Use of Harsh Wire Bonding to Evaluate Various Bond Pad Structures

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Abstract

IC bond pad structures having Al metallization and SiO_2 dielectric have been traditionally designed with full plates in underlying metallization layers, connected by vias. In addition, pads having bond over active circuitry (BOAC) which are much more sensitive to pad cracks, are likely present in the same IC. Cracks in the pad dielectric weaken the bond reliability and may cause electrical leakage or shorts to circuitry under the pad. Cracks are more likely to occur during Cu wire bond due to higher bonding stress as compared to Au alloy wire bonding. Experimental data from bonding with 1mil Au or Cu wires reveals dramatic differences in pad robustness against cracking, depending upon the underlying metal structures and patterns. A "harsh" Au wire bond recipe is also developed to produce the stress effects of Cu wire bond in experiments without having to upgrade older bonding equipment for Cu wire. Cratering test after wire bond is used to evaluate pad cracking. Ball shear testing followed by a cratering test further reveals pad cracking tendencies. Design principles for increased pad robustness to cracking are developed based on the data. Reliability data verifies the effectiveness of the design principles. Proper design of interconnects beneath the pad can greatly increase pad robustness to cracking, allowing much more margin in bonding stress, enabling the option of Au or Cu wire bond on the same IC without pad cracking.

Key words: wirebond, circuit under pad, BOAC, Au wire, Cu wire, bond pad

Introduction

Gold (Au) wire bonding often has very little process margin because the pad structure is fragile. Wire bonder recipes are often intended to avoid issues with the pad structure, such as too much pad aluminum (Al) displacement, bond lifting, dielectric cracking, divots in the dielectric, and cratering of the silicon (Si). Additionally for circuit-under-pad (CUP) or bond-over-active-circuitry (BOAC) designs, deformation of Al in the interconnects below the "pad window" or subtle shifts in the semiconductor device electrical behavior should be avoided. Deformation and cracking are found together on traditional pad structures that have experienced too much stress. But deformation in the Al of CUP pads is detrimental even if there are no cracks, due to local increase in electrical resistance and degraded electromigration reliability.

Traditional pad structures are not sufficiently robust to tolerate a switch to the higher mechanical stress needed for successful copper (Cu) wirebond without significantly increasing pad Al thickness or making other processing changes that add cost or require unacceptable design or manufacturing tradeoffs. Successful Cu bonding on highly sensitive BOAC pads is a big challenge.

Bond pads we will consider have a Si substrate and 2 or more layers of Al-based metallization. Metallization includes thin titanium-nitride (TiN) barrier layers above and below the Al (actually Cu –doped Al with 0.5% Cu) conductor film. The bond pad metal is the exposed Al of the thin "metal top" (MT) layer within the pad window, where the wirebond makes contact. The pad window is surrounded by the passivation films covering the die surface. In these experiments the pad structure of interest includes all of the features enclosed by the drawn pad window, meaning everything physically within or below the pad window opening down to the Si substrate. These are the structures expected to receive highest stress during bonding on the pad Al.

The traditional bond pad structure has sheets of metal in all metal layers across the entire pad window. Tungsten (W) plug vias in the dielectric layers between the metal levels electrically connect all of the levels to the pad.

Mechanical stress from both wafer probe and wirebond can cause pad damage, with wirebond expected to exacerbate a weakness or crack already present from probing. This is a serious reliability concern, but will not be considered here; most of these experiments use unprobed pads to avoid any pre-damage. Fig.1 shows examples of cracks from harsh palladium-doped Au (AuPd with 1% Pd) wire bonding and even harsher Cu wire bonding on a traditional pad structure that does not have top vias in the pad window. "Parenthesis" shape cracks near the ball contact edge are typical, with cracks initiating perpendicular to the direction of ultrasonic vibration. A crack across the middle of the pad may also occur, often associated with concealed damage from wafer probe (not shown).

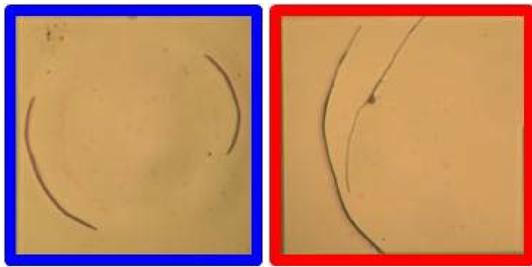

Figure 1. Pad cracks after: (left) 1 mil AuPd (1% Pd) wire ball bond, (right) 1 mil Cu wire ball bond

Experiments

This project explores the bond pad structure's robustness to cracking through the use of harsh ball bonding using Au wire, intended to simulate the higher mechanical stress which may actually occur during a Cu wirebond process. "Harsh" Au ball wirebond recipes were developed to purposely cause nearly 100% of traditional pads to crack, as observed in the usual "cratering test" (etching to remove the bond ball and pad Al, then microscope inspect for damage). Au wire diameter is 1mil, and pad dimensions are generally 75um x 75um, with pad Al thickness of 1um or less for most tests, and up to 3um for one test. A few designs were also bonded with AuPd and Cu wires to confirm that the Au wire "harsh" bonding is sufficiently similar.

Wafers were fabricated in 2-level metal up to 5-level metal processes in 4 different CMOS technologies having Al / SiO_2 interconnect. Various experimental pad structures were fabricated along with the "traditional" pads, then all were mechanically stressed by standard or harsh Au wirebond. Experimental pad structures consist of various metal layout densities within the pad window in the underlying layers, and a patterned polysilicon layer. These are to simulate circuitry under pad in all layers. Some structures include ESD protection devices beneath as well, and all can be electrically tested to detect electrical shorts from pad to underlying circuitry. For convenience in referring to the interconnect metal layers in the bond pad stack, we designate the top metal as layer "MT" or Metal-Top, layers below as Metal-Top-minus-one "MT(-1)", Metal-Top-minus-two "MT(-2)", and so forth. Some example MT(-1) patterns are shown in Fig. 2.

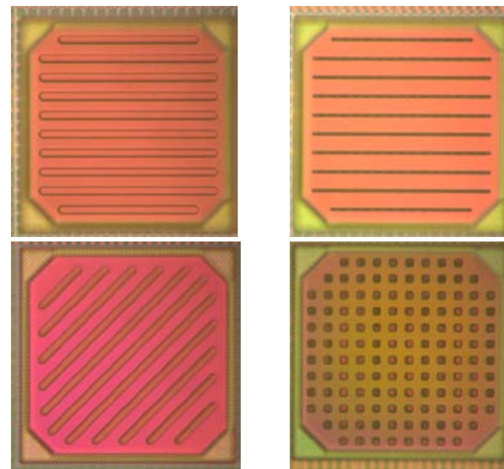

Figure 2. MT(-1) experimental designs, with slots and holes

Slots or holes were used to lower the pattern density of MT(-1), with more variety than those shown here. Other MT(-1) designs placed dummy metal fill in the pad window, or left out the MT(-1) completely in the pad window. Similar design variations in MT(-2) and MT(-3) were included as well.

A sample of at least 3 die were analyzed for each pad structure and bonding condition, each die typically having 30 to 40 pads bonded. Bonded pads were sample tested for bond pull strength and wire ball shear, and all pads were inspected after cratering etch. Additional data was obtained on smaller sample sizes by etching away the barrier to

get a clear view of damage to underlying features, or scaning electron microscope (SEM), polished cross section SEM (XSEM), or cross section by focused ion beam (FIB). TiN barrier and top dielectric films *bending* on top of a deformed underlying metal layer is detectable by a "ripple effect" seen optically in microscope inspection, having an appearance similar to ripples on a pond. Ripple effect is easily observed (but in poor detail) at low magnifications. We were able to adjust lighting and sample tilt sufficiently to observe ripple at higher magnifications on standard microscopes, though the photos don't reveal as much detail. Ripple is best observed using a differential interference contrast (DIC) microscope. Wire pull strength test (PST) and ball shear test (BST) data is gathered on smaller sample sizes.

Harsh bonding recipes for Au ball bond produced the desired results by increasing the ultrasonic power and reducing the stage temperature. The pancake shaped bond often becomes more flattened, usually with larger diameter than targeted for production. We assume that the lower pad temperature causes less of the ultrasonic energy to be absorbed at the bonding interface or dissipated across the pad Al, causing more of the energy to transfer into the top SiO_2 and into the underlying Al of MT(-1). Later in the experimentation, a second capillary style was tried, forming a more bell shaped bond that appeared to cause even more cracking in harsh recipes due to the increased downforce and ultrasonic energy coupling at the ball's outer edge. Fig. 3 shows some example Au ball shapes resulting from harsh bonding recipes.

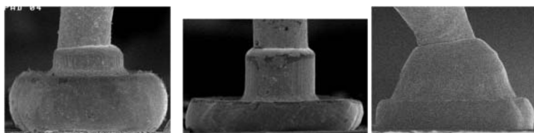

Figure 3. Example bond ball shapes in 1mil Au harsh bonding recipes, (left) tall ball, (middle) flattened ball, (right) bell-shaped ball

Results

Traditional pads are highly damaged in the harsh bonding conditions, showing strong ripple and serious cracking. Bonding stress includes the dynamic downward force of the ball combined with ultrasonic vibration, with the highest stress concentrated under the ball contact edge in our harsh recipes. Extra care had to be taken in the sample preparation and cratering etch sequence so as to not pull apart the pads by laterally stressing the wires, and not etching away all the underlying pad metal Al through the cracks causing the top SiO_2 to break off before cratering inspect.

Fig. 4 shows an FIB cut across a crack, from harsh bonding. Some MT(-1) Al was etched through the crack during crater etch. An important thing to note is the difference in MT(-1) deformed Al thickness on each side of the crack.

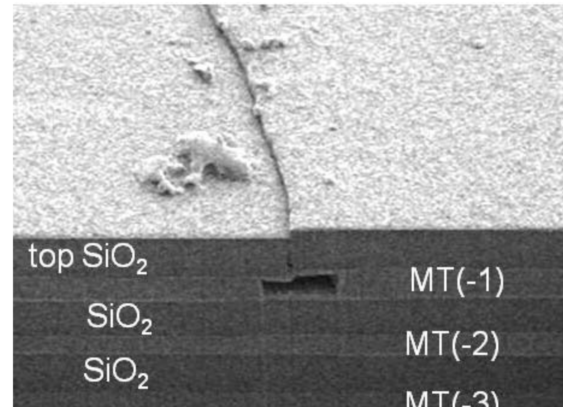

Figure 4. FIB cross section through a pad cracked in harsh bonding, after crater test.

Standard Au wire bonding typically caused 10% to 50% cracking to the weakest traditional pads (pad structures with top vias and full sheets of metal in all interconnect layers below the pad window). Without top vias under the pad window, 0% to 20% cracked pads is typical in these experiments. There was no cracking response for standard bonding in any experimental pad design. The ripple effect is always observed on bonded traditional pads, cracked or not, top vias or not, optimized or harsh bonding -- indicating that bonding consistently deforms MT(-1) Al into local "valleys" and "hills" (see Fig. 5).

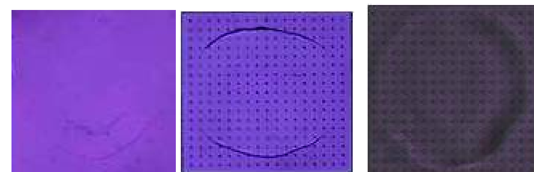

Figure 5. Standard bonding cracks in traditional pad structures: (left) no top vias, (middle) with top vias, (right) ripple example

Harsh Au wire bonding: 60% to 80% of traditional pads crack, and 90% to 100% when there is an array of top vias in the pad window. Traditional

pads showed strong ripple effect, whether cracked or not, whether top vias or not. Barrier lifting also occurred on some of the traditional pads with top vias. Fig. 6 shows examples of cracked pads from harsh bonding (in cratering test) and the ripple view.

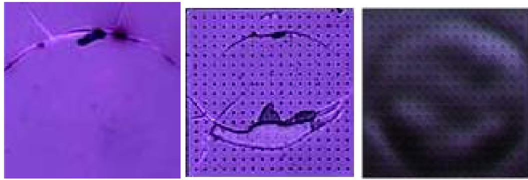

Figure 6. Harsh bonding cracks in traditional pad structures: (left) no top vias, (center) with top vias, (right) ripple example

Every experimental pad structure showed less cracking, reduced or nonexistent ripple effect, and no barrier lifting or SiO_2 divots as compared to traditional pads. No crack was found that was not accompanied by strong ripple effect in that location. Pads having greatly reduced MT(-1) pattern density improved significantly, with 0% to 13% cracking overall. Fig. 6 shows a XSEM of a standard Au ball bond on a cracked experimental pad having full sheets of metal, illustrative of the method used to analyze in detail (we can see Au-Al intermetallic (IMC) formation, pad metal displacement (PMD), bending and cracking of SiO_2 layers, and deformation of Al in metallization layers).

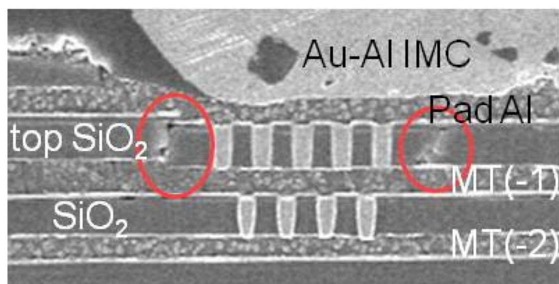

Figure 6. XSEM of cracks near the ball contact edge in an experimental pad design having full sheets in metal layers, but top vias only near the pad window. Al deformation in MT(-1) and top SiO_2 cracking occur near the ball contact edge.

Full metal sheets: Pad structures containing a full metal sheet across the pad window in any underlying layer showed ripple effect, decreasing in magnitude as the effective top dielectric thickness increased: MT(-1) full sheet pads cracked as much as the traditional pads regardless of the pattern in metals below MT(-1) with strong ripple effect observed, MT(-2) full sheet (with patterned or absent MT(-1)) in the pad window) had less than 10% of the pads cracked and reduced ripple effect, MT(-3) full sheet (with patterned or absent MT(-1) and MT(-2) layers in the pad window) had less than 1% of the pads cracked and weak ripple effect observed. Fig. 9 shows a cross section SEM of standard bonding an experimental pad design having full sheets of metal in all layers. The MT(-1) is not deformed nearly as much as in Fig. 7, showing how deformation leads to cracking.

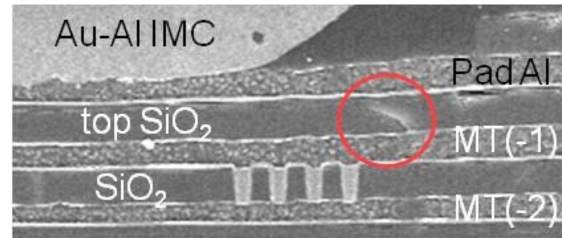

Figure 7. XSEM of a crack in a pad structure having full sheets in metal layers. Note how the crack near the ball contact edge initiates on the bottom side of the top SiO_2, where the MT(-1) Al transitions from a slight "valley" and slopes up into a "hill".

Fig. 8 shows a cross section SEM of a harshly bonded pad, showing huge deformation in the Al of MT(-1), and including cracks below MT(-1) in the SiO_2 as well.

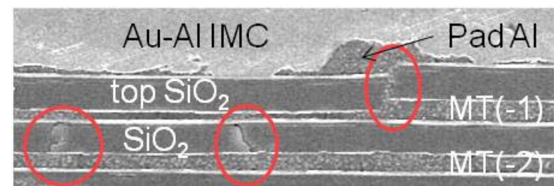

Figure 7. XSEM of cracks near the ball contact edge (just out of view to the right) from harsh bonding on a traditional-style pad structure. Note the drastic difference in MT(-1) Al thickness due to the mechanical stress. Sufficient stress reached the MT(-2) to deform it as well, initiating cracks in the SiO_2 above it.

Fig. 9 is another example of cracks occurring over MT(-1) near the ball contact edge.

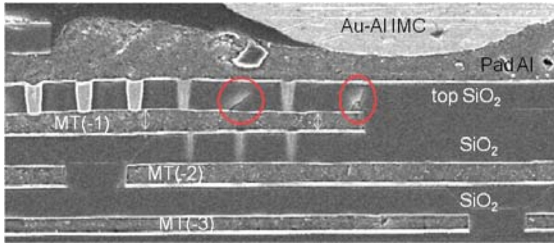

Figure 9. XSEM of cracks in an experimental pad design having reduced pattern density in underlying metal layers, but with metal and top vias in the region of the ball contact edge. The cracks initiate from the bottom side of the top SiO_2.

The role of MT(-1): MT(-1) patterning plays the most important role in determining robustness to cracking for harsh bonding on thin pad Al, if full metal sheets are removed from underlying levels in the pad structure. Some experimental pad structures simulate CUP applications with MT(-1) patterns of 4um wide metal "busses" and 57% pattern density in the pad window. These pads showed 5% to 13% of pads cracking from harsh bonding (some of which may be attributable to a full metal sheet in an underlying layer), with slight ripple effect detectable above the MT(-1) metal busses. MT(-1) patterns with <50% uniform density across the pad had even fewer cracks and no ripple, *unless there was a full sheet of metal beneath* in MT(-2) or MT(-3), which caused both cracks and ripple. MT(-1) patterns with <50% density *and* limited maximum metal width between spaces, slots or holes consistently showed 0% cracks and no ripple. No obvious interaction of cracks and MT(-1) layout was observed.

Effects of MT(-2) and MT(-3): For pad structures having reduced density MT(-1) across the pad window, cracking is already greatly reduced, and there appears to be little dependence on MT(-2) or MT(-3) *as long as they are not full metal sheets*. The presence of MT(-2) features and vias below are beneficial in reducing cracks from harsh bonding. For pad structures having MT(-1) absent in the pad window, up to 93% pattern density in MT(-2) has been shown to be robust to cracking from harsh bonding.

For CUP applications, MT(-1) absent, and MT(-2) bus patterns of up to 4um metal width and overall pattern density of 57% is also robust.

Effects of MT(-4), poly, Si devices: Patterned MT(-4) and polysilicon layers were included in the tests, but no effect was observed. No detectable shift in Si device parameters was observed in any test.

Effect of Pad Al thickness: Harsh bonding recipes caused a high percentage of traditional pads to crack for pad Al thickness of 0.55um and 0.8um. Table 1 shows additional data from a technology having thicker pad Al options, on traditional pads. The percentage of cracked pads reduces as pad Al thickness increases.

Bond Type	**1um pad Al**	**3um pad Al**
Standard Au bond	8%	0%
Harsh Au bond	18%	2%

Table 1. % of traditional pads cracked for two pad Al thicknesses

For the experimental pads without a full sheet of metal beneath the pad window, no cracks or ripple were observed for 1um or thicker pad Al.

Other relevant tests: PST and BST data for both standard and harsh Au wire bonding indicate that pads robust to cracking perform as well or better than traditional pads in comparative tests. PST *followed by cratering test* is not usually done, because it is known that traditional pads are too fragile. For the experimental pads, PST *followed by cratering test* showed no cracking or craters. BST *followed by cratering* is not usually done because traditional pads are fragile. In these experiments, 99% of 120 traditional pads were cracked after standard bonding followed by ball shear *then cratering test*; while no experimental pads out of 697 showed cracks, divots, or craters.

Discussion

Cracking and ripple effect together help show how the application of high stress to a bond pad structure containing brittle SiO_2 dielectric film over a ductile Al film leads to cracking. This is caused by the dielectric bending in conformance to the Al valleys and hills (We ignore the thin TiN films for simplicity). Fig. 10 demonstrates a case for a harshly bonded traditional-style pad, where large tensile stress on the top side of the top SiO_2 film bending over the Al "hill" caused a crack to initiate, resulting in a divot that pulled out in the cratering etch.

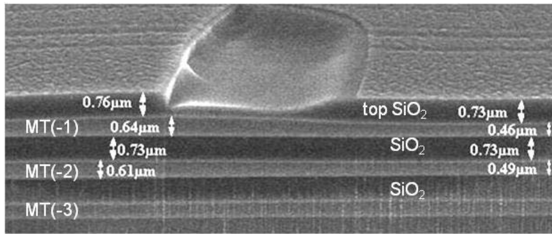

Figure 10. FIB cross section of a pad structure having full metal sheets, after harsh bonding and cratering etch. The MT(-1) "hill" is 1.4x the thickness of the neighboring "valley".

The presence of top vias further weakens the SiO_2, creating the weakest pad structure of any that were tested. It becomes clear that such cracks may be prevented if the SiO_2 doesn't bend significantly. This may be accomplished by limiting the width of SiO_2 above MT(-1) in the region of high bonding stress, and eliminating the use of full sheets of metal in underlying levels of the pad structure. Increasing pad Al thickness may be used to greatly reduce cracking, but this is not a complete solution for harsh bonding.

Non-BOAC pads can be designed for improved robustness to cracking, replacing traditional pads, and facilitating a switch to Cu wirebond without the requirement of thick MT. Cu wire bond replacing Au not only reduces cost, but lower electrical resistance and stiffer wire behavior during packaging are significant advantages. Also, Cu's much lower rate of intermetallic formation at the bond interface can lead to improved reliability as compared to Au wirebond at higher operating temperature.

One can also follow the simple principles of reduced metal pattern density and limited metal width between spaces, slots, or holes. This will facilitate successful design of free-form CUP circuitry in all interconnect layers beneath the pad window to produce a robust pad structure, and enables the concept of Cu wire bond on BOAC pads without the need for thick MT.

Additional positive results were later obtained using actual AuPd wirebond (more bonding stress in this recipe than for Au) and Cu wirebond (even more bonding stress). Figure 11 shows the cratering test cracking data for sets of 50 die of each selected pad design, bonded with AuPd wire or with Cu wire. The pads most robust in harsh Au bonding are the same designs that showed no cracking in AuPd and Cu bonding tests.

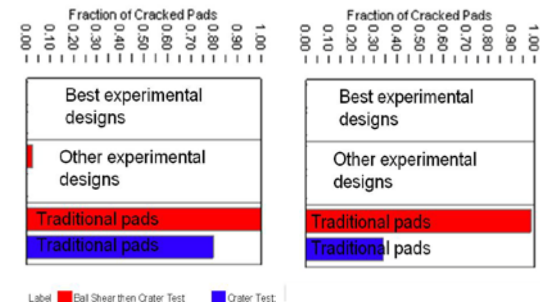

Figure 11. (left) 1mil AuPd wirebond results, (right) 1mil Cu wirebond results; including crater test after ball shear.

PST and BST testing was done to compare 240 "robust" pads to 60 traditional pads ball bonded with 1mil AuPd wire. All samples passed, with no statistical difference in values observed. PST and BST testing was also done to compare 360 "robust" pads to 60 traditional pads ball bonded with 1mil Cu wire. All samples passed, with no statistical difference in values observed. As usual, traditional pads showed cracking.

Reliability Test Results

Reliability testing was first done for one lot of Au wire bonded parts in a technology having 0.55um pad Al thickness, comparing traditional pads (with and without top vias) to a pad design having 4um wide parallel metal busses and 57% pattern density in MT(-1). Harsh bonding this time was with 1.2mil Au wire, which caused cracking on many traditional pads but not on the experimental pads. 20-pin SOIC Though parts with cracks were stressed in parallel with parts having no cracks, no electrical changes in leakage or shorting were detected over 1khrs high temperature operating life (HTOL), 2000hrs high temperature storage life (HTSL), or 2000cyc temperature cycling (TC), 200cyc thermal shock (TS) -55C to 150C. As well, special tests were done such as TC first, then HTSL, and vice versa, all with passing results and no degradation found. A few plastic packages began to come apart, causing invalid "opens" fails after 1500cyc TC, verifying that the stress was indeed harsh. One possible conclusion is that cracks already present from bonding do not appear to propagate further or at least don't cause new fails. It is clear that standard reliability stress tests don't seem effective in propagating or detecting cracks in

pads, and thus it may be assumed that products with cracked pads might be commonplace…

Based on the success of "robust pads" in every result, two new CUP pad designs were fabricated in another technology for reliability stressing: 4-level metal, with 0.8um pad Al thickness. One design with MT(-1) absent under the pad window, has 4um wide metal busses with 53% overall metal density in MT(-2), including circuitry in MT(-3), various electrical nodes, and full ESD protection circuitry beneath. The other design added MT(-1) circuitry to the previous design, with an overall MT(-1) pattern density of 43%, no top vias, but adding some via connections to the appropriate MT(-2) nodes from MT(-1).

These CUP pads were subjected to a barrage of harsh stresses, including harsh probing, harsh Au wire bonding, harsh AuPd bonding, and Cu bonding, again confirming previous results with no issues found. Reliability testing was done after assembly in 20-pin SOIC plastic packages, with parallel testing of 300 parts with 1mil Au wire and 300 parts with 1mil Cu wire bonding. Sample sizes in each stress are the usual amounts for a one-lot extrinsic reliability test, ie 80 parts each in HTSL. Standard and extended reliability testing was completed, followed by PST, BST, and cratering tests. No reliability fails or issues were discovered (see Table 2). Of special interest in this case was the PST, BST, and cratering test results comparing after stress and at various read points with the initial test values. No degradation in performance, and no issues of any kind were discovered in these additional tests.

Rel Test	Stress	Duration	Result
MSL2	Moisture preconditioning, 3 x 260C		PASS
Biased HAST	130degC 85% RH,	215hrs	PASS
HTSL	175degC	1000hrs	PASS
TC	-65C to 150C, air to air	2000x	PASS
PST	Bond pull strength, 5 die	Initial, 2 read points, and after stress	PASS
BST	Wire Ball Shear, 2 die	Initial, 2 read points, and after stress	PASS
Cratering	Etch away ball and Al, all pads	Initial, after stress, and after each PST and BST	PASS

Table 2. Rel test data for two CUP designs, including Au and Cu wirebond

Our confidence in standard reliability test stressing to detect the presence of cracks is low. "Before stress" and "after stress" PST, BST, and cratering tests and follow up analyses are helpful to learn about cracks and weak bond pads.

Conclusion

Harsh bonding experiments on various pad structures, analyzed by cratering test, aid in our understanding of the pad cracking mechanism and how to prevent cracks. Traditional pad designs having full sheets of metal under the pad window, and especially those with top vias, are the weakest in terms of pad cracking from bonding tests. The importance of underlying Al-based metal structures, their pattern density, and limiting the metal width between spaces, slots or holes is shown. These principles can easily be used in both successful pad design and successful BOAC pad design. "Robust" pad designs are demonstrated to be resistant to cracking and other damage from harsh bonding. Ripple effect exists for all cracks found, and is present whenever there is a sufficiently wide metal feature in the pad structure. Ripple effect is not observed in robust pads. Sample BOAC pad designs, having circuitry in all interconnect levels below the pad window and Si devices beneath, were reliability tested, demonstrating no pad cracking, and positive results overall for both Au and Cu wirebond on thin pad Al.

Acknowledgements

We recognize the significant contributions of the engineers and technicians of the Pocatello Prototype Operation, and Materials Analysis Lab, especially Lynda Pierson; also reliability test engineers and technicians in ON Calamba, Philippines, and assembly engineers and technicians in ON Carmona, Philippines. Special thanks to Jim Workman and Craig Christensen.