HEAT PIPE EMBEDDED ALSIC PLATES FOR
HIGH CONDUCTIVITY – LOW CTE HEAT SPREADERS

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ABSTRACT

Heat pipe embedded aluminum silicon carbide (AlSiC) plates are innovative heat spreaders that provide high thermal conductivity and low coefficient of thermal expansion (CTE). Since heat pipes are two phase devices, they demonstrate effective thermal conductivities ranging between 10,000 and 200,000 W/m-K, depending on the heat pipe length. Installing heat pipes into an AlSiC plate dramatically increases the plate's effective thermal conductivity. AlSiC plates alone have a thermal conductivity of roughly 200 W/m-K and a CTE ranging from 7-12 ppm/°C.   Silicon alone has a thermal expansion coefficient of 3 ppm/°C, which makes AlSiC a much closer CTE match than tradition copper (17ppm/°C) and aluminum (25 ppm/°C) heat spreaders. An equivalent sized heat pipe embedded AlSiC plate has effective thermal conductivity ranging from 400 to 500 W/m-K..

KEYWORDS: High Thermal Conductivity, Heat Spreader, Low Coefficient of Thermal Expansion (CTE), Vapor Chamber, Electronics Cooling, Heat Pipe

NOMENCLATURE

Q   Power, W
k   Thermal Conductivity, W/m-K
A   Area, m^2
x   Thickness, m
ΔT Temperature Difference, °C or K
AlSiC   Aluminum Silicon Carbide
HP   Heat Pipe

1 BACKGROUND

1.1 Electronics Packaging

Thermal management is important for the performance and reliability of today's high power and high density microelectronics systems [1]. Ideal packaging materials must have high thermal conductivity and CTE values that are compatible with the integrated circuit device, attached substrates and assembly, while remaining light weight and affordable. Packaging materials with device and substrate compatible CTE values minimize the thermally induced stresses during power cycling [2]. Thermal stresses often result in the delamination of substrates that disrupts the thermal dissipation path causing electronics thermal failure. CTE compatibility allows substrates/solder layers to be optimized by reducing thickness to take full advantage of packaging material thermal conductivity and the integrated cooling systems.

Lightweight, high strength, high stiffness packaging materials minimize failures due to shock and vibration in service as well as shock that occurs during high speed automated assembly. Lightweight materials also eliminate orientation dependences for integrated heat sink lids applied on top of microprocessors and in flip chip applications. Larger and more functional packages designs can be considered to enable the integration of many electronics systems with lighter weight packaging materials [3].

1.2 AlSiC

Aluminum silicon carbide (AlSiC) is a metal matrix composite (MMC) well suited for electronics packaging. As shown in Fig 1, AlSiC is composed of discrete silicon carbide particles surrounded by a continuous Al-metal phase.
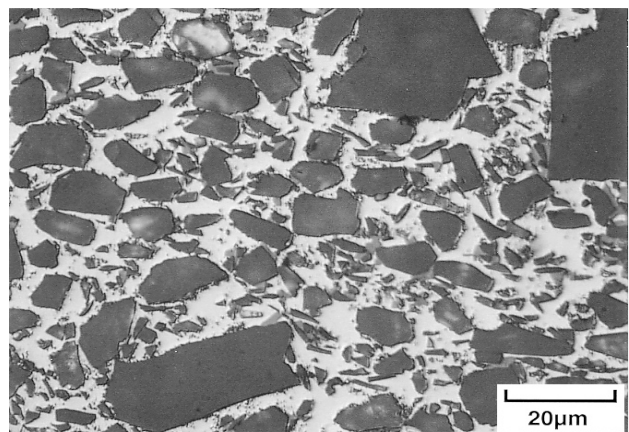

Fig 1: AlSiC Microstructure with the discrete SiC particles surrounded in a continuous Al-metal phase

The coefficient of thermal expansion (CTE) can be specifically tailored with CTE values ranging from 7-12 ppm/°C by controlling the composition of Al and SiC, so that direct integrated circuit device attachment is possible [4]. AlSiC has a low density of 3 g/cm^3 which is favorable for weight sensitive applications. Its strength and stiffness are approximately three times greater than that of pure aluminum, making AlSiC ideal for structural thermal management solutions as well [5].

1.3 Heat Pipes

Heat pipes transport heat by two phase flow of a working fluid [6,7]. Shown in Fig 2, a heat pipe is a vacuum tight device consisting of a working fluid and a wick structure. The heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The vapor, carrying the latent heat of vaporization, flows towards the cooler condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The vapor space of the heat pipe is at saturated conditions, so the temperature difference within the vapor space is driven be the pressure difference between the evaporator and condenser ends of the heat pipe. This means the end to end heat pipe temperature difference is driven largely by the conduction losses through the pipe wall. Typically only a few degrees Celsius [8,9].

Copper/water heat pipes are standard for electronics cooling. Water and copper are known to be compatible for long term operation. In the temperature range of typical electronics cooling environments (25°C to 125°C), water has the best combination of physical properties (surface tension, latent heat, viscosity, etc.) for heat pipe performance. Copper also has the highest thermal conductivity of any engineering metal, making it ideal for heat transfer applications. Copper's flexibility makes it ideal for conforming to different desirable geometries, allowing them to be bent and flattened to conform to flat input surfaces or avoid structures. Since heat pipes are essentially isothermal along their length, their effective thermal conductivity can range from 10,000 to 200,000 W/m-K [10].

1.5 Specialty Composites

One approach used to isothermalize multiple electronics on a single mounting plate uses high thermal conductivity composite heat spreaders. Conventional composite like CuW, and CuMo have reached their physical and economic limitations and can no longer offer breakthroughs in cost and performance [11,12].

High performance graphite fibers with high axial thermal conductivities may be used to reinforce Al, Cu, and Mg alloys, but are unfavorable because of high costs and tedious fabrication processes. Carbon fiber in continuous spool form costs on the order of $1200/lb. In the woven form, the available geometry is limited [12].

Another approach used to create high conductivity heat spreaders uses diamond. Cu-diamond composite materials have been made by combining diamond particulates and Cu

powder in a high temperature and high pressure environment. Pure diamond has a thermal conductivity of 2000 W/m-K. By adjusting the volume percent of diamond in the metal matrix the thermal conductivity of the composite can be controlled. Similarly to the graphite composites, the high costs of producing such materials limits this technology to niche applications [13].

1.4 Heat Pipe Embedded Plates

Heat pipe embedded aluminum plates are used as heat spreaders and in some cases also as a structural member in electronics packaging. Embedding heat pipes increases the effective thermal conductivity by several factors without negatively affecting the plate's mass, strength, or corrosion resistance. In general, the performance of a heat pipe embedded Al plate is equivalent to that of the high end specialty composite materials, but cost much less to manufacture.

Typical applications involve mounting multiple high power electronic devices on the heat pipe embedded Al plate, which collects and moves heat with minimal temperature gradients. Fig 3 is an image of a heat pipe embedded Al plate. Here the heat pipes are soldered into straight and bent grooves to optimize heat transport.

The layout of the embedded heat pipes may be optimized based on the heat source profiles and locations. A higher number of heat pipes may be embedded in areas on the plate where large heat sources are attached. Even with the embedded heat pipes, the plate weighs less than an equivalently sized conventional Al plate.

Depending on the application, survivability in cold ambient conditions requires the heat pipes to be tolerant of numerous freeze/thaw cycles. Also surface coatings and finishes may be applied to the heat pipe embedded Al plates to provide weather resistance as required by specific applications.
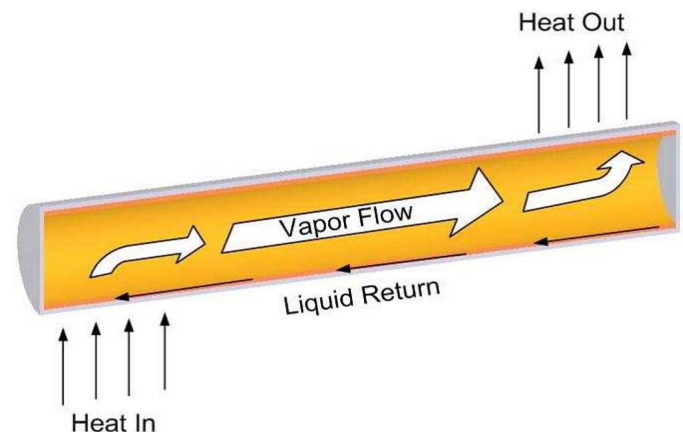

Fig 2: The operation of a heat pipe is illustrated. Heat applied to one end of the heat pipe evaporates liquid off a wick. The vapor carrying its heat of vaporization moves toward the colder end of the heat pipe where it condenses. The wick returns fluid to the evaporator.
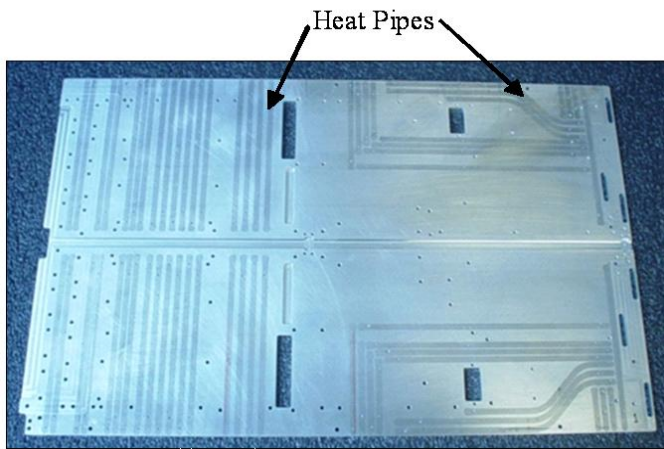
Fig 3: Heat pipes soldered into an Al cold plate greatly increase the thermal conductivity of traditional Al plates.

Traditionally, heat pipe embedded heat spreaders use aluminum or copper as a base material. These devices are proven to effectively spread heat from electronic components when using a thermal interface material. By replacing the plate material with AlSiC, the same advantages of heat pipe embedded plates will be retained with the added benefit of direct integrated circuit attachment.

2 EXPERIMENTAL

2.1 Fabrication

AlSiC plates from CPS Technologies were obtained for this study. SiC is abrasive and is difficult to machine, so the AlSiC plates delivered from CPS were pre-formed with the necessary features and dimensions. Four identical plates were made and measured 6" x 8" x 0.160". These plates were functionally graded from a SiC rich face to an Al rich face. The Al rich side of the plate raised pads of pure aluminum and three 0.113" deep grooves made especially for heat pipe embedment. Since the heat pipes are embedded into the Al rich side of the plate, post process machining may be performed to remove excess solder. Figure 4 shows an image of the AlSiC plate prior to heat pipe embedment.
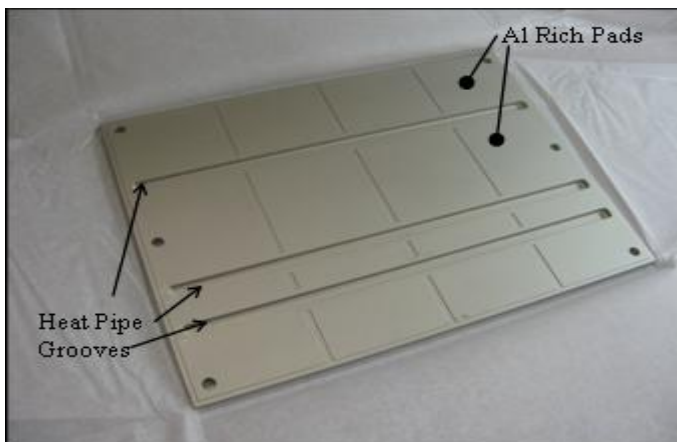

Figure 4: AlSiC Plate Prior to Heat Pipe Embedment

Figure 5: Heat Pipe Embedded AlSiC Plate. Here the Al-rich side of the plate was final machined to provide a smooth surface.

Heat pipes fabricated at ACT were soldered into the grooves within the Al rich face, using 63Sn:37Pb solder. The heat pipes consisted of a flattened 4mm - 0.012" wall copper water heat pipe.

Two different wick structures made of copper with different geometries (proprietary to ACT) were used in this study, henceforth named Wick #1 and Wick #2. Two plates were made using each type of heat pipe.

Post solder machining was performed to remove excess solder. Minimal tool wear was observed, confirming the benefit of the functionally graded AlSiC plate. The low CTE of the SiC rich face of the plate will provide an excellent surface for electronic attachment, while the Al rich face provides an optimum surface for joining to the ultimate heat sink, which is typically Al. An image of the final machined heat pipe embedded AlSiC plate is shown in Figure 5.

2.2 Thermal Testing

The thermal performance of a pure AlSiC plate was compared to that of four heat pipe embedded plates. For this study, two different heat pipe wick structures were investigated (Wick #1 and Wick #2). Power ranging from 25W to 150W was applied to the center of the SiC rich side of the plates. Cartridge heaters were placed within a copper block with a 20mm x 20mm base area. This provides a maximum heat flux of $37.5W/cm^2$. The plates were edge cooled by flowing water through aluminum blocks at a rate of 25gph that were attached to the Al Rich side of the plate using clamps. Grafoil was used to minimize interface resistance between the plates and the heating and cooling sources. Figure 4 illustrates the test setup.
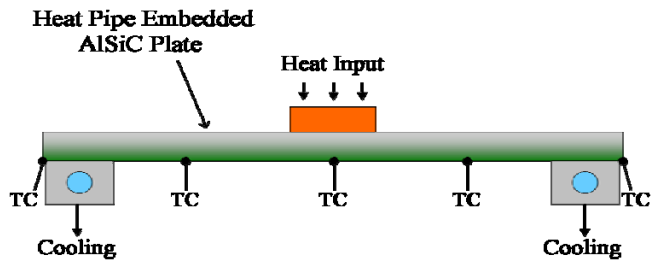
Fig 6: Heat Pipe Embedded Plate Test Apparatus. Heat is supplied through a 20mm x 20mm area located in the center of the plate, and the edges a cooled using liquid flow through cooling blocks.

Temperatures were recorded at five different locations across the width of the plate using k-type thermocouples, placed on the Al rich side of the plate. This configuration provides data showing the temperature gradient from the heat source to sink, which may be used to determine the plates effective thermal conductivity.

2.3 Freeze/Thaw Testing

Heat pipes embedded into the AlSiC plates use water as a working fluid, so wick design is essential for freeze thaw survivability. When designed properly, the heat pipe wick absorbs all of the working fluid. This prevents the working fluid, in this case water, from pooling within the pipe, thereby avoiding harmful expansion during freezing.

The heat pipe embedded AlSiC plates using different wick structures were exposed to as many as 400 thermal cycles ranging from -55°C to 125°C, at the Honeywell KCP FM&T. The plates were tested such that the heat pipes were in the horizontal position. Once thermal cycling completed, the plates were returned to ACT for thermal testing. The thermal testing procedure described previously was followed.

3 RESULTS

3.1 Temperature Gradients

Figure 5 shows plots of the temperature gradients across the AlSiC only plate, as well as across a heat pipe embedded AlSiC plates using Wick #1 and Wick #2 prior to freeze thaw testing. When 150W was applied to the center of the AlSiC only plate the maximum temperature observed was 124°C, and the temperature difference (ΔT) across the plate was 92.6°C.

The same heat flux was applied to the heat pipe embedded AlSiC plates directly above the two heat pipes closest to each other. Here the heat pipe embedded AlSiC plates with Wick #1 and Wick #2 had respective maximum temperatures of 84°C and 75°C.

3.2 Effective Thermal Conductivity

A comparison can be made between the AlSiC-only plate and heat pipe embedded plates using Fourier's Law (Eq 1) to determine the heat pipe embedded AlSiC plate effective thermal conductivity (k). By using data collected at 150W

input power, the power (Q), plate area (A), and plate thickness (x) are the same for all plates and can therefore be disregarded for the comparison. Using the known thermal conductivity of AlSiC (k=200 W/m-°K) and the experimentally measured ΔT, the effective thermal conductivity of the heat pipe embedded AlSiC plates may be determined. This relation is shown in Eq 2. The effective thermal conductivity for the heat pipe embedded plates using wick structure #1 were found to be 492 W/m-K, and plates with wick structure #2 were found to have an effective thermal conductivity of 417W/m-K. +

Eq 1: Fourier's Law

$$Q = \frac{kA}{L}\Delta T$$

Eq 2: Relation for determining effective Thermal Conductivity

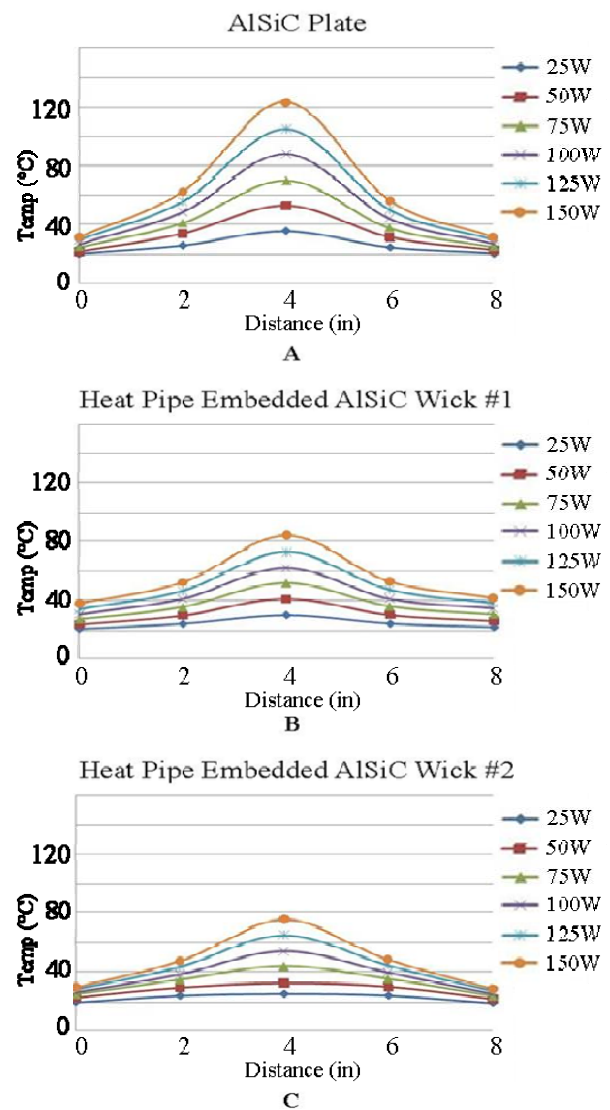$$k_{AlSiC}\Delta T_{AlSiC} = k_{HP-AlSiC} Al_{HP-AlSiC}$$

Figure 7: The temperature profiles across the A) Pure AlSiC plate, B) Heat pipe embedded AlSiC plate #1, and C) heat pipe embedded AlSiC plate #2, with heat inputs ranging from 25W to 150W.

Effective thermal conductivity is largely affected by plate and heat pipe geometry. Heat pipes transfer heat through two-phase heat transfer and are essentially isothermal. This allows heat pipe embedded plates of different lengths (L) to maintain very similar temperature gradients. As the plate length L increases, with constant ΔT, thermal conductivity also increases. The effective thermal conductivity of a heat pipe embedded plate may also be increased by reducing plate ΔT through optimizing heat pipe location.

3.3 Post Freeze Thaw Analysis

Plates exposed to thermal cycling from -55°C to 125°C were tested for post freeze thaw thermal performance. Plates using both wick structures showed similar results to those observed during pre freeze thaw testing. The plate with wick structure #1 has an effective thermal conductivity of 528 W/m-k, while wick #2 showed a thermal conductivity of 298 W/m-K.

Heat pipe failure would result in an effective thermal conductivity measured similar to that of a pure AlSiC plate, and this was not observed. The difference between the pre and post freeze thaw thermal conductivity for the plate made with Wick #1 heat pipes may be attributed to error between testing. The lower effective thermal conductivity observed in the plate built with wick #2 heat pipes may be attributed to testing error and degradation of the solder joint between the heat pipe AlSiC plate interface caused by CTE mismatch.

Initial results shows that the heat pipe embedded AlSiC plates survive freeze thaw testing. Only two plates were thermally tested after freeze thaw testing. Further investigation would require a statistically significant number of plates be examined before drawing any concrete conclusions regarding the heat pipe-AlSiC plate interface.

4 CONCLUSION

Embedding heat pipes into AlSiC plates significantly increases the effective thermal conductivity and is proven to be freeze thaw tolerant. Embedding heat pipes into AlSiC reduces the temperature gradient by over 50% in comparison to the AlSiC only plate. AlSiC has a thermal conductivity of 200 W/m-k and a CTE similar to that of silicon when compared to traditional aluminum and copper heat spreaders. Embedding heat pipes into AlSiC plates improved the effective thermal conductivity to 417-492 W/m-K. For this study a very general design was used to embed the heat pipes into the AlSiC. The effective thermal conductivity of the AlSiC heat pipe embedded plate could be further increased by optimizing the heat pipe layout.

5 ACKNOWLEDGEMENTS

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