THE BASICS OF METAL THERMAL INTERFACE MATERIALS (TIMS)

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INTRODUCTION

Modern electronics require an extremely large number of circuits to perform their many impressive feats. For example, a modern smartphone can have several billion logic circuits in the main microprocessor. This circuit density creates a significant amount of heat that must be dissipated. If the heat is not adequately dissipated, the life expectancy and performance of the circuits are significantly reduced.

A revolution in thermal interface materials (TIMs) and designs has been a result of this necessary heat transfer. This paper will discuss the progress in this important field.

A typical application of TIMs is represented in Figure 1. The silicon die in red in Figure 1 generates heat. TIM1 helps to conduct the heat to the IC lid, a metal cover and heat-spreader, usually made of copper that protects the IC. TIM2 then conducts the heat from the lid to the heat sink. The heat sink typically has fins, as shown in Figure 1, to aid in the transfer of heat out of the IC package.

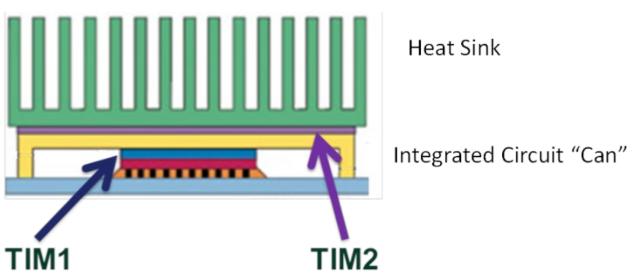

Figure 1. TIM1 and TIM2 are shown as applied to a typical Integrated Circuit (IC) package. The IC is in red.

Today, however, significant differentiation in application requirements has driven the need for the development of multiple types of TIM materials. As a result, a TIM classification system is useful for guiding selections of materials to meet specific application requirements. In addition, testing and evaluation of TIMs is critical to proper selection for a specific application. It is also important to recognize that thermal conductivity alone is not the sole criteria for the selection of a TIM. The following sections will discuss these classifications and applications.

Key words: Thermal Interface Materials (TIMs), heat transfer, wetting, Integrated Circuit (IC), metal, solder

THERMAL INTERFACE MATERIALS: FUNCTIONS

TIMs are critical for the transfer of heat from a semiconductor source to its external environment. However, due to the the wide variety of electronic designs and use conditions, numerous TIM designs and materials have evolved. Many of these functions and classes of TIMs are summarized in Figure 2.

While the primary purpose of a TIM is to help transfer heat from a hot surface to a cold one, there are actually many other attributes that could be critical for certain applications. Selecting the TIM with the lowest thermal resistance (Rth) may not always be the best route. Sometimes, the TIM needs to be electrically isolating or provide some structural fastening. In cases like these, the attributes of the thermal interface materials need to be re-prioritized.

In many applications, minimizing Rth is critical. In these cases, the TIM material must have the highest thermal conductivity. Materials like metals and liquid metals, carbon nanotube (CNT) arrays, and reflowed solders are often used in these applications. CNTs are also called vertical aligned carbon nanotube arrays (VACNTAs.)[2] This minimized Rth requirement will typically rule out thermal greases, as their Rth is usually much higher than metals or CNTs.

MAXIMIZING THE PERFORMANCE OF TIMS

TIMs have been used for more than 100 years, but maximizing their thermal performance is a continued driving force for high performance applications. Thermal contact resistance, or interfacial resistance, typically dominates overall TIM resistance. Therefore, high surface wetting, to minimize thermal contact resistance, is a critical TIM performance criterion. After wetting, the next most important factor is driving to the thinnest clamped or applied TIM thickness. Hence, when clamping force is used, it should be applied so that not only is the TIM thin, but good surface wetting is achieved. See Figure 3.

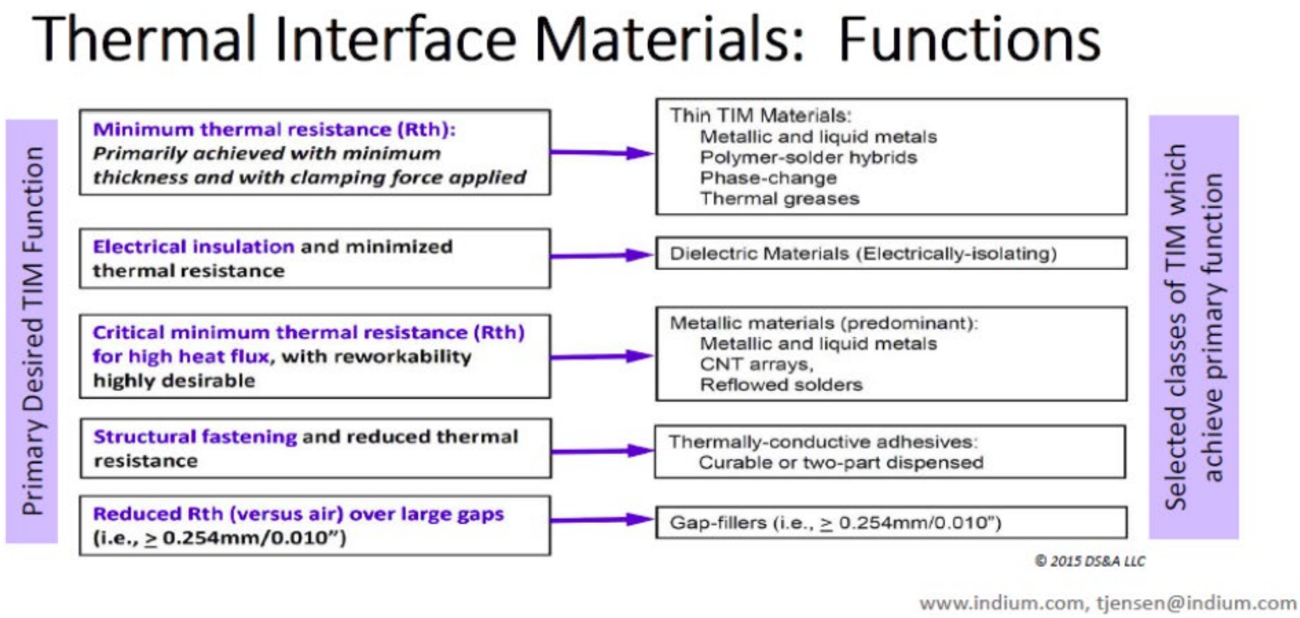

Figure 2[1]**.** Thermal Interface Material: Functions and the classes to meet these functions.

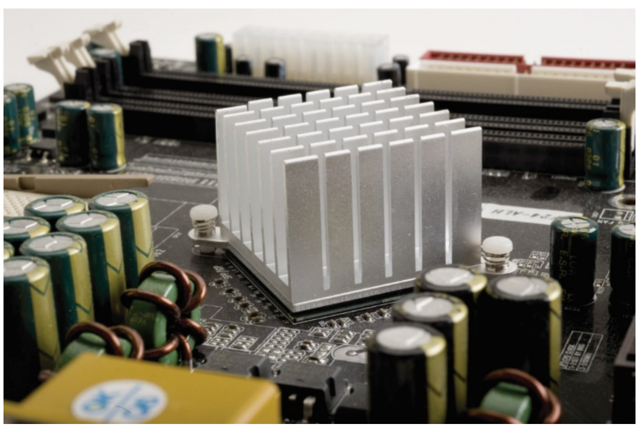

Figure 3. The screw holes enable good clamping forces.

Once the contact resistance is minimized, the TIM material's bulk thermal conductivity becomes increasingly important. This requirement can be a challenge for thermal greases, which typically have lower bulk thermal conductivity than metals. For a thermal grease, the low thermal conductivity challenge can be minimized if one can create an extremely thin bondline.

PERFORMANCE CRITERIA FOR TIMS

An application for a thermal interface material in a given high-performance design must be assessed against a defined list of specialized criteria (not just bulk thermal conductivity). Oftentimes a TIM has non-thermal performance attributes that are essential to success. These attributes could include:

1. Required thermal resistance value to meet stated heat transfer requirement
2. Suitability for applicable surface flatness, roughness, and available clamping force
3. Required product life and reliability
4. Higher operating temperature range
5. Resistance to extreme mechanical stress due to power cycling
6. No dry-out of a carrier compound due to temperature exposure
7. No compound pump-out due to mechanical stress during product operation

Before evaluating thermal interface materials, it is important to define all the requirements that will be needed for that TIM to be successful in the final application. A common mistake is to be so focused on thermal performance that other critical attributes are neglected until the TIM is implemented onto the final product.

OVERVIEW OF METAL TIMS

Metal TIMs have the advantage of having some of the highest bulk thermal conductivities of TIM materials. These TIMs can be in the form of solder, liquid, or phase change metals, compressible materials that plastically deform to the surface features of the objects and hybrid metals that include phase change wetting. See Figure 4; in this figure, object 1 is the heat sink and object 2 is the can of the IC package. In other examples, objects 1 and 2 might be different entities.

Many of the metal TIMs use metals that have high isotropic thermal conductivity and low yield and flow strength. The low yield and flow strength enables the TIMs to conform to the object's surface roughness and irregularities, thus having low thermal interface resistance. In addition, these TIMs will recover from deformation at low temperatures.

Thermal grease may experience “pump-out,” which occurs during use of the electronic product as thermal cycling and CTE mismatches actually pump the thermal grease out of its application space, sometimes leading to thermal failure. Solid metal TIMs, however, are not subject to the pump-out failure mode.

As mentioned before, the key to TIM performance is to minimize interfacial thermal resistance. In most cases, soldered metal TIMs perform well in this arena, which will typically form intermetallic interfaces with the objects.

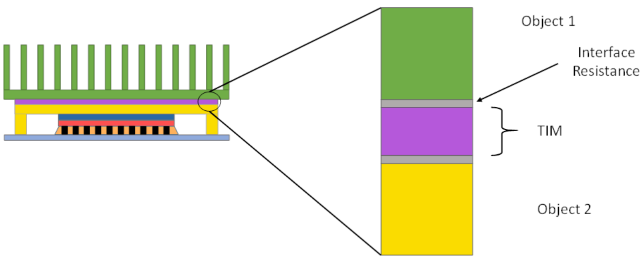

Figure 4. A magnified view of where TIM 2 fits in to support the transfer of heat from the IC to the finned heat sink. Note the interface resistance between TIM 2 and object 1 and object 2.

SOLDER TIMS APPLICATION OVERVIEW

Solder TIMs have high bulk thermal conductivity and, after soldering the intermetallics that form between the objects, will have low interfacial thermal resistance. Since the two objects are soldered together, you also have the benefit of mechanical fastening of the heat sink.

Solder TIMs are typically only used in TIM 1 applications for several reasons. First, in order to use a solder TIM, appropriate metallization is needed on both surfaces being soldered. This will add cost and will be avoided unless absolutely needed. Second, a solder TIM will need to undergo a reflow process. Most TIM2 applications are done after the circuit board is completely assembled. Additional reflow passes can result in failures and reliability issues elsewhere on the board. Additionally, voiding will occur in any reflowed solder joint. These voids reduce heat transfer. Moreover, if an additional reflow is required in the process, the voiding can become even worse. See Figure 6.

For successful TIM soldering, the metallization selection is critical for both surfaces. If the surface is not highly solderable, it can result in high-voiding and poor wetting, both of which will negatively impact thermal performance.

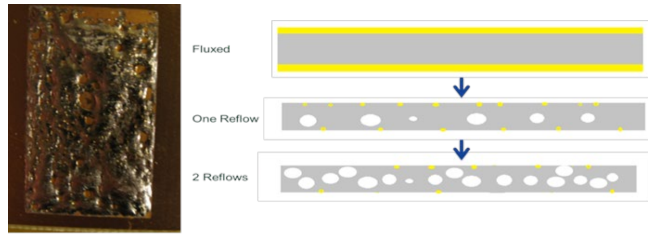

Figure 5. On the right, a schematic of a fluxed soldered TIM is shown. After one reflow, voids form. After two reflows, the voiding is worse. The image on the left shows the voids after pulling apart the objects.

The rigidity of the TIM bond and the intermetallics can result in poor performance in powered thermal cycled testing.[3] Therefore, alloy selection and process optimization are critical for overall success.

LIQUID METALS APPLICATION OVERVIEW

Figure 6. Liquid metal

Liquid metals have high thermal conductivity and excellent wetting to surfaces of objects. In addition, no soldering or surface metallization is required, and a very thin bond line can be obtained.

However, the liquid metal must be contained so that it doesn’t spread, and it can be difficult to handle and apply. Fortunately, once applied, its surface tension will typically keep it where it is desired.

The performance of liquid metals is significantly better than thermal greases. See Figure 7.

There are numerous liquid metal TIM options. Most liquid metal TIMs are gallium-based metal, with additions of indium, tin, and zinc. By varying these metal constituencies, melting points of 8ºC to 30ºC can be obtained. A table of some of the liquid metal TIM alloys is in Figure 8.[5]

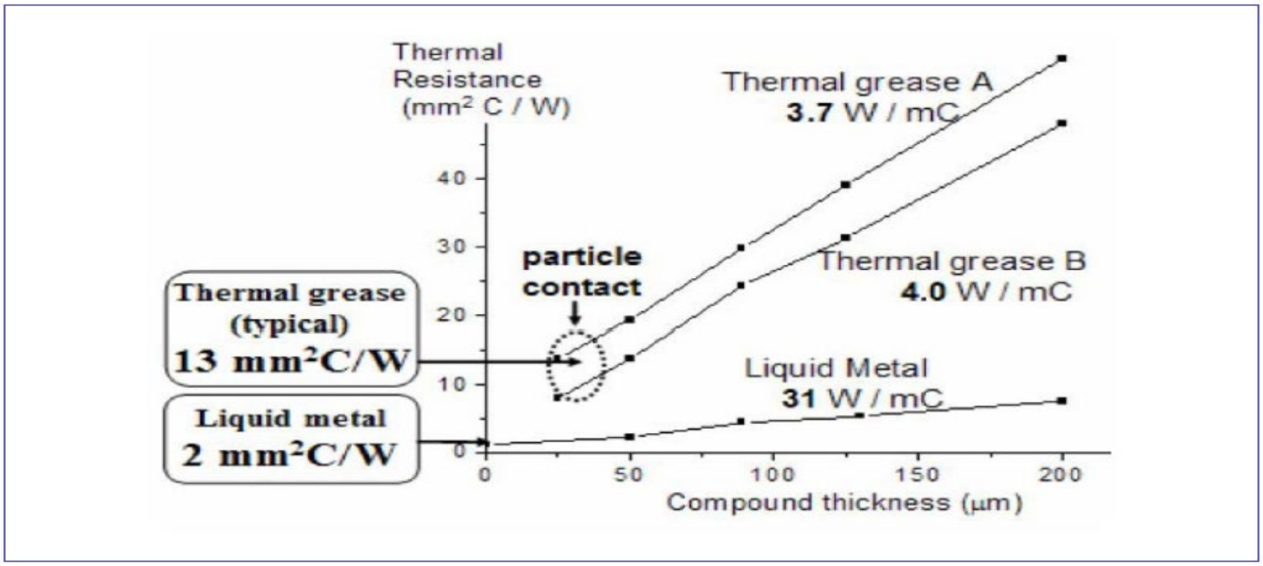

Figure 7. The thermal resistance of liquid metals is close to a factor of ten less than that of thermal greases.[4]

Indalloy® Number	Liquidus	Solidus	Composition	Density (lb/in³)	Specific Gravity	Thermal Conductivity (W/mK)	Electrical Resistivity (10^{-8} Ω-m)
46L	7.6°C	6.5°C	61.0Ga/25.0In/13.0Sn/1.0Zn	0.2348	6.50	15*	33*
51E	10.7°C	10.7°C	66.5Ga/20.5In/13.0Sn	0.2348	6.50	16.5 (1)	28.9 (1)
51	16.3°C	10.7°C	62.5Ga/21.5In/16.0Sn	0.2348	6.50	16.5 (1)	28.9 (1)
60	15.7°C	15.7°C	75.5Ga/24.5In	0.2294	6.35	20*	29.4 (2)
77	25.0°C	15.7°C	95Ga/5In	0.2220	6.15	25*	20*
14	29.78°C	29.78°C	100Ga	0.2131	5.904	28.1 (3)	14.85 (4)

* Estimated

Figure 8. A Table of Liquid Metal TIM Alloys

Liquid metal TIMs can often be applied with a brush or swab type applicator, as shown in Figure 9. The process of applying the liquid metal can also be automated. The right image in Figure 9 is a liquid metal TIM after it has been applied by jetting dots onto the surface of the die.

Figure 9. The left image shows the application of liquid metal TIM alloy. The right image is that of liquid metal TIM alloy after a jetting application.

The metals in these liquid TIMs are not known to be toxic, although it is always best practice to use any such materials with care and to study the material safety data sheets (MSDS).[vi]

PHASE CHANGE METAL TIMS

Phase change metal TIMs are solid at room temperature for easy assembly and then melt at a certain higher temperature.

This phase change absorbs significant heat without any increase in temperature. In addition, the liquid phase exhibits low interfacial resistance. See Figure 10.

One of the challenges of phase change metals is that they require a wettable surface. If there is any oxide formation on the surface, wetting will be inhibited (even if the virgin surface is wettable). In addition, pump-out is possible in the liquid phase.

PATTERNED METALLIC TIMS

Flat metallic TIMs have been used for almost half a century in telecom, military, and aerospace applications for RF devices and discrete power semiconductors. Patterned metallic foils (see Figure 11) have been designed to extend the use of preforms where increased compliancy without an increase in metal thickness is desired. These TIMs can be optimized for many applications by varying the alloys, the patterning, and the TIM thickness.

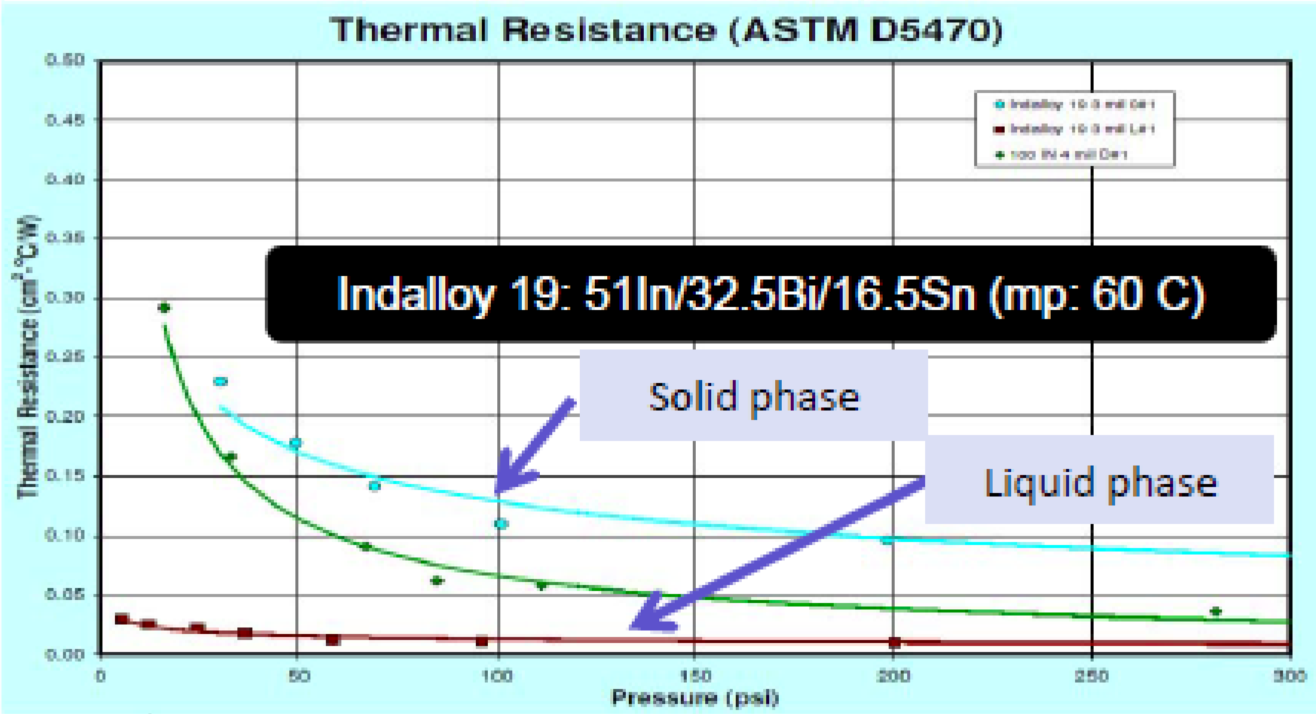

Figure 10. The thermal resistance of the liquid phase is less than one tenth of the solid phase.

Figure 11. Patterned Metal TIMs.

Figure 12 shows the performance of a patterned TIM as compared to a metal shim and thermal grease. Note that as pressure increases, the thermal resistance of a patterned TIM (here called a Heat-Spring) decreases significantly compared to a metal shim or thermal grease. The dark green line shows the performance of a flat foil. The light green line shows the reduction in thermal resistance that is achieved by patterning the surface of the metal. The pattern on the surface allows the metal to plastically deform at a much lower pressure and fill in air gaps along the surfaces and reduce the interfacial resistance.

SOLID LIQUID HYBRID (SLH) METAL TECHNOLOGY

Solid liquid hybrid (SLH) metal technology combines metal that is both liquid and solid at room temperature. The liquid metal provides wetting and low interfacial thermal resistance, while the solid metal creates a structure to contain the liquid metal and minimize the risk of pump-out. The solid metal must have limited solubility in the liquid metal.

There are two common approaches to creating a solid/liquid hybrid TIM. The first approach (shown in the top image) is achieved by mixing a slurry of liquid metal and solid powder of a metal or alloy that is not highly soluble in the gallium. The second approach, would be to mix the materials during the actual application. After jetting or dispensing the liquid metal, a solid preform of a highly soluble metal or alloy can be placed on top. The gallium diffuses through the grain boundaries creating a hybrid material, as shown in the lower pictures of Figure 13.

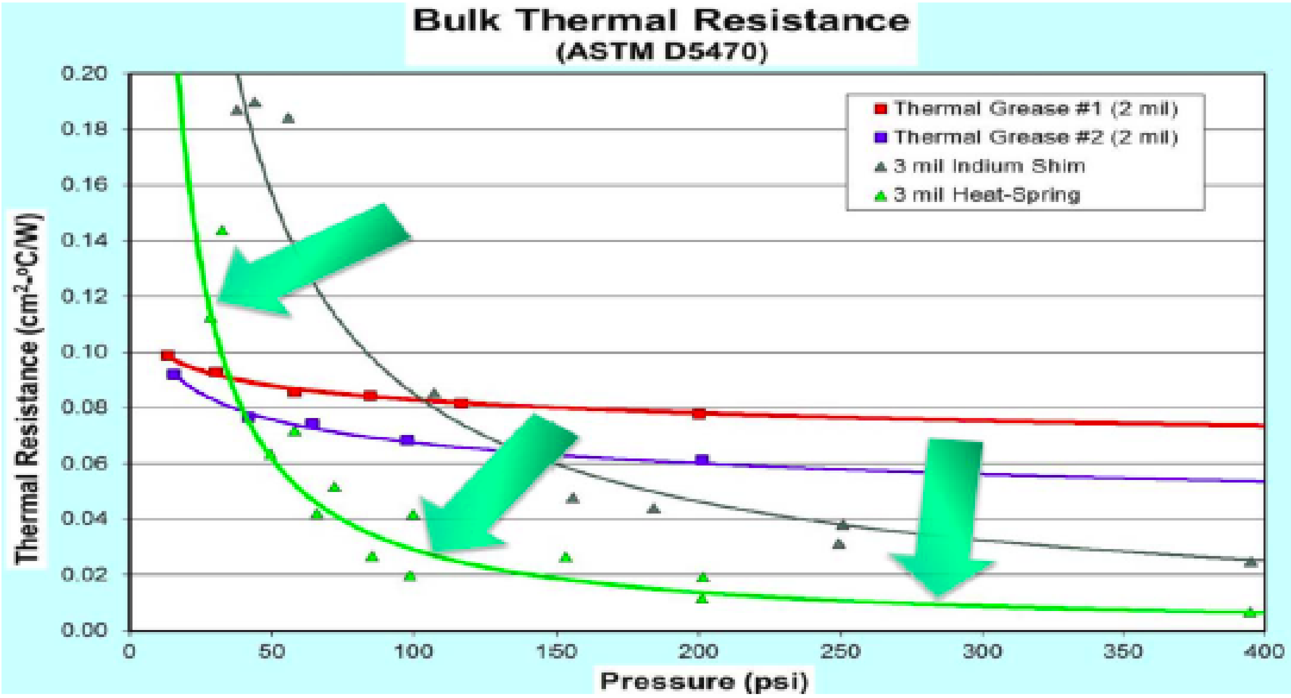

Figure 12. As pressure increases, the thermal resistance of a patterned TIM (here called a Heat-Spring) decreases significantly compared to a metal shim or thermal grease.

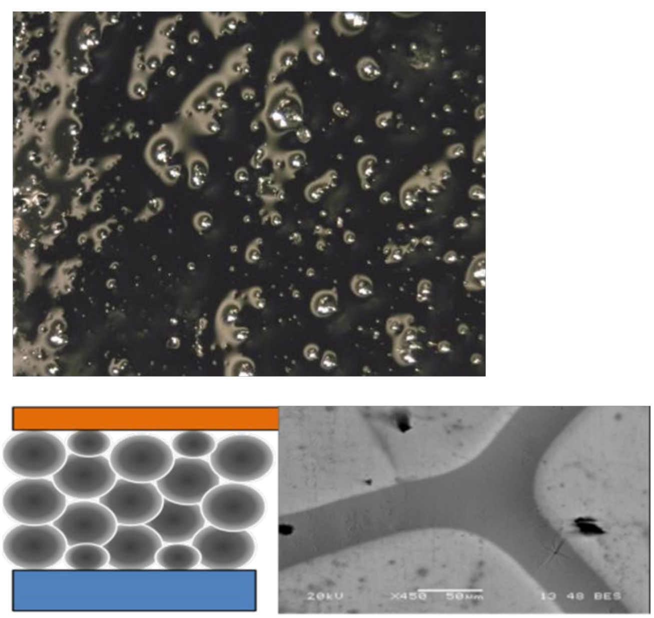

Figure 13. Solid/liquid hybrid TIMs. Top image represents a slurry approach while the bottom images represent an approach where the materials are mixed at the time of use.

LEVERAGING THE POWER OF THE PHASE DIAGRAM

Pure gallium melts at about 30ºC. Adding about 15% atomic weight of indium reduces the melting point to about 15ºC. This melting temperature reduction is the result of the phase diagram. See Figure 14.

The gallium liquid metal flows along the indium grain boundaries as seen in Figures 15 and 16. Note in Figure 15, after only 10 minutes, the gallium has completely flown into the indium metal.

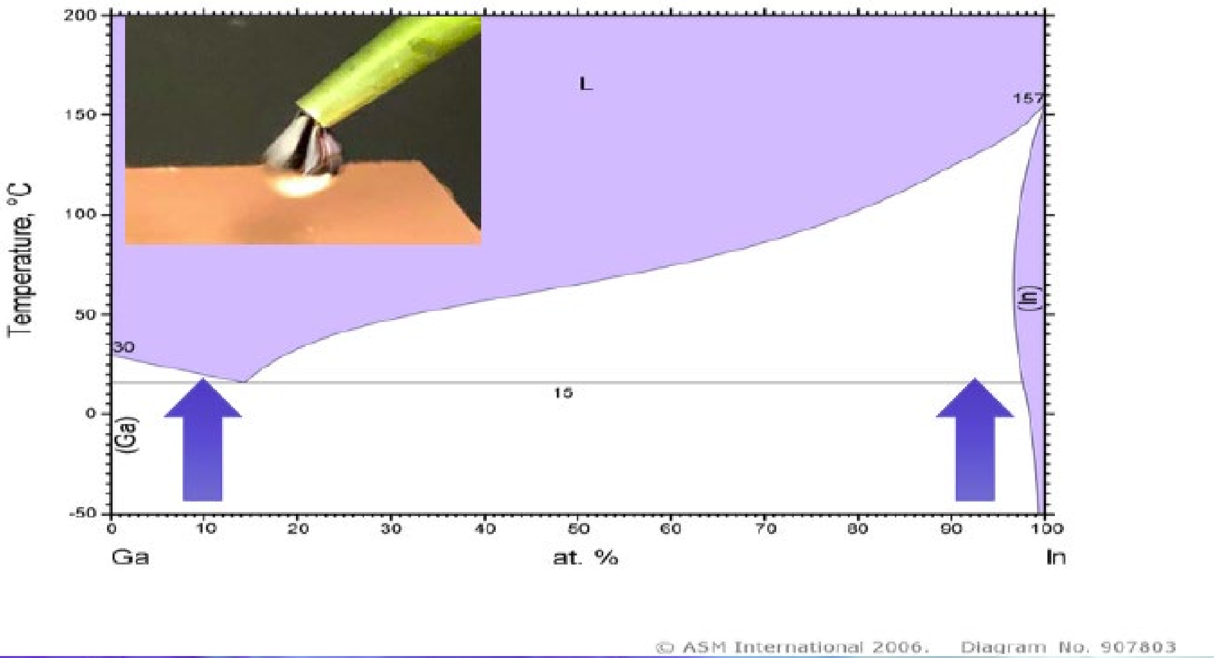

Figure 14[7]**.** A gallium alloy of 15% atomic weight of indium reduces the melting point by about 15°C.

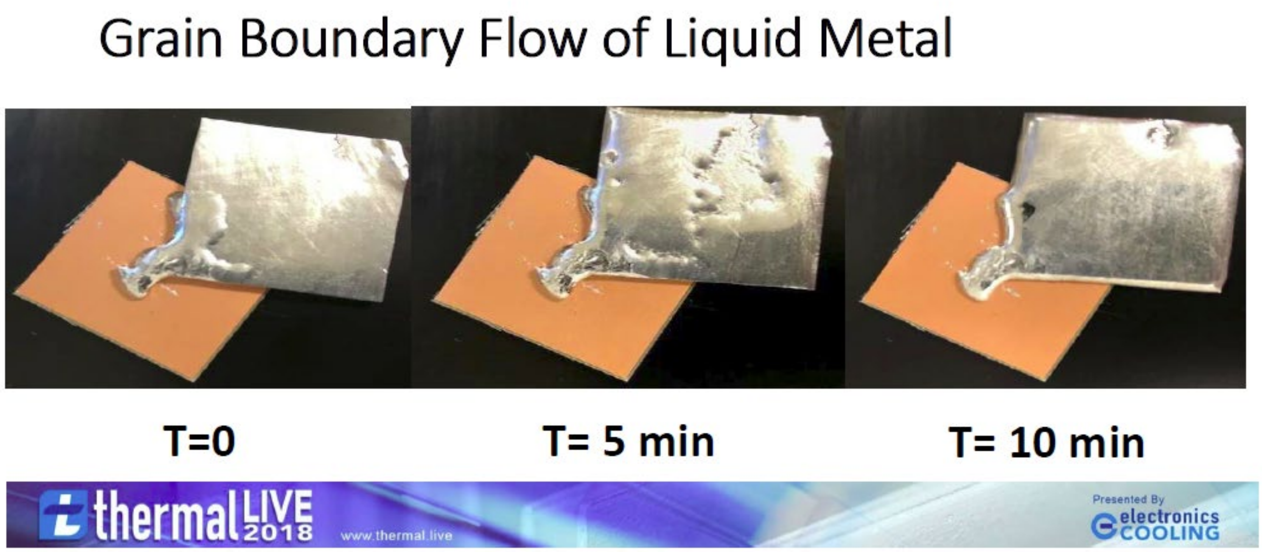

Figure 15[8]Gallium flowing into indium along grain boundaries.

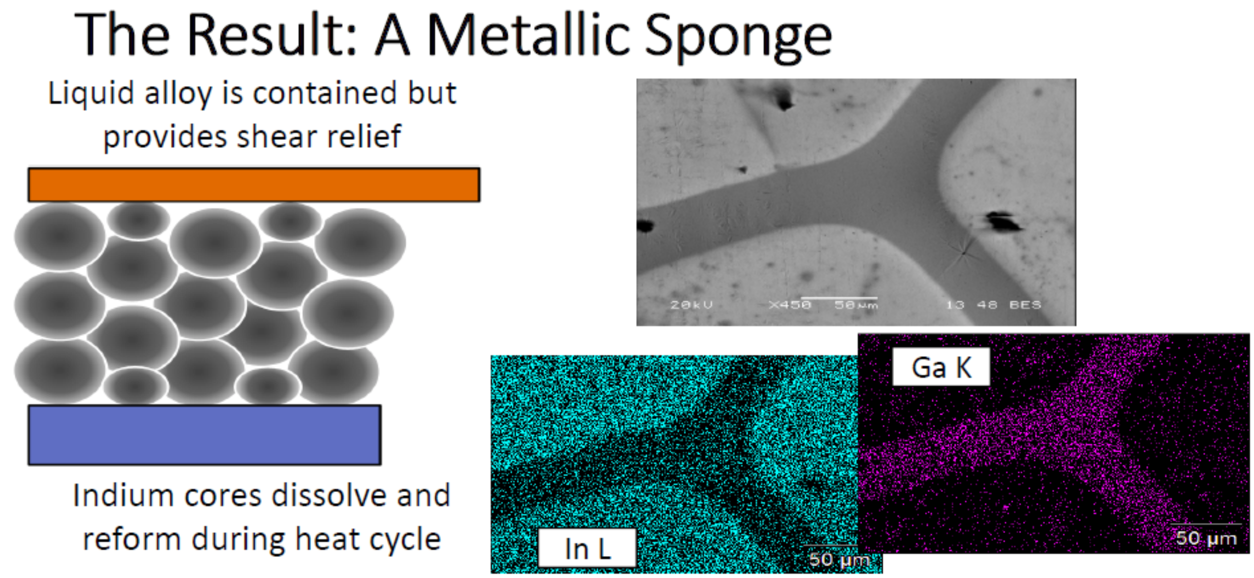

Figure 16. The flow of gallium through indium grain boundaries. This effect is much like that of a metal sponge.

The liquid metal is contained, but it provides shear stress relief. The indium core dissolves and reforms after every heat cycle. Power cycling does not appear to reduce thermal conductivity, even after 20,000 cycles. Moreover, it actually slightly improves over time as seen in Figure 17.

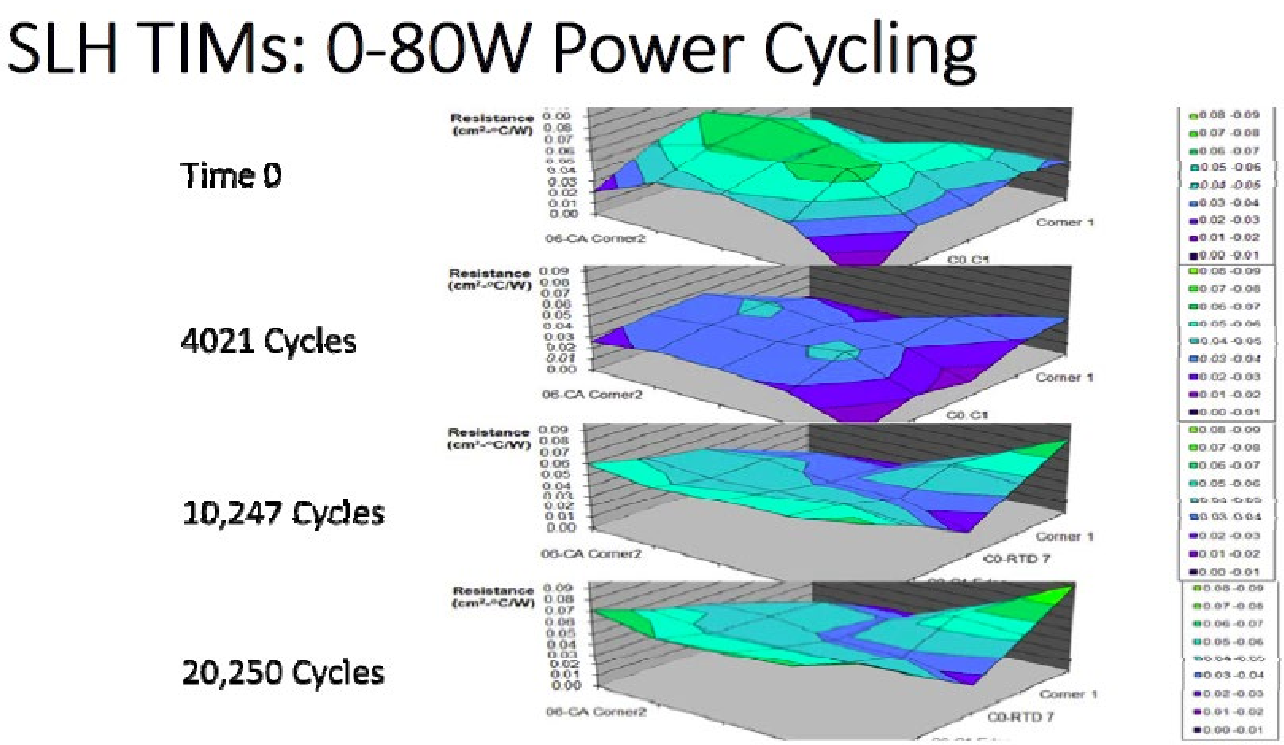

Figure 17. Power cycling does not degrade the thermal performance of SLH TIMs. The thermal conductivity actually improves slightly.

ALLOY COMPATIBILITY CONCERNS

Some metals are not compatible with certain TIM liquid metals; most noteworthy is aluminum's incompatibility with gallium. Aluminum is soluble in gallium. Since gallium is liquid at 30°C, gallium can essentially dissolve aluminum in electronic use conditions. See Figure 18. Anodizing or other surface treatments to the aluminum may alleviate this concern.

Figure 18. [9]Gallium will dissolve (corrode) aluminum. Anodizing the aluminum may alleviate this concern.

CONCLUSIONS

Metal TIMs can enable high heat dissipation and have a long life cycle, as they are not subject to pump-out. Many metal TIMs are available to meet a wide variety of demanding applications. Advancements in metal patterning have improved the effectiveness of metal TIMs by improving their compressibility. In other applications, combining liquid and solid metal TIMs has enabled TIMs to be used on surfaces that were typically not solderable.

Link to workshop:
https://event.on24.com/wcc/r/1812729/D2DA1674572FD20EFAF0E8B193D33A24?partnerref=Indium

RESOURCES

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