The Effects of Wire Bond Parameters on Fine-Pitch Reliability

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Abstract

Device reliability is becoming a greater issue as interconnect dimensions continue to shrink. For wire bonded devices, bond pad pitch has reached 40µm in production while the intricacies of interconnection and reliability have increased substantially. The effect of bonding control, wire-to-bond diameter ratios, and metrology of fine and ultra-fine pitch bonds are being studied throughout the industry.

This paper examines the effect of common wire bond parameters (USG power, bond force, contact velocity and bond time) on the reliability of 40µm pitch devices. A study was conducted wherein a commercial 99.99% gold bonding wire was bonded on aluminum pad test die (>1µm thick, Al-Si-Cu) with an automatic ball bonder. Parameter combinations were chosen so that the bonded ball diameter, height, and shear strength were nearly constant across experimental cells. Reliability testing was conducted using an accelerated, high-temperature storage test wherein the as-bonded samples were exposed to elevated temperature (175°C) for increasing times and then pull tested at the ball bond.

Results show that bond force had the largest effect on reliability and suggest that there are necessary minimums for as-bonded intermetallic coverage (IMC) and as-bonded ball shear strength in order to pass accelerated reliability testing. However, uncontrolled factors also appear to influence reliability, as passing minimum shear and IMC were not sufficient to guarantee reliability. This paper discusses the methodology of the experiment as well as the results and recommendations for fine pitch wire bonding.

Key words: wire bonding, reliability, parametric effects

Introduction

The reliability of a semiconductor device is an important part of its design and manufacture. As many devices are subjected to extreme conditions such as large thermal excursions (e.g., automotive, processors) or vibration and impact (e.g., mobile phones, PDAs, digital music players), each part of the device, from the materials to the assembly, must be robust.

In general, initial wire bond quality directly relates to device longevity - a weak bond will not survive as well as a strong bond. [1, 2] The quality of a ball bond has long been judged by its shear strength and, sometimes, by the amount of intermetallic coverage (IMC) seen on the bottom of the ball in the as-bonded condition. The general belief is that a bond with high shear strength and good IMC is robust and reliable. As device pitch decreases, however, subtle differences in bond strength, metrology and, perhaps, the manner in which equally strong bonds are made cannot be ignored. [3]

Real-time device reliability is difficult to study, as expected lifetimes are generally tens of thousands of hours. For this reason, accelerated tests such as thermal cycling and high temperature storage (HTS) are used. HTS is used to evaluate ball bond strength (as opposed to encapsulation or package reliability) and involves storing an encapsulated device at 150°C for 1000 hours. To pass the test, the device must not show open circuits during subsequent electrical testing. [4]

Recently, however, companies have developed a faster test to shorten the assemble-test-adjust development cycle in wire bonding. This test consists of aging the wire-bonded device, unencapsulated, for up to 200 hours at 175°C and then pull testing the bonds. In some cases, a lifted ball is considered a failure, while, in others, high-strength ball lifts are considered to have passed. [5, 6] Although the correlation of this test to actual device reliability during use is unknown, it has become the de-facto standard for in-house testing and ensures, at a minimum, that the bonds are not inordinately weak.

This study was designed to address two questions:

1. What are the "as-bonded" metrics that indicate good device reliability?
2. Will wire bonds of similar size and strength have the same reliability if created using different wire bond parameters?

More specifically, we sought to determine if as-bonded measurements (shear/area or IMC) can be used to predict reliability during accelerated testing and if ball bonds with similar as-bonded quality, but made with different parameters, have equivalent reliability.

Materials and Methods

The devices used for this study were patterned test die with top metal >1µm thick of Al-Si-Cu. The die were attached to PBGA substrates using silver-filled epoxy. K&S CIC™ capillaries and K&S AW66 (99.99% gold) wire (18µm diameter) were used. A K&S Maxµm™ wire bonder was used for device assembly and shear and pull testing were performed using a Dage 4000 tester. Hisomet optical microscopes were used for ball diameter and height measurement.

Twenty-seven wire bond parameter sets were developed using three levels of contact velocity (c/v), three of USG power, three bond force levels, and three bond times. Targeted ball bond diameter was 31µm and ball height was 7µm.

Wire bond parameters were developed using a method of monitoring ball squash during impact. Three reasonable contact velocities (labeled here as low, medium, high) and three reasonable bond forces (low, medium, high) were established in initial tests. Three bond times for each bond force were chosen and the USG power necessary to produce the targeted ball size was derived through experimentation. This gave twenty-seven parameter sets for the study (see Table 1).

Samples from each of the DOE cells were measured after bonding for ball diameter, ball height, first bond shear strength, and first bond pull strength. The as-bonded intermetallic coverage (IMC) for 20 balls from each experimental cell was measured by dissolving the bond pad in a warm, aqueous solution of KOH and photographing the undersides of the released ball bonds in an SEM. The ball contact area and IMC areas were measured using image analysis software.

Additional samples were subjected to accelerated thermal testing at 175°C in nitrogen. Pull tests were performed after 24, 72, and 192 hours of exposure.

Table 1. Parametric cells for the DOE

	C/V	Power	Time	Force
1	L	H	L	L
2	L	M	M	L
3	L	L	H	L
4	L	H	L	M
5	L	M	M	M
6	L	L	H	M
7	L	H	L	H
8	L	M	M	H
9	L	L	H	H
10	M	H	L	L
11	M	M	M	L
12	M	L	H	L
13	M	H	L	M
14	M	M	M	M
15	M	L	H	M
16	M	H	L	H
17	M	M	M	H
18	M	L	H	H
19	H	H	L	L
20	H	M	M	L
21	H	L	H	L
22	H	H	L	M
23	H	M	M	M
24	H	L	H	M
25	H	H	L	H
26	H	M	M	H
27	H	L	H	H

Results and Discussion

While the parameter sets were designed to result in the same bonded ball size and similar shear strengths, there was some variation between experimental cells. Sample sizes of 20 for ball height, 40 for diameter, and 40 for shear were used to provide sufficient data.

Figure 1 shows the average and range (maximum-minimum) of ball diameters for each of the cells. The significance of the variation in bonded ball diameter will be addressed later.

Figure 2 shows the average and range for the bonded ball height. Variation from cell to cell is not easily estimated due to the granularity in the ball height measurements (1µm step size). No correlation was seen between reliability and bonded ball height.

The strength of the first bonds was measured by standard ball shear testing. Results are shown in Figure 3. The values ranged from about 5 to 7 g/mil^2 (76-106 MPa). It was anticipated that the ball size and shear strength for all of the cells would be similar so that

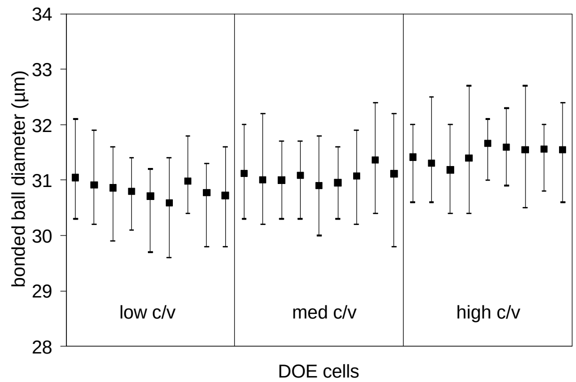

Figure 1. Bonded ball diameters for the 27 DOE cells.

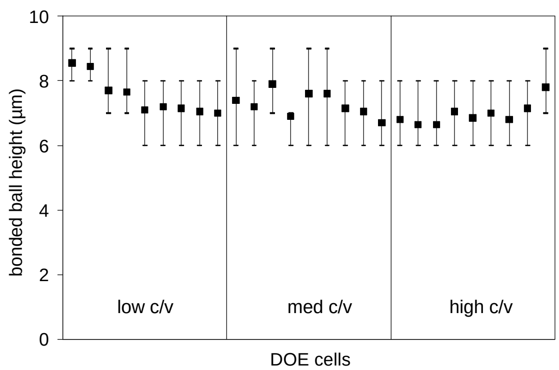

Figure 2. Bonded ball height for the 27 DOE cells.

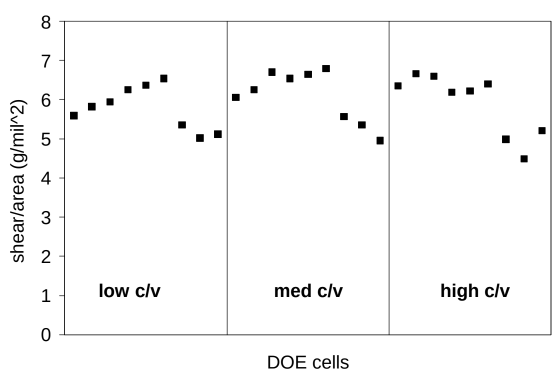

Figure 3. As-bonded shear strength for the 27 DOE cells.

differences in strength after HTS would indicate what influence bond parameters had with no confusion from differences in first bond. The effect of this variation was insignificant as we will see later.

The first bonds were also evaluated by pulling the wire just above the ball bond. Sample sizes for pull testing were 100 for as-bonded samples. Effort was made to pull directly above the ball so that no torque was applied which could roll the bond off the pad and result in an artificially low strength measurement. Results of the as-bonded pull test are shown in Figure 4.

Besides ball size and strength, the quality of the bond was also characterized by the amount of Au-Al intermetallic formed. Typical intermetallic photographs are shown in Figure 5 for nine of the 27 experimental cells (the light-colored area in the center of the ball is the Au-Al intermetallic). Calculated values for IMC are shown in Figure 6. Sample size for IMC was 20 for each DOE cell.

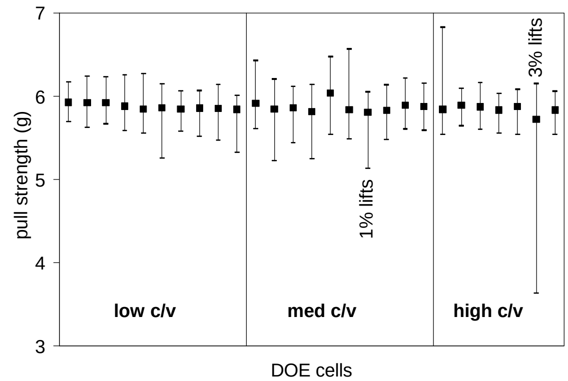

Figure 4. As-bonded pull strength (above the first bond) for the 27 DOE cells.

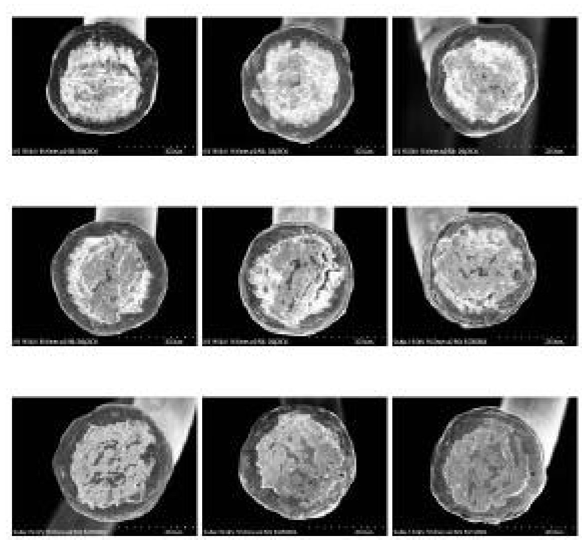

Figure 5. Example photos of as-bonded intermetallic coverage (IMC) for a sample set using SEM visualization.

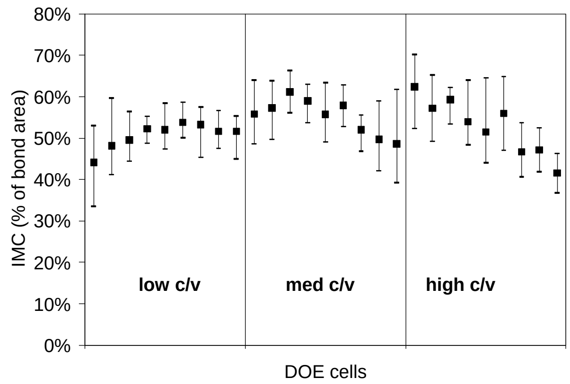

Figure 6. As-bonded intermetallic coverage (IMC) for the 27 DOE cells (from SEM photographs).

Pull tests were performed on samples exposed to 175°C in nitrogen for 24, 72, and 192 hours. Pull data are shown in Figures 7-9 as box-and-whisker plots. Maximum and minimum pull strengths are indicated by the upper and lower bars, while the box illustrates the middle 80% of the pull values. The mean values are not shown, but are generally in the center of the box. Sample size was 200 pulls for each cell at each HTS time.

Some cells showed ball lifts rather than wire breaks during pull testing. The ball lift data for all HTS times are not shown here, but the lifts after 192 hours HTS are discussed later.

Figures 7-9 correspond respectively to the low, medium, and high c/v parameter sets. (Note: Each graph is for a specific c/v setting and the x-axis is divided into three parts for low, medium, and high force. For each force area there are three parameter sets and each parameter set has four HTS times.) The shapes of the box-and-whisker plots indicate that the upper limit is defined by the wire break strength (about 6 grams) and that there are a small number of low-pull-strength values for each data set. These minimums are used to determine which samples pass the test.

Each figure indicates two or three parameter combinations which sustained high pull strengths out to 192 hours HTS. For each figure, there is some indication that the medium force parameter gave the best results.

When the data presented in the previous figures are analyzed and replotted, certain trends can be seen. Figure 10 shows as-bonded ball shear strength versus parameter setting and indicates that c/v and force have the largest effect on shear strength. (Note: depending on the parameter ranges investigated and the specific experiment, other research can show different levels of significance and influence.)

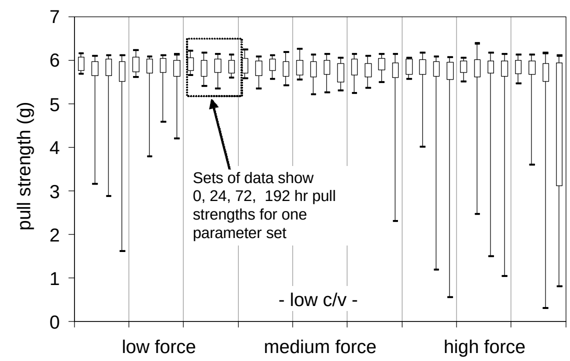

Figure 7. Pull strength for LOW C/V cells after 175°C HTS.

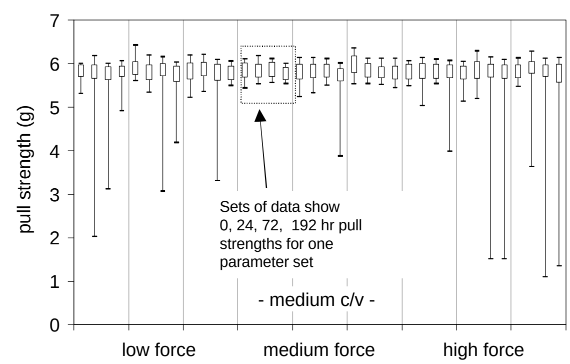

Figure 8. Pull strength for MEDIUM C/V cells after 175°C HTS.

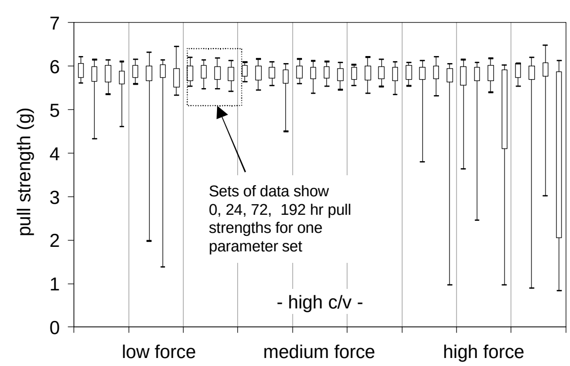

Figure 9. Pull strength for HIGH C/V cells after 175°C HTS.

USG and bond time had smaller effects, which is not surprising as, by design, the USG/time parameter combinations were confounded. I.e., the combinations were: 1) high USG/low time, 2) medium USG/medium time, and 3) low USG/high time. Therefore, while the data suggest that lower USG gives a stronger bond, this was also the long bond time setting. Any conclusions, therefore, must be made with care.

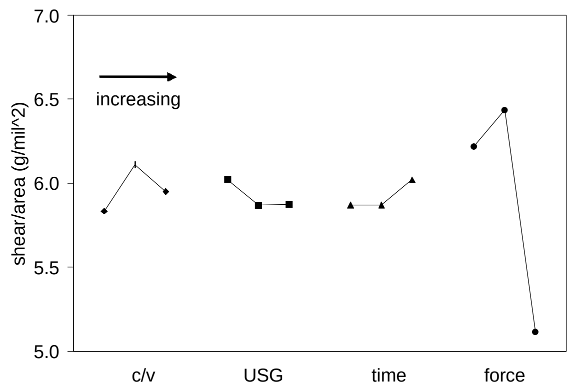

Figure 10. First bond shear strength vs. bond parameters.

As-bonded IMC data are shown in Figure 11 as a function of bond parameters. The shapes of the curves are similar to those for shear strength (Figure 10) and Figure 12 combines the two to show a trend where shear strength increases with IMC. Consistent with previous studies, this result gives evidence to the validity of the results.

While pull strength is an important measurement by which to judge bond quality, the strength distribution is asymmetric as the wire break strength creates an upper boundary. By tracking the number of bonds lifted during pull test after 192 hours HTS (see Figure 13), we can more easily see the effect of bond parameters on bond quality. The data indicate that c/v and force have a strong effect and that the medium values resulted in the fewest lifts. Also, the combination of low USG/long bond time gave the best results for those parameters. The curve shapes are approximately inverse to those of shear/area vs. parameter (Figure 10), suggesting a correlation between high shear and few ball lifts. This is consistent with previous work and is shown directly in Figure 14.

Figure 14 illustrates that there is a minimum shear strength required for reliability (as defined by ball lifts during pull). Additionally, the data indicate that bonds with equivalent shear strengths can sometimes lift during pull test. A secondary mechanism or influence must, therefore, be at work. From this study, the authors suggest targeting 6 g/mil^2 (91MPa) normalized shear strength for fine pitch reliability.

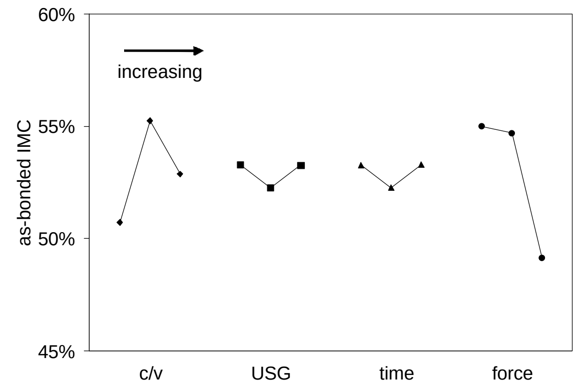

Figure 11. As-bonded intermetallic coverage vs. bond parameters.

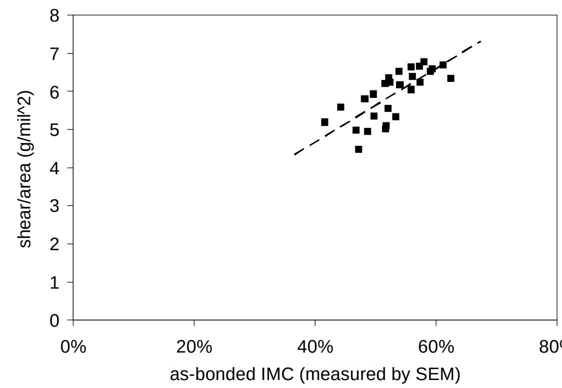

Figure 12. Normalized shear strength vs. as-bonded IMC.

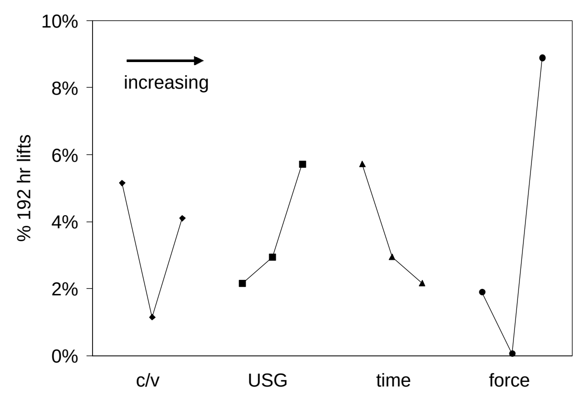

Figure 13. Ball lifts during pull test after 192 hrs, 175°C HTS vs. bond parameters.

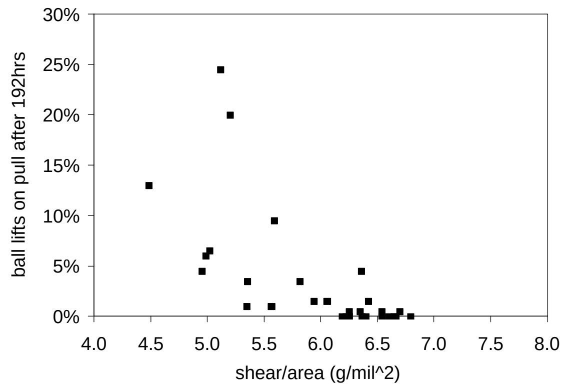

Figure 14. Pull strength after 192 hrs, 175°C HTS vs. normalized shear strength.

Pull strength data are shown in Figure 15 plotted against as-bonded IMC. As stated earlier, there is an upper bound to first bond pull strengths defined by the wire break strength. Low pull strengths at low IMC values indicate weak bonds and ball lifts during pull test. As with shear strength, there is a minimum IMC necessary for reliability - about 55% coverage for this study.

At the beginning of the Results and Discussion section, the variation of ball diameter between experimental cells and its effect on the data analysis was mentioned. In short, smaller bonded balls may be more prone to lift during pull test simply due to geometry. Figure 16 shows that bonded ball diameter did not directly influence the rate of ball lifts and our data are not, therefore, convoluted by this variation.

As the influence of IMC on shear strength and the correlation of shear strength to ball lift has already been established, it is not surprising that the rate of ball lift correlates to IMC. Figure 17 is approximately an inverse plot of Figure 15 and again suggests a minimum IMC of about 55% for reliability

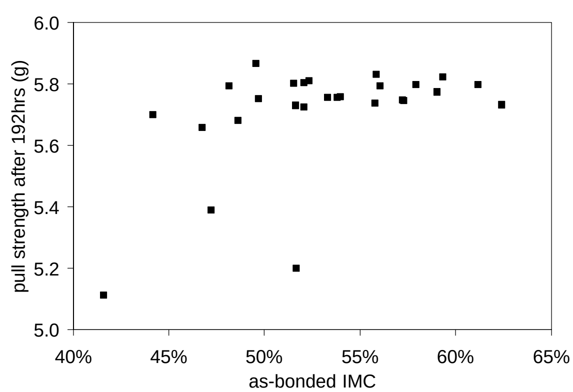

Figure 15. Pull strength after 192 hrs, 175°C HTS vs. as-bonded IMC.

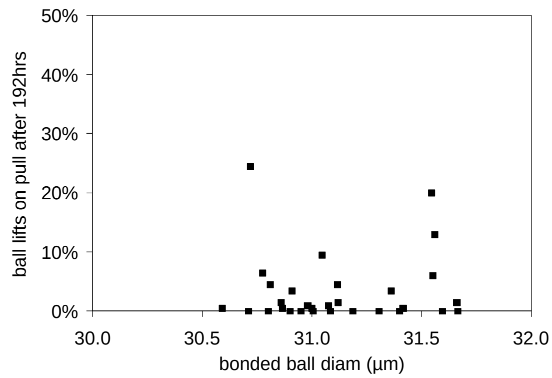

Figure 16. Ball lifts on pull after 192 hrs, 175°C HTS vs. bonded ball diameter.

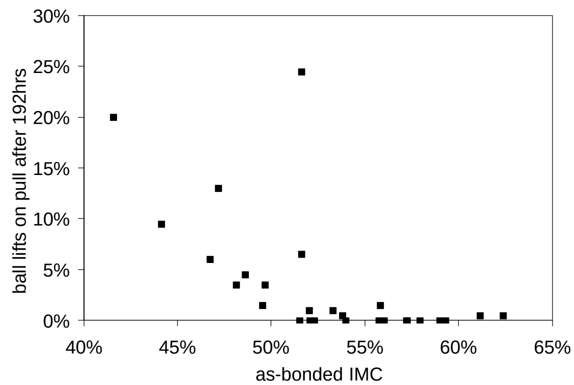

Figure 17. Ball lift during pull test after 192 hrs, 175°C HTS vs. as-bonded IMC.

Conclusions

Wire bonding at very fine pitches raises difficulties not only in assembling the bond, but also in metrology and reliability testing. Small changes in wire bond parameters can significantly influence ball size and strength which can directly affect the reliability of the bond. More subtle variations which are not readily identified also influence device reliability. This is illustrated when two "identical" ball bonds (same size, IMC, shear strength) respond differently to accelerated reliability testing.

This study attempted to determine which wire bond parameters affect device reliability using an accelerated HTS followed by wire pull testing. Within the parameter ranges used, bond force had the largest effect on reliability (as determined by ball lifts during pull test) and the combination of low USG power/long bond time showed the fewest ball lifts on pull. Contact velocity had little or no effect.

Additionally, this study looked at how well as-bonded metrics, specifically, ball shear strength and intermetallic coverage, predict device reliability using the same accelerated HTS testing. Results show that minimum shear strength and IMC are necessary for reliability, but are insufficient to guarantee a reliable bond. From this test, the authors suggest targeting 6g/mil^2 (91 MPa) for as-bonded shear strength for 50µm pitch and finer. Additionally, IMC coverage should be at least 55% as measured by SEM.

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