Optimizing the performance of the Au-Si system for high temperature die attach applications

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Abstract

The operation of electronic packages under exceptionally harsh environments presents a significant challenge for the microelectronics industry, for example, in down-hole, well-logging and turbo-machinery applications. High temperature Au based solders are one potential candidate for die attachment for harsh environments and is already used in limited cases. For Au-Si die bonding, some of the Si is provided by diffusion from the Si die itself. Therefore, the interfacial reaction between the Si and Au-Si thin foil solder preform is a key factor in the control of the die bonding process. Unfortunately, during the die bonding process, defects such as voids, delaminations, and impurities are not unusual. These defects are caused by the assembly process, chemical impurities, soldering reactions, and thermal stresses. Understanding these defects is critical for the reliable performance of the devices after bonding. In this paper, optimization of the Au-Si eutectic die bonding has been performed and near 100% bonded area confirmed by scanning acoustic microscopy achieved consistently. Die attach reliability was investigated by thermal shock and thermal cycling treatments, after which the bonded area showed some signs of degradation. Shear strength testing and microstructural analysis were also carried out. Die bond optimisation gave a significant improvement in both bonded area and reliability.

Key words: Au-Si eutectic, die bonding, reliability, scanning acoustic microscopy, die shear.

1 Introduction

There is a growing desire to install electronic power and control systems in high temperature environments in order to improve the accuracy of critical measurements and to reduce the cost of cabling to and from remote and hostile locations. Air and ground vehicles are potential candidates for the use of high temperature electronics (HTEs) as there are both regions of high temperature (due to combustion) where sense/control is required and engineering limitations on the ability to provide active cooling to electronic circuitry in these areas. HTEs also offer the potential to operate under harsh but valuable environments such as down-well (including geothermal applications), inside turbomachinery, combustion zones, etc. These requirements have posed a challenge to the traditional limit of 125^{o}C for the high temperature exposure of electronic systems [1], and also require resistance to high pressures, vibrations and potentially corrosive environments [2, 3].

Materials used in electronic package assemblies are intended to survive exposure at high temperature and work reliably. Electrical performance, thermal management and reliability of an electronic system strongly depends on the type of die attach material used [4, 5]. The present work focuses on the materials that mechanically attach the die to a substrate ensuring it does not detach/fracture over the operational lifetime. The die attach material also (i) creates a thermal path to conduct the heat away from the base of the die, (ii) acts as an intermediate material to partially offset any differences in the coefficient of thermal expansion (CTE) between the die and the substrate, therefore lowering stresses at the interface, and (iii) provides for electrical grounding if the material used to secure the die is sufficiently conductive.

Eutectic die bonds also known as solders are generally binary or ternary metallic compositions. Solders can be divided into hard solders and soft solders where hard solders have generally much higher melting point, elastic modulus and yield stress. Hard solders include Au-Si, Au-Sn and Au-Ge. Au-based eutectics tend to lead to increased stresses and strains in the die, because of both increased differences in the coefficient of thermal expansion within the die/attach/substrate combination, and a higher elastic modulus. These strains lead to interfacial shear and other stresses, and the tendency for premature failure. Peeling stresses at the edge of the die can cause horizontal crack and die lifting, while tensile stresses in the center of the die can cause vertical crack propagation, leading to die cracking. Overall die fracture and

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fatigue behaviour depends on the modulus of the die attach, on the difference between thermal expansion of the die and substrate, and on the fracture toughness and fatigue of the die. Figure 1 illustrates the temperature dependence of the elastic modulus and tensile strength of Au-based eutectic die attach materials.

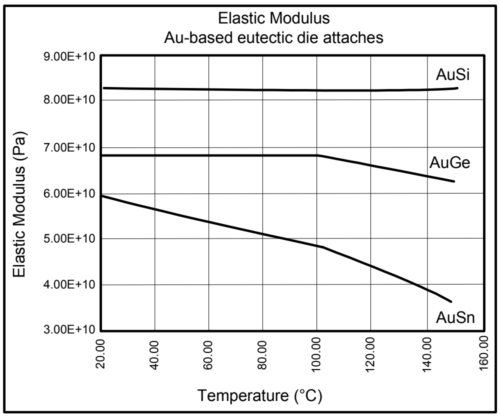

Figure 1: The elastic modulus of Au-based eutectic die attach materials as a function of temperature [3].

Solder alloys used for electronic applications must have small two-phase region (liquid+solid) for ease of processing by reflow, and if the two-phase region is too large, the joints have the opportunity to move with respect to one another during solidification, and solidification shrinkage can be problematical. As a result, irregular, coarse and sometimes cracked joint surfaces may occur. Therefore, most solder alloys for interconnects are near-eutectic alloys. Au-Si is used as a high thermal performance die attach material for high power microwave and RF Si-based devices.

Au-Si eutectic solder has good overall wetting and flow characteristics during die bonding to a substrate metallization [6]. The equilibrium binary Au-Si phase diagram is shown in Figure 2. While the melting points of Si and Au are 1414^{o}C and 1064^{o}C respectively, a eutectic alloy containing 97.15% Au and 2.85% Si by weight melts at a much lower temperature of 363^{o}C.

Bonding with solder preforms is relatively inexpensive and simple to implement, although solder alignment and thickness control can be hard to ensure reproducibility and the solder is easily oxidized, which can compromise bond integrity. The Au-based preform composition may be varied in the range 2 to 6wt% of Si. In general, Au-2wt%Si has good wetting and flow characteristics during die bonding. On the other hand, die cracks can develop using Au-

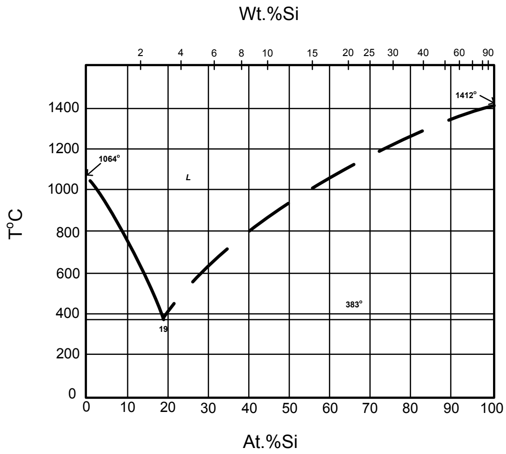

Figure 2: Au-Si equilibrium phase diagram.

4wt%Si preforms at a reflow temperature of 425 ^{o}C, possibly due to void formation and uneven stresses. Stresses can be minimized by using a thicker preform (perhaps up to 1mm), a high die bonding temperature (500 ^{o}C or higher) and a slow cooling rate.

Die bonding occurs generally at temperatures higher than 400^{o}C, and concerns include the effects of such high processing temperature on the actives/passives/wirebonds elsewhere in the package [7]. Die cracking may occur particularly on larger devices (> 6mm × 6mm) as a result of excessive stress due to the the high modulus of the Au-Si eutectic. Also the formation of SiO_2 is another issue arising during the eutectic die bonding [6]. Despite significant study [6, 8–10], one of the main barriers to the more widespread use of Au-Si is the perceived inherent variability of the die attach bond quality. Therefore, the focus of the current work is to explore the factors controlling bonded area, to optimise them for maximum bonded area, and to then explore the inherent variability within many bonds formed under optimum conditions.

2 Experimental procedure

2.1 Materials and manufacturing

Ceramic substrates of Al_2O_3 tiles 10mm × 10mm were used, which had been metallized with Au thick film (10 μm) by screen printing and then fired. The dies (Si) had dimensions of 4.62mm × 4.64mm × 0.5mm. The Au-Si preforms were 5mm square and 25 μm thick. Both components were cleaned in HF (7%) for 10 seconds in order to remove any oxide layer. Preforms were stored in dry N_2 atmosphere. A preform was placed in between the Au metallization of the substrate and the base of the Si die and then heated to above the Au-Si eutectic temperature. When the preform and die were placed on the substrate, a light scrubbing action with the bond head was initiated - a common industrial practice to promote Si diffusion into the Au and the formation of a eutectic reaction at the interface. A cover gas of 90% N_2 was used to inhibit metal oxides from forming, together with an active component H_2(10%) to help reduce metal oxides. Bonding took place within a Cammax EDB65 industrial die bonder.

2.2 Optimization of bonding parameters

The critical scrubbing action that ruptures the oxide films during die bonding is generally difficult to regulate/automate leading to a wide variability in bond quality. This inherent variability can obscure systematic attempts to improve lifetimes and reliability. In this study, the most important parameters that control bond quality were identified, followed by optimization of the manufacturing process to achieve the largest bonded area between die and substrate. The choice of process variable to be varied and those to be held constant relied on initial experiments and operator experience. Critical process parameters were identified initially as:

i) Temperature of the heating stage.

ii) Force of the scrubbing head.

iii) Scrubbing frequency.

iv) Scrubbing time.

A complete matrix of experiments of all combinations of many settings of each parameter would be too time consuming; therefore, a simple experimental design was employed, based on a "low" and "high" value for each parameter. All possible combinations, in a full factorial of 2^4 experiments were undertaken (Table 1). Three repeats for each combination were performed, which resulted in 48 experiments and associated measurement of bonded area in total. Subsequently, the optimum combination of parameters was studied to ascertain the inherent variability of bonds made to optimum parameters.

The quality of the bond was assessed by scanning acoustic microscopy (SAM) as the percentage of the die bonded area, using C-SAM apparatus at a frequency of 300MHz. To generate the SAM images, the ultrasound was directed from the top side of the Si die. The field of view was 22.5 × 22.5 mm with 2048 × 2048 pixel size. All the die attaches were examined using THRU-scan inspection technique to examine the extent of interfacial delamination under near-identical imaging conditions.

Table 1: The process parameter combination of the experimental design for Au-Si eutectic die bonding: sixteen-run, two-level. T - temperature of the heating stage; F - force of the scrubbing head; S_f - scrubbing frequency; S_t - scrubbing time.

T (^{o}C)	F(g/mm^2)	S_f (Hz)	S_t (s)
400	0.5	3	1.5
400	0.5	3	3.5
400	0.5	7	1.5
400	0.5	7	3.5
400	3.5	3	1.5
400	3.5	3	3.5
400	3.5	7	1.5
400	3.5	7	3.5
450	0.5	3	1.5
450	0.5	3	3.5
450	0.5	7	1.5
450	0.5	7	3.5
450	3.5	3	1.5
450	3.5	3	3.5
450	3.5	7	1.5
450	3.5	7	3.5

Selected assemblies were cross-sectioned, ground and polished for microstructural analysis in the as manufactured, isothermal aged, thermal cycled and thermal shocked condition using scanning electron microscopy (SEM-JEOL840A) operating at an accelerating voltage of 15kV and beam current of 3×10^{-9}A. Energy-dispersive X-ray spectroscopy (EDS) was occasionally used to study the composition at the interfaces.

Die interfaces were subjected to increasing die shear force to failure using a Dage 4000-Series bond tester. The results were considered in the context of the MIL-STD-883 standard [11] and in each case the failure modes were recorded.

2.3 ANOVA method

The experimental results were studied by calculating the mean, the variance, and signal-to-noise (S/N) ratio. The S/N ratio represents the general trend of response of the percentage bonded area to each varied parameter. In this case, this ratio was calculated in the larger-the-better case (SN_L) as bonded area was intended to be maximised.

$$S/N = -10 \log\left(\frac{1}{n} \sum \frac{1}{y^2}\right) \quad (1)$$

where n is the number of observations and y is the measured bonded area. The ANOVA method identifies the factors with largest and smallest contribution to bond quality. The factors of low influence were then fixed in the next set of experiments, while the factors with the greatest influence on bonded area were studied in more detail.

Once the experimental design matrix was completed, a more focused experimental design was performed and afterwards, a number of nominally identical die assemblies were manufactured under optimum conditions in order to study inherent variability of bond quality.

2.4 Thermal exposure

Selected Au-Si die attaches were subjected to isothermal ageing at 300^{o}C for different periods of time: 1, 4 and 12 weeks. Some die attaches were also submitted to accelerated ageing at 350^{o}C for 800h.

2.5 Thermal cycling

Thermal cycle testing was performed in collaboration with GE-Aviation Systems who provided access to industrial thermal cycling facilities. An optimized batch of die attaches was subjected to thermal cycling (TC) and thermal shock (TS). The TC and TS profiles were selected according to GE-AS and were typical of those used in industry, based on the MIL-STD-883 standard [11]. Figure 3 illustrates the test regime used for both TC and TS testing. The transfer time between the maximum and the minimum temperature was ≈ 30min and ≈ 5min for TC and TS, respectively.

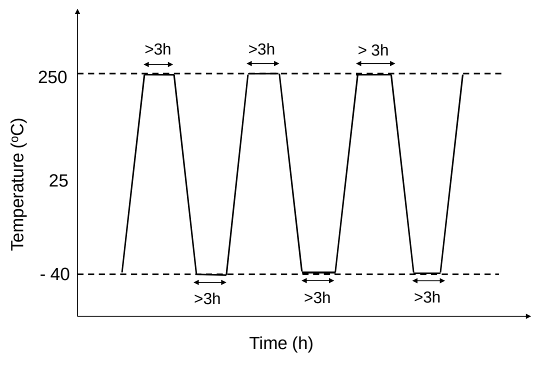

Figure 3: Test regime used for thermal cycling.

3 Results

SAM investigation showed that all 48 die attaches from the combinations in Table 1 contained delaminations at the die to Au-Si and Au-Si to Au interfaces. There was also voiding, and some interfaces were nearly completely debonded. Figure 4 shows some of the typical SAM images, with black representing bonded area and white representing unbonded area. The

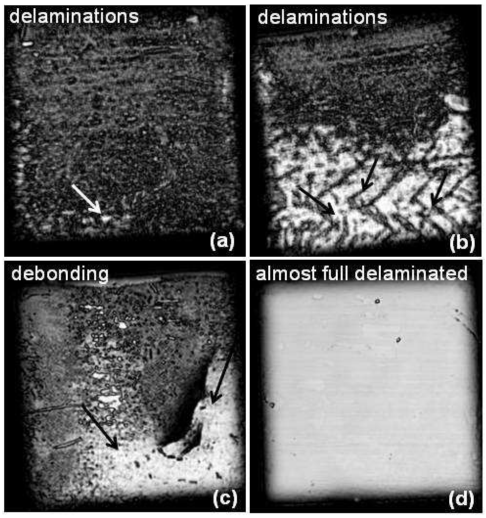

Figure 4: SAM images of Au-Si attaches [12].

total percentage of defect area in each region of interest varied from 0.5% (Figure 4(a)) to 98% (Figure 4(d)) with the largest single debond spanning the whole range from 0.1 and 88% area respectively - emphasizing the variability in bond quality even when using semi-automated assembly [12]. Even for a constant set of conditions, the bonded area varied from sample to sample.

Figure 5 shows the raw data distribution of total bonded area for all the 48 die attaches, with a bi-modal shape and peaks at 10-20 and 80-90% area bonded.

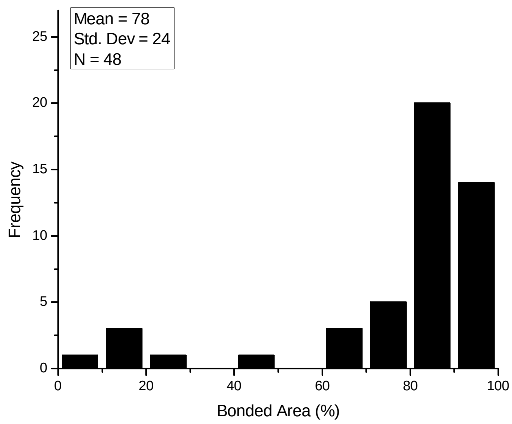

Figure 5: Bonded area distribution of 48 die attaches (16 conditions) shown in Table 1.

Figure 6 shows the corresponding failure shear loads of the interfaces for the conditions in Table 1. Shear loads ranged from 5 to 75kg, had a near normal distribution, with more than half of the die attaches failed at the interface, while the rest failed at the Si die. The mean failure load lay in the region 30-40kg.

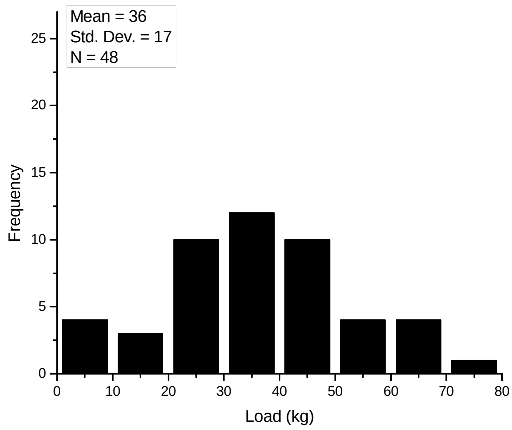

Figure 6: Shear strength distribution of 48 die attaches (16 conditions) shown in Table 1.

3.1 Identifying the most influential die bonding parameters

After calculating the S/N ratio, the ANOVA method was used to identify the most critical parameters affecting bond quality comparing the "within variation" with "between variation". The level of significance was calculated for each process parameter and for interactions of parameters.

This analysis suggested that temperature and force of the scrubbing head had a comparatively low influence on bond quality. Although substrate temperature was initially thought critical to solder reflow, as long as the temperature was above the eutectic temperature, the relative importance of the temperature was low. Regarding the force of the scrubbing head, the amount of force applied must be sufficient to break the oxide layer and hold the die in place. Moreover, excessive force could damage the component by introducing micro-cracks that might affect, for instance, the electrical performance. During the scrubbing, the load force was translated into frictional heat by cyclically moving the die left to right (or back and forth). Both the time for force application and additional thermal energy due to friction determined the overall extent of the solder reflow. However, overall the relative influence on bond quality was weak.

Substrate temperature and scrubbing force were then fixed at the "best" combination of 450^oC and 3.5g/mm^2 respectively. Three levels were then allocated for each of the two remaining, more influential scrubbing variables: scrubbing frequency - 2, 5 and 8Hz, and scrubbing time - 1, 2.5 and 3.5s. This second batch required 27 separate experiments.

The percentage of debonded area in these first level optimized die attaches was again evaluated by SAM. As intended, the overall bonded area increased, and was always more than 80% with a much reduced spread of bonded area (Figure 7). However, delaminations at both interfaces (Si die to solder, and solder to Au from the substrate) were still present.

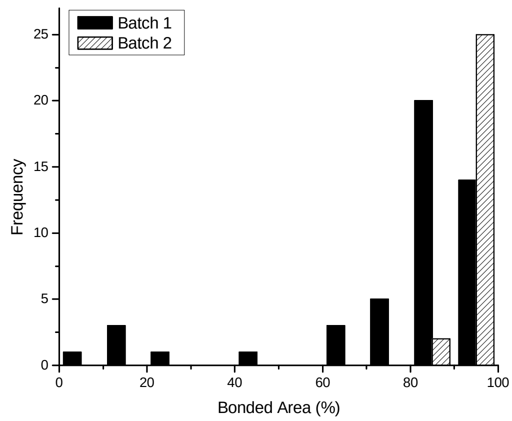

Figure 7: Bonded area distributions comparing batch 1 (48 samples) with batch 2 (27 samples).

All the solder bonds failed at the Si die in die shear testing, and failure loads increased. Figure 8 illustrates the distribution of the failure load in shear for both batch 1 and batch 2 bonds. The shaded vertical line at ≈ 40kg load shows approximately the load where failure outside the Si die transitioned to failure inside the Si die. By comparing the shear test loads with the bonded areas from the SAM images, a correlation between the increased bond area by SAM and high failure loads in shear was established.

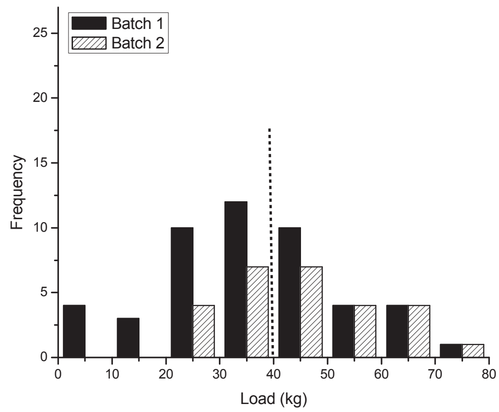

Figure 8: Shear strength distributions comparing batch 1 (48 samples) with batch 2 (27 samples).

The following 3D plots illustrate the effect of the most critical eutectic die bonding parameters of scrubbing frequency and time on bonded area and shear load to failure. Figure 9 shows that a long scrub or too higher frequency generally reduced bonded area. This behaviour is qualitative consistent with the scenario: (1) it was surface oxide and contamination that must be disrupted for a high area bond; (2) it was important not to undermine the planarity of the Si or substrate by over scrubbing; (3) additional oxidation by too hot or too long thermal exposure must be avoided; and (4) excessive frictional heat can undermine bonding.

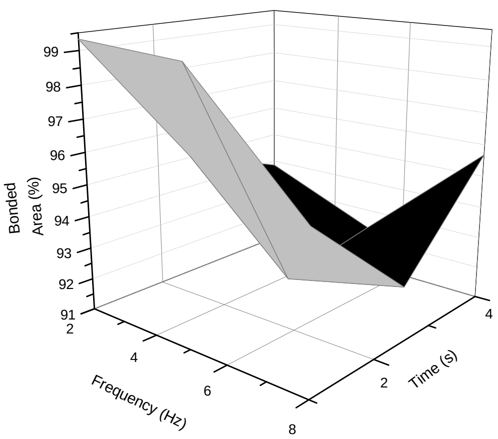

Figure 9: Effect of scrubbing frequency and time on the bonded area of die attaches from batch 2.

As mentioned before, the load point where failure started occurring at the Si die rather than at the interface was ≈ 40kg and occurred at the lowest scrubbing frequency and time (Figure 10).

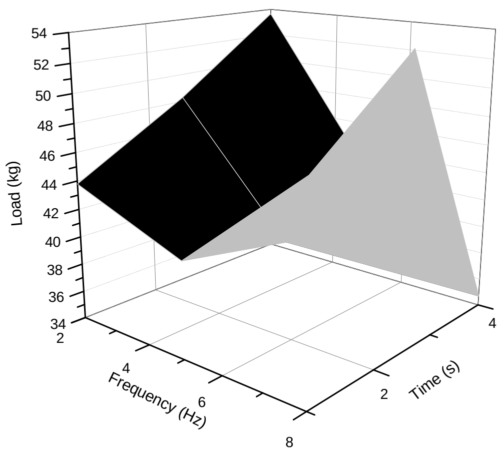

Figure 10: Effect of scrubbing frequency and time on load to force failure of die attaches from batch 2.

In summary, the parameters of the die bonding process for which the bond quality was maximized were the following: temperature of the heating stage - 450^{o}C, force of the scrubbing head - 3.5g/mm^2, scrubbing frequency - 2Hz, and scrubbing time - 1s. A large number batch of Au-Si die attaches were then manufactured under these conditions for thermal exposure assessment.

3.2 Thermal exposure

The optimized batch of die attaches was characterized by SAM and SEM. Die attaches subjected to thermal exposure at 300^{o}C for 1, 4 and 12 weeks had bonded areas varying from 93.7 to 99.3%, 84 to 99.4%, and 77.4 and 93.6%. Samples that underwent accelerated ageing at 350^{o}C for 800h had a much wider variability in bonded area ranging from 26.3 to 94.5%, and the mean bonded area measured was 65.4%. Figures 11 (a) and (b) show two examples of SAM images of die attaches after 800h and 350^{o}C. White areas depict voiding, and grey areas represent the bonded area.

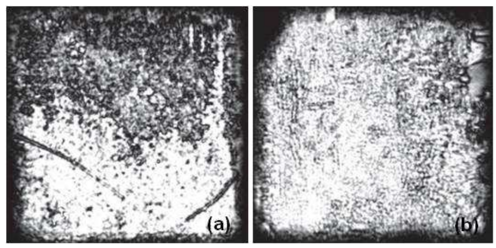

Figure 11: SAM images of Au-Si die attaches, from the optimized batch, subjected to accelerated ageing at 350^{o}C for 800h.

Selected die attaches submitted to accelerated ageing were cross-sectioned and observed in the SEM (Figure 12). Solidification gave rise to epitaxial growth of both Si and Au along the interface. As a consequence, numerous small Si islands were formed. The fillets around the sides of the Si die were partially cracked/dectached from the Si die, and occasionally were not present. Occasionally fractured fragments of Si were found in the fillet region. There was also some significant voiding along the Au-Si interface.

3.3 Thermal cycling

To investigate the robustness of the bonded dies and any correlation with SAM data of the bonded area, die attaches from the optimized batch were subjected to thermal cycling and thermal shock. The purpose was to examine

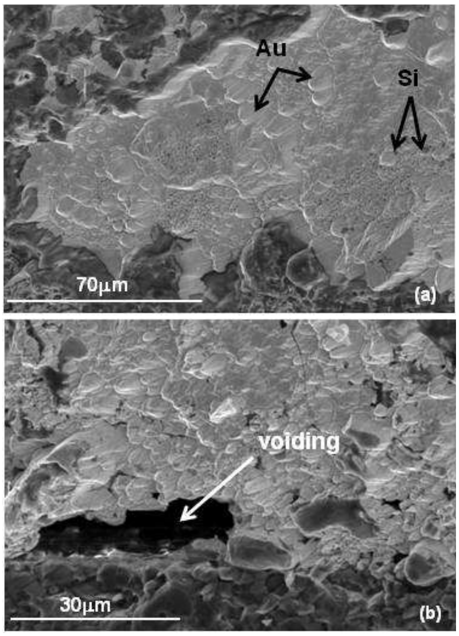

Figure 12: Cross-sections of Au-Si die attaches, from the optimized batch, after accelerated ageing at 350^{o}C for 800h.

if there was any change in the area bonded after these treatments.

Figure 13 shows the mean bonded area of the optimized die attaches before and after being subjected to TS and TC treatments. The die assembly sub-batches as manufactured (equivalent to 0 cycles) had a very similar initial mean bonded areas of 94 and 94.4%. For the TC cycles, the 94% bonded area was reduced to 92.4 and 92.3% after 10 and 40 cycles respectively and all measurements were close to being within inherent accuracy/error of the measurement itself.

After 10 cycles of TC, the bonded area was reduced only slightly from 94.4 to 91.7%, and again within the error of the SAM measurement. On increasing the number of cycles up to 40, the mean bonded area decreasing only very slightly to 92.6%. Although there was some degradation in terms of the bonded area during TC and TS, mean bonded area remained above 90%.

Figure 14 illustrates the distribution of bonded areas after 40 cycles of both TC and TS. Eleven of the fourteen die attaches tested had a bonded area above 90%. TS induced a slightly more "damage" compared with TC, although even the worst sample had a bonded area of 82.5% against 77.5% for TC treatment.

Figure 15 show SEM images of the cross-sections of the die attaches after 40 cycles of TS and TC. After TS testing, there were some signs of delamination and voiding along the interface (Figure 15 (a)). The Si die was occasionally fractured and few fragments of Si moved into one of the fillets. There were small cracks (around 10 μm) located along the interface and some voiding after TC testing. Crack propagation resulted from the stresses derived from the differences in the coefficient of thermal expansion of the Au-Si and the ceramic substrate. Reflow temperatures exceeding 400^{o}C for Au-Si places thermal loads on the rest of the package; very occasionally, one of the fillets partially vanished, and the Si die appeared fractured in the lower corner as shown in Figure 15 (b). Both TS and TC cross-sections regions contained Au dendrites in a eutectic Au-Si matrix.

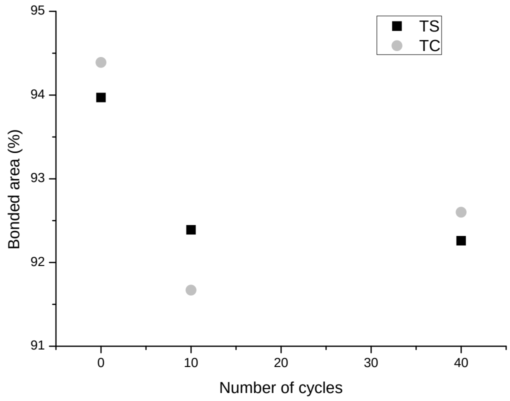

Figure 13: Mean bonded area for optimized die attaches as manufactured (0 cycles), after TS and TC for 10 and 40 cycles. Six die attaches (three each) were tested for 10 cycles; fourteen die attaches (seven each)were tested for 40 cycles. [Std. dev for TS 0, 10 and 40 cycles: 2.3, 1.0 and 4.1; std. dev for TC 0, 10 and 40 cycles: 3.7, 5.0 and 8.4]

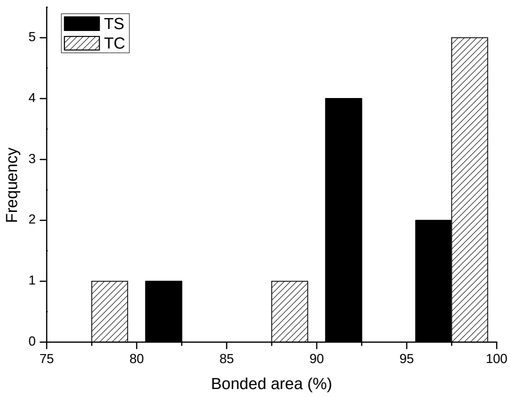

Figure 14: Bonded area distributions comparing optimized die attaches subjected to thermal shock (TS) and thermal cycling (TC) for 40 cycles each.

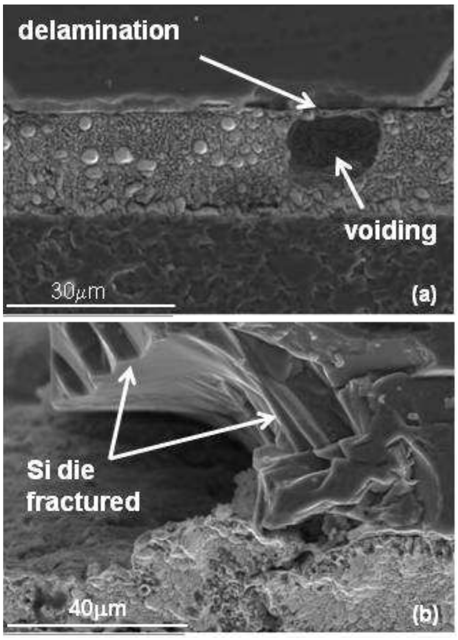

Figure 15: Cross-sections of Au-Si die attaches from the optimized batch: (a) after TS; (b) after TC (both for 40 cycles).

4 Conclusions

The operation of electronic packages under extreme conditions is a significant challenge for the microelectronics industry. The generally accepted microelectronic temperature limit is 125^oC, but there is a strong push to extend this temperatures up to 250^oC in down-hole and turbo-machinery applications.

Au-Si eutectic solder is a promising candidate for die attachment for high temperature use. Unfortunately, Au-Si bonding quality is generally inherently variable under standard assembly practice, primarily because wetting behaviour can vary distinctly from assembly to assembly and even within the area of a single die attach itself. In these cases, the Au-rich or Si-rich bonding interface may change from fully liquid to partially solid and the critical wetting and flow characteristics may be restricted.

In this study, Au-Si bond quality has been assessed by bonded area measurements using SAM and by die shear testing. Steps were undertaken to reduce variability in the Au-Si eutectic bonding process. Optimization of the manufacturing process was achieved by choosing compatible and well-controlled die bonder parameters. Scrubbing parameters (time and frequency) were more influential on bonded area than temperature of the heating stage and the force applied to the scrubbing head.

Accelerated testing was used to induce failure based on thermal cycling and thermal shock, and was performed on selected die attaches manufactured under the optimum parameters. These die attaches were tested for 40 cycles of TS and TC, and the bonded area was again measured by SAM after testing. Although the results indicated bond degradation, most of the samples tested (more than half) had high bonded area ranging from 92.5 to 97.5%. Cross-sections of the bonded areas after TS and TC occasionally showed some voiding and delamination, and small cracks along the Au/Au-Si interface due to coefficient of thermal expansion differences in the assembly.

Further work should now focus on more extended testing at a range of temperature and times, and correlation with in-service performance. The work here suggested that when the primary manufacturing can be controlled carefully, Au-Si is promising for HTE applications.

Acknowledgements

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