THERMAL IMPEDANCE AND THERMAL STRESS IN ELECTRONIC ASSEMBLIES

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INTRODUCTION

Thermal management has become an increasingly important topic in electronic packagings with the advance of VLSI and ULSI technologies. In an electronic packaging structure using "adhesive" or "solder" for bonding between different parts that are made of different materials, it is often observed that the thermal transfer of the assembly is drastically different from the most comprehensive theoretical predictions. These theoretical models tend to be based on the bulk thermal properties of the various materials used in such an assembly while taking great care in accounting for lateral and even radiation thermal dissipation(1,2,3,4). This fact has been observed for all levels of microelectronic packaging, including die, component and substrate-attachments. This phenomenon has been documented not only in the use of the organic based adhesives such as epoxies(5,6), it has also been reported in the use of the inorganic adhesives such as tin/lead and other solders(7,8), as well as in the use of silver-glasss type of adhesives(9,10).

This apparent discrepancy between theoretical predictions and experimental results has caused concerns for both reliability and design engineers. Uncontrolled temperature increase can cause intermetallic changes as well as stress increases between various levels of passivations and packagings. Detailed studies are needed to clarify the use of the bulk thermal conductivity data of materials from standard ASTM type testing in predicting the thermal transfer efficiency in an electronic assembly which is typically in the order of 2 to 3 mils in bondline thickness. This is critical for proper thermal management design in electronic devices. Lack of proper temperature control has been attributed to cause more than 55% of device failures(11) even though proper thermal management provision have been designed into the systems for long-term reliability. It has also been demonstrated that vibration causes at least 20% of the electronic failures. Humidity causes
another 20% of the failures.

In this paper, we summarize some of the data and evidence generated both in our laboratory as well as some of the results from customers using different types of materials. We will also analyze data that has been available from literature that has been published but not necessarily reported in a format that would elucidate the same phenomenon(12,13,14). We will also present some evidence of stress induced changes in thermal impedance in some of the electronic assemblies.

BULK THERMAL CONDUCTIVITY AND ITS MEASUREMENT METHODS

There are basically two commonly used methods to determine the bulk thermal conductivity of a material: ASTM methods C518-85 and C117.

Both of the ASTM methods are used primarily to determine materials of a thermally insulating nature. The required sample size has traditionally been designed to be very large in XY dimension of several inches, and relatively thick in the Z-dimension(1/4 inch to 1 inch depending on the edge effect between thickness and width or diameter). It is obvious that the thickness is drastically different from that of adhesive bonded microelectronic devices which have a typical thicknesss of 2 to 10 mils. The significant difference between a bonded structure and the independent bulk samples is believed to lie primarily in thickness difference as well as the lesser known effect of the bonding interfacial surfaces.

THERMAL TRANSFER IN AN ELECTRONIC ASSEMBLY

Figure #1 is a schematic illustrating an adhesive used in bonding electronic devices. There are basically 3 factors that affect the thermal transfer from the heat source(in this case being the power-device) to thermal ground plane: the interface between the device and adhesive, the bulk thermal properties of the adhesive used, and the interface between the adhesive and the heat sinking plate.

If one were to plot the temperature difference between the junction of the power-device(or immediately above the interface, to be precise) and the immediate area under the surface of the heat-sinking plate, one would normally expect the difference to approach zero when the thickness of the adhesives reduces to zero. (This is illustrated schematically in Figure #2). The steeper slope represents a less thermally conductive material, while a gentle slope describes a material which is very thermally conductive. This is generally true for the more classical theoretical model used to estimate the thermal transfer efficency of such an assembly(1,2,3,4).

Figure #3 is a plot of some of the test data from the literature(5,6,7,8,9,10). Because of experimental uncertainty, which changes the actual thermal impedance of such an assembly, we have attempted to use a "normalized" scale to illustrate the behavior schematically. It is clear that for some thickness, much beyond 6 mils, the thermal impedance is very much dependent on the thickness of the adhesives. However, when the bondline thickness reduces to 2-3 mils, the dependence on thickness, as well as the bulk thermal conductivity, is much less. In fact, in many cases, the thermal impedance does not change much from 1, 2, to 3 mils(9). From silver epoxy adhesive to diamond-based adhesive or solder joint, the difference in thermal impedance is typically in 10-30% only which is no where close to one's intuition may suggest. In fact, for most part, there is no difference between a very good thermally conductive epoxy joint to that of solder joint.

INTERFACIAL THERMAL RESISTANCE: THEORETICAL CONSIDERATIONS

Thermal conductivity or heat transfer in a single crystal insulating material structure can be theoretically calculated in physics using models of thermally excited phonons, or quantized elastic waves and their interaction. It is not as straight forward once we get into the same material with different grain boundaries, even if they are of the same atomic structure. Each of the grain boundaries is expected to scatter phonons and thus reduce the bulk thermal conductivity. Besides the grain boundaries, defects and other forms of discontinuities will also cause scatterings, and thus increase the thermal resistance of a solid(15).

The discontinuity scattering of phonons is common to all assemblies involving different species of layer materials. Figure #4 is a schematic illustration of scattering due to the interfacial discontinuity. This kind of scattering phenomenon is similar to optical and electromagnetic scattering in a discontinuous interface.

Diamond is one of the more perfect single crystals in its natural state and is also the most thermally conductive material when used in its single crystal form. They are used in the most critical thermal management areas(16). Most practical materials are almost always ceramics with lots of defects, or polymeric materials that do not behave like any easily modelled ionic compound. Thus the thermal conductivity of such materials are normally much lower than that of metals(the exception being diamond crystals, as mentioned earlier). In the case of metals, thermal and electrical characteristics are a function not only of the phonon but also of a strong function of the electronic waves and their interaction with phonons, defects and discontinuity(15). It is also well known that most of the metals used in electronic applications are modified with other atomic elements to change or improve their mechanical properties, their thermal expansion properties, or melting points when used as solder materials. The difference between alloys and pure elements can be as much as several orders less in electrical conductivity, and one or more orders less in thermal conductivity for the more common alloys(17).

In the bonding interface, intermetallic alloys are in forms which are substantially different from the bulk of materials. These intermetallic alloys may be even less perfect "alloys" than the solders that are used. It may be expected that such an interface will result in a strong scattering phenomena for both phonon and electron movements. It is thus expected that such an interface reduces the heat transfer and cannot be normally calculated without proper assumption of its presence in a normal heat transfer model, which tends to be simply classical in nature. The surprising aspect of this phenomenon is that some experimental results seem to suggest that such interfacial effects are very significant when the bondline thickness is in the range of 2-3 mils(5,6,7,8,9,10).

When organic adhesives such as epoxies are used, as a pure material, it must be noted that all organic materials are poor electrical conductors as well as poor thermal conductors. There is yet to be developed any reasonable model to account for thermal conductivities in this class of materials. Thermal conductivity of such materials are normally improved with filling of thermally conductive materials such as metallic particles, alumina, and even diamond(18). The bulk thermal conductivity of the base adhesive can be increased from 10 to 100 times when properly filled with suitable thermal fillers. Such an adhesive, when used to assemble electronic devices has been demonstrated to show similar thermal transfer to that of the metallic solders(7,8), and silver-glass adhesives(9,10). Table #1 and #2 are summaries of data from literature listed.

The similar thermal transfer efficiency in both the solder assembled and adhesive assembled devices is somewhat surprising. However, considering the thermal contribution of "adhesives", which are normally thin in comparision to the bulk heat spreaders, ICs, or components, it is not too difficult to project from interfacial considerations(19).

From material to material, for the same thickness of bondline, we have demonstrated that diamond-based adhesives tend to give 15-30% less thermal impedance in comparison to silver or alumina-based adhesives. It is clear to us that more systematic studies may be necessary to provide a comprehensive data base for more powerful IC packaging.

In some applications, we have been able to optimize the various parameters of adhesive materials, surface preparations, and heat-sinking material selection and processing to gain 50-100% reduction in thermal impedance, in comparison to more traditional methods.

VOIDS, MICROSCOPIC DELAMINATION, & STRESS RELAXATION

The reduction of thermal transfer due to voids can be easily visualized in an electronic assembly. However, it is not well understood that voids in the bulk material are not as detrimental as voids in the interface of bonding. Voids in the bulk reduce thermal conductivity as a function of volume fraction, as well as internal scattering of phonon transmission. Voids in the interface of bonding cause a drastic reduction because of the acute scattering of phonon in this area. The effect of voids on bulk thermal conductivity is summarized in Table # 3. It is clear that voids have a non-linear effect on the bulk thermal conductivity of a material. A few percent change can increase the thermal resistance by over an order.

In the case of fully encapsulated electronic packages, the interface of adhesive and die can become separated without causing electronic failures. In the case of higher thermal conduction requirements, such delamination can eventually cause thermally induced failures. The delamination is essentially a large void in the interface that drastically increases the thermal impedence and thus eventual thermal runaway and failure.

A lesser known fact is that while the same electronic assembly, using different type of adhesives or solders, may initially possess similar electrical contact resistance, thermal impedance, and bond strength, these properties tend to change over time. In the case of electrical contact resistance, it has been documented that adhesives that contribute to internal stress in an assembly, because of their high rigidity, also cause an increase in electrical contact resistance over thermal cyclings(20). The change can be as much as several times, or even orders of magnitude, depending on the actual stresses(21). Figure #5 is a plot of typical changes that have been observed for adhesives with different glass-transition temperatures. It is clear that adhesives with higher Tg, or higher rigidity, show faster and larger changes in electrical resistance. There is not much data available for the related thermal impedance. There is a high likelihood, however, that thermal impedance changes are coupled with the electrical impedance changes.

It has also been documented that more rigid adhesives, while exhibiting higher bond-strength immediately upon "curing" or "soldering", also show 50% to 200% change in bond-strength upon thermal cycling, and in some cases, delamination or cracking of devices also occurs(22,23,24). Figure #6 is a graph of the typical change in bond strength as a function of thermal cyclings. It is clear that while demonstrate outstanding initial bond strength upon assembly, they also show a much larger change in bond-strength over thermal cyclings. It is interesting to note that while over 200 cycles have been performed on these aluminum heat-sink to alumina attachments, the decrease in bond-strength still does not show up as failures.

This kind of change in electrical impedance, and bond-strength can be attributed to the change in microstructure of the adhesives in the interfaces. We will term such change before gross failures such as delamination or fracture to be "stress-relaxation". While there is not a detailed study on thermal inpedance, there is plenty of evidence that similar changes are also true for thermal transfer in an electronic assembly. While many detailed studies may be required to elucidate such phenomenon, there are some indications that those long-term thermal failures may in deed be related to interfacial changes. Such interfacial voiding provides a mechanism for eventual thermal runaway and thus failures in an electronic assembly. In avionic electronics, where devices go through more thermal cyclings than the usual 100 cycles military electronic requirement, these cyclings contribute more than 55% of the failure mode. Vibration is also coupled to stress management due to the thermal excursions experienced in such electronic devices. In the case of high thermal mis-match, thermal pads or greases are normally used instead of the thermally conductive and stress-absorbing flexible adhesives; these also showed higher failure rates in solder joints during vibration testings.

THERMAL IMPEDANCE vs EFFICIENCY OF THERMAL GROUND PLANE

Most of the thermal impedance data are collected based on one particular configuration of die, substrate, heat-sink and heat removal efficiency of the fan or coolant. While all of the tests are valid in that particular configuration, they may be drastically different if one changes any of the parameters. It is quite confusing when one tries to generalize such data. In fact, the thermal impedance that has been measured depending on these parameters can vary all the way from 0.1-0.2 C/Watt, to 5.0 C/Watt or higher(25,26). The lower thermal impedance tends to correspond to those systems closer to "infinite" heat-sink provisions such as heat-exchanger or coolant-cool. Those configurations that have limited heat removal, such as using natural heat convection only, tend to demonstrate a higher thermal impedance. The summary of data, due to thermal removal efficiency of the transfer, is shown in Table #4.

CONCLUSIONS AND SUGGESTIONS FOR BETTER THERMAL MANAGEMENT

It is clear that thermal impedance can be reduced effectively with less interfaces in an electronic assembly. However, because of the stress problems(27, 28), the thermal stack-up of some of the older electronic devices tend to be cumbersome. With the advances of "stress-free" adhesives, the design has been drastically simplified and thermal impedance drastically reduced(20). Both matched and mis-matched materials in CTEs can be bonded with large bond area. The "window" of choice of materials and size of parts to be assembled have been expanded drastically. Proven examples include: silicon to copper and aluminum larger than 2"x2", alumina to aluminum of over 5"x5", microwave "Duroid" of over 8"x4" to aluminum, and PWB to aluminum of over 12"x12", etc.

Another factor that is commonly ignored is that the use of pure aluminum or copper will be preferred to that of commercial aluminum, which is normally fortified with copper. This will increase the bulk thermal conductivity of the heat-spreader or heat-sink being used.
Still another factor will be to provide a clean, non-coated, non-plated surface for bonding. A lot of mechanical engineers tend to plate copper with nickel or anodize the aluminum surfaces to enhance the appearance of the structures. It is anticipated that such an additional interfacial material-layer will contribute significantly to the total thermal management of the device.

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