

Packaging of High Temperature 50 kW SiC Motor Drive Modules for Hybrid-Electric Vehicles

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Abstract

As the demand for hybrid- and fully-electric vehicles continues to rise, the requirements of the requisite power electronics systems (namely the power density, size, and weight) are rapidly surpassing the limits of current technology. As such, a large effort has been focused on the development of wide band gap semiconductor technology, such as Silicon Carbide (SiC), which promises benefits including higher current densities, higher voltage blocking capabilities, and operation at temperatures vastly exceeding silicon. In order to fully take advantage of these benefits, it is paramount that the entire system be designed to handle these elevated conditions. Arkansas Power Electronics International, Inc., in collaboration with the University of Arkansas and Rohm, Ltd., has developed a high-temperature (250+°C), high-performance 50kW integrated motor drive incorporating SiC based switch technology, multi-chip module (MCM) gate driver, and high-temperature packaging techniques.

This discussion presents the overall design of a 600V 180A fully functional single phase half-bridge module containing eight paralleled Rohm 30A SiC DMOSFETs per switch position. Specifically, the high-temperature packaging of these systems is discussed in detail, including: power and driver substrates, base plate materials, transient liquid phase (TLP) die attach, wire bonds, passivation, and housing materials. The thermal performance of the system under power is also addressed, with key focus on reducing the thermal resistance of each layer. Finally, the high-temperature electrical test results of the fabricated prototype systems are presented, followed by plans for future work.

Key words: Silicon Carbide (SiC); High-Temperature; Power Electronics Packaging

1.0 Introduction

Silicon Carbide (SiC) based semiconductor devices offer a tremendous advantage over conventional switch technology, including the possibility for 10x the power density, 10x the breakdown voltage, 1/10th the switching losses, higher switching frequencies, and operation at considerably higher temperatures [1][2]. SiC has the potential to not only increase the performance of current systems, but also may act as an enabling technology - providing the opportunity to incorporate electrical systems in applications where the ambient

temperature, weight, and/or size restrictions previously prohibited their use. While technically impressive, a number of major limiting factors are present which to-date have confined the commercial potential of SiC to high-cost, high-performance systems or extreme environment applications. These factors include a higher cost, limited commercial availability, lack of proper device characterization, packaging issues, and reliability concerns.

The goal of this work was to ambitiously address these issues; acting as a bridge from SiC

Table 1. Candidate base plate materials.

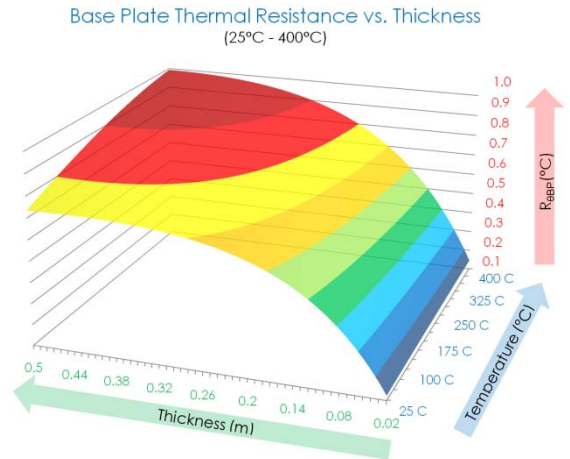
Material	Thermal Cond. (W/mK)		CTE (ppm/°C)		Density (g/cm ³)
	25°C	250°C	25°C	250°C	
Cu	386	381	16.7	17.6	8.9
Al	237	235	23	24.7	2.7
Mo	138	129	5.2	5.3	10.3
Kovar	14	15.5	6	5.1	8
AlSiC (40 % SiC)	190	n/a	8	8.75	3
CuMo (20 % Cu)	210	165	7.2	7.5	9.9
CuMo (30 % Cu)	220	186	7.8	8.3	9.7
CuW (20 % Cu)	170	145	8.2	8.6	15.7

Reference: Material Property Database - http://www.jahm.com/pages/about_mpd.html

research prototype systems to commercially available high power density SiC based solutions (such as motor drives and power conversion systems). The research presented in this discussion comprises of the development of a high-performance 50kW SiC motor drive targeted specifically for implementation in a hybrid-electric vehicle at a junction temperature of 250+°C. The power and gate drive stages are integrated into a single housing, resulting in a compact overall package. Operating at elevated temperatures provides the benefit of reduced cooling requirements (lowering weight), removal of thermal shielding materials, and placement near or at the point-of-use (reducing cabling and improving signal quality). These features will ensure that the developed system remains competitive and able to meet the demands of current and future power conversion needs. The following discussion outlines and elucidates the main design aspects of the system packaging including: the general design philosophy, components and materials, assembly processes, and electrical test results.

1.1 Design Overview

The impetus of this approach is integration; the consolidation of a number of disparate high-temperature components and techniques into an enclosed functional high-temperature system. This research group (consisting of APEI Inc., the University of Arkansas, and Rohm, Ltd.) was formed to concentrate their high-temperature expertise to advance and merge their previous developments [3][4][5] on the path towards commercialization of SiC technology. Additional focus was centered on scalability; designing the structures and processes to 'grow' in power and operational temperature as device and material technology continues to improve and mature. While the presented system was designed as a 3-phase motor drive, the principal approach is flexible enough to accommodate a number of topology possibilities in the same fundamental housing.

**Figure 1: Base plate thermal resistance surface.**

The module encloses two key elements: a power stage consisting of eight paralleled SiC double diffusion MOSFETs (DMOS) fabricated by Rohm Corporation, Ltd. per switch position and a high-temperature silicon on insulator (HTSOI) based gate drive. Two substrates are located in close proximity to accommodate these elements: a single layer power substrate and a multiple layer multi-chip module (MCM) substrate. Bare die devices are utilized to save space, reduce parasitic impedances, and increase temperature of operation (through custom packaging with more resilient material systems). Power devices are attached utilizing a robust high-temperature die attach with high electrical and thermal conductivity. Gate drive devices and components are mounted with either a high-temperature silver-glass epoxy or solder (where appropriate). The module housing is an injection molded glass reinforced polyamide capable of withstanding the operational temperatures.

1.2 Package Materials

Base Plate

The core function of the base plate in a power module is to provide thermal spreading and structural support to the rest of the assembly. As such, the ideal requirements of the base plate material would be one with a very high thermal conductivity (k) and a coefficient of thermal expansion (CTE) closely matched to that of the attached components (in this case, the power substrate). These material requirements are exacerbated in a high-temperature setting, where minimizing thermal stresses is crucial for long term survivability. Candidate materials which were under consideration for this module are displayed in Table 1. Included are base metals (high k, high CTE), alloys such as kovar (low k, low CTE), and composite materials which exhibit a compromise between the two.

It was decided that a CuMo metal matrix composite (MMC) base plate with 80% Mo and 20% Cu was the best solution for this system. It has the benefit of a respectably high k value, a CTE which can be tailored to meet a variety of substrates, is readily machined, able to be plated, and is relatively lightweight. The base plate x and y dimensions were designed to meet the area requirements provided by Rohm, Ltd., power substrate layout geometry, driver board sizing limitations, and adequate room for mounting holes. The thickness was designed for optimal thermal performance. While the base plate provides thermal spreading (which is vital for efficient heat removal), it also contributes a significant thermal resistance ($R_{\theta_{bp}}$) due to its relatively large thickness in comparison with the other layers. The key to an effective base plate design is to reach a balance between the two effects. Figure 1 is a surface depicting the effects of both thickness and temperature on the thermal resistance of a CuMo base plate. The specific values represent the case of a single 4.8mm x 4.8mm power die and assuming the heat sink material is copper (for thermal spreading calculations). As the figure describes, the thermal resistance increases readily with thickness, up to a point where thermal spreading begins to limit the slope. Temperature has a noticeable effect which worsens as the plate gets thicker. Utilizing this curve in conjunction with thermal simulations, a base plate thickness of 0.15 in. was selected as a good compromise. At this thickness, temperature effects are minimal, the thermal resistance is acceptably low, and the thermal spreading width is sufficient.

Power Substrate

The system was designed to carry a maximum of 200A continuous; hence the power substrate is limited to options where this current can be carried

safely. Suitable materials include both Direct Bond Copper (DBC) [6], and Direct Bond Aluminum (DBA) [7]. Both substrate varieties are fundamentally similar in that they are thick sheets of a pure metal directly bonded to a ceramic substrate (Al_2O_3 , AlN, or Si_3N_4). In comparison, DBC has the advantage of a lower resistivity ($1.7e^{-6}$ vs $2.65e^{-6}$ $\Omega\cdot cm$), higher thermal conductivity (390 vs. 240 W/m $\cdot$ K), and ease of etching. DBA exhibits the distinguishing factors of improved thermal cycling reliability (due to the stronger nature of the metal-ceramic bond and aluminum's greater resistance to strain hardening), reduced weight (2.70 vs 8.94 g/cm 3), and the potential for a mono-material wire bond interface (Al-Al) which greatly limits high-temperature metallurgical interfacial issues. Ultimately, the decision for this particular application was chosen to be DBA due to its superior thermal cycling performance and high-temperature reliability [8].

For optimal thermal performance, a ceramic base of AlN was selected. Three Al thicknesses are available (8, 16, and 24 mils), which are analogous to standard DBC thicknesses (5, 8, and 12). While the thicker metal layers are capable of carrying more current (corresponding to lower trace widths), they become increasingly difficult to pattern tightly due to prolonged etching durations. To decide the most useful metal thickness, a study was performed to determine the trace width required for 200A continuous for each setup. The difference in electrical resistance, represented in Figure 2, between 16 and 24 mil thicknesses becomes negligibly small as the trace width increases. In effect, with wide enough traces (>300 mil) a 16 mil substrate will be just as effective at carrying current as the thicker 24 mil variety. Figure 3 depicts the effect of temperature on the resistance of the 16 mil thick metal layer. As

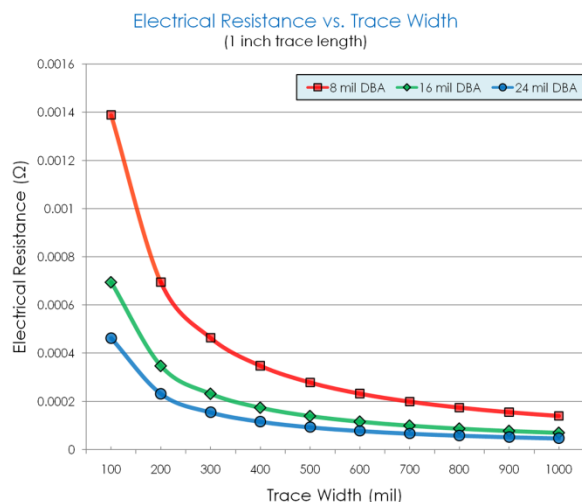


Figure 2. DBA metal thickness resistance curves.

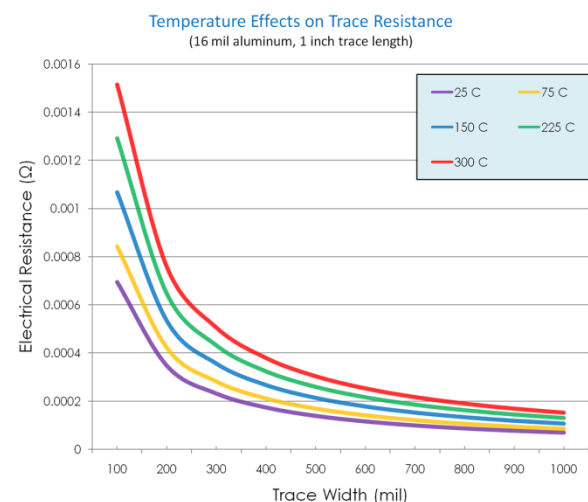


Figure 3. Temperature effects on DBA resistance.

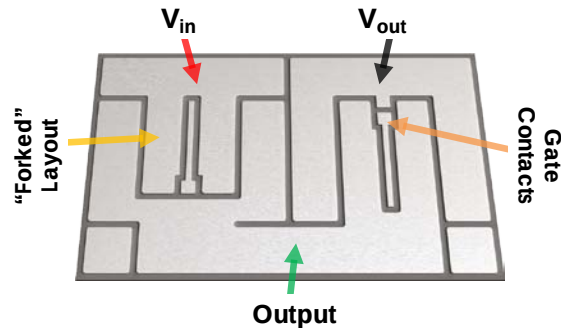


Figure 4. Forked DBA power layout.

shown, the effects of temperature are reduced for larger trace widths. The key is to design the minimum width after the 'knee' of the curves in order to ensure the design will be largely insensitive to temperature. Accordingly, the minimum trace width was selected to be 350 mils at a metal thickness of 16 mils. The heat generated under these parameters at 200A will be ~10-15W, which is acceptably low and will be distributed evenly across a large area for efficient heat removal.

One of the more challenging power substrate design issues was creating a layout that properly accommodated a large number of paralleled power devices (eight die per switch position). It was found that the initial approach which positioned the die in linear paths resulted in a highly unbalanced inductance between the switches and the source. This imbalance resulted in unacceptably high current spikes at the furthest devices down the line. In order to limit this, a number of layout approaches were considered, including: radial, forked, segmented, and distributed arrangements. While a radial pattern had optimal inductance matching, it wasted a lot of space on the substrate to achieve this. The forked path approach was selected as the best tradeoff of current spiking and layout size. The final layout (depicted in Figure 4) utilized two forks to create matched 'sets' of die which had equalized impedances, effectively halving the magnitude and duration of the current spikes.

Gate Drive Substrate

A high level of integration was essential for the gate drive and control substrate to physically fit inside the size restraints of the module. To this end, the drive circuitry and the substrate technology had to be selected with size reduction as the most prominent design factor. The multi-chip module method was implemented as the prime space saving technique. Principally, this approach involves surface mounting multiple bare, unpackaged devices on a single

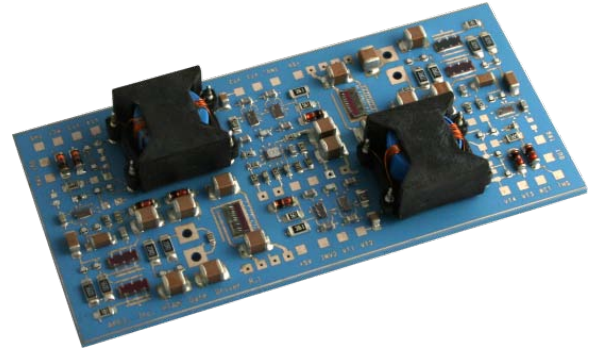


Figure 5. LTCC MCM gate drive board.

substrate, allowing for each component to be placed in close proximity with a net reduction in signal impedances. This consequently 'frees' the designer to implement a higher-temperature and more robust material system than standard packaging allows.

A fine line, multi-layered substrate is crucial to fully take advantage of the MCM technique - there is simply not enough room for electrical interconnection on the upper surface. APEI, Inc. utilizes two primary multi-layer high-temperature substrate technologies: polyimide laminate and low temperature cofired ceramic (LTCC). Polyimide laminates are capable of operating in temperatures up to 250°C; however, significant issues with via integrity are encountered past that threshold. This restricts the over-temperature capability of the structure as well as drastically limiting the high-temperature assembly options. LTCC, conversely, is quite capable of operating at extremely high temperatures (APEI, Inc. utilizes LTCC substrates in >450°C high g-force wireless telemetry sensors [9]) and has a closely matched CTE with the bare die devices, making it an ideal solution for this application. Moreover, it offers a wide selection of metallurgical systems, extremely high frequency capability, potential for integrated passives, and ability to incorporate advanced features such as blind and open cavities.

DuPont's LTCC material system [10] was employed with the substrates fabricated at the University of Arkansas High Density Electronics Center (HiDEC) facility. This particular design consisted of two plane layers, three primary signal layers, redundant signal layers, and spacer layers for additional thickness. The buried metal layers are silver, while the via material and exposed surface metals required careful selection in order to avoid issues such as solder leaching, wire bond metallurgical problems, corrosion, and electromigration. DuPont Micro Circuit Materials provided the research team with a wide variety of

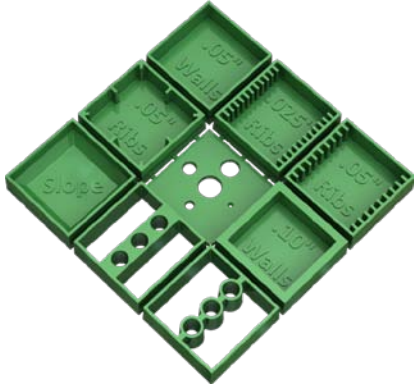


Figure 6. Injection molded test card design.

paste types for experimentation (publication pending), resulting in a surface layer which is wire bondable (Au, Pt, and Al), solderable, and resistant to high-temperature corrosion effects at the wire bond interfaces. The assembled board (pictured in Figure 5) was mounted to the package housing with a locking collar, effectively fastening the ceramic structure in place with a firm compressive force.

Module Housing

The module housing serves an assortment of purposes, including: isolation and protection of the sensitive electrical components, structure and support to the gate drive, mounting points for IO connections, and support for the power contacts. Material selection was quite difficult due to the limited number of plastic materials which were physically capable of withstanding the $>250^{\circ}\text{C}$ continuous temperatures. A number of alternatives were considered, including metal sidewalls with glass frit or ceramic through hole isolation, cast ceramics, machined ceramics, and ceramic fabrics (such as nextel) woven into a rigid frame. Ultimately, none of the alternatives were found to be practical due to cost, complexity, and structural concerns. It was decided that high-temperature glass reinforced polyamides were the most sensible housing material. These materials offer significant advantages over other high-temp plastics (PEEK, teflon, etc.) because they are comparatively inexpensive and capable of injection molding into very complex geometries. The specific plastic chosen was designed for prolonged service at elevated temperatures with a deflection temperature of 270°C and a melting temperature of 305°C .

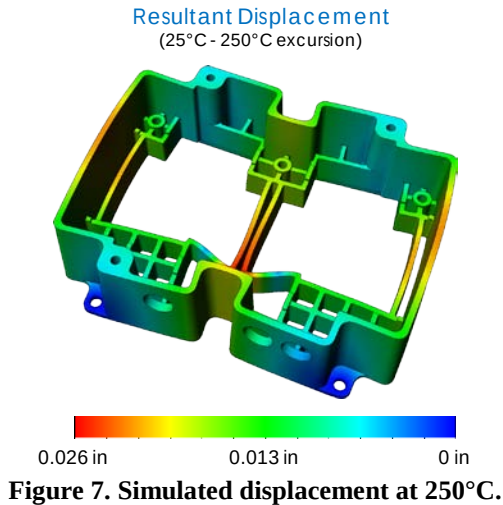
To qualify the plastic and discern which reinforcement features best retained structural integrity after high temperature thermal cycling, a test 'card' of varying elements (displayed in Figure 6) was conceived and injection molded with the candidate material. The card was designed such that

each element would easily 'snap' out of the assembly so they could be isolated and tested individually. Features included were increased wall thicknesses, ribs at different thicknesses, sloping transitions, windowed openings, lids with open elements, and metal feed through openings. Three tests were performed: (1) 100 hour exposure to 250°C , (2) 100 hour exposure to 300°C (just below the melting point), and (3) 50 thermal cycles from 25°C to 250°C according to the guidelines specified in MIL-STD-883G Method 1010.8.

Following the exposures and cycles, each sample set was visually inspected for cracks, discoloration, and sagging geometry. Each were weighted and the deflection, if any, was measured. Additionally, the parts were drop tested from a height of 10 feet to check for fractures due to brittleness. The results were excellent. Few defects or disfigurements were encountered with the 250°C exposure and the thermal cycled parts. The best performing features were found to be the thick ribs, curved features at high stress points (edges), and thin windows reinforcing large open features. While the samples subjected to the 300°C exposure tests were structurally sound, the material significantly discolored and became much harder and more brittle than expected.

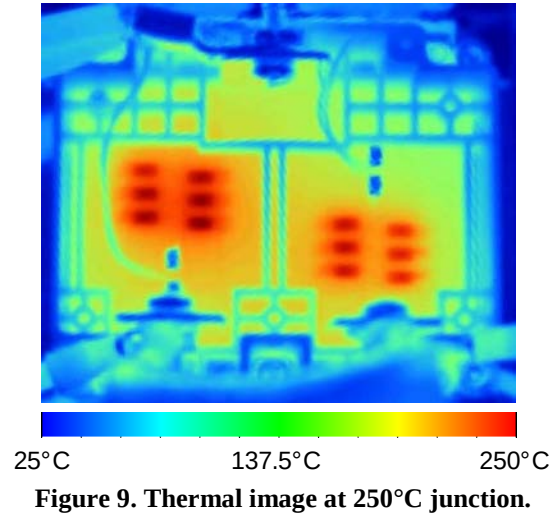
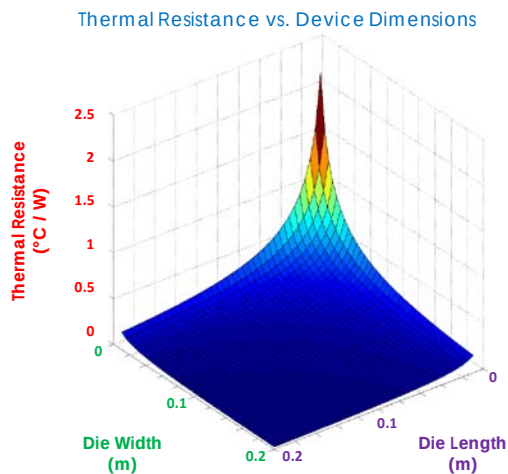
The housing was designed as three elements: sidewalls, gate drive board collar, and lid. The sidewalls were dimensioned to 'form fit' to all of the functional components. Planar ledges were created as the seat for the ceramic driver board, with added registration features for alignment. This particular design incorporates vertical power contacts which feed through the lid. Future revisions will embed the metal tracks in an over-molding operation to simplify the assembly process.

Reinforcement features were added wherever possible, and optimized through thermal simulation. Simulation results of the optimized design are displayed in Figure 7, representing the displacement of the model at the peak temperature. The deformed shape is exaggerated by a factor of 5 in order to show detail. The studies were performed as a thermal excursion to 250°C with a stress free reference of 25°C . The model is restrained at the bolt locations as a fixed geometry, and a 'sliding' restraint on the bottom surface, allowing lateral growth but preventing expansion 'into' the plane (i.e. the base plate). As depicted, the maximum displacement is an acceptably low 0.026 in and is found at the upper side edges and at a stress relief feature across the middle (designed to bend and relieve stress from the main structural elements).



Thermal Design

Thermal analyses and simulations were performed under a range of operating conditions and ambient temperatures to ensure the most thermally efficient design possible within the size restraints. Spacing between devices was selected to prevent thermal crowding and layer thicknesses selected for the best compromise between thermal spreading and thermal resistance. The junction-to-case thermal resistance at 250°C was calculated to be 0.37 °C/W *per device* and verified through thermal imaging. Thermal resistance is strongly related to the area of the devices. As SiC processing technology and cost continue to improve, device sizes will increase and result in markedly reduced thermal resistances. Figure 8 depicts the thermal resistance of this system as a function of die area. As described by the surface, the thermal resistance will be optimal at or after the 'knee' of the curve, which occurs at approximately 7.5mm per side (56.25 mm²).



A Lytron CP30 vacuum brazed liquid cold plate was utilized as a high performance method of removing the heat from losses in the switches. The interface between the base plate and the cold plate was a concern due to the lack of viable traditional interface material options. Many of the silicone based systems dry out after prolonged exposure to high-temperatures. A non-silicone based thermal interface compound was chosen to fix this problem. It features a low interfacial thermal resistance of 3.8×10^{-5} °C·m²/W and is rated up to 360°C operation. A thermal image of the module operating at maximum junction temperature is displayed in Figure 9.

1.3 Assembly Processes

TLP Die Attach

The reflow processes, material systems, and alignment hardware were devised to facilitate high lead solders (95Pb/5Sn), lead free alloys (95.5Sn/3.8Ag/0.7Cu, etc.), and high temp gold alloys (80Au/20Sn, 88Au/12Ge, etc.) to adapt to and meet a variety of customer needs. While each of the previously listed joining systems has advantages (availability, excellent wetting characteristics, predictability), they each have maximum operating temperature limitations and a drastically reduced thermal conductivity at elevated temperatures [11]. While gold solders can achieve higher temperatures at a slightly higher thermal conductivity, their use introduces restrictions in surface plating to prevent gold leaching or a low temperature alloy from forming. In response to these issues, an advanced joining technique utilizing a transient liquid phase (TLP) bonding system was developed to create an optimal bond with increased strength and thermal conductivity across the entire range of temperature operation. This technique was utilized for both the power device and substrate attaches.

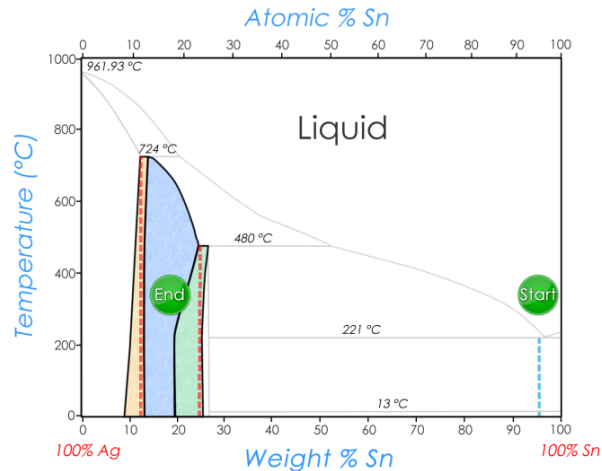


Figure 10. Ag - Sn phase diagram

TLP bonding [12] is a joining process during which a metal or alloy with a low melting temperature (typically Sn or In) is placed in close proximity with a high melting point base metal (Ag, Ni, Au, Cu, etc.) under moderate pressure, and subsequently brought to its melting point. As the metal layer begins to melt, it diffuses into and dissolves a portion of the base metal, altering the composition of the molten alloy. Holding at an isothermal temperature allows diffusion to continue until the composition reaches a state where it solidifies, resulting in an extremely strong bond. The key advantage of this approach is that the processing temperature is well below the melting temperature of the final bond, reducing processing stresses and eliminating the need for a solder hierarchy during assembly (where each bond has to be below the melting temperature of the previous attach). TLP bonding is significantly faster and requires less pressure than solid state diffusion bonding due to the liquid phase accelerating the process.

The developed attach is a Ag-Sn system (phase diagram presented in Figure 10) particularly suited for TLP processes due to the multiple high temperature stable alloys present at higher silver concentrations. A stable alloy is considered one which does not change structure (crossing a horizontal line on the diagram) across the temperature range of interest, represented by the highlighted areas in Figure 10. The target end composition is 75% weight Ag or higher, requiring a substantial level of diffusion. The key to minimize process time is to maximize the Ag-Sn contact area and to design the thermal processing conditions to stay in the liquid region as long as possible (solid state diffusion is considerably slower).

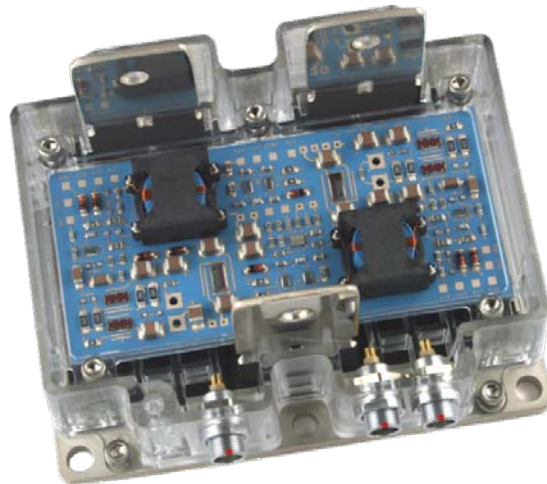


Figure 11. Fully assembled module.

The preforms for this material system consist of a thin (1 mil) 96.5Sn/3.5Ag alloy foil (melting point 221°C) placed between two thin (1 mil) pure Ag foils. The pure Ag foils were electroplated with a thin layer of Sn to enhance surface wetting. The layers were then isostatically laminated together on a machined surface (to ensure flatness, remove small air pockets, and prevent layer separation prior to bonding) and subsequently cut to shape. A series of precision graphite fixtures were machined to provide alignment, heat transfer, and weight to the parts during processing. Further discussion of this bonding process is detailed in [13].

Driver Board Assembly

A variety of bond pad and backside metallization types were encountered with the driver board components, each requiring consideration. The LTCC surface metallization was selected to accept small gauge Al, Au, or Pt wire bonds. Specific bond wire type and diameter was selected on a case-by-case basis. Component attaches were either attached with solder or with a conductive glass-Ag high-temperature epoxy capable of 300°C continuous operation. As mentioned, the driver board was compressively fixed to the sidewalls through a plastic locking collar.

1.3 Electrical Test Results

The fully assembled single phase power module is displayed in Figure 11 with the lid removed and transparent sidewalls attached to show detail. Testing at 250°C junction was performed up to 160 A peak current, 300 V buss voltage, 15 kHz switching frequency, and 1 kHz output current frequency. The power waveforms are illustrated in Figure 12. The upper line (bright green) is the input buss voltage, the middle line (light blue) is the output current, and the

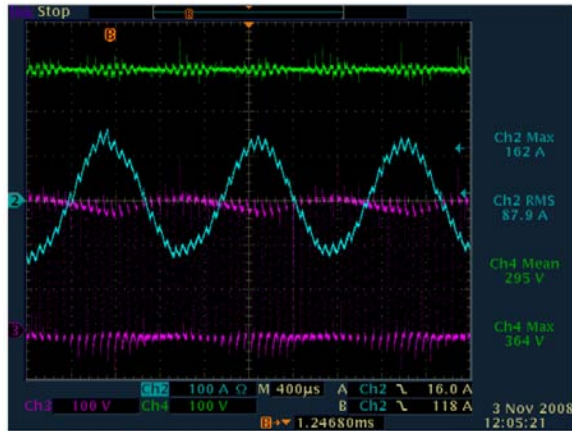


Figure 12. Power test waveforms.

lower trace (pink) is the drain-source voltage of the high side switch. Detailed discussions of the electrical design and testing of the system is presented in [14]

1.4 Conclusion

The preceding discussion presented the design, fabrication, and results of a SiC based 50 kW inverter targeted as a motor drive for hybrid-electric vehicle applications. The general design philosophy was summarized, material selection and design constraints listed, assembly processes detailed, thermal performance discussed, and electrical testing outlined. Future improvements to the system will include over-molding the power contacts to embed them in the module housing, utilizing larger die for better thermal performance, further improvements in the TLP attach process, integrating passives into the driver substrate, and higher power testing and characterization.

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