Use of Wire Bonding to Study Bond Pad Damage from Wafer Probe

Stevan Hunter[1,3], Jonathan L. Clark[2], Darin Hornberger[2], Lance Rubio[2]

[1]**Idaho State University;** [2]**Brigham Young University Idaho**; [3]**ON Semiconductor**, Pocatello, ID, USA

contact: stevan.hunter@onsemi.com This work sponsored by ON Semiconductor

Abstract

Harsh wafer probing and harsh wire bonding have been used in previous work by our group to study cracking and ripple effect on various bond pad designs in technologies having aluminum (Al) alloy based metallization in SiO_2 dielectric. One outcome of the previous experimentation is the confirmation that cracks due to wafer probe may not be visible even in a careful cratering test. Probing stress can bend the top SiO_2 of the pad downwards, causing high tensile stress to the underside of the film. Cracks initiating in this region easily go undetected in routine monitor procedures, unless they propagate to the top surface and break the barrier film above. Latent probing cracks can result in reliability issues for circuit under pad (CUP) bond pad designs. A typical probe crack in a CUP pad's top SiO_2 layer, detected in a cratering test, may actually be accompanied by one or more hidden cracks at the bottom of the film, which may only be detected in a focused ion beam (FIB) cross section. This study uses harsh probing to create cracks in various bond pad test structures and then follows them through the wirebond process, including harsh bonding experiments. Previously undetected probe cracks may be enhanced, lengthened, and made easier to detect in wirebond monitoring and in a cratering test after wirebond. Cracks due to wirebond have different characteristics than probe cracks. Distinguishing features of both crack types are compared after bonding. Monitoring of the ripple effect in both probe and bond helps to predict and track bond pad cracking tendencies. Methods to reduce cracking from both probe and bond are reviewed.

Keywords: bond pad, probing, wirebonding, bond pad cracks

Introduction

Cracks in the top silicon dioxide (SiO_2) film of bond pads having aluminum-based (Al) metallization layers are a reliability concern, especially when there is circuitry under the pad (CUP). Cracks initiate due to stress from probing, bonding, or both. Our previous work has shown much about the mechanisms of cracking, characteristics of cracks from harsh probing and wirebonding, and how to design pad structures to prevent cracks [1-4]. Cracking tendency of pad structures is witnessed by observing the "ripple effect" in the destructive "cratering test", where wirebonds and pad Al are removed to permit inspection by optical microscope. Ripple is easily seen in dark field and lower magnifications, whereas cracking can be more difficult to observe, requiring high magnification. [5,6].

The tendency for a pad to crack depends greatly upon the actual pad structure as well as the stresses to which it has been subjected. Cracks may be detected during wirebond process characterizations on new products. Then the question may arise as to whether the cracks are due to the earlier probing or due to the bonding. Of special interest to reliability engineers "latent damage" that may exist after probing, such as weakened SiO_2. In traditional bond pads, probe cracks tend to initiate in the lower surface of the top SiO_2 film but may not extend up to the top surface to break the barrier film there, thus escaping detection in a cratering test inspection. Such potential reliability issues could go unnoticed in product qualifications and in early manufacturing.

Bond pads in this study have Al metal on the top, for probe contact and wirebonding. Below the pad Al are a number of other thin film layers, including a "barrier" layer (often titanium nitride (TiN)), an SiO_2 layer which may contain tungsten (W) vias, then an Al-based metal layer followed by another SiO_2 layer, another metal layer below that, and so on. Figure 1 illustrates the simplified metal and via layers in example bond pad structures.

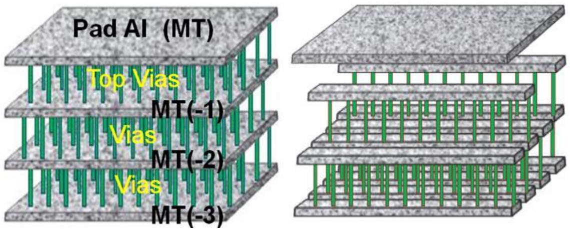


Figure 1 Illustrations of bond pad structures with Al-based metallization and SiO_2 dielectric surrounding metal sub-layers. The traditional pad structure is most prone to cracking (left); an example circuit under pad (CUP) structure (right).

Probe Damage to the Pad Structure

IC die probing refers to the physical contact of an electrically conductive tip which must break through or break up the native Al oxide (Al_2O_3) on the pad Al surface to facilitate electrical testing of the IC circuitry. Figure 2 is a photo of the cantilever probe tips of one probe card used in our experiments.

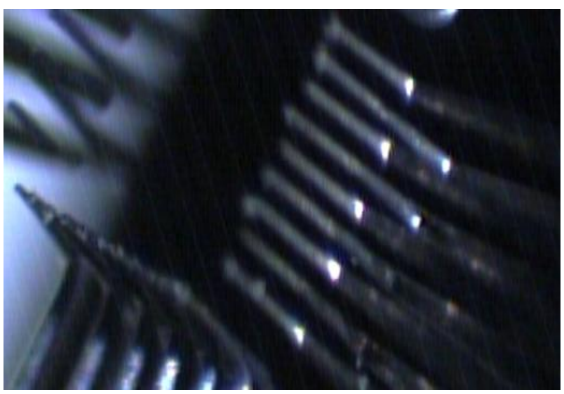


Figure 2 Cantilever probes micrograph. Tips are still dirty with Al nodules from a harsh probing run. This probe card has two tiers of 1mil diameter probe tips, for 40 pads in a rectangular pattern.

The force applied by each probe tip to the pad Al depends upon its spring force and the overdrive (or overtravel) of the wafer chuck on the tester, which moves the wafer into final "electrical test" position after the probes have all made initial contact. In this process the pad Al easily deforms, leaving a microscopic "probe mark" each time a probe touches. Figure 3 shows some probe mark examples.

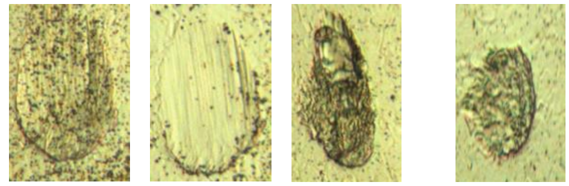


Figure 3 Probe mark micrographs showing various characteristics. The two marks on the left are not very invasive and are less likely to cause cracking. The two on the right are deeper and more likely to result in cracks beneath.

In this study we're concerned with probe tip stress coupling into the underlying pad sub-layer films. Harsh probing conditions purposely cause cracking. Figure 4 is a harsh probe mark in cross section.

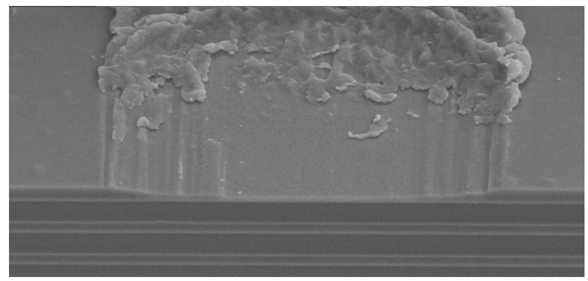


Figure 4 A focused ion beam (FIB) cross section through a harsh probe mark shows that there is almost no pad Al thickness remaining in the deep scrub region.

Monitoring for probe cracks is destructive (cratering test or FIB) and labor intensive, and not feasible for routine monitoring at wafer level.

Products having thin pad Al, 0.5 to 0.8µm, are of special concern in probing because the thin Al may not adequately protect the pad structure from probe downforce and scrub action. Circuit under pad (CUP), also known as bond over active circuitry (BOAC), may be required along with thin pad Al for minimal die size. The combination of thin pad Al with CUP pads is challenging, because the probe stress may now deform actual circuitry and cause cracks that result in electrical shorts. These challenges have been discussed in detail in our previous work [7].

Perhaps the most likely scenario for discovering cracks from either probing or bonding in a manufacturing situation is during a bonding process characterization for a new product, or following a change in a process step prior to or including bonding. Bonds may not adhere well, or cracks or craters may be found upon further testing. In these cases, previous damage from wafer probe must be considered as a factor. Experimental data can help us to differentiate between pad damage from probe and pad damage from wirebond.

Experiment

This experiment consisted of using 3 different cantilever probe cards to harshly probe various pad structures in a CMOS technologies having pad Al thickness of 0.8μ, followed by 1mil gold (Au) wire ball bonding. 16 different pad structures, not including the traditional pads, were probed, bonded, and analyzed for cracks. Structures include a variety of pattern densities in MT(-1) and MT(-2). Pads with MT(-1) densities of 75% and above all have arrays of holes, while the others are mostly MT(-1) lines and spaces. MT(-2) has fairly wide metal lines. Control groups consist of unprobed pads, unbonded pads, and mechanically weak and strong extremes in pad structures. The *high force* probe card had been used in previous experiments, allowing comparison with our previous data. A *low force* card and a *small-tip* card were also used (details will be shown below). The harsh probing conditions in this experiment are *6 repeated touchdowns at 4mils overdrive* on the tester, the same for all three probe cards; each probing on different parts of the same wafer. Figure 5 is a photo of part of a probed test pads die.

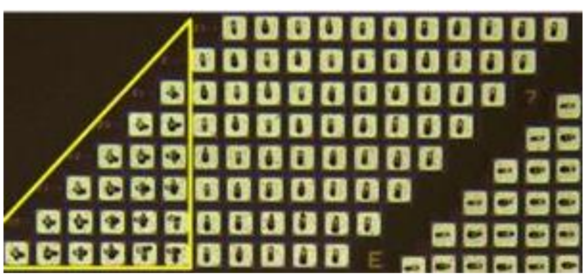


Figure 5 A portion of the experimental test chip with large probe marks on the pads seen after harsh probing. All pads to the right are probed in a single test of 6 touchdowns at 4mils overdrive. Highlighted on the left are cross-probed pads, harshly probed twice, with one scrub direction perpendicular to the other.

The arrangement of the pad rings on each die are such that certain pads are probed twice during the probing sequence by different probe tips, the second probe scrubbing perpendicular to the first. We refer to this as *cross probing*. Cross-probed pads actually received 12 touchdowns at 4mils overdrive as a worst case scenario for probe cracking. Cross-probing in this manner permits analysis of the same pad structure probed in two different directions, which will be discussed later.

After probing, the wafers were sawed to singulate the test die. Die from each probe card, and some unprobed die, were then ball bonded with 1mil Au wire. Some bonds used a standard bonding recipe and others used a harsh recipe, having lower temperature and higher ultrasonic power (to simulate the stress of Cu wirebond without having to have the special bonding equipment required for Cu wire). Some probed die from each probe card were left unbonded. Figure 6 shows example Au wirebonds on some of the test pads in this experiment. Figure 7 shows the actual bond ball shapes of the standard and harsh bonding recipes used.

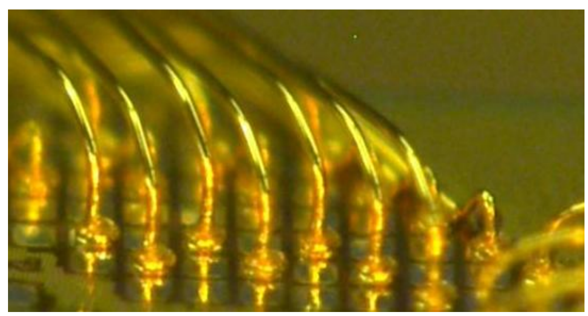


Figure 6 Wirebonds on top of harshly probed pads

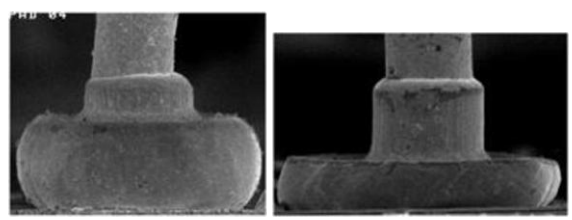


Figure 7 Scanning electron micrographs (SEM) of 1mil Au wire ball bonds used in this experiment: (left) standard bonding recipe; (right) harsh bonding recipe, with higher ultrasonic power and lower substrate temperature. In past experiments, more cracking was caused on weak pad structures by the "harsh" bonding recipe.

An important, reasonable assumption is that probing cracks which would be visible in a probe cratering test will also be at least as visible after bonding in the bonding cratering test. We can't actually test both on the same die because the crater etch after probing removes the pad Al, making those pads unbondable. For comparison, probe-cracked pads were photographed after crater etch, and wirebonded pads of a different test die that had been probed identically were also photographed after crater etch. Probe cracks from a particular tip of a particular probe card on the same pad structure can then be compared for visible damage after probe vs. after bonding. Only pad structures having top vias or high pattern density in the MT(-1) layer are expected to crack from the harsh probing [3,5]. Our expectation was that probe cracks, and even hidden damage from probing, may be "enhanced" by the bonding stress to become more easily detected. Pad structures that are the most mechanically robust are not likely to crack in probing, but perhaps have latent damage that could be "revealed" after bonding?

Wirebond Cracks

The unprobed, "bonded only" pads showed cracking for both bonding recipes on the traditional pads, having full sheets of metal layers below the pad window, without top vias. All other pad structures in the experiment were sufficiently strong to prevent cracks for both bonding recipes. Examples of the traditional pad bonding cracks, as observed by microscope inspection after the destructive "cratering etch", are shown in figure 8.

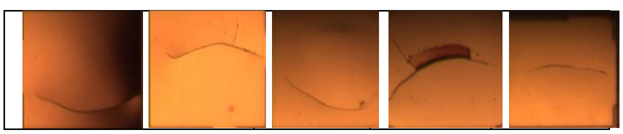


Figure 8 Pad cracks as observed on traditional pad structures without top vias in the pad window, following "standard bonding" and then cratering test.

Ball bonding cracks are often recognizable by their shape and position in relation to the ball bonding region. These bonding cracks initiate perpendicular to the ultrasonic motion during bond and tend to be located near the bond contact edge. Two bonding cracks may appear opposite each other on a pad, or there might be just a single crack as seen from this experiment. A second type of bonding crack, a straighter line across the middle of the bond region, is most often observed when the pad has been probed, although probing was not actually necessary for this crack to appear on a weak traditional pad structure, shown in the rightmost photo of figure 8.

Associated with the bonding cracks are the optical ripples, which are seen easily in dark field microscope view and at lower magnifications. The deformed sub-layer Al films and bending SiO_2 from ball bonding often give the appearance of water ripples in a pond. The sharpest ripples illustrate where the stresses to the pad sub-layers were highest, with significant sub-layer Al films deformation and greatest potential for cracking of the top SiO_2 [5,6]. Figure 9 shows the large ripple associated with the traditional bond pads in this experiment.

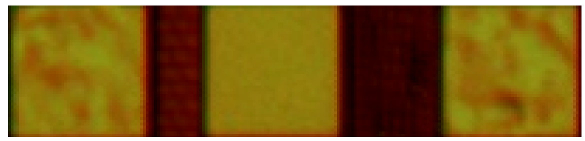


Figure 9 Traditional pads after the cratering test, showing high ripple for "standard bonding", (left and right pads), and no ripple for the unbonded (middle pad). Such ripple in a pad suggests a high probability of cracks.

Data Analysis: Probe Cracking vs Pad Structure by Probe Card

Examples of probe tip photos from each of the three probe cards are shown in figure 10 after probing (not cleaned first). The *low force* and *high force* tips are about the same diameter, both being significantly larger than the *small-tip* tips.

Figure 10 Probe tip micrographs to show relative sizes. High Force, avg. 1mil dia. (left); Small-tip, avg. 0.7mil dia. (center); Low Force, avg. 1mil dia. (right)

Individual probe tips were measured for their gram-force at 2mils overdrive. Assuming a linear spring force as is customary for cantilever probes, the gram-force and stress to the pad is estimated for each probe card at 4mils overdrive in table 1.

Table 1 Average tip force and stress for the three different probe card tips

Probe Type	Meas. gF at 2mils Overdrive	Est. gF at 4mils Overdrive	Tip Area in mil^2	Stress in gF per mil^2
High Force	4.5	9	0.8	11
Small-Tip	2.2	4.4	0.4	11
Low Force	2.2	4.4	0.8	5.5

The tip stress on the pad Al is thus predicted to be about equal for the *high force* and *small-tip* probes, and only half as much for the *low force* probes. But the *small-tip* probes concentrate the stress in about half the area as compared to the other probes. The *low force* card is most representative of a card that would be used in manufacturing for thin pad Al products. Figure 11 shows an example probe tips and their corresponding probe marks.

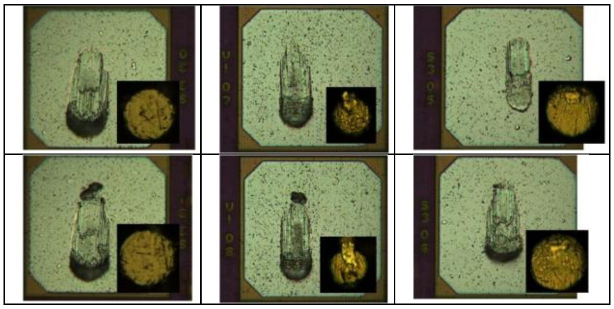


Figure 11 Example probe marks and probe tip photos from a long and short tip length pair from each card. *High Force* (left); *Small-tip* (center); *Low Force* (right).

Note how the large tip marks are not as wide as the tip diameter, while the *small-tip* marks are as wide as the tips. Measurements on the probe cards revealed that the *small-tip* probes have about 5° lower bend angle, 100°, while the other two cards have tips at about 105°. Higher bend angle seems to make the tip "heel" do the scrubbing. Four mils of overdrive causes all of the tips to scrub about the same, regardless of the tip angle, though we see that probe marks from the *low force* tips are actually slightly shorter.

Many of the probe crack findings comparing the three probe cards with unbonded pads were reported previously [8], though with less detail than will be discussed here. In summary, the *small-tip* probe card caused nearly as much probe cracking as the *high force* probe card, confirming that the stress per probe tip is indeed a significant factor in causing cracks. But more latent or hidden damage was discovered from the *small-tip* card, suggesting an increased reliability concern when probing with small tip size. The *low force* card only caused visible cracks on the pads having very high density MT(-1) patterns or top vias -- the pad structures known to be mechanically weakest.

As observed in all of our previous experiments, lower pattern density in the MT(-1) layer is the most important pad structural factor in preventing cracks, other than thickening the pad Al. The probe cracks data for all three probe cards among the various pad structures is summarized in figure 12. The x-axis is the pattern density of the MT(-1) layer, with 0 indicating no metal in the pad window and 0.96 being a full sheet of metal with sparse holes removing only 4% of the metal. Traditional pads crack essentially100% in harsh probing and are not included in the plot.

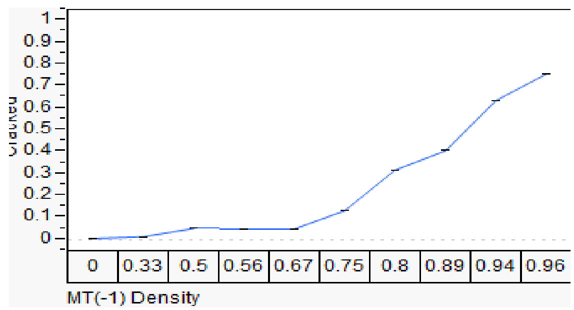


Figure 12 Fraction of pads cracked in probing vs pattern density of the MT(-1) layer within the pad window for all 3 probe cards combined. Probing with 6 touchdowns at 4mils overdrive, not including cross probed pads

This probe cracking trend closely matches trends reported from our previous harsh probing experiments [1]. High MT(-1) pattern density pads are the weakest, showing the most ripple and cracking when harshly probed. But we notice unexpected cracking at 75% MT(-1) density and subtle cracking tendencies below 75% MT(-1) which invite further investigation. Figure 13 shows a breakdown of the cracking from each probe card within each MT(-1) pattern density value.

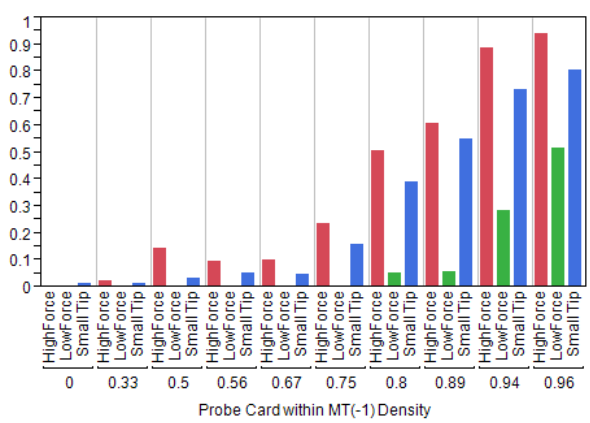


Figure 13 Fraction of pads cracked after probing, comparing the 3 probe cards, with the x-axis being the

MT(-1) pattern density, for 16 different pad structures in the experiment. Harsh probing conditions are: *6 repeated probe touchdowns at 4mils chuck overdrive*.

The *low force* card data are the green bars. Only the weakest of the structures were cracked by these probe tips in the harsh probing conditions. Cracking begins at 80% MT(-1) pattern density and increases from there. This probe card is most like a cantilever probe card that might be used in manufacturing for CUP pads having thin pad Al, and it appears that there is a good process window without cracking for MT(-1) pattern density at 75% or less.

The *high force* card data are in the red bars of figure 13, showing the most cracking in every case but one. Cracked pads increase dramatically from 67% MT(-1) density and higher on this card. Two of the pad designs at 75% MT(-1) density have top vias, contributing to increased cracking at that position on the chart. Cracking at lower than 75% MT(-1) in these harsh probing conditions is found to be due to interactions with relatively wide MT(-2) features. Using such strong cantilever probe tips and these harsh probing conditions should certainly be avoided if cracking is to be prevented in a manufacturing situation.

Cracking from the *small-tip* probe card is indicated by the blue bars, which closely follow the red bars of the *high force* cracks in figure 13. The *small-tip* tips exert only half the force per tip as compared to the *high force* card but still apply about the same stress in a smaller area, so the relatively high amount of cracking observed makes sense.

The *small-tip* card is the only card that cracked a pad designed with no MT(-1) at all beneath the pad window, at 0 on the x-axis. Cracking of this style pad is rare, based on our extensive previous experimentation. When MT(-1) is not present under the pad window, there is simply a stack of SiO_2 layers between MT(-2) and pad barrier film, with more than twice the usual SiO_2 thickness in total. This thicker sheet of SiO_2 does not tend to initiate cracks. It cannot bend as easily under the probe tip and cannot so easily stress the MT(-2) Al in a small spot to deform it into the local "valley" associated with probe crack initiation. We attribute this particular *small-tip* cracked pad having no MT(-1) to the probe stress being applied in the smaller area of the pad Al interacting with the center of wide a metal line in MT(-2). Though the *high force* tips cracked more pads of every other design, the small tip area with similar stress per probe is seen to cause more hidden damage, which can also result in such a visible crack observed in the cratering test.

This hidden cracking damage from the *small-tip* card raises more reliability concerns and will be discussed in more detail later. It appears to be more risky to use smaller probe tips in manufacturing.

Now we'll turn to the cross-probed pads analysis. The experimental pads having metal lines and spaces, which we usual refer to as "slotted" designs, were probed in the first probing with the scrub in parallel with the lines and slots. Probing over a "slot" or space, no crack is expected. Probing over the center of a wide metal line can deform the metal and cause cracking. Thus, the exact probe position in relation to the metal sub-layer features is important in harsh probing [1,8]. In this experiment this phenomenon accounts for the probe cracks when MT(-1) density is 67% or less.

When we add in the cross-probed results, we see much more cracking tendency in the slotted MT(-1) and MT(-2) designs relating to the probe scrubbing *across* the lines and slots, coupled with the fact that these pads have received the probing stress twice. Figure 14 shows the cracking for probing parallel to sub-layer lines and slots in blue and for probing perpendicular to lines and slots in red.

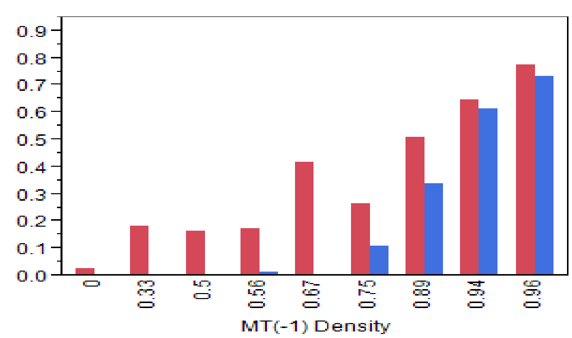


Figure 14 Fraction of pads cracked in probing vs pattern density of the MT(-1) layer, from the cross-probed pads only: blue bars are cracked pads from the standard probe direction, red bars are cracked from probing in the cross-probe direction.

MT(-1) is designed with arrays of holes for the 75% through 96% designs in this case. So cross-probing on these "symmetric" designs simply adds more stress following the initial probing, and the additional cross-probed cracking we see in red is expected. Note how as the MT(-1) density increases (pad becoming more susceptible to ripple and cracking), the initial probing already had cracked nearly as many pads as did the cross-probing afterwards. Of course there are more total cracks found int eh cross probed pads.

The significant cross-probe cracking of pad designs having lesser MT(-1) density is due to the change from scrub parallel to perpendicular relating to the sub-layer metal lines and slots. The data confirms two different cracking mechanisms over patterned metal interconnects, which we have previously reported but not explained. Illustrations of probing in parallel and perpendicular to MT(-1) circuit lines are shown in figure 15.

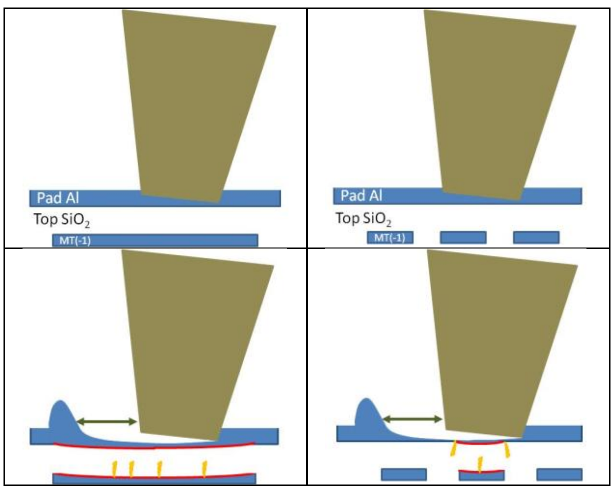


Figure 15 Probe tip touchdown and scrub illustrations for 2 pad structures with MT(-1) lines and slots: (left) probe scrub parallel to MT(-1) line; (right) probe scrub perpendicular to MT(-1) lines. (Lower left) scrub in parallel may deform the Al into a valley and initiate cracks in the bottom of the SiO_2; (lower right) scrub perpendicular to metal lines may cause cracks to initiate at both top and bottom.

The pad Al deformation is simplified in the cross section of cantilever tip probe marks shown in the bottom row of figure 15, with a "gouge" where initial touchdown and scrubbing occurs, and a "prow" where Al material has been "bull dozed" by the probe tip, building up at the farthest extent of the scrub.

As illustrated in figure 15, harsh probe scrubbing above a metal line, in the same direction as the metal line, can cause cracks to initiate above the Al "valley" formed. Harsh probe scrubbing *across* sub-layer metal lines tend to initiate cracks corresponding to the edges of the sub-layer metal features. The sub-layers involved may be MT(-2) features, not just MT(-1) in these harsh probing conditions. Even when the MT(-1) has arrays of holes for 75% or less pattern density, sufficient to prevent the majority of MT(-1) deformation and top SiO_2 cracking, MT(-2) features beneath can still interact with harsh probing, resulting in crack initiation of the top SiO_2. Recall that the cantilever probe tip retracts along the same path that it forges, imparting stress again on the return trip. This reverse-direction scrub action may be important in the further initiation of cracks in the case of probing *across* metal lines and spaces.

Probe cracks and hidden or latent damage from probing may be enhanced in the bonding process, assuming that the bonding takes place over the top of the probe mark. We would expect that a weakened point in the SiO_2 may initiate a crack and an existing probe crack may be enlarged or propagate in bonding. If both the probe mark and bond are centered within the pad, we expect that any damage found in the pad center most likely initiated in probing, and damage that looks like it follows the bond ball edge(s) is likely from bonding. This method of judging appears to work in general. But of course we usually won't know exactly where the probe mark was when randomly performing a cratering test after bonding.

Tables 2, 3, and 4 below show example pad cracking photos for the three probe cards, on the pad structures that cracked most. Cracks from the same probe tip and pad structure are shown after probe and after bond. Microscope magnifications are all the same in these tables.

Probe Cracks Appearance after Probing and after Bonding: High Force Probe Card

Table 2 ***High force*** **probe card cracks for the 5 most-cracked pad structures. Probe scrub direction is downwards, and ultrasonic motion up and down, in these photos. Colorations are from etchant seeping through cracks to the MT(-1) Al film beneath.**

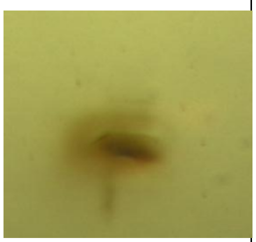
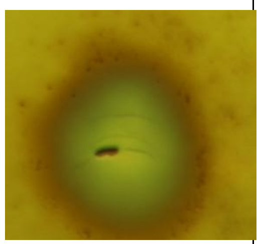
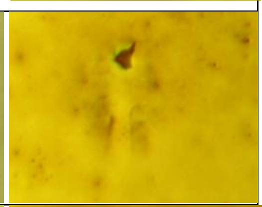
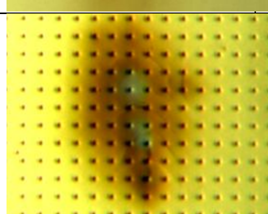
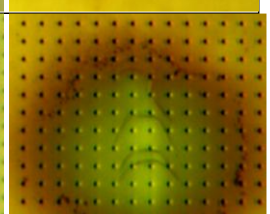
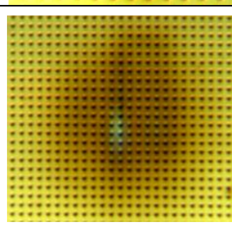
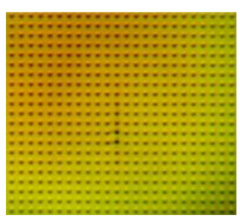
MT (-1)	*High Force* Probe Cracks	*High Force* Probe Cracks after Bonding
A 96 %		
B 94 %		
C 89 %		
D 75 %		
E 75 %		

Table 2, Row A shows gross probing ripple and cracking in a 96% MT(-1) density pad structure. The MT(-1) layer is essentially a full sheet except that small holes are sparsely placed to reduce the overall density by 4%. We observe that this pad behaves almost as if there were no holes in the MT(-1), like the weak traditional pad structure. The photo after bonding shows cracks propagating across the pad, leftward and rightward, perpendicular to the ultrasonic (US) bonding motion. Such extensive cracking can be mechanically weakening beneath the bond potentially resulting in bond lifts during wire pull as well as lifting and cratering in bond shear tests.

Table 2, Row B, 94% MT(-1) density. In this pad type, some cracks after bonding are slightly longer than they were after probing, showing a small enhancement effect from bonding. In addition, we find barrier lifting associated with the cracks.

Table 2, Row C, 89% MT(-1) density, shows different ripple and generally smaller cracks in probing, where the cracks are interacting more with the array of larger holes in the MT(-1) metal layer. The cracks do not appear to lengthen after bonding, but we see some undesirable barrier lifting again.

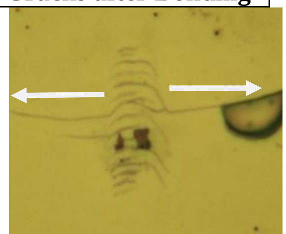
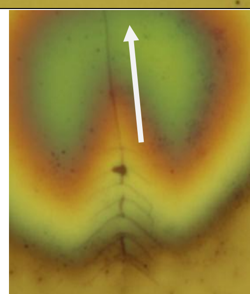
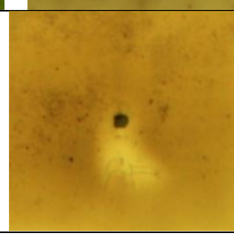
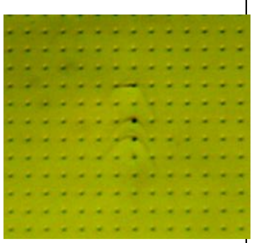
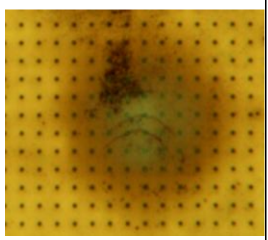
Table 2, Row D, 75% MT(-1) density, with sparse top vias. The top vias weaken the structure, leading to cracks. Cracking becomes slightly worse after bonding, highlighting the weakness of this pad structure. This agrees with our previous data indicating that regardless of the pad structure, the addition of top vias leads to more cracking in harsh probing and bonding situations [1, 2].

Table 2, Row E, 75% MT(-1) density, with dense top vias. The cracking we see on this pad structure appears very small and minor in comparison to the preceding crack photos. However, we find a significant amount of hidden probe damage in these pads. Probe stress appears to be relieved by a different mechanism than cracks that reach the top surface, including the separation of vias from the surrounding SiO_2 film. Slight lengthening of visible cracks appears to occur due to bonding, but in general, the damage is sub-surface, undetected in the cratering test. The mechanical reliability of this pad is very poor at the probe mark location due to the high amount of hidden damage.

Probe Cracks Appearance after Probing, after Bonding: Small-tip Probe Card

Table 3 shows *small-tip* probing cracks after probing and after bonding, in the cratering test.

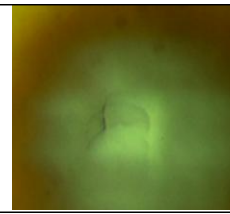
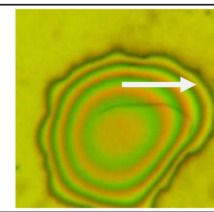
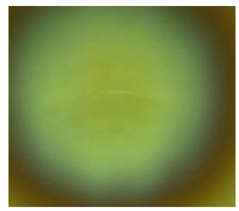
Table 3 *Small-tip* probe card cracks

MT (-1)	*Small-tip* Probe Cracks	*Small-tip* Probe Cracks after Bonding
A 96 %		
B 94 %		
C 89 %		
D 75 %		

Summarizing the *small-tip* probes cracking results, with example photos in table 3, cracks are very similar to the *high force* probe card cracks. Probe crack propagation across the pad after bonding is seen a little more dramatically for the *small-tip* card, likely due to more hidden damage that is being enhanced during bonding. Note that on the pad in row B, 96% MT(-1) density, the bonding ultrasonic motion was right and left, not up and down like in the rest of the photos, so the probe cracks extension looks vertical instead of horizontal. Photos for row E with dense vias are not included because the cracking is very difficult to see optically, but this will be discussed later.

Probe Cracks Appearance after Probing, after Bonding: *Low Force* Probe Card

Table 4 Low force probe card cracks

MT (-1)	*Low Force* Probe Cracks	*Low Force* Probe Cracks after Bonding
A 96%		
B 94%		

The *low force* card only cracked pads of the very weakest designs, so there are fewer example photos. These probe tips exert only half the stress as on the other cards due to the large tip diameter and lower force per tip. We see the same tendency for the probe cracks to lengthen across the pad after bonding, perpendicular to the ultrasonic motion.

Cracking results among the three probe cards show that the pad structures which tend to crack most easily are the same structures that tend to have the cracks enhanced in bonding. MT(-1) pattern density is the key factor in determining pad mechanical strength when pad Al is thin. The presence of top vias enhances cracking, even if the MT(-1) pattern beneath is strengthened.

Additional Pad Damage Resulting from Probing

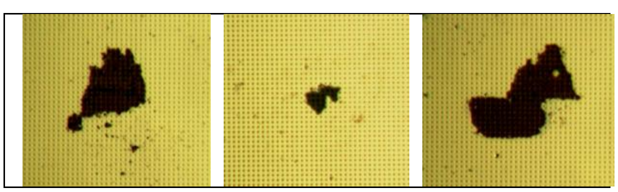


Figure 16 Barrier lifting examples on pads with top vias.

Barrier lifting occurs due to loss of adhesion between the pad barrier film and top SiO_2 in harsh probing. In our experience, barrier lifting is routinely observed in cratering tests whenever top vias are present in the structure, especially after bonding. But as seen in the probe crack photos after bonding in tables 2 and 3, small regions of barrier lifting may accompany the severe cracking on the other weak pad structures as well. Figure 17 shows examples of some of the more extreme damage that was found in this experiment.

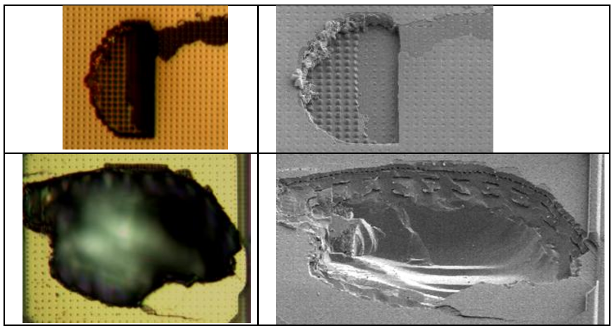


Figure 17 Optical and SEM photos of craters associated with top vias and harsh probe cracking: (top) barrier lifting and severe probe cracks enhanced by bonding led to etching of sub-layer Al and breaking away of pad SiO_2 layers; (bottom) crater after bonding, with the cracking going deep into the Si.

This severe pad damage of figure 17, observed after bonding, is rare in this experiment, occurring only on harshly probed pads having top vias.

Hidden probing damage from the *small-tip* probe card has been shown previously [8]. We include the photos here to highlight further details. Figure 18 is an optical micrograph of a harsh probe mark, and the cracking as seen in the cratering test after probing. This pad structure is the same as in row E of Table 2, but was probed by the *small-tip* card.

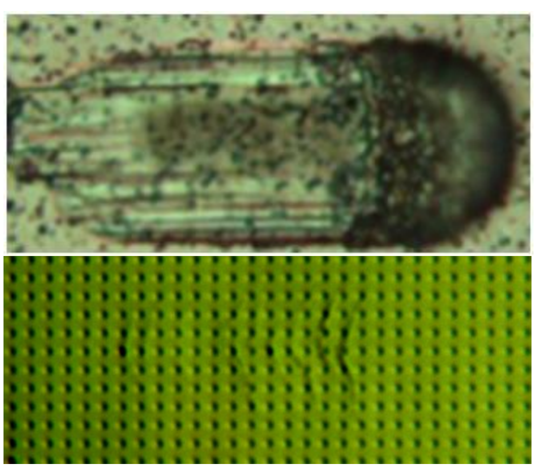


Figure 18 Probe mark, and probe cracking from small-tip harsh probing on a pad with dense top vias, and MT(-1) having a pattern density of 75%

Figure 19 is an FIB of this probe cracking.

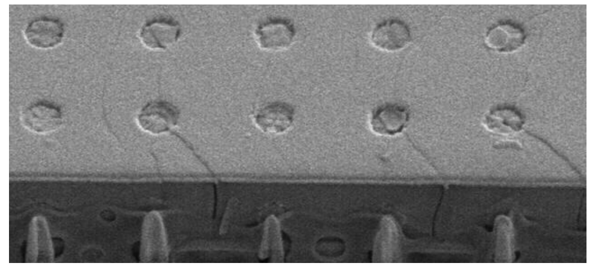


Figure 19 SEM image of cracked pad barrier film and top vias in cratering test after harsh probing, with focused ion beam (FIB) cross section showing the expected vertical cracks in the top SiO_2 film as well as unusual "wavy" lateral cracking of the SiO_2. The white cones along the bottom are portions of top vias.

The top surface cracking on this harshly probed pad is barely visible among the dense top vias, but the local hidden damage is severe, apparently enhanced by the smaller probe tip. In our extensive experimenting with bond pad structures, we find that such hidden damage is unique to pads having top vias, worse as vias are more closely spaced. The structure is mechanically weak in the probed region, and the damage will be enhanced by bonding, but remains localized in this case due to the patterned MT(-1) beneath. Previous data shows that for MT(-1) in a full sheet (100% density), local damage from cracking among top vias is likely to propagate cracks across the pad in bonding, as shown in figure 20.

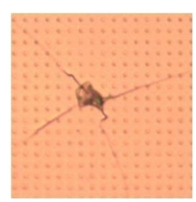


Figure 20 Probe damage enhanced as cracks propagating across the pad after bonding on a pad structure having top vias and a full sheet of MT(-1)

Figure 21 is an FIB of a similar pad harshly probed by the *small-tip* probe card, cut perpendicular to the probe scrub this time. Hidden damage in the SiO_2 between vias is localized laterally where the probe stress was highest, at the "crowns" of the curved probe cracks.

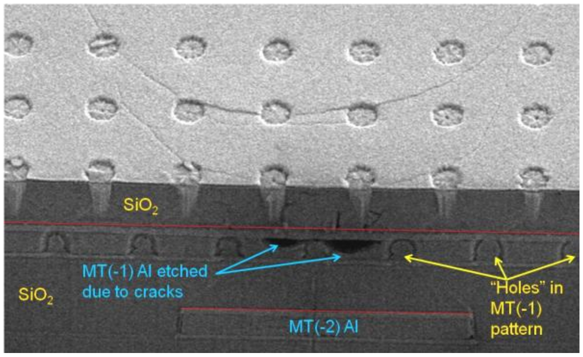


Figure 21 FIB cross section after harsh probing and crater etch showing cracking among dense vias from the *small-tip* probe card (cut is perpendicular to the probe scrub)

The cracking occurs directly over the position of the MT(-2) wide line running parallel to the probe scrub. Red reference lines are to draw attention to the fact that the MT(-2) Al has dipped down in the center, causing a similar dip in the patterned MT(-1) layer above. Some of the cracks extend from the MT(-1) up to the to surface, allowing the crater etch to seep in and remove some Al from the MT(-1) in between the array of holes. Cracks among these vias are not simple vertical cracks. This hidden damage has a significant lateral cracking component in the SiO_2 film, and the mechanical strength of the structure has been destroyed in this region.

Figure 22 is an FIB cross section showing the hidden damage of a *small-tip* harshly probed pad with sparse top vias, as in Table 3, Row D.

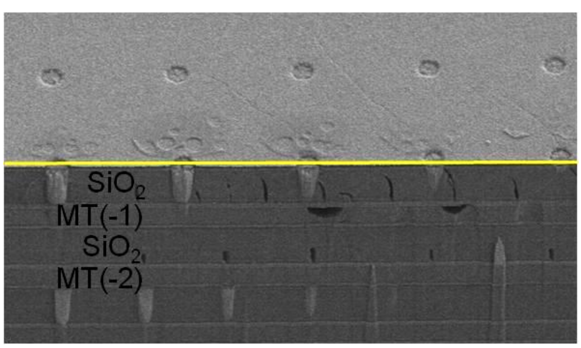


Figure 22 FIB cross section after a cratering etch of the pad structure having 75% MT(-1) density (the MT(-1) holes are not seen in this view) and sparse top vias, probed by the *small-tip* card. Though there are some large cracks breaking the surface, most are hidden in the sub-surface portions of the top two SiO_2 layers. Probe scrub direction was right to left.

This hidden damage may be greater because of the reduced contact area of the tips, concentrating the stress in a smaller region as it scrubs. There are even cracks in the bottom of the top-SiO_2-minus-1 film, which is unusual in our experience.

Summary

This experimental data is in agreement with our previous work. Pads having thin pad Al, top vias in the pad window, and high pattern density in the MT(-1) layer, are very susceptible to SiO_2 cracking due to probing stress. Lowering the pattern density of the MT(-1) layer and removing top vias are very significant factors in making the pad structure more robust against cracking.

This data confirms that higher local stress of probe tips in harsh probing conditions results in more pads cracked. Increased hidden damage in the pad SiO_2 layers is observed from harshly probing with the *small-tip* probe card, especially with top vias present.

For CUP pad designs having sub-layer metal lines running through the pad window, lower MT(-1) and MT(-2) pattern densities are important to ensure robustness against cracking, as reported previously. When such cracks do occur from harsh probing, they don't appear to propagate further during bonding. Harsh probing *across* the sub-layer metal lines results in an additional cracking mechanism that isn't present when probing in parallel to sub-layer metal lines or probing over large area features. Arrays of holes in the MT(-1) and MT(-2) layers are better for making the pad structure insensitive to the harsh probe scrub direction and the ultrasonic direction in bonding.

Bonding process enhancement of probe damage occurs in weak pad structures, resulting in crack propagation across the pad in the direction perpendicular to the ultrasonic motion in bonding, due to the high tension produced in the top SiO_2 film. Any probe damage in the top SiO_2 of a weak pad structure is likely to result in increased crack length after bonding. The appearance of cracking across the middle of the pad from the approximate probe mark position is a fairly certain indication that there was probing damage originally. Interestingly, only pads with MT(-1) of 89% density or higher in this experiment, show the tendency to propagate cracks across the pad during bonding. This is witnessed by cracked pads from all three probe cards, as well as in our previous studies in pad cracking. Stress in bonding, coupled with existing probe ripple and SiO_2 cracks, is being relieved through crack propagation perpendicular to the US motion. Pad structures that are mechanically stronger are less likely to crack from harsh probing, and for the same physical reasons are less likely to propagate probe cracks across the pad during bonding. Probe damage that may occur on a more robust pad will not likely become visible even after bonding; this is good in that the damage stays localized, but bad in that the damage will continue to be unseen and may be passed along to the customer.

Barrier lifting and even cratering is observed after bonding, relating to the original probe damage. Both of these are seen to occur most frequently when top vias are present.

All of the above can aid designers, test engineers, and assembly engineers in understanding the various process interactions and tradeoffs relating to Al – SiO_2 bond pads, probing, and wirebonding.

Conclusions

Mechanically weak pad structures crack the most in harsh probing, as reported previously. Multiple types of cracking are observed due to harsh probing of various pad structures with various probe tips. High stress probing with smaller tips causes more hidden cracking in the pad SiO_2 layers, especially when top vias are present. Bonding can cause probing cracks to propagate across the pad. Probe damage after bonding can result in barrier lifting and even cratering, especially when top vias are present.

The data imply that engineers should place restrictive limits on probe tip force, tip diameter, chuck overdrive, and the number of probe touchdowns to prevent pad ripple and crack initiation during probing of CUP pad structures having thin pad Al. Harsh probing should be avoided in practice because of the risk of cracking as well as hidden damage that is not easily detectable in cratering tests. The use of weaker pad structures having thin pad Al, top vias, and high densities in metal sub-layers should be avoided for high reliability situations. The cratering test after bonding appears to be a reasonable test on weak pad structures to detect damage from both probing and bonding, however additional characterization and monitoring are required in CUP pads manufacturing and high reliability pad situations due to concerns regarding hidden probe damage.

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