SURFACE TOPOGRAPHICAL CHARACTERIZATION OF GOLD ALUMINIDE COMPOUND FOR THERMOSONIC BALL BONDING

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ABSTRACT

Relatively little information is available on the growth patterns of gold aluminide compound in accurate 3D measurement as compared to 2D images of the projected surface. A 3D surface imaging technique by using infinite focus microscope was proposed in this paper to observed and explain the effects of bonding parameters on growth pattern of gold aluminide compound formed between a 25μm 4N gold wire and aluminum pad metallization. Two bonding factors which were varied were ball bonding force and ultrasonic current, while bonding time and temperature were kept constant. The 3D surface measurement provides topographical and colour information of bonded region which indicates that optimum bonding condition has a significant effect on uniform growth and wide coverage area of gold aluminide compound. Results illustrated by this technique were used as additional information to the conventional method includes cross-section optical image or SEM micrographs to gain a better understanding on the physical behaviour of gold aluminide compound.

INTRODUCTION

As technological advances have produced smaller semiconductors with finer Al pad and Au wire sizes, the formation of gold aluminide compound between gold wire and aluminized pads of a Si chip is becoming one of the major concerns in the microelectronic packaging. Formation and growth of gold aluminide compound is diffusion controlled [1] and assisted by moderate pre-heating of substrates. To make solid-state diffusion practical, bonding force is required to squeeze most atoms or ions through perfect crystal structure by vacancy migration mechanisms while ultrasonic vibration activates dislocations in the crystalline lattice and increase atomic diffusion, by supplying the activation energy for the diffusion process [2,3]. With time and temperature the gold aluminide compounds continues to growth and will even proceed under ambient conditions [4]. Therefore, thermal aging is widely used as a screening test to determine the reliability of the gold ball bonds [5-7].

Normally to observe the formation of gold aluminide, cross-sectional metallographic inspection and optical micrographs underside of the bonded balls were commonly used [8-10]. While tactile methods were usually used to provide surface topographies information [11]. Although several detail information on the growth of gold aluminide are understood by those techniques however accurate measurement of intermetallic compound surface topographies and coverage area are still becoming a major concern. Rough surfaces as formed by gold aluminide compound are challenging for tactile analysis which produce errors caused by the tip radius of the stylus which can cause mechanical misrepresentation of the true surface. Lighting reflective and contrast cause too much variation when capture with conventional optical system while cross-section measurement is difficult because of edge effects [12].

Aim of this study was to perform an analysis on the surface topography of the gold aluminide compound region underside of the bonded ball affected by bonding parameters (ultrasonic current and bonding force). Bondability of the ball bonds were investigated during the initial formations of intermetallic. Further analysis on this case has been done by observing the coverage area and growth patterns of the gold aluminide in terms of the volume and surface roughness. This additional information will help in providing a physical understanding of the gold aluminide behaviour for gold wirebonding.

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EXPERIMENTAL SET UP

Electrical connection was performed using KnS8028 thermosonic ball bonding machine by maintaining the bonding temperature at 180ºC. A commercially available 25.4 µm (1mil) gold wire diameter with 99.99% purity was bonded on 65 µm Al bond-pad-pitch. Problems experienced during wire bonding process in this study were either a non-stick on pad or smashed bonds. Normally to determine the optimum bonding parameter setting, the significant key parameters must be fixed. The most significant factors that affect the ball bonding formation were ultrasonic current, bonding force, time, temperature and scrub mode. During the optimization process, two factors namely bonding force and ultrasonic current for ball bond were varied, while bonding time and temperature were kept constant and scrub mode was turn on. In scrub mode, applied bonding force and ultrasonic current can be reduced [3]. The design matrix of the variable parameters are given in Table 1. Bonding process were tuned for each evaluation to get optimize bonding performance by controlling the ball diameter, ball height and loop height within the control specification. Run 2 to run 5 were the combinations of minimum and maximum value for run 1 (centre point). The chosen of the range was from the previous screening process.

Table 1. Design of experiment using 2^k factorial.

Sample	Factors	
	Ultrasonic Current (mA)	Bonding Force ($x10^{-3}$ N)
Run1	70	294
Run2	50 (-)	147 (-)
Run3	50 (-)	441 (+)
Run4	90 (+)	147 (-)
Run5	90 (+)	441 (+)

(-) = minimum value; (+) = maximum value

Evaluation on the influence of bonding parameters on the bonded balls strength was carried out by shear strength tests using XYZ Tec Condor testing machine. Observations on the intermetallics coverage area underside of the bonded balls have been performed by infinite focus microscope (IFM). The method used to remove bonded ball from the Al bond pad was referred to the method that used by Breach and Wulff [12]. The solution has been prepared by dissolving 3 g KOH pellets in 100 ml water. Bonded specimens were placed into the solution at 70 °C for 20 min, and then rinsed with deionised water.

RESULTS AND DISCUSSION

Close up on the underside of the ball bonds demonstrates that the various combinations of ultrasonic current and bonding force have resulted in various levels of gold aluminide coverage. Intermetallic coverage can influence the bonding reliability as well as determine the diffusion reaction in the Au-Al system that affected by bonding parameters setup. Figure 1 shows the coverage area underside of the bonded ball for all combinations of ultrasonic current and bonding force.

Figure 2 shows the shear testing results. Highest shear strength achieved with combination of the highest bonding parameter but poor formation of bonded ball did not reflect the true reliability of the bond especially after thermal aging test. Because of ball shear results is highly dependent on ball bond size, a higher shear force could be related to the larger ball size. Ball shear individually does not truly measure the bond line quality and is not a suitable parameter for wire bond optimization. Therefore, for wire bond optimization we propose a 3-dimension (3D) surface imaging technique by using infinite focus microscope (IFM) to observe and explain the effects of bonding parameters on growth pattern of gold aluminide compound as an additional method to measure and predict the reliability of the bonded ball.

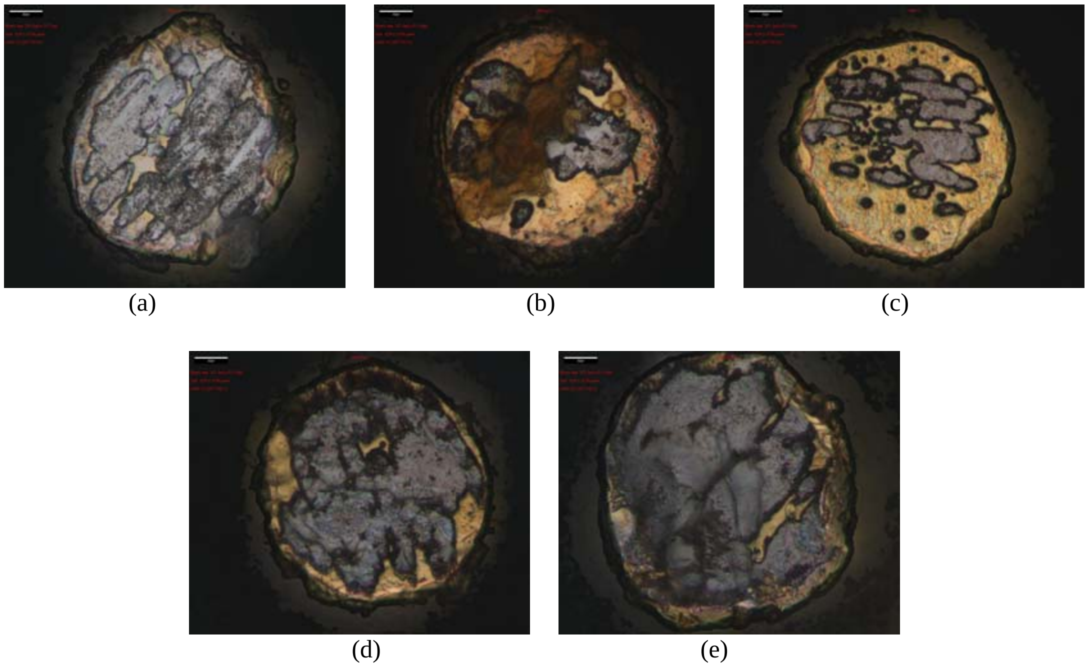


Figure 1. Optical image underside of a typical gold ball after removal from a bondpad for; (a) Run 1 (b) Run 2 (c) Run 3 (d) Run 4 and (e) Run 5.

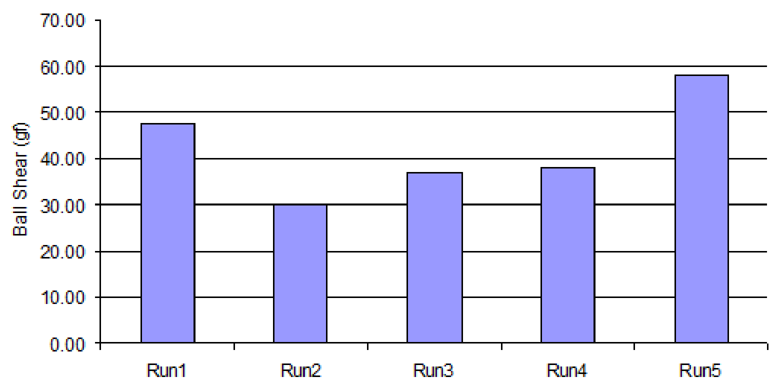


Figure 2. Shear strength results for each Run.

Volume Analysis

In order to discern the gold aluminide surface differences that formed between different combinations of bonding parameter, a stack of 2D microstructural images were converted into 3D dataset. The z-position of the cutting plane was adjusted to cross over the region between the gold and gold aluminide surface. Adjustment was determined based on the observation in 3D viewer, where thin intermetallic areas were also included in the volume calculation.

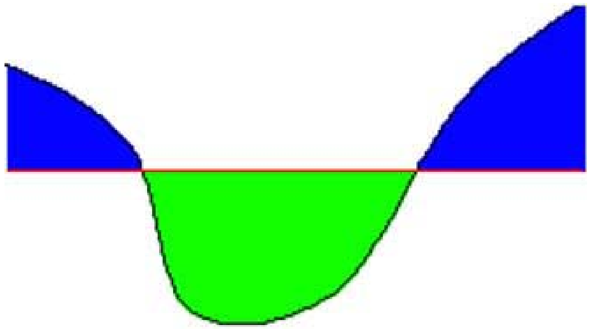
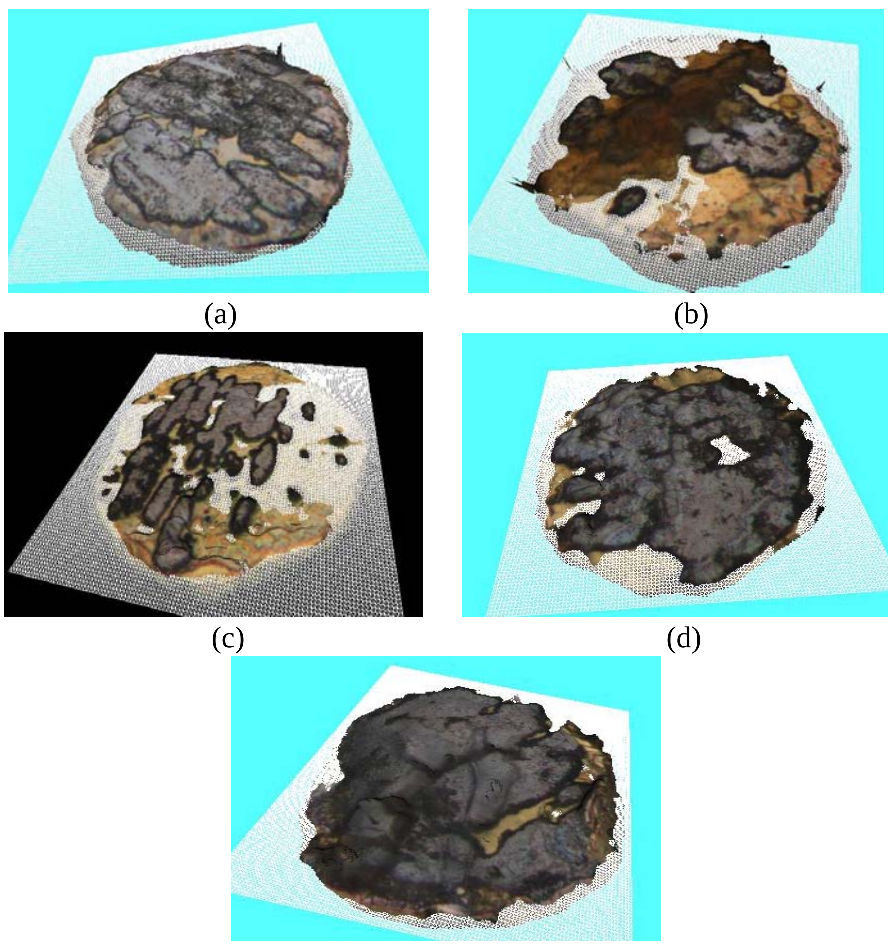


Figure 3. Volume above (blue) and below (green) the cutting plane represent the calculated volumes.

This information was sometimes difficult to determine by visual inspection in 2D viewer. There are three modes can be specify in order to compute a cover surface for volumes analysis includes top cover mode, bottom cover mode and cutting plane mode. The cutting plane mode has been chosen for this purpose of study. The calculated volumes compatible to the part of the volume below and above the plane is schematically illustrate by Figure 3.

Traceable calibration standards allow the verification of measurement results. Figure 4 shows the calculated volume area below and above the cutting plane which represent the volume of unbonded and bonded regions for entire combinations of bonding parameter.



(a) (b) (c) (d) (e)

Figure 4. Bonded and unbonded bonded region separated by the cutting plane.

Computed results of bonded and unbonded volume were present in Table 2. The higher the load, has forced the Au and Al to come into intimate contact and results to the increasing in the total gold aluminide coverage area. Normally, more than 60% of gold aluminide coverage is required and should be formed over the contact area of the bonded ball to ensure good reliability of the interconnection [13,14].

Table 2. Computed results of bonded and unbonded volume.

Sample	IMC Volume (μm^3)	Gold Volume (μm^3)	IMC Coverage %
Run 1	11650	4592.7	71.72
Run 2	4108.8	7591	35.12
Run 3	7683.5	6569.5	53.91
Run 4	9898.5	5004.3	66.42
Run 5	14163	2722	83.88

Note : IMC is an acronym to intermetallic coverage

Run 2 and run 3 shows the distinctive features of gold aluminide formation with less than 60% coverage and prove to have less shear strength compared to others. It is predicted that lack of ultrasonic current gave non-uniform bonded region and lack of intermetallic coverage especially at the centre of the ball bond. For higher bonding force, the bonded region increase significantly. Although run 5 is seen to consist of highest coverage and achieved highest shear strength however excessive bonding force and ultrasonic current had alter the ball shape leading to smashed ball bond. It could be concluded that the combination of adequate force and ultrasonic current produced robust and reliable bondability as demonstrated by run 1.

Roughness Analysis

The surface roughness was measured on all the samples at 4 lines (A, B, C and D) as shown in Figure 5. As the distribution of the gold aluminide compound was not uniform, cross sectional analysis somehow difficult to reveal the correct position and actual growth pattern of gold aluminide.

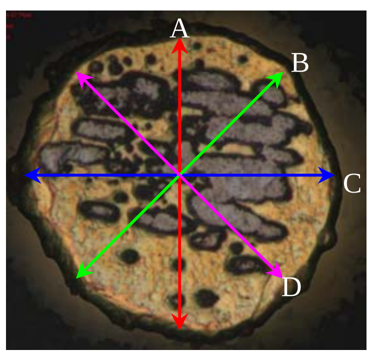
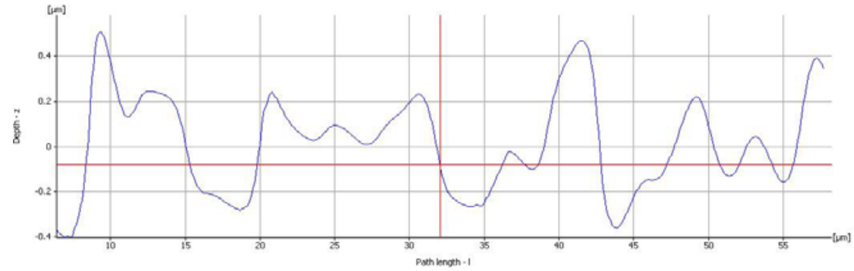
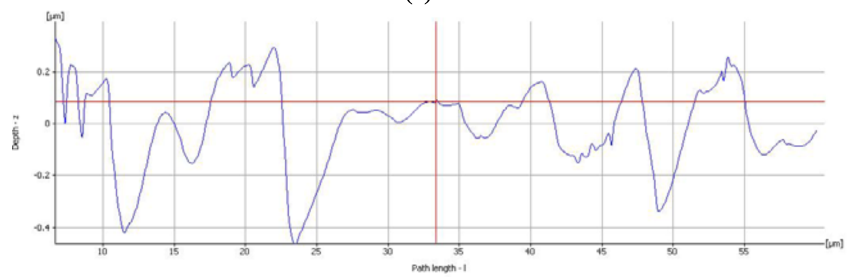


Figure 5. Analysis area at 4 evaluation lines (A, B, C and D) for sample of run 3.

Figure 6 represents the roughness profile over the evaluation lengths. The results indicated that different evaluation lines will provided different profile of roughness which represents by the value of average roughness (Ra). Based from the IFM manual, average roughness is define as the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length. Sometimes there are surfaces that differ in the shape of the profile but have the same Ra. Even there are surface that have similar shape, they may have different spacing between features. To distinguish between surfaces that differ in shape or spacing other parameters need to be calculated including root mean square roughness (Rq), total roughness (Rt), skewness (Rsk) and kurtosis (Rku). The detail measurements on the peaks and valley and profile shape and spacing for all the samples were shown in Table 3.



(a)



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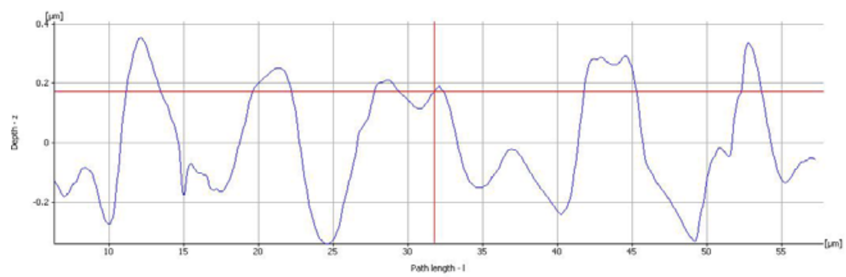
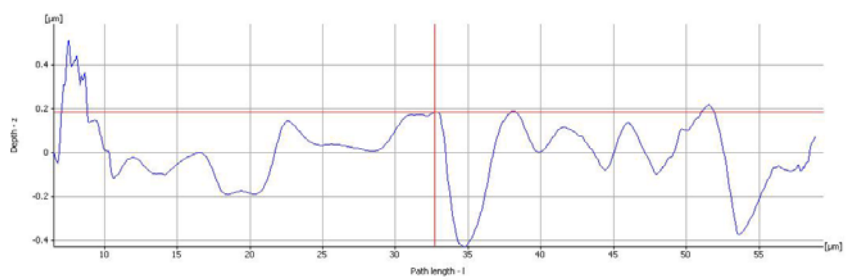


(c)



(d)

Figure 6. Shows the comparison of R_a values that represents various average roughness profile for the texture on underside of the bonded ball over the evaluation length for sample of run 3.

Results show that lower and excessive amount of gold aluminide represent by Run 2, 3, 4 and 5 give Ra values greater than those obtained by Run 1. Therefore Run 1 was seen capable to provide more uniform growth and coverage of gold aluminide. Unusual conditions such as sharp spike and burr on the gold aluminide growth can be detected through Rt values. Run 4 and 5 exhibited unconsistent Rt values which mean that there are some points on the gold aluminide region that have extremes in the roughness affected by excessive combination of bonding parameters.

For detail understanding on the roughness profile and texture the amplitude distribution function (ADF) was used. ADF is a probability function that gives the probability of a profile of the surface to have a certain height, z, at any position x. Skewness is another parameter that describes the shape of the ADF which is a simple measure of the asymmetry of the ADF. Run 1, 4 and 5 presents the surfaces with a positive skewness which illustrate that gold alluminide surfaces were more dominant compared to gold (unbonded) area. Surfaces with negative skewness as shown by Run 2 and 3 represents lower amount of gold aluminide compound.

Table 3. Computed measurements of average roughness (R_a), root mean square roughness (R_q), total roughness (R_t), skewness (R_{sk}) and kurtosis (R_{ku}) on the texture underside of the bonded ball for all samples.

Sample	R_a	R_q	R_t	R_{sk}	R_{ku}
Run 1 (70mA 294mN)					
Line A	0.08251	0.109	0.518	0.483378	2.91065
Line B	0.07725	0.1095	0.5997	1.76608	5.82985
Line C	0.05836	0.07774	0.3706	0.113226	2.96778
Line D	0.04992	0.065	0.3263	0.486614	2.99586
Run 2 (50mA 147mN)					
Line A	0.247	0.328	1.902	0.114407	3.56934
Line B	0.1912	0.3461	2.608	-0.32624	7.4031
Line C	0.358	0.503	2.806	0.372631	3.87887
Line D	0.216	0.368	2.598	0.871823	7.27604
Run 3 (50mA 441mN)					
Line A	0.1757	0.2118	0.910	0.3611	2.40021
Line B	0.1279	0.1619	0.7932	-0.697671	3.22753
Line C	0.1604	0.1827	0.6951	0.120444	1.87596
Line D	0.117	0.1548	0.9383	-0.284451	3.88072
Run 4 (90mA 147mN)					
Line A	0.1566	0.195	1.078	0.00313	2.66481
Line B	0.07059	0.08809	0.4273	0.203682	2.60182
Line C	0.09248	0.128	0.8181	0.888571	4.83963
Line D	0.07492	0.1256	1.137	3.70823	24.7587
Run 5 (90mA 441mN)					
Line A	0.1003	0.1325	0.812	1.27525	4.83003
Line B	0.282	0.446	3.402	0.5411706	8.02346
Line C	0.23	0.301	1.547	0.121136	3.2143
Line D	0.241	0.418	3.179	2.29997	13.6749

CONCLUSION

2D optical inspection of the intermetallic demonstrated a reasonable comparison between probable bonded and unbonded region, but cannot provide an accurate measurement of intermetallic coverage. 3D surface measurement provides topographical and colour information of the bonded region which indicates that optimum bonding condition has a significant effect on uniform growth and wide coverage area of gold aluminide compound. Combination of adequate bonding force, 294mN and ultrasonic current setting, 70mA produced robust and reliable wirebonding process. The highest shear strength has been achieved with the high value of bonding parameters (441mN 90mA) which highly dependent on ball bond size regardless of poor formation of ball bond. While lowest value of bonding parameters (147mN 50mA) has given lowest shear strength caused by porous surface or lower intermetallic coverage amount. Higher shear strength sometimes do not represents good reliability of bondability as IFM 3D surface analysis characterized that combination of higher values of bonding parameter (run 4 and run 5) had caused severe deformation (bulk atom flows) of gold aluminide growth surface. Results illustrated that the IFM 3D surface analysis technique could be used to provide more detail information rather than only using the conventional method by analyzing the SEM micrographs on the cross-section area to gain a better understanding on physical behaviour of gold aluminide compound.

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