Presented at IPC Printed Circuits Expo®
SMEMA Council APEX®
Designers Summit 04

When are Conductive Adhesives an Alternative to Solder?

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Conductive adhesives (CAs) have been an important problem-solving class of assembly materials for decades, but primarily as die attaches products, ever since they replaced metallurgical systems. Renewed and intensified interest in lead-free (L-F) electronic assembly has moved CAs back into the spotlight. Although lead-free solders, both new and very old, have been studied for several years, they are a partial solution at best. One may conclude that: (1) lead-free alloys do work, (2) there is no drop-in replacement, and (3) their higher processing temperatures are detrimental.

The expected increase in soldering temperatures is cause for concern over potential damage to laminates, packages and some semiconductors. New alloys will also require modifications to some soldering equipment. High temperature L-F processing could bring significant and costly "collateral damage". BGAs could require pre-bakes, PWBs may degrade and optoelectronic components could fail or suffer reduced lifetimes. The next-generation sub-micron CPUs, with evolving low k dielectric layers, may not tolerate excessive soldering temperatures. These problems may be "fixed", but not truly solved. Cost-adding work-around strategies include higher performance laminates, upgraded molding compounds and in-process cooling, but considerable time and money will be needed to re-engineer, re-test and re-qualify.

Polymer Solders (Conductive Adhesives) have provided a good alternative for temperature-limited assembly for decades. These well-tested joining materials process like solder on the same equipment. Fluxing or cleaning is never required. And they run at more than 100 degrees lower than solder. Both reflow and batch ovens can be set at 110°C to 150°C to quickly harden these polymer systems. Adhesives are used to assemble SMTs to a variety of systems including medical devices, memory modules, and computers. Chances are that LEDs in your business phone and ink jet printer are assembled with conductive adhesives. Perhaps the flip chips driving your flat panel display are adhesively bonded.

This paper will compare Polymer Solders to L-F alloys to show limitations and advantages for the technology. There are important restrictions, especially lower mechanical strength revealed in the drop test. But adhesives research has been energized after years of simple incremental improvements and fresh new approaches will be summarized that include intrinsically conductive polymers (ICP) and Nanomaterials.

Keywords : *conductive adhesives, silver, lead-free, low-temperature, Nanoelectronics, solderless, epoxy, degradation.*

Lead-Free Alloy Processing

Unimpeded by a conspicuous lack of scientific evidence for negative environmental impact by electronic Sn/Pb, the industry has jumped onto the run-away lead-free (L-F) train and can't seem to get off. Sadly, the electronic lead-free initiative is no solution to the real lead problem that kills and debilitates children since toxic lead-bearing paint remains on old walls. While some point out that the train is "hell-bent" not "hell-bound", the replacement alloys may subject assemblies to Dante's Inferno. The cost of new alloys will not be in the solder, but in the side effects of HEAT! While lead-free is heating up, can the process stay cool? The cool answer maybe to go solderless, but first let's explore the lead-free alloys.

Lead-free alloys were probably discovered 7,000 years ago as naturally-occurring materials and so the concept is rather ancient[1]. Extensive work on lead-free alloys has not led to anything even close to a drop-in replacement for centuries old tin-lead solder. While the jury is still out for selecting the alloys that will become standard, a consensus is close. Choices are complex for many reasons. There are "mine fields" of patents that can restrict the choices and the final jury that determines the standard L-F alloy could well be one of the courts. The accepted alloy will be based on tin and will probably contain copper, silver or both. This group of alloys is referred to as "SAC" for Sn, Ag and Cu and ITRI and NEMI are recommending them. Most large solder manufacturers point out that binary systems are preferred, but a tertiary system is feasible. Alloys of more than 3 metals greatly increases the level of manufacturing difficulty and control when we consider all the myriad forms for solder in use today. Furthermore, 4 and 5 metal alloys cannot be applied by plating. The addition of antimony, zinc and even rare metals can't be ruled out but the rationale may be to circumvent patents.

Many material scientists have felt that even tin-lead solder processes required too high a temperature. Nearly all-electronic organic materials are made more expensive because of the soldering process requirements. Excellent dielectrics like polyesters have been bypassed because of incompatibility with the tortures of soldering. Now, we are ready to add insult to injury (or the converse) by raising the temperature and reducing the number of circuit and packaging material choices. The temperature "bar" has been raised.

The processing temperatures for SAC alloys range around 240^{o}C to 260^{o}C. The L-F alloys do not wet as well as Sn/Pb, but higher temperatures and the use of N_2 improves the situation. Unfortunately, while higher temperatures improve soldering, laminates, SMT-packages, CSPs, standard packaging materials and semiconductors are subjected to added stress and more thermal degradation. Since decades of metallurgical work have not identified a general purpose L-F alloy with reasonable processing temperatures, the likely scenario is a move to processing at 260^{o}C or higher. More and more reports are being published describing damage to soldering equipment caused by the lead-free alloys. The industry will need to fortify the numerous materials that will be subjected to the new, harsher conditions. But there may be another solution that is compatible with today's materials or even low cost, lower temperature types. We will now explore that versatile, gentler and more sophisticated world of organic polymers.

Introduction to Polymers

Polymers have been the enablers of the electronics industry for many decades. The majority of electronic products are not possible without a legion of polymers. These include laminates, die attach adhesives, packaging encapsulants, underfills, wire coatings and a host more. Polymers are used for their excellent insulative properties, high strength, thermal stability, lightweight, ease of use and low cost. But why have polymers become so pervasive since other dielectrics are available?

Polymers are easily shaped into flat sheets for laminates; 3-dimensional forms for packaging, thin coatings for solder masks or any other form required. Processing simplicity and versatility are important attributes. The key to ease-of-use is in the chemistry of these remarkable materials called polymers. We can begin with reactive ingredients that are liquids, called precursors, resins or pre-polymers. The ability to start off with liquids that are transformed into strong solids is one of the most valuable properties of any material. Not only can the onset be in liquid phase, the final product can be a tough, rock-hard structure that doesn't melt or dissolve in solvents. But, the polymer can also be a flexible or even elastic coating or film that can take millions of flexural cycles. Properties are engineered! A polymer-based disk drive circuit has been flexed 1-billion times without failing.

Polymerization – the Magic of Transformation

The polymer precursors must have reactive chemical groups that can form linkages, or chemical bonds, with co-reactants or with one another. The most common systems in electronics are epoxies. The epoxy group is a highly reactive structure composed of oxygen and two carbon atoms in the shape of a ring. This group reacts with a variety of other agents and those that are specifically designed to produce polymers are called hardeners. The epoxy resin will have two (or more) epoxy groups that react with the hardener. Likewise, the hardener will have two (or more) reactive groups. This produces a polymer chain made up of repeating blocks of epoxy and hardener. Many other reactions occur that produce links between the growing chains, called cross-links. The final result is a network of polymer chains that are connected in a 3-dimensional array to produce a strong, non-melting mega-molecule that retains whatever shape it had when the linkages formed.

Conductive Adhesives

Polymers are the workhorse insulators for the electronics industry so does it even make sense to consider them for electrically conductive assembly joining materials? The answer is maybe. Although intrinsically conductive polymers (ICP) are known, none have been developed with the right balance of electrical and mechanical properties required for joining materials. Often, conductivity is only in one geometric plane and mechanical strength is low.

The strongest polymers are excellent dielectrics. However, polymers are greatly modified by fillers, insoluble agents that are added to produce composites. The filler, more than the type of polymer, determines the class of product. An epoxy can be used for package molding compound, underfill, die attach or SMT conductive adhesive based on the type and amount of filler.

Conductive Adhesive Fillers

All useful fillers for conductive adhesives are initially electrically conductive and must remain so. Virtually all are metals or metal-coated materials. Carbon has been used to make high resistance adhesives that have extremely limited use. But carbon nanotubes (CNT) and nano-fibers can be highly conductive. The most useful type for SMT assembly is the isotropic conductive adhesive (ICA). This is a highly filled composite that is equally (isotropically) conductive in the X, Y and Z planes. This can only be accomplished with good conductive filler that is stable throughout the life of the product. Although metals remain conductive, they typically form oxides on their surfaces that are good insulators and therefore barriers. This means that practical fillers for making conductive adhesives cannot form an insulative oxide. Nobel metals, like gold, do not oxidize and can be used. However, lower cost silver forms a conductive oxide that makes it useful. Silver also can be precipitated into fine powder and is malleable enough so that it can be milled into useful shapes such as flake. While copper, or another widely available and lower cost metal would be preferred, none have been successful. Copper oxidizes and no inhibitors or coatings have produced a truly successful product. Silver-coated copper has been used with limited success but can cost more than silver because of the processing difficulty and low volume.

Work continues to produce conductive fillers from base metals and some approach may ultimately succeed. Success has been wanting in this area but efforts continue and are increasing. One on-going research program seeks to apply thin layers of intrinsically conductive polymers to copper flake. This approach could boost mechanical strength and conductivity but progress has been slow. Solder-coated metal may also hold promise but unusual problems crop up in dealing with micron-range metal particles.

Toronaga, Inc. began exploring a different concept several years ago using copper particles in materials called Ormet, for organic-metal. The adhesive-like products combine fine copper powder with solder ingredients in an epoxy adhesive matrix that had oxide-reducing chemistry. During the curing process, the copper and other metals formed alloys in a sintering type process to produced electrical pathways of continuous metal within the polymer binder.

Conductive Adhesive Compositions

The isotropic conductive adhesives have been used in high volume for SMT assembly for decades. More recently, certain areas of flip chip assembly have switched to conductive adhesives. The ICA materials consist of polymer binder, a substantial amount of silver filler, wetting agents and rheological additives. The binder is typically a blend of epoxy liquid resins, hardener and accelerator. The resins and hardener determine the pre-cure and post-cure characteristics while the accelerator influences the rate and temperature of curing.

The filler is much more complex that just simple metal particles. The typical composition is a blend of precisely fabricated powder and flake designed to fit together. Fine powder becomes interspersed between flakes to fill gaps. Both are treated with surfactants and proprietary coupling agents (aid in creating metal-to-metal contact). The morphology of the flake is the most important since “flagstone like” micro-particles must over-leaf one another to make electrical pathways. Figure 1 shows the complex orientation in cured adhesive.

Figure 1 – Conductive Adhesive SEM

Even when the particle shape and surface is optimized, adhesive formulating is a tricky balancing act with as much art as science. Producing the greatest amount of inter-particle contact maximizes electrical conductivity. Having minimum particle contact so that the polymer is a continuous phase maximizes mechanical strength. Said differently, best electrical properties require a minimum amount of epoxy in their path while great mechanical strength is achieved with less filler. The best we can do with this model is to compromise and achieve enough conductivity for most applications while allowing mechanical properties to be the dependent variable. Some would argue that conductive adhesives need more conductivity and strength, so let’s look at properties.

Properties

Solder has been the *de facto* standard for electronics so all joining materials are compared to solder. Eutectic Sn/Pb is the present standard for comparison for CAs and L-F solders. Table 1 compares the two products. The CA values are a generic average of commercial products. Some adhesives are up to an order of magnitude more conductive. Some are stronger than solder, but none are more conductive and stronger.

Table 1 – Adhesives vs. Solder

Characteristic	Sn/Pb Solder	Polymer Solder
Volume Resistivity	.000015 ohm.cm	.00006 ohm.cm
Typical Junction R	10 - 15 m	<25 m
Thermal Cond.	30 W/m-deg.K	3 - 5 W/m-deg.K
Shear Strength	100%	40 - 110%
Mechanical Shock	Good	Poor
T & H (85%/85C)	no change	product specific
Finest Pitch	12 mil?	down to 6 mils
Min. Proc. Temp.	210 - 220C	25 - 150C
Envir. Impact	negative	minor?
Thermal Fatigue	yes	can be minimal

Electrical

The first apparent deficiency for adhesives is volume resistance that is several times higher. However, this is not a problem for 95% of the applications. First, the resulting junction resistance is only half as much as would be predicted from volume resistivity. This is because adhesive joints need only ½ the thickness and shorter resistance paths result. As should be expected, the adhesive joint follows Ohm’s Law. We should also note that internal package resistance could be higher than that of the adhesive joint. High frequency performance is good since electrical conductivity tends to improve at higher frequencies since the adhesive flake can act like a capacitor (capacitor conductivity increases with frequency).

Junction Stability

Since solder forms a true metallurgical junction between circuit pads and components, stability is not an issue unless mechanical integrity is compromised. But adhesives form pressure contacts where filler particles touch the opposing metal surfaces. This is the most fundamental difference between the two joining materials. For adhesives, a good mechanical joint is not a guarantee of electrical properties. Worse yet, good initial conductivity is no assurance of future performance. A PWB, for example, can oxidize in the presence of adhesives. This does not happen with solder joint in place. The silver filler particles within the polymer matrix can initially provide a good electrical path that is later interrupted by oxide formation as shown in Figure 2.

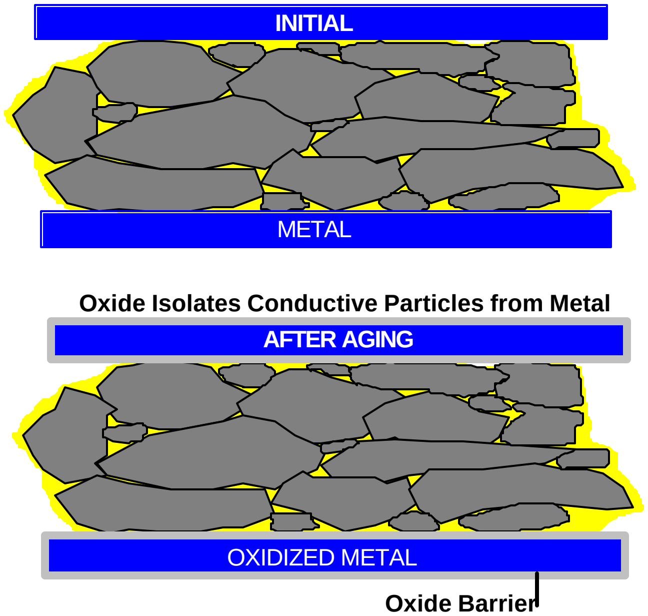

Figure 2 – Junction Stability Problem

There is usually no problem within the adhesive structure and volume resistivity remains low and may even improve. But if oxide grows on the PWB pad and component lead, the conductive adhesive joint will experience high resistance and even act like an “open”. This problem was recognized in the 1980’s as SMT was becoming popular and adhesives were investigated for this relatively new assembly process. Even when gold-plated circuits were used, adhesive joints showed an increase under accelerated aging. The problem was the tin-lead coating used on nearly all SMDs. The industry addressed the issue and several solutions emerged.

AT&T, with its immense buying power, simply ordered silver-plated components. This allowed them to successfully build millions of business telephones on silver-conductor Polymer Thick Film (PTF) circuits. The AT&T products using conductive adhesives were successful and reliable and 15-year old products are in service today.

Contract assemblers required a more generic solution. One company, Poly-Flex Circuits (a Parlex Division) launched an intensive search to find a commercial adhesive with good junction stability. Finding none, they developed their own. Around 1990, while testing their own silver-epoxies, an oven thermocouple failed (according to one early developer). The circuit was all but “fried” since it was made of thermoplastic Mylar®. But the circuit and adhesive junctions were in tact so the circuit was placed in a humidity chamber more or less as a joke. Surprisingly, the partially ruined circuit had reasonably good stability. While frying circuits was not a practical solution, it was the key to solving the problem. Months later, a junction-stable adhesive, aptly named Poly-Solder®, was undergoing extensive testing.

Poly-Solder passed with flying colors and without the need to fry the circuit. The developers concluded that polymer shrinkage had forced the filler particles against the component and penetrated the oxide. The compressed particles were thought to also form miniature gas-tight junctions. Later, Dr. Johan Liu, now at Chalmers University in Sweden, did extensive analysis of Poly-Solder at the same institution with assistance from IVF-Gothenburg. Transmission Electron Microscopy (TEM) suggested that particles penetrated the oxide, but no absolute proof was established. Regardless of the mechanism, this conductive adhesive has been shown to have excellent junction-stability on solder surfaces, but not on aluminum perhaps because of its hard oxide. The product is able to pass 1000 hours at 85% rh/85^{o}C and actually improve in conductivity.

Others have addressed the stability problem using antioxidants and proprietary approaches. Claims are now made that some ICAs are sufficiently stable to be used with solder-coated components. We will assume that the problem has been solved by several and certainly by Poly-Flex/Parlex who has shipped commercial assemblies and has produced more than 500,000,000 CA joints. More than 22-million HP Ink Jet LED assemblies have been made with CAs. Figure 3 shows a mouse pad for laptops made using conductive adhesive. The pad is a printed resistor that detects location by measuring X and Y resistance where the pad is touched

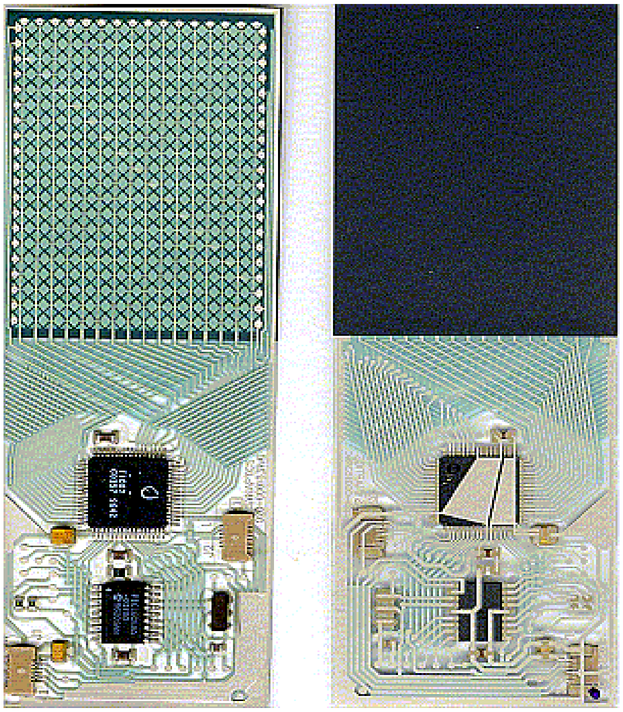

Figure 3 – Mouse Pad Assembled with ICA

Mechanical

Mechanical strength would appear to be reasonable from shear strength data. In some cases, adhesive strength is even greater than solder's. But bond strength does not tell the full story. The rate of force application must be added. Mechanical strength tests using die shear or tension pull methods apply force slowly and adhesives perform well. A mechanical shock test, such as dropping, shows conductive adhesives to be much poorer than solder. This may seem unexpected since epoxies are extremely tough. In fact, solder is a weak material compared to epoxy. So what's going on here?

The problem is in the composite nature of CAs. Figure 4 shows the issue in more detail. The epoxy binder is not really a continuous phase. It looks more like mortar in a wall made of stones with deficient mortar. The mechanical shock force is transmitted to a small boundary of epoxy that must withstand deformation. The forces exceed the bond strength and/or elongation limits of the micro-joint and there is structural failure. In some tests, bonds to the surface-treated silver are also fractured. If we could only reduce the filler level, the epoxy would have excellent performance. This is seen with epoxy underfills and encapsulants where the filler loadings permit the polymer to be a continuous phase. Unfortunately, just at the level where mechanical shock results improve, electrical conductivity falls off. However, progress continues in this area with new shapes for fillers.

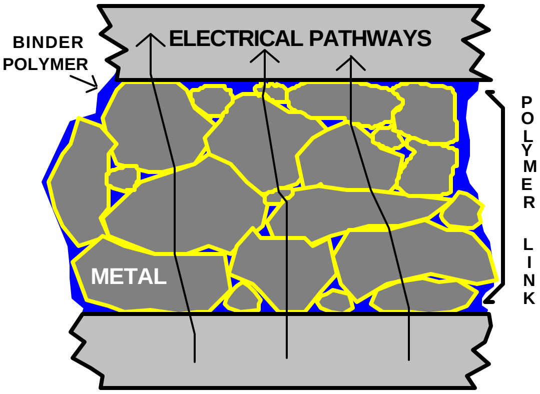

Figure 4 – Model of ICA

Is mechanical shock a "show stopper" for adhesives? Some industries, like automotive, will not consider any joining material that fails a drop test that involves dropping an assembly on edge from several meters. Others argue that the drop test is unfair because components are isolated that would normally benefit from the shock-absorbing properties of the housing. They point out that a calculator can be dropped but its glass LCD would fail if removed and dropped. The counter argument is that solder can pass so any solder alternative must pass. We may note that flexible circuits assembled with CAs do already, however, because of their lightness and compliancy. For now, adhesive developers are trying to pass the drop test without compromising all the other hard-won properties.

Thermal conductivity is also lower by about an order of magnitude and this could be an issue where the joints must carry substantial heat. Some have pointed out that flip chips must use bumps/joints to conduct heat away. However, several recent designs sink the heat away from the opposite side of the die. Thermally conductive underfills may help and they are coming.

SMT Assembly with Conductive Adhesives

SMT was the enabler for conductive adhesive assembly. Feed-through components have never been practical since there is no adhesive equivalent to wave soldering. Polymers cannot “wick & fillet” like molten metal that has a surface tension that is more than an order of magnitude higher. SMDs form ideal adhesive joints (butt joints) and their assembly process is similar to solder.

Adhesive Application

ICAs can be screen-printed, stenciled or needle dispensed and all processes are used commercially. Stencil printing gives the most precision and is preferred. Some PTF circuit shops use screen-printing because they have the capability of producing screens in-house. Needle dispensing is used for larger circuits with only a small component assembly zone, such as a membrane switch with a few LEDs clustered together.

The cardinal rule for adhesive application is “Don’t Apply Too Much”. While solder paste volume is reduced to about half during powder collapse on reflow, adhesive volume remains nearly constant. This means that only half the volume of adhesive is used. A 4-mil (100-micron) stencil will work well, but an 8-mil stencil will probably give poor print quality as the tackier adhesive clings to the excessive wall area. Stencils for flip chips can be 50 to 75 microns thick. Laser or electroformed stencils are preferred over etched. Laser machining produces a natural taper that helps release adhesive. The “hour-glass” shape of etched stencils can interfere with release. However, improved stencil polishing and smoothing methods have reduced the problem.

The customary rules for SMD stencil patterns apply here provided the thickness reduction is kept in mind. But adhesives will stay where deposited so if the features are oversized, material will not be drawn onto the pads like solder. The only situation with special rules is assembly to PTF-Polyester circuits. PTF conductor traces do not have the high bond strength found with copper circuits. Adhesive applied only to pads will tend to pull them off under mechanical stress. Most circuit layouts therefore have SMT pads that allow adhesive to contact the bare polyester where a very strong bond will form. Conversely, the stencil can be designed to accomplish the same result. Overall, the adhesive application process is similar to that used for solder and can be run with the same equipment.

Component Placement

The lower surface tension mentioned earlier, have some important ramifications. The adhesive during the curing step will not orient a misaligned component. Molten solder, with a surface tension of over 500 dyne/cm^2, will generate substantial alignment forces as tension attempts to reduce surface area of the liquid metal. Adhesives have surface tension values in the 35 – 40 dyne/cm^2 range and this will not move a component. Furthermore, the adhesive is typically too viscous to climb up the side of a component termination to produce a fillet. All this means is that more care must be taken in setting up the process. Lack of self-alignment is no longer considered an issue with modern placement equipment.

Package Restrictions

The butt joint, produced with two parallel surfaces, is the ideal joint structure for adhesives. Nearly all components produce this joint. The exception is the bothersome “J” lead. The J-lead was contrived with solder in mind and requires a fillet to achieve maximum strength. The adhesive’s lack of fillet forming dynamics makes the J-lead package the least desirable. However, J-leads can be used with adhesives with the following caveat. Only solder-plated, not solder-dipped leads should be used. The plated leads, signified by a duller, grayer color, have more surface area and can give a reasonable bond. The adhesive dispensing step is more critical and insufficient material will give low bond strength. Components must be placed accurately.

Curing/Hardening

Finally, we have reached the realm where adhesives excel. Conductive adhesives have a COOL profile compared to solder. And this profile is even COOLER compared to those required for the lead-free solders. Many adhesives are cured at only 130^o to 140^{o}C for polyester circuits. Compare this to the 260^{o}C target for L-F products. Some have speculated that materials would have been cheaper had adhesives been employed before solder. But solder was discovered in past millennia and made popular by Roman plumbers who used it to seal joints on the aqueducts. Materials experts in electronics have thus been forced to design laminates, coatings, masks and packaging materials with temperature ratings that can withstand the temperature shock called soldering. Few assemblies really need such high temperature materials except to survive soldering. And now, the world appears ready to raise the bar one more notch approaching the 300^{o}C region of the spectrum. Not only are the alloys higher melting, but also their poorer wetting may require a boost in the oven profile in the 260^{o}C range.

Potential casualties of higher temperatures include laminates, solder masks, epoxy molding compounds (EMC) and some ICs. The EMC suppliers are saying that the higher temperatures will cause more "pop corning" and that pre-drying will become the norm. Photo-electronic devices are sensitive to heat and opto-couplers are already adhesively bonded since even Sn/Pb solder processing is too severe. The new L-F solders will create more problems.

And what about the emerging high performance chips that are moving to low k dielectrics? The last performance boost was achieved by moving to copper interconnects. The next level requires low k materials. Just as the IC industry is on the verge of changing the dielectrics, the assembly industry is on the verge of changing the rules. What happens if ICs adopt organic low k materials and this is certainly a possibility? Can an IC with organic layers take the new heat? And what will the heat do to nano-porous inorganic insulators? One irony of the lead-free movement could be the failure of electronics to keep pace with Moore's Law after decades of success. (Moore's Law states that density doubles every 18-months). The IC industry is spending billions to convert to copper and low k dielectrics and it is unlikely that programs will be changed as assembly, viewed as a servant of semiconductors, debates issues. Just possibly, future ICs may not be able to take 260^{o} – 270^{o}C processing temperatures. What a conundrum!

And what about the newest Nanoelectronics and photonic devices? Will these organic systems take the heat of soldering? But more important, will they even use metallurgical connection technology. The world of electronic is on a path toward change, really monumental change that may make solder and soldering obsolete. The basic material of most of today's Nanoelectronics is the carbon nanotube made entirely of carbon. Will these structures be wire bonded and soldered? Possibly, but not likely! Polymer connection materials are the most likely. These future conductive adhesives could be based on metal-filled polymers, but CNT fillers are just as likely. Already, dozens or projects are underway to make CNT adhesives. And while the CNT conductive adhesives may play a role in Nanoelectronics, the performance may make them suitable for today's assembly.

Enter the COOL adhesives. But before you say that adhesives will never replace solder, be aware that large semiconductor producers have been quietly re-evaluating conductive adhesives. Also, please note that the inventor of the copper IC process has been filing and receiving patents for conductive adhesives. Giants of the industry plan R&D with purpose and we suggest that their interest in conductive adhesives is a hedge against future problems that could result with a boost in soldering temperatures. Perhaps millions or even billions of dollars could be saved.

What's more adhesives solve the temperature hierarchy problem that L-F will reintroduce. Flip chip modules and FC-BGAs are typically built using higher lead, higher temperature solders. This allows the package to be assembled to boards without melting the flip chip joints again. Eliminating lead solders will remove this essential temperature hierarchy. There are higher temperature alloys, to be sure, but thermoset adhesives do not melt once cured. This means that FCs could be used to build CSPs, BGAs and multi-chip modules without re-melt occurring. And since nickel or gold bumps are compatible with CAs, the bumps will not melt. Adhesives have another benefit in that no ? -particles are emitted that cause problems with memory chips, ASICS and high-density CPUs.

Good and Bad Applications

Most assemblies should work with CAs, but there are exceptions at this point in adhesive development. Very high current devices, such as power transistors or controllers, may not make sense. Large and heavy components are going to fare poorly in mechanical tests and should be avoided. Assemblies requiring substantial rework are also going to have problems since CAs are much more difficult to rework. Everything left is fair game. The fact is that adhesives are used in high volume but the applications are those where solder poses problems. The rule has been to use solder where it works and adhesives when there is a problem. Mylar circuits use adhesives. Photonic components on hard board use adhesives. But most of the industry uses solder simply because it works and has a long history. But if lead-free changes the rules it also changes the game making room for new players.

Performance Issues

Limitations

Stated earlier, the mechanical shock test is one of the areas of poorest performance for adhesives. Does it matter? Yes! Until better shock test results can be obtained, adhesives will have a more limited market. The two exceptions are flex circuits and flip chips. Once a flip chip is underfilled, lower joint strength is no longer an issue. In fact, underfill shrinkage tends to compress the filler to make it more conductive. Any concerns about silver migration are all but eliminated since the joints are encapsulated in a good dielectric. Cost for adhesives is higher with the present silver-filled products. A switch to copper or another base metal could offset this. However, today's adhesives could bring a lower "installed cost" if L-F solders require a host of more expensive materials, added processes and more cost for the solders themselves.

Advantages

There are only two important advantages for adhesives. They are much more compatible than solder. Adhesives adhere to almost anything including glass circuits. They don't leach away metals. This means they can be used with gold, thin-film circuits and indium-tin oxide circuitry found in flat panel displays. But the real advantage, and the one being made more important by L-F solders, is low temperature processing. The ability to process in a reflow or batch oven at 150ºC or lower, is a major plus. Indeed, if the L-Fs require about 160°C, this advantage could make CAs the *right choice* as it was for AT&T decades ago.

Newer Research and Developments

We have viewed the light, gray and dark regions of adhesives and found them both highly desirable but also wanting. Better mechanical properties are high on the want list. Better electrical and thermal conductivity would be nice. A good rework system is definitely needed. And concerns have been raised about the use of silver, a useful biocide, but one that can kill aquatic life.

Fortunately, every one of these problems is being worked on. Foster-Miller (Waltham, MA) is developing copper-based systems. Georgia Tech is working on novel rework concepts where materials depolymerize under specific conditions. IBM has developed new fillers that may increase mechanical strength and conductivity. Many others are active and we should expect breakthroughs, not just improvements.

Nanoelectronics and Nano-Materials

We are on the threshold of a major transformation in electronics from inorganic-based silicon to carbon-based organic Nanoelectronics. Carbon nanotubes have already been used to build electronic transistors that may ultimately replace the decades-old silicon and germanium devices. Figure 5 shows a carbon nanotube structures that may become the new building block of electronics for devices, printed circuits and materials including conductive adhesives.

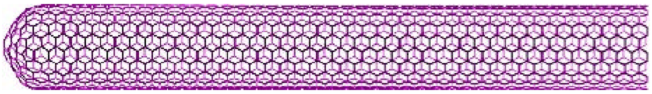

Figure 5 – Carbon Nanotubes (CNT)

Summary and Conclusions

Conductive Adhesives could save the industry millions, or perhaps billions of dollars by keeping assembly cooler if lead-free raises the heat. Polymer chemistry long ago solved the temperature problems that may never be solved by solder. While organic chemists have been lowering temperature curing, metallurgists are turning up the ovens to get the lead out.

Although conductive adhesives are being used and are gaining popularity, limitations are still a problem. High on the list is lower mechanical shock performance. Expect improvements! Expect breakthroughs and paradigm shifts in all of electronics.

Electronics has long been based on inorganic materials beginning with metals, glass and ceramics during the first half-century. Later, more inorganic materials were added with the solid-state revolution now at its peak and based mostly on silicon. We are now at the threshold of a much more significant events that will move electronics into the world on carbon-based organic materials. Nano-technology is delivering amazing results for Nano-electronics where quantum devices will keep us on track with Moores' Law, and even place us on a steeper curve of advancements. Carbon Nanotube electronic devices have been built by industrial, government and academic labs and the nearly billion-dollar National Nanotechnology Initiative (NNI) will accelerate progress. Sooner or later, we will embrace organic-based electronics and photonics. But circuits are also moving to carbon-based materials. We can reasonably presuppose that organic devices and circuits will no longer use metallurgical joints and that the entire system will be made with compatible organics. It is noteworthy that the human brain has trillions of links but not one is metallurgical.

References

1. Gilleo, K., "First 7000 Years of Soldering - Part 1 - metallurgy", Circuits Assembly, pp. 30-34, October 1994
2. Gilleo, K., "First 7000 Years of Soldering - Part II - polymers", Circuits Assembly, pp. 44 - 45, November 1994