APPLICATION NOTE

Hard Switched Silicon IGBT's?

Cut Switching Losses in Half with Silicon Carbide Schottky Diodes

By Jim Richmond

Replacing the Si Ultrafast soft recovery diode used as the freewheeling component in hard switched IGBT applications with a Silicon Carbide (SiC) Schottky diode reduces the switching losses in the diode by 80% and the switching losses in the IGBT by 50%.

Introduction

The Silicon IGBT, which combines the output and switching characteristics of a bipolar transistor and the ease of control of a MOSFET, has become the power switch of choice for hard switched, high voltage (greater than 500V) and high power (greater than 500 watts) applications. Typical applications include motor control inverters, uninterruptible power supplies, welding equipment and switched mode power supplies (SMPS).

The ever-increasing demand in power electronics for improved efficiency, reduced cooling, decreased size and weight, and stricter EMI/RFI and power quality requirements present new challenges to the designer. All of these requirements are greatly influenced by the high transient losses during IGBT turn-on when switching the inductive load found in hard-switched topologies. The reverse recovery current present at turn-off of the silicon freewheeling diode directly affects this IGBT turn-on transient. To compound matters, the diode reverse recovery current increases with increasing operating temperature, diode current, and di/dt.

The diode reverse recovery current and the IGBT switching losses can be drastically reduced by replacing the silicon freewheeling pin diode with a SiC Schottky Barrier Diode (SBD). Due to the material properties of silicon, Silicon Schottky diodes are not possible in the 200 plus volt range.

SiC Schottky Diodes

The SiC SBD is commercially available with 600 volt and 1200 volt ratings. The 600 volt diodes are available with 1, 4, 6, 10, and 20 amp current ratings. The 1200 volt diodes are available with 5 and 10 amp current ratings. 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 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 hard switched IGBT based application. This lowers the case temperature of the IGBT improving the system efficiency and possibly allowing for a reduction in size of the silicon IGBT. In order to measure the benefit of these high performance rectifiers, an inductive switching test circuit was used to measure the IGBT and diode switching losses. This allowed for a switching loss comparison between an ultrafast soft recovery silicon diode and the Cree ZERO RECOVERY® SBD, as well as the impact their reverse recovery has on the switching losses of a IGBT.

Switching Measurement

Figure 1 shows the inductive test circuit used for making the switching measurements. During operation, a double pulse is used to drive the IGBT gate. For the 600 volt device testing a 10 ohm gate drive resistor is used to set the di/dt to 750 A/µs. A 22 ohm resistor was used with the 1200 volt devices for a di/dt of 250 A/µs.

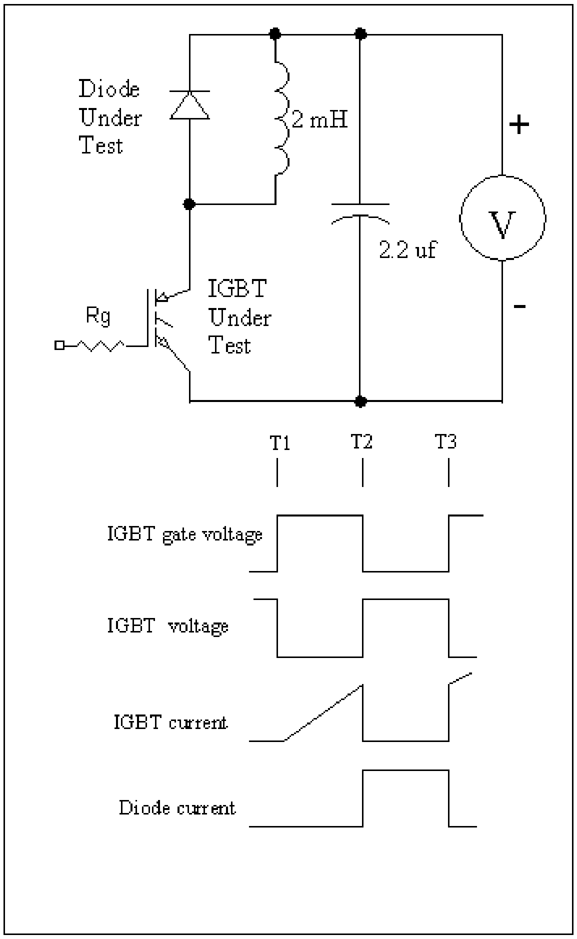

Figure 1. Inductive Test Circuit with operating waveforms.

At time T1, the IGBT is turned on and current through the inductor ramps up until it reaches the desired test current at time T2. At time T2, the IGBT is turned off and the inductor current is transferred to the diode. The IGBT turn-off losses and diode turn-on losses are measured at the T2 transition. The inductor current continues to flow through the diode until the IGBT is turned back on at time T3. Now inductor current is transferred from the diode back to the IGBT. The IGBT turn-on losses and diode turn-off losses are measured at the T3 transition.

600 volt Switching Comparison

Switching parameters were measured for a 15 A, 600 V ultrafast soft recovery silicon diode (similar to what would be co-packaged in a 40 A ultrafast IGBT) and a 10 A, 600 V SiC SBD, along with the switching losses of a 40A, 600 V Silicon IGBT. The losses were measured at a voltage of 500 V and current of 20 A.

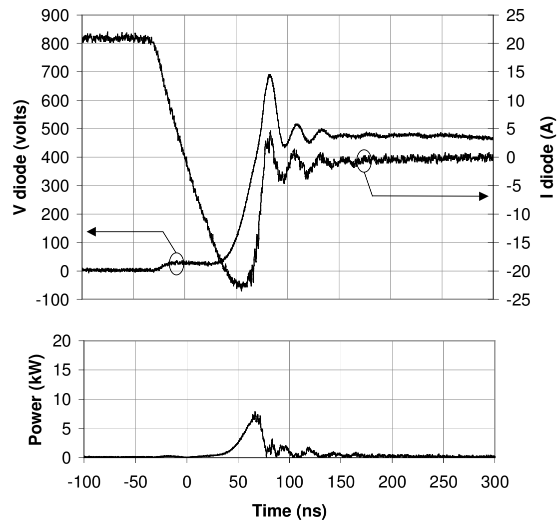

Figure 2. 600 volt Si Ultrafast diode turn-off voltage, current and instantaneous power at 150°C.

Figure 2 shows the turn-off voltage, current and instantaneous power measured at a junction temperature of 150°C of the Si ultrafast diode. This shows a peak reverse recovery current of 23 amps, a recovery time of 100 ns, and a peak instantaneous power of 7 kW. Also shown is the 200 volt overshoot caused by the high di/dt during the reverse recovery snap-off.

Figure 3 is the turn-off waveforms for the SiC SBD at 150°C. This shows a peak reverse recovery current of 4 amps, a reduction of 83%, a recovery time of 33 ns, a reduction of 67% and a peak instantaneous power of 0.5 kW, a reduction of 93%. The drastic reduction in switching power is due to the SiC SBD only having to dissipate a small capacitive charge, which happens while the diode voltage is low. The voltage overshoot seen in the Si diode is completely eliminated with the SiC SBD.

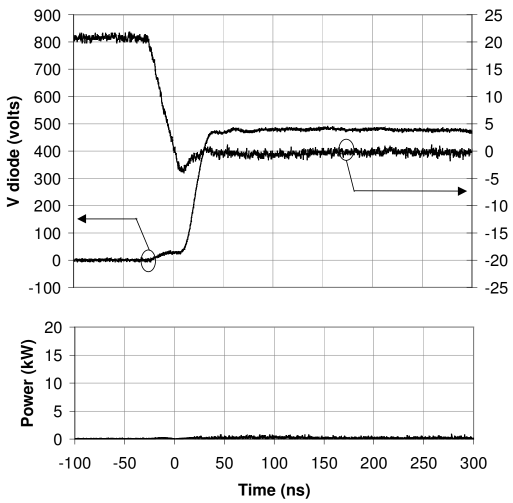

Figure 3. 600 volt SiC SBD turn-off voltage, current and instantaneous power at 150°C.

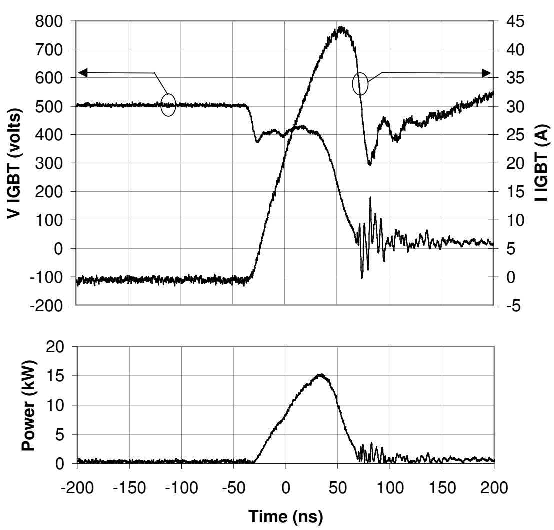

Figure 4. 600 volt IGBT turn-on w/ Si Ultrafast diode, voltage, current and instantaneous power at 150°C.

Figure 4 shows the turn-on voltage, current and instantaneous power measured at a junction temperature of 150°C of the IGBT with a Si ultrafast diode. During the IGBT turn-on the diode reverse recovery current is added to the IGBT current, resulting in a peak current of 44 amps. A peak instantaneous power of 15 kW is dissipated in the IGBT. Also shown are high frequency oscillations in the IGBT voltage caused when the Si diode snaps off. This is a major cause of RFI/EMI generation.

Figure 5 shows the turn-on voltage, current and instantaneous power measured at a junction temperature of 150°C of the IGBT with a SiC SBD. The use of the SiC SBD results in a peak current of 22 amps, a 50% reduction, and a peak instantaneous power of 7.5 kW, a 50% reduction. The high frequency oscillations in the IGBT voltage are also eliminated with the SiC SBD, resulting in reduced RFI/EMI generation.

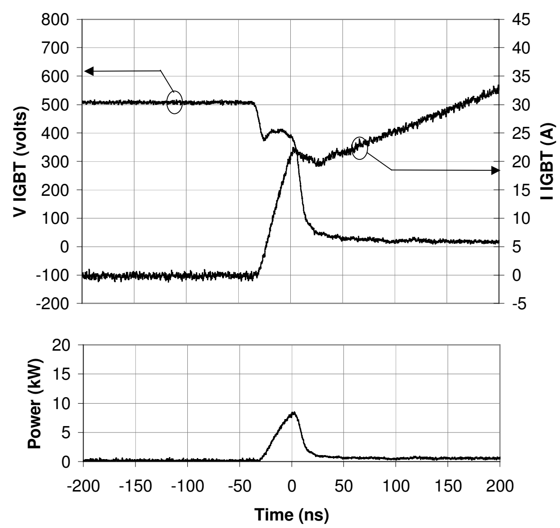

Figure 5. 600 volt IGBT turn-on w/ SiC SBD, voltage, current and instantaneous power at 150°C.

A comparison of the switching parameters of the SiC SDB with the Si ultrafast diode are shown for measurements taken at a junction temperature of 25°C in Table 1 and for measurements taken at a junction temperature of 150°C in Table 2. The total switching loss reduction (IGBT + Diode) is calculated to be 52% at 25°C and 56% at 150°C.

Ic = 20A, Vcc = 500V, Rg = 10 ohm				
Parameter	Units	Si Pin	SiC	% Reduction
Peak reverse current	Ipr (A)	13	4	69%
Reverse recovery time	Trr (nS)	83	30	64%
Recovery charge	Qrr (nC)	560	78	86%
Diode loss turn-off	Eoff Diode (mJ)	0.11	0.02	82%
Diode loss turn-on	Eon Diode (mJ)	0.03	0.02	33%
Diode loss total	Ets Diode (mJ)	0.14	0.04	71%
IGBT loss turn-on	Eon IGBT (mJ)	0.63	0.23	63%
IGBT loss turn-off	Eoff IGBT (mJ)	0.46	0.32	30%
IGBT loss total	Ets IGBT (mJ)	1.09	0.55	50%
loss total	Ets (mJ)	1.23	0.59	52%

Table 1: 600 volt switching parameter comparison between Si Ultrafast and SiC SBD at 25°C.

Ic = 20A, Vcc = 500V, Rg = 10 ohm				
Parameter	Units	Si Pin	SiC	% Reduction
Peak reverse current	Ipr (A)	23	4	83%
Reverse recovery time	Trr (nS)	100	33	67%
Recovery charge	Qrr (nC)	1220	82	93%
Diode loss turn-off	Eoff Diode (mJ)	0.23	0.02	91%
Diode loss turn-on	EonDiode (mJ)	0.03	0.02	33%
Diode loss total	Ets Diode (mJ)	0.26	0.04	85%
IGBT loss turn-on	Eon IGBT (mJ)	0.94	0.24	74%
IGBT loss turn-off	Eoff IGBT (mJ)	0.89	0.64	28%
IGBT loss total	Ets IGBT (mJ)	1.83	0.88	52%
loss total	Ets (mJ)	2.09	0.92	56%

Table 2: 600 volt switching parameter comparison between Si Ultrafast and SiC SBD at 150°C.

Figure 6 shows the turn-off currents of the Si ultrafast diode and the SiC SBD at 25°C and 150°C superimposed on one plot. The SiC SBD is unchanged with temperature, with a peak reverse current of 5 amps. The Si ultrafast diode shows strong temperature dependence, increasing from 13 amps at 25°C to 23 amps at 150°C.

Figure 7 shows the turn-on currents of the IGBT with a Si ultrafast diode and a SiC SBD at 25°C and 150°C, superimposed on one plot. The peak current in the IGBT with the SiC SBD is unchanged with temperature. The peak current of the IGBT with the Si ultrafast diode shows strong temperature dependence due to the reverse recovery temperature dependence of the diode.

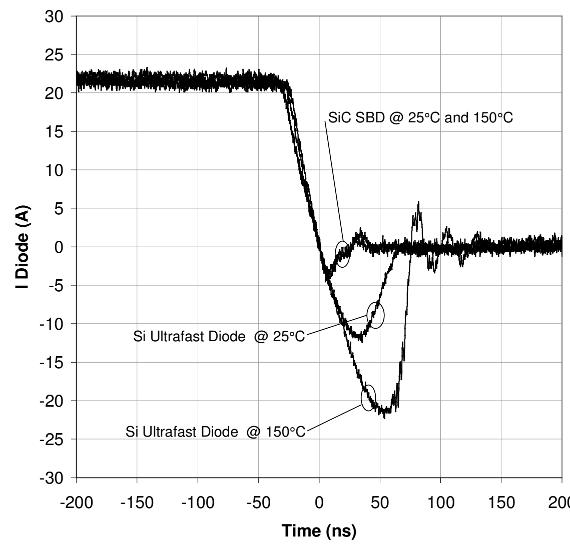

Figure 6: 600 volt turn off current of the Si Ultrafast diode and the SiC SBD at 25°C and 150°C.

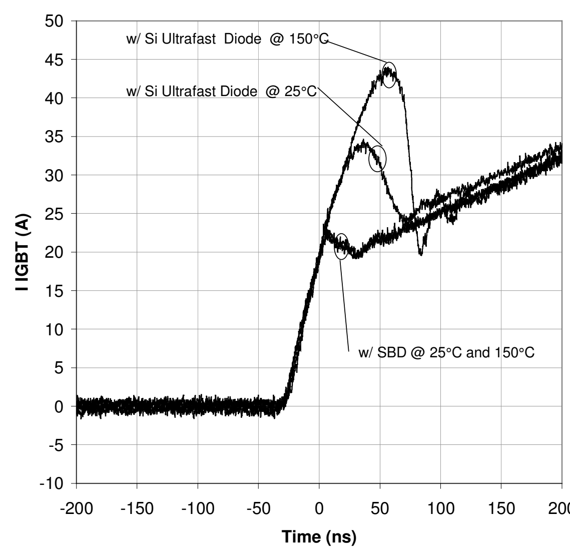

Figure 7: 600 volt turn-on current of the IGBT w/ the Si Ultrafast diode and the SiC SBD at 25°C and 150°C.

Figure 8 shows the total diode switching losses (turn-on and turn-off) in watts at switching frequencies from 10 kHz to 100 kHz and temperatures of 50, 100 and 150°C. The SBD has significantly lower switching losses (up to an 85% reduction) and shows no change with increased temperature.

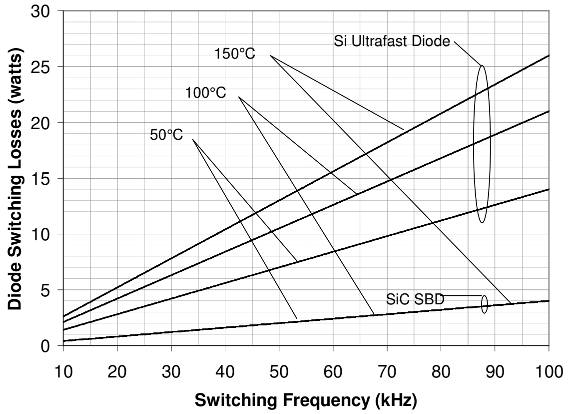

Figure 8: 600 volt switching power loss of the Si Ultrafast diode and the SBD at 50°C, 100°C, and 150°C.

Figure 9 shows the total IGBT switching losses (turn-on and turn-off) in watts at switching frequencies from 10 kHz to 100 kHz at 50, 100 and 150°C. The IGBT switching loss with the SiC SBD is about half that of the IGBT with the Si ultrafast diode. The IGBT with the SiC SBD also shows less increase in switching losses with temperature. The temperature dependence of the switching losses in the IGBT with the SiC SBD is due to the increase in IGBT turn-off time since the turn-on losses are unchanged with temperature. This dramatic improvement in the IGBT switching performance is due solely to the absence of reverse recovery in the SiC SBD.

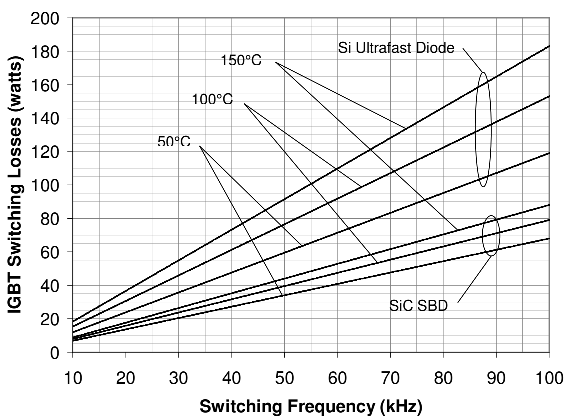

Figure 9: 600 volt IGBT switching power loss w/ the Si Ultrafast diode and the SiC SBD at 50°C, 100°C, and 150°C.

1200 volt Switching Comparison

The switching parameters were measured for an 8A, 1200 V ultrafast soft recovery silicon diode (similar to what would be co-packaged in an 11 A ultrafast IGBT) and a 5 A, 1200 V SBD, along with the switching losses of a 11 A, 1200 V IGBT. The losses were measured at a voltage of 1000 V and current of 5 A. The maximum temperature used in this testing was 125°C since the IGBT started going into thermal runaway when biased at 150°C.

Figure 10 shows the turn-off voltage, current and instantaneous power measured at a junction temperature of 125°C for the Si ultrafast diode. This shows a peak reverse recovery current of 6 amps, a recovery time of 148 ns, and a peak instantaneous power of 2.8 kW. The voltage overshoot seen with the 600 volt Si diode is not pronounced here due to the 1200 volt testing being done at a lower di/dt (250 A/µs vs. 750 A/µs).

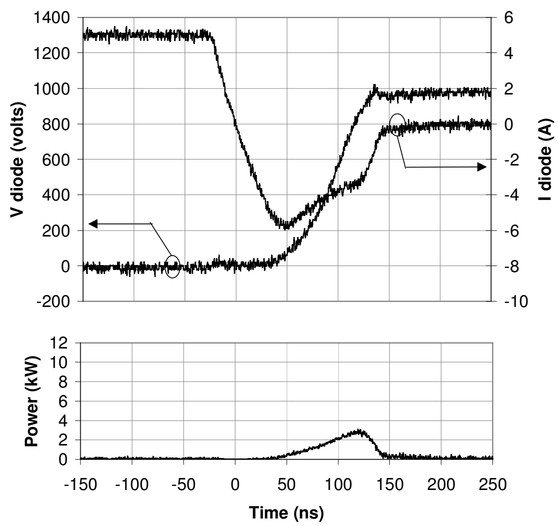

Figure 10. 1200 volt Si Ultrafast diode turn-off voltage, current and instantaneous power at 125°C.

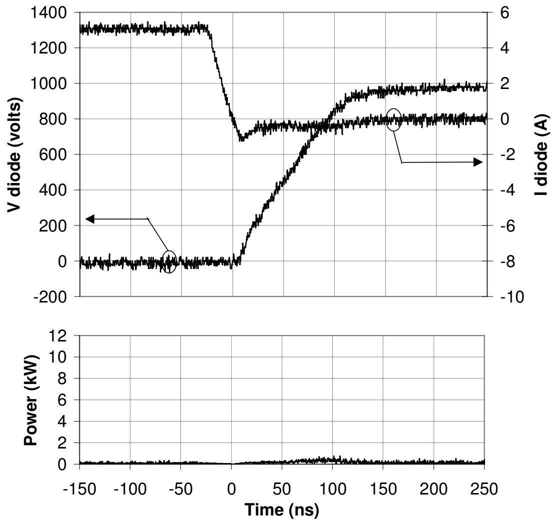

Figure 11. 1200 volt SiC SBD turn-off voltage, current and instantaneous power at 125°C.

Figure 11 is the turn-off waveforms for the SiC SBD at 125°C. This shows a peak reverse recovery current of 1 amp, a reduction of 83%, a recovery time of 30 ns, a reduction of 80% and a peak instantaneous power of 0.3 kW, a reduction of 89%. The drastic reduction in switching power is due to the capacitive charge of the SBD dissipating while the diode voltage is low.

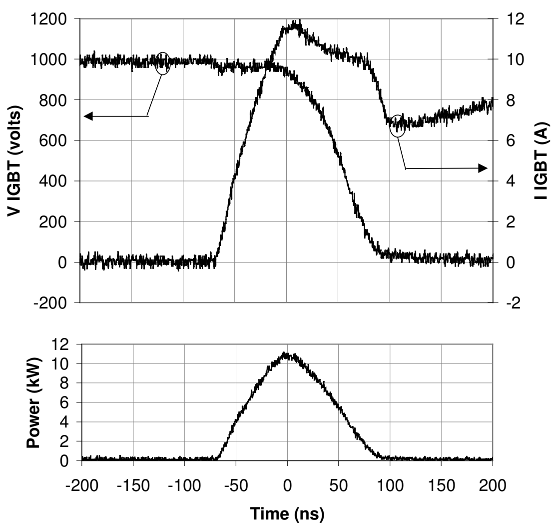

Figure 12. 1200 volt IGBT turn-on w/ Si Ultrafast diode, voltage, current and instantaneous power at 125°C.

Figure 12 is the turn-on voltage, current and instantaneous power measured at a junction temperature of 125°C for the IGBT with a Si ultrafast diode. During the IGBT turn-on the diode reverse recovery current is added to the IGBT current, resulting in a peak current of 11.7 amps. A peak instantaneous power of 11 kW is dissipated in the IGBT.

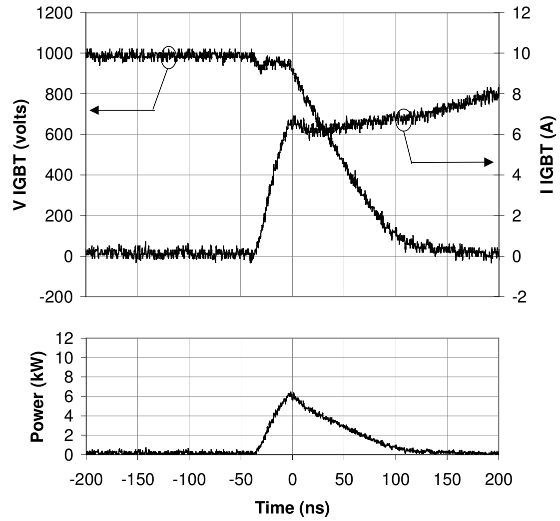

Figure 13. 1200 volt IGBT turn-on w/SiC SBD, voltage, current and instantaneous power at 125°C.

Figure 13 shows the turn-on voltage, current and instantaneous power measured at a junction temperature of 125°C for the IGBT with a SBD. The use of the SBD results in a peak current of 6.7 amps, a 42% reduction and a peak instantaneous power of 6.2 kW, a 44% reduction.

Figure 14 shows the turn-off currents of the Si ultrafast diode and the SiC SBD at 25°C and 125°C superimposed on one plot. The SiC SBD is unchanged with temperature, with a peak reverse current of 1 amp. The Si ultrafast diode shows a strong temperature dependence, increasing from 5 amps at 25°C to 6 amps at 150°C. The reverse recovery time of the Si ultrafast diode increases from 100 nS at 25°C to 148 nS at 125°C while reverse recovery time of the SiC SBD is unchanged with temperature.

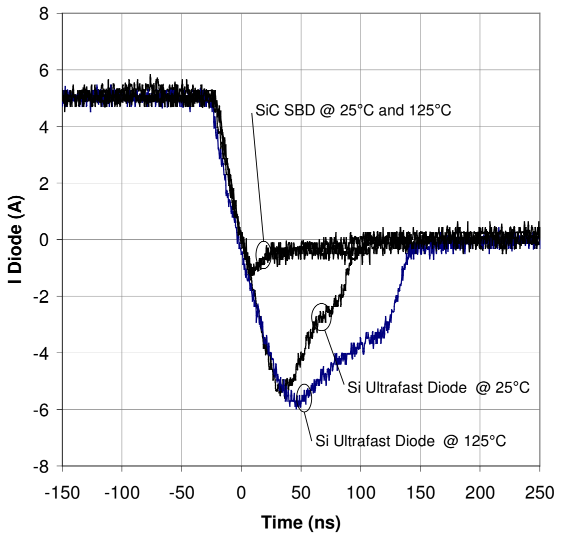

Figure 14: 1200 volt turn-off current of the Si Ultrafast diode and the SiC SBD at 25℃ and 125℃.

Figure 15 shows the turn on currents of the IGBT with a Si ultrafast diode and the SiC SBD at 25℃ and 125℃ superimposed on one plot. The peak current in the IGBT with the SiC SBD is unchanged with temperature. The peak current and reverse recovery time of the IGBT with the Si ultrafast diode shows a strong temperature dependence due to the reverse recovery temperature dependence of the diode.

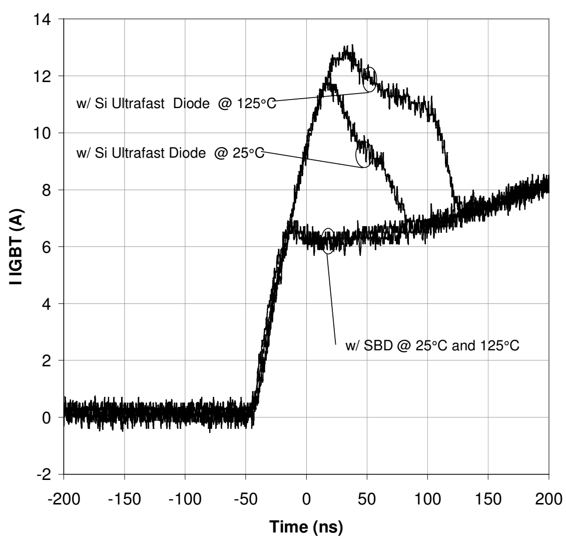

Figure 15: 1200 volt turn-on current of the IGBT w/ the Si Ultrafast diode and the SiC SBD at 25℃ and 150℃.

A comparison of the switching parameters of the SiC SBD with the Si ultrafast diode are shown for measurements taken at a junction temperature of 25℃ in Table 3, and for measurements taken at a junction temperature of 125℃ in Table 4. All measured parameters show a major improvement with the SiC SBD. The value of the SBD parameters are effectively unchanged with increased temperature while the Silicon Ultrafast diode parameters increase. The total switching loss reduction (IGBT + Diode) is 51% at 25℃ and 58% at 125℃.

Ic = 5A, Vcc = 1000V, Rg = 22 ohm

Parameter	Units	Si Pin	SiC	% Reduction
Peak reverse current	Ipr (A)	5.5	1	82%
Reverse recovery time	Trr (nS)	100	30	70%
Recovery charge	Qrr (nC)	295	20	93%
Diode loss turn-off	Eoff Diode (mJ)	0.08	0.02	75%
Diode loss turn-on	Eon Diode (mJ)	0.03	0.02	33%
Diode loss total	Ets Diode (mJ)	0.11	0.04	64%
IGBT loss turn-on	Eon IGBT (mJ)	0.73	0.28	62%
IGBT loss turn-off	Eoff IGBT (mJ)	0.33	0.25	24%
IGBT loss total	Ets IGBT (mJ)	1.06	0.53	50%
loss total	Ets (mJ)	1.17	0.57	51%

Table 3: 1200 volt switching parameter comparison between Si Ultrafast and SiC SBD at 25℃.

Ic = 5A, Vcc = 1000V, Rg = 22 ohm

Parameter	Units	Si Pin	SiC	% Reduction
Peak reverse current	Ipr (A)	6	1	83%
Reverse recovery time	Trr (nS)	148	30	80%
Recovery charge	Qrr (nC)	540	20	96%
Diode loss turn-off	Eoff Diode (mJ)	0.16	0.02	88%
Diode loss turn-on	Eon Diode (mJ)	0.03	0.02	33%
Diode loss total	Ets Diode (mJ)	0.19	0.04	79%
IGBT loss turn-on	Eon IGBT (mJ)	0.98	0.28	71%
IGBT loss turn-off	Eoff IGBT (mJ)	0.57	0.41	28%
IGBT loss total	Ets IGBT (mJ)	1.55	0.69	55%
loss total	Ets (mJ)	1.74	0.73	58%

Table 4: 1200 volt switching parameter comparison between Si Ultrafast and SiC SBD at 125℃.

Figure 16 shows the total diode switching losses (turn-on and turn-off) in watts at switching frequencies from 10 kHz to 100 kHz for temperatures of 25, 75 and 125℃. The SBD has significantly lower switching losses (up to a 79% reduction) and shows no change with increased temperature. Figure 17 shows the total IGBT switching losses (turn-on and turn-off) in watts at switching frequencies from 10 kHz to 100 kHz for temperatures of 25, 75 and 125℃. IGBT switching loss with the SBD is about half that of the IGBT with the

Si ultrafast diode. The IGBT with the SBD also shows less increase in switching losses with temperature. The temperature dependence of the switching losses in the IGBT with the SBD is due to the increase in the IGBT turn-off time, since the turn-on losses are unchanged with temperature. This dramatic improvement in the IGBT switching performance is due solely to the absence of reverse recovery in the SiC SBD.

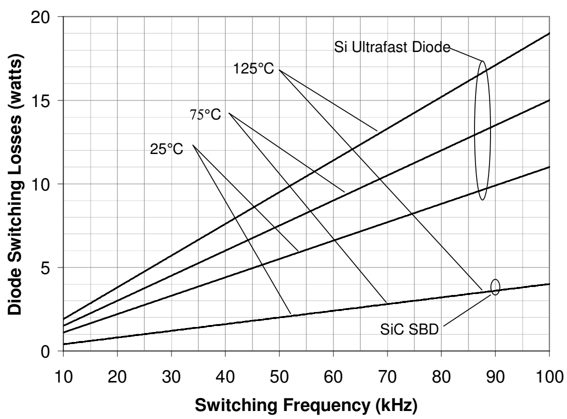

Figure 16: 1200 volt switching power loss of the Si Ultrafast diode and the SBD at 25°C, 75°C, and 125°C.

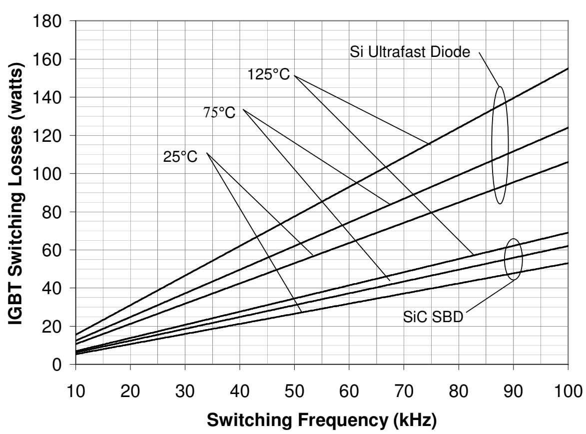

Figure 17: 1200 volt IGBT switching power loss w/ the Si Ultrafast diode and the SBD at 25°C, 75°C, and 125°C.

Conduction and Total Losses

Figure 18 shows the forward IV of the 1200 volt Si ultrafast diode and the SiC SBD at 25°C and 125°C. At 5 amps the SiC SBD diode has 0.75 volt lower forward drop at 25°C and 0.18 volt lower forward drop at 125°C. This results in reduced conduction losses for the SiC SBD.

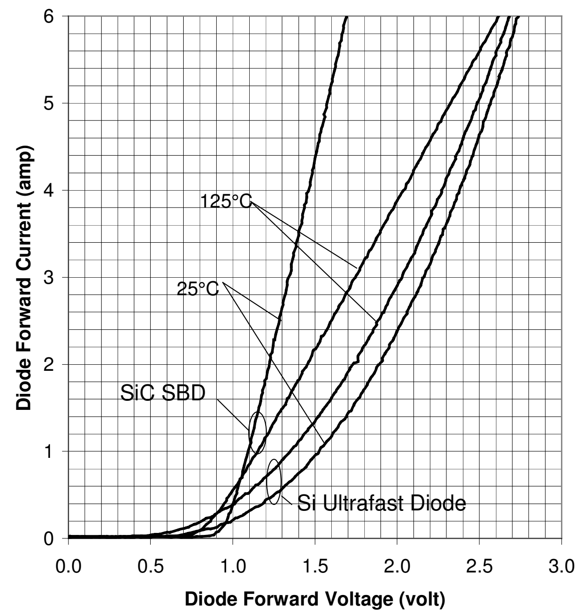

Figure 18: Forward voltage and current of the 1200 volt Si Ultrafast diode and the SiC SBD at 25°C and 125°C.

Table 5 shows the calculation of total losses for a 100 kHz converter operating at a 50% duty cycle with an average current of 2.5 amps using the 1200 volt devices. A device junction temperature of 125°C was used. The conduction loss for the IGBT is the data sheet value of 2.9 volt at 5 amps. With the SiC SBD, the total diode losses are reduced by 50% and the total IGBT losses are reduced by 51%. This gives a 51%, total loss reduction for the 1200 volt converter by simply changing the Si ultrafast diode to a SiC SBD.

	Si PiN	SiC SBD	% Reduction
Diode Switching loss (watt)	19	4	79%
Diode conduction loss (watt)	12.5	11.7	6%
Total Diode loss (watt)	31.5	15.7	50%
IGBT Switching loss (watt)	155	69	55%
IGBT conduction loss (watt)	14.5	14.5	0%
Total IGBT loss (watt)	169.5	83.5	51%
Total loss (watt)	201	99.2	51%

Table 5: Comparison of calculated losses in a converter with the 1200 volt Si Ultrafast diode and the SBD at 125°C.

Conclusions

The turn-on switching losses of the IGBT are strongly dependent on the reverse recovery characteristics of its freewheeling diode. The impact of the SiC SBD on the switching performance of the freewheeling diode and the IGBT is of great importance to the hard switched circuit designer. Based on the measurements presented above, there are significant advantages offered by SiC Schottky diodes. While the reverse recovery current of the Si ultrafast diode shows a strong temperature dependence, the SiC SBD is unaffected. At a high di/dt the Si ultrafast diode exhibits a voltage overshoot on turn-off due to snap off during reverse recovery, but the SiC SBD is unaffected. The snap off in the Si ultrafast diode causes oscillations in the IGBT voltage, which generate RFI/EMI. This oscillation is not present with the SiC SBD. The 50% reduction in switching losses can be applied in a number of ways to optimize the circuit design. The reduction in switching losses can be applied to increase efficiency, reduce cooling requirements, or reduce the current rating of the IGBT. The operating frequency can be increased in order to allow the use of smaller passive components, or to achieve acoustic requirements. The absence of a voltage overshoot eliminates the need for snubber networks. The absence of the high frequency oscillation reduces the RFI/EMI filter requirements. The replacement of the Si ultrafast diode with a SiC Schottky diode such as the Cree *ZERO RECOVERY*® SBD results in a substantial reduction in switching losses in both the diode and the IGBT resulting in a significant system level performance improvement.

Cree, Inc.
Power Products
4600 Silicon Drive
Durham, NC 27703 • USA
tel: 919-313-5300
fax: 919-313-5451
www.cree.com