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# EFFECTS OF PARAMETER MATCH ON BONDABILITY AND RELIABILITY IN THERMOSONIC GOLD BONDING

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## ABSTRACT

Wire chemistry and bonding conditions are found to affect the Au-Al intermetallic compounds formation and growth. Bonding achieved when these two metals come into intimate contact between each other by interactions of ultrasonic energy, force, temperature and time. Inter diffusion of the joining metals at the interface activated the formation of stoichiometric intermetallic. This paper investigates the effects of bonding parameter match (ultrasonic level and force) on the growth behaviours of gold aluminide compound during thermal aging. Samples were built with different combination of ultrasonic level and force for high temperature storage (HTS) test at certain elevated temperature and time. Measurements for bonded ball mechanical strength and observations on intermetallic compounds growth patterns were carried out. Discussions on these phenomena were based on the physical, thermal and atomic properties of the bonding elements. It is suggested that un-optimised ultrasonic level and force may have effects toward poor bonding between Au and Al. Therefore, achievement of uniform intermetallic coverage is one of the factors determining the reliability of the wirebond.

## INTRODUCTION

In semiconductor packaging Au-Al bonding system usually occurred by contacting the aluminized pads of a Si chip with Au bonding wire. The diffusion welding requires temperature range from 200ºC to 300ºC. To make solid-state diffusion practical, high energy is required to squeeze most atoms or ions through perfect crystal structure by vacancy migration mechanisms [1]. Besides force, Duan et al. [2] explained that ultrasonic vibration activates dislocations in the crystalline lattice and increases atomic diffusion, by supplying the activation energy for the diffusion process.

Specific troubleshooting information and control of wire bond process is essential to meet high demand on package reliability. As technological advances have produced smaller semiconductors and diminished respective Al pad and Au wire sizes, establishing a reasonable wire bond process parameter has become more difficult. Wire bond processes are traditionally optimised by conducting design of experiment (DOE), with wire bond set up parameters, including ultrasonic level and time duration, bonding tool force, and stage temperature as control factors. The response

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factors in these DOE are typically wire pull and bond shear tests [3]. Correlation between these factors and the growth patterns of Au-Al have been studied by Duan et al. [2]. In his study, for constant force and time, the ridged area of the bond pattern increases when more ultrasonic energy is applied. For constant force and ultrasonic energy, the ridged location of the bonded region moves closer to the bond center with time. For constant ultrasonic energy and time, the total area of the bond pattern increases in size with increasing load.

This paper focuses on two bonding parameters: ultrasonic level and bond force. The effects of these bonding parameters on bondability and ball bond reliability were investigated during the initial formations of intermetallic and growth patterns of Au-Al intermetallic at certain elevated time of HTS. Further analysis on this case has been done by observing the coverage area and growth patterns of the Au-Al intermetallic before and after thermal aging at 175ºC for 384 hours.

## EXPERIMENTAL METHOD

Samples for this test were prepared with a 100 kHz Esec 3006FX wire bonder using 25 µm gold (99.99% Au) wire. Bonding parameter matrix was carried out on bond pads with an opening of 90 µm and constant bonding temperature of 240ºC. During the evaluation process, two variable factors were used force (790 Nm, 880 Nm and 970 Nm) and ultrasonic level (19%, 21.5% and 24%) for 1$^{st}$ bond, while parameter for the 2$^{nd}$ bond were bond temperature, bonding machine, ultrasonic level, the type of capillary and bond pad construction were kept constant.

The samples were labelled as A, B, C, D and E for each combination of bonding parameter respectively, as shown in Table 1. Bonding process were tuned for each evaluation to optimise bonding performance by controlling the ball diameter, ball height and loop height within the control specifications. The setup bonding temperature was also measured with a K-type thermocouple sensor.

Table 1: Combination of the bonding parameter for sample A, B, C, D and E.

| Sample | Ultrasonic level (%) | Force (Nm) |
|---|---|---|
| A | 19 | 970 |
| B | 21.5 | 880 |
| C | 24 | 790 |
| D | 24 | 970 |
| E | 19 | 790 |

In order to assess thermal reliability as well as intermetallic growth patterns of the variables ultrasonic level and force, the samples were aged through high thermal storage test (HTS) at 175ºC for 384 hours. Great care during cross-sectioned is important to avoid smearing of soft gold across the bond pads [4]. Samples were

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then mounted with a commercial epoxy and stored for curing. Cured samples were wet-ground with small grit size 1200 sand paper to see the whole ball bond. Polishing was then proceeded with 3, 1 and 0.25 μm diamond suspension on silk cloths.

Observations on the intermetallics coverage area underside of the bonded balls have been performed by using scanning electron microscope (SEM) after removing the bonded balls. The methods used to remove the bonded ball were referred to Breach and Wulff [4]. The solution has been prepared by dissolving a 3 g KOH pellets in 100 ml water, and heated to 70 °C. Bonded specimens were placed in the solution for 20 minute, and rinsed with Deionized (DI) water.

Quantitative measurements on mechanical strength of bonded ball were carried out by ball shear and pull test using DAGE 4000 shear and pull tester with automated touchdown. Samples were measured before and after temperature of aging 175ºC for 384 hours.

## RESULTS AND DISCUSSION

Fig. 1 shows the optical images of unetched cross-sectional bonded balls. Initially, Au-Al intermetallic compounds were observed along the gold-aluminum interface as a thin layer for all the samples.

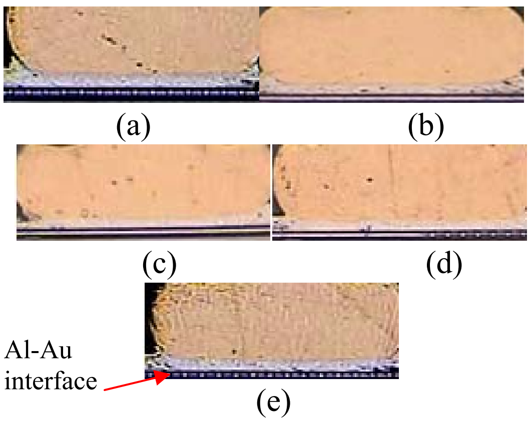


Figure 1: Optical microscopy images of as bonded ball for samples A, B, C, D and E.

The shear test was used to measure the relationship between the formation of Au-Al intermetallic compounds and the bonding joint strength. Average of shear and pull strength were interpreted clearly by the bar graph shown in Fig. 2. Sample A and E presented a slightly decrease in shear strength due to low ultrasonic level applied during bonding process that is not similarly to sample B, C and E. This can be explained by controlling the application of ultrasonic level during bonding will be a

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key factor to ball bond strength variability. In further analysis to the shear strength, measurement of the intermetallic coverage area under bonded ball was carried out to compare the different bond quality level based on the volume of intermetallic formation.

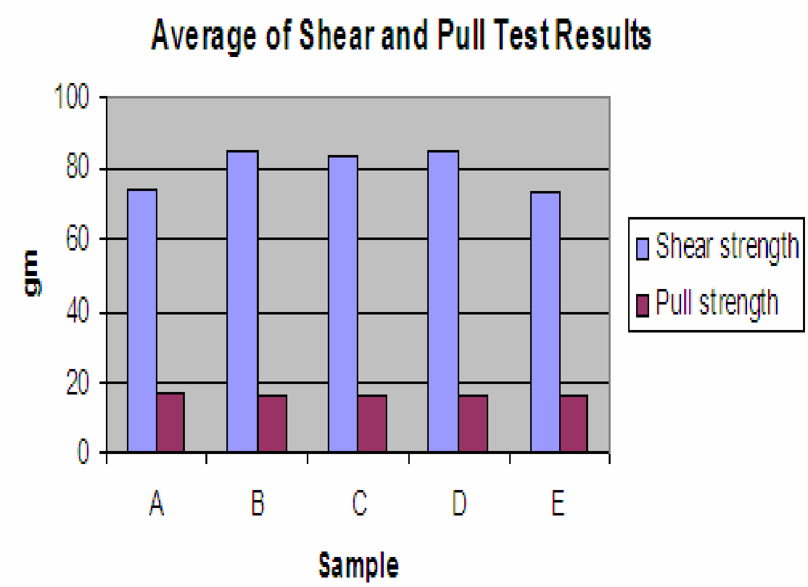
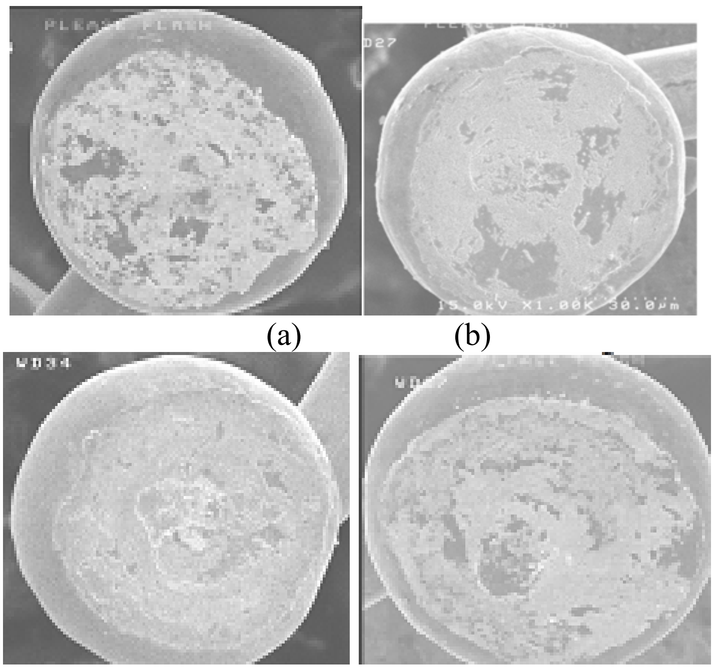



Figure 2: Average of achieved shear and pull strength for as bonded ball.



(a) (b)

(c) (d)

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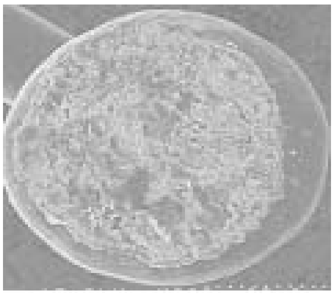

(e)

Figure 3: SEM images of the underside of a typical as bonded ball after removal from a bond pad.

High magnification images of SEM ball bonds demonstrates thick intermetallic coverage for samples B, C, and D, while samples A and E present thinner intermetallic compound as shown in Fig. 3.

Results indicate that various ultrasonic level and force have resulted to the variation of coverage level. There is a connectivity between the intermetallic regions and spaces where the ball has not been bonded to the Al pad metal [4]. Intermetallic coverage can influence the bonding reliability as well as to determine the diffusion reaction in the Au-Al system that affect the bonding parameters setup. The overall effect of bond force was smaller compared to the effect of ultrasonic level, However, lack of force gives thin bonded region especially at the center of the bonded ball. Ultrasonic level was much more influential where higher ultrasonic level will increase the bonded region significantly. Hund & Plunkett [5] suggest that optimization of the bond parameters can be obtained by maximizing shear strength.

This result is in good agreement with Murali [3] and Breach & Wulff [4] whereby applied compressive force maintain proximity between the joining surfaces and increasing in ultrasonic level has resulted in the increasing of the size for the total area of the bond pattern. The higher ultrasonic level cause severe deformation (bulk atom flows) and alters the shape of the wire bond resulting an increase in area of the bond pattern.

During aging, the shear and pull strength, intermetallic compounds coverage and cratering issue of the bonded ball were monitored. Fig. 4 presents a bar graph for average shear and pull strengths after underwent High Temperature Storage at 175ºC for 384 hours. In general, the shear strength after aging was found to decrease significantly compared to as the bonded shear strength, However pull strength test remained the same as before the aging process. Results indicate that sample A and E with combinations of force and the lowest ultrasonic level had give the lowest average readings shear strength.

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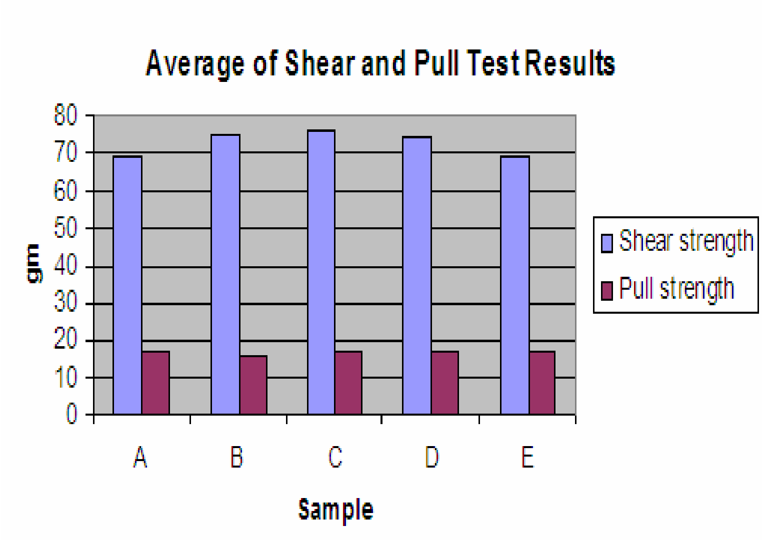
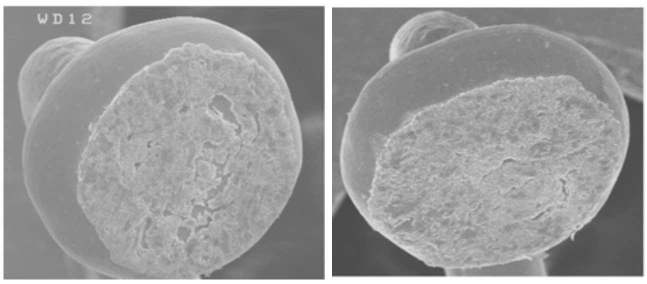



Figure 4: Average of achieved shear and pull strength after HTS at 175ºC for 384 hours.

A magnified SEM on the bottom surface of the ball bonds of intermetallic coverage area after HTS were presented in Fig. 5. Sample E showed less coverage area with spaces where the ball has not been bonded to the Al pad metal. This was probably due to the combinations of low ultrasonic level and force applied during the wirebonding process. SEM images showed that there is a large difference of Au-Al intermetallics distribution in gold area according to the variations of ultrasonic level and force.

Fig. 6 presents the optical microscopy images of Au-Al intermetallic growth patterns through the cross-section of the bonded ball after HTS at 175ºC for 384 hours. Low coverage can result in strongly localised growth through relatively few contact points, leading to ‘spikes' of intermetallics, excessive void formation and significant deterioration of strength [2]. On the other hand, bonding with lower ultrasonic level and force had performed to the non-uniform of Au-Al intermetallic compounds, while adequate ultrasonic level and force have been resulted to the uniform growth of Au-Al intermetallic compound patterns as demonstrated by samples B, C and D in cross-section images.




(a) (b)

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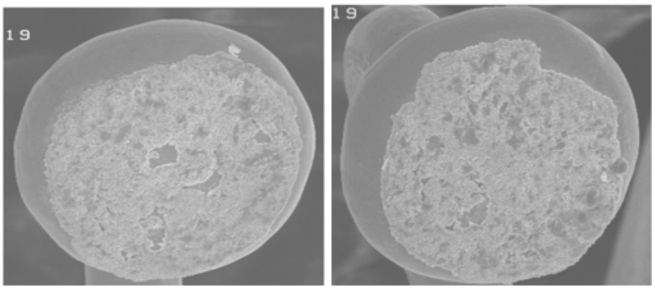

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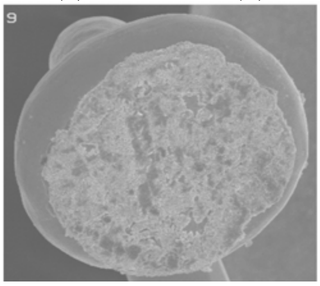
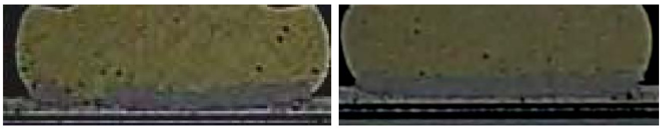


(e)

Figure 5: SEM images of the bottom of a typical gold ball after HTS at 175ºC for 384 hours.

Furthermore, in order solid-state diffusion to occur, a high energy is required to squeeze most atoms or ions through perfect crystal structure by vacancy migration mechanism [3]. Duan et. al [2] also explained that ultrasonic vibration can activates dislocations in the crystalline lattice and increases atomic diffusion, by supplying the activation energy for the diffusion process.



(a) (b)

(c) d)

(e)

Figure 6: Optical microscopy images of bonded ball after HTS at 175ºC for 384 hours for samples A, B, C, D and E.

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Sample A and E showed non-uniform cross-section of Au-Al intermetallic growth patterns result compared to sample B and C. This clearly demonstrates that combination of low force and ultrasonic level induced the poor bonding between Au and Al. Numerical and experimental studied by Tee & Zhang [6] conclude that HTS life is much longer for the bond with uniform intermetallic compound than that of initial non-uniform intermetallic compound. Uniform intermetallic growth illustrated by the cross-section, however, does not guarantee a high coverage. This is because, the cross-section images does not present the actual coverage area. Other method such as 3D imaging system may be needed for further analysis.

Analysis on a sheared region illustrate that there is a passive region on the bonded aluminum bondpad which is no intermetallic reactions were observed on this area as shown in Figure 7. This condition can be explained by poor combinations of ultrasonic level and bond force. Chang et al. [7] suggested that improper wirebonding technique will produce inhomogeneous bonding interfaces in which non-bonding areas are widely distributed.

Although detailed intermetallic phases were not characterised in this study, the changing relative amounts of coverage with ultrasonic level and force presented important roles to achieve robustness in wirebonding process.

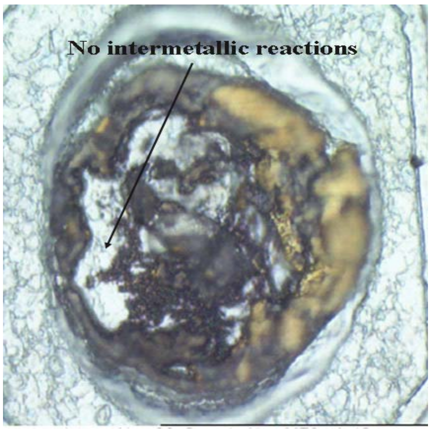


Figure 7: Optical images of the sheared region after HTS at 175ºC for 384 hours.

## CONCLUSION

The effect of ultrasonic level on the average of bond strength and morphology of Au-Al intermatellic coverage was found to be influential than the effect of bond force. It is suggested that the actual constructive parameter in the wirebonding process is an ultrasonic level. The shear strength was found to increase as ultrasonic level increased. The bond force was being set up as a dependent to the ultrasonic level. Combination of adequate force and ultrasonic level setting may produce robust and reliable wirebonding processes.

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## REFERENCES

[1]. S. Murali, (2006); "Formation and Growth of Intermetallics in Thermosonic Wire Bonds: Significance of Vacancy–Solute Binding Energy," *Alloys and Compounds*, **426**, 200-204.

[2]. J. Duan, L. Han, J. Li and J. Zhong, (2006); "Microstructural Characteristics of Au/Al Bonded," *Interfaces*, China, Mechanical-Electronical Engineering College, Central South University.

[3]. J. F. Shackelford, (2000); "Introduction to materials science for engineers," (5th ed.), New Jersey, Upper Saddle River.

[4]. C. D. Breach and F. Wulff, (2004); "New Observations on Intermetallic Compound Formation in Gold Ball Bonds: General Growth Patterns and Identification of Two Forms of Au4Al," *Microelectronics reliability* , **44**, 973-981.

[5]. T. D. Hund, and P. V. Plunkett, (1995); "Improving Thermosonic Gold Ball Bond Reliability," *IEEE 05669-0550*3.

[6]. T. Y. Tee, and X. Zhang, (2005); "Numerical and Experimental Correlation of High Temperature Reliability of Gold Wire Bonding to Intermetallics (Au/Al) Uniformity," *Thin Solid Films*, **504**, 355-361.

[7]. H. S. Chang, K. C. Hsieh, Teo, T. Martens, and A. Yang, (2004); "Wirebond Void Formation during High Temperature Aging, " *TCPT* , **27**, 155-160.

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