Silicon Carbide Diode Basic and Datasheet Understanding

*e*SiC Silicon Carbide Diode

Power Master Semiconductor named “*e*SiC” 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.

This application note includes the basic of Silicon Carbide Shottky Diode technology and explains the datasheet parameters of *e*SiC Silicon Carbide Schottky Diode, based on the device part number as ‘PCW120D40D1’.

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1. Silicon Carbide Schottky Diode Basic

1.1. Basic Structure of High Voltage Diode

Figure 1 is shown the basic structure of Diode, SiC Schottky diode, Si Schottky diode and Si PiN junction diode structure. 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 PiN junction, PiN junction diode is bipolar device, hole and electron, or minority and majority carrier. 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 which only have majority carrier, electron, so ideally there is no reverse recovery charge, it has only a capacitive charge. Silicon Schottky structure is difficult to achieve the high breakdown voltage, such as 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 2 is shown 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 (storage time). 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 extremely reduce turn-on loss of MOSFETs in CCM operated boost PFC. Figure 3. shows MOSFET waveforms at turn-on transition. The pink waveforms shows excessive drain current of 20A, expect inductor current, which is caused by the reverse recovery current of Si diode. However, the purple line shows a very low current by negligible displacement current of SiC diode. Therefore, MOSFET turn-on losses of 361uJ were measured with Si diode and 154uJ were measured with SiC diode, which reduce to 207uJ compared to MOSFET with Si diode. Finally, MOSFET turn-on losses are dramatically reduced about 57% by SiC diode as comparing with Si diode as shown in Figure 3. Therefore, SiC diode allow to increase the switching frequency and speed, lowering the size of passive components, snubber-circuits and EMI filters in power converters.

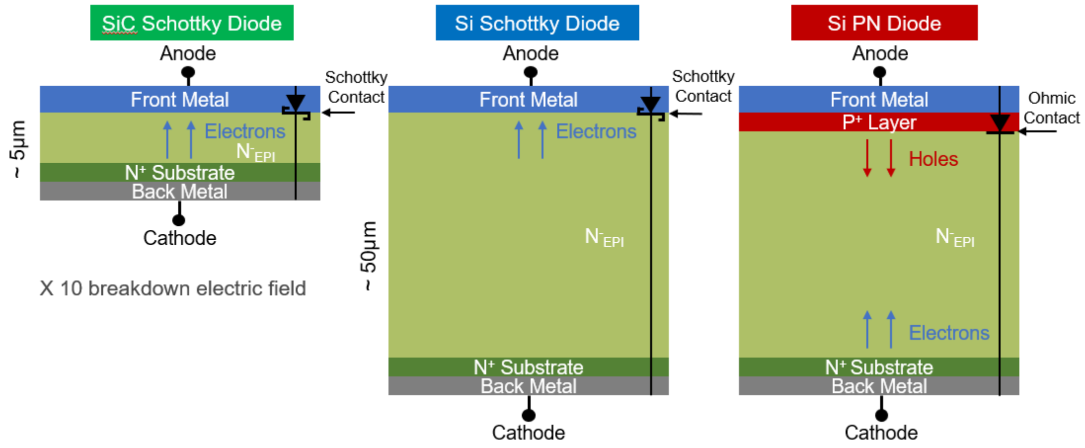
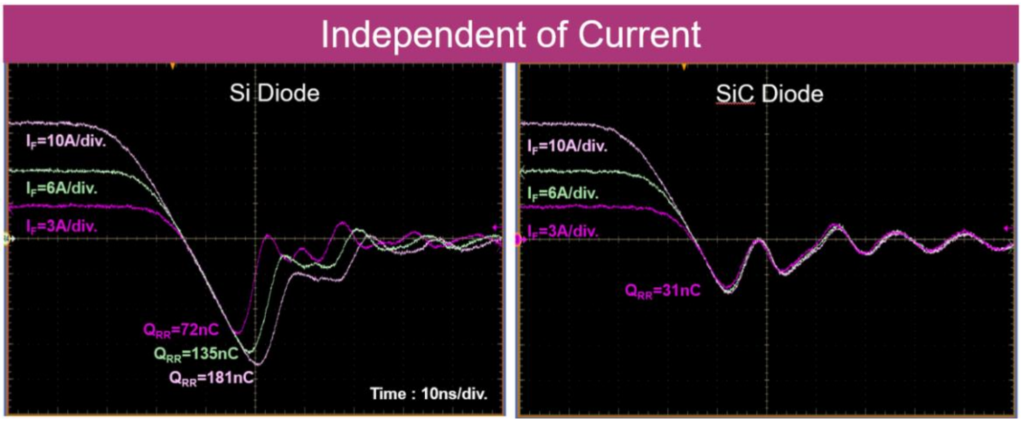
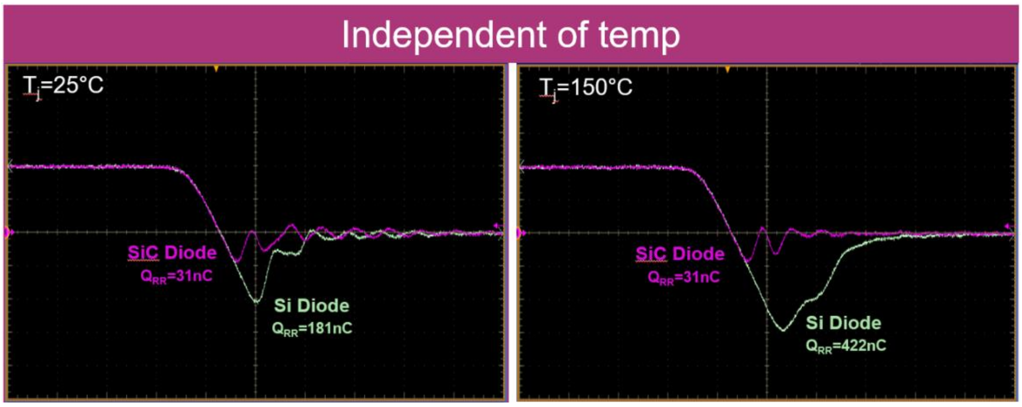


Figure 1. The Basic Structure: SiC Schottky, Pure Schottky and PiN Junction Diode Structure



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



(b) Reverse recovery behavior vs. temperature @ 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 FRD (650V / 10A)

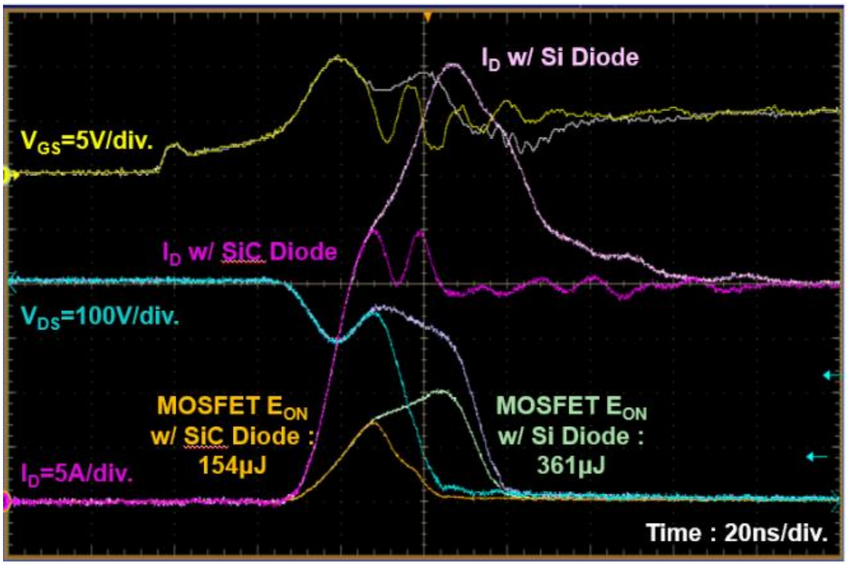
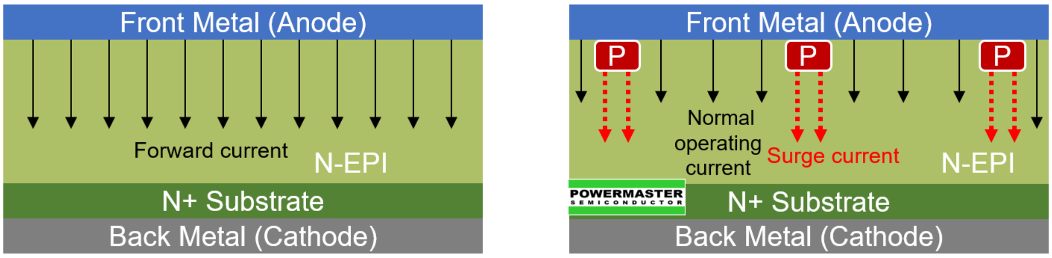


Figure 3. Turn-on switching loss of MOSFET with Si FRD and SiC diode in CCM PFC

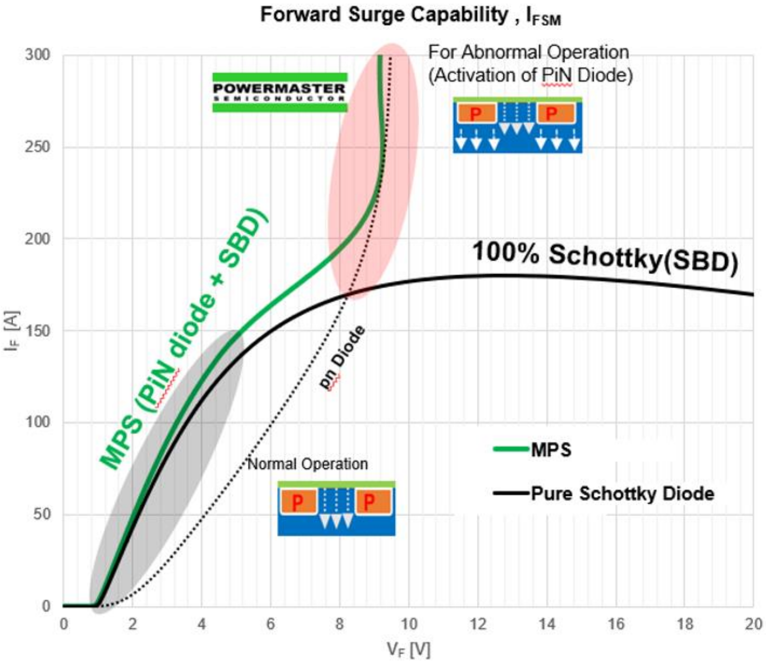
1.2. *e*SiC Silicon Carbide MPS Diode Technology

A Merged PiN-Schottky (MPS) consists of inter-digitated Schottky and p+ implanted areas. PMS's newly developed *e*SiC 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 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

2. Datasheet Classification and Nomenclature

2.1. Datasheet Classification

The Datasheet classified as the product development stage:

- Advanced Datasheet in the design stage
- Preliminary Datasheet in the qualification stage
- Final Datasheet in the mass production stage

Advanced Datasheet describes the target data for the developing product. The data from advanced datasheet is a designing target specification. The value in the advanced datasheet is not final data and not guaranteed as in the final datasheet. The letter of “Advanced Datasheet” is marking on the issuing the datasheet. The device marking on the package is “ES”(Engineering Sample) for this product, this is not issuing any product change notification (PCN)

Preliminary Datasheet is issued at the stage of device qualification. Most of static characteristic is decided however is applicable to change the datasheet parameter before mass production. It is also not final guaranteed specification. The device marking on the package is “CS”(Customer Sample) for this product, this is not issuing any product change notification (PCN).

Final Datasheet is the final guaranteed datasheet from mass production. If there is any data value change, PCN must be issued. There is no marking on the datasheet such as “Final Datasheet”.

2.2. Nomenclature

Device part number contains a lot of information such as technology, package, voltage rating and generation, etc. Figure 1 shows Power Master Semiconductor's SiC Diode, *e*SiC Silicon Carbide Diode nomenclature

PCW120D40D1 is PMS Semiconductor's the 1st Gen *e*SiC Diode Technology, TO-247 3L, 1200V, Dual Die, 40A as shown in Figure 5.

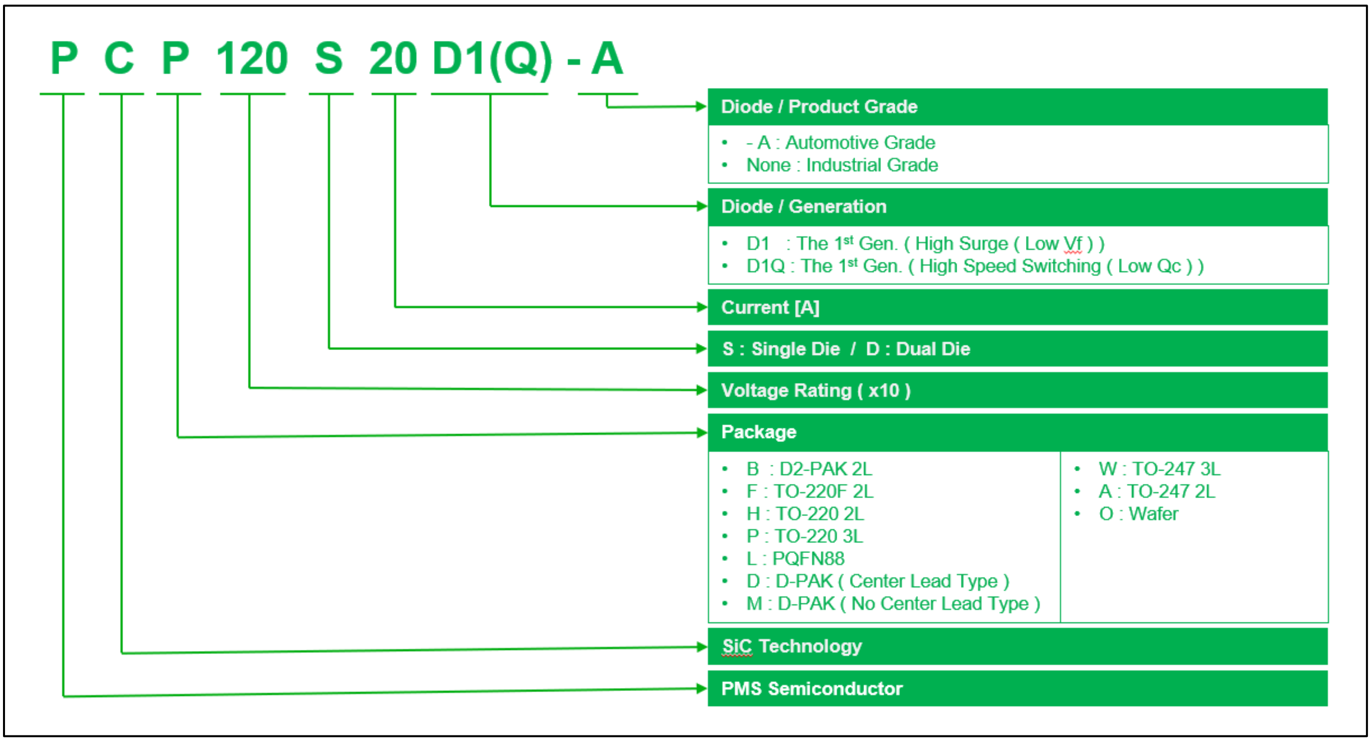
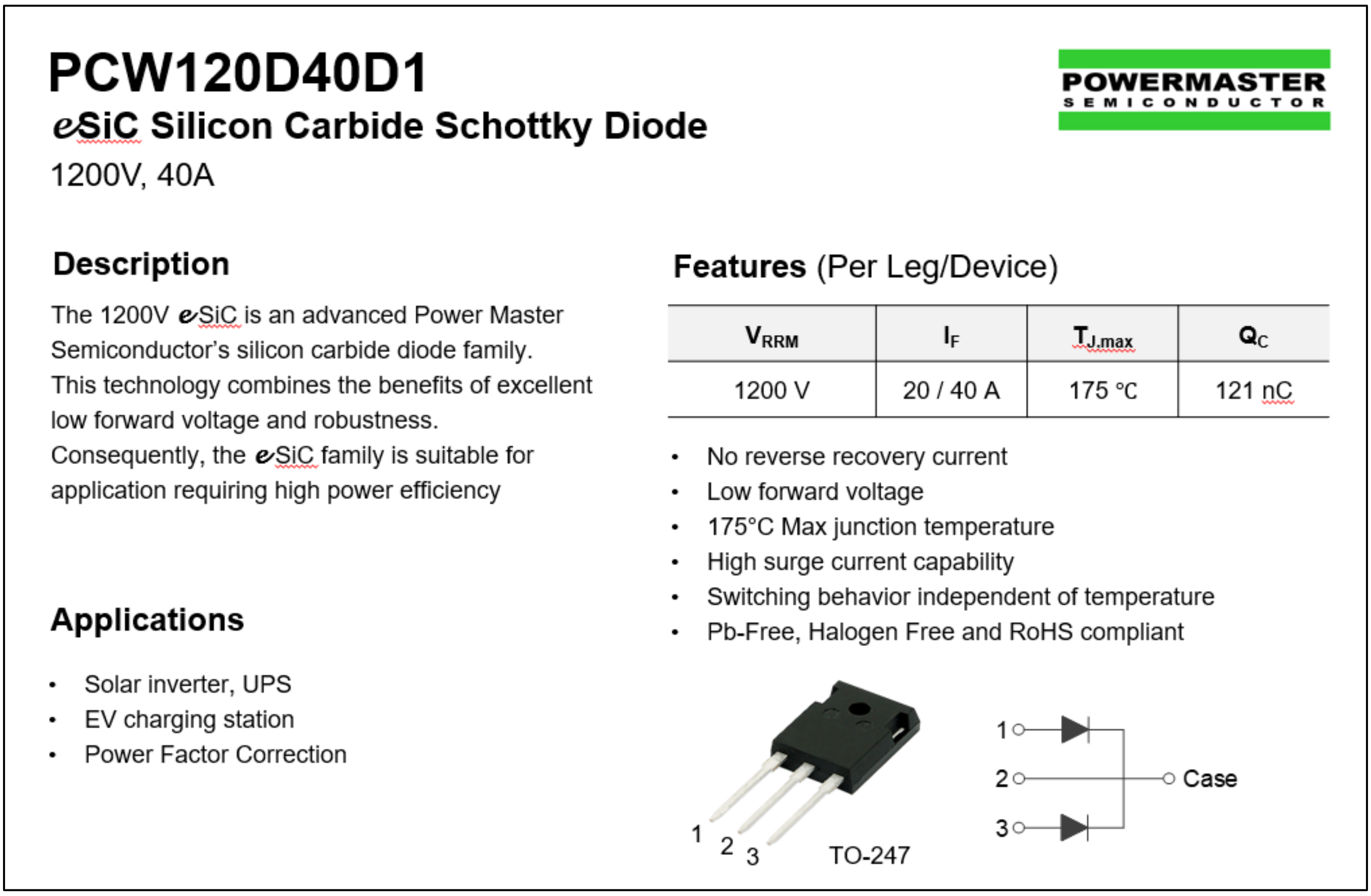


Figure 5. *e*SiC Silicon Carbide Diode nomenclature scheme

3. Datasheet explanation

3.1. General Information

The first page has Description, Applications, Features and Package photo and Terminal connection as Figure 6.



PCW120D40D1

eSiC Silicon Carbide Schottky Diode

1200V, 40A

Description

The 1200V eSiC is an advanced Power Master Semiconductor's silicon carbide diode family. This technology combines the benefits of excellent low forward voltage and robustness. Consequently, the eSiC family is suitable for application requiring high power efficiency

Applications

- Solar inverter, UPS
- EV charging station
- Power Factor Correction

Features (Per Leg/Device)

V_{RRM}	I_F	$T_{J,max}$	Q_C
1200 V	20 / 40 A	175 °C	121 nC

- No reverse recovery current
- Low forward voltage
- 175°C Max junction temperature
- High surge current capability
- Switching behavior independent of temperature
- Pb-Free, Halogen Free and RoHS compliant

Figure 6. General Information

PCW120D40D1 is dual die device in TO-247 3 lead package, features are commented as per leg and device. In case of I_F, forward current per leg is 20A, and forward current of device is 40A because of two dies.

This kind of terminal connecting device is called as "common cathode device".

There is a single die device such as PCA120S20D1 as shown in figure 7, which is two lead package of TO247. A designer can select the device by topology and power rating in their application.

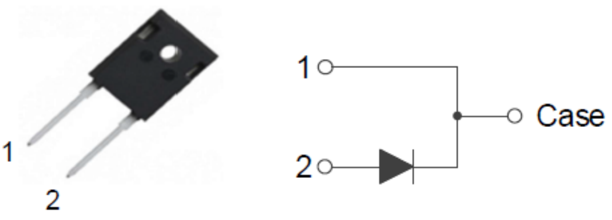
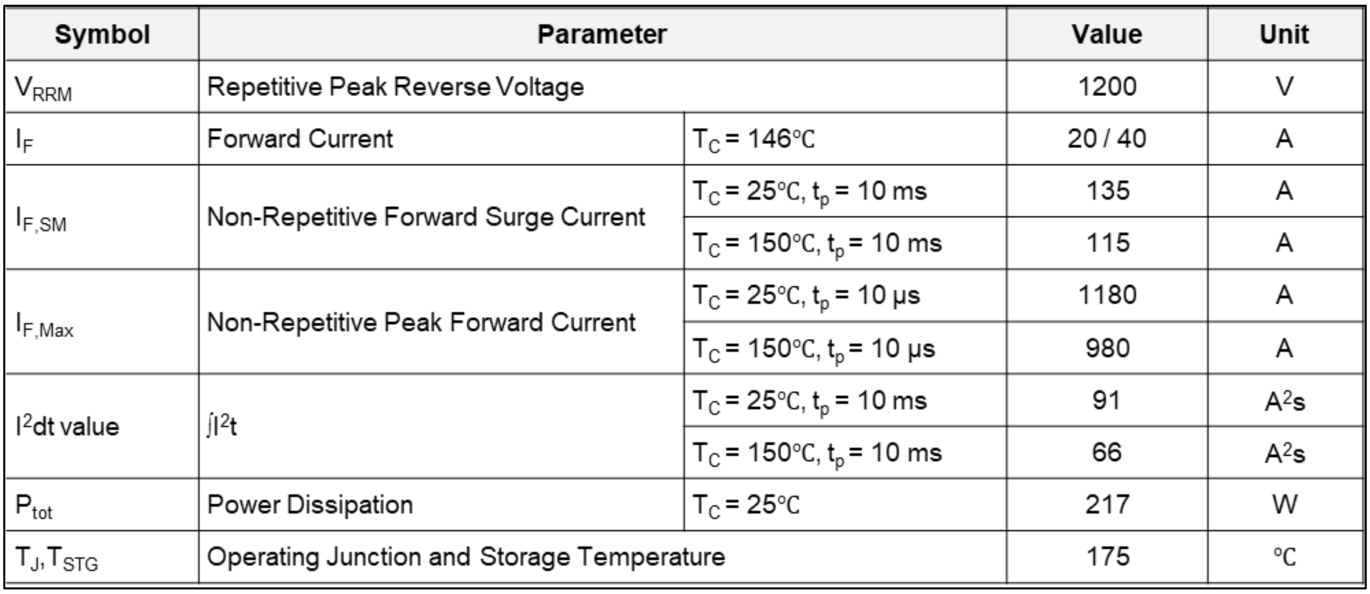


Figure 7. PCA120S20D1 Package configuration for the reference.

3.2. Absolute Maximum Ratings

The value in absolute maximum ratings is the maximum device capability in terms of "temperature condition is "T_C=25°C unless otherwise noted". "T_C=25°C" means the cooling condition is infinite cooling system to sustain the case temperature as 25°C as an ideal condition. No matter what the condition is such as delivering, handling, soldering, assembling, testing, storing as well as actual device working, the device is limited under the value.

(Per Leg / Device & Per Leg, T_C=25°C unless otherwise noted)



Symbol	Parameter		Value	Unit
V_{RRM}	Repetitive Peak Reverse Voltage		1200	V
I_F	Forward Current	T_C = 146°C	20 / 40	A
$I_{F,SM}$	Non-Repetitive Forward Surge Current	T_C = 25°C, t_p = 10 ms	135	A
		T_C = 150°C, t_p = 10 ms	115	A
$I_{F,Max}$	Non-Repetitive Peak Forward Current	T_C = 25°C, t_p = 10 μs	1180	A
		T_C = 150°C, t_p = 10 μs	980	A
I^2dt value	$\int I^2t$	T_C = 25°C, t_p = 10 ms	91	A^2s
		T_C = 150°C, t_p = 10 ms	66	A^2s
P_{tot}	Power Dissipation	T_C = 25°C	217	W
T_J, T_{STG}	Operating Junction and Storage Temperature		175	°C

V_{RRM}: Repetitive Peak Reverse Voltage (Per Leg)

Symbol	Parameter	Value	Unit
V_{RRM}	Repetitive Peak Reverse Voltage	1200	V

This symbol of V_{RRM} stands for "V = Voltage, R = Repetitive, R = Reverse, M = Maximum". V_{RRM} is the maximum allowable repetitive peak reverse voltage under there is no avalanche breakdown mode from cathode to anode. The applied volage from cathode to anode should be lower than the rated value because this voltage is one of critical value to make the device safe. This volage is related with long-term reliability of device.

I_F: Forward Current

Symbol	Parameter		Value	Unit
I_F	Forward Current	T_C = 146°C	20 / 40	A

This symbol of I_D stands for "I = Current, F = Forward", I_F is the maximum allowable continuous current from anode to cathode at the given temperature condition. 20A of I_F is one leg forward current, and 40A of I_F is the device total forward current for two diodes.

In figure 7, there are several forward current by duty cycles for square wave current, I_F in the datasheet is specified as continuous forward current at Duty = 1. Other duty cycles forward current is shown in the figure 8 as dependent by case temperature.

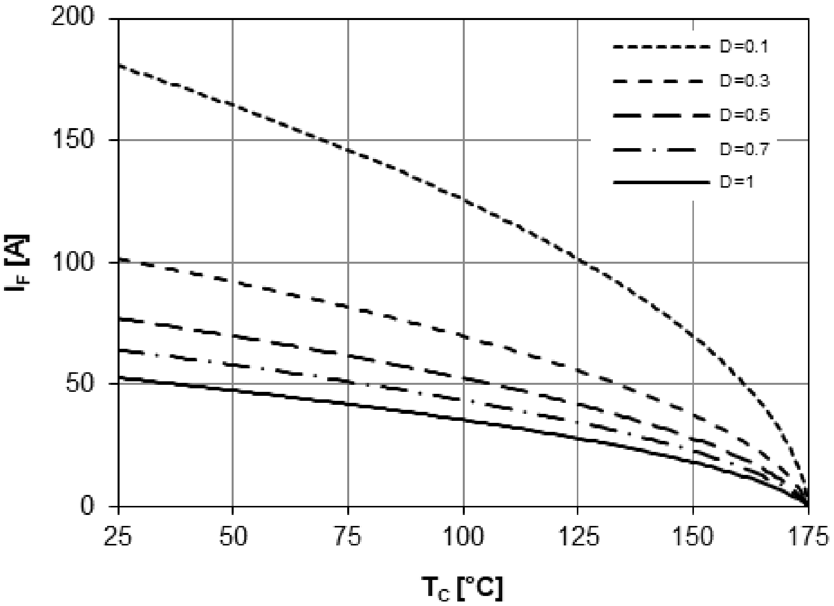


Figure 8. Current Derating (Figure 2. in the datasheet)

$I_{F,SM}$: Non-Repetitive Forward Surge Current

Symbol	Parameter		Value	Unit
$I_{F,SM}$	Non-Repetitive Forward Surge Current	T_C = 25°C, t_p = 10ms	135	A
		T_C = 150°C, t_p = 10ms	115	A

This symbol of $I_{F,SM}$ stands for "I = Current, F = Forward, S = Surge, M = Maximum", $I_{F,SM}$ is the non-repetitive forward surge current at the give temperature and pulse duration from anode to cathode. t_p is the time of pulse, it comes from AC RMS frequency such as 50Hz, it's time of pulse is 10ms. $I_{F,SM}$ is specified the peak surge current with a single half-sine wave at an initial junction temperature of 25°C. This value is a reference value such as PFC application at the charging mode of initial PFC capacitor under the capacitor voltage is zero.

$I_{F,Max}$: Non-Repetitive Peak Forward Current

Symbol	Parameter		Value	Unit
$I_{F,Max}$	Non-Repetitive Peak Forward Current	T_C = 25°C, t_p = 10us	1180	A
		T_C = 150°C, t_p = 10us	980	A

This symbol of $I_{F,Max}$ stands for "I = Current, F = Forward, Max = Maximum", $I_{F,Max}$ is the non-repetitive peak forward current, this is for the SMPS design. t_p = 10us, it means the switching frequency is 100KHz, so this value should be calculated by an actual application frequency, transient thermal resistance, and cooling condition. This value is a reference value of current during short time under abnormal operation such as AC drop-out test.

I^2t value:

Symbol	Parameter		Value	Unit
I^2t value	$\int I^2 dt$	T_C = 25°C, t_p = 10ms	91	A^2s
		T_C = 150°C, t_p = 10ms	66	A^2s

This symbol of I^2t is the permissible absolute maximum rating for the integration of surge current by time period, it is called as fusing current as limited by electrical and mechanical property. I^2t is the equation linked with $I_{F,SM}$.

P_{tot}: Power Dissipation

Symbol	Parameter		Value	Unit
P_{tot}	Power dissipation	Tc = 25°C	217	W

P_{tot} is the maximum power dissipation at the given temperature condition, it is related with thermal resistance as shown in the Equation 1).

$$Equation\ 1)\quad P_{tot} = \frac{T_J - T_C}{R_{thJC}}$$

P_{tot} is derated by case temperature as shown in Figure 9.

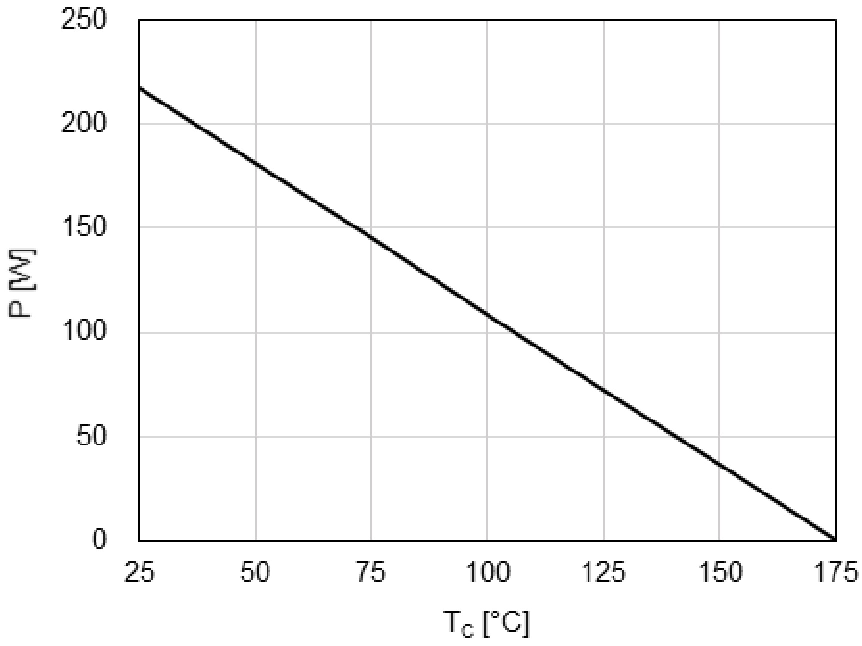


Figure 9. Power Rating (Figure 1. in the datasheet)

T_J, T_{STG}: Junction Temperature Range

Symbol	Parameter	Value	Unit
T_J, T_{STG}	Operating and Storage Temperature Range	175	°C

T_J stand for “T = Temperature, J = Junction”, junction is normally called as die of device, so it is the permissible die temperature during operating a device.

T_{STG} stand for “T = Temperature, STG = Storage”, it is storage temperature, storage temperature is same as operating temperature.

3.3. Thermal Characteristics

Thermal characteristics is indicated with thermal resistance. Thermal resistance is a similar concept with electrical resistance. There are two thermal resistances, one is steady state thermal resistance as $R_{\theta JC}$ and $R_{\theta JA}$ which have a value in the datasheet, another is transient thermal resistance such as $Z_{\theta JC}$ in Figure 10.

Symbol	Parameter	Value	Unit
$R_{\theta JC}$	Thermal Resistance, Junction to Case, Max. (Per Leg / Per Device)	0.69 / 0.35	°C/W

The symbol is defined as “R = Resistance, ϴ = Thermal, J = Junction of die, C = Case of package surface, A = Ambient”. $R_{\theta JC}$ is the thermal resistance between junction to case with heat sink condition, and $R_{\theta JA}$ is the thermal resistance between junction and ambient without heat sink condition.

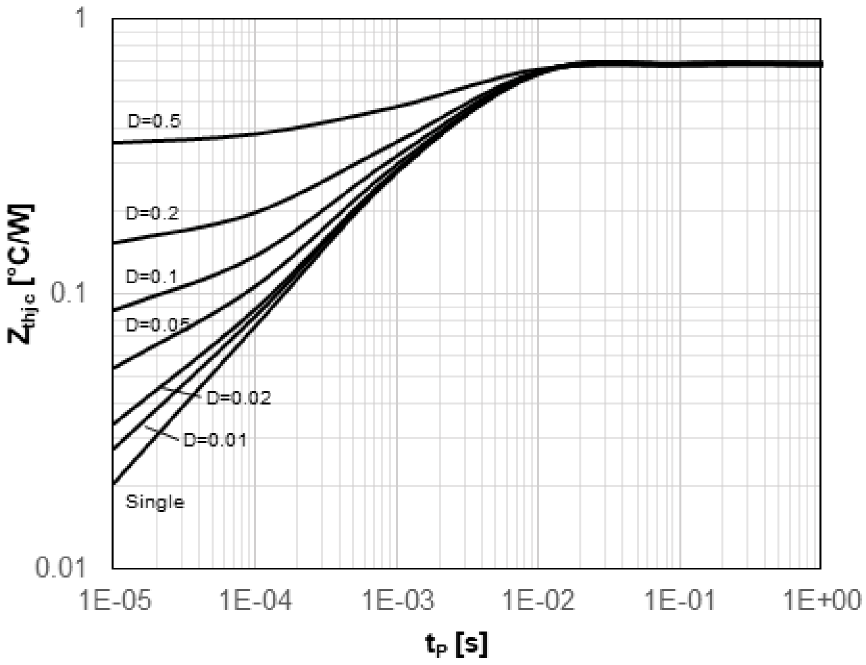


Figure 10. Transient Thermal Response (Figure 8. in the datasheet)

t_p > 1sec: $Z_{\theta JC}(t)$ value goes to be saturated as steady state in all lines, this steady value is called as $R_{\theta JC}$.
$t_p \leq$ 1sec: $Z_{\theta JC}(t)$ value are various by duration and duty of pulse. this is transient thermal resistance as $Z_{\theta JC}$.

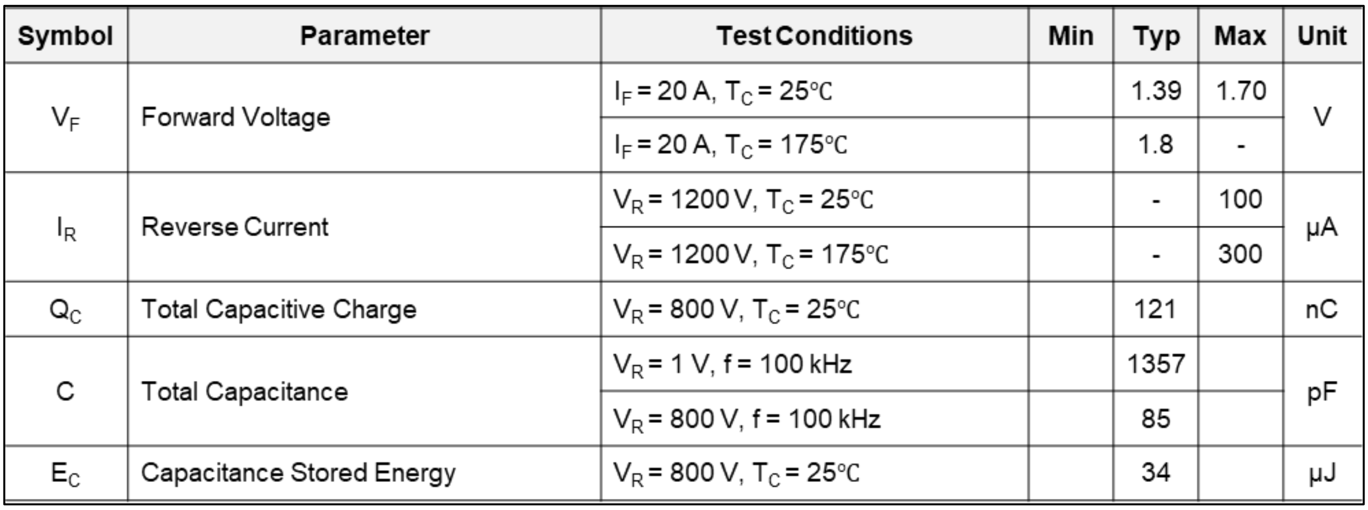
Thermal resistance is possible to calculate Junction Temperature as Equation 2) and 3)

$$Equation\ 2)\quad Steady\ State{:}\ T_J = T_c + R_{\theta JC} \times P_{D\_Average}$$

$$Equation\ 3)\quad Transient\ State{:}\ T_J = T_c + Z_{\theta JC}(t_p) \times P_{D\_Pulse}$$

3.4. Electrical Characteristics (Per Leg, T_C = 25°C unless otherwise noted)

The electrical characteristics are the device performance and capability under Tc=25°C per Leg.

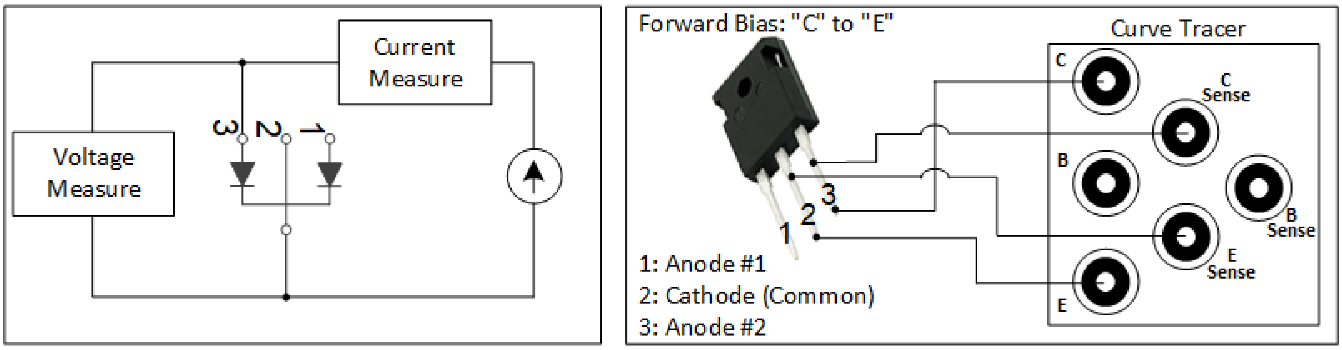


Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
V_F	Forward Voltage	I_F = 20 A, T_C = 25°C		1.39	1.70	V
		I_F = 20 A, T_C = 175°C		1.8	-	
I_R	Reverse Current	V_R = 1200 V, T_C = 25°C		-	100	μA
		V_R = 1200 V, T_C = 175°C		-	300	
Q_C	Total Capacitive Charge	V_R = 800 V, T_C = 25°C		121		nC
C	Total Capacitance	V_R = 1 V, f = 100 kHz		1357		pF
		V_R = 800 V, f = 100 kHz		85		
E_C	Capacitance Stored Energy	V_R = 800 V, T_C = 25°C		34		μJ

V_F: Forward Voltage per Leg

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
V_F	Forward Voltage	I_F = 20A, T_C = 25°C		1.39	1.70	V
		I_F = 20A, T_C = 175°C		1.8	-	

V_F is defined as "V = Voltage, F = Forward", V_F is the forward voltage drop from anode to cathode as the rated current and case temperature, test circuit and connection is as shown in Figure 10. V_F is different from forward current (I_F) and case temperature as shown in Figure 11.



In the left circuit, current source is using to flow the specific current from drain to source, curve trace has this current control function.

Figure 11. V_F Test Circuit (left) and Device connection with Curve Tracer (right) per Leg

In Figure 12, there are the curves to providing the forward voltage vs. forward current by each temperature. The forward voltage drop is increased by higher temperature at the constant forward current about 16A level in case of PCW120D40D1, this cross over point is different by device. SiC diode shows the positive temperature coefficient characteristics, this typical forward characteristic is able to use for a parallel diode and share the lager value of forward current.

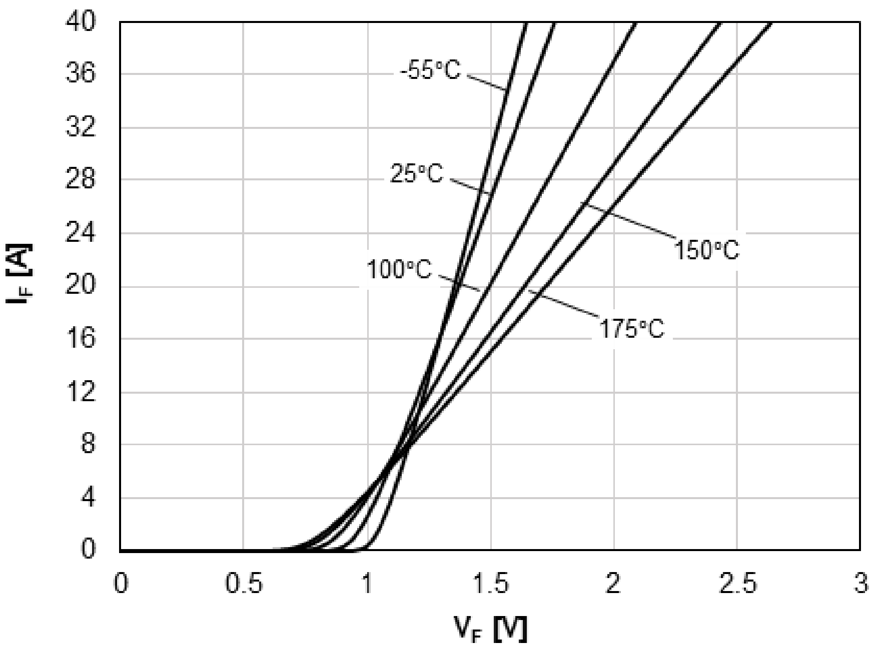


Figure 12. Forward Characteristics (Figure 3. in the datasheet)

I_R: Reverse Current

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
I_R	Reverse Current	V_R = 1200V, T_C = 25°C		-	100	µA
		V_R = 1200V, T_C = 175°C		-	300	

I_R is defined as "I = Current, R = Reverse", the meaning of "Reverse" is the reverse biasing from cathode to anode, I_R is a similar with a leakage current at the peak reverse voltage, V_{RRM} from cathode to anode as shown in the Figure 13.

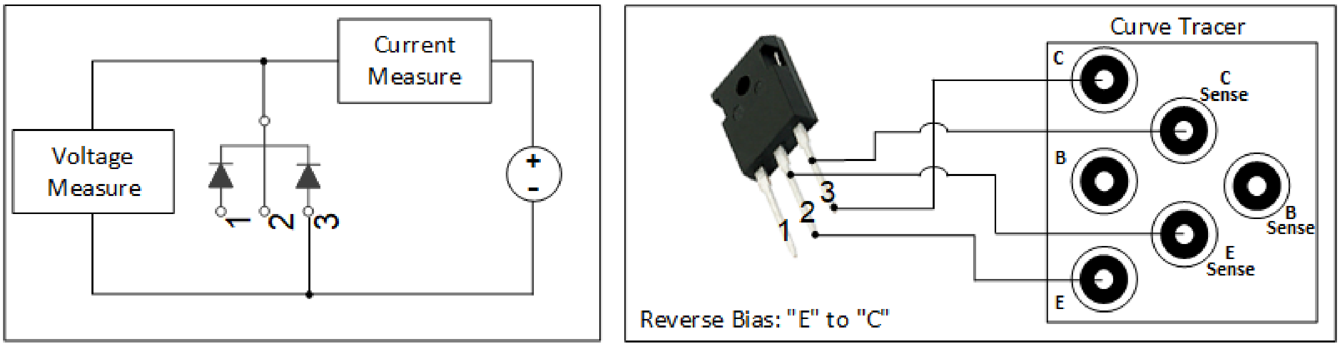


Figure 13. BV_{DSS} and I_{DSS} Test Circuit (left), and Device connection with Curve Tracer (right) per Leg

In Figure 14, there are several curves by case temperature, SiC diode reverse leakage current is very lower, because SiC diode is a majority carrier device as the unipolar device.

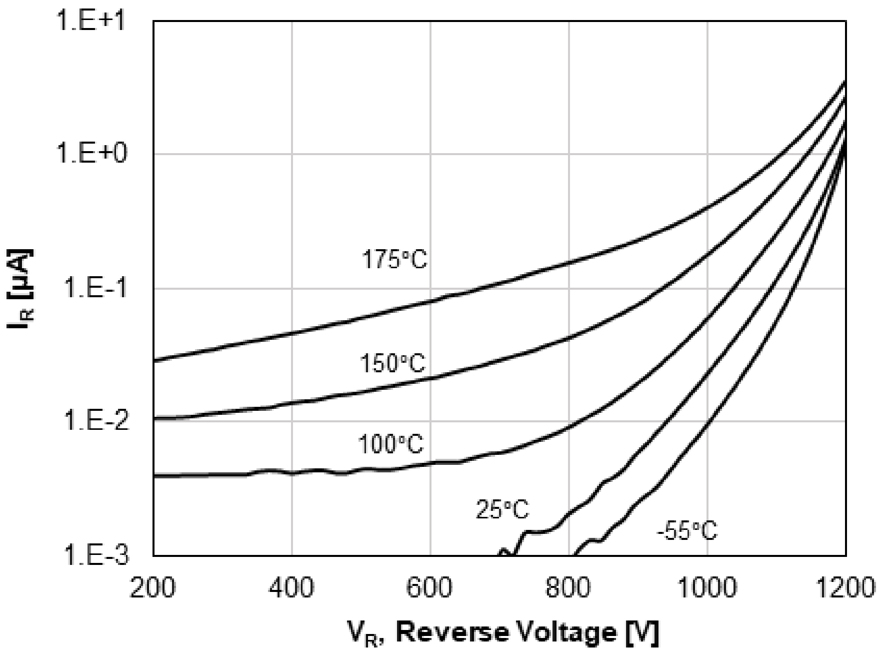


Figure 14. Reverse Characteristics (Figure 4. in the datasheet)

Q_C: Total Capacitive Charge

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
Q_C	Total Capacitive Charge	V_R = 800V, T_C = 25°C		121		nC

Q_C is defined as "Q = Charge, C = Capacitive", Q_C is the typical capacitive charge amount at the rated reverse voltage. In the SiC Schottky diode, Q_C is representing value of total charge amount instead of Q_{rr} in Si PiN diode. In the view of Si PiN diode, there are two charge amounts in actual, one is Q_{rr} and another is Q_C, however Q_C is very small than Q_{rr}, so Q_C is ignored in Si PiN diode. The Q_C curve by reverse voltage is shown in Figure 15.

C: Total Capacitance

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
C	Total Capacitance	V_R = 1V, f = 100 kHz		1357		pF
		V_R = 800V, f = 100 kHz		85		

C is defined as "Q = Charge, C = Capacitance", C is the total capacitance between Anode metal and Cathode metal as the physics of capacitance as proportionally increasing or decreasing by distance and area. SiC diode is unipolar device, so reverse recovery characteristic is not shown as Si PiN diode which is a bipolar device. Therefore, capacitance is to be a major importance parameter for switching performance. The Capacitance curve by reverse voltage is shown in Figure 16.

E_C: Capacitance Stored Energy

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
E_C	Capacitance Stored Energy	V_R = 800V, T_C = 25°C		121		uJ

E_C is defined as “Q = Charge, C = Capacitive”, E_C is the typical capacitive energy stored between anode metal and cathode metal. it is useful to calculate the switching loss of SiC diode. This energy is charging and discharging by conducting forward current or reverse biasing. E_C curve is shown in Figure 17.

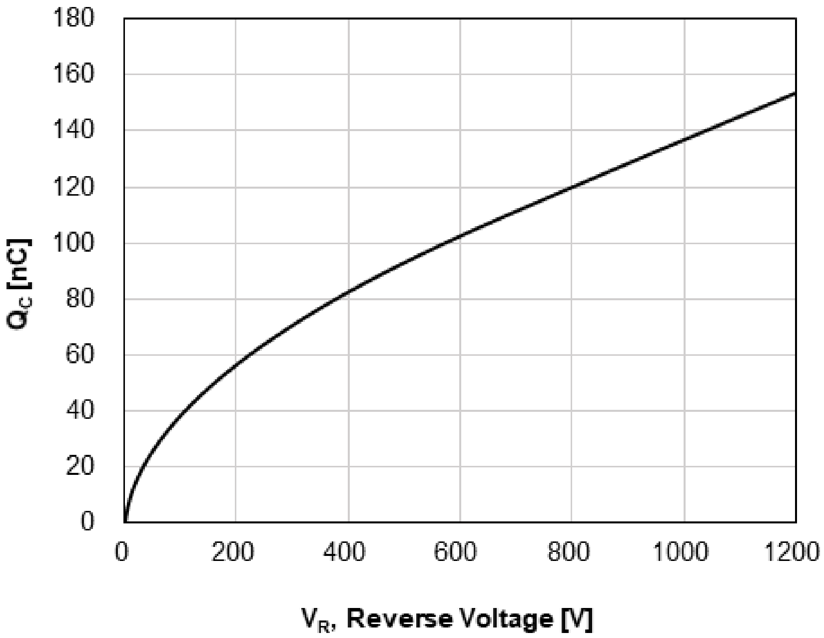


Figure 15. Capacitive Charge Characteristics (Figure 5. in the datasheet)

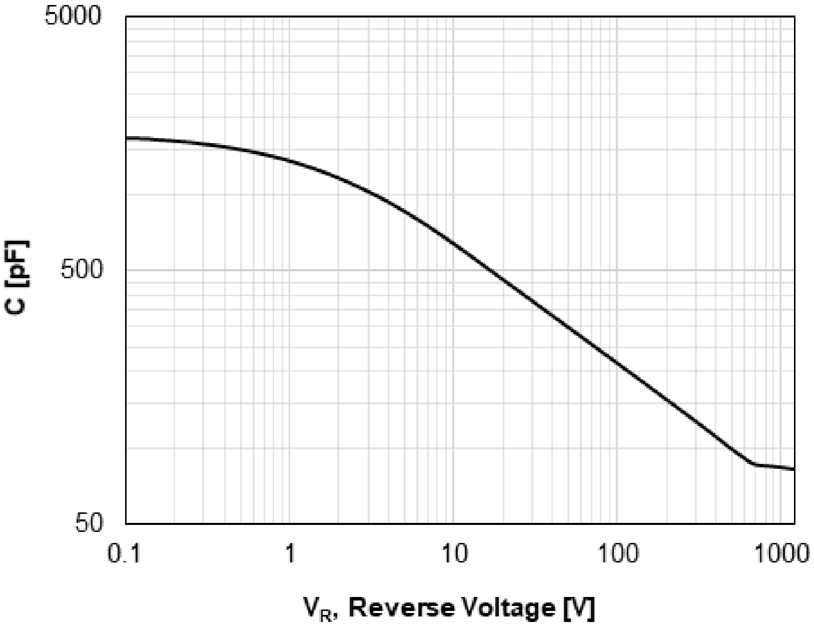


Figure 16. Capacitance Characteristics (Figure 7. in the datasheet)

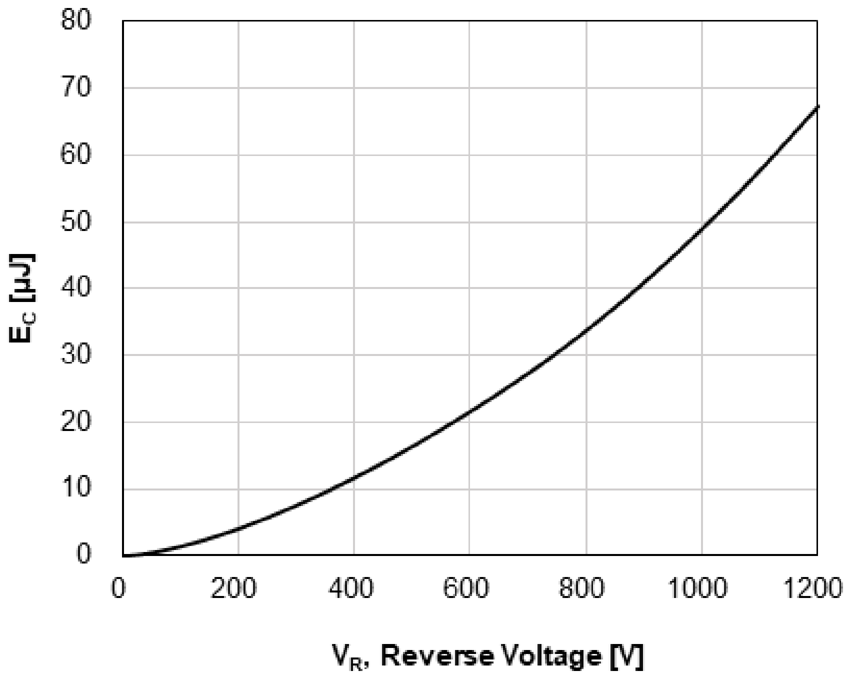


Figure 17. Capacitance Stored Energy (Figure 6. in the datasheet)

4. Document Revision History

Major changes since the last version

Date	Description of change
31-May-2022	First Release

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