Silicon Carbide Power Semiconductor Module Development for a High Temperature 10kW AC Drive

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Abstract—A silicon carbide power module has been developed to demonstrate a high-temperature, 10kW AC drive application. Several goals for this development include temperature dependent parameter evaluation of parallel-connected transistors and junction barrier Schottky diodes at 150ºC operating temperature. Next, design of a high-thermal conductivity substrate to cool the modules based on predicted losses. Finally the integration into a variable speed AC drive using a DSP-based V/F motor controller. Test results for the 10 kW AC drive are provided to demonstrate power module performance up to 180ºC.

Keywords—Silicon Carbide; AC Drive; Power BJT; Junction barrier schottky diode; high temperature.

I. INTRODUCTION

Silicon carbide (SiC) possesses many favorable properties making it ideal for high-temperature, high-frequency and high-power applications. More specifically, these properties are: wide bandgap, copper-like thermal conductivity, high breakdown electric field strength (approximately 10 times that of Si), and high saturated drift velocity (higher than GaAs).[1] An all silicon carbide power module has been developed and demonstrated in a 10kW AC induction motor drive. Emphasis is placed on design for high temperature operation. This includes characterization of the SiC diode static and dynamic behavior up to 150ºC and measurement of detailed switching performance of the bipolar junction transistor.[2]

Also discussed is the design of the half-bridge power module package used in this inverter. This design focuses on the high temperature die-attach, dielectric layer, and use of a custom forged copper pin-fin heatsink. The power module accommodates three parallel connected transistors, and one diode per switch. Fig. 1 is a top view of one of the half-bridge modules.

The power semiconductor modules are then assembled as a 10kW AC drive prototype by attaching three modules to an oil cooling channel. The modules share a common DC-bus and capacitor interconnection via a laminated printed circuit board, Fig. 2.

Control is provided by way of a Texas Instruments DSP based on the 2800 family processor. A simple V/F open loop induction motor control is used with provision for hardware over-current trip and time-overcurrent events in any of the three phases.
This paper summarizes the device performance of SiC diodes and BJTs as applied to an AC drive. It explains one approach for high temperature power semiconductor packaging to withstand the 150°C baseplate temperature. Finally the authors conclude with some operational results of this 10 kW AC drive at temperature.

II. SILICON CARBIDE DEVICE EVALUATION

The diode used in the power module is based on a design that combines the best of the Schottky diode’s high switching speed and PiN diode’s reverse leakage performance. This merged PiN Schottky (MPS) diode is also referred to as a junction barrier Schottky (JBS) diode.[3] The reverse breakdown characteristic of both the BJT and diode was measured to be 1200V on average. Unlike similar silicon diodes, the leakage current in the SiC JBS diode does not increase exponentially with temperature.

Another benefit to the JBS structure is the positive temperature coefficient of the forward voltage drop shown in Fig. 4. This allows for simplified parallel operation of these diodes for higher power applications. The strong temperature dependence does however double the power dissipation in the JBS diode at 150°C. The power dissipation however is still lower than comparable silicon fast recovery epitaxial diodes in the same voltage range.

The most benefit from the SiC JBS diode comes in the form of reverse recovery current. Not only is the recovery of the diode a small fraction of the forward current but the temperature dependence is negligible. Fig. 5 shows this characteristic for a similar 30A SiC JBS diode.

The SiC bipolar junction transistor (BJT) was chosen as a primary high power device due to its demonstrated reliability in single-pulse tests at the US Army Research Laboratory (ARL). Funding was therefore provided to CREE Corp. to develop a high-power version of the transistor to evaluate its capability in an AC motor drive application.

It was determined that a 60A 300V power module would be built using in-house ARL packaging of the CREE transistors. ARL researchers choose a configuration of 3 paralleled 20A transistors and one anti-parallel newly available 50A junction-barrier schottky (JBS) diode. The new power module application required data collection of at least five BJT parameters to determine suitability of this device for AC drive applications. These parameters were reverse breakdown voltage, switching loss, gain, forward voltage drop, and current sharing of paralleled devices. An inductive clamp pulse tester was used to measure these quantities. Measured items also included rise and fall times of voltage and current across the devices. The additional benefit of the pulse tester was to push the devices to maximum current at maximum temperature under single-pulse conditions, allowing a safe measurement of gain to insure the reliability of the data taken using the curve tracer. A summary of the switching losses and current fall-time is detailed in Fig. 8 for the parallel connected devices in the power module.
Fig. 6. BJT Turn-on energy as a function of temperature.

Fig. 7. BJT Turn-off energy as a function of temperature.

Fig. 8. BJT turn-off time as a function of temperature.

Switching losses were similar to an equally rated insulated gate bipolar transistor (IGBT) discrete device package; turn-on losses being lower than turn-off losses. The main difference in performance was that switching losses at higher temperatures were half that of a similarly rated IGBT.

Gain for the BJT module was also measured to aid in gate drive design. Originally a low gain ($\beta$:5~10) was expected at high temperature. However, curve tracer measurements showed much higher gain and only a modest reduction at high temperature (from 35 to 29 on average), Fig. 9. A fixed gate drive current of 100mA per device was therefore chosen based on the gain measured at 150°C to insure device saturation at all temperatures. Overall gate drive current to the module was set to 300mA.

The graph of Fig. 10 summarize the on-state saturation voltage at 1A of each of the six transistors built into the half-bridge module at 25°C, 75°C, and 150°C. The results of Fig. 10 show that on-state voltage is similar to that of commercially available IGBTs at the SiC BJT’s maximum operating temperature. SiC transistors had an obvious advantage over IGBTs at lower temperatures. This advantage was magnified at 150°C. The current distribution of these three devices operating in parallel was uniform. Sharing was also guaranteed in these devices at 150°C due to the increase in forward voltage drop as a function of temperature. This positive temperature coefficient behavior was also demonstrated in test results of previous generation BJT devices.

Fig. 9. BJT device gain over temperature within a power module.

Fig. 10. BJT saturation voltage vs. temperature within a power module.
III. MODULE PACKAGING

The construction of the power module is based on a half-bridge BJT-Diode configuration. The design is composed of three parallel connected BJTs per switch and one antiparallel diode, Fig. 11. An aluminum nitride (AlN) substrate 22mm x 42.6mm was chosen as the foundation for the SiC power module. Construction on the AlN substrate required patterning a solderable surface for the metal tabs to provide a bonding location for the SiC BJTs and diodes used in the half-bridge. E-beam deposition of titanium, platinum, and gold was used to metallize the top layer of the ceramic. Mounting and connection tabs for the SiC die were prepared by plating 0.25mm thick steel tiles with gold and then brazing these onto the prepared AlN substrate along with the SiC die all in one step. Steel tiles provided a level surface to assure uniform bonding between the SiC die and ceramic. Also important was the CTE match of the steel tiles (Kovar) with the SiC die. The complete AlN ceramic pad was then attached to the copper pin-fin heat spreader using a polyimide silver epoxy paste. The complete exploded view is shown in Fig. 12.

Large area die-attach of the devices, and Kovar tabs was accomplished using a low temperature gold-tin braze, an alloy of Au/Sn20, with a melting point of 280°C. Once all devices and gold plated steel tabs were mounted, a hotplate at 325°C provided the heat used to bond all components together in one step onto the AlN substrate. Finally gold 10mil wire-bonds were used to complete the die to pad interconnections for both the BJT and diodes.

Thermal simulations were done to evaluate the performance of the oil-cooled heatsink. The steady state simulation modeled each SiC device as a constant volume heat source: 33.3 W for each BJT, or 200 W for each of the three modules, and 25 W for each Schottky diode, or 50 W for each of the three modules. These numbers were derived from requirements for the BJTs to carry 200 W total with an average 1V drop, and for the Schottky diodes to carry 50 W total with a 1V drop.

Fig. 14 shows a contour plot of the temperatures on the assembly surface, assuming a flow of 150°C oil at 3 gpm. The maximum temperature calculated in this simulation is approximately 250°C, an increase of 100°C above the case temperature. The location of our RTD sensor (bottom right) agreed with the 170°C temperature observation within 10°C.
IV. AC DRIVE PERFORMANCE

A dynamometer using a DC motor load was employed for the evaluation of this AC drive. The switching frequency was chosen as 2kHz to minimize switching losses on the SiC power module. The DC link voltage was limited to 300V for the purposes of driving a 208VAC motor.

A simple V/F open-loop induction motor control was used with protection by measurement of rate-of-rise (di/dt) overcurrent trip for each of the three phases. This protection technique was chosen to ignore low frequency induction motor startup currents.

The power readings and phase currents for the end of a high-temperature run were taken using a high bandwidth power analyzer on both the input DC power and output AC power. Drive efficiency was measured at about 93.6% at the 7.4 kW output power level operating at 150℃ inlet oil temperature. Peak heat spreader temperature measured at the RTD was observed to be 180℃. The maximum tested current was 35A RMS and 50A peak at 300VDC.

V. CONCLUSIONS

The development of a new generation of silicon carbide junction barrier schottky (JBS) diodes and epitaxial BJTs are critical to the demonstration of this high power and temperature inverter. The switching performance and conduction losses of the SiC BJT exceed the performance of similarly rated IGBTs. Though a successful demonstration has been presented, reliability issues remain. High temperature and current density operation forces degradation of the BJT. BJT gain is permanently reduced and diode reverse leakage is greatly increased when these devices are operated above 150℃ and 150A/cm². New fabrication techniques are being studied to improve these issues and it is expected that the promising performance of the BJT will make it the first of many reliable silicon carbide devices for high temperature power electronics applications.

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REFERENCES