3M

Technical Bulletin

Characteristics of Thermal Interface Materials

January, 2001

General:

The purpose of this publication is to define and clarify the technical terminology commonly associated with thermal interface materials, in particular 3M's family of conductive adhesive tapes and interface pads. It is intended to elucidate the relationships between several well-known indicators of thermal performance (thermal conductivity, thermal resistance, thermal impedance, thermal interface resistance) and to alert the user to the danger of narrowly focusing on thermal conductivity as the only critical property relating to thermal management. Its aim is to enable a meaningful discussion of the product characteristics that govern the real-life performance of thermal interface materials.

This document should be used in conjunction with other 3M publications, including the data pages for the particular thermal interface material and "Heat Flow Calculation for 3M Thermally Conductive Adhesive Transfer Tapes."

Thermal Interface Materials

Thermal interface materials are those which are useful for establishing an effective thermal path between a heat-generating component (e.g., a transistor) and a heat-sink attached to it (see Figure 1).

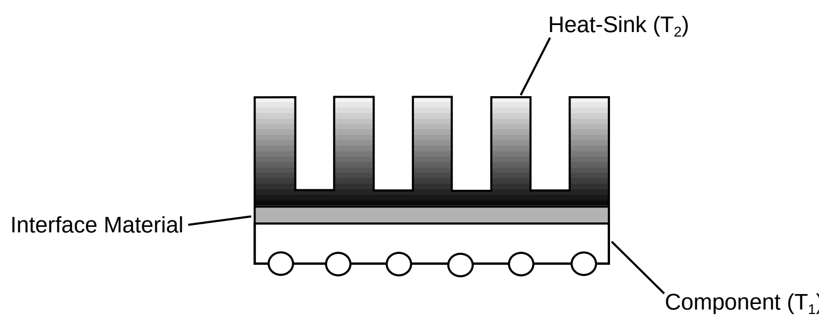

Figure 1: Typical thermal interface application: providing a thermal path between a hot component and a heat sink.

There are a large variety of thermal interface materials; thermal greases, phase change materials, thermal tapes and gap filling thermal pads. Many interface materials are comprised of a base material (grease or polymer) with added fillers (typically ceramic particles) to increase the thermal conductivity relative to the base material.

Thermal Conductivity

For the case of one-dimensional heat-flow (which is assumed to prevail for the purposes of this document), thermal conductivity (k) is defined as follows (Fourier's Law:)

EQUATION 1:

$$k = \frac{q \cdot t}{A \cdot \Delta T}$$

where: q = heat flow (or power) in Watts
t = length of heat path (i.e., interface thickness) in meters
A = area in meters
ΔT = temperature difference across the interface, in degree C

(Thermal conductivity is often expressed in reduced units of W/mK or "Watts per meter-Kelvin")

It is important to remember that thermal conductivity is a material (i.e., "bulk" or "intrinsic") property and does not depend on the geometry of the test assembly. It simply describes the ability of a given material to transfer heat through internal heat conduction. Most critically, it does not account for any interfacial effects that may impede heat-flow, often to a significant degree.

Thermal Resistance and Thermal Impedance

Thermal resistance (R) is an empirical property derived from the often-used (though sometimes misleading) analogy between electrical and thermal conduction:

EQUATION 2:

$$R = \frac{T_1 - T_2}{q} = \frac{\Delta T}{q}$$

where: T_1 =component temperature
T_2 = heat-sink temperature

(Thermal resistance is commonly expressed in units of °C/W or "degree-C per Watt")

Thermal impedance (Z) is defined as the temperature gradient per unit of heat flux, (q / A), passing through the interface. It is calculated by simply multiplying thermal resistance by the component area:

EQUATION 3:

$$Z = \frac{\Delta T}{\left(\frac{q}{A}\right)} = R \cdot A$$

(Thermal impedance is expressed in units of °C-in^2/W – "degree-C inch squared per Watt" or °C-cm^2/W – "degree-C centimeter squared per Watt")

Thermal resistance and thermal impedance are <u>not</u> material properties and should be determined individually for each component/heat-sink configuration. In contrast to thermal conductivity, impedance and resistance reflect the geometry of the assembly, i.e., the size of the component area ("footprint") and the thickness of the interface material. In addition, they account for any effects that impact on the ability of the material to transfer heat between the component and the heat sink (interface resistance). Therefore, thermal resistance or impedance are important practical characteristics that often more accurately reflect heat-dissipating capability than thermal conductivity, which neglects interfacial effects. Since they differ only by a constant factor (i.e., the component area), thermal resistance and thermal impedance are basically interchangeable, and we will continue to use them as such throughout this publication.

Thermal Interface Resistance

The thermal resistance that arises when two dissimilar materials make contact – no matter how perfect that contact may be – is called the "true" thermal interface resistance. In addition, every real surface, however smooth-appearing, exhibits some degree of non-flatness, whether on a macro-scale (run-out, concavity, convexity) or at a microscopic level (surface roughness). Air entrapped in these irregular surface features will inevitably contribute to an increase in thermal resistance at the interface. The combined effects of true interface resistance, incomplete wet-out, and surface roughness are commonly grouped together under the term "thermal interface resistance."

Thermal interface resistance (or - impedance) can be reduced by employing an interface material that is capable of establishing intimate contact with the substrates, i.e., one that is highly conformable and displaces as much air as possible upon contact.

Measuring Thermal Conductivity and Interface Resistance

The thermal conductivity of interface materials can be measured using a number of experimental methods, including steady-state and transient techniques. Several ASTM Test Methods describe various experimental schemes, the most popular of which (D5470) employs separate heating and cooling elements, with the interface material sandwiched in-between ("guarded hot-plate" apparatus).

The thermal impedance (Z) of a sample is calculated according to equation 3: the temperature drop across the interface is measured; q and A are known. Care is taken to ensure that the interface material is properly applied to the mating surfaces. Interface impedance ($Z_{interface}$) and bulk conductivity are then determined by plotting thermal impedance as a function of thickness for the material in question (Figure 2 and Equation 4). The zero-thickness intercept of the straight line connecting these points is defined as the interface impedance; the line's slope is equal to the reciprocal of bulk thermal conductivity (1 / k):

EQUATION 4: $$Z = Z_{interface} + \frac{t}{k}$$

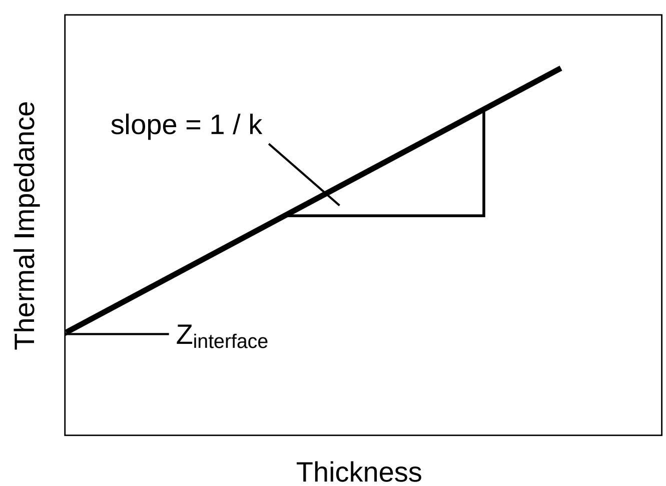

Figure 2: Dependence of thermal impedance on the thickness of the interface material. Interface resistance is determined from the intercept, conductivity from the slope.

Apparent Thermal Conductivity

It is a common practice to calculate an "apparent" or "effective" thermal conductivity from a single measurement of thermal impedance (Z) at one thickness (t) of a particular interface material.

EQUATION 5:
$$k_{eff} = \frac{t}{Z}$$

For a given material, the effective thermal conductivity will always be smaller than the true (bulk) thermal conductivity, because k_{eff} incorporates the combined effects of true interface resistance, incomplete wet-out and surface roughness. It is important to distinguish between the two definitions of thermal conductivity (k vs. k_{eff}) when discussing the performance of thermal interface materials.

Thermal impedance is generally a very useful property because it enables direct comparisons between different interface materials. It can also be utilized to predict the reduction in component operating temperature when a thermally conductive interface material is used in place of one that has not been thermally enhanced. From equation 3, the expected temperature drop is equal to the heat flux, q / A, (i.e., the amount of power being generated over a given area) multiplied by the difference in thermal impedance between the thermally conductive and non-thermally-conductive material (ΔZ):

EQUATION 6:
$$\Delta T_{n\text{-}TC \rightarrow TC} = \Delta Z \cdot \frac{q}{A}$$

Figure 3 gives a graphic illustration of this relationship for a real data set involving two adhesive films, one thermally conductive, the other a non-thermally-conductive grade. As the heat flux increases, the thermally conductive material provides progressively more benefit in terms of lowering the operating temperature of the component (here, a TO-220-type resistor). In this particular case, switching to the thermally conductive material decreases the resistor temperature by about 3°C at 10 W/in^2 but by almost 14°C when the heat flux increases to 40 W/in^2. (The slope of the line is equal to the difference in thermal impedance between the two interface materials.) This dependence is an important consideration when choosing an interface material for a particular application, low power applications do not require highly thermally conductive interface materials. Customer knowledge of the heat flux generated by the component is required to make the proper thermal interface selection.

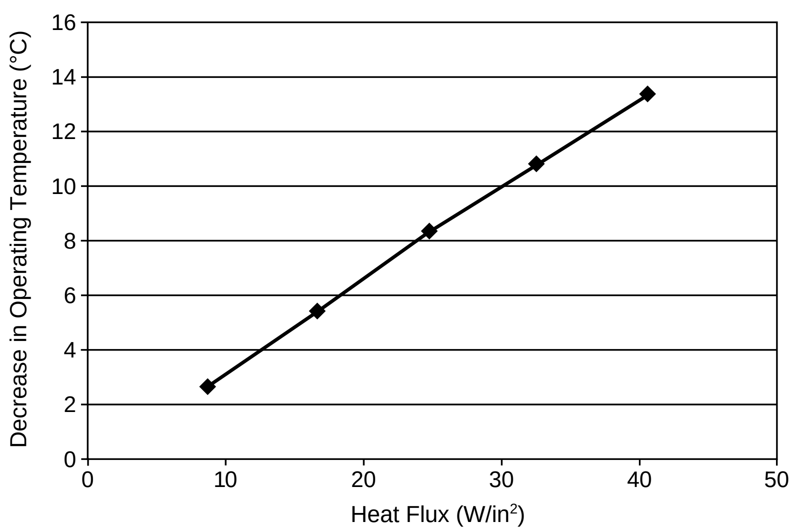

Figure 3: Decrease in operating temperature for a TO-220-type resistor when a thermally conductive interface material is used in place of a non-thermally-conductive medium. The higher the heat flux the more useful a material with high thermal conductivity will be in a given application.

Apparent Thermal Conductivity *(continued)*

Figure 4 shows a schematic that compares two interface materials, "A" and "B", and illustrates an interesting – and not uncommon – scenario. While material "A" exhibits high bulk thermal conductivity (indicated by the flat slope of the line), its interface impedance (or resistance) is rather high, accounting for a large fraction of total thermal impedance. Material "B", on the other other hand, is lower in thermal conductivity (the lines has a steeper slope) but exhibits much lower interface resistance. Thus, material "B" would actually be preferable in this application at thicknesses below t* – despite its lower thermal conductivity! Above t*, "A" would be the material of choice. This scenario is a good illustration of how a soft, conformable interface material of moderate thermal conductivity (represented by "B") can often compete favorably with a less conformable material of high bulk thermal conductivity ("A"). As such, this example demonstrates how an exclusive focus on thermal conductivity can sometimes lead to a poor choice in interface material.

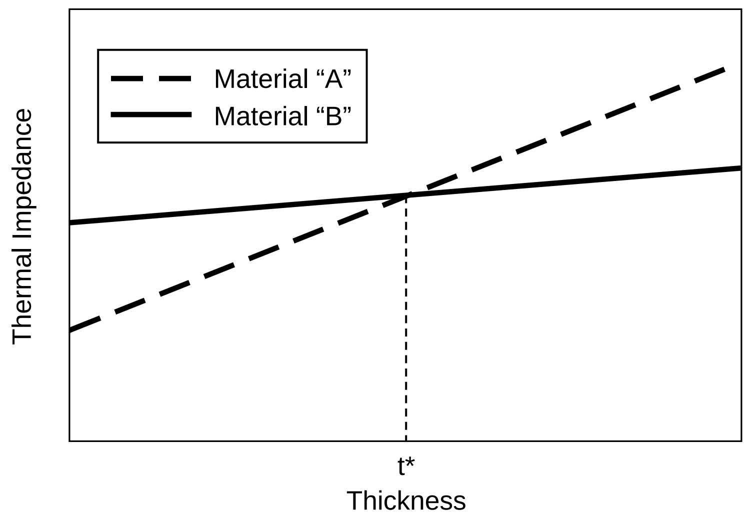

Figure 4: Thermal impedance for two different interface materials. Material A represents a thermally conductive material with a large interface resistance; material B represents one with lower thermal conductivity, but significantly lower interface resistance.

Thermal Interface Design Considerations

Thickness:
As mentioned, the thermal impedance can be reduced by using a thin interface material, if practical. The interface material must wet out the substrates and not entrap too much air. Thicker interface materials may be required to achieve this wetting and air-exclusion process. Some designs do not allow for very thin thermal interface materials (e.g., sinking heat to a chassis or heat spreader where a gap- filling function is required.)

Area:
A small area of contact requires an interface material with low thermal impedance to ensure proper cooling. Sometimes components are available from manufacturers in several sizes. If a design permits, the larger package can be cooled by interface materials with lower conductivity.

Interface Resistance:
Interface materials with superior conformability will exhibit improved wetting of the substrates, resulting in lower interfacial resistance compared to materials with a stiff/boardy construction or materials with a rough surface. Smooth substrates will also help reduce interface resistance. Any type of surface contamination should also be avoided.

Thermal Interface Design Considerations *(continued)*

Power Output:
Typically, low-power components do not require interface materials with high bulk conductivity; at low-power conditions, the cooling difference between low and high bulk conductivity materials is very slight, as shown in Figure 3. High-power components do often require an interface material with low impedance (very thin and/or very conductive) and possibly a very high cooling capability of the heat sink.

Component manufacturers can provide the designer with the power output and operating temperature for their parts. These can be used to calculate the required total impedance of the thermal path (see "Heat Flow Calculation for 3M Thermally Conductive Adhesive Transfer Tapes" for some example calculations.)

Summary

The goal of selecting any thermal interface material should be to provide an adequate thermal path for cooling of the component, plus any other additional features (such as adhesion or gap filling) that may be desired. The total thermal impedance of the interface should be low enough to keep the component running below the rated temperature.

Thermally conductive interface materials contain added fillers (typically ceramic particles) whose thermal conductivity is much greater than that of the binder (typically a polymer or grease). To achieve increasingly high levels of thermal conductivity, these materials must utilize higher loadings and/or more expensive fillers. Typically, price increases with increasing thermal conductivity, while physical properties suffer. High filler levels often result in reduced conformability and poorer handling properties. Proper selection of thermal interface materials involves balancing thermal properties and cost. Users should carefully determine the actual thermal impedance requirements for their design.

For Additional Information

To request additional product information or to arrange for sales assistance, call toll free 1-800-362-3550 or visit www.3M.com/bonding. Address correspondence to: 3M Engineered Adhesives Division, 3M Center, Building 220-7E-01, St. Paul, MN 55144-1000. Our fax number is 651-733-9175. In Canada, phone: 1-800-364-3577. In Puerto Rico, phone: 1-787-750-3000. In Mexico, phone: 52-70-04-00.

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