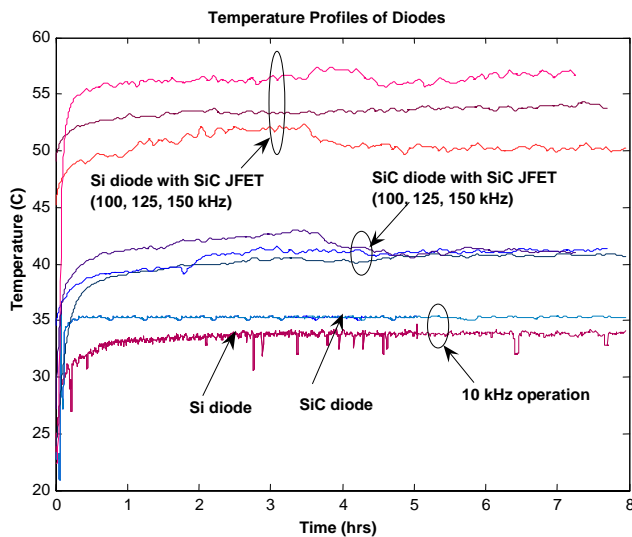


Fig. 10. Temperature profile for diodes at different operating frequencies.

Since Si IGBTs are limited in their switching frequency, the buck converters with Si IGBTs were tested separately at lower switching frequencies. The temperature profiles of the switches and diodes for 200 V, 50% duty cycle and in a frequency range of 15–25 kHz are shown in Fig. 12. Fig. 12 shows that the temperature profile of the Si IGBT with a SiC Schottky diode does not change much with switching frequency. However, the temperature of the IGBT with a Si diode increases with switching frequency. This also shows

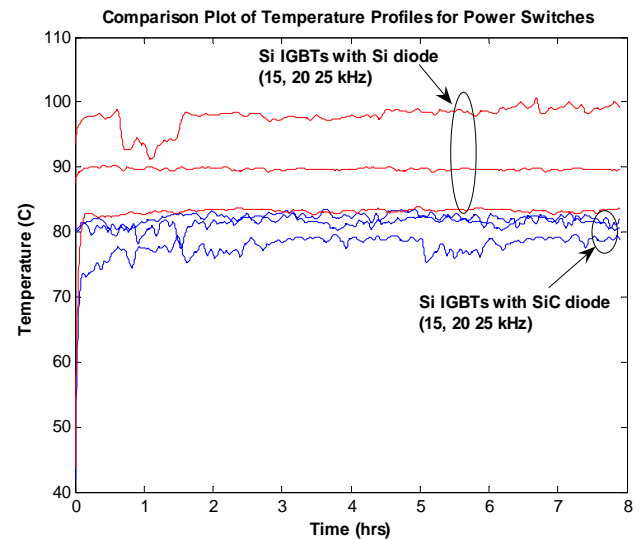


Fig. 12. Temperature profiles of Si IGBTs at different operating frequencies.

The SiC diodes have shown better thermal performance than the Si devices at higher power levels and higher frequencies. However, at lower frequencies and for the same power levels, the Si diodes had lower losses and hence were operating at lower temperatures.

The SiC JFETs were at lower temperatures than the Si IGBTs for all the operating conditions, even without heat

sinks. The temperatures of the SiC JFETs operating at 150 kHz were comparable to the temperatures of Si IGBTs operating at 10 kHz for the same power levels. This significant difference in operating temperatures will result in reduced heat sink size and volume when SiC devices are used.

V. CONCLUSION

Endurance tests were conducted using buck converters. Four buck converters were built with different combinations of Si IGBTs, SiC JFETs, Si pn and SiC Schottky diodes. The converters were operated an average of 7.5 hours a day for six months. The experiments revealed that the SiC JFETs had better performance in terms of operating temperatures for the same power levels with the same load. The SiC Schottky diodes had better thermal performance at higher frequencies since they have lower reverse-recovery losses compared with the Si diodes.

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