High temperature Au-based solder reliability in electronic packages for harsh environments

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Abstract

The operation of electronic packages in high temperature environments is a significant challenge for the microelectronics industry, and poses a challenge to the traditional temperature limit of 125°C for high electronic systems, such as those used in down-hole, well-logging and aero-engine applications. The present work aims to develop understanding of how and why attach materials for Si dies degrade/fail under harsh environments by investigating high temperature Au based solders. Au-2wt%Si eutectic melts at < 400°C and offers high temperature stability but high temperature processing and complex manufacturing steps are the major drawbacks. Changes in the die attach material were investigated by isothermal ageing at 350°C, thermal shock and thermal cycling treatments. Die attach reliability investigated by thermal shock and thermal cycling showed that the bonded area degraded. Nevertheless, most of the samples tested had high bonded area ranging from 92.5 to 97.5%. The failure behaviour of the die attach materials included cracking of die and/or attach material, delamination and voiding. Scanning acoustic microscopy images provided a rapid assessment of delamination and other defects and their location within the package. Microstructural analysis and die shear testing were also carried out, along with the high temperature endurance of a SOI test chip for signal conditioning and processing applications at 250°C. All functions evaluated have shown stable performance at 250°C for up to 9000 hours.

Key words: Au-Si eutectic, die bonding, reliability, scanning acoustic microscopy, die shear, SOI devices, signal conditioning circuits.

1 Introduction

There is significant commercial need to extend the operation of electronic devices into hostile, high temperature environments at up to 250°C for prolonged durations. A leap from current temperatures of 25°C to above 200°C in combination with high pressures, vibrations and potentially corrosive environments such as those found down oil or gas wells means that specialist semiconductors, passives, circuit boards and assembly processes will be needed to meet target performance specifications [1, 2]. Similar environments can also be found within space, geothermal power and high-end automotive applications [2].

Figure 1 shows a typical Sondex-Wireline product that is inserted down a well and measures down-hole pressures, temperatures, casing surface roughness, oil/gas/water flow rate, fluid density, 3D position, etc, transmitting this data back to the surface in real time via a trailing cable. The electronics are contained within the central 2.5 cm diameter stainless steel pressure housing, using highly dense circuit boards often up to 10s of cm in length.

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The efficient operation of a well is vitally dependent upon the information from the down-hole sensors with errors or failures potentially resulting in the complete removal of the probe, and interrupted well operation that might cost more than $1 million/day.

Figure 1: Caged full-bore flowmeter.

Reliability data concerning electronics systems tested under standard harsh environment of cycles between -55°C to +125°C established over many years and enshrined in the MIL-HDBK-217 standard [3] may not be used for reliability assessment at higher temperature, as failures modes may change, becoming more dominated by diffusion and creep rather than fatigue [4].

An electronic package includes interconnecting wire-bonds that carry the current to/from the package periphery to the Si die, the die attach materials, leadframe materials, plastic encapsulants, and others. Electrical performance, thermal management and reliability

of an electronic system strongly depends on the type of die attach material used [5, 6]. In this study, attention is focused on the critical die attach materials that mechanically attach the die to a substrate ensuring it does not detach/fracture over the operational lifetime. The maximum use temperatures for die attaches are those at which the die attach material melt/soften to a level that no longer keeps the die in place during operation.

Eutectic die bonds also known as solders are generally binary or ternary metallic compositions. Eutectic solder alloys are typically supplied as a thin preform or in ribbon form, and are generally assumed to be a reliable bonding material, even they are expensive. Au-Si eutectic solder has good overall wetting and flow characteristics during die bonding to a substrate metallization [7]. According to the Au-Si binary phase diagram shown in Figure 2, the melting points of Au and Si are 1064^{o}C and 1414^{o}C, respectively, whereas the eutectic point has a melting point of 363^{o}C. Above the eutectic temperature, the Au-rich and Si-rich regions in the bond line region start to dissolve in one another, together with the Au from the metallization. Once the liquid or solid/liquid composition reaches equilibrium for that temperature, there is no more driving force for dissolution. The final average composition of a die attach perform is typically at the eutectic composition of Au-3.4wt%Si.

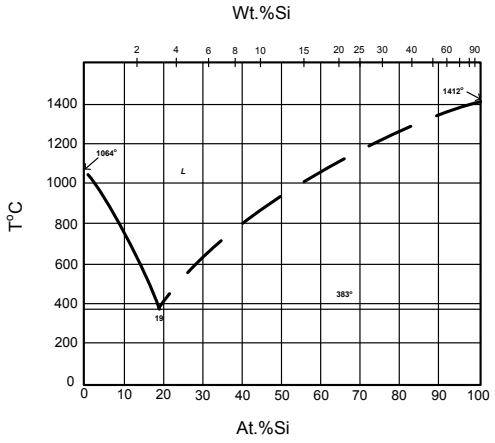

Figure 2: Au-Si equilibrium phase diagram.

The use of Au-Si eutectic preforms or pure Au preforms to initiate this bonding reaction between the Si die and Au metallization and improve the bonding is common [8]. Die bonding occurs generally at temperatures higher than 400^{o}C, but concerns include the effects of such high processing temperature on the actives/passives/wirebonds elsewhere in the package [9].

2 Experimental procedure

2.1 Materials and manufacturing

Ceramic substrates of Al_2O_3 tiles 10mm $\times$ 10mm were metallized with Au thick film (10 μm) by screen printing and fired afterwards. The Si dies had dimensions 4.62mm $\times$ 4.64mm $\times$ 0.5mm. The solder preforms used were eutectic Au-Si, 5mm square and 25 μm thick. Figure 3 shows a scanning electron microscopy (SEM) micrograph of the Au-Si preform as received. The microstructure revealed Au-rich near spherical particles surrounded by a Au-Si eutectic structure.

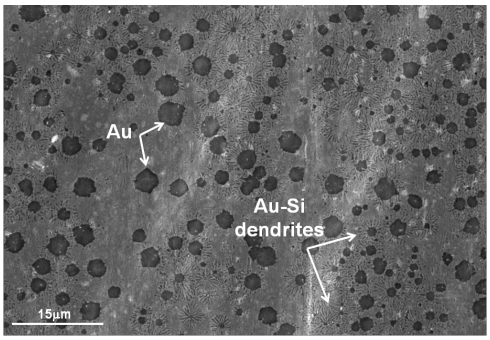

Figure 3: SEM micrograph of a Au-Si preform as received.

The components were cleaned in HF (7%) for 10 seconds in order to remove any oxide layer. The substrate was secured on a heated workstage of a Cammax EDB65 die bonder operating at a temperature just above the eutectic temperature. To bond dies to metallization layers using Au-Si, a preform foil was used. The preform was placed in between the upper Au metallization of the substrate and the base of the Si die. When the preform and die were placed on the substrate, the bonder initiated a light scrubbing action with the bond head. This scrubbing generated just enough friction to rupture residual oxide films and accelerated interdiffusion and melting, thereby creating the bond. N_2 (with 10 % H_2) was used as a cover gas in order to prevent oxidation.

2.2 Accelerated ageing

Selected Au-Si die bonds were subjected to accelerated ageing at 350^{o}C for 500 and 850 hours.

2.3 Thermal cycling and thermal shock

Thermal cycling and thermal shock tests were performed at GE-Aviation Systems.

An optimized batch of attached dies were subjected to thermal cycling (TC) and thermal shock (TS) treatments. 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 [10]. Figure 4 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.

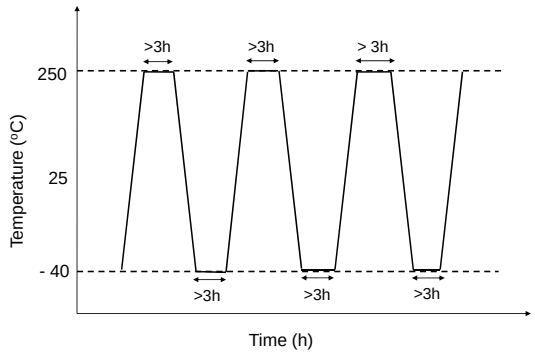

Figure 4: Test regime used for thermal cycling.

2.4 Assessing bond quality

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 image. All the die bonds were examined using a THRUscan inspection technique to examine the extent of interfacial delamination under near-identical imaging conditions.

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 (EDX) 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 [10] and in each case the failure modes were recorded.

2.5 High temperature endurance

In order to demonstrate the packaging technologies developed on electronic circuits relevant to down-well and aeroengine applications, end-user requirements were provided by Sondex Wireline and Vibro-meter UK, with an emphasis on signal conditioning and processing of outputs from sensors. A SOI based integrated circuit was designed and manufactured by GE Aviation Systems with analogue signal conditioning, ADC/DAC (Analogue to Digital Conversion/Digital to Analogue Conversion) and simple logic control. Initial results of endurance testing up to 2000h at 250^{o}C were previously reported in [11, 12]. These endurance tests were extended up to 9000h at 250^{o}C.

For the high temperature endurance study, SOI devices were assembled in HTCC packages (Figure 5) with Au-Si as the die attach material.

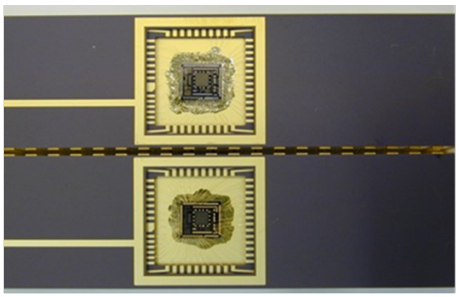

Figure 5: SOI devices assembled in HTCC packages for assessment of long term electrical performance at 250^{o}C [12].

3 Results

Figure 6 shows a general overview of the AuSi die bond microstructure. EDX was used to identify the different components of the package and distinguished the Al_2O_3 substrate, the Au metallization, and the Au-Si eutectic (Figure 6).

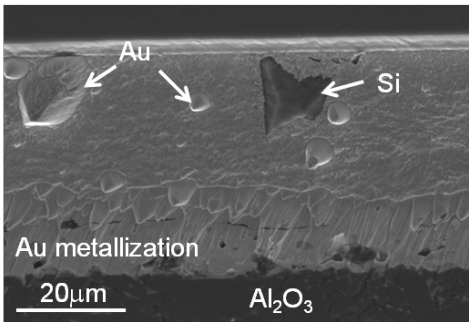

Figure 6: Cross-section of Au-Si die bond as manufactured.

If not carefully optimised and then carefully controlled, Au-Si die bonding leads to a wide variability in bond quality, and is one of the main barriers to the more widespread use of

the Au-Si. The variability is due to the critical scrubbing action that ruptures the oxide films during die bonding which is generally difficult to regulate/automate. The inherent variability can obscure systematic attempts to improve lifetimes and reliability. Although every application has its own specific set of requirements, with some machine parameters more critical than others optimisation is required for every application to minimize bond quality variations.

In this case, the design of the methodology was dependent on the variables to be studied. Factors that could influence the Au-Si eutectic die bond quality were previously identified in importance in [13]: temperature of the heating stage, force of the scrubbing head, scrubbing frequency, and scrubbing time.

The subsequent experimental design allocated two levels for each parameter. Bond quality was assessed by measuring the percentage of bonded area (SAM) and shear load to failure. The analysis based on signal to noise (S/N) ratio and ANOVA method 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 microcracks that might affect, for instance, the electrical performance. Both the time for force application and additional thermal energy due to friction determined the overall extent of the solder reflow. However, overall their relative influence on bond quality was weak [13].

In a second experimental design, both temperature of the heating stage and force of the scrubbing head were kept constant at the "best" combination and three levels were then allocated for each of the two remaining, more influential scrubbing variables: scrubbing frequency and scrubbing time. Although all die bonds showed evidence of delamination at both interfaces (Si die to solder and solder to substrate interfaces), the overall bonded area increased, and was always more than 80%, along with a much reduced spread of bonded area.

Figure 7 illustrates the effect of the most critical eutectic die bonding parameters of scrubbing frequency and time on bonded area. A long scrub or too higher frequency generally reduced bonded area, and is qualitatively 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.

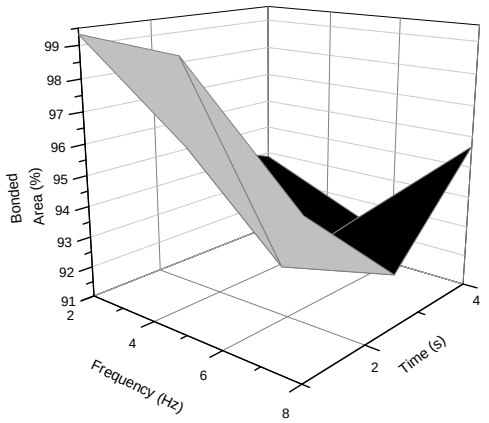

Figure 7: Effect of scrubbing frequency and time on the bonded area of Au-Si die bonds [13].

All the solder bonds failed on the Si die of the bond line in die shear testing, and failure loads increased compared to the first experimental design. The load at which failure occurred in the Si die rather than at the interface was $\approx$ 40kg and occurred only for the lowest scrubbing frequency and time.

The optimised bonding parameters were: 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 batch of Au-Si die bonds were then manufactured under these optimum conditions for isothermal ageing and reliability assessment. The quality was again assessed by SAM. Digital image analysis (DIA) was performed on each sample to quantify the amount of unbonded area (defects) and the largest single defect present within each.

3.1 Accelerated ageing

Thirty Au-Si die bonds underwent accelerated ageing at 350^{o}C. From these, five were removed after 500 hours of thermal exposure, with the remained receiving 850 hours.

Although there was no visual degradation of the die bonds apart from a slight dark coloration in the Au-Si solder, SEM cross-sections revealed 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 disappeared altogether. There was also some significant voiding along the Au-Si interface.

The initial percentage of unbonded area varied from 1 and 2.9%, and the largest single defect within the assemblies varied from 0.05 to 0.26%. After 500 hours at 350^{o}C the percentage unbonded area increased to a spread of 1.2 to 16%. The largest single defect also suffered an increase spanning the region 0.31 to 1.87%.

Extending ageing to 850 hours widened variability in unbonded area. The specimens contained initially a percentage of unbonded area that ranged from 0.6% to 17.2% with the largest single defect varying from 0.04% to 5.57%. The unbonded area increased to 5.5% to 73.7% with a mean of 34.6%. The largest single unbonded area ranged from 0.23% to 73.38%.

Table 1 summarizes the respective variation in bonded area ranges of the aged specimens before and after thermal treatment. All die bonds degraded, evidenced by a reduction in the measured bonded area after ageing at 350^{o}C, consistent with the voiding at the Au-Si interface. The final bonded area was in the range of 84 to 98.3% with a mean bonded area of 94.1% and a standard deviation of 6.5%. Increasing the ageing time to 850 hours increased variability to 26.3% to 94.5%. The mean bonded area was 65.4% and the standard deviation was 25.8%.

Table 1: Bonded area range for Au-Si die bonds before and after accelerated ageing at 350^{o}C for 500 and 850 hours.

t (h)	Initial BA (%)	Final BA (%)
500	97.1-99.0	84.0-98.3
850	82.8-99.4	26.3-94.5

The boxplot in Figure 8 shows the distribution of the bonded area for the solder bonds that were submitted to accelerated ageing at 350^{o}C for 500 and 850h. The mean value was reduced and the spread increased, although note the number of samples tested for each condition was not constant: 5 specimens for 500h and 25 samples for 850h. At 500h, above the first quartile, all the the specimens had bonded areas higher than 91%.

Figure 9 shows examples of SAM images of the die bond after accelerated ageing for 500 and 850h at 350^{o}C. White areas depict debonded areas whereas grey areas represent bonded areas.

The solder bonds after accelerated ageing at 350^{o}C showed an increased die shear force

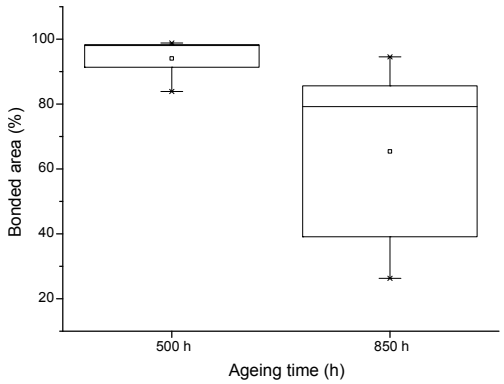

Figure 8: Boxplot of bonded area of Au-Si die bonds after accelerated ageing at 350^{o}C for 500 and 850 hours.

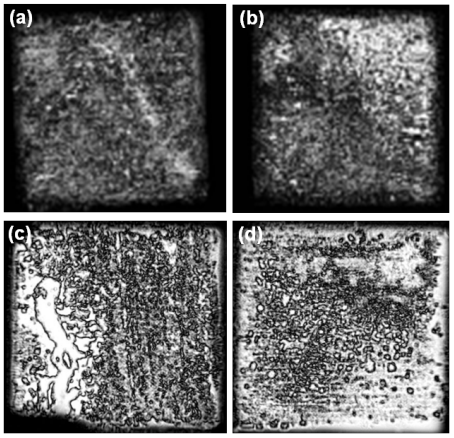

Figure 9: SAM images of Au-Si die bonds, from the optimized batch, subjected to accelerated ageing at 350^{o}C: (a), (b) for 500h; (c), (d) for 800h.

to failure. The boxplot in Figure 10 shows the distribution of the shear load to failure for these die bonds. Solder bonds subjected to 500 hours presented a mean load to failure of 32kg. An outlier was observed at 8kg. 75% of the specimens had shear load failures in the range 33 to 43kg. All the solder bonds suffered from separation of both Si die and die attach material and also Au metallization from the substrate. For the solder bonds subjected to 850 hours of accelerated ageing, the spread of failure loads was greater. The mean shear load was 13kg. Only 25% of the specimens had shear loads between 20 and 34kg. In this case, the majority of the specimens ended with separation of the Si die from the die attach material, although some dies remained with some solder. By comparing the shear test loads with the bonded areas from the SAM images, a correlation between the decreased bond area by SAM and lower failure loads in shear was established.

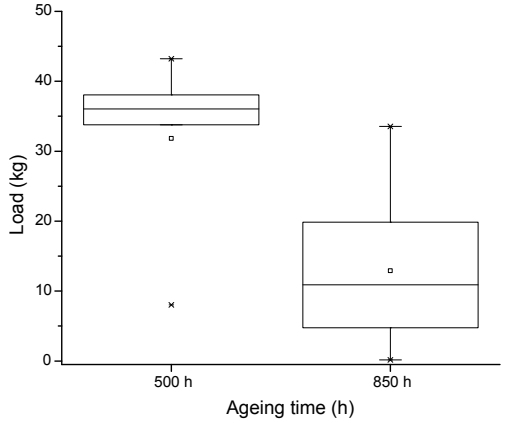

Figure 10: Boxplot of shear load to failure of Au-Si die bonds after accelerated ageing at 350^{o}C for 500 and 850 hours.

3.2 Thermal cycling and thermal shock

Au-Si die bonds from the optimized batch underwent thermal cycling and thermal shock in order to investigate the robustness of the bonded dies and any correlation with SAM data of the bonded area. The objective was to study if there was any change in the area bonded with these treatments.

Once again there was no visual degradation of the die bonds after treatments. Only a slight dark coloration in the Au-Si solder was evident and occasionally a few Si dies had cracked edges.

Cross-sections of solder bonds subjected to thermal shock revealed some signs of delamination and voiding along the interface. On the other hand, solder bonds subjected to thermal cycling exhibited small cracks (approximately 10 μm) located along the interface and some voiding as well. Crack propagation was a result of stresses derived from the differences in the coefficient of thermal expansion of the Au-Si and the ceramic substrate [13].

Specimens submitted to thermal cycling for 40 cycles contained an initial percentage of unbonded area that ranged from 0.6 and 9.9%. The largest single defect within the assemblies varied in the range 0.1 to 2.7%. After testing, the unbonded area increased to 2.2 to 24.8%.

On the other hand, specimens that underwent thermal shock had an initial unbonded area in the range 4.1% to 9.5% with the largest single defect varying from 0.37 to 5.82%. 40 cycles after, the unbonded area increased to 4.7% to 16.7%.

Table 2 summarizes the variation in bonded area of the die bonds before and after thermal treatment. All the die bonds suffered degradation in bond quality evidenced by the reduction in the measured bonded area. This degradation was consistent with the voiding found at the Au-Si interface in both cases. The final bonded area of TC40 solder bonds fell in the range of 75.2 to 97.8% with a mean bonded area of 92.6% and a standard deviation of 4.3%. TS40 solder bonds had a bonded area ranging from 83.3% to 95.2%. The mean bonded area was 92.5% and the standard deviation was 4.2%. Although there was some degradation in terms of the bonded area during TC and TS, the mean bonded area remained very high and above 90%.

Table 2: Bonded area range for Au-Si die bonds before and after 40 cycles of thermal cycling (TC) and thermal shock (TS).

	Initial BA (%)	Final BA (%)
TC40	90.1-99.4	75.2-97.8
TS40	90.5-95.9	83.3-95.3

The boxplot in Figure 11 illustrates the distribution of the bonded area for the Au-Si die bonds after 40 cycles of thermal shock and thermal cycling. For TS40, an outlier was observed at 83.3%. Considering only the data above quartile 1, 75% of the specimens had bonded areas above 91%. For TC40, the spread of results was higher. Nevertheless, 75% of the specimens had bonded areas higher than 88%.

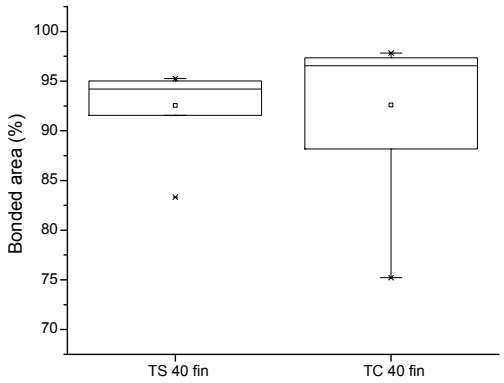

Figure 11: Boxplot of bonded area of Au-Si die bonds after thermal shock and thermal cycling for 40 cycles.

The Au-Si die bonds also required an increased die shear force for failure and the boxplot in Figure 12 shows the distribution of the shear load to failure.

Solder bonds subjected to TS40 had a mean load to failure of 44kg with 75% of the specimens presenting shear loads higher than 32kg. All the solder bonds failed in the Si die, except one specimen in which a portion of the Si

die was removed with part of the solder and Au metallization from the substrate still attached to it. For the solder bonds subjected to TC40, the spread of results was higher, which is in accordance with the bonded area shown in Figure 11. The mean shear load was 62kg and only 25% of the specimens had low shear loads to failure between 24 and 37kg. In this case, all the solder bonds failed at the Si die and one specimen did not fail.

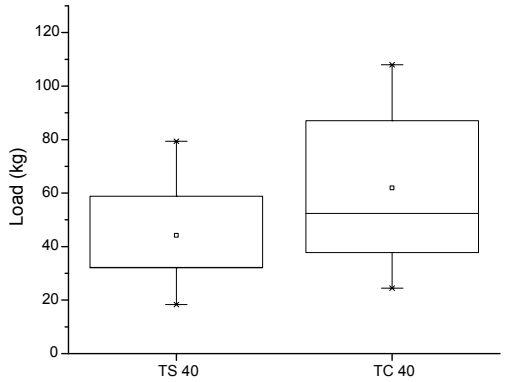

Figure 12: Boxplot of shear load to failure of Au-Si die bonds after thermal shock and thermal cycling for 40 cycles.

Figure 13 shows examples of SAM images of die bonds after thermal cycling and thermal shock for 40 cycles. Again white areas depict debonded areas whereas grey areas represent bonded areas.

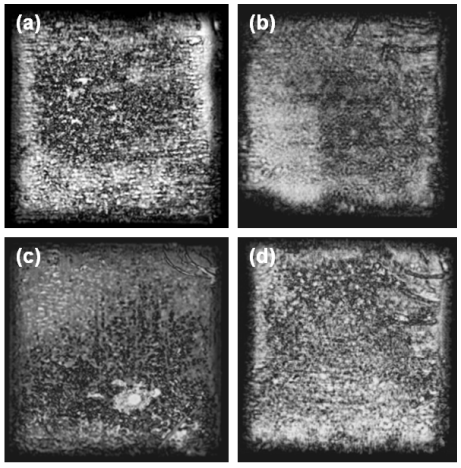

Figure 13: SAM images of Au-Si die bonds, from the optimized batch, subjected to 40 cycles of (a), (b) thermal shock; (c), (d) thermal cycling.

3.3 High temperature performance of SOI devices

The packages were stored at 250^{o}C for up to 9072 hours, with device electrical performance measurements performed at 25^{o}C, 125^{o}C and 250^{o}C after storage for 0, 3360, 4704, 7056 and 9072 hours.

Table 14 shows an example of a function tested - bandgap function - in which the test condition was applying 7V to VDD RBP, and measuring the voltage on bandgap pin.

	Voltage measurement (V)				
T (°C)	0h	3360h	4704h	7056h	9072h
25	2.61	2.61	2.61	2.62	2.62
125	2.66	2.66	2.66	2.64	2.64
250	2.70	2.69	2.69	2.69	2.69

Figure 14: Voltage measurements for the bandgap function tested after high temperature storage for different periods of time.

In general there was stable performance for the bandgap voltage, and for all the functions evaluated, which indicated that the device architecture and packaging technology could withstand the continuous 250^{o}C environment for at least 9000 hours. Failure analysis of the devices will be undertaken when the electrical performance of the various functional blocks show significant signs of deterioration.

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^{o}C, but there is a strong push to extend this temperatures up to 250^{o}C 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.

Au-Si bond quality has been assessed by bonded area measurements using SAM and by die shear testing. Thermal cycling and thermal shock of Au-Si die bonds manufactured under

the optimum parameters showed that although the bonded area degraded, most of the samples tested (more than half) maintained a high bonded area above 90%. A correlation between the decreased bonded area by SAM and lower failure loads in shear was established. Cross-sections of the bonded areas after thermal cycling and thermal shock 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.

High temperature SOI devices representative of analogue signal conditioning and processing functions, mounted in HTCC packages and bonded using Au-Si solder, have shown stable performance at 250^{o}C for up to 9000 hours.

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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