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Silicon Carbide Diodes Characterization at High Temperature and Comparison With Silicon Devices

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Commercially available silicon carbide (SiC) Schottky diodes from different manufacturers rated at 200, 300, 600, and 1200V, were electrically tested and characterized as a function of temperature up to 300 °C. Electrical tests included both steady state and dynamic tests. Steady state tests produced forward and reverse I-V characteristic curves. Transient tests evaluated the switching performance of the diodes in either a hard-switched DC to DC buck converter or a half-bridge boost converter. For evaluation and comparison purposes, the same tests were performed with current state-of-the-art ultra fast silicon (Si) pn-junction diodes of similar ratings and also a Si Schottky diode. The comparisons made were forward voltage drop at rated current, reverse current at rated voltage, and turn-off peak reverse recovery current and reverse recovery time. In addition, efficiency measurements were taken for the buck DC to DC converter using both the SiC Schottky diodes and the Si pn-junction diodes at different temperatures and frequencies. The test results showed that at high temperature, the forward voltage drop for SiC Schottky diodes is higher than the forward drop of the ultra fast Si pn-junction diodes. As the temperature increased, the forward voltage drop of the SiC Schottky increased while for the ultra fast Si pn-junction diodes, the forward voltage drop decreased as temperature increased. For the elevated temperature steady state reverse voltage tests, the SiC Schottky diodes showed low leakage current at their rated voltage. Likewise, for the transient tests, the SiC Schottky diodes displayed low reverse recovery currents over the range of temperatures tested. Conversely, the Si pn-junction diodes showed increasing peak reverse current values and reverse recovery times with increasing temperature. Efficiency measurements in the DC to DC buck converter showed the advantage of the SiC Schottky diodes over the ultra fast Si pn-junction diodes, especially at the higher temperatures and higher frequencies.

I. Introduction

NASA Glenn Research Center has an ongoing effort in the development of advanced components for Power Management and Distribution (PMAD) electronics for space applications [1]. This effort encompasses the development of advanced magnetic materials, advanced dielectrics, and advanced semiconductors that will allow the construction of inductors, transformers, capacitors, rectifiers and switching devices capable of operating at high temperature. High temperature operation of power electronics directly addresses NASA's technology development objectives of reducing the mass, volume, thermal requirements and launch costs of its space power systems. These technology development objectives have become more relevant under NASA's new exploration initiative which will require larger power systems for deep space interplanetary spacecraft as well as reusable launch vehicles for manned missions to the Moon and Mars.

Silicon Carbide (SiC) has shown promise to become a semiconductor material that will allow rectifiers and switching devices to operate reliably at elevated temperatures. The important SiC properties that can provide significant improvements in power electronics performance include an energy bandgap (3.26eV) that is approximately three times higher than the bandgap of silicon (Si), an electric field breakdown strength (2.2E6V/cm) that is ten times higher than Si's strength, and a thermal conductivity (3.0-3.8 W/cm K @ room temperature) that is approximately 2 times higher than silicon's conductivity. These properties provide the following advantages. The higher energy bandgap allows operation of the semiconductor devices at temperatures that exceed 300C. The higher electric field breakdown allows the devices to operate at higher voltages and higher current densities. In addition, SiC's higher electric field breakdown can allow the fabrication of devices with lower series resistance because of the shorter channel length needed to withstand a given voltage. Furthermore, SiC's higher thermal conductivity can produce devices with vastly improved heat transfer capability, enabling the use of smaller die, smaller package sizes, and smaller heat sinks.

Present limitations of SiC are rooted in the fact that current methods of growing SiC produce materials with defects such as micro pipes and screw dislocations [2]. These defects account for the low yield of usable material available from present SiC wafers. The high cost of SiC wafers and processing methods, as well as the limited number of SiC wafer suppliers, has also hindered the development of SiC power devices in the commercial market. At the present time, SiC power switches such as MOSFETs, Static Induction Transistors (SITs), or Bipolar Junction Transistors (BJTs) are not commercially available. However, SiC Schottky diodes have recently become available commercially. Static and dynamic characterization of these new devices is critical for designers to understand their performance and to take maximum advantage of the technology. From a technology perspective, it is important to compare the performance of these new SiC devices with present state of the art Si ultra fast pn- junction diodes with similar voltage and current ratings.

Static and dynamic characterization of commercial SiC Schottky diodes at room temperature was reported in [3]. The present report presents the results of static and dynamic characterization of commercial SiC Schottky and Si pn-junction diodes as a function temperature. Steady state tests involved the generation of forward and reverse current-voltage (I-V) curves for temperatures up to 300 °C. Dynamic tests involved the operation of the diodes in a DC to DC buck converter or a half-bridge boost converter. For the dynamic tests, the reverse current recovery behavior and reverse recovery time were measured over the temperature range of 25 to 150 °C. The efficiency of the buck converter was also tested using a SiC Schottky diode and an ultra fast Si pn-junction diode. These efficiency measurements were made for different temperatures and different switching frequencies. The objective of this paper is to present the relevant trends in the performance between the SiC Schottky and Si pn-junction diodes over the temperature range investigated.

II. Test Results

Table 1 lists the commercial SiC Schottky diodes that were used for this experimental investigation and also the Si pn-junction diodes with similar ratings that were used for comparison. The SiC Schottky diodes have voltage ratings of 200, 300, 600, and 1200V with current ratings from 1A up to 10A. Almost all of the Si diodes are ultra fast pn-junction diodes due to the unavailability of high voltage Si Schottky diodes. The only Si Schottky diode in the list is the IR 10CTQ150 rated at 150V and 5A. It is important to mention that the SiC Schottky devices have a maximum operating temperature limit of 175 °C according to the manufacturer's specification sheet. In some cases the tests were run at temperatures above 200 °C which exceeded the package's design temperature specification.

SiC Schottky				Silicon pn			
Vendor	Part #	Voltage (V)	Current (A)	Vendor	Part #	Voltage (V)	Current (A)
Microsemi	UPSC 200	200	1	IR(Schottky)	10CTQ150	150	5
Infineon	SDT10S30	300	10	IXYS	DSEP8-03	300	10
Microsemi	UPSC 603	600	4	Microsemi	1N6628	600	4
Infineon	SDT06S60	600	6	IR	HFA08TB60	600	8
Cree	CSD 10060	600	10	IXYS	DSEI8-06A	600	8
Cree	CSD 20060	600	(Dual) 10	IXYS	DSEP9-06CR	600	9
Cree	CSD 10120	1200	(Dual) 5	IXYS	DSEP30-12A	1200	30

Table1. SiC Schottky and Si ultra fast pn-junction diodes tested

Steady State Test Results and Discussion

Steady state tests involved the generation of forward and reverse I-V curves at case temperatures usually over the temperature range of 25 to 200 °C but in some cases up to 300 °C for the SiC Schottky diodes. The test was performed by mounting the diode on a hot plate and adjusting the diode's case temperature with a temperature controller. The device terminals were connected to a Tektronix 370B digital storage programmable curve tracer.

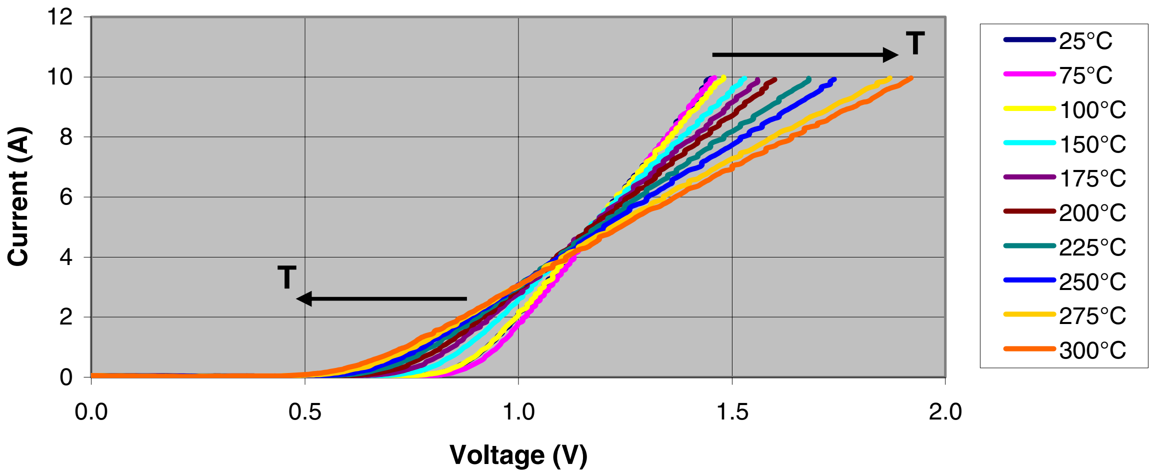


Figure 1. Forward I-V characteristic curves at various temperatures for the Infineon SDT10S30 (300V/10A) SiC Schottky diode.

Figure 1 shows the forward I-V curves of the Infineon SDT10S30 (300V/10A) SiC Schottky diode as a function temperature. The family of curves clearly shows how the forward behavior of the SiC Schottky diode changes as the temperature is increased from 25 to 300 °C. At current levels less than 4 A, the diode's forward voltage drop decreases as the temperature increases. In this region, the exponential behavior of the current flowing across the Schottky barrier can be observed. As the forward current increases above 4 A, the diode's bulk resistance dominates the forward behavior and the forward voltage drop of the Schottky diode increases as the temperature increases. The result is a crossover of the forward I-V curves for increasing temperature.

Figure 2 demonstrates the reverse voltage behavior of the Infineon SDT10S30 (300V/10A) SiC Schottky diode as the temperature increases from 25 to 300 °C. The plot clearly shows how the reverse blocking voltage decreases and the leakage current increases as the case temperature increases. Thus, the reverse voltage at which the diode's leakage current attains a specific value will be reduced as the temperature increases.

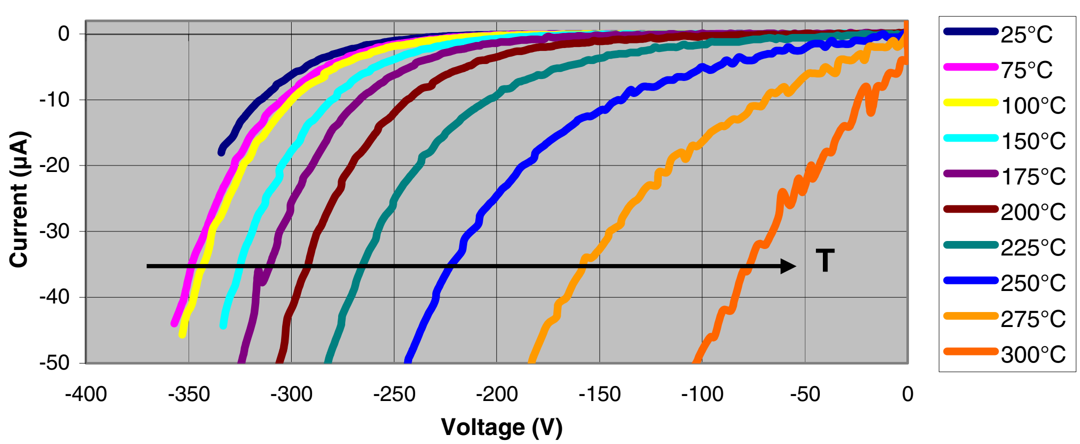


Figure 2. Reverse I-V characteristic curves at various temperatures for the Infineon SDT10S30 (300V/10A) SiC Schottky diode.

Figures 3 and 4 give a comparison between the high temperature forward and reverse voltage behavior of the Infineon SDT10S30 SiC Schottky diode and the IXYS DSEP 8-03 ultra fast Si pn-junction diode both rated at 300V, 10A. Figure 3 clearly shows the difference between a Schottky diode, which is a majority carrier device, and a pn-junction diode, which is a minority carrier device. As the temperature increases from 25 to 200 °C the forward voltage drop at rated current of the SiC Schottky diode increases as discussed above. But in contrast, the Si pn-junction diode's forward voltage at rated current decreases as the temperature increases. A discussion of the temperature dependence of the I-V characteristics of Si pn-junction diodes can be found in [4].

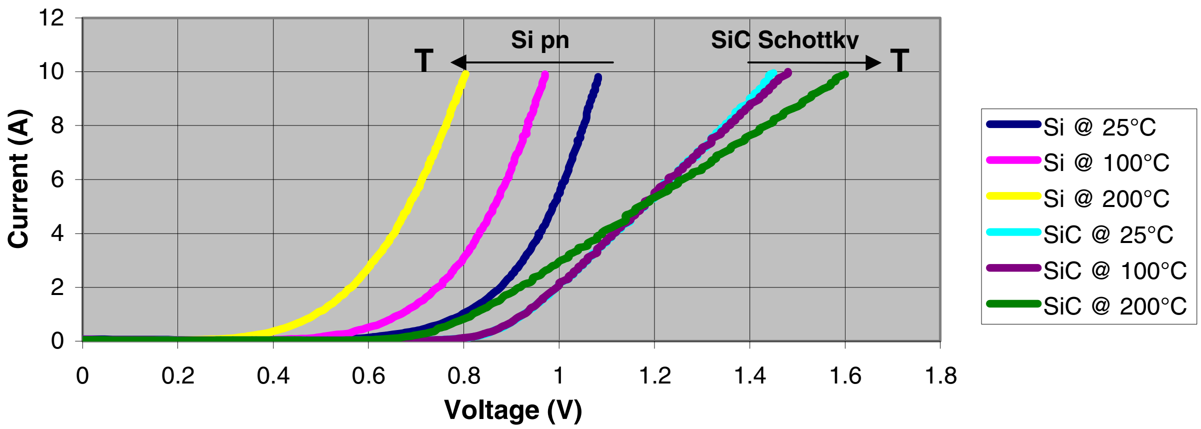


Figure 3. Forward I-V characteristic curves at various temperatures for the Infineon SDT10S30 SiC Schottky and the IXYS DSEP 8-03 ultra fast Si pn-junction diode both rated at 300V/10A.

From Figure 3 alone, one might be tempted to conclude that the Si pn-junction diode has the most efficient and desirable behavior at high temperature. However, Figure 4 shows a different scenario for the reverse characteristics at high temperature. Figure 4 demonstrates that at 200 °C the Si pn-junction diode's reverse voltage blocking capability is lost as the diode takes on the characteristics of a conductor. The high leakage current is due to thermally activated intrinsic carriers in the junction of the pn diode. However, at 200 °C the SiC Schottky diode still exhibits very low leakage current and high reverse voltage blocking capability (approximately 300V at 200 °C). This difference in leakage current is due to the larger energy bandgap of SiC as compared to Si.

Figures 5 and 6 show the forward and reverse I-V curves as a function of temperature for the Cree CSD10120 (1200V/5A) SiC Schottky diode and the IXYS DSEP30-12A (1200V/30A) ultra fast Si pn-junction diode. The electrical behavior of these high voltage devices was similar to the behavior of the 300V devices. Although not shown, very similar results were obtained for the forward and reverse I-V curves as a function of temperature for the Infineon SDT06S60 (600V/6A) SiC Schottky diode and the IR HFA08TB60 (600V/8A) ultra fast Si pn diode.

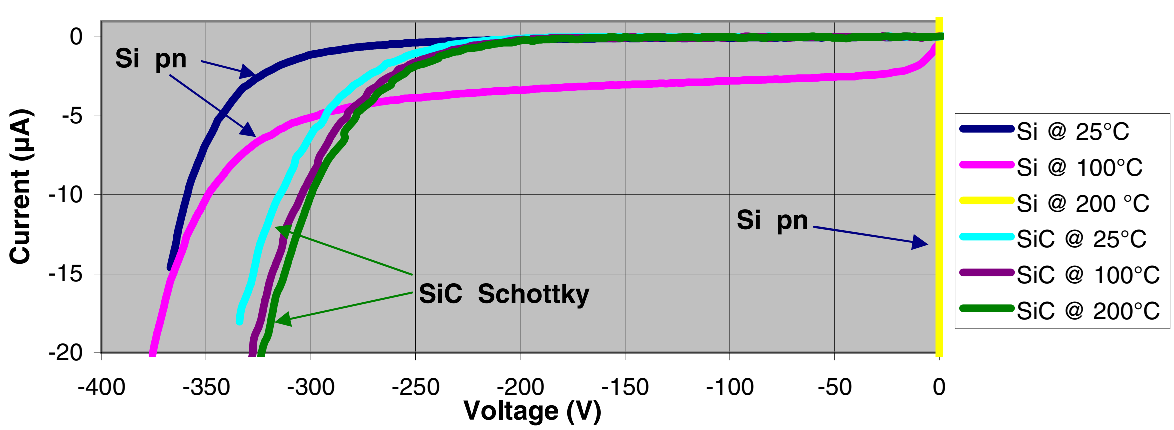


Figure 4. Reverse I-V characteristic curves at various temperatures for the Infineon SDT10S30 (300V/10A) SiC Schottky diode and the IXYS DSEP 8-03 (300V/10A) ultra fast Si pn-junction diode.

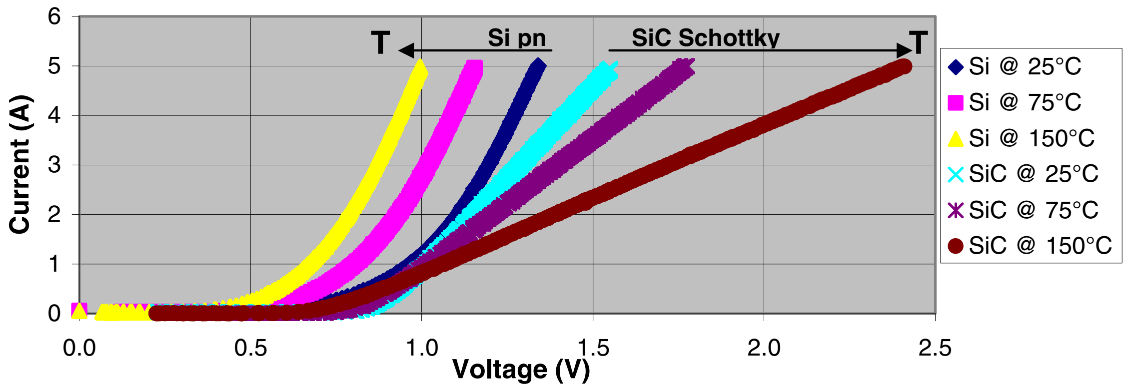


Figure 5. Forward I-V characteristic curves at various temperatures for the Cree CSD1020 (1200V/5A) SiC Schottky diode and the IXYS DSEP30-12A (1200V/30A) ultra fast Si pn-junction diode.

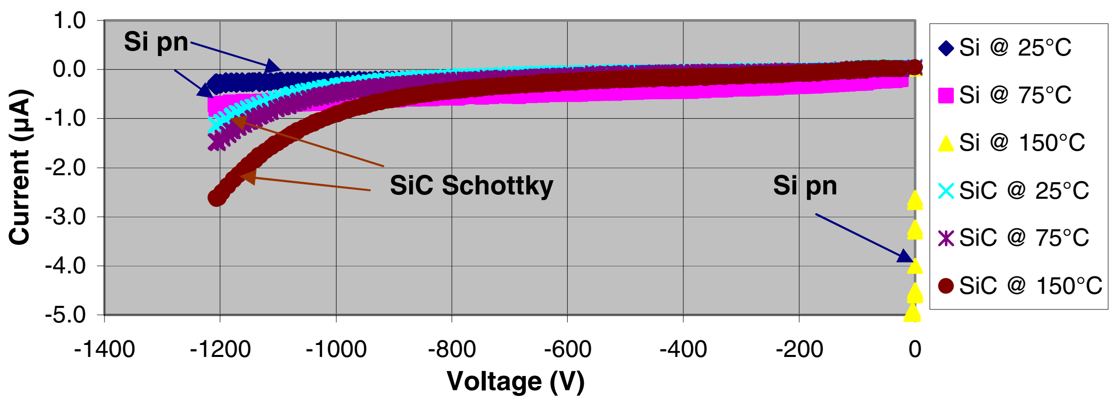


Figure 6. Reverse I-V characteristic curves at various temperatures for the Cree CSD1020 (1200V/5A) SiC Schottky diode and the IXYS DSEP30-12A (1200V /30A) ultra fast Si pn-junction diode.

Figure 7(a) compares the forward I-V characteristics of the IR 10CTQ150 (150V/5A) Si Schottky diode and the Microsemi UPSC200 (200V/1A) SiC Schottky diode. These tests were an attempt to compare SiC Schottky diodes with Si Schottky diodes having somewhat similar ratings. Figure 7(a) shows a substantial difference between the forward I-V curves of the two devices. At 100 °C and 1 A the SiC Schottky diode gives a forward voltage drop of approximately 1.5 volts while the Si Schottky diode gives a forward voltage drop (at rated current) of approximately 0.6 volts. This difference can be explained if we examine the reverse I-V plot of the SiC diode. The reverse characteristic curve in Figure 7(b) shows that the Microsemi 200V SiC Schottky device tested can actually block voltages higher than 600V. The silicon Schottky device has a reverse voltage block capability of approximately 200V. This fact reveals that, although these Schottky diodes have similar datasheet voltage and current ratings, they are in fact very different devices. In addition, the difference in current ratings and die sizes indicate that, at rated current, the two devices are most likely operating at very different current densities.

Figures 8 and 9 compare the forward and reverse I-V characteristics of two commercial SiC Schottky diodes from different manufacturers. The devices are an Infineon SDT06S60 (600V/6A) SiC Schottky diode and a Cree CSD20060 (600V/10A) SiC Schottky diode. Figure 8 shows that both diodes have forward I-V curves with similar shapes. At room temperature the forward voltage drop for both diodes at their rated current is 1.5 volts. However, as the temperature increases the Infineon diode showed a lower voltage drop at rated current. At 200 °C, for example, the forward voltage drop at rated current (6 A) for the Infineon device is approximately 1.78 volts versus 2.33 volts at rated current (10A) for the Cree device. Once again, the diodes different current ratings, die sizes and operating current densities can account for this difference. For the reverse I-V curves (Figure 9), both SiC Schottky devices exhibited similar characteristics but the Infineon diode showed lower reverse leakage current at rated voltage for all temperatures from 25 to 200 °C.

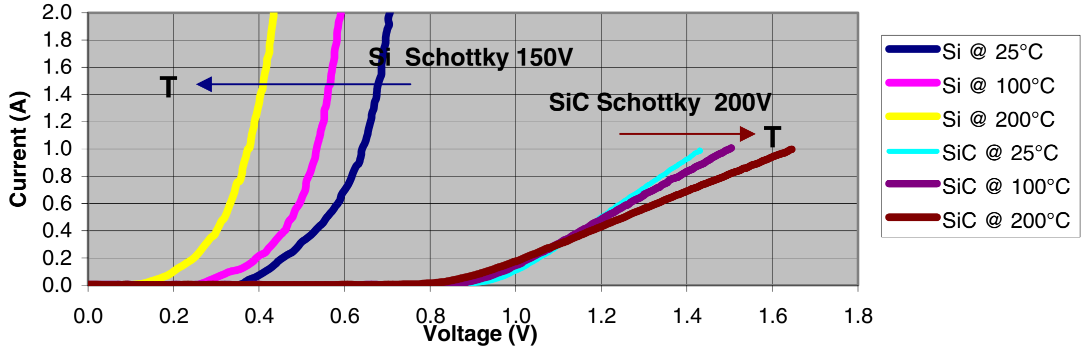


Figure 7(a). Forward I-V characteristic curves at various temperatures for the IR 10CTQ150 (150V/5A) Si Schottky diode and the Microsemi UPSC200 (200V/1A) SiC Schottky diode.

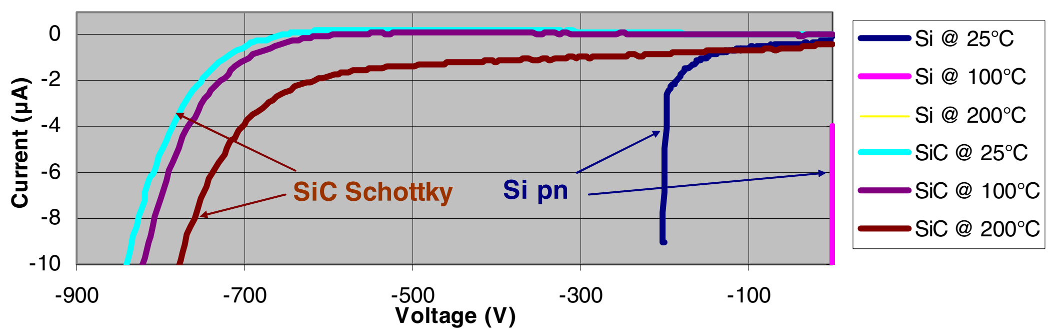


Figure 7(b). Reverse I-V characteristic curves at various temperatures for the IR 10CTQ150 (150V/5A) Si Schottky diode and the Microsemi UPSC200 (200V/1A) SiC Schottky diode.

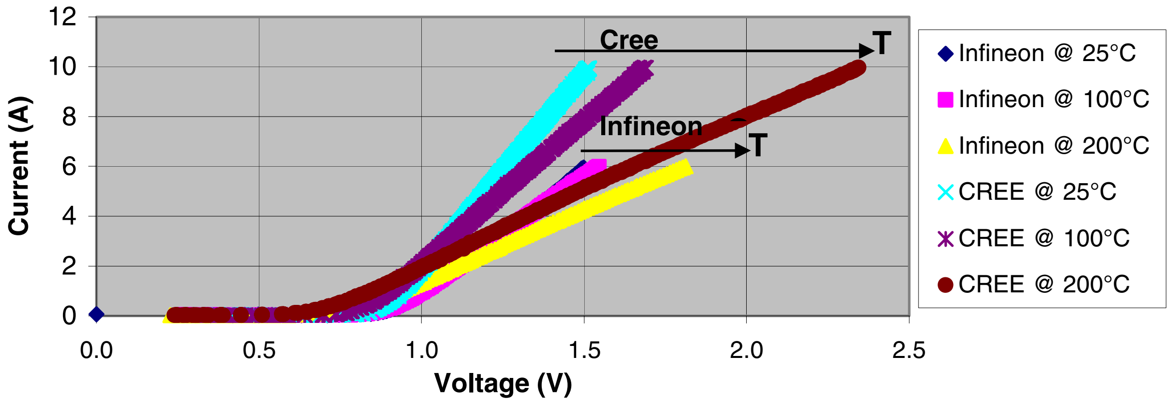


Figure 8. Forward I-V characteristic curves at various temperatures for the Infineon SDT06S60 (600V/6A) SiC Schottky diode and the Cree CSD20060 (600V/10A) SiC Schottky diode.

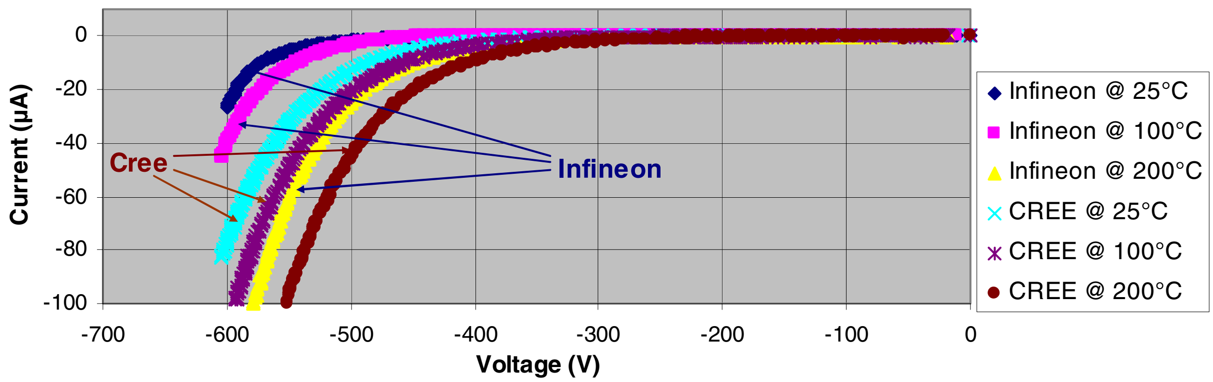
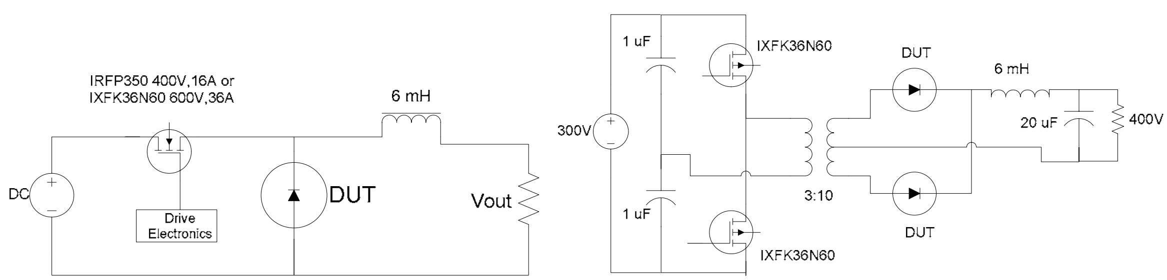


Figure 9. Reverse I-V characteristic curves at various temperatures for the Infineon SDT06S60 (600V/ 6A) SiC Schottky diode and the Cree CSD20060 (600V/10A) SiC Schottky diode.

A. Transient Test Results and Discussion

To test the transient behavior of the SiC Schottky and Si pn-junction diodes at temperature, the devices were connected either as freewheeling diodes in a buck converter or as rectifier diodes in a half-bridge boost converter. Figure 10 shows a schematic for each of these circuits. For these tests, the diode (DUT) was mounted on the hot plate and the diode's case temperature was increased from 25 to 200 °C. Transient current and voltage waveforms were captured for the DUT's turn-off at different temperatures. This allowed the comparison of reverse recovery currents and reverse recovery times for the turn-off transition. The buck converter was used for devices rated from 150V to 600V. Depending on the diode's voltage and current rating, the buck converter's input voltage was adjusted from 75VDC to 450VDC with the output voltage varying from 40VDC to 310VDC. The resistive load current was between 1A and 7A, and the switching frequency and duty cycle were 40 kHz and 50 to 75 percent, respectively. For devices rated at 1200V the half-bridge boost converter was used, mainly because this transformer isolated topology with a center tapped full wave rectifier, allowed the diodes to be tested at voltages between 800V and 1000V. That is, the center tapped secondary winding configuration produces twice the secondary voltage across the DUT. The input voltage range for the half-bridge converter was 100-300VDC, with an output voltage range of 200 to 400VDC. The switching frequency and duty cycles were 40kHz and 30 to 40 percent, respectively. The load current for the half-bridge converter was adjusted between 1 and 2 A.



(a) (b)

Figure10. DC to DC converter circuits used for transient tests (a) Buck (b)Half-Bridge Boost.

Figure 11 compares the turn-off transient current waveforms of the Microsemi UPSC200 (200V/1A) SiC Schottky diode with the IR 10CTQ150 (150V/5A) Si Schottky diode. Both devices were operated in the buck DC to DC converter with an input voltage of 126VDC and a peak current of 1A. Figure 11 clearly shows that the peak reverse recovery current for the Si Schottky diode increases considerably with increasing temperature. However, the peak reverse recovery current of the SiC Schottky diode showed no noticeable change as the temperature was increased from 25 to 150 °C, as seen by the reverse recovery curves lying on top of each other. Also the peak reverse recovery current of the SiC Schottky diode is considerably lower than that of the Si Schottky diode. This difference in behavior between the Si and SiC Schottky diodes is very relevant in terms of the switching losses and the efficiency of the DC to DC converter operating at high temperature and high switching frequency. Figure 12 shows similar transient current behavior for the Infineon SDT06S60 (600V/6A) SiC Schottky diode and the IXYS

DSEI 8-06A (600V/8A) ultra fast Si pn-junction diode. These diodes were operated in the buck converter with an input voltage of 400DC and a peak current of 3A. In this comparison the peak reverse recovery current for the Si pn-junction diode increased from 4A at 25C to 8.5A at 150 °C while the SiC Schottky diode's peak reverse recovery current stayed at approximately 1.2A for all three test temperatures.

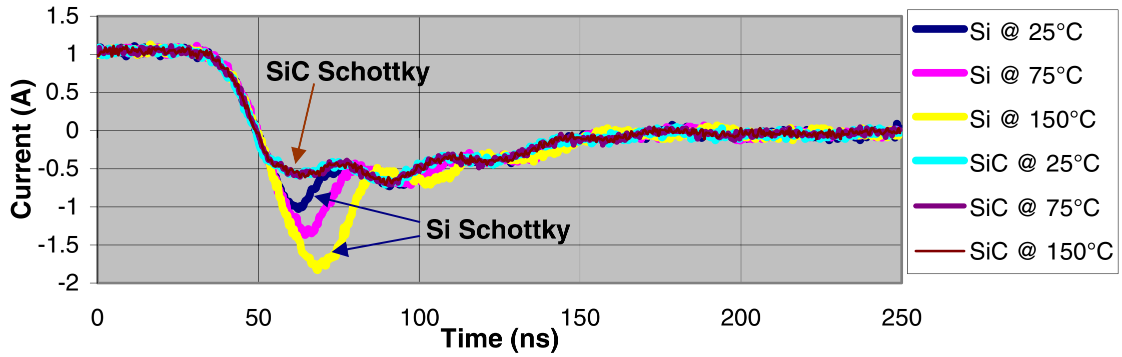


Figure 11. Reverse recovery current at various temperatures for the IR 10CTQ150 (150V/5A) Si Schottky diode and the Microsemi UPSC200 (200V/1A) SiC Schottky diode in the buck converter with Vin=126VDC.

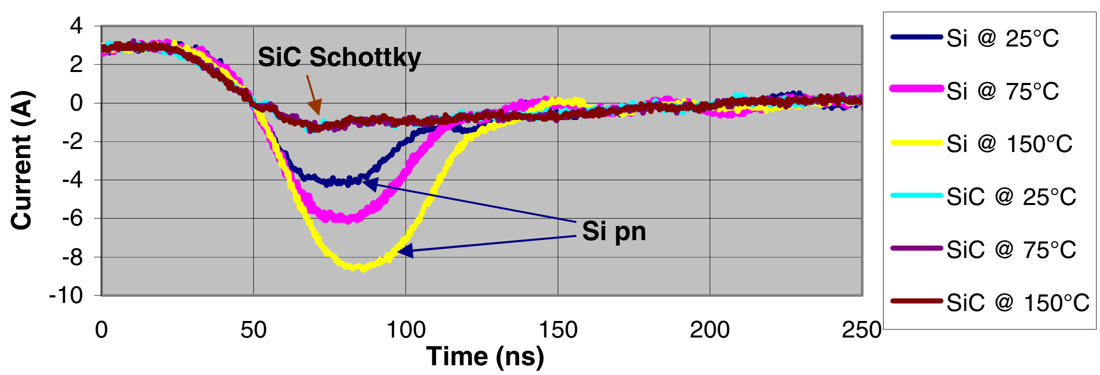


Figure 12. Reverse recovery current at various temperatures for the Infineon SDT06S60 (600V/6A) SiC Schottky diode and the IXYS DSEI 8-06A (600V/8A) ultra fast Si pn-junction diode in the buck converter with Vin= 400VDC.

Figure 13 shows the transient current waveforms for various temperatures for the Cree CSD10120 (1200V/5A) SiC Schottky diode and the IXYS DSEP30-12A (1200V/30A) Si pn-junction diode. The current waveform's shape in figure 13 is different from the current waveforms shown in figures 11 and 12 because the 1200V diodes were tested in the half-bridge boost converter as rectifiers in order to obtain the required high voltage. The reverse recovery current characteristics, as the case temperature is increased, are similar to what we discussed previously for the results shown in figures 11 and 12. The Si pn-junction reverse recovery current increased significantly when the temperature increased while there is virtually no change for the SiC Schottky reverse recovery current. In addition, Figure 13 shows very clearly that the Si pn-junction diode's reverse recovery time (the time it takes the diode to fully block reverse voltage) grows considerably as the temperature increases from 25 to 125 °C. This characteristic has a profound effect on the maximum temperature and switching frequency at which the Si pn-junction diode is able to operate efficiently in a switching converter. No noticeable change was observed in the SiC Schottky reverse recovery time.

In order to compare the turn-off switching transients of the diodes, the voltage and current turn-off waveforms of the IR HFA08TB60 (600V/8A) Si pn-junction diode and the Cree CSD10060 (600V/10A) SiC Schottky diode are plotted in figure 14. These diodes were operated in the buck converter at different input voltages (approximately 400V for the SiC Schottky and 300 V for the Si pn-junction diode). The Si pn-junction diode's voltage waveforms (Figure 14a) show that it takes a slightly longer time to reach the input voltage level of 300V while the reverse current waveforms show that the peak reverse current increases significantly as the temperature is increased from 25 to 150 °C. For the SiC Schottky diode there is no noticeable deviation in either the voltage or current waveforms (Figure 14b) as the temperature is increased from 25 to 200 °C. Figure 14a also shows that the switching losses of the Si pn-junction diode will increase with temperature while figure 14b shows that the switching losses of the SiC Schottky diode are independent of temperature.

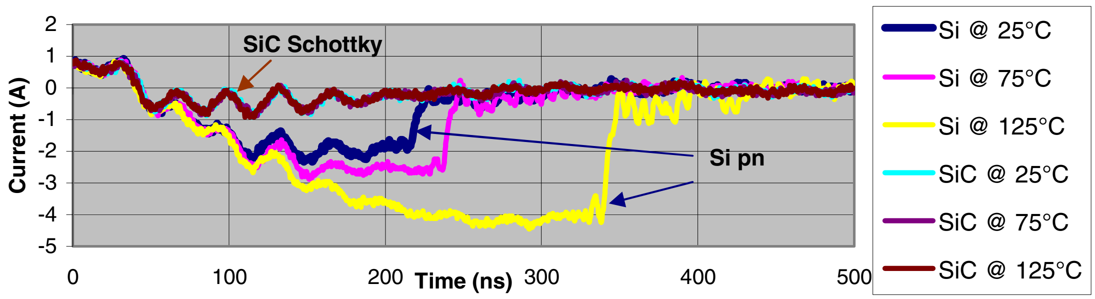


Figure 13. Turn-off transient current curves at various temperatures for the Cree CSD10120 (1200V/5A) SiC Schottky diode and the IXYS DSEP30-12A (1200V/30A) ultra fast Si pn-junction diode in the half-bridge boost converter for Vin= 250VDC (1000VDC across diode).

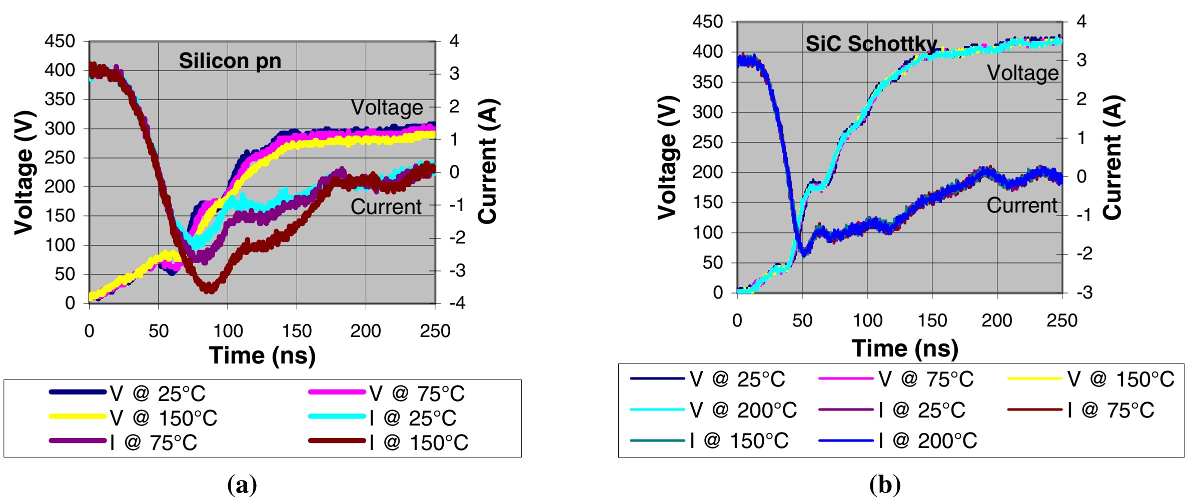


Figure 14. Turn-off transient voltage and current curves at various temperatures for (a) the IR HFA08TB60 (600V/8A) ultra fast Si pn-junction diode (600V/10A) and (b) the Cree CSD10060 SiC Schottky diode in the buck converter (Vin=300V for Si device, Vin=400V for SiC device).

B. Efficiency Tests

From the steady state I-V characteristic curves we can conclude that at elevated temperatures the forward voltage drop of the ultra fast Si pn-junction diodes is lower at rated current than the forward voltage drop of the SiC Schottky diode. Therefore, the Si pn-junction diode should be more efficient in terms of on-state conduction losses for increasing temperature. On the other hand, the transient current and voltage tests show that the SiC devices exhibit superior reverse recovery behavior over the 25 to 150 °C temperature range and, thus, the SiC Schottky diodes should give lower switching losses. In view of that, efficiency measurements were made on the DC to DC buck converter (Figure 15) using both an ultra fast Si pn-junction diode and a SiC Schottky diode. For these tests the diodes were mounted on a hot plate and diode's case temperatures was varied from 25 to 150 °C. The switching frequency was also varied from 40 kHz to 150 kHz in order to identify efficiency trends for the buck converter using both diodes.

Figure 16 plots the efficiency versus temperature of the buck converter operating with the Infineon SDT06S60 (600V/6A) SiC Schottky diode and the IXYS DSEI8-06A (600V/8A) Si pn-junction diode for three different switching frequencies. The buck converter operating conditions for these measurements are: Input Voltage = 400VDC, Output Voltage = 300VDC, Duty Cycle = 75 percent (25 percent for diode), and peak diode current = 2A. The most evident trend in figure 16 is that the efficiency of the buck converter using the SiC Schottky diode shows no noticeable change with increasing temperature for all three switching frequencies. The reason for this is that, even though the on-state voltage increased for a given current for increasing temperature (see Figure 8), the transient voltage and current showed no noticeable change with increasing temperature (see Figure 14). For the SiC Schottky diode it can be concluded that, even though the on-state losses might increase slightly with temperature, the switching losses show no noticeable increase with temperature and thus, the efficiency is practically independent of temperature over the temperature range tested. However, for the Si pn-junction diode, the efficiency decreased with temperature for all three switching frequencies tested. In this case, even though the on-state voltage decreased for a given current for increasing temperature (see Figure 3), the peak reverse current and recovery time increased with temperature (see Figure 14). For the Si pn-junction diode it can be concluded that, even though the on-state losses might decrease with temperature, the switching losses increase with temperature because the converter efficiency decreases as the temperature increases. In addition, Figure 16 also shows that for both the SiC Schottky diode and the Si pn-junction diode, an increase in switching frequency reduces the converter efficiency due to the effect of the switching losses. However, the SiC Schottky diode shows a significant efficiency advantage over the Si pn-junction diode especially at the higher temperature and higher switching frequency. For example, at 150 °C, and 150 kHz, the efficiency of the converter using the SiC Schottky diode is 97 percent. For the same conditions when the Si pn-junction diode is used, the converter efficiency decreases to 94.8 percent.

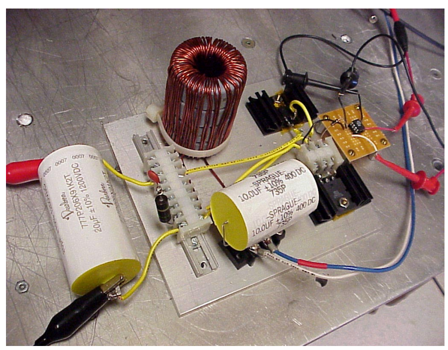


Figure 15. Buck converter used for efficiency and transient tests.

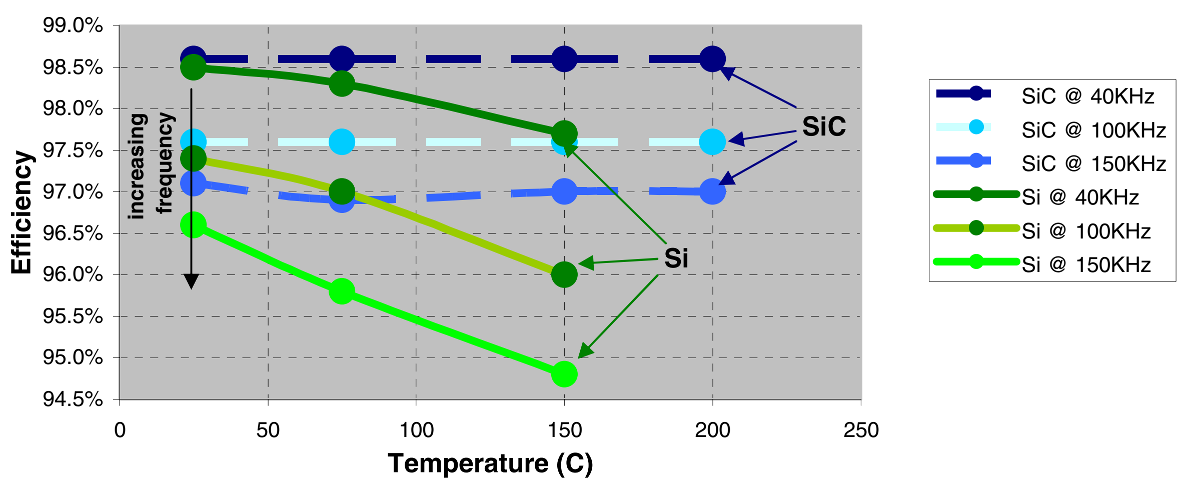


Figure 16. Buck converter efficiency as a function of temperature and switching frequency using either the Infineon SDT06S60 (600V/6A) SiC Schottky diode or the IXYS DSEI 8-06A (600V/ 8A) ultra fast Si pn-junction diode.

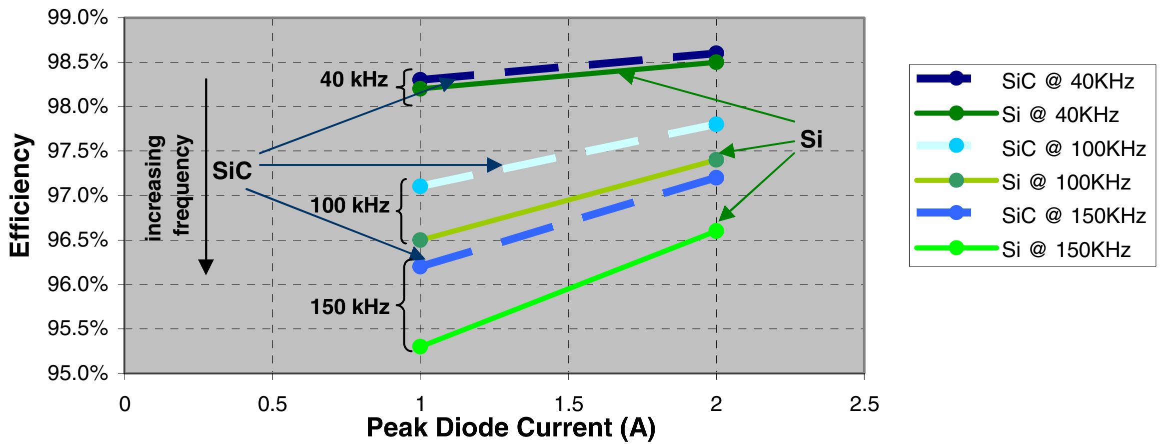


Figure 17. Buck converter efficiency at room temperature as a function of peak diode current and operating frequency using either the Infineon SDT06S60 (600/6A) SiC Schottky Diode or the IXYS DSEI 8-06A (600V/8A) ultra fast Si p n-junction diode.

Figure 17 plots converter room temperature efficiency versus peak diode current with frequency as the parameter. For this test case, the buck converter operating conditions were Vin = 400VDC, Vout = 300VDC, and duty cycle = 75 percent. The diode peak current was varied from 1A to 2A. Figure 17 shows that the converter is more efficient at 2A than at 1A. Figure 17 also shows that at room temperature and 40 kHz switching frequency, the converter efficiency for the SiC Schottky diode is very similar to the efficiency for the ultra fast Si pn-junction diode. As the converter switching frequency is increased from 40 kHz to 150 kHz, the efficiency advantage of the SiC Schottky diode over the Si pn-junction diode becomes quite noticeable. For example, at room temperature and a switching frequency of 150 kHz, the SiC Schottky diode gives a converter efficiency of 96.2 percent while the Si pn-junction diode reduces the converter efficiency to 95.3 percent. This shows that SiC Schottky diodes can still offer efficiency advantages at room temperature, as long as the converter is operating at high switching speeds. A detailed study on the effects of switching losses of SiC Schottky diodes and Si pn-junction diodes in the efficiency of power converters can be found in [5].

III. Conclusion

A number of commercial SiC Schottky diodes were tested and compared with state-of-the-art silicon ultra fast Si pn-junction diodes. For the steady state forward I-V tests over the temperature range (25 to 200 °C) investigated, the ultra fast Si pn-junction diodes outperformed the SiC Schottky diodes in terms of lower forward voltage drop at rated current. At rated current, the Si pn-junction diode's forward voltage drop decreased as a function of temperature while the forward voltage drop of the SiC Schottky diode increased with temperature due to the device's bulk resistance. For the steady state reverse I-V tests over the temperature range (25 to 200 °C) investigated, the SiC Schottky diodes showed superior reverse voltage blocking capabilities compared to the ultra fast Si pn-junction diodes. This was expected because SiC has a larger bandgap than Si. The generation of intrinsic carriers for reverse voltage depends on both the bandgap and the temperature. In the transient tests the SiC Schottky diodes displayed lower peak reverse recovery currents and faster recovery times than the ultra fast Si pn-junction diodes. The SiC Schottky diodes showed no noticeable change in the peak reverse recovery currents and recovery times with increasing temperature while the Si pn-junction diodes showed increasing peak reverse recovery currents and recovery times as the temperature increased. In the converter efficiency tests, conducted at room temperature and low switching frequency (40 kHz), the efficiency of the SiC Schottky diode was comparable to the efficiency of the ultra fast Si pn-junction diode. But as the temperature and converter switching frequency increased to 200 °C and 150 kHz, the efficiency of the SiC Schottky diode compared to the ultra fast Si pn-junction diode became significantly better and showed the clear advantage of using the SiC Schottky diode for high temperature and high frequency operation.

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13. ABSTRACT ***(Maximum 200 words)***

Commercially available silicon carbide (SiC) Schottky diodes from different manufacturers rated at 200, 300, 600, and 1200 V, were electrically tested and characterized as a function of temperature up to 300 °C. Electrical tests included both steady state and dynamic tests. Steady state tests produced forward and reverse I-V characteristic curves. Transient tests evaluated the switching performance of the diodes in either a hard-switched DC to DC buck converter or a half-bridge boost converter. For evaluation and comparison purposes, the same tests were performed with current state-of-the-art ultra fast silicon (Si) pn-junction diodes of similar ratings and also a Si Schottky diode. The comparisons made were forward voltage drop at rated current, reverse current at rated voltage, and turn-off peak reverse recovery current and reverse recovery time. In addition, efficiency measurements were taken for the buck DC to DC converter using both the SiC Schottky diodes and the Si pn-junction diodes at different temperatures and frequencies. The test results showed that at high temperature, the forward voltage drop for SiC Schottky diodes is higher than the forward drop of the ultra fast Si pn-junction diodes. As the temperature increased, the forward voltage drop of the SiC Schottky increased while for the ultra fast Si pn-junction diodes, the forward voltage drop decreased as temperature increased. For the elevated temperature steady state reverse voltage tests, the SiC Schottky diodes showed low leakage current at their rated voltage. Likewise, for the transient tests, the SiC Schottky diodes displayed low reverse recovery currents over the range of temperatures tested. Conversely, the Si pn-junction diodes showed increasing peak reverse current values and reverse recovery times with increasing temperature. Efficiency measurements in the DC to DC buck converter showed the advantage of the SiC Schottky diodes over the ultra fast Si pn-junction diodes, especially at the higher temperatures and higher frequencies.

14. SUBJECT TERMS

Silicon carbide diodes; High temperature power electronics; Silicon carbide Schottky diodes characterization; SiC devices; High temperature

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