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

Ty McNutt, Brice McPherson, Brandon Passmore, Zach Cole, Bret Whitaker, Adam Barkley, Brad Reese,
Robert Shaw, Alex Lostetter

Arkansas Power Electronics International, Inc. 535 W. Research Center Blvd., Fayetteville, AR 72701, USA
Ph. 479-443-5759, email: tmcnutt@apei.net, www.apei.net

Power module, wide bandgap, silicon carbide, gallium nitride, high temperature, high frequency

Abstract

APEI, Inc. has developed high performance, high temperature power modules for extreme environment systems and applications to exploit the advantages of wide bandgap semiconductors. These power modules are rated >1200V, >200 °C, and are designed to house any wide bandgap power device.

INTRODUCTION

For a modern power electronic system to be competitive it must lie on the leading edge of performance – power density, switching speed, operating temperature, functionality, and efficiency must be increased to meet the specific needs of a broadening electronic marketplace. Currently available silicon (Si) based technology is struggling to keep up. In response to this, there is a strong industry desire to look beyond silicon, focusing on wide band gap semiconductor materials such as gallium nitride (GaN) and silicon carbide (SiC). Substantial effort has been devoted in the past decade to mature and commercialize wide band gap power devices, and hence, multiple high performance SiC components are now commercially available.

The high performance power modules presented within this discussion are newly developed products, employing the design techniques, advanced materials, and manufacturing processes developed by APEI, Inc. to meet the demands of current and upcoming power electronic systems.

HIGH POWER, HIGH TEMPERATURE POWER MODULES

The HT-2000 module shown in Figure 1 is capable of junction temperatures up to 250 °C, voltages up to 1200 V, and currents greater than 100 A (depending on the size, type, number of devices inside, and thermal management system) [1]. Advanced lightweight materials and a small footprint result in a surprisingly lightweight assembly (135 g). The HT-2000 was designed to have an extremely low inductance, high current path by minimizing the module thickness (<11 mm), utilizing the entire module width for conduction, minimizing wire bond length and loop height, and matching the power and gate drive current path length between each device identically to ensure simultaneous switching. Individual gate resistors and additional components (capacitors, diodes, etc.) may be implemented internally to the gate drive path to best suit the device type and operational conditions of a given application, thus enabling very high switching frequencies (>500 kHz).

Figure 1. Flexible interconnection scheme of the HT-2000 series has four unique quadrants allowing for half- or full-bridge configuration (top view), while providing a lightweight, low volume solution (end view).

A novel interconnection scheme is employed which allows configuration as either a half or full bridge configuration through external bussing of the module's independent quadrants. There are six external power connectors, two each for the positive rail, negative rail and output. For both configurations, the rail nodes are shorted externally, and the difference is how the outputs are connected. Full-bridge operation keeps the outputs separate, while half-bridge connects them together. Independent gate signal and source kelvin connectors allow for independent control of each quadrant.

Characterization data of the HT-2000 series power module housing Rohm Semiconductor's Trench MOSFET (TMOS) is presented in the following. Each TMOS die is rated at 900V blocking and an $R_{DS,ON}$ of ~20 mΩ. Although the modules allow for easy integration of anti-parallel diodes, none were used in these modules, as the TMOS body diode was used for reverse conduction. Figure 2 displays the 25 ºC on-state characterization data for the TMOS module (configured as full-bridge with four TMOS die in parallel) at gate voltages of 0V, 10V, and 20V.

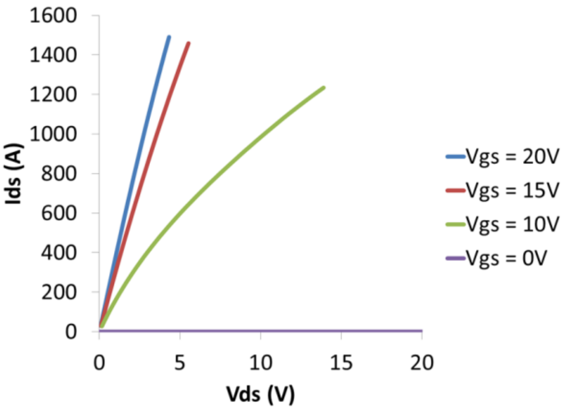

Figure 2. HT-2000 TMOS module on-state with four TMOS die in a single quadrant at 25 °C.

HIGH POWER, HIGH TEMPERATURE INTELLIGENT POWER MODULES

APEI, Inc.'s new intelligent power module, the X-5, is a full-bridge power module, as shown in Figure 3, measures 1.6 × 2.3 × 0.46 cubic inches (L × W × H) and consists of four switch positions, each comprised of two paralleled 20 A Cree SiC MOSFETs and one anti-parallel 20 A Cree SiC Schottky diode. AlN-based power substrates were used due to their superior thermal properties (thermal conductivity = ~150 W/m·K and coefficient of thermal expansion= 4.5 ppm/K) as compared to direct bond copper Al_2O_3 (thermal conductivity = 35 W/m·K and coefficient of thermal expansion = 8.4 ppm/K) based substrates [2]. The baseplate is comprised of a metal-matrix composite material.

Figure 3. High frequency, intelligent SiC power module capable of > 1 MHz switching capability.

Thermal analysis is a vital part of determining the performance limitations of a system. The model of the SiC-based X-5 power module consists of a baseplate, power substrate, diodes, MOSFETs, and the appropriate solder attach layers. Detailed temperature dependent properties were used for the simulations.

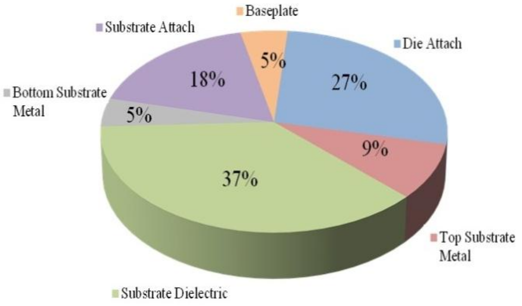

Figure 4. Percent of total package thermal resistance for each layer in the X-5 module. The substrate dielectric makes up the largest portion of the thermal resistance.

Detailed 2-D calculations were utilized to determine the thermal resistance of each of the layers in the model of the X-5 module. Figure 4 shows a pie chart of the thermal resistance breakdown of the module from the die to the bottom of the baseplate. Since the baseplate is a high performance material, its thermal resistance is relatively low. However, the AlN substrate material makes up the largest portion of the total thermal resistance. Since AlN is currently the highest thermal conductivity power substrate material available, it was used as the power substrate material in the X-5 module.

The thermal performance of the X-5 module was analyzed in further detail by measuring Rj-c. Rj-c is an important figure of merit that determines the rise in temperature of the power die for a specific power loss. As shown in Figure 5, the experimental and modeled junction-to-case change in temperature (ΔTj-c) was 17 °C and 15 °C, respectively. For a total power loss of 95.5 W dissipated by all of the power die at once, Rj-c is roughly 0.18 °C/W. This is a very low Rj-c value which is a derivative of using advanced packaging materials and assembly processes.

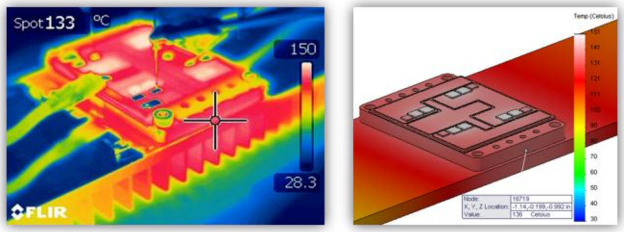

Figure 5. Individual module thermal performance (experiment left, simulation right) for a PHEV application [3] using a passively cooled heatsink and a vented case.

Traditional busbar systems require multiple pieces, which add weight and volume. Additionally the busbars are often a significant source of parasitic impedance. In an attempt to reduce all of these factors, APEI, Inc. introduced an integrated bus board which consists of a circuit board directly soldered to the AlN substrate. Transitioning from a traditional discrete sheet metal busbar system to a circuit board with integrated bus traces soldered directly to the substrate lowers the overall module inductance. It also drastically reduces the part count and module height by replacing or eliminating many connectors and fasteners that would otherwise be necessary. This method also makes more room available for several high frequency bus capacitors to be located extremely close to the switching components to further reduce inductance through this path. Such an integrated board must be able to withstand the high temperatures generated by the power devices on the substrate to allow for these new design options.

Parasitic modeling and analysis is another vital tool in understanding the parasitic parameters attributed to the package. FastHenry [4] was used to model the current paths of interest that connect between nodes of the full bridge. The simulated parasitic resistances and inductances of these over a range of frequencies are shown in Figure 6. A power converter producing approximately a 500 kHz square wave also generates higher frequency harmonics which contribute to the impedance. However, their contribution to the net current falls off at a rate of $1/n^2$ [5]. Therefore, since the resistance increases with frequency at a much lower rate and the inductance actually drops very slowly with frequency, the power loss is dominated by the fundamental switching frequency and the power losses associated with the harmonics are negligible. For comparison, the inductance values calculated for the full-bridge X-5 module 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 [6].

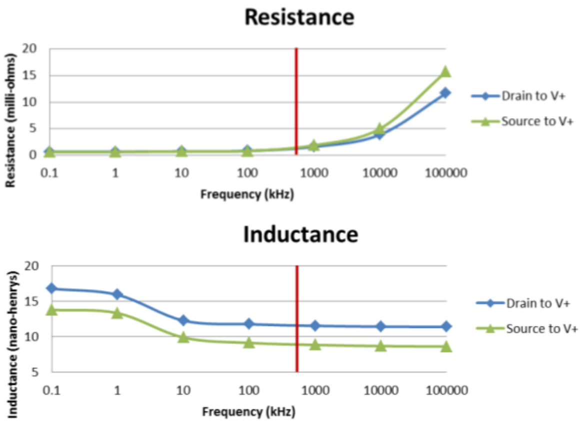

Figure 6. The resistances and inductances of the X-5 power traces over frequency. A red line marks the 500 kHz operational point.

At $V_g = 20$ V, the on-state resistance was on the order of 40 mΩ for both quadrants, as shown in Figure 7, without showing any signs of saturation.

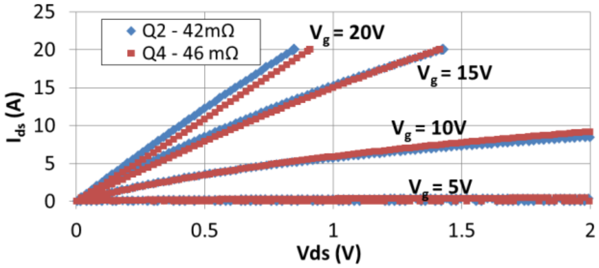

Figure 7. On-state characteristics of the X-5 power module for two of the four switch positions. Each switch position contains two SiC MOSFETs and one SiC Schottky diode.

In addition, the X-5 power module was demonstrated in the optimized Plug-in Hybrid Electric Vehicle (PHEV) charger unit demonstrated to 6 kW [3]. The module was able to switch at over 1.2 MHz in the charger configuration acting as the hard switched PFC front end of the high performance unit. Figure 8 shows the switching waveforms of the module during operation.

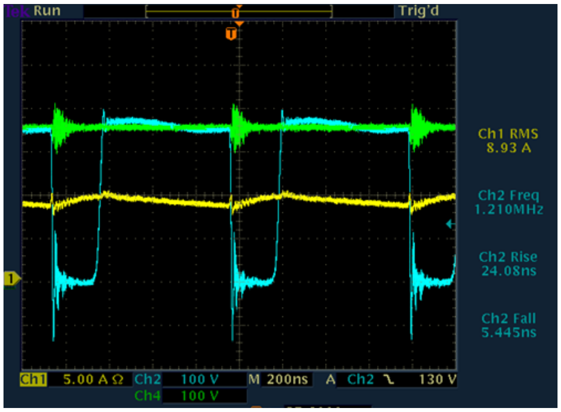

Figure 8. Oscilloscope capture of the X-5 power module operating in a PFC front end stage of the PHEV charger unit at 1.2 MHz.

HIGH TEMPERATURE DISCRETE POWER PACKAGES

At the module level, multiple devices are co-packaged in various topologies (half-bridge, full-bridge) and paralleled in order to reach the current level desired (or until the available area in the module is occupied). While this is a powerful approach for very high current levels (>100A) and for large, integrated systems, there are few options at the discrete level (single switches and a diode, if necessary) for currents in the 50-100A range that offer low inductance, high temperature capability, and flexibility of use. Standard discrete (or small footprint) wire bonded power packages include transistor outline (TO) packages, and small outline transistor (SOT) Isotop packages. While these packages are effective for conventional silicon (Si) devices, limitations are clearly encountered with the high frequency, high current density performances characteristic of wide band gap devices.

TO style packages are often current limited due to small cross sectional area of the pin contacts, have a thin base plate which is not effective for heat spreading, and only have one mounting point at the edge of the package, making it difficult to form an efficient thermal path between the package and the heat removal system. Isotop packages are capable of higher currents due to their blade style connections and have improved mounting features; however, they can suffer from a high lead inductance and are generally constructed with materials not capable of reaching temperatures above 175°C.

Accordingly, APEI, Inc. has developed the power package described in this section, which responds to the issues associated with wire bonds, parasitic impedances, heat removal, current density, physical mounting and ease of use. It includes the following highlights:

- High performance design (1200 V, 50-100A, 250°C)
- Wire bonded or wire bondless capability
- Capable of housing both lateral and vertical devices.
- Low profile, minimum distance
- Bolted electrical connections for system integration
- Multiple mounting locations for consistent thermal connection.

This discrete power package consists of a number of primary elements, including the base plate (structural support, heat spreading, and thermal connection), power substrate (electrical interconnection and isolation), lead frames (external connections), an upper substrate (for topside electrical interconnection), and injection molded housing (mounting, isolation, and protection). These features are identified in the exploded view provided in Figure 9.

This package is designed to employ a variety of base plate material options in order to best meet the needs of a given system and operational environment. The base plate is formed with either a base metal (e.g., copper) or a metal matrix composite depending on application and service temperature.

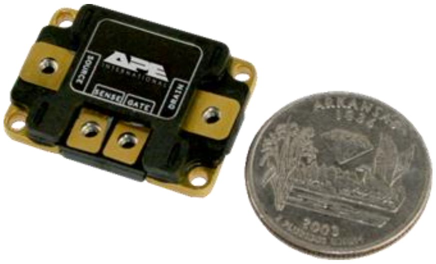

Figure 9. APEI, Inc.'s X-6 power discrete package for high temperature operation of a single switch position.

The power substrate is a bonded ceramic-metal structure which can either be direct bond copper (DBC), direct bond aluminum (DBA), or another alternative. These substrates are capable of carrying very high currents, and are formed with high thermal conductivity engineered ceramics, such as aluminum nitride (AlN). The upper interconnection substrate is designed based on the device type and pad layout.

While similar in size to a TO-254, this package includes bolted electrical contacts accomplished by "captive" fasteners contained in the plastic and trapped in place by the conductive lead frames. This technique is ideal for bolting to buss bars, electrical contacts, or PCB boards, as the fastener is freely allowed to move vertically – pulling into the lead frame (and connected surface) instead of pulling the lead frame downwards in the case of a rigid fastener. Another highly attractive feature, is the inherent building block approach of the package, as shown in Figure 10. The package can be configured as a single switch, paralleled switches, bridges, or series connected.

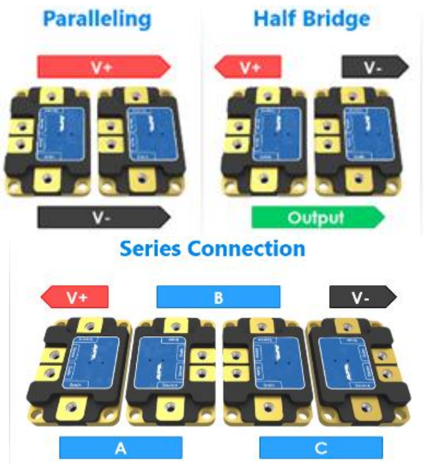

Figure 10. Building block approaches for X-6 discrete package.

CONCLUSIONS

The high performance power modules presented are newly developed products, employing the design techniques, advanced materials, and manufacturing processes developed by APEI, Inc. to meet the demands of current and upcoming power electronic systems. Each of the high performance, high temperature power modules aim to exploit the advantages of wide bandgap semiconductors. The power modules presented are rated >1200V, >200 °C, and are designed to house any wide bandgap power device.

REFERENCES

1. A.B. Lostetter, et al, "High Temperature Silicon Carbide Power Modules for High Performance Systems," International Conference on Silicon Carbide and Related Materials, Cleveland, OH, Sept. 2011.
2. R. K. Ulrich and W. D. Brown, "Advanced Electronic Packaging," New Jersey: John Wiley & Sons, Inc., 2006, p. 566.
3. Z. Cole, et al, "Packaging of High Frequency, High Temperature Silicon Carbide (SiC) Multichip Power Module (MCPM) Bi-directional Battery Chargers for Next Generation Hybrid Electric Vehicles," IMAPS Conference 2012, San Diego, CA, Sept. 2012.
4. Matton Kaman, et al., "FASTHENRY: A Multipole-Accelerated 3-D Inductance Extraction Program," IEEE Transactions on Microwave Energy and Techniques, Vol. 42, No. 9, pp. 1750-1758, Sept. 1994.
5. R. K. Ulrich and W. D. Brown, "Advanced Electronic Packaging," New Jersey: John Wiley & Sons, Inc., 2006, p. 203.
6. Shengnan Li, "Packaging Design of IGBT Power Module Using Novel Switching Cells," Ph.D. dissertation, University of Tennessee, 2011.