

High-temperature Characterization of a 1200 V Power Module with 36 mm² of SiC VJFET Area

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Abstract

This is the first high-temperature static and dynamic characterization of a half-bridge power module using 1200 V, 45 mΩ depletion-mode vertical JFETs. With only 36 mm² of JFET area, the peak pulsed current is measured to be nearly 500 A at room temperature (transistors not saturated), decreasing to 230 A at 250 °C (transistors saturated). Total switching losses are less than 3.2 mJ from 25 °C to 250 °C and show negligible dependence on junction temperature. The achievement of this level of performance with such a small SiC transistor area is important, since die area directly impacts achievable module footprint (system-level power density and cost), device capacitance (switching losses), and semiconductor cost.

Keywords: silicon carbide, JFET, power module, high temperature

1. Introduction

There are many technological benefits associated with silicon carbide (SiC)-based power modules, including high power output and low losses at elevated temperature, allowing designers to use less sophisticated thermal management; the ability to switch at higher frequencies, which reduces the size and weight of filter inductors and capacitors; and a more compact circuit board with simplified topology, which leads to smaller modules with higher power, lower parasitics, and a reduced component count. When combined, these benefits result in unprecedented conversion efficiency and power density. One group has recently demonstrated a record power density of 30 kW/L using SiC JFETs in a complete three-phase inverter; at 15 kW output, the module performed at 99% efficiency and was capable of operating at 200 °C [1].

When evaluating SiC for a given application, one important consideration is the total SiC die area necessary to achieve a given power output, as this directly impacts the achievable power density, device capacitance (i.e., switching losses), and total module and semiconductor costs. In this work, we report the high-

temperature static and dynamic characteristics of a half-bridge power module that uses 36 mm² (total transistor die area) of 1200 V, 45 mΩ depletion-mode SiC vertical-trench junction field-effect transistors (VJFETs) in each switch position.

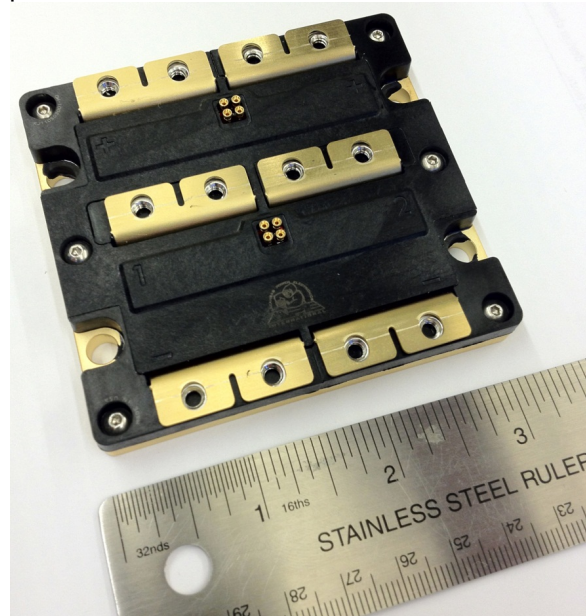


Fig. 1. Photograph of the HT2000 power module from APEI [2].

2. Module and Device Details

The power module was designed and manufactured by APEI using their HT2000 package [2], which measures 7.5 cm (L) x 8.1 cm (W) x 1.2 cm (H) and is fully flexible to use as a half bridge, full bridge, or series-connected switches. The module reported in this work was configured as a half bridge with two switch positions. A picture of the assembled unit is shown in Fig. 1. The HT2000 uses a proprietary layout that optimizes package parasitics.

This is the first module to use the 1200 V, 45 mΩ SiC depletion-mode VJFETs announced by SemiSouth in 2011 [3]. Each switch position uses four VJFETs connected in parallel, with four 1200 V, 30 A SiC Schottky diodes in antiparallel. The SiC VJFET structure is made with a trench design which, when compared with planar device architectures, allows the transistor to use more of its chip area for conducting current. A simplified schematic cross-section is shown in Fig. 2. The current path is purely vertical, whereas planar device structures require a portion of the current path to be lateral before turning and flowing down through the drift layer and substrate. Consequently, to achieve a given current rating (or on-state resistance), the die size of a planar device must be larger than that of a device whose entire current path is vertical, increasing both its capacitance (switching losses) and its cost.

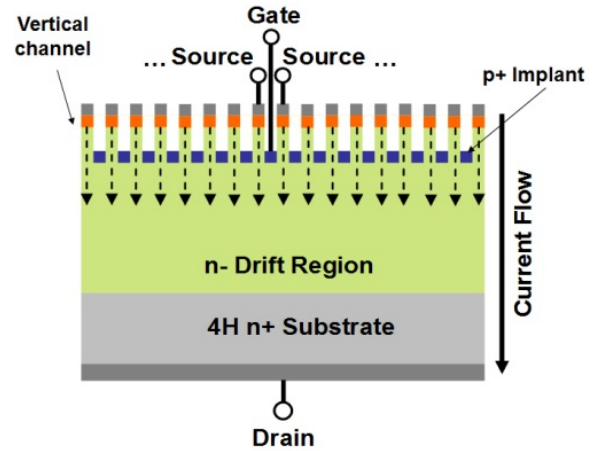


Fig. 2. Simplified cross-section of the SiC VJFET, illustrating the vertical current path enabled by the trench structure.

3. Forward Characteristics

3.1 Pulsed Measurements

The module's forward characteristics were measured using a Tektronix 371 curve tracer with pulse lengths of approximately 150 μs (negligible self-heating). A hot plate was used to set the junction temperature from 25 °C to 250 °C. On-state resistance of the low-side switch position was extracted from the linear portion of the output curves for each junction temperature.

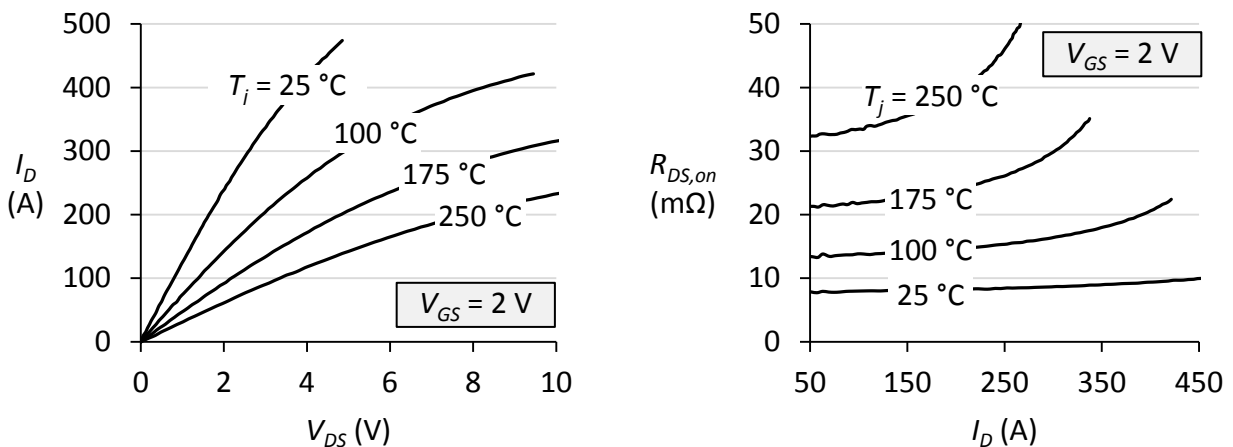


Fig. 3. (Left) Output characteristics and (right) on-state resistance vs. output current of the module's low-side switch at four different junction temperatures ($V_{GS} = 2\text{ V}$).

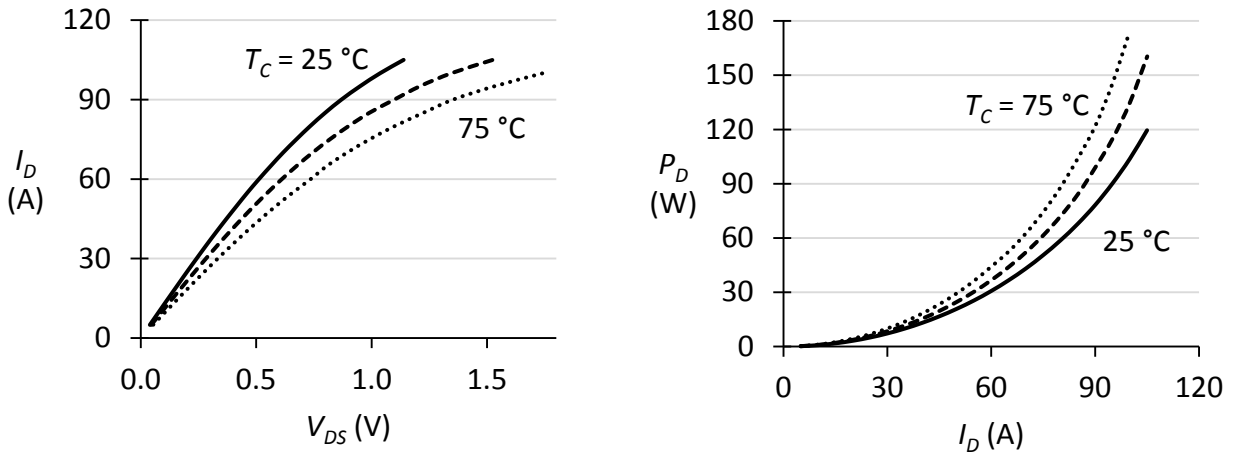


Fig. 4. Measurements of the module's continuous operation. (Left) Output curves and (right) power dissipation for case temperatures of 25 °C, 50 °C, and 75 °C ($V_{GS} = 2$ V).

As seen in Fig. 3, the module's peak current is nearly 500 A at $T_j = 25\text{ °C}$ and 250 A at 250 °C. The room-temperature measurements were limited by the power of the curve tracer; the transistors were still not saturated at $V_{DS} = 4.9$ V and $I_D = 479$ A. The on-state resistance shown increases from 8 m Ω at $T_j = 25\text{ °C}$ to 33 m Ω at 250 °C for an output current of 100 A. It is worth noting that in the power module used, up to 126 mm² of die would fit in each switch position [4]; this means the output current and on-state resistance could increase and decrease, respectively, by a factor of more than 3.

3.2 Continuous Measurements

Measurements were also made to determine the range of conditions under which the module can safely operate in a continuous mode at a given case temperature. A NESLAB thermal bath was used to circulate thermally conductive oil through a form-fit cold/hot plate to maintain a constant case temperature while the measurements were made.

Figure 4 shows the module's continuous-mode output characteristics and power dissipation at three case temperatures (25 °C, 50 °C, and 75 °C). At the highest measured case temperature of 75 °C, the power module is capable of safely and continuously sourcing 100 A of output current ($V_{DS} = 1.7$ V) while dissipating 174 W.

4. Switching Characteristics

Switching measurements were made using the double-pulse clamped inductive load test circuit schematically illustrated in Fig. 5. For a given dV/dt , turn-on and turn-off switching energies and stability may be accurately measured and evaluated with this technique.

The module was hard-switched at 400 V (limited by input capacitor rating) and a load current of 100 A, driven by a two-stage gate drive concept which is described elsewhere [5].

Figure 6 shows representative turn-on (top) and turn-off (bottom) transients at speeds of 8.0 V/ns and 15.7 V/ns, respectively. Figure 7 is a plot of the module's measured total switching energies (turn-on + turn-off) versus junction temperature. Also included on the plot are data for a similarly rated silicon IGBT module, taken from the manufacturer's datasheet [6]. Two points are clear: First, the switching losses of the SiC JFET module are more than 80% lower than the Si IGBT power module. Second, the SiC power module's switching losses are basically insensitive to increases in junction temperature, while the IGBT module increases drastically as the junction temperature rises. An additional point to be made is that the highest junction temperature given on the Si IGBT module's datasheet was 150 °C; the SiC JFET module was measured up to 250 °C.

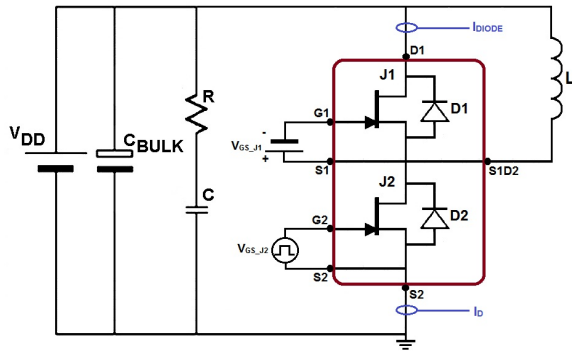


Fig. 5. Clamped inductive load test circuit.

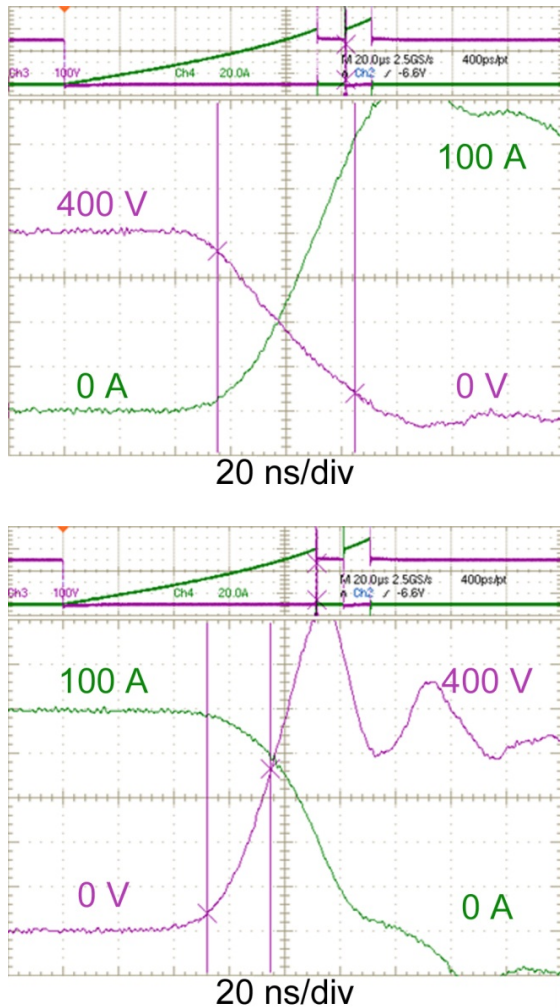


Fig. 6. Switching transients at (top) turn-on and (bottom) turn-off in a clamped inductive load test circuit at 400 V, 100 A, and a junction temperature of 100 °C.

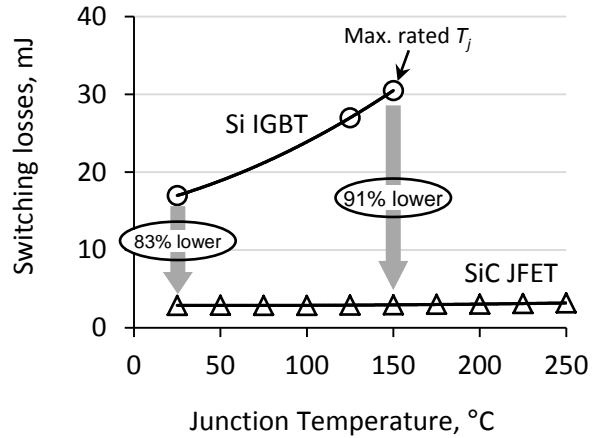


Fig. 7. Switching losses vs. junction temperature of the SiC JFET module and a similarly rated Si IGBT module.

5. Summary

As the offering of SiC transistors becomes increasingly diverse, an important figure of merit is the total transistor die area necessary to achieve a given current output and on-state resistance. The ability to use fewer transistors improves module yield and reliability, as well as reducing switch capacitance for lower switching losses. The die size figure of merit also extends equally well to applications in which high-temperature performance is required.

With 36 mm² of total SiC VJFET area (per switch position), the half bridge power module reported here delivers more than 1200 A/cm² at a junction temperature of 25 °C and nearly 700 A/cm² at 250 °C. Sourcing 100 A of current, the module's on-state resistance is 8 mΩ at 25 °C and 33 mΩ at 250 °C. Switching losses are more than 80% lower than a similarly rated silicon IGBT power module and exhibit almost complete insensitivity to junction temperature for the range studied in this work.

Acknowledgments

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References

- [1] S. Sato, Y. Zushi, K. Matsui, Y. Murakami, and S. Tanimoto, "30 kW/L Three-Phase AC 400 V All-SiC Inverter." To be published in the *Proceedings of the International Conference on Silicon Carbide and Related Materials*, Cleveland, Ohio, U.S.A. September 11-16, 2011.
- [2] Arkansas Power Electronics International, Inc., www.apei.net.
- [3] SemiSouth Laboratories, Inc., www.SemiSouth.com.
- [4] Brice McPherson and Ty R. McNutt of APEI, Inc., *Private communication*. August 2011.
- [5] R. Kelley, D. Sheridan, V. Bondarenko, and J. Casady, "1200 V Enhancement-mode SiC VJFET Power Modules." *PCIM Europe*: Nuremberg, Germany, May 2011.
- [6] Datasheet for FF150R12RT4, www.infineon.com.