AlSiC Baseplates for Power IGBT Modules: Design, Performance and Reliability

By M. A. Occhionero, K. P. Fennessy, R. W. Adams, and G.J Sundberg
Ceramics Process Systems
Chartley, MA 02712-0338
marko@alsic.com

ABSTRACT

Improved baseplate materials are required to provide superior reliability and heat transfer as IGBT power density increases. The key is for the baseplate thermal coefficient of expansion (TCE) to be matched to the module design and to have sufficient thermal conductivity (κ). Aluminum Silicon Carbide (AlSiC), a metal matrix composite material, provides a TCE that is compatible with the attachment of dielectric substrates and IGBT silicon devices. Matching the AlSiC baseplate TCE to other materials within the IGBT module can provide more than two times longer module life by minimizing thermal stresses that cause high cycle fatigue failure. A matched TCE also eliminates the need for stress compensating compliant layers and expansion graded thick solders that increase thermal resistance and complexity of assembly. The TCE of AlSiC can be adjusted for the IGBT module design by control of the SiC volume fraction in the AlSiC composite. The AlSiC average TCE can be controlled between 7.5 and 12 ppm/°C (30 – 150°C). An AlSiC composition was chosen for the IGBT module with a TCE value of 8.39 ppm/°C (30° - 150°C) and a κ value of 180 W/mK.

IGBT modules with AlSiC baseplates have equivalent power dissipation and more than two-fold increased reliability over the same module with a Cu baseplate. The IGBT module reliability improves with the AlSiC baseplate because the TCE is matched to the IGBT module design. Cu baseplates have a κ value of 398 W/mK. However, the Cu baseplate TCE of 17 ppm/°C requires thermal stress compensation layers between the Cu baseplate and the dielectric ceramic. The benefit of the high Cu κ value is not fully realized because of the thermal resistance penalty associated with the stress compensating layers.

The Ceramics Process Systems AlSiC module baseplates are cost-effectively fabricated to net-shape, attaining close dimensional tolerances with minimal machining. Additionally, this process allows for the fabrication of engineered bow profiles in the cast module base. The AlSiC process flow will also be outlined to illustrate how the process is used to fabricate IGBT baseplates with integrated advanced high thermal conductivity (>1000 W/mK) heat-spreading materials and recirculation cooling paths for higher power applications. Design rules, process capability, fabrication and assembly of AlSiC module baseplates will be discussed in terms of current production designs.

1. INTRODUCTION

The increasing power demands, higher power densities, higher switching speeds, and increasing reliability constraints require IGBT designers to consider thermal management design and material solutions. The IGBT module can see multiple and varying thermal excursions in traction applications. It is therefore important to have materials in the assembly that have similar thermal expansion coefficient values (hereafter referred to as TCE) to avoid, warping, bowing, assembly component delamination and component cracking that ultimately result in the failure of a component.

AlSiC[1] module baseplates are increasingly being used to provide thermal management solutions for IGBT modules. A module baseplate made of AlSiC material provides compatible TCE behavior to the IGBT components and assembly. The AlSiC TCE can be tailored to the specific assembly application to meet the bow requirement to optimize the thermal interface when mechanically attached to a cold plate. AlSiC is an ideal material choice since it has a high thermal conductivity value[2] that provides excellent

[1] AlSiC – Aluminum Silicon Carbide metal matrix composite material.
[2] Thermal Conductivity value 180 W/mK.

heat spreading. Unlike other thermal management materials like CuMo and CuW, AlSiC is a lightweight[3] and high stiffness material[4], making it suitable for weight sensitive and high shock environments. AlSiC is also less costly in comparison to CuMo and CuW thermal management materials.

The Ceramics Process Systems AlSiC fabrication process will be discussed in this paper. Module baseplates can be cost-effectively net-shape manufactured to close dimensional tolerances. This process also supports engineered bow profiles for improved thermal interface coupling between baseplates and cooling systems. Baseplates with recirculating cooling flow paths can also be fabricated using this process and will be discussed in this paper.

2. AlSiC FABRICATION AND MATERIAL

The Aluminum Silicon Carbide (AlSiC) material system offers the packaging designer a unique set of material properties that are suited to high performance advanced thermal management designs. The Ceramics Process Systems AlSiC is a composite material of Al-metal and SiC particulate. These constituents are combined to achieve an intermediate TCE behavior that is between the high TCE value of Al-metal and low value for SiC. Thermal conductivity values for AlSiC materials are similar to Al-metal and the AlSiC TCE value(s) are compatible with direct device and substrate attachment. An AlSiC microstructure is shown in Figure 1.

Furthermore, AlSiC CTE can be designed to fit the behavior required for the specific application. Changing of the Al/SiC ratio composition can modify the CTE behavior[1]. The AlSiC-9 composition, which has a TCE value of 8.39 ppm/°C (30 – 150°C), is most commonly requested for IGBT applications. The material properties for AlSiC-9 are given in Table 1.

The Ceramics Process Systems AlSiC fabrication process is described elsewhere[1]. Briefly, this process consists of the fabrication of a porous SiC preform of known porosity to the shape of the final product. The SiC preform is infiltrated with Al-metal inside tooling that has the final dimensions and shape of the part using a pressure casting process.

Since the infiltration tooling and preform define the final shape of the product the process results in a near net-shape final part. In other words the composite material is fabricated to the exact shape and form of the final product. This process eliminates the need for costly machining operations resulting in most cases with the AlSiC component being more cost-effective than the machined counterpart.

This casting process also allows functional features to be incorporated into the AlSiC component during Al-metal infiltration. Features such as feedthrus, seal rings[1,2] and substrates[3] can be hermetically captured in the AlSiC composite during casting and eliminates the need for solder and braze assembly later. Additionally enhanced heat-spreading and cooling features may also be incorporated in this same process, including cooling

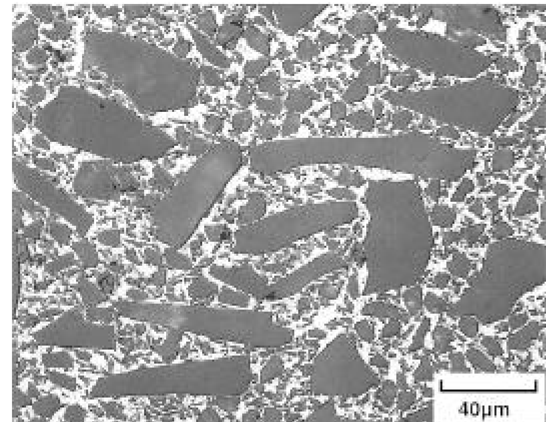

Figure 1: Optical micrograph of polished AlSiC-9 microstructure showing discrete SiC particulate (dark contrast) in a continuous Al-metal phase (bright contrast).

Table 1: AlSiC-9 Property Summary

	CPS AlSiC-9
Property	AlSiC-9
Al-Metal A356.2	37 vol%
SiC Particulate	63 vol%
Thermal Conductivity (W/mK) @25°C	180
Specific Heat (J/gK) @ 25°C	0.741
CTE (30 - 150°C)	8.39
Density (g/cm^3)	3.01
Young's Modulus (GPa)	188
Shear Modulus (GPa)	76
Strength (MPa)	488

[3] Density value 3.0 g/cm^3

[4] Young's modulus value of ~190 GPa similar to stainless steel.

tubes, hydraulic fittings, and vapor chambers, high performance heat-spreading materials like Pyrolytic Graphite (hereafter referred to as PG) [4].

3. AlSiC IGBT BASEPLATES

AlSiC is an ideal material choice for IGBT baseplate since the AlSiC TCE is compatible with the TCE of dielectric substrates commonly used in traction applications such as aluminum oxide (Al_2O_3) and aluminum nitride (AlN). In these applications AlSiC is usually Ni-metallized to allow solder or brazing attachment of direct bond Cu (DBC) Al_2O_3 or AlN substrates. The AlSiC TCE is slightly higher than dielectric substrate TCE value. After cooling from brazing or soldering assembly this TCE difference results in the dielectric being put into slight compression. Both the TCE matching and slight compressive state reduces the probability of delamination and or cracking of the dielectric substrate(s).

This is not the case for Cu-based IGBT baseplate counterparts. Cu has a much higher TCE value, 17.8 ppm/°C[5], compared to the dielectric substrate values of 4.5 to 6.5 ppm/°C[6]. IGBT assemblies using Cu base-plates often include stress compensating layers to accommodate thermally induced stresses caused by the large TCE difference. These additional layers contribute to a higher thermal resistance of the Cu baseplate IGBT assemblies.

The AlSiC TCE can be tailored to the specific assembly application. to meet the final assembled bow requirements. Bow optimization can improve the thermal interface between the module base with mechanically attachment to a cold plate for improved heat dissipation.

In addition AlSiC baseplates can also be fabricated with a convex bow to enhance the module base/cold plate interface while maintaining a flat surface for dielectric substrate attachment. This bow can be engineered and cast into the final product. A schematic illustrating the bow is shown in Figure 2. Bow deflection values of 0.2 mm (0.007 inch) to 0.3 mm (0.012 inch) with tolerance of +/- .0036 to 0.063 mm (+/- 0.0014 to 0.0025 inch) have subject to customer's specifications been fabricated on baseplates approximately 140-mm square (5 inches)

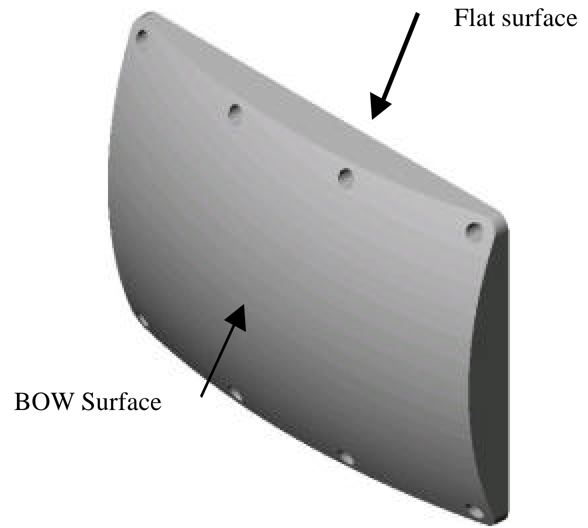

Figure 2: Schematic of AlSiC-9 IGBT base-plate showing cooler contact bow surface and flat substrate surface.

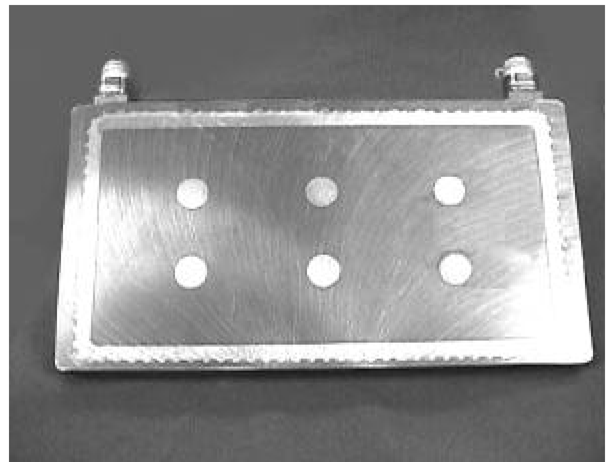

Figure 3: Assembled AlSiC Cooler halves. Top surface has been ground to remove weld relief.

4. AlSiC COOLERS

AlSiC coolers have also been fabricated. These systems are used for high power dissipation applications 2000 – 3000 kW. Figure 3 shows an assembled AlSiC cooler. Both halves of the cooler were as-cast (no machining), including the 6 holes

[5] as measured between 30-150°C

for weld attachment in the top half of the part with the pin fins (not shown). It is important to note that the hydraulic fittings shown in the bottom half of this product were incorporated in the infiltration process.

The two halves are assembled together via welding. Al-metal rich areas were provided at all the weld surfaces to allow for friction stir welding of Al-metal welding techniques. Figure 4 shows a cross section of a friction stir weld joint. All products, with friction stir weld joints passed testing at the service pressure of 1.5 Bar and the maximum test pressure at 8 Bar. To test the limits of the assembly the system was pressurized to a burst failure at nearly 40 Bar. At the writing of this paper only preliminary thermal cycling data has been gathered. At present there has been no degradation after nearly 100 cycles testing between –55° and 85°C.

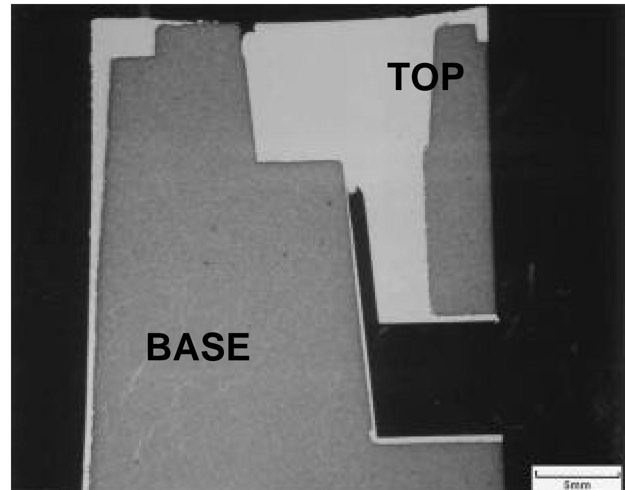

Figure 4: cross section of a friction stir weld joint. Gray contrast is the AlSiC composite; Light contrast is the Al-metal. The Al-metal area connecting the Top and Base is the area of friction stir weld.

5. AlSiC INTEGRATED COOLERS

The AlSiC fabrication process has been used to integrate cooling tubes. This application is less costly than the previously described product since it requires no post processing and is applicable for intermediate power applications.

In this case, the SiC preform is overmolded over tubing (with attached hydraulic fittings) that is fixtured in the SiC preform tooling. The overmolded SiC/Tubing assembly is inserted into the infiltration tooling and is infiltrated together. The infiltration process infiltrates the preform and captures the tubing in a single process step. The process provides an intimate chemical/mechanical bond between the tubing and the AlSiC composite material for a low -thermal resistance transfer interface. An example of a captured tube product is shown in Figure 5. This product has the same physical size as the product in Figure 3. Figure 6 shows the corresponding ultrasonic image of the product to reveal the location of the tubing. The spiral twist along the axis on the tubing is provided for turbulent fluid flow for high heat transfer.

Figure 5: AlSiC cooler with captured tubing.

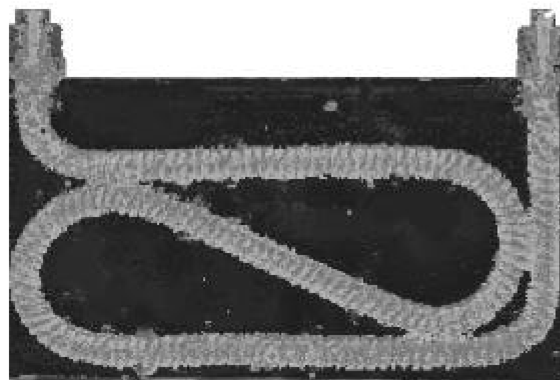
Figure 6: Corresponding ultrasonic imaging showing the location of the captured tubing of AlSiC product shown in Figure 4.

6. AlSiC INTEGRATED HEAT SPREADERS

Another method to improve heat dissipation is the incorporation of high performance heat-spreading materials such as Pyrolytic Graphite within the AlSiC composite. AlSiC provides a functional envelope to capture PG material and cost-effectively locate it in the area(s) that require improved heat spreading performance. An example of captured PG in AlSiC is shown in Figure 7.

PG has a high thermal conductivity value of ~1700 W/mK within the plane of the material and a ~10 W/mK thermal conductivity normal to the plane.

Recent qualitative tests on a microprocessor lid configuration have illustrated the improved thermal spreading performance for these AlSiC/hybrid composites[4]. These results are briefly discussed below.

In this experiment, microprocessor lids were prepared with and without PG insert material. The microprocessor lid was approximately 41 mm square by 2 mm high. The microprocessor lid was fixtured to a large heat sink to promote lateral heat spreading in the plane of the AlSiC lid (schematically represented in Figure 8). The fixture also allowed for an unobstructed view of the lid surface with an IR camera. A 10 W SCR (1 cm^2) was clamped to the opposite side of the lid. Thermal grease was used at thermal interfaces between the lid and heat sink and lid and die.

The die was energized and an IR thermography video was taken for evaluation. AlSiC lid and AlSiC/PG lid reached steady state after 30 seconds. These images are presented in Figure 9.

The uniform shade of the AlSiC/PG composite sample indicates that there is improved lateral heat spreading in contrast to the AlSiC control sample. Temperature difference across the lid surface (taken a points T2 and T3) found a 2°C difference for the AlSiC control lid as compared to a 0.1°C difference for the AlSiC/PG lid. Also the temperature rise for the AlSiC control was 5.4°C as compared to 0.6°C for the AlSiC/PG composite (measured at T2). More importantly the temperature at the interface between the SCR and the lid was 55°C versus 45°C for the AlSiC control and AlSiC/PG lids, respectively. This was nearly a 20% decrease in the operation temperature for this die in the given experimental configuration.

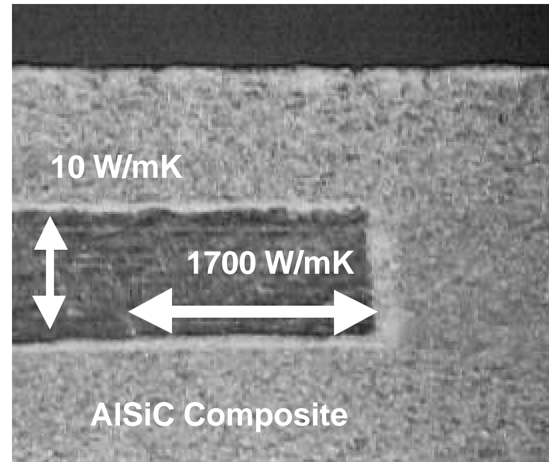

Figure 7: AlSiC Cross section showing PG in dark contrast the AlSiC composite is in light gray contrast.

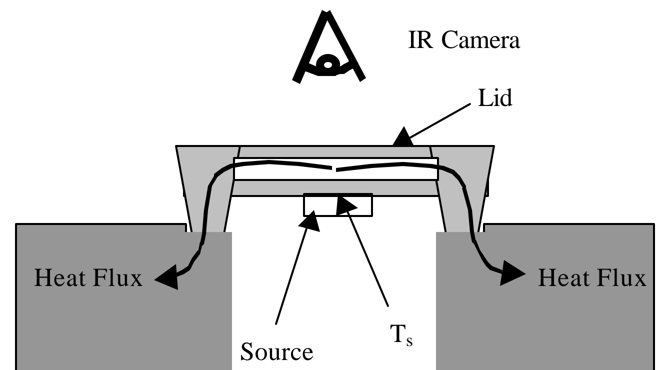

Figure 8: Cross section schematic of lid in test

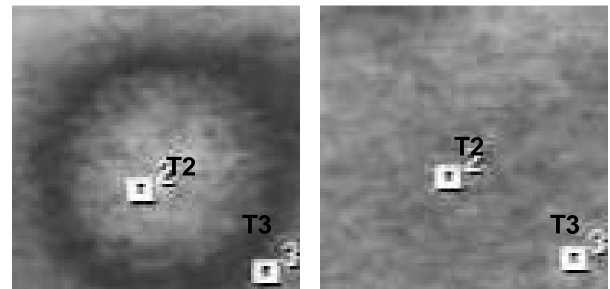

Figure 9: IR thermal images of AlSiC microprocessor lid surfaces for and AlSiC control sample (L) and an AlSiC/PG hybrid sample (R). Pictures taken at 30 sec after energizing the die. The area show represents only the lid area.

7. CONCLUSIONS

AlSiC is an ideal material for thermal management solutions for IGBT modules baseplates. The compatible TCE value results in improved reliability of IGBT assemblies by reducing the magnitude of thermally induced stresses. The net-shape fabrication process provides baseplates that are cost competitive. Functional geometrical features such as

a convex bow surfaces for improved thermal interfaces between module base and heat sink can be net-shape (without machining) cast during fabrication.

AlSiC components are assembled into efficient cooler systems for handling high power (2500 – 3000 kW) dissipation applications. Additionally a more cost effective AlSiC cooler assembly solution was described that simplified assembly by integrating cooling tubes (and hydraulic fittings) during the casting process.

High performance heat spreading materials like PG can be integrated in AlSiC components using the CPS fabrication process. The AlSiC envelope adds form and functionality to high-performance heat-spreading materials like PG, cost-efficiently locating the these high performance materials where they are needed in a material with a device compatible TCE. A preliminary investigation these systems show a dramatic heat dissipation capability. More work to fully characterize these systems is ongoing.

8. BIBLIOGRAPHY

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