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EDITORIAL COMMENTARY

Thermal Interface Materials

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Cooling is critically needed for reliability, power and further miniaturization of microelectronics. Heat sinks are obviously important for heat dissipation. However, thermal interface materials (TIMs) are needed to improve thermal contacts, such as the thermal contact between a heat source (e.g., a microprocessor) and a heat sink. This commentary is directed at clarifying some misconceptions related to the design and testing of TIMs.

CONFORMABILITY

A thermal interface material (TIM) is sandwiched between the two proximate surfaces so as to improve their thermal contact. The surfaces are never perfectly smooth, even after fine mechanical polishing. Thus, in the absence of a TIM, the two surfaces touch each other at points and air pockets exist among the points at the interface. The air pockets can be microscopic in size. Because of the thermal insulation nature of air, the interfacial air should be displaced from the interface by the TIM. As long as the TIM is more thermally conductive than air, its displacement of the air enables it to improve the thermal contact. As a result, the conformability of the TIM is critically important. Because the air pockets can be microscopic in size, the conformability of concern is on the microscopic scale. If the TIM is not conformable enough, parts of some air pockets remain at the interface. Just having high thermal conductivity is not adequate for the TIM; high conformability is essential. A high value of the thermal conductivity cannot imply high effectiveness as a TIM. For example, solid diamond is outstandingly high in the thermal conductivity, but it is not conformable at all (due to its high hardness). Therefore, solid diamond is not effective as a TIM.

Thermal pastes are the most widely used form of TIM. A thermal paste consists of a solid component and a liquid component. The solid component is mainly used to enhance the thermal conductivity of the paste, in addition to controlling its rheology.

Regardless of the degree of roughness of the proximate surfaces, and regardless of the thermal conductivity of the TIM, the thicker the TIM, the larger the thermal resistance within the TIM. Therefore, to minimize the thermal resistance of the thermal contact, it is best to have the TIM fill all the air pockets completely with negligible amount beyond that needed to fill the air pockets. For this purpose, the spreadability of the TIM and the feasibility of the TIM to be thin are helpful. Spreadability tends to be an attractive characteristic of thermal pastes. When the degree of roughness of the proximate surfaces is low, the spreadability and thinness are particularly important. The feasibility of a thermal paste to be thin depends largely on the solid component of the paste. For this feasibility, the solid component is preferably very thin in the direction perpendicular to the plane of the thermal contact. Examples of such solid components include nanoclay and graphene. Because of the tendency of nanofibers or nanotubes to clump together, such that there is a high proportion of air within each clump, these nanomaterials are not effective for providing a small thickness, even though each unit of the nanofiber or nanotube is small in diameter. Furthermore, the air decreases the thermal conductivity.

The conformability is to be distinguished from the resiliency, which refers to the springiness. A material can be resilient without the ability to fill small air pockets. This is the case when the organic molecules in the TIM are long compared to the size of the air pockets. Therefore, for the sake of the conformability, long molecules such as those that

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are typically in polymers (e.g., the widely used silicone) should be avoided. On the other hand, relatively short molecules (e.g., polyol ester) are disadvantageous in their ability to resist elevated temperatures. The resistance to elevated temperatures (as high as 150°C) is required for some microelectronic applications. The effects of elevated temperatures include mass loss, viscosity increase and thermal cracking. This shortcoming may be alleviated by the addition of minor amounts of antioxidants (e.g., a half-hindered phenolic primary antioxidant and a thiopropionate secondary antioxidant).

For a thermal paste, the conformability is commonly derived from that of the liquid component. However, it can also be derived from that of the solid component, when the solid component is highly compressible. Examples of compressible solid components are carbon black and fumed alumina, the compressibility of which results from the fact that the material is in the form of porous aggregates of nanoparticles. The solid-state conformability of the carbon black can be further enhanced by using low-structure carbon black, i.e.., carbon black with a relatively small aggregate size. In contrast, fibers, nanofibers and nanotubes are too long for filling the microscopic air pockets. In addition, these fibrous materials tend to be preferentially in the plane of the thermal contact, so that the thermal conductivity is low in the direction perpendicular to this plane.

The thermal conductivity of a thermal paste increases with increasing solid content, whereas the conformability decreases with increasing solid content. As a result, the solid content needs to be optimized. One of the pitfalls of thermal paste design is the use of an excessively high solid content. This pitfall results from the focus on the thermal conductivity, with the neglect of the conformability.

Because of the high importance of the conformability, the use of an expensive thermally conductive component in a TIM may not be cost effective. For example, silver is high in the thermal conductivity, but it is much more expensive than carbon black.

Solders have long been used as TIMs, due to the high thermal conductivity of the metal or metal alloy that constitutes the solder. Although liquid metals can flow, their interaction or reactivity with some mating surfaces limits their conformability and spreadability.

THERMAL CONDUCTIVITY

The relevant thermal conductivity is that in the direction perpendicular to the plane of the thermal contact. Thus, TIMs with thermally conductive fibers that are primarily in the plane of the thermal contact are not effective. In a carbon nanotube array, the nanotubes are essentially in the direction perpendicular to the plane of the thermal contact, but they suffer from inadequate conformability; the air between the nanotubes in the array limits the thermal conductivity and it is difficult for the array to be very thin. The inconvenience associated with transferring the array from the growth substrate to the position between the two proximate surfaces is an additional disadvantage.

The rougher the two proximate surfaces, the deeper the air pockets at the interface, and hence the larger the thickness of the TIM that is needed to displace the air. The thicker the TIM (i.e., the larger is the bond line thickness), the more important the thermal conductivity of the TIM. For a TIM that excels due to its conformability, the proximate surfaces should have a low degree of roughness, so that the depth of the air pockets is small.

In practice, the two proximate surfaces may be not exactly parallel to one another, or one of the surfaces may be slightly curved. Under such situations, the TIM must be thick enough to fill the resulting gaps. As a result of the large thickness, the thermal conductivity of the TIM is important for the gap filling, although conformability remains important. Gap-filling TIMs are commonly in the form of resilient elastomer-based pads that are inadequate in both the thermal conductivity and conformability. Thermal-paste-coated thermally conductive sheets and solder-filled flexible graphite are options that alleviate these shortcomings of elastomer-based pads.

In spite of the importance of the thermal conductivity for some situations mentioned above, the TIM's thermal conductivity alone cannot indicate adequately the effectiveness of a TIM. The conformability of the TIM must not be overlooked.

EVALUATION METHODOLOGY

The conformability, spreadability and thermal conductivity are all relevant to the effectiveness of a TIM. The spreadability is particularly relevant to thermal pastes. Although these three properties can be measured separately, the separate measurements add to the work of TIM evaluation and the combining of the three properties to arrive at a single description of the behavior is difficult.

The evaluation of a TIM is most effectively performed by measuring the thermal resistance of the sandwich, which includes the TIM and the two interfaces on its two sides. The compositions of the two surfaces may be the same or different, depending on the application situation. The thermal resistance is in the direction perpendicular to the plane of the thermal contact. Such measurements can be made by using a guarded hot plate (a steady-state method with one-dimensional heat flow) or laser flash analysis (a transient method). Evaluation of a TIM simply by measuring the thermal conductivity of the TIM (i.e., measuring the thermal resistance within the TIM) is misleading, as it ignores the two interfaces and the associated thermal resistance, which increases with decreasing conformability of the TIM.

When a TIM is not an adhesive, pressure must be applied to the sandwich in the direction perpendicular to the plane of the thermal contact in order to hold the sandwich together and to achieve a thermal contact of a controlled quality. The higher the pressure, the greater the extent of squeezing of the TIM by the asperities of the proximate surfaces, and the greater the extent of filling of the air pockets by the TIM. As a consequence, the higher the pressure, the better the thermal contact. When a thermal paste involves a compressible solid component, the pressure also serves to cause the solid component of the paste to conform to the surface topography of the proximate surfaces.

The applied pressure, the roughness of the proximate surfaces and the thermal conductivity of the sandwiching materials all affect the quality of the thermal contact. Thus, the comparative testing of various TIMs should be conducted under controlled pressure and controlled roughness and for the same sandwiching material.

A TIM may be tested by measuring the extent of cooling provided by the TIM when it is used in an operating electronic device package. Although this approach of testing is close to the application environment, it does not allow determination of basic properties, such as the thermal contact conductance of a TIM sandwich. The basic properties enable comparison of the performance for various TIMs that are investigated by various research groups. Because of the differences in the electronic device package among various research groups, comparison of the results on the TIM performance across research groups is difficult when the TIM evaluation involves electronic device packages.