

SiC Puts New Spin On Motor Drives

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Silicon carbide enables the creation of near-perfect high-voltage diodes whose speed and power-handling capabilities open new applications in variable-frequency motor drives. This will lead to higher density power modules that operate at higher junction temperatures.



For the past two decades, Insulated Gate Bipolar Transistors (IGBTs) and their associated silicon (Si)-based Free Wheeling Diodes (FWDs) have been the mainstay switching devices in 3-phase inverters. With recent advances in the ability to grow high-quality single-crystal silicon carbide (SiC) wafers, the time has come to recognize the true potential this technology has to offer. The advantages of SiC over its counterpart Si and gallium arsenide (GaAs) power-switching devices become apparent upon viewing their characteristic differences (Fig. 1).

The implementation of this technology in the field of motor control will come in two phases. The first phase will be the replacement of the Si PiN diode with a SiC Schottky Barrier Diode (SBD). The second phase will be the replacement of the IGBT with a SiC-equivalent transistor. This work

is in progress and will permit further switching-loss reduction, leading to higher density power modules that can operate at significantly higher junction temperatures.

Schottky diodes are inherently capable of high-speed switching (< 50 nS), but previously have been based on Si technology, and thus limited to practical applications of < 200-V breakdown voltage due to the moderate field strength of Si. However, with SiC, the breakdown field strength is

approximately a factor of 10 greater than Si. Therefore, the rated voltages can be a factor of 10 greater, permitting the use of these efficient high-speed devices in high-voltage inverters.^[2]

The SiC SBD's greatest advantage over its counterparts in high-power switching applications is its characteristic zero reverse recovery current, even at the highest junction temperature operation allowable. The SiC SBD, being a majority carrier, does not have any stored minority carriers, resulting in its minimal reverse recovery charge (Q_{rr}) during turn-off. However, a small

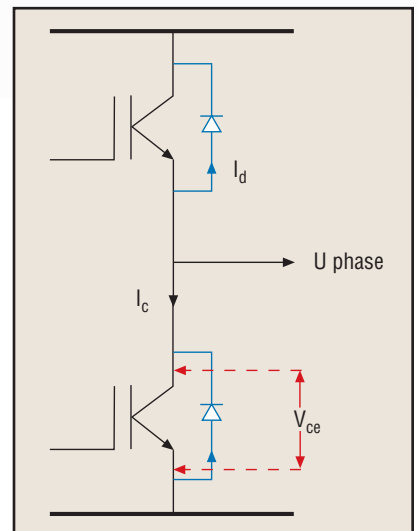


Fig. 2. One phase-leg of a 3-phase inverter.

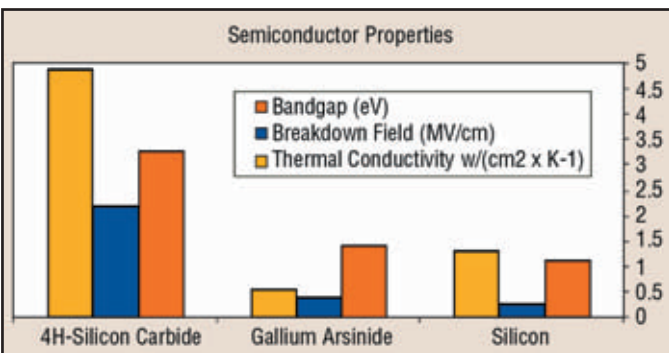


Fig. 1. Characteristic differences between Si, GaAs and SiC technologies.^[1]

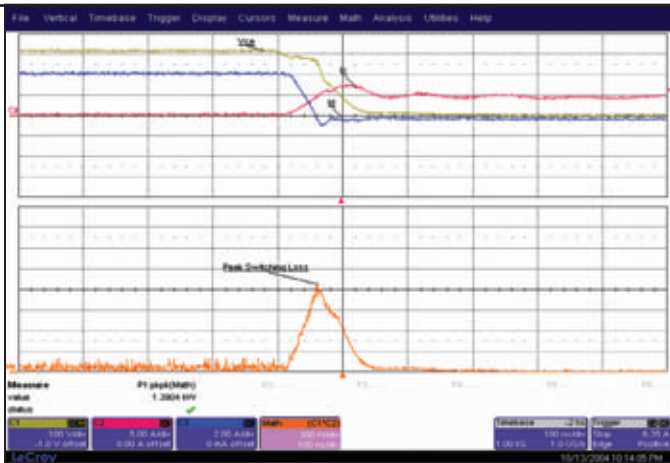


Fig. 4. Lower IGBT turn-on and upper FWD turn-off with SiC-based parts in VFD operating at 4.2 A (rms) output, 10-kHz PWM @ 40°C ambient.

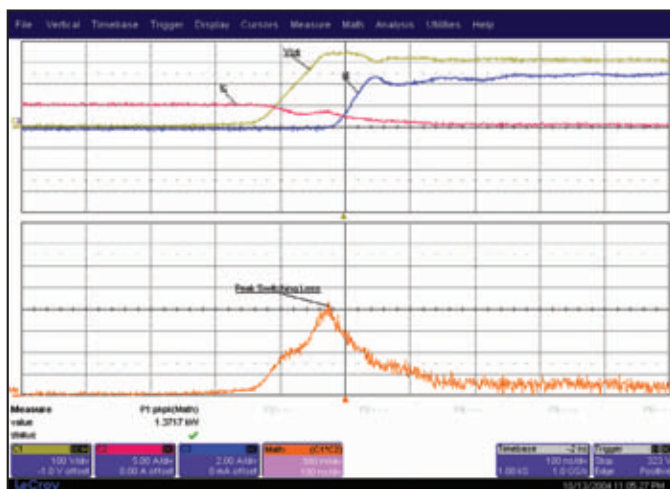


Fig. 5. Lower IGBT turn-off and upper FWD turn-on with Si-based parts in VFD operating at 4.2 A (rms) output, 10-kHz PWM @ 40°C ambient.

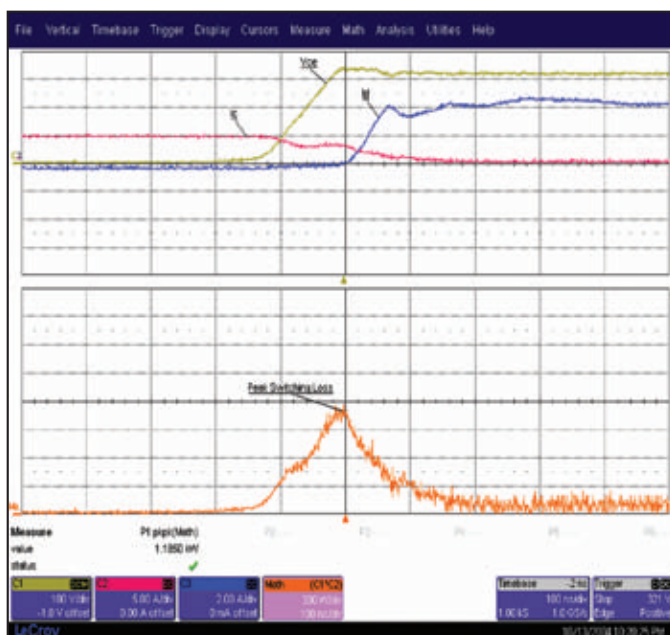


Fig. 6. Lower IGBT turn-off and upper FWD turn-on with SiC-based parts in VFD operating at 4.2 A (rms) output, 10 kHz PWM @ 40°C ambient.

By far, the majority of VFDs on the market today utilize power module technology. Typically, in drives of this size, the module contains both the inverter and rectification sections, and if need be, a seventh IGBT for dynamic braking. The power module is mounted to a heatsink, and typically the thermal interface is some form of silicon grease with a thermal resistance between module base-plate and heat sink, somewhere in the region of 0.1°C/W to 0.2°C/W.

Because the IGBTs used in this VFD have their metal tabs floating at collector voltage, the thermal interface is actually a heatsink type of isolation material, with all the TO-220 packs being torqued down to the heatsink by means of a small metal bar across all six of them. The metal bar is then fastened to the heatsink by means of a screw at either end. This is not an ideal interface and yields a 6.87°C/W thermal resistance after measuring the IGBT case temperatures.

At 40°C ambient, with the Si FWDs, the IGBT junction temperature calculated out to 77.5°C and the FWD junction temperature to 70.8°C. With SiC FWDs, the IGBT junction temperature dropped to 70.4°C and the FWD junction temperature to 64.5°C. This represents approximately a 9% decrease in junction temperatures for both the IGBT and FWD. Note that this IGBT percentage difference in junction temperature will actually increase as steady-state junction temperatures increase, by virtue of the characteristic increase in reverse recovery current inherent with Si devices. Looking at the delta in IGBT junction temperature with respect to ambient, the SiC FWDs present an 18.5% reduction.

For VFDs that operate at steady-state junction temperatures close to 120°C with Si FWDs, this reduction represents a significant improvement. It not only gives the extra headroom for increased power output, but also offers greater overload capability within the same package. Another important benefit is the fact that every 10°C decrease in steady-state junction temperature represents a doubling of the device's life expectancy.

PWM Carrier Frequency

PWM carrier frequency is another VFD variable that can benefit from these reduced inverter losses. Look at the example again from the perspective of increasing PWM frequency but maintaining the same power output. With the switch to SiC FWDs, the PWM frequency can be increased to 22.24 kHz before realizing the same inverter losses with Si FWDs. This is a significant increase and could be especially helpful when dealing with more specific applications where the audible carrier frequency noise is a concern. The VFD carrier frequency is now outside the human hearing range.

Another option the design engineer can take advantage of with these improvements is to investigate the possible increase in power output of the VFD package by switching to SiC FWDs and maintaining the same PWM frequency. In this example, the power output of the VFD can increase approximately 20% while maintaining a 10-kHz PWM frequency to match the equivalent inverter losses seen with the Si FWDs. However, note that when evaluating increased power output, the dc bus capacitors, dc link choke and input bridge may or may not need to be modified to handle the increase, depending on design margin. This needs to be evaluated by the design engineer on a case-by-case basis.

EMI Considerations

Since CE approval became mandatory in 1996 for all electrical equipment to be sold in Europe, EMI reduction to qualify

for CE approval has become an integral part of every new VFD design program. Apart from passing several immunity tests, CE approval for VFDs also requires passing conducted emissions and radiated emissions, as outlined in the Industrial Generic Standard EN61800-3 guidelines for Adjustable Speed Electrical Power Drive Systems.

For the VFDs used in this article, an external RFI filter is required to comply with conducted emissions guidelines. The filter was not available during testing, so the focus here is on the radiated emissions difference between the VFD with Si and SiC FWDs. The units were tested in a certified indoor 10-meter anechoic chamber with 30 meters of shielded output cable driving an unloaded 1-hp motor. Peak data obtained from scans with both VFDs is shown in Fig. 8.

The improvement in radiated emissions is instantly apparent. The main reason for this reduction is again due to the inherent zero reverse recovery property of the SiC devices. As manufacturers of Si PiN diodes try and improve switching times, the reverse recovery currents in these devices become more “snappy.” The increased di/dt also can contribute to an increase in the peak voltage across the diode at recovery, adding to the VFD radiated EMI levels. The elimination of the recovery current in the SiC devices leads directly to the improved emissions spectrum observed.

In the 30-MHz to 40-MHz region, which is typically the noisiest realm with VFDs, the SiC diodes yield a 7 dB reduction at the highest peak around 34 MHz. Furthermore, there is a general 3-dB to 7-dB peak reduction across the 50-MHz to 200-MHz spectrum. This represents a significant improvement, especially to the VFD design engineer who spends many hours trying to find every last dB reduction possible in order to fall under the required limits.

Conclusion

Until now, the primary market for these higher voltage SiC SBDs has been predominantly in the switch-mode power supply and power factor correction markets. SiC enables the creation of near-perfect high-voltage diodes, and the advantages offered by this unique technology open up many new possibilities and opportunities in the motor drive and hybrid electric vehicle markets. The benefits realized by simply replacing the Si FWD with a SiC equivalent (thermal, EMI, frequency and reliability) are compelling.

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1. Hodge, Stuart Jr., “SiC Schottky Diodes in Power Factor Correction,” Cree Inc., http://powerelectronics.com/mag/power_sic_schottky_diodes_3/.
2. Wright-Patterson AFB, OH, “Silicon Carbide Schottky Diodes

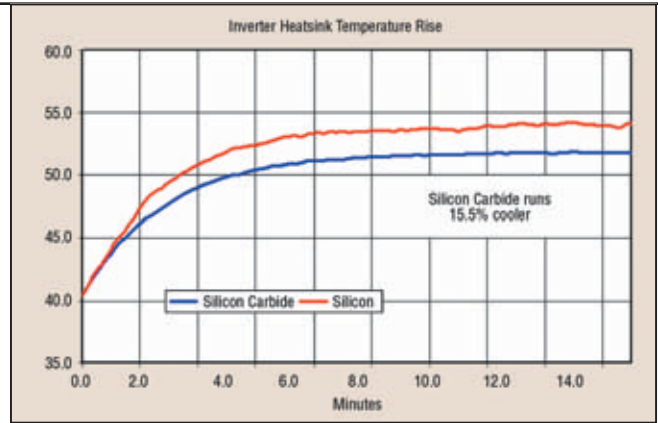


Fig. 7. Heatsink temperature profiles.

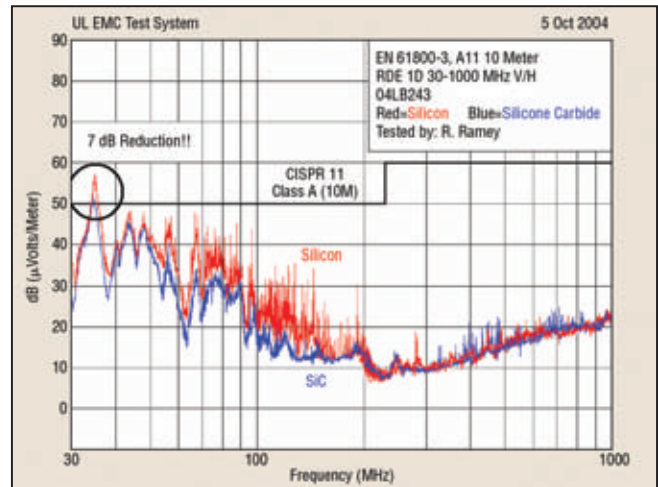


Fig. 8. Radiated EMI scans.

Parameter	Units	Si Pin	SiC SBD	Percent Reduction
Peak reverse recovery current I_{rr}	A	4.8	0.8	83%
Reverse recovery time t_{rr}	nS	112	20 *	82%
Recovery charge Q_{rr}	nC	241	28	88%
Switching loss per IGBT	W	1.2	0.7	41%
Switching loss per FWD	W	0.3	0.01	96%
Total switching loss per IGBT/FWD**	W	1.5	0.71	53%

* SiC t_{rr} is only due to junction capacitive charging.
 ** Assuming a 0.8 output power factor.

Table. Summary of inverter switching losses.

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3. Singh, Ranbir, and Richmond, James, “SiC Power Schottky Diodes in Power Factor Correction Circuits,” Cree Inc., <http://scdms05:8000/ftp/pub/CPWR-AN01.pdf>.

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