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PERFORMANCE MATERIALS

Thermal Management 101:

An Introduction to Thermal Interface Materials

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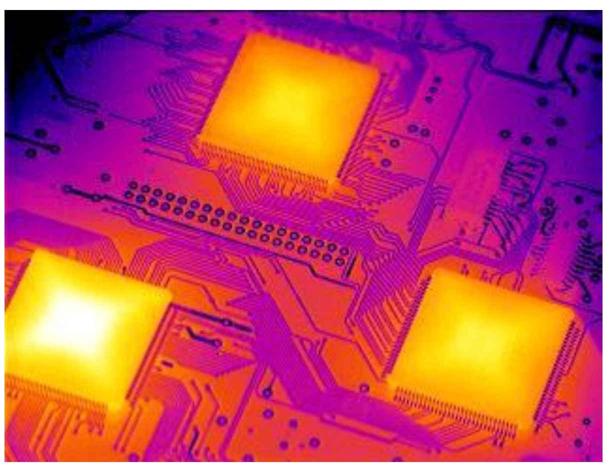
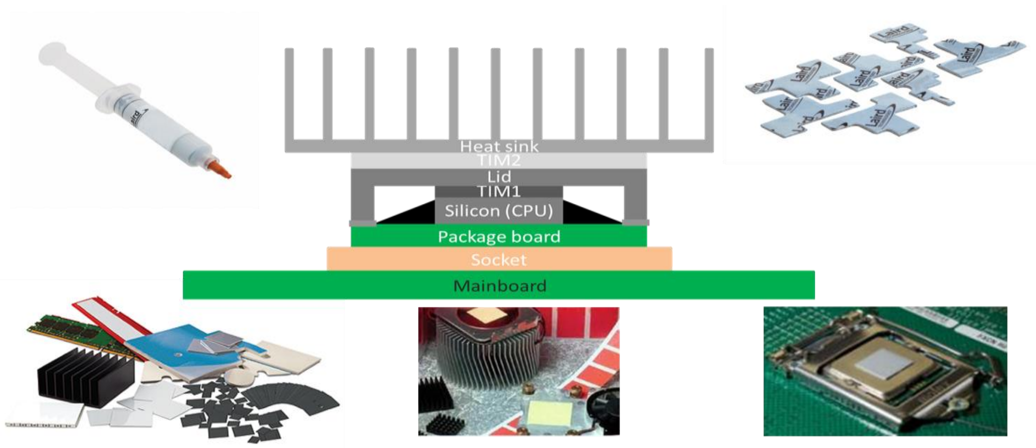


This introduction to thermal interface materials will include a working description, an examination of functions, different types and common test methods used to characterize them. We will also discuss alternative thermal pathways for heat removal that do not use thermal interface materials. Finally, our discussion will focus on a unique alternative solution that is an EMI/thermal hybrid material.

What is a TIM?

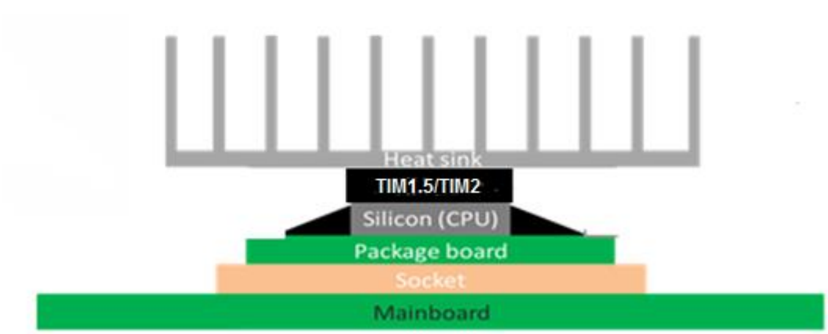
A thermal interface material (TIMs) describes any material that is inserted between two parts in order to enhance the thermal coupling between these two components. A majority of applications are related to the heat dissipation of the system. The TIM is inserted between the heat producing device (the heat source) and the heat dissipation device (heat sink).



(TIM2) is material that is between the heat sink and the lid.

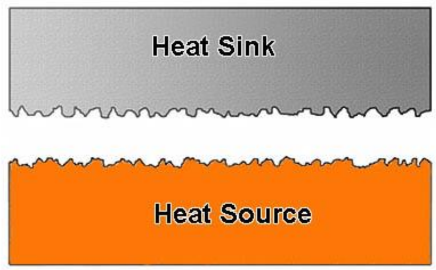
(TIM1) is a material that is between the IC and the lid.

Do note that TIM1.5 is an alternative design where the material sits directly on the bare die and interfaces to the heat sink. This design has no lid present. It is also sometimes referred to a TIM2 since the material still interfaces to the heat sink.

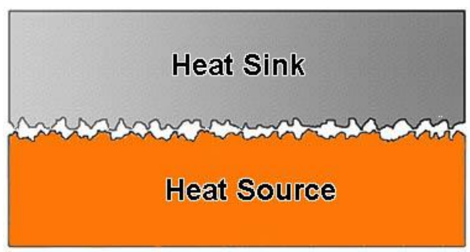


Why do we need TIMs?

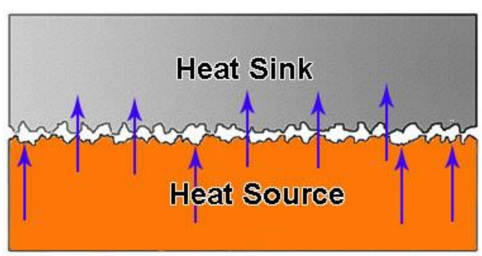
A view of the two surfaces of a heat sink and a heat source shows the rough machined surface. Machined surfaces can lead to few contact points between surfaces of the heat sink and the heat source.



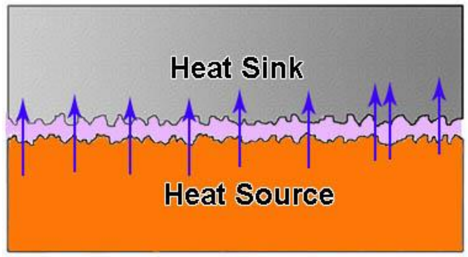
As the two surfaces are brought closer together, the rough surface creates insulating air gaps due to the multiple voids which create contact resistance between the two surfaces. These voids create a thermal barrier for heat transfer.



Envision the flow of heat from the heat source into the heat sync with the air gaps present. Even though the heat sink and heat source have been brought close together, the voids still create a thermal barrier between the two surfaces.



Now envision a thermal interface material between the heat sink and the heat source. A TIM fills the voids and eliminates air by introducing a material that has a higher thermal conductivity than air into the heat path that wets the surface between the heat sink and the heat source.



Even though the heat sink and the heat source are still farther apart from each other (than if they were in physical contact with each other), the heat will transfer more rapidly due to the presence of a material that has higher thermal conductivity than air in the interface. Thus, a TIM helps to minimizes resistance of heat flow into, through and out of an interface.

A few terms to know

Let's explore some technical terms to help understand some of the important properties of TIMs known as gap fillers.

Let's start with this equation:

Total Thermal Resistance (R_{th}) = Resistance $_{material}$(R_m) + Resistance $_{contact}$ ($R_{c1+}R_{c2}$)

The total thermal resistance = resistance of the material + sum of the contact resistance.

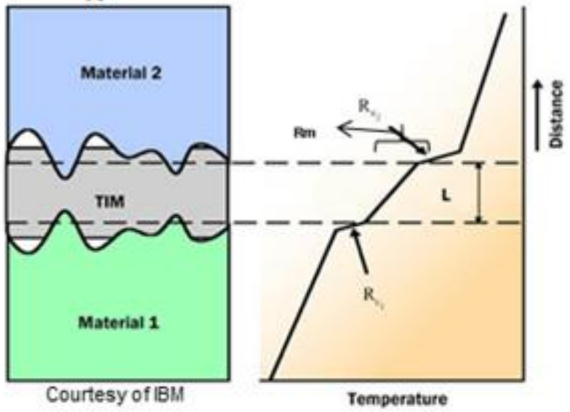
What does that mean?

Total Thermal Resistance - is the measure of how quickly heat passes into, through and out of a material. A low number equals a faster passage of heat. Above all this is the most important value that quantifies heat transfer within your system. This is because it includes all terms that affect the heat transfer within the application.

Some of these terms include the following.

k = Thermal Conductivity (W/mK) L = thickness $R_m = \frac{L}{k}$

$R_{th} = \frac{L}{k} + R_{c1} + R_{c2}$ (Kmm²/W or °Cin²/W)



- Minimize total thermal resistance and to maximize the rate of heat passage:
  - Increase k
  - Decrease L
  - Decrease R_c

Contact Resistance - Not just the measure of the surface of the TIM but also the surface of the application where the TIM is applied. The sum of the contact resistance can represent two similar surfaces or two different surfaces (one smooth one rough) depending on where the material is placed in application.

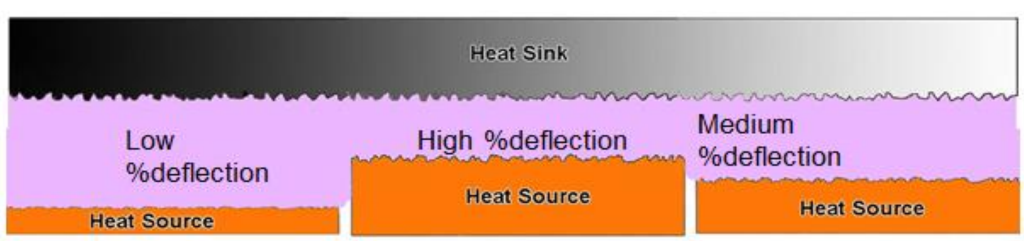
Thermal Conductivity - This is the measure of how quickly heat passes through a material once it is within it. **A high number equals fast passage of heat**

To minimize total thermal resistance, you can increase the thermal conductivity or decrease the contact resistance.

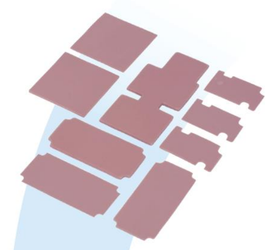
Gap fillers, explained

A gap filler is a class of TIMs that fills “a large gap” between heat-generating and heat-dissipating surfaces.

Often you use one gap filler to cover multiple heat sources within an application. A gap filler material is expected to be compliant enough deflection to multiple thicknesses in application without generating too much pressure within the system.



- Gap fillers are usually silicone based. Why? It is because silicone has so many attractive properties such as surface wetting, high thermal stability, and physical inertness. The silicone is normally used as the binder within a gap filler system.
- The silicone matrix is then filled with thermally conductive fillers - BN, ZnO, or alumina. These fillers make up the functional portion of the gap filler which give it its thermal properties.
- Standard thicknesses of gap fillers tend to be 0.25-5mm (10-200 mils) and most have thermal conductivity ranging from 0.5 to 10 W/mK
- They have deflection of 10 to 70 percent without excessive pressure. Gap fillers need to be relatively compliant to achieve high deflections without generating excess pressure within an application.
- Gap fillers are delivered between release films on a roll, as sheets or in cartridges for automated dispensing



- Gap filler applications
    - Automotive electronic control units (ECUs)
    - Telecommunications, gap filler are often found in control units
    - Microprocessors
    - LED lighting
    - Memory

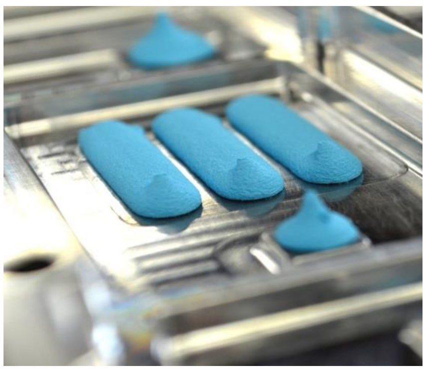
In general, optimal properties of gap filler materials include:

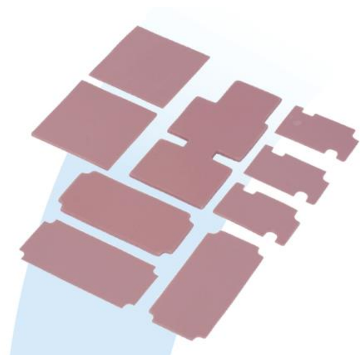
- Low total thermal resistance
- High thermal conductivity
- Low contact resistance (good surface wetting)

If you think back to the equation of the thermal resistance, the two driving terms to a low thermal resistance are a high thermal conductivity and low total contact resistance. Here are typical gap filler properties.

- Easy to use and handle
- Low outgassing/low bleeding. *Excessive out-gassing can cause silicone to condense and build up on optical applications. You don't want silicone migrating into parts of the application.*

- High volume resistivity - Usually you would want no electrically conductive materials within the system, thus delivering to the material a high-volume resistivity.
- Easy to rework. Materials are easy to remove and do not lock the system together after an application or use.
- Unique colors. This is important to help vision systems distinguish between gap filler materials and the substrates to which they are being applied. Colors also are important because they help distinguish between varying materials.





Gap fillers can be in sheeted versions or they can be designed to be dispensable.

Some of the benefits and characteristics of sheeted materials are:

- No equipment is needed for the application. This means no upfront capital costs
- Low modulus, providing for:
    - Low stress during deflection
    - Low steady state stress
- Finishing options to change surface adhesion. *Some gap filler surfaces are naturally tacky. However, this can be controlled on one side of the material depending on the desired finish.*

Some of the benefits and characteristics of dispensable materials are:

- "Multi-application friendly" - *There is the need to purchase one material only, versus multiple thicknesses of the same gap filler sheeted versions.*
- Automated process - Fast application time that can also be helpful to reduce human error
- Highly conformable at low pressures
- Cured in place option for improved reliability
- Low abrasion to prevent wear and tear on equipment

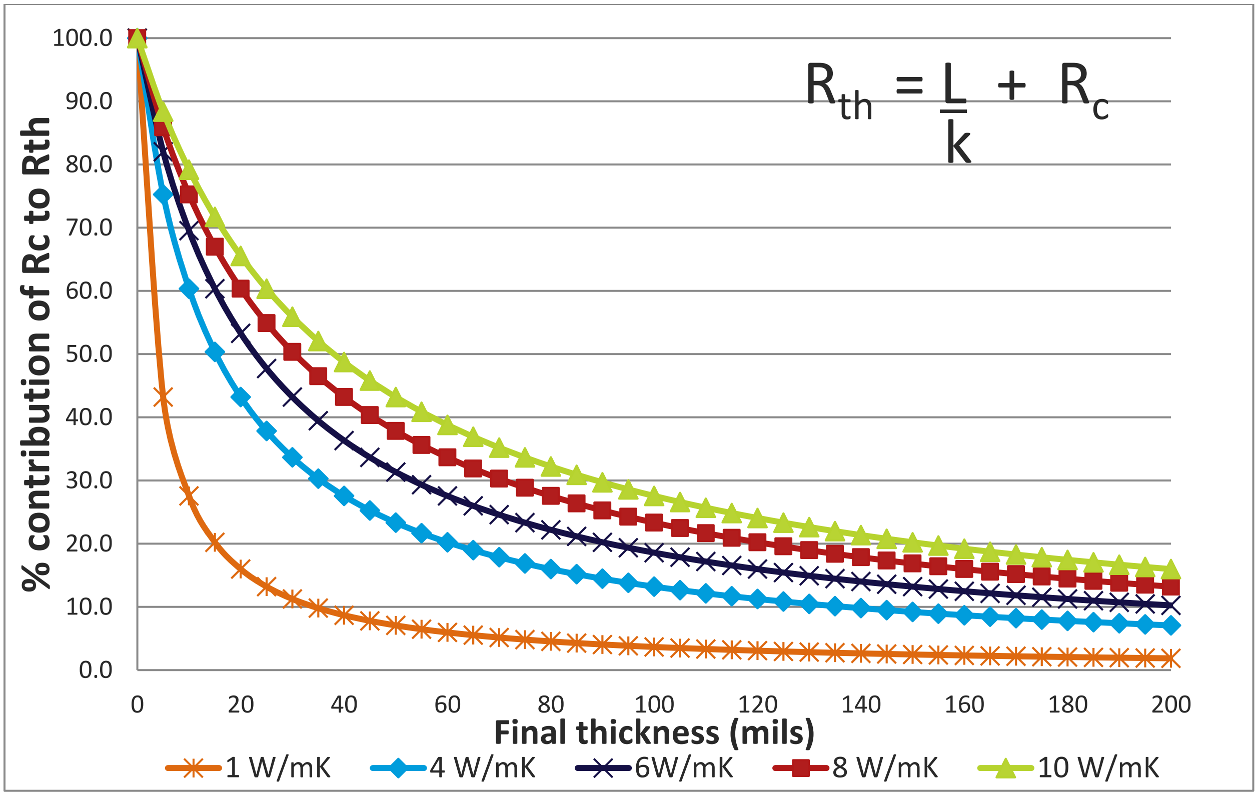
Now that we have discussed gap fillers, let's focus on how to select one with the optimal properties for your application.

Remember from our earlier discussion this equation: **the total thermal resistance = the distance the heat must travel divided by the medium of the heat it travels in + the sum of the contact resistances.**

Your goal in your application is always to achieve the lowest thermal resistance. Often, design engineers will distinctively gravitate towards the highest Tc material.

Yet it is important to understand the roll of contact resistance in determining the overall thermal resistance of the system.

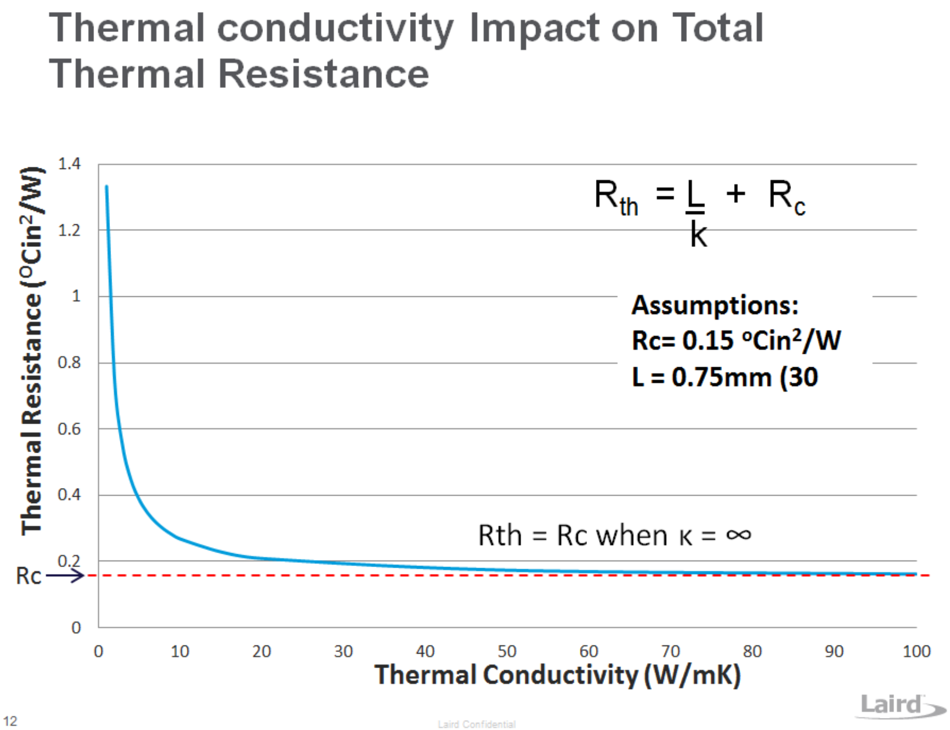
As example, let's demonstrate the relationship between final thickness and thermal conductivity for a specific contact resistance we have chosen. Let's set for example, 0.15 as our specific constant resistance for this demonstration. (The 0.15 is an arbitrary number, selected from experimental data, in the effort to better determine an approximate average of our materials.



The bond line of the application becomes thinner and as the thermal conductivity of the material increases the contribution of the contact resistance to the total thermal resistance increases.

In a theoretical situation, when you keep the thickness constant, as the thermal conductivity increases, the whole term gets smaller and the contact resistance becomes more important. It becomes the driving force within the equation. The result is that the thermal conductivity becomes infinitely high.

This then leads to the two remaining terms: Thermal resistance = contact resistance. With infinity high thermal conductivity, the thermal resistance will always be limited by the contact resistance.



The thermal resistance will always be limited by the contact resistance.

When the thermal conductivity is infinitely high for a given thickness, the plot of the thermal resistance versus the thermal conductivity will asymptote out to the contact resistance.

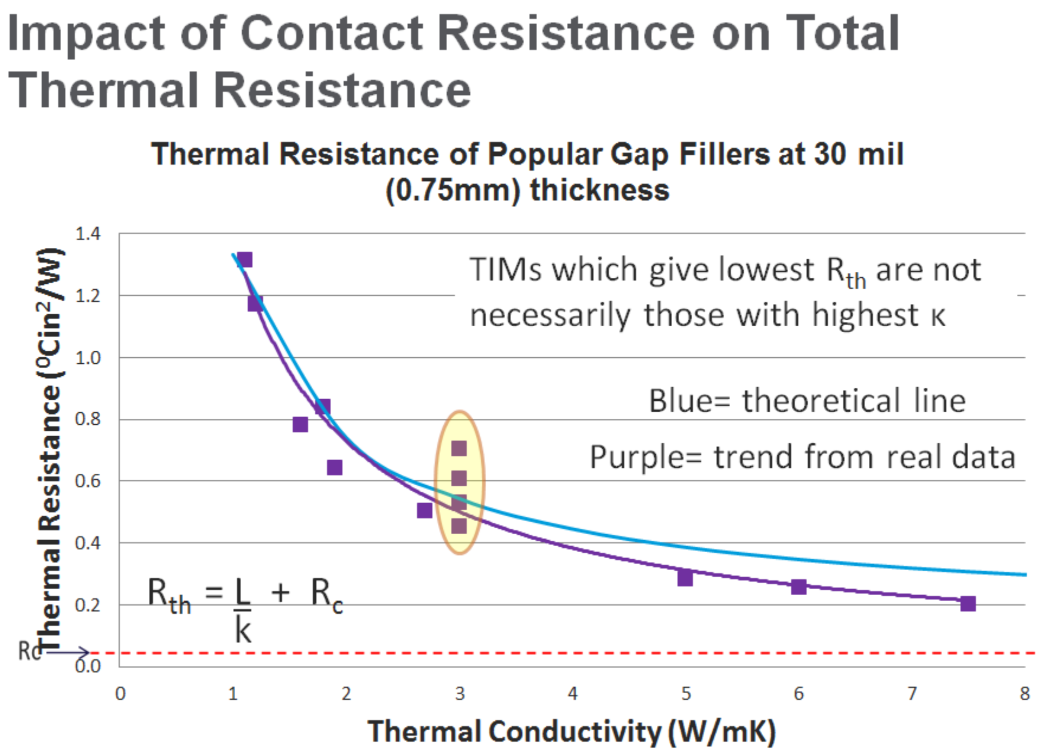
No matter how thermally conductive a material could be, you will never get a thermal resistance lower than the sum of the contact resistances.

Contact resistance is not only the surface of the thermal interface material but also the substrate where the material is used.

And, the TIMs offering the lowest thermal resistance are not necessarily those with the highest thermal conductivity.

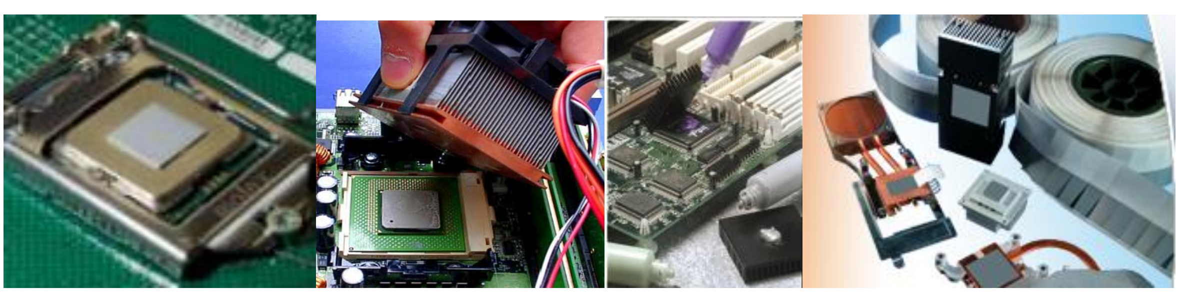
Varying Thermal Resistances

Four different materials all can have four4 different thermal resistances even though they all have the same thermal conductivity at 3.0. The total thermal resistance is completely dependent on the different contact resistances of these materials.



In summary, it is very important to choose gap fillers that provide low contact resistance. In cases of thin bond line or high thermal conductivity, the contact resistance will drive the thermal performance of the material. It is also important to remember that contact resistance will depend on not only the surface softness and wettability of the material but also the smoothness of the surfaces in the application.

Greases, phase change materials



Other types of thermal interface materials include thermally-conductive greases and phase change materials.

These differ from gap fillers. It is because they are generally used in applications with a thin bond line - typically 50 microns or less - where the meeting surfaces are relatively flat. These types of materials do no fill a significant gap within the application. The main function of these grease and phase change material TIMs is to wet the surfaces of the heat source and the heat sink to intimately interface those two surfaces together. Generally these are materials are used under constant applied pressure.

- Greases or phase change materials can be silicone or non-silicone based. The silicone is normally used as the binder within a gap filler system.
- The silicone matrix is filled with thermally-conductive fillers - BN, ZnO, or alumina. These fillers make up the functional portion of the gap filler and furnish it with thermal properties.
    - Filled with thermally conductive fillers - BN, ZnO, alumina
    - Dispensable or screen printable
    - Shear thinning, non-slumping, and non-dripping
    - Thermal conductivity of 0.5 to 7 W/mK
    - Delivered as tabbed parts on rolls, tabbed strips, in bulk cans, syringes or cartridges
    - Greases: Flows and wets surfaces at room temperatures
    - PCM wets surfaces when heated to device operating temperatures

The optimal properties of grease and phase change materials are the following.

Desirable, closely similar properties to gap filler materials. They include:

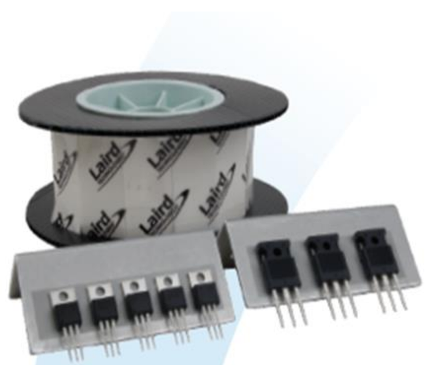
- Low total thermal resistance
    - High thermal conductivity
    - Low contact resistance (good surface wetting)
- Low outgassing/low bleeding

- High-volume resistivity
- East to apply
  - Naturally tacky tabbed parts
  - Screen print and dispense
- Easy to rework
- Resistant to pump out
- Long-term reliability
- Soften and flow at or below operating temperature of device (pcm)

Some common applications for these materials are

- Notebook and desktop computers: CPU, GPU, APU, memory
- Miscellaneous electronic devices that generate heat
  - Arcade games, game consoles, power supplies, LEDs, braking systems, set top boxes

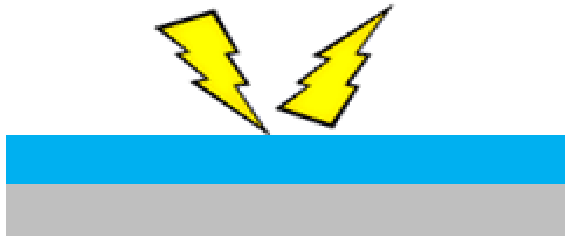
Thermally Conductive Electrical Insulators



This class of TIMs provides high electrical isolation while maintaining thermal transfer.

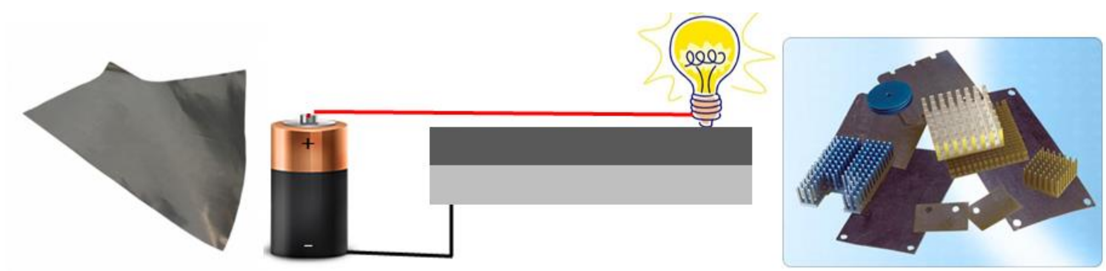
There are two main types of thermally conductive electrical insulators: one is Si-based and the other is epoxy based.

These types of materials provide high thermal transfer with high electrical isolation



- Typically silicone based material
- Can be coated on insulating plastic films or fiberglass
- Epoxy based adhesive materials
    - Require cure
- Applications
- TO-220/240
- Amplifier components
- Anywhere both heat transfer and high electrical isolation are needed

Electrically and Thermally Conductive Materials



These materials provide thermal transfer with high electrical conductivity to either ground, or, act as an electrical conduit.

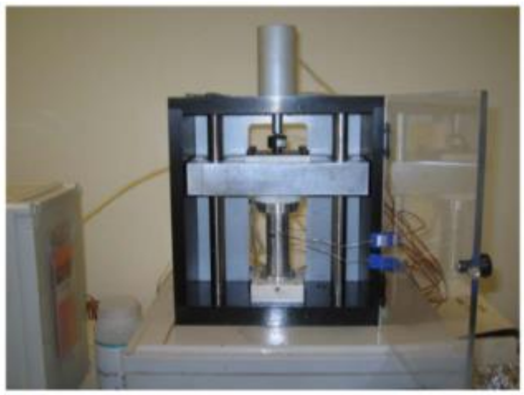
These can be flexible graphite sheets or electrically conductive elastomers and adhesives.

Another class of this material includes electrically-conductive adhesives that are typically filled with silver.

Testing TIM properties

How are tests conducted to determine the thermal properties of TIMS?

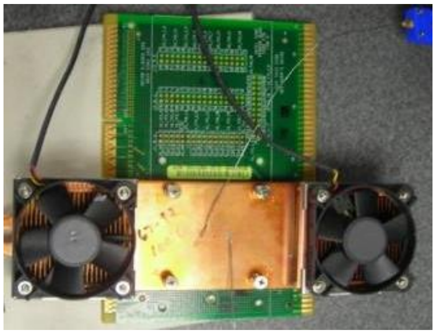
Some measure the physical properties of the material, such as thermal resistance and thermal conductivity. Other tests can simulate a TIMs' "in-application" use.



ASTM D5470 is the primary measurement for TIMs. It is a direct measurement of the thermal resistance. Thermal resistance, as discussed previously, is a very important property of a TIM which measures the quantification of the passage of heat into, though, and out of the material. This method can also be used to determine thermal conductivity. This method is the primary quality control technique applied within testing labs of Laird Performance Materials.

Another method of measuring thermal conductivity is the "Hot Disk." This technique assesses thermal conductivity by measuring the passage of heat once it is within the material.

Alternative in-application TIM testing

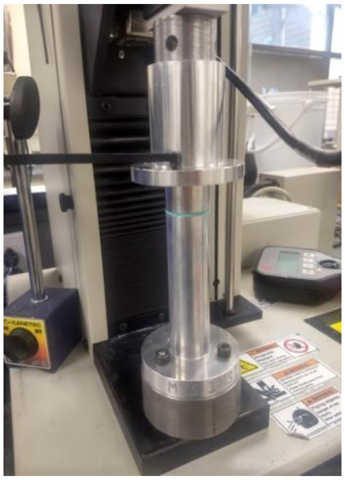


Alternative testing can be used to simulated in-application use of TIMs. One is PC simulator testing. A second is a thermal test vehicle.

A third is video card testing. These methods are very similar to real word applications and can simulate real in- application issues such as the flexing of boards due to heat exposure and different thermal expansions of the materials.

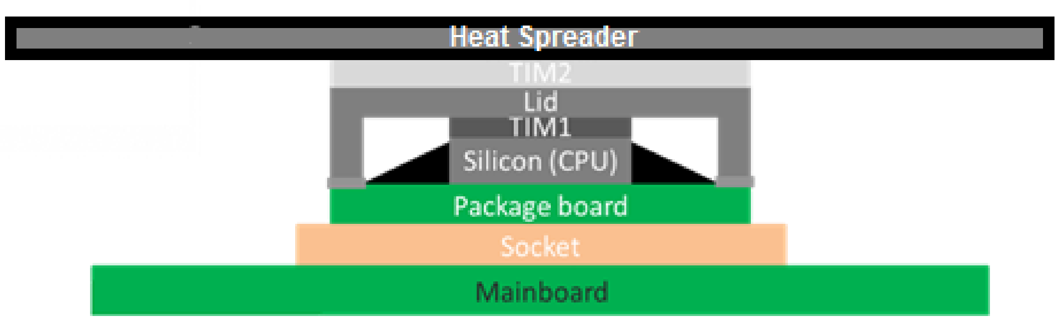
A discussion about deflection

Examining deflection for a moment, all agree gap fillers need to be compliant and conformable. Here are some attributes of the better examples.



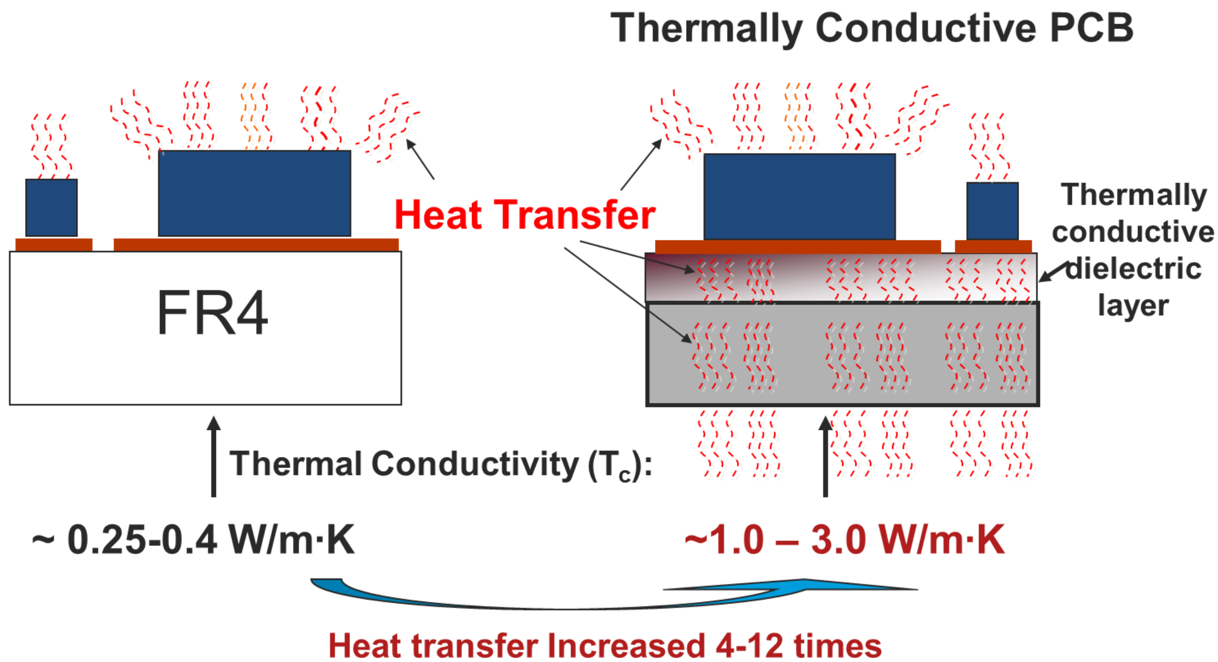
- Low molecular weight extractables
    - Bleed - extractable due to pressure
    - ASTM E595 - outgassing test - 125^{0}C in vacuum for 24 hours
        - Total mass loss
        - Collected volatile-condensed matter - 25^{0}C collector plate
    - D4-D10 content (silicone only)
        - Measured low-molecular weight silicone that may volatize and coat surfaces in other places such as optical drives. There could be added health risks.
- Bond line thickness
    - Measured between disks. This testing can be completed to examine the bond line at various temperatures or pressures
- Viscosity
    - This testing examines viscosity at various temperatures or shear rates
- Melt point via DC. This is very important to PCM materials.
- Thermal stability using TGA – This is important to help determine a materials' reliability over time.
- Density – Helium pycnometer
- Peel Test – Liner from material. This tests how the material will peel from its liner. Is it easy to remove before use?
- UL 94V0 Flammability Testing

Removing heat: still more alternatives



Switching gears, let's examine alternative thermal pathways for heat removal. When using a regular TIM, the heat is removed from the application directly out of the top through the IC. Following is a discussion on a few ways to remove the heat in different pathways from the application.

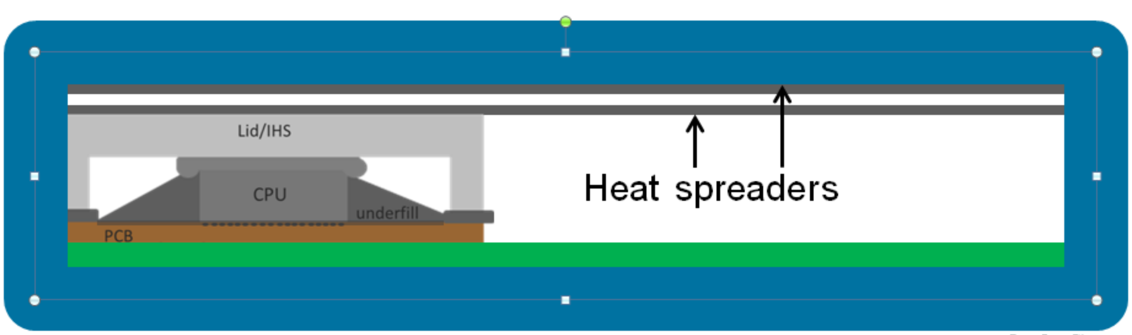
Thermally Conductive Printed Circuit Board Materials

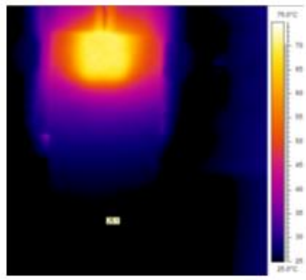


When a material application has a thermal conductivity of only 0.25-0.4 w/mk, the application allows heat to escape the application *only* through the top of the assembly.

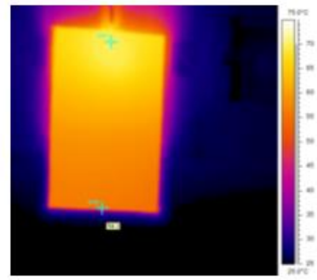
With a thermally-conductive PCB possessing a thermal conductivity of 1-3 w/mk, the heat can be removed from the system on both the top and the bottom of the assembly. This use of the PCB increases the rate of heat transfer four to 12 times.

Heat Spreading





Poor heat spreader



High performance heat spreader

Another concept for alternative heat removal is the uses of heat spreading. A heat spreader is attached to the top of the lid in an application. This allows for a more even distribution of heat within the system.

A hybrid solution – and space saver

The final heat transfer concept – due principally to the ever-increasing miniaturization of electronics cramped for space and the transition toward 5G – is a hybrid solution. Noise from the IC can create unwanted signal paths and reradiate from other components such as heat sink. They act like an antenna. Energy can be transferred to other unwanted locations and cause a plethora of challenging EMI/EMC issues as well. One hybrid/thermal solution is a thermal hybrid material that sports dual-functionality.

This helps protect sensitive electronics while enabling more compact designs. These unique materials (known as CoolZorb) are silicone-based and simultaneously protect electronics from both EMI and heat. These types of materials have the same characteristics (high thermal conductivity, conformable) as gap fillers, yet also have additional components within the system to provide some characteristics of an absorber material. Combined, a hybrid/thermal also provides an EMI radiation barrier by absorbing electromagnetic energy.

Summary

Our discussion about TIMs has included the main types and functions of each material and a look at the importance of thermal resistance and its relationship to contact resistance, thermal conductivity, and bond line thickness.

Advancements in the material sciences are certain to lead to still more exciting solutions in the years and decades ahead during the march toward 5G.

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