SiC Power Diodes Provide Breakthrough Performance for a Wide Range of Applications

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***Abstract*—The electrical performance of silicon carbide (SiC) power diodes is evaluated and compared to that of commercially available silicon (Si) diodes in the voltage range from 600 V through 5000 V. The comparisons include the on-state characteristics, the reverse recovery characteristics, and power converter efficiency and electromagnetic interference (EMI). It is shown that a newly developed 1500-V SiC merged PiN Schottky (MPS) diode has significant performance advantages over Si diodes optimized for various voltages in the range of 600 V through 1500 V. It is also shown that a newly developed 5000 V SiC PiN diode has significant performance advantages over Si diodes optimized for various voltages in the range of 2000 V through 5000 V. In a test case power converter, replacing the best 600 V Si diodes available with the 1500 V SiC MPS diode results in an increase of power supply efficiency from 82% to 88% for switching at 186 kHz, and a reduction in EMI emissions.**

***Index Terms*—Fast recovery rectifier, merged PiN Schottky diode, PiN diode, reverse recovery, SiC diode, SiC rectifier.**

I. INTRODUCTION

SILICON CARBIDE (SiC) power devices are expected to show superior performance compared to devices made with other semiconductors. This is primarily because 4H-SiC has an order of magnitude higher breakdown electric field (2–4 × 10^6 V/cm) and higher temperature capability than conventional Silicon (Si) materials. The high breakdown electric field allows the design of SiC power devices with thinner and more highly doped voltage blocking layers. A comparison of the ideal breakdown voltage versus blocking layer doping concentration is shown in Fig. 1 [1]. The more highly doped blocking layer (more than 10 times higher) provides lower resistance for SiC devices because more majority carriers are present than for comparably rated Si devices. A comparison of the voltage blocking layer thickness for a given breakdown voltage is shown in Fig. 2 [1]. The thinner blocking layer of SiC devices (1/10th that of Si devices) also contributes to the lowering of the specific on-resistance by a factor of 10. The combination of 1/10th the blocking layer thickness with ten times the doping concentration can yield a SiC device with a factor of 100 advantage in resistance compared to that of Si devices. Because SiC has a larger band gap (3.26 eV for 4H-SiC [2] vs. 1.1 eV for Si), SiC devices can be made to operate reliably at much higher temperatures than their Si counterparts (300 °C for SiC versus 150 °C for Si).

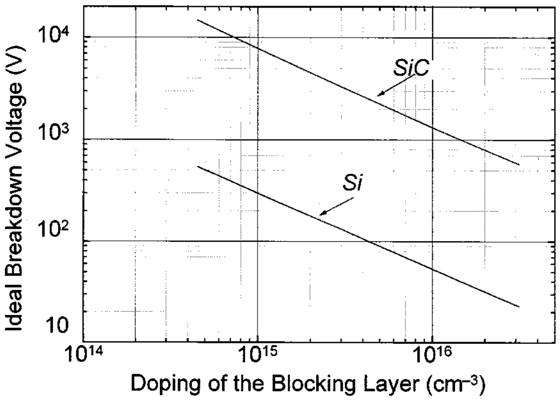

Fig. 1. Comparison of the ideal breakdown voltage of Si and SiC devices for different doping levels.

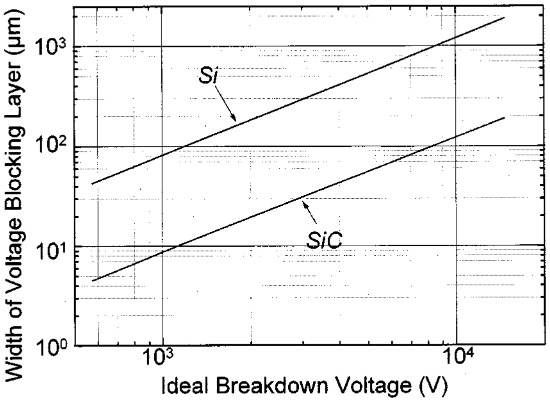

Fig. 2. Comparison of the blocking layer thickness as a function of the ideal breakdown voltage for SiC and Si.

Generally speaking, there are three classes of SiC power rectifiers:

a) Schottky diodes, which offer extremely high switching speed but suffer from high leakage current;
b) PiN diodes, which offer low leakage current but show reverse recovery charge during switching and have a large junction forward voltage drop due to the wide band gap of 4H-SiC;
c) merged PiN Schottky (MPS) diodes, which offer Schottky-like on-state and switching characteristics, and PiN-like off-state characteristics.

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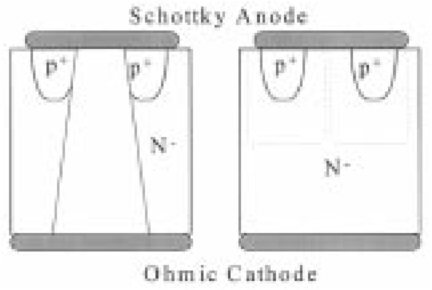

Fig. 3. MPS diode forward on-state current flows through the Schottky anode (left), while reverse leakage current is limited by depletion from adjacent p^+ grids (right).

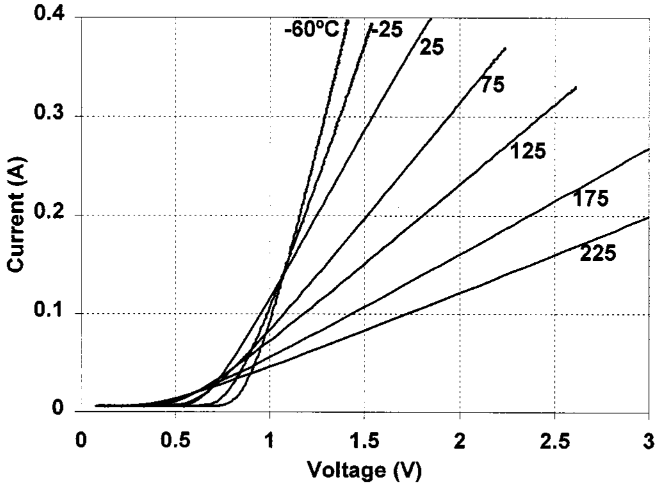

Fig. 4. Measured temperature dependence of the on-state characteristics for a 1500-V, 0.5-A (0.0045 cm^2) rated SiC MPS diode.

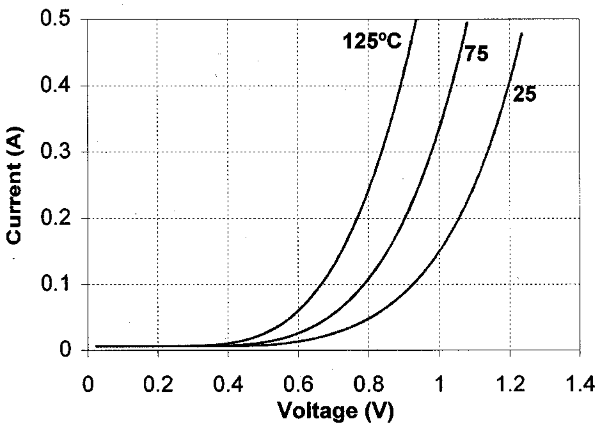

Fig. 5. Measured temperature dependence of on-state voltage for a 1000-V, 1-A rated ultra-fast Si PiN diode (MUR1100).

In this paper, SiC power diodes are compared with Si power diodes with voltage ratings from 600 V through 5000 V. It is shown that a 1500-V SiC MPS diode provides superior performance over Si diodes with voltage ratings of 600 V to 1500 V, and a SiC PiN diode has superior performance compared to Si diodes with voltage ratings from 1200 V to 5000 V.

II. THE 1500 V SiC MERGED PiN SCHOTTKY DIODE

Recently, SiC Merged PiN Schottky (MPS) diodes have been developed that combine the advantages of both Schottky

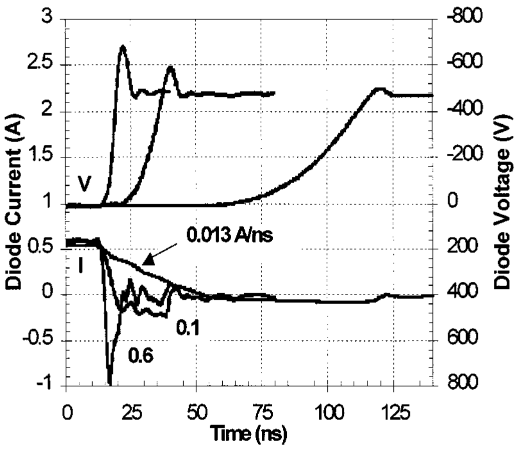

Fig. 6. SiC MPS diode reverse recovery characteristics at different di/dt values.

and PiN diodes [3], [4]. These diodes show great potential for switching power supply applications. The main features of the SiC MPS diodes are

1) low voltage drop in the on-state like the Schottky;
2) low leakage in the off-state like the PiN;
3) fast switching characteristics like the Schottky;
4) good high temperature characteristics.

A. Device Design

A cross section of a 4H-SiC MPS rectifier operating in the forward-bias (left) and reverse-bias (right) conditions is shown in Fig. 3. An MPS diode consists of interdigitated Schottky and p^+-implanted areas. For on-state drops of <3 V, only the Schottky regions of the diode conduct, and thus the device is also referred to as a junction barrier Schottky (JBS) diode. The on-state voltage drop of the MPS diode is determined by

1) the resistance of the drift region;
2) the metal-SiC barrier height of the Schottky metal;
p
3) the relative area of the Schottky versus the p^+ implanted regions.

For reverse bias conditions, the depletion regions from adjacent p^+ implanted regions pinch off the leakage current arising from the Schottky contacts of the device. The leakage current in the Schottky regions occurs due to Schottky barrier lowering at the metal-n^- junction. The presence of the adjacent p^+-implanted regions reduces the electric field and leakage current at the metal-SiC junction because of two-dimensional charge sharing. This property is especially useful when the diode is operating at elevated temperatures since the effect of Schottky barrier lowering is enhanced with increasing temperature.

The remainder of this section describes the detailed characterization of prototype MPS diodes fabricated by CREE. The detailed design of the 1500-V MPS diodes used in this study is described in [4]. The MPS diodes were made using a 20-μm, $N_D = 2E15$-cm^{-3} epitaxial layer over 4H-SiC n^+ substrate to obtain the desired blocking voltage of 1500 V. Ni is used as the Schottky metal to obtain a metal-SiC barrier height low enough to give a low on-state voltage, while still enabling effective pinch-off during the off state. The optimized diodes pro-

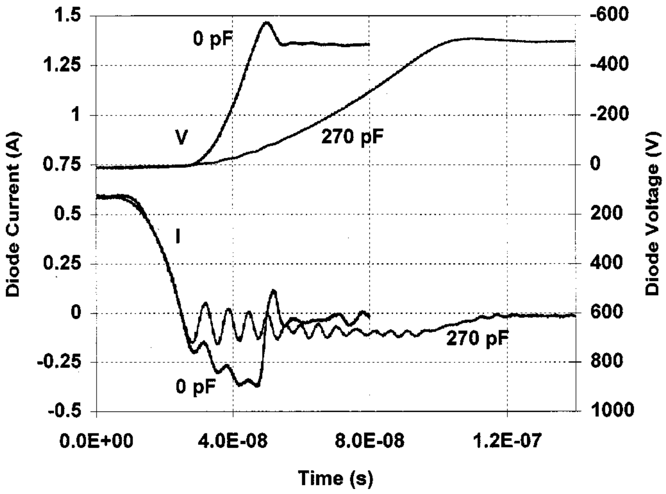

Fig. 7. SiC MPS diode reverse recovery characteristics with and without an added drive capacitance.

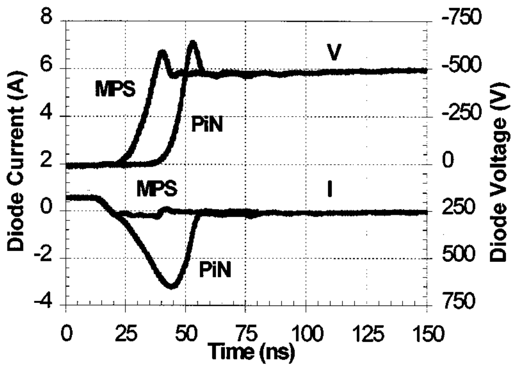

Fig. 8. Comparison of the reverse recovery characteristics of the SiC MPS and Si PiN diode MUR1100 at $di/dt = 100$ A/μs.

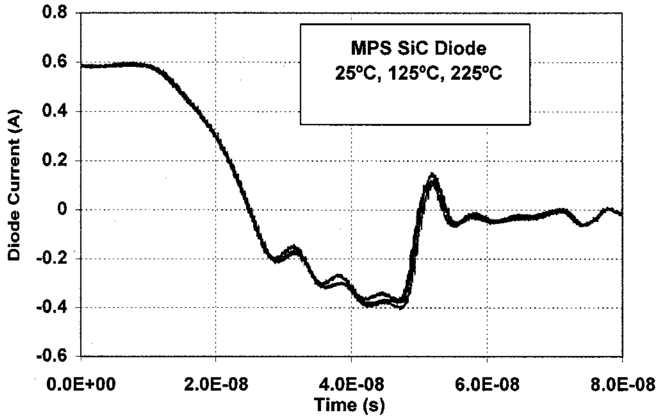

Fig. 9. Measured temperature dependence of the reverse recovery characteristics for a 1500-V, 0.5-A (0.0045 cm^2) rated SiC MPS diode.

duced in [4] have a 2-μm wide p$^+$ implanted region with 4-μm spacing. Several device areas giving current ratings from 0.5 A to 4 A were produced, although the results shown in this paper are for the 0.0045 cm^2 samples having a 0.5 A current rating. It is expected that the practical die sizes will continue to increase as the material defect density decreases and wafer cost is reduced.

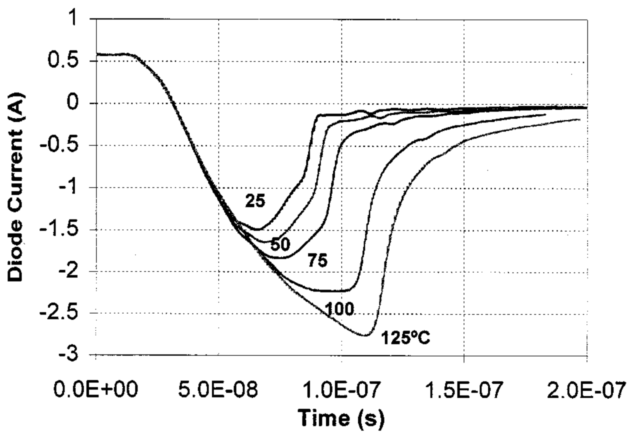

Fig. 10. Measured temperature dependence of the reverse recovery characteristics for a 1000-V, 1-A rated ultra-fast Si PiN diode (MUR1100).

B. Static Characteristics

The measured temperature dependence of the on-state characteristics for a 1500-V, 0.5-A (0.0045 cm^2) rated SiC MPS diode is shown in Fig. 4. The decrease in the slope of the on-state voltage curves with temperature is indicative of the reduction of mobility with increasing temperature for a majority carrier device. The built in potential is also reduced with temperature because the thermal energy of electrons in the metal surmount the Schottky barrier height at a lower forward voltage. Although this positive temperature coefficient of resistance increases the on-state loss at high temperature, it is beneficial for paralleling and large area current sharing. As can be seen from the -60°C curve in Fig. 4, these devices continue to perform well at low temperatures. The carrier freeze out effect is not an issue for these diodes because they are designed with a highly doped p^+ region.

For comparison, Fig. 5 shows the measured temperature dependence of on-state voltage for a 1000-V, 1-A rated ultra-fast Si PiN diode (MUR1100). The on-state voltage of the 1500 V SiC MPS diode is comparable to that of the Si PiN diode for conditions of one-half the rated current and 25 °C (i.e., 1.3 V at 0.25 A for the SiC MPS diode and 0.5 A for the Si diode). Future MPS SiC diodes are expected to have slightly better on-state and blocking characteristics through further optimization.

C. Switching Characteristics

The reverse recovery test system uses a 6LF6 vacuum tube in place of the usual MOSFET switch to achieve low parasitic capacitance at the anode of the DUT, and extremely fast switching speed [5]. Using this circuit, the forward current value, the di/dt values, and the dv/dt values for the DUT can be readily varied. The test circuit can test up to 9 A of combined forward and reverse DUT current, and the applied voltage to the DUT can be up to 2000 V.

For the tests described in this paper, a 500-V supply is used and tests are performed for various values of di/dt and dv/dt where dv/dt is controlled by placing various capacitors across the tube driver. Varying dv/dt makes it easier to identify the portion of the diode recovery due to charge storage and the portion due to device capacitance. Adding values of capacitance to the

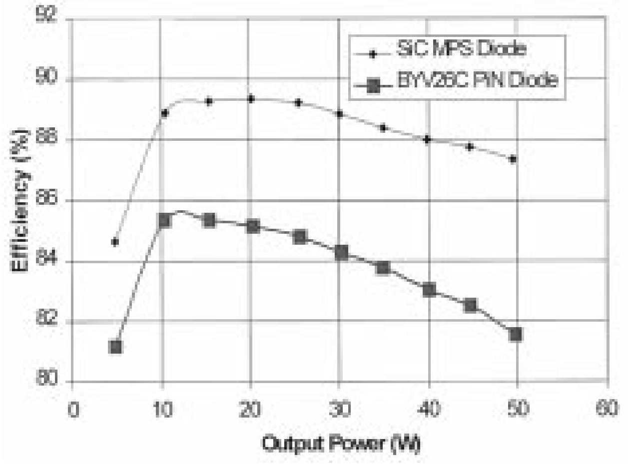

Fig. 11. Power supply efficiency comparison between the SiC MPS diode and an ultra-fast reverse recovery Si diode at 186 kHz.

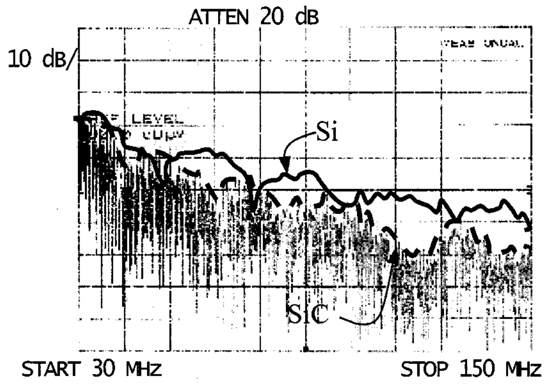

Fig. 12. Comparison of EMI spectrum envelope for the switching power supply with Si and SiC diodes.

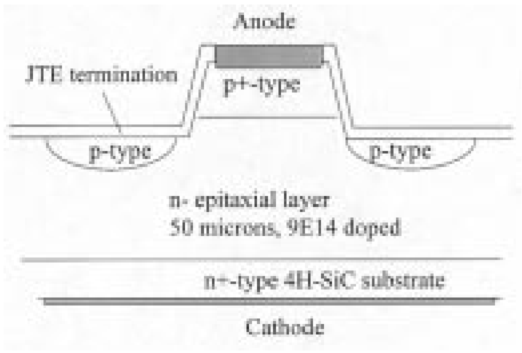

Fig. 13. Structure of the planar PiN diode using JTE termination.

output of the tube emulates the conditions of using anti-parallel switching devices of different output capacitance in an application circuit. By independently controlling the supply voltage, di/dt, and dv/dt, the new test circuit enables testing the diode for the full range of conditions that occur for various application conditions.

Fig. 6 shows the measured turn-off characteristics of the MPS diode for three different di/dt values without an external driver capacitance. Fig. 7 shows the comparison of the turn-off characteristics with and without an external driver capacitance. These results show that even for the fastest turn-off, the recovery of the SiC diode is mostly capacitive in nature. This conclusion is reached by observing that the reverse voltage rise occurs during the entire reverse current period, and that the capacitive current is reduced with the added driver capacitance.

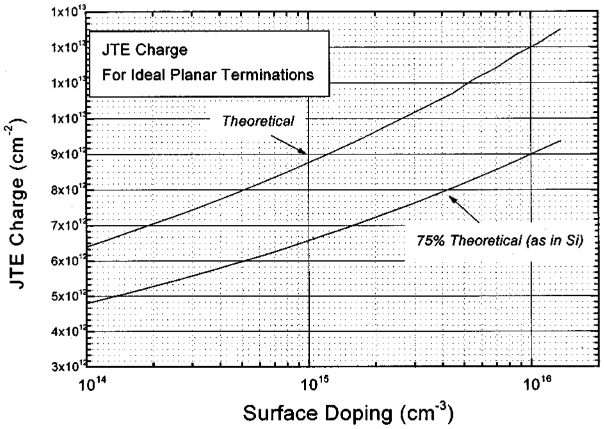

Fig. 14. Ideal JTE charge versus surface doping N. In Si devices, 75% of theoretically determined values are used.

The internal diode capacitance can be readily calculated from these waveforms. For example, the middle turn-off speed curve in Fig. 6 (di/dt equal to 0.1 A/ns) has a maximum dv/dt equal to 60 V/ns and the maximum reverse current is 0.2 A at this point. Using these values, the capacitance is calculated to be 3.3 pF for this diode when the reverse voltage is equal to several hundred volts. This value is consistent with the junction depletion capacitance value calculated using the blocking region doping concentration.

Fig. 8 shows a comparison of the reverse recovery waveforms between an ultra-fast 1000-V Si PiN diode and the 1500-V SiC MPS diode. In contrast to the MPS diode, the bulk of the reverse recovery current in the Si diode occurs before the voltage rises. This indicates that charge storage is far more important than junction capacitance in the Si diode. As can be seen in the figure, the voltage rise is delayed for the Si diode relative to the SiC MPS diode, even though the tube is turned on at the same time for both devices. The reverse recovery current in the Si diode is huge in comparison to that of the SiC diode. Furthermore, the nature of the charge-storage-type recovery for the Si diode means that the anti-parallel switch (e.g., IGBT, MOSFET, or CoolMOS) in a hard-switched power converter experiences the full supply voltage at full current (load current plus diode current) during the switch turn-on. In contrast, the anti-parallel switch experiences less voltage during turn-on with the SiC MPS diode because the voltage begins to rise at the beginning of the diode recovery.

Figs. 9 and 10 show the temperature dependence of the reverse recovery waveform for the SiC MPS diode and the ultra-fast Si diode for the same di/dt value of 50 A/μs and a forward current of 0.6 A. Because the SiC MPS diode switching is dominated by junction capacitance, there is virtually no temperature dependence of the reverse recovery waveform over the range of 25 °C through 225 °C. The capacitance results in a peak reverse current of 0.4 A and a recovery time of 20 ns. For the ultra-fast Si diode, the peak reverse recovery current increases from 1.5 A to 2.7 A, and the recovery time increases

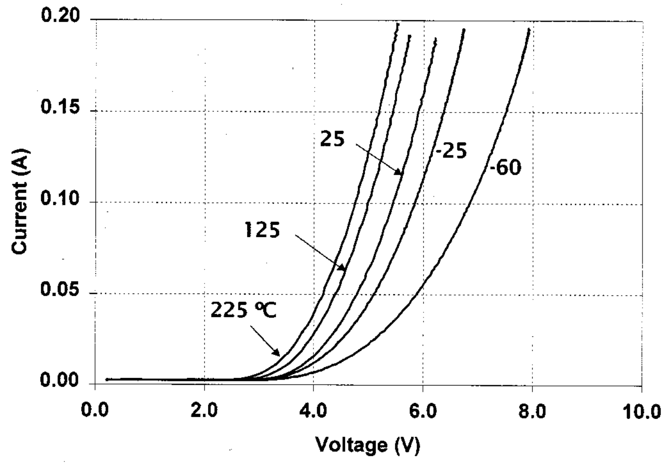

Fig. 15. Temperature dependence of on-state characteristics for the 5000-V SiC PiN diode.

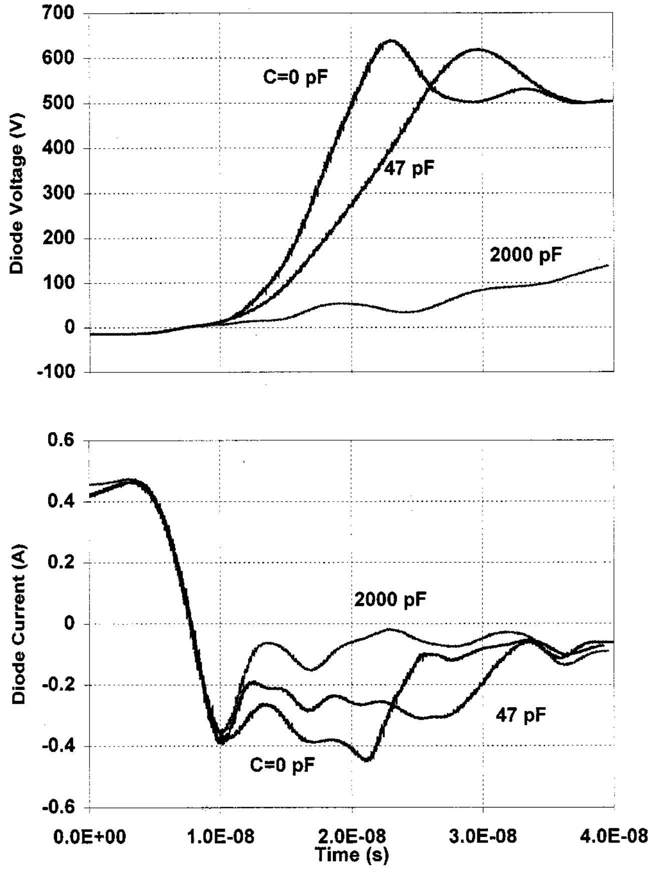

Fig. 16. Driver capacitance dependence of reverse recovery current and voltage waveforms for the 5000-V SiC PiN diode.

from 50 ns to 100 ns as the temperature is increased from 25 °C to 125 °C. This occurs because the minority carrier lifetime increases with temperature. As a result, the Si diode recovery charge increases by approximately a factor of four over the 100 °C temperature range.

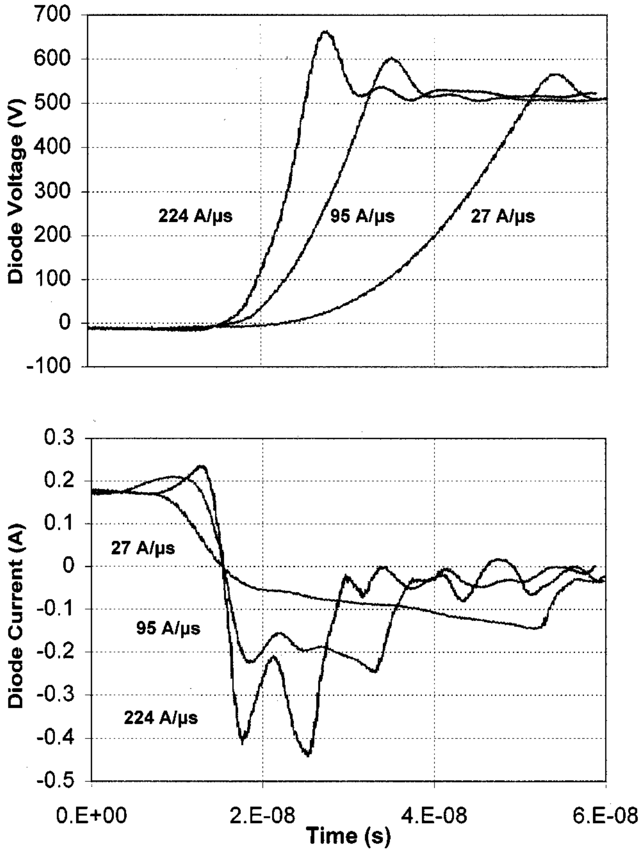

Fig. 17. The di/dt dependence of reverse recovery current and voltage recovery waveforms for the 5000-V SiC PiN diode.

D. Power Supply Performance Evaluation

The 1500-V rated SiC MPS can be directly applied to existing commercial power supply products. For low-current devices (rating of less than 1 A), the application is mainly in auxiliary power supplies for an inverter that may be used for motor drives, harmonic filters, and voltage source converters. For high-current devices, the applications are practically unlimited and include power supplies, motor drives, and switching amplifiers.

In [5], a 50-W power supply circuit was designed for a 500-V to 100-V step-down application. This test circuit uses a Cool MOS™ transistor for the switch [6], [7][1]. With conventional ultra-fast reverse recovery diodes, the switching frequency is limited. In initial testing, several commercially available ultra-fast Si diodes were destroyed at 100 kHz switching because of excessive reverse recovery losses. Because the 1000-V Si diodes cannot operate under these conditions, the final comparison is made between the 1500-V SiC MPS diode and a 600-V Si diode (BYV26C).

Fig. 11 compares the efficiency measurement results with both SiC and Si diodes at a switching frequency of 186 kHz. The experimental results indicate that the system efficiency with a SiC MPS diode is between 88% and 89% for most load conditions. By comparison, the system efficiency with the BYV26C Si diode varies between 85.5% and 83% under the same load range. The full-load efficiency is 88% with the SiC diode compared to 82% with the Si diode, a 6% efficiency improvement.

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[1] Cool MOS is a trademark of Infineon Technologies, Germany. Certain commercial products or materials have been identified in order to specify or describe the subject matter of this paper adequately. This does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are the best for the purpose.

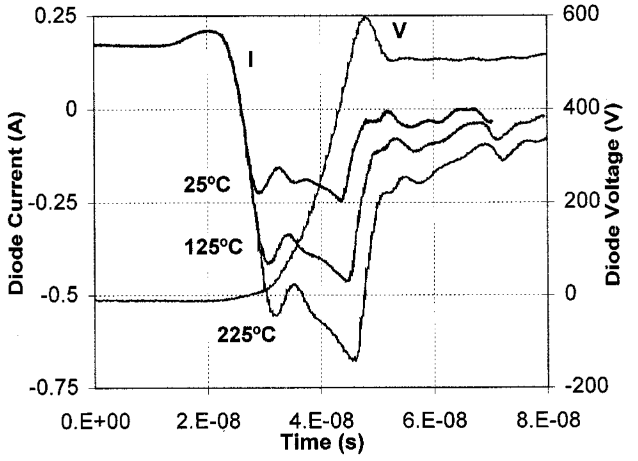

Fig. 18. Temperature dependence of reverse recovery current with zero driver capacitance for the 5000-V SiC PiN diode.

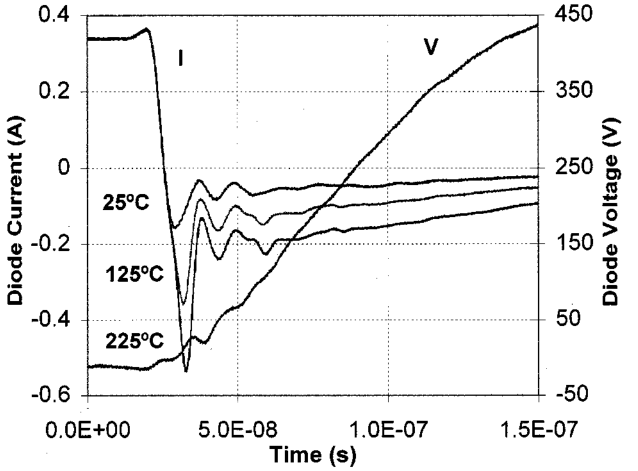

Fig. 19. Temperature dependence of reverse recovery current with 2000 pF driver capacitance for the 5000-V SiC PiN diode.

The diode reverse recovery has been considered to be a major source of EMI [8]. With nearly zero reverse recovery current, the SiC MPS diode is expected to emit less EMI high frequency noise components. Experiments were conducted to compare the EMI performance between the above-mentioned Si and SiC diodes under the same converter conditions. Fig. 12 shows the experimental EMI spectrum for the frequency range from 30 MHz to 150 MHz. For comparison purposes, the EMI spectrum of the Si diode is only shown with the envelope. The major EMI reduction with the SiC diode appears in the frequency range of 70 MHz to 150 MHz.

III. THE 5000 V SILICON-CARBIDE PiN DIODES

Recently, high voltage SiC PiN power diodes have been fabricated having a blocking voltage capability of 5000 V [9]. These diodes show great potential for high voltage power supply applications. The main features of these high voltage diodes are

1) voltage drop in the on-state comparable to stacked Si diodes;
2) switching speeds that are much faster than any of their Si counterparts;
3) good high temperature characteristics.

High voltage ($>$5000 V) diodes are used in high voltage and pulse power supply applications. Television and monitor supplies for cathode ray tubes (CRT's) are common examples. For these applications, the diode needs to block high voltages and operate under high frequency conditions. Traditional designs may use a stack of fast recovery Si diodes in series for these high voltage applications. The 5000-V SiC diode, with a near zero reverse-recovery characteristic, can easily penetrate into the high volume display market and into supplies for a wide range of applications including lasers, x-ray systems, traveling wave tubes, ion pumps, electrostatic systems, copy machines, missile guidance systems, night vision systems, and radar jamming systems.

A. Device Design

The device studied in this paper has an active area of 0.002 cm^2, resulting in a current rating of 0.25 A. These devices were fabricated by CREE and are the result of a further optimization of the devices produced in [9] to improve the edge termination. Devices with areas up to 0.04 cm^2 and improved performance have also been produced and are the topic of future publication. The 5000-V blocking voltage was achieved using a 4H-SiC n^- layer with a thickness of 50 μm and $N = 8E14$ cm^{-3}, grown by chemical vapor deposition (CVD) in a hot-wall reactor. To prevent premature breakdown of the device, the voltage-blocking layer was exposed and junction termination extension (JTE) was used as the planar edge termination method as shown in Fig. 13. The dose of p-type implant at the periphery of the device edge is determined from Fig. 14 using the surface doping N. The JTE-terminated zones were passivated using a 3 μm thick SiO$_2$ layer.

B. Static Characteristics

The measured temperature dependence of the on-state characteristics for a 5000-V, 0.25-A (0.002 cm^2) rated SiC PiN diode is shown in Fig. 15. Because the band gap of 4H-SiC is much higher than that of Si (3.26 eV for SiC versus 1.1 eV for Si), the built-in junction potential is much larger and the diode does not begin to conduct until nearly 3 V is applied. However, for high voltage SiC diodes, the reduced voltage drop across the blocking layer more than compensates the higher built in potential. The decrease in on-state voltage with temperature is indicative of the decrease in built-in potential with temperature, and the increase in lifetime with temperature for a conductivity modulated device. This decrease in on-state voltage with increasing temperature also occurs in high voltage Si diodes. As can be seen from the $-60\,^\circ$C curve in Fig. 15, these devices continue to perform well at low temperatures.

C. Switching Characteristics

The reverse recovery switching tests are performed using the same test circuit as described in the previous section [5]. The tests are performed for various values of di/dt and dv/dt where dv/dt is controlled by placing various capacitors across the tube driver. Fig. 16 shows the current and voltage waveforms of the 0.25-A, 5000-V SiC PiN diode for three different driver capacitor values. As the driver capacitance is increased from 0 pF to 2000 pF, the voltage rate of rise is decreased and the internal diode capacitor current is reduced.

TABLE I
Comparison of Various
Figures-of-Merit of the 5000-V SiC Diode with Several
Commercially Available Si Diodes at 25 °C

	Repetitive Peak Reverse Voltage V_{RRM} (V)	**Forward Voltage Drop V_f (V)**	**Reverse Recovery Time t_{rr} (ns)**
SiC PiN	5000	5.7	6
VMI X50FF3	5000	12.5	30
VMI X20FF3	2000	7.5	30
VMI 1N6523	3000	5.0	70
VMI 1N6524	4000	7.0	70
Philips BYX105G	5000	10.9	600
Philips BYX106G	5000	12.7	350
Philips BYX107G	5000	15.8	175
Philips BYX108G	5000	27.7	50

For the case where no driver capacitance was added ($C = 0$ pF), the reverse current waveform consists of a stored charge recovery portion followed by the capacitive portion. For the case of the highest driver capacitor value (2000 pF), dv/dt is substantially reduced and the current required to charge the internal diode capacitance is minimal. Thus, the waveform consists of a stored charge recovery portion followed by a small current tail due to the decay of the remaining stored charge.

Fig. 17 shows the di/dt dependence of the 5000-V diode switching waveform with no external driver capacitance added. For the lowest value of di/dt (27 A/μs), the reverse recovery current is determined by the device capacitance, whereas a stored charge recovery peak becomes more evident as the di/dt is increased, i.e., 95 A/μs and 224 A/μs curves.

The temperature dependence of the 5000-V diode switching waveforms is shown in Figs. 18 without an added driver capacitance, and in Fig. 19 with an added 2000 pF driver capacitance. It is evident from these curves that the peak reverse recovery current increases by approximately a factor of four as the temperature increases from 25 °C to 225 °C. In addition, the size and decay time of the current tail increase substantially with temperature.

D. Comparison of Si and SiC Devices

The forward voltage drop of the 5000-V SiC diode is determined from Fig. 15 to be 5.7 V at 25 °C and 0.125 A (one-half of the device rated current). Using the switching measurements of Fig. 16, the reverse recovery time is determined to be 6 ns. This is done in the customary way of using the di/dt where the peak reverse recovery current is equal to the forward current, and extrapolating the current after the reverse current peak to zero current. For SiC devices, it is important to use the 2000 pF driver capacitance case so that the stored charge recovery current component can be separated from the device and package capacitance component of current. For Si devices, the capacitive component of current is not evident because the stored charge component is so much larger.

Table I compares various figures-of-merit of the 5000-V SiC diode with several commercially available Si diodes in the voltage range of 2000 V through 5000 V. The silicon diode data is taken from manufactures specifications, which are typically measured at a current density of 20 A/cm^2 due to thermal limitations of these high voltage devices. The SiC diodes on the other hand are measured at a higher current density of 60 A/cm^2 in this work. The Si diodes are designated as "fast, very fast, and ultra fast" by the vendor depending on the trade-off between forward drop and reverse recovery time. In general, the trade-off gets worse with higher blocking voltage capability. The VMI Si diodes in the table improve their on-state voltage versus switching speed trade-off by stacking several lower voltage die in series although this increases cost. As can be seen from the table, the 5000-V SiC diode offers a better trade-off than any of the Si diodes, even those with much lower blocking voltage capability. The device capacitance (not shown in the table) due to the junction depletion capacitance and the parasitic package capacitance is comparable for all of the devices (3–5 pF).

IV. Conclusion

In this paper, a variety of measurements and test circuits are applied to silicon carbide power diodes in order to compare their application performance to commercially available silicon power diodes. It is shown that a newly developed 1500-V SiC merged PiN Schottky (MPS) diode has virtually no reverse recovery current and has a forward voltage drop comparable to silicon devices optimized for various voltages in the range of 600 V through 1500 V. It is also shown that a newly developed 5000-V SiC PiN diode offers a better trade-off between forward voltage and reverse recovery time than that of silicon diodes optimized for various voltages in the range of 2000 V through 5000 V. Even at this early stage of development, the silicon carbide power diodes demonstrate an overwhelming advantage over a wide range of optimized commercially available silicon diodes. Further refinement and optimizing of silicon carbide diode characteristics for targeted applications will lead to dramatic improvements in power supply performance.

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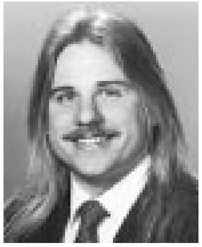

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