

Thermal Management Materials Choices

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Introduction

The rise in the heat flux and total power dissipated from semiconductor devices has been well documented in semiconductor packaging industry forecasts. [1, 2, 3] This increasing heat flux (power per unit area, or power density) is not limited to microprocessors and server processors. This general trend affects a variety of commercial and military power semiconductor devices as well as integrated circuits (IC).

The primary determinant of a thermal solution for a semiconductor device or module is the overall heat dissipation. However, at a macro level, the localized heat flux is typically a more critical concern for device reliability. Hot spots with extremely high heat fluxes are a significant concern in the thermal management of processors, RF, wide band gap, power LED, and other semiconductor devices.

The thermal solution for an application encompasses more than the heat removal technology applied to the surface of the semiconductor device. This solution can contain both active and passive components, and extends from the heat source (die junction), through heat spreaders and heat sinks to the ultimate heat sink, typically, ambient air or a cooling water source.

The multiple component materials and the interface materials between these components define the thermal resistance

of a system. Thermal design involves selecting the materials and configuration that optimize the overall cost when weighed against the desired performance and reliability of the finished goods. As these designs progress, the interface materials are often identified as a significant percentage of the total thermal resistance. As total power dissipates and/or localized heat flux increases, careful analysis and selection of appropriate interface materials is increasingly important. Figure 1 shows the different interface levels of a typical stack-up where D= TIM1 and B= TIM2.

A common means of reducing the thermal interface resistance is the use of direct die

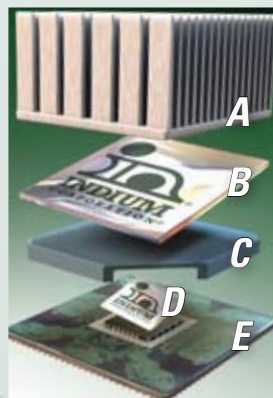


Figure 1.

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solder attach for an active semiconductor device mounted to a baseplate, spreader plate, lid, or other package component. This first-level thermal interface material (TIM1) provides a thermal path from the active device to a first-level heat spreader.

TIM1 materials choices include:

- Thermal greases and gels
- Die-attach adhesives (polymeric materials filled with comminuted conductive material)
- Phase-change thermal interface materials
- Pure indium (In) and In alloy solder

Heat Spreader:

- Copper (Cu) or aluminum (Al)
- Aluminum-silicon-carbide (AlSiC) composite
- Copper-tungsten (CuW) composite

TIM1 materials choices include:

- Thermal greases and gels
- Compressible soft metal TIM
- Gap filler pads

Thermal performance (conductivity, thermal expansion compatibility, and surface contact) and reliability of interface and package materials are examined in this paper. The thermal interface materials and the external heat sinks (or other thermal solutions) are generally within the control of the system-level thermal design engineer. Increasingly important as a critical component of the thermal design engineer's role is his/her understanding TIM material performance. This has also led to continued development of TIM material testing methodologies for both direct material comparison and in thermal performance characterization. [4, 5, 6]

As discussed above, the increases in power density drive advances in material development, analysis, and application. The application of metal thermal interface materials has merged two previously separate areas within the electronics materials market. Solders are generally perceived as electrical connectors while polymer greases and adhesives serve as the thermal medium. In reality, solders offer high bulk thermal conductivity as compared to the modest conductivity of organic thermal interface materials.

High-volume desktop and server processors extensively use compliant reflowed solder TIMs with their very high bulk thermal conductivity. In these package designs the solder displaces organic thermal interface materials.^[7] The application of solder as the TIM is progressing forward in areas ranging from RF devices, high power light-emitting diodes (LEDs), and power semiconductor devices. Of course, package reliability, must be demonstrated for change. This presentation seeks to address this.

The interest in metal TIMs is occurring in parallel with the development of metal particle filled materials with near-metallic performance. Organic materials such as phase-change TIMs and polymer solder hybrids (PSHs) perform quite well when compared to traditional thermal greases, but also to liquid metals and phase-change metal alloys. These materials achieve conductivity at levels approaching the metal TIM while maintaining some of the surface wetting and compliancy of the polymer base. [8, 9]

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Material Design for CTE Compatibility

Reducing or eliminating the thermal stresses due to thermal expansion mismatch across an interface leads to another area within semiconductor packaging that is experiencing considerable advancement. Materials are being developed to mate the coefficient of thermal expansion (CTE) with other package materials (substrate, solders and TIM1, adhesives, dielectrics) or the semiconductor die.

Below are listed some of the semiconductor package materials engineered for CTE compatibility to other packaging components:

Copper-tungsten (CuW) alloys (typically 85%Cu /15%W)

- Copper-molybdenum (CuMo) alloys and copper-molybdenum-copper (CuMoCu) laminates
- Kovar™, a low-conductivity material containing 54% iron (Fe), 29% nickel (Ni), 17% cobalt (Co)
- Aluminum-silicon-carbide (AlSiC), metal matrix composites produced by powder compaction or spray forming. Properties can be engineered by adjusting the SiC content
- Aluminum nitride direct-bonded copper (DBC) substrates
- Diamond-silicon-carbide, a composite manufactured with similarly variable ratios of diamond and silicon-carbide powders
- Carbon-, graphite-, and diamond-composite materials
- Other metal matrix composite materials

A good example of the integration of CTE (coefficient of thermal expansion) compatible materials is the high power Insulated Gated Bipolar Transistor (IGBT) semiconductor module segment. These modules control enormous amounts of electrical energy that generate considerable heat in the process. Solder is used for the critical attachment of the semiconductor chips to the direct-bonded copper (DBC) substrate. Heat is conducted from the chip through the solder interface and the DBC substrate. Aluminum nitride is the material of choice due to its low CTE (5 ppm/°C) and high thermal conductivity (150170 W/m•K).

Virtually all manufacturers of IGBT modules (1700+WAC) of traction and heavy drive applications, power modules for hybrid electric vehicle (HEV) drives systems, and automotive 42V starter/alternators currently utilize CTE-compatible package components. The most common materials used are

from tungsten-copper (CuW) or aluminum-silicon-carbide (AlSiC) composites. CuW composites are engineered with a CTE of 6-9 ppm/°C and thermal conductivity of 170-220 W/m•K. The AlSiC materials have a CTE which can be tailored from 8-12 ppm/°C also with thermal conductivity of 170-200 W/m•K.

The longer-term market requirement for high heat dissipating semiconductor package materials is for the development of a package material with a thermal conductivity exceeding that of Cu and Cu alloys, to better dissipate heat from both hot spots and higher device heat loads. Design requirements for the highest heat flux active devices are now driven by transition to silicon carbide, silicon nitride, aluminum nitride, and related semiconductor materials, which are capable of higher operating temperatures, as well as operating with higher localized heat fluxes. The first such applications are being driven by active devices, typically SiC, for phased-array radar transmit/receive modules in the defense and aerospace markets. The leading-edge commercial market applications are driven by high power LED module requirements and the previously-mentioned highest-power IGBT and RF semiconductor devices.

Market Applications

Applications and uses for engineered thermal materials, which offer a combination of high thermal conductivity and specific CTE values relevant to package material compatibility, include a disparate selection of military, aerospace, vehicle, and commercial electronics market segments. These include:

- Semiconductor module baseplates with direct die solder attach for extremely high heat flux wide band-gap (WBG) semiconductors for phased-array radar and other military electronics applications, with exceptionally low thermal resistance thermal paths to a second-level thermal solution
- RF and wireless module baseplates for GaAs, SiC, and other semiconductors
- High heat flux thermoelectric cooler submounts for optoelectronics modules
- High heat flux power LED array submounts for solid state lighting, heads-up displays, vehicle lighting, and related applications
- IGBT power semiconductor module baseplates for high

reliability applications with semiconductor dies solder to direct bond copper (DBC) on dielectric materials for traction, hybrid electric vehicle, and other motor and drive system applications

- Lids and baseplates for high heat flux processor die and other integrated circuit applications
- Active cooling components for high heat flux direct die solder attach requirements

The increases in average power dissipation and in hot-spot heat fluxes have driven a number of applications to use direct die solder attach with In-based or other compliant metal alloys. These alloys have a high bulk thermal conductivity as a heat transfer material and are replacing more traditional types of TIMs.

Found in Aerospace and radar systems, WBG semiconductor materials include silicon carbide (SiC) and gallium nitride (GaN), and operate at higher temperatures with substantially higher heat flux.

Thermal Resistance of a Metal TIM

Metals are characterized by positive ions forming a structure within a communal sea of their valence electrons—maintaining the net neutral charge. The high thermal and

electrical conductivity of metals results from the mobility of these valence, or free, electrons. A linear relationship between the electrical and thermal conductivity of metals (referred to as the Wiedemann-Franz law) is shown in Figure 2.

Other types of solids are formed with the covalent or ionic bonds where the electrons are tightly constrained between donor and acceptor atoms. These materials can form in crystalline bonded structures (e.g. diamond, quartz, sapphire) or solids formed by weaker van der Waals and hydrogen bonds (like ice, sulfur, and most polymers). In these solids, electrical conductivity is generally poor due to limited electron mobility, and the vibration modes (phonons) are limited to the atomic motion in the lattices or molecules. Atoms with low atomic weight in tightly bonded structures are more easily able to conduct heat (e.g. diamond, aluminum nitride, boron nitride). Generally, compounds of heavier atoms are less conductive (e.g. zirconia, lead oxide). Organic polymers and weakly bonded materials (e.g. sulfur, iodine) similarly have limited ability to conduct heat.

In composite thermal materials, such as ceramic and metal-loaded thermal grease, silver-filled epoxies and glasses, and carbon nanotube-filled polymers, thermal conductivity is limited by the polymer or silicone fluid. This is a result of the poor coupling of the vibration frequencies (phonons) between

the particle and fluid components. This phonon mismatch limits the thermal conductivity of these materials to $<10 \text{ W/m}\cdot\text{K}$, with typical values of $1\text{--}3 \text{ W/m}\cdot\text{K}$. To achieve any benefit of the particle loading, the concentration must be high enough that particle-particle contacts are made.

On the other hand, metallic interfaces have a minimum conductivity of $\sim 15 \text{ W/m}\cdot\text{K}$ for the Bi base alloys and >50 for the Pb-free SAC, Au/Sn and In alloys. The high conductivity of a metal is necessary, but not sufficient, for effective heat transfer. These interface materials must be in good contact with the heat transfer surfaces. The polymer and silicone fluids of thermal greases and die-attach adhesives readily wet the contact surfaces. Metal interfaces require either a reflow operation (soldering or melting

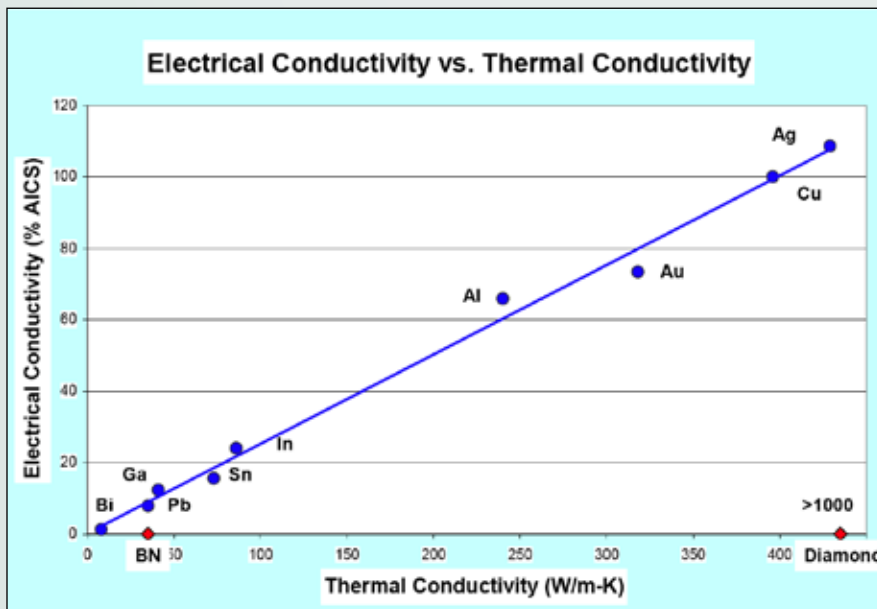


Figure 2 – Plot of the linear relationship between thermal and electrical conductivity of metals. The data for thermally conductive dielectrics boron nitride (BN) and diamond are shown for reference.

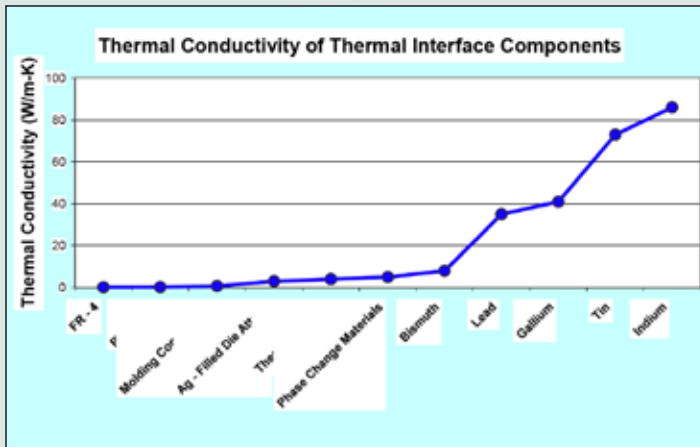


Figure 3 – Comparison of thermal conductivity of components in electronic thermal solutions.

of phase-change metals) or pressure to form intimate contact.

A solder joint is a metallurgical bond between dissimilar metals. At the interface between the two metals, a composition gradient is formed containing intermediate phases of the major components in the joint materials. In the most common solder joint, a tin (Sn) solder forms an interface with copper (Cu). Some of the Cu dissolves in the liquid Sn solder and forms the intermetallic phases with the composition Cu_3Sn and Cu_6Sn_5 . These intermetallics form as two layers on Cu surface which continue to grow at a rate limited by solid state diffusion after soldering is complete.

Generally, the intermetallic phases are ordered compounds that exist over small composition ranges. The atomic attraction that leads to the ordered structures generally results in reduced ductility compared to the parent metals. These compounds have electrical and thermal properties that reflect the bonding structure.

Figure 4 is a plot of the thermal and electrical conductivities data from the NIST Materials Performance Division^[10]. This plot highlights two important behaviors common to the intermetallics of any solder system. First, the curves of the conductivities are far from a linear interpolation between the elemental properties of Cu and Sn. The deviation is negative as a reflection of addition constraints on the valence electrons. Secondly, both conductivity curves follow the same relationship. The electronic contribution to thermal conductivity reflects that the intermetallic compounds retain

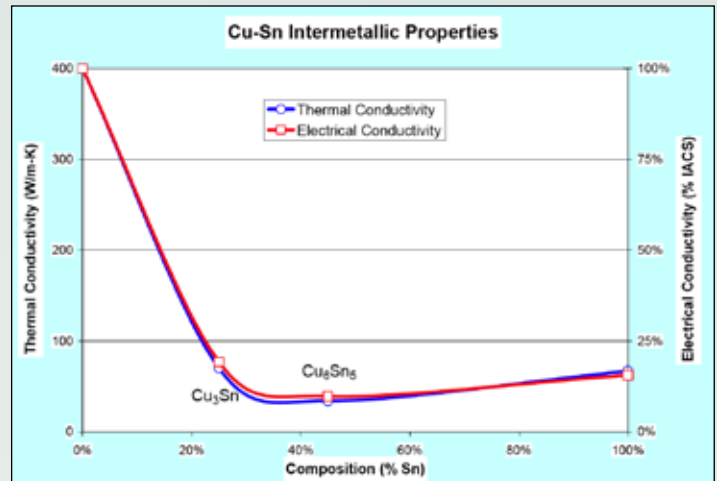


Figure 4 – Thermal and electrical conductivity of intermetallics in the solder joint trend together. This behavior demonstrates free electron component of thermal conductivity.

their metallic characteristics. Since the free electrons are available in each component of the interface, the electrical and thermal resistance of the interface is low.

In a solder interface, the contact resistance is determined by the quality of the solder joint. As discussed above, the electronic component of heat transfer dominates. In an ideal solder joint the contact resistance resulting from the thickness of the interface layer ($\sim 1 \mu\text{m}$) is minimal—a value of $<0.0003 \text{ cm}^2 \cdot ^\circ\text{C/W}$. The bulk resistance of a typical $100200 \mu\text{m}$ thick solder interface is roughly $0.02 \text{ cm}^2 \cdot ^\circ\text{C/W}$.

Measuring this low thermal resistance directly in the ASTM D5470 test stand presents certain challenges. A solder joint between two test blocks presents the difficulty of a small difference from a standard. For testing coupons made with a solder joint, the resistance between the metering blocks and the sample substrates is considerably larger than

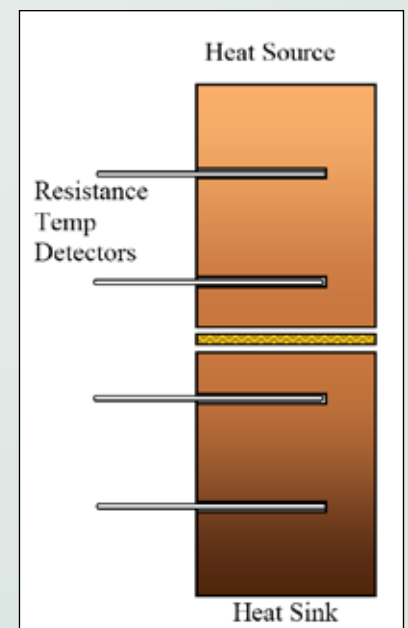


Figure 5 – Simple schematic of ASTM D5470 test configuration.



Figure 6

the interface to be measured. The difference in the interface resistance is overwhelmed by uncertainty in the measurement of the multiple series interfaces.

To demonstrate the performance of the solder TIM, a non-wetting, low melt solder was reflowed between the test blocks. An InBiSn alloy with a melting point of 60°C was used for the interface. The alloy was tested before melting. Next, the sample was heated above the melting point and tested in the liquid phase. The test block was cooled to solidify the alloy and the resistance was measured a third time. As expected, the resistance of the interface drops when the alloy is melted—the contact resistance is essentially eliminated. The conductivity of this material is ~15 W/m•K.

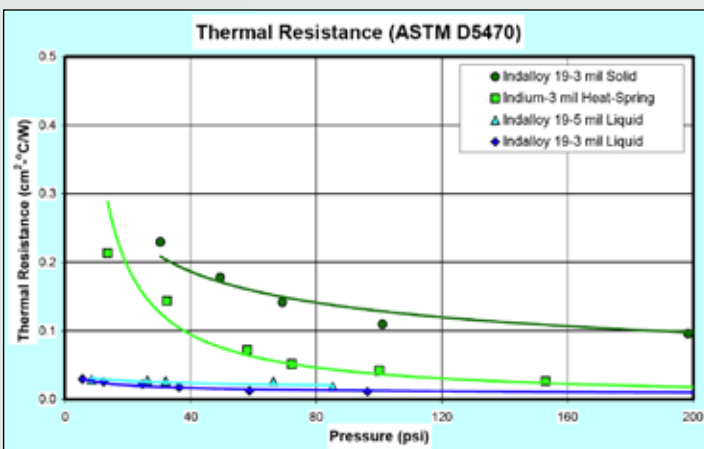


Figure 7 – Data from ASTM D5470 test of metal thermal interfaces. Indalloy 19 is a phase change metal TIM which melts at 60°C. The compressible metal TIM (or Heat-Spring™) is shown for comparison.

The metal TIM makes its contact with the surface either by fusion (as in the case of solder TIM represented by the Indalloy 19) or with the application of sufficient pressure in the case of the Heat-Spring™ compressible TIM.

To achieve this level of thermal resistance, polymeric interface materials must be extremely thin—10 μm or less. Machining heat sink surfaces to the flatness and smoothness necessary and then assembling the die to the heat sink with sufficient coplanarity exceeds the capability of high volume manufacturing.

Note the thermal resistance of the thermal greases are clustered around 0.1 cm²·°C/W. These materials are filled with BN, Al₂O₃, Al, and Ag particles in a range of loading concentrations. The reported thermal conductivity of these materials range from 2-5+ W/m•K. Die-attach adhesives use similar particle loading with epoxy rather silicone grease as the fluid component. The thermal resistance of the epoxies behave similarly.

Phase-change materials exhibit a wide range of thermal behavior. Some are very fluid and behave similar to thermal grease (and are relatively insensitive to application pressure). Others, like Material E in Figure 8, behave more like a compressible pad and require clamping pressure to achieve acceptable thermal contact.

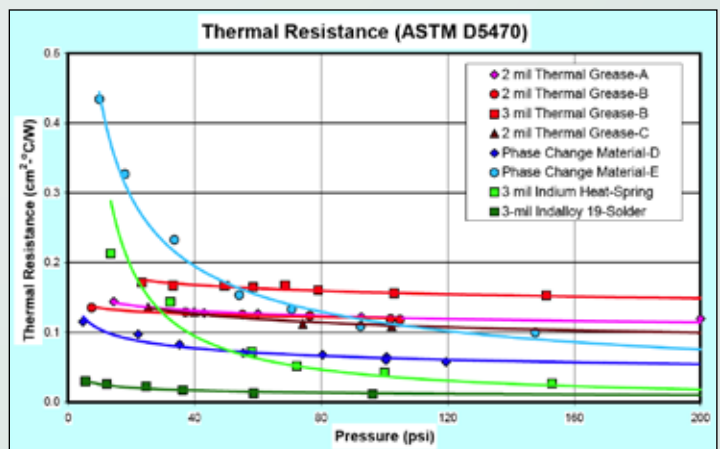


Figure 8 – ASTM D5470 Thermal resistance measurements of polymer and metal thermal interface materials used in electronics cooling.

Effects of Defects in Thermal Interface Materials

In application, voids may occur within the interface material from a variety of sources. During installation, air pockets can be caused by incomplete spreading of grease or epoxy, or gas pockets from entrapped flux or volatiles can form in solder joints. During service, additional mechanisms act to degrade the interface. In the composite materials, the fluid can migrate or volatilize and leave residual particles in the interface without adequate contact.

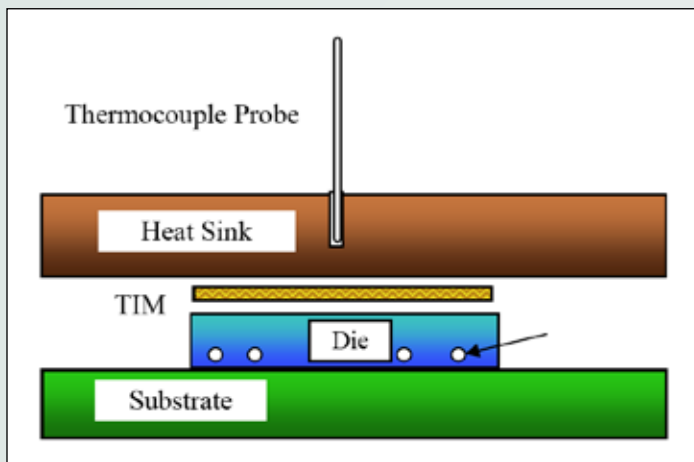


Figure 9 – Schematic of thermal test vehicle used to develop temperature profiles of thermal interface.

To understand the failure modes of the thermal interface materials, data is collected using thermal test vehicles (TTV). These test vehicles consist of a mechanical model made in the same production process as the components with an embedded heater and temperature probes. This type of device can be loaded into environmental chambers to simulate operational exposure.

The lifespan of thermal grease is often limited by the separation and migration of the silicone fluid. As the migration proceeds, the center of the die first experiences increased temperatures during service. Eventually this mode spreads over the entire interface.

A similar type of failure mode results during power cycling of the TTV. The differential expansion of the materials in the TTV results in a diaphragm pumping action on the TIM. Materials that do not resist this motion gradually thin out and develop voids in the center of the die. This progression is seen in Figure 11.

Metal interface materials do not contain the fluid components of the polymeric compounds, making them insensitive to pump-out and drying out.

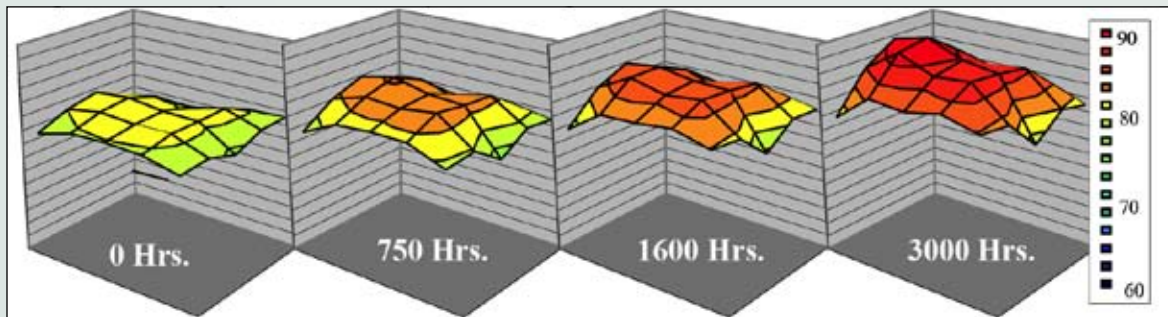


Figure 10 – Temperature profile evolution of thermal grease TTV interface during thermal exposure at 90°C.

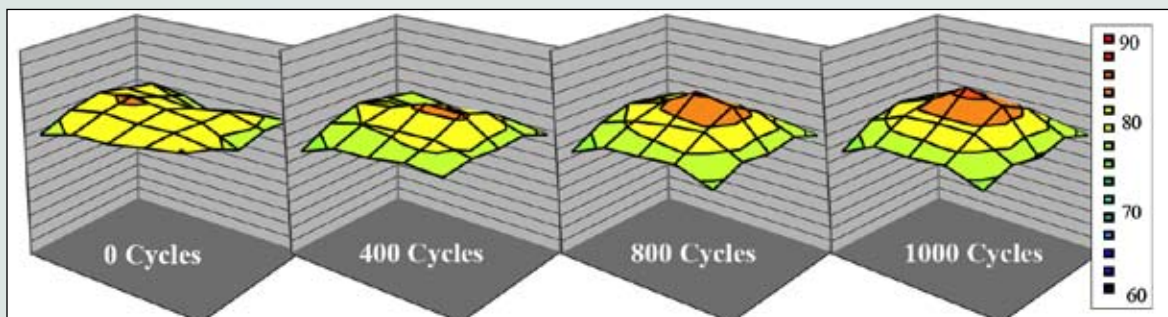


Figure 11 – Temperature profile of thermal grease developed during power cycling of a thermal test vehicle.

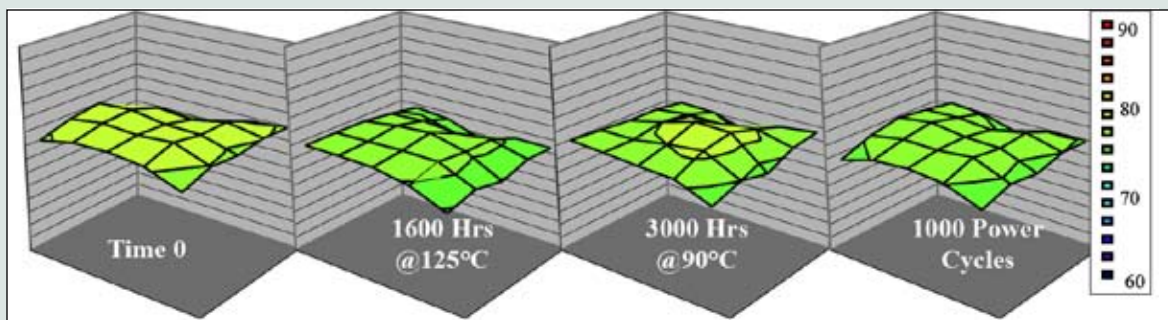


Figure 12– TTV temperature profiles of indium Heat-Spring reliability testing.

Testing Thermal Resistance of a Solder Joint

Thermal resistance testing of solder joints required modification of the standard ASTM D5470 test configuration and a separate calibration standard. The test blocks and a standard were precision-machined and drilled from a single bar of OFHC copper. The uncertainty of measurement was determined by running multiple tests on the standard block reversing the orientation and location of the probes. ^[4a]

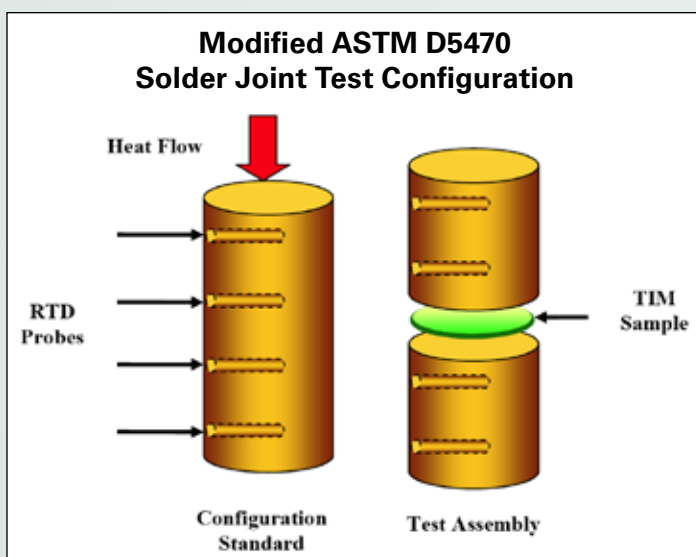


Figure 13

The 100-ohm platinum RTDs were calibrated for precision of measurement by bundling the 4 probes together and immersing them in a temperature-controlled flow water bath. The probes tracked changes in the bath temperature to within 0.02°C. The precision was confirmed by installing the probes in the configuration standard and equilibrating with the ambient overnight. The maximum difference between probes was 0.016°C.

The geometry of all probe holes was confirmed with a comparator to be within 0.03 mm of the target location. The actual measured locations were used in the thermal resistance calculations. The geometry and instrument uncertainty yields uncertainty in the measurement of thermal resistance of $\pm 0.003 \text{ cm}^2\text{-}^\circ\text{C/W}$.

A larger source of uncertainty is due to the probe stem loss from the limited insertion depth. Each probe conducts heat along its length which lowers the measured temperatures. Controlled contact with the internal diameter of the probe holes, as well as insulation along the probe length, are used to minimize this variation.

Since the uncertainty caused by this source is not well defined, a calibration standard was used to empirically define the total uncertainty in measurement. The solid Cu bar should show no interface discontinuity. The total error in measurement is discerned in this value for the standard. The block was inserted in both up-down orientations and the temperature probes were swapped between holes to get a measure of the expected repeatability.

For the standard bar, the resistance data was centered on a mean of -0.0001 with a standard deviation of 0.006 $\text{cm}^2\text{-}^\circ\text{C/W}$. As expected this variability of measurement is somewhat more than the instrument and test block geometry. It does demonstrate the method has the sensitivity for the measurement of the low resistance solder joints.

For the experiment, In solder and an Ag-filled (70-80% particle load) epoxy were tested. Figure 14 shows the expected result - a solder joint has a resistance of roughly an order of magnitude smaller than a high-performance epoxy die-attach material (0.029 versus 0.23 $\text{cm}^2\text{-}^\circ\text{C/W}$).

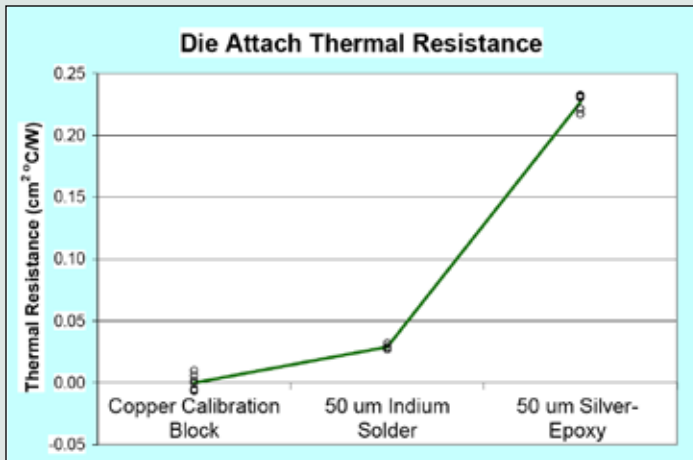


Figure 14

Limitations and Summary

The semiconductor industry constantly strives toward higher performance in speed and complexity. Each stage of this development creates new challenges in thermal management—more heat has to be removed from smaller packages. The technologies to achieve this level of performance have also created new constraints on thermal interfaces. Devices are manufactured to finer and finer pitch interconnects which are inherently more delicate. Dies are thinned to improve utilization and reduce package heights.

These changes in technology affect the types of interface materials suitable for these applications. Clamping and adhesive forces have limits to prevent issues with damage to the BGA or flip-chip connections, or to the semiconductor components themselves.

Solder materials are used as thermally conductive materials, based on their ability to minimize any mismatch in the coefficient of thermal expansion (CTE) between the active device and the material used for the first-level heat spreader (baseplate, substrate, or lid) material. The requirement for CTE compatibility also applies to different package components such as the baseplate, substrate (ceramic or organic), die-attach adhesive implemented as a TIM1, and the edge seal adhesive used to attach the lid to the package substrate. Overall package reliability enhancements are achieved with thorough examination of all relevant material combinations through the complete module stack-up.

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