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Understanding Evolution Of SiC Schottkys Is Key To Device Selection

by Thomas Barbieri, Cree, Durham, N.C.

Silicon carbide (SiC) power devices are being specified more frequently in a growing number of power electronics applications, especially in solar inverter designs. In particular, SiC Schottky diodes have been favored by design engineers seeking to develop new inverter designs that are more compact, more efficient, and more reliable than those based on silicon power devices.

During the 10+ years since SiC diodes were introduced, both their device design and reliability parameters have undergone significant evolutionary changes. These changes have resulted in a broadening portfolio of SiC Schottky diodes available on the commercial market. As such, discerning design engineers should be aware of the differences between these diodes and take them into consideration during the design cycle.

This article will characterize the evolution of modern SiC Schottky diodes, from Schottky barrier to junction barrier to merged p-i-n structure, and illustrate the differences in their performance, reliability, and robustness. Cree devices are used as examples in this discussion, but the reader should note that the various device types presented are available from multiple sources.

High-Voltage Woes For Early SiC Schottky Barrier Diodes

Just as with any product, there are different levels of quality and performance available in today's SiC Schottky diode market. Much of this stems from the actual structure of the device. Let's begin by examining the structure of a simple Schottky barrier diode.

A Schottky barrier diode (SBD) is one of the simplest semiconductor devices. In its most basic form, it consists of a metal-semiconductor junction. The earliest SiC Schottky diodes used this structure. However, these simple devices very rapidly ran into problems in the field.[1,2]

One of the key requirements of a SiC Schottky diode is that it must block high voltages (>300 V) under reverse bias. An observed vulnerability in these early SiC SBDs was leakage currents gradually increasing with time until the device catastrophically failed.[1]

There are many factors associated with the Schottky barrier that contribute to the inherent weaknesses in the design (Fig. 1). On macroscopic levels, surface imperfections and non-planarities on the SiC epitaxial layer will create large structural defects when the Schottky metal is deposited upon it. Additionally, the formation of various silicides and carbides is likely at the interface between the two materials.

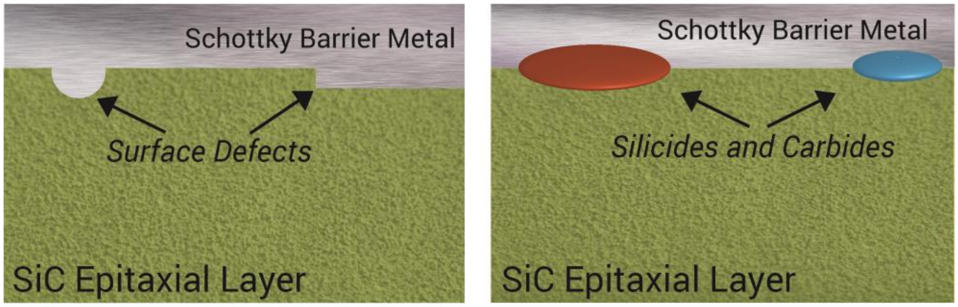

Fig. 1. Typical surface contact defects between SiC substrates and Schottky barrier metal.

On a microscopic level, the Schottky metal and SiC semiconductor will have different crystal structures and lattice parameters, which results in significant atomic-level incongruities at the junction. All of these factors lead to structural defects across the plane of the junction. Under reverse bias, these defects act as initiation points for leakage currents. Additionally, due to localized temperature increases associated with the leakage currents, the defects can grow larger with time;[3] and, as the defects grow larger, they carry more leakage current, progressing until the device can no longer block the specified voltage.

Junction Barrier Design Improved Reliability

The solution to this problem was to incorporate a design known as the junction barrier Schottky, or JBS.[4] The primary modification of the JBS design is the addition of regularly spaced p^+ wells located just below the Schottky barrier. Fig. 2 demonstrates how this improvement substantially increased the reliability and robustness of the diode.

Fig. 2a displays a basic SBD under reverse bias. The electric field gradient extends across the thickness of the n- drift layer, with the peak electric field value occurring at the barrier, exactly where the defects are. In the case of the JBS diode, the p^+ wells create a series of homojunctions with the surrounding n- drift layer.

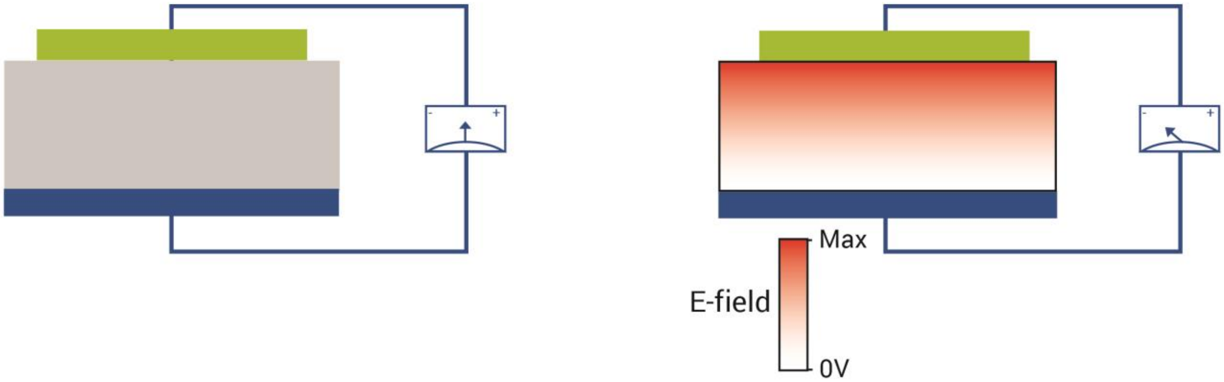

Fig. 2a. Structure (left) and electric field distribution under reverse bias (right) of a pure Schottky diode.

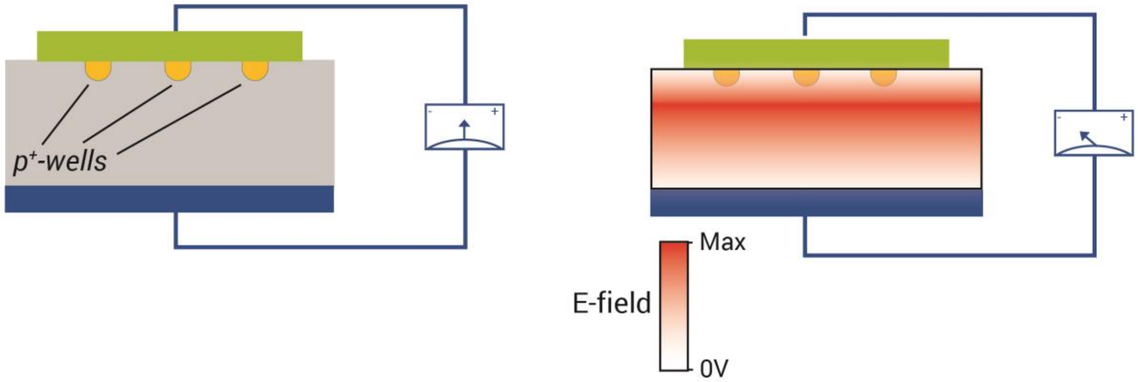

Fig. 2b. Structure (left) and electric field distribution under reverse bias (right) of a JBS diode.

As with any semiconductor junction, a depletion region exists at the interface of the p^+ wells and the n- drift layer. When reverse bias is applied to the Schottky diode, the electric field associated with the p-n depletion region impinges against the applied electric field. As can be seen in Fig. 2b, the resultant peak electric field is at the bottom of the p^+ wells, far from the defects of the Schottky barrier. Consequentially, the JBS diode has significantly lower leakage currents and higher breakdown voltage than basic Schottky barrier diodes.

Merged P-I-N Structure Enhances Surge Current Handling

After more than a decade of innovation and on-going product development, the SiC junction barrier Schottky diode has evolved into the merged p-i-n Schottky, or MPS.[5] MPS diodes have all of the advantages of JBS diodes under reverse bias while also including a unique feature under forward bias.

In the MPS structure, the p^+ wells have been altered to form a p-i-n junction with the substrate material. During normal forward operation, these p-i-n junctions remain inactive, not contributing to the forward current. However, during forward transient events, the p-i-n junctions turn on, dramatically increasing the forward current-carrying capability of the diode (Fig. 3.) This results in a device with much greater forward surge current handling capability than a simple Schottky diode.

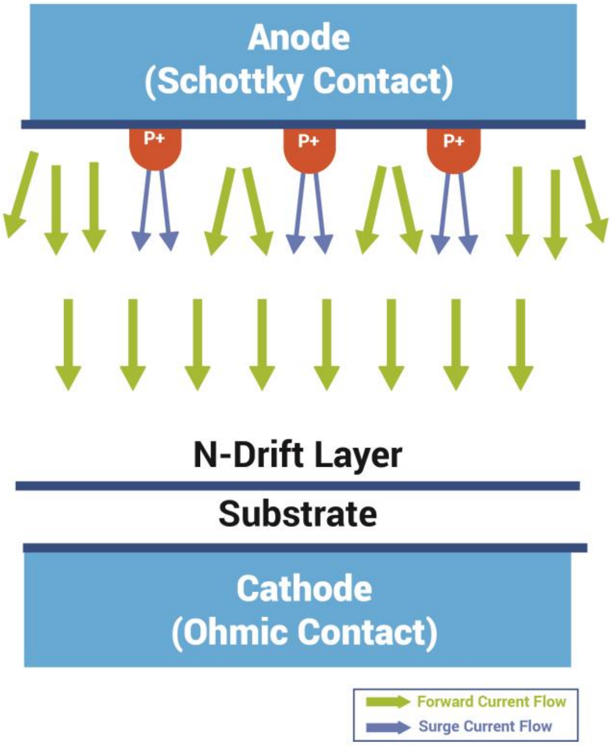

Fig. 3. A structural diagram of a Cree MPS diode under transient surge conditions.

Fig. 4 compares a curve tracer measurement of an MPS diode and a pure Schottky diode under forward current. During high surge-current conditions, pure Schottky diodes can transition into thermal runaway and potentially be destroyed due to the associated high forward-voltage drop. Alternately, under these same conditions, MPS diodes transmit the same high current with minimal increase in forward voltage drop, and are thus much more rugged and robust devices than pure Schottky diodes.

Field data supports this conclusion. Cree has been offering commercially available JBS and MPS SiC diodes for more than ten years, and has accumulated an estimated one trillion device hours in the field. The total failures in time (FIT) rate for this population is 0.095, which is less than one-twentieth the comparable value for silicon devices, a long-established technology (Table 1.)

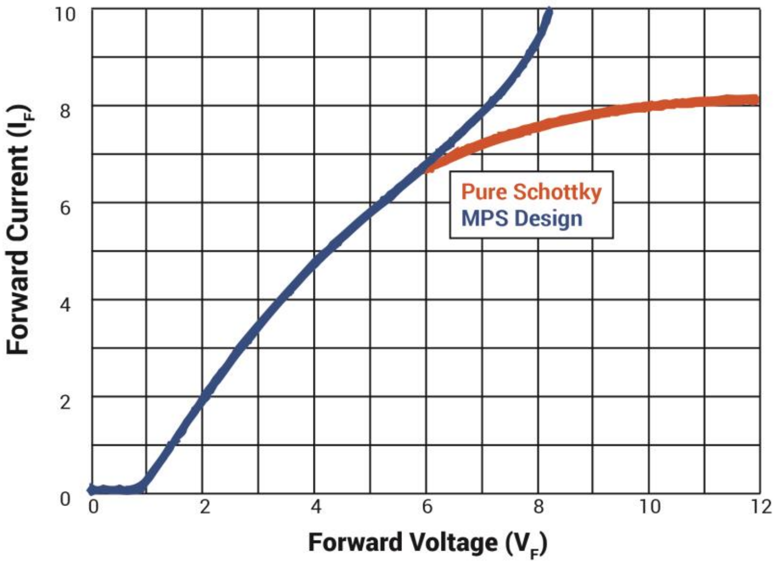

Fig. 4. Curve tracer measurement of an MPS diode (blue trace) and a non-MPS diode (red trace). The activation of the p-i-n diodes causes the upward divergence of the MPS diode above 6 V.

Table 1. FIT data for Cree's SiC MPS and JBS Schottky diodes

Product	Device structure	Device hours	FIT (fails/billion hours)
CSDxxx60	JBS	483,000,000,000	0.05
C2Dxx120	JBS	171,000,000,000	0.43
C3Dxxx60	MPS	481,000,000,000	0.02
C4Dxxx120	MPS	46,800,000,000	0.04
Total		1,183 billon	0.099

In recent years, pure SBD devices have reemerged in the SiC Schottky diode marketplace in an effort to provide customers with a lower-price option. While it must be assumed that these manufacturers have found an acceptable solution to the failure mode of the original SiC SBD devices, these modern SBDs still retain the inherent flaw of having the peak electric field at the Schottky junction; and, as such, still have higher leakage currents and lower breakdown voltages than MPS diodes.

Moreover, they also completely lack the advanced forward surge protection of the MPS diodes. 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. Recent analysis has shown that these modern pure Schottky diodes demonstrate unstable operation after continuous avalanche testing, an effect not observed in MPS devices.[6]

How can informed consumers determine whether the diode they are purchasing is SBD, JBS, or MPS? Device manufacturers don't necessarily broadcast the structure of their SiC diodes, but this information is usually available upon request. If not, a quick comparison of datasheet values can provide insight into the device structure.

For instance, simple SBD devices will have higher reverse-leakage currents than comparable JBS and MPS devices, particularly at higher temperatures. Furthermore, MPS diodes will have greater forward-surge ratings than both JBS and SBD. The difference is difficult to quantify due to variations in measurement parameters, but the MPS surge will be at least 2x greater than a comparable SBD.

As an example, Table 2 compares the datasheet values of Cree MPS diodes to typical commercially available SBD diodes.

Table 2. A comparison of Cree MPS diodes to commercially available SiC SBD diodes. (Comparisons are based on specifications provided in publicly available datasheets.)

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

To go one step further, the enterprising engineer can acquire several samples of each diode and test them in the laboratory to explore device behavior that is not normally contained in datasheets. As displayed in Figs. 5 and 6, placing the diodes under extreme forward and reverse bias will also reveal their structure.

Under forward bias at 5x to 10x the rated current, MPS devices exhibit an upward parabolic turn as the p-i-n diodes turn on. In contrast, the SBD devices exhibit a curve that flattens asymptotically as the device saturates and heads toward failure. Additionally, under reverse bias, the SBD has higher leakage than both the JBS/MPS devices, and begins to transition into breakdown at lower voltages than the JBS/MPS diode.

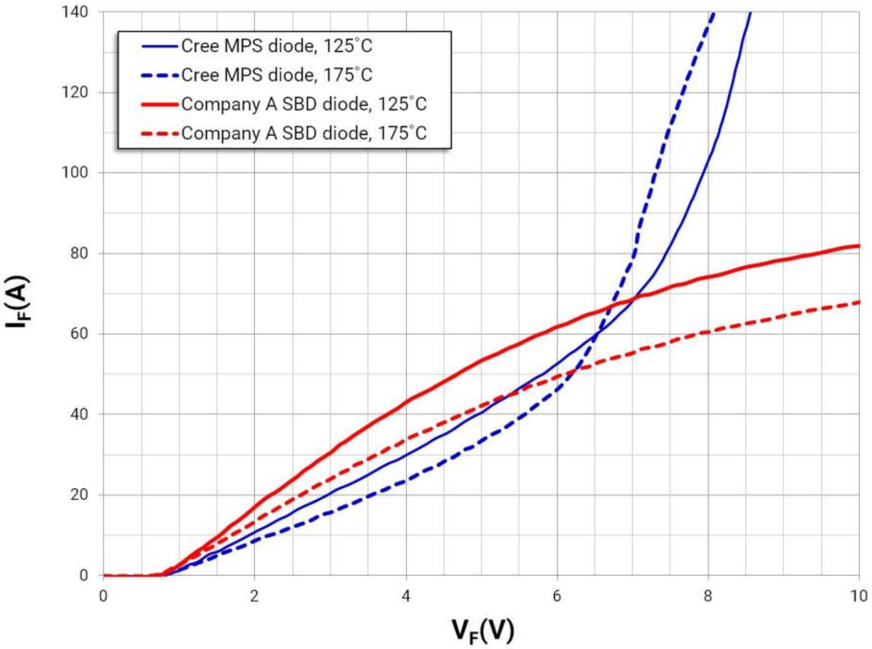

Fig. 5. Forward bias comparison of a 10-A MPS diode from Cree versus a 10-A SBD diode from company A.

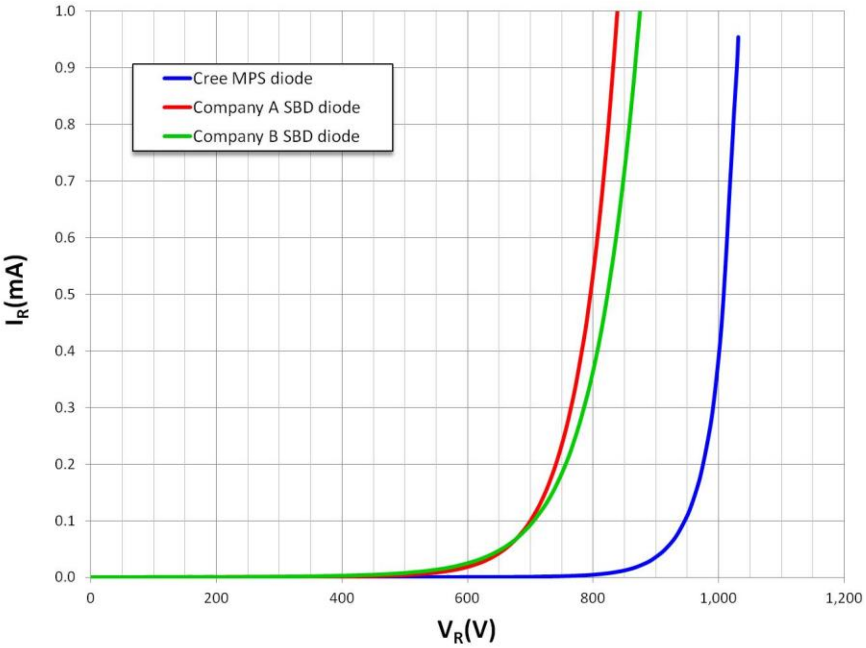

Fig. 6. Reverse bias comparison of a 650-V MPS diode from Cree versus 650-V SBD diodes from company A and company B at 125°C.

Conclusion

All new technology must go through the technology lifecycle. SiC Schottky diodes that use the junction barrier Schottky or merged p-i-n Schottky structure have been on the commercial market for more than a decade. As such, it can be argued that these diodes have transitioned into the maturity phase of their lifecycles, and the initial issues and field failures associated with their market introduction have long been resolved. In contrast, although pure SiC Schottky barrier diodes were originally introduced before JBS and MPS diodes, current SBD devices should still be considered to be within the introductory phase due to the long hiatus between their initial introduction and recent reentry into the commercial market.

Some SBD manufacturers have already released their second generation, but many are still in their first design iteration. Although there is no reason to assume that these manufacturers aren't taking every precaution to produce a high-quality, reliable product, there is a higher risk of infant mortality failures inherent in these younger technologies; and, unfortunately, the limited size of the current field FIT data prevents a firm conclusion from being drawn.

Commercial SiC MPS diodes, such as those offered by Cree are currently on their fifth design iteration, and there is a substantial amount of field data supporting the high reliability of this design. Thus, when combined with the enhanced surge capability and higher breakdown voltage of the MPS design, engineers should feel confident designing with this established technology, which is rugged, robust, and reliable.

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About The Author

Thomas Barbieri has spent the past 14 years of his career filling various roles within the semiconductor industry, He started with Freescale Semiconductor, where he acted as a process engineer for MEMS sensors and as a failure analysis engineer/materials characterization specialist supporting all semiconductor products. For the last 8 years, Tom has been with Cree, having served as an R&D scientist with the Materials business unit and a product engineer with the LED Components business unit, prior to joining Cree Power as a marketing engineer.

Prior experience included an assistant professorship in the Physics Department of Simmons College. Tom received his PhD in Materials Science and Engineering from Cornell University in 1999.

For further reading on SiC power devices, see How2Power.com's section on Silicon Carbide and Gallium Nitride Power Technology.