600 V, 1- 40 A, Schottky Diodes in SiC and Their Applications

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ABSTRACT

The SiC Schottky Barrier Diode (SBD) is commercially available in the 600-1200 V / 1-10 A range. The main advantage of a high voltage SiC SBD lies in its superior dynamic performance. The reverse recovery charge in the SiC SBD is extremely low (< 20 nC) and is the result of junction capacitance, not stored charge. Furthermore, unlike the Si PiN diode, it is independent of di/dt, forward current and temperature. The maximum junction temperature of 175°C in the SiC SBD represents the actual useable temperature. The ultra low Q_{rr} in SiC SBDs results in reduced switching losses in a typical CCM PFC Boost Circuit. This lowers the case temperature of the MOSFET improving the system efficiency and allowing for a reduction in size of the MOSFET silicon. In order to measure the benefit of these high performance rectifiers, a 250 Watt PFC test circuit was compared with an ultrafast Silicon Diode as well as SiC SBD. An overall decrease of 27% in switching losses is measured when the circuit uses a SiC diode as compared to a Si diode. At full load condition, the circuit efficiency increases from 90% with the Si diode as compared to 93% with the SiC diode.

INTRODUCTION

The trend to reduce the size and weight of electronic systems is primarily driven by market demands for increasing power densities. In order to achieve this goal without reducing the functionality, it is necessary to reduce the size and weight of the Switch Mode Power Supplies (SMPS) in these systems. The Silicon Carbide SBDs offer many advantages in this respect: (a) Low Q_{rr} and reduced switching losses in the diode and the MOSFET, (b) Higher junction temperature operation up to 175°C, (c) Reduction in the number of MOSFETs by 50%, (d) Faster switching up to 500 kHz to reduce the EMI Filter size and other passives, and (e) Reduction or elimination of the active or passive snubber. Some of these ideas have already been demonstrated by Infineon Technologies [1]. The Power Factor Correction (PFC) circuits can be divided in two broad categories: Boost converter driven in (1) Discontinuous Conduction Mode (DCM) and (2) Continuous Conduction Mode (CCM). The CCM circuit, which is currently utilized in PFCs rated >300W, will greatly benefit from an ultra fast SiC SBD. The Si ultra fast recovery diodes have high Q_{rr} (~ 100 nC) which increases significantly with di/dt, forward current and temperature. On the contrary, the Q_{rr} of SiC SBDs is relatively independent of these parameters. GaAs SBDs are available up to 250 V. However, the PFC circuit usually requires devices rated at ~ 600 V.

SILICON CARBIDE

Although there are about 170 known crystal structures, or polytypes of SiC, only two (4H-SiC and 6H-SiC) are available commercially. 4H-SiC is preferred over 6H-SiC for most electronics applications because it has higher and more isotropic

Table 1: Key electronic properties of Si, GaAs, and 4H-SiC

Property	Silicon	GaAs	4H-SiC
Band gap, E_g (eV)	1.12	1.5	3.26
Electron mobility, μ_n (cm^2/Vs)	1400	9200	800
Hole mobility, μ_p (cm^2/Vs)	450	400	140
Intrinsic carrier concentration, n_i (cm^{-3}) at 300 K	$1.5x10^{10}$	$2.1x10^6$	$5x10^{-9}$
Electron saturated velocity, v_{nsat} ($x10^7$cm/s)	1.0	1.0	2.0
Critical breakdown electric field, E_{crit} (MV/cm)	0.25	0.3	2.2
Thermal conductivity, Θ (W/cm•K)	1.5	0.5	3.0-3.8

electron mobility than 6H-SiC. Table 1 compares the key electronic properties of 4H-SiC to Si and GaAs. The higher breakdown electric field strength of SiC enables the potential use of SiC SBDs in 600-2000 V range. Specific benefits of SiC electronic properties are:

- The 10x higher breakdown electric field strength of SiC reduces the specific on-resistance compared to the Si and GaAs SBDs. This is illustrated in Fig. 1. At 600 V, a SiC SBD offers a R_{on} of 1.4 mΩ-cm^2, which is considerably, less than 6.5 mΩ-cm^2 for a GaAs SBD and 73 mΩ-cm^2 for a Si SBD. This means that the SiC SBD will have a much smaller foot-print.

- The higher bandgap results in much higher schottky metal-semiconductor barrier height as compared to GaAs and Si, resulting in extremely low leakage currents at elevated junction temperatures due to reduced thermionic electron emission over the barrier.

- The very high thermal conductivity of SiC reduces the thermal resistance of the die.

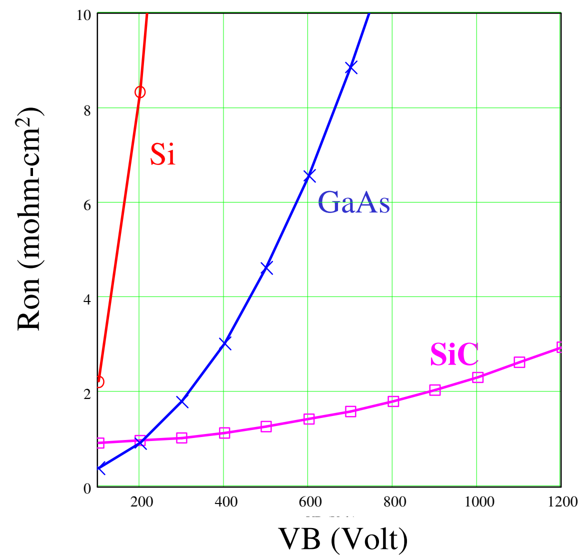

Fig. 1 Specific on-resistance of Si, GaAs and 4H-SiC SBDs as a function of the breakdown voltage.

The power electronic systems operating in the 600-1200 voltage range currently utilize silicon PiN diodes, which tend to store large amounts of minority carrier charge in the forward-biased state. The stored charge has to be removed by majority carrier recombination before the diode can be turned off. This causes long storage and turn-off times. The prime benefits of the SiC SBD lie in its ability to switch fast (<50 ns), with almost zero reverse recovery

charge and the high junction temperature operation. The 600 V GaAs SBDs can be made but suffer from limitations with regards to the high junction temperature operation and 5x bigger foot-print for the same current rating. The comparable Silicon PiN diodes (Si SBDs are not viable in the 600 V range because of their large on-state voltage drops) have a reverse recovery charge of 100-500 nC and take at least 100 ns to turn-off. This places a tremendous burden on other switching elements in the system in terms of the required forward safe operating area and the switching losses incurred.

CHARACTERISTICS OF SiC SBDs

Fig. 2 shows a typical temperature dependent forward characteristic of a 10 A / 600 V 4H-SiC SBD. The on-resistance increases with temperature due to the reduction in the electron mobility at elevated temperatures. The diode shows 10 A at a V_F of 1.5 V at 25°C. The current reduces to approximately 5.7 A at the same V_F at 200°C. This negative temperature coefficient of forward current allows us to parallel more than one die in a package without any unequal current sharing issues. This behavior is unlike high voltage Si PiN diodes. Fig. 3 shows the reverse characteristics of the 10 A / 600 V SBD. The typical leakage current is less than 50 µA at 600 V at 25°C which increases to 70 µA at 200°C – a very nominal increase for such a wide temperature range.

The devices were packaged in plastic TO-220 packages with a thermal impedance of 1.1°C/W. The current de-rating curve for a packaged part is shown in Fig. 4. These parts are rated for a maximum junction temperature of 175°C. For a case temperature of up to 150°C, the junction temperature remains below 175°C. When the case temperature is above 150°C, the current has to be appropriately de-rated to keep the junction temperature below 175°C.

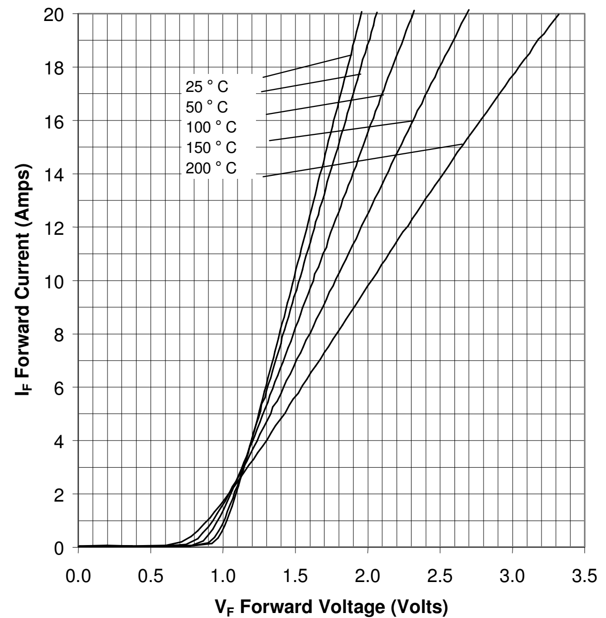

Fig. 2 The forward characteristics of a 10 A/600 V 4H-SiC SBD.

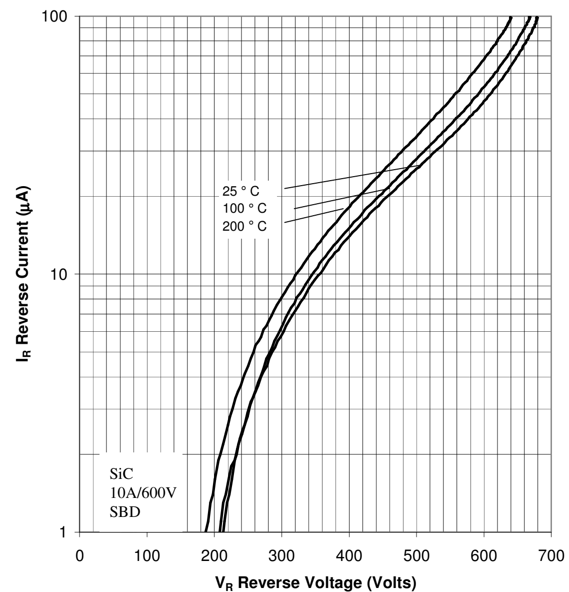

Fig. 3 The reverse characteristics of a 10 A/600 V 4H-SiC SBD.

The reverse capacitance vs. voltage curve is shown in Fig. 5. At 10 V reverse bias, the

input capacitance is about 240 pF, which drops to 90 pF at 100 V and saturates to 50 pF above 300 V. This capacitance is comparable to low voltage Si Schottky Diodes.

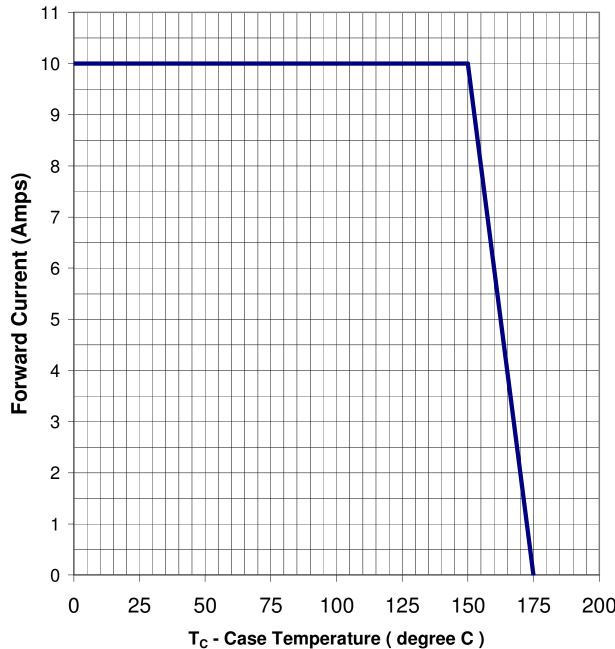

Fig. 4 The current derating curve for the 10 A/600 V SiC SBD.

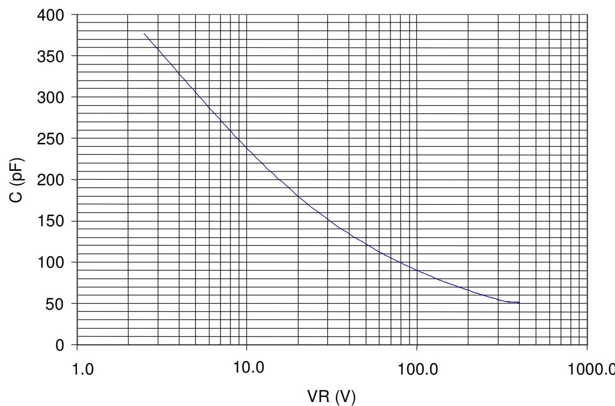

Fig. 5 The reverse capacitance vs. voltage curve for the 10 A/600 V SiC SBD.

The turn-off characteristics of the 10 A/600 V 4H-SiC SBD are compared with a Si FRED at different temperatures (Fig. 6). The SiC diode, being a majority carrier device, does not have any stored minority carriers. Therefore, there is no reverse recovery current associated with the turn-off transient of the SBD. However, there is a small amount of displacement current required to charge the Schottky junction capacitance (< 2 A) which is independent of the temperature, current level and di/dt. In contrast to the SiC SBD, the Si FRED exhibits a large amount of the reverse recovery charge, which increases dramatically with temperature, on-current and reverse di/dt. For example, the Q_{rr} of the Si FRED is approximately 160 nC at room temperature and increases to about 450 nC at 150°C. This excessive amount of Q_{rr} increases the switching losses and places a tremendous burden on the switch and diode in typical PFC or motor control applications.

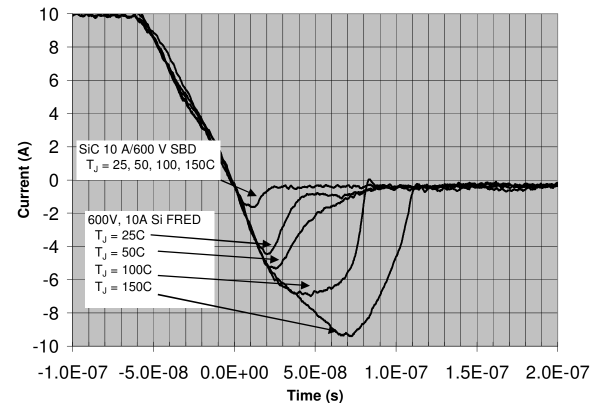

Fig. 6 Turn-off switching waveform of the 10 A / 600 V SiC SBD in comparison to Si FRED (IXYS DSEI 12-06A).

In a switching application, the diode will be subjected to peak currents that are greater than the average rated current of the device. Fig. 7 shows a repetitive peak forward surge current of 50 A at 25°C for the 10A / 600 V SiC SBD. This 60 Hz half sine wave measurement indicates a repetitive peak current of 5X the average.

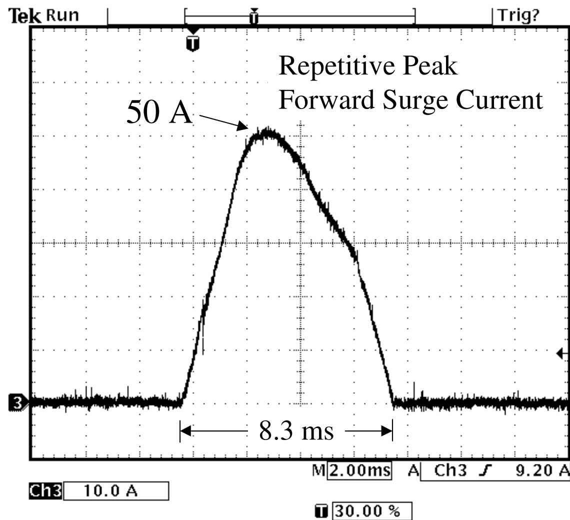

Fig. 7 Repetitive peak forward surge current at 25°C utilizing half sine wave.

The quality of the SiC wafers has been continuously improving over the last 5 years. It is now possible to make larger area chips. Fig. 8 shows an example of a single SiC SBD chip rated at 600 V / 30 A. This device showed a leakage current of 70 μA at a reverse bias of 600 V. As was mentioned before, the negative temperature coefficient of the current makes it possible to easily parallel several chips in a single package without encountering current sharing problems. An example is shown in Fig. 9, where three chips of the type shown in Fig. 8 were packaged together to provide an 80 A / 600 V part. This package had a leakage current of 125 μA at 600 V and 25°C. This demonstrates that the SiC SBD technology is scalable to higher currents. While the material is continuously improving, relatively high current parts can be obtained now by paralleling several chips in a package.

RELIABILITY STUDIES OF THE SiC SBD

SiC is inherently a very robust and reliable material. Our 600 V SBDs have undergone extensive reliability testing and can be used as an example of SiC device reliability. To date the diodes have completed a total of 145,000 device hours of High Temperature Reverse Bias Testing (HTRB), 11,000 device hours of continuous current "burn in" testing, and 35,000 device hours of power cycle testing with no failures.

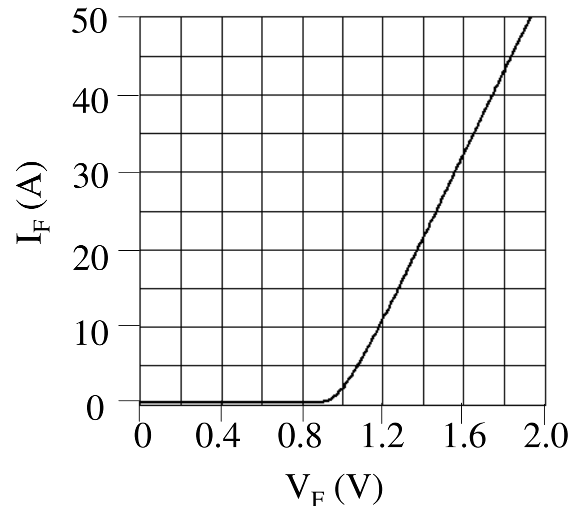

Fig. 8 Single chip SiC 600 V / 30 A Schottky Barrier Diode.

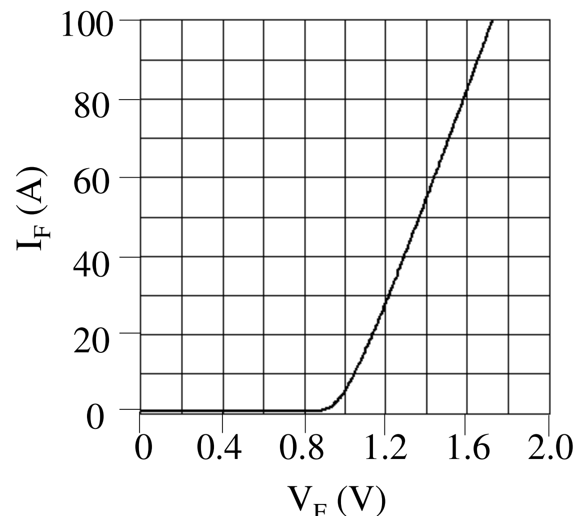

Fig. 9 A packaged SiC 80 A / 600 V part using three chips.

The HTRB testing involved seven separate lots with test conditions of -600 volts DC at a temperature of 200°C. The "burn in" was

done at the rated device forward current, with the device junction temperature held at 200°C. The power cycle consisted of 7 minute on/off cycles (3.5 min. on / 3.5 min off) with the on-current set to the device rated current, a maximum junction temperature of 175°C and a junction temperature delta of greater than 100°C during the cycle.

POWER FACTOR CORRECTION (PFC)

One of the largest applications for SiC Schottky rectifiers in the near future is in the continuous conduction mode (CCM) power factor correction (PFC) circuit. In traditional off-line AC-DC power supplies used in computer and telecom applications, the AC input sees a large inductive (transformer) load which causes the power factor to be substantially lower than 1. A PFC circuit allows the AC input line to see near-unity power factor, as required by new legal requirements. As shown in Fig. 10, chopping the full wave rectified input with a fast switch (MOSFET), and then stabilizing the resulting DC waveform using a capacitor accomplishes this function. When the MOSFET is ON, it is necessary to prevent the current to flow from the output capacitor or the load through the MOSFET. Hence, when the FET is ON, the Diode is OFF, and vice versa. During the switching transient when the Diode is turning OFF and the MOSFET is turning ON, the reverse recovery current from the Diode flows into the MOSFET, in addition to the rectified input current. This results in a large inrush current into the MOSFET, requiring a substantially large sized MOSFET, than that required if the Diode had no reverse recovery current. This large MOSFET represents a substantial cost in this circuit. These switching losses also limit the frequency of operation in the circuit, and hence its cost, size, weight and volume. A higher frequency would allow the size of the passive components to be correspondingly smaller. Many fast silicon rectifiers also show "snappy" reverse recovery, which results in a large EMI signature, which are also unacceptable to the new European requirements. A fast rectifier with smooth switching characteristics will allow for high efficiency PFC circuits, which also comply with new legal requirements.

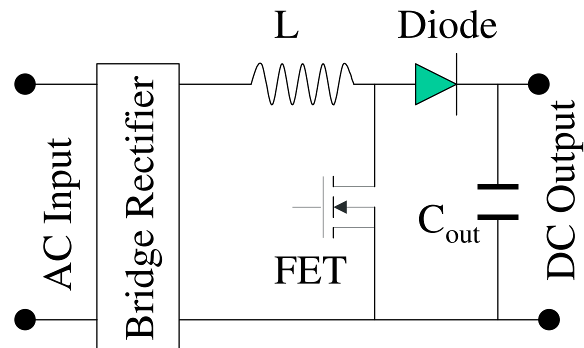

Fig. 10 A simplified schematic of a power factor correction (PFC) circuit.

A 4H-SiC diode is such a rectifier. This near-zero reverse recovery SiC Schottky rectifier offers low switching losses while still showing comparable on-state performance of conventional silicon rectifiers. Due to the majority carrier transport properties of these rectifiers, they show only a capacitive current during their turn-off transient, which flows through the power MOSFET. In order to measure the benefit of these high performance rectifiers, a 250 Watt PFC test circuit was compared with an ultrafast Silicon Diode as well as SiC SBD.

This test circuit used a 14 A, 500 V International Rectifier MOSFET (IRFP450), and a 6 A, 600 V ultrafast IR Si PiN diode (HFA08TB60). The input voltage was kept at a constant 120 V RMS, and the output voltage was 370 V DC. The operating

frequency was 90 kHz, and the gate resistance at the MOSFET was 50 Ω. The current rating of the MOSFET was higher than the average rating to accommodate the reverse recovery current of the diode, and to maintain a high efficiency of the circuit. Under full load condition, a 600 Ω resistor was utilized, while at half load condition, 1200 Ω was used. Voltage and current measurements were taken on both the MOSFET as well as the diode, in order to estimate the power losses in these components. The input and output power was also measured to calculate the efficiency of the circuit. Under full load conditions, the temperature on the MOSFET case was measured with and without an external fan on the device. After all these measurements were taken using the ultrafast Si diode, they were repeated using Cree's 4 A, 600 V SiC SBD (CSD04060).

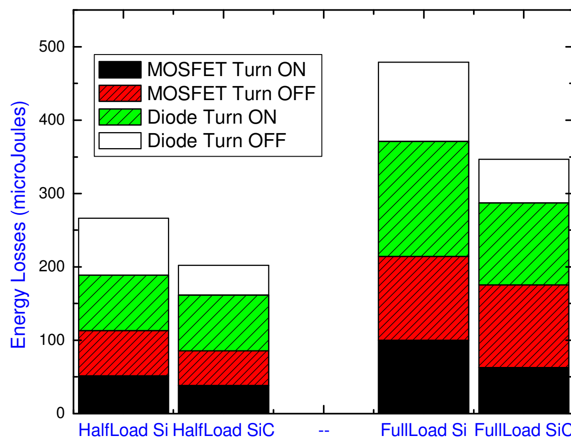

Fig. 11 Comparison of switching losses in PFC with Si and SiC diodes.

Fig. 11 shows the comparison of the switching energy losses per switching cycle in the MOSFET and Diode under half load and full load conditions. Further, the turn-ON and turn-OFF losses within each device are separated. Under half load conditions, the total switching losses decrease by about 25% from 266 µJ to 200 µJ when the Si diode is replaced by SiC SBD. The 50% decrease during Diode turn OFF losses, and 27% decrease during MOSFET turn ON are primarily responsible for this overall reduction in losses when a SiC SBD is used in the circuit as compared to when a Si diode is used. The MOSFET turn OFF losses and Diode turn ON losses are similar when Si and SiC Diodes are used in this circuit.

Under full load conditions, Diode turn OFF losses decrease by 44%, MOSFET turn ON losses decrease by 39%, and Diode turn ON losses decrease by 29% when a SiC diode is used in this circuit as compared to a Si diode. The MOSFET turn OFF losses remain similar in both cases. An overall decrease of 27% in switching losses is measured when the circuit uses a SiC diode as compared to a Si diode. It is worth noting that diode turn ON losses are significantly lower as compared to Si PiN diodes under full load conditions because of a slower turn ON process in a PiN diode as compared to a SBD under higher current operation. These results also show that the dominant reduction in switching losses occurs due to the small reverse recovery losses in the SiC diode as compared to the case with Si diodes.

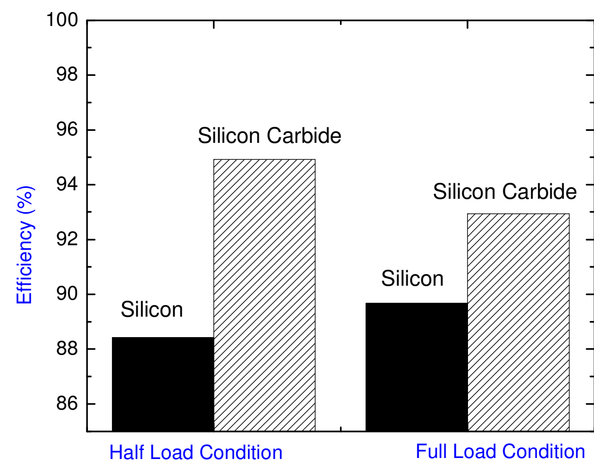

Fig. 13 Comparison of overall efficiency of PFC with silicon and SiC diodes.

Fig. 13 shows the comparison of the measured efficiency of the entire PFC circuit between Si and SiC diodes. At half load condition, the circuit efficiency increases from 88.4% with the Si diode to 95% with the SiC diode. At full load condition, the circuit efficiency increases from 90% with the Si diode as compared to 93% with the SiC diode. Ostensibly, the slightly higher on-state losses in the SiC SBD result in the relatively smaller gain in the overall circuit efficiency under full load operating condition.

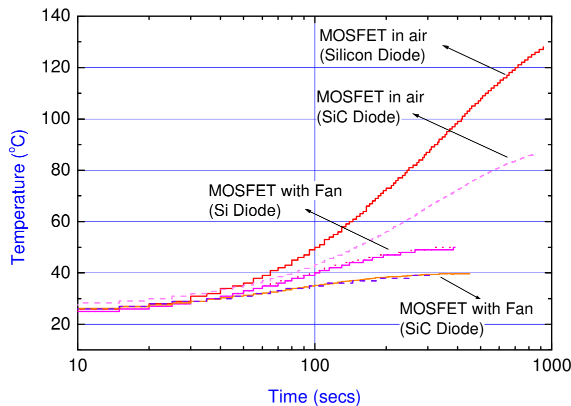

Fig. 14 The MOSFET case temperature in a PFC with Si and SiC diodes

Fig. 14 shows the measured MOSFET case temperature as a function of time after initial power up. Initially, the devices were in thermal equilibrium at room temperature. This measurement was done when a full load operating condition was impressed on this circuit. Two conditions were used for these measurements: the first was without a fixed position and speed fan, for case cooling ("in air" condition); and the second was with such a fan. With no fan, the temperature does not stabilize even after 15 minutes of the circuit power up. However, the temperature on the MOSFET was 41°C lower (86°C vs. 127°C) when a SiC SBD was used as compared to when a Si diode was used. When the fan was used for appropriate thermal dissipation, the MOSFET case temperature was only 40°C when a SiC SBD was used as compared to 50°C when a Si PiN diode was used. This increases the thermal "headroom" a circuit designer needs for more rugged operation of the circuit.

Based on the measurements presented above, the most significant system advantages offered by SiC SBDs vis-à-vis Si PiN diodes in a PFC circuit are higher circuit efficiency and lower FET case temperature. These advantages can be very effectively harnessed for lowering the cost of the circuit. For a given efficiency, a higher frequency of operation of the circuit can result in smaller (and hence cheaper) inductors and MOSFETs, which are typically the most expensive components in the PFC circuit. For an identical case temperature, a smaller and cheaper MOSFET and heat sinks can be used in the circuit. Another simple circuit modification to lower the total circuit losses involves reducing the gate resistor of the MOSFET. A higher gate resistor is used in typical PFC circuit in order to limit the di/dt in the Si PiN diode, which might result in excessive reverse recovery current, and EMI emissions. Since SiC SBDs can operate under very high di/dt, a smaller MOSFET gate resistance can be utilized. Such a modification will result in lowering the MOSFET turn-OFF losses, which showed little change with direct replacement of SiC SBD with Si PiN diode in the PFC circuit described above.

CONCLUSION

It may be concluded that SiC SBDs offer significant advantages over silicon PiN diodes in power electronic applications such as PFC. SiC SBDs are commercially available in 600-1200 V, 1-10 A range and can be utilized today to enhance the

performance of the PFC circuit by improving the efficiency, reducing the switching losses in the diode and the MOSFET, reducing the MOSFET case temperature and reducing the number of MOSFETs. Additionally, they can be used to simplify or even eliminate the snubber circuits, reducing the heat sink size, or increase the frequency and reduce the size of the magnetic components. In a typical 250 W PFC circuit, an overall decrease of 27% in switching losses is measured when the circuit uses a SiC diode as compared to a Si diode. At full load condition, the circuit efficiency increases from 90% with the Si diode as compared to 93% with the SiC diode.

ACKNOWLEDGEMENTS

The authors acknowledge the funding from the United States Air Force, contract number F33615-00-2-2004 and useful discussions with Joe Weimer and Jim Scofield at the Air Force Research Laboratories, Dayton, Ohio.

REFERENCES

[1] C. Miesner, R. Rupp, H. Kapels, M. Krach, and L. Zverev, “thinQ!™ Silicon Carbide Schottky Diodes: An SMPS Circuit Designer’s Dream Coomes True!,” at http://www.infineon.com/cmc_upload/documents/027/313/WhitePaper_SiC.pdf.