Impact of Ultra-Low On-Resistance SiC MOSFETs On Electric Vehicle Drive-Train

Three market / technology forces are moving in concert to create an opportunity for SiC MOSFETs to be an enabling technology in the Battery powered Electric Vehicle (BEV). The pull of the developing traction-drive requirements for BEV drive-train, which can utilize SiC to cut inverter losses by ~78 % in the EPA drive-cycle, can offer BEV designers increased range or reduced battery costs for the same range.

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Cree/Wolfspeed has had SiC wafers commercially released since 1991, diodes since 2001, and MOSFETs since 2011. The SiC power device market continues to mature and grow each year, now well above $200 million per year and increasing in 2017.

SiC development over time

First, continued advances in diameter expansion, volume, quality, and cost of SiC bulk wafers has reached a point where high-volume 150 mm fabrication facilities can utilize SiC wafers as pictured in Figure 1. At Wolfspeed, nearly 18 metric tons of 150 mm SiC wafers were shipped in calendar year 2016 [1] to support markets such as LED, RF, and power, with continued growth forecast for 2017 and beyond. 200 mm diameter SiC wafers have also recently been demonstrated in R&D, as continued wafer diameter expansion development continues. The quality of the SiC wafers has also improved consistently over the years, with median micropipe defect density falling to 0.2 /cm^2 in 2016, enabling large area SiC MOSFETs to be fabricated with high-yield, and meeting automotive AEC-Q-101 qualification.

Second, SiC MOSFETs, first released in 2011, have continued to improve in terms of on-resistance per unit area. For example, the first generation SiC MOSFETs (CMF product series at Wolfspeed [2]) released in 2011 had 25°C specific R_{DSON} of ~8 mΩ·cm^2, rising to 11mΩ·cm^2 at 150°C. The second generation (C2M), released in 2013, dropped on-resistance per unit area substantially, and 1200 V third-generation (C3M [3]) SiC MOSFETs have now been commercially released beginning in 2017 with yet another drastic reduction, especially at operating temperature.

For example, as shown in Figure 2, C3M 1200V SiC MOSFETs (C3M0075120K) have specific RDSON of only 4.4 mΩ·cm^2 at 150°C, which is 60 % lower than the original CMF transistor. The device design aspects are described elsewhere [4]; all three generations are planar DMOS structures, with the third generation utilizing a more compact cell pitch, and optimized doping in the drift region to lower the resistance of the MOSFET over the temperature range. The peak electric fields in the SiC MOSFET are the same or lower than previous generations, so reliability and ruggedness are not compromised.

SiC for automotive applications

Third, the world-wide proliferation of BEVs to accommodate fuel efficiency and CO2 emission standards is driving the need for a different semiconductor technology in the drive-train inverter. Bus voltages vary between 400V-900V typically, depending upon the power of the drive-train inverter, and whether the battery voltage is boosted or not. Since the drive-train inverter is driving a motor, inverter frequencies are typically limited to 20 kHz, with higher-frequencies only benefitting to operate above the audible noise frequency range. Subsequently, most inverter efficiency losses are conduction losses, especially at the light-load conditions typical in BEV

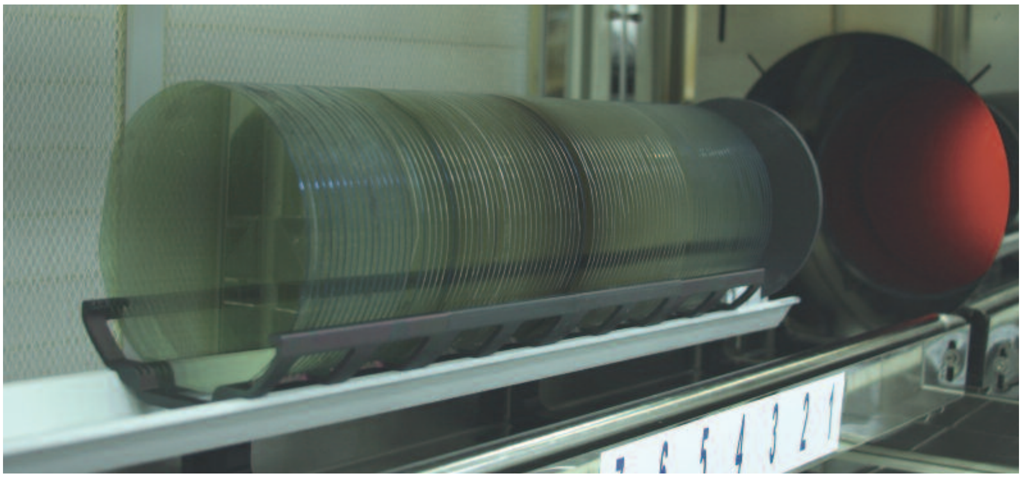

Figure 1: 150 mm diameter SiC substrates are now in common use for global fabrication of SiC power devices. Nearly 18 metric tons of 150mm diameter SiC wafers were produced by Wolfspeed in 2016 [1]

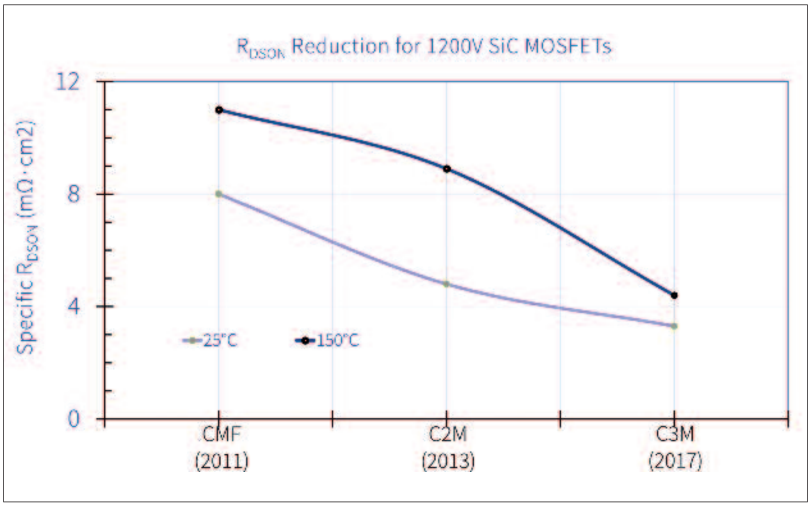

Figure 2: 1200 V SiC MOSFETs introduced since 2011 have drastically lowered on-resistance per unit area, with the third generation SiC MOSFET (C3M product series) enabling a 60 % drop in the 150°C specific RDSON values compared to the originally introduced SiC MOSFET. These latest generation SiC MOSFETs have closer cell pitch and a more optimized doping profile, while maintaining the same or better reliability and ruggedness as the previous generations

operation.

The semiconductor of choice thus far, the silicon IGBT, has an inherent knee-voltage at light-load (due to its bipolar nature) which cannot be easily reduced, even in paralleling copious amounts of Si IGBTs together. However, SiC has 10X higher electric field strength (~3 MV/cm) than Si, so the unipolar SiC MOSFET structure is well-suited for power switch transistors of 650 V, 900 V, and 1200 V, which enables several key-features such as

- SiC MOSFETs have no on-state knee-voltage as found in Si IGBTs.
- SiC MOSFETs can easily be operated in parallel to reduce on-state losses to ≤ 1-2 mΩ.
- SiC MOSFETs can utilize third quadrant conduction, unlike Si IGBTs, by using the SiC body diode during the dead-time (which is quite short with SiC operation), and then opening the SiC MOSFET channel the third quadrant providing the same low on-state losses in reverse conduction as found in forward conduction. The combination of body diode use in dead time and synchronous channel rectification eliminates the need for an external anti-parallel SiC diode, saving space and cost with minimal efficiency impact at frequencies up to 50 kHz.
- SiC MOSFETs can eliminate ~78 % of the inverter losses in a typical BEV EPA drive-cycle [5].

Recent results

Wolfspeed, among other suppliers, has been developing low-RDSON SiC MOSFETs for power modules in BEV drive-train applications. The basic SiC MOSFET technology can be scaled from 650-900-1200 V by simply adjusting the drift region epitaxy (blocking layer) and edge termination. The basic MOSFET layout remains the same for all devices in this voltage range, leading to ease of assembly into power modules.

In Figure 3, an example of a traditional top-side wire-bonded approach for module construction is illustrated using the 3rd-generation SiC power MOSFET chips. This module can accommodate either 650 V, 900 V, or 1200 V interchangeably with very small differences in chip layout. For 900 V, a low resistance 10 mΩ SiC MOSFET (CPM3-0900-0010A) is commercially available [6], and has been used to construct 900 V versions of this power module [5,7] which have been characterized for static and dynamic losses. Using the measured data from a 900 V, 2.5 mΩ SiC half-bridge power module (four MOSFETs per switch position), Ford compared the performance to their 700 V Si IGBT based inverter in a 90 kW motor drive, and found an average 78 % reduction in inverter losses over a standard EPA drive-cycle [5].

More recently, much attention has been focused on the use of sintered SiC power modules [8-10], which offer potential advantages by eliminating wire bonds on the chip assembly. One primary targeted benefit is increased Intermittent Operating Life (IOL) as wire bond fatigue or die attach is often a cause of IOL failure. Better (dual-sided) cooling, better heat spreading, and increased short-circuit rating are other potential benefits being explored. A recent example from Delphi [10] was demonstrated using five double-side sintered, 650V, 7 mΩ SiC MOSFETs in parallel in a 1.7 mΩ single switch configured module as shown in Figure 4. The sintering was performed on Wolfspeed 650 V, 7 mΩ SiC MOSFETs with both top and bottom chip metallurgy of Ni:Au.

The resulting module performance was impressive, with a low 1.7 mΩ RDSON measured up to 750 A in the module at 25°C, increasing modestly to 2.3 mΩ at 175°C, as shown in Figure 5 (top). Power cycling was performed as well on this first module prototype, with DC setup currents of 520 A for each phase (shoot-through current), and a ΔT_J of 100 K from 50°C to 150°C target settings. Using a 25 s period

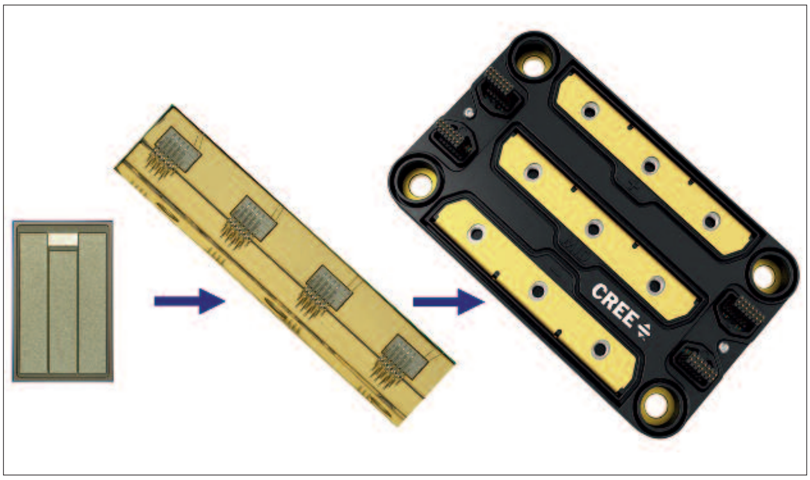

Figure 3: Wolfspeed's SiC MOSFETs (left) can be scaled from 650 V/7 mΩ to 900 V/10 mΩ to 1200 V/13 mΩ with simple modifications to blocking region and edge termination. The SiC MOSFETs can be easily paralleled to create a very low on-state resistance power module. In this example image (center and right), four of the 3rd generation 900 V/10 mΩ SiC MOSFETs (CPM3-0900-0010A) are placed in parallel to make up one switch of a half-bridge low-profile 62 mm power module (right). The resulting half-bridge SiC power module is rated at 900 V, 2.5 mΩ, 400 A. The module can allow up to twice as many chips to be assembled, which would cut the on-state resistance further to 1.25 mΩ

Figure 4: **The 650 V, 1.7 mΩ, 750 A Delphi SiC module contains five 650 V, dual-side sintered,, 7 mΩ SiC MOSFETs in a single switch configuration**

(all three phases running), with 10 s off-time, the on-state drop was measured after 36,000 cycles for six modules. None of the modules exceeded 5 % increase over the 36,000 cycles as shown in Figure 5 (bottom).

In parallel to the 650 V and 900 V development, similar work is progressing with 1200 V SiC MOSFETs. With a chip area of 32 mm², room-temperature R_{DSON} is 13 mΩ, and 175°C R_{DSON} is 23 mΩ.

Conclusions

The combination of larger diameter (150-200 mm) SiC wafers with increased materials quality, coupled with advances in SiC MOSFET design (lowering 1200 V rated specific R_{DSON} at 150°C by 60 % from 2011-17), have enabled ultra-low (<15 mΩ) resistance SiC MOSFETs to be commercialized. A 900 V, 10 mΩ SiC MOSFET was released commercially in January 2017.

The pull of the developing traction-drive requirements for BEV drive-train, which can utilize SiC to cut inverter losses by ~78 % in the EPA drive-cycle, can offer BEV designers increased range or reduced battery costs for the same range. Today the development activity is focused on efforts to improve SiC performance and reliability, such as recently demonstrated by 650 V, 7 mΩ MOSFETs used for dual-side sintered, 1.7 mΩ power modules for automotive drive-train inverters, that has already shown very good power cycling data to go with the impressive low on-state performance.

Literature

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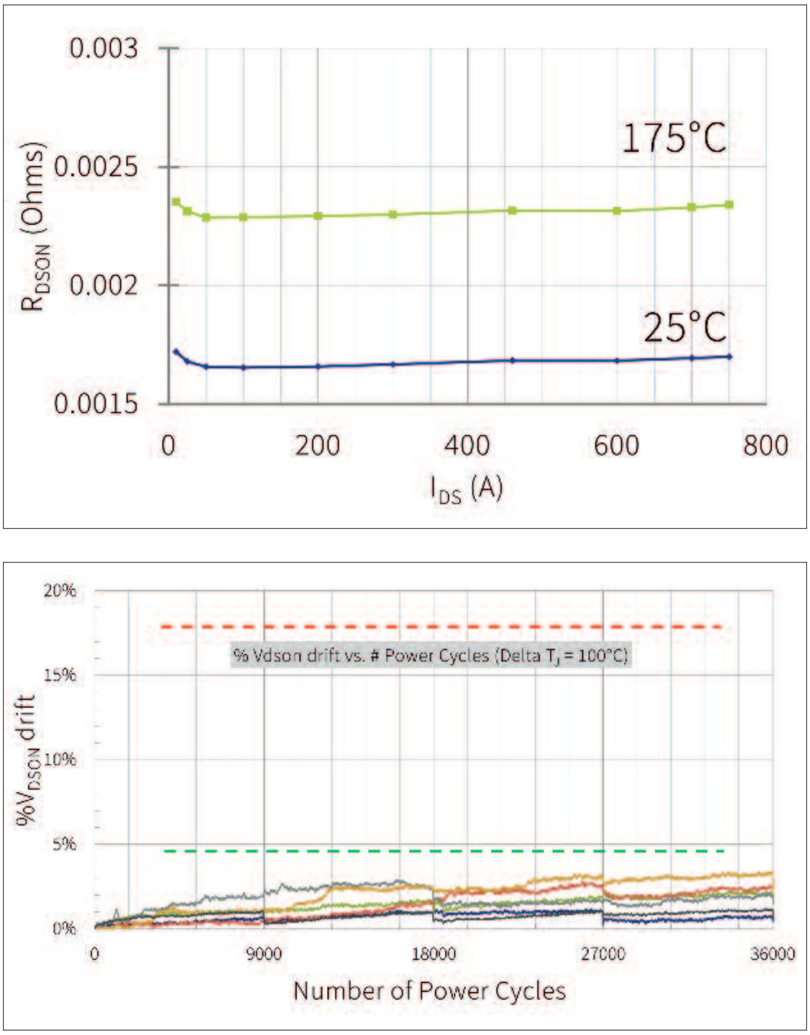

Figure 5: **The 650V, 1.7 mΩ, 750A Delphi SiC module shown in Figure 4 is tested up to 750A for RDSON values of ~2.3 mΩ at 175°C (top); six of the same SiC modules subjected to 36,000 power cycles with ?TJ of 100 K from 50°C to 150°C passed successfully with <5 % change in on-state voltage drop**