Understanding non-thermal property impact on thermal performance: Improve your ability to recommend the right thermal interface material

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Given the choice between a 10 w/mk thermally conductive pad and a 2 w/mk thermal pad, which one would offer the best overall thermal performance between a standard heat sink and a heat generating device?

The difficulty in answering this question indicates that there is more to specifying a thermal material than just looking at the thermal performance data. This paper highlights other material properties and characteristics that impact thermal performance and how they should be taken into consideration when selecting a thermal material.

Mechanical Properties

It is almost impossible to specify a thermal material without taking a close look at the mechanical properties of any candidate material. Mechanical properties such as modulus and adhesive performance are important design considerations because of their impact on contact resistance at the interface and long term reliability.

Modulus

There are many ways to measure and describe the modulus of a material. In this paper, modulus simply refers to the hardness, compressibility, or ability of a material to conform to various surfaces. Typical data sheets will list durometer or compression modulus, or provide a stress/strain curve to give an indication of a material's modulus.

For any application, but particularly for those involving thin bond lines (<50 microns), selecting a material that can minimize the contact resistance is preferred. High contact resistance occurs because of surface roughness, non-planar mating surfaces or height mismatches in the assembly. Selecting a material with the wrong modulus can lead to air gaps between the interface material and the mating surface. Air is a strong thermal insulator and will prevent efficient transfer of heat.

In the introductory example, if the application at hand requires a thin bond line and the 10 w/mk material has a high modulus, it's unlikely that the hardness of the material will accommodate mismatches between various chip heights or easily conform to the surface, thus leaving an air gap over the shorter chips or microscopic air gaps at the interface. In contrast, imagine that the 2 w/mk pad has a low modulus that can easily compress to accommodate the taller chips and still mate with the shorter chips, thus eliminating any air gaps. In this case, one would expect that the 2 w/mk material might well outperform the 10 w/mk material.

Instead of using a low modulus 2 w/mk thermal pad, what if the engineer decided to employ a 2 w/mk thermal grease? A grease by definition does not cure and has a much lower modulus than any elastomeric or gel-like thermal material. A grease could easily overcome any surface roughness inherent on heat sinks or chip surfaces and further improve the thermal performance. In general, a lower modulus, softer material will minimize contact resistance at the surface and improve overall thermal performance. This is most important at thin bond lines, where the surface resistance is dominant.

Adhesive Properties

Like modulus, there are many ways of assessing adhesive properties: tensile strength, lap shear, and die shear tests are just a few. Adhesives are used for two purposes in thermal designs. First, adhesive properties are often desired to ensure that there will not be any delamination of the thermal material from the mating surface. Secondly, many designs rely on the thermal material to serve two functions, as both mechanical fastener and heat transfer material.

Focusing on adhesion to prevent delamination, this problem usually occurs over time, after repeated temperature cycles as assemblies are powered on and off. To eliminate this problem, adhesion packages can be added to the thermal material to ensure long-term intimate contact between the thermal material and the mating surface. The adhesive properties are usually designed to be compatible with chip, module or heat sink surfaces. Aluminum, copper and nickel are common surfaces requiring good adhesion. Specialized materials from Dow Corning also adhere to gold for metallization in high-end package designs.

Typically, design engineers will ask for reliability data that proves there is no delamination after long term testing. Common tests to demonstrate this are HAST testing at 85ºC and 85% relative humidity for 1,000 hours; thermal bake tests at 150ºC for 1000 hours; or thermal cycling tests from -40ºC to 100ºC. These tests are usually performed by building a device and subjecting the material and device to the stated conditions, and then testing the thermal resistance. The idea is that if thermal resistance is stable, then there has not been any delamination or formation of air gaps, as performance has stayed constant. The industry commonly refers to long term reliability performance as end of life performance, versus end of line, which refers to the performance immediately after assembly. Selecting a thermal material requires attention to both end of line and end of life performance.

Material Composition

In addition to its effect on mechanical properties, the filler system can directly impact thermal performance. It is important to understand the particle size distribution of any thermal interface material, since thermal performance is dependent on bond line thickness. The heavier the bond line, the farther the heat has to travel to get out of the system. One way of improving thermal performance is by reducing the bond line. Consider an application in which the 10 w/mk and 2 w/mk materials from the introductory example are thermal greases instead of pads. Assume that the 10 w/mk material was loaded with 150 micron alumina particles and that the 2 w/mk material was loaded with 10 micron particles.

If these two greases were applied to an aluminum heat sink and pressed onto a CPU chip, which one might be expected to outperform the other? The 10 w/mk material with its 150 micron particles can only compress to 150 microns at best and will have a much thicker bond line than the 2 w/mk material. Recall that resistance can be calculated by dividing the bond line thickness by the bulk thermal conductivity $R = BLT/K$. Doing the math, one would expect the 2 w/mk grease to outperform the 10 w/mk material by a factor of 3.

The filler system also can impact the viscosity of any wet-dispensed or screen-printed material. In general, high bulk thermal conductivity requires higher filler loadings relative to polymer content. This in turn increases the viscosity, which can have both positive and negative effects on thermal performance. First the positive: higher viscosity formulations, particularly highly thixotropic materials, tend to stay in place better. This is particularly important for non-curing materials like greases and phase change materials. For thin bond line applications with wide temperature cycles, low viscosity materials tend to pump out over time, resulting in high end of life thermal resistance. High viscosity materials will be less prone to pump-out and more reliable over time.

For thick bond line applications, highly thixotropic, higher viscosity materials can be applied more easily. Dow Corning has developed a non-curing thixotropic grease that can be applied at 1 mm bond lines and can even be mounted vertically without dripping. The negative side to using high viscosity materials is that they may be more difficult to print or apply evenly, leaving hot spots or air gaps in the assembly which would be detrimental to thermal performance. Choosing the right thermal product requires an understanding of how the filler system will affect bond lines and whether it will spread easily to cover the intended interface uniformly.

Summary: Three Common Errors in Specifying Thermal Materials

1) Recommending the material with the highest bulk thermal conductivity.

In general, higher bulk thermal conductivity translates to more filler, higher costs, and higher viscosity. With exception of cost, these are not necessarily negative, but may be unnecessary for the particular application in question. High viscosity may improve long term reliability, but on the other hand could increase processing and application costs, depending on the application method.

2) Assuming that highest bulk thermal conductivity = best thermal resistance. Not true!

For a number of reasons, it is entirely possible that a highly loaded material with bulk thermal conductivity of 10 w/mk will not perform as well in an application as a 2 w/mK material.

First, the 10 w/mk material is likely to have a much higher modulus due to its filler loading or crosslinking, which does not allow the material to overcome the surface roughness or planarity differences on the substrate. A higher modulus material will have a higher contact resistance and thus inhibit thermal transfer. Contact resistance becomes a more dominant factor as the bond line becomes thinner.

Second, it is entirely possible that the particle size distribution of the 10 w/mk has larger particles and hence requires a thicker bond line or larger gap across which heat transfer must occur. If the 2 w/mk material is capable of achieving a much smaller bond line, overall thermal performance will likely be better.

3) Failing to test end of line performance vs. end of life performance.

End of line refers to thermal performance just after assembly, while end of life refers to thermal performance after long term reliability testing or long term use. Reliability is an important consideration. If the thermal material cracks, dries out, migrates or hardens over time, this can lead to a degradation in thermal performance. A material that offers 10 w/mk end of line but degrades to 2 w/mk at end of life is not as desirable as a high reliability material that tests 2 w/mK end of line and 2 w/mk end of life.

A basic understanding of the key material properties and how they impact thermal performance is critical to appropriate material selection for a given application. The wise engineer will also look much deeper than just the bulk thermal performance, and will take into consideration other parameters such as bond line thickness, modulus, and reliability when specifying or making material recommendations.

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