Non-Destructive Top Layer Bond Pad Cross Section

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Abstract

Contaminated and corroded aluminum bond pads can lead to a number of reliability failures. Poor wirebondability, false failures at electrical probe due to high contact resistance, opens on RDL layers due to incomplete sputter, and various early life failures during JEDEC testing can all be attributed to excess oxidation and corrosion on aluminum bond pads.

Understanding what layers exist on the bond pad surface is critical. Oxides, hydrates, oxyfluorides and various soups of materials can be confirmed from combinations of Auger, SIMMS and FTIR but there is a chance the die can be damaged and the spot sizes can be problematic picking up information outside the bond pad target. Layer analysis of the pad can also be difficult since sputtering rates vary based on the contaminants on the pad and any thermal processing.

How does one evaluate bond pads without a destructive test? Is there a process for accurate bond pad evaluation while minimizing die damage? Sure. The cycle time and costs of these tests can also be a concern particularly for a customer wanting a quick response from failure analysis.

A better method is to bond the die with a gold stud bump followed by selectively etching away the gold. Etching the gold highlights the intermetallics and shows how much of the gold alloyed with aluminum versus blocked oxides. Voiding can be demonstrated, that might be misconstrued as Kirkendall voiding, by cross sectional analysis.

Key words

Aluminum pad cleaning, bond pad corrosion, gold etch, wirebond reliability,

I. Introduction

Contaminated and corroded aluminum bond pads directly contribute to test yield loss, a multitude of assembly and production issues and various reliability failures. Restated, high contact resistance due to excess "oxidation" and corrosion on aluminum bond pads leads to poor wirebondability, false failures at electrical probe, opens on RDL layers and early life failures during JEDEC testing. This paper will show that yield loss at some back-end process have the same failure mode as some front end processes.

Undesirable oxides, hydrates, hydroxides, fluorides, oxyfluorides and various atomic and molecular species can be confirmed from combinations of Auger, SIMMS and FTIR to populate bond pads on CMOS die. Unfortunately these tests are expensive and time consuming. Limits in sample size that can fit into the tool can be an additional constraint. Only the most expensive tools can be used to evaluate large wafer sections and the beam size (focal spot) of those tools can be larger than the target area. The result is erroneous data as the beam sputters adjacent areas registering the material along with target data. Finally, and equally as important, the beam from these tools is not passive as it mills down into the pad during analysis. The energy from the beam can damage the die both electrically and mechanically. Material can also be sputtered from the pad creating electrical shorts on adjacent pads. Another analytical techniques involves cross sectioning and polishing; both time consuming and costly.

Cross sectioning is the most destructive and time consuming of all the techniques. Sectioning is a hit or miss process as even with the utmost care and preparation; one might miss the target layer which determines the location of defect. With layers as thin as 50 to 100 angstroms the opportunity to reprocess the sample is lost along with the root cause. Combined with the lack of precision and destructive analysis, the "implied" results of cross sections miss another critical parameter, voiding, which will be discussed later. Due to inaccuracies, statistical validation requires multiple samples processed at increasing cost and delays before failures can be confirmed, reliability data accepted and production released.

Even when the location is chosen correctly the preparation cannot reveal true voiding nor can it guarantee sample prep and polishing wasn't the source of the detected failure. Polishing can introduce voids and scratches as the polishing media has defined geometry. A better process would cut the cycle time, minimize process induced variation and reduce the number of samples required to validate results. Such a process would include a selective etch of gold to aluminum. An etch with benign results on aluminum can cut the cycle time and leave the pad intact; non-destructive. After removal of the gold ball the intermetallics can be directly inspected as well as the degree and type voiding (metal to metal diffusion, corrosion or physical/mechanical process induced voiding). As the selective etch does not attack aluminum or the gold-aluminum intermetallics, target pads can be re-wirebonded preserving the integrity of the known good die.

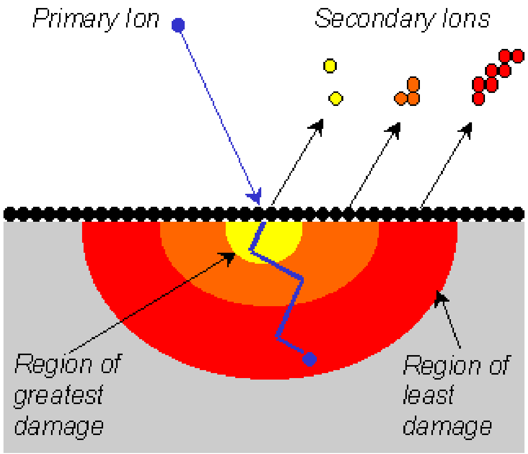

Figure 1. Damaged induced from ion milling. Image courtesy of Physical Electronics

II. DISCUSSION

In this first part of the paper a general and historical overview of pad corrosion will be discussed including how corrosion contributes to test, reliability, and assembly failures of known good die. Next the process for etching the gold will be provided to introduce a "non-destructive" analytical process for quick and reliable assessment of bond pad integrity. Data will then be presented showing pads in various stages of corrosion, etching and the effects of removing the corrosion layers from the pads.

It's a incorrect to simplify the top layer on a bond pad as Al_2O_3, aluminum oxide. There are morphs of "aluminum oxide" with the two most familiar as the oxide that are the large granular nodules on common sandpaper and the other is the mineral sapphire. This oversimplification of aluminum oxidation is not what exists on the surface of an aluminum bondpad nor will it be formed during CMOS wafer processing. One needs to understand bondpad surface morphology to understand the how and why wirebonds don't stick, why poor bond strength occurs, and when sputtering rates during RDL need to be "adaptable" to definitively assign failure modes in a cause and effect analysis. While ion milling rates are based on a aluminum oxide standard, which is hard and durable, the layers on a silicon wafer have little native oxide, are soft and easily sputtered. With inaccurate sputter rates, it's entirely possible the corrosion layer can be removed before the tool begins analyzing the targeted layer leading the failure analysis engineer to incorrect conclusions.

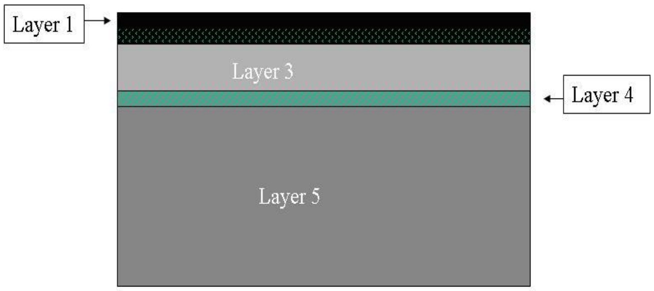

Figure 2. Bond pad and layers:
Layer 1 – corrosion skin
Layer 2 – AlF layer
Layer 3 – Aluminum pad metal
Layer 4 – Adhesion metal (Ti or TiW)
Layer 5 – Substrate (Si)

An analyst might also detect other materials that are part of the mounting process further skewing results. Samples are mounted on special fixtures with a coating that prevent samples from charging and repelling the beam. The sample is then placed in the source chamber which must be pumped to low vacuum levels to prevent reading absorbed atmospheric layers on the die pads. In addition to becoming a potential source of contamination, the conductive coating prevents reclamation of the die for additional electrical validation or reinsertion into production. The layer of "cured conductive epoxy" becomes a permanent part of the sample and is typically neither solderable or wirebondable.

There are two reasons the reliability of the data comes into question. First, as previously stated, samples are coated with a material foreign to the standard CMOS process. Since this coating is not part of the in-situ CMOS processes nor is it part of the qualified packaging material set data obtained is not "usable" as "real" data. That is to say the results would be used for evaluation purpose only since a fully qualified product has a qualified material set as part of final device.

Next, in addition to differing "compositional" layers, there can be deltas in the thickness of these layers over the wafer surface and within an individual die. Layer(s) might be 50 angstroms thick or the layers can be hundreds of angstroms thick. A combination of elemental and molecular milling can be used to verify thickness and composition of corrosion layers on bond pads but the sputter standard is not 100% accurate. Primary aluminum corrosion by-products of hydroxides, hydrates, oxyfluorides, fluorides, and partial aluminum oxides might also include species of silicon, boron, phosphorus, copper, etc, as contributors to "dirty pads". One might mill too deep or not deep enough. How far does the milling need to penetrate into the bond pad? The depth is unknown without milling. And according to physics one cannot study a subject without altering.

LAYERS and HARDNESS

As stated earlier the sputter rate of analytical tools is based on aluminum oxide, a hard and durable material. The Mohs hardness is listed as 9 (corundum is a mineral of Al_2O_3), one of the hardest materials on earth. Yet the surface contaminants have been measured (using a nanohardness tester) revealing hardness ranges similar to gypsum (softer than a fingernail). Depending when and where the analysis is conducted in the wafer processing, the hardness will differ.

Figure 2. Hardness of various materials. Courtesy of Indiana Geological Society.

For example partial oxides of aluminum can become hydrates and hydroxides with continued exposure to moisture. Yielding even softer layers with the consistency and texture of household bar soap how does one determine the milling values to accurately evaluate bond pads? How does one know what to look for in the layers? And how is this done without damaging the sample? Is there a non-destructive test for analyzing the layers without damaging the die?

Ion milling is not the answer. Milling leaves a "hole" in the pad that can damage the die electrically and mechanically. The hole is the artifact that remains as the beam sputters layers to identify the chemical signatures of the pad. As each layer is sputtered away for analysis a hole is drilled deeper and deeper changing the thickness of the bond pad metal. A change of metal thickness would be considered a major change negating, and without requalification, the results to reference status only.

In some cases this author has seen delamination beneath the ion milled pads as a direct result of the reduction in pad metal thickness. Similar thinning can occur during electrical test from the probe needle as it gouges the metal layer. When the metal is thinned the subsequent bonding can penetrate the barrier metal placing aluminum and/or gold directly in contact with silicon. Aluminum spikes and Au/Si intermetallics both contribute to electrical and mechanical failures in the device. Due to the beam width, milling can overlap adjacent areas to the pad. Milling active Si can also damage the die mechanically and electrically as discussed earlier and shown in figure 1.

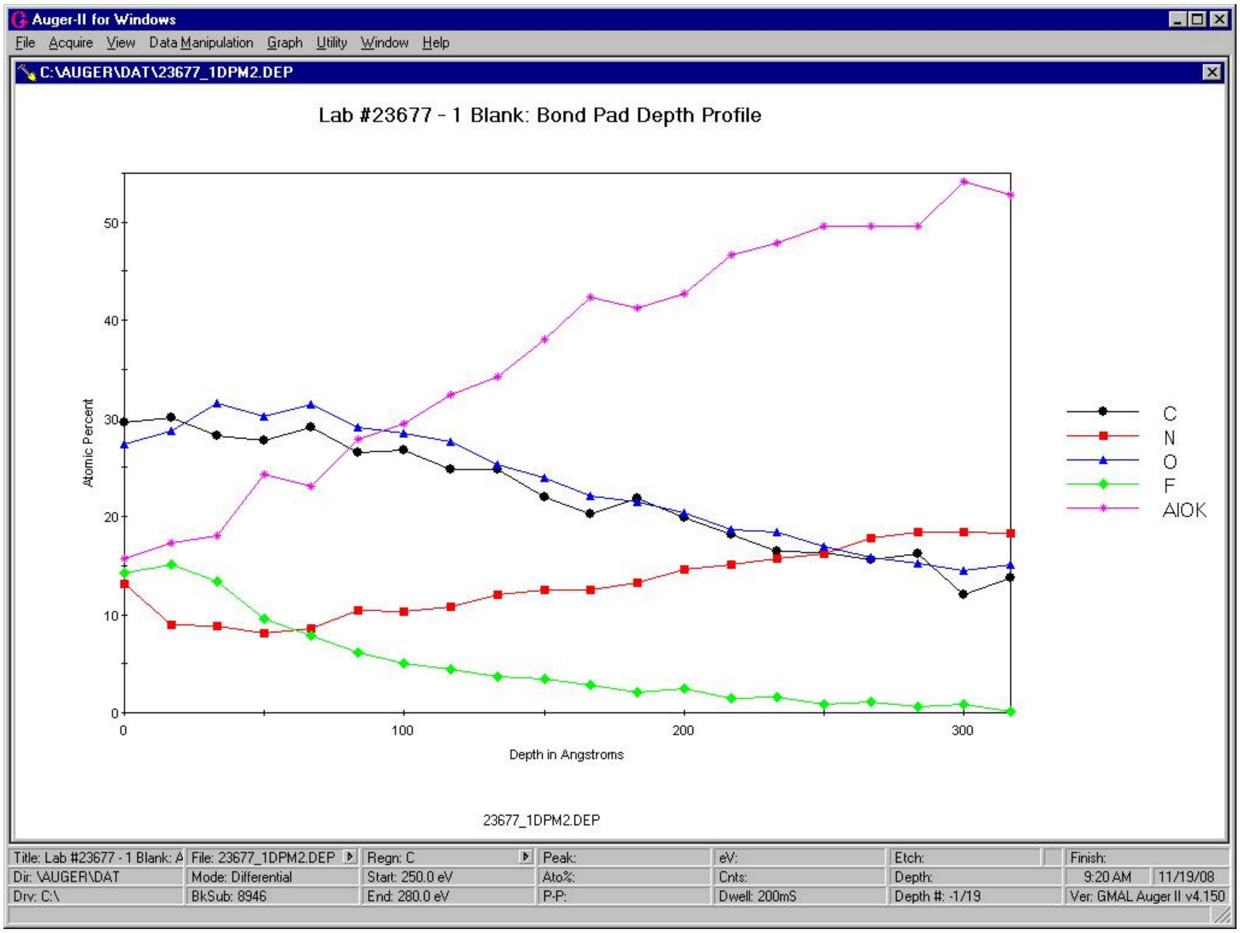

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Figure 3. Ion milling elemental depth analysis. Bond pad sitting in N2 purged dry box two weeks after wafer saw. Note that fluorine levels are detected at 300A depth in the pad. Corrosion makes up close to 50% of the material detected at that depth.

IMPROVED PROCESS

A better method to evaluate the integrity of a wirebond pad is to bond the die with a gold stud bump followed by selective etching away the gold. The process describes the steps to follow when using a single die or smaller section of wafer. A larger wafer would follow the same stages except the need for a carrier wafer is eliminated.

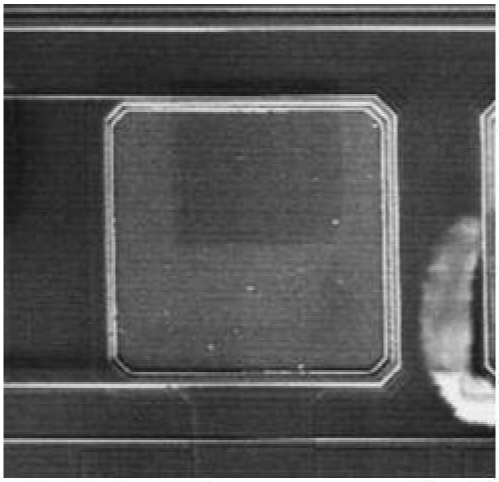

Figure 4. Aluminum pad with ion milling. Note milling extends into the active die area.

First the die is inspected and the condition of the bond pads noted and documented. This would be a good time to image the target pad making note of any obvious features. The sample is then mounted onto a removable sample holder. The die is mounted with polymer followed by a 20 minute cure at 120C. The sample is then allowed to come to room temperature. As needed, the sample can be dry etched in O2 plasma to remove any organic contaminants.

Once the sample has been allowed to come to ambient conditions it should be reinspected optically for damage that might have occurred during mounting, curing and plasma ash. (Care should be used to assure dissipation of any sputter gases and minimizing the O2 time as to not change the molecular species on the pad.) After imaging, any assignable defects are noted then the sample is moved to staging for adding a gold ball. Settings for the wire bonder should duplicate the setting used for qualified product builds. The sample is then placed on the bonder and allowed to equalize to process conditions reflecting time on tool and temperature.

The gold ball bond will only bond to aluminum when aluminum and gold are in direct contact. This contact will occur when contaminants and corrosion on the aluminum are displaced enough to allow intimate contact of the target metals. Only then will an intermetallic of Au-Al form yielding a strong adhesive bond of the gold wire to the aluminum die pad. Ball bonds are placed on the target aluminum pads of the sample die. Once the processing is complete the test die can either be removed or left on the sample holder. The bonded pads and die are once again inspected to document any damage that might have occurred.

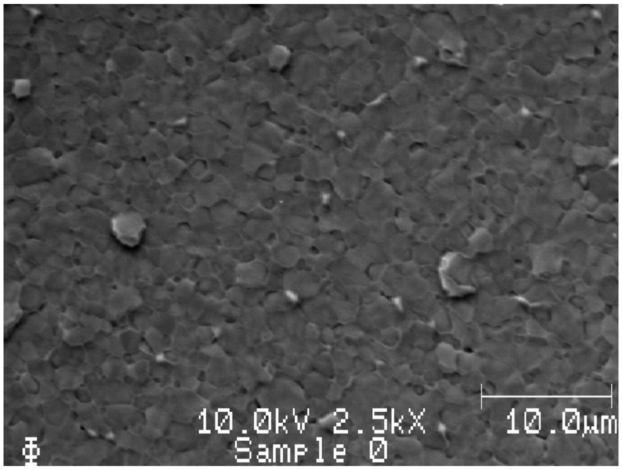

Figure 5. Aluminum pad bond pad (Auger) after two weeks in dry box. Note grains are not clearly defined due to the top corrosion layer.

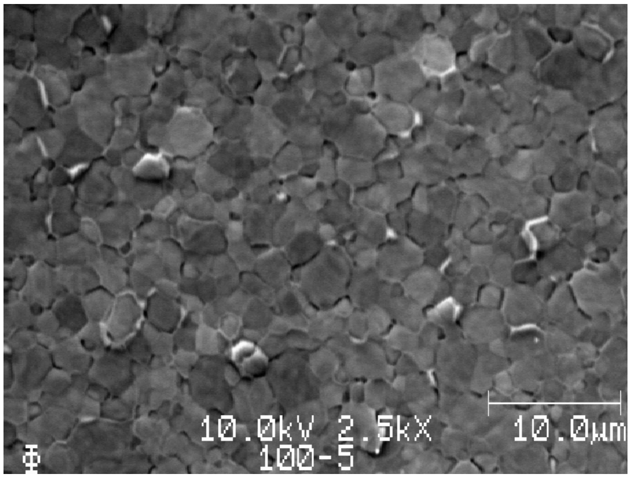

Figure 6. Aluminum pad bond pad (Auger) after two weeks in dry box plus cleaning Note grains are clearly defined indicating the corrosion layer has been removed.

If no damage is observed the die can be non-destructively processed to determine the bondability of the pads. In the next step in a typical wire bondability test there would be bump shear or wire pull test. But here is where a new test method can be inserted. While shearing the gold ball can cause pad metal delamination and scrapping of the die, selective etching leaves the die pad intact, functional and reworkable.

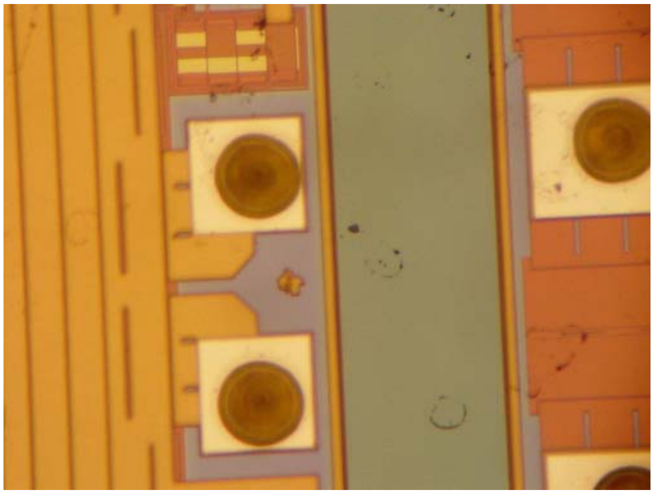

Figure 7. Gold ball bumps on 2 week old aluminum bond pads.

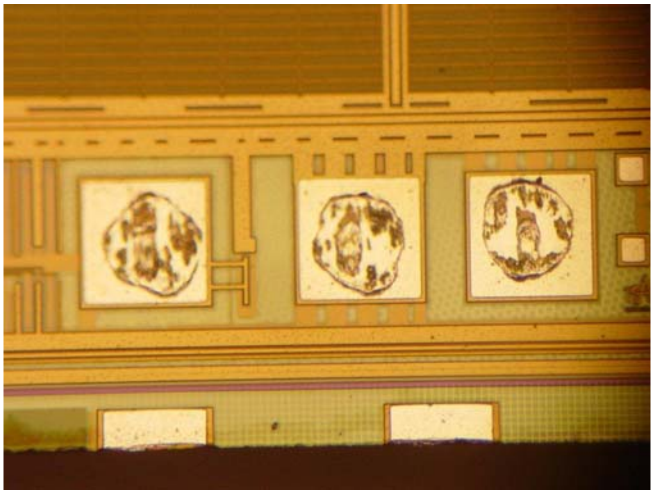

Figure 8. Gold ball removed from aluminum pads. Note the absence of IMC formation under the original pad. Also note the impression remaining after the bump has been removed.

The die plus gold ball bonds are immersed into a selective etch that removes gold and leaves the aluminum metal intact. The selectivity of the etchant has one additional benefit, the Au-Al intermetallic is not etched with the gold. An artifact of the bond imprint remains behind after the gold ball is removed since the etch does not attack the base aluminum base metal. A clean “footprint” of the original bond pad image is clearly imageable and the ball bond area relative to the complete area of the pad can be compared.

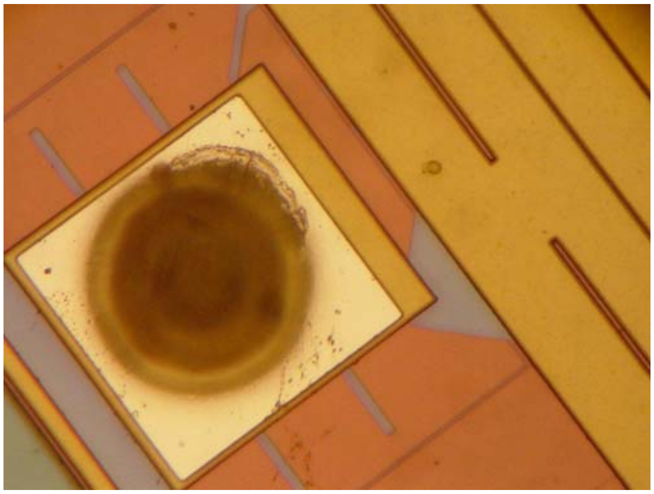

Figure 9. 2nd gold ball on etched aluminum pad. Note the area where the original bump has been etched in the upper center of the pad.

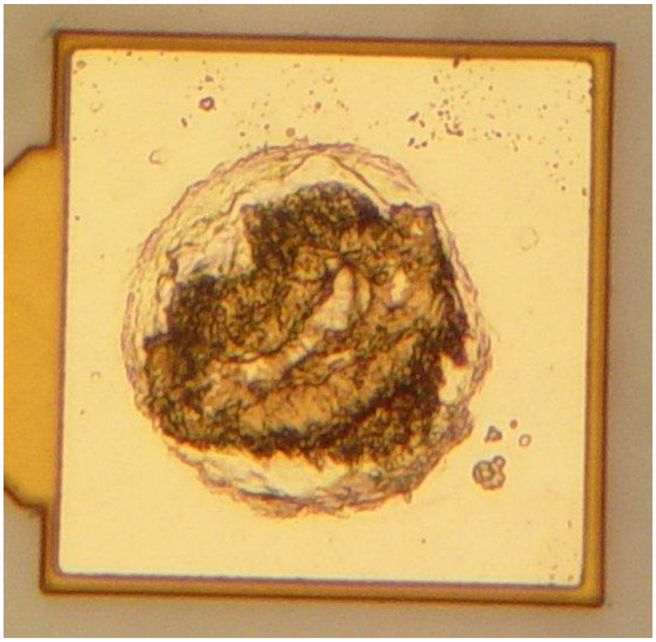

Figure 10. 2nd gold ball etched. Not increased amount of IMC formation compared to original pads.

The image also can be compared to show another important feature of this process. Not only is the area of the bond impression obvious, the degree of intermetallic (IMC) formation is readily discernible as well. The percentage of IMC formed can be measured and compared to the total area under the impression, the area of the ball bond impression and then the area of the IMC not formed under the impression. This ratio serves to demonstrate the degree of bonding between the gold ball bond and aluminum pad.

Acceptable levels of IMC formation and voiding are established by internal customers, JEDEC and external customer requirements. The results show post etch pads with IMC formation as low as 20% and as high as 85% or more. Without the etch process the only method for evaluating IMC formation is destructively. Baseline studies can be used to directly correlate IMC formation with ball shear strength to provide pass-fail historical results by implementing a bump etch inspection stage. Once an acceptable percentage of IMC formation has been established a full non-destructive solution should be implemented. A suggestion is this “pass/fail” criterion is established based on bump size and pad metal conditions (thickness, alloy, etc).

Selective etching provides an unanticipated gift for failure analysis. Polishing can add voids and milling can skip over voids. During bonding the metals intermingle to form a continuous layer when the layer is smooth and unblemished. On a flat “hard” surface layer the gold spreads out during the bonding cycle to form a flat continuous bond layer, void free, at time zero. Unfortunately most aluminum bond pads will not have a “flat”, coplanar and defect free surface. At the minimum aluminum bond pads have a probe impression in the center region of the pad that might be up to 0.5 microns or deeper. (Some probe impressions can be deep enough that adhesion and barrier metals are exposed.) The pad also has topography as a result of grain boundaries, surface contamination, corrosion and galvanic corrosion (aluminum containing alloys of copper) that look like pits. (Aluminum metal is also pushed up during probe to create a pile-up just beyond the probe tip indentation.)

IMC FORMATION VOIDING

The “pitting” of the pad leads to surface voiding but the largest defect is by far the probe mark. When the gold ball bond is attached to the die bond pad the goal is a compressed coplanar interface between aluminum and gold. Since the Al pad is not flat -and- the gold is trying to displace corrosion, contamination and “pile-up” layers from the probe mark to form a good bond its not difficult to understand how poor bonding can occur. When the post impact can be directly measured in the x, y and z etch pad evaluation is conducted to determine the amount of IMC formation, the degree of voiding under the ball dimensions and plotted in the bond area. Selective etching allows direct viewing of the ball impact area, the area of IMC formation and the area of voiding in the ball bond. Adding a tool with a z-measurement stage eliminates subjective and implied results by providing directly viewable and measurable artifacts on the pad.

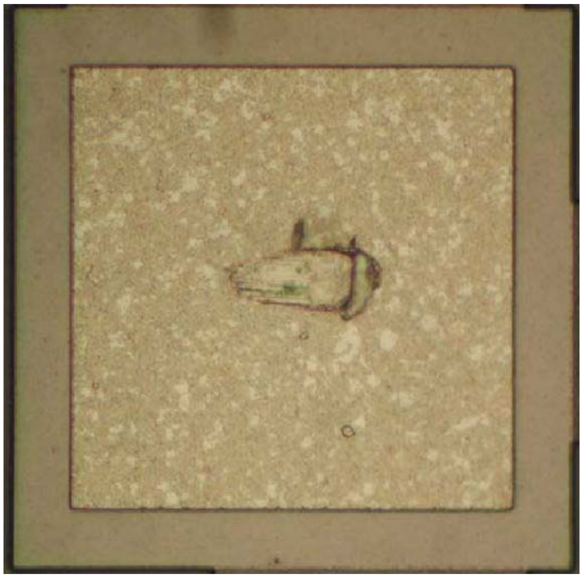

Figure 11. Probe mark on aluminum bond pad showing metal pit and pileup

Measureable “z-artifacts” should be documented prior to bonding. These are the artifacts that will contribute to poor bonding and might be misconstrued as a source of failure. Pitting and other surface topography is readily evident and measureable with non-destructive optical inspection. Some pits will be more noticeable particularly those due to galvanic corrosion. Thus some voiding will be induced prior to time zero bonding and should be documented.

Selective etching allows one to correctly assign voiding due to probe, galvanic corrosion, fab induced etch corrosion, surface topography due to pitting, Kirkendahl voiding. The gold ball bond to aluminum and subsequent IMC formation could cause Kirkendahl voiding so its good practice to document locations prior to bonding. Not only does adding the gold ball bond induce an intermetallic that leads to Kirkendahl voiding, it’s well understood that fluoride and chloride impurities can cause Kirkendahl-like Horsting voiding. Non-destructive testing helps improve reliability predictors.

CLEANED PAD IMAGING

Pads can be cleaned in both wet and dry processes to reduce the corrosion thickness. In this case a wet process developed by CVI was used to remove the corrosion layers. The parts were then bonded to compare to die that were not cleaned. It's clear from the imaging that cleaning the pads can demonstrate a significant increase in IMC formation and a reduction in voiding. A good experiment would be to clean a group of pads and run an uncleaned controlled group though temp cycling to determine if Horsting and Kirkendahl voids can be eliminated or reduced.

III. Conclusion

In addition to fast and cost effective results, accurate and direct root cause can be assigned using selective etching of gold balls on aluminum pads. As discussed earlier in the paper, techniques using mounting and milling can take hours or days. Those older tests are destructive and can only generated implied and suggestive results. The selective gold etch process requires only a short time to mount the die and place a gold stud bump. The etching and subsequent imaging of the pad provides accurate data in less than a few hours from start to finish.

If little intermetallic bonding is detected between the aluminum pad and gold ball, coupled with higher levels of voiding, decreased bond strength will likely be the result. Bonds will fail shear testing and possibly the wire pull test as well. By inspecting the area under the ball non-destructively the analyst/engineer can quickly determine root cause and direct process improvements efforts. This author was able to review die bonds on older die with high corrosion levels on the aluminum pad as a control for such an experiment. The pads were cleaned and the area under the ball reinspected. New shear values were found to exceed 22 grams from an initial value of 6 grams. IMC formation was shown to increase from around 20% to over 80%.

Voids that might have been attributed to Kirkendall voiding can now be assigned with a higher degree of confidence. Not likely due to density changes or solid state diffusion (Kirkendahl voiding) but rather assignable bond pad surface conditions can be correctly listed as the root cause of some voiding. The gold etch process provides a method to directly determine if Horsting voids can be eliminated during life test by elimination of corrosion layers containing halogens.

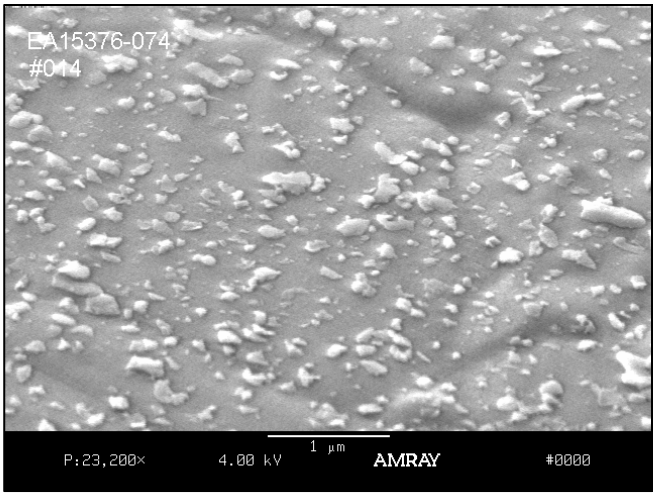

Figure 12. Aluminum pad with corrosion materials on the surface. These materials might falsely show pitting after sectioning and some can lead to Horsting voiding.

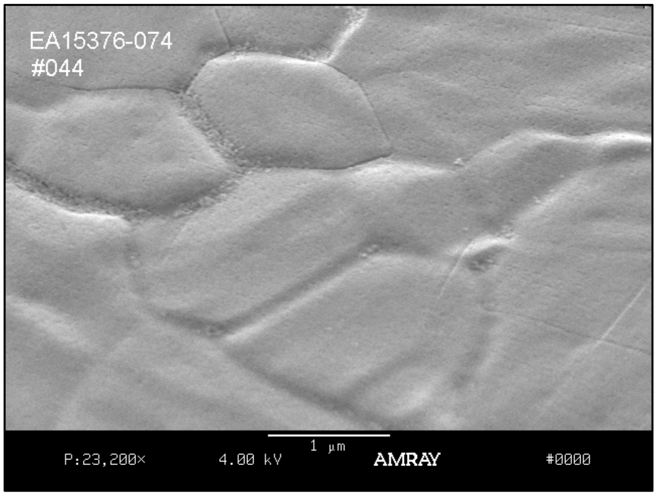

Figure 13. Cleaned pad. Note that there are still small amounts of corrosion within the grain boundaries.

In the past even when bond shear or pull strength exceeded the minimum pass fail criteria the bond could not be accurately evaluated without damage. Cross sections took time and held up production. Aluminum etch processes destroyed the aluminum and any evidence of corrosion on the pad. A new process is available that does not damage the die, is cost effective, and fast.

Acknowledgment

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