Guidelines for Improving Intermetallic Reliability

Lee Levine, Sr. MTS, Advanced Packaging
Phone 215-784-6036, Fax 215-659-7588, llevine@kns.com
Matt Osborne, Ph.D. MTS
Phone 215-784-6444, Fax 215-659-7588, mgosborne@kns.com
Frank Keller, Manager Advanced Packaging
Phone 215-784-6350, Fax 215-659-7588, fkeller@kns.com
Kulicke & Soffa Ind. Inc.
2101 Blair Mill Road,
Willow Grove, PA 19090

Abstract

As wire bonding continues to advance, new challenges are resolved. In ultra-fine pitch bonding (<50µm pitch), efforts to maximize wire diameter have resulted in specialized Contained Inner Chamfer (CIC) capillaries, that reduce friction between the wire and feed hole, allowing the use of larger diameter wire without feed and interference problems. New wires have been developed that provide significantly improved intermetallic reliability after thermal aging of small diameter ball bonds. Bonders with improved Z-axis control provide greater control of impact forces for improved intermetallic formation and coverage.

Introduction

As wire bonding technology moves to ever-finer pitch, ball bond size and shape continue to change. Smaller balls and, subsequently, finer wires are required for fine pitch. Smaller diameter wire has inherent mechanical and electrical limitations; it is weaker, less stiff and has lower conductance than larger diameter wire. While package design and process optimization have minimized the ball diameter for I/O density, they have, simultaneously, maximized the wire diameter for mechanical robustness. While greater mechanical robustness improves the process, it also, introduces new failure modes during testing.

Specialized CIC capillaries, which reduce friction between the wire and the feedhole, allow the use of larger diameter wire without feed and interference problems. They also capture the ball within the chamfer portion of the capillary and produce a higher strength bond with a wire diameter greater than would otherwise be possible for the same ball diameter. As a result, larger diameter wire can now be used, benefiting both fine pitch and mechanical robustness.

Bond parameters also play an important role in improving long-term reliability. Optimization of bond parameters by use of DOEs should always be done. In ultra-fine pitch bonding, it is even more important to achieve higher strength levels than previously required for larger diameter ball bonds. Better machine controls and programmable parameters are now available for achieving higher strength bonds without increasing cross-section diameter. Higher ultrasonic frequency transducers have the capability to achieve high strength with less deformation and smaller diameters than lower frequency transducers[1]. The higher frequency increases the strain rate during deformation, transmitting energy across the soft ball to the bond interface more efficiently.

The welding of gold ball bonds to aluminum bond pads is characterized by the formation of an intermetallic weld nugget composed of gold, aluminum and trace elements found in the wire and the bond pad. During the bond life, this intermetallic develops, thickens, and eventually fails by the formation of Kirkendall voids. Choice of dopants for the wire bond alloy can play a significant role in minimizing the Kirkendall voids and provide for a more reliable bond. New wire alloys are now available with improved reliability for ultra-fine pitch bonding.

Bond pad composition and thickness also play an important role in long-term reliability. Starving the system for aluminum and maintaining low temperatures were the traditional methods for avoiding Kirkendall voiding. With the advent of ultra-fine pitch ball bonding and device operating temperatures higher than ever, this is not always possible. The use of diffusion barriers[2,3], with only a very thin aluminum cap layer, has been described in the literature as a method for achieving reliable 1000 hr aging at 200^{0}C. Improved bond pad metallurgy for long-term reliability is recommended.

Upper and Lower Bounds for Bond Strength

The transition to ultra-fine pitch bonding has been accomplished, in part, by a change in the shape and aspect ratio of ball bonds[4]. As pitch decreases, the wire diameter required to produce a ball must also decrease. The reduction in wire diameter is accompanied by reduced strength, stiffness and conductance. Larger diameter wire is more robust and easier to handle in a production environment. To minimize the reduction in wire diameter, new CIC capillary designs that contain a larger portion of the free air ball within the chamfer of the capillary have been incorporated in the wire bonding process. These designs maximize the wire diameter feasible for the desired ball diameter/pitch. They also provide an increased aspect ratio between the wire diameter and the bonded ball cross-section. Figure 1 shows conventional standard pitch and ultra-fine pitch CIC bonds, illustrating the shift in aspect ratio that has accompanied the transition to ultra-fine pitch bonding.

For standard pitch processes, the ratio of the bonded ball cross-sectional area to the wire cross-section is often as large as six. When area ratios are large, it is unacceptable for wire bonds to fail pull-testing by lifting. Now, with ultra-fine pitch bonding, the cross-sectional areas are comparable. During pull testing, high–strength lifts, with failures in the aluminum bond pad metallization, can occur. Figure 1 defines high-strength lifts in as-bonded devices meeting a minimum strength criterion of 110 MPa (the strength of aluminum). Commonly,

0-7803-8582-9/04/$20.00 c2004 IEEE

ball diameter is measured optically from above the ball. Therefore, the cross-section for calculation of stress in Figure 1 is adjusted for the edge radius of curvature and, also, assumes an 80% intermetallic coverage. These bonds are the strongest bonds (Upper Bound) in the population and do not represent a reliability risk.

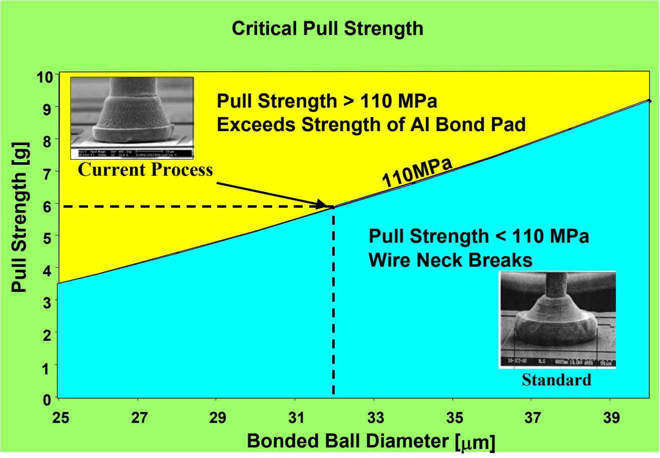

Figure 1.: Critical Strength for As Bonded Lifts

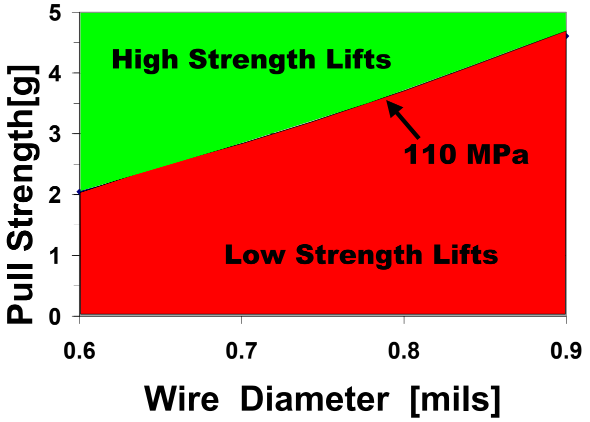

Figure 2.: High Strength lift Criteria After Thermal Age

After thermal aging, wire bonds decrease in pull strength and can also begin to fail by a lift mode. Failures occur near the top of the intermetallic layer and are often accompanied by the presence of voids. Geometry plays a significant role in the occurrence of the failure; larger balls fail by lift less often than smaller balls. Figure 2 proposes a criterion for a lower bound definition of high-strength/low-strength lifts after aging. It again uses a cutoff of 110 MPa to distinguish between high and low-strength bonds. In this case, the wire cross-sectional area is used for the stress calculation.

Bond Parameters

Accelerated aging tests (specifically 192 hrs at 175^0C) have become the normal acceptance criteria for predicting long-term reliability. However, industry standard post-bond tests, the pull test and shear test, are no longer sufficient metrics to predict long-term reliability. Other post-bond responses, such as intermetallic coverage and uniformity must also be used.

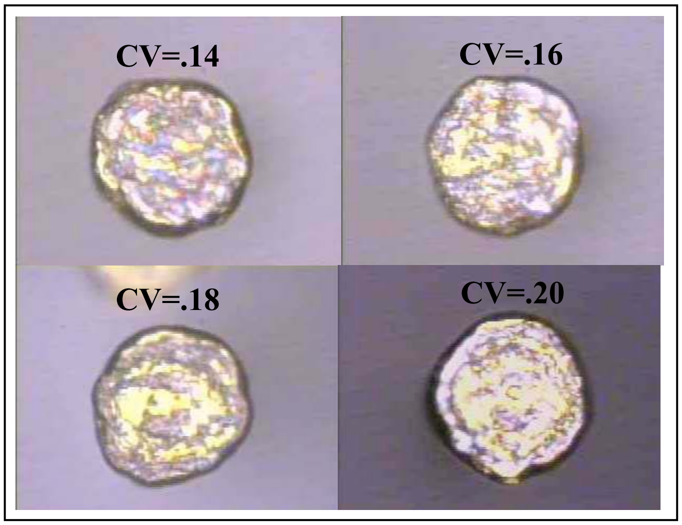

Figure 3.: The Effect of Impact on Intermetallic Formation

Figure 3 shows the effect of impact force on the quality and uniformity of intermetallic coverage in 45μm diameter ball bonds. At higher impact force (proportional to Constant Velocity (CV) at impact), the intermetallic formation is not uniform and has less coverage, even though the shear strength is approximately the same. During initial qualification, it is very important to inspect the quality and uniformity of the intermetallic. A simple potassium hydroxide etch is recommended to release the balls and allow for inspection of the bond interface. Optical inspection of the intermetallic provides a reasonable comparison, but cannot provide an accurate measurement of intermetallic coverage. Lighting and contrast cause too much variation for acceptable gage capability. Measurement of intermetallic coverage, as a percentage of the cross-section, requires use of SEM with EDS. Even then, the measurement is difficult because of edge effects.

Wire

Previous works[5] have demonstrated that proper choice of dopants has a significant effect on the quality and reliability of the intermetallic weld. With proper dopant chemistry, well-bonded, ultra-fine pitch wire bonds can withstand more than 192 hrs aging at 175^0C without degradation of the intermetallic. Through significant work, wire alloys have been developed that can both withstand thermal aging and have the high-strength, high-stiffness characteristics required for a robust ultra-fine pitch bonding process with less than 25μm (1 mil) wire. Figure 4 shows the thermal aging behavior of a 15μm wire diameter, (28μm ball diameter for a 35μm process) high-reliability wire. Bond pull strength is well above the 110 MPa level with all of the bonds failing as neck breaks, the preferred breaking mode. Figure 5 shows metallographic cross-sections for the same alloy after aging as much as 500hrs (bonded ball diameter 40μm). Intermetallic growth is smooth and uniform, void-formation is minimal, typical of high-reliability bonds.

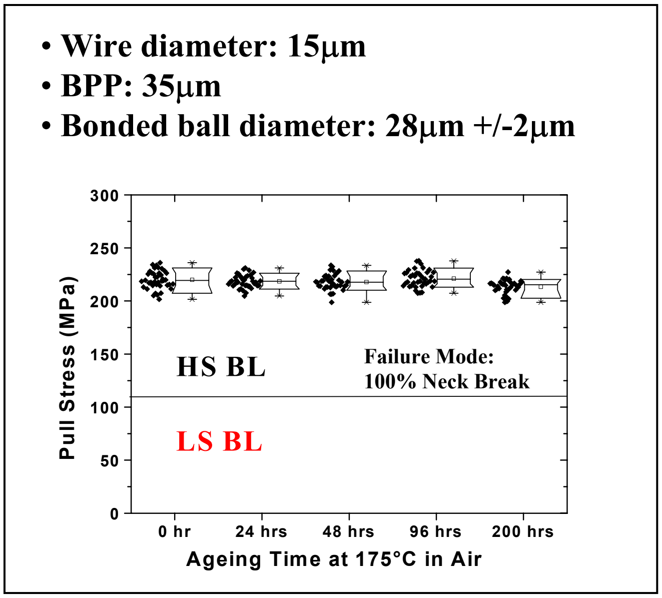

Figure 4.: Reliability for Ultra-Fine Pitch

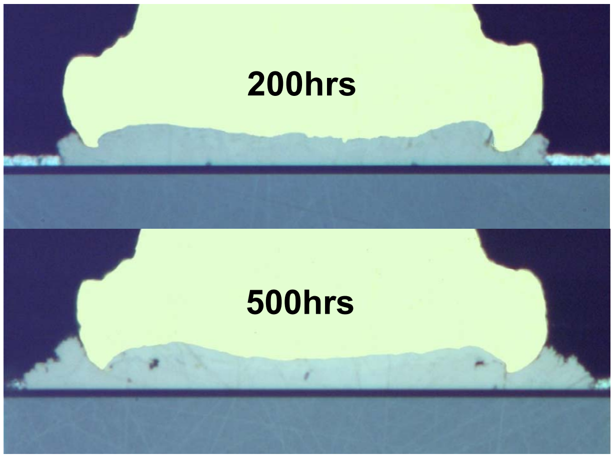

Figure 5.: Cross-Sections of Ultra-Fine Pitch Ball Bonds Thermally Aged at 175^{0}C

Recommendations

Figure 6 is a summary of recommendations. The use of DOE techniques for wire bonding optimization, especially with fine and ultra-fine pitch processes, is always essential. Maximizing wire diameter through the use of a constrained capillary design provides improved intermetallic coverage and a more robust process. The use of DOEs to optimize the intermetallic coverage and assure that it is uniform is an important part of the qualification process. Optimization of the shear strength, while still maintaining uniform coverage, is also important. The wire bond pull test is dependent on resolution of forces: pull testing, with the hook directly above the edge of the ball, focuses the forces on the ball bond and provides best gage capability. Bonding on probe marks has a minor effect on pull strength when bonding occurs, but a significant effect on bond defects that can significantly decrease yield. In ultra-fine pitch processes with very high I/O, this effect on yield can be unacceptable. Rectangular bond pads, with separate regions targeted for probe and wire bonding, can resolve the yield problems.

Figure 6 Recommendations

- Optimize intermetallic coverage and uniformity.
- CIC Capillaries improve intermetallic coverage
- Use a qualified high-reliability wire alloy
- Optimize shear strength by DOE
- Pull Test above the ball
- Bond off probe mark

Figure 6.: Recommendations

Conclusions

Wire bonding continues to advance, providing high-reliability fine-pitch interconnects. The process continues to change and adapt, providing needed solutions to new packaging requirements. Advanced wire bonders are now in high-volume production at 45µm pitch and are in development at 35µm pitch. New tools and materials, designed to provide robust, high-reliability intermetallic bonds, have been developed to meet these challenges.

Acknowledgments

Thanks to Chris Breach and Frank Wulff from K&S Bonding Wire for intermetallic cross-sectioning and work on AW-66X.

References

1. L. Levine, “The Ultrasonic Wedge Bonding Mechanism: Two Theories Converge” ISHM 1995 pg 242-246
2. H. Ueno, “Reliable Au Wire Bonding to Al/Ti/Al Pad” *Jpn J. Appl. Phys, vol 32, pt1, no.5A, 1993*, pg 2157-2161
3. C. Passagrilli, “Au Wire Bonding in Plastic Packages: Reliability Improvements for High Temperature (200C) and High Current Applications” *Advancing Microelectronics*, March/April 2003, pg25-27
4. L. Levine, J. Brunner, S. Haggenmüller “Guidelines for Quality Must Change”, EPP Europe, Jan/Feb 2003, pg 50-52
5. Inderjit Singh, Lee Levine, Jon Brunner, “Reliability Ground Rules Change at <50µm Pitch”, Proceedings Semicon West, July 2003