Silicon Carbide in Automotive

Some of the first markets to use SiC include the server, industrial, telecom, lighting, and induction heating power supply markets. Since then, SiC has also penetrated the solar, UPS inverter, drives, and avionics markets. Most recently, SiC power components have begun to permeate automotive applications such as on-board and off-board chargers, and on-board auxiliary power supplies in electric vehicles (EVs) and hybrid electric vehicles (HEVs). **Jeffrey B. Casady, Ph.D., Business Development & Programs Manager, Cree Power & RF, Durham, USA**

The SiC power semiconductor industry has penetrated many markets since the first full release of SiC diodes in 2001, SiC power transistors in 2011, and SiC power modules in 2012 [1-4]. Now, for the first time, 900 V SiC power transistors are being considered for automotive EV/HEV drivetrain inverters and (when applicable) boost stages.

SiC Diodes

For automotive applications, voltage ratings of 600 V to 900 V are most common. SiC diodes are a mature technology, with over 100 different products in the market and over 13 years of field history. Cree alone manufactures more than 70 diode products with voltage ratings ranging from 600 V to 1700 V, current ratings spanning 1 A to 50 A, and package options including through-hole, surface mount, and bare die. Several other power semiconductor vendors also offer SiC diodes.

Cree 650 V and 1200 V SiC diodes are currently designed in, and being shipped for, multiple on-board and off-board charger products in mainstream commercial automotive markets. Using SiC, customers can achieve compact power densities and lower heat dissipation not possible in Si. The SiC diodes used are fully automotive qualified. Not only do the customers value the compact size, lower heat dissipation, and higher efficiency SiC offers, the reliability is a key selling point as well. After more than 13 years in the market, the failure-in-time (FIT) rate of SiC diodes is better than Si, and is less than one fail per billion hours of operation for Cree.

SiC MOSFETs

For SiC, 1200 V and higher MOSFETs have been fully released in the marketplace since 2011, and these MOSFETs are currently being used in automotive for auxiliary power supplies and off-board chargers connected to three-phase power. 650 V to 900 V SiC MOSFETs in development are targeted at automotive OEMs and Tier One suppliers as pre-released products in 2013-14 for primarily on-board drivetrain applications.

Last year, the Cree C2M0080120D 1200 V SiC MOSFET was designed into the HEV/EV power converter (auxiliary power supply) pictured in Figure 1, which achieved a 25 % reduction in product size and reduced peak power losses by 60 % according to the manufacturer, Shinry Technologies [5]. This converter was designed for use in an HEV/EV bus using a 750 V DC input and 27 V DC output with an active clamp topology. The DC-DC topology with SiC MOSFET is active clamp forward topology. Key improvements enabled by the SiC MOSFET include: raising efficiency from 88 % to 96 %, reducing size and weight by 25 % to 60 %, and eliminating cooling fans, which realized reductions in both cost and audible noise

By using 1200 V SiC MOSFETs in its 3- to 10-kW DC-DC converters in place of comparable Si components, Shinry achieved considerable efficiency improvement and significant size and weight reduction that were not possible with Si components due to the inherent switching efficiency advantages of SiC relative to Si power switches. The benefits achieved in this example are typical of automotive applications that adopt SiC technology in place of Si. With SiC adoption, users can expect to achieve one or more metrics – system cost, power density, form, fit, and/or function – that are not attainable with Si [6-7]. Consequently, the 1200 V C2M SiC MOSFETs (available in a TO-247 package with 25-, 40-, 80-, 160-, or 280-m? ratings or multiple module platforms) are now employed in the on- and off-board HEV/EV chargers and auxiliary power supplies manufactured by a number of customers. Like IGBTs, the C2M family of SiC MOSFETs is also well suited for paralleling to be used in higher current rated applications [8].

In addition to substantive performance gains, the SiC MOSFET has some other salient advantages. For example, SiC MOSFETs contain a rugged built-in body diode, which eliminates the need for an external anti-parallel Schottky diode in some applications. Body diodes are not present in Si IGBTs and are often unused in Si super junction MOSFETs as well due to poor turn-off performance. In SiC MOSFETs, the body diode has a minimal turn-off loss, enabling reliability improvements in the system. The built-in body diode also reduces the part count, which cuts costs and mitigates implied

Figure 1: **DC/DC converter manufactured by Shinry Technologies for an HEV/EV bus application**

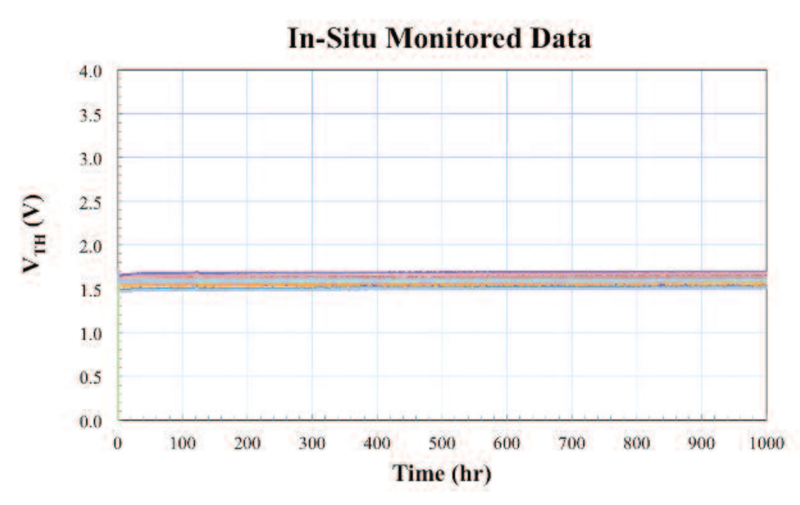

Figure 2: A bias of -15 V applied to Cree's C2M0160120D 1200 V SiC MOSFETs for 1,000 hours at 150°C, which exceeded the maximum recommended value of -10 V in the datasheet. Test results measure an average threshold voltage shift of a negligible 10 mV over the duration

reliability concerns from additional components, wire bonds, and die attach.

Reliability testing conducted on C2M080120D SiC MOSFETs at 150°C for 1,000 hours, constant gate voltage of -5 V, and constant diode current of 10 A reveals that the use of this body diode is very stable. A total of 39 parts were sampled and the only voltage shifts measured were a negligible 0.68 mV shift in the body diode forward voltage drop and a similarly low 4.5 mV shift in the MOSFET on-state voltage [7]. SiC MOSFETs are also extremely stable at higher temperatures. Per Figure 2, a bias of -15 V was applied to C2M0160120D 1200 V SiC MOSFETs for 1,000 hours at 150°C, which exceeded the maximum recommended value of -10 V in the datasheet. Despite this fact, test results measured only a slight 10 mV average shift in V_{TH} and a modest 3.2 mΩ in R_{DSON} [7].

900 V SiC MOSFET Breakthrough

New MOSFET technology will enable even better efficiency, cost, and gate driver control via breakthrough improvements in the on-resistance per unit area, which has progressed from 5 mΩ·cm² in 1200 V commercial SiC MOSFETs (such as the C2M0160120D) to 2-3 mΩ·cm² in 900 V SiC planar MOSFETs [9]. This latest SiC MOSFET technology still uses the same basic, reliable, planar DMOS structure shown in Figure 3, which allows 900 V SiC power transistors to provide breakthrough performance with specific RDSON reductions of over 40 % when compared to the best available 1200 V Si MOSFETs on the market today. This development will enable more cost effective, lower voltage SiC power transistors that exhibit more efficient switching capabilities at higher frequencies. These SiC MOSFET design improvements and their subsequent performance benefits provide opportunities to reduce the overall system cost in next-generation automotive traction inverters.

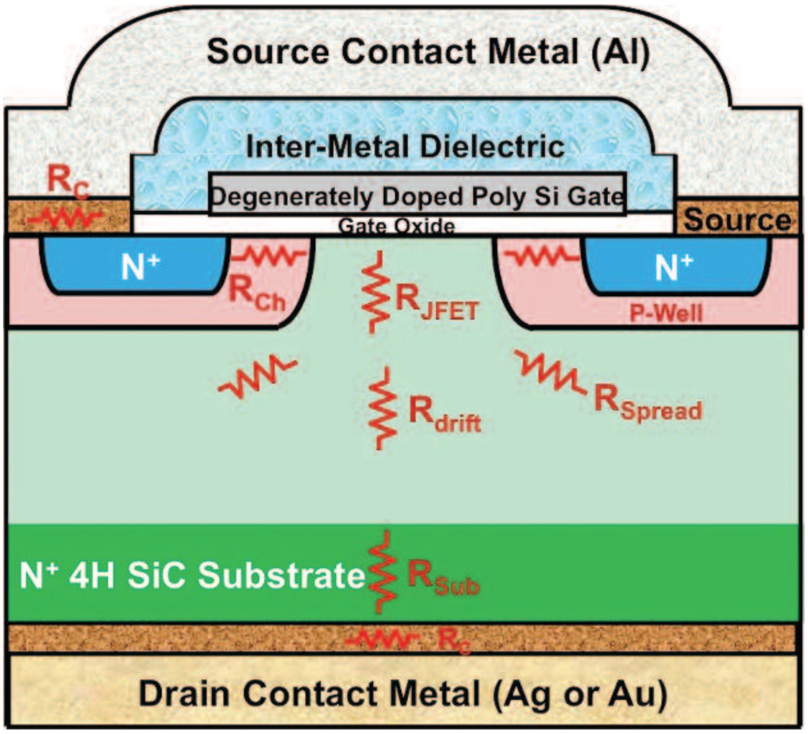

Figure 3: Cree commercially released the Planar SiC double-implanted metal oxide semiconductor (DMOS) structure shown here in 2011. A second-generation (C2M) family was released in 2013, and development samples are being sampled to key customers in 2014. Each generation retains the same basic structure, but specific on-resistance improves with each new series

900 V SiC MOSFET vs. Si Super Junction MOSFET

To benchmark the performance of the new 900 V SiC MOSFET, we can compare the energy stored in the output capacitance (E_{OSS}) of the 900 V SiC MOSFET with advanced super junction Silicon MOSFETs available commercially at 650 V and 900 V. In Figure 4, the E_{OSS} of Cree's 900 V SiC MOSFET is contrasted at 150°C with 900 V Si super-junction and found to be approximately three times lower over the measured R_{DSON} values. In fact, the E_{OSS} of the 900 V SiC MOSFET is comparable (20-30 %) to a 650 V Si super junction MOSFET even though the SiC MOSFET offers 50 % higher breakdown voltage for greater safety margin and also uses the internal body diode.

Another advantageous feature of the 900 V SiC MOSFET is that its high temperature conduction losses are notably reduced relative to Si or GaN. Figure 5 [9] illustrates the normalized R_{DSON} of the 900 V SiC MOSFET, a 600 V GaN transistor, and a 600 V Si super junction transistor compared up to 150°C. At 150°C, the GaN transistor R_{DSON} has increased almost twice (1.85) as much as the 900 V SiC MOSFET, and the 600 V Si super junction transistor has increased almost 2.5 times as much.

900 V SiC MOSFET vs. 650 V Si IGBT

When comparing a 900 V, 65 mΩ SiC MOSFET to a 600 V, 30 A IGBT under the same test conditions (400 V, 150°C, and 10 A), the switching energies measure approximately 60 µJ for the 900 V SiC MOSFET and 260 µJ for the 600 V Si IGBT, which means that the SiC MOSFET exhibits switching energies that are over a

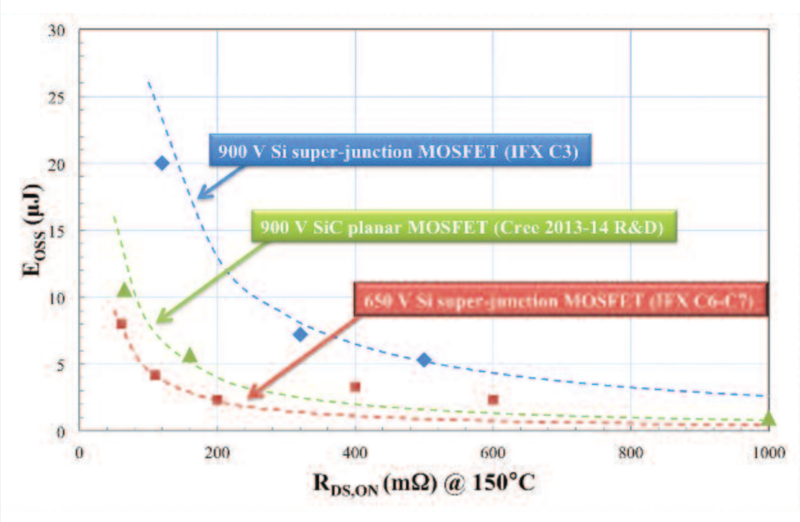

Figure 4: EOSS over RDSON range for Cree's new 900 V SiC MOSFET compared to Si SJ MOSFETs at 650 V and 900 V. The new 900 V SiC MOSFET offers substantially (3X) better performance than the 900 V Si SJ MOSFETs, and is comparable to 650 V Si SJ MOSFETs

factor of 4 lower than those of the Si IGBT despite having a 50 % higher rated blocking voltage, use of an internal body diode, and bi-directional conduction without a knee voltage.

Estimated impact of 900 V SiC MOSFET on specific power and power density in automotive traction inverters at this early stage is limited, but demonstrations elsewhere strongly suggest the potential of obtaining high power densities (well above 20 kW/l) with very high (99 % peak) efficiency [10]. For customers with 400-700 V bus voltages, Cree's new 900 V SiC MOSFET allows system level performance and cost not possible with 650 V Silicon IGBTs or MOSFETs. Higher breakdown voltage, lower on-state and switching losses, reduced part count (through use of the MOSFET body diode), and enhanced ruggedness are now able to be realized at a system level. With other SiC power components, such as the 650 V diodes and 1200 V SJ MOSFETs already in production on automotive platforms, this new 900 V SiC MOSFET will be ready for timely evaluation in traction inverter designs for HEVs/EVs.

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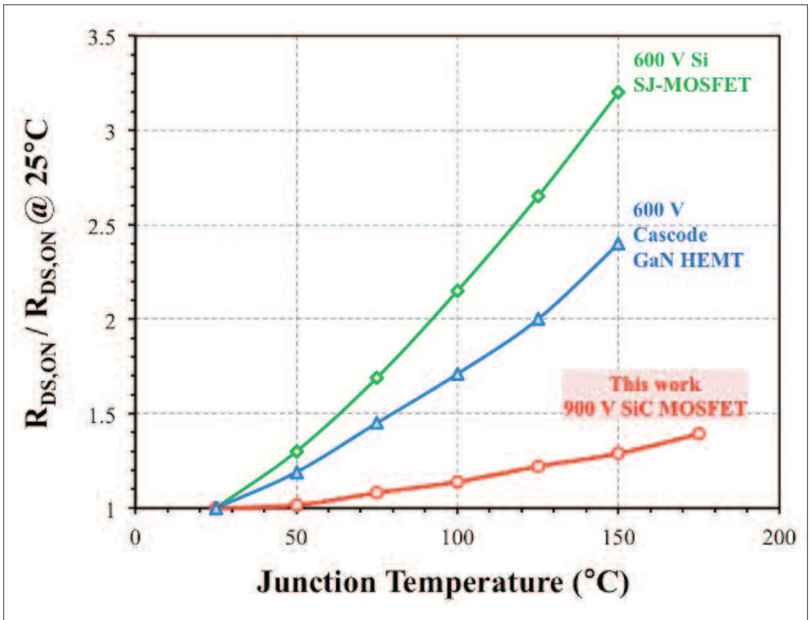

Figure 5: New breakthrough 900 V SiC MOSFETs have a much lower increase in RDSON over temperature relative to both 600 V Si and GaN power transistors

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