

Novel Thermal Interface Material with Aligned Conductive Fibers

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Abstract

Thermal management remains a critical issue in the design of computer and telecommunication systems. As the complexity and power level in the semiconductor devices continues to grow, IC designers and manufacturers require improved technologies to effectively remove the heat generated. In order to manage this escalated need for heat dissipation, packaging technology has improved through the use of more thermally efficient packages, increased dumping of heat into boards, increased heat sink size and more efficient use of forced convection. At the same time, thermal interface materials, which promote heat transfer within a package, or from a package to a heat sinking device, have not changed dramatically. As a result the thermal resistance of interfaces, as a fraction of total junction to ambient resistance, has grown dramatically, pointing to a strong need for improved interface materials.

Conventional thermal interface materials call for filling a polymeric carrier (grease, phase change material, silicone, etc.) with highly conductive particles to produce a material with low to moderate thermal conductivity. This approach works well when gaps between components can be minimized (e.g., bond line thickness of 0.001" or less). When gaps are larger, conduction of heat within the interface material (i.e., from particle to particle) dominates the interface thermal resistance and poor performance results. A new class of interface materials has been developed which overcomes this limitation. These materials feature an aligned array of conductive fibers. This structure allows one fiber to span the gap between the two surfaces, resulting in very high thermal performance, even for large gaps. Because the fibers have a high aspect ratio, this material has a high degree of mechanical compliance, making it ideal for application such as interfaces within multichip modules, mobile products or gap filling applications where variations in interface thickness can be absorbed with little or no thermal penalty. This material has been shown to be very robust with respect to thermal and mechanical cycling, and will not pump out or dry out from the interface during actual use. The theoretical and experimental bases for thermal and mechanical properties are developed and discussed, including demonstrated bulk thermal conductivity values of 50 W/mK. Demonstrated applications are also presented and discussed.

Key Words: thermal interface, fibers, thermal resistance, compliance, interface material

Introduction

The percentage of a device's thermal budget consumed by interface materials has grown dramatically in recent years as electronic packages have significantly improved thermally and heat sinking devices have grown larger and more efficient. In contrast, many of the improvements in thermal interface materials have revolved around ease of use issue (i.e., replacing a grease with a pre-applied phase change material), and improvements in interface thermal resistance have not kept pace with improvements in other packaging components.

Desired properties for an interface material include high thermal conductivity, ability to "wet out" a surface and hence exhibit a low thermal contact resistance, mechanical compliance, long term reliability and in some applications, the ability to rework components without replacing the interface material.

Conventional Interface Material Approach

The conventional approach to addressing these issues involves filling a polymeric material (grease, phase change material, silicone, rubber, etc), with thermally conductive particles, as illustrated in Figure 1.

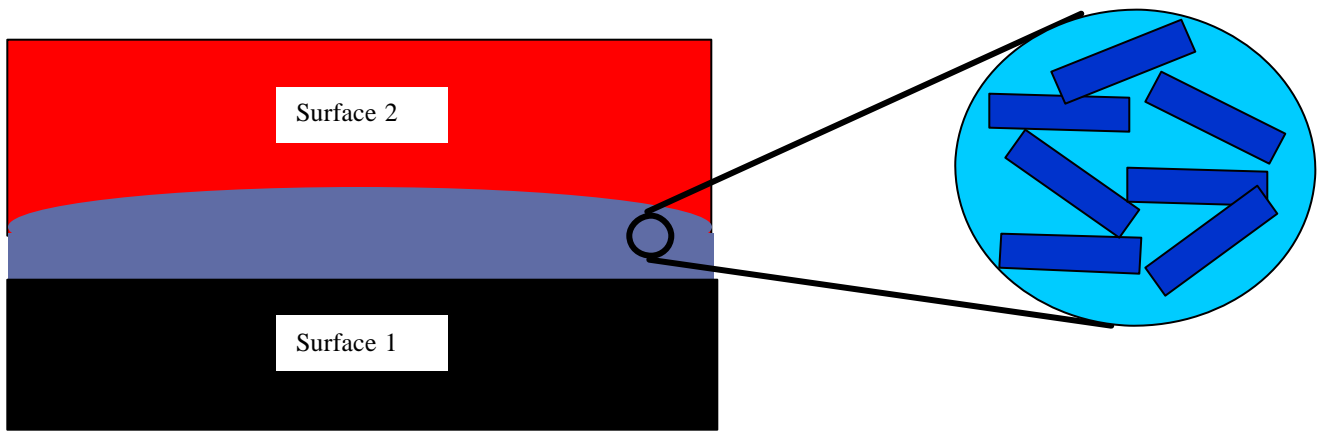


Figure 1. Microstructure of conventional thermal interface material consisting of a polymeric carrier filled with thermally conductive particles or flake. Point contact between particles limits heat transport

Reliability in this type of system is usually strongly dependent upon the polymeric carrier. Drying out of the polymer or pumping out of the polymer and filler can create voids or loose particle to particle contact, reducing performance. The elastomeric versions of this type of material are usually considered to be reworkable, while, in general the grease and phase change type interface materials must be cleaned and replaced if a component is to be reworked.

The high degree of loading typically used may inhibit mechanical compliance. Greases and phase change materials become stiffer but can be deformed relatively easily. Elastomeric materials become a great deal stiffer in the filled state and may not exhibit the degree of compliance necessary to accommodate warpage or variations in height at reasonable pressures. If these deviations from planar surfaces are not met the interface contact area will be reduced and interface thermal resistance will increase.

With this type of arrangement, wetting out of the surface is usually a function of the polymer system used. For grease or phase change type interface materials, which wet out surfaces quite well, the thermal contact resistance is low. To achieve a significant degree of thermal conductivity, however, the material must be highly loaded with thermally conductive particulate or flake. Loading in excess of 60-70 volume percent conductive fillers such as alumina, silica, boron nitride, graphite, silver or other metals is common. Forcing particle to particle contact creates a heat transfer path and increases the thermal conductivity of the polymeric system to approximately 1 W/mK for typical systems and up to 4 – 8 W/mK for very specialized materials. While these values are significantly better than the

unadulterated polymer, they are still relatively low, and bulk thermal resistance due to heat conduction within the material becomes a bottleneck as interface thickness increases.

Alternate Interface Material Approach

Conventional interface materials are limited by relatively low thermal conductivity, as the resistance to heat transport generated by particle to particle contact limits the efficiency of the conductive filler used. An alternate to filling a carrier with flake or particulate material would be to use an aligned structure of thermally conductive fibers, as shown in figure 2. These fibers create a continuous thermal path from one surface to another, and hence give rise to a composite interface material with an inherently high conductivity, as particle to particle contact does not limit the bulk thermal conductivity. As this high conductivity can be achieved with a comparatively low volume fraction of conductive fibers, the material can be made very compliant, especially if fibers of suitable aspect ratio (fiber length/fiber diameter) are chosen.

The fibers are held in place by some thin layer of adhesive and encapsulated in a gel or elastomeric material to prevent broken fibers from escaping the interface. Choosing an encapsulant material that wets the fibers will result in a tent like structure at the free fiber tips which gives some degree of wetting out at the fiber tips, while not inhibiting the inherent compliance of the velvet like fiber structure. Since this structure does not depend on particle to particle contact, some degree of drying out of the encapsulant does not affect thermal performance. Also, this material is easily reworkable and will remain in place

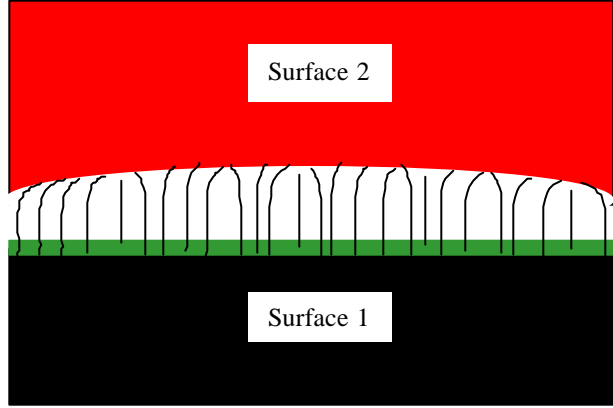


Figure 2. Interface material composed of aligned thermally conductive fibers. Single fibers provide a continuous path for heat transport from one surface to another.

and not be subject to pumping out of material since all the conductive elements (fibers) are anchored in place. Johnson Matthey Electronics, under the trade name Gelvet™, makes material that displays this aligned conductive fiber structure. An SEM photo of the microstructure of this material, showing the encapsulant and oriented fibers, is shown in Figure 3.

The materials set of choice for this type of interface material will be a high thermal conductivity fiber which has a small diameter, is readily available and relatively inexpensive. In general carbon, or graphite fibers meet all of these characteristics. The work detailed in this paper uses 10 μm diameter carbon (graphite) fibers, with axial thermal conductivities of 800 and 1100 W/mK.

Performance Characteristics of Aligned Fibrous Interface Materials

Thermal Performance

The key feature of an aligned fibrous interface material is its inherent high thermal conductivity. When the fibers are aligned in the direction of heat transport (i.e. spanning the interface gap), the theoretical thermal conductivity of the resulting material can be given by

$$k_{interface} = k_{fiber} A_{fiber} + k_{polymer} (1 - A_{fiber}) \quad (1)$$

where k represents thermal conductivity and A the area fraction occupied by the aligned fibers. For a typical structure with 10% of the area occupied by carbon fibers having a conductivity of 1100 W/mK,

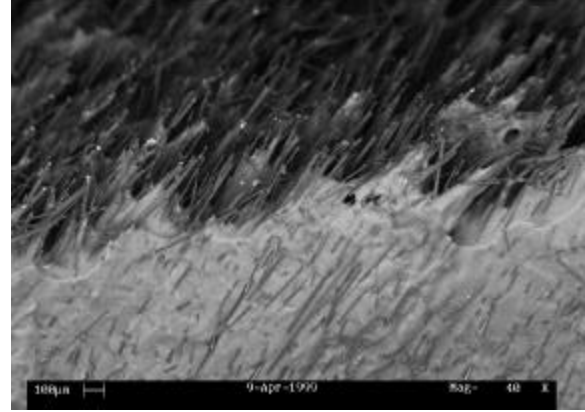


Figure 3. Scanning Electron Micrograph showing aligned fibers in polymeric encapsulant. Note fibers are continuous from one surface to another.

this gives a composite interface thermal conductivity of approximately 110W/mK. Actual measurements, taken per the ASTM standard [1], give a thermal conductivity of 50-90 W/mK for this material.

In this test thermal resistance is measured for several thicknesses of material. Since total thermal resistance, θ , may be written as

$$q = q_{contact} + q_{bulk} \quad (2)$$

substituting for θ_{bulk} gives

$$q = q_{contact} + \frac{t}{kA} \quad (3)$$

where t is the thickness of the interface. Differentiating with respect to thickness gives

$$\frac{d(qA)}{dt} = \frac{1}{k} \quad (4)$$

where the slope of an area normalized thermal resistance versus thickness is inversely proportional to the interface material's thermal conductivity.

An example of this type of measurement is given in figure 4, which plots thermal resistance versus thickness for a number of samples tested at relatively low interface pressure, 7 psi. The slope of the best fit lines is 0.4796 K in/W, which is equal to $1/k$, the material's thermal conductivity. The conductivity is then 82 W/mK. This is in good agreement with the

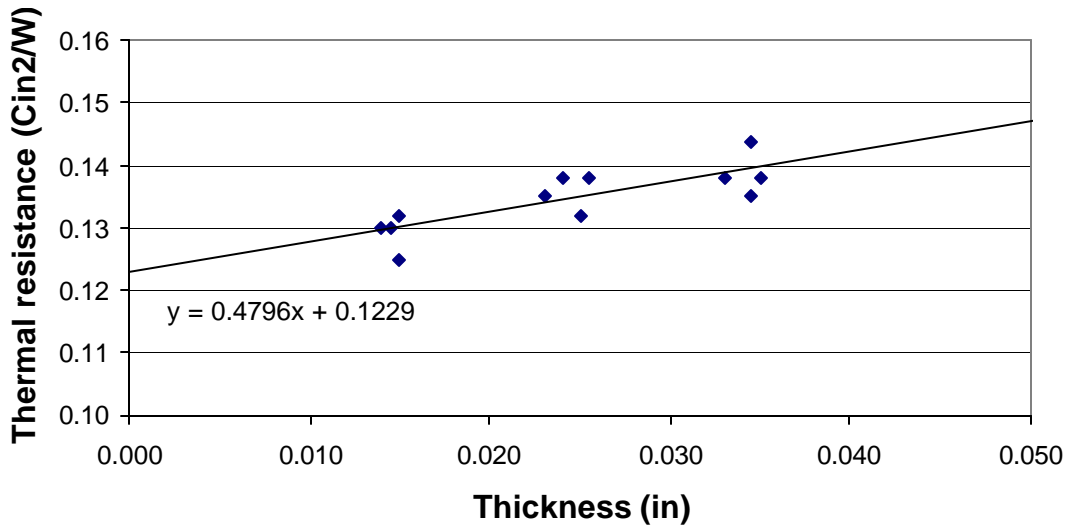


Figure 4. Thermal resistance of aligned fibrous interface material as a function of thickness. Slope of best fit line is the material bulk conductivity. For a high conductivity material, thermal resistance is a weak function of interface thickness.

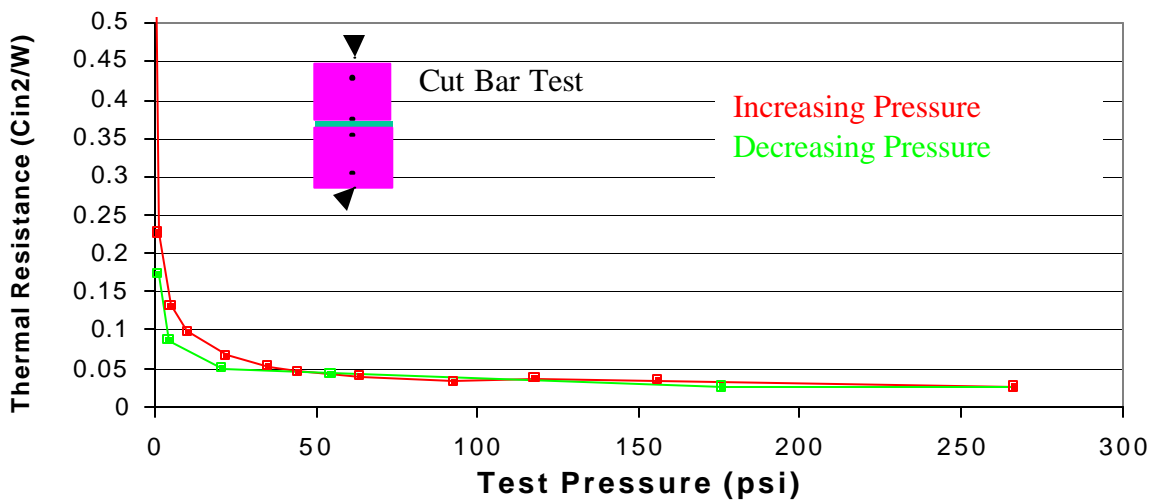


Figure 5. Pressure sensitivity of aligned fibrous interface. High thermal contact resistance is overcome at moderate (50 psi) pressures.

theoretical value, as some of the fibers may be broken, or as shown schematically in figure 2, not span the entire distance between the two surfaces and hence not participate fully in transport of heat between the two surfaces.

The intercept of this plot is considered the contact resistance (for the test apparatus surfaces) of this material. It is notable that this material's thermal performance is a very weak function of material thickness, and that contact resistance plays the largest role in the thermal resistance, particularly for thinner materials (i.e. less than 0.020"), at low pressures. As

the pressure increases, as shown in figure 5, the thermal resistance can decrease dramatically.

Benchmarking has indicated that the thinner versions of this material are able to perform on par with typical greases and phase change materials for moderate bond line thicknesses and interface pressures. As the mating surfaces deviate from planarity, the effect an increased interface thickness does not significantly affect the thermal resistance of these aligned materials, while the thermal resistance of most other interface materials increases dramatically [2]. This effect is due to the differences

in bulk thermal conductivity between the aligned interface materials and conventional materials.

Mechanical Compliance

The aligned fibrous structure presents a very compliant interface compared to highly loaded structures. When the fiber aspect ratio is high, it takes very little force to bow, or elastically buckle, the fiber. A compliance curve for a 0.020" thick material encapsulated in a compliant polymeric matrix is shown in figure 6, while the compliance at 15 psi is plotted for several thicknesses in figure 7. Compliance of a material may be tailored by varying the type of fiber used or the length of fiber (material thickness), with little thermal penalty, due to the high inherent thermal conductivity resulting from this structure. This compliance is useful in absorbing stack-up tolerances for assemblies or accommodating die of differing height in multichip modules.

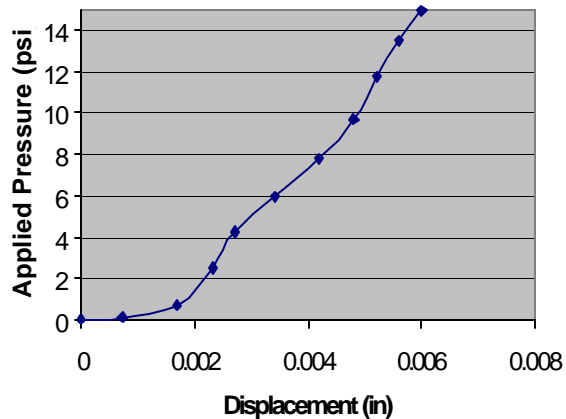


Figure 6. Compliance curve for 0.020" material.

Reworkability and Reliability

This material is produced in sheet form and may be reapplied to any component surface or shape. As it resembles a sheet or gasket and maintains this form, the component to which it is attached may be disassembled and reworked without necessitating replacement of the interface material. Numerous assembly cycles for a heat sink application and thousands of cycles for a burn-in application have been observed with little degradation to the interface material.

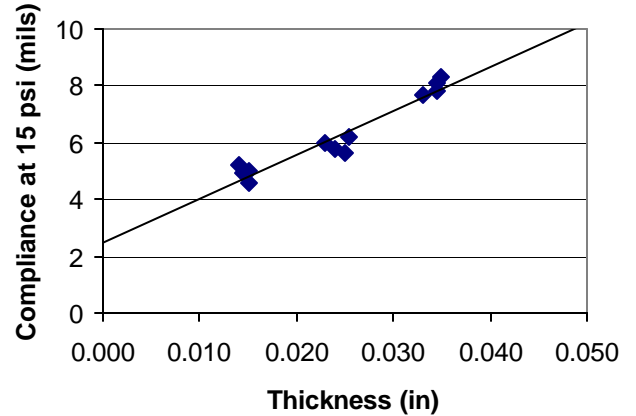


Figure 7. Compliance as a function of thickness for aligned fibrous interface.

This material has been demonstrated not to pump out in thermal, mechanical or power cycling, as the fibers are anchored in an adhesive. The carbon fibers do not degrade with temperature, hence the properties of the material are not affected by a bake test for an assembly. Through appropriate choice of encapsulant and adhesive, low outgassing, residue and high temperature applications may also be serviced.

Material Limitations

There are some current limitations to this type of material. The thickness can not be reduced much below 0.015" at this time, as it becomes difficult to properly orient fibers that are shorter than this. As the carbon fibers used are very strong in tension and compression, but brittle in shear, this material does not exhibit good abrasion resistance and is not suitable for applications that require shear resistance. The temperature limits of the preferred adhesives and encapsulating material restrict their use to temperatures under 110 C, although substitutions for these materials may be made to extend the temperature range if a thermal penalty can be absorbed. Also, the selection of carbon fibers produces a material that is electrically conductive, which may be unattractive for some applications.

Demonstrated Applications

This material has been demonstrated as a heat sink to die interface, heat sink to package interface, as a gap filling pad and a simulated multichip module interface. In the heat sink to die interface, this

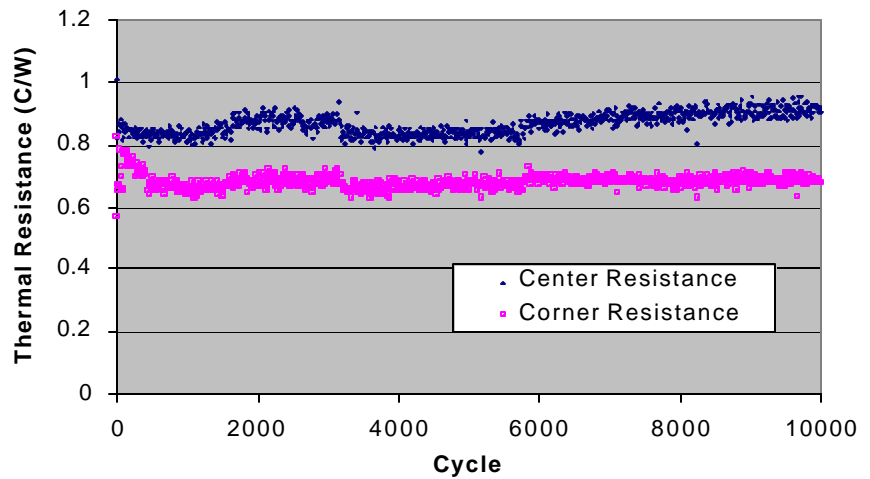
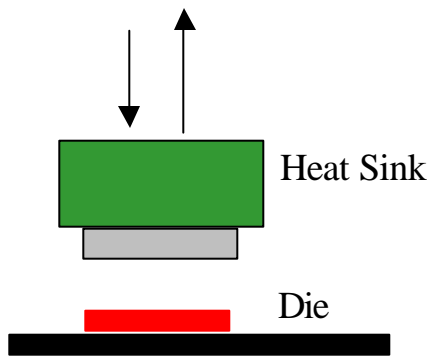


Figure 8. Material stands up to repetitive assembly of die burn-in testing with no degradation in thermal performance. Motion of heat sink is stright up and down, die temperature is 100°C.

material has been used in an application and in a repetitive die burn-in or package test use. In die burn-in use several thousand cycles of use have been observed without thermal degradations, as shown in figure 8. This exploits the robust and compliant nature of this type of structure and the fact that material does not need to be reworked with each cycle.

Applications where stack-up tolerances or varying package heights demand a fairly large degree of compliance, this material performs well, as the increase in thickness necessary to gain significant compliance does not come with a large thermal penalty.

The high inherent thermal conductivity plays a major advantage in gap filling applications, as poor bulk thermal conductivity dominates the thermal resistance of competitive. For Gelvet™ materials the bulk conductivity remains low, and in thickness greater than 0.040" this material has a thermal resistance up to three to five times lower than competitive materials.

Summary

Improvements to interface material technology in recent years have concentrated on ease of use and preapplication of material to components. The thermal performance of these materials has, in general not changed substantially, and is not likely to change substantially when relying upon heavy degrees of loading with a thermally conductive

particulate filler, where conduction of heat from particle to particle limits heat transport. A new class of interface materials, utilizing aligned fibrous thermal conductive elements to span the gaps between mating surfaces with one fiber overcomes some of the limitations presented by conventional interface materials. This class of materials performs well when stack-up tolerances, different die or package heights and/or large gaps require the interface thickness to be larger than 0.002". Other applications of this material have focussed the reworkability of these materials.

References

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