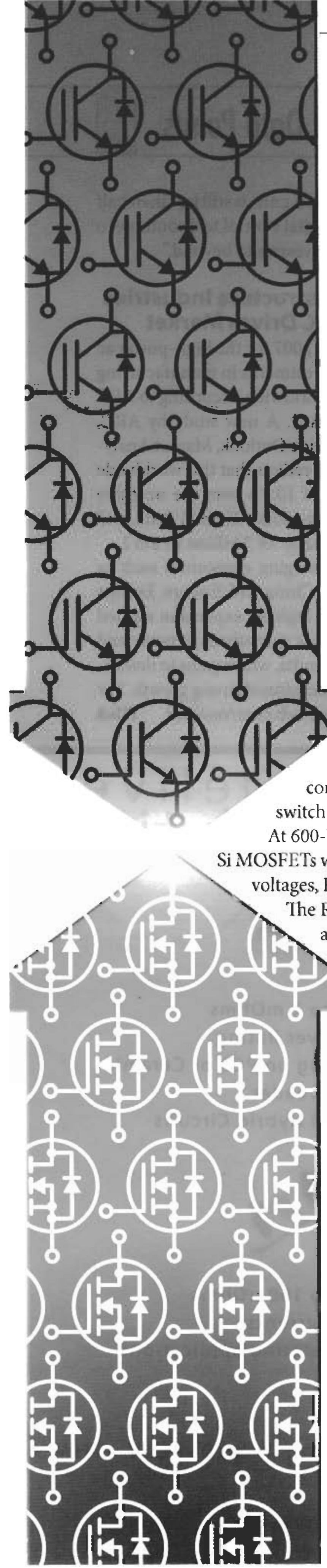

Silicon Carbide MOSFETs Challenge IGBTs

SiC technology has undergone significant improvements that now allow fabrication of MOSFETs capable of outperforming their Si IGBT cousins, particularly at high power and high temperatures.

By Michael O'Neill,
Applications Engineering Manager, CREE, Durham, N.C.

In light of recent silicon carbide (SiC) technology advances, commercial production of 1200-V 4H-SiC[1] power MOSFETs is now feasible. There have been improvements in 4H-SiC substrate quality and epitaxy, optimized device designs and fabrication processes, plus increased channel mobility with nitridation annealing.[2] SiC is a better power semiconductor than Si, because of a 10-times higher electric-field breakdown capability, higher thermal conductivity and higher temperature operation capability due to a wide electronic bandgap.

SiC excels over Si as a semiconductor material in 600-V and higher-rated breakdown voltage devices. SiC Schottky diodes at 600-V and 1200-V ratings are commercially available today and are already accepted as the best solution for efficiency improvement in boost converter topologies. In addition, these diodes find use in solar inverters, because they have lower switching losses than the Si PIN freewheeling diodes now used in that application.

At 600-V and 1200-V ratings, IGBTs have been the switch of choice for power conversion. Previously, Si MOSFETs were handicapped in those applications by their high on-resistance ($R_{DS_{ON}}$). At high breakdown voltages, $R_{DS_{ON}}$ increases approximately with the square of the drain-source breakdown voltage $V_{DS_{MAX}}$.[3] The $R_{DS_{ON}}$ of a MOSFET consists of the sum of the channel resistance, the inherent JFET resistance and the drift resistance (Fig. 1). The drift resistance (R_{DRIFT}) is the dominant portion of the overall resistance, where d equals drift-layer thickness, q equals electron charge, μn equals channel mobility and N_D equals doping factor.

The new generation of SiC MOSFETs cuts drift-layer thickness by nearly a factor of 10 while simultaneously enabling the doping factor to increase by the same order of magnitude. The overall effect results in a reduction of the drift resistance to 1/100th of its Si MOSFET equivalent.

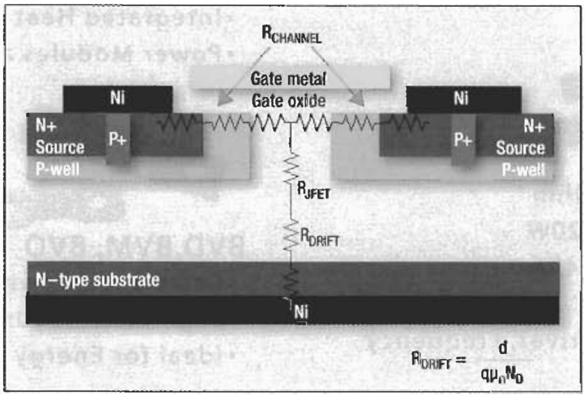

Fig. 1. *Cross-section of DMOSFET power transistor shows its resistive components: the channel resistance, the inherent JFET resistance and the drift resistance that combine to produce a relatively high on-resistance.*

The improved SiC MOSFET discussed here is an engineering sample of a 1200-V, 20-A device with a 100-mΩ $R_{DS_{ON}}$ at a 15-V gate-source voltage. Besides its inherent reduction in on-resistance, SiC also offers a substantially reduced on-resistance variation over its operating temperature. From 25°C to 150°C, SiC variations are in the range of 20%, compared with 200% to 300% for Si. The SiC MOSFET die is capable of operation at junction temperatures greater than 200°C, but the engineering sample is limited in temperature to150°C by its TO-247 plastic package.

Compared with a Si IGBT, a SiC MOSFET has a substantial advantage in conduction losses, particularly at lower power outputs. By virtue of its unipolar nature, it has no tail currents at turn-off, thereby leading to greatly reduced turn-off losses. Table 1 shows the switching loss difference when compared with a standard off-the-shelf 1200-V IGBT.

The switching losses of a SiC MOSFET are less than half those of a Si IGBT (1.14 mJ versus 2.6 mJ, respectively). Combining this switching-loss reduction with the lower overall conduction losses, it is clear that the SiC switch is a much more efficient device for high-power-conversion systems.

Three-Phase Solar Inverter

To demonstrate its application as a solar inverter, a 7-kW, 16.6-kHz three-phase grid-connected system was implemented. This B6 topology, developed by the Fraunhofer Institute ISE, uses a split-link dc capacitor with a connection of the neutral conductor to the center point of both capacitors. The unit connects to a 400-V grid, using 1200-V IGBTs as the standard power-conversion devices. These IGBTs were replaced by 1200-V SiC MOSFETs, and the significant performance difference is clearly visible in Fig. 2. Table 2 shows the maximum efficiency and European-efficiency improvements that were achieved.

As seen by the Fig. 2 curves, the SiC devices offer a performance advantage over their Si IGBT counterparts. Maximum efficiency increased by 1.92%, and the overall Euro-efficiency rating improved by 2.36%. This equates to a 50% reduction in overall losses in the system.

Another performance-parameter improvement of note was the system's reduction in heatsink temperature at full-rated power output. At a 25°C ambient, the final steady-state heatsink temperature with the IGBTs was 93°C versus 50°C with the SiC MOSFETs.[3]

There are several different ways of looking at the system benefits obtainable by using a full SiC-based solution in a photovoltaic (PV) power converter:

- *Cost of inductive components.* The volume of an inductive component depends most significantly on the system switching frequency. A good approximation is a reduction close to the reciprocal of the times factor increase in switching frequency, taking into account filling factor and winding technique. The cost of inductive components decreases by about 50% for a two to three times increase in switching frequency (which is entirely possible with this technology). To keep the third harmonic beneath the lower conducted emission floor of 150 kHz, the practical limit for hard switching is just below 50 kHz in these systems.

	E IGBT, 1200-V Infineon BSM 15GD 120 DN2 I_D (max.) = 15 A at 80°C	SiC DMOSFET, 1200-V CREE engineering sample I_D (max.) = 10 A at 25°C to 150°C
V_{DS}	600 V	800 V
Load	Inductive	Inductive (L_L = 500 µH)
V_{GE}	15 V	0 V/15 V
R_G	82 Ω	10 Ω
E_{ON} at I_D = 10 A	1.6 mJ	0.8 mJ
E_{OFF} at I_D = 10 A	1.0 mJ	0.34 mJ

Table 1. *Switching loss comparison.*[2]

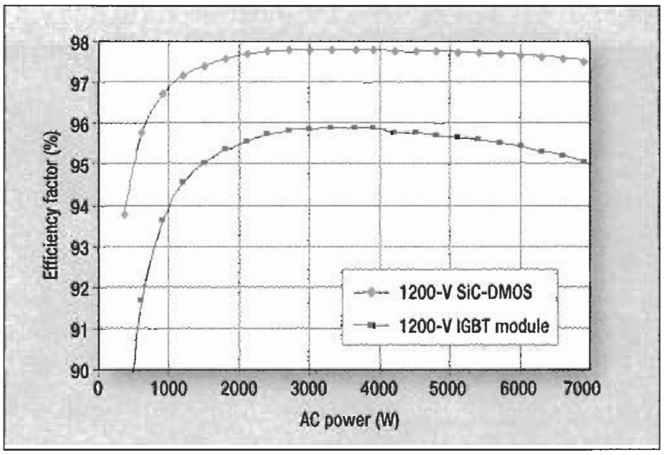

Fig. 2. *Comparison of 1200-V SiC DMOSFET and 1200-V Si IGBT efficiencies in a three-phase inverter shows that at the same voltage rating, the higher-efficiency SiC DMOSFETs provide a performance advantage over their Si IGBT counterparts.*[3]

- *Reduced cooling requirements.* Reductions of up to 50% or more in heatsink temperature are possible with this technology. A comparable reduction in heatsink sizing is possible while still maintaining the higher-efficiency advantage that this technology enables. This solar inverter example of reduction in heatsink sizing should allow a reduction in production cost of around 5%, while still delivering increased annual benefit through feed-in tariffs from the grid. A feed-in tariff is an incentive structure to encourage the adoption of renewable energy through government legislation.
- *Annual feed-in benefit.* A common PV system with 7 kW in Germany produces approximately 7000 kWh per year with a feed-in tariff of 0.49 euro/kWh. (In June 2008, the euro approximately was worth US$1.60.) The annual benefit is approximately 3430 euros. The three-phase inverter given in the previous example showed an increase in Euro efficiency of 2.36%. This equates to an annual gain of 81 euros per year with this particular system. This is the estimation for central Europe. However, if looking at southern Europe, where the

	Max. efficiency (η)	Euro efficiency*
Fairchild IGBT	$\eta_{MAX} = 95.89\%$	$\eta_{EURO} = 95.07\%$
CREE's SiC DMOSFET	$\eta_{MAX} = 97.81\%$	$\eta_{EURO} = 97.43\%$
Efficiency gain	$\Delta\eta_{MAX} = 1.92\%$	$\Delta\eta_{EURO} = 2.36\%$

$^*\eta_{EURO} = 0.03 \times \eta_{5\%} + 0.06 \times \eta_{10\%}\% + 0.13 \times \eta_{20\%} + 0.1 \times \eta_{30\%} + 0.48 \times \eta_{50\%} + 0.2 \times \eta_{100\%}$

Table 2. *Measured efficiencies (single-phase inverter).*[2]

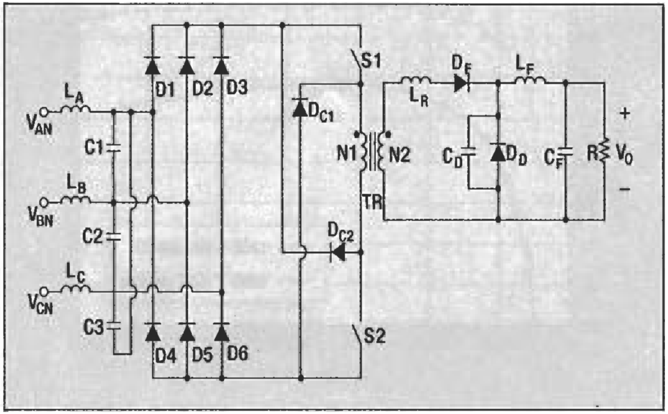

Fig. 3. *Three-phase 3-kW, HPF, two-switch forward converter initially employed 1200-V IGBTs, which were replaced by 1200-V SiC DMOSFETs that improved system efficiency.*[5]

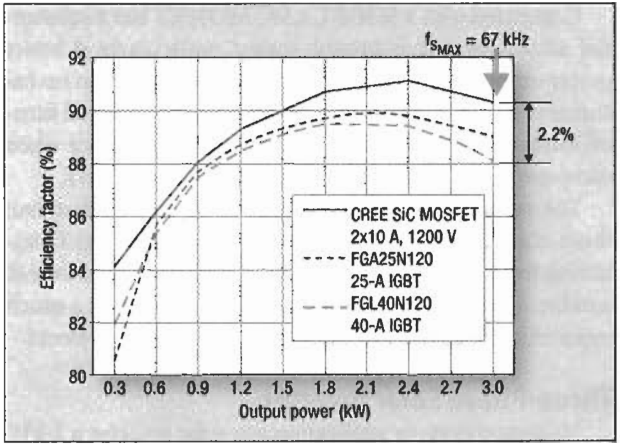

Fig. 4. *Efficiency profile comparison at 67 kHz shows a higher SiC efficiency at 3-kW output and throughout the entire load curve, as well as a case-temperature reduction with the MOSFETs relative to the IGBTs.*[5]

irradiation level is about twice that in Germany, the annual benefit can be even greater, as shown in a table in the online version of this article.[4]

Three-Phase High-Power-Factor Rectifier

A three-phase six-switch rectifier followed by an isolated dc-dc converter is typically used in three-phase applications that require high power factor (HPF) and galvanic isolation between input and output. The rectifier shown in Fig. 3 (a 3-kW zero current switching resonant topology) can achieve the same goal with only two switches. When switches S1 and S2 are turned on, the stored energy in C1 to C3 is quickly moved to the secondary-side resonant capacitor (C_D) through the transformer (T_R) and resonant inductor (L_R). The discharging time is designed to be approximately equal to one-half of the resonant period (T_O). For an optimal design, T_O should be relatively shorter than the switching period (T_S) to achieve a low total harmonic distortion.

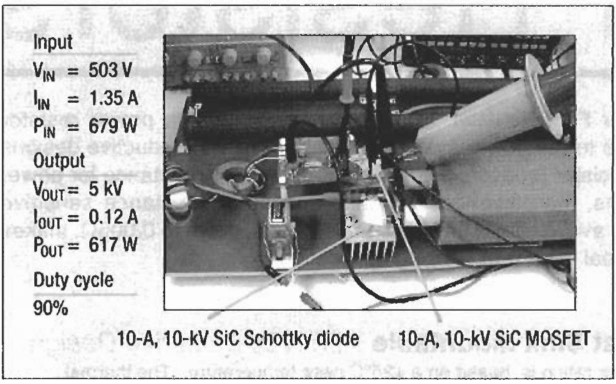

Fig. 5. *Result of a 10-kV SiC MOSFET combined with a 10-kV SiC Schottky diode and an air-core inductor in a boost circuit that accepts a 500-Vdc input and produces a 5-kVdc output, at 20-kHz switching frequency.*[6]

The system was run initially at full load with a pair of standard 1200-V, 25-A-rated IGBTs. These devices were then replaced by a pair of standard 1200-V, 40-A IGBTs, and the system was re-run at full load. The efficiency versus output power curves were recorded.

The IGBTs were then replaced by a pair of 1200-V, 20-A-rated SiC MOSFETs and the exercise repeated. As seen in Fig. 4, the SiC devices resulted in a 2.2% increase in efficiency at a 3-kW output and substantial efficiency improvement throughout the entire load curve. Also of note was a 25°C case-temperature reduction with the MOSFETs versus the 40-A-rated IGBTs and a 36°C difference when compared with the 25-A-rated devices.[5]

10-kV, 10-A SiC MOSFET in a Boost Converter

SiC technology shows significant improvements in the 1200-V MOSFET arena, as revealed in the two previous examples. The performance improvement becomes even greater when compared to Si power switches rated at 6.5 kV and above.

Recently developed was a 10-kV, 10-A SiC MOSFET. The 10-kV device exhibits a drain-source forward voltage drop of only 4.1 V, while conducting full-rated 10-A drain current with a 20-V gate-source voltage. This is equivalent to a specific on-resistance characteristic of only 127 mΩ/cm^2. The drain-source leakage current measured 124 nA at a 10-kV blocking voltage. In a direct comparison with a standard 6.5-kV Si IGBT in a clamped inductive switching test fixture, a SiC MOSFET exhibited 1/200th of the total switching energy of the IGBT. This unipolar SiC MOSFET's turn-on delay time was only 94 ns compared with 1.4 μs for the IGBT and the turn-off time was only 50 ns instead of the IGBT's 540 ns.

To analyze in-circuit performance, a 10-kV SiC MOSFET was combined with a 10-kV SiC Schottky diode and an air-core inductor in a standard boost-circuit topology (Fig. 5). The circuit was designed to boost a 500-Vdc input to a 5-kVdc output at a switching frequency of 20 kHz. The system ran at 91% efficiency throughout the power band up

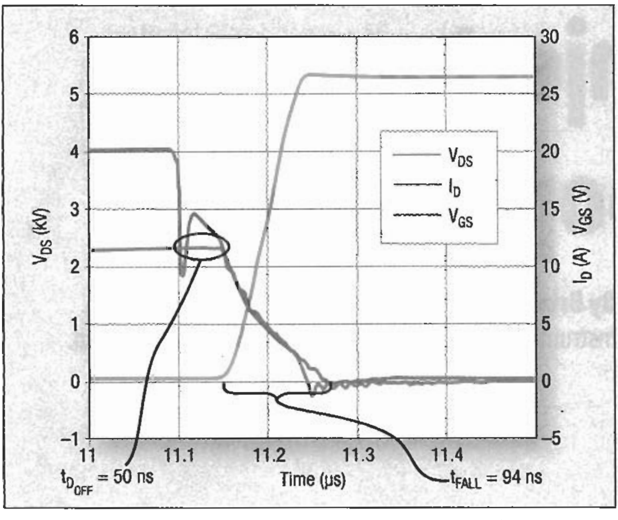

Fig. 6. *A 10-kV SiC MOSFET running at 20 kHz and dissipating 600 W exhibited about 1.5-µs drain current turn-off transient.*[6]

to 600 W. Considering that this same circuit with standard Si MOSFET switches would only be capable of running at a few hundred Hertz switching frequency, there is an even greater performance advantage with SiC material at these voltage levels. The waveform shown in Fig. 6 exhibits the exceptionally fast turn-off transient of this system.[6]

With the most recent advancements in SiC materials processing and device design, it will soon be possible to produce reliable MOSFET switches for the commercial marketplace. Considering the recent surge in interest in alternative energy systems, SiC technology is now ready to further improve their benefits. The reduction in power losses that this technology will provide in a PV system's power conversion section will enable more efficient usage of PV panel energy, in turn providing more power to the grid and allowing a reduction in future fossil-fuel generation. **PETech**

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