POWERMASTER SEMICONDUCTOR
Masters of Power Solution

eSiC Silicon Carbide Diode D1 Series

Power Master Semiconductor's 1st Generation SiC Diode Technology

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1. Introduction

Power Master Semiconductor named "eSiC" for Silicon Carbide device solution. Power Master Semiconductor has been designing, developing, manufacturing through in-house for Silicon Carbide device which is the advanced leading-edge technology for high-voltage and high-power applications. The eSiC Diode D1 series are an advanced Power Master Semiconductor's first generation of silicon carbide diode family. 650V, 1200V and 1700V eSiC Diode D1 series is developed to provide optimized solution for various power conversion systems such as consumer, industrial and automotive applications.

2. What is Silicon Carbide Schottky Diode?

2.1. Basic Structures of High Voltage Diodes

Figure 1 shows the basic structure of Diodes such as SiC Schottky diode, Si Schottky diode and Si PN junction diode. For high voltage diode in SMPS application, a diode should have a fast-switching characteristics to make a better efficiency. These kinds of silicon diode are called as FRD (Fast Recovery Diode) which have PN junction. PN junction diode is bipolar device, hole and electron, or minority and majority carrier as charge carriers. The hole, minority carrier, have slow mobility than majority carrier, electron. Silicon FRD have a special process to make fast switching such as lifetime killing process. Through the special process, silicon FRD have a fast-switching characteristic which have low reverse recovery characteristic. However, silicon FRD is not free from the reverse recovery charge causing by minority carrier. Pure Schottky diode is a unipolar device that operates without the effect of injected carrier modulation. Therefore, during reverse recovery, it behaves almost like a perfect diode switching very rapidly from forward conduction to reverse blocking. This makes the Schottky diode an ideal device for use as a rectifying diode in very high frequency, and fast switching applications. The breakdown voltage can be increased by thickening N-epi layer and lowering the carrier concentration, therefore, silicon Schottky structure is difficult to achieve the high breakdown voltage over 300V, because silicon material has a lower bandgap performance. Silicon Carbide diode generally has a Schottky structure, Silicon Carbide diode is called as SiC SBD (Silicon Carbide Schottky Barrier Diode) that have high breakdown voltage because Silicon Carbide material has a wide bandgap characteristic, which is the leading-edge material for high-voltage and high-power application.

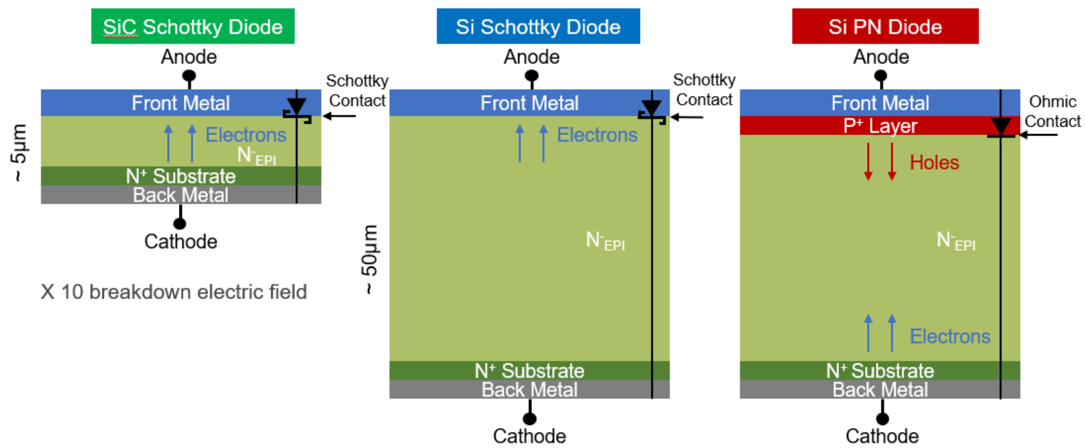
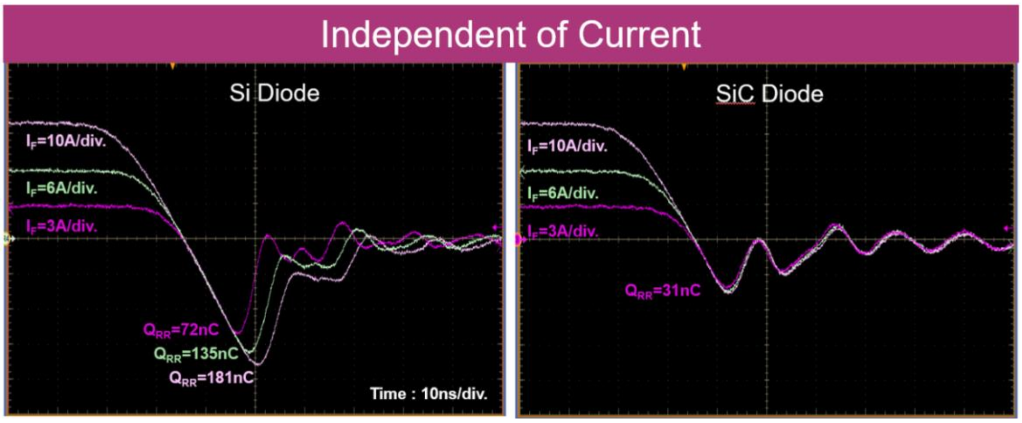
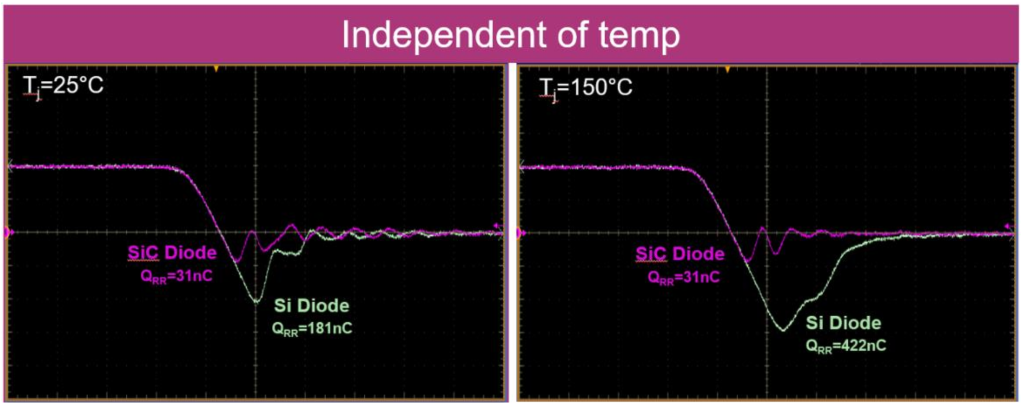


Figure 1. The Basic Structure: SiC Schottky, Si Pure Schottky and Si PN Diode Structure

Figure 2 shows the reverse recovery behavior in the inductive load condition. As shown in Figure 2, reverse recovery behavior of Si Diode is characterized by strongly depends on forward current (I_F), di_F/dt and temperature because stored charge in the P-N junction during a forward conduction should be removed until they disappear. In contrast, reverse recovery behavior of SiC diode is independent of forward current (I_F), di_F/dt and temperature because there is no reverse recovery charge (Q_{rr}) but there is only small reverse recovery current flows by metal-semiconductor junction capacitance. Thanks to these characteristics, SiC diode enable to increase system efficiency by extremely reducing turn-on loss of MOSFETs in CCM operated boost PFC.



(a) Reverse recovery behavior vs. forward current(I_F) at V_{DD}=400V, I_F=3/6/10A, di/dt=700A/μs, T_J=25°C



(b) Reverse recovery behavior vs. temperature at V_{DD}=400V, I_F=10A, di/dt=700A/μs, T_J=25°C & 150°C

Figure 2. The switching characteristics: SiC Schottky Diode and Si Diode (650V / 10A)

Figure 3. shows MOSFET waveforms at turn-on transition. The light pink waveform shows higher peak drain current of MOSFET which is caused by larger Q_{RR} of Si diode. However, the dark purple waveform shows a very low peak drain current of MOSFET by much smaller Q_C of SiC diode. Therefore, MOSFET turn-on losses of 361μJ were measured with Si diode and 154μJ were measured with SiC diode, which reduce to 207μJ compared to MOSFET with Si diode. Finally, MOSFET turn-on losses are dramatically reduced about 57% by using SiC diode as comparing with Si diode as shown in Figure 3. Therefore, SiC diode allows to increase the switching frequency and speed, lowering the size of passive components, snubber-circuits and EMI filters in power conversion systems.

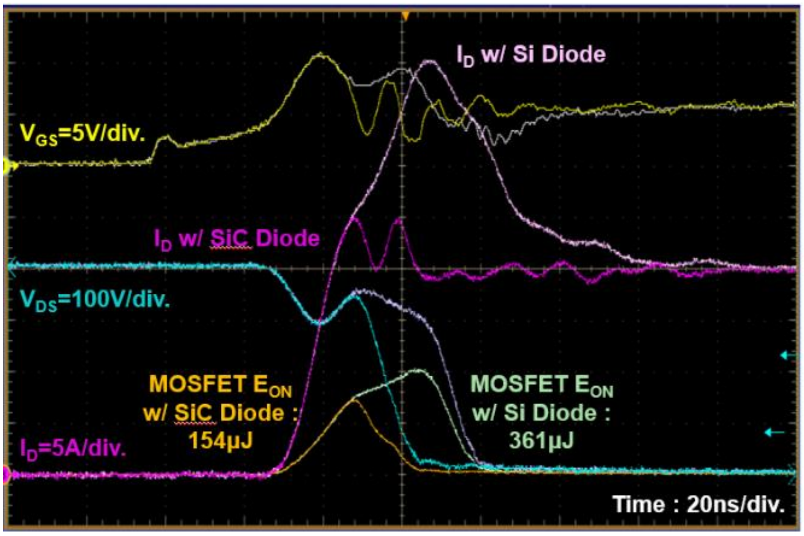
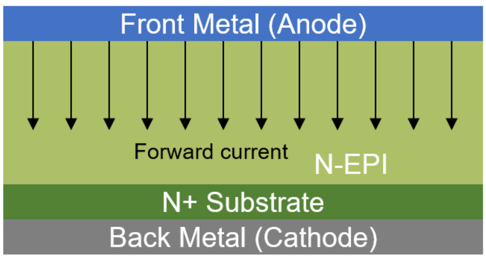
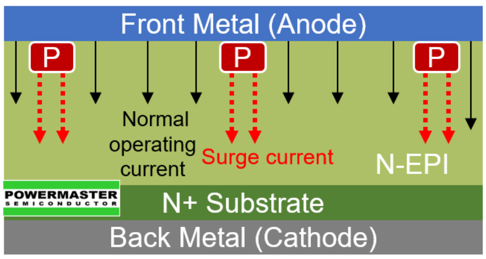


Figure 3. Turn-on switching loss of MOSFET with Si Diode and SiC diode in CCM PFC

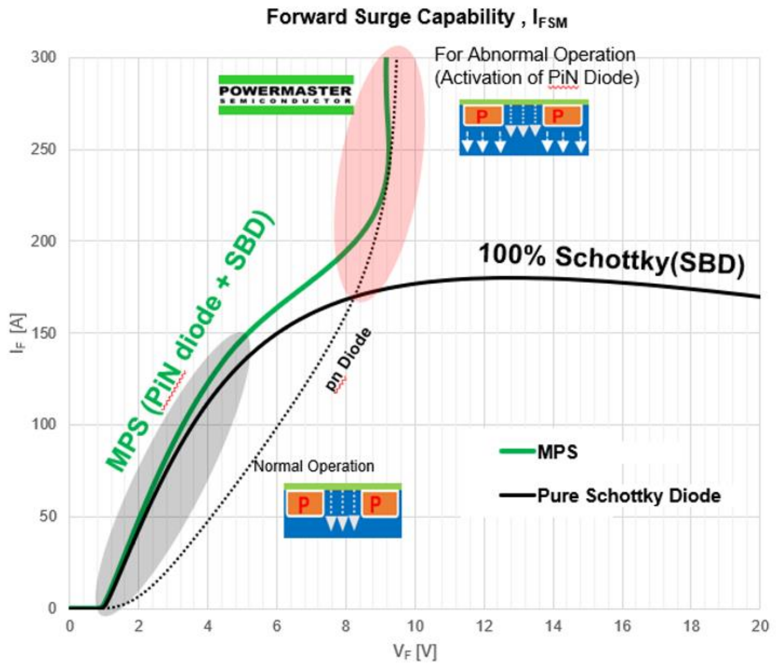
2.2. SiC Silicon Carbide MPS Diode Technology

A Merged PiN-Schottky (MPS) consists of inter-digitated Schottky and p+ implanted areas. Power Master Semiconductor's newly developed eSiC Silicon Carbide MPS diode combines the best features of both Schottky and PiN diodes to obtain low on-state voltage drop, low leakage in the off-state and excellent surge capability. On the anode side the MPS diode consists of alternating PiN and metal-semiconductor junctions as shown in Figure 4 (b). Figure 4 (c) shows the I-V curve under forward bias of an MPS diode in comparison to a pure Schottky diode. Forward characteristics of MPS diode is similar to pure Schottky diode at low current. At higher current operation, p-doped regions are activated and minority carriers, holes, are injected. The device becomes bipolar and the current-voltage characteristics is similar to that of a PiN diode which has excellent surge capability. Thanks to its forward characteristics, MPS diode possesses a much higher surge current ruggedness than a pure Schottky diode. Under reverse bias, the p-doped regions shield the electric field from the Schottky contact and the field strength at the Schottky junctions is reduced. As a result, the high reverse leakage current of a Schottky diode is avoided. Since MPS diodes are usually operated in the unipolar mode, they combine the abilities of fast switching and low losses of a pure Schottky diode with the high surge current capability of a PiN diode and without significantly increasing the leakage current.





(a) Pure Schottky Diode (b) MPS Diode



(c) I-V Curve Comparison between Pure Schottky diode and MPS Schottky diode

Figure 4. Vertical structure of Pure Schottky diode and MPS Schottky diode, I-V Characteristics

3. Power Master Semiconductor's 𝓮SiC Silicon Carbide Diode Technology

High voltage SiC diode (> 650V) is widely using in many power conversion systems such as AC/DC, DC/DC, DC/AC applications. Power Master Semiconductor introduced the 650V, 1200V and 1700V 𝓮SiC Diode D1. This technology combines the benefits of excellent low forward voltage and high ruggedness for applications requiring high efficiency and reliability.

3.1. Target Applications

As shown in figure 5, The 𝓮SiC Diode D1 series is designed to target the high performance in the various applications such as server / telecom powers, PV inverters, UPS, EV chargers for DC EV charging piles and on-board chargers. 𝓮SiC D1 series include low Q_C version for high frequency application such as PFC stage for server and telecom power, UPS and boost stage for solar inverter applications and low V_F version bridge diode for solar inverter and DC EV charging station applications.

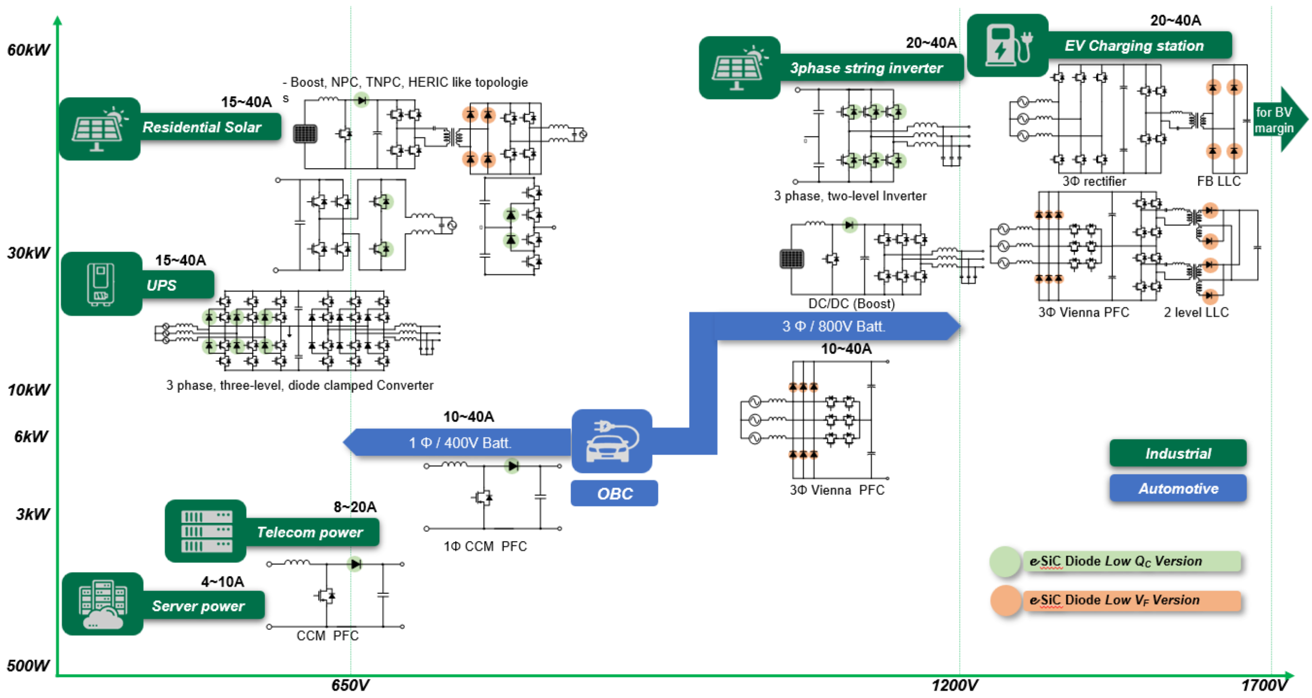


Figure 5. eSiC Diode D1 Series - Target applications

3.2. Features and Benefits

The target performance of eSiC Diode D1 series is to provide a well-balanced trade-off between forward voltage drop (V_F) and capacitive charge (Q_C) with low leakage (I_R) and high surge current capability (I_{FSM}). Therefore, eSiC Diode D1 enables to offer high performance, cost-effective, and robust solution with a wide range of package options as shown in figure 6.

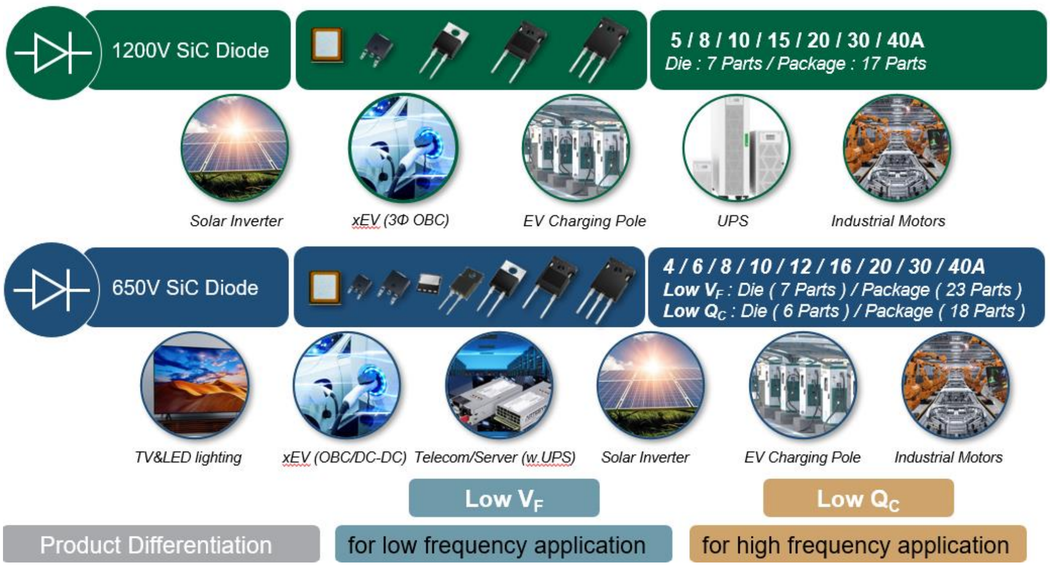


Figure 6. eSiC Diode D1 portfolio

650V / 1200V *e*SiC DIODE D1 SERIES

Key Features

- Low forward voltage, V_F
- High surge current capability
- No reverse recovery current
- 175°C Max junction temperature
- Switching behavior independent of temp. and current

Key Advantages

- Low Conduction loss
- High reliability capability
- Significant reduction of MOSFET or IGBT turn on loss
- Less Power loss at high temperature

Application Benefits

- Higher system efficiency (CCM PFC) than Si diodes
- High Performance/Cost Ratio
- High reliability capability
- Suitable for wide range of applications
- Reduction of EMI
- Reduction of cooling requirements

3.3. 1200V *e*SiC Diode D1 – Key Electrical Characteristics

The key electrical parameters of 1200V *e*SiC Diode is compared to those of competitor devices (including the best competitor). Power Master Semiconductor's the first-generation SiC diode, 1200V *e* SiC Diode D1 has very competitive performance against the competitor's SiC diodes. Table 1 shows the key parameter comparison of Power Master Semiconductor's 1200V/20A *e*SiC Diode D1, PCH120S20D1 and the competitor's SiC diodes. 1200V *e*SiC Diode D1 shows the lowest leakage current (I_R) and excellent avalanche capability (I_{AS}) with well-balanced V_F and Q_C trade-off against the latest competitors.

Table 1. Key parameter comparison of Power Master Semiconductor's 1200V / 20A *e*SiC Diode D1, PCH120S20D1 and the competitors.

Specification	PCH120S20D1	Comp. C	Comp. I	Comp. R	Comp. S
V_F @ T_C=25℃	1.39 V	1.43 V	1.53 V	1.48 V	1.31 V
I_R @ T_C=175℃	3 uA	415 µA	148 µA	42 µA	11 µA
Q_C @ V_r=800V	121 nC	102 nC	78 nC	92 nC	137 nC
I_{FSM} @ 10ms	210 A	220 A	304 A	104 A	216 A
I_{AS} @ L=350uH	50 A	41 A	37 A	4 A	54 A

3.4. 1200V *e*SiC Diode D1 – Competitor Benchmark

The key parameters of SiC diode are forward voltage drop(V_F), capacitive charge (Q_C) and surge current capability (I_{FSM}). Figure 7 shows the 1200V *e* SiC Diode D1 performance position against the competitors. As shown in this spider chart, 1200V *e* SiC Diode D1 offers very competitive trade-off between capacitive charge, Q_C and forward voltage drop (V_F) and high avalanche capability with the best-in-class leakage current against the competitor's SiC diodes. 1200V *e*SiC Diode D1 has competitive I_{FSM} capability. I_{FSM} (non-repetitive forward surge current) capability is required for more design margin from customer side for abnormal operation test such as start-up, AC drop out test, output short and so on. Power Master Semiconductor's *e* SiC Diode D1 has highly optimized and well-balanced performance for higher efficiency and ruggedness. Therefore, 1200V *e*SiC Diode D1's outstanding parameters result in the higher system efficiency and reliability for target applications.

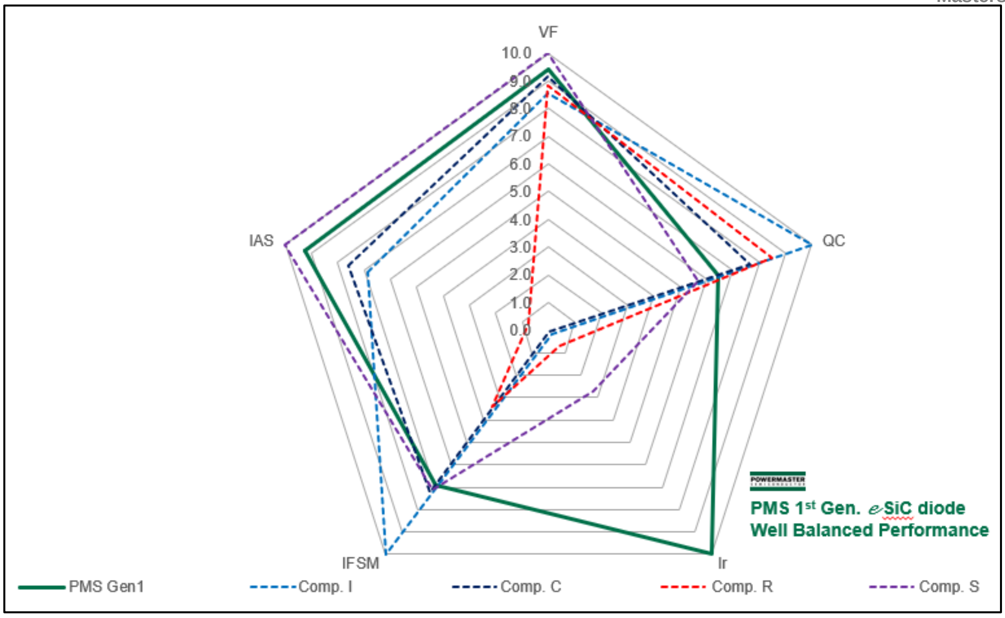


Figure 7. 1200V/20A *e*SiC Diode D1 performance position against the competitors (Note1: 10 is the best, 0 is the worst)

3.5. 1200V *e*SiC Diode D1 – Forward Voltage Drop, V_F

The forward voltage (V_F) is the one of key parameter for SiC diode because it is directly related to the conduction loss of SiC diode. Conduction loss of diode is calculated by Equation 1. To reduce conduction losses, the forward voltage drop, V_F in conduction mode has to be reduced.

Equation 1)

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

Where I_F is the forward current through the diode.
There are two components for V_F as shown in Equation 2. The threshold voltage V_{th} for the start conducting current of the diode (low current) and bulk resistance, R_{bulk} represents the overall diode resistance.

Equation 2)

$$V_F = V_{th} + (I_F \cdot R_{bulk})$$

Different from Si diode, the SiC Schottky diode's bulk resistance dominates the forward behavior and the forward voltage drop increases as the temperature and the forward current increases. SiC Schottky diodes are suitable for parallel operation compared with Si diodes due to the positive temperature coefficient. As shown in figure 8, Power Master Semiconductor's *e*SiC Diode D1 series has the outstanding the forward voltage drop performance against competitor's SiC diodes. SiC diode shows Positive Temperature Coefficient (PTC) at high current operation. *e*SiC Diode D1 shows lower temperature dependency of V_F compared to competitor's SiC diodes as shown in figure 9.

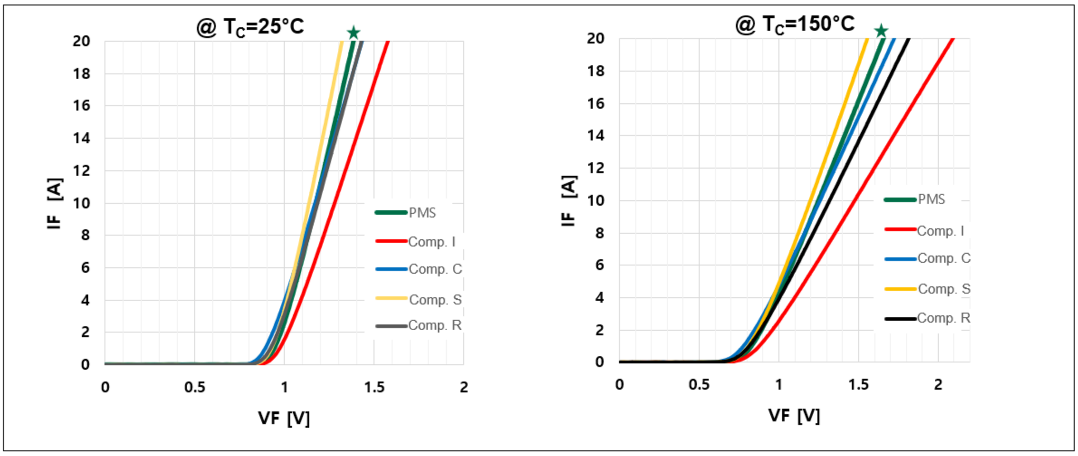


Figure 8. Forward Voltage Drop, V_F Comparison of 1200V/20A eSiC Diode D1 and Competitors at T_C=25°C and 150°C

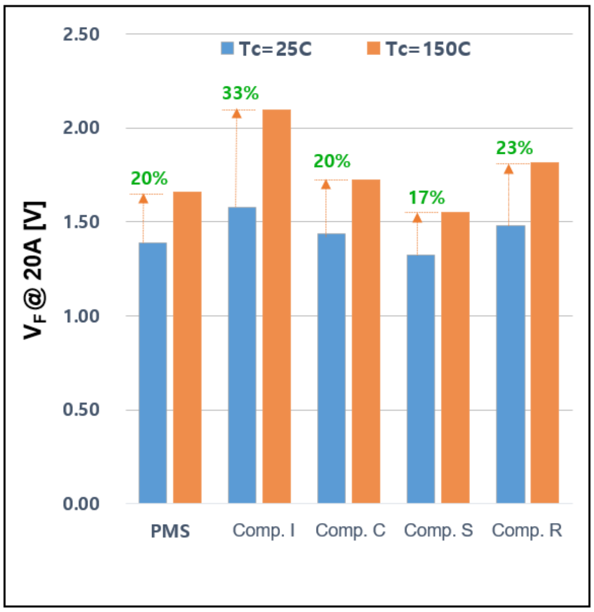
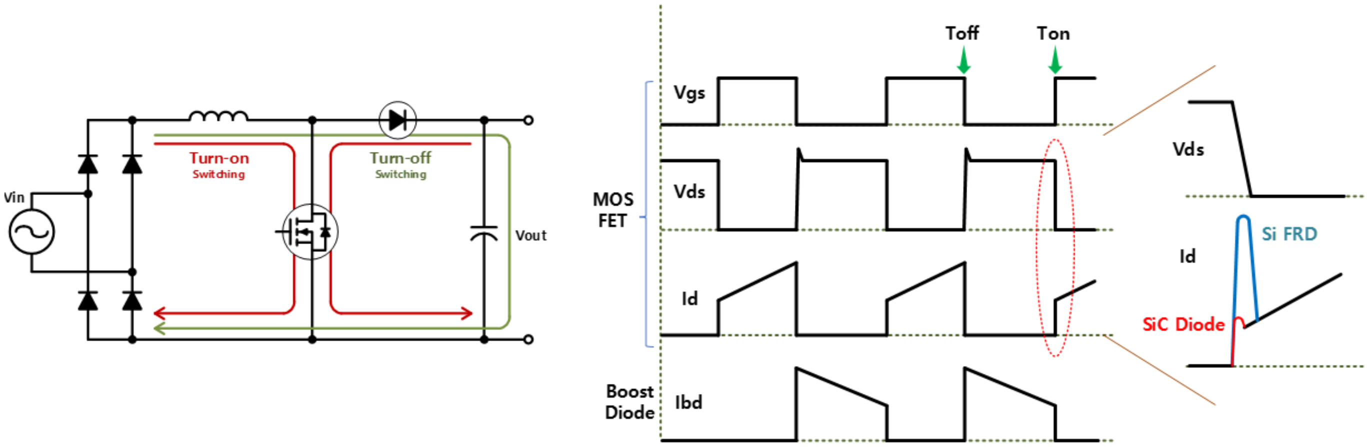


Figure 9. Temperature Dependency of Forward Voltage Drop, V_F Comparison of 1200V/20A eSiC Diode D1 and Competitors at T_C=25°C and 150°C

3.6. Low V_F version (eSiC Diode D1) and Low Q_C version (eSiC Diode D1Q)

Figure 10 shows CCM boost PFC circuit and its operation modes including current and voltage waveforms, to illustrate the low Q_{rr} requirement as a boost diode in CCM boost PFC. Initially, boost diode conducts the input current with some amount of stored minority charge present in the diode. During the turn-on switching transition, the MOSFET turns on while the boost diode turns off. Inductor current flows through the MOSFET, including boost diode's reverse recovery and discharge current, in addition to the rectified input current. Therefore, diode reverse recovery charge

(Q_{rr} and Q_C) is directly impact to MOSFET turn-on loss. It can be easily increased the system efficiency using SiC diode instead of Si FRD as a boost diode, because the extremely lower Q_C of SiC diode greatly helps to minimize MOSFET turn-on switching losses.



(a) Boost PFC Circuit (b) Operation Waveforms in CCM boost PFC

Figure 10. Turn-on Losses Impact of MOSFET by Q_C of SiC Diode in Boost CCM PFC

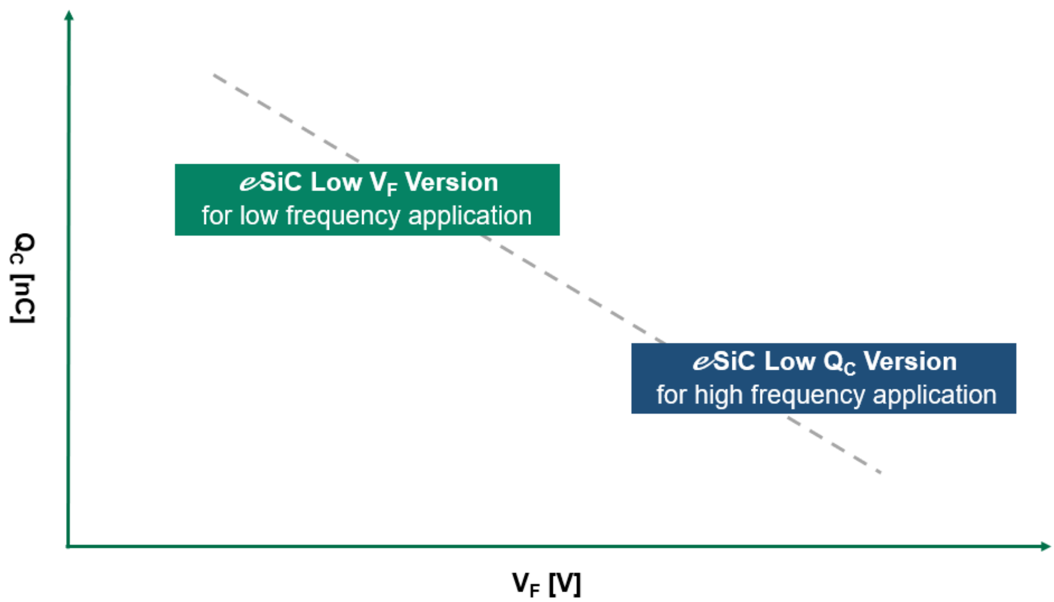


Figure 11. Low V_F version and Low Q_C version of 650V *e*SiC Diode D1

SiC diodes are mainly used as a boost diode or hybrid set of SiC diode and Si IGBT for 2-level topologies by reducing switching turn-on loss for high frequency applications. SiC diodes are also used a AC input or DC output rectifiers for low frequency applications as shown in Figure 5.

Power Master Semiconductor offers optimized eSiC Diodes D1 product portfolio for each target topologies and applications. Power Master Semiconductor designed two flavors of eSiC Diode D1 and D1Q to help address various topologies and design requirements. As shown in Figure 11, eSiC Diode Low Q_C version (D1Q) is targeted for high frequency applications such as boost diode or 2-level topologies that switching losses are more critical and eSiC diode Low V_F version (D1) is optimized for low frequency applications such as input or output rectifiers that conduction loss is more critical. Figure 12 shows the power loss analysis of SiC diode in 1kw boost converter. V_{in}=230V_{AC}, F_{sw}=20/100kHz. As shown in Figure 12, the switching loss is more critical for high frequency operation (100kHz) at whole load ranges and the conduction loss is more critical for low frequency operation (20kHz) especially at heavy load.

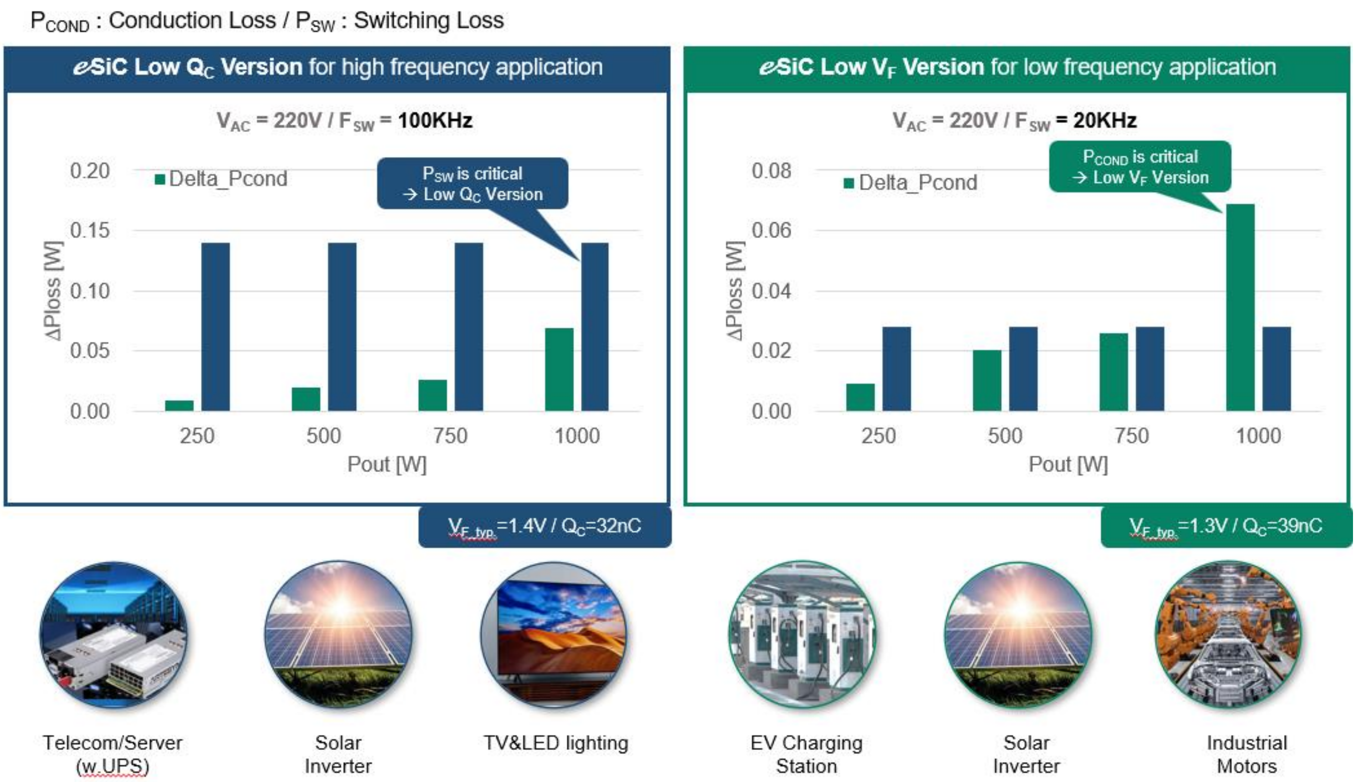


Figure 12. Power Loss Analysis of Low V_F version and Low Q_C version under Different Switching Frequency

4. Conclusion

The eSiC Diode D1 is an advanced Power Master Semiconductor's SiC Diode family by utilizing MPS technology. This technology combines the benefits of high surge current capability and excellent performance with lower V_F and Q_C for both low and high frequency applications. Consequently, the eSiC Diode D1 family is suitable for many applications requiring superior efficiency and higher system ruggedness.

5. eSiC Silicon Carbide Diode D1 Product Portfolio & Nomenclature

5.1. 650V / 1200V / 1700V eSiC Diode D1 Product Portfolio

Table 2. 650V eSiC Diode D1 Product Portfolio

650V eSiC Diode Lineup

TV Power / LED | Server / Telecom Power | EV Charging Station | EV OBC

	Package / I_F	Die	DPAK	D2PAK	PQFN88	TO-220F 2L	TO-220 2L	TO-247 2L	TO-247 3L
Low V_F for Low Freq. Applications	40A								PCW65D40D1
	30A								PCW65D30D1
	20A	PCO65S20D1		PCB65S20D1		PCF65S20D1	PCH65S20D1	PCA65S20D1	PCW65D20D1
	16A	PCO65S16D1					PCH65S16D1		PCW65D16D1
	12A	PCO65S12D1				PCF65S12D1	PCH65S12D1		
	10A	PCO65S10D1	PCD65S10D1	PCB65S10D1		PCF65S10D1	PCH65S10D1		
	8A	PCO65S08D1		PCB65S08D1		PCF65S08D1	PCH65S08D1		
	6A	PCO65S06D1				PCF65S06D1	PCH65S06D1		
	4A	PCO65S04D1				PCF65S04D1	PCH65S04D1		
Low Q_C for High Freq. Applications	40A								PCW65D40D1Q
	30A								PCW65D30D1Q
	20A	PCO65S20D1Q		PCB65S20D1Q		PCF65S20D1Q	PCH65S20D1Q	PCA65S20D1Q	PCW65D20D1Q
	16A	PCO65S16D1Q					PCH65S16D1Q		PCW65D16D1Q
	12A	PCO65S12D1Q		PCB65S12D1Q		PCF65S12D1Q	PCH65S12D1Q		
	10A	PCO65S10D1Q				PCF65S10D1Q	PCH65S10D1Q		
	8A	PCO65S08D1Q				PCF65S08D1Q	PCH65S08D1Q		
	6A	PCO65S06D1Q				PCF65S06D1Q	PCH65S06D1Q		

Table 3. 1200V / 1700V eSiC Diode D1 Product Portfolio

1200V eSiC Diode Lineup

Solar inverter | UPS | EV Charging Station | Industrial Motor

Package / I_F	Die	D2PAK	TO-220 2L	TO-247 2L	TO-247 3L
40A	PCO120S40D1			PCA120S40D1	PCW120D40D1 PCW120D40D1Q
30A	PCO120S30D1			PCA120S30D1 PCA120S30D1Q	PCW120D30D1
20A	PCO120S20D1	PCB120S20D1	PCH120S20D1	PCA120S20D1	PCW120D20D1
15A	PCO120S15D1		PCH120S15D1	PCA120S15D1	PCW120D15D1
10A	PCO120S10D1	PCB120S10D1	PCH120S10D1	PCA120S10D1	PCW120D10D1
8A	PCO120S08D1		PCH120S08D1		
5A	PCO120S05D1		PCH120S05D1		

1700V eSiC Diode Lineup

Package / I_F	Die	D2PAK	TO-220 2L	TO-247 2L	TO-247 3L
25A	PCO170S25D1			PCA170S25D1	
10A	*PCO170S10D1			*PCA170S10D1	
5A	*PCO170S05D1			*PCA170S05D1	

* Coming Soon

For more product information, please visit https://www.powermastersemi.com

5.2. Nomenclature

Device part number contains a lot of information such as technology, package, voltage rating and generation, etc. Figure 13 shows Power Master Semiconductor's SiC Diode, *e*SiC Silicon Carbide Diode nomenclature

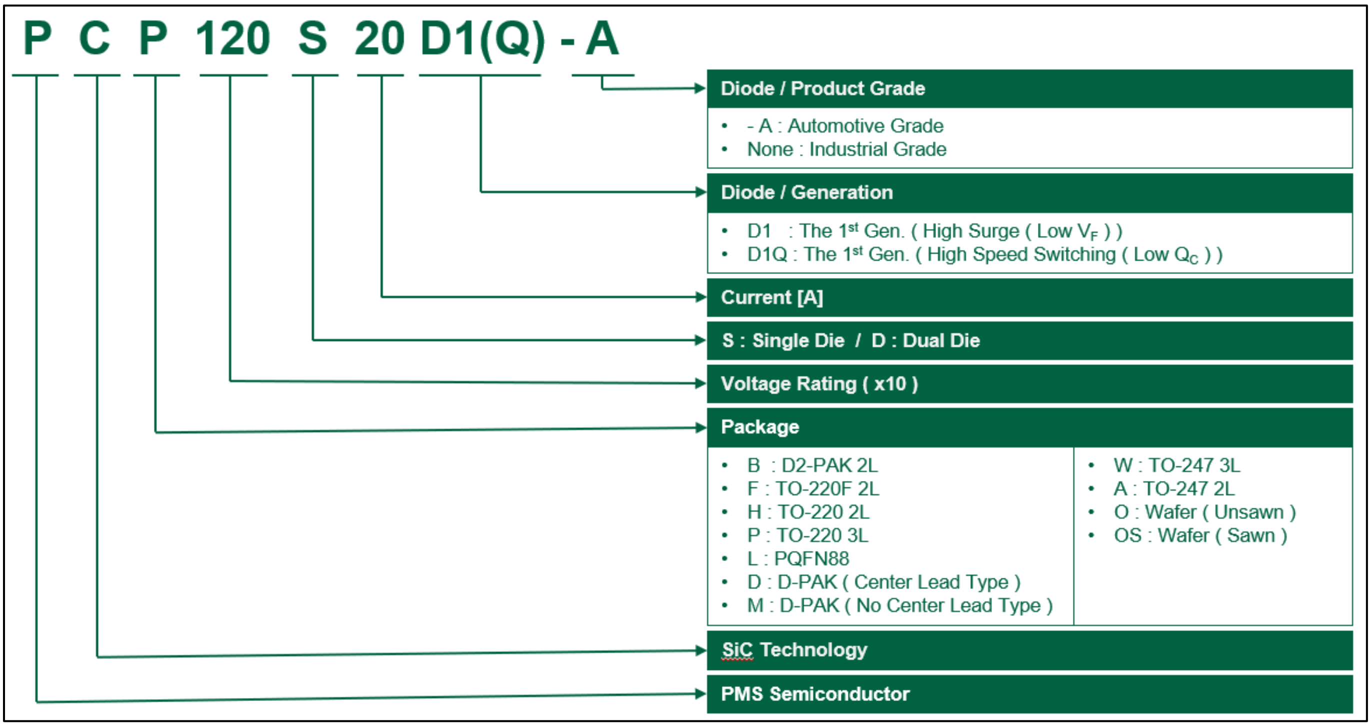


Figure 13. *e*SiC Diode nomenclature scheme

6. Document Revision History

Major changes since the last version

Date	Description of change
26-Dec-2022	First Release

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