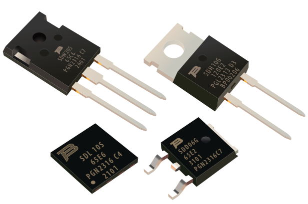
Comparing Silicon Carbide Schottky Diodes to Silicon Diodes in Power Conversion Designs

WHITE PAPER



Bourns® Silicon Carbide Power Schottky Diodes

INTRODUCTION

Now, more than ever, Silicon Carbide (SiC) Schottky Diodes are being applied to more areas of power conversion to help significantly improve performance and energy efficiency compared to similarly rated silicon diodes. SiC Schottky Diodes are also increasingly used in power electronic circuit designs that have much higher voltages than can be accommodated by traditional silicon diodes.

This widespread adoption of SiC Schottky diodes brings two other major benefits: (i) costs can be reduced, making more applications economically practical, and (ii) because of their higher efficiency modern designs can meet newly-enacted energy efficiency requirements.

This white paper offers a comparison of SiC Schottky Diodes and Silicon-based Diodes for power conversion designs. It covers the available package sizes, from surface mount packages for space-constrained applications to tab mount packages to obtain the highest power handling capability. It also presents how SiC Schottky Diodes supply high power density through higher voltages and robustness, highlighting the up to a two percent efficiency gain in DC EV charger applications compared to silicon-based solutions. Designers will also learn about how SiC Schottky Diodes have been shown to offer up to 33 percent higher power density compared to silicon-based solutions, helping them to create smaller designs that meet higher power requirements in the same space.

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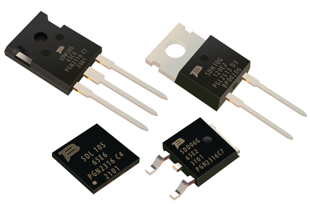

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THE SILICON PN JUNCTION TO SILICON CARBIDE DIODE REVOLUTION

Using SiC to make Schottky Barrier Diodes (SBDs) increases the possible breakdown voltage from 200 volts to well over 1000 volts because of the high band gap of the semiconductor. Just the differences in semiconductor materials results in enhanced operational benefits for SiC Schottky diodes, which are shown in the table below:

Table 1. | *Semiconductor Parameters for Silicon and Silicon Carbide*

Parameter	Si	SiC
Band Gap (eV)	1.1	3.25
Breakdown electric field E_{br} (MV/cm)	0.25	3
Electron mobility µn (cm^2/V·s)	1450	900
Saturation electron drift velocity V_S (10^7 cm/s)	1	2.4
Thermal conductivity ø (W/cm·°K)	1.48	4.2

The higher band Gap and breakdown electric field values for SiC lead directly to the higher breakdown voltage. Even though the electron drift velocity is higher, the mobility is lower so SiC-based devices are slightly slower than those made with silicon. However, this becomes an advantage in preventing polarity reversal currents from changing too quickly, which means EMI in the system is reduced. Plus, the thermal conductivity of SiC is more than double that of silicon, leading to superior thermal performance as heat flows away from the active junction area faster. The improved power handling (heat removal) capability of SiC enables these devices to handle higher current for both pulsed and continuous current operation. It also enables SiC devices to operate at higher power and at elevated environmental temperatures with the junction being operational to +175 °C for its full life expectancy.

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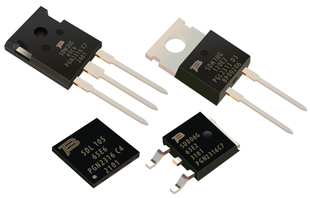

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FORWARD VOLTAGE AND POWER DISSIPATION

Due to the low potential barrier at the metal-semiconductor interface, the low forward voltage drop of a SiC Schottky Diode allows for efficient movement of electrons from the cathode to the anode. The power dissipation, which is the current multiplied by the junction voltage, is minimal and contributes to the overall efficiency increase in applications. The junction voltage varies with current and temperature. However, unlike silicon junction diodes, the forward voltage increases with temperature in SiC Schottky Diodes. This increase allows simple parallel connections to produce extremely high current ratings without using ballast resistors and without the danger of thermal runaway in one diode. Contrarily, if silicon diodes are connected in parallel, there is a danger that one will be hotter than the others and conduct more current because of its reduced forward voltage drop. This, in turn, would cause it to operate even warmer still, leading to a runaway condition. If a runaway condition occurs, it would then destroy the entire bank of diodes causing catastrophic circuit failure.

Like all diodes, the forward voltage of a SiC Schottky Diode increases with current. The maximum current allowed is limited by the bond wires and the rate at which heat can be removed from the junction area. Since the heat produced in the junction must flow from the junction through the semiconductor material of the cathode to the mounting surface for removal, a silicon carbide semiconductor is superior at removing heat so it can run at higher maximum operating junction temperatures. An added advantage is that the SiC substrate is thinner, which makes the thermal path from the junction to the mounting surface shorter.

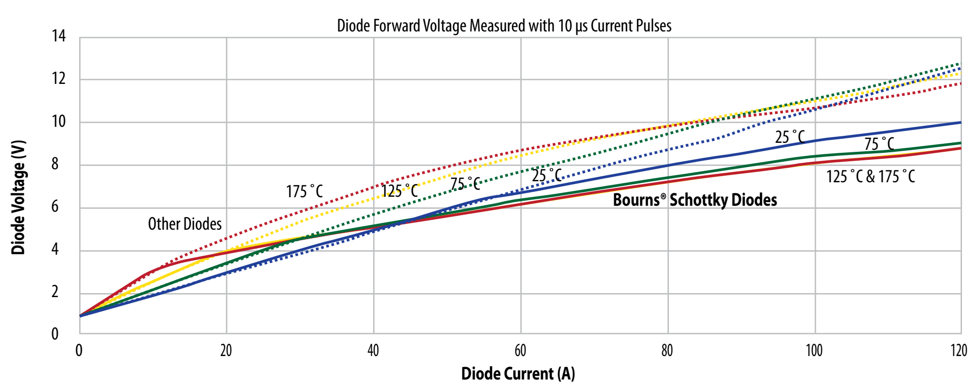
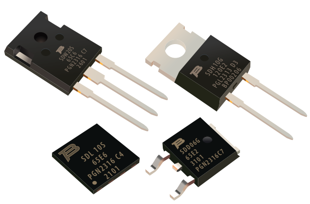


Figure 1. *Diode Forward Voltage vs. Current Over Temperature*

Measurements shown in Figure 1 compare Bourns® SiC Schottky Diodes and industry-standard silicon Schottky Diodes for rectangular pulse widths of 10 µs. Bourns® SiC Schottky Diodes exhibit a negative temperature coefficient of resistance, illustrated by the decrease in forward voltage with temperature. This is beneficial when designers need to parallel two or more devices to increase the power capability to accommodate large area current sharing. The fact that the diode forward voltage and operating resistance decrease at elevated temperatures is also advantageous to help prevent thermal runaway in parallel connections.



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SIC SBD REVERSE RECOVERY CHARACTERISTICS

For diodes made from silicon carbide semiconductor material, the faster reverse recovery speed and reduced reverse charge recovery is a result of the lower capacitance of their internal construction. Since the diode capacitance is constant over temperature as indicated by the constant stored charge, Q_{rr}, the reverse recovery time will be constant over temperature, which is better for stabilizing power switching applications.

Figure 2 shows the definition of the reverse recovery time. When forward bias is removed, the forward current decreases and keeps on flowing past zero at a rate of dI_f/dt, removing the excess charge stored in the depletion region. The reverse current is the flow of excess charge, reaching the maximum reverse recovery current, I_{rrm}. It decreases until all the stored charge is removed. The reverse recovery time is the time required to remove the excess charge. It is measured from the beginning of the reverse current to a linearized time when the current returns to zero and the stored charge is removed.

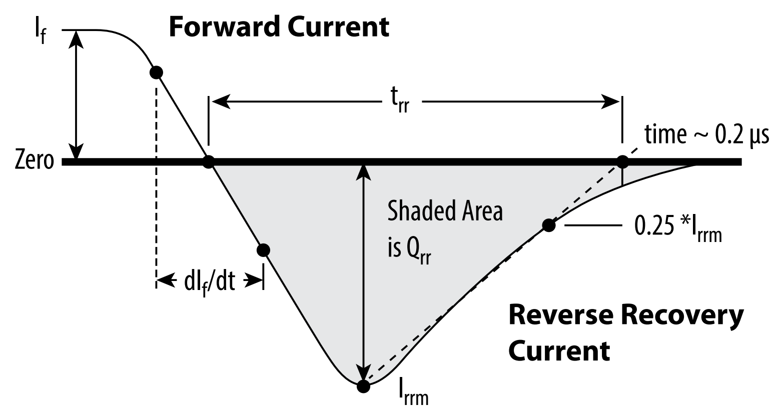
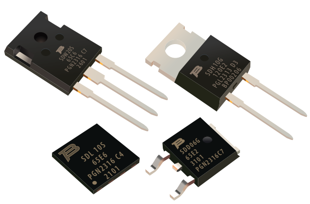


Figure 2. How Reverse Recovery Time (t_{rr}) and Maximum Reverse Recovery Current (I_{rrm}) are Defined



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SIC SBD REVERSE RECOVERY CHARACTERISTICS (Continued)

The reverse recovery of PN and Silicon Carbide Diodes is shown in Figure 3. Notice that the maximum recovery current of the PN diode is approximately six times larger than the SiC Diode. The reverse recovery time t_{rr} is a function of forward current and the rate of change as it is turned off. This function sets the maximum reverse recovery current, I_{rrm}.

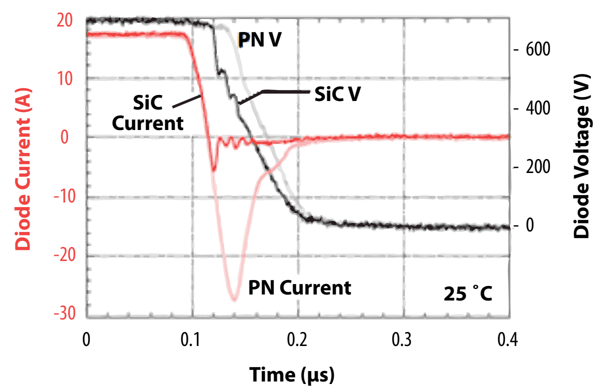
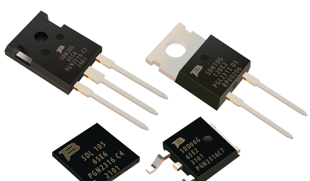


Figure 3. | *Reverse Recovery Current and Time for PN and SiC Diodes*

In silicon high-speed junction PN Diodes, a high level of transient current flows when the current switches from forward to reverse, which leads to large losses when switching to the reverse bias condition. When current is applied in the forward direction, minority carriers accumulated in the drift layer contribute to electrical conduction until they disappear (also referred to as the diode storage time) when the diode is switched from forward conduction to reverse. This increases both the recovery time and the recovery current as the forward current flows and temperature increases, causing significant loss.

In contrast, SiC Schottky Barrier Diodes (SBDs) are majority carrier devices that do not use minority carriers for electrical conduction so, in principle, the minority carrier accumulation does not occur. As a result, only a small amount of current flows for discharging the junction capacitance, achieving considerably lower losses than silicon Fast Recovery Diodes (FRDs). This transient current is largely independent of temperature and forward current, making stable high-speed recovery possible under virtually any circuit condition. SiC SBDs also tend to deliver noise reduction to applications due to fast changes of reverse recovery current.
Since Silicon PN Diodes are bipolar semiconductors that depend on the injection of minority charge carriers, they exhibit a large reverse recovery charge. During the conduction state of the diode, charge carriers are injected into the device and need to be removed from the device before a voltage can be blocked, or, in other words, before a space-charge region can be built-up. A higher charge carrier concentration will result in a high reverse recovery charge. Moreover, the reverse recovery charge is dependent on forward current and the device's junction temperature. The advantage of using SiC Schottky Diodes is that because they are majority carrier devices, they show virtually zero reverse recovery charge. Looking at the switching waveforms in Figure 3, the reverse recovery current peak is minor compared to a fast Si PN Diode. Only the displacement current from the junction capacitance is visible. This leads to significantly lower turn-off losses. Furthermore, since the dynamic characteristic of a Schottky Diode is capacitive in nature, the reverse recovery characteristic of a SiC Schottky Diode is independent from forward current, di/dt, and device junction temperature.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CONCLUSION

As shown in this paper, Bourns® SiC Schottky Barrier Diodes have distinct advantages compared to the usual choice of Silicon-based PN Diodes. In most applications with operating voltages over 600 V, using SiC SBDs, with their inherent lower voltage drop and reverse recovery loss, will increase the design's energy efficiency, particularly when employed in applications that operate at elevated temperatures. Utilizing SiC SBDs also helps to reduce heat sinking requirements, simplifies the thermal design and reduces the thermal impedance since the semiconductor material has much higher thermal conductivity.

SiC SBDs are particularly well-suited for high voltage and high current systems with frequencies of 100 kHz or below. This is because SiC SBDs have lower switching losses and lower forward conduction losses than similarly rated Silicon-based PN Diodes. Their overload durability is also enhanced and the waveforms during switching are softer, resulting in lower EMI from the application.

Silicon Carbide Diode technology is mature and proven, but has still been shown to have tremendous future potential. As a leader for more than 75 years in the development of innovative technologies and component solutions, Bourns' new SiC Schottky Diodes are designed to deliver enhanced application efficiencies.

Each application is different and may require design tradeoffs. That is why it is helpful to have a good understanding of the differences between the various power semiconductor rectifying devices. This knowledge allows designers to select the power electronics device that is best suited to meet the specifications for their particular application, especially those developing DC-based EV chargers and On-Board Chargers. As shown in this paper, energy efficiency can increase up to 2 % with 33 % higher power density when replacing silicon-based solutions with SiC Diodes. This allows engineers to design smaller applications while supporting higher power in the same space.

ADDITIONAL RESOURCES

For more information on the complete line of Bourns® SiC Schottky Diodes please visit:

- www.bourns.com/products/diodes/silicon-carbide-sic-schottky-barrier-diodes

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