Reliability Ground Rules Change at <50 µm Pitch

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Abstract

Qualification of a new 40µm pitch wire bonding process requires significant process improvements and evaluations demonstrating process capability and reliability. Recent changes in the morphology of the ball bond, required to achieve high yield manufacturing with the largest diameter wire possible at this pitch, have changed the failure mode for high quality bonds. With newly developed high-strength bonding wire long-term aging is a critical task. Choice of failure criteria and test requirements are critical to success. These must assure long-term reliability and must also reflect reality. Ultra-fine pitch bonding on probed bond pads can significantly effect process yields and intermetallic formation. Device designs that separate probe and wire bond placement within a rectangular bond pad are preferred.

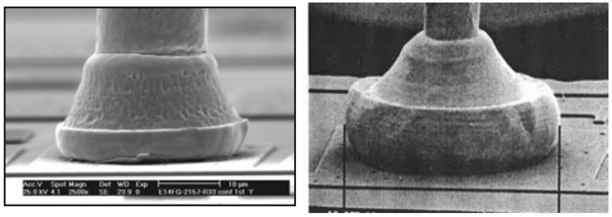
Introduction

The semiconductor industry's growth, as defined by Moore's Law, continues to drive us toward finer lines and higher I/O. In assembly, this requires wire bonding on increasingly finer pitch devices. Currently, 50µm pitch wire bonding is in full scale production and 40µm bonding is in the late stages of qualification for the 130nm technology node. To achieve process capability at this pitch, significant system improvements are required by wire bonding equipment. Enhancements to placement accuracy, ball size and shape control, tools as well as bonding parameters are all needed. The Kulicke & Soffa Maxum™ bonder has these capabilities. All bonding described within this paper was performed on this machine.

Wire diameter of 18µm (0.7mil) is recommended for 40µm bonding. Handling this wire diameter requires a significant learning curve when compared to 25 µm wire, which is currently the norm of most factories. The 7µm diameter difference reduces the strength by 51% and stiffness by 76%. Strength and stiffness are two critical mechanical properties that define a wire's behavior during assembly and molding.

Typically, a bond pad opening of 35µm is required for a 40µm process. Bonding at this scale requires production of a 32µm diameter ball. The ball diameter, viewed from above with an optical microscope, is actually a radiused edge resulting from the deformation of the spherical ball. This radius allows use of a 32µm ball diameter, without interference from the passivation edge.

Figure 1. Standard and Contained Ball Shapes



Contained Standard

Note Difference in wire diameter to ball diameter aspect ratio

To achieve the high shear strength (83.5MPa (5.5g/mil^2) is a typical minimum average) required for a ball bonding process, standard capillaries deform a significant portion of the ball volume under the face of the capillary. During the deformation under the capillary face, significant ball control is lost. Different regions of the thin section under the capillary face deform preferentially, depending on grain orientation. Grain orientation is randomized by the casting process during ball formation. This random deformation is difficult to control. New Contained Inner Chamfer (CIC) capillaries from Kulicke & Soffa capture a significantly larger portion of the ball volume within the capillary chamfer. This capability provides for better diameter control and higher strength, while enabling the use of a larger wire diameter than would otherwise be usable to produce the same ball diameter with a standard capillary design. Very little deformation occurs under the CIC capillary face. Deformation is controlled within the capillary chamfer. It is only through the CIC design that an 18µm diameter wire could be used for producing a 32µm ball bond with high strength. The CIC capillaries are an essential element of ultra fine pitch development.

The morphology of a ball bonded with a CIC capillary is significantly different than that of a standard ball bond. The shape and ratio of the wire diameter to ball bond diameter are different. In addition, the wire diameter to ball diameter ratio is significantly larger with a CIC capillary. A larger diameter wire is beneficial to the wire bonding process as it is stronger and stiffer, enabling better process capability through subsequent operations (molding). Figure 1 shows a comparison of the two ball bond shapes.

Ball shape changes for improved control and strength

For standard wire bonding processes, the dominant destructive failure location during wire bond pull testing is within the Heat Affected Zone(HAZ), the wire segment above the ball. The HAZ undergoes a rapid heating and cooling during the firing of the Electronic Flame-Off(EFO) that melts the wire tip and forms a new ball for subsequent bonding. The HAZ is heated to a temperature just below the melting temperature of the gold wire. While it doesn't melt, it does fully recrystallize. Fully recrystallized grain structures are weaker than the bulk wire. Therefore, the HAZ is the weakest segment of the wire. Changes to the wire alloy chemistry can minimize the length of the HAZ, but can't eliminate it. Now, with CIC type capillaries the diameter is larger and the HAZ may not be the weakest segment of the interconnection.

The increased wire diameter provided by CIC capillaries combined with stronger wire alloys have increased the pull strength to a range where the strongest wires in the population exceed the tensile strength of Al. In any mechanical system subject to destructive testing, the weakest link will always be the one that fails. When the wire diameter to ball diameter ratio was typical of the standard process (photo in Figure 2), ball lifts were an unacceptable failure mode. With bonding morphology radically changed, as shown in the Current Process photo of Figure 2, high strength pull tests with fracture in the Al bond pad must be accepted and standards for acceptance must be changed.

Figure 2 Critical Strength for As Bonded Lifts

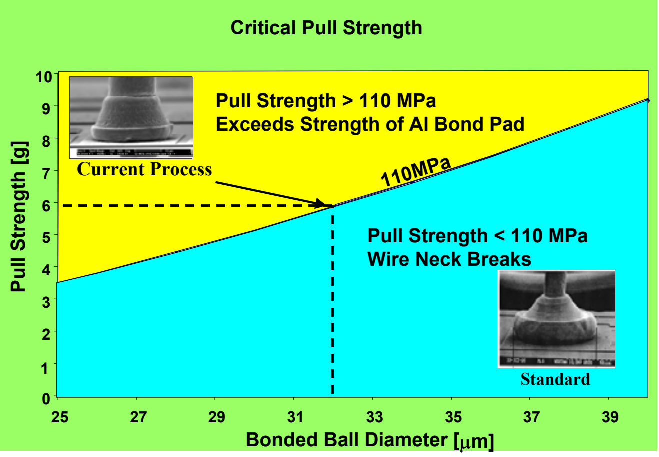
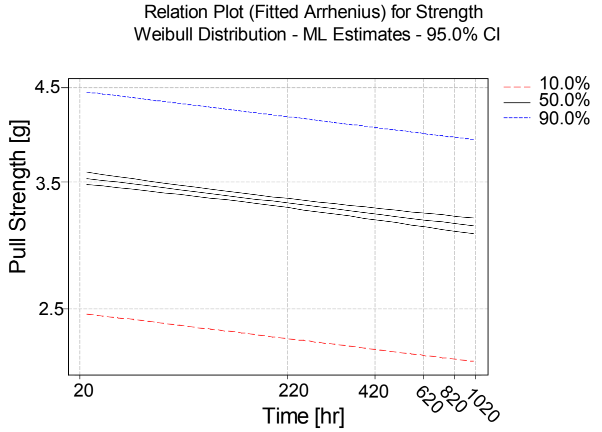


Figure 2 models the stress on the ball bond interface during the pull test. The model takes into account the radius of the ball edge and assumes an intermetallic coverage of 80%. For current 40μm processes using 18μm wire, the strongest balls in the population will have pull strengths in the 5-6g range. Fracture of the Al bond pad may occur during initial testing. These are good bonds and are not a reliability risk.

Pull testing of ultra-fine diameter ball bonds should be performed with the pull test hook located so that the wire above the ball is pulled vertically. When testing the strength of second bonds, a separate test should be conducted locating the hook as close as possible to second bond. Shifting the pull test hook location either close to the ball bond or close to second bond focuses the force (geometry defines the resolution of forces) on the bond of interest so that its' properties can be optimized.

Intermetallics and High Temperature Storage (HTS) testing

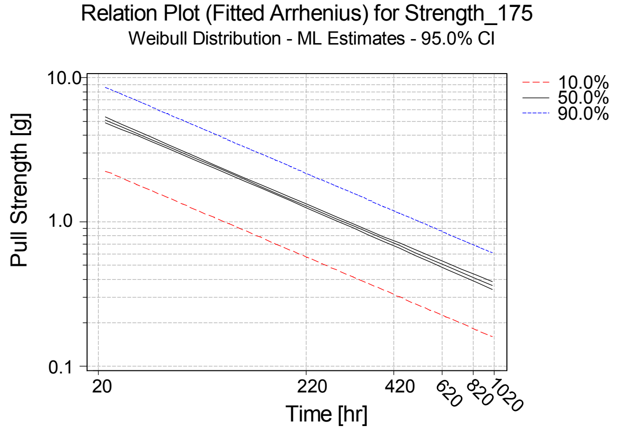
Figure 3. Weibull Plot of Pull Strength Aging @ 150^0C



The bonding of gold ball bonds to Al bond pads is characterized by the formation of an intermetallic weld nugget, typical of other welding processes. Studies of the physical properties of the intermetallic phases have been performed[1,2,3]. However, as the diameter of the ball decreases, there are reliability concerns that must be monitored and understood.

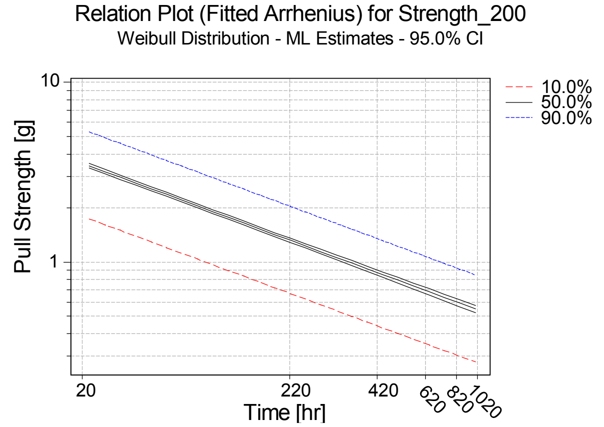
Figures 3, 4, 5 are Weibull plots of pull strength for 32μm ball bonds HTS at 150,175, 200^0C for up to 1000 hours.

Figure 4. Weibull Plot of Pull Strength Aging @ 175^0C



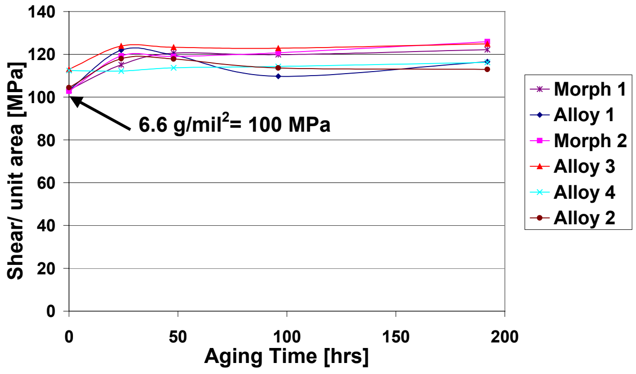
HTS testing is the normal accelerated test method for evaluating the intermetallic weld. During HTS, the intermetallic grows, consuming all of the Al bond pad. Historically, bonds have been pull tested and shear tested after HTS to determine their strength and to gauge their

Figure 5. Weibull Plot of Pull Strength Aging @ 200^0C



reliability. High quality ball bonds have been shown previously to increase in shear strength during HTS[4,5]. Other tests have shown that the pull strength of high quality bonds will degrade over time in HTS. Previously, it was common to use a criterion such as "50% of the original average pull strength" as a failure definition[6]. The JEDEC standard bake test criteria requires aging for 1000 hr at 150^0C, but does not specify any pull testing requirements. The JEDEC standard specifies open/short testing of molded devices as a failure criteria. With recent increases in normal device operating temperatures, there has been an effort to further accelerate this test. Testing unencapsulated devices for 192 hours at 175^0C followed by a destructive pull test has become a defacto standard. Weibull plots of pull strength at 175^0C and 200^0C exhibit a different, steeper slope than at 150^0C. This signifies a difference in activation energy normally associated with different failure mechanisms.

Figure 6. Effect of Aging @175^0C on Shear/U.A



Choice of Failure Criteria

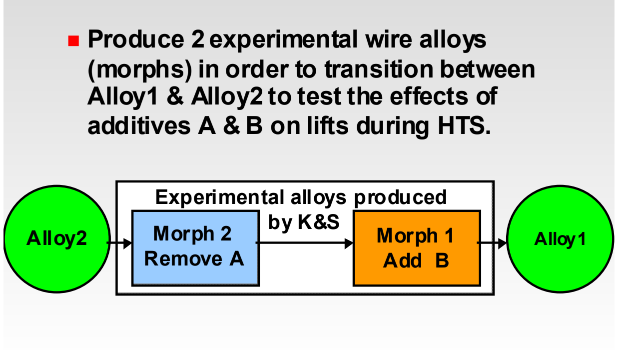
The wire bond pull test requires a determination of failure mode after each wire is pull tested. Ultra-fine pitch ball lifts cannot adequately be observed with the 40X microscope mounted on pull test equipment. That microscope is adequate for aligning the hook and conducting the test, but not for final inspection. Inspection with good optics at 400X is required. Because the wire diameter/ball diameter ratio is high (approaching 1), it is not unusual to observe many ball lifts with high pull strength values. We tested and defined a number of failure criteria in our experiments including shear strength, lifts observed at 400X and the number of wire bonds within the sample (N=100) with pull strength < threshold. For our threshold values, we used both a level of 2.0g and 1.2g. Two grams was used as a threshold for 52μm pitch bonding with 0.9 mil wire. Scaling the 2.0g level with 0.9 mil wire for 0.7 mil wire resulted in the 1.2g threshold. We tested both.

Using these criteria, we concluded that:

1. Shear strength does not show that there is a problem. Figure 6 is a plot of shear stress for wire bonds aged at 175^0C for up to 192 hours. Both shear force and stress (force/ball cross sectional area) increase 10-20% during aging.
2. Visual inspection at 400X fails to account for high strength lifts that we believe are good bonds.

Setting a minimum threshold level is a reasonable method, but could be considered arbitrary. We have not yet established a relationship between a minimum strength level and any functional specification (i.e. electrical continuity). Further work is required. A comparison of strength with other materials provides a benchmark, but is not a satisfactory criteria.

Figure 7: Alloy Morphing DOE



- Produce 2 experimental wire alloys (morphs) in order to transition between Alloy1 & Alloy2 to test the effects of additives A & B on lifts during HTS.

Alloy2 → Experimental alloys produced by K&S: Morph 2 Remove A → Morph 1 Add B → Alloy1

The effect of Wire Alloy Chemistry on HTS

In our work, we encountered a device that was reporting lifts after aging at 175^0C for 192 hr. Field reports showed that two wires (Alloy 1 & Alloy 2) had very different long-term aging responses, with alloy 2 having significantly more lifts (visual inspection @ 400X). Both alloys are commercially available and have many successful applications. To test the effects of alloy chemistry on the lift response, two "Morph" alloys were produced. The Morph Alloys provided a two-step transition between Alloy 2 and Alloy 1. Figure 7 describes the changes in chemistry "Morphing" between Alloy 2 and Alloy 1. Two additional alloys were included in this experiment.

The bonding process was optimized using screening experiments to provide a 42μm diameter ball with shear strength between 91-105 MPa (6-7g/mil^2). Bonded devices were then aged at 175^0C for 0 (unaged baseline), 24, 48, 96, 192 hours. The experiment was randomized and blocked for increased statistical confidence.

Figure 8 is a rank sum analysis of pull tests that failed visually by "lift" at 400X. This analysis ranks the alloys at each time period and scores them from best (1) to worst (6). The scores are summarized across the aging time intervals to provide an overall rank sum score. Figure 8 shows the rank sum for the six alloys along with the additive trends.

From this experiment, we have concluded that for ultra-fine pitch ball bonds, alloy chemistry has an effect on long-term aging properties. Specific applications require qualification to meet quality assurance standards. Long-term aging should be a part of this process. Specific acceleration factors (temperature, time, atmosphere) must be carefully chosen to induce failures analogous to the service conditions they attempt to accelerate.

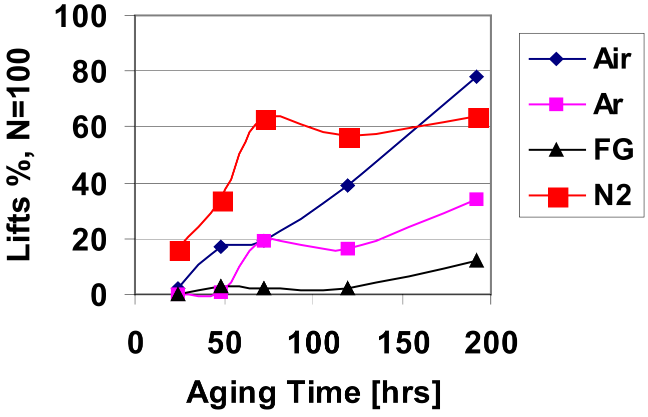
Figure 8. Experiment Results

Additives vs Rank Sum Lifts				
Alloy	A	B	Lifts/Cell	Rank Sum Lifts
Morph 1	↓	↑	1.34	1
Alloy 1			1.48	2
Morph 2			2.00	3
Alloy 3			2.47	4
Alloy 4			8.22	5
Alloy 2			11.93	6

The effect of Aging Atmosphere on HTS

Additional DOEs were run to look at the effects of aging under alternate environmental conditions (Nitrogen(N2), Air, Argon (Ar), Vacuum, Forming Gas (FG) (95% N2, 5%H2)). From these experiments, we concluded that atmosphere did have a statistically significant effect on aging behavior. Forming gas (reducing atmosphere) and vacuum aging, significantly reduced lifts. Figure 9 shows the effects of aging atmosphere on the % Lifts (N=100) aging at 175^0C.

Figure 9. Effect of Aging Atmosphere on Lifts @400X



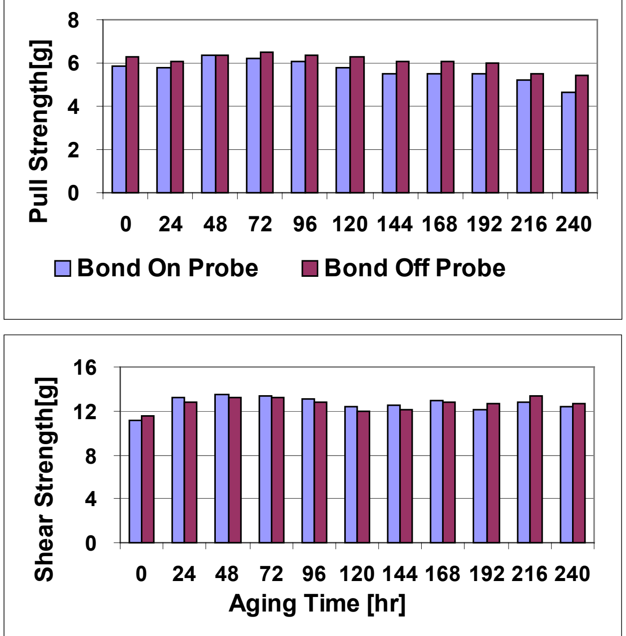
The Effect of Probe Marks on Ball Bond Reliability

The actions of cantilever probe pins often have significant effects on wire bonding reliability and yield. As the pin swipes across the bond pad to make electrical contact, it plows the surface, digging a trench and leaving debris on the trench sides and at its end. In ultra-fine pitch bonding the effects are even more significant because the high pin counts (700-1000 wires/device) associated with these devices make even low defect rates/wire become very large defect rates/device. Bonding on the debris field left after probing can often result in a defective bond. Figure 10 shows the results of pull testing and shear testing 42μm diameter ball bonds with the bonds intentionally located to either align with the probe mark or miss the probe mark entirely. Bonding off the probe mark resulted in slightly higher pull strength. The effect on shear strength was insignificant. This confirms previous testing demonstrating minor effects on the strength levels, but a higher incidence of defective bonds. Our conclusion is that if the bond is successfully made, probe marks have little effect on the strength. But there is a higher incidence of bonds that are not formed at all and therefore a higher defect rate when bonding on probe. Often operators increase bond parameters trying to eliminate these defects and this, in turn, causes additional problems because the process is no longer at its optimum. In addition, the growth of the intermetallic weld may be effected by bonding on probe. Diffusion reactions are significantly effected by the concentration of both Au and Al. The probe trench is a region where the concentration of Al is seriously depleted and the debris around the probe is a region of excess Al. This can seriously effect the growth and distribution of intermetallic phases.

Design Rule Modifications to Accommodate Probing

For ultra fine pitch bonding, a design modification has been offered that enables both probing and bonding without probe interference. Rectangular bond pads have long been used for the ultrasonic wedge bonding process. Although they consume valuable real estate on the chip, they have a large benefit in higher yields. By probing at one end of the pad and bonding at the other, interference is eliminated and yield is improved. New bonder features allow easy programming of

Figure 10. Bond On/Off Probe Mark



the placement offset required to accomplish this task.

Conclusions

Successfully implementing a high-yield, reliable ultra-fine pitch wire bonding process requires a significant engineering effort. Detailed evaluations and analysis of the process, materials and tools issues are required. Successful implementation is made easier by good engineering choices for the equipment, materials and tool sets. If they provide excellent process capability, the task becomes manageable.

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