SiC Power Devices and Modules Maturing Rapidly

The SiC power semiconductor industry has matured to a point which is surprising even industry analysts, and leading to significant (> $100 M in 2010, and expected to eclipse $200 M in 2013, $400 M in 2015) market penetration according to industry analysts from IMS or Yole. The announced 150 mm wafers will allow the SiC power semiconductor industry to scale up volume at a much reduced cost structure as device vendors switch over their fabs. **Jeffrey B. Casady, Product Portfolio Planning Manager, Cree Power & RF, Durham, NC, USA**

The underpinning of the SiC industry, just as for any other semiconductor industry, is the maturity of the SiC wafers. First offered commercially in 1991, over 20 years of industry growth has led to increased volume, increased wafer diameter expansion to 100 mm in 2005, 150 mm in 2012 [1], and dramatically reduced defect densities allowing the larger die necessary to penetrate up to the MW level markets.

People often mistakenly attempt to compare SiC wafer diameter and costs with Si, without considering that the inherent material advantages of SiC allow for up to 10 times more die product per comparable Si wafers. The decrease in cost of SiC wafers due to increased production volume actually allows SiC device manufacturers to reach cost parity at a system level today [2] which explains the rapid market growth SiC power devices are experiencing. For example, the SiC wafer maturity has allowed cost-competitive solutions in Light Emitting Diodes (LED) to be offered to the market, as Cree now manufacturers and ships millions of LED die per day on SiC wafers [3], and now the SiC power device market is also experiencing market gains. The 150 mm diameter wafers are now readily available to further allow much improved volume and cost structure (example wafers shown in Figure 1).

SiC diodes

The first released SiC power semiconductor devices released were SiC diodes in 2001. There has been substantial diode revenue for more than ten years, and the $100+ million market (Yole) in 2010 was primarily for SiC diodes.

Quietly, the SiC diode industry is continuing to mature rapidly, with over 100 different SiC diode part numbers on the market from Infineon, Cree, Rohm and others (over 60 at Cree alone), breakdown voltages available ranging from 600 V to 1700 V, current ratings available from 1 A to 50 A, and a wide assortment of package options – through-hole, ceramic, bare die for modules and surface mount.

With over a decade of product experience, and over 100 different products, the SiC diode product family is delivering not only dramatic efficiency improvements, but also field data reliability which is astounding. Currently, after over ten 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. Indeed, SiC's reliability is attracting customers who want not only energy-efficient, cost-effective solutions, but also ultra-high reliability in their components.

The SiC diode market is continuing its expansion. Outside of the mature high end server / telecom power supplies for data centers and growing PV inverter business, it is penetrating new markets such as

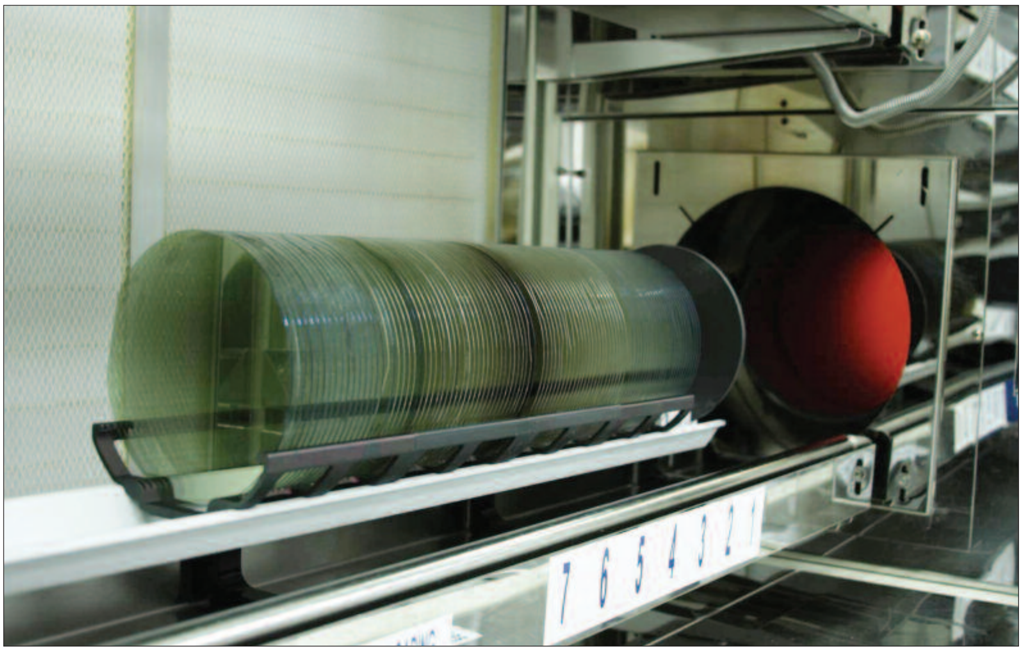

Figure 1: Example lot of 150 mm diameter SiC wafers

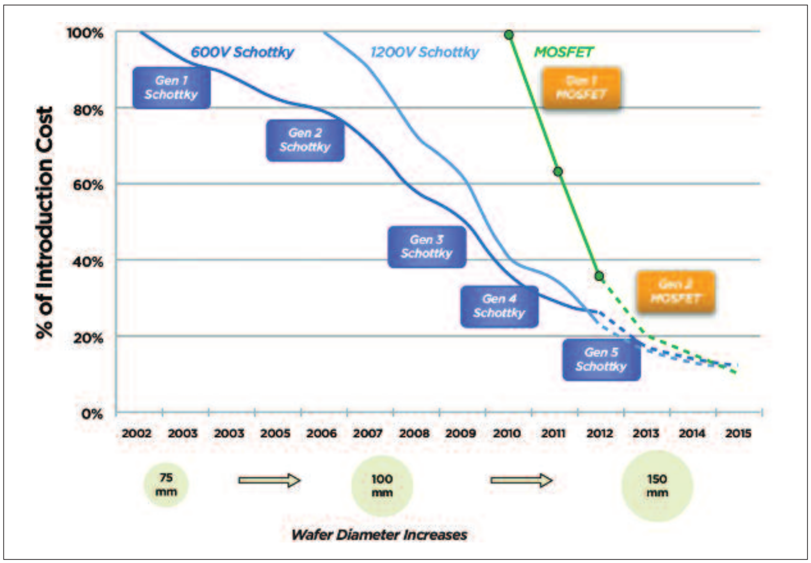

Figure 2: **Cost reduction curves on a normalized basis for one manufacturer (Cree) which is illustrative of the SiC power device industry**

Intelligent Power Modules (IPMs) for motors/fans, hybrid modules for drives, UPS inverters, LED light bulbs and fixture drivers. Customers are reducing overall system cost with SiC in ways not available with traditional Si. And with 150 mm substrates available within most design windows, very high-volume users can now work with SiC diode vendors to achieve costs and volumes significantly different than what has been possible to date, as illustrated in Figure 2.

SiC MOSFETs

In 2011, the SiC industry achieved a major milestone as the first commercial SiC MOSFETs were released [4]. Cree and Rohm both released 1200 V, 80 to 160 mΩ MOSFETs, in plastic through-hole packages, and bare die for modules. Rohm also produced 600 V MOSFET's in 2011 [5], and Infineon [5] announced selective sampling of a SiC JFET in 2012. Nearly two years since initial release, many customers are now using SiC MOSFETs in applications ranging from industrial power supplies to commercial inverters and converters. Example application notes have been published for 100 kHz, 10 kW boost converters [6] as well as auxiliary power supplies.

According to the latest Cree sales data, for SiC MOSFET's to date, there has not been a single field failure when operated within their datasheet limits. This fact leads to a FIT rate of less than 20 fails per billion device hours, and field accelerated lifetime data predicts a MTTF of one million years at 75 % of continuous rated voltage. Additionally, measurements of the avalanche energy capability show that the 1200 V SiC MOSFET has the highest rated avalanche energy of any 1200 V power switch (1200 V, 80 mΩ SiC MOSFET from Cree measured EAS of 2.2 J, EAR of 1.5 J, compared to Si IGBT EAS of 10-100 mJ).

What's next? Many new commercial releases of SiC MOSFET's are expected in 2013. Just as SiC diodes experienced after their release over a decade ago, the MOSFET's are maturing rapidly, and new generation / broader product families are already being sampled and are targeted for full release in 2013 at major power electronics exhibits. Last year [7] it was publicly announced at PCIM that large (50 A) MOSFETs would be available with 1700 and 1200 V ratings. These new ratings will allow higher power applications in motor drive, UPS, PV inverters, and traction drive markets among others to utilize SiC technology.

Additionally, newer generations of MOSFET technology are being released, which enable better efficiency, cost, and gate driver control through improvements in the on-resistance per unit area (from 8-9 mΩ cm^2 to 5 mΩ cm^2) and transconductance [8,9]. These improvements will also allow even more efficient switching at higher frequencies, driving the cost reduction that so many customers are seeking for their inverter boxes which contain a substantial amount of inductors and magnetic due to the efficiency and frequency limitations of silicon. As an example of switching energy, a SiC MOSFET will typically have five to seven times lower switching energy than comparably rated Si IGBTs (for example see Figure 3).

SiC Modules

Silicon carbide modules (using both the MOSFET and the diode) are now becoming available as well. From 2011-12, companies such as Vincotech, POWERSEM, Danfoss, Microsemi, and others began releasing SiC modules with both SiC power transistors and diodes. In late 2012 and into 2013, the SiC device vendors themselves are now starting to release SiC modules [10], and it is widely expected the larger module vendors such as Fuji, Semikron, Mitsubishi and Infineon will also begin releasing modules based on technical articles and trade presentations. The modules being released have gone through full, standard JEDEC qualification, along with more stringent power cycling out to 20 M cycles with no failures.

For less than 50 kW, one of the more popular "All SiC" example modules is the 1200 V MNPC topology used by many vendors, including Vincotech [11, 12]. The switching is very fast, with no tail current in the SiC FETs, unlike the Si IGBTs. The MPNC topology allows for not only fast switching, but also low-inductance and fewer voltage overshoots for greater EMI compatibility.

As most of the PV inverter market is now designing for not only high-efficiency (~99%), but high-frequency (30-100

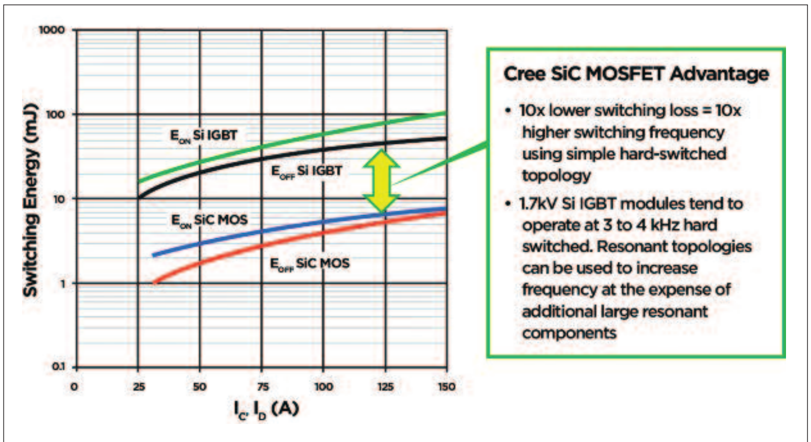

Figure 3: **Illustrative advantage of SiC MOSFET's comparing a 1.7 kV dual 100 A Si IGBT module compared to a 1.7 kV, 100 A dual module using Cree SiC MOSFETs**

Figure 4: **Both SMA (2011) and REFUsol (2012) released commercial PV inverters with all-SiC modules using both FETs and diodes. The REFUsol inverter (note "Silicon Carbide Inside") is shown here. Image courtesy of REFUsol**

kHz), to achieve reliable, efficient, and higher-frequency for lower cost/kW, variations of this topology are receiving extreme interest. These modules first appeared on the PV inverter market in 2011 (SMA) and 2012 (REFUsol). The SMA Solar Technology AG's Sunny Tripower 20000TLHE-10 was the first to be certified by Photon International in December 2011, using SiC FETs and SiC diodes, in an all-SiC module. The rating it received from Photon was the highest for its power rating (22 kW) that had ever been achieved. Then, shortly after, in July 2012, Photon gave another A+ rating to REFUsol's GmbH's 020K-SCI, which is a 20.2 kW three-phase inverter (shown in Figure 4).

Both of these inverters, the first PV inverters to use entirely SiC FETs and SiC diodes, received the top two efficiency rankings in their class according to Photon International, with efficiencies in the 98.2-98.6 % range. Even more striking, not only were peak efficiencies higher, but the range of input power where the efficiencies were above 98 % was much larger than with Si power switches [12] in three level topologies. The next phase of PV (and UPS) inverter design promises to be even more interesting, as designers take further advantage of rapidly improving SiC transistors and diodes to move the inverter frequency up, while maintaining very high efficiency, using fairly simple, rugged topologies with low part counts.

The larger, more economical power die in SiC, coupled with 150 mm wafer diameter availability, are also now driving design activity in new markets such as UPS, motor drive, traction-drive, and utility-scale solar inverters at power levels above 50 kW to as high as MW level. Designers new to SiC are sometimes surprised as the features of SiC allow for higher-frequency, lower-loss (and therefore lower current) operation. For example, a typical 1,000 A IGBT single-switch module used in a 250 kW inverter, half-bridge design, is often operated at a much lower (300 to 600 A) current level due to the losses in the module generating thermal issues. So, when designing with a SiC replacement module, a 1,000 A module using Si IGBTs can be replaced with a more efficient SiC module, that allows a much higher fraction of its rated current to be used. When matching losses, anticipating using matching two-level half bridge topologies, it is possible to lower the SiC rating by 1/3 to 2/3 relative to the Si module rating based on the efficiency gains (see Figure 5). SiC FETs allow for synchronous rectification possibilities as well, furthering that advantage.

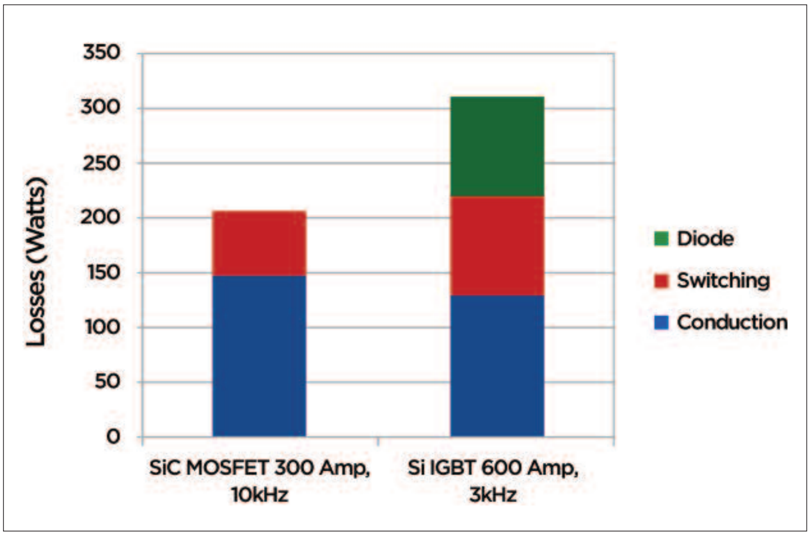

Figure 5: **SiC has reached cost parity from the system perspective in volume, and now modules are being developed and released to take advantage. Depending on topologies used, a 1700 V SiC MOSFET module can be much more efficient than a 1700 V Si module which contains twice the current rating, operating at three times lower switching frequency**

Literature

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