Effective Thermal Management with Different Thermal Interface Materials for Different Applications

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INTRODUCTION:

Proper and effective thermal management and heat dissipation for electronic devices from computers to LED lighting to solar panels are critical for its performance and reliability[1] [2]. Thermal conductivity of a thermal interface adhesive or compound is commonly used as a "gauge" of how good it may be in helping to dissipate heat from a device. This should not be the only measure for the potential effectiveness as a thermal interface for different application conditions and requirements.

Various applications and requirements need to include at least the following:

1. Whether the interface must also serve as a mechanical fastener (i.e. adhesive). If yes,
    a. How large is the bonding area? Bonding areas larger than a square centimeter will require a more flexible adhesive.
    b. Are the coefficients of thermal expansion (CTE) on the device and the heat-sink different? This is true with the CTE of silicon (3ppm/°C) and aluminum (23 ppm/°C) or copper (18ppm/°C). Using these materials the adhesive should be more flexible to absorb different shear stress and interfacial peel.
    c. Is the expected operational temperature higher than a commercial specification of 85°C or above the military scale of 150°C?
    d. Is the expected operational temperature expected to be lower than usual, -20°C or -55°C? Again, lower temperature will induce proportionally higher internal and interfacial stresses that are best accommodated with more flexible thermally conductive adhesive.
2. Whether the interface must also serve as mechanical fastener (i.e. adhesive). If no,
    a. While thermal grease is typically the easiest to apply and get the best performance, is thermal grease acceptable for the expected life of the device without the traditional worry of "thermal cycling pumped out" or "dry out" over higher temperature operations? Typically the issue of higher swings of operational temperature from ambient becomes more of a concern. The larger physical gap of the interface of more than 75 microns will reduce capillary forces and thus be more susceptible to the lower energy surface greases (e.g. silicone based) to be pumped out over long-term.
    b. How large is the bonding area? Larger bonding areas than a square centimeter will require more compliant flexible adhesive.
    c. Are the coefficients of thermal expansion (CTE) on the device and the heat-sink very different? Typically, this is true with the CTE of silicon (3ppm/°C) and aluminum (23 ppm/°C) or copper (18ppm/°C). Again, using these materials the adhesive should be more flexible to absorb different shear stress and interfacial peel.

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[1] *Arik, M, Petroski, J., and Weaver, S., "Thermal Challenges in the future generation solid-state lighting applications: Light Emitting Diodes", Pro. of the ASME/IEEE ITHERM-Conference, San Diego, 2002.*

[2] *AI Technology, Inc. website: http://www.aitechnology.com/products/solar/uv-stable-protective-back-sheets/*

THERMAL RESISTANCE AND TRANSFER THROUGH THERMAL INTERFACE MATERIALS

To visualize the various contributions to the overall thermal dissipation of heat generated by a semiconductor device, the following is an illustration of the general heat flow path.

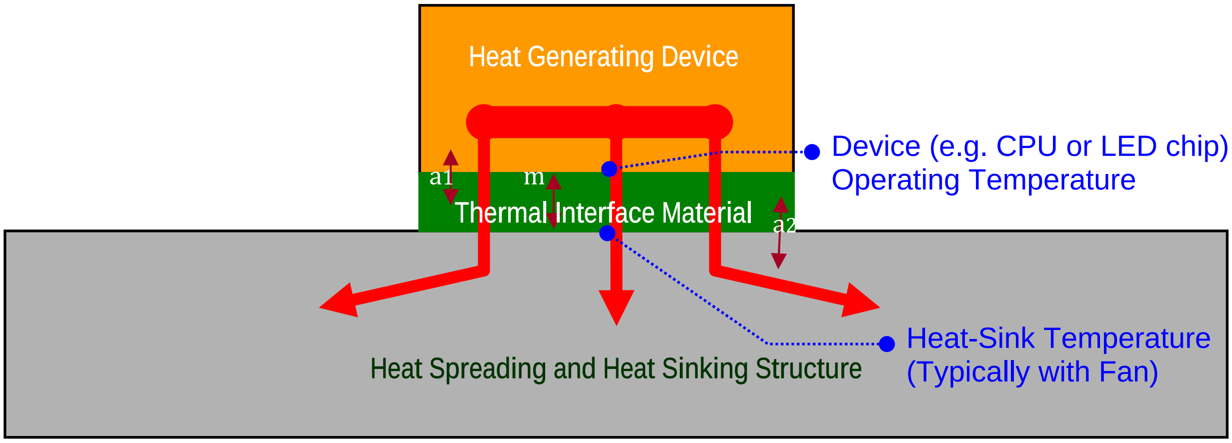

Figure #1: Thermal Resistance Effective Measurement for Thermal Interfacial Material Resistance. For a thin bond-line of 10-50 microns, it is a combination of the interfacial resistance between the joining surfaces that is typically comparable to the contribution due to the thickness and thermal resistance of the adhesive interface material.

For larger gaps or spacing between the heat generating device, the heat spreading and heat sink structure it must also increase the intrinsic thermal conductivity of the thermal interface material that increases in significance. The following is a summary of the contributing factors.

One can use a simple model of putting a series of voids along the interface within the bulk thermal interface material.

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

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

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

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

For a more in depth understanding on various contributing factors in the thermal interface resistance due to the application of thermal interface materials, the following drawing is a summary of the heat flow in detail.

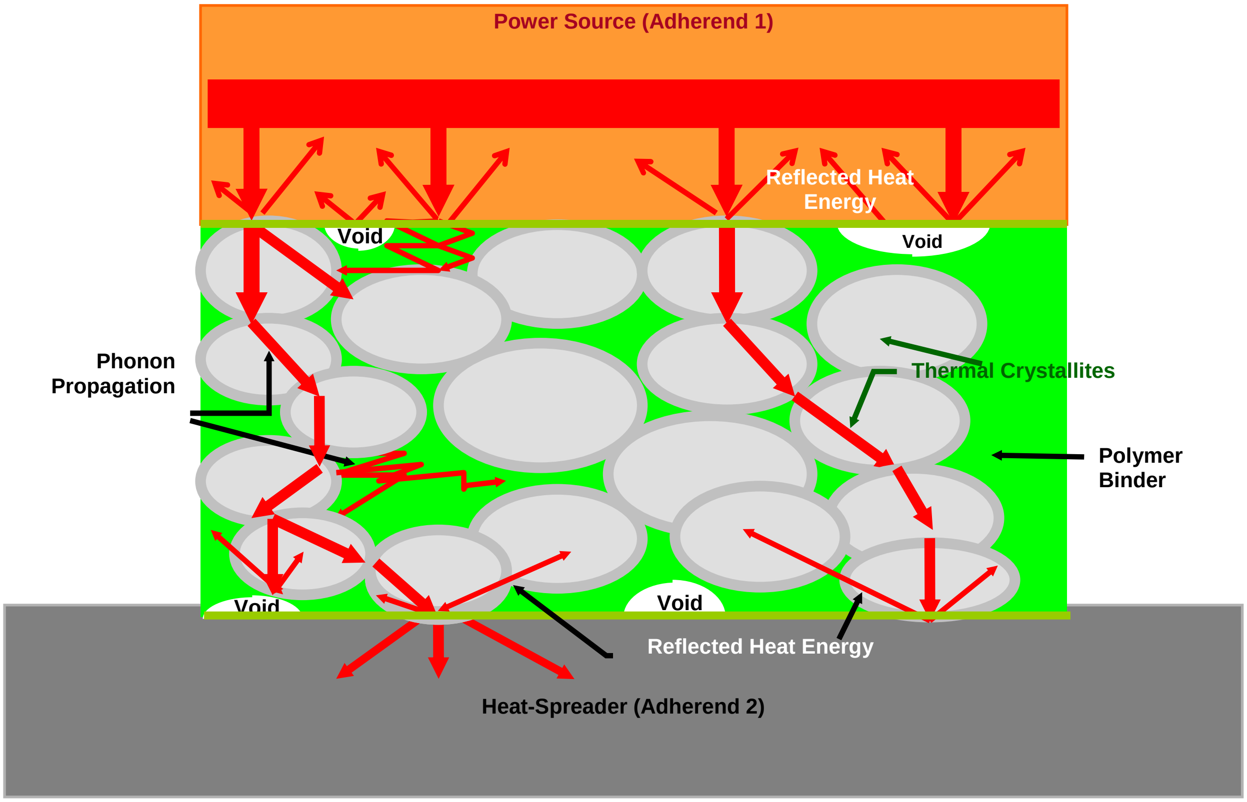

Figure #2: Representation of Thermal Transfer Mechanism through a Thermal Interface Material (Adhesive, Grease, Gel, Phase-Change Pad, Compressible Conformal Gap Pad)

Heat is generated by the heat generating semiconductor that conducts heat to all sides. The typical thin semiconductor device depends on heat to be carried out at the two surfaces. The heat propagation within a semiconductor is fundamentally phonon or lattice vibration and propagation[3]. Once the phonon or heat energy hits the boundary with the thermal interface materials, part of the phonon will be reflected back and part of it is coupled to the thermal interface material to transmit heat to the heat spreading and sinking structure.

The “coupling” or effectiveness in heat transfer depends on the phonon propagation or lattice vibration energy from the semiconductor interface to the fillers and the polymer matrix binder depends on factors that cannot be easily predicted. However, one thing that will dramatically decrease the effectiveness is the creation of voids embedded along the interface layer along the boundary. As illustrated above, such voids will cause a drastic difference in acoustic characteristics and thus a major reflection of energy (or lack of heat transfer).

The different interfacial coupling at the boundaries can be very different for different thermal interface materials. Some of the experimental results[4] done at NREL also reflect the same. A representative result is quoted below for ease of discussion:

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[3] *“Introduction to Solid State Physics:, Fourth Edition, pp. 159 (1971)*

[4] *Thermal Interface Materials for Power Electronics Applications*; Preprint; S. Narumanchi, M. Mihalic, and K. Kelly; *National Renewable Energy Laboratory;* G. Eesley, *Delphi Electronics; Presented at Itherm 2008; Orlando, Florida; May 28–31, 2008 http://www.nrel.gov/docs/fy08osti/42972.pdf*

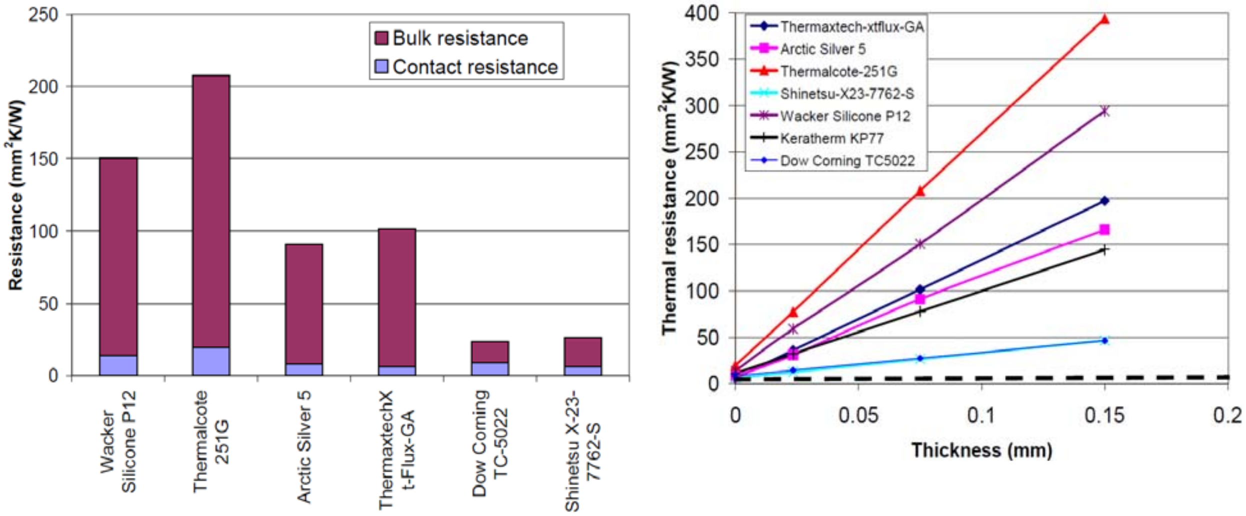

Figure #3: Summary of Test Results from NREL Studies for Discussion Purpose

Similar finding and results were found and reported by other studies[5] [6]. The difference in the contribution from contact resistance and the bulk resistance (or the bulk thermal conductivity of the thermal interface materials) can be quite different even for similar overall thermal resistance and the vastly different overall thermal resistance. A thermal interface material having lower bulk resistance may have higher interfacial thermal resistance (e.g. Shinetsu X23-7762-S vs Dow Corning TC5022 and similarly for the Artic Silver 5 vs ThermaltechX in Figure #3).

While measurement of the bulk thermal is useful by itself, is not as predictive as the effectiveness of such interface materials. Being that the “acoustic” or “phonon” coupling of such soft interface materials to the semiconductor and the metal heat-sink are not quite understood and thus even less predictive, the experimental and in-situ measurement of actual assemblies are the only means in the reliability of thermal management results.

While in some cases the actual structure cannot be rigged to perform the direct measurement, based on the effect of coupling between the different materials, it will be acceptable to have the same type of heat generating device material whether it is silicon or GaP to the heat-spreading and/or heat sinking structure such as copper or aluminum.

One of the easier simulation tests is the use of a CPU as a heat generating device as in Figure #1. The heat sinking structure is a heat-sink equipped with fan like those used in computers CPU and GPU thermal management. The same method is used extensively by gaming professionals in assessing the thermal interface resistance. AI Technology, Inc. uses such configuration for comparative thermal resistance measurements in quality testing for materials used for high power devices.

Figure #4 below is a picture of the DUAL CPU system used for the comparative thermal interface effectiveness measurement. A thermocouple is inserted into the copper heat-sink at

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[5] *Private Communication”; Dr. J. Chang; Sandia National Lab,; Test performed in 1990*

[6] *“Thermal Impedance and Thermal Stress in Electronic Assemblies”; K. Chung et al., 1991-10-01; AI Technology, Inc.; Publishing Agency: MINNOWBROOK; Document # 234791-005;* http://www.theriac.org/riacapps/library/?found=234791-005

the thermal interface material and the heat-sink junction to measure the effect of the interface material on the heat dissipation directly.

Figure #4: Picture of the Configuration used in this Comparative Thermal Interface Measurement Test

Figure #5 below is a representation of test results using this configuration in comparison to various common thermal interface materials. The difference in performance between the different thermal interface materials can be dramatic. The “Traditional Phase-Change Pad” is the pad used by the original manufacturer.

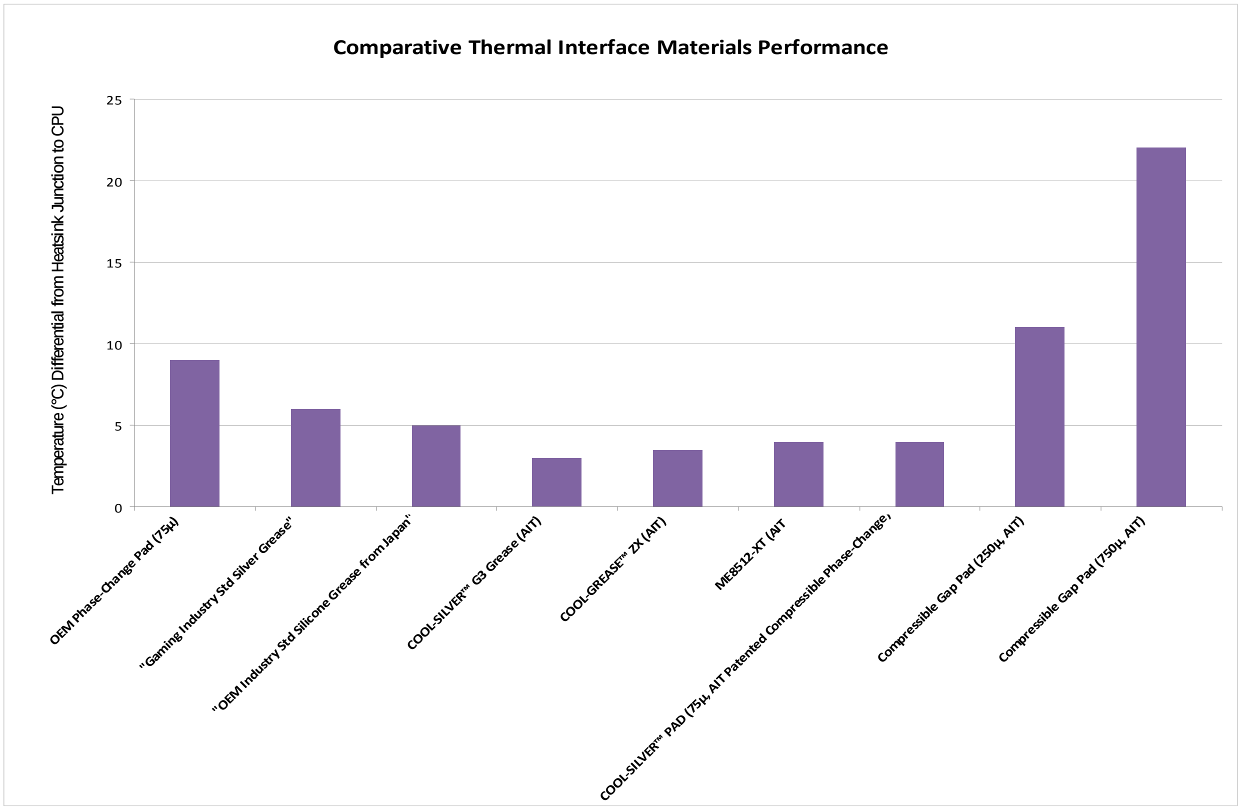

Figure #5: Temperature Differential between Heat-sink Junction and the CPU. It is clear that the best thermal greases and gels can be quite a bit better than traditional phase-change pads. The more advanced compressible phase-change pads and adhesives may be very close to the performance of the best of greases even without going through the phase-change temperature. A high performance compressible gap pad at 10 mils thickness can perform close to standard phase-change pad at much thicker 3 times more gap height.

When to Use Different Types of Thermal Interface Materials:

Thermal Grease, Thermal Gel, Phase-Change Pad, Compressible Phase-Change Pad; Compressible Conformal Gap Pad; Thermal Tape or Paste Adhesives

Choosing the best thermal interface material will depend on the specific application method and operating conditions. The variety of factors that affect the thermal interface material selection can be summarized in the following examples.

Thermal Grease:

The biggest concern in using thermal grease (traditionally made of silicone liquid as a binder) is the proven concern of “pumped out” or “dry out” over thousands of thermal cycles in computer processor applications.

The “pumped and dry” action results from the mobility of the binding liquid. At higher temperature the liquid resin lowered its viscosity. At the thermal interface, there is a competition between the natural capillary forces that hold the liquid inside the device interface and the surface tension of the liquid to the heat-sink surface. For very low surface tension liquids such as silicone, they migrate out over time and thus “dry out” over time.

The competition between capillary force that tends to hold in the liquid binder and the surface tension induced migration will be in favor of migration if the thermal interface gap is larger than 10-20 microns.

A more reliable grease to use against such “pumped” out phenomenon is to use a thermal that is NOT SILICONE based and preferably binder liquid that has higher surface tension liquid polymers. COOL-GREASE™ series of silver (COOL-SILVER G3), ceramic blends (COOL-GREASE ZX) and diamond (CGR7019-LB) (available from AI Technology, Inc.) thermal greases are made of non-silicone and liquid resins similar to epoxy resins. These have been proven to have the best performance in direct competition for the gaming communities that are looking for even the smallest difference in temperature rise on their CPU and GPU.

Thermal Gels:

A possible choice for grease-like thermal interface is thermal gels. Gels in definition are those liquid greases that will cross-link chemically over a long time at elevated operating temperatures (in-situ curing) or simply become gel up by raising the temperature to a higher temperature (typically over 100°C for a short time).

These thermal gels can be made out of silicone resins or epoxy resin or other chemically cross-linkable resins. COOL-GEL™ series of silver (CGL7014), ceramic blends (CGL7013) and diamond (CGL7019-LB) (available from AI Technology, Inc.) thermal gels are made of non-silicone and flexible epoxy based resins.

Thermal Gap Filling Pads:

In some specialized applications where heat is generated from various height components and there is a high need to dissipated the heat to a heat-sink or an external metal casing, thermal gap pads are specially designed for such applications.

They are gel-like compounds that form sheets of 0.05 mm to 0.5 mm or thicker that can be placed and compressed to shape with the components. One side of these thermal gap pads is typically dry and non-tacky to facilitate servicing. While traditional thermal gap pads are mostly made of silicone, COOL GAPFILL™-DT is one of the more unique thermal gap pads that is NOT SILICONE based and based on modified epoxy gel. COOL GAPFILL™-TT is another special gap pad that is tacky on both sides for applications where servicing is not expected to be performed frequently.

Depending on the application, other COOL-GAPFILL™ with thermal fillers such as silver and diamonds are available. These gap fill pads help eliminate air gaps between components and the heat-sink while conforming to the curvature and warp of matching surfaces. They are soft and easily of compressible to the different heights of multiple components and remain stress-free with outstanding mechanical shock absorption.

Compressible Phase-Change Materials and Traditional Phase-Change Materials:

Traditional phase change pads similar to those illustrated in the comparative performance of Figure #4 provides the "standard" coming out of factories of original equipment manufacturers. While they do the job, their performance can be a few hundred percent less than the best thermal grease and the best phase-change interface pad.

COOL-SILVER™ PAD and CPR7019 are some of the examples of a new class of patented compressible phase change pads that not only phase-change to a liquid form to eliminate trapped air along the interface, it is also compressible and conforming to the slight or large curvature of the electronic devices. The performance is similar to the best of thermal greases. Some gaming enthusiasts even find them better than traditional thermal greases in lowering the temperatures of their CPU and GPU.

Thermal Paste Adhesives:

Thermal paste adhesives are typically used for bonding semi-conductor dies onto lead-frames or sub-mount substrates. Being it is the first thermal interface among the multiple thermal stack that may be encountered by almost all of the electronic devices from CPU, GPU, Memory Modules to LED lighting devices.

Thermal interface resistance should be as low as possible and thus the bond-line thickness should be as thin as possible, preferably in the range of 10-20 microns. The flexibility of the adhesive to absorb the thermal interface stress must also be part of the equation for long-term reliability.

Flexible epoxy die-attach and stress-absorbing high temperature die-attach thermal adhesives were pioneered by AI Technology over 25 years ago. In Figure 4, the thermal performance result of ME8512 that is used by many LED lighting device manufacturers is shown to be comparable to the best thermal greases.

Similar thermal performance can be found in the thermal tape-film adhesives as well. COOL-BOND™ pressure sensitive adhesive tapes have found much acclaimed use for the gaming and hobbyist communities. The same thermal performance is available with many different types of combination functional additives such as silver, ceramic and diamond.