High Temperature (> 200 °C), High Frequency (> 1 MHz) Multi-Chip Power Modules

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Silicon carbide (SiC) power devices have recently become commercial products from several vendors, resulting in the ability of system engineers to begin designing and deploying systems around these state-of-the-art devices. In order for these systems to exploit the advantages of wide bandgap devices, power packaging, gate drivers and bus work to the system power bus must all take into consideration the increased performance capability of SiC devices. As such, a high speed full H-bridge power module (Fig. 1) was developed to allow a low parasitic power path to the control circuit and system bus. The module uses a light weight metal matrix composite (MMC) baseplate, a metalized Aluminum Nitride (AlN) substrate, and a high temperature PCB with high frequency bus capacitors for the power stage. The module is completed with a tightly coupled gate driver for high speed switching. The full H-bridge is comprised of 4 switch positions, with each having two paralleled 1200 V, 80 mΩ SiC MOSFETs and one anti-parallel 20 A SiC Schottky diode. Each power substrate consists of four switch position and is patterned in-house using AlN-based power substrates for the superior thermal properties (thermal conductivity = ~150 W/m•K and coefficient of thermal expansion= 4.5 ppm/K) as compared to Al_2O_3 (thermal conductivity = 35 W/m•K and coefficient of thermal expansion = 8.4 ppm/K). The baseplates are directly bolted to the heat sink and high temperature thermal interface material is used to reduce the thermal resistance between the two interfaces.

Traditional bus bar systems require multiple pieces, which add weight and volume, and are a significant source of parasitic impedance. In an attempt to reduce all of these factors, an integrated bus board PCB is directly soldered to the substrate. Transitioning from a traditional discrete sheet metal bus bar system to a PCB approach soldered directly to the substrate lowers the overall module inductance, and drastically reduces the part count and module height by replacing or eliminating many connectors and fasteners. This method also makes room available for high frequency bus capacitors to be located extremely close to the switching components with minimal inductance between the components. The integrated board materials were designed to withstand the high temperatures generated by the power devices on the substrate to allow for these new design options.

Separate gate drive boards were designed to interface with each full bridge power module such that a short gate and source Kelvin interconnection length is achieved. Stand-offs provides a thermal buffer for the gate drive circuitry without adding significant inductance. Fig. 2 shows the measurement of extremely low junction-to-case thermal resistance of 0.15 °C/W. The measurement verifies the high thermal conductivity of the packaging materials and the minimal voiding in the layers between the power die, power substrate, and baseplate due to the optimized assembly process, as seen in the equal current sharing between switch positions.

Current paths of interest in the module for parasitic analysis are those that connect between nodes of the full bridge (Fig. 3). Due to the symmetry inherent in the substrate layout, the paths from drain or source to either side leg of the full bridge are equal. The simulated parasitic resistances and inductances of these over a range of frequencies are shown in Fig. 4. At 500 kHz (targeted system frequency), the resistances and inductances were less than 1.2 mΩ and 12 nH, respectively. As a comparison, the inductance values calculated for the full bridge module presented here are approximately the same as those found for a proposed 1.5” square packaged low-inductance half-bridge topology; half that of a conventional 1.5” square comparison half-bridge topology. The reduction in parasitics allows for an increase in di/dt corresponding to a reduction in switching losses. Moreover, this also translates into an important reduction of the transient over-voltage condition present across the die during switching transients (by reducing the energy stored in module parasitic inductances prior to switching).

Extremely fast turn on and turn off times were measured using the developed high frequency SiC power module. A clamped inductive load was used to perform a switching test representative of a hard-switched power converter. The rise and fall times of the power devices were measured with an isolated voltage probe and oscilloscope. A maximum voltage of 400 V was applied to the clamped inductive load, which was then connected to the drain of a single switch position and returned to the power supply via the source connection of the same single switch position. A maximum turn on current of 30 A was achieved through the adjustment of the gate waveform pulse width and number of repetitions. The switching waveforms are displayed in Fig. 5. Under these conditions, rise and fall times of 16.1 and 7.5 ns were observed, respectively. It is also important to mention that no voltage/current overshoot was observed which contributes to additional losses in the system and increases chances of failure. The X-5 modules were also used in a 6.3 kW AC-DC converter enabling operation to 1.2 MHz (Fig. 6). The high switching frequency and high temperature capability enabled a power density of 115 W/in^3 (52 in^3) and 5.2 kW/kg (1.165 kg).

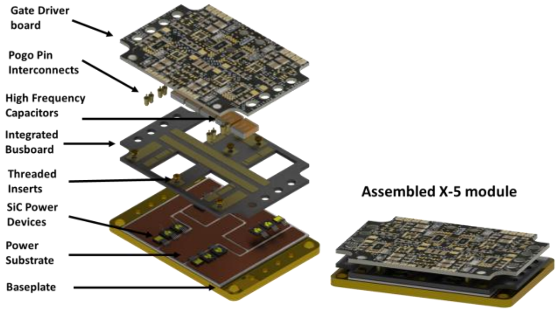

Figure 1. View of the high temperature, high frequency MCPM with an integrated gate driver assembled with dimensions.

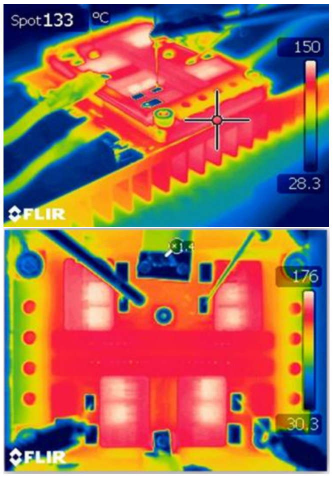

Figure 2. A thermal image showing (top) the maximum junction and case temperature and (bottom) excellent current sharing between each of the switch positions. The junction-to-case thermal resistance was 0.15 °C/W.

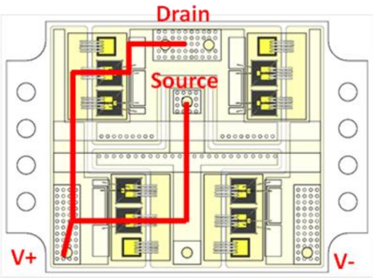

Figure 3. A schematic of the traces in the X-5 power module that were modeled to determine the resistances and inductances.

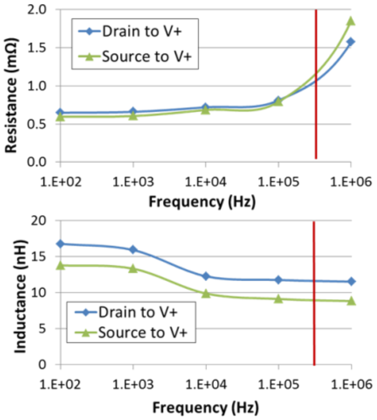

Figure 4. The resistances and inductances of the traces over frequency. A red line marks the 500 kHz operational point.

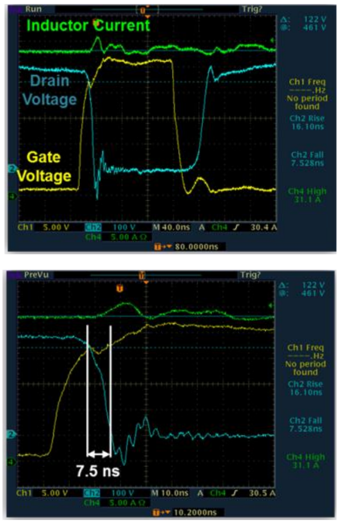

Figure 5. (top) 400 V / 30 A clamped inductive load switching waveforms of the high frequency module and (bottom) a magnified image of the turn on waveform showing a 7.5 ns transition time.

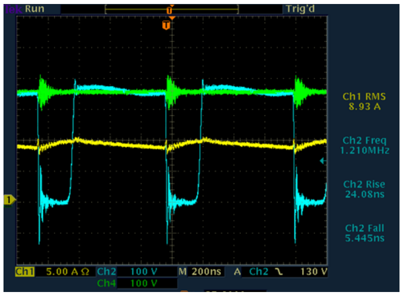

Figure 6. A 6.3 kW AC-DC converter using the X-5 power module operating at 1.2 MHz. The high switching frequency and high temperature capability enabled a power density of 115 W/in^3 (52 in^3) and 5.2 kW/kg (1.165 kg).