Fundamentals of Heat Transfer in Thermal Interface Gap Filler Materials

Introduction

This paper focuses on the primary function of a thermal gap filler – its ability to transfer heat from one surface to another. The selection process for a gap filler can sometimes be confusing because most thermal considerations are left to the end of the design cycle when the selection process must be performed under a tight schedule. This paper will describe steps to making the selection process simpler.

- R_{jc} = Thermal resistance from the die to the top of the package
- R_{TIM} = Thermal resistance of the thermal gap filler
- R_{HS} = Thermal resistance for the heat sink

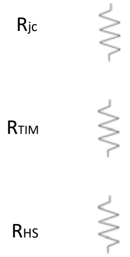


Figure 2. In a basic thermal solution in electronic assembly, the most common thermal resistances are the case of the component, the thermal gap filler (TIM), and the heat sink.

Terms and Units

Prior to beginning a discussion on heat transfer in thermal interface gap filler materials, a number of terms and units require definition. The most common term is thermal resistance. This is the reciprocal of conductivity that includes contact resistance. It is not just thermal resistance of the bulk material, but also contact resistance between the hot and cold sides.

Thermal gap fillers are a particular type of thermal interface material (TIM) used to fill in gaps between cold and hot surfaces. Unlike greases or phase change materials that only reduce contact resistance between two surfaces in numeric contact, gap fillers act as a thermal heat transfer medium between two separated surfaces; for example, a cold plate that is a millimeter away from a voltage regulator, or a processor that might be two millimeters away from a large heat sink. These intentional gaps are designed in and actually have tolerances.

A common unit is Watts/mK, which indicates heat flow required through a given thickness and area, and the resulting temperature gradient. Temperatures are always gradients and not absolute. This applies to other units such as thermal resistance, whether in °C^2/Watt or °C/Watt. These are just temperature gradients per power; the absolute temperature is more a function of the ambient. Watts/mK do not include contact resistance when discussing TIMs. Just like ASTM 5470, for example, the delta of the thermal resistance and the change in thickness are used to calculate conductivity. Thermal resistance or thermal impedance is shown in values of °C^2/Watt or as °C/Watt if the geometry is called out explicitly.

Common methods of analyzing a thermal solutions is through a resistive network analysis

Thermal conductivity $k = \left(\frac{q}{A}\right)\left(\frac{\Delta z}{\Delta T}\right) \quad \frac{W \cdot m}{m^2 \cdot K} = \frac{W}{m \cdot K}$

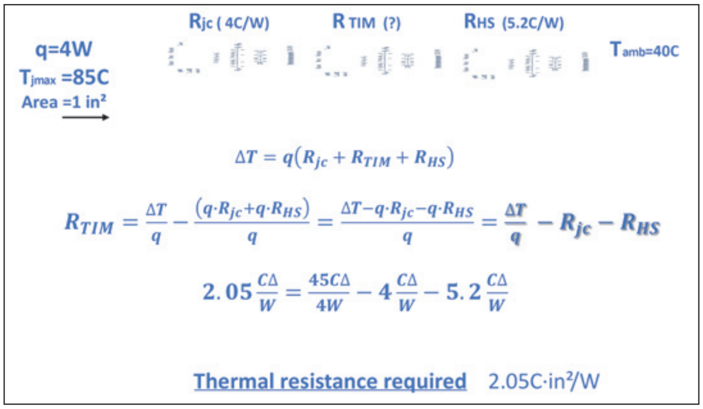
Thermal resistance* $\frac{1}{k} = \left(\frac{A}{q}\right)\left(\frac{\Delta T}{\Delta z}\right) \quad \frac{m^2 \cdot K}{W \cdot m} = \frac{m \cdot K}{W}$

(Thermal Resistivity)

Figure 1. A common method of analyzing a thermal solution is through a resistive network analysis.

Power dissipation is presented in joules per second, and heat flux is the amount of heat per specific area. Heat conduction per mass can be expressed using Fourier's Law. Since thermal gap fillers are used for thermal conduction — not radiation or convection — it's appropriate to apply Fourier's Law of Conduction, which is based on observation and requires some assumptions. First, there is steady-state heat conduction. When looking at thermal gap fillers, transient response of the material is of little concern since the mass is relatively small and steady state is reached fairly quickly. Temperature goes down as you move away from the heat flow. Another assumption is that the heat source surface is an isothermal surface.

Another term is homogenous. A thermal interface material, especially a thermal gap filler, is actually not homogenous. It's made up of fillers of different sizes and different thermal conductivity. These particles are suspended in a binder that is a silicone; we can assume it's homogenous when it comes to analyzing a thermal gap filler in a thermal solution for an electronic assembly.



$$\Delta T = q\left(R_{jc} + R_{TIM} + R_{HS}\right)$$

$$R_{TIM} = \frac{\Delta T}{q} - \frac{\left(q \cdot R_{jc} + q \cdot R_{HS}\right)}{q} = \frac{\Delta T - q \cdot R_{jc} - q \cdot R_{HS}}{q} = \frac{\Delta T}{q} - R_{jc} - R_{HS}$$

$$2.05\frac{C\Delta}{W} = \frac{45C\Delta}{4W} - 4\frac{C\Delta}{W} - 5.2\frac{C\Delta}{W}$$

Thermal resistance required 2.05C·in²/W

Figure 3. A simple resistive network.

Finally, we assume that the material is not reacting to heat or increasing in temperature, either by latent heat or chemical reaction that would cause an endo- and exothermic reaction.

Resistive Network Analysis

With Fourier's Law, we can pick any point and get heat flux through that point. The direction of heat flow is a vector for a given temperature field. We can take fairly complex shapes and temperature functions and determine how many Watts/m^2 and the direction heat is traveling. We can assume heat flows in the direction of the temperature gradient, since two points that are the same temperature will not have heat flowing between them.

In the case of a TIM, we're not working with temperature for the gradient in all directions; in fact, we're doing one-dimensional steady-state heat transfer. We can eliminate other factors, such as the heat flow in the X and Y direction and focus on the heat flow through the gap filler itself. Since we're only concerned about heat flow in the Z axis of the gap, the only concern is the relationship among heat flux, thermal conductivity of the material, and the temperature gradient in one direction. This is what's used to solve a resistive network, and it's basically a rearrangement of thermal conductivity. When looking for an appropriate thermal gap filler, look for the conductivity or resistance needed to satisfy a condition; basically, a temperature gradient.

Probably the most common way to start any type of thermal analysis is by creating a resistive network that represents the actual components that make up the thermal solution. A resistive network allows you to visualize the different heat paths to ambient and quantify them so you can calculate temperature gradients and eventually actual temperatures. Start by converting thermal conductivities to thermal resistances. Figure 1 shows an asterisk next to thermal resistance. This is because the term is sometimes referred to as thermal resistivity if it includes the unit of area and thickness, and in some cases, you see it as K/Watt or °C/Watt.

To build a resistive network, simplify the resistances to a temperature gradient per unit power, K/Watt or °C/Watt. This is done with the ratio of the gap filler pad, meters to millimeters squared — the ratio to thickness and surface area. That is multiplied by thermal resistance for every component in the heat path to ambient. Most thermal interface materials will have thermal resistance data, so use median values and not the conductivity.

In this analysis, surface areas are fixed and the thickness of the material will be another variable. Being able to pick different material thicknesses will help from a mechanical standpoint. In a basic thermal solution in electronic assembly (Figure 2), the most common thermal resistances are the case of the component, the TIM, and the heat sink. In this analysis, we use an aluminum thin heat sink that's the same surface area as the gap filler pad. It is 25 x 25 mm with a 30-millimeter height.

A resistive network is a series of resistances, each typically a component of the thermal solution. Resistances can be in parallel if there is some other path to heat flow. You can apply resistances for heat flow through the PCB or through some other medium. This analysis involves a three-resistance network. The sum of all three will provide an overall thermal resistance for the system; you can also determine temperature gradients for a specific component within the system. Typically, each component has a thermal resistance and should be a homogenous K value. Each resistance is joined by a node indicating points where temperature and/or temperature gradient is measured.

In Fourier's Law, we simplified the equation for heat transfer in one dimension only and rearranged it to solve for conductivity for a temperature gradient and a given heat flux. This can be converted to thermal resistances independent of surface area and thickness. Not locking in a thickness allows us to pick varying thickness for flexibility on the mechanical side, specifically when it comes to stress created by the gap filler under compression. A material that is too thick will create too much stress; if it's too thin, it will not make good contact. We can say that heat flow is equal to the temperature gradient over the total resistance of the thermal solution, or we can solve for temperature gradient for a specific power and resistance. In this case, the total resistance is not known, since we still need to know the resistance of the gap filler.

Sample Resistive Network

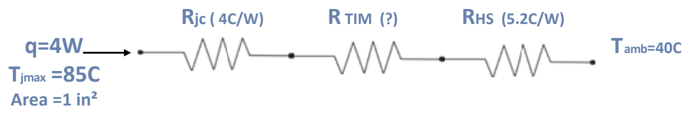
A simple resistive network is shown in Figure 3. We have a component that will run at one Watt, but in some cases, it may run as hot as five Watts long enough to reach steady state. First, we want to understand the environment, and that's the ambient temperature (40 °C). The ambient can run much hotter, depending on location.

Next, what is the max temperature for the junction? This varies with the type of component. In this example, the product will be out in the field for a long time. This part of the unit won't be serviced, so we can be conservative and keep the junction temperature about 85 °C. Taking these two temperatures, we need a thermal solution that will ensure a temperature gradient junction to ambient of no more than 45 °C.

To build the network, we use the three resistances to create a basic model of the thermal solution, starting with R_{jc}, which is the resistance junction to case. This is very different from R_{ja} or R_{ca}, which are resistances to ambient. We need to know the resistance from the junction to the top of the case with the gap filler because we're using conduction and want to focus just on the thermal resistance of the case, not how well it gets heat out to ambient.

Next to thermal resistance is the gap filler (RTIM) and thermal resistance for the heat sink (RHS). The resistance value is in units of °C/Watt. We're assuming even heat flow through the component, through the TIM, and up to the heat sink with the same cross-section area. Previously, we started with Fourier's Law and simplified it to one-dimensional heat transfer. With this, we can calculate power density, connectivity, and temperature gradient. But we want to know what the thermal resistance is just for the gap filler. What resistance will give us the temperature gradient for a given power?

Let's plug in the resistance of the heat sink and the junction to case, as well as the power and total temperature gradient to calculate the missing resistance, which is the thermal resistance of the gap filler pad. This is the maximum thermal resistance. If we go with the lower resistance, we get a lower temperature gradient. It would perform better, but with higher performance comes higher cost. Figure 4 shows that the TIM — to satisfy the requirement of 4-Watt power density or 4-Watt to a 1" square surface area with a max junction tip at 85 °C and a max ambient at 40 °C – would require thermal resistance of 2.05 °C·in²/Watt.



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$$2.05\text{C/W} = \frac{45C\Delta-(4W\cdot 4\,\frac{C}{W}+4W\cdot 5.2\,\frac{C}{W})}{4W}$$

MAX Thermal resistance required 2.05C·in²/W

Figure 4. In this case, the TIM would require thermal resistance of 2.05°C·in²/Watt.

The next step is choosing the material, generally starting with a catalog or data sheet. There are many different thermal resistances for a specific material grade, but also different thickness of materials. There are varying thermal resistances as you change thickness, but there is also variance in thermal resistance as the material is compressed. If we fine-tune the gap, we can select a thicker material to ensure against stress in components. Thicker pads tend to be more compliant than thinner. At a certain point, compression is acceptable, but at lower compression, the resistance climbs well above the maximum. If you are on the lower side of compression due to tolerance stackups, there's a possibility you'll have a thermal resistance higher than what's calculated.

Real-World Applications

The preceding example made assumptions about the thermal solution; specifically, the gap filler. In a real-world application, there are certain factors that will impact the actual temperature gradient and what you calculate versus what actually happens. Assuming heat flux is even

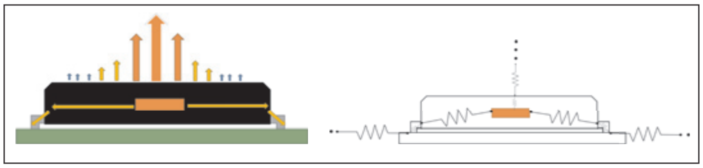

Figure 5. In real-world applications, not all the heat is going to go through the gap filler material up to the heat sink.

over the entire surface of the component is a big factor; if you assume 4 Watts over an inch square but the heat flux is much smaller, you end up with a hot spot and a higher junction temperature.

The assumption may be that all the heat flow is actually going through the gap filler and through the heat sink out to ambient. These are the key paths that will allow some heat to flow out, keeping junction temperature down. Also, the more the materials are compressed, the better the thermal resistance. Part of that is improving contact resistance; by compressing it more, you're reducing that gap and there is less of a medium for the heat to transfer through, resulting in a better thermal resistance.

One assumption made was that the heat flux is even over the entire surface area of the component, and you have the same heat flux as you go through the gap filler and up through the heat sink base. In the previous example, the max thermal resistance of the gap filler was calculated based on 1" square, but the area may be a fraction of that.

In the example, the component was treated as one heat source, but the die in the package is the heat source and is typically much smaller than the actual package. This means you end up with a hot spot and a lot more power per area than first thought, so it's difficult to say exactly what the ratio is of die to package. All the heat is not going to travel through the entire surface area on top of that package, so it's a good idea to add some margin to your max data, or calculate it based on half the surface area. If you're working with a bare die where the heat source is exposed, you won't have to deal with this issue.

Also, not all the heat is going to go through the gap filler material up to the heat sink (Figure 5). The package is soldered to a PCB; metal leads and ground planes as well as other PCB traces make very good thermal vias and help dissipate some of the heat. There are other ways to pull the heat out through the traces. Very tight heat flux on the package can be compensated by other heat transfer mediums.

Compression also affects thermal resistance. Creating more compression is definitely going to reduce thermal resistance. If there's a possibility the gap will be larger due to tolerances, always check the thermal resistance for that compression.

Tools and Resources

There are many tools that will help you understand the overall thermal solution. The most common are CAD software simulations. They can be fairly costly but they provide a detailed understanding of the heat flow, temperatures, and temperature gradients. Some software specializes in electronic assemblies; otherwise, you have to physically create the component, which can be very time-consuming.

Thermocouple loggers and dataloggers are fundamental tools when working in any type of thermal condition. Many of these loggers have multiple channels to monitor packages, PCBs, and heat sinks, and can create a heat map and temperature gradients. Thermal cameras also are helpful in monitoring different temperatures. They offer more flexibility than a thermocouple. Instead of looking at discrete points, you can look at the entire layout. When a die is much smaller than the package and it creates a hot spot, a thermal imaging camera can determine where those hot spots are.

Of course, one of the best tools is online educational resources. With the Internet, there are many places with resources — not only vendors but also universities and magazines. These resources help you learn as you find all the little mistakes that can happen.

Author

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Visit https://www.fujipoly.com/usa for more information.