Powering up with silicon carbide

Silicon carbide promises power devices with superior performance, but can it deliver commercial product at the right price? Mike Cooke reports.

A number of companies are hoping that the superior properties of silicon carbide (SiC) will make device production competitive over silicon (Table 1). However, despite significant progress in working the material, costs are still high. Not only does SiC have to compete with silicon-based devices, more recently there has been gallium nitride (GaN) to contend with. Like SiC, GaN is a wide-bandgap material.

Table 1. Some typical material properties.

	Si	SiC-4H	SiC-3C	GaN
Bandgap (eV)	1.1	3.2	2.4	3.4
Critical field (10^6V/cm)	.3	3	1.3	3.5
Electron mobility (cm^2/V-s	1450	900	380	2000
Electron saturation velocity (10^6cm/s)	10	22	20	25
Thermal conductivity (Watts/cm^2-K)	1.5	5	3.6	1.3

Wide-bandgap materials tend to have high critical fields for breakdown and also can be used at higher temperatures than normal for traditional silicon-based semiconductor devices. Other attractive features of SiC-based devices, compared with silicon, include lower specific on-resistance, faster switching speeds, and higher thermal conductivity.

Use of SiC can lead to devices with reduced power losses. This, possibly combined with higher-temperature operation, reduces or even eliminates the need for cooling equipment, creating opportunities for complete system downsizing and the lightening of electronic components for automotive and industrial uses. The higher thermal conductivity allows any heat generated to be dissipated more easily.

US defense organizations, such as the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research (ONR) and the US Air Force have been particularly keen contributors to research on SiC (and GaN). The US Navy and Air Force are attracted by the prospect of reduced size for power distribution in confined spaces and in applications where there are strict weight budgets.

In June, US market researcher MarketsandMarkets reported its expectations for the SiC semiconductor device market as having an expected compound annual growth rate (CAGR) of 37.67% between 2012 and 2022. This is calculated based on a 2012 revenue figure of $218m, which is expected to reach $5.34bn in 2022. The 2012 total power semiconductor device market is estimated at $34bn.

Another economic analysis from IMS Research suggests that the combined SiC and GaN market could be more than $3bn by 2021, giving it a 9% slice of the total. IMS also sees the market for next year reaching $250m, with SiC Schottky diodes making up just over half the sales. The main use for these power devices is

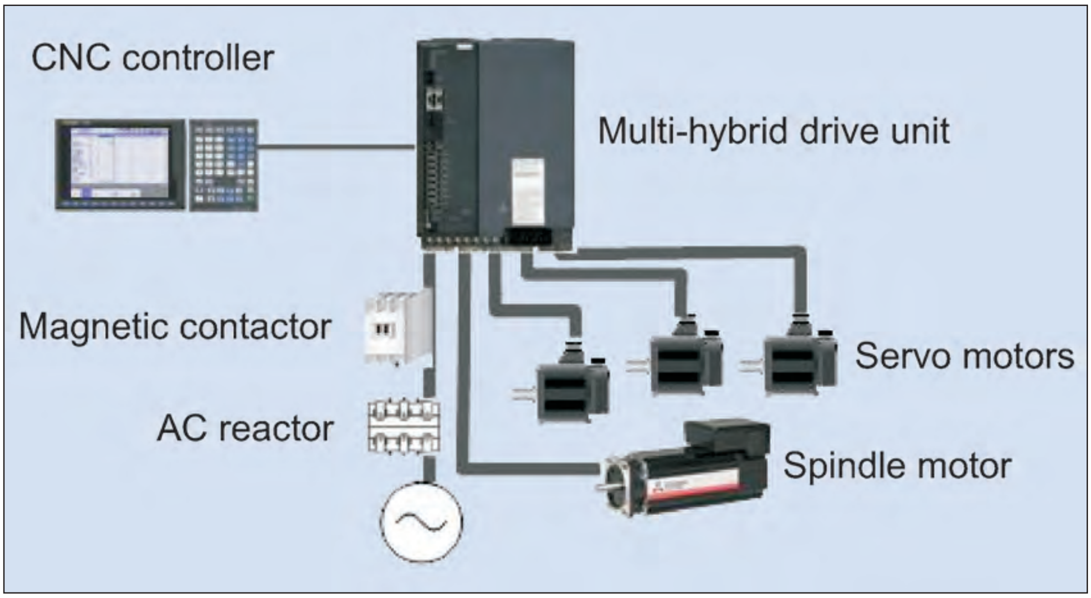

Figure 1. Numerical control system configuration with a Mitsubishi MDS-DM2-SPHV3-20080 module.

likely to be in AC–DC power supplies with power factor correction (PFC).

A more negative signal for SiC market prospects came in October 2012 with news of the probable closure of the company SemiSouth Laboratories, a spin off from the silicon carbide (SiC) R&D activities at Mississippi State University (MSU).

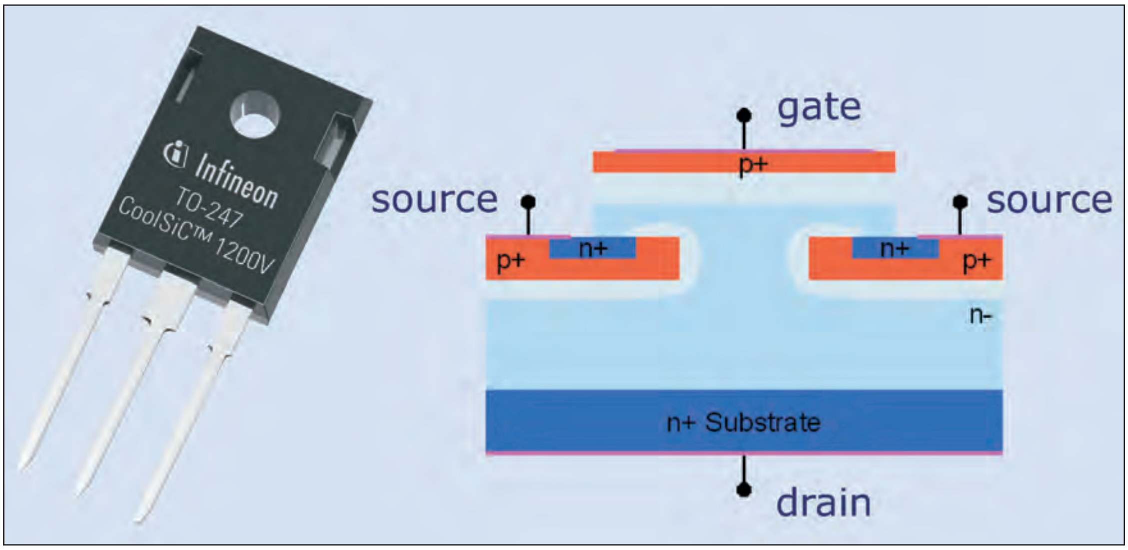

Figure 2. Infineon's CoolSiC 1200V SiC JFET family with direct drive technology, and schematic of JFET.

The news has been largely based on comment in the third quarter financial report of Power Integrations, a strategic investor in SemiSouth: in detail, Power Integrations made a pre-tax charge of $59.2m to cover the likely closure of SemiSouth. Power Integrations made more than one capital investment in SemiSouth for the purchase of tools, etc.

MSU retains some legal rights over certain assets. At the time of writing, SemiSouth had not filed for bankruptcy.

To give an impression of what companies are doing, here we give a review of some recent announcements and SiC product portfolios and applications.

Mitsubishi Electric has made a number of announcements of SiC-based products. The latest is a drive unit for use with computerized numerical controllers (CNCs), as used in automated machine tools. Sales of the product are to begin in early December 2012.

The SiC-based Mitsubishi MDS-DM2-SPHV3-20080 module mediates between the control signals of the CNC and the varying power requirements of spindle and servo motors (Figure 1). The device is described as being "a multi-hybrid, multi-axis integrated-drive unit for drive control of spindle and servo motors".

The module contains SiC Schottky-barrier diodes (SBDs) that allow higher-speed switching than silicon-based components. In certain conditions, the spindle motor speed can be double that of Mitsubishi's previous drive unit. Reduced power losses allow up to 15% increase in spindle torque. The device also includes power shut-off functions with reduced size and wiring.

Mitsubishi Electric has previously commercialized SiC-based power modules for inverters in air conditioners, hybrid electric vehicles, and railcars. Such devices could also find use in more general domestic appliance and industrial applications. The SiC modules on offer from Mitsubishi are either 'hybrid', meaning that they contain a mix of component technologies — SiC SBDs, silicon-based insulated gate bipolar transistors (IGBTs) etc, or 'full', meaning that the module contains only SiC-based components.

An example of a 'full' module is the prototype forced-air-cooled three-phase 400V output inverter with all-silicon carbide (SiC) power modules announced by Mitsubishi in May 2012 that boasts a power density of 50kVA per liter with 156kVA output. The aim of the prototype was to meet the needs for smaller and lighter power-electronics equipment in automotive, industrial, and other applications.

The module is rated at 1200V/300A. This was achieved by lowering the electrical resistance of the module with low-resistance wiring connecting the power semiconductor chips directly to the main terminals. The power chips also needed to be low loss, and high-speed protection circuits were used to protect the module from large destructive currents during short circuits.

Infineon markets SiC junction FET (JFET) and diode devices. The latest JFETs from Infineon form a family of 1200V-rated devices distributed under the CoolSiC trademark (Figure 2) that are aimed at replacing IGBTs in solar power inverters (DC–AC converters).

The devices use the lower switching losses of SiC-based technology to operate at high switching frequency. SiC parts allow the use of smaller passive components, resulting in overall size reduction, lower weight and reduced system cost.

The components use normally-on JFETs, so Infineon has developed what it calls 'direct drive technology', where the JFET is combined with an external low-voltage MOSFET and a dedicated driver IC, which ensures safe system start-up conditions as well as fast and controlled switching.

The CoolSiC JFET also includes a monolithic body diode with a switching performance comparable to that possible with external SiC Schottky devices. The

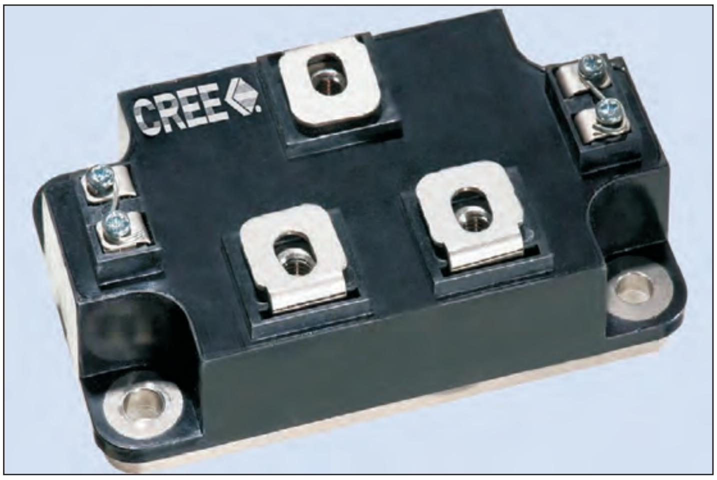

Figure 3. Cree's CAS100H12AM1 1200V, 100A SiC half-bridge module, which uses the firm's Z-FET MOSFET and Z-Rec diode parts.

company is expecting production ramp-up in first-half 2013.

The company began marketing SiC products in 2001. Infineon has also developed its fifth generation of SiC Schottky barrier diodes under the thinQ! trademark. The device is rated at 650V. These devices are designed for use in power factor correction (PFC) and boost stages for high-end server and telecom switched-mode power supply (SMPS), PC Silverbox and lighting applications, solar inverters and uninterruptible power supply (UPS) systems.

The company believes that its SiC SBDs would enable improved efficiency, along with reduced electromagnetic interference (EMI), increased system reliability and cost/size savings due to reduced cooling requirements. The company also produces IGBT power modules for various applications such as photovoltaic inverters that include SiC Schottky diodes.

Cree produces a range of MOSFETs and Schottky diodes. The company boasts that its MOSFETs are the first fully qualified, commercially available SiC power MOSFETs.

In May, the company announced a range of 50A devices, including the industry's first 1700V-rated MOSFET. The devices are available in die and packaged form for use in power modules (Figure 3) such as inverters, UPS, and motor drive units. The company believes its devices offer cost-of-ownership savings through reduced size, lower-cost bill of materials (BOM), and improved efficiency.

The higher current rating of 50A is enabled through the use of larger dies. The previous generation of Cree products was rated at 20A. Cree believes its new products will make it possible to replace conventional silicon IGBTs in high-power, high-voltage applications. Cree also produces SiC substrates and was the first to develop 75mm, 100mm and, most recently, 150mm wafers.

Raytheon has facilities in the UK (Glenrothes, Scotland) that are capable of processing 40,000 100mm SiC wafers per year. The capability is offered on a foundry basis. The company is also developing the high-temperature capabilities of SiC in a UK government research project, announced in July 2012. The aim is to overcome the present limitation of SiC devices where driver-ICs have a lower temperature rating than the high-temperature SiC components.

The new work will be based on lower-cost 3C-SiC epitaxial layers on silicon wafers. The researchers plan to develop 3C-SiC on Si hetero-epitaxy, IC processes, and the design and development of a demonstrator driver IC. However, the 3C crystal structure is not as high performance as the more common 4H material. In particular, the critical field is smaller due to the narrower bandgap. In theory, the higher cubic symmetry of 3C-SiC over the hexagonal symmetry of 4H-SiC should give it an edge in terms of mobility and saturation velocity. Such higher electron transport performance may be achieved with higher-quality material growth.

Even before the recent UK funding, the company had developed 400ºC SiC transistors and 300ºC SiC CMOS-based integrated circuits (Figure 4).

Microsemi offers a variety of products incorporating SiC devices including SiC Schottky diodes in industry-standard discrete packages, SiC transistors (MOSFETS and JFETS) in multi-chip power module packages, and SiC RF static induction transistor (SIT) devices aimed at UHF and L-band frequencies.

The company's most recent announcement was a range of 1200V SiC Schottky diodes for solar inverters, welding, plasma cutters, fast vehicle charging, oil exploration, and other high-power, high-voltage applications needing high power density, high performance and reliability. The devices are in production now. Microsemi adds that it is the only manufacturer to offer SiC Schottky diodes in large surface-mount backside-solderable D^3 packages, enabling increased power density and lower manufacturing costs.

In 2010, the company announced RF power SiC transistors rated at up to 2200W aimed at weather radar and over-the-horizon radar using UHF pulses for military and aerospace markets. For RF power at higher frequencies (such as S-band and above) the company recently announced a GaN-on-SiC RF transistor.

Rohm claims the first mass-produced 'full SiC' power modules with the industry's most compact format and switching losses reduced by 85% compared with IGBT-based modules (Figure 5). The intended applications include industrial equipment, EVs/HVs, and solar power.

The company also offers a range of Schottky diodes and MOSFETs. The company has also worked with Kyoto University and the University of Arkansas to create an intelligent, high-temperature power module (with a junction temperature of 250ºC, 150A-class).

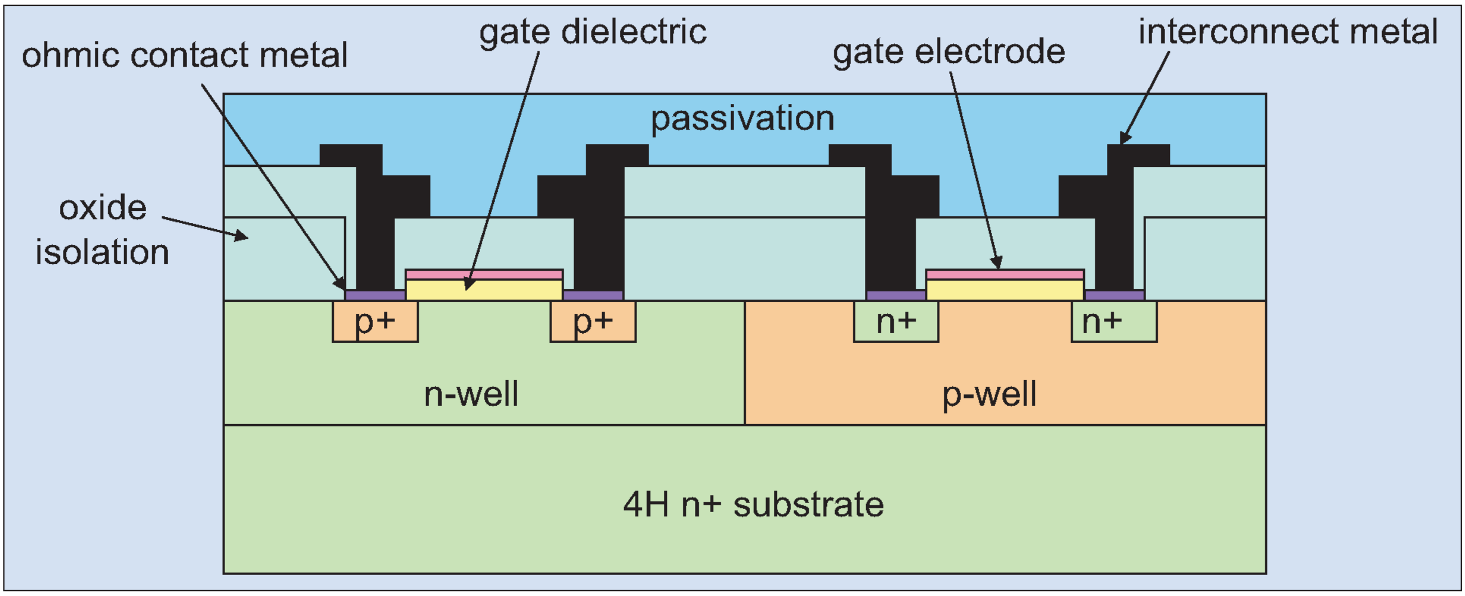

Figure 4 Raytheon's schematic cross-section for SiC CMOS.

Another product under development is a 300A trench MOSFET.

Rohm bought the SiC wafer producer SiCrystal of Germany in 2010.

Another company that is buying SiC capabilities is Fairchild, which acquired Sweden's TranSiC in April 2011. TranSiC produces bipolar junction transistors under the BitSiC tradename. TranSiC sees the advantages of its technology as being high-temperature performance up to 250°C, high efficiency, and compact size. BitSiC devices are normally-off and provide low conduction losses, low switching losses, high blocking voltage, high operating temperatures, and high surge current capability. Among applications that TranSiC sees as advantageous for them are down-hole drilling, PV inverters, switched power, and hybrid electric vehicles.

GE Aviation and GE Global Research are developing and expanding SiC device production and GE has announced SiC-based power conversion products for air-, land- and sea-based platforms. The line includes AC–DC, DC–DC and DC–AC converters and special-purpose power supplies such as battery chargers and frequency converters. Since the company is working with US defense, some of the information about its products can be rather sketchy. However, GE Aviation estimates that the use of SiC devices could reduce aircraft weight by more than 400 pounds (about 180kg).

Finally, STMicroelectronics has developed 1200V SiC diodes that increase inverter yields by 2%. The company is also developing MOSFETs with the aim of 50% energy savings compared with IGBT-based power systems. ■

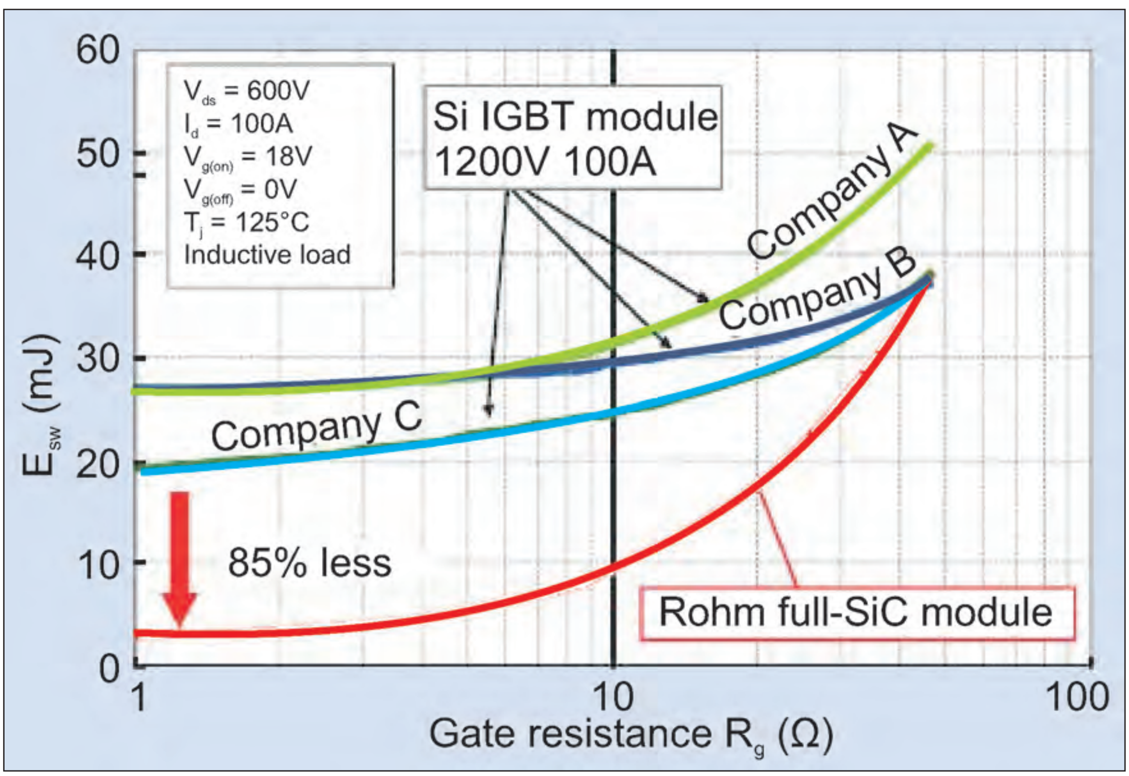

Figure 5. Comparison of Rohm full-SiC power module switching energy vs gate resistance with IGBT-based products.

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