

## **Low T<sub>g</sub> Epoxy Adhesives for Thermal Management**

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### **ABSTRACT**

The complexity of microelectronic circuits, their scale of integration, and clock speed requirements have been increasing steadily. All of these changes have the effect of increasing the power density of the micro-circuits. IC's with a power of several watts and area of over a square centimeter are quite common. Thus, there is more heat generated per device at die, component, and substrate-attach levels of electronic packaging.

In order to maintain reliability of finished products, the junction temperature of the constituent devices must be kept low. It has been demonstrated that thermal management can be one key to lowering the cost and increasing the performance life of microelectronic products. The cost effectiveness of lowering device temperature has been demonstrated to be dramatic in comparison to the cost of thermal management materials(1,2).

Proper thermal management of advanced microelectronic devices has to be addressed at all levels. One should address the problem from the basic level of die-attach, through component attach, and eventually substrate-attach to thermal drains.

Thermal management is almost invariably coupled with a thermally induced stress problem. The increase in temperature at the device level also means a larger fluctuation of temperature from the ambient. Each cycle of on-off for the device represents one thermal cycle. Stress induced failures due to coefficient of thermal expansion (CTE) mismatch is much more acute for higher power devices.

In this paper, we will also address the thermally induced stress on the microelectronic product at all levels of packaging with major emphasis on component and substrate levels. We will demonstrate various ways and examples of reducing or eliminating this stress, which is a major cause of device failures. One of the proven methods is through the use of low  $T_g$  epoxies with high thermal stability.

## 1. INTRODUCTION

The growth trend of higher integration of ICs such as 1 Megabit, and 4 Megabits devices will be accelerated rapidly in the next few years. On the circuit board level, it will require design engineers to look into overall cost effective solutions rather than take a band-aid approach to solving thermal problems. These changes, in terms of power density and the increase in physical size of both the dice and components, have reached a critical point in that the conventional methods of electronic packaging are producing less reliable, if not completely unreliable devices, when the dice are 1cmX1cm or larger.

## 2. FUNCTIONAL ANALYSIS OF ADHESIVES IN MICROELECTRONICS

At the die-attach level, the heat source is the functional device. It is the first level of heat transfer to the outside world and thus should be addressed carefully with a good thermally conductive adhesive. Since the carriers are normally copper or other metals or ceramics with good thermal conductive properties, the problem is rather universal.

At the component level of packaging, the circuits may be single or multi-layer ceramic hybrid circuits, multi-layer printed wiring board circuits(PWB), or traditional printed wiring boards. There are many more variations and methods available to the engineers at this level of packaging for thermal management.

Figure 1 is an illustration of die and component levels of microelectronic packaging. There are differences and similarities of the functional requirements. Successful assembly with proper thermal management of the device as will be discussed in detail includes both good thermal dissipation and mechanical stress reduction. Some of the thermal management schemes are rather complicated and can be relatively expensive.

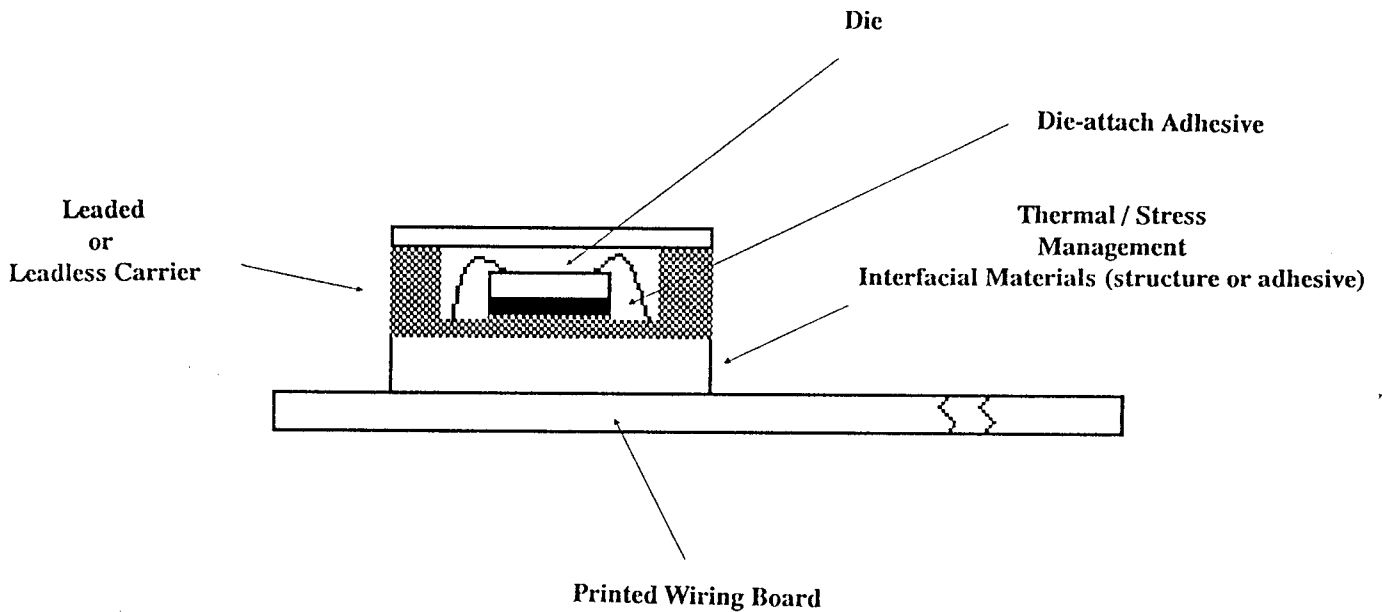


Figure 1: Thermal Management for Die and Component Packaging

In order to construct better solutions in electronic thermal management, it will be useful to examine the basic premises of electronic packaging. The basic functions of all electronic packaging are similar and can be summarized below for considerations.

i. Mechanical Supports:

This means that once the components are attached or anchored down properly, be it mechanical or adhesive bonded, it is expected that the device will be able to pass all of the operational environments. The operational environments include power-on and off for tens of thousands of cycles, which can be similar or worse than the standard MIL-STD-202 tests of thermal cycling from -65 to 150C. Thermal cycling tests represent extremes in temperature that the components might see in military operation.

A reliable mechanical attachment should also be able to pass the mechanical stress of acceleration in the case of avionics, and constant vibration of various magnitudes and frequencies as in the case of automotive electronics.

The components and systems must also be able to withstand (1) high temperature operation such as 150C continuous duty, (2) the chemicals associated in normal manufacturing environment, and (3) humidity and thermal exposure during operation.

In the worst case, they should also be able to withstand corrosive salt fog environments and certainly should not cause undue corrosion on other components.

Mechanical supports at the die-attach level are limited to the use of die-attach adhesives unless chips are flipped. At the component level, the components are ordinarily soldered to interconnect pins or pads, which act as mechanical supports.

Once the devices and circuits have been packaged and tested to function in their own right, they may be required to be "joined" to heat sinking plates or other means to transfer away from the device. This could be in the form of substrate attach such as those of ceramic hybrids. In the case of PWB, the board may be bolted to a metal chassis.

ii. Electrical and Interconnection Support:

In some cases, the adhesives used to assemble the die or components should provide the necessary ground or drain for the electronic flow. However, in most component assembly operations, the adhesives should provide electrical isolation; the exception being the use of adhesives to replace that of solders.

Substrate attach, in most cases, requires electrical isolation but a good thermal conductive path. The exception being microwave devices which require a high electrically conductive material for grounding purposes.

iii. Thermal Dissipation and Stress Management:

In order that the device function properly and exhibit long-term reliability, they should be designed to operate as close to ambient temperature as possible. Higher temperatures of operation will normally result in shorter life of devices. Thus proper heat-sinking provisions should be made for all heat generating devices. These provisions must be addressed at all levels from die to systems with the proper choice of adhesives and other materials.

Conventional methods at the component level include the use of heat spreader, thermal pad or gasket, a thermal grease; or a thermally conductive adhesive. Often the main problem is not normally the heat dissipation capability of the material, but rather the differential in the coefficient of thermal expansion which can be quite high and will result in excessive stress which eventually will cause the device to fail. Thus, thermal management invariably also involves the management of stress in the assembly.

### 3. PRIMARY MECHANISM FOR FAILURES: STRESSES

Mechanical stresses are induced primarily because of the the difference in coefficients of thermal expansion of the different materials involved in electronic packaging. There are basically two ways to reduce or avoid thermally induced stresses on all of the devices.

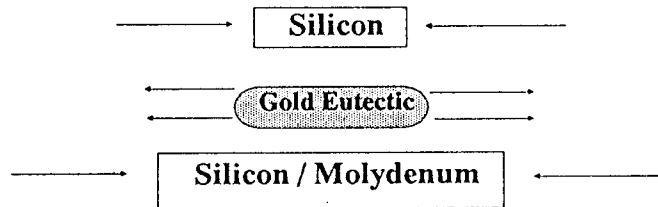
#### STRESS REDUCTION BY CTE MATCHING

One of the solutions is to match the coefficient of thermal expansion for the die or component to that of the lead-frame or substrate to that of the "adhesive" used. This is analogous to that of steel and concrete reinforcement. While there is some chance of matching the dice (silicon with 3ppm/C of CTE) or component (Ceramic with 7 ppm/C of CTE) to that of exotic metals, metal laminates or alloys such as Kovar, Copper/Invar/Copper or Molybdenum, etc., the adhesives are the main problem in this approach. Common

Tin-based solders have CTE of over 17 ppm/C, gold-eutectic has CTE of over 20 ppm/C, traditional epoxies have CTE of over 45 ppm/C, and glass-based adhesives have CTE of over 13 ppm/C.

The difficulties of matching all three components involved in the assembly can be readily appreciated. If the CTE's are not matched closely, and the modulus of the adhesive is on the high side when compared to that the base materials such as silicon, alumina or copper, then the stresses involved are very high. Figure 2 is a basic illustration of the potential stresses involved.

$TCE_{Si} = 3 \text{ ppm}/^{\circ}\text{C}$                        $TCE_{\Lambda} = 20 \text{ ppm}/^{\circ}\text{C}$                        $TCE_{Si} = 3 \text{ ppm}/^{\circ}\text{C}$   
 $E_{Si} = 60 \times 10^6 \text{ psi}$                        $E_{\Lambda} = 10 \times 10^6 \text{ psi}$                        $E_{Si} = 60 \times 10^6 \text{ psi}$   
*Soldering Temperature = 225 °C; Ambient Temperature = 25 °C; Low Temp. Exposure = -55 °C.*



**Potential Tensile Stress in "Adhesive"/Solder Cool To Ambient:**

$$\begin{aligned}
 s_{Si} &= \epsilon_{\Lambda} \times E_{\Lambda} = \sigma_{\Lambda} \\
 &= (\alpha_{\Lambda} - \alpha_{Si}) \Delta T \times E_{\Lambda} \\
 &= 17 \times 10^{-6} \times 200 \times 10 \times 10^6 \text{ psi} \\
 &= 34,000 \text{ psi} \\
 &\text{when } T = 25^{\circ}\text{C}
 \end{aligned}$$

Figure 2: Stresses For Device Assembled with CTE Matched Substrates but CTE Mis-Matched Adhesive

In the case of CTE mis-matched substrates, the stress can be higher or lower depending on the substrates and "adhesives" involved. Figures 3 and 4 are some of the more typical examples of die-attach and substrate-attach applications. It is clear that stresses will increase with more rigid (high modulus) "adhesives", higher CTE mis-match, and larger temperature excursion from "bonding" process.

$$\begin{aligned} TCE_{Si} &= 3 \text{ ppm}/^\circ\text{C} \\ E_{Si} &= 60 \times 10^6 \text{ psi} \end{aligned}$$

$$\begin{aligned} TCE_A &= 45 \text{ ppm}/^\circ\text{C} \\ E_A &= 10 \times 10^6 \text{ psi} \\ \text{Cure Temperature} &= 150^\circ\text{C}. \end{aligned}$$

$$\begin{aligned} TCE_{Cu} &= 17 \text{ ppm}/^\circ\text{C} \\ E_{Cu} &= 17 \times 10^6 \text{ psi} \end{aligned}$$

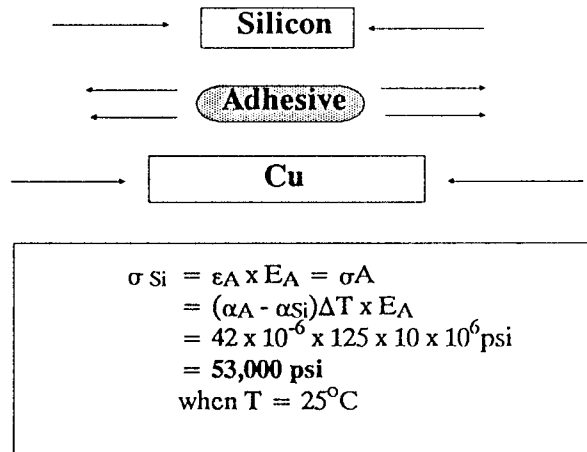


Figure 3: Stresses For Device At Die-Attach Level

$$\begin{aligned} TCE_{Al} &= 27 \text{ ppm}/^\circ\text{C} \\ E_{Al} &= 10 \times 10^6 \text{ psi} \end{aligned}$$

$$\begin{aligned} TCE_A &= 45 \text{ ppm}/^\circ\text{C} \\ E_A &= 10 \times 10^6 \text{ psi} \\ \text{Cure Temperature} &= 150^\circ\text{C}. \end{aligned}$$

$$\begin{aligned} TCE_{Al_2O_3} &= 7 \text{ ppm}/^\circ\text{C} \\ E_{Al_2O_3} &= 67 \times 10^6 \text{ psi} \end{aligned}$$

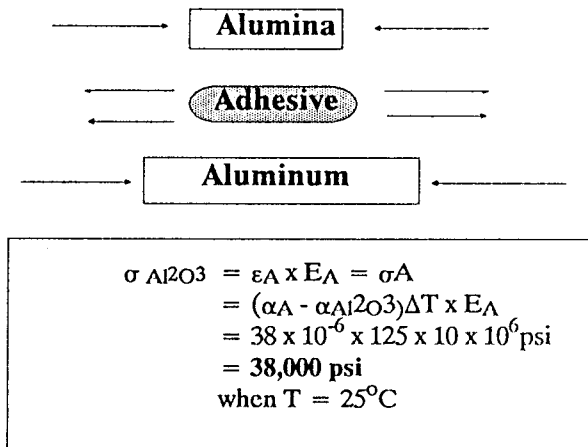


Figure 4: Stresses at Component or Substrate-Attach Levels

The stresses involved are induced because of thermal excursions during the life of the device. These temperature excursions occur during the "curing/bonding" process of the "adhesive", during the powering up of the device, and during storage and operating in various climates. While the device might appear to be properly assembled, the internal stress being stored in the materials will sometimes cause the component to crack or the assembly to delaminate.

This kind of high stress in the interface of the assembly will exist even if great care is taken to match the coefficients of thermal expansion of the device and the substrate or carrier as illustrated in Figure 2. Take for example the silicon on silicon assembly being proposed for some higher performance devices. Since silicon expands and contracts at 3 ppm/K, and solders or adhesives generally have CTE of 20-50 ppm/K, the stress level for large die will be extremely high even if it is not apparent in the finished assembly in terms of warpage. Delamination may occur when the device is subjected to thermal cycling tests.

There are many 2-dimensional and 3-dimensional calculations of the internal stresses involved in this type of 3-layer assembly (References 1, 2, 3). In this paper, we are presenting a simple 1-dimensional elastic model only. While absolute magnitude of stresses might not be accurate theoretically, the order of magnitudes are rather similar to those based on 3-dimensional models. The stresses can be easily over 30,000 psi. This stress level is much too high for long term stability and reliability of the component.

### STRESS REDUCTION BY INCREASING BOND-LINE THICKNESS

In the 3-dimensional models, one can also predict that the stress levels will be reduced with smaller devices such as conventional semi-conductor dice in the neighborhood of less than 3 milli-meter. It is also predicted that the stress level will be reduced if the bond-line thickness is increased from 0.001 of an inch (1 mil) to 0.003 or to 0.007 inch. But the magnitude of stress level changes only slightly.

Since die sizes are increasing to over 1cmX1cm, the component sizes are also increasing correspondingly. Indeed, in the die-attach level, stress induced failures are only prominent when die sizes are in this area of "large area dice".

Increasing bond-line thickness from 1 mil to 3 mils is generally recommended for die-attach because of the negligible thermal impedance penalty. Experimentally, it has been shown that an increase in bond-line thickness from 1/2 mil to 3 mils resulted in no or very little difference in the thermal impedances. This behavior can be explained by the fact that the interfacial thermal impedance between the assembly layers involving the organic and inorganic adhesives is much higher than that contributed by the lower bulk thermal conductivity of the adhesive materials (References 4, and 5).

In the case of component and substrate attach, because of the generally lower power density, it is recommended that 6 mils or higher thickness be used.

## STRESS REDUCTION BY USING LOW $T_g$ (COMPLIANT) EPOXIES

An alternative but effective way to reduce the stress level of bonded assemblies is the use of extremely flexible adhesives. The effect of the reduction in the elastic modulus of the adhesive can be readily calculated and illustrated in Figures 5, and 6 below.

Polymers as materials in general go through a rubber-to-glass transition depending on the molecular structure of the materials. Silicones are the most flexible with glass-transition temperature ( $T_g$ ) in the range of  $-55$  to  $-100^\circ\text{C}$  and are thus very compliant over the normal temperature range of device operations. Polyurethanes and some of the acrylics are generally also flexible down the temperature range of  $-20$  to  $-45^\circ\text{C}$ . However, because of their poor thermal stability beyond  $125^\circ\text{C}$ , they are generally not chosen for electronic applications. Epoxies are generally known to be high strength and possess good adhesion to most materials and have been extensively used in electronic industry. The glass-transition temperatures of epoxies are generally high, in the range of  $50$  to  $250^\circ\text{C}$ , however they have been extremely useful for small die and small area component applications.

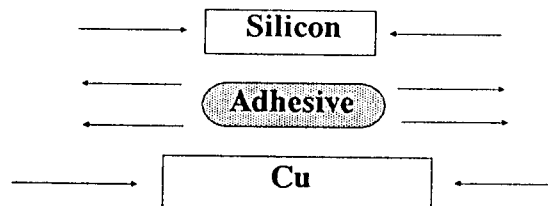
In the most difficult cases of large area devices and extreme mis-matched in CTE, silicone-based adhesives are sometimes used. However, because of problems with silicone in terms of molecular migration which hinders with future adhesion and other processing, the use of silicone in some companies is generally avoided at almost any cost. Also because of their inherent weakness to withstanding the various chemicals in cleaning of assemblies, they are not suitable for most electronic packaging application.

AIT has pioneered a series of flexible epoxy pastes and films for die-attach, component-attach and substrate-attached which have proven successful in these assemblies. The glass transition temperatures have been engineered to be below  $25^\circ\text{C}$  and yet maintain adequate chemical and solvent resistance during electronic manufacturing processes. The application examples as illustrated in Figures 5 and 6 are actual proven cases of manufacturing applications.

$$\begin{aligned} TCE_{Si} &= 3\text{ppm}/^\circ\text{C} \\ E_{Si} &= 60 \times 10^6 \text{ psi} \end{aligned}$$

$$\begin{aligned} TCE_{\Lambda} &= 120\text{ppm}/^\circ\text{C} \\ E_{\Lambda} &= 0.02 \times 10^6 \text{ psi} \\ \text{Cure Temperature} &= 150^\circ\text{C}. \end{aligned}$$

$$\begin{aligned} TCE_{Cu} &= 17\text{ppm}/^\circ\text{C} \\ E_{Cu} &= 17 \times 10^6 \text{ psi} \end{aligned}$$



$$\begin{aligned} \sigma_{Si} &= \epsilon_{\Lambda} \times E_{\Lambda} = \sigma_{\Lambda} \\ &= (\alpha_{\Lambda} - \alpha_{Si}) \Delta T \times E_{\Lambda} \\ &= 117 \times 10^{-6} \times 125 \times 0.02 \times 10^6 \text{ psi} \\ &= 290 \text{ psi} \\ &\text{when } T = 25^\circ\text{C} \end{aligned}$$

Figure 5: Stress Reduction of Die-Attach With "Stress-Free" Epoxy



**ALUMINA TO ALUMINUM USING FLEXIBLE, ZERO-STRESS EPOXY (ADHESIVE).**

$$\begin{aligned} TCE_{Al} &= 27 \text{ ppm}/^\circ\text{C} \\ E_{Al} &= 10 \times 10^6 \text{ psi} \end{aligned}$$

$$\begin{aligned} TCE_{\Lambda} &= 120 \text{ ppm}/^\circ\text{C} \\ E_{\Lambda} &= 0.02 \times 10^6 \text{ psi} \\ \text{Cure Temperature} &= 150^\circ\text{C}. \end{aligned}$$

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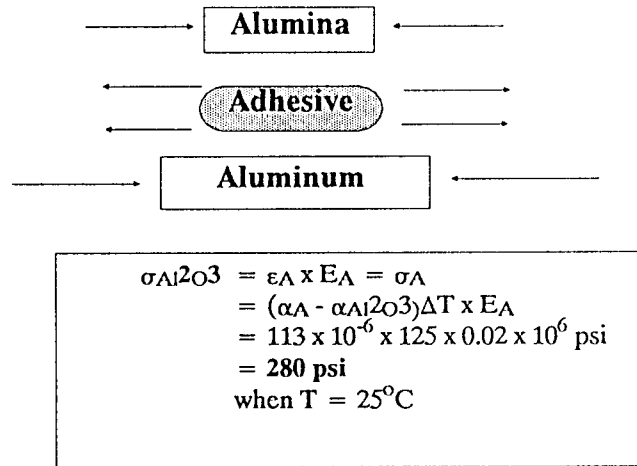


Figure 6: Stress Reduction of Component and Substrate  
-Attach With Compliant Low T<sub>g</sub> Epoxy.

The thermal stability of these low T<sub>g</sub> epoxies are also outstanding even when compared with the traditional epoxies with high T<sub>g</sub>. Figure #7 is a typical weight loss(TGA) analysis of a diamond-based adhesives(ME 7159 and similarly for ESP 7359).

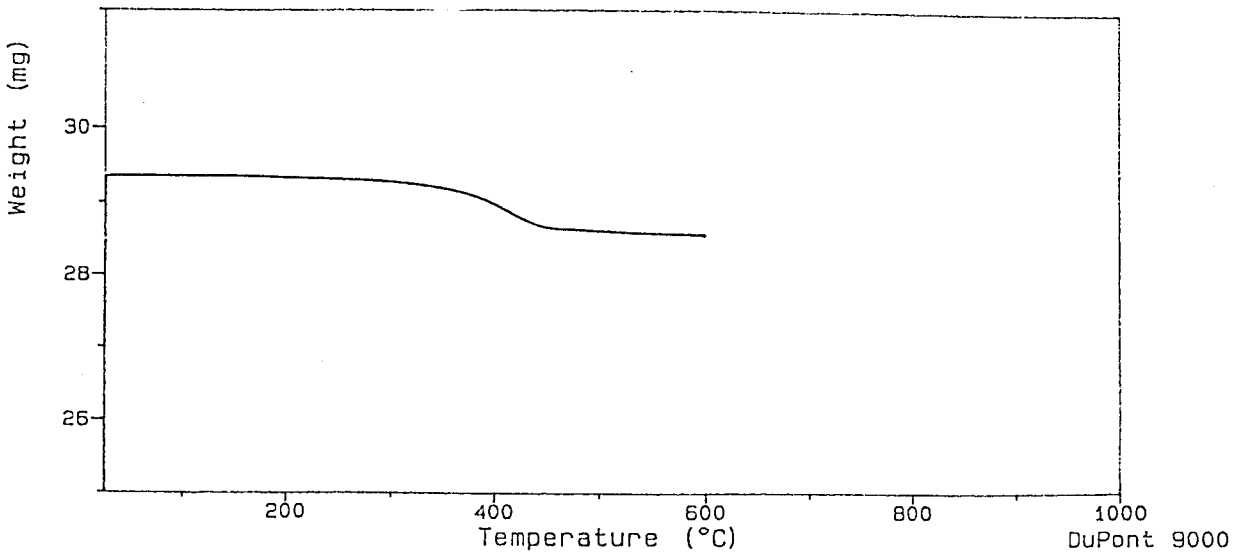


Figure 7: Thermal Stability of AIT "Stress-Free" Low T<sub>g</sub> Epoxy(ME 7159)

## 5. THERMAL CONDUCTIVITY OF ADHESIVES AVAILABLE

While stresses can be reduced and managed effectively by the use of flexible adhesives such as the AIT products illustrated, there is still the practical problems of thermal conductivity of the adhesive used.

Traditional virgin epoxies have thermal conductivity in the range of 1-2 Btu-in per square inch per hour per degree F(X0.144 to convert to w/mK), it is a rather good thermal insulator.

In order to enhance the thermal conductivity of the these materials, the thermal management products are filled with thermally conductive fillers such as silver, alumina, boron nitride, and aluminum nitride. In addition, AIT has also successfully developed a diamond-filled adhesive that has been used successfully when extreme thermal requirements exist. Basic characteristics of a few thermal management materials can be summarized in Figure 8.

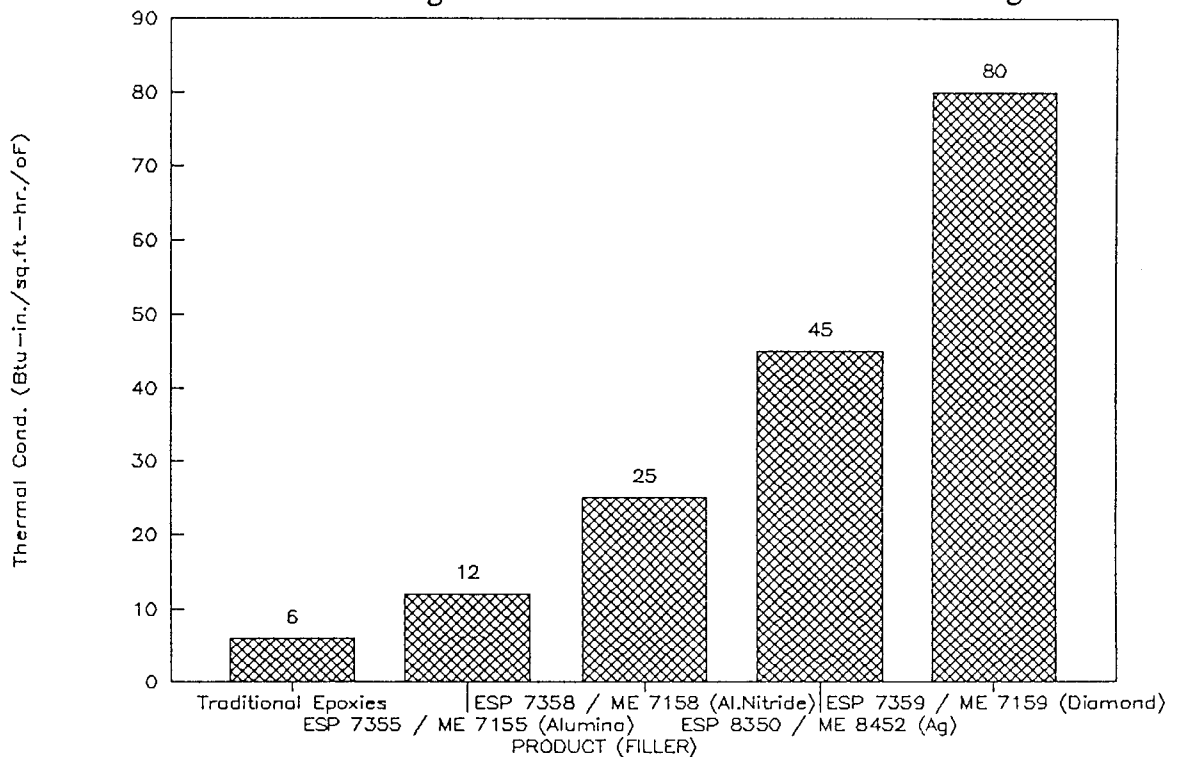


FIGURE 8: THERMAL CONDUCTION CHARACTERISTICS OF AIT "STRESS-FREE" ADHESIVES

## 6. Z-AXIS CONDUCTIVE "STRESS-FREE" FILM ADHESIVE

Uni-directional conductive adhesives have been introduced recently to accommodate some of the more stringent interconnection applications, when the lines and spacing between signal paths are reduced down to the range of 2-5 mils. The obvious advantages of a

unidirectional conductive interconnect is obvious and can open up different methods of packaging electronic devices. Such materials can be used not only as flex-circuit jumper adhesives, but also in die-attach applications, such as those of flipped chips and even TAB devices.

However, in order for the adhesives to be used in die-attach and component-attach, the Z-axis adhesives have to be both thermally conductive and compliant enough for stress-free bonding. AI Technology has integrated both of these properties in its Z-axis adhesives, in both the paste and film adhesive formats.(Ref #7)

## 7. SOLUTIONS vs COST EFFECTIVENESS

Before the availability of the novel flexible epoxy products there were many different approaches used to address the thermal management of higher power devices. One of the most typical examples was illustrated in Reference #6 as a standard solution. The thermal interface of the structure as illustrated in Figure #1 comprises of LCCC being soldered onto a network which is in turn soldered onto a Molydenum-copper expansion matching heat-sink which is then "loosely" interfaced with the aluminum chassis. While the heat-sinking approach seems to work, it is extremely cumbersome and relatively high priced in terms of assembly processes and materials.

Figure 9 represents a simpler assembly solution made possible by the availability of novel flexible epoxies.

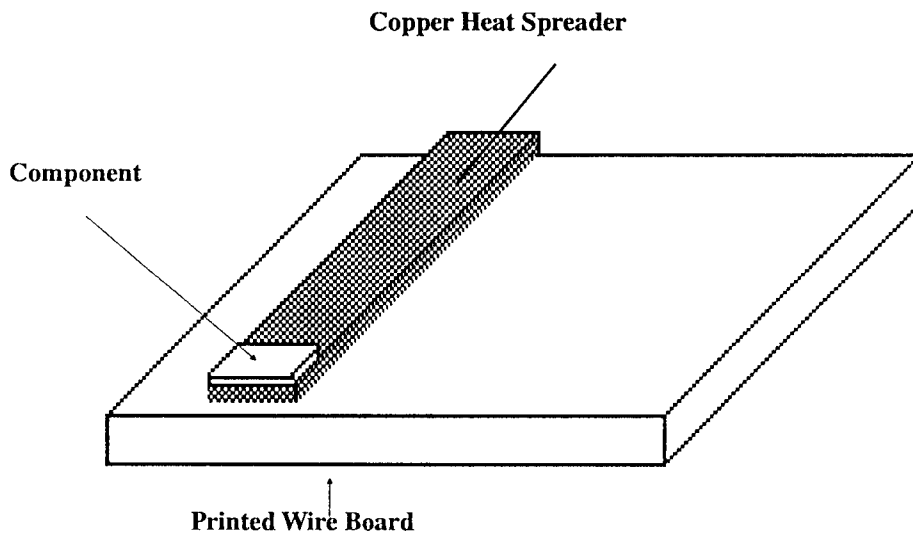


FIGURE 9: USE OF "STRESS-FREE" ADHESIVE AS THERMAL INTERFACE

## 8. MULTI-CHIP MODULE ASSEMBLY

Recent advances in multi-chip modules in commercial applications represents still another method of thermal management. Figure #10, is a illustration of the problem. Several chips or dice are directly assembled to the newtork which forms the functional module. Normally, dice are directly assembled to the more massive carrier which is made of copper aluminum, molydenum or silicon. The stress levels using conventional adhesives, however, have been demonstrated to be sufficiently high so as to result in an unreliable assembly. However, "stress-free" compliant high thermal conductivity adhesives(both silver- and diamond-based) have been proven to work when tested for 1000 hours at 150°C and more than 1000 thermal cycles from -55°C to 150°C. Power density of over 30 watts per square centimeter has been demonstrated under proper thermal heat-sinking.

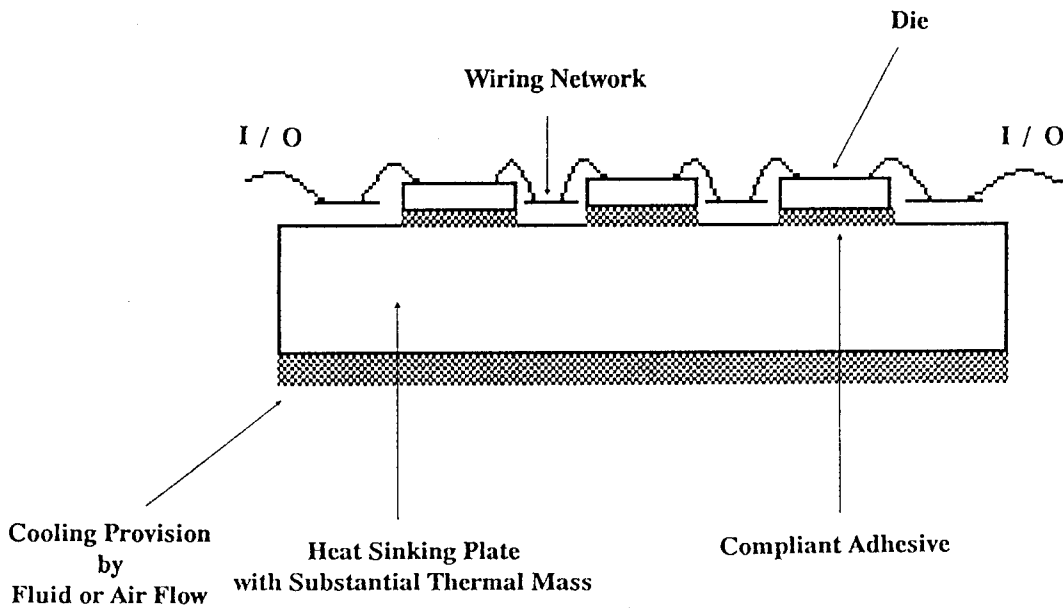


FIGURE 10: MULTI-CHIP MODULE WITH POWER REQUIREMENTS

Thus if process steps and number of materials used can be reduced, materials such as the diamond adhesive can be very cost effective.

## 9. CONCLUSIONS

The use of thermally conductive flexible epoxy pastes and films has been well established in large area die-attach, component-attach, and substrate-attach applications. They have been in production use in both military based electronics and some commercial automotive electronics. Most of these materials have been proven to work under NASA outgassing specifications and also MIL-STD-883C Method 5011.2

In fact, novel methods have been developed as a result of the availability of these stress-absorbing adhesives. A novel approach to thermal management at the component level: A "via" is actually provided for the thermally conductive adhesive to transfer heat from the component to the heat sink plane made out of aluminum or copper.

Several square inches of alumina based hybrid circuits have been directly heat-sunked to copper and aluminum base-plates. Finally, multi-layered boards with areas as large as 10 inches by 10 inches have been successfully bonded directly onto aluminum chassis using these compliant adhesives.

## ACKNOWLEDGEMENTS

It is our pleasure to thank all of our colleagues who have worked with us over the years on their applications. The names of individuals have not been included due to proprietary nature of some of their programs. While each of the examples chosen is common to at least two customers, they are presented only to illustrate the capability of materials presented.

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