Advanced Thermal Interface Materials for Enhanced Flip Chip BGA

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Abstract

Increased functionality and performance requirements for microprocessors and ASICs have resulted in a trend to package these devices in the flip-chip BGA form factor (FCBGA). Because these devices use in excess of 40-100 Watts of power, their packages must dissipate heat in an extremely efficient manner. Most semiconductor companies have developed some type of thermally enhanced FCBGA package that provides heat dissipation through the back of the die to a heat spreader. This design works very well, but is highly dependent on the ability of the thermal interface material (TIM) to transfer thermal energy efficiently from the back of the die to the heat spreader. The TIM is often the limiting factor for heat dissipation, either because it does not conduct heat adequately, or because it fails to maintain intimate contact between the back side of the die and the heat spreader.

A family of advanced thermal interface materials for high-power FCBGA packages is discussed. These silver-filled adhesives provide for high reliability on laminate FCBGA packages. Laser flash thermal testing is utilized to demonstrate that these materials not only have low bulk thermal resistance, but also very low interfacial, or contact resistance. These adhesives have a low modulus and high adhesion, which enables them to flex and remain bonded as the laminate package undergoes stress during temperature cycling. Data also show that this family of TIMs has very low moisture absorption, which contributes to excellent adhesive reliability during HAST (highly accelerated stress test). Reliability data on laminate test packages will be presented. This family of materials has been shown to pass more than 1000 cycles of temperature cycling B (-55 to +125°C, liquid-to-liquid) and 200 hours HAST (121°C, 100% relative humidity), after JEDEC Level 3 preconditioning and three reflow simulations at 220°C on a laminate package with 10 x 10 mm die. Total thermal resistance of less than 0.10 cm^2K/W has been achieved, at a 25µm bondline thickness.

Thermal interface materials must continuously improve to keep pace with ASIC and microprocessor technology. The development of these novel thermal interface materials will enable the next level of performance, both in terms of thermal dissipation and package reliability.

Introduction

The demands of the electronics industry have pushed electronic assemblies to operate at increased speeds and in smaller form factors with higher reliability. These industry requirements create thermal management challenges for the electronic assembly's semiconductor components. In particular, the recent development of thermally enhanced flip chip BGA packages for high I/O ASIC and microprocessor devices has driven semiconductor adhesive suppliers to develop new thermal interface materials to support this package design. Thermal interface materials (TIMs) including conductive pastes, greases, phase change materials (PCMs), thermal pads and films are used as the interface between the flipped IC and an integrated heat spreader.

Figure 1 shows a typical cross-section of a thermally-enhanced FCBGA that uses a conductive paste TIM. The flipped IC is attached to a laminate substrate via solder balls and is underfilled with an encapsulant material. A heat spreader is attached to the back of the die via a thermally conductive material, the TIM. The heat spreader is then attached to the BGA board with a lid seal adhesive.

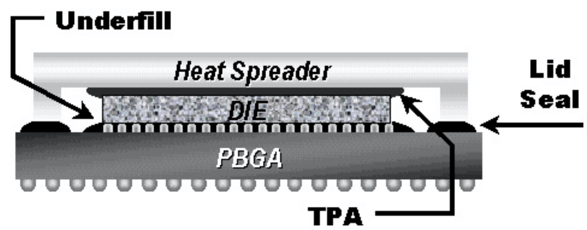

Figure 1. A simplified presentation of Flip-Chip Ball Grid Array.

System level thermal solutions are complex, with a number of factors contributing to their success. The designer must select the proper thermal compounds, heat spreaders, heat sinks, fin designs, and device location. At the package level, the thermal interface material employed in a thermally enhanced flip chip BGA must provide four main functionalities:

1. Sufficiently low thermal resistance to maintain the IC operating temperature in its target range,
2. A low stress bond between the coefficient of thermal expansion (CTE) mismatched silicon die and the (typically copper-based) heat-spreader,
3. Good adhesion and consistent thermal performance after standard JEDEC preconditioning, temperature cycling, and moisture resistance testing, and
4. Good compatibility with current adhesive dispensing equipment processes.

Low Thermal Resistance

The thermal requirements of FCBGAs depend upon the amount of power dissipated by the IC during operation. While ASICs today may range from 2-10 watts of power, microprocessors can consume upwards of 40-100 watts. A typical thermal resistance requirement for a TIM being used to package ASIC devices is less than 0.5 cm^2K/W, while the microprocessor TIM requirement is generally less that $0.12 cm^2K/W$. Lower thermal resistance is desirable, since it means more heat can be removed from the device. In order to meet these thermal resistance targets conductive filler such as silver is used to provide thermal performance.

Reliability Performance

Although laminate-based FCBGAs are a new packaging technology, the package must survive standard reliability tests such as JEDEC preconditioning plus reflow simulation, temperature cycling or temperature shock, and HAST or pressure cooker test (PCT) moisture resistance testing. Today's market requirements for package reliability generally dictate that the TIM must experience no delamination or loss of thermal performance after:

- JEDEC level 3 preconditioning plus 3 reflow simulations at 220ºC
- 1000 temperature cycles (-55ºC to 125ºC)
- 200 hours PCT exposure (121ºC, 2 atm, 85% RH)

A combination of material properties must be present to allow these reliability requirements to be met, including low modulus, low moisture absorption, and high adhesion.

Minimal Stress

Minimizing the stress that develops as a result of the CTE mismatch between the heat spreader and the IC is a significant challenge when developing a high performance TIM. The typical CTE of a copper-based heat spreader is around 18 ppm, while the CTE of the silicon based IC is about 7 ppm. Expansion and contraction of these materials during the temperature cycling of the device can cause significant stress. Since the IC is rigidly bonded to the laminate substrate by an underfill encapsulant, if the backside of the IC is rigidly bonded to the copper heatspreader there is a significant potential for catastrophic failure through cracking the silicon, the underfill and/or the solder interconnect. Thus it is vitally important that the TIM have the ability to absorb much of the stress generated by the various package components. Typically, stress-absorption is associated with a very low modulus adhesive. Most designers request that TIMs for laminate-based flip chip BGAs have a modulus less than 300MPa at 25ºC, although to date this isn't an exact modulus limit, and is dependent on the specific packaging materials and geometries in question.

Process Compatibility

While not critical to the performance of the device during use, it is also important to consider the ease of use the material provides to the package assembly process. Paste-based TIM materials are easily incorporated into mainstream component manufacturing processes. It is important that these pastes have a good rheology for dispensing and have sufficient worklife to facilitate a robust manufacturing process.

Each of the above market driven material targets present their own challenges for the material supplier. In this paper we will discuss each target in detail and will present data on a unique family of adhesives that meets these challenges.

Materials Evaluated

There are two main components to a thermal interface material: the conductive filler and the polymer carrier. Suppliers have employed many different polymer technologies in thermal interface materials, including polyimides, epoxies, siloxanes, and acrylates. Additionally, a wide range of conductive fillers has been used to achieve the thermal conductance of the composite. These fillers include ceramics, like alumina and boron nitride, but also include metals like silver and copper. Silver flake is particularly attractive because of its intrinsic high conductivity and high resistance to oxidation.

A new family of thermal interface materials has been developed and tested for use in packaging ASIC and microprocessor devices. These products are silver-filled pastes, and will be referred to as thermal paste adhesives, or TPAs. Three TPAs will be discussed. TPA-1 is a current generation material that is appropriate for laminate-based ASIC packages with moderate thermal requirements. TPA-2 is also appropriate for laminate-based packages but has improved thermal performance that is designed to meet the needs of high-power microprocessor devices. TPA-3 has extremely low thermal resistance and was developed for ceramic flip chip BGA packages.

Experimental Methods

Thermal Resistance

Thermal resistance measurements can be carried out using a number of different methods including the guarded heater method (ASTM: D 5570),[1] transient laser flash, synthesized dynamic models,[2] thermal test dies to measure θja,[3] and the modified hot wire technique[4]. In our TIM development we used the transient laser thermal flash method to measure thermal resistance.

In transient thermal resistance testing, one side of the specimen is exposed to a laser pulse of defined energy[5]. The measurement of rise in the temperature on the other side and use of a one-dimensional diffusion model affords the calculation of the thermal conductivity and heat capacity. For this method, it is important that the laser pulse is shorter as compared to the transit time of the heat. We utilized a thermal flash instrument from Holometrix which uses a Nd: Glass laser of wavelength of 1060 nm and a pulse width of 300 µsec, which is considerably shorter than the transit time of heat waves (~10 msec). The thermal resistance was calculated using commercially available software that uses literature-based analysis routines to match a theoretical curve to the experimental curve[6]. The measurements were carried out on specimen made by sandwiching the adhesive between two aluminum disks, about 1 mm thick each, as shown in Figure 2. The adhesive thickness can easily be varied and resembles bond line thickness in real world applications. We also have the capability of measuring the thermal diffusivity, heat capacity and thermal conductivity at temperatures up to 300ºC.

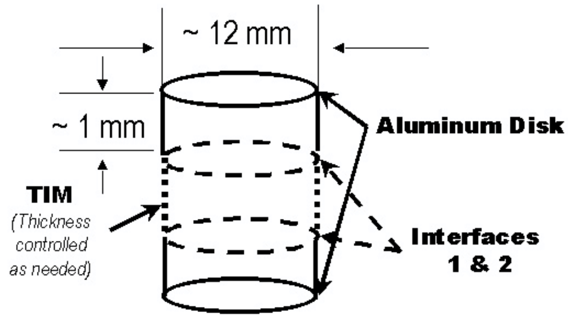

Figure 2. Preparation of specimen for thermal measurements.

Mechanical and Rheological Properties

- Adhesion testing was conducted at room temperature on a Dage series 4000 die shear tester, per Ablestik test method MT-4.
- Modulus measurements were carried out on a Rheometric Scientific DMTA Mark III, per Ablestik test method MT-12.
- Viscosity was measured at room temperature on a Brookfield Model DV-II+ viscometer, per Ablestik test method PT-42.
- Work life was characterized by measuring the viscosity over time, per Ablestik test method PT-59. For our purposes, we define work life as the time at which viscosity increases by 25%.

Reliability

The most common reliability tests for first level TIMs in FCBGA packages are popcorn testing (moisture preconditioning and reflow simulation), temperature cycling, and HAST or PCT. These tests are carried out on the final package, in both the material selection and qualification stages. They are designed to ensure that the package will survive throughout the assembly process as well as the entire life cycle of the product in its final application.

The test package used at Ablestik for testing reliability of TIMs consists of a 10 x 10 mm bare silicon die bonded to a pre-baked FR4 board (42 x 42 x 1.5 mm). Part construction is illustrated in Figure 3.

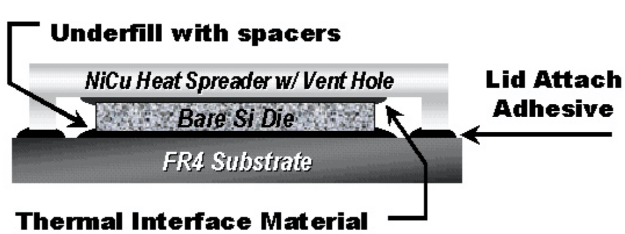

Figure 3. Ablestik standard test package.

The die was attached using an underfill adhesive (with spacers added for bondline thickness control) to ensure the die warpage achieved was consistent with what we would expect from a flip chip that has been bumped, bonded to the substrate, reflowed, and underfilled (including underfill cure). This approach allows great flexibility when evaluating various die and package size combinations without requiring multiple substrate designs.

After underfill cure, the TPA was dispensed onto the top of the die. The lid seal (sometimes the same material as TIM) was then dispensed on the edge of the substrate. The nickel-plated copper lid (38 x 38 x 1.4 mm) was then manually placed on top of the die and pushed down. A micrometer was used to verify bondline thickness. Further pressure was applied if the bondline was too thick. The adhesives were then co-cured and subjected to either of the following reliability tests:

1. Popcorn/ T-Cycle Testing - 10 parts were first subjected to JEDEC Level 3 moisture preconditioning, followed by three IR reflow simulations with a peak temperature of 220ºC. After checking for delamination via acoustic microscopy, the same parts were then subjected to 1000 air-to-air temperature cycles (-55ºC to 125ºC). The parts were scanned again to check for delamination.
2. PCT – 10 parts were exposed to PCT conditions of 130ºC, 85% RH, 2 atm for 200 hours. They were then scanned to check for delamination.

Results and Discussion

Thermal Resistance

The total thermal resistance of thermal interface materials in a package is the sum of bulk resistance from the TIM and thermal resistance at the interfaces, i.e. interfacial thermal resistance at the two interfaces between the TPAs and aluminum disks as given in Equation 1[7,8,9,10].

$$\text{Total Thermal Resistance} = \text{Interfacial Thermal Resistance}_{1,2} + \text{Bulk Thermal Resistance of TIMs} \quad \text{[Eq. 1]}$$

Where interfacial thermal resistance$_{1,2}$ are the thermal resistance at interfaces 1 and 2, between the TIM and the aluminum disks as shown in Figure 2. Interfacial thermal resistance is primarily caused by two factors.

1. A thin polymer coating between the conductive particle in the TIM and the die or heat sink. This phenomenon is illustrated in Figure 4.
2. The presence of of voids or air gaps at the interface between the TIM and die or heat sink. This problem is shown in Figure 5.

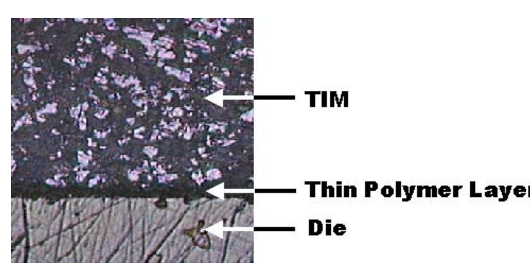

Figure 4. Thin polymer layer between conductive particles and the die.

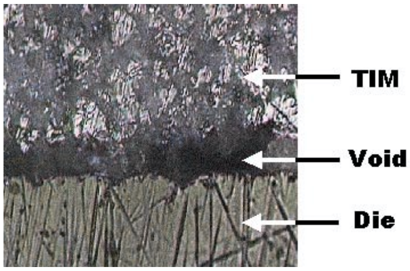

Figure 5. A void at the interface between the TIM and die.

Thus, if the conductive particles in the TIM are in direct contact and there are no voids or air gaps at the interface, one would expect a small interfacial resistance. Not only do voids or air gaps potentially increase the interfacial resistance significantly, they also have a detrimental effect on other material properties such as adhesion and overall package reliability.

The bulk thermal resistance of the TPA is a function of the lubricant on the metal particles, the processing parameters of curing, the resin system, and the shape, morphology and volume fraction of metal flakes in the adhesive[12-15]. Thus, one type of metal flake in a particular resin system may give excellent properties but is potentially incompatible with other resin systems. The performance of a particular metal flake in a resin system is very complex and is beyond the scope of this paper.

Table 1 shows the thermal resistance of the TPAs after various treatments. At a 25 µm bond line thickness, TPA-1 has a thermal resistance of 0.46 cm^2K/W after cure. This is low enough to meet the requirements for most ASIC devices. TPA-2 has significantly better thermal resistance after cure, with 0.10 cm^2K/W at 25 µm, which meets the targeted performance for high-powered microprocessors. For ceramic packages, the resistance of TPA-3 is better still, at 0.09 cm^2K/W.

Table 1. Total thermal resistance of TPAs after various treatments, 25 µm bond line thickness.

Treatment	TPA-1 Resistance (cm^2K/W)	TPA-2 Resistance (cm^2K/W)	TPA-3 Resistance (cm^2K/W)
Cured (90 min @ 150°C + 60 min @ 100°C)	0.46	0.10	0.09
Cured + 4 hrs @ 150°C	0.37	0.10	N/A
Cured + 4 hrs @ 150°C + 96 hrs PCT (121°C, 2 atm, 85% RH)	0.31	0.08	N/A

In use, thermal performance must be maintained after a part has been subjected to a variety of stresses. As these data show, in addition to the low resistance observed after cure, we noted a significant drop in resistance after additional thermal and moisture exposure. This is key information because it indicates that thermal performance of these materials *does not degrade* after such testing. These results, at first glance, are surprising since thermal resistance does not usually decrease. However, repetition of the experiments yielded the same results. These data clearly indicate no delamination or voiding after treatments which was also confirmed by acoustic microscopy. We theorize that this behavior could be resulting from the following sources:

1. Since the thermal resistance is highly dependent on the effective volume fraction of silver, evaporation of low boiling diluents still present in the material after curing may result in an increase in thermal conductance.
2. Wong and coworkers[16] have recently shown that the crosslink density of the resin has a significant effect on the conductivity of adhesive. Thus, an increase in the crosslinking results in an increase in conductivity. In this case it is possible that following the post cure treatments, the crosslink density of the resin has increased leading to lower thermal resistance values.

Clearly, more detailed study is needed to fully understand this behavior.

Mechanical and Rheological Properties

Mechanical and rheological properties of the TPAs are summarized in Table 2.

Table 2. Mechanical and rheological properties of TPAs.

Property	TPA-1	TPA-2	TPA-3
Viscosity (@ 25°C, 5 rpm), cps	40,000	55,000	12,500
Thixotropic Index	4.5	N/A	4.5
Work Life, hrs	16	16	24
Die Shear Strength, kg	6	9	20
Modulus, MPa	280	280	4800
Moisture Absorption, %	<0.1	<0.1	<0.6

Viscosity and TI

The viscosity and thixotropic index (TI), (see equation 2) play an important part in the dispensability, and therefore ease of use, of adhesives. Viscosity must be low enough that the paste can be easily dispensed and all three TPA materials meet this requirement. TI is an indication of how much a paste shear thins. In general, a higher TI material will give better dispensability. When TI is low, “tailing” of the paste can be observed which slows down the dispensing process and reduces the overall UPH of the production line. Thus, TI is very important in cases where the dispensing pattern is complex or the dispensing dots/lines are very close to each other. The TI of TPA-1 is 4.5. It does not tail and has good dispensability. Figure 6 shows the viscosity of TPA-1 at various shear rates. The shear-thinning nature of this material is highly desirable for ease of manufacturing.

Thixotropic Index = (viscosity at 0.5 rpm) / (viscosity at 5.0 rpm)……………………….[Eq. 2]

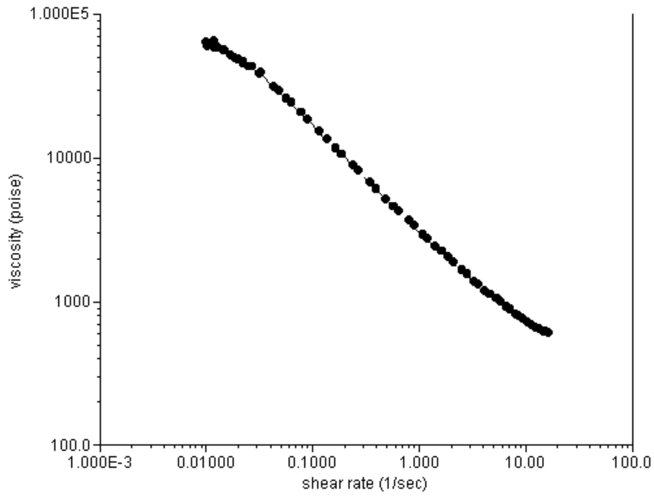

Figure 6. Viscosity vs. shear rate for TPA-1.

Die Shear Strength

Die shear strength (DSS) is a measure of the adhesion strength of a given material. Figure 7 shows the DSS for Si die (3 x 3 mm) bonded to a Ni-coated copper lead frame using variations of TPA-1 at different levels of silver flake. The loading level of silver has a profound effect on the adhesion between Si and Ni/Cu, with adhesion decreasing as loading increases. This is not a surprising result since as the silver flake volume fraction is increased the resin percent is decreased and there is less resin available for bonding the Si to the Ni/Cu. This leads to a decrease in the adhesion values.

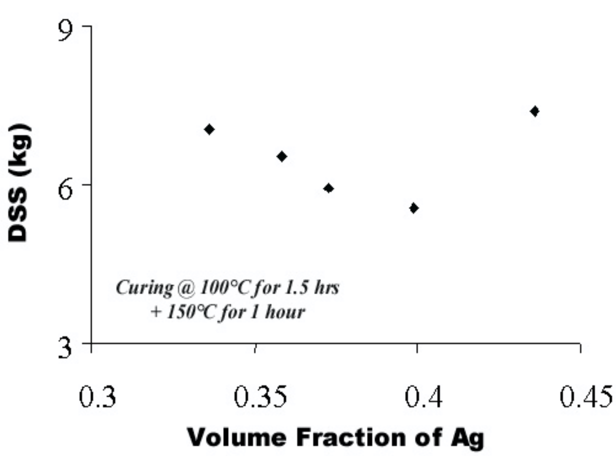

Figure 7. Die shear strength vs. silver loading for TPA-1.

Modulus

Modulus of an adhesive is an indication of how much stress it will absorb and/or contribute to the overall package. An adhesive that is excessively stiff will not absorb much deformation due to CTE mismatching in package components. The modulus of these TPAs clearly shows that TPA-1 and TPA-2 are very low stress materials with room temperature modulus of 280 MPa. They are suitable for use in laminate packages where the materials have extreme mismatches in CTE. TPA-3 is a more stiff material and is best suited to applications where there is not as much stress, such as ceramic packages.

Moisture Absorption

Moisture absorption is an important factor in the reliability performance of an adhesive. If the material absorbs excessive moisture it is likely to fail during popcorn testing. All three TPAs have extremely low moisture absorption, with TPA-1 and TPA-2 absorbing less that 0.1% moisture at saturation. This indicates that these materials should provide outstanding moisture resistance.

Reliability

The results of reliability testing in a given package are dependent on both the key TIM properties (high adhesion, low stress, and low moisture absorption) and the process in which the TIM is applied.

Current Generation TIM

Figure 8 shows the acoustic scan of a phase change material (PCM, Material A) used on an 8 x 8 mm die with a B-Stageable epoxy lid seal in a FCBGA package which has been subjected to 1000 cycles of liquid-to-liquid temperature shock, -55ºC to +125ºC. Dark areas indicate lack of bonding. Clearly, this material does not provide intimate contact with the bonding surfaces. As discussed in the introduction, these PCMs depend on clamping pressure to maintain a bond, and thus a thermal path. It is highly undesirable to use clamps in these FCBGAs. Therefore, one must rely upon the lid seal material to provide the pressure required for contact maintenance. The cured epoxy lid seal does not provide sufficient pressure, especially since its modulus lowers as the temperature of the part increases. Thus, contact is not maintained and thermal performance suffers.

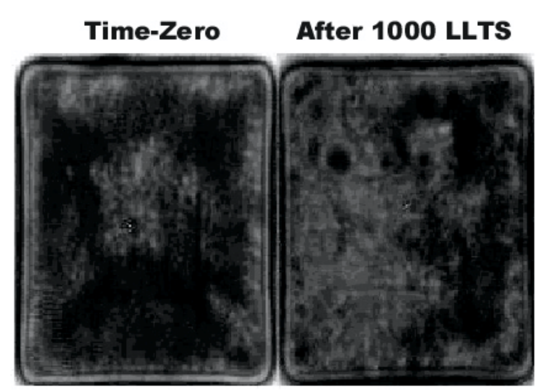

Figure 8. PCM on an 8 x 8 mm die before and after temperature shock. Picture Courtesy of Universal Instruments.

High Stress TPA for Ceramic Packages

Figure 9 shows a representative acoustic scan of TPA-3 used in the standard Ablestik laminate test package after 500 temperature cycles. A high stress epoxy was used for the lid seal. The delamination seen in the corners of the die was verified through C-Scan and cross section to be at the TPA/lid interface. The high modulus of TPA-3 (4800 MPa) does not provide sufficient stress absorption for a laminate package with large die and copper-based lids. This material, with its outstanding thermal performance, is *very appropriate for a ceramic package*. However, a lower stress material is needed for laminate FCBGAs.

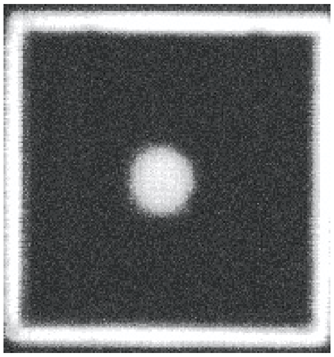

Figure 9. TPA-3 on Ablestik laminate test package after 500 temperature cycles.

Low Stress Silicone TIM

Figure 10 shows the performance of a low stress, low adhesion, silicone TIM (Material B) in the standard test package, after 1000 temperature cycles. In this representative scan, more than 50% of the die surface has delaminated during this test. While low stress (typically less than 300 MPa at 25ºC) is needed to prevent cracking and delamination during reliability tests, adhesion is also critical for packages which do not have fastening (applied pressure) of the final assembly. Many commercially available silicone-based TIMs have such low adhesion they are unable to meet the reliability requirements of these packages.

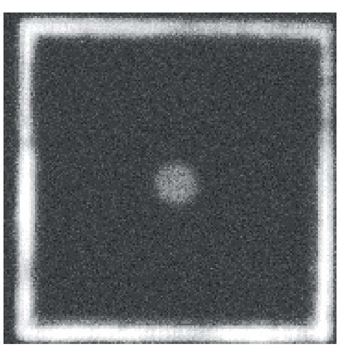

Figure 10. Silicone TIM on Ablestik laminate test package after 1000 temperature cycles.

Next Generation TIM

TPA-1 passed JEDEC Level 3 preconditioning, followed by three IR reflows at 220ºC and 1000 temperature cycles (-55ºC to +125ºC), as well as 200 hours of PCT (130C, 85%RH, 2 atm) in the standard laminate test package. Figures 11 and 12 show typical acoustic scans for these parts.

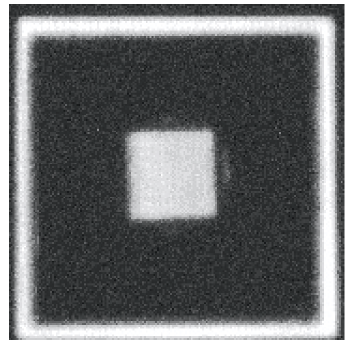

Figure 11. TPA-1 after JEDEC L3 + 3 x 220ºC IR + 1000 temperature cycles.

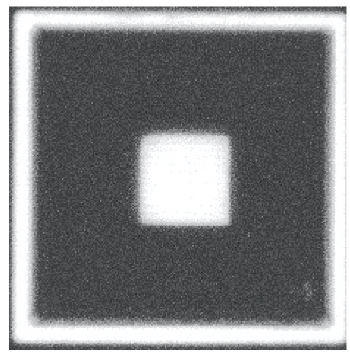

Figure 12. TPA-1 after 200 hours PCT.

Reliability tests are still ongoing for TPA-2. Since the critical material properties of this TPA such as modulus, adhesion, and moisture absorption are equal to or better than TPA-1, it is expected that the reliability in the same test package will be similar.

Conclusions

A new family of silver-filled thermal paste adhesives has been evaluated for use in high performance FCBGA packages for ASIC and microprocessor devices. These materials have been shown to have outstanding thermal performance with total resistance of less than 0.10 cm^2K/W at a bondline thickness of 25 µm. They demonstrate good adhesion and contribute to excellent package level reliability. These TPAs also have good dispensability and rheology that enables them to be easily incorporated into standard dispensing processes common in the industry today. With these key material properties, the developed TPAs achieve the demanding thermal management targets for today's high performance ASICs and microprocessors. TPA-1 has been recently comercialized as Abletherm® 3185 Thermal Paste Adhesive.

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