Lead-Free Die Attach Reliability Assessment for High Temperature Environments

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Abstract

The increasing demand for electronics capable of operating at temperatures above the traditional 125°C limit is driving major research efforts. Wide band gap semiconductors have been demonstrated to operate at temperatures up to 500°C, but packaging is still 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 toxic materials in electronic products; lead being a major concern due to its widespread use in solder attach. In this investigation, a series of Pb-free die attach technologies have been identified as possible alternatives to Pb-based materials for high temperature applications. This paper describes the fabrication sequence used to create attachments with these materials. The long term reliability is also determined by accelerated thermal cycling and physics-of-failure modeling.

Key words: die attach, reliability, lead free, accelerated testing, high temperature electronics

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 and monitoring equipment, chemical processing systems, and space/earth explorations. Critical elements of these systems are the subsystems 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 have the potential to 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. Unique materials and manufacturing processes are required for die attachment at high temperatures, however. 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 (Tₚ > 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 the fundamentals of 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 nano-
powders 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 introduces 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.

**Die Attachment Technologies**

This investigation focuses on the reliability of 
a series of die attach technologies as they pertain 
to 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 pretend 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 round robin test 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 assembly temperatures on a 
lower range that can fulfill the requirements for a 
reliable bonding process. G. Q. Lu [5] developed a 
silver based solder paste along with a pressure 
assisted sintering process intended for die attach 
applications. In his work he reported physical 
properties measured on sintered samples and 
compared them to pure silver and eutectic Sn-Pb 
solder. A summary of his findings is presented 
within table 1.

**Table 1: Summary of properties measured on 
sintered silver and solder joints [5].**

<table>
<thead>
<tr>
<th></th>
<th>Sintered Silver Joint</th>
<th>Soldered Joint (Sn63Pb37)</th>
<th>Pure Silver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joining Temperature (°C)</td>
<td>240</td>
<td>210</td>
<td>-</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>40</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Metallization</td>
<td>Ag</td>
<td>Cu/Ag/Ni</td>
<td>-</td>
</tr>
<tr>
<td>Joint Shear Strength (MPa)</td>
<td>50</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Electrical Resistivity (Ω-cm)</td>
<td>2.4 X 10⁻⁵</td>
<td>1.4 X 10⁻⁵ to 5 X 10⁻⁵</td>
<td>1.5 X 10⁻⁶</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>80</td>
<td>43</td>
<td>428</td>
</tr>
</tbody>
</table>

Data from Matweb

In this research, the material and technique 
developed by G.Q. Lu was used for the 
manufacturing of test specimens for reliability 
testing. The Si wafers were metallized by 
evaporation techniques whereby the Ti-Ag layers 
were obtained as shown in figure 2. Dice were 
attached to Al₂O₃ DBC substrates with an Ag over 
Cr-Ni metallization. Details of the substrates can be 
seen in figure 1.

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

The assembly process consisted of the 
deposition of the 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 where the final joint was achieved.

b) Au-Sn Solid Liquid Inter-Diffusion

The maximum allowable application temperature of a metallic attachment is 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. Thermo-mechanical residual stresses are created within the attachment material as a result of the CTE mismatch between the die and the substrate. This stress is proportional to the product of the CTE difference and the temperature delta between the processing and room temperature. 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 to some specific proportion with a high melting point material. The whole system is held isothermally at a processing temperature above the melting point of the first constituent, but below that of the high melting point material. Formation of a liquid phase enhances wetting and atomic diffusion, the latter being the mechanism responsible for the melting point shift which is the key enabler of high temperature resistant nature of this system.

For this investigation an Au-Sn system has been selected as an additional alternative. 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 the schematic of the specimen fabricated for the reliability assessment of this alternative. The die bonding to the substrate was accomplished using a wafer bonder where a processing temperature of 315°C for 10 minutes was used. The bond required no flux during the process; a controllable atmospheric pressure was regulated as well as the external applied pressure on the die.

c) Silver Filled Epoxy

Epoxy die attaches are the most widely used material for consumer electronics where application conditions remain below 100°C. For high temperature environments hard solders are the preferred alternative due to their melting points and excellent thermal / electrical conductivities. However, the complexity and process control required during these assembly processes are giving way to exploration of high temperature resistant epoxies. 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. The die and substrate metallization for these specimens are identical to those showed in figure 1.

d) High Lead Die Attach

It is critical in evaluating the reliability of Pb-free alternatives to 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 will be used as the reference. This comparison will provide an initial assessment of the relative reliability of Pb-free technologies.

**Experimental Procedure**

The reliability assessment of these attachment technologies will be conducted using a series of accelerated testing experiments and physics-of-failure (PoF) modeling. In order to obtain reliability data in terms of time-to-failure (TTF) a series of test specimens have been 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 all exactly the same. These differences have to be considered within the PoF models used to assess reliability. Subsequent normalization of the data provides the capability of performing a relative reliability comparison of the proposed technologies without being affected by intrinsic responses of the material/method under test. The fabrication matrix for this investigation is summarized in table 2.

<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-Al$_2$O$_3$</td>
</tr>
<tr>
<td>(b) Au-Sn SLID</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>DBC-Al$_2$O$_3$</td>
</tr>
<tr>
<td>(c) H20E Epoxy</td>
<td>5mm X 5mm</td>
<td>10 mm X 10 mm</td>
<td>DBC- Al$_2$O$_3$</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 $\Delta T$), distinct strain values can be generated. Two different thermal profiles have been generated for this investigation (HT and LT). The high temperature profile (HT) will 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 $\Delta T$ of 240°C at a $T_{\text{mean}}$ of 65°C. The low temperature profile (LT) will 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 $\Delta T$ of 205°C at a $T_{\text{mean}}$ of 47.5°C.

The combination of two die sizes (5 mm and 10 mm) with two thermal profiles (HT and LT) gives a total of four strain levels per attach technology for the S-N plot. The samples will be taken out of the temperature cycling chamber after every 50 cycles for inspection using X-ray or SAM imaging, depending on the material. Failure is defined based on crack propagation through the bond area as observed by X-ray/SAM. A joint is considered to have failed when the crack/delamination exceeds 20% of the bonding area. Initial characterization of the as-built samples is used as the base line for failure definition. Time-to-failure data for each of the attach technologies will be analyzed based on a parametric statistical distribution. The TTFs along with the calculated strain range values for the various attach technologies will be used to generate the S-N curves. Provided that failure by fatigue is observed, fitting the Coffin-Manson model to each of the obtained S-N plots will yield the necessary characteristic empirical constants for the comparison of the different attach systems. The test methodology has been summarized in the following flowchart (figure 3).

![Figure 3. Test methodology flowchart for the round robin reliability assessment.](image-url)
Results and Discussion

Sintered Silver Nano-Particles Paste

Test specimens fabricated with this technology have been characterized by means of scanning acoustic microscopy to define an as-built baseline for the reliability analysis. Figure 4 (a) shows a typical SAM image of an as-built specimen prior to thermal cycling. All samples under test are being inspected every 50 cycles where the progression of damage is assessed in terms of image analysis. Figure 4 (b) and (c) shows SAM images of the same specimen after 50 and 100 low temperature cycles, respectively.

![SAM Images](image1)

**Figure 4.** SAM images of a typical 10mm X 10mm sample fabricated using the Ag nano-particle paste. (a) As-built SAM image (b) Image after 50 LT cycles (c) Image after 100 LT cycles.

Au-Sn 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 accomplishment of this objective has been studied by measuring the melting point of the formed metallurgical joint using Differential Scanning Calorimetry. The microstructure and elemental composition of the bond interface was 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 the Sn atoms dissolve into the Au rich matrix. 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 indeed a function of the layer thicknesses. A theoretical calculation of the average bulk composition of the bond was obtained; this analysis assumed equilibrium conditions with complete diffusivity of the constituents. Based on the thicknesses from figure 2 and necessary materials properties [10], 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 [11].

The validity of this theoretical calculation was confirmed by experimental data obtained from a cross sectional analysis. The specimen under test was studied using SEM / EDS these results are presented in this section. A micrograph of the joint is shown in figure 5, where a bond line thickness of ~6 µm can be observed.

![SEM Image](image2)

**Figure 5.** Backscattered SEM image of an Au-Sn bond. Attachment was obtained at 315°C with a 10 minutes isothermal hold.

An EDS dot map, figure 6, across the Au-Sn interface revealed a homogeneous distribution of the main constituents, clearly indicating that the Au-Sn interdiffused into each other forming an uniform bond in terms of elemental distribution. The silicon
die and the nickel metallization on the substrate were clearly identified.

![Figure 6. EDS dot map showing the Au and Sn distribution in the interface (red ellipse).](image)

A line scan across the bond interface was used to confirm the data from the dot map; results are shown in figure 7. It is evident that the Au-Sn material is concentrated on the attachment as given by the profile; note that silicon and nickel is clearly separated by the presence of the die attachment.

![Figure 7. EDS line scan across the bond interface showing the elemental profile.](image)

A quantitative compositional analysis at the bond interface was obtained by x-ray spectroscopy over a defined area or spectrum. Results from five random locations along the bond line are given in table 3.

<table>
<thead>
<tr>
<th>Spectrum Area</th>
<th>Au at.%</th>
<th>Sn at.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.06</td>
<td>7.94</td>
</tr>
<tr>
<td>2</td>
<td>92.35</td>
<td>7.65</td>
</tr>
<tr>
<td>3</td>
<td>94.38</td>
<td>5.62</td>
</tr>
<tr>
<td>4</td>
<td>94.62</td>
<td>5.38</td>
</tr>
<tr>
<td>5</td>
<td>91.66</td>
<td>8.34</td>
</tr>
</tbody>
</table>

**Avg. 93.01 = 95.4 Wt.% Au 6.99**

Experimental data obtained from this analytical technique, 95.4Wt.% Au, is in agreement with the theoretical calculation of 94.8Wt.% Au.

**Silver Filled Epoxy**

Test specimens fabricated with the silver filled epoxy die attachment have been characterized by scanning acoustic microscopy. All samples were inspected initially to define the as-built condition and subsequent imaging is schedule at every 50 cycles. Initial observations of a large die (10mm X 10mm) subjected to the low temperature profile ($\Delta T = 205^\circ C$) showed (figure 8) a significant degradation of the attachment. This is observed by the progression of the white area as function of cycling history.

![Figure 8. 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 (c) Image after 100 LT cycles.](image)
High Lead Alloy

Passive temperature cycling of specimens fabricated with the lead rich alloy has shown no signs of deterioration after 850 LT cycles for any of the die sizes. High temperature thermal cycling is yet to produce any discernable damage after 400 cycles. These observations are confirmed by the x-ray imaging of the specimens under evaluation. Figure 9 shows the progressive x-ray images of a SD cycled under the LT profile, as can be observed there is no evident sign of damage after 850 cycles.

Figure 9. X-Ray images of a typical small die specimen (5mm X 5mm) subjected to the low temperature cycling conditions. (a) As built image, (b) 250 LT cycles, (c) 550 LT cycles, and (d) 850 LT cycles.

Summary

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 were 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. Continuous monitoring of remaining technologies will provide the data for the parametric statistical analysis needed for the final reliability modeling.

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