AN-1014

Understanding the Benefits of SiC Schottky Diodes compared to Silicon Diodes

Content

1. What is SiC (Silicon Carbide) Schottky Diodes

Wide Bandgap (WBG) devices have recently gained significant attention as promising alternatives to traditional silicon (Si) devices. Over the past several years, Silicon Carbide (SiC) Schottky diodes have rapidly emerged as key components in various power electronics applications, including electric vehicles, data-center power systems, high-efficiency switching power supplies, and the renewable energy market. A SiC crystal consists of an equal number of carbon and silicon atoms, with each carbon atom covalently bonded to a silicon atom. SiC exists in over 100 different crystal structures, known as polytypes, with 4H-SiC being the most widely preferred in the industry.

Taiwan Semiconductor has introduced a 650V Silicon Carbide (SiC) Schottky diode product featuring advanced technology for power conversion. This innovation significantly reduces parasitic capacitance and reverse recovery charge compared to silicon diode technology. Additionally, the initial 650V SiC Schottky diodes provide high surge current handling capability and are optimized for industrial applications.

In this document, we will induct the Silicon Carbide (SiC) Schottky diode and compare it with the silicon diode, understanding some differences between these two products is crucial for effective use.

1.1 Physical properties and features of SiC Introduction

In physics, all solid-state elements have electrons that are either bound to the nucleus of the element or free to move at a higher energy level, known as the valence band and the conduction band, respectively. The bandgap determines the energy required for electrons to transition from the valence band to the conduction band. The physical and electrical properties of wide-bandgap materials govern the functional and application characteristics of power semiconductors constructed with them. Silicon has been the primary semiconductor material since the 1950s, with a bandgap of 1.12 eV (electron volts). The latest wide bandgap (WBG) semiconductors are based on new and emerging materials, typically featuring bandgaps two to three times that of silicon. Due to the small lattice constant of WBG semiconductors, the bonding strength between atoms increases, resulting in high breakdown fields and thermal conductivity. The physical properties are presented in Table 1.

Table 1: Physical property constants of Silicon and wide bandgap

Property	**Unit**	**Silicon**	**SiC**
Band gap	eV	1.12	3.26
Electron mobility (μ_e)	cm^2/ V-sec	1400	900
Electric breakdown field (E_c)	MV/cm	0.3	2.8
Thermal conductivity (λ)	W/cmK	1.5	4.9
Saturated electron drift velocity (V_{sat})	cm/sec	1.0×10^7	2.5×10^7

Figure 1 displays properties suitable for various applications. SiC exhibits higher thermal conductivity and a higher breakdown electric field, making it more suitable for high-power applications. These include high-voltage requirements for electric vehicles, data centers, and railway traction systems, where higher voltage operation and superior heat dissipation are critical. SiC is a superior material to silicon in terms of power handling and fast charging capabilities. The devices offer higher operating temperature capabilities, thereby increasing achievable power density and optimizing performance across a growing range of applications.

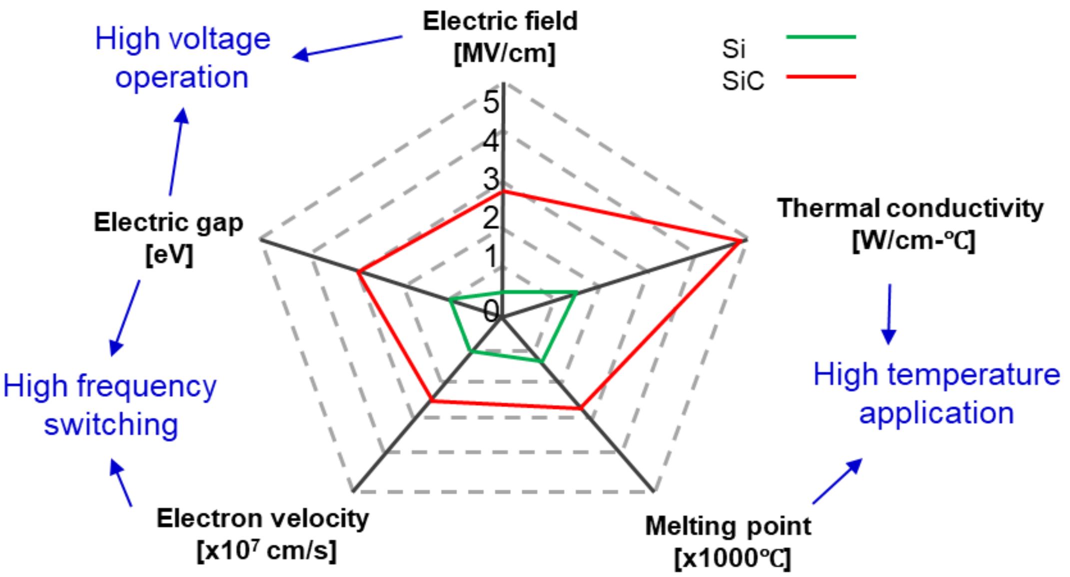
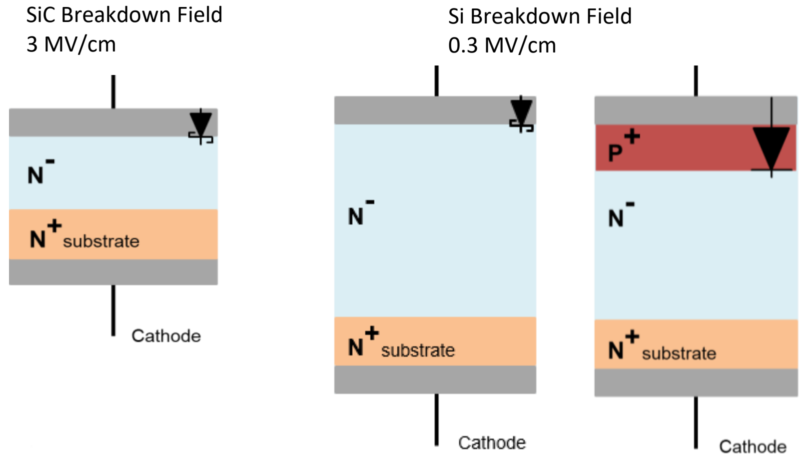


Figure 1 The characteristics of applications

1.2 Device structure and the characteristics

SiC has a much higher dielectric breakdown field, about 9 times greater than silicon. This allows SiC power devices with high breakdown voltages which ranging from 600 V to two thousand volts to be made with a thinner drift layer that has a higher impurity concentration compared to silicon devices. This results in smaller and more efficient power devices. Figure 2 illustrates the structure between the SiC Schottky diode, Silicon Schottky diode and PN junction diode structure. For high-voltage diodes used in SMPS (Switched-Mode Power Supply) applications, fast-switching characteristics are important for better efficiency. Traditional silicon diodes designed for this purpose are called FRDs (Fast Recovery Diodes). These diodes use a PiN junction, which is a bipolar structure involving both electrons (majority carriers) and holes (minority carriers). However, holes move more slowly than electrons, which limits their switching speed.

To improve switching speed, silicon FRDs undergo special processes like lifetime killing, which reduces the time required for the carriers to recombine. This helps silicon FRDs achieve faster switching and lower reverse recovery characteristics. However, they still experience some reverse recovery charge due to the presence of minority carriers. In contrast, a pure Schottky diode is a unipolar device, meaning it only uses electrons (majority carriers). Because of this, it ideally has no reverse recovery charge, only a small capacitive charge. However, silicon Schottky diodes are limited in achieving high breakdown voltages (above 200V) due to silicon's lower bandgap properties. SiC diodes, on the other hand, typically have a Schottky structure and are known as SiC SBDs (Schottky Barrier Diodes). Thanks to the wide bandgap properties of SiC, these diodes can handle much higher breakdown voltages, making them ideal for high-voltage and high-power applications. SiC SBDs are considered cutting-edge devices in modern power electronics.



(1) SiC Schottky diode (2) Schottky diode (3) PN diode

Figure 2. The basic structure between SiC and Silicon

1.3 Schottky barrier diodes technology

In the SiC SBDs, a simple design is used where the Schottky metal is directly connected to the drift layer. This is called the pure Schottky structure. While, as the temperature rises, the resistance of the drift layer increases. This causes self-heating, which limits the current flow during a forward surge. As a result, the peak surge current (I_{FSM}) of SBDs is lower compared to silicon FRDs. In some system circuits that don't use a bypass diode, the high inrush current during startup or other events can potentially damage the SBDs.

The merged PiN-Schottky (MPS) structure is used in the latest generation of SBDs to improve the peak surge current (I_{FSM}) capability by about twice compared to the pure Schottky structure. As shown in Figure 3, the diode's epitaxial layer includes p-doped regions labeled as p^+. At low current levels, the current flows mainly through the Schottky regions. During surge currents, such as the inrush current to a capacitor when the system is turned on, the p regions become active and provide additional current-carrying capacity. This dual current path, illustrated in Figure 3, significantly enhances the diode's ability to handle surge currents. Furthermore, the MPS structure also reduces the overall voltage drop compared to a standard Schottky diode, improving efficiency under high-current conditions.

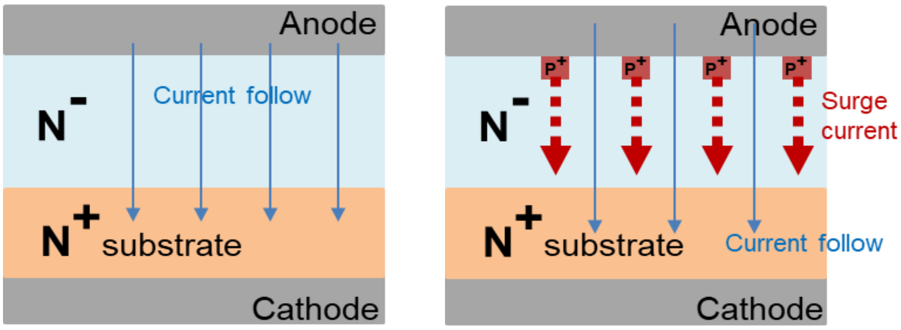


Figure 3(a). The SiC diode structure between Schottky and MPS

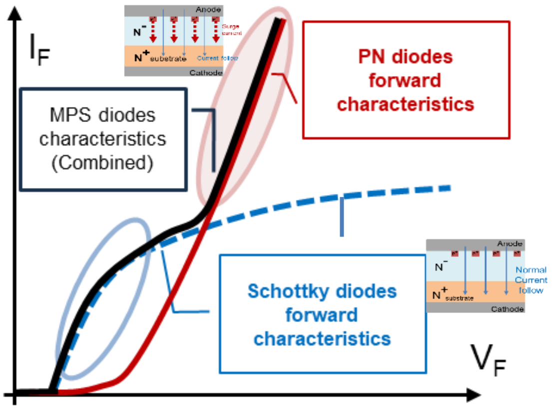


Figure 3(b). MPS Diodes I-V characteristics comparison with Schottky and PN Diode

2. The SiC Schottky diode features

This section highlights the features introduced by the MPS structure and explains the benefits it brings to the new SiC diode devices.

2.1 Forward characteristics

For a system to operate efficiently, power losses must be minimized. In a SiC Schottky diode, the conduction losses (P_{cond}) are typically the main source of energy loss because there is no reverse recovery charge. Conduction losses can be calculated using the formula:

$$P_{cond} = V_F \times I_F$$

Here, I_F is the current flowing through the diode, and V_F is the forward voltage during conduction. To reduce conduction losses, the forward voltage (V_F) must be minimized. The forward voltage V_F has two components:

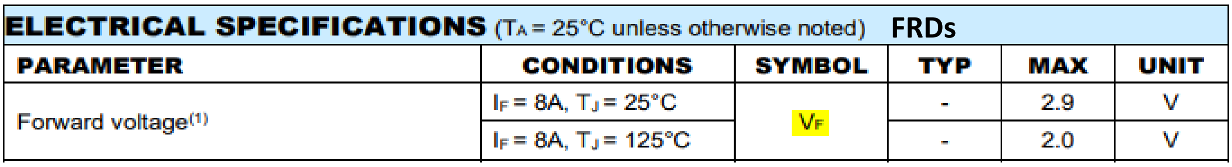
- Threshold voltage (V_{th}): The minimum voltage required for the diode to start conducting.
- Differential resistance (R_{diff}): The resistance of the diode during operation.

The forward voltage can be approximated as:

$$V_F = V_{th} + (I_F \times R_{diff})$$

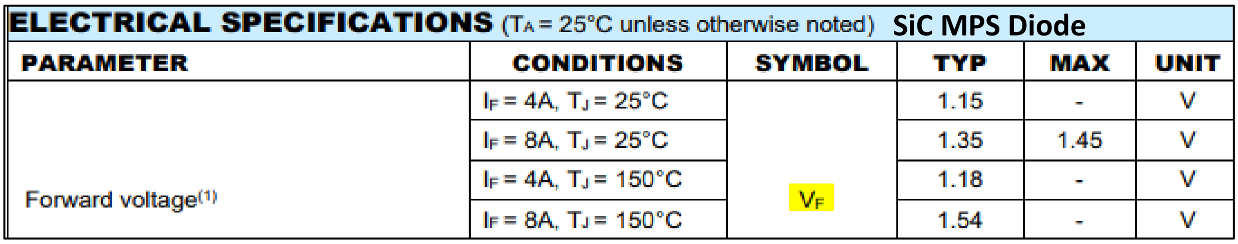
By reducing R_{diff}, the diode's conduction losses can be significantly lowered. Table 2 shows the forward voltage of a SiC MPS diode rated for 8 A, compared with the same current rating from FRDs. A SiC MPS has a lower forward voltage (1.45V < 2.9V).

Table 2 Example V_F between FRDs and SiC MPS diode



ELECTRICAL SPECIFICATIONS (T_A = 25°C unless otherwise noted) **FRDs**

PARAMETER	CONDITIONS	SYMBOL	TYP	MAX	UNIT
Forward voltage(1)	I_F = 8A, T_J = 25°C	V_F	-	2.9	V
	I_F = 8A, T_J = 125°C		-	2.0	V



ELECTRICAL SPECIFICATIONS (T_A = 25°C unless otherwise noted) **SiC MPS Diode**

PARAMETER	CONDITIONS	SYMBOL	TYP	MAX	UNIT
Forward voltage(1)	I_F = 4A, T_J = 25°C	V_F	1.15	-	V
	I_F = 8A, T_J = 25°C		1.35	1.45	V
	I_F = 4A, T_J = 150°C		1.18	-	V
	I_F = 8A, T_J = 150°C		1.54	-	V

From Figure 4, which compares the I-V curves of FRDs at high and low temperatures, the dotted line represents the characteristics of FRDs, which has a negative temperature coefficient. In contrast, the SiC MPS diode exhibits a positive temperature coefficient, indicating a key difference.

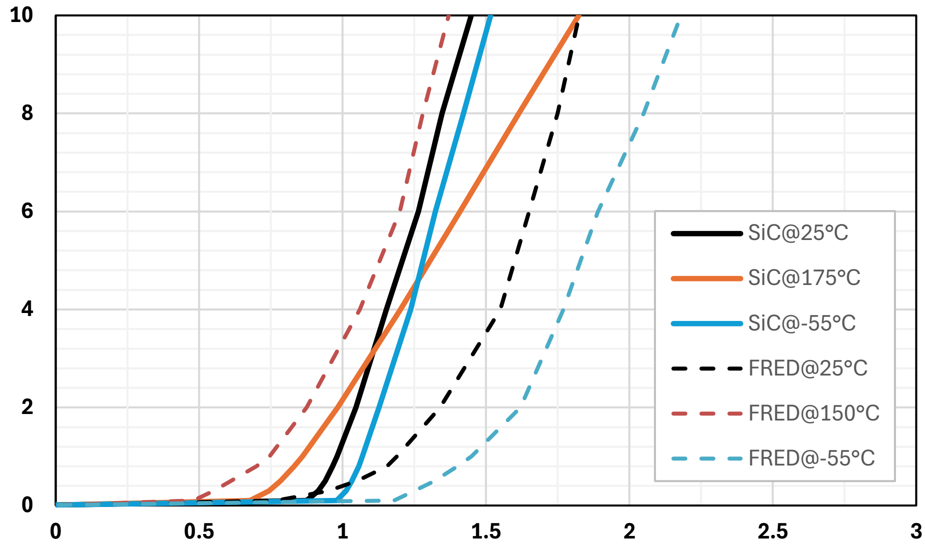


Figure 4. I-V curve comparison of MPS diodes and FRDs at three temperatures

2.2 Recovery characteristic

In silicon FRD diodes, a large surge of current flows briefly when the current direction switches from forward to reverse. This causes energy loss during the transition to the reverse state. The loss happens because minority carriers stored in the drift layer during forward conduction take time to disappear (storge time). Higher forward current or temperature increases the recovery time and current, leading to more energy loss. The recovery losses calculation as:

$$Q_{rr} = {}^{1}/_{2} \cdot I_{RM} \cdot t_{rr}$$

$$P_D = V_R \cdot Q_{rr} \cdot F_{sw}$$

On the other hand, SiC SBDs use majority carriers for conduction, so they don't rely on minority carriers. This means there's no buildup of minority carriers. Only a small current flows to discharge the junction capacitance, reducing energy loss significantly compared to silicon FRDs. This current is also stable regardless of temperature or forward current, allowing for fast and reliable recovery in any condition. Additionally, SiC SBDs generate less noise from the recovery current.

Figure 5(a)~ 5(c) show how SiC SBDs dramatically reduce recovery current compared to silicon FRDs, no matter the temperature or current level. SiC SBDs I_{RM} (reverse recovery current), t_{rr} are lower than silicon FRDs. SiC SBDs recovery charge is 33% of silicon FRDs.

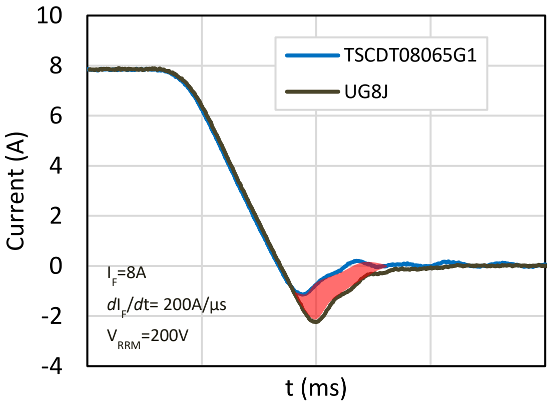


Figure 5(a). Reverse recovery comparison

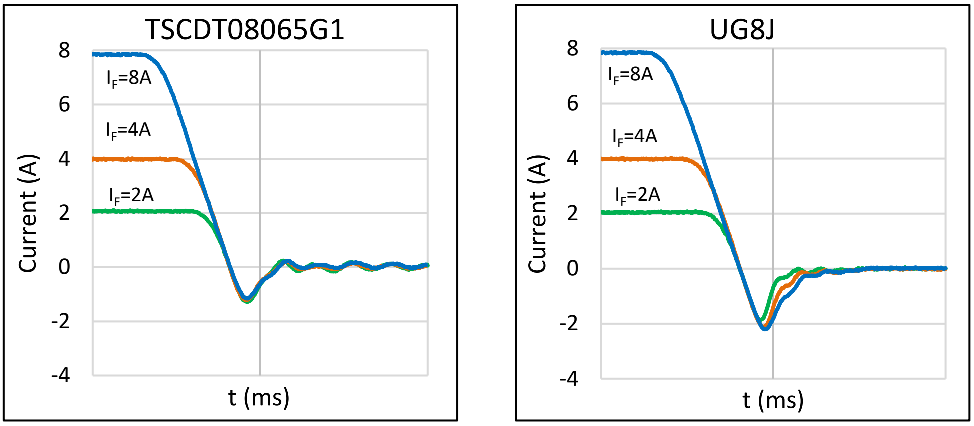


Figure 5(b). Reverse recovery independent of current

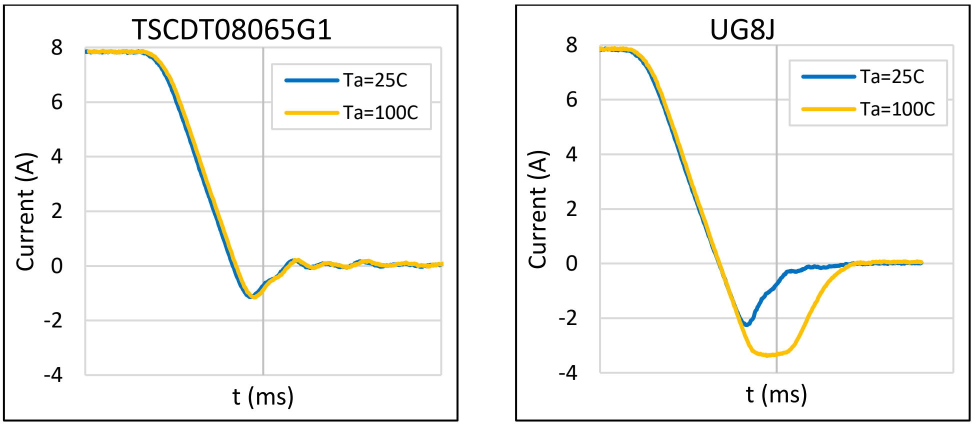


Figure 5(c). Reverse recovery independent of temperature

Figure 5 shows the reverse recovery behavior under an inductive load condition. For a silicon diode, the recovery behavior is strongly affected by the forward current, di_F/dt, and temperature. In contrast, the recovery behavior of a SiC diode is not influenced by these factors.

2.3 Total Capacitance

The total capacitance between the anode metal and cathode metal in a SiC diode follows the basic principles of capacitance. Since the SiC diode is a unipolar device, as a result, capacitance becomes a key parameter affecting switching performance. The capacitance curve as a function of reverse voltage and measured at 1 MHz frequency at Tj = 25°C, which is shown in Figure 6.

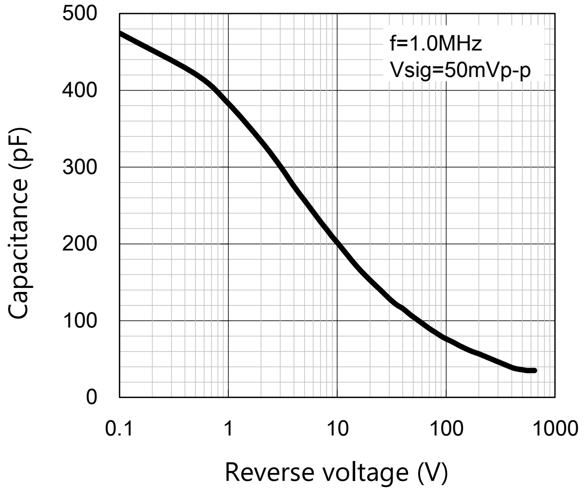


Figure 6. Typical junction capacitance

2.4 Total Capacitive Charge

In the SiC Schottky diode, Q_C represents the total charge amount instead of Q_{rr} in silicon diode. The Q_C curve by reverse voltage is shown in Figure 7. For a silicon diode, there are two charge types, one is Q_{rr} and another is Q_C, however Q_C is very small compared to Q_{rr}, and is negligible in silicon diode.

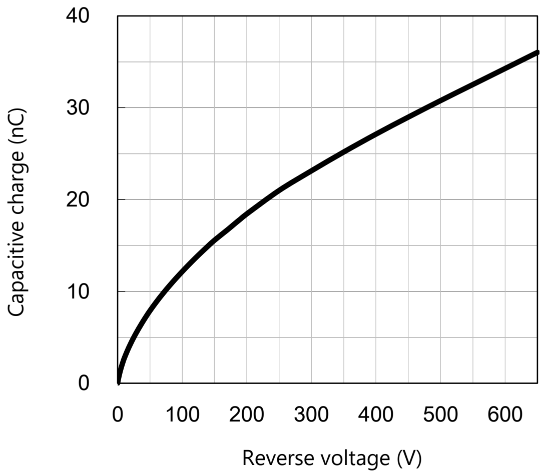
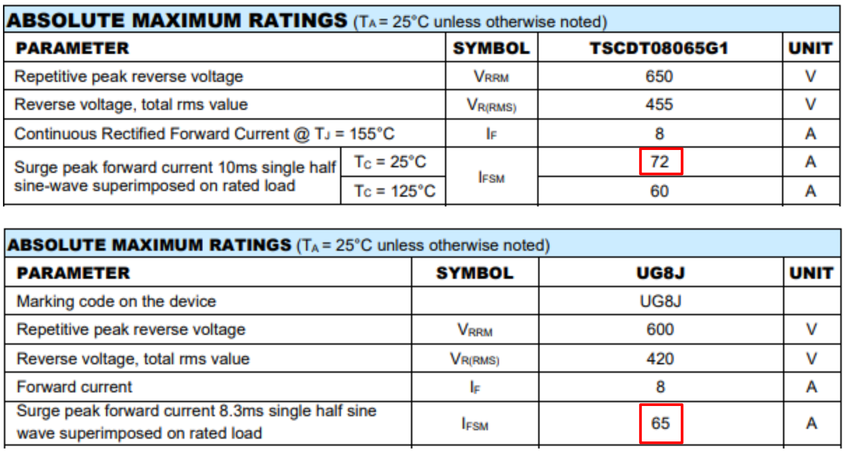


Figure 7. Typical capacitive charge

2.5 The Surge capability

One of the key characteristics is the surge current capability, the MPS diode possesses a much higher surge current ruggedness than a pure Schottky diode, and compared with FRDs (PN diode), SiC MPS diode also has higher forward surge current capability even the test condition is 10ms (>8.3ms, FRDs) in Table 3. In addition, TSC MPS diode has better surge current characteristics than other competitors illustrated in Figure 8, which shows TSCDT08065G1 has a lower V_F in the different current condition.

Table 3 TSCDT08065G1 and FRDs I_{FSM} comparison



ABSOLUTE MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

PARAMETER		**SYMBOL**	**TSCDT08065G1**	**UNIT**
Repetitive peak reverse voltage		V_{RRM}	650	V
Reverse voltage, total rms value		$V_{R(RMS)}$	455	V
Continuous Rectified Forward Current @ T_J = 155°C		I_F	8	A
Surge peak forward current 10ms single half sine-wave superimposed on rated load	T_C = 25°C	I_{FSM}	72	A
	T_C = 125°C		60	A

ABSOLUTE MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

PARAMETER	**SYMBOL**	**UG8J**	**UNIT**
Marking code on the device		UG8J	
Repetitive peak reverse voltage	V_{RRM}	600	V
Reverse voltage, total rms value	$V_{R(RMS)}$	420	V
Forward current	I_F	8	A
Surge peak forward current 8.3ms single half sine wave superimposed on rated load	I_{FSM}	65	A

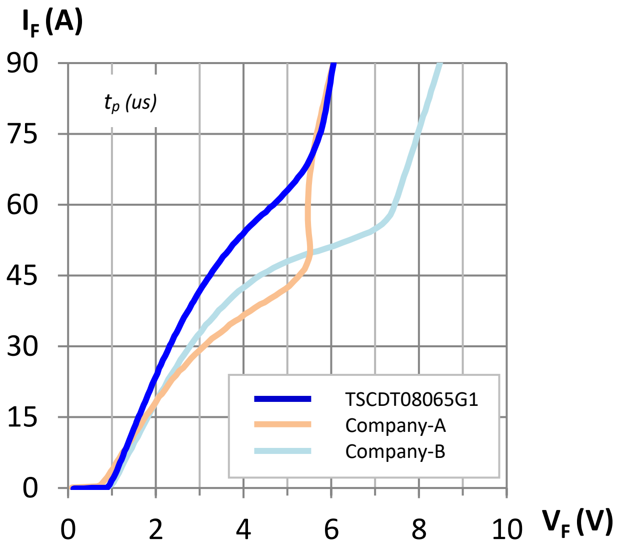


Figure 8. I-V curve in the surge current comparison

3. Application of SiC Schottky Diodes

The absence of reverse recovery charge makes SiC Schottky Diodes an ideal choice for applications demanding high efficiency and low EMI. They also enable higher frequency operation, reducing the size of magnetic components and enhancing overall system design. This results in improved efficiency and increased power density. SiC diodes are particularly beneficial in reducing switching losses in continuous conduction mode (CCM) applications, such as PFC circuits, where their advantages are well recognized.

Figure 9 shows the TSCDT08065G1 and competitors in the PFC (CCM) 800W SMPS test result. The input voltage is 115Vac and switching frequency is 70kHz. From the efficiency curve, TSCDT08065G1 has a higher ~0.2% in light load to middle load.

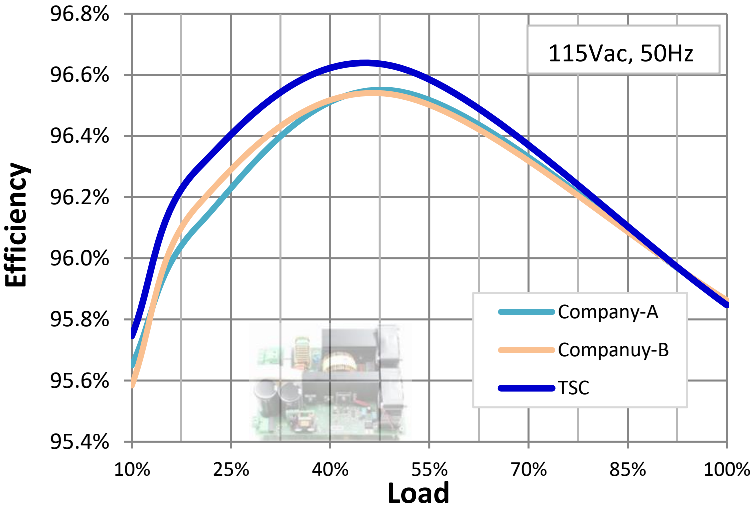


Figure 9. Efficiency curve in 115Vac

When measuring VF and QC for the components, it was found that the TSCDT08065G1 has the best performance in VF, while its QC value is in the middle among the three illustrated in Figure 8. And Figure 11 shows TSCDT08065G1 has a higher ~0.04% at light load from the efficiency curve which input voltage is 230Vac.

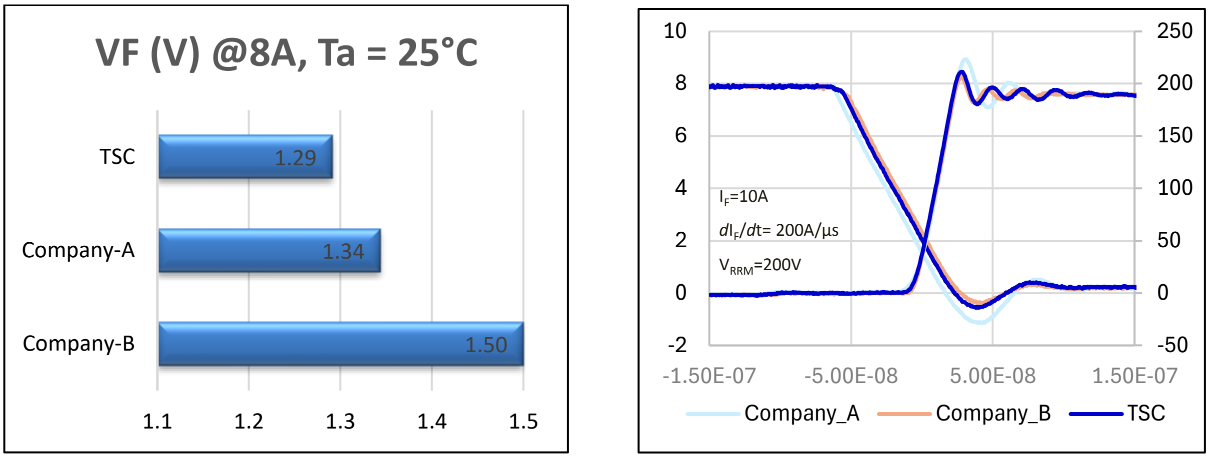


Figure 10. V_F and Q_C comparison

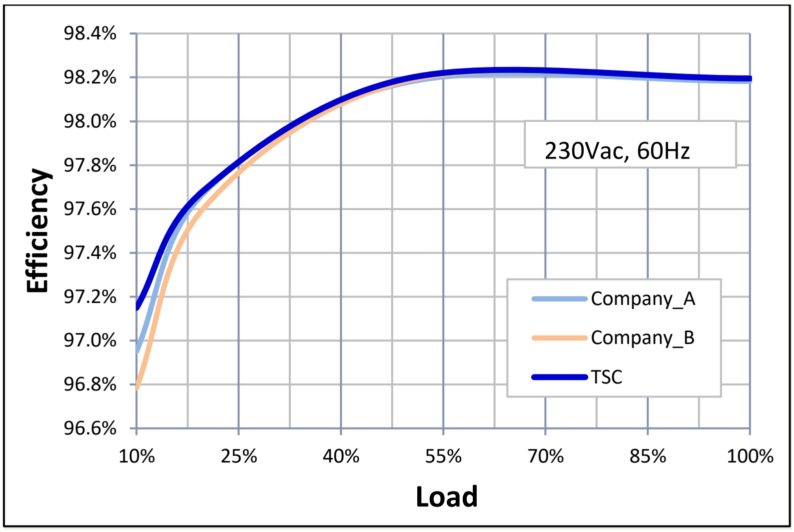


Figure 11. Efficiency curve in 230Vac

4. Summary

The SiC MPS (Merged PN-Schottky) diode offers significant advantages, making it ideal for a variety of applications and markets:

- *High Efficiency* : Lower conduction and switching losses compared to silicon diodes. No reverse recovery charge, resulting in improved switching performance.
- *High Frequency Operation* : Supports higher switching frequencies, enabling smaller and lighter magnetic components.
- *High Voltage Capability* : Wide bandgap properties allow operation at higher voltages (650V–1200V and beyond).
- *Improved Surge Current Handling* : The MPS structure enhances peak surge current (IFSM) capability, making it more robust under high inrush conditions.
- *Better Thermal Performance*: Higher thermal conductivity allows for better heat dissipation, enabling reliable operation at elevated temperatures.

TSC's SiC MPS diode can offer significant performance improvements in high-efficiency power electronics, enabling the development of compact, energy-efficient, and high-performance systems. Its adoption is rapidly growing in automotive, renewable energy, data centers, and industrial markets, where efficiency, reliability, and power density are critical. For further information, please visit Taiwan Semiconductor.

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