SiC Schottky Diode Device Design: Characterizing Performance & Reliability

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As power electronics design engineers seek to develop new power conversion systems that achieve smaller, more efficient, and more reliable systems — such as solar inverters, battery charging systems, and server power supplies — they are increasingly specifying silicon carbide (SiC) power devices in place of conventional silicon power devices. SiC Schottky diodes have proven to be a particularly popular choice for these applications, which has motivated many manufacturers to develop and/or increase their selection of commercially available products. Since their introduction some 10+ years ago, the device design, performance, and reliability of SiC diodes have continued to evolve and develop, providing new choices for design engineers. The differences between the available SiC devices must be taken into consideration when specifying the optimum devices for a given application. The following article will highlight the design evolution path of SiC Schottky diodes and characterize the differences in their reliability and performance.

Today, SiC Schottky diodes are commercially available with different levels of quality and performance, most of which can be ascribed to the actual device design. The earliest SiC diodes employed a basic Schottky barrier diode (SBD) structure, but these simple devices experienced a high incidence of problems in the field [1,2]. A SiC Schottky diode must block high voltages (>300V) under reverse bias as a basic operating requirement, and these early SiC SBDs were prone to increased leakage currents over time until the device experienced catastrophic failure [1]. One of the root causes of these early failures was intrinsic to the simplicity of the device structure. As shown in Figure 1, the basic structure of a Schottky barrier diode consists simply of a metal-semiconductor junction.
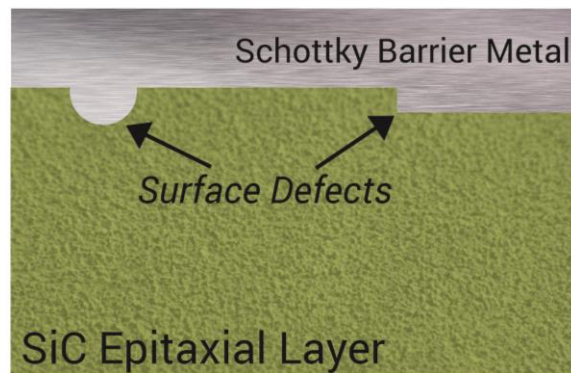
Figure 1: Typical SiC substrate with Schottky barrier metal showing surface contact defects

Figure 1 also illustrates that, on a macroscopic level, various non-planarities and surface imperfections on the SiC epitaxial layer create structural defects when the Schottky metal is deposited. In addition, on the atomic level, the Schottky metal and SiC semiconductor typically exhibit different lattice characteristics and crystal structures, which results in lattice-level incongruities at the junction. Threading defects, known as dislocations, can work their way through the entire thickness of the SiC epitaxial layer, creating pits at the surface. All of these factors lead to structural defects across the plane of the junction, which become localized points of high electric field concentration when the device is under reverse bias. As a result, significantly higher leakage currents stem from these surface defects, as compared to the bulk material. The defects will experience localized increases in temperature due to the elevated leakage current, thereby creating hot spots that can degrade over time [3], resulting in the leakage current increasing until the device is no longer capable of blocking the required voltage.
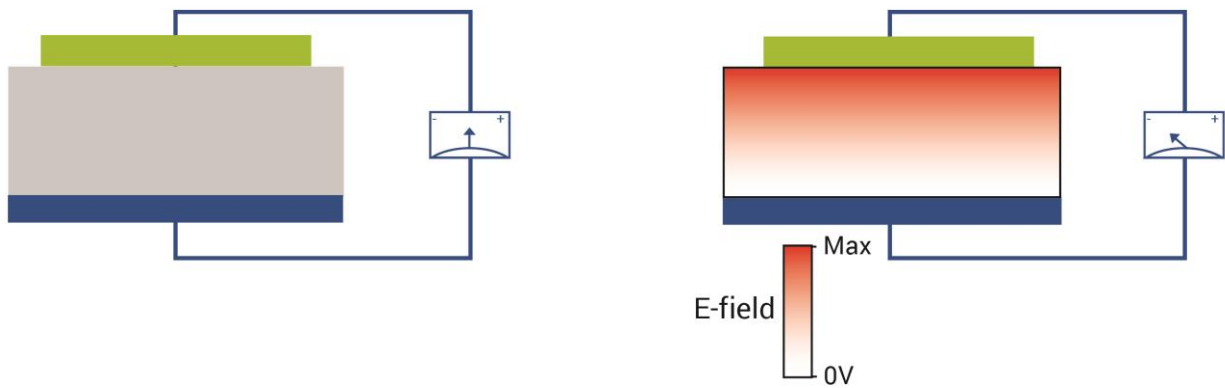

Figure 2(a): The configuration of a pure Schottky diode structure (left) and electric field distribution under reverse bias (right).
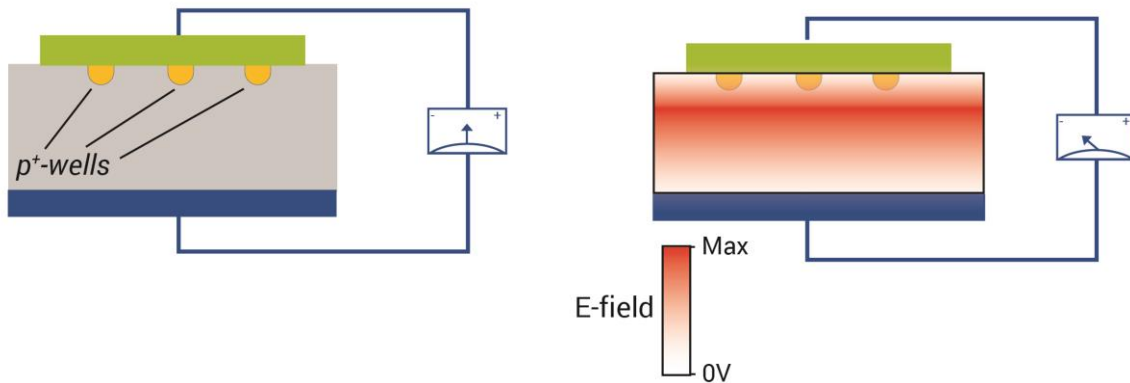
Figure 2(b): A Junction Barrier Schottky (JBS) diode structure (left) and electric field distribution under reverse bias (right).

To solve this problem, early SiC manufacturers moved towards the Junction Barrier Schottky, or JBS design [4]. Figure 2 illustrates the revision of the basic Schottky device to the Junction Barrier Schottky [4]. With the addition of regularly spaced P+-wells located just below the Schottky barrier, this enhanced design significantly increased both the reliability and robustness of the diode. In a conventional SBD under reverse bias, shown in Figure 2a, the gradient of the electric field extends across the thickness of the N$^-$ drift layer, with its peak electric field value occurring at the barrier, placing maximum stress on the pits, imperfections, and other defects existing at the Schottky interface. However, within the JBS diode, shown in Figure 2b, the P+-wells create a series of homojunctions with the surrounding N$^-$ drift layer. The depletion region at the interface of the P+-wells and the N$^-$ drift layer is a characteristic of any semiconductor junction. Subsequently, when reverse bias is applied to the diode, the electric field associated with the p-n depletion region impinges against the applied electric field. The resulting peak electric field level moves to the bottom of the P+-wells, located a distance from the defects of the Schottky barrier. As such, this design results in a diode with lower leakage currents and higher breakdown voltages than conventional Schottky barrier diodes.
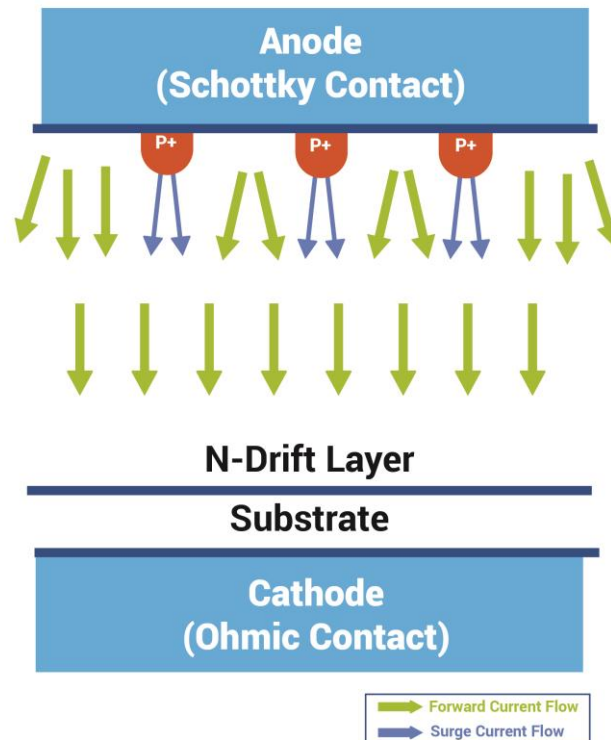

Figure 3: A Wolfspeed™ MPS diode structural diagram exhibiting transient surge conditions

The SiC Junction Barrier Schottky diode underwent further evolution over a period of more than ten years of continued innovation and device improvement to become the Merged PIN Schottky, or MPS [5]. While still exhibiting all of the advantages of JBS diodes under reverse bias, the MPS diodes also exhibit a unique feature under forward bias. Here, modification of the device construction results in the P+-wells forming a P-i-N junction with the drift layer and the substrate. These P-i-N junctions will remain inactive during normal forward operation, and do not contribute to the forward current. During forward transient events, however, the P-i-N junctions turn on, creating a dramatic increase in the diode's forward current-carrying capability (Figure 3). This device design produces a diode with significantly higher forward surge current handling capability than the conventional Schottky diode.
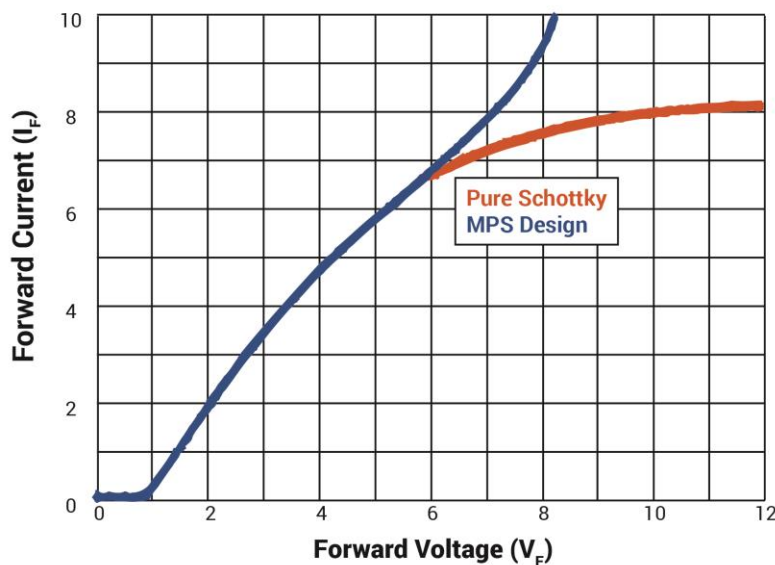

Figure 4: Measurements performed on a curve tracer showing the forward bias characteristics of an MPS diode (blue trace) and a non-MPS diode (red trace).The activation of the P-i-N diodes causes an upward divergence of the MPS diode above 6V.

Curve tracer measurements of an MPS diode and a pure Schottky diode under excessive forward current are compared in Figure 4. During high surge current conditions, pure Schottky diodes have the potential to transition into thermal runaway and eventual destruction due to the resultant high forward voltage drop. However, under identical conditions, the MPS diodes handle the same level of current with only a slight increase in forward voltage drop, demonstrating a significantly higher degree of device ruggedness than pure Schottky diodes. This conclusion is supported by field data that has been collected by Wolfspeed, A Cree Company, over the course of more than a decade of commercial diodes being deployed, accumulating an estimated 2 trillion device hours in the field. The total FIT rate (failures in time) for this population is 0.27, or

less than 15% of the comparable value for silicon devices, a long-established technology.

Product	Device Hours	FIT (fails/billion hrs)
CSDxxx60	864,000,000,000	0.2
C2Dxx120	210,000,000,000	1.4
C3Dxxx60	1,050,000,000,000	0.1
C4Dxxx120	95,000,000,000	0.3
Total	2,219 Billion	0.27

Table 1: FIT data for Wolfspeed's SiC MPS and JBS Schottky diodes

In an effort to provide design engineers with a lower cost option, some SiC device manufacturers have reintroduced versions of "pure" SBD devices. These SBDs still exhibit the inherent interfacial vulnerability with the proximity of their peak electric field to the Schottky junction, and therefore still exhibit lower breakdown voltages and higher leakage currents than MPS diodes. They also lack the MPS diodes' advanced forward surge protection†. Recent analysis has shown that, after continuous avalanche testing, these newer, basic Schottky diodes demonstrate physical damage in the device structure and degradation of the breakdown voltage, while MPS devices exhibit stable operation under the same conditions [6].

Depending upon the rigorous demands of their system, design engineers may wish to determine whether their specified diodes are designed as SBD, JBS, or MPS devices. While component manufacturers don't typically publish their SiC diode structure as part of their datasheets, the information is often available on request, and a comparison of datasheet values can also reveal the device structure. For example, conventional (basic) SBD devices have much higher reverse leakage currents than JBS and MPS devices of comparable ratings, especially at higher temperatures. Additionally, higher forward surge ratings indicate that the device in question is an MPS diode, as compared to JBS and SBD devices. While the specification can be difficult to quantify due to measurement parameter variations, the MPS surge rating is typically double that of a comparable SBD.

Table 2 contrasts the datasheet values of Wolfspeed MPS diodes with conventional SBD diodes, demonstrating typical differences between the leakage currents and forward surge capabilities of the different designs.

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† Ideally, a comparison of FIT data for MPS vs. SBD devices should have been included with Table 1. However, since commercially available SiC SBD devices have only been on the market for a brief period of time, field data is limited.

Diode Structure	Non-repetitive Forward Surge, $I_{F,SM}$ (A)		Reverse Leakage Current, I_R (µA) @ T_J=175°C	
		T_C=25°C, 10ms half sine	T_C=25°C, 10µs pulse	Typical	Max
Wolfspeed C4D05120A 1200V 5A Schottky	MPS	46	400	40	300
Company A 1200V 5A SiC Schottky	SBD	23	87	65	n/a
Company B 1200V 6A SiC Schottky	SBD	25	100	>650	>1500

Table 2: Comparison of Wolfspeed™ MPS diodes and commercially available SiC SBD diodes [7]

To further verify the type of diode being specified, a resourceful engineer can test individual diodes in the lab to examine device characteristics that are not included in datasheets. As seen in Figures 5 and 6, placing the diodes under extreme forward and reverse bias causes them to exhibit noticeably different behavior. When 5–10x the rated forward current is applied, an MPS device will show an upward parabolic turn, indicative of the turn-on of the P-i-N diodes. In contrast, an SBD device will saturate under these conditions, as demonstrated by an asymptotically flattened curve. At this point, the device is potentially headed toward failure. When applying reverse bias, the SBD device also shows higher leakage current than equivalently rated JBS/MPS devices, and begins the transition to breakdown at a lower voltage than the JBS/MPS diode.
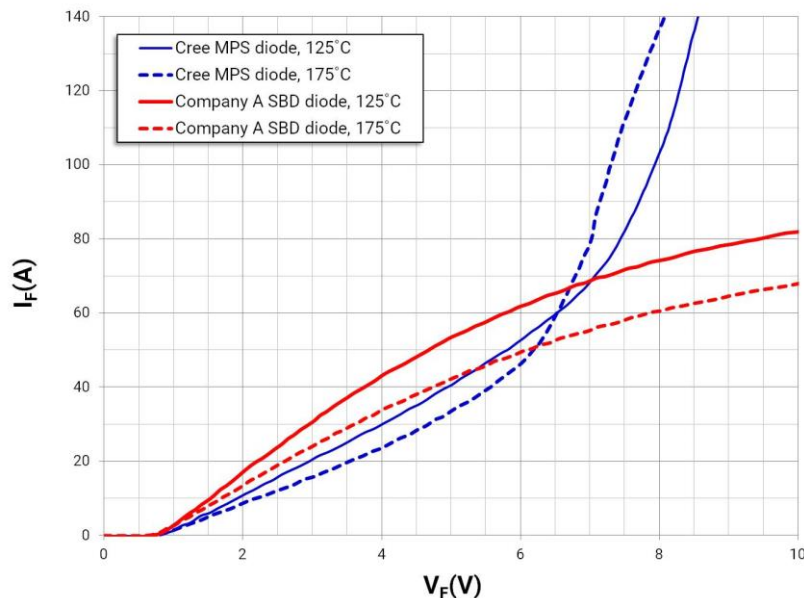
Figure 5: Forward bias comparison of a Wolfspeed™ 10A MPS diode vs. a 10A SBD diode from Company A
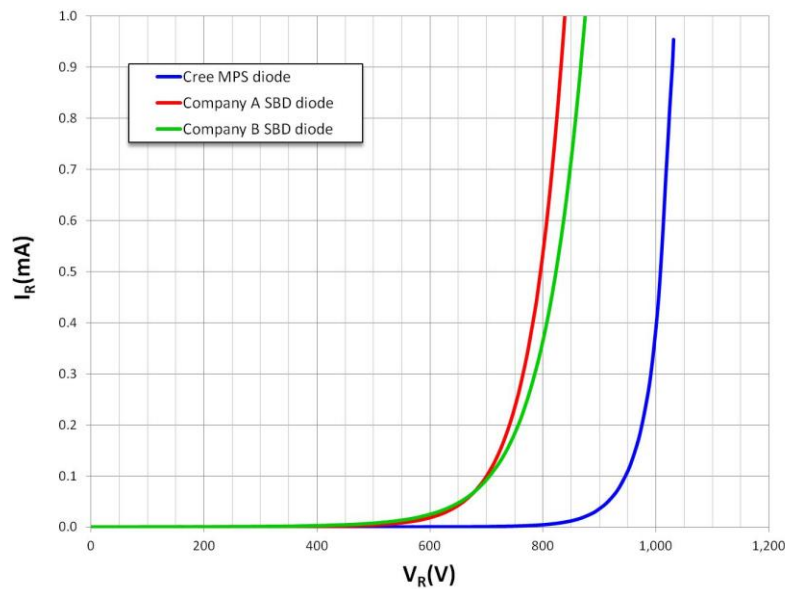

Figure 6: Reverse bias comparison of a Wolfspeed™ 650V MPS diode vs. 650V SBD diodes from Company A and Company B at 125°C

Conclusion

The modern generation of enhanced SiC Schottky diodes — those that employ the Junction Barrier Schottky or Merged PIN Schottky design — have been commercially available for more than a decade. Thus, these diodes have arguably entered the maturity phase of their lifecycles, with initial issues and field failures associated with product introduction long resolved. Although pure SiC Schottky barrier diodes were originally introduced before both JBS and MPS diodes, the current generation of basic SiC SBD devices is still considered to be in its introductory phase due to the long gap between initial design and their relatively recent commercial availability. Several manufacturers have already released their second generation of SBD devices, but many are still in the first design stage. While most manufacturers take every precaution to produce a reliable, high quality product, the fact remains that these younger technologies will likely experience a higher risk of infant mortality. The relatively limited size of the current FIT field data makes a firm conclusion impossible to draw.

Wolfspeed SiC MPS diodes, on the other hand, are now on their fifth design iteration in commercial release, with significant field data to support their reliability and performance. Combined with the higher breakdown voltage and enhanced surge capability of this MPS design, engineers should have confidence specifying this established device technology, which contributes to a rugged and reliably-performing end product and system.

References

1. Acharya, K.; Shenai, K. Proceedings, Power Electronics Technology Conference, October 2002, 672-677
2. M. Holz et al., Microelectronics Reliability, v47 (2007), 1741–1745
3. R. Rupp et al., Materials Science Forum, vols. 483-485 (2005), 925-928.
4. J. Richmond et al, IEEE Workshop on Power Electronics in Transportation (WPET), 2004, Detroit.
5. R. Rupp, et al., Proceedings of the 18th International Symposium on Power Semiconductor Devices & IC's, June 4-8, 2006, Naples, Italy.
6. R. Rupp et al., as presented at the 26th International Symposium on Power Semiconductor Devices & IC's, June 15-19, 2014, Waikoloa, Hawaii.
7. Publicly available datasheets
8. A. Agarwal et al.,"600 V, 1- 40 A, Schottky Diodes in SiC and Their Applications", at http://www.cree.com/~/media/Files/Cree/Power/Articles%20and%20Papers/PWRTechnicalPaper1.