Fast Switching 1200V Normally-Off SiC VJFET Power Modules

An all SiC based power module for use in high frequency and high efficiency applications has been developed. Using parallel combinations of 1200V enhancement mode SiC VJFETs and Schottky diodes, a total on-resistance of only 10mΩ was achieved at 100A drain current in a commercially available standard module configured as a half-bridge circuit. Careful attention to module layout, gate driver design, and the addition of optimized snubbers resulted in excellent switching waveforms with low total switching losses of 1.25mJ when switching 100A at 150°C. **David C. Sheridan and Jeffrey B. Casady, SemiSouth Laboratories, Starkville, USA**

A significant percentage of the targeted market for SiC power transistors will favor devices integrated into a module for higher power and complexity. It is often preferable to have higher power components in module form rather than multiple discrete devices in order to save both cost and area in the overall system design. Implementing modules also allows a much higher performance as gate drivers and control components can be placed close to the active switches, reducing parasitic capacitance and inductances, and allowing faster switching performance. It is also beneficial to the device manufacturer because of the ability to parallel smaller and hence higher yielding devices to reach the higher power levels is much easier in a power module than with discrete technology.

With significant progress being made in SiC VJFET, MOSFET, and BJT technology, this ability to create high voltage and higher current modules with smaller discrete devices is a natural progress for market adoption, but until recently, only few switching characterization reports of these types of all-SiC modules have been published [1-3]. In this article we show the full switching performance characterization of normally-off 1200V SiC VJFET switches in a half bridge module.

Using a standard module

The modules used were standard SP1 configurations offered commercially [4]. Thesemodules have a low profile and are built with AlN substrates for improved thermal performance. Figure 1 shows a picture of the completed module.

As shown in Figure 2, the modules contain a half-bridge (phase leg) configuration consisting of two series switches with anti-parallel diodes across each switch. Each switch position contains

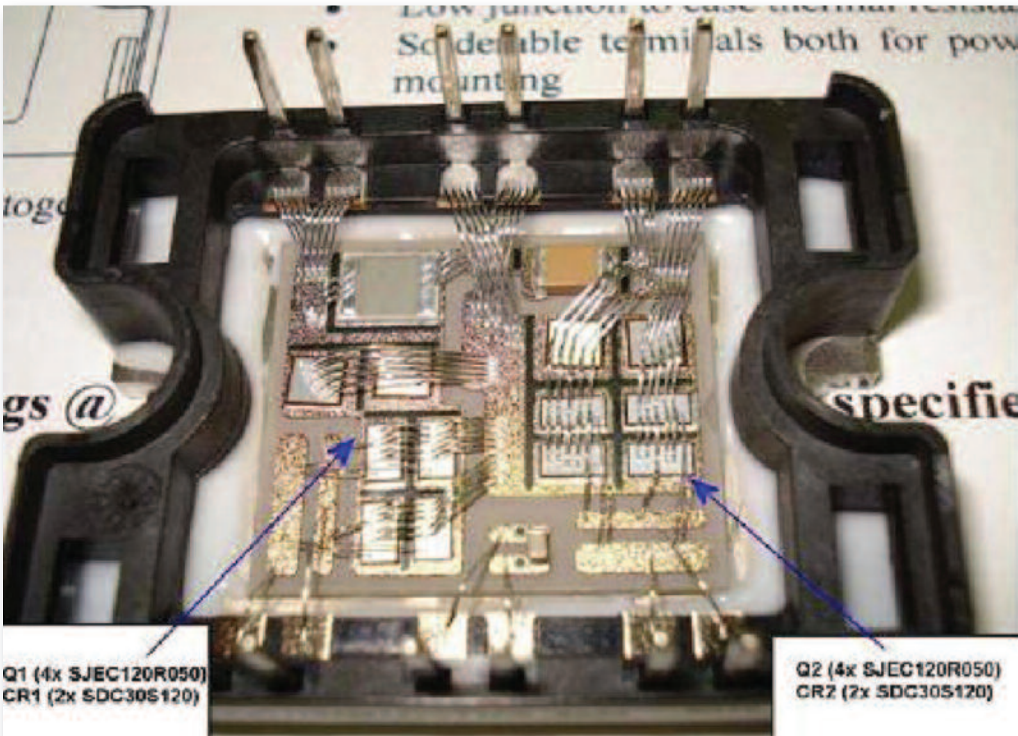


Figure 1: Photograph of the SP1 half bridge module showing JFET and diode scale

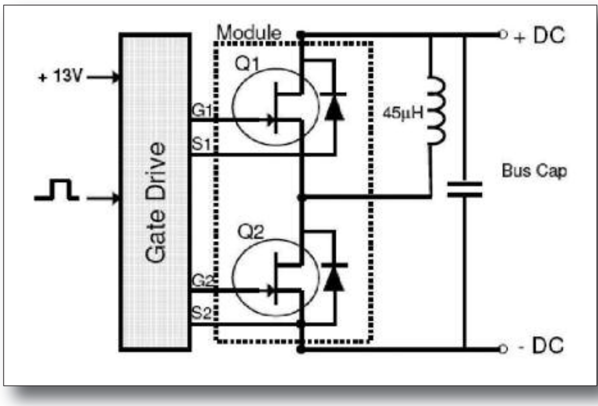


Figure 2: Schematic of the SiC module in the inductive switching test circuit without snubbers

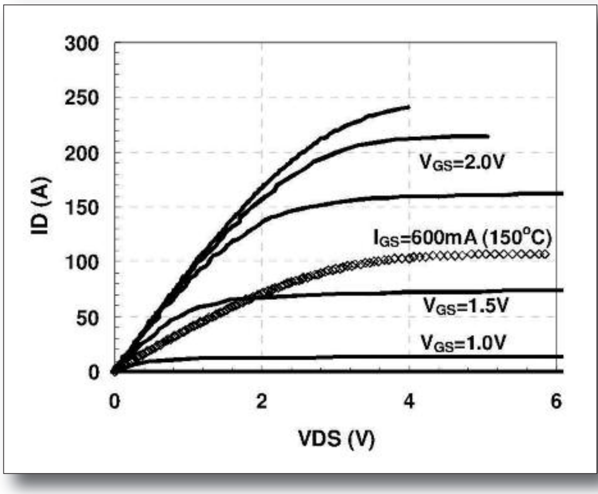


Figure 3: Output characteristics of a single switch in the module at 25°C (solid lines) and output for 150°C and I_{GS}=600mA (circles)

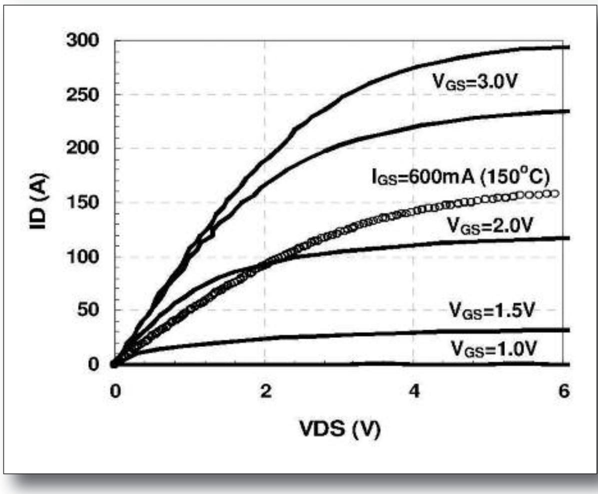


Figure 4: Output characteristics of higher current VJFET design [x] at 25°C (solid lines) and output for 150°C and I_{GS}=600mA (circles)

8 x 4.5mm^2 (2 x 2.25mm^2 active) enhancement-mode VJFETs (SJEP120R100 [5]) with 2 x 1200V/30A SiC Schottky diodes (SDP30S120 [5]). Each 4.5mm^2 VJFET die is targeted to have <100mΩ on-resistance and a threshold voltage of ~1V while capable of 1200V blocking voltage.

The VJFET and Schottky die only account for approximately half of the available layout area. Other layout features include source Kelvin connections and internal capacitor and snubber components.

Electrical optimization

The output characteristics of the module are shown in Figure 3. At ID=100A, the module on-resistance was 10mΩ which corresponds to a low 2.7mW-cm^2 specific on-resistance.

Maximum saturation current was over 200A at 25°C, reducing to over 100A at 150°C.

Devices with optimized channel design parameters for higher saturation current have shown up to 50% improvement in high-temperature saturation current [6] could be used if required by the application (Figure 4). Modules built with these higher current devices output ~150A at 150°C, appreciably increasing the available high temperature current.

Threshold voltage changes over temperature were modest as the nominal 1.15V V_{TH} was reduced by ~2mV/K to 0.9V at 150°C (Figure 5). At 150°C, the on-resistance increased to 27mΩ as expected from the 2.7 X reduction in majority carrier mobility and absence of interface effects seen in SiC MOSFETs.

For module characterization of switching performance, standard double pulsed measurements were conducted. The two positions in the half-bridge module served as the upper and lower switches, while the upper internal SiC Schottky acted as the freewheeling diode. An external 45µH inductor served as the load. Gate drive design was built from a custom discrete two-stage gate drive reference design [7] and scaled to support the larger die area and half-bridge topology. The two-stage design fist supplies a large 25A current pulse for ~100ns to quickly charge the required capacitances, and then reduces the drive current to a low adjustable continuous current level of ~500mA to maintain the VJFETs in a low $R_{DS(on)}$ conduction state across all temperatures. Modules were switched at a bus voltage of 600V and a drain current from 25A to 100A to characterize the switching losses.

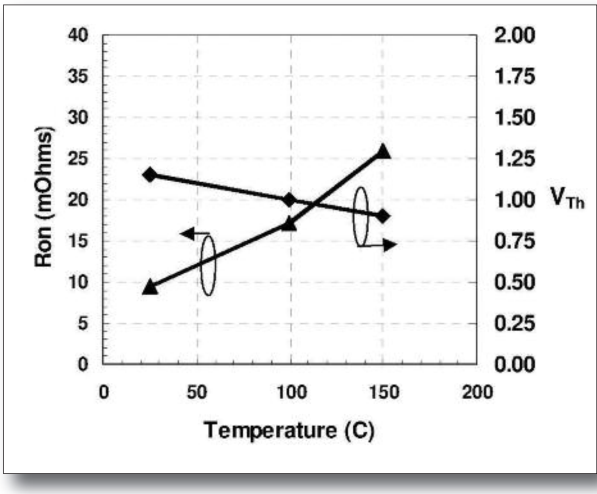
Although careful attention was given to layout of the module components to reduce the bond wire lengths and parasitic inductances, initial module waveforms were far from ideal. Significant ringing and oscillations appeared on both the output bus as well as reflections into the gate circuitry.

At these currents and power levels, the attractive properties of SiC transistors and diodes that allow fast switching and zero reverse recovery also bring new challenges to control the system interaction without minimizing the performance. In these module measurements of di/dt in the range of 5-8A/ns and dV/dt from 10-50V/ns are not uncommon. These transients resonating with the leakage inductance of the power circuit and active component capacitances resulted in unacceptable module performance. To alleviate the effect of the oscillations, optimized components for an internal RC snubber were added across the DC bus of the half-bridge module that immediately led to markedly improved waveforms.

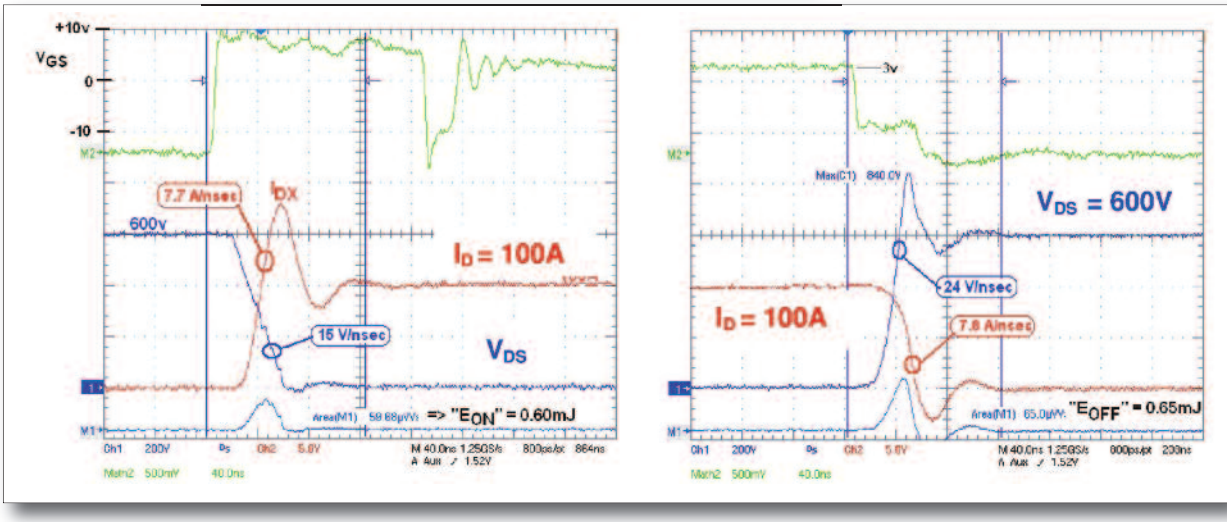
On the gate side additional phenomenon may occur when switching at high dV/dt. Since there is a natural capacitive divider formed between the C_{GD} and the C_{GS} of the VJFET (similar to the MOSFET), high dV/dt occurring at the drain of the lower switch can cause current flowing through this divider, through the gate circuitry and cause unwanted turn-on of the upper switch. This cross-conduction effect can cause higher module losses as well as potential damaging currents in the gate circuit.

SiC switches in general are more prone to cross-conduction phenomena due to

Figure 5: Module R_{DSon} and threshold voltage from 25°C to 150°C



BELOW: Figure 6: Waveform capture of the turn-on (a) and turn-off (b) waveforms under inductive switching of I_D=100A and V_{DS}=600V at 150°C



the smaller die size (higher R_G) and larger CGD per unit area and given voltage rating. For this module, $R_{G,INT}$ ~ 1Ω, C_{GD} ~ 400pF, with a fast dv/dt of 20V/ns gives a rise in V_{GS} of 8V. This is several volts above the threshold voltage of ~ 1V. To prevent this effect, additional Gate-Source capacitors were added close to the die to and all measurements were conducted with a negative gate rail of V_{GS}=-13V.

Further reduction of gate oscillations was achieved by placing an additional small RC snubber across the Gate-Source capacitors. Examples of the turn-on and turn-off waveforms for I_D=100A and T_c=150°C are shown in Figures 6a/b.

Energy loss measurements vs load current and temperature are shown in Figure 7. At a load current of 100A, E_{ON} and E_{OFF} were measured to be 600µJ and 650µJ, respectively, for a total loss of E_{SW}=1.25mJ. Note that since the measurement was taken at the module terminals, the drain current contains both VJFET and snubber current components. In comparison to other technologies, these results are 5-10x better than Si IGBT modules, and 45% lower losses than the best reported SiC MOSFET module results [8]. Because of the unipolar device, both E_{ON} and E_{OFF} remain low across the measured current range,and are independent of temperature.

Conclusions

As SiC devices migrate to higher power levels, multi-chip power modules offer a practical and necessary solution for a wide range of applications. However, the high speed transients capable in SiC devices at high voltages and currents highlight the need for careful design considerations for gate drive, wiring, layout, and module parasitic. With high speed, normally-off 1200V SiC VJFET technology, we have shown record low switching performance (1.25 mJ) in an optimized commercially available (Microsemi SP1) module configuration. Parasitic oscillations and cross-conduction were investigated and shown to be well controlled with the optimized internal snubbers and use of a negative voltage rail.

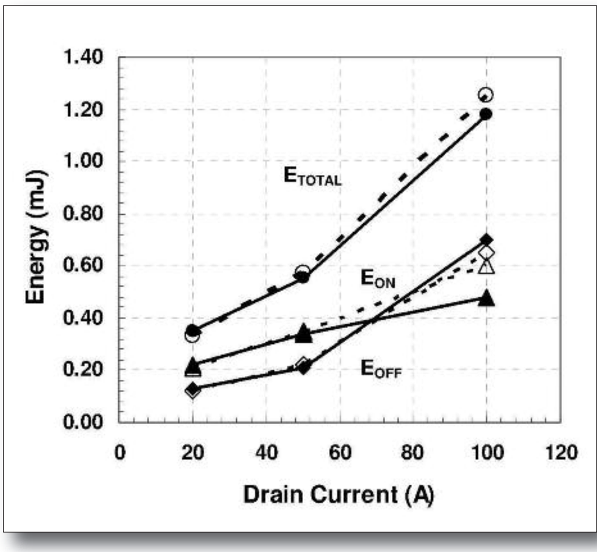


Figure 7: Module switching energy components vs drain current at 25°C (solid lines) and 150°C (dashed lines)

Literature

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