Ball-Grid-Array Package Thermal Management

Kevin Chung, Ph.D.
AI Technology, Inc.
9 Princess Road, Lawrenceville, NJ 08648
Tel: (609) 896 3838 Fax: (609) 896 3315
Website: http:\\www.aitechnology.com E-mail: aitech@tigger.jvnc.net

ABSTRACT

One of the main driving forces for the electronic market place has been the rapidly increasing power of central processing unit (CPU) and related component for personal computer (PC). The power being consumed by PC microprocessors have been steadily increasing from a few watts for X386 to more than 35 watts for "Pentium". They are scheduled to reach over 100 watts within the next few years. These powerful chips are typically packaged in Pin or Ball-Grid-Array packages either in flip-chip or traditional die-attach modes. The thermal management is extremely challenging for both inside and outside of the package. This paper will compare some of todays solutions and interface materials in terms of performance, manufacturability and long-term reliability.

1. OVERVIEW

While most of the microprocessors made by Intel today are still in the traditional wire-bond, pin-grid-array multichip packages, AMD, Cyrix-National and LSI Logic have already used flip-chip packages. The thermal management of these single chip and multichip packages involves several levels of thermal interfacing. Figure 1 is a schematic representation of typical requirements.

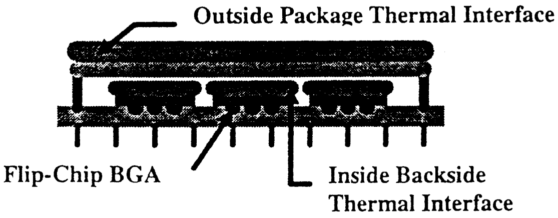

Figure 1: Schematic Representation of Flip-Chip for High Power Microprocessor

In order to provide the widest choice and thermal management solution, the thermal interface resistance inside the chip must be as low as possible. Otherwise it will be the system's thermal bottleneck along the thermal resistance stack-up where both the silicon die and metal heatspreader have low thermal resistance.

While it is imperative to build in the lowest thermal resistance component packaging design, it is also important to realize the impact of application environment and long-term changes of the interfaces.

In the manufacturing processes and the different constraints in providing fasteners or pressure in attaching to heatspreaders or heatsinks for inside and outside of power electronic packages, different formats of interface materials offer different options for manufacturing.

2. THERMAL MANAGEMENT IS A SYSTEM SOLUTION

In most of the searches for better thermal solution, it is important to separate the effects of heatspreader or heatsink, and air-flow characteristics as well as the thermal resistance contribution of the interface materials. For the same configuration of heatsink and air-flow, lower thermal interfacial resistance does, in general, give lower overall system temperature rise. However, in case of lesser heatsink design or insufficient air-flow, both the low and high thermal resistance materials may not yield significant temperature differences.

Figure 2 is an illustration of such an effect of the thermal bottleneck in a particular configuration. In the data collected, when the powers generated were low, the thermal resistance for a fixed air velocity, different thermal resistance of interface material is quite prominent. When the power input increase, the thermal resistance also increases and levels off at certain point for that particular heatsink or spreader configuration under the same air-flow.

These plateau values in Figure 2 are different for different thermal interface materials and reflect the efficiency of these materials under this particular configuration. However, it does not reflect the "true"

0-7803-4486-3/98/$10.00 ©1998 IEEE

thermal resistance of the junctions that may be several times lower as indicated in the lower power data.

In most cases, more improvement can be realized with changes in heatsink and air-flow than with changes in interface materials.

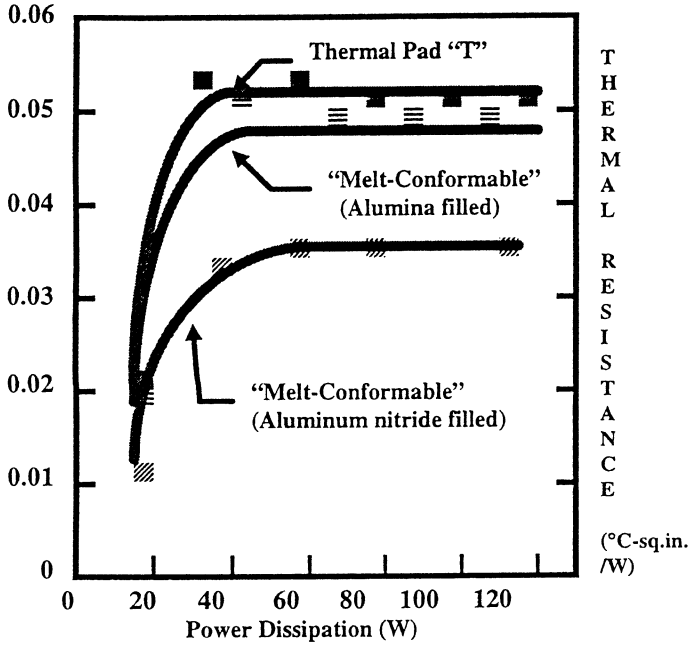

Figure 2: Thermal Resistance of a Large Area Power Supply Tested with Wind Tunnel Cooling

Besides the major contribution from heatsink and heatspreader design, the processes of manufacturing for inside and outside of power components or modules may yield different sets of criteria on the characteristics of interface materials. The infrastructure available for placing material is typically limited to paste-like materials . While there are many options of providing mechanical fasteners as part of the finished product or applying pressure during part of the manufacturing processes. Inside of most of the power components or modules illustrated in Figure 1, greases or adhesives have been the chosen material formats. While outside of the packages, all of the different formats of interface materials such as greases, paste-adhesives, thermal gaskets, and pads adhesive and interface materials have all been deployed successfully.

The key to success for using interface materials besides thermal characteristics is the process in attach device to heat-sink or heatspreader such that molecular intimacy between the coupling surfaces is provided by the interface materials.

In the case of using pads that melt-flow, performances are best realized if they are allowed to flow to assure airs along the interfaces are completely eliminated. Figure 3 below is an illustration on how different shapes of preform that are more desirable to simulate the flow of paste adhesives or greases.

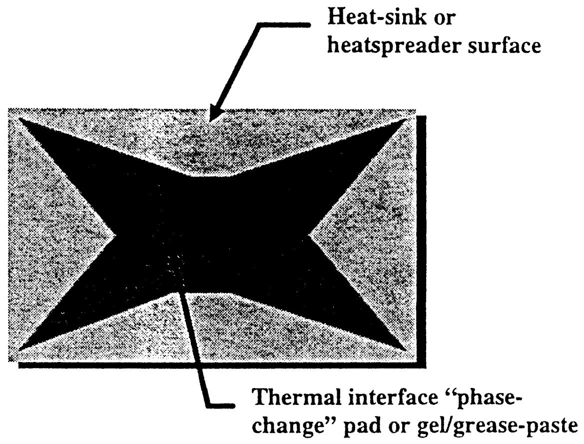

Figure 3. Shape or pattern of interface material is critical in large area application. The cross-hatch pattern have been proven to provide the best coverage and repel interfacial trapped airs during the flow process. Preforms of "phase change" interface material have proven to provide the sam thermal performance as that of the best of thermal grease or gels.

Shaping of preforms similar to that illustrated in Figure 3 have been used successfully for both thermal adhesives and interfaces for large area devices. The shapes have been designed to simulate the experience of large area die-attach adhesive application. Preforms similar to the shape will flow and form shape of square or rectangle depending on the dimensions along the X-Y axis.

3. THERMAL INTERFACE SOLUTIONS

There are three different classes of materials that are commonly used in providing thermal interfaces between power generating devices and heat-sinks or thermal ground-plane. These are liquidous thermal greases that flow easily, conformable silicone-based thermal gaskets, and more recently "melt-flowable" or "phase-change" thermal pads. These three classes of materials have their specific characteristics that give them certain advantages in specific applications.

Historically, thermal greases is one of the first interface compounds used in bridging the air-gap when the device presses against the heat-sink. The liquidous characteristic allows them to easily flow to fill those air-gap. There are many thermal greases available in the industry each with different polymer liquid and thermal fillers. Their performances also vary quite dramatically. The best of this class of thermal interface materials still out-perform all of the thermal gaskets and most of the thermal pads. Their performances, depending on the base polymer, can dramatically degrade over time. Data in terms of initial comparative thermal interface resistance, their weight loss differences over time, and their long-term thermal performance will be discussed in the later section. One way to mitigate the instability over time for thermal greases is to incorporate cross-linking similar to that in the thermal adhesives. A new class of thermal interface with gel-like physical structure has been introduced and found to have the lowest thermal resistance in the most stringent power density requirement such as flip-chip ball-grid-arrays and multichip modules.

Thermally conductive filled silicone rubber gaskets have been used where greases tend to be both unsightly and unreliable over long period of time. The performances of these silicone gaskets also vary broadly in their system performance depending on the thermal fillers and the ability to conform and their relaxation properties in compression over time. The thermal interface resistance of these thermal gaskets is typically 2-6 times worse in system performance in the case of CPU in PC. While they have been successful in power supplies, audio equipment, and motion control industries where the power density is relatively low, they prove to be inadequate in the higher power density of P5 and P6 microprocessors.

A new class of materials that can undergo dramatic reduction in viscosity from solid phase to liquidous phase has been adopted and proves useful providing solution as thermal interface for CPU and heat-sinks. One of the first of these products has been a simple sandwich structure of wax/metal foil/wax. These foil-wax materials can be made into pads of any shape and size and are very cost effective. However, they have been found to be inadequate in thermal performance when power densities of CPU are being increased to over 40 watts.

This novel new classes of "melt-flowable" thermoplastic based pads have been developed and proven to provide 100-600% improvement over those of filled silicone thermal gaskets and wax-foil when contact areas are significant. Some of these pads are tacky and some dry to touch at ambient temperature. All of these second generation thermal pads will melt-flow at designed temperatures from 50 to 100°C. The area immediately under the power devices will remain molten while the device is in operation while the outside "rim" will be solid, where the temperature is lower. They have been proven to have no long-term weight loss and degradation that are common for all thermal greases.

All of these pads have an additional advantage of capable being pre-applied onto heat-sink or power devices. Unlike traditional thermal pads, the interface provided by these second-generation pads between the power device and heat-sink is intimately coupled together much like "thermal adhesive" bond. These improvements have been made without sacrificing the ease of upgrade and reworkability. This class of thermal interface materials represents the "third generation" solution for thermal management of power devices.

These "melt-conformable" pads have been combined with mica sheet to form a dielectrically reinforced thermal interface medium providing more than 5000 V per layer of pad. This configuration of material properties helps to eliminate the mess and inconsistency in applying grease with mica sheet.

Table 1 is a summary of the different material format and their characteristics in terms of both performance and ease of application.

Table 1: Different Format of Interface Materials

	Thermal Greases	Thermal Gel	Thermal Gaskets	"Melt-Flow" Pad
Thermal Conductivity	1.5-16 W/ m-°K Depends on filler crystallites	1.5-16 W/ m-°K Depends on filler crystallites	1.5-6 W/ m-°K Depends on filler crystallites	1.5-16 W/ m-°K Depends on filler crystallites
Interfacial Resistance	0.05-0.9 °K / sq.in.-W Depends on filler crystallites & polymer matrix	0.05-0.9 °K / sq.in.-W Depends on filler crystallites & polymer matrix	0.2-1.2 °K / sq.in.-W Inability to conform to surface roughness	0.05-0.15 °K / sq.in.-W Depends on extent of flow in reducing interface trapped airs
High Voltage Insulation	Not applicable because of its inability to provide defined thickness	Not applicable because of its inability to provide defined thickness	Typically good for 1000V or more depending on the thickness. Poor puncture resistance.	Mica reinforced pads have proven to provide 5000V/layer. Outstanding puncture resistance.
Power & Thermal Cycling	Poor and found to cause failures	Very stable up to >7500 cycles.	Decreases over time due to rubber relaxation	Very stable up to >7500 cycles.
Thermal Stability	Generally bad for >60°C	Proven to be stable up to>150°C	Stable up to>180°C	Proven to be stable up to>150°C
Mechanical Fastener	Need <3 psi	Need <3 psi	Need >10 psi	Need <5 psi

4. THERMAL ADHESIVE VS INTERFACE

Thermal adhesive by definition provides both thermal couplings between power generating device and heatsink or heatspreader as well as permanent and consistent bonding. In the case of thermal interface, mechanical fasteners are inherent assumed to provide the long-term mechanical support.

In the case of thermal interface applications, lesser mechanical stresses considerations are required.

The main reliability factor is that the same material amount remains in place without creating voids over usage life. In the case of silicone-based thermal greases, they have been proven unreliable because its long-term weight loss and thus creating voids within the interfacial material and dramatically increases its thermal resistance to cause device failure. While some weight loss may be controlled by suitable choice liquid binder, some changes in characteristics still occur over long-term exposure to higher temperature. In the case of properly engineered solid polymer binders (not all "phase-change" material are the same), the weight loss can be eliminated completely when function at temperature less than 125°C.

In case of adhesive bonding, the long-term reliability of the thermal adhesive will be directly related to its ability to withstand thermal expansion induced internal stresses without delamination in the power cycling during usage. In addition, the adhesive must also maintain its bonding integrity under sometimes harsh operating or testing conditions. Notably, some adhesives may be sensitive to moisture exposure. Figure 4 is a summary of some typical adhesives tested at different condition. A detailed analysis may be found in many literature [3].

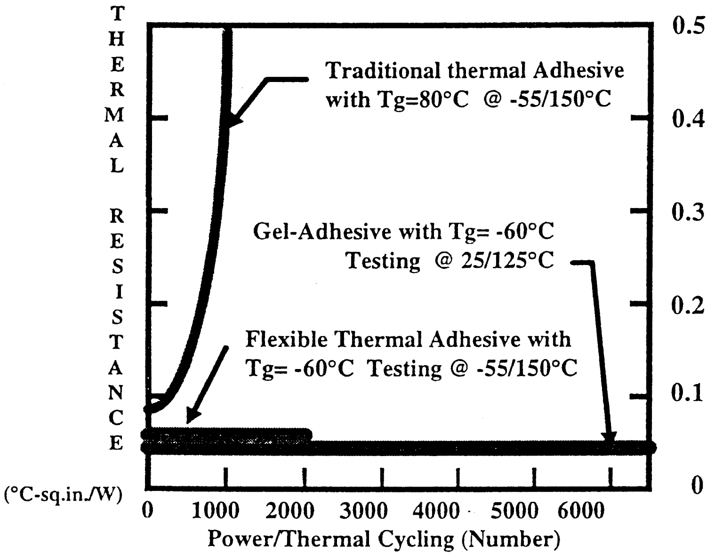

Figure 4: Thermal Resistance of Adhesive Bonding as a Funciton of Thermal/power cycling

5. THERMAL CONDUCTIVITY AND THERMAL INTERFACE RESISTANCE

Thermal conductivity in single crystal is well understood in quantum mechanical phonon and electronic transport theory [4]. For the glassy amorphous materials, only phenomenological understanding is possible. In the cases of gaseous state, thermal transfer within the bulk is primarily mechanical kinetic process among molecules[2]. In the case of liquidous and rubbery state of amorphous materials, one may assume that the primary thermal transport is dominated by the kinetic motion process.

In the case of filled adhesive and thermal interface materials, the transport phenomena will include: elastic phonon transport within the crystallites along with electronic transport for metallic particles, the amorphous "kinetic" transport through the matrix adhesive resin, and the scattering between the interfaces of the crystallites and adhesive matrix. Because of the significant scattering of phonon transport, the combined thermal conductivity of a filled system may be as much as two orders of magnitude below that of the crystallites. Figure 6 is an illustration of the various coupling mechanisms in achieving thermal transfer through a thermal interface material filled with conductive crystallites.

Different thermal enhancement fillers are also available to achieve the thermal transfer rates for a specific application requirement. With appropriate amount of aluminum oxide, aluminum nitride, silver or diamond fillers, different systems can be selected to provide the required thermal transfer rate in the most cost-effective manner. Figure 5 is a summary of results of some of these filled systems.

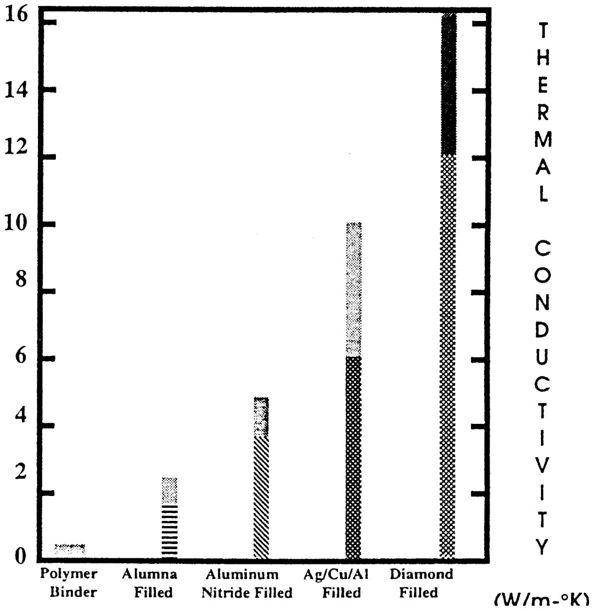

Figure 5: Thermal Conductivity of Typical Polymer and Materials Filled with Different Fillers

Different shapes for the same filler species depict the different fill ratio and resin-dependent aspects of the filled thermal materials. However, it is clear from Figure 6 that there are significant difference in bulk thermal conductivity of the filled materials, they are all substantially less than its thermal fillers as a bulk. As will be illustrated in subsequent section 6, when bondlines are thin, the interfacial thermal resistance becomes prominent.

For any fixed mating surfaces with control thickness, the bulk thermal conductivity of the filled materials will play a significant role if thickness is more than 50 microns. In the measurement of thermal resistance in actual device represent the adhesive and the adherend surfaces. That is, the total thermal impedance of the joint is:

$$\Theta t = \Theta a1 + \Theta m + \Theta a2$$
$$= \Theta a1 + \Theta a2 + 100\, t/k$$

where $\Theta a1$ and $\Theta a2$ are the thermal resistance between adhesive and adherend 1 and 2, respectively; and t is the thickness in *cm*, and k is the thermal conductivity in *W/m-°K.*

Different materials (with same or different bulk thermal conductivity) may show dramatically different contact resistance in the same system as illustrated in Table 2 below and Figure 8 in section 7. In order to deduce the actual thermal conductivity of the thermal materials, different thickness of bond-line must be assembled. The measured thermal resistance must be plotted to allow the calculation of the gradient of thickness dependence for the bulk thermal conductivity. Combination effect of the thermal interface resistance of the contact surfaces and the bulk thermal conductivity of the interface materials. The contribution may be similar or in the case of thinner bondline of 1 mil, contact resistance may be the major factor in the system performance.

In the more traditional thermal measurement per ASTM F 433 method of "Guarded Heat Flow Meter", a very thick material of 250 mil is used so that the contribution of interfacial resistance is minimized.

As described in section 7 below, thermal impedance of the interface material becomes significant if the thickness is significantly above 3 mils. Table 2 is a summary of some of the common materials used in electronic materials, their thermal conductivity, and the estimated thermal resistance without consideration of the interfacial resistance. It is quite apparent from the illustration in Table 1 that there may be significant differences in bulk thermal conductivity of interface materials. The interface resistance plays a dominant role in specific material coupling when bondline is thin. In fact, if coupling is adequate, there are very little differences in the overall thermal resistance for reasonably thermally conductive interface adhesives, pads or greases.

Table 2. Comparative Thermal Resistance and Thermal Conductivity of Various Thermal Greases, Gaskets and Pads As a Function of Compression Forces (Directly related to the thickness of interface layers)

Interface Materials	Thermal Resistance at 3-4 psi @55°C	Thermal Resistance at 7-8 psi @55°C	Thermal Resistance at 19-20 psi @55°C
COOL-GREASE™ CGR 7018	0.03/0.09	0.03/0.06	0.03/0.06
COOL-GREASE™ CGR 7015	0.05/0.17	0.05/0.16	0.05/0.06
Thermal Grease X	0.23	0.19	0.11
Thermal Grease Y	0.25	0.20	0.20
Thermal Grease Z	0.76	0.72	0.59
Bare Joints (Al to Alumina)	0.86	0.75	0.48
COOL-PAD™ CP 7508	0.036/0.1	0.036/0.06	0.036/0.06
COOL-PAD™ CP 7505	0.05/0.1	0.05/ 0.08	0.05/0.08
Aluminum-Wax Laminate	0.53	0.47	0.39
Silicone Gaskets (Typical)	0.60	0.44	0.18
raphite Composite	0.55	0.45	0.31
Thermal "gums" (preforms)	0.22	0.22	0.22

The effectiveness of thermal interface pad in thermal coupling between the thermal source and heat-sink will be primarily depending on its ability to fill all air gaps between them It is also quite clear that if air pockets are trapped between the interface, its contribution will be dramatic. In a recent study[5], a 20% delamination or trapped air-pockets will contribute as much as 0.3°C-sq.cm./W increase in thermal resistance. The effectiveness of thermal interface pad in thermal coupling between the thermal source and heat-sink will be primarily depending on its ability to fill all air gaps between them.

Besides the thermal conductivity and the thermal impedance resulting from the transport through the interface material, there are also interface resistance between the mating surfaces and interface material. Figure 6 is an illustration of different transport mechanisms that that co-exists in such complex material combination.

The basic thermal transport in crystalline solid is phonon vibration and if conductive, partly through electronic conduction. In the case of an amorphous solid or liquid, it is much more complex with primarily molecular kinetic motion. When boundaries existed, reflection and scattering will dramatically reduces the thermal transfer efficiency.

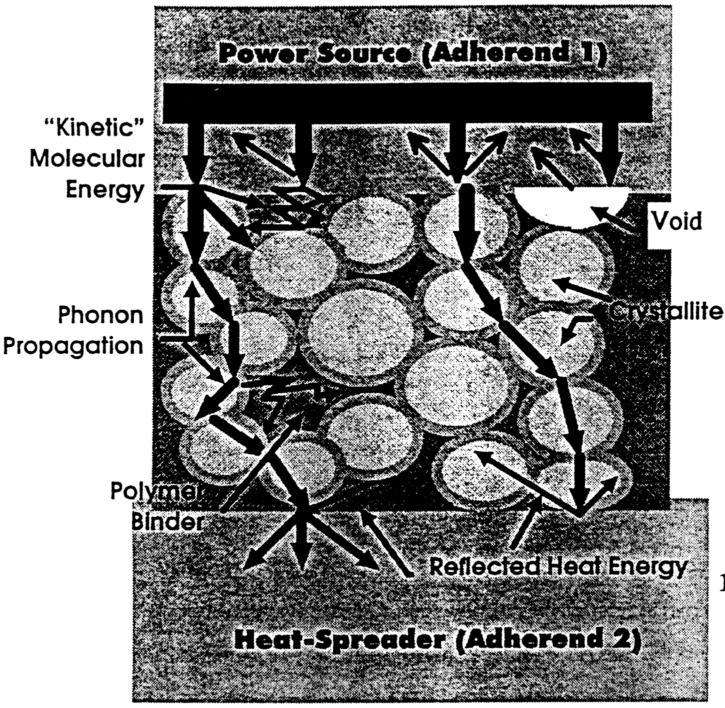

Figure 6: Thermal Transfer Mechanism Through an Interface Material

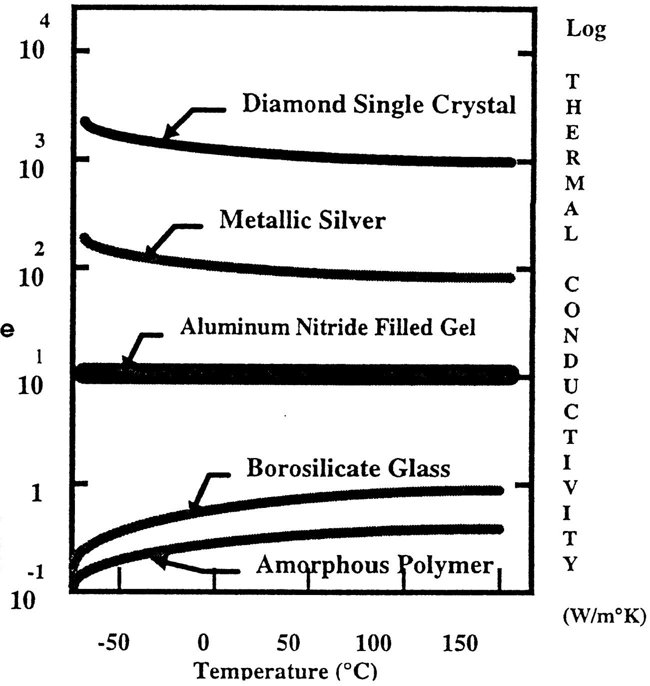

Figure 7: Temperature Dependence of Single Crystal, Metal, Amorphous Materials and Their Composites

6. HEAT TRANSPORT MECHANISM AND TEMPERATURE DEPENDENCE OF THERMAL CONDUCTIVITY AND INTERFACIAL RESISTANCE

For single crystal perfect materials, it is well known that thermal conductivity via phonon transport and scattering will predict higher thermal conductivity at lower temperature. This fact has been well documented for both metals and inorganic crystalline materials alike[1].

In the case of amorphous materials such as those of inorganic and organic glasses, the thermal conductivity aided by electronic and molecular mobility that are increasing with increasing temperature much like that of the kinetic process in gases.

The temperature dependence of the thermal conductivity in filled interface materials is a result of the combination of several thermal transport mechanisms. When they are properly engineered for optimal thermal transfer, they tend to have a low temperature dependence. The decreasing thermal transport via phonon and electron with increasing temperature tends to be balanced by the increasing thermal conductivity as a function of temperature of the binding amorphous resin. Figure 7 is an illustrated trend of the most representative materials.

In the cases of thermal interface materials such as pads and greases, the thermal transport phenomenon is rather complex. Almost all of these materials are a composition of two basic phases: resin or binder such as silicone grease, silicone rubber, wax, or thermoplastic polymer; and thermal fillers such zinc oxide, alumina, aluminum nitride, boron nitride, copper, silver, aluminum, and diamond crystallites. These two-phase systems are expected to be dominated with both phonon transports inside the crystallites and scatters significantly from one crystallite to the resin matrix and vice versa. Unlike electronic transport for electrical conductivity in similar silver filled system, the thermal conductivity of the filled polymers do not exhibit sharp order of magnitude change at the "percolation threshold" where the conductors are in close proximity of each other through out the material so that electrons can hop over from one conductor filler to the next.

In fact, even the simple "rule-of-mixture" approximation for mechanical properties does not apply for thermal conductivity of filled polymer. Even when the binder resins are filled to 60% by volume, the bulk thermal conductivity is far less than 1/2 of that of the thermal fillers. The bulk thermal conductivity is typically orders of magnitude less than that of the crystallites.

Diamond is the most thermally conductive crystal that tends to exhibit the characteristic of decreasing thermal conductivity as a function of temperature. The same temperature dependence is observed for silver and other metals. The opposite trends of temperature dependence for both the glassy amorphous solids are also shown. The results of the filled interface materials have been measured and represented in the zone covering from diamond filled to alumina filled systems. There are more than two orders of magnitudes drop in thermal transfer efficiency in a filled system to that of the single crystals. In comparison to electronic transport via electronic quantum mechanical hopping between grains of crystallite, it is at least one order of magnitude less effective thus reflecting the weak coupling with the resin binder.

7. THERMAL INTERFACE RESISTANCE OF CONTACTING SURFACES

In additional to the thermal conductivity and the thermal impedance resulting from the transport through the interface materials, there are also interface resistance between the adhesive material and the adherend surfaces. In the ideal case of intimate contacts without voids, the total thermal impedance of the joint may be summarized as:

$$
\begin{aligned}
\Theta_t &= \Theta_{a1} + \Theta_{a2} + \Theta_m \\
&= \Theta_{a1} + \Theta_{a2} + 100\ t/k
\end{aligned}
$$

where Θ_{a1} and Θ_{a2} are the thermal resistance between adhesive and adherend 1 and 2, respectively; and t is the thickness in *cm*, and k is the thermal conductivity in *W/m-°K.*

Figure 8 is a summary of thermal interface resistance for a variety of thermal greases with a fixed configuration of heat-sink and power source. Thermal resistance is measured across the interfacial junction by varying thickness of the interfacial joints. Because of the ability of grease to full in all bow, warpages, and surface roughness, one can assume similar molecular intimacy between interface material and coupling surfaces.

The systematic measurement of thermal resistance of various greases and materials tested in the same contact area of 1 sq. in.[7] shows two major conclusions. The first being that the interfacial resistance is significant when the bondline thickness is thin and in the order of 0.05°C-sq.in./W for anodized aluminum to gold-plated contact in the heat source. The second being that interfacial materials with different resin binds can have dramatic effects on the interfacial resistance.

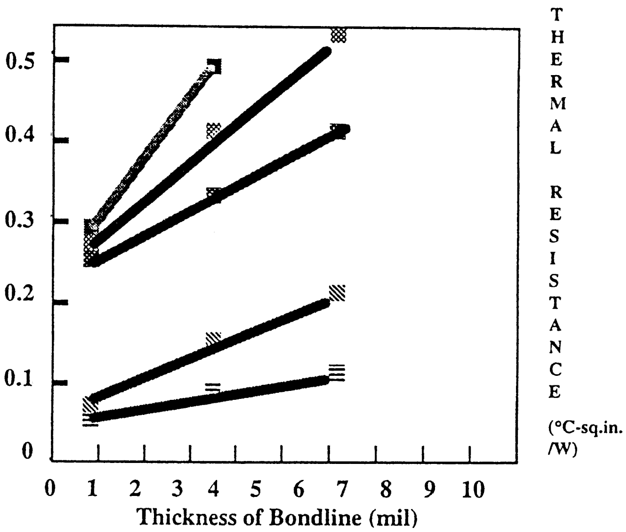

Figure 8. Thermal Resistance As a Function of Thickness for Different Thermal Interface Greases

The second observation from the testing with different greases shown in Figure 8 above, basically leaves system design engineers with no choice but to measure the system performance for any interface materials that they want to use.

The bulk thermal conductivity of the interface materials is represented by the slope of the thickness dependence. The highly thermally conductive interface materials will have low thickness dependence. That is they are much more forgiving if the flatness of the mating surfaces cannot be controlled at low cost. This is one of the more important aspect in designing any electronic systems.

It should emphasize that the measurements of Figure 8 can only be used for comparison purpose. Each set-up of measurement, depending on the efficiency of heat-sink devices used may show different results. The results have been normalized to unit square inches.

8. INTERFACE AIR-GAPS, MICRO-VOIDS AND THERMAL RESISTANCE

Most of the thermal failures are the result of thermal impedance, caused by interfacial delamination or voiding by depletion of a grease binder. A proper choice of resin binder that will not migrate like silicone liquids and will not delaminate or degrade like some of the less flexible resins that are essential for long term reliability[8,9].

Voiding of any kind along the interface can increase the thermal resistance by several orders of magnitude [5,7] as illustrated in the Table 3 below. One can use a simple model of putting a series of voids along the interface within the bulk thermal interface material.

$$\Theta m = \Theta a1 + \Theta a2 + \Theta m$$

$$= \Theta a1 + \Theta a2 + \Theta(\textit{void-free zone}) + \Theta(\textit{void-laden zone})$$

$$\textbf{where,} \quad \Theta(\textit{void-laden zone}) = \Theta v \times (\text{Void } \%)$$

The effect of voids or air bubbles trapped inside the interface materials are not as dramatic in terms of its effect on the thermal resistance. There are some data from the ceramic alumina system.

Table 3: Estimated Thermal Resistance from Bulk Thermal Conductivity and Interfacial Voids

Material	Thermal Con-ductility (k, W/m-°K)	Thermal Impedance for 2-mil Interface (t/k, °C-sq.cm./W)	*Estimated Impedance with 2-mil & 0.30°C-sq.cm./W Interface Resistance*	Estimated Impedance with 2-mil Interface & 1-mil "Delamination"	Estimated Impedance with 2-mil Interface & 1-mil "Delamination"
Air	0.026	19	*20*	20 (100%)	20 (100%)
Resin Only (No fillers)	0.30	1.7	*2.0*	2.4 (5%)	3.5 (20%)
Alumina Filled Cool-Pad (CP7505)	2.0	0.25	*0.55*	1.3 (5%)	2.8 (20%)
Aluminum Nitride Cool-Pad (CP7508)	4	0.13	*0.46*	0.90 (5%)	2.9 (20%)

Table 4 is a summary of different density of alumina sintered to 100% of its theoretical density. The imperfection of the crystallites of alumina decreases the thermal conductivity of the 96% alumina close to 100%. Trapped air bubbles of 11% decrease the bulk thermal conductivity by another 100% while 18% corresponds to drop by as much as 500%. Clearly the conventional "rule-of-mixture" averages of does not apply in this type of void-material composite. Voids and imperfections seem to have dramatic effects on the phonon scattering causing drastic decreases in thermal conductivity.

Table 4: Bulk Thermal Conductivity as a Function of Voids and Imperfection in the Bulk Materials

	Density (gm/cc)	Thermal Conductivity (W-m/°K)	Estimated of Voids (%)
Sintered 100% Alumina	3.95	37	0
Sintered 96% Alumina	3.85	16	0
Sprayed Alumina #1	3.49	8.2	11
Sprayed Alumina #2	3.23	2.7	18

It is expected that because of transport mechanism differences between a crystalline material such as alumina and amorphous materials used as interface binders are substantially different, they will show different void dependence.

There are limited documented results of effects of voids in the amorphous materials. From the system results we were able to obtain, the thermal conductivity and thermal impedance overall do not show the strong function. In fact, one may expect that because of the kinetic process of thermal transport are more volume and mass dependent, the traditional "rule-of-mixture" may have some validity.

9. "MELT-FLOW" THERMAL PADS VS THERMAL RUBBER GASKETS

Thermal gaskets with zinc oxide filled silicone rubbers have been used for many years as replacement of mica sheets for transistors and other power devices. While such rubbers are compliant, they can only compress to conform to the overall bow and warpage. The microscopic roughness of the surface cannot be filled normally with the thermal gasket and results in the decrease of the performance of the interface. The microscopic voids and trapped air as demonstrated in section 5 degrade the interfacial performance by 100-600%[5,7].

The ability of the material to fill all interfacial gaps of bow, warpage, and roughness showed a more prominent effect than that of the intrinsic thermal conductivity of the materials as illustrated in Figure 9.

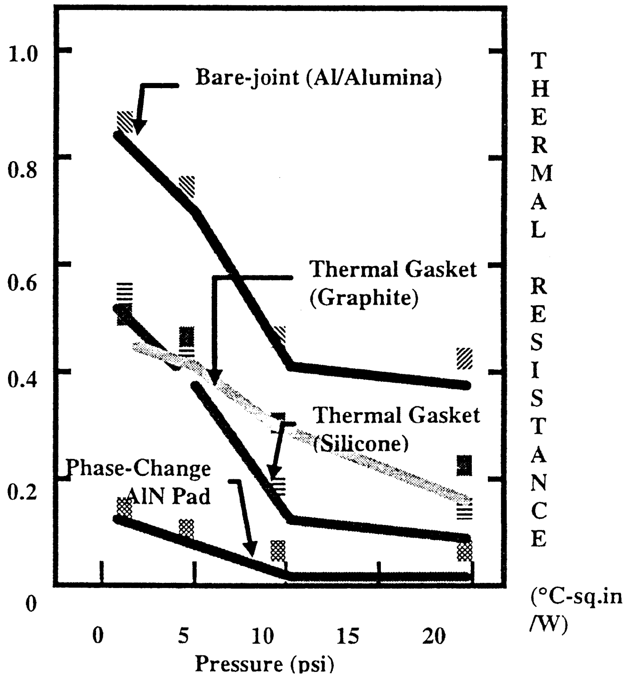

Figure 9: Pressure Dependence of Thermal Interface Resistance for Some Typical Compliant Materials

These new class of "phase-change" interface pads can be handled as thermal gasket and can be die-cut into any shape and sizes. They can also be made into reel for tape-and-reel in-line operation. Once the pads are to conform as the traditional thermal greases placed with mechanical fastener, the manufacturing process is complete. The "phase-change" pad will melt when powering up of the device.

10. "MELT-FLOW" THERMAL PADS VS THERMAL GREASES

Thermal greases and gels remain in their liquidous form before and during operation. They can easily be dispensed between the coupling interfaces. If reasonable care is exercised, they are able to fill all gaps and voids for intimate thermal coupling.

A properly engineered "melt-flow" thermal pad performs the same as that of the thermal grease during the operation when the interface is at or above its designed liquidous temperature. Most of the second generation thermal pads described and tested have a "phase-change" temperature at or around 50°C. Besides being able to melt-flow and fills in all the gaps and voids without excessive pressure, they must not lose weight during the life of the operation designed for the system.

Figure 10 is the pressure dependence of thermal resistance for the thermal greases with the same amount of volume fraction of aluminum nitride filled as that of the melt-flowable second generation thermal pad. All of the measurements are performed at around 60°C.

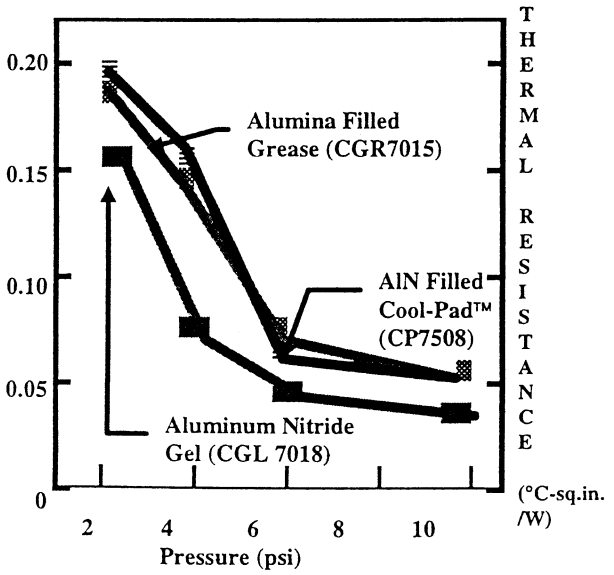

Figure 10: Pressure Dependence of Thermal Resistance at 60°C for Greases and "Phase-Change" Pad

At higher pressures at 60°C or higher temperatures of over 80°C where the second generation thermal pads are as easy to flow as that the thermal greases, their performance are comparable.

The advantages of this "phase change" thermal pad over that of the thermal greases is in the handling ease for volume production. The latter must be metered and dispensed during the assembly process and tends to be messy. The second generation thermal pads can be picked and placed like a dry pad. They can also be pre-applied onto heat-sink or power devices. The process can be easily controlled and cost effective when the area of contact is large.

11. FACTORS THAT AFFECT INTERFACE THERMAL RESISTANCE

There are four basic factors that affects the thermal transfer from one surface to another, that is trapped voids on both surfaces, thickness of interface materials, thermal conductivity of the interface materials, and interfacial effects of the surfaces. These factors are illustrated in Figure 11.

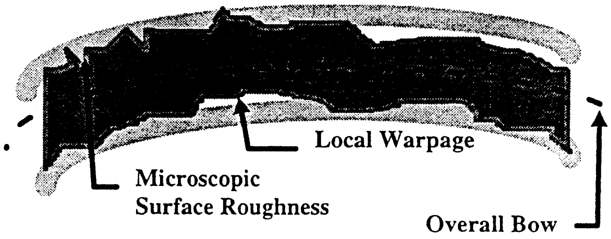

Figure 11. The main factors contributing to thermal resistance across any mating surfaces are: (1) the ability of interface materials to fill in overall bow, local warpages, and microscopic surface roughness; (2) the thickness induced by the bow and warpages or material characteristics; (3) the thermal conductivity of the interface material; and lastly (4) the surface cleanliness that prevents close coupling between interface material and mating surfaces.

The most important factor in achieving ultimate low thermal resistance between two coupling surfaces is that of *trapped airs and voids between the surfaces and interface material.* This represents the majority contribution and in most cases may be as much as 50% of the thermal resistance measured value.

The third controlling factor in thermal resistance across two interfacing parts is the *overall average thickness* of the interfacial material that is required to fill the interface gap. This thickness should be no less than overall surface flatness that includes the overall bow and warpage of the two surfaces. If the interfacial materials must be 6 mils or thicker because of the bows and warpages of the heat-sink and CPU combination is 6 mils, then the *bulk thermal conductivity* of the interface material becomes significant(the second controlling factor). It is obvious that the second and third factors are coupled together for any particular set of mating surfaces.

If the surface flatness can be controlled to less than 3 mils, the interfacial resistance plays as important role as that of the bulk thermal conductivity of the interfacial material. This lesser understood *"interfacial resistance"* seems to depend on two aspects: coupling interface material with the surfaces and the intrinsic characteristic of the two surfaces. The physics of thermal transfer across a solid state material depends on phonon transport [1] between across the materials and "reflection" and "transmission" across the surfaces. The physics of transfer is more dependent on molecular kinetics[2] if the interface material is in liquidous state. This interfacial resistance is the fourth controlling factor in the overall thermal resistance.

12. CONCLUSIONS

A new class of interface materials has been developed and deployed for the more stringent CPU applications in PC industries. These second generation thermal pads unlike that of the first generation thermal gasket melts at slightly elevated temperature above ambient to flow and fill in gaps between mating surfaces for grease-like performance. In the system level, they have been proven to be effective in providing less than 0.10°C/W for 1.0 square inch contact area for outside of power components and modules.

At ambient temperatures they can be pre-cut into preforms of desirable shapes and thickness. They can also be pre-applied onto heat-sink or power devices before final assembly. The ease of handling is ideal for the larger area applications where dispensing may take additional time and slow the production rate.

The bond strengths of such interface material are relatively low even at ambient temperature and allows easy rework and upgrade.

The reliability of such interface pads is also improved because of their stability in terms of weight loss or degradation at elevated temperatures.

However, for inside of components and modules, when pressure-induced flow may not be easily accomplished, a grease-like paste that will form gel in-situ has proven to provide one of the lowest thermal resistance. The gel structure maintains the same consistency at both low and high temperatures for consistent performance.

If thermal adhesive must be used, coefficient of expansion differences between the adhesive and adherends must be carefully considered. In most electronic component and module construction, a flexible adhesive that remains compliant over the low and high temperatures has been found to be the only reliable long-term solution.

References

[1] C. Kittel, "Introduction to Solid State Physics", pp.135-263, John Wiley & Sons, 1971.

[2] V.M. Faires, " Thermodynamics", pp.32-66, 1970.

[3] Kevin Chung, "Second Generation Die and Substrate Attach Flexible Film Adhesive", pp. 191, International Symposium on Microelectronics, 1997.

[4] H.B.G. Casimir, Physica 5, pp.495, 1938. C.E. Inglis, Trans. Roy. Inst. Naval Architects, Vol. 60, pp. 219, 1913.

[5] R. Viswanath and C.P. Chiu, "Organic PGA- A Performance Comparison with Ceramic PGA", 13th Semi. Thermal Measurement and Management Symposium Proceedings, pp.119-130, 1997.

[6] E. Tse, Astec Corp., Private Communication, 1997

[7] H. Hinshaw, Thermally Corp., Private Communication, 1996.

[8] G.S. Ganesan, G.L. Lewis, T. Anderson, and H.M. Berg, "Organic Contamination in IC Package Assembly and It's Impact on Interfacial Integrity", ECTC Proceeding, pp.68-70, 1996.

[9] K. Chung et.al., "Z-axis Conductive Adhesive for TAB and Fine Pitch Interconnects", ECTC Proceeding, pp.345-354, 1991.

[10] A. Villani, Digital Equipment Co., Private Communication, 1996.

[11] C.P. Chiu, G.L. Solbreckken, and Y.D. Chung, "Thermal Modeling of Grease-Type Interface Material in PPGA Application", 13th Semi. Thermal Measurement and Management Symposium Proceedings, pp.57-63, 1997.