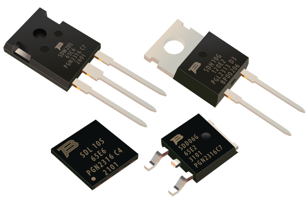
APPLICATION NOTE

Performance Differences Between SiC and Silicon-based Diodes in Meeting Efficiency and Density Requirements



Bourns® Silicon Carbide Schottky Barrier Diodes

INTRODUCTION

The trend to increase system performance in servers, chargers, and motor control inverters continues. Designers have managed to continue the performance evolution with little expansion to physical form factors or to their thermal management subsystems, resulting in higher energy densities in these critical applications. To accomplish this, power conversion subsystems are required to reduce their volume while increasing output. The net outcome is unparalleled levels of output and efficiency in extremely small volumes. With density and efficiency requirements in mind, Silicon (Si) based devices are stretched to their physical limits when attempting to perform competitively in power-dense spaces.

As a relatively new entrant into power electronics, the Wide Band Gap (WBG) material Silicon Carbide (SiC) has emerged as a market-changing technology that can support the high power densities required by next-generation applications. Typical applications include desktop and PC power supplies, server power supplies, telecom power supplies, TV SMPS, AC-DC power management units, Uninterruptible Power Supplies (UPS), air conditioner Power Factor Correction (PFC) and photovoltaic applications (solar boost converters, inverter topology, micro-inverters, etc.).SiC has quickly become a mainstay for power system designs featuring increased performance at higher breakdown voltages compared to Silicon-based devices. In particular, SiC offers key performance differences when compared to Si: better thermal performance, enhanced reverse recovery characteristics, less leakage current and an improved Figure of Merit (FOM).

This paper provides a detailed explanation of the key performance differences between Bourns® SiC Schottky Barrier Diode (SBD) devices and traditional Si PN Junction Diode devices. To highlight the performance characteristics of both device types, multiple relevant test results are provided. These data points illustrate how SiC-based diodes can help designers meet ongoing performance demands in next-generation power applications.

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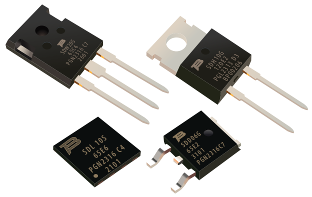

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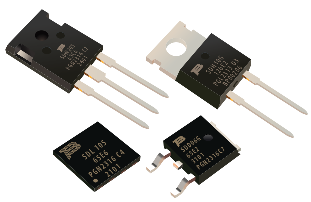
SIC SCHOTTKY DIODE VS. SI PN JUNCTION DIODE THERMAL AND REVERSE RECOVERY CHARACTERISTICS

Understanding the reverse recovery characteristics of a PN junction is crucial in high-frequency and fast-switching applications. A diode with a smaller reverse recovery characteristic allows for quicker switching and reduces the chance of unwanted energy losses, voltage spikes and electromagnetic interference.

A Si PN junction, being a semiconductor-to-semiconductor junction, forms a depletion region between the P- and N- type materials. During forward biasing, the depletion region stores charge to allow for current to pass. At reverse bias, this stored charge must recombine for a short duration, allowing for current to pass in the reverse direction. This phenomenon is called the reverse recovery time. Physically, SBDs have a metal-to-semiconductor junction that allows for current flow without forming a considerable depletion region at the barrier. Due to the lack of a depletion region forming at the junction, SBDs have a significantly reduced recovery characteristic. The metal-to-semiconductor junction paired with the SiC material allows for SBDs to be used in applications at much higher switching frequencies and reverse breakdown voltages.

Bourns® SiC SBDs boast a 650 V and 1200 V V_{RRM} for use in switching topologies and rectification with forward currents ranging from 5-10 A and are available in several package styles such as: TO-220, TO-247, TO-263, TO-252, and DFN. Bourns also offers two SiC SBDs as a common cathode in a TO-247-3 package. Bourns® SiC SBD products can be viewed at: www.bourns.com/products/diodes/silicon-carbide-sic-schottky-barrier-diodes.

To show the difference in reverse recovery characteristics, tests were performed on two diodes: 1) Bourns® SiC SBD Model BSDH06G65E2 (I_F = 6 A, V_{RRM} = 650 V, TO-220 package) and 2) Standard Si PN Diode (I_F = 5 A, V_{RRM} = 600 V, TO-220 package). A 360 W offline Power Factor Correction (PFC) boost converter providing a nominal output voltage of 390 V and a regulated output at ~644 mA of load current was used for comparison testing. The PFC converter accommodated an input voltage range of 85 to 265 VAC and used average current mode control at a frequency of 120 kHz. The boost diode of the circuit was tested with both the Bourns® SiC SBD and a commonly-used Si PN Diode. A simplified test circuit is shown in Figure 1.



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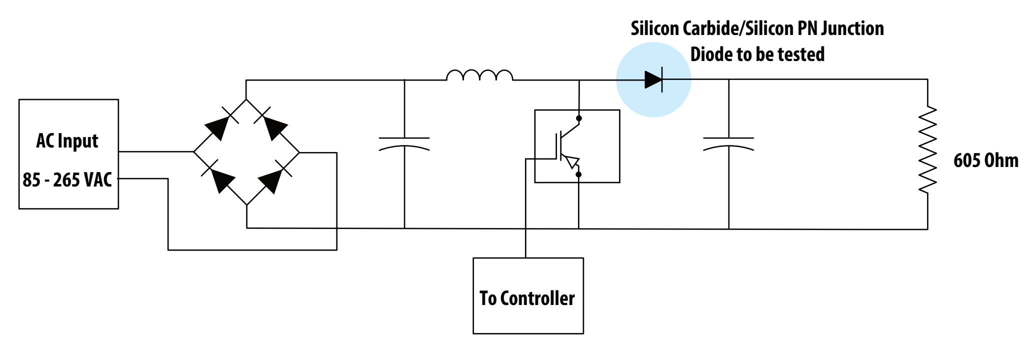


Figure 1. Simplified PFC test circuit for SiC SBD and Si PN Junction Diode comparison.

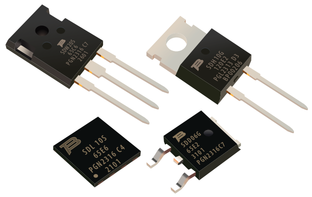
To show improvements in efficiency, temperature measurements of the diodes were taken during operation of the PFC circuit. An input voltage of 90 V was tested with both SiC SBDs and Si PN Junction Diodes. As testing took place, a clear distinction between heat signatures of the SiC SBD and the Si PN Junction Diode were observed. Table 1 documents the finding.

Table 1. Temperature measurements at 90 V of the PFC circuit.

Input Voltage	Bourns® SiC SBD (Model BSDH06G65E2) 6 A, V_{RRM} = 650 V	Si PN Junction 5 A, V_{RRM} = 600 V
90 VAC	86.2 °C	98 °C

As seen, the SiC SBD's performance characteristics allowed for significantly cooler operation than the Si PN Junction Diode. This improvement in temperature indicates an efficiency increase with SiC SBDs. To further understand the efficiency increase, current measurements were recorded for both SiC SBDs and Si PN Junction Diodes at the same input voltages. At the peak of the AC input, and using a Tektronix TCP0030A current probe[1], images of the waveform during the reverse recovery time of each diode were captured. Figure 2 shows the difference in reverse recovery current waveforms. The scope images reveal reverse recovery time as a major source of lost power in the system. With the worst case being 90 V, the Si PN Junction Diode experienced much higher power dissipation during the transition to the off-state when compared to the SiC SBD. Given this, it is clear why there is a difference in the temperature readings in Table 1.

1. The Tektronix TCP0030A has a bandwidth of 120 MHz. Using this probe to capture waveforms that are expected to have transition times on the order of a few nanoseconds in the case of SiC SBDs may result in inaccurate magnitudes. The following measurements are for the purpose of demonstration. For example, the probe matches what would be expected in the case of Si PN Diodes, but data captured for the SiC SBDs do not display an enhanced reverse recovery time compared to Si PN Junction Diodes. However, the probe does display the lack of temperature dependence in the case of SiC SBDs (as will be demonstrated further in the paper).



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SIC SCHOTTKY DIODE VS. SI PN JUNCTION DIODE THERMAL AND REVERSE RECOVERY CHARACTERISTICS (Continued)

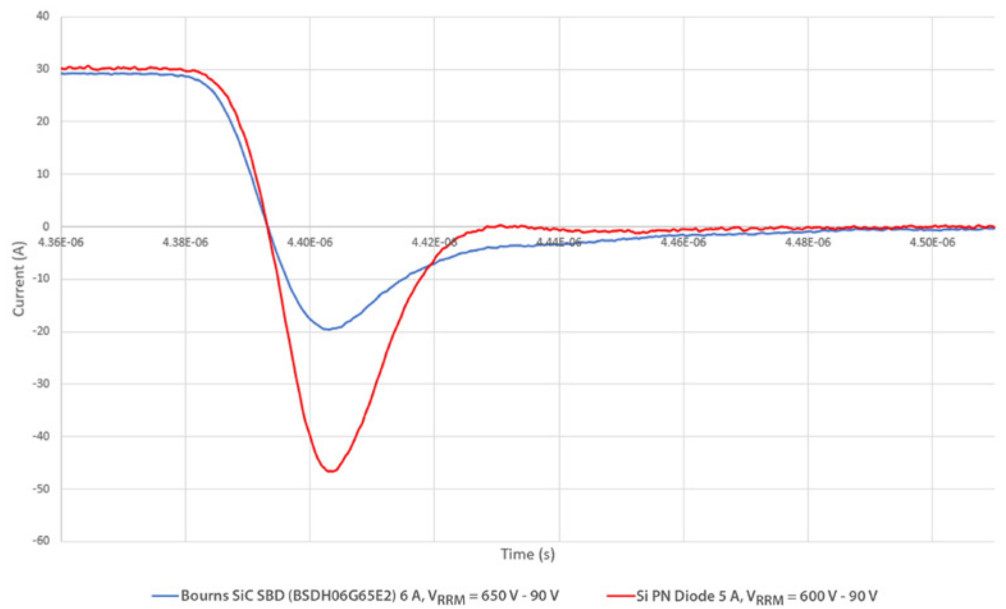
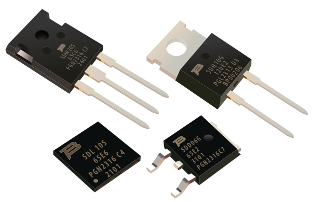


Figure 2. Reverse recovery characteristics measured in the PFC circuit of SiC SBD and Si PN Junction Diodes.

It is also important to compare the SiC SBD and Si PN Junction Diode behaviors at varying input current. By varying the voltage from 90 V, this illustrated that the Si PN Junction Diode exhibits drastic changes in reverse recovery due to its temperature dependence. The reverse recovery characteristics of an SiC SBD, on the other hand, are not temperature dependent. As seen in Figure 3 and 4, the reverse recovery of the SiC SBD does not change between voltage levels, whereas the Si PN Junction Diode varies greatly.



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SIC SCHOTTKY DIODE VS. SI PN JUNCTION DIODE THERMAL AND REVERSE RECOVERY CHARACTERISTICS (Continued)

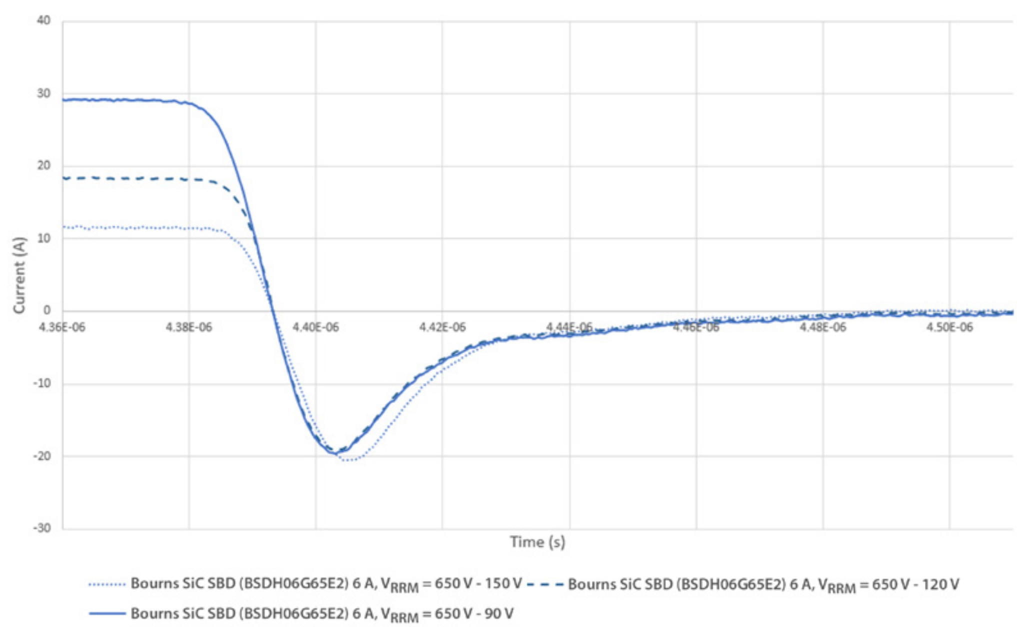


Figure 3. Bourns® SiC SBD reverse recovery characteristics at varying input voltages to the PFC test circuit.

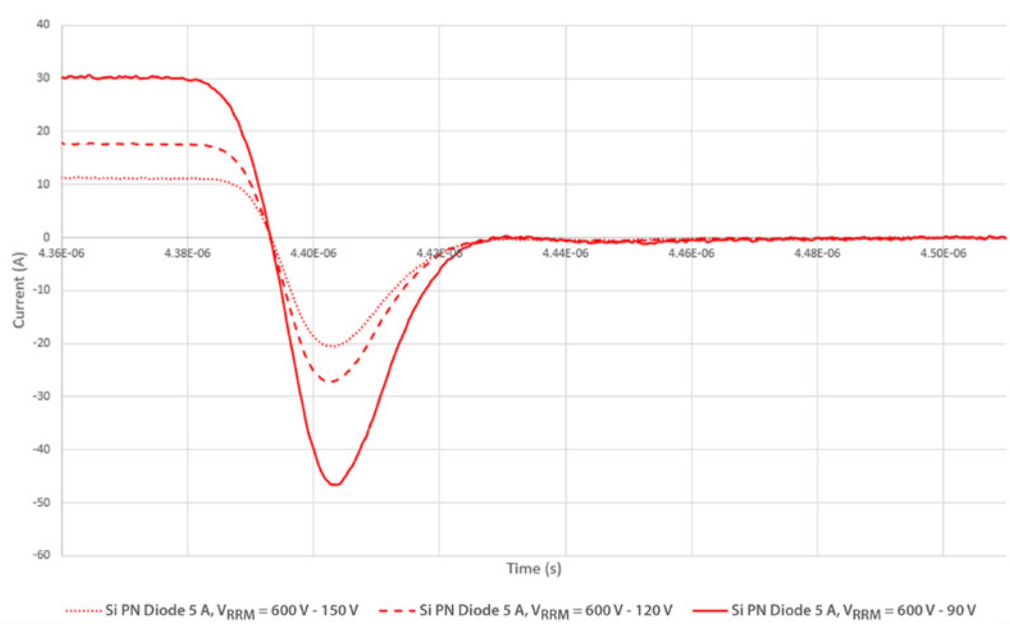
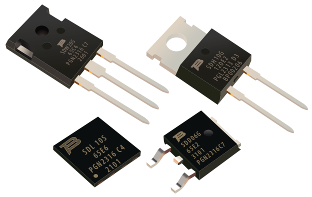


Figure 3. Si PN Junction Diode reverse recovery characteristics at varying input voltages to the PFC test circuit.

Performance Differences Between SiC and Silicon-based Diodes in Meeting Efficiency and Density Requirements



Bourns® Silicon Carbide Schottky Barrier Diodes

SIC SBD VS. SI PN JUNCTION DIODE COMPARISON OF TEMPERATURE COEFFICIENT EFFECTS ON CONDUCTION CHARACTERISTICS

In modern designs of EV (Electric Vehicle) charging stations, server power supplies, Uninterruptible Power Supplies (UPS), and other kilowatt applications, there is a need to parallel devices. Conventionally, power Si PN Junction Diodes would be paralleled. Paralleled Si PN Junction Diodes are prone to thermal runaway due to their negative temperature coefficient. As shown in Figure 5, an increase in junction temperature will also allow for higher currents at the same forward voltage. This means that a singular diode in a parallel configuration can quickly overheat where temperature between the diodes is not shared properly. Of course, this means increased complexity in design because it becomes paramount that both diodes must have similar junction temperatures throughout all range of operation. This is typically achieved using ballasting resistors which adds to power loss in the system.

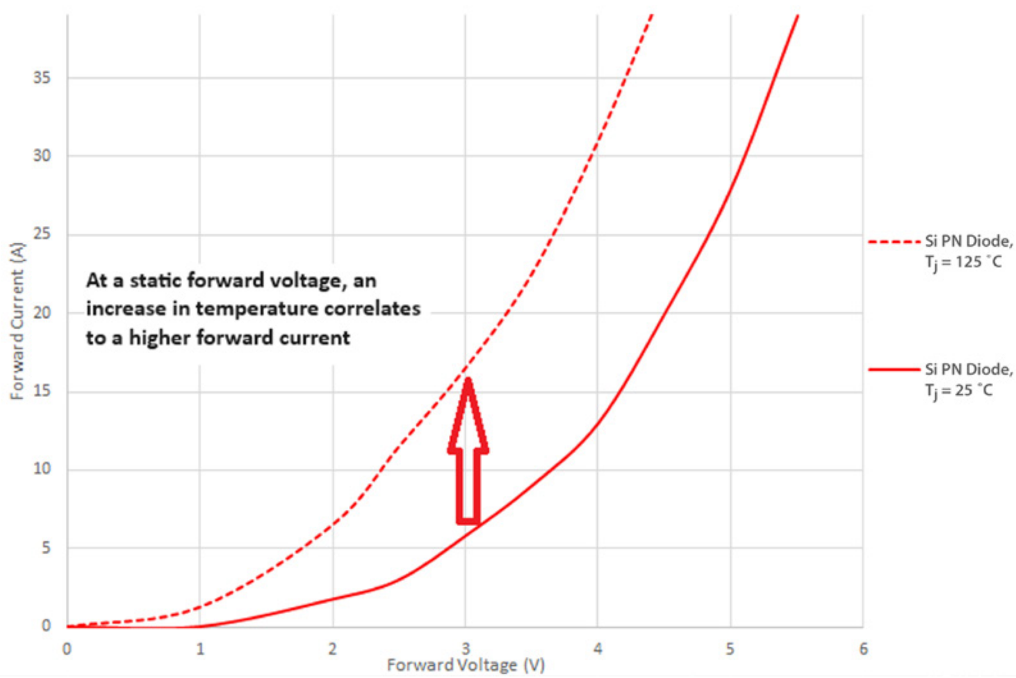
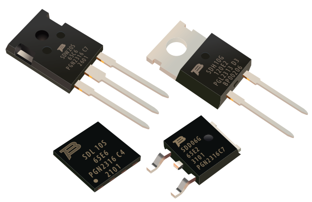


Figure 5. V_F vs. I_F of a Si PN Diode showing the negative temperature coefficient characteristic.



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SIC SBD VS. SI PN JUNCTION DIODE COMPARISON OF TEMPERATURE COEFFICIENT EFFECTS ON CONDUCTION CHARACTERISTICS (Continued)

In contrast, Bourns® SiC SBDs have a positive temperature coefficient. As shown in Figure 6, an increase in junction temperature decreases the forward current at the same forward voltage. Unlike the Si PN Junction Diodes, this allows for current sharing without the possibility of thermal runaway. For clarity, SiC SBDs in parallel will share current evenly without external design such as ballasting resistors. This makes SiC SBDs far easier to design-in, increases power efficiency as external resistors are not needed for balancing, and decreases the board space needed to have parallel diodes over conventional Si PN Junction Diodes.

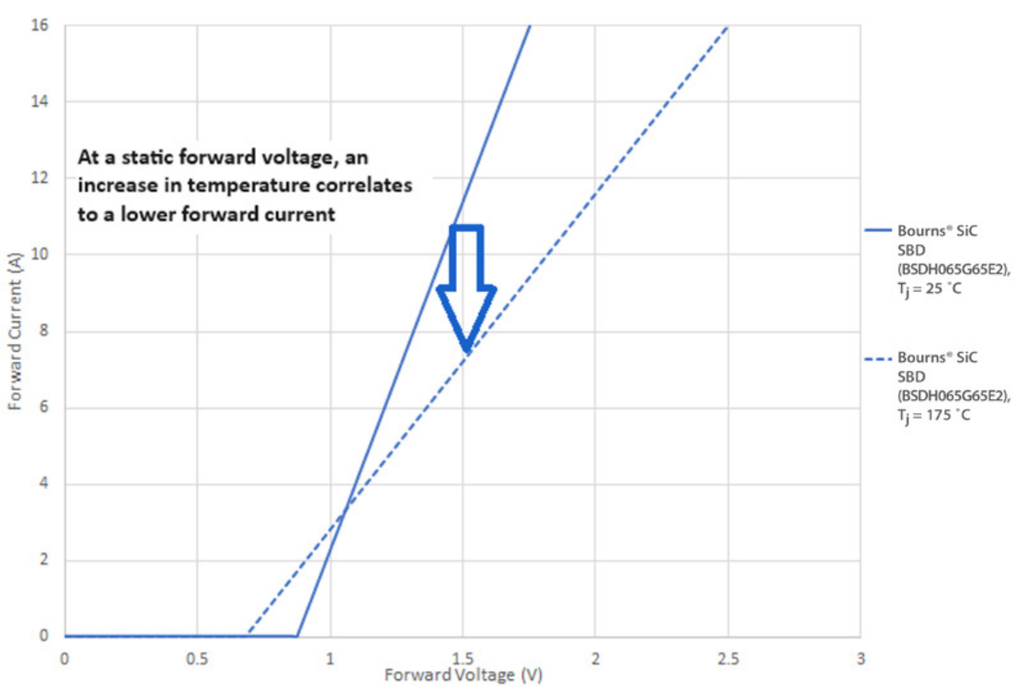
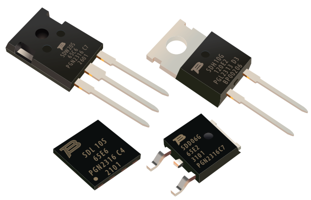


Figure 6. V_F vs. I_F of a Bourns® SiC SBD showing the positive temperature coefficient characteristic.



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SIC SBD VS. SI PN JUNCTION DIODE LOW LEAKAGE CURRENT

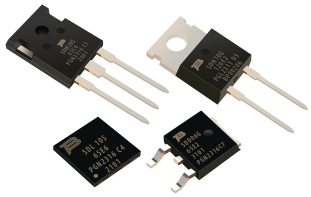
Leakage current refers to the small amount of current that flows through a diode when it is reverse-biased, meaning the voltage at the cathode terminal is higher than the anode terminal. Leakage current represents an unnecessary power drain in a circuit. Even though the current is small, it can negatively affect the overall system's efficiency level and lead to increased operating costs over the system's service lifetime. Many applications, such as servers and cloud computing systems, vigorously pursue each milliwatt of power loss. In these instances, every metric of efficiency is critical.

A comparison of leakage current between Bourns® SiC SBDs and Si PN Junction Diodes is shown in Table 2 and highlights that the Bourns® SiC SBDs have similar leakage current characteristics to the 600 V PN Junction Diodes typically used in switching applications.

Table 2. Comparison of reverse leakage current gathered from data sheets.

Product	Typical I_R at $V_R = V_{RRM}$	Max I_R at $V_R = V_{RRM}$
Bourns® SiC SBD (Model BSDH06G65E2) 6 A, V_{RRM} = 650 V	0.3 µA @ 25 °C 15 µA @ 175 °C	30 µA @ 25 °C 150 µA @ 175 °C
Si PN Junction Diode 5 A, V_{RRM} = 600 V	— 25 µA @ 125 °C	20 µA @ 25 °C 250 µA @ 125 °C

Another important characteristic about leakage current is temperature dependency. At 25 ˚C, many Si PN Junction Diode data sheets indicate the maximum leakage current is 20 µA. At 125 °C, Si maximum leakage current is 250 µA. This represents a 12.5x increase during temperature rise from 25 °C to 125 °C. The Bourns® SiC SBD leakage current has only a 5x dependency increasing from 25 °C to 175 °C.



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SIC SBD VS. SI PN JUNCTION DIODE FORWARD VOLTAGE AND RECOVERY CHARGE FIGURE OF MERIT (FOM)

SiC SBDs have low forward voltage drop. Forward voltage drop (V_F) times capacitive charge is a key Figure of Merit (FOM) for power efficiency and it is much lower in the Bourns solution. SiC SBDs also have significantly lower energy loss and reverse charge (Q_{rr}). This translates to more switching power and less energy required in the turn-on and turn-off phase of the switching devices. Lower heat eliminates the need for heat sinks, thus reducing space and weight.

A typical Figure of Merit for comparing diodes is to use the typical forward voltage multiplied by the reverse recovery charge at 25 ˚C. Based on the two device's data sheets, the corresponding FOMs for the respective diodes are listed in Table 3.

Table 3. FOM for the diodes at T_J = 25 °C.

Product	V_F	Q_{rr}	V_F x Q_{rr} (FOM)
Bourns® SiC SBD (Model BSDH06G65E2) 6 A, V_{RRM} = 650 V	1.7 V	9 nC	15.3
Si PN Junction Diode 5 A, V_{RRM} = 600 V	2.9 V	110 nC	319

When comparing FOM for diodes, a smaller number is desired. Bourns® SiC SBD FOM is significantly lower than a similarly-rated Si PN Junction Diode. It is important to note that the FOM shows, at a top-level, the losses at both conduction and switching from an on-state to an off-state. Meaning, during operation, energy dissipated between both conduction and switching are important factors to consider especially when higher frequency switching is used. For example, in a Switched-Mode Power Supply, a higher operating frequency can reduce the size, weight, and cost of magnetic components. Using the FOM metric, the Bourns® SiC SBD is 20x better at reducing conduction and switching losses than a Si PN Junction Diode component.

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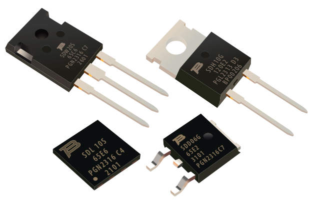

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CONCLUSION

The future of power design will rely heavily on Silicon Carbide Diodes to meet density and efficiency requirements. Leveraging the capabilities of Silicon Carbide provides the power to deliver a leap in efficiency gains by offering lower switching/reverse recovery losses and reduced temperature dependency on critical performance parameters such as leakage. This paper has illustrated the positive performance differences between SiC and Si that can aid designers in advancing their next-generation power applications.

With the introduction of Bourns' wide band gap technology, the Company continues its 75-year history of innovation. Bourns offers a broad portfolio of solutions based on advanced technologies that can help reduce the carbon footprint of its customers' systems. Bourns' strong product offering of leading-edge solutions including Silicon Carbide, low-leakage circuit protection, and high-efficiency magnetics is designed to not only help maximize efficiency and meet ongoing size, performance and circuit requirements, but also to keep its customers competitive.

BOURNS®

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