Resolution of a Fine Pitch Wire Bonding Reliability Problem

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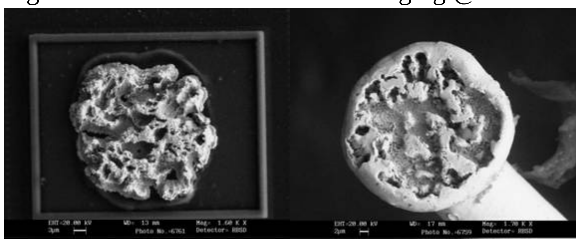
Abstract

Ultra-fine pitch ball bonds with small weld cross sections must be carefully optimized to avoid premature intermetallic failures. Conventional pull and shear testing, in the "as bonded" condition, will not detect devices prone to failure. Thermally aging devices for 24 hours at 175^{0}C, followed by pull testing, will accelerate the failure and enable detection. A series of Designed Experiments (DOE) were conducted to determine robust operating conditions that will maintain long-term reliability. Capillary and wire selection played a significant role in achieving a high reliability solution. Optimum choice of capillary and wire enabled a high reliability process across the entire tested parameter range. Sub-optimum capillary and wire selections failed in all trials of the same process range. Optimization and testing were critical to long-term reliability.

The Problem

As device density and I/O requirements increase, the size and pitch of bond pads and ball bonds, subsequently, must decrease. Circuit Under Pad (CUP) devices provide better utilization of valuable Si area, but increase reliability problems because the circuit and dielectric layers under the pad are more sensitive to cracking during wire bonding. In addition, smaller ball bonds (weld cross sections) required by fine pitch, high-density devices, present new challenges for high reliability packaging[1]. As the size of the weld decreases, efforts to maximize the wire diameter have successfully decreased the ratio of welded cross sectional area to wire cross sectional area. As a result, pull strength and shear strength/area specifications have been maintained, while the welded area has been reduced. However, problems with lifted bonds during pull test, failures during pull testing after High Temperature Storage testing (HTS), and intermetallic reliability failures for small ball bonds have increased. New developments in higher reliability wire and capillaries are providing more uniform, higher strength welds with superior HTS performance and enhanced process reliability. Machine parameters, which have a significant effect on bond quality, also must be optimized to achieve a high-reliability process.

Figure 1. Lifted Bond after 168 hrs aging @175^{0}C



This paper describes the results of a recent set of experiments that resolved a reliability failure on sensitive Circuit Under Pad (CUP) devices. Intermetallic reliability problems were reported with 40µm diameter ball bonds on customer-specific devices. The problem was initially detected as a field failure. Electrical testing revealed an open circuit, while subsequent failure analysis revealed lifted balls after removal of molding encapsulation (de-capping) with fuming nitric acid. Accelerated testing by 175^{0}C High Temperature Storage (HTS) and pull testing simulated the failure, producing lifted balls and low minimum pull test results for the baseline control.

Figure 1 shows SEM photos of a lifted ball bond. The bonded device was encapsulated, and then thermally aged at 175^{0}C for 24 hours. Encapsulation was removed by decapping with fuming nitric acid. The device was, then, pull tested, resulting in a ball lift. Pull test sample size was 100 wires, with acceptance criteria noted as "No Lifts".

The Experiment

Selection of capillaries and wire are independent variables that cannot easily be randomized within an experiment. They are, therefore, treated as categorical variables within the experiment plan. The same Taguchi L-9

Figure 2 Summary of No Lift DOE Cells

Categorical Combinations				
# of cells with No Lifts after 24 hr Bake				
Wire	Cap 1*	Cap 2*	Cap 4*	Cap 3*
99.9% Au	0/10	5/10	9/10	10/10
99.99% Au(1)	0/10	0/10	3/10	10/10
99.99% Au(2)			5/10	6/10
Not in Plan				

+ center point experiment was conducted for each combination of planned capillary and wire.

The Taguchi L-9 experiment offers an efficient design for screening. It enables the study of four independent variables at three levels, with only nine experimental runs. When a center point (all four independent variables at their mid-levels simultaneously) is included, the ten cells provide a very powerful tool for screening complex processes.

A series of ten separate Taguchi L-9 + center point experiments were conducted using a different categorical combination of capillary and wire for each DOE. Figure 2 shows the combinations tested and the number of trials with "No Lifts" for each combination. The same experiment was executed for each combination. Four bonder parameters (Constant Velocity, Power, Bond Force and Contact Threshold) were varied at three levels in each experiment. Prior to running each DOE, the Free Air Ball (FAB) size was adjusted to yield a bonded ball diameter of 39 - 40µm and ball height of approximately 10-12µm, with the center point bonding parameters. Free air balls required adjustment because the capillary inner geometry (chamfer angle and diameter) was different for each capillary and the ball volume required minor adjustment to compensate for the differences. Parameter ranges for the DOEs were selected based on earlier screening experiments.

The DOEs demonstrated that the optimum capillary and wire combination had a strong, statistically significant effect on reliability, as measured by % lifts after pull testing devices aged at 175^{0}C for 24 hours. Ranking the best wire and capillary by rank-sum methods determined that Capillary # 3 and the 99.9 % Au alloy wire produced the best results. This combination successfully eliminated lifts for all cells. The specific 99.9% alloy wire was chosen specifically for intermetallic reliability. Chemistry of the <1000 ppm dopants added to the 99.9% Au plays a significant role in intermetallic reliability and mechanical properties.

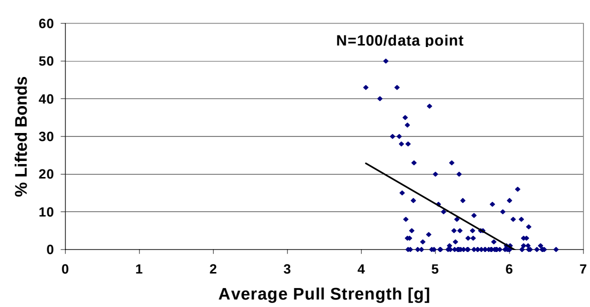
Bond parameters had less significant effects than the capillary and wire. Table 1 summarizes the % lifts contrast for all of the trials in the experiments. The only slightly significant parameter effect was bond power. Higher bond power had less lifts (confidence level 90%, slight significance). The optimal capillary and wire combination demonstrated "No Lifts" over the entire test range, signifying a large, robust bond window. The worst combination of capillary and wire presented many lifts over the entire parameter range, with no cells free of lifts. Sample size for each experiment cell was one device (166 wires bonded, N=100 wires pull tested after HTS).

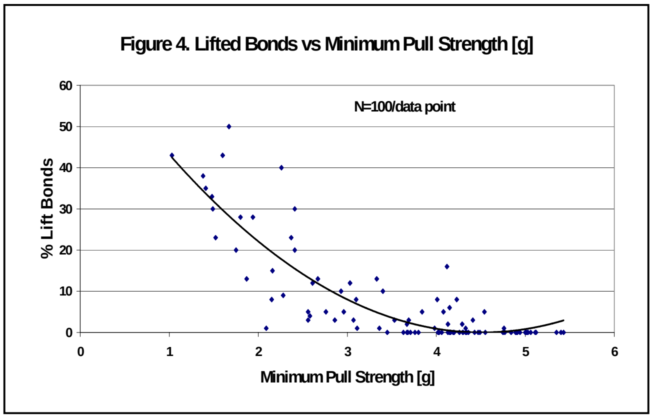
Table 1: Contrast of Lift% after 24 hr High Temp Storage, [N=100]

			Capillary	Cap 1*	Cap2*	Cap 4*	Cap 4*	Cap 1*	Cap2*	Cap 4*	Cap 3*	Cap 3*	Cap3*
			FAB	1.28	1.3	1.28	1.26	1.3	1.32	1.28	1.28	1.28	1.28
			Wire	99.9%Au	99.9%Au	99.9%Au	99.99%Au(2)	99.99%Au(1)	99.99%Au(1)	99.99%Au(1)	99.99%Au(1)	99.9%Au	99.99%Au(2)
Constant			Contact	Capillary x Wire Categorical Combinations									
Velocity	Power	Force	Threshold	Lift %									
0.16	60	7	40	16	1	0	13	8	30	23	0	0	1
0.16	65	9	50	8	5	0	3	12	50	5	0	0	0
0.16	70	11	60	10	0	0	0	10	8	0	0	0	0
0.19	65	11	40	6	3	0	0	2	20	0	0	0	1
0.19	70	7	50	12	2	0	1	28	13	13	0	0	1
0.19	60	9	60	9	0	0	3	30	23	3	0	0	0
0.22	70	9	40	5	0	0	0	28	15	0	0	0	0
0.22	60	11	50	20	0	3	5	33	43	35	0	0	8
0.22	65	7	60	1	0	0	0	5	40	38	0	0	0
0.19	65	9	50	2	3	0	0	4	43	5	0	0	0
Green ALL Legs No Lifts after 24 hr HTS													
Yellow Some Legs with Lifts after 24 hr HTS													
Red ALL Legs with Lifts after 24 hr HTS													

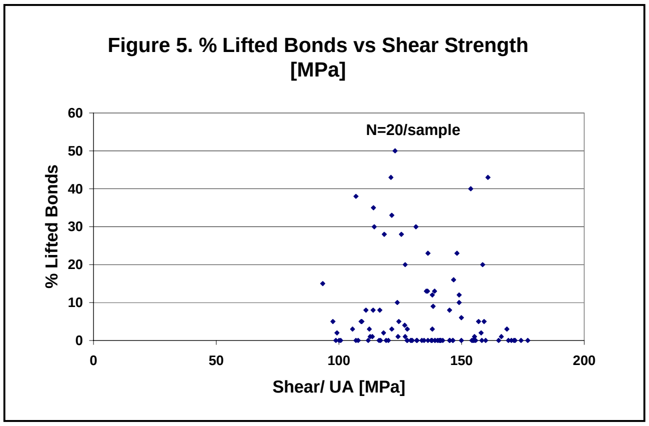
Further analysis of the underlying data is shown in Figures 3 through 5. In Figure 3, % lifts are plotted against average pull strength. This shows that as lifts increase, average pull strength decreases slightly. But the trend is not strong and average pull strength is not a good predictor of lift failures. Shear strength [MPa] (Figure 5) is also not a good predictor of lifts. Earlier papers have demonstrated that pull strength is a much better indicator of ball bond quality than shear strength for ultra-fine pitch ball bonds. Figure 4, Minimum Pull Strength vs. % Lifts, does show a strong correlation. Bonds that lift are, typically, significantly weaker than good bonds and the Minimum Pull Strength decreases significantly when there are increased incidences of lifted bonds. All of the experiments with "No Lifts" had Minimum Pull strength values after 24 hours of thermal aging and decapping of >3.75 grams.

Figure 3. % Lifted Bonds vs Average Pull Strength [g]





Additional testing is required to confirm that the elimination of pull test lifts after 24hr HTS correlates well with the elimination of electrical test failure in molded product.



RESULTS

Wire

Gold bonding wire has normally been specified as 4 - 9's purity (99.99% Au). This percentage rate allows as much as 100 parts per million (ppm) of impurities. Typically, gold for bonding wire is refined to a higher purity level, with controlled levels of impurities added to enhance mechanical properties. Two different 99.99% Au alloys (designated (1) and (2)) were tested in these experiments. Micro-alloying within this 100ppm range has been shown to enhance strength, stiffness, elevated temperature properties, grain size and properties of the Heat Affected Zone (HAZ) above the ball[2]. With larger diameter balls from earlier technology nodes (>70µm pitch), intermetallic reliability was not a significant problem. As long as mechanical bond strength (pull test, shear strength, cratering) was maintained, bond quality could be assured.

Ultra-fine pitch ball bonds present a new challenge. Bonds with high-strength mechanical properties in the "As Bonded" state cannot, necessarily, be shown to maintain that reliability through HTS, which have resulted in field failures. New, high-reliability alloy compositions have been developed with slightly increased dopant levels (99.9 % Au). These compositions retard the degradation of intermetallic compound phases, without a loss in electrical conductivity.

Capillaries

Capillary geometry has a significant effect on load distribution (stress) during bonding. Stress distribution and ultrasonic transmission significantly effect bond quality and reliability. Ideally, bonds should be uniform and cover >80% of the cross section. Etching "As Bonded" devices with 30% KOH for 20 -30 minutes will release bonds from the die and allow inspection of the weld surface for uniformity and coverage. Numerical measurement of coverage is difficult to calculate repeatably and, also, requires SEM techniques.

Capillary design has been shown to have a significant effect on uniform intermetallic coverage in some applications. Geometry of the inner chamfer angle effects the vertical component of stress applied during bonding. Lower stress is advantageous when bonding on sensitive, low-K structures because they have a strong tendency to fracture.

Bonding Process

Improvements in controlling the bonding process have enabled tighter, more uniform application of process variables. Ultrasonic energy and bond force are the two most significant process parameters. New control algorithms enable significantly better control of contact sensing between the ball and the bond pad. Initial impact provides approximately 85% of the total de-formation required for a "good" ball bond, with ultrasonic energy providing the additional 15%. Good process optimization and reliability requires controlling deformation of the ball and underlying pad structures.

Conclusions

The 10 described DOEs enabled the development of a high-reliability process that met acceptance and accelerated testing requirements. High reliability 3N's wire, developed for long-term reliability of the intermetallic weld, was required to achieve the best results. Optimized selection of capillary geometry, to achieve uniform, high-coverage intermetallic formation was also required. With the optimum capillary and wire, a large process window was achieved. A large process window is a sign of a stable, robust process, which is a required for a successful manufacturing environment.

In difficult, ultra-fine pitch packaging applications with delicate CUP devices, optimizing the wire bonding process and developing high reliability ultra-fine pitch production processes are challenges. Joint programs, with cooperation between contract assemblers, materials and equipment suppliers, enable the fastest, most efficient solution to difficult packaging applications. New wire and capillaries developed specifically for high reliability, ultra-fine pitch applications, are essential elements in the solution. Newest generation wire bonders, with better control and contact sensing algorithms, enable more uniform, repeatable bonding. Control and understanding of the process requirements, along with the use of good statistical DOE techniques, provide the tools to achieve this solution.

Acknowledgements

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