High-Voltage SiC Power Modules for 10 – 25 kV Applications

The development of power electronic devices with higher operating voltages (6.5 kV+) has enabled more power to be transmitted for a given current and reduced the number of switches required to reach those voltage levels in multi-level converters. Silicon Carbide (SiC) power devices – with their significantly higher blocking voltages (into the tens of kilovolts), higher switching frequencies, and higher operating temperatures (200°C) – have had a major impact on the ability of power electronics engineers to develop power modules that are more compact, operate at higher voltages, and require less thermal management than power modules designed with conventional Silicon devices. **Brandon Passmore, Development Engineering Manager, Chad O'Neal, Development Engineer, Electronics Packaging, Wolfspeed, Research Triangle Park,USA**

Designing and manufacturing these new compact, SiC-based high voltage power modules requires important consideration regarding insulation materials, creepage/clearance design, an optimized parasitic design, external bussing connection scheme, and high temperature and environmental testing. The two SiC power modules described in this article clearly demonstrate the potential for SiC devices in high-voltage applications, including energy storage, grid-connected power electronics, electric rail, and shipboard power systems.

SiC power module for 15 kV applications

A low profile power module has been designed around the latest generation of high-voltage SiC device technology, enabling increased operating voltage while minimizing both the module's size and the need for extensive thermal management. Compared to 6.5 kV Si-based solutions, this SiC-based power module is one-third the volume and half the weight, and has 10X higher switching speeds and 2X the breakdown voltage with reduced cooling requirements. At the system level, this translates into more than 10 % increased efficiency with a 50 % reduction in energy losses, which increases the power density of the system. As such, this novel SiC power module represents a powerful new building block for power electronics systems that require simplified design and increased operating efficiency.

Shown in Figure 1, this power module is a half-bridge configuration with eight SiC power devices per switch position: four SiC switching power devices and four SiC Schottky diodes. This module design can employ a wide range of different high-voltage devices, including SiC MOSFETs rated for 10 kV / 40 A or SiC IGBTs rated for 15 kV / 80 A. The module design also includes an integrated temperature sensor that monitors the die junction temperature during operation.

Internal bonding variations within the module include a standard wire-bond die interconnect, as well as an option for flip-chip mounting. The substrates, baseplates, and housing are standard for both module configurations to standardize manufacturability. After the baseplate and substrate are joined with high-temperature solder, the four separate half-bridge subassemblies are tested before incorporating them into the module. This enables separate testing and quality control for the subassemblies, providing design engineers with a critical opportunity to rework the device prior to final assembly.

Subdividing the module's switch positions also improves the thermal-mechanical characteristics, reducing the effects of bowing due to thermal expansion mismatches in the materials used. The subassembly baseplates are made from a low coefficient of thermal expansion (CTE) metal-matrix composite material with a low

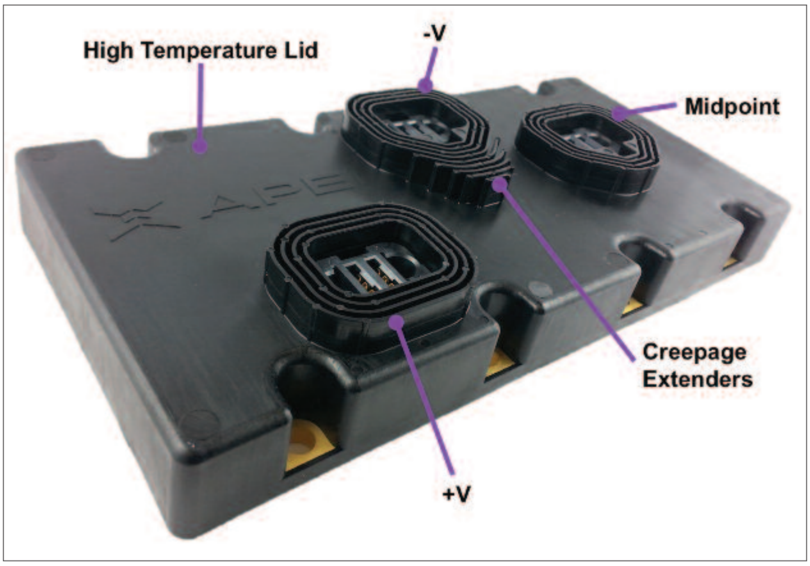


Figure 1: **15 kV SiC power module rated at 200°C operation - key characteristics include reworkability, modularity, and small form factor**

Figure 2: Clamped inductive load switching waveform (V_{bus} = 8 kV, I_{switch} = 28 A, Rg = 2.5Ω) for a submodule of the 15 kV power module

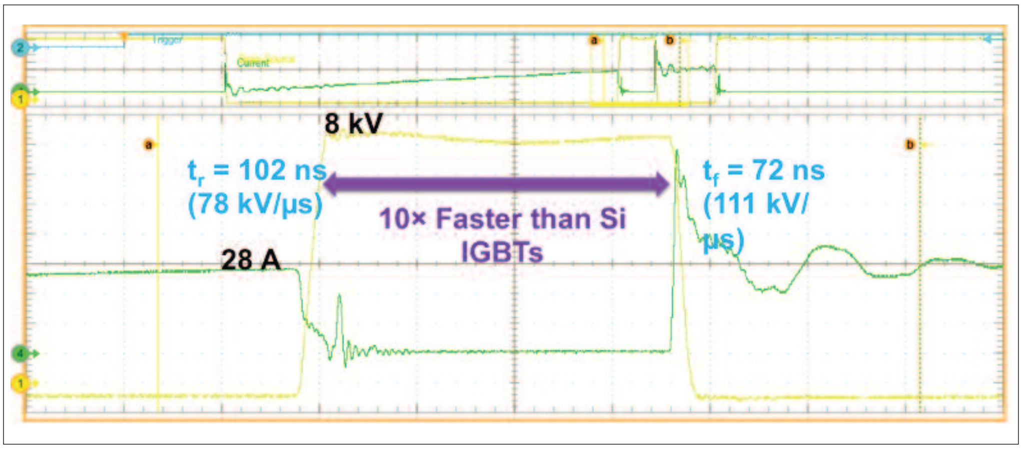
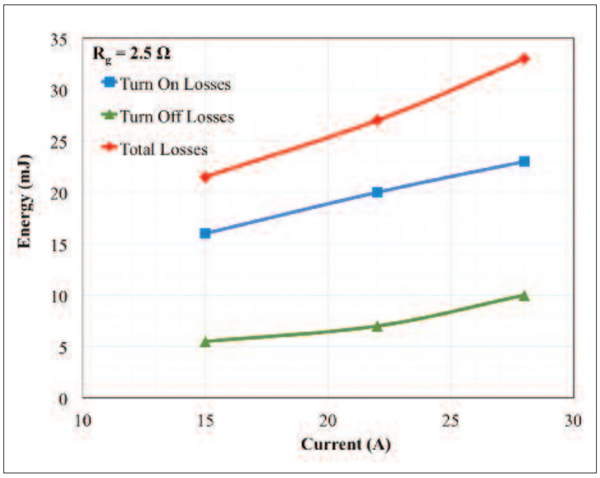


Figure 3: Switching energy as a function of current at 8 kV for a submodule - total switching losses are 70X lower than a Si-based 6.5 kV / 250 A IGBT power module



density, which contributes to the 80 % weight reduction, as the baseplate is often the heaviest component of the module. Moreover, since there are typically multiple modules per system, this module weight reduction can contribute to a significant reduction of the total system weight.

The module housing is molded from a high temperature plastic, which provides protection from higher temperature environments and allows for high-temperature operation. In addition, the high temperature plastic housing was designed to meet UL and IEC creepage (Pollution Degree 2) requirements based on 15 kV operation. Internal clearances are maintained with a high temperature Silicone gel.

To demonstrate the high performance packaging design coupled with the superior dynamic characteristics of 10 kV SiC MOSFETs, the improvement in dynamic characteristics for a submodule can be seen in Figure 2, which illustrates the clamped inductive load test results for the module at 8 kV /28 A. Using a gate resistor of 2.5 Ω, the submodule exhibits switching speeds up to 111 kV/µs, which equates to a 10X improvement in switching speed over conventional Si IGBTs. The switching energy plots, shown in Figure 3, demonstrate the turn-on, turn-off, and total energy data for the submodule.

Power Module at 24 kV / 30 A using SiC IGBTs

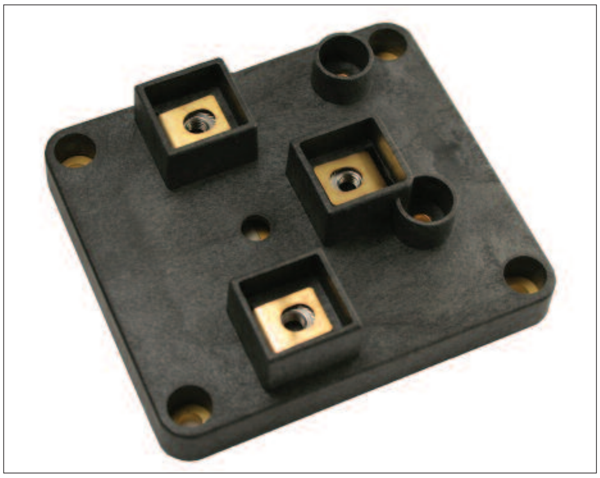
An evaluation module using high-voltage (24 kV) SiC IGBTs was recently developed under a contract with the U.S. Army Research Lab (Cooperative Agreement Number W911NF-13-2-0023) to meet a specific requirement for an ultra-high voltage module with a compact footprint. The internals of the module were designed to withstand 24 kV operation and are shown in Figure 4. As designed, the terminal spacings do not meet clearance spacings to withstand breakdown in open air. Thus, the module was designed to operate in a dielectric fluid.

The module can be internally configured for several different basic topologies, including an IGBT diode co-pack, boost chopper, or half-bridge configuration, providing design engineers with several building block topology choices for implementing this type of module into a broad range of high-voltage applications.

The module is specifically designed for high temperature (200°C) operation, employing dielectric potting material in the interior of the module and high temperature plastic for the external housing. The power module was carefully designed using finite element modeling and advanced CAD tools to determine mechanical stresses, thermal gradients, electric field strengths, and overall module parasitics. Additionally, the baseplate material was selected to have a closely matched coefficient of thermal expansion with the thick ceramic substrate used to electrically isolate the high voltage SiC IGBTs from the baseplate.

In previous work performed by Wolfspeed [1], the electrical performance of the module for reverse blocking and switching performance over temperature is presented in Figure 5. The clamped inductive load testing was performed at 14 kV / 22 A, demonstrating a switching speed of 46 kV/µs, with some degradation noted as the temperature rises to 125°C. However, it is worth noting that this device

Figure 4: 24 kV / 30 A SiC IGBT power module



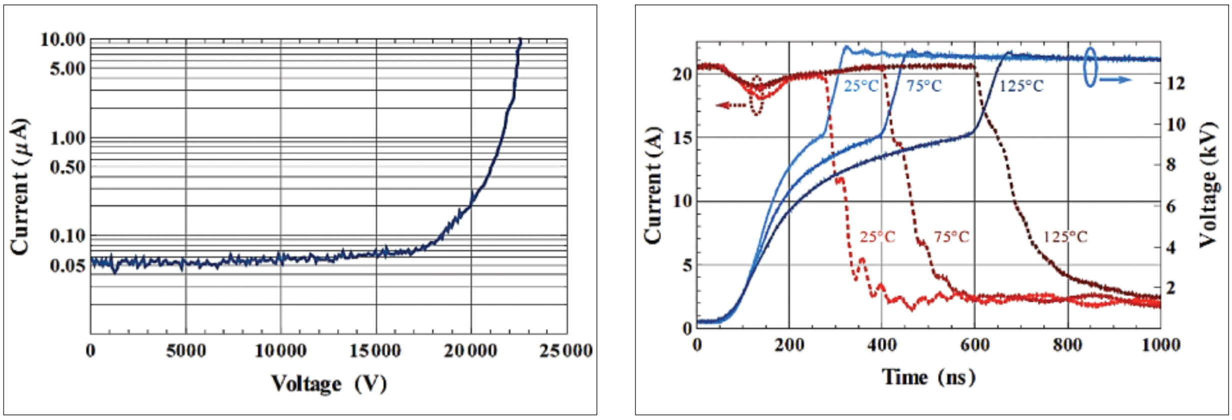


Figure 5: **Reverse leakage for 24kV SiC IGBTs (left) and dynamic characteristics for 24 kV / 30 A SiC IGBTs over temperature**

and its performance will improve substantially as development progresses. Overall, the 24 kV SiC IGBTs exhibit extremely fast switching speeds.

Conclusions

The two high voltage, high temperature SiC power modules demonstrate the extremely fast switching characteristics of high voltage SiC-based transistors. Module packaging designed especially for these and other wide bandgap power devices enables reduced physical size and complexity in multi-level systems, the elimination of external cooling systems, and a significant increase in both efficiency and power density at the system level. Specifically, the high voltage and thermal characteristics of SiC power devices will enable power electronics design engineers to significantly reduce the number of topology levels compared to conventional silicon power modules. Although the cost of the SiC devices is often seen as a barrier to adoption, their cost is continually being reduced as production volume increases. Furthermore, since the integration of SiC devices enables a reduction of overall system cost and significantly increases performance, it will not be necessary for SiC devices to reach true cost parity with Silicon in order to make the overall value proposition for system integrators successful.

Literature

[1] E. V. Brunt, L. Cheng, M. O'Loughlin, C. Capell, C. Jonas, K. Lam, et al., "22 kV, 1 cm2, 4H-SiC n-IGBTs with Improved Conductivity Modulation," in 26th International Symposium on Power Semiconductor Devices & IC's, Waikoloa, Hawaii, 2014, pp. 358-361.