Improving Intermetallic Reliability in Ultra-Fine Pitch Wire Bonding

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Abstract:

Today's ultra-fine pitch wire bonded devices operate at hotter temperatures and demand higher reliability. Standard accelerated test methods, such as the JEDEC High Temperature Storage Life test (HTS) (JESD-22A-103B) require 1000 hours with electrical testing of molded devices as the acceptance criteria. New shorter tests (192 hours at 175°C) with pull test failure mode of unmolded devices as their acceptance criteria are now common. The new tests may not accurately predict long-term electrical performance.

Introduction

As innovation in the semiconductor industry continues to progress, IC device features shrink in size according to the roadmap specified by the ITRS. Smaller features, higher density, and increased I/Os demand finer pitch wire bond interconnects. Currently, leading-edge volume production is taking two design approaches: in-line and multi-tiered. In-line peripheral bond pad designs are currently at 40µm pitch, with 35µm in development. Multi-tiered wire bonds over active circuitry (4 rows of 60µm pitch, staggered bond pads around the die periphery) are in final stages of qualification. This wire bond design provides an effective 15µm pitch, yet uses a larger wire diameter (25µm) than an equivalent in-line single row design (17µm). Larger wire diameter improves electrical performance and provides higher strength and stiffness as well as better molding yields. In-line, single row bond pads require the smallest ball bonds and finest wire diameter.

The Intermetallic Weld

Wire bonds are welded interconnections, characterized by the formation of an intermetallic bond between the Al bond pad and the Au ball. During the IC life, the very thin intermetallic layer, formed during the initial ultrasonic welding process, grows in thickness and consumes the entire Al bond pad under the Au ball. The growth of the intermetallic layer is diffusion controlled. Diffusion reactions are principally dependent upon time, temperature, and chemical concentration of the diffusing species. Initial bond quality can play an important role, but thermal conditions during the IC life dominate the reaction.

In the Au/Al bond there is a differential rate of diffusion: Au goes into Al much faster than Al goes into Au. The result is a net buildup of vacancies at the Au-rich side of the intermetallic stack (towards the ball). The vacancies coalesce to form Kirkendall voids. At the end of their useful life, bonds increase in electrical resistance and become open, largely because of void formation.

Accelerated Testing

Today's ICs, operating at higher temperature levels than in the past, push the limits of reliability requirements. The JEDEC HTS (condition B) is an example of an accelerated test for long-term reliability. It requires aging molded devices at 150°C for 1000 hrs then electrical (open/short) testing as its acceptance criteria. For perspective, accelerated testing (defect activation energy = 0.75eV) of 1 week (168 hours) at 150°C is equivalent to over 100 years life at room temperature[1].

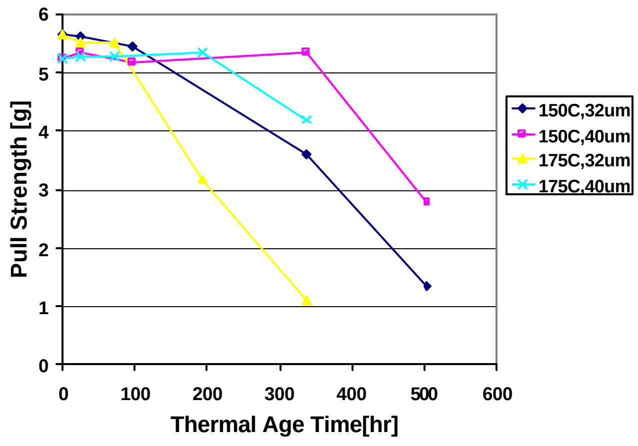
The demand for faster accelerated test methods is very strong because qualification costs are high and time-to-market demands are severe. Development of new highly accelerated tests requires significant statistical and process development for validity. New test criteria should correlate with real failures and result in similar failure modes. Imposition of non-standard test conditions should be avoided.

Aging temperature has a significant effect on the dynamics of failure reliability. Plotting strength degradation as an Arrhenius relationship reveals a change in Weibull slope that occurs between 150°C and 175°C[2]. The normal interpretation of a slope change in the Weibull plot is an underlying physical reaction, such as a phase change or transformation. Accelerated testing that produces a phase change reaction otherwise not occurring during normal life of the product has questionable validity. High temperature aging (192 hours @ 175°C) of unmolded devices, with subsequent pull testing, has recently been used to characterize bond quality and predict how bonds will behave in the long term. Recently two separate researchers have reported that by adding a thin metallic barrier layer, either on top of the bond pad or near the top surface, they were able to achieve over 1000 hours aging at 200°C with acceptable electrical test results[3,4]. Solutions that effect the intermetallic by changing the bond pad surface chemistry will be more robust.

Experiments- Size and Temperature Effects

Ball bond morphology has changed significantly in the past few years, driven by the continuing trend towards finer pitch and denser packaging[5]. Previously, the ball bond was large, often 75-90µm in diameter with wire diameter at 25-30µm (aspect ratio 3). Current leading-edge 40µm pitch packages have a ball diameter of 31µm, with a wire diameter of 17µm (aspect ratio 1.8). The decrease in the aspect ratio of ball/wire has led to changes in the failure mode of good, high-quality ball bonds when they are destructively pull tested. Previously, a ball lift was an unacceptable failure mode, even if the pull strength was at an acceptable level. Now, we see fractures within the Al bond pad metallization at pull strength levels that correspond to the full tensile strength of Al. In a mechanical structure, the weakest link will always be the one to fail. Under these circumstances, high strength pull tests that fracture within the Al bond pad at strength levels corresponding to the tensile strength of Al (110 MPa) should be acceptable. They represent the best portion of the population and should not be downgraded for their higher quality. Acceptance criteria need to be modified to reflect this condition.

Figure 1 Effect of Ball Size on Pull Strength [g]



Size also has an effect on the results of thermal aging tests and other accelerated test methods. Figure 1 and 2 show the results of an experiment where bonds of two diameters, 32µm and 40µm, were produced on the same device. Parameters were adjusted to produce equivalent initial shear strength/area for the two sizes. Samples were aged at two temperatures, 150°C and 175°C. It can be seen from the graphs that both temperature and ball size have significant effects on the results. The difference between 150°C and 175°C has a large effect on both pull strength and the incidence of failure by ball lifts in the pull test. The smaller bonded ball has a much higher incidence of lift failure than the larger bonded ball. As the ratio of bonded ball/wire cross section decreases, the incidence of lifted ball failures during pull test increases. New wires, developed for long loops and better molding with stronger Heat Affected Zones (HAZ) above the ball, often increase the ball lift failure mode.

Figure 2. Effect of Ball Size on Lifts %

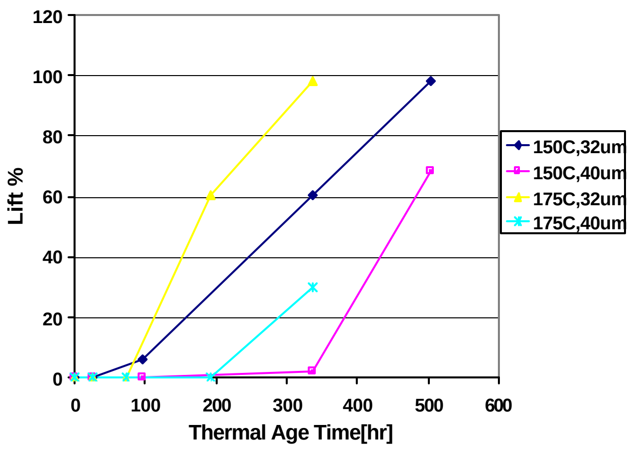
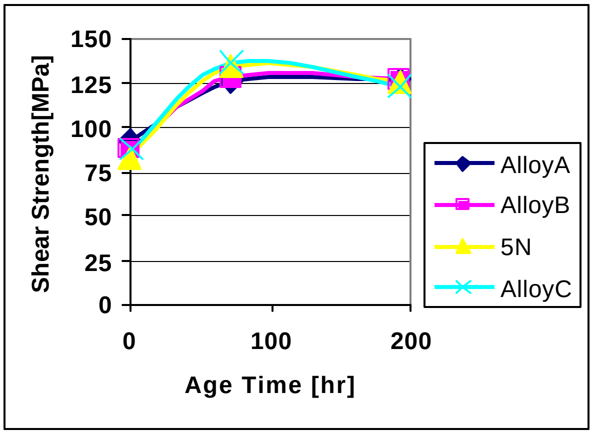


Figure 3 shows the results of shear testing after accelerated aging at 175°C. High-strength bonds normally increase in shear strength as they age[6]. They do not exhibit the same strength degradation that occurs in the pull test. Previously shear strength has been the definitive test for bond quality, pull strength did not reflect the true strength of the bond and was limited by the strength of the wire cross-section. Now we see pull strength failure mode as the crucial pass/fail parameter, even though shear strength is at a high level. The validity of the pull test in ultra-fine pitch wire bonding has been questioned[7].

Figure 3. Effect of Thermal Age @175^{0}C on Shear Strength [MPa]



Experiments- SEM and Metallography

As the intermetallic grows, it eventually consumes the entire aluminum bond pad under the ball. After the Al is consumed Au continues to diffuse outward into the bond pad, forming a "bloom" of low-density intermetallic material outside the periphery of the bond. Most of the "bloom" material is composed of high-Al intermetallic compounds rather than the high-Au concentration compounds found directly under the ball. Figure 4 is a typical SEM photo of both the ball and intermetallic fracture interface for a lifted bond after accelerated testing at 175°C for 192 hrs. Regions of both porous, brittle fracture and ductile fracture typical of a good bond are seen. The "bloom" of low-density, high-Al intermetallic compounds can be seen around the periphery in the lower photo. The annular depression corresponds to the area directly underneath the capillary chamfer diameter.

Figure 4. SEM of Pull Test Fracture Surfaces

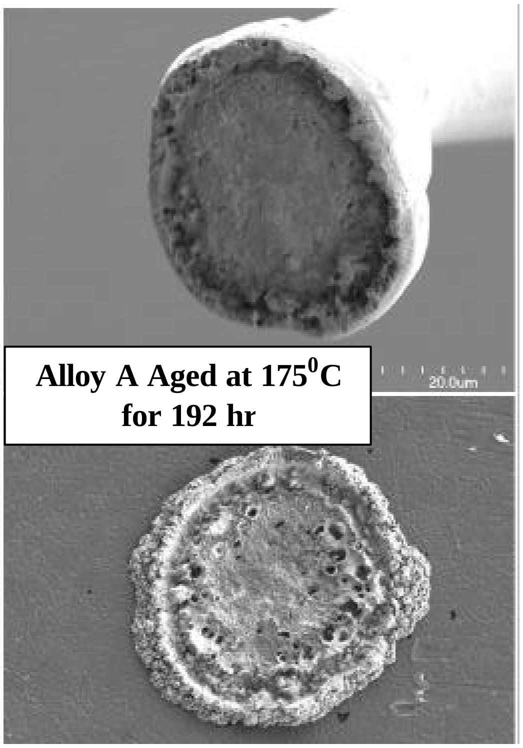


Figure 5 Alloy A Intermetallic Cross Sections By Oil Immersion @ 1000X

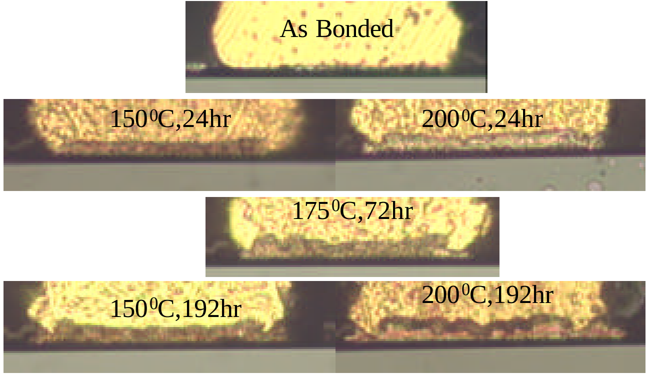


Figure 5 shows metallographic cross sections of bonds from a four-wire alloy experiment. Samples bonded with the four wires were aged at 150, 175, and 200°C for 24, 72, and 192 hours. Metallographic samples were chosen using a 2^2 + center point factorial sampling plan. Use of DOE techniques for sampling metallographic cross sections enabled us to minimize metallography while maximizing our observed results. Oil immersion microscopy was used as it provides improved color contrast and higher magnification than normal air gap lenses (the refractive index of the oil allows an increased numerical aperature of the lense). The images show the increased intermetallic thickness as temperature and time increase. In the 200°C, 192 hour sample, the second high-Au decomposition phase ($Au_5Al_2 \rightarrow Au_4Al$) is visible. It is at the interface between the 5:2/4:1 phases where Kirkendall voiding occurs.

Figure 6. Effect of Wire Alloy on Lifts and Strength

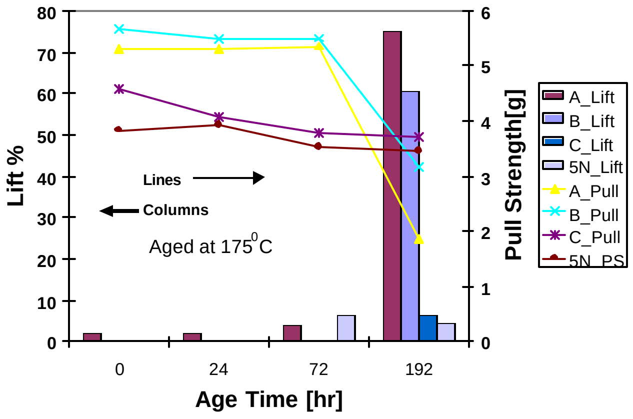


Figure 6 provides data demonstrating some of the effects of wire chemistry on accelerated aging of small diameter ball bonds. It has been demonstrated that wire chemistry, even within the 100ppm maximum total impurities required by 99.99% Au wire, can have a significant effect on bond reliability. Higher purity, 99.999% Au wire was included as a baseline in this comparison. The 5N wire had fewer lifts, because it started out with significantly lower tensile strength and had a weaker HAZ. New alloys designed for both higher strength and reliability (such as K&S Bonding Wire's AW-66) show more lifts than the 5N wire due to their stronger HAZs.

Conclusions

Assembly of ultra-fine pitch devices represents new challenges to back-end semiconductor manufacturing. All of the critical manufacturing processes must work together with front-end design functions to develop robust designs and processes that meet the exacting yield and productivity standards that the industry has established. Wire bonding will meet the required challenges. New machines and controls, such as the K&S Maxum Plus, which are capable of achieving the low impact, low stress requirements of ultra-fine pitch ball bonding, will be required for this task. High-reliability wire alloys, such as the AW-66, will produce ultra-fine pitch bonds with excellent long-term reliability. New capillary developments, such as the K&S CIC capillary, can increase the intermetallic uniformity and coverage for ultra-fine pitch bonding.

References:

[1] H. Charles, et al.,"Wirebonding: Re-inventing the Process for MCMs," Proc. 1998 International Microelectronics Symp., pp 645-655, 1998

[2] Inderjit Singh, Lee Levine, Jon Brunner, "Reliability Ground Rules Change at <50µm Pitch", Proceedings Semicon West, July 2003

[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] H. Ueno, “Reliable Au Wire Bonding to Al/Ti/Al Pad” *Jpn J. Appl. Phys, vol 32, pt1, no.5A, 1993*, pg 2157-2161

[5] L. Levine, J. Brunner, S. Haggenmüller “Guidelines for Quality Must Change”, *EPP Europe*, Jan/Feb 2003, pg 50-52

[6] K. Dittmer, et al.,”Influence of Bonding Conditions on Small Ball Bonds due to Intermetallic Phase (IP) Growth,” Proceedings HDP/MCM Denver, April 6-9, 1999, pg 403-408

[7] V. Sundararamen, D.R. Edwards, W.E. Sibido, H.R. Test, “Wire Pull on Fine Pitch Pads: An Obsolete Test for First Bond Integrity?” *Proceedings ECTC*, 2000

Biography

Lee Levine has been with Kulicke & Soffa’s, Ball Bonder Division. Willow Grove, PA for 18 years. In 1999 he received the John A. Wagnon Technical Achievement Award from the International Microelectronics and Packaging Society. He has been granted four patents and has more than 40 published works. Mr. Levine received a bachelor’s degree in metallurgy and materials science engineering from Lehigh University, Bethlehem, PA.

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Dr. Clauberg received a B.S. in chemistry from the University of Tennessee, and M.A. and Ph.D. degrees in physical chemistry from Harvard University. He has been with K&S for three years working in the areas of innovative interconnection technologies, copper passivation, improved device cleaning procedures, intermetallic reliability and low temperature wire bonding. He holds 6 patents and has published more than a dozen technical papers and presentations.

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