Reliability assessment of high temperature lead-free device attach technologies

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Reliability Assessment of High Temperature Lead-Free Device Attach Technologies

Pedro Quintero, Timothy Oberc, Patrick McCluskey
Department of Mechanical Engineering
University of Maryland
College Park, MD 20742
pquinter@umd.edu

Abstract

The demand for electronics capable of operating at temperatures above the traditional 125°C limit continues to increase. Devices based on wide band gap semiconductors have been demonstrated to operate at temperatures up to 500°C, but packaging them remains a major hurdle to product development. Recent regulations, such as RoHS and WEEE, increase the complexity of the packaging task as they prohibit the use of certain materials in electronic products such as lead, which has traditionally been widely used in high temperature solder attach. In this investigation, a series of Pb-free die attach technologies have been identified as possible alternatives to Pb-based ones for high temperature applications. This paper describes the fabrication sequence for each system and assesses their long term reliability using accelerated thermal cycling and physics-of-failure modeling. The reliability of the lead rich alloy was confirmed during this investigation while early failures of the silver filled epoxy demonstrated their inability to survive high temperatures. An empirical damage model was developed for the silver nanoparticle paste based on fatigue induced failures. Encouraging reliability data has been presented for the gold-tin SLID system where bond quality was demonstrated to be a critical factor on its failure mode and mechanism.

Introduction

The development of electronics and microsystems that can operate at temperatures in excess of the traditional maximum [1] of 125°C is a critical enabling technology for the creation of next generation electronic systems for a wide range of military and commercial applications; including avionics, hybrid-electric automotive electronics, deep well drilling, chemical processing systems, and space/earth explorations. Critical elements of these systems are the sub-assemblies for power control, distribution, and management. The last several years have seen the advent of silicon carbide (SiC) power devices operating at temperatures well above 125°C [2]. These devices provide higher switching speed and lower on-state losses with higher thermal conductivity. Developing reliable technologies for packaging is now the main hurdle to successful operation of SiC based power electronics at high temperature.

This work focuses on the first-level interconnection process known as die attach, the primary function of which is to mechanically secure the semiconductor chip to a lead frame or substrate, and to ensure it does not detach or fracture over an operational lifetime that may include power and temperature excursions. One of the most common approaches for packaging SiC devices is to mount the back of the chip on a ceramic substrate with a suitable die attach and route the signals from the top. However, unique materials and manufacturing processes are required for die attachment at high temperatures. The silver filled epoxies [3], used in commercial, small signal devices, fail at temperatures near 200°C as do the eutectic tin-lead solders. High temperature solders fail at temperatures near 300°C, limited by their melting point and the associated creep/stress relaxation deformation mechanism at elevated temperatures. Furthermore many of these solders contain high concentrations of lead, which is being phased out due to environmental concerns. Gold based eutectics (Au-Sn, Au-Ge, Au-Si) are a suitable alternative, but high processing temperatures (T_p > 300°C) are required for the assembly process. New attachment techniques [4-7] have been proposed that promise bonding at temperatures below 250°C, while remaining functional to temperatures well in excess of 400°C. These new approaches rely on solid-solid sintering [4], where the compaction of metallic powder at temperatures below the melting point assisted by pressure, produces a mechanical/electrical/thermal connection between the die and substrate that will not melt until much higher temperatures are reached. Formation of micropores is an intrinsic characteristic of this technique. The resulting pore density is high enough to reduce the stiffness of the joint [7], thus lowering die and substrate stresses, while the small pore size minimizes crack initiation. These physical characteristics of the metallic compactions suggest that improved reliability is possible over conventional attach methods and materials. Further investigations have suggested the use of nanopowders to reduce the externally applied pressures [5, 7]. This variation of the technique uses the surface energy of noble metal nanoparticles to promote sintering at low pressures.

This paper investigates novel technologies developed specifically to replace Pb-based attaches in high temperature applications (Ta > 200°C), and assesses their relative reliability through a series of accelerated testing experiments and fundamental physics-of-failure modeling.

Attachment Technologies

This investigation focuses on the reliability of a series of die attach technologies being considered for high temperature applications. Attachment technology refers both to the particular metallurgical system as well as to the assembly process required for fulfilling the intended functionality. This work does not claim to optimize the material composition nor the manufacturing process particular to each of the alternatives. In each instance, the test specimens were built using the best known method as reported in literature. This section presents the die attachment technologies selected for
the comparative study along with a brief description of the material and manufacturing sequence.

a) Sintered silver nano-particle paste

A promising material that can be used for high temperature applications is silver (Ag), both based on its melting point (962°C) as well as on its electrical and thermal conductivity. Silver is commonly used in hybrid microelectronics and co-fired multilayer structures as a metallization. However, a major challenge is to lower the processing temperature to levels that will be tolerable to the devices being attached, thus minimizing potential reliability problems introduced during manufacture. Unlike solder reflow, die attach materials undergoing sintering densify without melting; this enables lower assembly temperatures that can fulfill the requirements for a reliable bonding process. A silver nano-particle solder paste based on this pressure assisted sintering process has been reported for die attach applications [5]. Physical properties measured on this sintered material exhibited superior characteristics when compared to the typical eutectic Sn-Pb alloy [5].

In this investigation, the material and technique developed in reference 5 was used for the manufacturing of test specimens for reliability testing. The Si wafers were metallized by evaporation techniques to produce the Ti-Ag layers shown in figure 1. Dice were attached to Al₂O₃ DBC substrates having an Ag over Cr-Ni metallization. Details of the substrates are provided in figure 1.

Thermo-mechanical residual stresses are created within the attachment material as a result of the CTE mismatch between the die and the substrate, and the temperature change between the processing and room temperatures. As a result of this relationship, when a lower processing temperature is used the strain on the attachment is reduced and the reliability of the package is enhanced. However, for high temperature environments the selected material must have a high enough melting point to survive its mission.

There has been a series of attempts to form joints that are resistant to high temperature using relatively low processing temperatures [8, 9]. The technique relies on the fundamentals of solid liquid inter-diffusion where a low melting point constituent is mixed in some specific proportion with a high melting point material. The whole system is then held isothermally at a processing temperature above the melting point of the low melting point constituent, but below that of the high melting point constituent. Formation of the liquid phase enhances wetting and atomic diffusion, the latter being the mechanism responsible for the melting point shift that makes the final alloy stable to high temperatures.

For this investigation, a Au-Sn system was selected as a representative candidate for this approach. Materials were deposited on a silicon wafer and Al₂O₃ substrates using physical vapor deposition techniques. The thickness of each layer was chosen to control the final equilibrium composition of the attachment material. Figure 2 shows a schematic of the specimen fabricated for reliability assessment of this alternative. The die bonding to the substrate was accomplished using a wafer bonder at a processing temperature of 315°C for 10 minutes. The bond required no flux during the process; both the atmospheric pressure and the external applied pressure on the die were regulated by the die bonder.

Figure 1. Schematic diagram of test specimens for the sintered silver nano-particle paste (not to scale).

The assembly process consisted of the deposition of attach material followed by die placement. The system was then subjected to an isothermal pre-heat step intended for binder evaporation from the paste. Isothermal processing at 300°C followed the pre-heating step was used to achieve the final joint.

b) Gold enriched solid liquid inter-diffusion (SLID)

The maximum allowable application temperature of a metallic attachment is typically limited by the melting point of the alloy being used. For elevated temperature environments, a suitable attach technology has to be selected based on this physical property which requires a processing temperature above its melting point when a reflow process is used.

Figure 2. Schematic representation of the Au-Sn SLID samples. (a) Metallization sequence and layer thicknesses at the Si die. (b) Metallization sequence and layer thicknesses for the alumina DBC substrate (not to scale)
c) Silver filled conductive epoxy

Filled epoxy materials are the most widely used die attaches in consumer electronics where application conditions remain below 70°C. Now, however, exploration is underway of temperature resistant epoxies for higher temperature applications. For this investigation, an electrically conductive silver filled epoxy designed for high temperature environments will be tested. The specific material is Epo-Tek® H20E. Samples were assembled following the manufacturers recommendations in terms of deposition and bond line curing schedule [19]. The die and substrate metallization for these specimens are identical to those shown in figure 1.

d) High lead (Pb) alloy

It is critical in evaluating the reliability of Pb-free alternatives to also evaluate a Pb-based high temperature solder attach in parallel as a control. In the present case, data from samples built with a high lead alloy, Pb2.5Ag2Sn, using a vacuum reflow furnace under an inert atmosphere were used as reference. This comparison will provide an initial assessment of the relative reliability of Pb-free technologies.

Experimental Procedure

The reliability assessment of these attach technologies was conducted using a series of accelerated testing experiments and physics-of-failure (PoF) modeling. In order to obtain reliability data in terms of mean time-to-failure (MTTF) a series of test specimens were manufactured as described in the previous section. Due to the fact that different attach materials require unique manufacturing methods and specifications, the test specimens cannot be exactly the same. These differences must be considered within the PoF models used to assess reliability. Normalization of the reliabilities was planned in order to allow for direct comparison across technologies regardless of the material/method under test. The fabrication matrix for this investigation is summarized in table 1.

Table 1. Fabrication matrix for reliability testing

<table>
<thead>
<tr>
<th>Attachment Technology</th>
<th>Small Die (SD)</th>
<th>Large Die (LD)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Ag-nano</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>DBC-Al2O3</td>
</tr>
<tr>
<td>(b) Au-Sn SLID</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>DBC-Al2O3</td>
</tr>
<tr>
<td>(c) H20E Epoxy</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>DBC-Al2O3</td>
</tr>
<tr>
<td>(d) High-Pb</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>Cu</td>
</tr>
</tbody>
</table>

When test specimens are subjected to thermal cycling, the mismatch in coefficient of thermal expansion between the substrate and die will cause stresses to be placed on the attach material. By subjecting a statistically significant number of samples to different temperature cycles (given by ∆T), distinct strain values can be generated. Two different thermal profiles were generated for this investigation (HT and LT). The high temperature profile (HT) was designed to subject the samples to temperature cycling from -55°C to 185°C with a 5 minute dwell at -55°C and a 10 minute dwell at 185°C for a ∆T of 240°C at a Tmean of 65°C. The low temperature profile (LT) was designed to subject the samples to temperature cycling from -55°C to 150°C with a 5 minute dwell at -55°C and a 10 minute dwell at 150°C for a ∆T of 205°C at a Tmean of 47.5°C.

The combination of two die sizes (5 mm “SD” and 10 mm “LD”) with two thermal profiles (HT and LT) provided a total of four strain levels per attach technology for the S-N plot. Samples were taken out of the temperature cycling chamber after every 50 cycles for inspection using X-ray and/or SAM imaging, depending on the material. Initially, failure was to be defined based on crack propagation through the bond area as observed by X-ray/SAM. A joint would have been deemed a failure when the crack/delamination exceeded 20% of the bonding area. Initial characterization of the as-built samples was used as the base line for failure definition. Subsequent thermal cycling during experimentation demonstrated that the failure definitions for each of the technologies required some modification for reasons that will follow during discussion of the experimental results.

When available, time-to-failure data for each of the attach technologies was then analyzed based on a parametric statistical distribution. The MTTFs along with the calculated strain range values for the various attach technologies were then used to generate the S-N curves. Provided that failure by fatigue was observed, the Coffin-Manson model was used to fit the S-N plots in order to determine the necessary characteristic empirical constants for the comparison of the different attach systems.

Results and Discussion

Sintered silver nano-particle paste

Test specimens fabricated with this technology were characterized by means of scanning acoustic microscopy to define an as-built base line for the reliability analysis. Figure 3 (a) shows a typical C-SAM image of an as-built specimen prior to thermal cycling. All samples under test were inspected every 50 cycles; damage progression was studied based on image analysis. Figure 3 (b) shows SAM image of the same specimen after 200 low temperature cycles, no discernable degradation is obvious from these images.

![Figure 3. C-SAM images of a typical 10mm X 10mm sample fabricated using the Ag nano-particle paste. (a) As-built SAM image (b) Image after 200 LT cycles.](image)

Figure 3. C-SAM images of a typical 10mm X 10mm sample fabricated using the Ag nano-particle paste. (a) As-built SAM image (b) Image after 200 LT cycles.

The intrinsic porosity of this sintered material affected the SAM’s capability to resolve the progression of damage through the joints. This condition forced a change in the failure criterion to one in which time to failure is defined as the number of cycles for complete die separation from the...
Fracture surfaces of failed specimens were evaluated using scanning electron microscopy. This fractographic analysis provided evidence of localized fatigue damage of the attach material. Figure 4 depicts the backscattered image of a typical failed sample. At lower magnification (a) a region of vertical shrinkage cracking is observed on the outer perimeter, while mussel shell markings are observed in regions of the fractured joint. Vertical shrinkage cracking has been identified as a failure mechanism of sintered nano particle materials [10]. Areas of fatigue damage are shown in more detail in the higher magnification image (b). These localized damage regions were primarily observed at bigger distances from the center of the die. These observations suggest that this silver nano paste does not form a continuous uniform joint at the die/substrate interface and, as expected, the highest thermo-mechanical strains are obtained in a narrow band where stresses approach a maximum at the largest distance from the neutral point.

The scope of this investigation included not only performing a relative reliability assessment of novel attach technologies but also to provide a life prediction model when possible. For solder materials, shear strain is commonly used as the independent variable while cycles to failure is the dependant response of the system. Typically, such fatigue life curves follow the Coffin-Manson relationship [11] shown below:

\[
N_f = 0.5(\Delta \gamma / e'_f)^{1/c}
\]  

(1)

where \(N_f\) is the number of cycles to failure, \(c\) is the fatigue ductility exponent, \(\Delta \gamma\) is the inelastic engineering shear strain range per cycle, and \(e'_f\) is the fatigue ductility coefficient. The maximum total engineering shear strain experienced by the solder joints must be known to develop fatigue life curves and the subsequent damage model. It is assumed that during thermal cycling, all the strain occurs in the attach material and not in the die or the substrate. Under these conditions, the maximum total engineering shear strain that occurs in the solder joint during one complete thermal cycle can be determined by knowing the geometry, coefficient of thermal expansion (CTE) of the substrate and die, and the total change in temperature during the cycling (\(\Delta T\)). The following expression was used to determine a first order approximation of strain in the bond [11], assuming (1) the die and substrate are rigid compared to the attach material, (2) the solder dimensions are much smaller than the die diagonal length, and (3) the attach is of constant volume:

\[
\Delta \gamma = (L_d \cdot \Delta T \cdot \Delta \text{CTE}) / 2t
\]  

(2)

where \(L_d\) is the diagonal length of the die, \(\Delta T\) is given by the thermal profile, \(t\) is the bond line thickness measured during the fabrication step, and \(\Delta \text{CTE}\) is the difference between the CTE of the Al₂O₃-DBC substrate and the Si chip. For the CTE of the Al₂O₃-DBC substrate, an effective CTE value was calculated to be 7.12 ppm/°C. A bond line thickness of 0.003” was attained during the fabrication process. Substitution of all the experimental conditions into equation 2 resulted in the following approximate shear strain range values: \(\Delta \gamma_1 (\text{HT-LD}) = 0.159, \Delta \gamma_2 (\text{LT-LD}) = 0.136, \Delta \gamma_3 (\text{HT-SD}) = 0.079, \) and \(\Delta \gamma_4 (\text{LT-SD}) = 0.068.\) Time to failure data (\(N_f\)) for all the specimens was obtained by inspection every 50 cycles. This life data was analyzed for each test condition using a two parameter Weibull distribution, where the mean time to failure was calculated along with the two sided 90% confidence level. Figure 5 shows a combined probability plot for all the experimental conditions. From this graph, the beta value (given by the slope) for the HT-LD condition is evidently different from the others. Changes in beta values suggest a different failure mechanism. In this instance the other three experimental conditions showed betas much closer to each other. It is widely known that beta values close to 1 represent constant failure rate populations and that, in these cases, failure may be attributed to an overstress rather than a wear out mechanism. In this investigation the data set for the first condition, given by the larger die and larger temperature swing (HT-LD), has been ruled out as a thermo-mechanical fatigue issue. It has been suggested that a complex state of stress could have been the cause of these early failures. Warpage of the ceramic substrate was observed on the failed specimens, suggesting a possible out of plane stress condition had existed.

![Figure 4. (a) Substrate fracture surface. Distinct vertical cracking is observed at the left (this area is outside of where the die was bonded). To the right, fractured joint, the mussel shell markings of metal fatigue are evident. (b) Detailed image of the observed fatigue damage.](image)

![Figure 5. Weibull probability plot for the silver nano paste experiment. Beta values for each experimental condition are given on the right margin.](image)
Life cycle data from conditions exhibiting beta values of 2.8, 3.3, and 3.3 was used for the S-N plot in figure 6, these values suggested a wear out mechanism that may be modeled as fatigue damage. Fitting the strain based fatigue model, eq. 1, resulted in the estimation of parameters that are not in agreement with the values obtained in the literature for metals fatigue [11,12] where typical values of “c” range from -0.43 to -0.87 and “ε’” has been found to fall between be 0.003 to 2.12. The inconsistency of these estimated parameters with what has been published suggests that a different damage model should be chosen for this sintered porous material. Researchers studying fatigue damage modeling on sintered metals [13, 14] reported that the Coffin-Manson model was not able to properly predict the experimental fatigue life, which in all cases was shorter than what was theoretically calculated. This discrepancy grew with increasing porosity of the sintered metals. Investigators have suggested that appropriate corrections to damage models need to be made in order to take into account the porosity notch effects. In our investigation a power function was fitted (R² = 95.4%) to the experimental data obtaining the following expression:

$$N_f = 187.7 (\Delta\gamma)^{-0.42}$$

Figure 6. Low cycle fatigue life curve (log-log) for the silver nano particle paste. Markers represent the mean life at each strain level as calculated from a two parameter Weibull distribution, error bars represent the upper and lower limit for a 90% confidence level.

Gold enriched solid liquid inter-diffusion

The transient character of this metallurgical technique required a more comprehensive microstructural characterization of the bond. This technology has been designed to provide a relatively low melting point fabrication process while resulting in a high temperature resistant attachment. The success in accomplishing this objective is determined by measuring the melting point of the formed metallurgical joint using Differential Scanning Calorimetry. The microstructure and elemental composition of the bond interface were investigated by scanning electron microscopy and energy dispersive spectroscopy.

The initial deposition of Au and Sn was presented in figure 2, where it is evident that an Au-Sn eutectic layer is present in both the substrate and the die. This material has an initial eutectic composition of 80Wt.% Au – 20Wt.% Sn, with a single melting point of 280°C. The presence of this layer is the key enabler for the low temperature fabrication process, where a temperature of 300°C to 325°C can be used for bond formation. The melting of this layer enhances the diffusion process where additional Au dissolves into the Au-Sn alloy. When sufficient time is provided at the processing temperature, a new Au-rich alloy is formed. The average bulk composition of this newly formed material is defined by the mass balance of its main constituents, which is a function of the layer thicknesses. A theoretical calculation of the average bulk composition of the bond was obtained; assuming equilibrium conditions with complete diffusivity of the constituents. Based on the thicknesses from figure 2 and necessary materials properties [15], the final composition through the attachment material is 94.8Wt.% Au – 5.2Wt.% Sn. An alloy having this composition will exhibit a melting point of 498°C as given by the phase diagram [16].

The validity of this theoretical calculation was confirmed by experimental data obtained from a cross sectional analysis. A micrograph of the joint is shown in figure 7, where a bond line thickness of ~6 µm can be observed.

Figure 7. Backscattered SEM image of an Au-Sn bond. Attachment was obtained at 315°C with a 10 minutes isothermal hold.

Au-Sn alloys are commonly referred to as hard solders because they can tolerate higher stresses than soft solders, such as Sn-Pb and SnAgCu alloys, prior to plastically deforming. Many of these hard solders also feature higher melting temperatures than their traditional counterparts. As a result of this additional strength and ability to withstand increased temperatures, hard solders are significantly more resistant to creep and thermal fatigue during thermal cycling [17, 18]. Although Au-Sn attachments are better equipped to survive repeated thermal cycling, they tend to cause more damage to their respective chips [17] by failing to absorb the strain energy generated by the thermal mismatch between the device and the material on which it is mounted. This transfer of damage to the attached device means that failure of the system may occur within the die chip itself.

Thermal cycling of the subsequent 94.8Wt.% Au – 5.2Wt.% Sn bonds yielded encouraging results. Not surprisingly, it was observed that the initial as-built quality of bonds strongly influenced their survivability during cycling. SAM imaging of all samples was used to determine which
bonds were able to partially or fully attach the dice to the DBC substrates. Those samples deemed “fully attached” from the SAM images successfully survived 650 to 800 thermal cycles while partially bonded samples quickly damaged the silicon devices through cracking.

Based on the observed behavior of the Au-Sn SLID joints during thermal cycling, the earlier definition of failure was never met by any of the fully attached devices. Instead, cracking of the silicon devices from partially attached samples precipitated failures outside of the bond itself, therefore rendering the earlier definition of failure inapplicable. This being the case, subsequent references to failure of the Au-Sn SLID samples will be used to convey destruction of the silicon die.

Images of a typical, partial Au-Sn die bond as a function of HT cycling history are shown in figure 8 below. The rough, dark band around the periphery of the as-built image in figure 8 represents the area in which a bond had occurred between the die and substrate. The smooth, light-gray areas are those in which the die and substrate failed to form a joint. As the partial bond was subjected to subsequent HT thermal cycles, it was clear that damage was occurring to the silicon die, as evidenced by the progressing crack in the images. A correlating image of the sample from the stereo microscope shows that the cracking observed was indeed through the device attached with the partial Au-Sn bond.

Subsequent thermal cycling of the fully bonded device demonstrated that no observable damage to the die or Au-Sn attach had occurred during 800 HT thermal cycles. All samples that exhibited similar visual characteristics and area coverage as the one shown in figure 9 survived to the conclusion of thermal cycling.

All failures of the Au-Sn SLID samples subjected to LT and HT thermal cycling were observed within the population characterized by partial bonds. In addition, these failures took place through the dice themselves, not within the Au-Sn attachment. Any significant areas of detachment between the die and substrate within the Au-Sn SLID bond led to cracking within the chip during thermal cycling. Catastrophic failure of a given sample occurred when cracking through the die had completely severed the attached portions of silicon from the bulk of the device and subsequently, the die came free of the substrate. It is hypothesized that the decreased bond areas of the partially attached samples imposed elevated, localized stresses within each die, which then led to cracking and possible separation of the devices from their Au-Sn bonds. In the case of the partially bonded sample from figure 8, chunks of silicon broke free from the die and remained attached to the substrate in a predictable manner: they were located in the attached areas characterized by the rough and dark features found in the SAM images. Evidence of this scooping of the silicon from the bulk of the die can be seen below in figure 10. The image of the substrate locale, as viewed through the stereo microscope, shows the locations of the remaining silicon. The as-built SAM image of the sample was also included for reference.

In contrast to the partially bonded sample shown above, figure 9 exhibits the SAM images of a typical, fully bonded device subjected to HT thermal cycling. As evidenced by the as-built image, the rough and dark features can be seen over the entire area of the 10mm by 10mm silicon die. Prior analysis of failed partially bonded devices signified that SAM images with these characteristics indicated an attachment between the die and substrate by way of the Au-Sn bond.

Figure 8. Images of a typical, partially bonded 10mm X 10mm sample fabricated using Au-Sn SLID. (a) As-built SAM image (b) SAM image after 50 HT cycles (c) SAM image after 100 HT cycles (d) Stereo microscope image after 100 HT cycles.

Figure 9. Images of a typical, fully bonded 10mm X 10mm sample fabricated using Au-Sn SLID. (a) As-built SAM image (b) SAM image after 800 HT cycles.

Figure 10. Images of a typical, partially bonded 10mm X 10mm sample fabricated using Au-Sn SLID. (a) Stereo microscope image of substrate following failure (b) As-built SAM image.
Thermal cycling and C-SAM imaging of the Au-Sn SLID samples demonstrated that the attach method may be a promising alternative for high temperature applications, provided that joint quality can be controlled to yield fully bonded samples as those shown in figure 9. The extended temperature applications afforded by Au-Sn SLID in conjunction with the observed reliability of fully bonded dice during thermal cycling clearly warrant further investigation of the attach technology.

**Silver filled conductive epoxy**

Test specimens fabricated with the silver filled epoxy were characterized by scanning acoustic microscopy. All samples were inspected initially to define the as-built condition and subsequent imaging was scheduled at 50 cycles intervals. From the images obtained at the first inspection after 50 cycles (figure 11) it was observed that for all samples, the degradation of the joint was well beyond the defined failure criteria. Delamination of this material is evident by the progression of the white area as function of cycling history. This data confirmed that this attach technology is not suitable for high temperature applications.

**High lead alloy**

Passive temperature cycling of specimens fabricated with the lead rich alloy has resulted in no deterioration after 1700 cycles for any of the die sizes. This data confirmed the excellent reliability of this lead rich alloy, which is actually the most widely used system (due to the RoHS exemption) for high temperature applications.

**Conclusions**

A series of lead-free die attach technologies for high temperature applications have been presented in this paper along with their specific fabrication procedures. A reliability assessment based on passive thermal cycling was proposed as a tool for comparison, where physics-of-failure modeling in conjunction with failure analysis was used for characterization purposes. Initial degradation of the silver filled epoxy was evident from the SAM characterization, confirming that organic attachments are not a reliable alternative for high temperature environments. Survival of all the high lead specimens after 1,700 cycles confirmed the excellent reliability of this system. It was found that the sintered silver nanopaste showed a fatigue induced failure mechanism, which did not fit the well known strain based Coffin-Manson model. A power function was fitted to the empirical data and a damage model has been proposed, with the pore notch effect theorized as the cause for this discrepancy. The Au-Sn SLID system proves to be a reliable alternative for high temperature applications, but its sensitivity to bond quality was evident from the observed results. Efforts with this technology should be placed on the optimization of the process yield.

**Acknowledgments**

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**References**


![Figure 11: SAM images of a typical 10mm X 10mm sample fabricated using the silver filled epoxy. (a) As-built SAM image (b) Image after 50 LT cycles.](image-url)