AN-PJ1002

PANJIT SiC Schottky Barrier Diode Electrical Characteristics

To learn more about PANJIT International Inc., please visit our website at
www.panjit.com

Table of Contents

1 Revision History

Rev.	Revision Description	Edit by	Date
Rev.00	Document release	DM Kim	2021/03/10
Rev.01	Line-up table update	DM Kim	2021/07/14
Rev.02	Line-up table update	DM Kim	2021/10/19
Rev.03	Line-up table update	DM Kim	2022/01/10
Rev.04	Line-up table update	DM Kim	2022/03/28
Rev.05	Line-up table update	Kevin Lee	2023/03/20

2 Introduction of PANJIT SiC Schottky Barrier Diode Product Family

Silicon Carbide (SiC) is one of the wide-band gap materials widely used in power semiconductor devices. Since this material can overcome the performance limitation caused by silicon substrate-material, most power semiconductor companies have already developed SiC material based power devices. Silicon (Si) based power diode with PiN structure was good enough to be used under 40kHz switching frequency as a function of freewheeling diode solution in the hard switching applications, however, in order to get higher power density, increasing switching frequency is trending in power conversion system design. Due to the system design trend, power conversion system designers are willing to accept higher efficiency device solutions. One of the key requirements to achieve a higher frequency system is to reduce the switching loss caused by the freewheeling diode reverse recovery current. Therefore, Schottky Barrier Diode (SBD) can be the solution to gain the lowest switching power loss as operating as freewheeling diode due to no reverse recovery current characteristic. However, it is unrealistic to develop silicon base Schottky Barrier Diode (SBD) exceeding 200V since the high leakage current is one of the drawback; SiC substrate material has a superior characteristic of low leakage current at high breakdown voltage area, so it is perfect to be the material of the SBD that needs to exceed 600V. Recently, PANJIT has released the 1st generation 650V and 1200V SiC Schottky Barrier Diode (SBD) to support high-end power conversion system designs with higher switching frequencies and bigger power densities. PANJIT SiC Schottky Barrier Diode (SBD) Gen.1 line-up is shown on Table 1 to support various system power rating solutions.

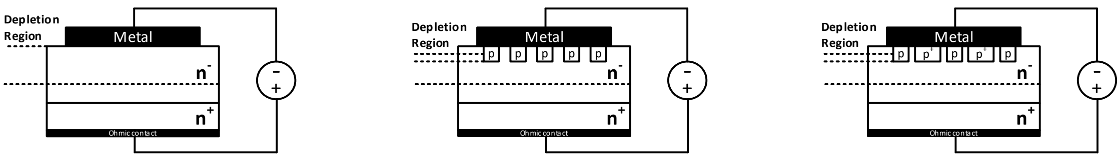
Table 1. PANJIT Gen. 1 650V/1200V SiC Schottky Barrier Diode Line-up

Series	BV (V)	I_f (A)	V_f Typ. (V)	 TO-252AA	 TO-263	 TO-220AC	 TO-247AD-2LD	 TO-247AD-3LD
SiC Diode 650V	650	4	1.5	PCDD0465G1 PCDC0465G1*	PCDB0465G1 PCDE0465G1*	PCDP0465G1		
		6	1.5	PCDD0665G1 PCDC0665G1*	PCDB0665G1 PCDE0665G1*	PCDP0665G1		
		8	1.5	PCDD0865G1 PCDC0865G1*	PCDB0865G1 PCDE0865G1*	PCDP0865G1		
		10	1.5	PCDD1065G1 PCDC1065G1*	PCDB1065G1 PCDE1065G1*	PCDP1065G1		
		12	1.5			PCDP1265G1		
		16	1.5			PCDP1665G1		
		20	1.5			PCDP2065G1		PCDH2065CCG1 PCDH2065CCG1-AU
		30	1.5					PCDH3065CCG1 PCDH3065CCG1-AU
		40	1.5					PCDH4065CCG1 PCDH4065CCG1-AU
SiC Diode 1200V	1200	5	1.5	PCDD05120G1 PCDC05120G1*		PCDP05120G1		
		8	1.5	PCDD08120G1 PCDC08120G1*		PCDP08120G1		
		10	1.5	PCDD10120G1 PCDC10120G1*	PCDB10120G1 PCDE10120G1*	PCDP10120G1		
		15	1.5			PCDP15120G1		
		20	1.5		PCDB20120G1 PCDE20120G1*	PCDP20120G1	PCDH20120G1	PCDH20120CCG1 PCDH20120CCG1-AU
		30	1.5					PCDH30120CCG1 PCDH30120CCG1-AU
		40	1.5					PCDH40120CCG1 PCDH40120CCG1-AU

* NC 1 Pin

2.1 Basic Structure of Schottky Barrier Diode

As shown in Figure 1 (a), the conventional structure of Schottky Barrier Diode (SBD) is based on the structure of a semiconductor junction directly connected to a metal which can be operated as a diode. The benefit of this structure is having no reverse recovery current with a low forward voltage drop while the biggest drawback is higher leakage current when the reverse voltage bias is applied to Schottky Barrier Diode (SBD). Junction Barrier Schottky (JBS) structure is introduced to overcome the high leakage current of the conventional SBD. As depicted on Figure 1 (b), there is an additional PN junction to extend the depletion region. In reverse voltage biased status, maximum electric field can be moved to be under P-type junction so that it can reduce the electric field on the junction between the metal and N-type. As a result, leakage current can be minimized compared with the conventional SBD. Despite of this benefit of JBS structure, a possibility of relatively lower surge current capability still remains. Merged PN Schottky (MPS) structure can be an alternative solution to resolve lower surge current capability of JBS structure, so PANJIT SiC Schottky Barrier Diode (SBD) adopted MPS structure to gain lower leakage current while maintaining higher surge current capability.



(a) Conventional SBD *(b) SBD with JBS* *(c) SBD with MPS*

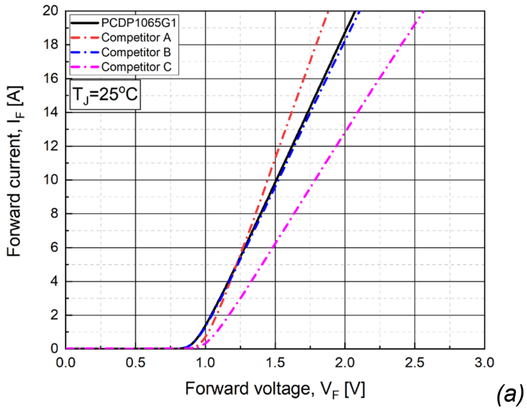
Figure 1. The structures of Schottky Barrier Diode

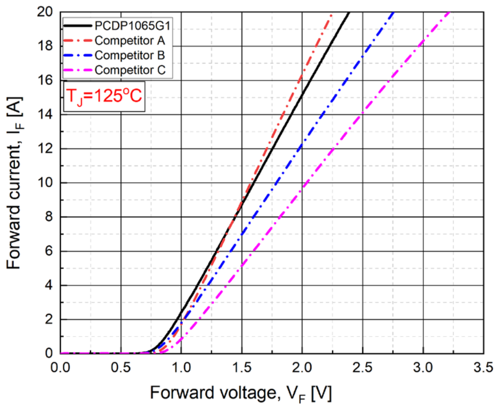
3 PANJIT SiC SBD Electrical Characteristics

The key parameters of SiC SBD are forward voltage drop (V_F), junction capacitance (C_J) and surge current capability ($IFSM_{@10msec}$, $IFSM_{@10usec}$) so, the optimization among these key parameters is crucial for developing outstanding SiC SBD devices. PANJIT SiC SBD is developed by optimizing these key parameters for achieving higher power density and ruggedness performance.

3.1 Forward Voltage Drop Characteristic of PANJIT SiC SBD

- **Room and high temperature forward voltage drop, V_F**





Forward Voltage Drop, V_F @ 25°C

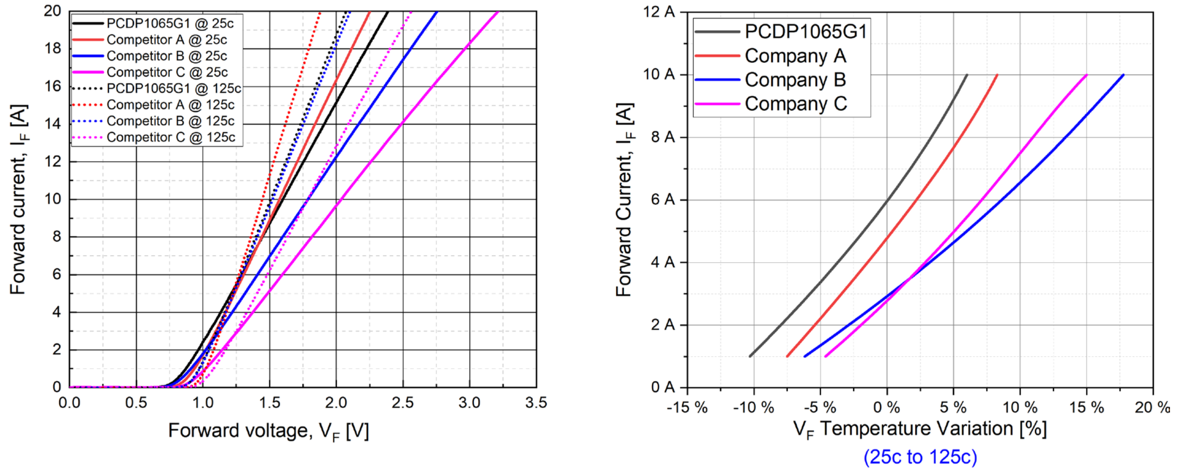
(b) Forward Voltage Drop, V_F @ 125°C

Figure 2. Forward Voltage Drop Performance Comparison

Depending on the system operating condition, SiC SBD can be operated at various load conditions. At the light load condition, device performance with low current at low temperature is important while at the heavy load operation, device should have good performance with high current at high temperature. A clear understanding of the performance difference of forward voltage drop (V_F) at low temperature and high temperature is important to achieve an outstanding performance in the system operation. As shown in Figure 2, PANJIT SiC SBD shows the most outstanding performance below 5A @ room temperature and superior among competitors below 7A range @ high temperature. This will affect the system conduction loss calculated by I_F *x* V_F *x turn-on ratio*. PANJIT SiC SBD can be a proper solution to get optimize efficiencies for overall system load conditions.

- **Temperature dependence of forward voltage drop, V_F**

Generally, SiC SBD shows Negative Temperature Coefficient (NTC) at low current, and it is changed to Positive Temperature Coefficient (PTC) at high current like depicted in Figure 3 (a). Optimization of temperature coefficient is required to get better temperature dependency at heavy load condition. PANJIT SiC SBD V_F value at high temperature decreases in the range under 6A which is beneficial for heavy load operating conditions. Due to the temperature dependence of V_F value, PANJIT SiC SBD V_F value at high temperature has the lowest value up to 7A.



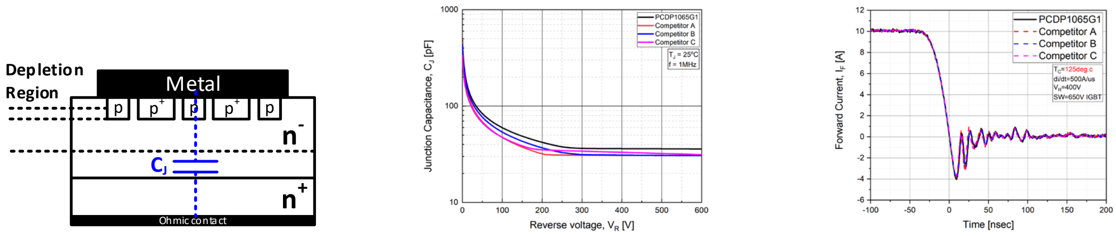
(a) V_F @ 25°C and 125°C *(b) V_F variation depending on temperature*

Figure 3. Temperature dependency of forward voltage drop, V_F

3.2 Junction Capacitance Characteristic of PANJIT SiC SBD

- **Energy loss by the junction capacitance**

There are several junctions in SBD structure, each junction can be affected as capacitor called as junction capacitance which can be varied by depletion area defined by applied reverse voltage, so it should be measured at various voltage range as shown in Figure 4 (b). As explained in the previous chapter, SBD structure does not have reverse recovery current, however, as depicted in Figure 4 (c), reverse current during turn-off stage is still observed. This is originated by charging energy of the junction capacitor and it can make additional power losses in the system. The junction capacitance charging losses can be calculated in the C-V characteristic (Figure 4 (b)). Since this charging energy comes from capacitance, it is independent to temperature, di/dt and forward current.



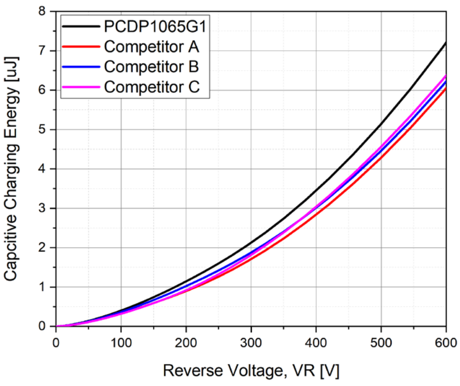
(a) Junction Capacitance of SBD *(b) C-V characteristic* *(c) Reverse current waveform*

Figure 4. Junction Capacitance Characteristics

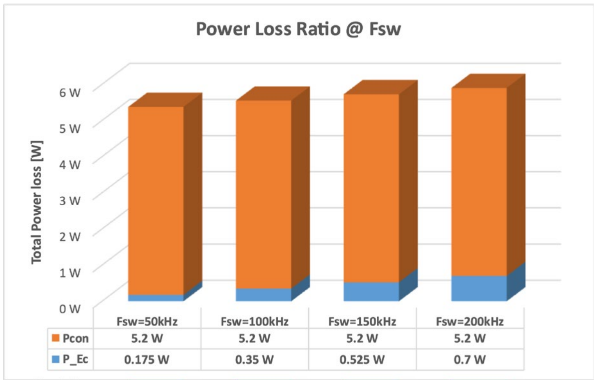
The equation to calculate charging energy losses, Ec is,

$$E_C = \int_0^{V_R} C(V) \times V \times dV$$

The calculation result from this equation is shown in Figure 5 (a). PANJIT SiC SBD shows slightly higher capacitance charging losses, thus causes slightly higher power loss at higher frequency and light load efficiency. PANJIT SiC SBD focuses on balanced performance, the junction capacitance charging losses will be slightly sacrificed to achieve other performance benefits. As shown in Figure 5 (b), the portion of capacitor charging loss, P_Ec, is smaller portion than the conduction loss, Pcon, so the sacrifice on capacitive charging energy is not severely affected to a system power loss performance.



(a) Junction capacitor charging loss



(b) Simple power loss calculation

Figure 5. Junction Capacitor Characteristics

3.3 Surge Current Capability Characteristic of PANJIT SiC SBD

- **Surge current capability on CCM Boost PFC**

When a system including PFC circuits starts-up or heavy output load such as short circuit is applied, huge current will be applied to SiC SBD. In this case, surge current may destroy diode device so proper surge current capability is a critical parameter for ensuring the power conversion systems safety operation. Basically, it's not easy to calculate the amount of excessive current flowing into the diode device, however, we can estimate the amount of in-rush current base on the system power rating and DC-link capacitance. DC-link capacitor that needed for specific power ratings can be calculated by the below equation,

$$C_{O1} \geq (2 \times P_O \times t_{hold})/\left(V_O^2 - V_{O\_min}^2\right) \text{ or } C_{O2} \geq P_O/(2 \times \pi \times f_{line} \times \Delta V_O \times V_O)$$

where, P_O = system power, V_O = output voltage, f_{line} = grid frequency

The minimum requirement of DC-link capacitance can be chosen from the biggest value between C_{01} and C_{02}. After deciding the DC-link capacitance value, the current capability required for each system power ratings can be simulated as the result shown in Table 2. As introduced in Table 1, PANJIT has several line-up products of SiC SBDs to support various system power ratings, so that a proper part number can be chosen by considering surge current capability and system power rating shown in Table 2. If a power conversion system designer wants to focus on cost effective solution, one step lower current rating of PANJIT SiC SBDs can be chosen from table 1.

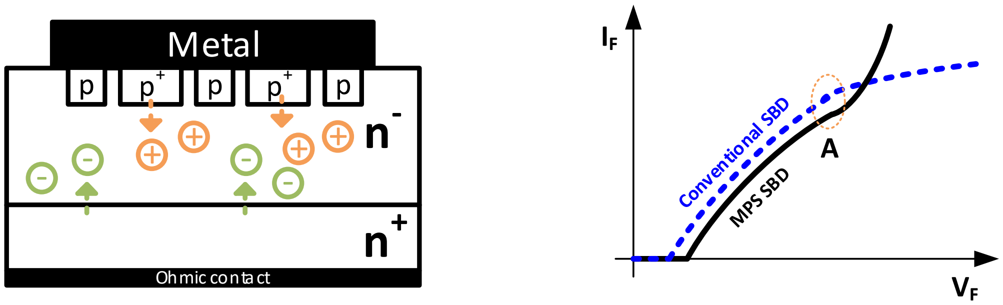
Table 2. Surge Current Specification and Recommended Part Number

System Power	Hold-up time (t_{hold})	Line Frequency	Output Voltage Typ. / Min.	DC-Link Cap.	Required $IFSM_{10usec}$	Recommended Part Number
300 W	16.6 msec	60 Hz	400V / 340V	224 uF	215 A	PCDP0665G1
500 W				374 uF	266 A	PCDP1065G1
1000 W				748 uF	465 A	PCDP1665G1
1500 W				1122 uF	772 A	PCDP2065G1

2000 W				1495 uF	954 A	PCDP1665G1 x 2pcs
2500 W				1869 uF	1154 A	PCDP1265G1 x 3pcs
3000 W				2243 uF	1400 A	PCDP2065G1 x 2pcs

- **Surge current capability comparison, $IFSM_{@10msec}$ and $IFSM_{@10usec}$**

To ensure proper system level reliability, surge current capability should also be considered. There are two kinds of surge current test specification described in the official datasheet; IFSM @10 or 8.33msec and IFSM@10usec. IFSM @10 or 8.33msec is a typical condition to check the diode performance used for rectification circuit at low frequency sinusoidal current. SiC SBD is used as a high frequency freewheeling diode in general, thus IFSM@10usec is the condition used by several semiconductor suppliers to ensure proper performance for customers' end application. PANJIT has done the same. As a result of MPS structure, which is explained in the previous chapter, the performance of IFSM@10usec was outstanding to support system level surge current requirement. Although conventional SBD structure provides a benefit from a slightly lower forward voltage drop, it has severely low surge current capability. The reason of this phenomenon can be explained by looking at the forward voltage drop curves at high current rating in Figure 6. The resistance value of n^- layer becomes higher at low current rating and the bias voltage is surpassing cut-off voltage. So, in forward bias, holes and electrons are injected from p layer and n layer to n^- layer as depicted in Figure 6 (a). Then, n^- layer becomes high concentration which results as lower resistance. For the conventional SBD case, forward voltage drop will be saturated at higher current as shown in Figure 6 (b) point A due to limited holes. Meanwhile, MPS SBD is capable to inject more holes and electrons from added p^+ layer, so as a result, n^- layer can have much lower resistance with conductivity modulation similar to p-n junction diode. Table 3 shows the IFSM @10usec result of PANJIT SiC SBD compared with competitors. Competitor A shows quite low surge current capability so there is a possible to show lower reliable behavior; the surge current of competitor B is too high, so it is better to be optimized. PANJIT SiC SBD is well optimized for surge current capability which can satisfy the system level surge current requirement.



(a) Conductivity modulation at high current *(b) I-V characteristics*

Figure 6. Forward Voltage Drop Comparison

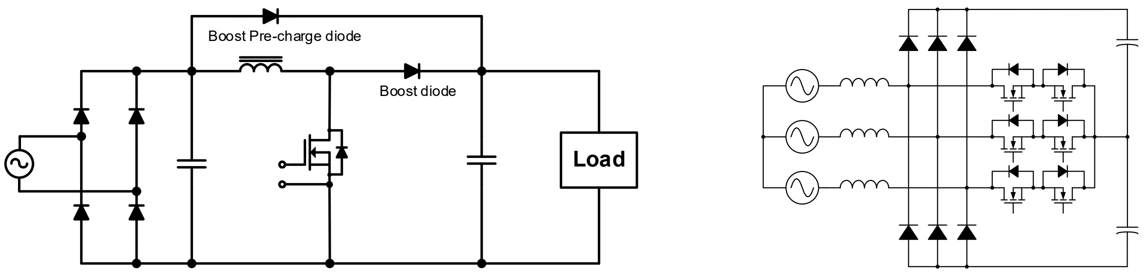
Table 3. IFSM @ 10usec Test Result

IFSM 10usec	650V/10A SiC Diode IFSM 10usec Test Result							
	300A	400A	600A	700A	800A	900A	1400A	1500A
PCDP1065G1	Pass	Pass	Pass	Fail	-	-	-	-
Competitor A	Pass	Fail	-					
Competitor B	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail

Competitor C	**Pass**	**Pass**	**Pass**	**Pass**	**Fail**	-	-	-

4 System Performance Evaluation (CCM Boost PFC and Vienna PFC)

PFC circuit is one of key applications for SiC SBD. 650V SiC SBD is needed for CCM boost PFC in power conversion systems such as server / telecom / PC power supply unit, home appliance and UPS. As for solar power application, Boost converter is used for boosting input voltage up to the voltage that PV invert needs and CCM Boost PFC performance can be comparable with Boost converter system so that's why CCM Boost PFC is chosen to see the electrical performance for several applications. 1200V SiC SBD can be adopted for Vienna PFC which is widely used in UPS and EV charging station with 3-phase system due to their output voltage. The circuits depicted in Figure 7 (a) & (b) are CCM boost and Vienna PFC, respectively. 650V SiC SBD is applied to boost diode on CCM boost PFC and 1200V SiC SBD is applied to rectification diode in Vienna PFC circuit. In this chapter, the performance comparison of the efficiency test result between PANJIT's SiC SBD and competitor's devices will be presented.



(a) Circuit diagram for CCM Boost PFC

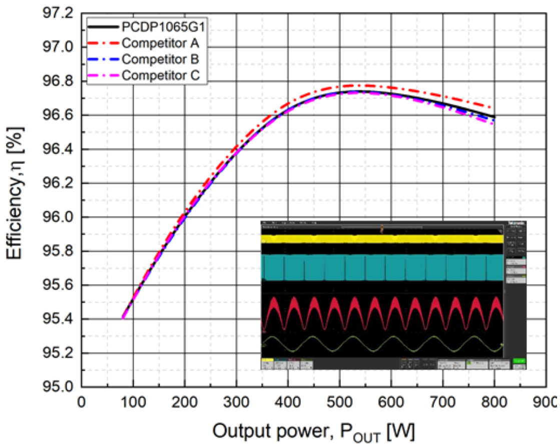
(b) Circuit diagram for Vienna PFC

Figure 7. Circuit Diagram for CCM Boost and Vienna PFC

4.1 PANJIT 650V SiC SBD in CCM Boost PFC Circuit

In the CCM boost PFC circuit with 650V SiC SBD, the efficiency test was conducted to see the electrical performance in PFC circuit. SiC SBD can be used for freewheeling operation and there is great benefit for system performance due to not having reverse recovery characteristics. In this application note, PANJIT SiC SBD, PCDP1065G1 (650V/10A), was tested to compare with the tier 1 competitors in the market. Competitor A showed the best efficiency however, as explained in Table 3, it has poor IFSM@10usec performance which may cause severely affect to the system reliability. The surge current of competitor B is superior to others but the efficiency is slightly lower than PANJIT SiC SBD. It can be concluded from the surge current capability and the efficiency test result, PANJIT SiC SBD is well optimized between electrical performance while ensuring the system reliability. Therefore, PANJIT SiC SBD can allow the system designers to choose the solution in the perspective of leading edge system efficiency and good reliability.

- Input Voltage, Vin: 110Vac / 60Hz
- Output Voltage, Vout: 400Vdc
- Output Power Ratings, Pout: 800W
- Gate Resistor of Main Switch, Rg: 5ohm
- Switching Frequency, Fsw: 65kHz



(a) System evaluation test condition

(b) Efficiency test result

Figure 8. Efficiency Test Result at 800W CCM Boost PFC

4.2 PANJIT 1200V SiC SBD in 3-Phase Vienna PFC Circuit

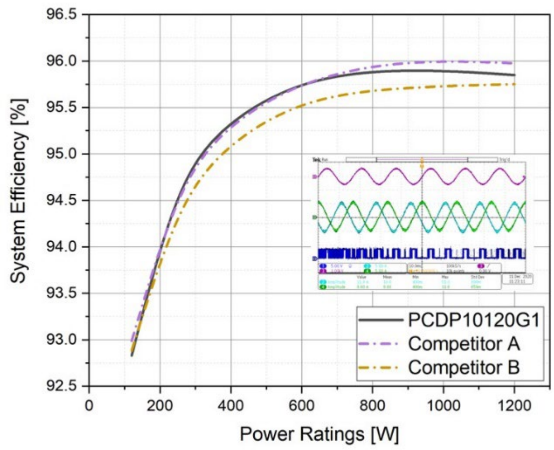
As explained previously, Vienna PFC is one of preferable topologies for 3-phase systems. Since Vienna PFC needs to use 1200V diodes if the output voltage is over 600V, the system designer can use PANJIT 1200V SiC SBD to their system. As for system efficiency performance, the test result is shown in Figure 9. The same design concept of PANJIT 650V SiC SBD is adopted to design PANJIT 1200V SiC SBD so that the optimization is the first priority compared with competitors as shown in Table 4. All of the performance mentioned in the table is suitable for the system ruggedness and electrical performance so, PANJIT 1200V SiC SBD performance is suitable for 3-phase Vienna PFC compared with competitors in the market.

Table 4. Device Performance Summary

	IFSM @ 10usec	UIS @ L=10uH	Efficiency
PCDP10120G1	Mid	Mid	Mid
Competitor A	Mid	Worst	Best
Competitor B	Best	Best	Worst

- Input Voltage, Vin: 120$V_{L\text{-}N}$ / 60Hz
- Output Voltage, Vout: 600Vdc
- Output Power Ratings, Pout: 1200W
- Switching Frequency, Fsw: 50kHz

(a) System evaluation test condition



(b) Efficiency test result

Figure 9. Efficiency Test Result at 1200W 3-Phase Vienna PFC

5 Summary

PANJIT has released the 1st generation 650V & 1200V Schottky Barrier Diode (SBD) which are well optimized between electrical performance while ensuring the system reliability. PANJIT SiC SBD product series targets PFC circuits in power conversion systems such as server / telecom / PC power supply unit, home appliance, UPS, PV inverter, and EV charging station. PANJIT SiC SBD products would be a great solution for the system designers to select for increasing the system efficiency and reliability.

COMMENTS
Your feedback will help us to continuously improve the quality of this document. Any information that you feel wrong or unclear, please send your proposal to: sales@panjit.com.tw