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Wire Bond Reliability for Power Electronic Modules - Effect of Bonding Temperature

Wei-Sun Loh[1], Martin Corfield[1], Hua Lu[2], Simon Hogg[3], Tim Tilford[2], C Mark Johnson[4]
[1] Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD.
[2] School of Computing and Mathematical Sciences, University Of Greenwich, Park Row, London SE10 9LS
[3] The Institute of Polymer Technology and Materials Engineering (IPTME), Loughborough University, Loughborough, LE11 3TU, U.K.
[4] School of Electrical and Electronic Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.
Tel.: +44 (0) 114 222 5890. Email: w.s.loh@sheffield.ac.uk.

Abstract

In this paper, thermal cycling reliability along with ANSYS analysis of the residual stress generated in heavy-gauge Al bond wires at different bonding temperatures is reported. 99.999% pure Al wires of 375 µm in diameter, were ultrasonically bonded to silicon dies coated with a 5µm thick Al metallisation at 25°C (room temperature), 100°C and 200°C, respectively (with the same bonding parameters). The wire bonded samples were then subjected to thermal cycling in air from -60°C to +150°C. The degradation rate of the wire bonds was assessed by means of bond shear test and via microstructural characterisation. Prior to thermal cycling, the shear strength of all of the wire bonds was approximately equal to the shear strength of pure aluminum and independent of bonding temperature. During thermal cycling, however, the shear strength of room temperature bonded samples was observed to decrease more rapidly (as compared to bonds formed at 100°C and 200°C) as a result of a high crack propagation rate across the bonding area. In addition, modification of the grain structure at the bonding interface was also observed with bonding temperature, leading to changes in the mechanical properties of the wire. The heat and pressure induced by the high temperature bonding is believed to promote grain recovery and recrystallisation, softening the wires through removal of the dislocations and plastic strain energy. Coarse grains formed at the bonding interface after bonding at elevated temperatures may also contribute to greater resistance for crack propagation, thus lowering the wire bond degradation rate.

1. Introduction

Thick aluminum wire bonding is the most commonly employed interconnect technology in power electronic modules. The reliability of Al wire bonds depends on the bond strength between the Al wire and the IGBT chip [1]. However, the wire bonds are susceptible to heel crack [2] where failure arises from flexing due to thermal expansion or overworked bond heel during ultrasonic bonding [3]. Additional fatigue failures are caused by thermo-mechanical damage mechanisms caused by the mismatch of thermal expansion coefficients (CTE) between the aluminum wire and silicon die at the contact interface. This failure mode is aggravated by wide thermal cycling ranges.

A recent study by Jin Onuki [4] has shown that the deterioration rate of the Al wire bonds may possibly be reduced by increasing the grain size with heat treatment. Furthermore, work by Komiyan et al. [5] has also shown that bonds formed at elevated temperatures with low ultrasonic energy could also exhibit high bonding strength. This was attributed to the ease of deformation at the bonding interface, and enhancement of the actual bonded area, resulting in a reduction of voids. However, at present there is little information on the deformation mechanism and Al grain structure changes after the bonding process, and their significance in affecting the crack propagation rate at the bonding interface. This paper will focus on the thermal cycling reliability to predict how grain structure, and thus the material properties change with bonding temperature, and how material property changes affect the residual stress in the bond heel using finite element analysis. Conclusions are drawn concerning the application of high temperature bonding as a mechanism for enhancing the thermal cycling reliability of wire bonds.

2. Wire bonding process

High purity (99.999%) aluminum wires of diameter 375µm were ultrasonically bonded to silicon dies coated with a 5µm thick aluminium top metal at 25°C (room temperature), 100°C and 200°C, using a ultrasonic power of 1.6W for 150ms. The temperature of the bonding samples were monitored throughout the bonding process. Figure 1 shows a schematic diagram of the high temperature heavy-gauge aluminum wire bonding experimental setup.

The wire bonded samples were then subjected to repetitive passive thermal cycling in air from -60°C to +150°C. The degradation behaviour of the wire bonds were evaluated by measuring the bond shear strength at regular intervals and via micro structural analysis by using optical microscopy and Electron Backscatter Diffraction (EBSD).

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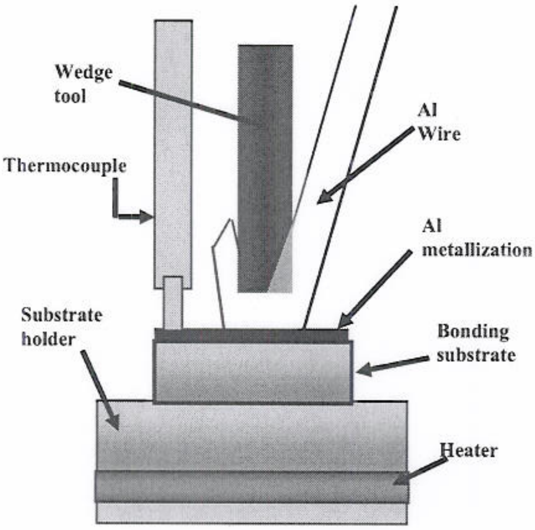

Figure 1: Schematic representation of the high temperature ultrasonic Al wire bonding experimental setup.

3. Reliability of high temperature bonded Al wire bonds

The mean shear force required to shear the wire bonds increases steadily with bonding temperature, however, this increase is directly porportional to the average increase in bond foot area, as listed in Table 1. Therfore, the mean shear strength for the Al wire bonds bonded at RT, 100°C and 200°C remains almost constant and approximately equal to the shear strength of 99.999% pure aluminum (50MPa) [6]. This implies that good wire bonding has been achieved over the full range of bonding temperatures used in the present study.

Table 1: Average size, mean shear force and normalised shear stress of the wire bonds bonded at RT, 100°C and 200°C respectively.

Bonding Temp. (°C)	Average bond foot area (mm^2)	Mean shear force (N)	Normalised shear stress (MPa)
25 (RT)	0.32	16.1	50.3
100	0.38	18.5	48.4
200	0.40	19.4	47.5

The normalised shear force drops steadily with increasing thermal cycles irrespective of bonding temperature, as shown in figure 2, due to a reduction in bonded area resulting from fatigue crack propagation. The shear strength of room temperature bonded samples was observed to decrease more rapidly with thermal cycling, suggesting a higher crack propagation rate across the bonding area.

Wire bond lift-off for the room temperature bonded Al wires occurs after 1500 thermal cycles. In contrast, bond lift-off was observed for 100°C bonded wires at 2100 thermal cycles and 200°C bonded wires at 2400 cycles. As the shear strength of the wire bonds is sensitive to the length of the fatigue crack [7], it can be assumed that the degradation rate of the wire bonds depends strongly on the crack propagation rate at the bonding interface. This may indicate that, high temperature bonding inhibits crack propagation, giving rise to improved reliability.

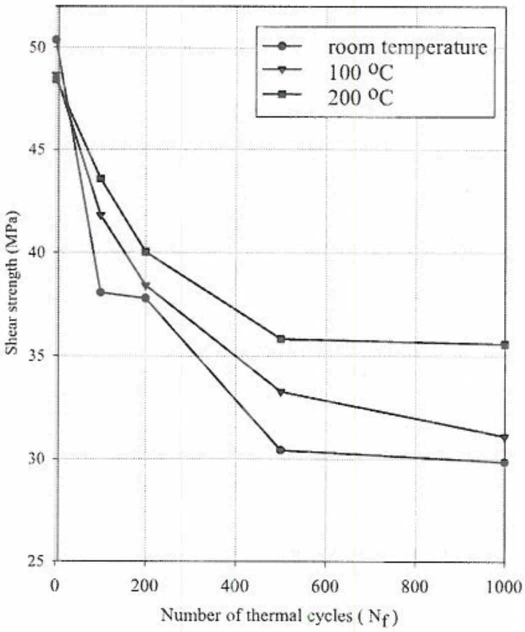

Figure 2: Mean shear strength for Al wire bonds, bonded at (a) RT, (b) 100°C and (c) 200°C as a function of thermal cycles

4. Grain structure analysis

Cross section analysis

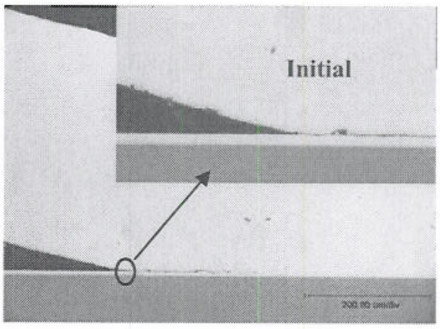

Figure 3: Cross section of an aluminum wedge bond bonded at RT showing crack initiation after bonding. The inset shows a magnified view of the initial crack.

During ultrasonic bonding, Al wire is plastically deformed due to the applid bonding force and ultrasonic energy, increasing the dislocation density and strain energy at the bonding interface. Residual stress is produced by heterogeneous plastic deformation and thermal contraction resulting from CTE mismatch between the Al wire and silicon die after removal of the heat gradient. Pre-cracks are often found at the bond heel, a consequence of the mechanical deformation and unavoidable flexing of the wire when forming the wire loop during the bonding process, as shown in Figure 3.

A significant amount of thermo-mechanical stress is induced along the bonding interface especially at the bond heels due to the mismatch of CTE between the Al wire and the silicon substrate [8] during cyclic loading. The fatigue crack propagates from the bond heel towards the bond centre, along the plane just above the bonding interface, between the Al wire and metallization, leading to relaxation of the residual stress. The crack area widens by continued shear deformation.

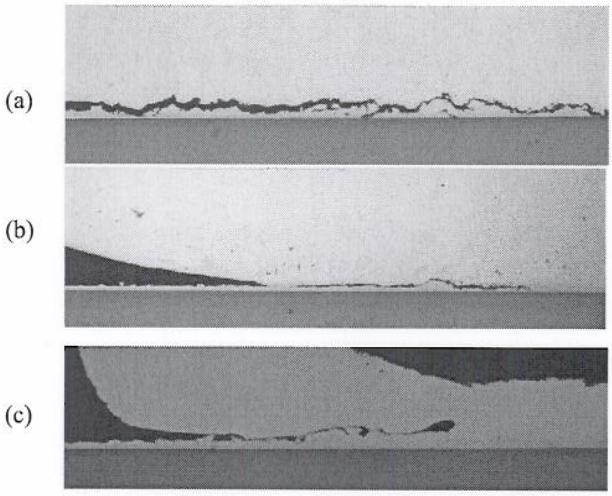

Figure 4: Fatigue crack (magnification x100) after 1500 thermal cycles for wire bonds joined at (a) 25˚C, (b) 100˚C and (c) 200˚C, respectively.

As shown in Figure 4, for room temperature bonded samples, the fatigue crack propagates along the bonded area and eventually shears off the wire bonds after 1500 thermal cycles. The fatigue crack in 200˚C bonded samples is much shorter than in 100˚C bonded samples suggesting that high temperature bonding has suppressed crack propagation in the wire bonds.

EBSD pattern analysis

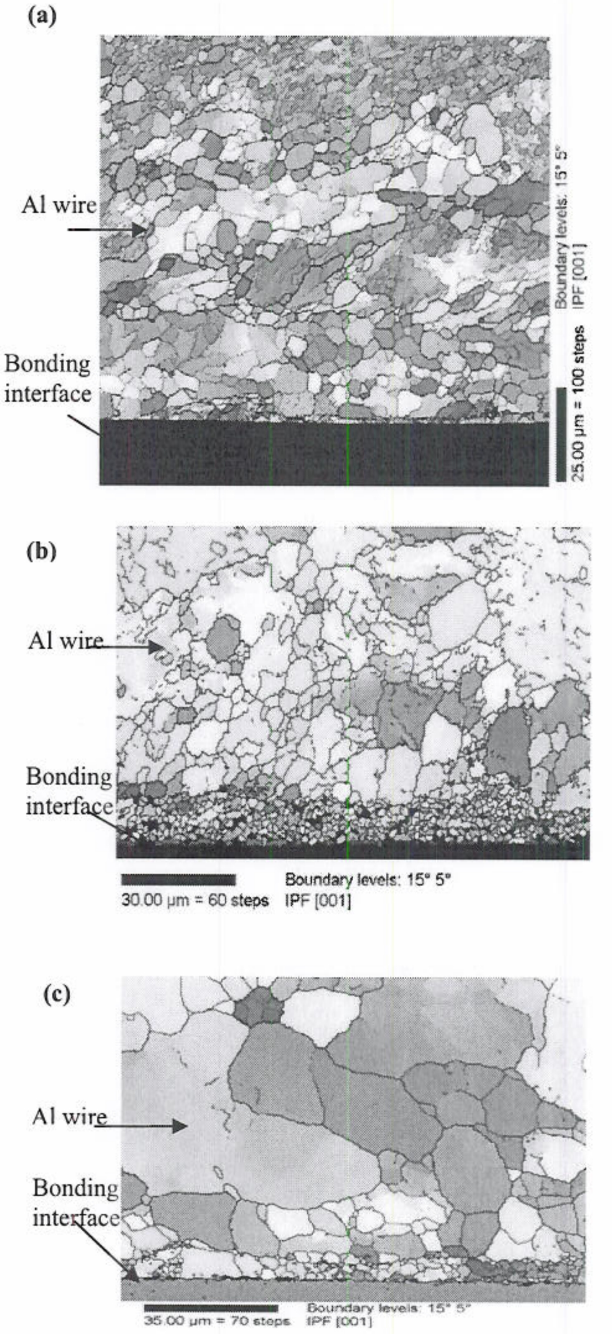

Figure 5: EBSD analysis for heavy-gauge Al wire bonds, bonded at (a) RT, (b) 100°C and (c) 200°C

The EBSD pattern represents crystallographic orientation of the selected bonding area as shown in Figure 5(a-c). The black shaded areas found near the bonding interface are "non-index" areas where accurate information can not be obtained [9].

As shown in Figure 5(a), closely packed fine grains are formed near the bonding interface resulting from strain hardening due to accumulation of dislocations after plastic deformation of the Al wire bonds. The recovery and subsequent recrystallisation of the grains within the deformed area are promoted by the high temperature bonding process, as shown in Figure 5(b) and 5(c), leading to relaxation of residual stress along with re-arrangement/reduction in the density of dislocations near the bonding interface [10]. As mentioned in section 4, crack propagation is found to be much slower for samples bonded at high temperature which can be attributed to the grain structure changes at the interface. The presence of coarser grains along the bonding interface not only reduces the residual stress and dislocation density but also may give rise to much greater resistance to crack propagation. Consequently, it may be concluded that strong and reliable bonds can be achieved by high temperature bonding.

5. Computer modeling of the stress in wirebond

As mentioned in section 4, when the wire bonds are cooled down after bonding, residual stress is generated at the bonding interface. This stress inevitably affects the reliability of the wirebond structure.

The residual stress in wire bonds is usually expected to be higher for higher temperature bonding temperatures due to the greater temperature excursion. However the Al grain structures may vary with bonding temperature, as shown in Figure 5, and materials properties such as the yield stress will also be temperature dependent [2,11]. A lack of detailed information about the temperatures attained, deformation mechanisms and grain structure changes during the bonding process makes accurate quantitative analysis impossible. However, finite element analysis can be employed to investigate the effect of varying thermal load and material properties on the residual stress in the Al wire. ANSYS [12] has been used for this analysis.

Figure 6 illustrates a 3D model of the wire bond. This model contains a slice of the device along the wire and uses periodic boundary conditions to represent the effect of the array of wires. In order to further reduce the model size, a mirror plane symmetry of the structure is taken so that only half of the wire and the surrounding structure need to be included. The final model contains approximately 20,000 elements.

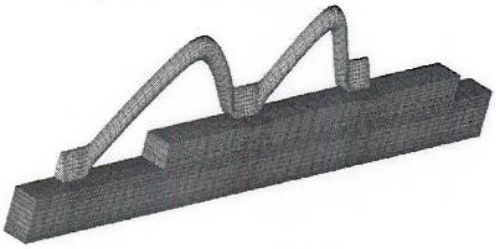

Figure 6: 3D Finite element model of the wire bond.

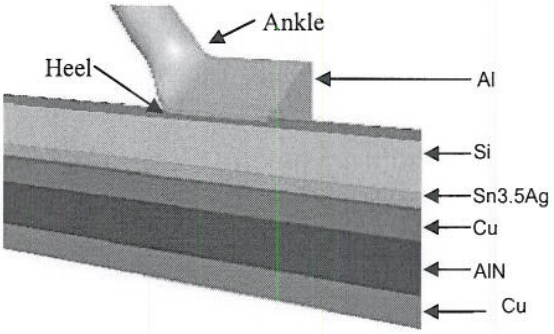

Figure 7: The layered structure of the wirebond heel.

Figure 7 shows the layered structure of the materials used in the model. Elastic-plastic material properties are used for Cu and Al. A creep law is used for SnAg solder and the material parameters can be found in [13]. Elastic material properties are listed in Table 2.

Table 2: Elastic properties of the materials used in the model. The unit of temperature is Celsius.

	E(GPa)	ν	CTE ppm/°C
AlN	310	0.24	5.6
Al	70	0.33	24.5
Si	113	0.29	3
Sn3.5Ag	54.05-0.193T	0.4	21.85+0.02039T
Cu	103.42	0.3	17

As the precise temperature-time conditions of the bondng process are unkown the investigation is limited to a constant thermal load as a driver for the residual stress calculation. It is recognised that this is a relatively crude approximation to the true temperature-time profile resulting from the ultrasonic bonding process, however it serves to illustrate the effects of variations in load and material properties. The deformation and stress in the model under a thermal load of ΔT= -190°C is shown in Figure 8. For the Al wire, the stress concentrates at the wire-die interface and at the ankle of the Al wire bond.

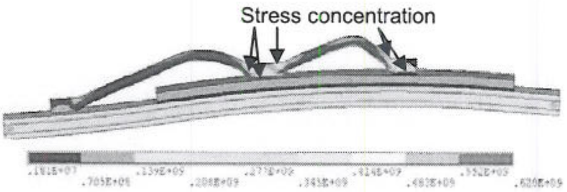

Figure 8: Stress distribution in wirebond under a thermal load of -190°C.

Pre-cracks are usually found at the wire-die interface after bonding and these will act as subsequent stress concentrators. The numerical model will focus on the detailed stress values at the wire-die interface, and will require a refined mesh of the interface region.

It was found that removing the wire loops above the wire-die interface, as illustrated in Figure 9, only affected the stress at the wire-die interface by just over 10%. This is relaitively small compared to the overall stress level. Therefore, in the following analysis, the wire loops were removed and the mesh at the interface has been refined to allow detailed paramteric analysis.

Consequently, a section of the bonded wire without ceramic substrate has been used in the following modelling analysis to predict the wire-die interfacial stress at the heel as shown in Figure 10.

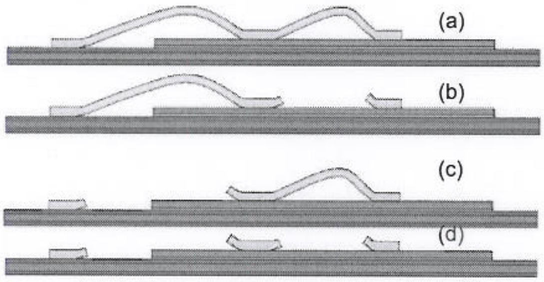

Figure 9: Wire bond models to evaluate of the Al wire loop on the stress at the wire-die interface.

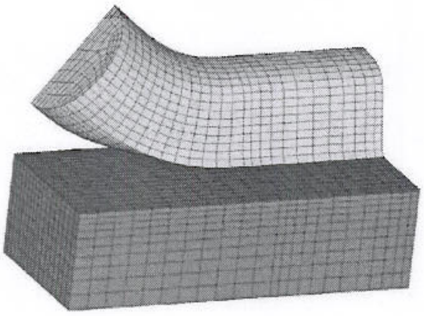

Figure 10: A simplified wire bond model which takes into account only the local CTE mismatch between the Al wire and the die.

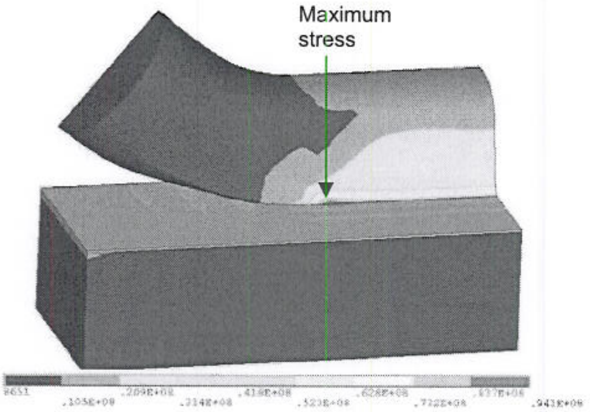

Figure 11: Typical residual von Mises stress distribution of the wirebond model at the room temperature.

Figure 11 shows the residual Von-Mises (V-M) stress when the temperature cools down from 200°C to 25°C, and the yield stress of Al is assumed to be 20 MPa. The maximum predicted V-M stress is about 94 MPa at the heel of the Al wirebond. In this model, there is no stress concentration at the ankle as the wire loop which contributes to the stress is excluded.

A total of 12 simulations have been carried out to analyse the effect of changes in the material properties and thermal load, on the predicted maximum stress at the heel of the Al wire.

The material properties which have been studied are the tangent modulus (E_t), the Young's modulus (E) and the yield stress (σ_y) of the Al wire. The material properties and the modeling results are listed in Table 3.

Table 3: Simulation results for the maximum stress in wire bond heel. T_{load} and σ_{max} are the temperature load and the maximum V-M stress respectively.

RUNS	E_t (GPa)	E(GPa)	σ_y(MPa)	T_{load}	σ_{max}
1	6.2	62	10	-75	49
2	6.2	62	20	-75	61
3	6.2	62	10	-175	94
4	6.2	62	20	-175	110
5	3.1	62	10	-75	35
6	3.1	62	20	-75	45
7	3.1	62	10	-175	58
8	3.1	62	20	-175	73
9	3.1	55.8	10	-75	35
10	3.1	55.8	20	-75	45
11	3.1	55.8	10	-175	58
12	3.1	55.8	20	-175	72

In Table 3, the material properties for RUNS#1 and #2, (modulus (E) and yield stress (σ_y)) are recognised values for standard Aluminium. The material properties and the tangent modulus will change with respect to the grain sizes. The results show that the predicted maximum

V-M stress at the wire-die interface is sensitive to changes in these properties.

It is clear that both the bonding process thermal load and the material properties govern the predicted residual stress level. Higher peak bonding temperatures may result in a much greater predicted residual stress if the material properties do not alter with bonding temperature. However, if the tangent modulus and the yield stress decrease with increasing bonding temperature, then a smaller increase or even a decrease in the residual stress would be expected. It is also important to note that CTE mismatch has been assumed to be the only cause of the residual stress. Other effects such as annealing i.e. recovery, recrystallisation and grain growth, which may occur during and after the bonding process are not accounted for in this analysis. Further experimental work is planned in order to establish the precise nature of the residual stress resulting from the bonding process.

6. Conclusions

The initial shear strength of the wire bonds prior to thermal cycling remains virtually constant with respect to bonding temperature, with no appreciable differences observed in the shear strength, with bonding temperature.

During thermal cycling, the mean shear strength of the wire bonds (for all bonding temperatures) drops significantly, due to the reduction in bonded area, resulting from fatigue crack propagation from the bond heel to the centre of the bond.

The shear strength of the room temperature bonded samples was observed to decrease more rapidly with thermal cycling than for those bonded at the higher temperatures; a result of a higher crack propagation rate across the bond. This suggests that high temperature bonding is a good candidate for enhancing the reliability of heavy-gauge aluminum wire bonds.

The combination of both heat and pressure induced by the high temperature wire bonding technology may assist in relaxation of the residual stress and re-arrangement/reduction in the density of dislocations at the bonding interface by means of recovery, recrystallisation and grain growth, thus lower the crack propagation rate.

Current computer modeling results have shown that the residual stress at the Al wire-die interface can be influenced by changes to the Al material properties resulting from changes in the grain structure. The stress at the wire-die interface is most sensitive to changes in the tangent modulus and yield stress. Further work is required to identify the conditions present close to the bond foot during the bonding process and the resulting changes in the wire material properties.

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