PRELIMINARY

The Benefits of Using a Cree Inc. IGBT/SiC Schottky CoPack in AC Inverter Applications.

Michael O'Neill, Applications Engineer, Cree Inc.

Cree Inc. recently announced the availability of a family of low inductance TO-220 silicon (Si) IGBTs copacked with Cree Inc.'s *Zero Recovery*® silicon carbide (SiC) Schottky diodes. These devices will be drop in compatible with today's existing all Si devices. The main applications that will benefit from these devices will be AC inverters such as Motor Drives, UPS and Solar Inverter systems. In the example that follows below we will focus on the three main areas where the Cree Inc. CoPacks present the most significant improvements;

1. **Switching losses.**
2. **Thermal performance.**
3. **EMI signature.**

The Silicon Carbide difference

For the past two decades IGBTs and their associated Si-based freewheeling diodes (FWD) have been the mainstay switching devices in three-phase inverters. With recent advancements in the ability to grow high-quality single crystal SiC wafers, the time has come to finally realize the true potential that this technology has to offer.

Schottky diodes are inherently capable of high-speed switching (<50nS), but previously have been based on Si technology, and thus limited to practical applications of <200V due to the moderate field strength of Si. By virtue of the fact that the electric breakdown field strength of SiC is almost 10 times that of silicon, the fabrication of high voltage unipolar Schottky diodes is possible. The SiC Schottky diode, being a majority carrier, does not have any stored minority carriers, resulting in its minimal reverse recovery charge (Q_{rr}) during turn-off. However, there is a small amount of displacement current required to charge the Schottky junction capacitance, which is independent of forward current, *di/dt* and most importantly temperature.

Si PiN diodes are bipolar and as a result are subject to minority carrier recombination during turn-OFF, resulting in a significant reverse recovery charge. This reverse recovery charge increases dramatically with temperature (typically a factor of 3 from 25°C to 125°C), thus dramatically increasing switching losses in both the FWD and the IGBT. This charge also changes significantly with respect to *di/dt* (again, typically a factor of 3 from 40A/µs to 160A/µs). ***Figures 1 & 2.*** show the difference in recovery currents and recovery times (t_{rr}) between a 600V, 15A fast recovery Si PiN diode and Cree Inc.'s 600V, 6A SiC Schottky diode.

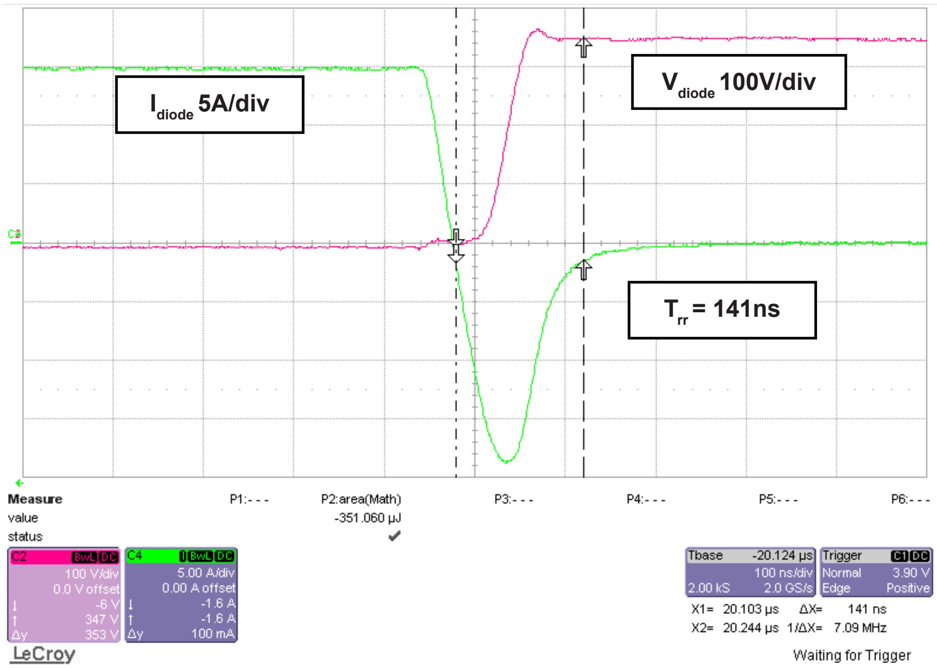

Figure 1. 15A fast recovery diode, turn-OFF (150°C)

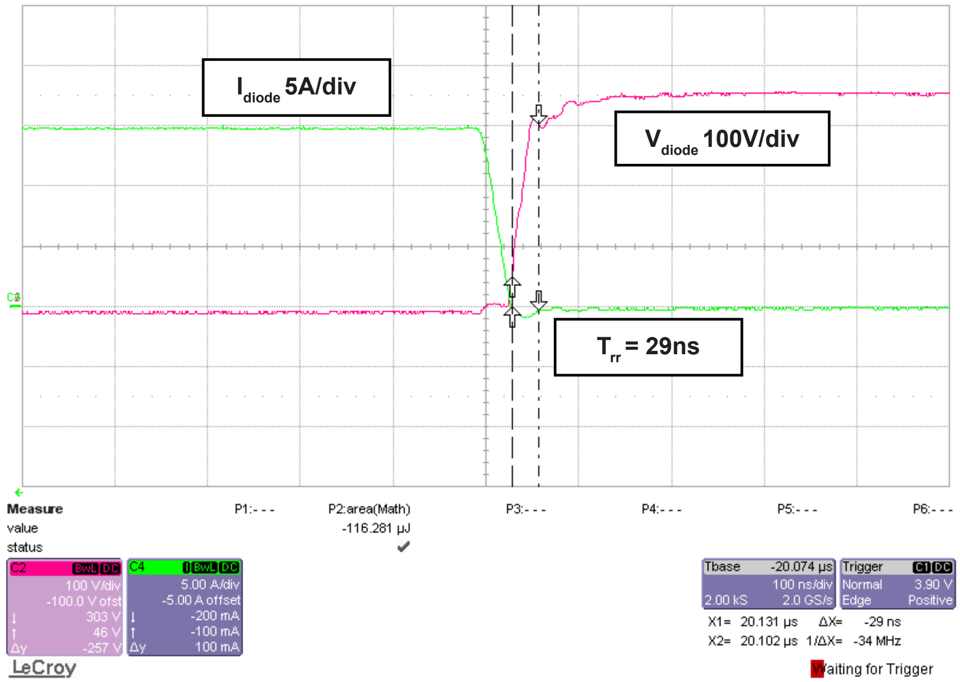

Figure 2. 6A SiC Schottky diode, turn-OFF (150°C)

Note that the Si device has a peak recovery current of 19A with a t_{rr} of 141ns whereas the SiC device has a peak current of 1A with a t_{rr} of only 29ns. Also, the SiC device has no voltage overshoot at turn-OFF. What this demonstrates is that the turn-OFF switching loss in the SiC Schottky is about 1% of the loss inherent in the Si PiN device during worst-case conditions. When the diode is placed in anti-parallel with an IGBT in a half-bridge circuit, the recovery currents also add to the turn-ON loss in the IGBT. The difference in turn-ON loss in the IGBT between a standard Si copack and the Cree Inc. CoPack with the same IGBT can be seen in ***Figures 3 & 4.*** The top two traces represent the IGBT collector-emitter voltage and collector current and the bottom trace represents the corresponding math waveform (V_{CE} * I_C). The area under the math waveform indicates the energy dissipated during the switching event in micro-joules.

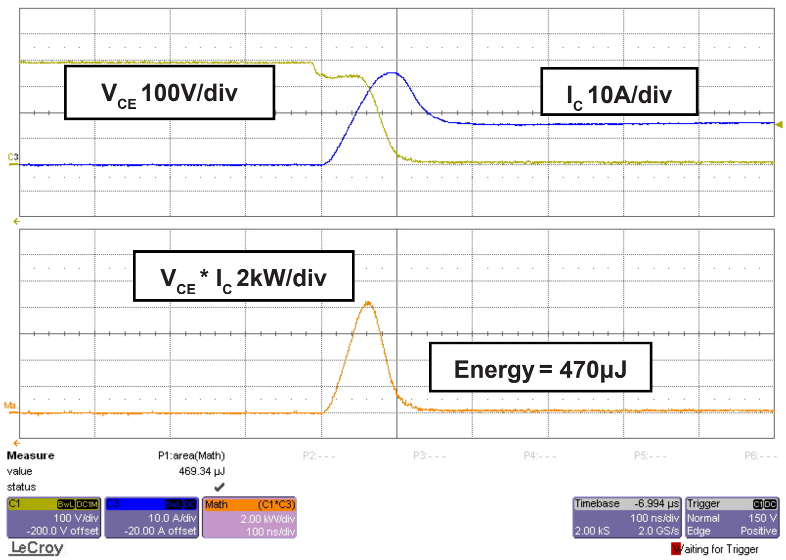

Figure 3. Standard IGBT/Si PiN copack, turn-ON (150°C)

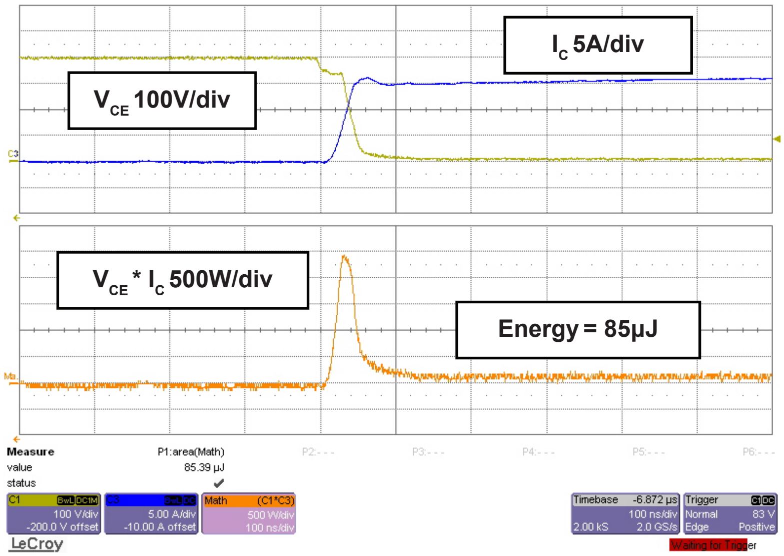

Figure 4. Cree Inc. CoPack with same IGBT, turn-ON (150°C)

Note the large overshoot in collector current at turn-ON in the all Si device that is not present in the Cree Inc. CoPack. This is due entirely to the reverse recovery current of the Si diode in the other copack of the half-bridge circuit, which was freewheeling load current prior to turning OFF. As can be seen, the energy dissipated in the IGBT in the Cree Inc. copack is 85μJ in comparison to 470μJ in the standard all Si part. This represents an 82% reduction in IGBT turn-ON energy with the Cree Inc. device when compared to it's equivalent all Si counterpart.

Motor Drive Example

A standard off-the-shelf motor drive utilizing standard all Si TO-220 copacks was selected for modification. The 15A, 600V standard copacks were removed and replaced with the Cree Inc. equivalent (CID150660). The three main areas of interest to be investigated will be overall loss reduction, thermal improvement and impact on EMI. The drive is a 2.3kW (3HP), 240V unit that operates at 16kHz PWM frequency. All the following readings were taken with the drive running at rated output of 9.8Amps at 50Hz in order to realize maximum losses.

1. Loss Reduction

Because this drive is specified to meet EN61800-3 First Environment Residential for EMI approval, the gate resistors had to be increased beyond the manufacturers recommended value in order to slow down turn-ON in the IGBTs. The manufacturer recommends 22Ω but the drive had 39Ω in-circuit. While this slowing down of the devices improves the EMI signature, it also contributes to higher switching losses.

With the Cree Inc. CoPacks the EMI signature was significantly improved (as will be seen later). In fact, the improvement was significant enough that the gate drive was modified to a steering circuit ***(Figure 5.)*** of 10Ω R_{GON} and 22Ω R_{GOFF} before a similar EMI signature to the all Si unit was achieved. This optimization yields the maximum possible Watts loss reduction while still being able to meet the EMI standard. The difference in IGBT turn-ON waveforms observed can be seen in ***Figures 6 & 7.***

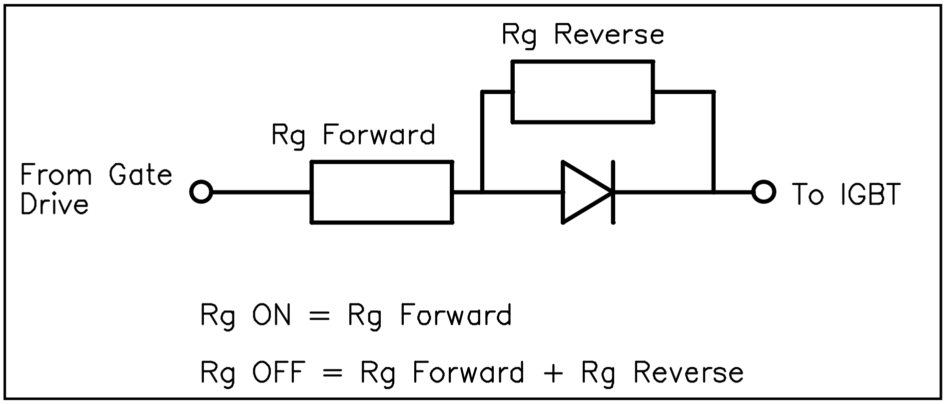

Figure 5. Gate-drive steering circuit

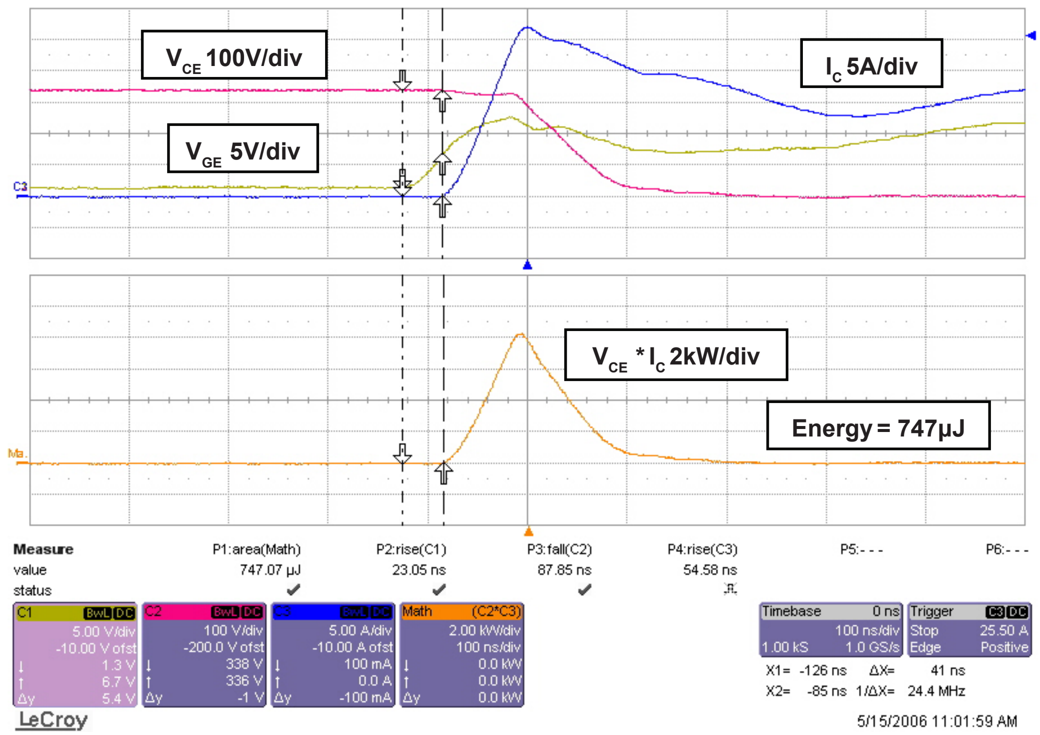

Figure 6. Standard copack IGBT turn-ON with R_G = 39Ω

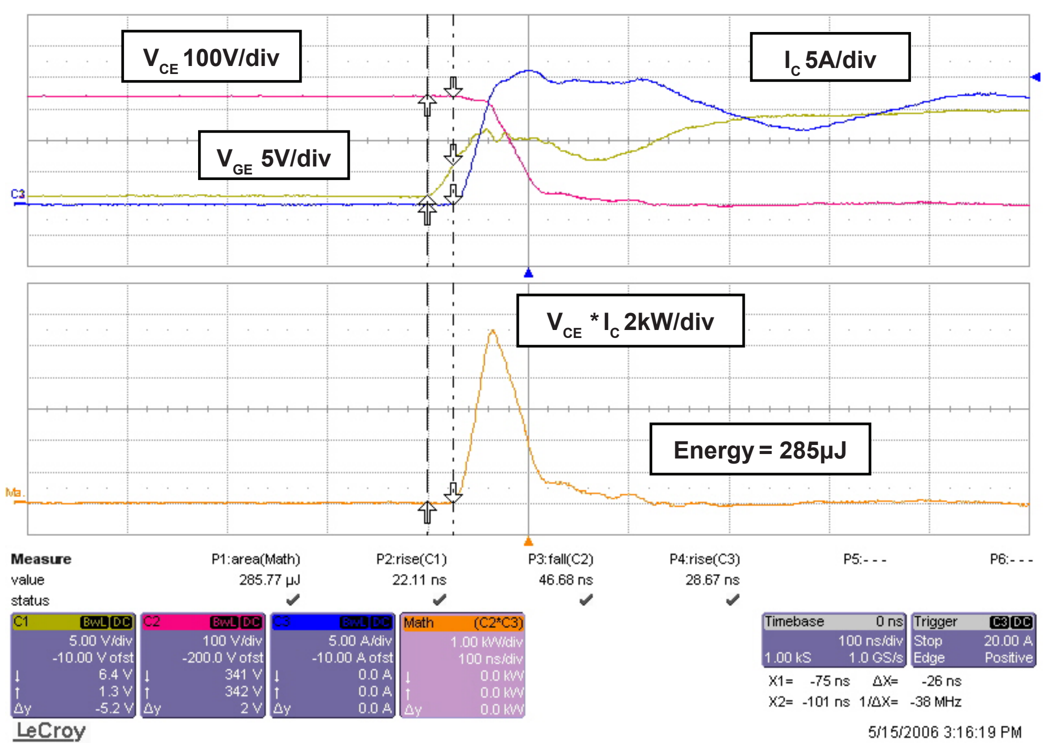

Figure 7. Cree CoPack CID150660 IGBT turn-ON with R_{GON} = 10Ω

With the all Si copack the IGBT turn ON switching loss measures 747µJ whereas a measurement of 285µJ is achieved with the Cree Inc. part. This represents a 62% reduction. The combination of a zero reverse recovery device and the ability to turn the IGBT ON harder allows this significant improvement.

Even though diode reverse recovery has no effect electrically on IGBT turn-OFF, there will be a slight decrease in IGBT turn-OFF energy. Because of the significant decrease in turn-ON switching loss the IGBTs in the system will run cooler. IGBT turn-OFF tail currents are dependent on junction temperature thus reductions on the order of 3% to 5% in turn-OFF switching loss can be expected at thermal stabilization. In this particular example, because the turn-OFF gate resistance could be reduced, a 24% reduction in turn-OFF is achieved.

Figure 8. shows the Watts loss difference per copack, in the fully optimized system, between the all Si device and the Cree Inc. part. The diagram shows the Watts losses, both switching and conduction in the IGBT and diode for each device in the system.

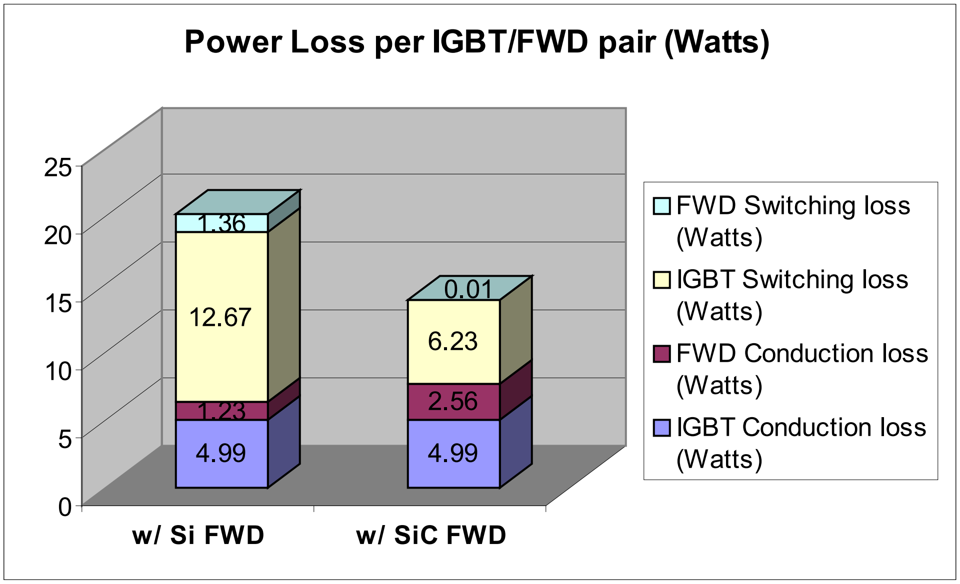

Figure 8. Watts loss comparison per device

The Cree Inc. part yields a dramatic 32% reduction in overall Watts loss in the drive's inverter section. The increase in conduction loss observed in the SiC Schottky is due to its smaller die size and device physics. This increase in conduction Watts loss is negligible however considering the significant reductions achievable in the switching losses of both the IGBT and FWD. Even with these higher conduction losses the diode still performs well within the drive design parameters in a full regenerative scenario by virtue of the much cooler overall system temperatures. 10µs non-repetitive and 8.3ms repetitive surge ratings on the SiC device are listed in the datasheet and show the device operates within all standard motor drive design guidelines.

2. Thermal Improvement

These CoPacks are non-isolated devices i.e. their metal tabs are floating at collector voltage. Because of this an isolating thermally conductive material needs to be placed between the device and the heatsink that they mount to. Using the following equations, monitoring the pertinent temperatures and knowing the thermal resistances it is possible to obtain a reasonable estimation of both IGBT and FWD junction temperatures.

$$\boxed{T_{J\,(IGBT)} = T_{AMBIENT} + ((P_{IGBT} + P_{DIODE})(R_{\theta sa} + R_{\theta cs})) + (P_{IGBT} * R_{\theta ijc})}$$

$$\boxed{T_{J\,(DIODE)} = T_{AMBIENT} + ((P_{IGBT} + P_{DIODE})(R_{\theta sa} + R_{\theta cs})) + (P_{DIODE} * R_{\theta djc})}$$

Where,

P = Power dissipated in each device (W)
$R_{\theta sa}$ = Heatsink to ambient thermal resistance (°C/W)
$R_{\theta cs}$ = Case to heatsink thermal resistance (°C/W)
$R_{\theta ijc}$ = IGBT junction to case thermal resistance (°C/W)
$R_{\theta djc}$ = FWD junction to case thermal resistance (°C/W)

With the standard all Si device and the drive operating at full rated load in a 40°C ambient, the model yields the following junction temperatures;

$T_{J(IGBT)}$ = 112.1°C & $T_{J(DIODE)}$ = 106.9°C

With the Cree Inc. part and the drive operating at full rated load in a 40°C ambient, the model yields the following junction temperatures;

$T_{J(IGBT)}$ = 88.5°C & $T_{J(DIODE)}$ = 86.4°C

The Cree part yields the following reductions in junction temperatures

$\Delta T_{J(IGBT)}$ = 23.6°C & $\Delta T_{J(DIODE)}$ = 20.5°C

A thermocouple was placed in a small hole drilled in the heatsink and the thermal profiles as shown in ***Figure 9.*** were recorded.

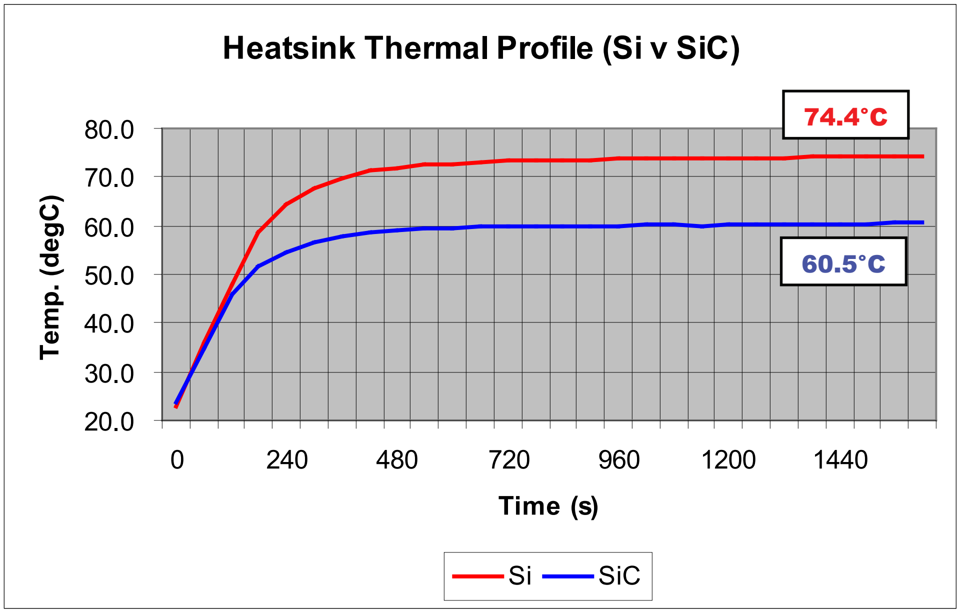

Figure 9. Heatsink temperature reduction

Note that the heatsink temperature rise from ambient (23°C) will be reduced from 51.4°C to 37.5°C or a 27% reduction.

By replacing existing all Si solutions with their SiC counterparts, the designer now has the ability to extract more power output from the drive for the same given size packaging. In this particular example, the drive output rating will be increased to 3.03kW (4HP). Also, with this particular family of drives and SiC technology employed, the 0.75HP drive will become a 1HP unit and the 1.5HP drive will be capable of a 2HP rating.

For new programs, SiC technology enables the use of reduced heat sinking and/or cooling leading to overall system cost reduction. The Cree Inc. device also presents the possibility of decreasing IGBT rating for the same application or allowing further headroom for higher short-term overload capability with the same IGBT. Considering that every 10°C drop in device temperature generally represents a doubling in MTBF, the impact of the Cree Inc. device on reliability is dramatic.

3. EMI Improvement

Another advantage of changing to SiC Schottky diodes that needs to be highlighted is the significant reduction in Conducted and Radiated EMI that results from the elimination of the large “snappy” recovery currents during diode turn OFF. ***Figure 10.*** shows a comparison of Conducted scans on one of the input phases of the drive with the limits being in accordance with European standard EN61800-3, first environment residential, unrestricted quasi peak.

Only the spectrum from 1.5MHz to 30MHz is shown, as there was virtually no difference between technologies at the lower end of 150kHz to 1.5MHz. The yellow trace represents the all Si “off-the-shelf” unit. The green trace represents the unit modified with the Cree Inc. CoPack in place of the standard all Si copack with no gate drive optimization. Note the overall reduction across the full spectrum with >5dB improvement near the peaks at 4.5MHz and 13MHz. The blue trace represents the unit with the Cree Inc. device with the gate drive optimized to achieve the best possible reduction in switching loss. Note the comparable magnitude in peak levels when compared to the all Si unit.

What has been accomplished is a significant reduction in overall inverter Watts loss and a very comparable Conducted EMI spectrum.

Figure 10. Conducted EMI comparison

Using a Lower Amperage Rated SiC Schottky.

For each amperage rating of IGBT offered, Cree Inc. also offers two different amperage rating SiC Schottky options. The above data was generated using a set of CID150660 parts. The CID150460 can also be used in this example. The SiC Schottky in the CID150460 has a rating of 9 Amps at T_{CASE} = 100°C as opposed to 13 Amps at T_{CASE} = 100°C for the CID150660. The forward voltage drop will be higher leading to greater diode conduction losses however, the switching losses in the diode and IGBT will still be reduced by the same amount.

This part gives the designer a lower cost option with slightly less performance than the CID150660 but still presents a significant improvement over the all Si solution.

If the CID150460 devices are used in the same drive, the Watts loss reduction shown in ***Figure 11.*** will be observed.

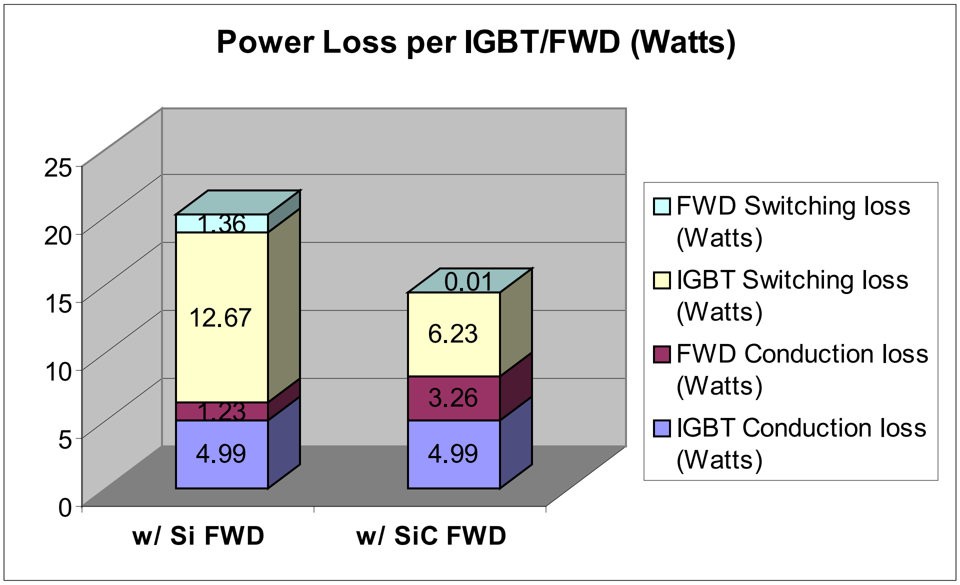

Figure 11. Watts loss comparison per device

Note the slightly higher FWD conduction loss than with the CID150660 however, an overall Watts loss reduction of 28% is still achieved. This part yields the following reduction in junction temperatures;

$$\Delta T_{J(IGBT)} = 21.5°C \;\; \& \;\; \Delta T_{J(DIODE)} = 15.2°C$$

Note the IGBT junction temperature has still dropped >20°C and the increase in diode power dissipation still yields a 15°C drop in junction temperature compared to the standard all Si device. Even with this higher conduction loss in the diodes they still perform within the drive design parameters in a full regenerative scenario by virtue of the much cooler overall system temperatures. The EMI signature improvement will be exactly the same. Also, the 10ms non-repetitive and 8.3ms repetitive surge ratings on the SiC device are listed in the datasheet and show the device operates within all standard motor drive design guidelines.

Figure 12. shows the difference in overall inverter Watts loss reduction between the CID150660 and the CID150460 in this particular drive example at various PWM frequencies. Note that the higher the PWM frequency the greater the benefit of SiC technology.

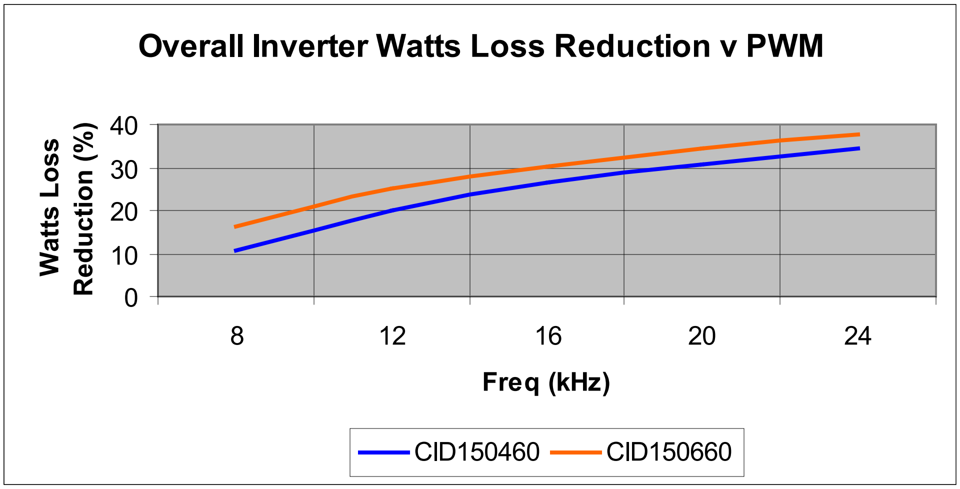

Figure 12. Performance differential with the lower amperage SiC Schottky.

Summary

SiC Schottky diodes in the freewheeling section of an inverter allow for efficiency, thermal and EMI improvements that are simply not possible with current Si based technology. Smaller amperage rated SiC diodes in the system are possible by virtue of the elimination of reverse recovery currents. These devices also enable the possibility of running an inverter at much higher PWM frequencies. In the example above with the CID150660 parts, it is possible to increase the PWM frequency to 34kHz (more than double the default) before realizing the equivalent inverter Watts loss with the standard all Si parts. Cree Inc. has designed in two different SiC Schottky amperage rated devices for each IGBT amperage rating offered, thus giving the designer the ability to select parts with cost/performance optimization in mind.

Utilizing Cree Inc. CoPacks presents many different improvement options to the overall system design. Whether it is increasing PWM frequencies to reduce magnetic and filtering component size and count, increasing power output capability to create higher output ratings from existing frame sizes, increasing system efficiency, improving reliability or any combination of the above, the possibilities are indeed compelling.

Cree, Inc.
4600 Silicon Drive
Durham, NC 27703
USA Tel: +1.919.313.5300
Fax: +1.919.313.5451
www.cree.com/power