Conductive Epoxy Adhesives to Replace Solder

These epoxies have rheology, thermal shock and low temperature cure advantages over conventional solder.

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The current interest in conductive surface mount adhesives (CSMAs) to replace tin/lead solder in printed circuit board (PCB) assembly has been sparked by both environmental and performance requirements.

Originally, ecological concerns relating to the possible toxicity of lead and lead vapors and to the handling, ozone depletion, and emission control problems associated with the solvents needed for flux removal, spurred interest in the adhesives. It was later found that a good epoxy CSMA can also provide the following process and performance advantages compared to solder:

- A low-temperature cure to avoid thermal damage to boards or heat-sensitive components. Epoxy adhesives can be cured in conventional IR ovens in the same time and temperature cycles (peaking at 210 to 220° C) now used for conventional solder reflow, or can be cured more slowly at temperatures as low as 130° C.
- Better rheology for screen printing. The particle size of the silver flakes used in epoxy CSMAs is smaller than those used in solder. Accordingly, epoxies can be more thixotropic and can permit finer deposition patterns than solder paste.
- Finally, the adhesives offer better toughness, as measured by their ability to survive thermal cycling without cracking the joints or losing electrical conductivity. Tin/lead solder is a relatively brittle metal, subject to joint fracture during thermal cool-down, or to creep-related fracture during cycling at relatively low stresses.

In theory, a good epoxy adhesive should be able to provide a tougher, more durable joint than that of solder. However, in recent practice, most of the silver-filled epoxy adhesives that have been recommended for CSMA have not shown significant thermal cycling advantages over solder. Reason: most of those adhesives were originally formulated for use as die attach adhesives, which are relatively brittle. Conductive surface mount adhesives do not require the specialized properties needed for die attach, but rather should be based on the epoxy technology that has historically been used to make high strength, structural adhesives. The silver-filled shock-resistant epoxy paste adhesive described in this paper* is a one-component thixotropic paste that can be applied by dot placement, stencil or screen printing.

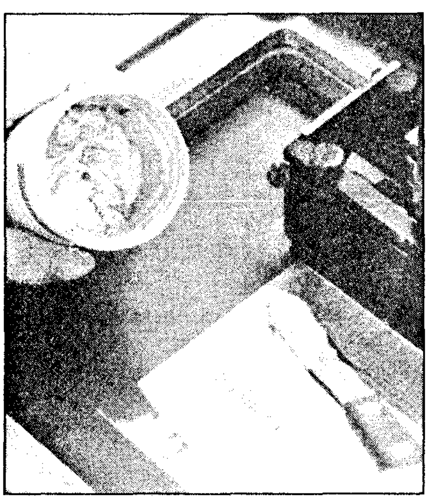


Figure 1, silver-filled epoxy is screen printed to test panel using a 200-mesh screen.

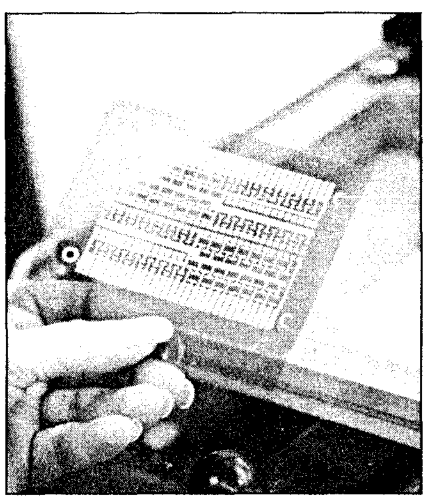


Figure 2, test panel after screen printing the epoxy. Dot, line width and separations are about 0.006".

Rheology for Stencil and Screen Printing

Figures 1 and 2 show the paste being applied to a test panel via a 200-mesh screen that deposits dot and line dimensions accurately at 150 µm (approximately 0.006") width and 150 µm separation. Figures 3 to 5 show the epoxy test pattern on a thick film metallized alumina hybrid substrate. Unlike solder creams or pastes, the epoxy contains no solvents and therefore does not add to emissions or dry out on the screen.

Table 1 lists the viscosity, composition and other physical properties of the adhesive. Compared to some solder creams used for placement of fine-pitch components, the epoxy has a lower base viscosity, a higher thixotropic index (defined as the ratio of the viscosity at 1 rpm to the viscosity at 5 rpm, measured by a Brookfield viscometer at 25° C), and contains smaller metal particles.[1] The epoxy contains silver flakes approximately 5 µm in thickness and 20 to 40 µm in length vs. spherical solder balls ranging from 40 to 150 µm in diameter.

During cure, the epoxy shrinks in volume by about 5 percent due to the contraction of the resin during crosslinking and, depending on cure temperature, vaporization of low molecular weight resin components. However, the solder dot shrinks in volume by 50 to 60 percent between application and the end of reflow.

By weight, solder paste typically consists of 85 to 90 percent solder balls dispersed in a high boiling terpene or other organic solvent, plus organic thickeners, fluxing agents and other minor ingredients. If a solder paste contains 86 percent tin-lead solder (with a specific gravity of 8.13) and 14 percent organics (sg = 1.0), the volume fraction of metal and organics in the paste is about 0.43.

Thus, after drying and reflow (when all of the nonmetallic components are absent), the metal volume is less than half the original solder paste volume. This is why it is frequently difficult, under fine-pitch components, to provide enough metal in the final solder joint. It is complicated by the tendency of the solder to wick up the metal leads, further depleting the metal left in the joint.

As shown in figures 3, 4 and 5, the epoxy paste can give good print fidelity and more useful adhesive qualities in the joint area because of its high thixo index, low volume shrinkage during cure, and because it will not wick up the lead away from the joint. The epoxy adhesive, with its low surface tension (typically about 40 dynes/cm compared to over 200 for molten solder) also tends to prevent lifting or "tombstoning" of chip capacitors or other small components.

Cure Time and Temperature

An advantage of epoxy CSMAs is its potential for low temperature curing. In a typical infrared (IR) reflow oven, the solder paste is first heated to about 100° C to drive off the solvents, then is brought up to 210 to 220° C to melt the solder and form the joint. The total oven time is typically 5 to 7 minutes. By contrast, with fewer volatiles, the epoxy adhesive can be quickly elevated in temperature and cured in the same time (see table 1).

However, unlike solder, the epoxy also can be cured at lower temperatures to avoid thermal damage to circuit components. The bond strength (capacitor push-off) data of figure 6 were obtained using an IR cure oven with a total residence time of 15 minutes and a peak temperature of 155° C.

Table 1
Properties of Conductive Surface Mount Adhesives

Description: One-component silver-filled epoxy

Appearance: Smooth thixotropic paste

Brookfield	at 1 rpm	500,000 cps
Viscosity	5	100,000 cps
TC at 25° C	10	40,000 cps

Thixotropic Index (Ratio 1 to 5 rpm) 5.0

Silver content: approximately 75 percent by weight

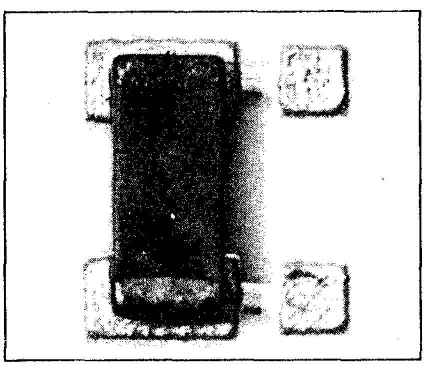
Specific gravity: 3.1

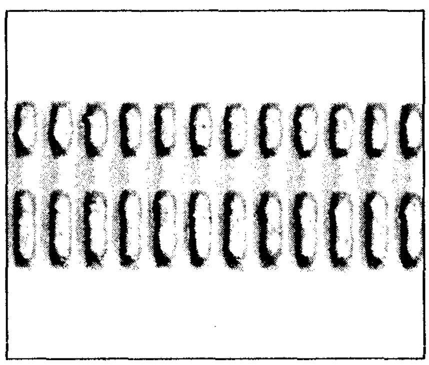
Possible IR Oven Cure Schedules:

Total Time in Oven	Peak Temp.
7 minutes at:	210° C
15 minutes at:	155° C
45 minutes at:	130° C

Repair Procedure

To remove or replace a defective component that has been surface mounted, the epoxy is heated (locally, using a hot iron or hot air jet) to 150 to 160° C. The push-off strength falls to a low value at this temperature and the component can be easily pushed off and replaced. Afterward, it is not usually necessary to clean the bonded area before placing a new component because the repair epoxy will bond to and conduct electrons through the small residue that may remain after push-off.





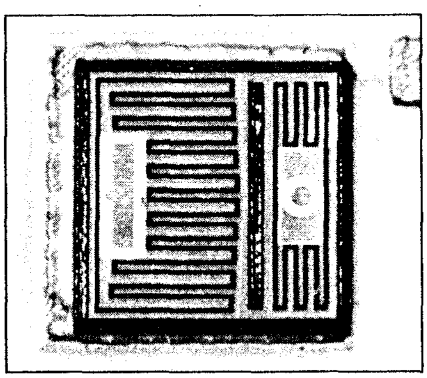


Figure 3, above left. Epoxy pattern after screen printing on thick film metallized hybrid circuit on alumina substrate.

Figure 4, above. Close-up of test circuit in figure 3. Fine-pitch circuit lines above are on 0.025" centers.

Figure 5, left. Epoxy adhesive is used to attach Darlington power transistor to alumina substrate.

Adhesion and Surface Preparation

Solder can only wet and form bonds to oxide-free metal surfaces. Therefore, copper leads and bond pads, which always have an oxide surface layer, can only be soldered if a strong fluxing agent is used to etch away the oxide.[2]

Epoxy adhesives are able to wet and adhere to a variety of surfaces, including unetched copper, silver, gold, FR-4, alumina, and other plastics and ceramics. Epoxies also adhere to metal oxides, permitting bonding to untreated copper leads (unless the copper has a highly contaminated oxide surface). However, epoxies do not adhere as well to solder or pretinned or solder-dipped surfaces. Thus, the surface pretreatments that are considered optimum for solder paste should *not* be used with conductive epoxy adhesives.

The best surface for epoxies is freshly cleaned bare copper. A short dip in "Oakite" or other proprietary cleaning solutions generally yields a clean, bondable surface. If considerable time will elapse between cleaning the lead and bonding the copper, the lead may be protected against reoxidation by immersion in a dilute BTA (benzotriazole) solution, or by the electrodeposition of a thin nickel layer.

The adhesives have a volume resistivity of 10^{-4} Ω-cm after cure. With any reasonable joint geometry, the adhesive contact area is much larger than the lead cross-section. Therefore, any resistance in series calculation shows that neither an epoxy joint nor a solder joint adds any significant electrical resistance to the circuit.

Thermal Conductivity and Heat Dissipation

When power devices requiring heat dissipation methods are used on a board the thermal conductivity of the epoxy adhesive becomes an important consideration. Table 2 lists thermal conductivity in the metric units of watts per m^2 (area) per ° C per m thickness.

When compared to other metals, 60/40 tin-lead solder is not very heat conductive. It is 10 times less conductive than copper and about five times less conductive than beryllium oxide (BeO). Nevertheless, it is much more conductive than any organic adhesive. Thermal conductivity of unfilled epoxies is only about 0.3 in the units of table 2. The addition of filler increases the thermal conductivity, but the best thermal adhesives still only have about one-tenth the conductivity of solder. Silver-filled epoxies provide the maximum thermal conductivity when electrical conductivity also is required.

The power Darlington of figure 5 is bonded with a silver-filled CSMA. If the bond area is 1 cm^2, the bond thickness 0.002", and the k value 3.3 (or 0.033 w/cm^2). The thermal impedence is less than 0.2° C per watt.

A silver-filled adhesive cannot be used if the power device requires electrical isolation from the heat sink. Usually, the device is soldered to a BeO spacer, which in turn is soldered to a metal heat sink.

One way to avoid the use of beryllia as well as solder, flux and cleaning solvents, is shown in figure 7. A thin (0.002" thick) epoxy tape, adhesive-filled with diamond powder, is used to bond the device directly to the heat sink. Diamond-filled adhesives provide the highest thermal conductivity when electrical insulation is also needed. If it is assumed that the device in figure 7 is generating 10 $watts/cm^2$, the thermal resistance for the diamond-filled epoxy tape can be calculated:

k = 2.4 w/m°K x 0.01 = 0.024 w/cm° C

Δx = 0.002" = 0.005 cm

Therefore ΔT, device to heat sink = 10 x 0.005 / 0.024 = 2° C

This is a higher thermal impedance than that for a BeO spacer, but still should be useful for most power devices.

One caveat to the bonding method of figure 7 pertains to thermal stress. If a standard, rigid epoxy adhesive, 0.002" thick, is used to bond a power device to a heat sink, very large thermal stresses can be generated during the heat-up and cool-down cycles. These stresses can be accommodated by a flexible epoxy adhesive. The matrix resin used in figure 7 is a soft elastomer, having a Shore A hardness of about 50 after full cure.

Silver Migration. All adhesives and inks containing silver particles, whether polymeric or glass-based, permit silver migration. Whenever a sufficient DC voltage gradient exists between a silver-containing adhesive or ink and a nearby (cathodic) conductor, silver ions can migrate toward the cathode where they reduce to form a conductive metal path. However, silver migration requires the presence of a *liquid* water film on the board surface between the silver anode and the nearby cathode. The most effective method to prevent migration is to prevent the formation of a water layer by applying a conformal coating or by using a silicone gel in any area where silver migration can exist.[3]

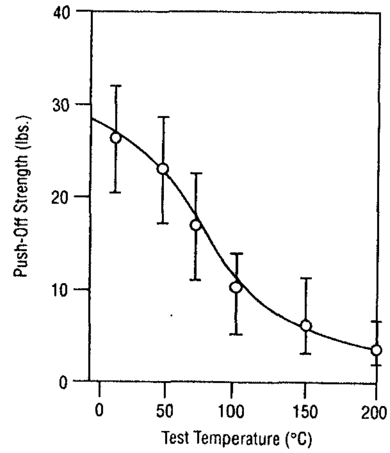


Figure 6, right. Capacitor push-off strength measured for epoxy adhesive after 15 minutes cure in IR oven. Peak temperature is 155° C.

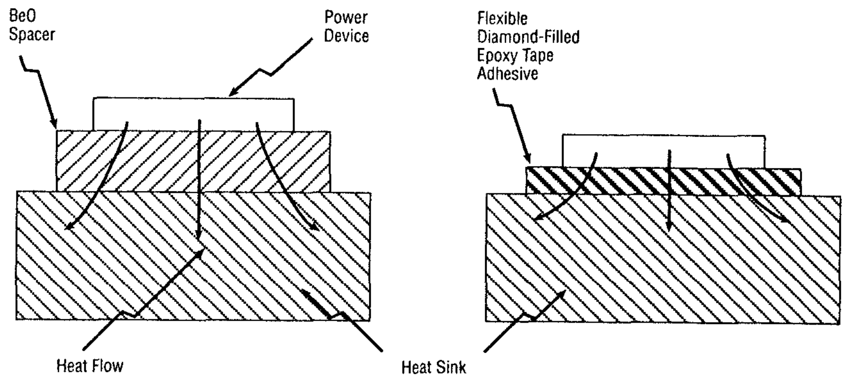


Figure 7, below. Flexible diamond-filled epoxy tape adhesive is used to mount power diode to heat sink. At a heat output of 10 $watts/cm^2$ the change in temperature across the 0.002" thick epoxy adhesive is less than 5° C.

Table 2
Thermal Conductivity Values

In Metric Units = $watts/m^2$°K/m = watts/m°C

Silver	420	Best present silver-filled epoxy tape adhesives	3.8
Copper	400		
Gold	290		
BeO	220-240	Silver-filled epoxy paste adhesive (in figure 1)	3.3
Aluminum	190-210		
Aluminum Nitride	110-180	Diamond-filled epoxy tape adhesive (in figure 5)	2.4
Tin-lead Solder	30-50		
Kovar	16	Best present thermally conductive oxide + BN filled epoxy adhesives	0.7-0.8
Alloy 42	17		
Boron Nitride	36	Unfilled epoxies, silicones and other polymers	0.25-0.30
Alumina	30-32		
96% Alumina	20		

Other units:	To convert to w/cm^2°C:	Multiply by 0.01
	To convert to BTU/hr ft^2°F/ft:	Multiply by 0.58
	To convert to BTU/hr ft^2°F/inch:	Multiply by 6.9
	To convert to $gcal/cm^2$sec°C/cm:	Multiply by 2.3 x 10^{-3}

References

1. "The Use of Solder Paste in Surface Mount Technology," Indium Corp., Technical Bulletin SMT-1, Rev. 1, Utica, N.Y.
2. Tleel, R.E., "How Pretinning, Testing Improve Solderability of Surface Mounted Components," *Surface Mount Technology,* p. 31, Oct. 1987.
3. Bolger, J.C., "Silicone Gels and Coatings for IC Packaging," Chapter 23 in *Polymeric Materials for Electronic Packaging,* ACS Symposium Series 407, 1989, ACS, Washington, D.C.

*Emerson & Cuming, LC-68.

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