Z-AXIS CONDUCTIVE ADHESIVE FOR TAB AND FINE PITCH INTERCONNECTS

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ABSTRACT

Solders are used extensively in both die-attach and component attach in the first and second levels of electronic packaging. With the commercialization of VLSI and ULSI devices, both levels of fabrication have encountered difficulties in both manufacturability and reliability.The manufacturing problem is mostly associated with the bridging of solder between finely spaced pitches in TAB and component attaches in surface mount circuit boards. The re liability problem stems primarily from the high modulus and mis-matched CTEs between part and substrate that are joined with solders. The combination of modulus, CTEs and high soldering temperature imparts extreme high stress when the parts are larger than 1 square centimeter in the bonded or joint area. Additional reliability problems arise from the fatigue failures during thermal cyclings because of the CTE difference between the parts and board materials. These limitations are inherent in most of the conductive silver adhesive based epoxies and other polymers. In this paper, the problems are analyzed and a novel solution of Z-Axis, *"stress-free"*, and thermally conductive adhesives are introduced. The adhesive system has been engineered to simulate all the desirable characteristics of soldering such as: fast "curing" speed(milli-seconds), ambient storage, low thermal and low electrical contact resistances, and reworkability. The drawbacks of solders, such as fatigue failures, stress-induced failures, and bridging are avoided. All of these basic properties and some of the applications are also discussed.

INTRODUCTION

Soldering in electronic circuit board manufacturing is as old as the electronics industry itself. One of the key advantages of soldering when compared with traditional adhesive bonding is that soldering is a reversible process and thus lends itself to be reworkable. Other aspects of advantages and disadvantages of typical soldering will be discussed later.

When the density of a circuit board is increased with the use of surface mount technology, tape-automated bonding, and chip-on-board technology, the potential for bridging becomes a real and daily problem in manufacturing. Soldering is becoming the bottle-neck in increasing the pitch density of electronic devices(1,2,3). In fact, typical soldering is limited to a pitch density with spacing more than 6 mils.

In this paper, the use of a Z-Axis, *"stress-free"* conductive adhesive in both paste and film formats will be discussed. The limitations in terms of pitch density, current carrying capability, migration resistance, reworkability and long term reliability will also be addressed.

COMPARATIVE PROPERTIES OF SOLDERING AND ADHESIVE BONDING

CONDUCTIVITY: Even though it is well known that alloys of metal such as solders are generally lower in conductivity than that of the pure metal, they are adequate in the range of 0.00002 ohm-cm. When an intermetallic is formed in the bonding process, the contact resistance is normally very low, in the milli-ohms range.

Most of the conventional conductive adhesives are in the range of 0.0002 ohm-cm in resistivity with contact resistance of typically much less than 10 milli-ohms. In a more advanced development, a patented process and material(**US patent #4695404**), allows AI Technology to achieve conductivity in the range of 0.00005 in the best mode and 0.000005 in most conductive adhesives with contact electrical resistance in the range of milli-ohms, similar to that of metallic solder joints. Figure #1 is an illustration of the conductivities of different material species used in electronics.

This type of material is obviously suitable for direct solder replacement in conventional PWB with pitch density of not more than 10 mils spacing. In fact, the use of such materials in precious metal based ceramic hybrids have successful for at least ten years. The problem of silver migration was avoided with an additional conformal coating.

The probability of bridging increases drastically when the spacing is reduced to less than 10 mils. This is true for either solder paste or conductive adhesive based technology of interconnection.

CURRENT CARRYING CAPABILITY: The current carrying capability of solder or adhesive used for bonding of components onto a circuit board is important for most circuit applications. Copper is rated to carry 7 amps per square millimeter on a continuous basis for commercial uses(4). Tin-lead solder type materials, being less conductive than copper, carry less current.

Typical silver-based conductive adhesives can carry current in the range of 20-30 amp per sq. mm. The best silver conductive adhesives can carry as much as 50-60 amp per square millimeter when they achieve resistivity as low as 0.00005 ohm-cm or below, as shown in Figure #2.

For conductive filled material, the adhesives once cured can carry varying current densities depending on the resistivity value of the material. Figure #2 is an illustration of the current carrying capability dependence on the absolute resistivity of the cured material. It is obvious that the material will be able to sustain more current if the ohmic resistance is lower. It is also important that both the resin binder systems and the conductive fillers will be thermally stable under those operating conditions.

While the current carrying capability cannot be measured intrinsically for Z-Axis conductive materials, it can be measured in the bonded configuration. The current density was determined to be in the range of 10 amps per square millimeter. The intrinsic current carrying capability will depend on the Z-Axis material type and should be characterized independently. However, current carrying capability of any bonded joint can be enhanced with larger contact pad area or supplemented with an isotropic conductive adhesive/coating if extra open space has been designed into the circuit for these power leads.

BONDING STRENGTH: The base of the adhesive is a novel, low glass-transition, *"stress-free"* epoxy. The bond strength was designed to be in the range of 1000 psi in the lap-shear mode.

More importantly is the internal stress that is built into the assembly under the bonding conditions(6,7,8,9,10). In most electronic applications, conventional adhesive being high strength with high modulus, the stress is too high to be reliable under thermal cycling conditions. In fact, initial high bond strength of over 2000 psi sometimes leads to delamination or fracture of components when the thermal coefficient of expansion differential is too much.

Figure #3 is an illustration of how internal stress is built up when two similar or dissimilar materials are bonded with adhesive with a sizable difference in thermal expansion coefficients.

The actual bond strength of the materials is related to the adhesive strength of the adhesive material minus the internal stress of the bonding assembly. This is the basic reason why sometimes the adhesive joint will delaminate by itself. It also explains why sometimes when the adhesive is very strong, the substrates may crack because the internal stress is higher than that of the internal strength of the substrates under the specific stress mode. Figure #4 is a schematic illustration of the measured bond strength in relation to the internal stress exerted by the TCE of the assembly.

FATIGUE RESISTANCE: Solder joints, being intermetallic in nature, are susceptible to fatigue failures when used with different substrates. Fatigue problems have been traditionally handled by mechanical design to allow for strain relief. Whenever possible, thickness of substrates is minimized to reduce the absolute strain in the solder joint.

Adhesive joints tend to be more compliant and less susceptible to fatigue failure. However, one has to realize that every adhesive has different properties in this area. The characteristic that one should look for in organic adhesives is the maximum elongation before breakage or the maximum strain allowed for the adhesives. Again this property is improved for the more compliant adhesives.

However, because of the internal stress induced by the TCE differences between the adhesives and substrates that are being bonded, the bond strengths also decrease during thermal cyclings. This is also the reason for parts to fall off after put in service for extended periods of time. Figure #5 is a schematics of such bond strength changes during thermal cyclings of -65°C and +150°C.

In this case the bond strength change is dependent on area of bonding for the common adhesives. While the limit of the bonding area is in the range of 1/2 square inch for alumina to aluminum for an adhesive species of 1 million psi of modulus, it can be bigger for alumina to stainless steel, or smaller other cases such as silicon to aluminum. Thus for most of the adhesives system which include solders, the stress problem have to be tested almost every time when either materials chosen or area of bonding are being changed. This is obviously unacceptable for engineers in the design and reliability discipline.

While such dependence is universal for all adhesives including solders, the "plasto-elastic" adhesives of AI's adhesives with lower Tg of -25°C are far more forgiving. They have been tested for alumina to aluminum up to 5x5 inches, "Duroid"("Teflon") based substrates to aluminum up to more than 30 square inches, polyimide multi-layer circuit to aluminum for up to 100 square inches. The ranges of applicability have been dramatically increased in comparison to less than 1 square cm for gold-eutectic, less than 1 square inch for tin/lead solders, and less than 1.2 square cm for silver-glass and conventional silver-epoxies.

For the electronic applications, where parts and substrates can be drastically different in TCE with the adhesives and between the parts and substates, one should consider and chose based on the long-term bond-strength stability rather than initial bond-strength. It is much preferrable to have an adhesive that has more adequate bond-strength of 1000 psi but do not change over time, over an adhesive of over 3000 psi but decreases over 50% with just 50 thermal cycles.

REWORKABILITY: This is one of the most important characteristics of a solder joint and is known to everyone involved in electronic manufacturing. Most of the epoxy adhesives that were introduced into the electronics industry all bear the same characteristic of high bond strength which has become "trade-mark" for epoxy adhesives. However, this characteristic which is considered a desirable characteristic also makes them very difficult to rework in the case of electronic applications.

The bond strength, or the reworkability, is directly related but not proportion to the rigidity or modulus of the adhesive. The *"stress-free"* adhesives that were pioneered by AI Technology reduce the modulus as much three orders, so that the adhesives can be creased without failure. In fact, they behave more like a plastic-rubber but maintain epoxy versatility and ease of application. Being rubber-like, they will maintain reasonable bond strength of 200-400 psi from 80-150°C(11, 12). At this bond strength they can be reworked by "torque" and by "prying" at the edge. Directly pulling or straight shearing is not recommended because of the 300 psi norminal bond strength will easily require more than 300 pounds if the bonding area is in the range of one square inch. The important point in reworking is to create a "stress-concentration" area so that the application of force of a few pounds can be translated to more than 500 psi locally while the bonding material is being torn away during reworking. The residues can be soaked and wiped off with a suitable non-toxic chemical agent or by mechanical scrubbing. Figure #6 is an schematic illustration of the reworkability of adhesives with different bond strengths and glass transition temperatures.

CONTACT RESISTANCE AND CHANGES: While fatigue/bond-strength reduction and stress induced delamination and cracking are relatively well documented phenomenon, there is one aspect of the electrical characteristic that is not well documented to be related to stress in a bonded assembly. The contact resistance of the a- bonding contact increases depending on the internal stess of the assembly during thermal cyclings. Being the internal stress depends on TCE differences between the adhesives and the parts being bonded, and also depends on the area of bonding, the stress level can be detrimental in some the case of large area while acceptable for other case that are substentially smaller in bonded area.

Figure #7 is a typical example of the contact resistance increase for a gold-to-gold bond using conductive silver adhesives of different rigidity with an area of 1.5x1.5 square inches. The reason for the change in contact resistance can be attributed to that of the stress-induced contact spacing changes inside the adhesives and between the gold substrate and adhesive interface. Since the conductivity of a metal filled adhesive/composite can be directly attributed to the tunnelling between adjacent conductive species(13).

BRIDGING: This phenomenon is also one of the best known defects in a soldering operation. While this defect can be improved with suitable manufacturing and chemical modification, there is an inherent limitation roughly in the order of 5 mils separation between the nearest conductive traces. This is barely usable for the outer lead bonding of tape-

In some of the more advanced electronic interconnections, such as inner lead bonding of TAB, the joints are achieved by thermo-compression between gold pads or gold-tin pads. The closest distance between conductive traces is in the range of 1-2 mils.

The use of conventional adhesives has similar limitation to that of solder paste. They are basically limited by the application technique be it stencilling, needle dispense, screening, etc.. Any closer spacing will cause bridging, just the same as in a solder joint(14, 15).

Uni-directional conductive adhesives and elstomers have been used extensivley for display applications for over 10 years with high reliability as commonly observed in calculators and watches. However, all of these applications involved high impedance circuits where 200 ohms of contact resistance is acceptable. There is limited information on applications in the low impedance devices.

The development of a Z-Axis conductive adhesive with a suitable conductive media instead of silver and yet maintaining low impedance will be an advancement in material technology. AI Technology has coupled its *"stress-free"* epoxy technology with Z-Axis technology for a conductive interconnect as close as 3 mils separation between traces. Interconnect in the range of 1 mil is under development.

MIGRATION RESISTANCE: Tendency for metals to migrate can cause soft errors and even shorting. It directly contributes to the reliability of the electronic assembly.

Traditional solders are reasonably resistant to migration. However, silver in traditional adhesives is one of the conductors that is known for its tendency to migrate. The tendency for materials to migrate is related to the energy required to release the outer most electron from the atoms or molecules (16, 17, 18). The actual migration of any elements depends on the interaction of the element with water.

It has been well documented that anodically stable metals like gold,. platinum, palladium are not susceptible migration. However, there are anodically passivated elements such as Ti, Zr, Al, and W which are not susceptible to migration. Nickel, tin, and kover, which dissolve anodically in water in small quantity are not problems in migration. The worst element is silver then lead, solder, copper, zinc, phosphor, and bronze.

Thus, the use of silver should be complimented with some form of protective coating if spacing between conductive traces is less than 20 mils. Other noble metals such as gold, palladium, and platinum are good for migration control but tend to be extremely expensive and are reserved for limited applications only.

Z-Axis conductive materials with non-silver, non-migrating metallic based products and with contact resistance of less than 5 milli-ohm have been successfully developed using *"stress-free"* adhesives(19).

CORROSION RESISTANCE: Corrosion resistance is related to the galvanic interaction between different metals(5) under a high moisture environment in the presence of an electrolyte such as ionic contamination. Tin lead/copper solder joints are somewhat susceptible to corrosion in exposed conditions. Silver with copper and other metals are typically not acceptable under extreme conditions, even in an adhesive environment.

The best joint for adhesives will be served with gold to gold contacts. We have developed products both conductive and Z-Axis conductive adhesives with "Silver-Sub" conductive fillers which are as conductive as silver but with corrosion and migration control like that of palladium or gold.

THERMAL STABILITY: Metallic joints are stable in terms of long-term heat aging at temperatures close to the melting points of the solders. In the case of conductive filled organics, the thermal stability is directly related to the fillers involved in the adhesive. Figure #8 is an illustration of different materials tested for thermal heat aging.

Silver and other precious metal-based adhesives have demonstrated thermal stability to temperatures as high as the polymer binder itself can withstand. "Silver-Sub" materials have been tested for thermal stability and can be used for 150^{o}C continuous duty applications.

Z-AXIS ADHESIVE IMPROVES PRODUCTIVITY AND MANUFACTURABILITY

The fact that one does not need to worry about the potential bridging between conductive pads eases the application of the adhesive for the interconnections. Thus, Z-Axis adhesives tend to enhance both the manufacturability and productivity of close pitched circuits and devices. Figure #9 is an illustration of how the Z-Axis conductive adhesives can be used to simplify the interconnection of electronic assemblies.

In addition, there will be no cleaning required for Z-Axis adhesives, saving both management and production time, as well as equipment and material cost of cleaning.

Engineering efforts have been invested in developing various formats of adhesives for choices of application methods under different manufacturing environments. For most of the applications requiring moderate to low contact resistance, nominal pressure is applied during the "flow" stage for milli-seconds during the adhesive bonding process with the final cure being finished without pressure. The adhesive systems include: 1-component, snap-curing(20 seconds/180^{o}C); 2-component,ambient curable; room temperature storable, tacky film with snap curing characteristics(20 seconds/180^{o}C); ambinet stroable, tack-free film with snap-curing characteristics(20 seconds/180^{o}C); and "reflowable" thermoplastic-based with high moisture resistance for ultra-fast bonding(milli-seconds/180-325^{o}C/5psi). The overall characterisitics are summarized in Table #1.

Z-AXIS CONDUCTIVE ADHESIVE IMPROVES THERMAL INTERFACE

One of the principle applications of Z-Axis adhesives will be to replace solder cream in surface mount applications. This type of change will obviously require some changes in the surface preparation other than "tinning" on the components. However, there are some major advantages, as described in the in the previous paragraph.

One additional advantage is the incorporation of thermal conductivity in the Z-Axis adhesives, so that both thermal management and component attach can be achieved at the same time. Figure #10a,b is an illustration of such an application demonstrating this additional advantage. The thermally conductive, Z-Axis conductive adhesives can be in the range of 12, 25, or 80 Btu-in/Sq. ft-hr-^{o}F, depending on the thermally functional additives being used. Both paste and film formats of Z-Axis adhesives are available(19).

Z-AXIS FILM ADHESIVE FOR TAB OUTER-LEAD & INNER-LEAD BONDING

Because outer lead bonding for TAB can be 6 mils or less, soldering can be a problem. The use of a Z-Axis adhesive will be ideal for this type of application. The fact that the adhesive is available in both a film or paste format also provides improvement in manufacturability.

The closest spacing allowed for the current system of Z-Axis conductive adhesive is 5 mils between closest pads of conductive traces(19). AI Technology is currently working on materials that will allow finer pitch(2 mils) inner-lead bonding. Figure #11 is an illustration on how Z-Axis conductive materials can be used in outer-lead bonding of the TAB devices.

Z-AXIS,THERMALLY CONDUCTIVE ADHESIVE FOR FLIP-CHIP APPLICATIONS

One technological difficulty inherent in Flip-Chip technology as invented by IBM(20) is thermal management of the power ICs. The chips being "hanging in the air" are not conducive to easy thermal transfer in this type of C4 configuration. However, because of the potential for extremely high I/O capability of C4 configuration, flip-chip is still the a technology of extreme importance. A *"stress-free"*, thermally conductive, Z-Axis conductive adhesive not only solve the inherent problems of flip chip thermal management, it actually enhances the wider use of the technology. The fact that the *"stress-free"* adhesive acts as a buffer between the die and substrate, the substrate is no longer required to be silicon or matched in TCE. The wider choice of substrate materials will enhance the wider acceptance and use in differnent applications.

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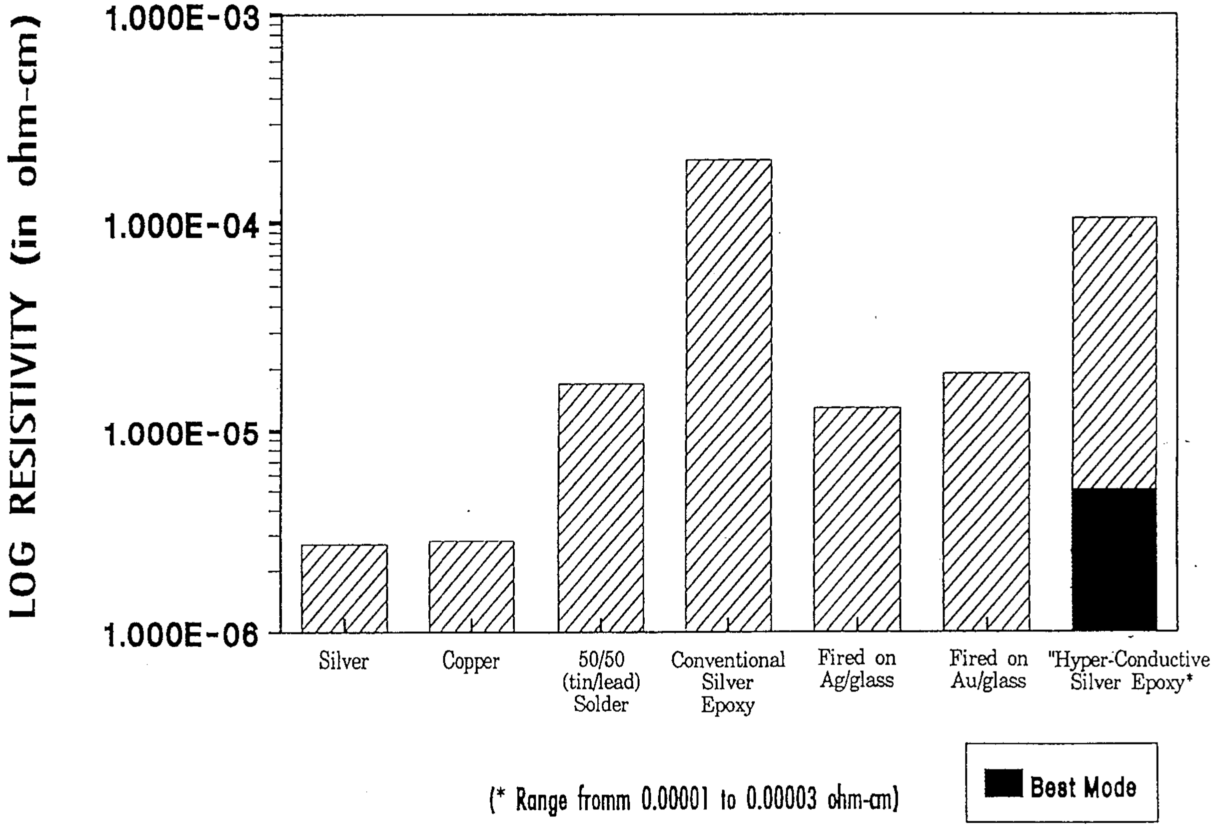
TABLE #1: SOME TYPICAL PROPERTIES OF Z-AXIS THERMALLY CONDUCTIVE ADHESIVES

Contact Resistance (milli-ohm/mm^2)	<10
Recommended Separation between Conductor Pads (mils/mm)	5/0.012
X-Y Dielectric Strength (V/0.005")	300
Glass Transition Temp.(°C)	-25
Lap-Shear Strength	1000 psi 7 N/mm^2
Device Push-off Strength	1500 psi 12.7 N/mm^2
Tensile Elongation (%)	>30
Hardness (Shore A)	80
Cured Density (gm/cc)	2.3
Linear Thermal Expansion Coeff. (ppm / °C)	110
Maximum Continuous Operation Temp. (°C)	150
Tensile Modulus (x10^{6}psi)	0.01
Poisson Ratio	0.45



(* Range fromm 0.00001 to 0.00003 ohm-cm)

FIGURE #1:

VOLUME (BULK) ELECTRICAL RESISTIVITIES OF SOME COMMON METALS, ALLOYS SOLDERS, AND ADHESIVES USED IN ELECTRONIC PACKAGING.

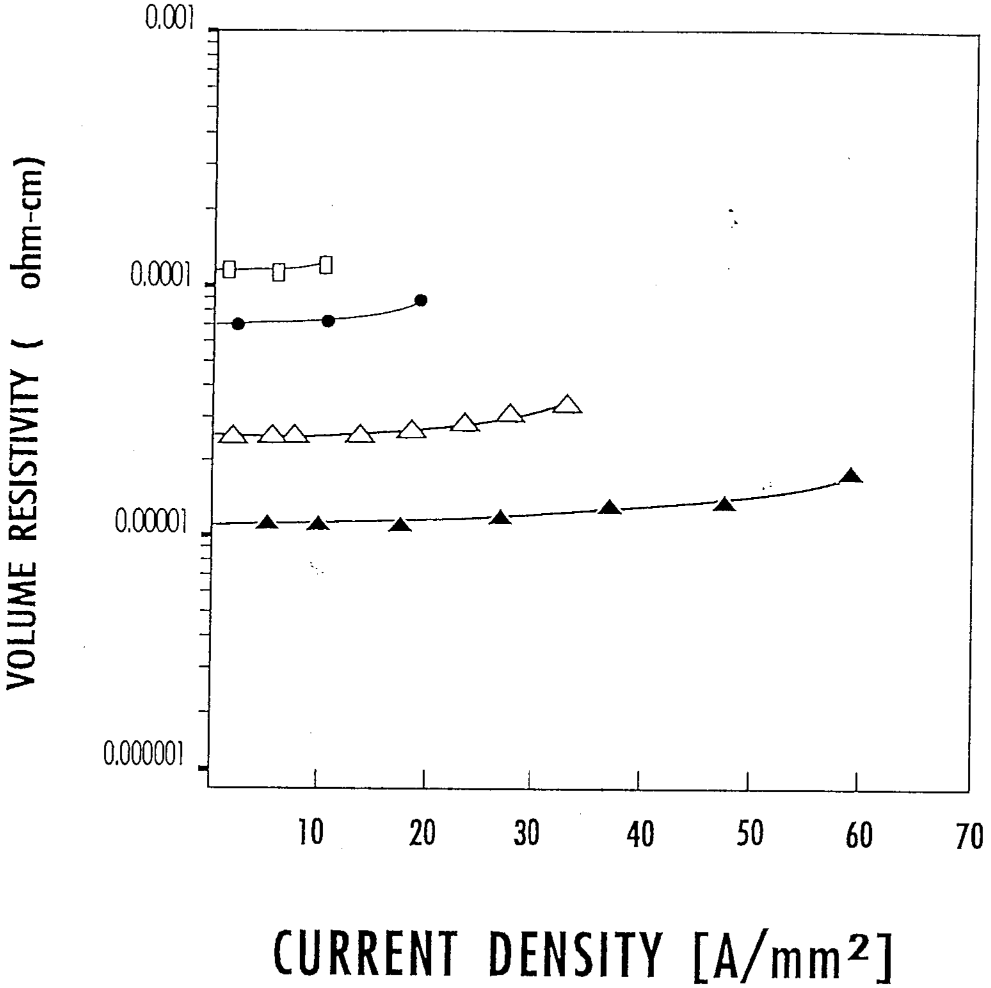


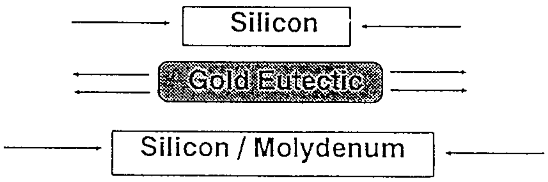
FIGURE #2:

CURRENT CARRING CAPABILITY AS A FUNCTION OF INTRINSIC RESISTIVITY OF SILVER-BASED ADHESIVES. RESISTIVITY INCREASES WITH MORE CURRENTS BEING CARRIED WITH ENENTUAL "BURN-OFF" IN THE ADHESIVE.

$TCE_{Si} = 3$ ppm/°C
$E_{Si} = 60 \times 10^6$ psi

$TCE_A = 20$ ppm/°C
$E_A = 10 \times 10^6$ psi

Soldering Temperature = 225°C; Ambient Temperature = 25°C;



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

$$
\begin{aligned}
\sigma_{Si} &= \varepsilon_A \times E_A = \sigma_A \\
&= (\alpha_A - \alpha_{Si})\,\Delta T \times E_A \\
&= 17 \times 10^{-6} \times 200 \times 10 \times 10^{6} \text{ psi} \\
&= 34{,}000 \text{ psi} \\
&\text{when } T = 25^{\circ}\mathrm{C}
\end{aligned}
$$

FIGURE #3: STRESSES FOR DEVICE ASSEMBLED WITH CTE MATCHED SUBSTRATES BUT CTE MIS-MATCHED ADHESIVE

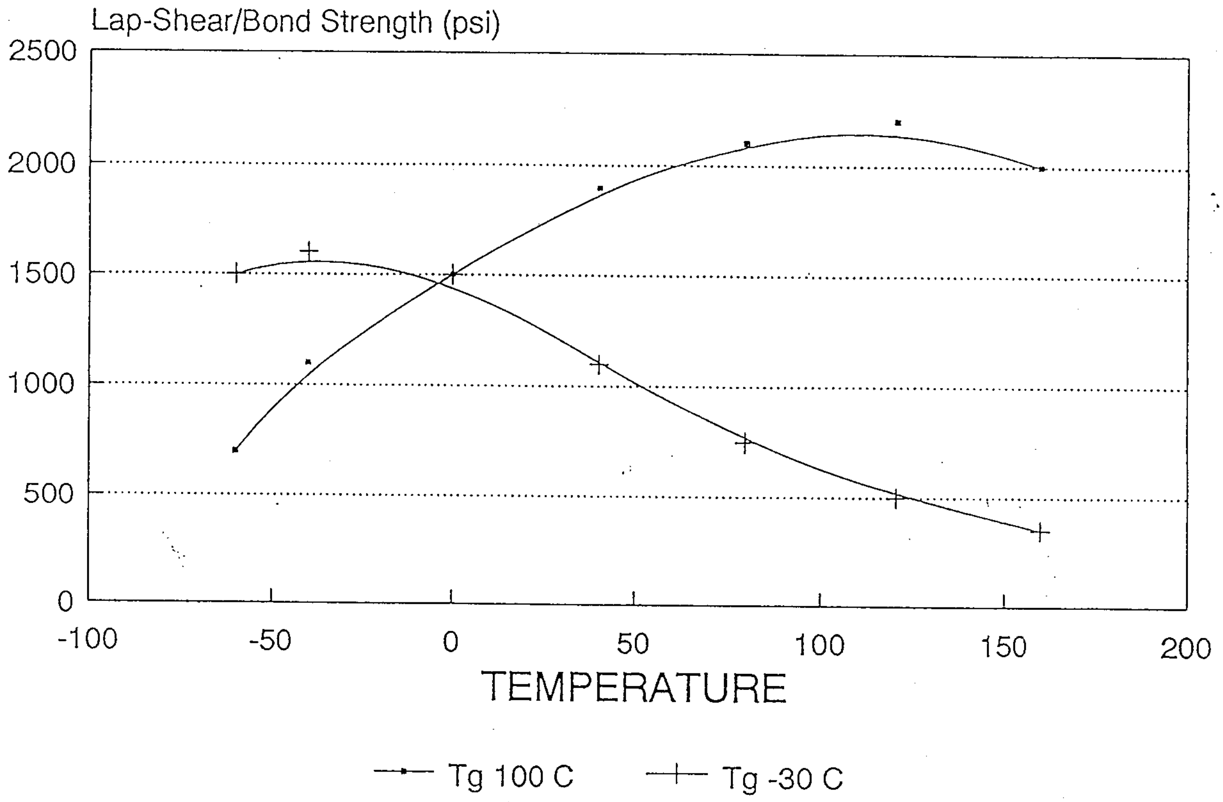


FIGURE #4: BOND STRENGTH OF ADHESIVE WITH DIFFERENT GLASS TRANSITION TEMPERATURES. BOND STRENGTH TENDS TO REACH MAXIMUM AT Tg AND DRPOS AT LOWER TEMPERATURES BECAUSE OF INTERNAL STRESSES. BOND STRENGTH ALSO DECREASES ABOVE Tg DUE TO THE DECREASE IN THE INTRINSIC STRENGTH OF ADHESIVES.

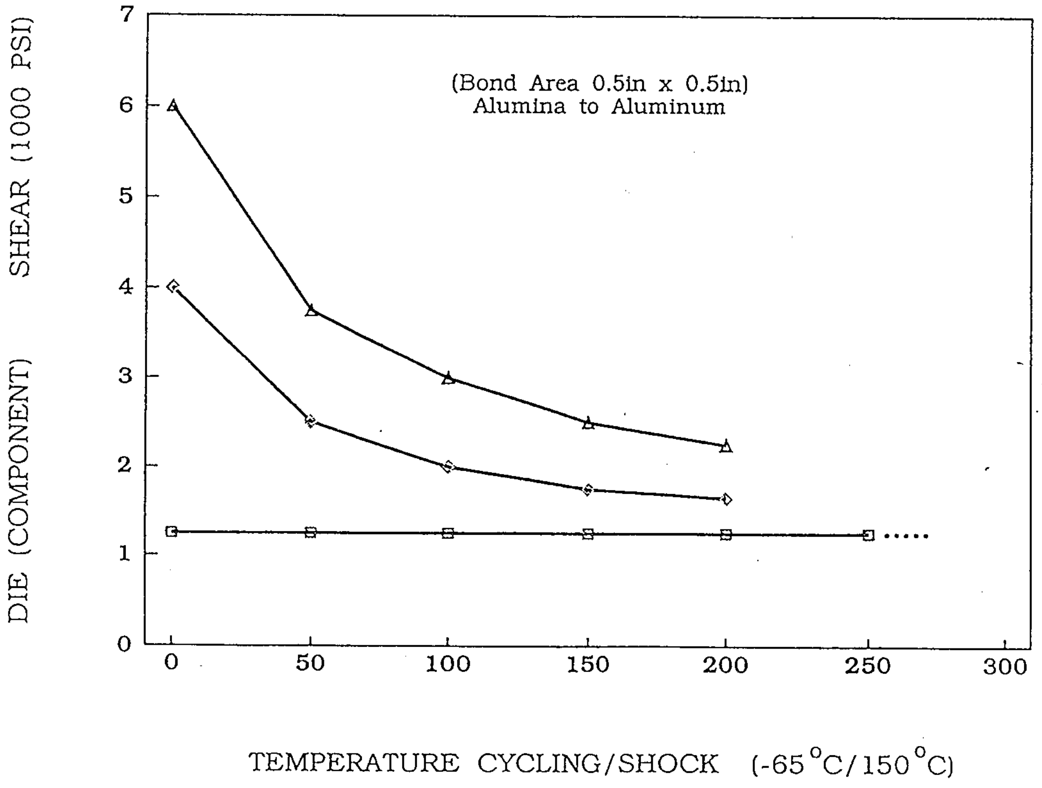


FIGURE #5: BOND STRENGTHS AS A FUNCTION OF THE NUMBER OF THERMAL CYCLES FOR A MISMATCHED SUBSTRATE. HIGH RIGIDITY ADHESIVES TEND TO POSSESS HIGHER BOND STRENGTH UPON ASSEMBLY BUT DECREASES RAPIDLY AND CONTINUOUSLY UPON THERMAL CYCLING. "STRESS-FREE" ADHESIVES TEND TO MAINTAIN CONSTANT AND ADEQUATE BONDING CHARACTERISTICS.

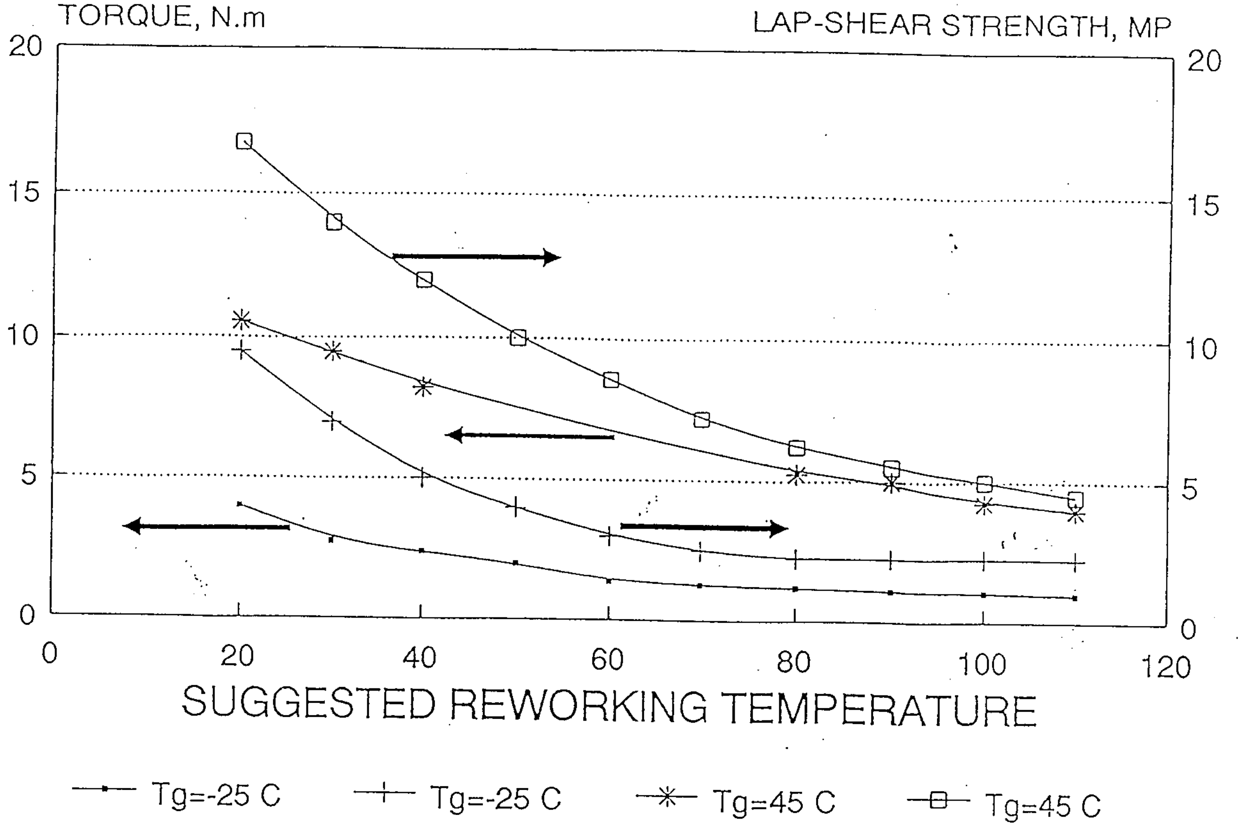


FIGURE #6: "STRESS-FREE" ADHESIVES BEING THERMOSETS MAINTAIN CONSTANT BOND STRENGTH OF 300-500 PSI WHICH CAN BE REWORKED WITH "STRESS-CONCENTRATION" INDUCED BY TORQUE, TWIST, OR TILT MOTION. TORQUE STRENGTH ALSO TENDS TO HAVE A LESSER TEMPERATURE DEPENDENCE THAN LAP SHEAR MODE OF STRESS.

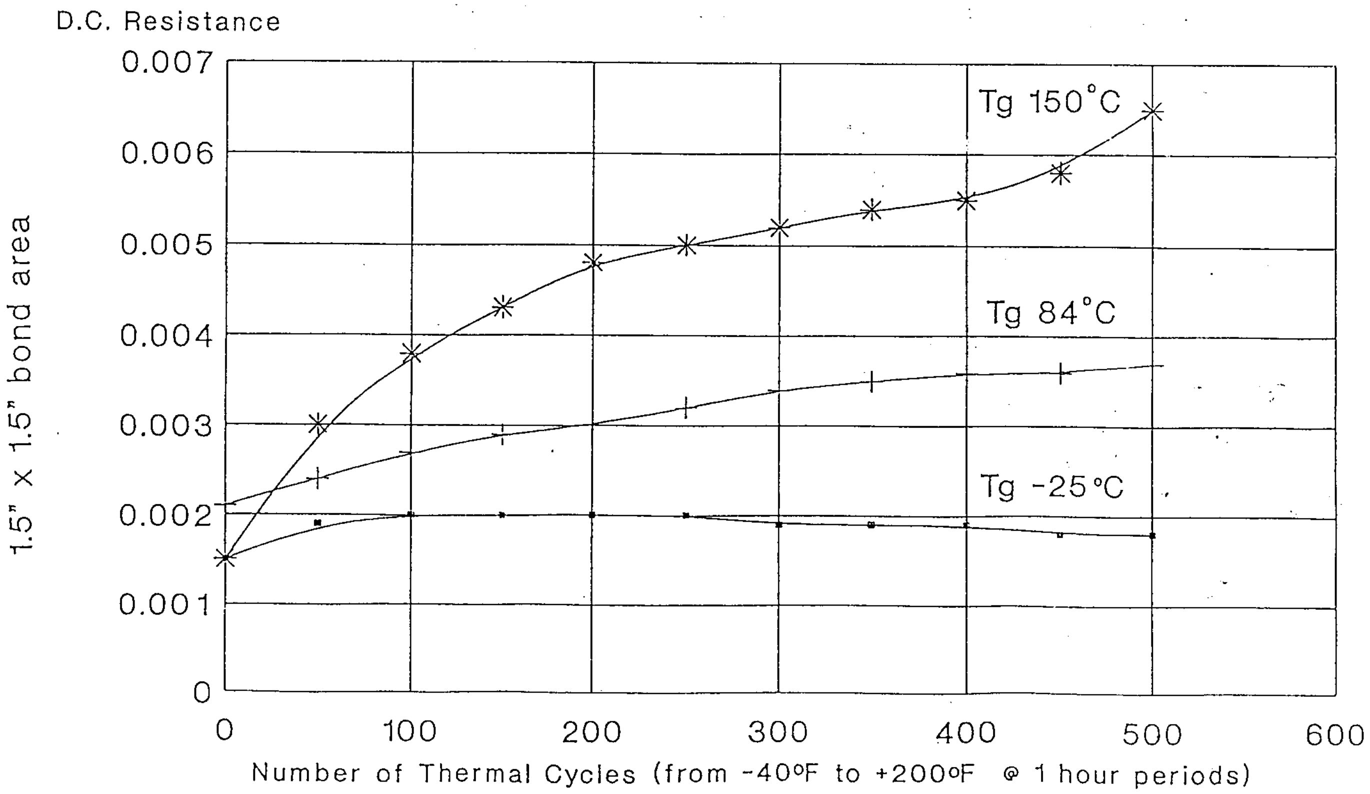


FIGURE #7: CONDUCTIVE ADHESIVES WITH DIFFERENT GLASS TRANSITION TEMPERATURES WHICH ALSO INDUCES DIFFERENT LEVELS OF INTERNAL STRESSES. THERMAL CYCLING MAY CAUSE "RELAXATION" OR "MICRO_VOIDING" ALONG THE BONDING INTERFACES AND THUS AN INCREASE IN CONTACT RESISTANCE. "STRESS-FREE" ADHESIVES SHOW NO CHANGE IN ELECTRICAL CHARACTERISTICS.

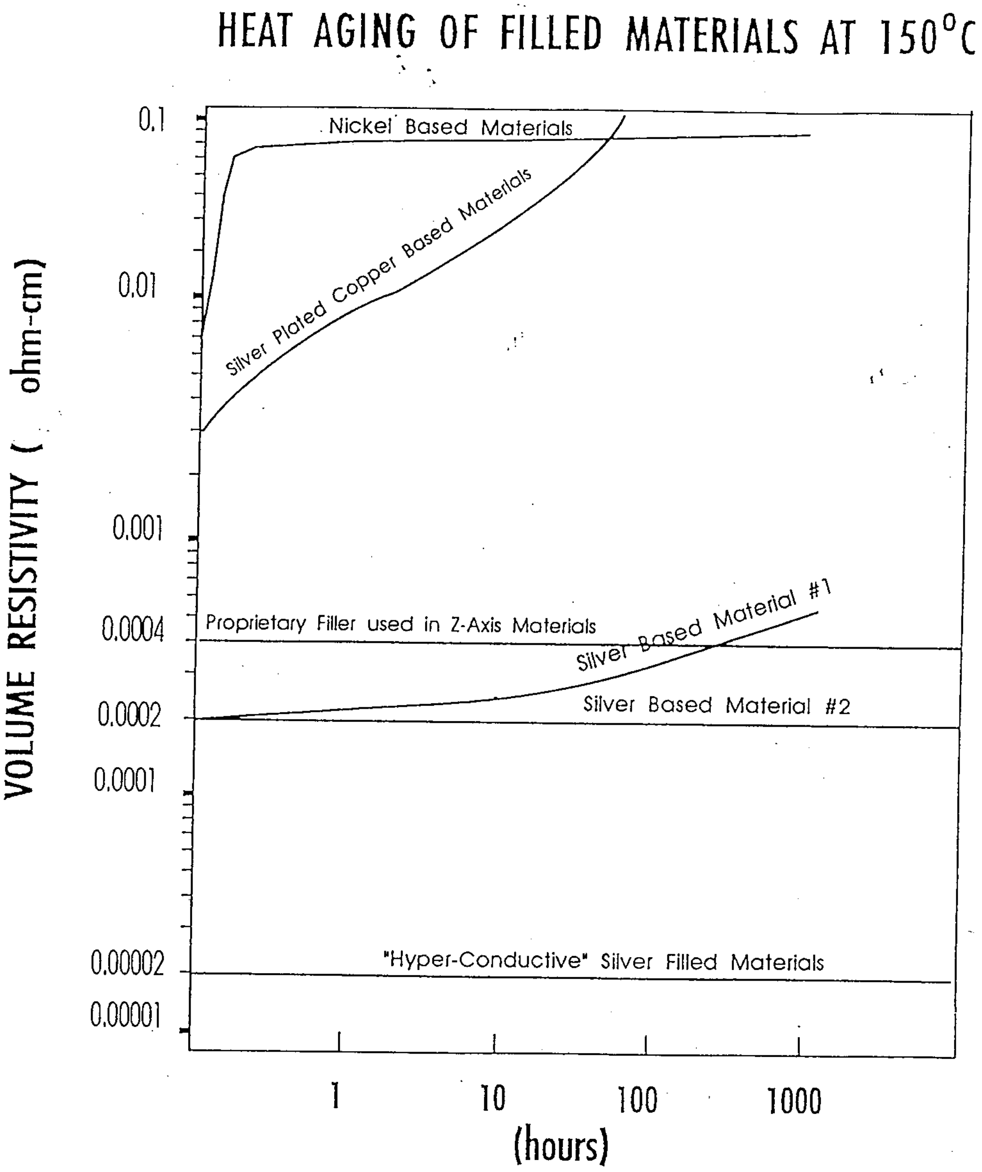


FIGURE #8:

HEAT AGING CHARACTERISTICS OR THERMAL STABILITY OF ADHESIVES USING DIFFERENT TYPE OF METALLIC FILLERS.

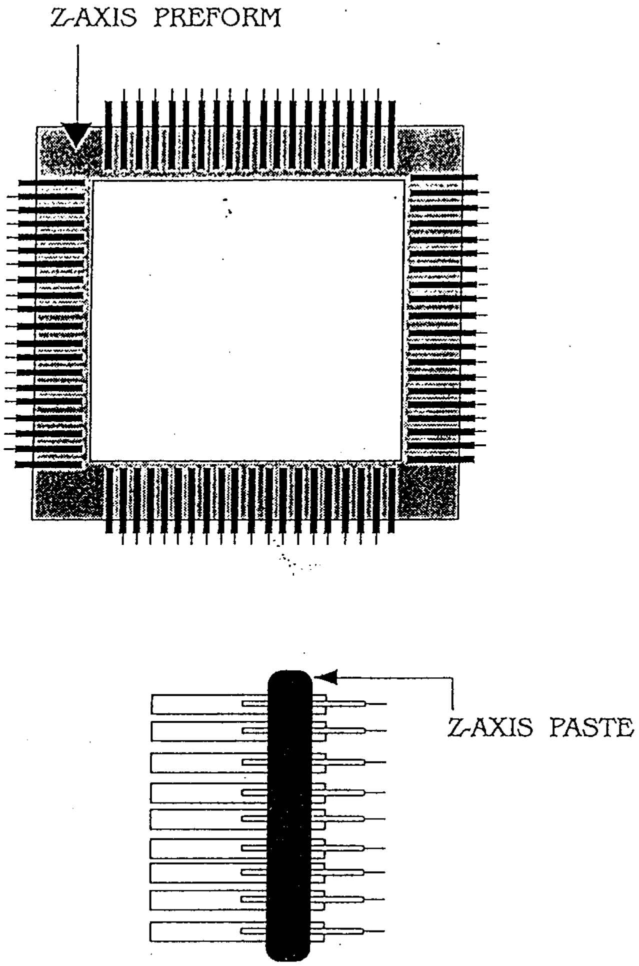


FIGURE #9: Z-AXIS ADHESIVES IN FILM AND PASTE FORMATS CAN BE USED IN COMPONENT ATTACH AND CONNECTOR BONDING WITHOUT BRIDGING.

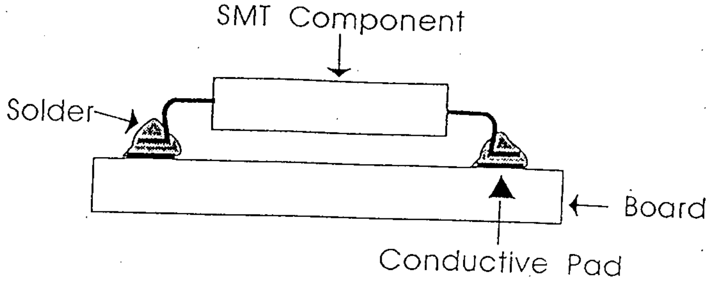


FIGURE #10 a.

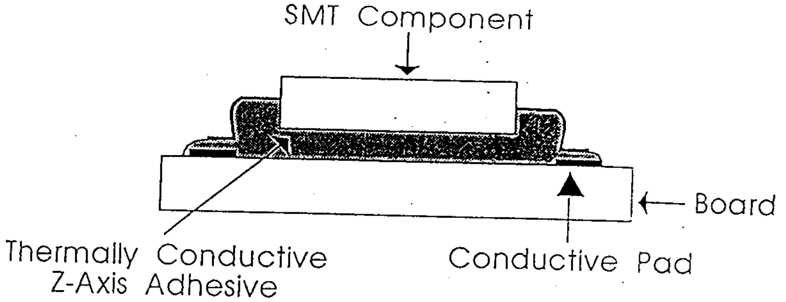


FIGURE #10 b.

Z-AXIS, THERMALLY CONDUCTIVE ADHESIVE CAN PERFORM ELECTRICAL INTERCONNECTION AND THERMAL SHUNTING AT THE SAME TIME.

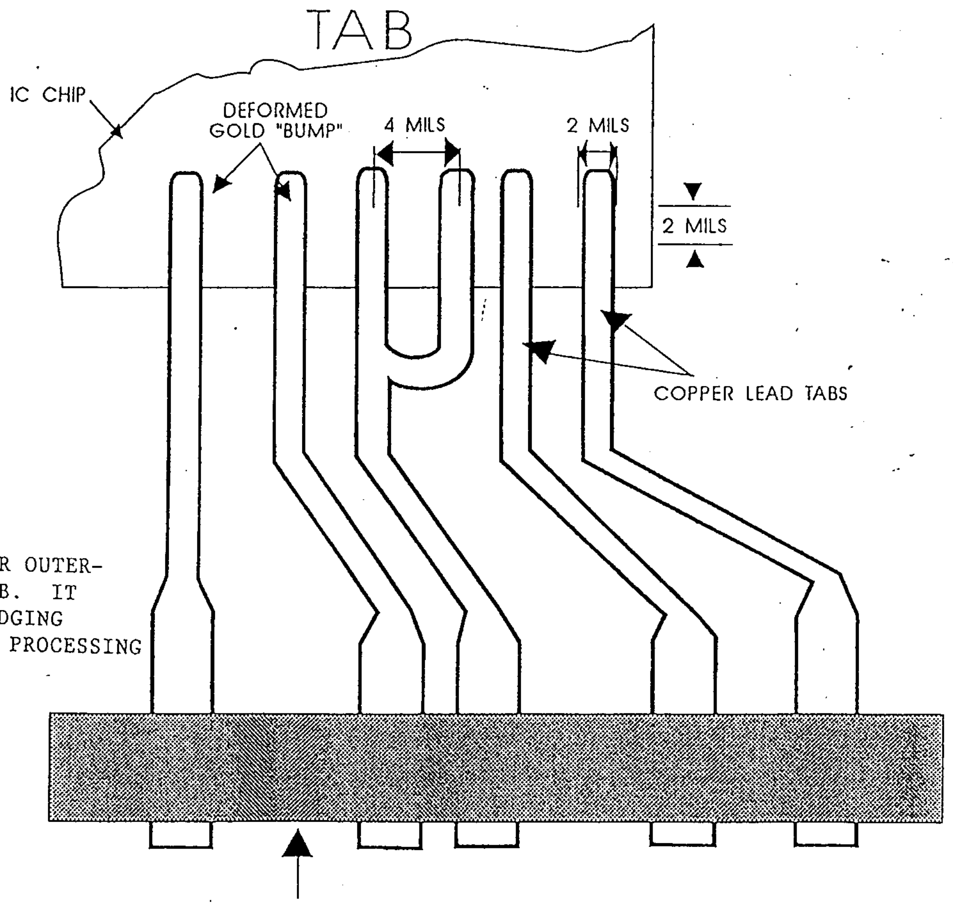


FIGURE #11:

Z-AXIS ADHESIVE FOR OUTER-LEAD BONDING IN TAB. IT ELIMINATES THE BRIDGING POSSIBILITY IN THE PROCESSING