Update - Body of Knowledge (BOK) for Copper Wire Bonds (July 9, 2018)

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Executive Summary

Copper wire bond technology developments continue to be a subject of technical interest to the NASA (National Aeronautics and Space Administration) NEPP (NASA Electronic Parts and Packaging Program) which funded this update. Based on this new research, additional copper bond wire vulnerabilities were found in the literature – Crevice corrosion, intrinsic degradation of palladium coated copper wire, congregation of palladium near ball bond interface leading to failure, residual aluminum pad metallization impact on device lifetimes, stitch cracking phenomena, package delamination’s that have resulted in wire bond failures and device failure due to elemental sulfur. A search of the U.S.A. patent web site found 3 noteworthy patents on the following developments: claim of a certain IMC (Intermetallic Compound) thickness as a mitigation solution to chlorine corrosion; claim of using materials with different pHs to neutralize contaminants in a package containing copper wire bonds; and a discussion on ball shear test threshold values for different applications. In addition, an aerospace contractor of military hardware had a presentation on copper bond wires where it was reported that there was a parametric shift and noise susceptibility of devices with copper bond wires which affected legacy design performance. A review of silver bond wire (another emerging technology) technical papers found that an electromigration failure mechanism was evident in device applications that operate under high current conditions.

More studies may need to be performed on a comprehensive basis. Research areas for consideration are suggested, however, these research and or qualification/standard test areas are not all inclusive and should not be construed as the element (s) that delivers any potential copper wire bond solution. A false sense of security may occur, whenever there is a reliance on passing any particular qualification, standard, or test protocol.

Introduction

In 2010, George G. Harman[1] (NIST Fellow) stated: “*Because of price and some mechanical/electrical properties, Cu wire is replacing Au in some applications* …”. As of today, there have been many reports of copper bond wire usage for commercial devices. This current NASA NEPP research is a sequel to the “Body of Knowledge (BOK) for Copper Wire Bonds"[2] that was published by NASA NEPP in 2015. Therefore, this BOK only focuses on the latest technology developments and perspectives for potential future research regarding copper wire bond reliability. The basic copper wire bond fundamentals are described in the aforementioned initial BOK. Some aspects of silver bond wire technology are also discussed.

Topics discussed in this updated BOK include the following: two recent U.S.A. patents on mitigating wire bond corrosion; crevice corrosion; aluminum bond pad corrosion; two papers regarding degradation of palladium coated copper wire bonds; palladium congregation in first bond of palladium coated copper wire; six new reports on the development of palladium coated copper wire with gold flash; importance of aluminum bond pad thickness; copper wedge bonds on silver and nickel-palladium-gold-silver metallization; wire bond shear test method revision; copper ball bond shear test threshold values in a U.S.A. patent; copper stitch bond cracks; copper wire bond failure due to corrosion/delamination resulted in device failures; copper bond pads; sulfur compounds in epoxy packages; destructive pull tests results on some commercial devices with copper wire bonds; silver wire bonds; and two 2017 NEPP Workshop presentations that cited copper wire bonds.

Potential research studies in the following areas may be considered: 1. researching the feasibility of implementing a stringent destructive bond pull test specification for copper wire bonds to assure a higher safety factor. 2. Investigating copper ball bond shear test statements that were reported in an U.S.A. patent for potential applicability in a shear test. 3. Investigating the appropriateness of a potential IMC thickness and /or IMC coverage specification in a qualification document.

U.S.A Patent Releases on Mitigation of Copper Wire Bond Corrosion

The following two patents show different approaches for mitigating the copper wire bond corrosion issue.

First, the US Patent Number 9,646,950 B2 which was dated May 9, 2017 is the leadoff to this BOK update. For the aforementioned patent, Kejun Zeng et al.[3] provided the following introductory summary which explained the need for obtaining an industry solution in order to mitigate chlorine induced copper bond corrosion:

"Applicants realized that semiconductor packages cannot be completely free of chlorine, since chlorine is involved in certain wafer manufacturing processes; further, molding compounds and laminate substrates may contain low ppm levels of chlorine; and leadframes may have chlorine in surface coatings because the plating baths contain chlorine. In short, efforts to make assembly and packaging systems cleaner are important but not enough.

It is equally important to prevent chlorine from migrating into metal interfaces and concentrating to the level at which corrosion of the copper-aluminum intermetallic compounds between copper ball and aluminum pad, or even the aluminum pad itself is triggered. Applicants solved the problem of copper-aluminum intermetallic corrosion even in relatively cleaned-up systems when they discovered a methodology of growing the intermetallic layer to a thickness where the interfacial bonding is so strong that the probability of crevice formation in the interface is reduced. In the methodology, continuous intermetallic layers of $CuAl_2$ *and* Cu_9Al_4 *are grown by one or more cycles at temperatures between 250 to 270° C. and time periods from 20 to 40s."*

Based on this process methodology for ensuring robust copper bonds on aluminum metallization, Kejun Zeng et al.[4] documented the following patent claim number nine:

"*9. The method of claim 1, wherein the layer of copper-aluminum intermetallic compound is about 273 nanometers thick.*"

Caution may be warranted on the implementation of any IMC thickness specification since it is not known which device types and device lifetimes this aforementioned patent was targeted. Since IMCs grow with time and temperature, there may be an unintended deleterious device effect if the IMC thickness is initially set at an inappropriate level. As an example, for a state of the art high speed device, it is not known if an initially high IMC thickness could result eventually in a lower device lifetime. For devices which may operate at high clock rates, the increased electrical resistance of an IMC layer with a growing IMC thickness may potentially impact device performance with operating time.

Second, an alternate approach to mitigating the copper wire bond corrosion issue is provided by US Patent Number 9,508,622 B2 dated November 29, 2016. Essentially, this patent uses materials with two different pHs to neutralize potentially corrosive contaminants to prevent corrosion of the copper wire bonds, copper wires and aluminum bond pads.

In this aforementioned patent, Leo M. Higgins III[5] documented a total of 20 patent claims of which the first one states:

"1. A method for encapsulating a semiconductor device, the method comprising: forming a plurality of wire bonds on a surface of the semiconductor device by bonding each of a plurality of copper wires onto corresponding ones of a plurality of aluminum pads; covering the plurality of wire bonds with a protective material having a first pH; and depositing encapsulating material over the semiconductor device and the protective material, the encapsulating material having a second pH, wherein the first pH of the protective material is for neutralizing the second pH of the encapsulating material."

Crevice Corrosion

M. van Soestbergen et al.[6] provided the following conclusion regarding crevice corrosion on studies performed on copper and silver bonding wires:

"From the results reported here, we conclude that aluminum smear [i.e. aluminum that has pushed been aside by the ball bond] *adjacent the bond ball can lead to an initial crevice. In this crevice an oxygen deficit can occur, which leads to a local acidification of the epoxy mold compound, and consequently a local increase in chloride concentration. Both these conditions will accelerate the corrosion process of the intermetallic layer formed between the bond ball and pad. Therefore, it is highly advisable to avoid aluminum smear, which can be achieved by using a sophisticated wire bond process."*

Aluminum Bond Pad Corrosion

O. Chyan et al.[7] had the following introduction on aluminum bond pad corrosion with copper wire bonds that is relevant to recent technological developments as follows:

"However, corrosion-related failures need to be minimized to ensure packaging reliability. Specifically, Aluminum (Al) bond pads are particularly susceptible to corrosion with a characteristic "mud-crack" appearance. Such corrosion can be a critical failure mode for Cu wire-bonded assemblies, especially under harsh conditions such as automotive environments. The emerging trend of wearable electronics also imposes new, more stringent packaging reliability requirements to ensure corrosion protection from sweat/mud/rain in all-terrain non-stop usage conditions. In addition, the recent transition to non-lead SAC (Sn-Ag-Cu) solder necessitates the use of stronger flux (2-3%) and higher reflow temperatures (~260°C) that can leave flux residues and ion contamination to initiate corrosion."

Additionally, an excerpt from the conclusion section of O. Chyan et al.[8] is presented:

"The corrosion mechanism of aluminum bond pad corrosion was established and the bimetallic contact in the presence of Cl^- ions was found to be the driving force for the reaction to propagate rapidly. Hydrogen evolution was observed for the first time and was attributed to the cathodic reaction of the corrosion electrochemical cell. A new inhibitor coating was found to give excellent corrosion protection by blocking the cathodic hydrogen evolution."

Three Papers Regarding Palladium Coated Copper (PCC) Wire

In the first NEPP BOK, it was stated that some package assemblers were using palladium coated copper wire instead of pure copper wire to prevent copper corrosion. The benefits of using palladium coated wire were documented as both reliability improvements and production enhancements. However, new research has provided more insight on issues regarding the degradation of palladium coated copper wire.

First, J. C. Krinke et al.[9] have performed research on palladium coated copper (pcc) bond wires and discovered that there was an intrinsic "*thermodynamically driven degradation mechanism of pcc-wires*" which was summarized in the conclusions of their technical paper as follows:

"We found an intrinsic degradation of pcc-wires at HTSL [i.e. High Temperature Storage Lifetime] *conditions above 150°C. The mechanism is driven only by temperature and we conclude that a crack of the Pd coating is necessary to start the degradation. However, more extensive investigations are necessary to understand the physical mechanism of the degradation in more detail.*

Pcc-wires from three different wire suppliers show the same degradation mechanism. An additional Au coating seems to have no influence. The effect can be observed in fully processed devices and also at non-molded pcc-wires from the spool. In our investigations bare Cu bond wires did not show this degradation mechanism.

Mission profiles of automotive applications often include a considerable proportion of time at temperatures above 150°C. The reliability of pcc bond wire connections may be affected by the described degradation.

The BPT [i.e. Bond Pull Test] *values in this investigation still fulfill the AEC-Q100 grade 0 requirements (1000h@175°C). However, after 1500h@175°C HTSL condition some BPT values are below the MIL standard limit for Au bonds after molding. Therefore this degradation mechanism has to be taken into account for mission profiles beyond AEC-Q100 grade 0."*

It should be noted that most NASA applications subject electronic parts to operating temperatures well below 150°C.

Second, in regards to voids in ball bonds produced from palladium coated wire, Chu-Chung (Stephen) Lee et al.[10] stated the following in the Abstract:

"Bare copper wire has presented several challenges to both first and second bond wire bonding processes, such as Cu-Al intermetallic compound (IMC) corrosion induced by the mobile chlorine in the epoxy resin of the mold compound, and the narrow second bond process window. Palladium (Pd) coated copper wire has been developed to overcome these two challenges. However, the use of Pd-Cu wire is not a panacea to all Cu wire bond problems. One unique anomaly for Pd-Cu wire is the Cu ball void [Chu-Chung (Stephen) Lee et al.[11]] *which is observed only with Pd-Cu and not bare Cu ball bonds during HTSL (high temperature storage life) tests. The mechanism of forming Cu ball voids was proven to be the galvanized corrosion mechanism with Pd-Cu coupling. Significant factors affecting the formation rate of Cu ball voids are baking temperature, EFO current settings, bonding parameters and mold compound additives."*

In addition, Chu-Chung (Stephen) Lee et al.[12] provided the following information in the "Summary and Conclusion" section:

HTSL test should only be carried out at 150°C for Cu wire parts. Parts baked at 150°C for 2000 hours do not show any sign of Cu voids and at 175C for 504 hours can show severe Cu voids. Any Cu void observed at 175°C or above temperature should not be considered as a failure and used to represent actual field condition."

Third, Ivy Qin et al.[13] investigated the differences between copper wire and palladium coated copper wire of which two of their conclusions were:

"*This work compared 1st bond and 2nd bond wire bonding processes, 1st bond reliability and IMC formation for Cu and PdCu wire. TEM shows that ~80 nm Pd coating dissolves into the Cu bulk during ball formation process, and almost no Pd is present at the bond interface in the as-bonded state. Therefore, the 1st bond bonding results of PdCu and Cu wire are very similar prior to bake. However, Pd congregates and diffuses back to the bond interface, especially, a Pd-rich layer forms in the peripheral interface. The congregation of Pd near the interface is detrimental to the bond strength, causing high peeling failure after bake.*

For 2nd bond bondability, PdCu wire tends to have an advantage. Tail pull strength in the measured samples was 50% higher with PdCu wire than Cu wire, indicating a more robust 2nd bond process …".

Development of Palladium Coated Copper Wire with Gold Flash

Recently, there have been the following 5 new reports on palladium coated copper wire with gold flash:

First, Chia-Yun Chang et al.**[14]** reported in the conclusions section that:

"*The corrosion resistance of PCA* [Palladium-coated Copper wire with gold flash] *was found to be good. Although the metallurgic mechanism of FAB* [Free Air Ball] *formation affected the palladium segregation, it did not affect the gold distribution. The neck zone and HAZ* [Heat affected Zone] *were both affected by heat after the EFO* [Electric Flame-Off] *process, so the grains grew while the hardness and strength reduced. The flash gold layer has many benefits, including enhanced bonding strength, mitigation of intermetallic compound production, and maintaining desirable interface electrical properties."*

Second, in regards to gold flash palladium coated copper wire (AFPC), based on experimental results of a wider stitch bond process window and higher stitch bond pull results with a lower standard deviation, S. Murali et al.**[15]** reported the following in the summary:

"*AFPC has better 2nd bond performance than PCC."*

Third, on July 6, 2017, Microchip Technology Incorporated issued an initial Product Change Notice – JAON-22CDLC928[16] on the notification subject entitled "CCB 3000 Initial Notice: Qualification of MMT as an additional assembly site using CuPdAu bond wire in selected products of the 150K and 160K wafer technologies in 28L SSOP package" in which the "Reason for Change" was defined as:

To improve productivity by qualifying MMT as an additional assembly site using palladium coated copper with gold flash (CuPdAu) bond wire."

Fourth, on February 20, 2018, Microchip Technology Incorporated issued a Product Change Notice – KSRA-01PQCU581[17] on the notification subject entitled "CCB 3093 Cancellation Notice: For the qualification of ASSH as a new assembly site for ATA6836C-TIQW Atmel catalog part number CuPdAu bond wire available in 28L SOIC package". For clarification, Atmel was acquired by Microchip in 2016. The following "Reason for Change:" was provided:

"*Microchip has decided not to qualify ASSH as a new assembly site for ATA6836C-TIQW Atmel catalog part number (CPN) using palladium coated copper wire with gold flash (CuPdAu) bond wire available in 28L SOIC package*".

In regards to this cancellation notice, it should be noted that the initial notification, dated June 01, 2017, is no longer posted on the Microchip PCN web site. However, for the same Atmel device part number, Microchip did release on October 2, 2017 the Product Change Notification – KSRA-01WWMB099[18] on the notification subject entitled "CCB 3095 Initial Notice: Qualification of ASSH as a new assembly site for ATA6836C-TIQW Atmel catalog part number (CPN) using gold (Au) bond wire available in 28L SOIC package." The following "Reason for Change" was provided:

"*To improve on-time delivery performance by qualifying ASSH as new assembly site*."

Fifth, on March 29, 2018, Microchip Technology Incorporated issued a Product Change Notice – LIAL-26JKUB646[19] on the notification subject entitled "CCB 3300, 3300.001 Initial Notice: Qualification of CuPdAu wire in selected products of the 0.18 um wafer technology available in 100L and 64L TQFP packages at MTAI assembly site." In summary, the change is from gold bond wire to palladium coated copper with gold flash bond wire with the following "Reason for Change':

"*To improve productivity by qualifying palladium coated copper with gold flash (CuPdAu) bond wire*".

Importance of Aluminum Bond Pad Thickness

A. Lassnig at al.[20] researched copper ball bond fatigue integrity on a 5 micron thick aluminum metallization using high temperature storage test temperatures at 150 degrees C. and 200 degrees C. and by using a novel ultrasonic fatigue fixture that could apply between 10^5 to 10^9 loading cycles to the ball bonds. The rationale for the special fatigue fixture was provided in the aforementioned technical paper:

"In contrast to standardized static test techniques this method is particularly sensitive to interfacial evolution like intermetallic compound formation and reveals the weakest link in a bonding interface."

A. Lassnig et al.[21] offered the most important conclusions:

"It is shown that the crack propagates through the Al pad material, final fracture however occurs in the most brittle site. This study reveals that lifetime of Cu-Al bonds is directly related to the amount of residual aluminum pad metallization.

For the reliability of the investigated Al-Cu ball bond interface it may be concluded that it is crucial to ensure a throughout, residual aluminum layer below the evolved intermetallic compounds. The manufacturer guarantees reliable bonds annealed at 150°C up to 10 000 h, this microstructural end of life corresponds to an annealing treatment at 200°C for 256 h."

It should be noted that the A. Lassnig et al.[22] adjusted their bonding profiles "*to ensure a residual pad thickness of 2-2.5 um below the Cu ball.*"

In applying finite element analysis to the wire bonding bond pad design, Chai Chee Meng et al.[23] have used the Mass-Springs equation and Infineon Technologies in-house materials models along with experimental test chip assessments as a basis for creating a virtual copper wire bonding prototyping technique which resulted in the following summary:

"Wire bond design and bond process virtual prototyping has been successfully developed and implemented for backend IC packaging development. The simulation assessment results have shown a very good correlation with the test chip sample measurement results. The explicit transient dynamic simulation result has highlighted higher risk of under-pad metallization damage during the wire bond process in the case of 6um thin Cu bond pad design as compared to 11um and 22um bond pad designs.

In addition to bond pad design, Chai Chee Meng et al.[24] have used finite element analysis for wire bond process optimization per the following summary assessment:

"The virtual prototyping results have provided supplemental information to the bond pull test and bond shear test assessment results which can help the development engineer to further optimize the process before physical prototyping. With the newly developed wire bond virtual prototyping methodology, screening of wire size and wire material, capillary selection and wire bond process parameters optimisation can now be implemented simultaneously and the assessments can help to fine tune the wire bond process such that qualification of new devices can be accelerated."

As a final note, to uncover those defects underneath bond pads that could lead to early-life electrical failures, it is important to ensure that any qualification includes appropriate tests that could detect such defects. These tests would be especially important to implement for devices that use materials such as the fragile low-k dielectrics and/or copper interconnects.

Copper Wedge Bonds on Silver and Nickel-Palladium-Gold-Silver Metallization

In order to improve the mechanical strength of the copper second bond (i.e. wedge bond), Rosalina Ismail et al.[25] performed a number of experiments where the ball bond was attached to aluminum metallization and the second bond was affixed to either a silver metallization or a nickel-palladium-gold-silver metallization and arrived at the following conclusions:

"The Cu second bond on Ag metallization was found to have higher value of pull strength compared with that of Ni/Pd/Au/Ag metallization. … The Cu second bond on Ni/Pd/Au/Ag metallization also exhibited a smaller contact diameter compared with that on Ag metallization and this may due to limited formation of mechanical interlocking and diffusion. The characteristic area was found to be useful in obtaining the pull strength of the second bond because it has a proportional relation with second bond pull strength."

Wire Bond Shear Test Method

In April 2017, the JEDEC Standard JESD22-B116B[26] (Wire Bond Shear Test Method) had a major update to include sections on copper wire bonds that had references to the following topics:

- Paragraph 2.1 "ball bond:"
- Paragraph 4.2.1 "Bond pad examination and acceptability criteria for both Al and Cu bond pad metallization"
- Paragraph 4.2 "Visual examination of bonds to be tested after decapsulation"

- Paragraph 4.2.2 “Copper bond and Cu wire examination and acceptability criteria”
- Paragraph 4.6.1.2 “Type 1 – bond lift – copper/aluminum, copper/copper, and gold/gold”
- Paragraph 4.6.2.2 “Type 2 – bond shear – copper/aluminum, copper/copper, and gold/gold”
- Paragraph 4.6.2.3 “Type 2 – bond shear on leadframe/substrate”
- Paragraph 4.6.3 “Type 3 – cratering”
- “Annex B (informative) Performing this test method on ultrasonic wedge bonds”
- “Annex C (informative) Performing shear testing when tool cannot reach below centerline (con’d)
- “Annex D (informative) Concerns with decapsulation processes for devices with copper wirebonds”
- “Annex E (informative) Bond contact area – Valid method for comparing shear force”

Reported Copper Ball Bond Shear Threshold Value in US Patent 9,257,403 B2

Now that a shear test method for copper wire bonds has been established in JEDEC Standard JESD22-B116B, one can find insight on what the actual shear test results could be by referencing the United States Patent US 9,257,403 B2 entitled “Copper Ball Bond Interface Structure and Formation” in which Tu-Anh N. Tran et al.[27] stated:

“To achieve an even higher level of temperature cycling reliability performance, such as the AEC Grade 0 automotive test standards, the minimum threshold value for the BSPA [average ball shear per squashed ball area] *metric≥9.0gf/mil*^{2}*. In selected embodiments, a highly reliable copper ball bond requires that a plurality of the specified geometric structural bond features are formed to have a ball shear strength/area measure that meets or exceeds a minimum threshold value (e.g., 7.5-9gf/mil*^{2}*), depending on the testing requirements.”*

As an example for illustration, for a 1 mil diameter pure copper wire, the minimum ball shear results that are required for copper ball bonds using the above cited value of 9.0gf/mil^2 for a 3 mil squashed ball bond diameter is calculated to be approximately 64 grams.

Copper Bond Stitch Cracks

M. van Soestbergen et al.[28] reported that:

“*Stitch crack is a recurring failure mechanism for many years in semiconductor packaging. Currently, the combination of highly filled mold compounds, and copper wire increases the risk for stitch cracks after temperature cycling (TC). Firstly, highly filled mold compounds generally have a Coefficient of Thermal Expansion (CTE) that is much lower than that of copper, and a much higher elastic modulus compared to traditional compounds, which results in a higher stress on the bond wire compared to traditional compounds having a CTE that matches the CTE of copper. Secondly, the copper wire experiences large plastic deformation while forming the stitch during wire bonding at elevated temperature, which leads to local ‘embrittlement’. The combination of both effects, i.e., increased stress, and resistance to fatigue, leads to a higher risk of cracking.*”

In addition, M. van Soestbergen et al.[29] used a simulation model to calculate the von Mises stress on a SO package with delamination and came to three conclusions of which the third says:

"*Delamination is a pre-requisite for stitch crack fails, as stresses increase significantly for delaminated copper-mold compound interfaces.*"

Copper Wire Bond Failure due to Corrosion/Delamination Resulted in Device Failures.

A semiconductor manufacturer had integrated circuit device failures due to copper wire bond failures. An independent failure analysis company provided the following SEM image of the corroded copper stitch bond remnant along with their failure analysis conclusion below Figure 1[30]:

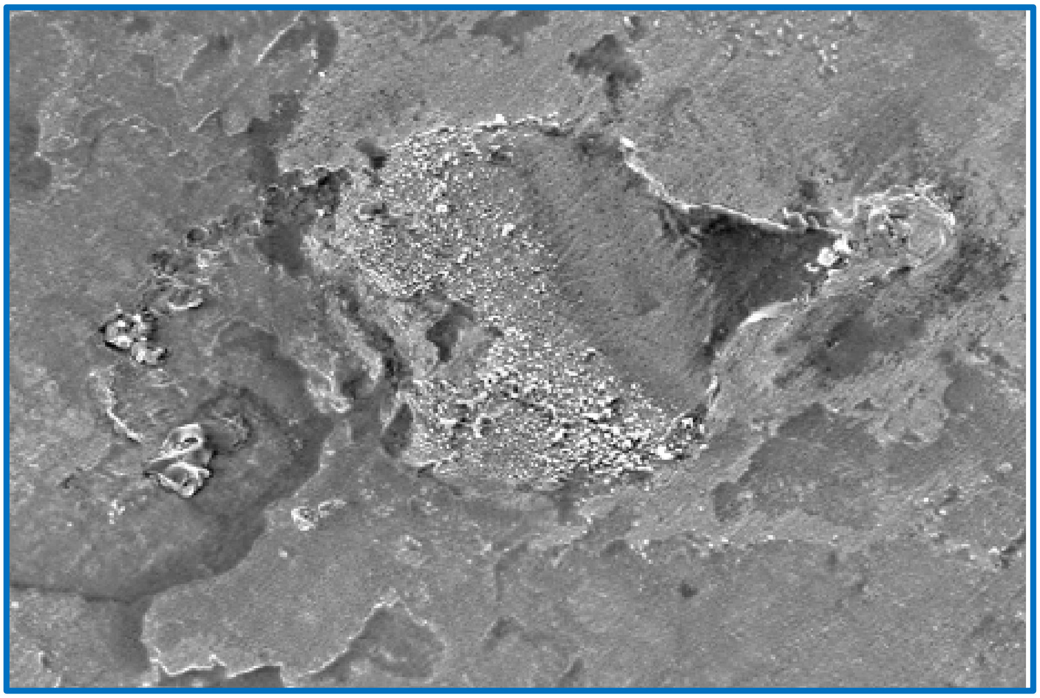

Figure 1: SEM image of a corroded copper stitch bond.

"*The failure of the devices was verified. No anomalies were noted during external or radiographic inspection. Electrical testing revealed open circuits in each of the failed samples. CSAM revealed varying degrees of delamination in all 16 samples. Optical and SEM inspection of the failed devices after cross-sectioning and mechanical decapsulation of the lead frame revealed that the copper stitch bond wires were corroded from chlorine contamination. Inspection of the non-failed samples with copper bond wires revealed early stages of corrosion from chlorine contamination. Four of the non-failed samples used gold bond wires which were resistant to corrosion, however, chlorine contamination was also noted on the lead frame of these samples.*

The failure of these integrated circuits was caused by the corrosion and open circuiting of the copper stitch bonds. The copper was corroded by chlorine contamination, most likely from solder flux, which wicked along the leads into the device via delamination between the lead frame and the encapsulant. The delamination was most likely caused by thermal shock during soldering.

It is recommended that CSAM be utilized to determine if future samples have delamination between the lead frame and the encapsulant."

Copper Bond Pads

In regards to alternate bond pad materials other than aluminum, Preeti S. Chauhan et al.[31] provided the following narrative:

"*Cu metallization has replaced Al as the preferred interconnect because it has better electrical performance and higher speed for fine-pitch application. However, Cu is harder than Al and prone to oxidation; therefore, it cannot be easily probed and wire bonded. Coating Cu pads with a noble metal, such as Au and Pd, or a harder metal, such as Ni, addresses these* problems [Tu Anh Tran et al.[32]]. *However, Ni is not bondable by itself, as it forms an oxide layer upon exposure to air. To provide a bondable surface, Pd or Au plating is applied on top of Ni. Electroless Pd is a cost-effective alternative that provides a bondable surface for Cu wire bonding. The NiPdAu surface finish has a diffusion barrier provided by Pd and Ni. …. The bonding of Au or Cu on a Cu pad is challenging because of the tendency of the copper metallization to oxidize. For this reason, bare copper pads are not used in the industry*."

In addition, copper bond pads with a protective organic coating were researched by Kan Wai Lam et al.[33] who concluded with five paragraphs of which the following two (i.e. first and last paragraphs) are provided:

"*The success of fine pitch copper wire bonding on copper pad is based on the development of an organic coating that is able to protect the copper bond pads from dicing till wire bond stage."*

"*The ball bonds formed by gold and copper wire bond on the organic coated copper bondpad are stable in ball shear strength up to a period of 1440 hours at 150°C."*

NEPP has not researched the entire universe of copper bond pad papers with organic coatings, but would caution the reader about the effects of contamination on gold bond pads that were documented by C. W. Horsting[34] who reported back in 1972 four conclusions of which the following two are presented:

"*The "bondlift" type of failure, observed in this study, was shown to be caused by the presence of impurities in the gold."*

"The failure mechanism appears to operate through formation of a voidlayer, which results from impurity accumulation ahead of the Aluminum-Gold diffusion front."

It is unknown whether or not a similar contamination related failure mechanism is possible with copper wire bonded to organic coated copper bond pads.

Sulfur Compounds in Epoxy Packages

In researching the root cause of an IMC layer crack during a high temperature storage test, Mingchuan Han et al.[35] reported the following:

"*Failure analysis showed element sulfur was found on the periphery of bonded ball and under the bonded ball. The Sulfur was suspected to be root cause to the IMC layer crack. … Regarding copper wire bond pad/IMC interfacial crack, IMC coverage and sulfur content of epoxy molding compound should be considered seriously*."

Mingchuan Han et al.[36] provided the following reason for using sulfur content in epoxy packages:

"Many molding compound contain specific components which are sulfur based compound which could improve adhesion to lead frames and resin to filler [Varughese Mathew et al.[37]]. … *Based on Control experiment, the sulfur content of epoxy molding compound plays vital role in device performance under thermal treatment."*

Silver Wire Bonds

Lee Levine[38] reported in 2016 the following:

"*Early problems with silver wire in 85°/85% relative humidity were resolved using silver-palladium alloy wire. Silver market share is now approaching 10%."*

Hao-Wen Hsueh et al.[39] researched silver alloy wire (Ag-8Au-3Pd) using the dynamic current tensile test (DCT test) and arrived at the following conclusion:

"In conclusion, the dynamic current tensile test is an effective method to simultaneously investigate the effects of electrical current, Joule heat, and tension on the reliability of fine wires. Compared to Pd-coated Cu wires, the tested Ag-based wires had lower tensile strength and elongation in the current stressing test because Cu features superior electromigration resistance than Ag. Massive electromigration induces many voids and cracks at the grain boundaries in Ag-based wires, both of which later propagate to form intergranular fractures. Hence, although Ag-based wires are applied in the microelectronics packaging industry, the working current must be lower than that in Cu-based wires to prevent failure."

Subramani Manoharan et al.[40] reviewed the advances in silver wire bonds and reported in 2017 their conclusion of which the following excerpt is provided:

"*With the increasing price of gold and reliability concerns with copper in harsh environments, silver is emerging as an alternative. Material properties of silver, such as elastic modulus, hardness and conductivity make it good wire bond material. … Failure modes, mechanisms and causes were presented that needs to be addressed before adopting silver in the harsh environment application. Intermetallic compound growth, corrosion and electromigration were identified to be possible failure mechanisms that could lower wire bond reliability*."

Serangapani Muarali et al.[41] experimented with silver alloy bonding wire and arrived at several conclusions including:

"*On thermal ageing, formation of silver-aluminide is slower than gold-aluminide, Kirkendall voids do not form at the interface." …. "However, ball shear of greater than 7.5g/mil^2 and 80-95% intermetallic distribution (centre and periphery, after pre-thermal treatment) perhaps stands as a good criteria to evaluate at the shop-floor for Ag ball bond."*

Jiaqing Xi et al.[42] experimented with 95% silver wire on high frequency RF devices in DRQFN and BGA packages and arrived at a number of conclusions of which the following are a sample:

"*… However, the hardness of copper makes it difficult to be used in many applications such as those with fragile bond pad structures and thin Al pad. For these applications, Ag-Alloy offers properties similar to* *those of gold while its cost is similar to that of PCC. Unfortunately, Ag wire cannot be used in all wire bond devices. In this study the following limitations for 18 um 95% Ag wire and other related factors are found.*

- *Free-Air-Ball (FAB) size less than 31um is prone to voids & nodes defect. Thus, in order to form a defect free Ag FAB a minimum 35 um ball size is required. The corresponding minimum bond pad opening (BPO) for 35um FAB is 45 um.*
- *Several Ag wire devices with 57 um BPO have been qualified and in high volume production without quality issue. However for Ag wire devices with 40 um BPO the risk of qualification failure is high due to small FAB size constraint."*
- *EDX shows all open failures are due to IMC corrosion by Chlorine. Migration of Chlorine during HAST condition will cause formation of Al oxide which result in the wire ball lift after reliability test*."

2017 NEPP Workshop at NASA Goddard Space Flight Center

At the 2017 NEPP Workshop, a number of failure analysis/test entities provided information on their test and capability resources; however, only one, which is in Addendum A, is cited in this BOK due to the specific references to copper wire bond technology. Refer to the following NASA NEPP link[43] which includes all the company presentations: https://nepp.nasa.gov/workshops/etw2017/talks.cfm

DLA Land and Maritime Engineering Practice Study

Muhammad Akbar et al.[44] had authored a DLA Land and Maritime report on copper wire bond test methodology development which provided copper bond inputs from various manufacturers.

Raytheon Integrated Defense Systems

Ken Rispoli et al.[45] authored a presentation report entitled "Assessment of Copper Bond Wire for Use in Long Term Military Applications" which had the following narrative:

"*Copper wire required bonding process changes resulting in parametric shifts and noise susceptibility that did not impact manufacturer's data sheet performance specifications. It DID effect legacy design performance as compared to devices with gold wire*."

Potential Future Work on Additional Copper Bonding Wire Research

1) Copper Bond Destructive Pull Strength Study

It is an expectation that the manufacturer's wire bond assembly operation produces copper wire bonds that are robust enough to have destructive bond pulls close to the minimum break strength published by the wire manufacturer. The basis for any discussion regarding destructive bond pulls should include this essential intrinsic wire material property. Therefore, bonding process optimization could result in destructive bond pulls at or near the break strength of the wire.

Studies to demonstrate and quantify the tensile strength degradation that could occur at every process step after wire bonding would be valuable. Also, may be expanded to end user operations such as device assembly onto substrates and any device deprocessing activities that occur at DPA.

After all this data is gathered, one could more accurately determine the minimum destructive bond pulls for each type of copper wire where the initial copper bonds had been optimized to their intrinsic mechanical integrity.

2) Copper Ball Bond Shear Value

Based on a U.S.A. patent, a minimum ball shear strength of greater than 9.0 grams per mil^2 of squashed copper ball has been reported by a semiconductor manufacturer for automotive AEC grade 0 standards. Research is needed to determine how applicable this reported copper ball bond shear value is. Other research efforts are needed to determine the appropriate ball bond shear values for all other wire types such as palladium coated copper wire.

3) Investigation into IMC Coverage/Thickness

Further research into both IMC coverage and IMC thickness as related to copper wire bond technology qualification is indicated. As discussed earlier, a semiconductor manufacturer reported a patent claim IMC thickness of 273 nm for copper bonds in a U.S.A. Patent. It is unknown as to what device types and device lifetimes that this reported IMC value is applicable. Other research efforts may be required to determine the appropriate IMC thickness and IMC coverage for the other wire types such as palladium coated copper wire.

Conclusion

This BOK highlighted three recent releases of U.S.A. patents that suggest future areas of study such as the reliability of wire bond performance for different composition palladium coated copper wires including palladium plated copper wire with gold flash. Furthermore, five references on silver wire bonds were cited in order to provide the latest insight on the use of silver alloy bonding wire. A minimum ball shear of greater than 7.5g/mil^2 was referenced for both copper and silver alloy ball bonds. Finally, the importance of maintaining a residual pad thickness of 2-2.5 um below the Cu ball bond was discussed.

Since copper wire bonds are manufactured within a narrow process window and vulnerable to a myriad of failure mechanisms, it may be reasonable to carefully consider usage of devices constructed with copper wire bonds in any high reliability application until the appropriate standards have been released and a database of objective device performance history is available.

Acknowledgements

The authors wish to thank the NASA Electronic Parts and Packaging Program (NEPP) for funding support of this project. Also, the authors are very grateful to Jay Brusse (ASRC Federal Senior Components Engineer) for his excellent review comments and suggestions that improved this document.

Three Important Disclaimers

First, the authors created and NASA NEPP published this BOK as an information source. Neither NASA, NASA NEPP, ARES Technical Services Corporation nor the authors shall be responsible for any errors, omissions or damages arising out of use of this information. It shall be recognized that NASA NEPP and the authors are not attempting to provide engineering or other professional services. If such services are required, the assistance and consultation of an appropriate professional should be obtained.

Second, nothing in this BOK shall be interpreted as an endorsement of copper wire bond usage for high reliability applications. For such applications, gold wire bond replacements with copper wire bonds may not be justifiable from either an economic perspective or a reliability perspective.

Third, although various entity web sites were cited in this project, please be advised that by quoting from these web sites, NASA, NASA NEPP and the authors are not endorsing/recommending these entities or their products/services. These web sites were provided for the following reasons: 1) for convenience, because the cited web sites did contain the most current technical and or marketing data that was easily publicly available; 2) for assigning the appropriate legal content credit as literary citations. Please be advised that the content on any particular web site link may be changed or that the link may be discontinued in its entirety.

References

1. George G. Harman. “Wire Bonding in Microelectronics. Third Edition”. Copyright © 2010, 1997, 1989 by The McGraw-Hill Companies, Inc. All rights reserved. Page 14.

2. Rutkowski, E., Sampson, M. J. “Body of Knowledge (BOK) for Copper Wire Bonds”. NASA NEPP: https://ntrs.nasa.gov/search.jsp?R=20150023424 2015.

3. Kejun Zeng, Amit Sureshkumar Nangia. U.S. Patent Number 9,646,950 B2 “Corrosion-Resistant Copper Bonds to Aluminum”. May 9, 2017. Assignee: Texas Instruments Incorporated, Dallas, Texas. Columns 1 and 2.

4. Ibid. Column 6.

5. Leo M. Higgins, III. US. Patent Number 9,508,622 B2 “Method for Protecting Copper Wire Bonds on Aluminum Pads of a Semiconductor Device from Corrosion”. November 29, 2016. Assignee: Freescale Semiconductor, Incorporated, Austin, Texas. [Note: NXP Semiconductors N.V. acquired Freescale in 2015].

6. M. van Soestbergen, A. Mavinkurve, J.J.M. Zaal, G.M. O’Halloran, R.T.H. Rongen, and M.L. Farrugia. “Crevice Corrosion of Ball Bond Intermetallics of Cu and Ag Wire”. NXP Semiconductors, Nijmegen, Netherlands. 2016 IEEE 66th Electronic Components and Technology Conference. 978-1-5090-1204-6/16 © 2016 IEEE DOI 10.1109/ECTC.2016.192 Page 779.

7. O. Chyan[1], N. Ross[1], M. Asokan[1], A. Lambert[1], S. Berhe[1], M. Chowdhury[2], S. O. Connor[2], L. Nguyen[3]. “Mechanistic Investigation and Prevention of Al Bond Pad Corrosion in Cu Wire-bonded Device Assembly”. 2017 IEEE 67th Electronic Components and Technology Conference. 2377-5726/17 © 2017 IEEE. DOI 10.1109/ECTC.2017.43 Page 1179.
   [1]Interfacial Electrochemistry & Materials Research Lab, University of North Texas, Denton, TX
   [2]Texas Instruments, Inc., Dallas
   [3]Texas Instruments Inc., Santa Clara.

8. Ibid. Page 1186.

9. J.C. Krinke, D. Dragicevic, S. Leinert, E. Friess, J. Glueck. “High temperature degradation of palladium coated copper bond wires”. Microelectronics Reliability 54 (2014) 1995-1999. Page 1999. Content lists available at ScienceDirect. Journal homepage: www.elsevier.com/locate/microrel ; http://dx.doi.org/10.1016/j.microrel.2014.07.097 0026-2714/© 2014 Elsevier Ltd. All rights reserved. Robert Bosch GmbH, Automotive Electronics, Dieselstr. 6, D-72770 Reutlingen, Germany.

10. Chu-Chung (Stephen) Lee, Tu Anh Tran, Varughese Mathew, Rusli Ibrahim and Poh-Leng Eu. “Copper Ball voids for Pd-Cu Wires: Affecting Factors and Methods of Controlling”. NXP Semiconductor Inc. 6501 William Cannon Drive West, Austin Texas 78735 USA. 2016 IEEE 66th Electronic Components and Technology Conference. 978-1-5090-1204-6/16 © 2016 IEEE DOI 10.1109/ECTC.2016.220. Page 606.

11. Chu-Chung (Stephen) Lee, Tu Anh Tran, Dan Boyne, Leo Higgins, Andrew Mawer. “Copper versus Palladium Coated Copper Wire Process and Reliability Differences”. 2014 Electronic Components & Technology Conference. 978-1-4799-2407-3/14 © 2014 IEEE. Freescale Semiconductor Inc. 6501 William Cannon Drive West, Austin, Texas 78735 USA. Pages 1539-1548.

12. Chu-Chung (Stephen) Lee, Tu Anh Tran, Varughese Mathew, Rusli Ibrahim and Poh-Leng Eu. “Copper Ball voids for Pd-Cu Wires: Affecting Factors and Methods of Controlling”. 2016 IEEE 66th Electronic Components and Technology Conference. Page 612. 978-1-5090-1204-6/16 © 2016 IEEE DOI 10.1109/ECTC.2016.220. NXP Semiconductor Inc. 6501 William Cannon Drive West, Austin Texas 78735 USA.

13. Ivy Qin[1], Hui Xu[2], Horst Clauberg[1], Ray Cathcart[1], Viola L. Acoff[2], Bob Chylak[1], and Cuong Huynh[1]. “Wire Bonding of Cu and Pd Coated Cu Wire: Bondability, Reliability, and IMC Formation”. 2011 Electronic Components and Technology Conference. 978-1-61284-498-5/11 © 2011 IEEE.
[1] Kulicke and Soffa Industries Inc., Fort Washington, PA, U.S.A
[2] Department of Metallurgical and Materials Engineering, The University of Alabama, Tuscaloosa, AL, U.S.A. Page 1495.

14. Chia-Yun Chang, Fei-Yi-Hung, and Truan-Sheng Lui. “Mechanical and Electrical Properties of Palladium-Coated Copper Wires with Flash Gold”. Journal of ELECTRONIC MATERIALS, Vol. 46, No. 7. 2017. DOI: 10.1007/s11664-017-5355-6. © 2017 The Minerals, Metals & Materials Society. Department of Materials Science and Engineering, National Cheng Kung University, T’ai-nan 701, Taiwan. Pages 4390 and 4391.

15. S. Murali, Tark Yong Deok, B. Senthilkumar and Zhang Xi. “Advancement in Thermosonic Bonding Wire”. 47th International Symposium on Microelectronics (IMAPS 2014). San Diego, California, USA 13-16 October 2014. Copyright © (2014) by IMAPS – International Microelectronics & Packaging Society. All rights reserved. Page 282.
Heraeus Materials Singapore Pte Ltd, Blk5002 #04-05, Ang Mo Kio Ave 5, TECHplaceII, Singapore 569871.

16. Microchip Technology Incorporated Product Change Notice – JAON-22CDLC928. “CCB 3000 Initial Notice: Qualification of MMT as an additional assembly site using CuPdAu bond wire in selected products of the 150K and 160K wafer technologies in 28L SSOP package.” July 6, 2017. © Copyright 1998-2018 Microchip Technology Inc. All rights reserved.
http://www.microchip.com/mymicrochip/NotificationDetails.aspx?pcn=JAON-22CDLC928

17. Microchip Technology Incorporated Product Change Notice - KSRA-01PQCU581. "CCB 3093 Cancellation Notice: For the qualification of ASSH as a new assembly site for ATA6836C-TIQW Atmel catalog part number CuPdAu bond wire available in 28L SOIC package". February 20, 2018. © Copyright 1998-2018 Microchip Technology Inc. All rights reserved. http://www.microchip.com/mymicrochip/NotificationDetails.aspx?pcn=KSRA-01PQCU581&opennew=n

18. Microchip Technology Incorporated Product Change Notice - KSRA-01WWMB099. "CCB 3095 Initial Notice: Qualification of ASSH as a new assembly site for ATA6836C-TIQW Atmel catalog part number (CPN) using gold (Au) bond wire available in 28L SOIC package." October 2, 2017. © Copyright 1998-2018 Microchip Technology Inc. All rights reserved. https://www.microchip.com/mymicrochip/NotificationDetails.aspx?pcn=KSRA-01WWMB099&opennew=n

19. Microchip Technology Incorporated Product Change Notice – LIAL-26JKUB646. "CCB 3300, 3300.001 Initial Notice: Qualification of CuPdAu wire in selected products of the 0.18 um wafer technology available in 100L and 64L TQFP packages at MTAI assembly site." March 29, 2018. © Copyright 1998-2018 Microchip Technology Inc. All rights reserved. https://www.microchip.com/mymicrochip/NotificationDetails.aspx?pcn=LIAL-26JKUB646&opennew=n

20. A. Lassnig [a], R. Pelzer [b], C. Gammer [a,c], G. Khatibi [d]. "Role of intermetallics on the mechanical fatigue behavior of Cu-Al ball bond interfaces". Journal of Alloys and Compounds 646 (2015) 803-809. Content lists available at ScienceDirect. Journal Homepage: http://www.elsevier.com/locate/jalcom 0925-8388/© 2015 Elsevier B.V. All rights reserved. Pages 808-809.
    a. University of Vienna, Faculty of Physics, Physics of Nanostructured Materials, Boltzmanngasse 5, 1090 Wien, Austria
    b. Infineon Technologies Austria AG, Siemensstrae 2, 9500 Villach, Austria
    c. National Center for Electron Microscopy, Molecular Foundry, Lawrence Berkeley National Laboratory, CA 94720, United States
    d. Vienna University of Technology, Institute of Chemical Technology and Analytics, Getreidemarkt 9, 1060 Wien, Austria

21. Ibid. Page 809.

22. Ibid. Page 804.

23. Chai Chee Meng, Markus Fink and Dr. Laurens Weiss. "Virtual Prototyping Methodology for Assessment of the Interaction Between Wire Bond Pad Design and Bond Process Parameters to Enhance the Robustness of Copper Wire Bond Interconnect". 978-1-5090-2037-9/16 © 2016 IEEE.

24. Ibid. Page 20.

25. Roslina Ismail, Fuaida Harun, Muhammad Nubli Zulkifli, Azman Jalar, Maria Abu Bakar, and Shahrum Abdullah. "Bondability of Second Copper Wire Bonds on Silver and Nickel-Palladium-Gold-Silver Metallization". IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 5, No. 10, October 2015. 2156-3950 © 2015 IEEE. Page 1544.

26. JEDEC Standard JESD22-B116B. "Wire Bond Shear Test Method". April 2017. ©JEDEC Solid State Technology Association 2017. All rights reserved. Refer to www.jedec.org under Standards-Documents/Copyright Information.

27. Tu-Anh N. Tran, John G. Arthur, Yin Kheng Au, Chu-Chung Lee, Chin Teck Siong, Meijiang Song, Jia Lin Yap, Matthew J. Zapico. US Patent Number 9,257,403 B2 “Copper Ball Bond Interface Structure and Formation”. Feb. 9, 2016. Assignee: Freescale Semiconductor, Inc. Column 12. [Note: NXP Semiconductors N.V. acquired Freescale in 2015].

28. M. van Soestbergen,[1] A. Mavinkurve,[1] S. Shantaram,[2] and J.J.M. Zaal[1]. “Delamination-induced stitch crack of copper wires”. 2017 18th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems. 978-1-5090-4344-6/17 © 2017 IEEE. Page 1.
[1] NXP Semiconductors, Gerstweg 2, 6534 AE Nijmegen, the Netherlands.
[2] NXP Semiconductors, Oak-hill, E3, Austin, TX, 78735.

29. Ibid. Page 4.

30. Proprietary report.

31. Preeti S. Chauhan, Anupam Choubey, ZhaoWei Zhong, Michael G. Pecht. “Copper Wire Bonding”. DOI 10.1007/978-1-4614-5761-9_1, © Springer Science+Business Media, New York 2014. Chapter 7. Page 115.

32. Tu Anh Tran, Lois Yong, Bill Williams, Scott Chen, and Audi Chen, “Fine Pitch Probing and Wirebonding and Reliability of Aluminum Capped Copper Bond Pads”. 2000 Electronic Components & Technology Conference. 0-7803-5908-9/00 ©2000 IEEE. Pages 1674 - 1680.

33. Kan Wai Lam, Hong Meng Ho[1], Serguei Stoukatch[1], Myrian Van De Peer[1], Petar Ratchev[1], Charles J. Vath, III[2], Augustin Schervan, Eric Beyne[1]. “Fine Pitch Copper Wire Bonding on Copper Bond Pad Process Optimization”. 2002 Int’l Symposium on Electronic Materials and Packaging. 0-7803-7682-X/02 ©2002 IEEE. Page 68.
ASM Assembly Products BV. Jan van Eycklaan 10, 3723 BC Bilthoven, The Netherlands.
[1]IMEC, Kapeldreef 75, Leuven 3001, Belgium.
[2]ASM Technology Singapore Pte. Ltd, 2, Yishun Avenue 7, Singapore 768924.

34. C. W. Horsting. “Purple Plague and Gold Purity”. RCA Corporation. Somerville, New Jersey. IEEE 10th Reliability Physics Symposium – Las Vegas, NV, USA (1972.04.5-1972.04.7). Page 158.

35. Mingchuan Han[a], Miao Wang[a], Lidong Zhang[a], Beiyue Yan[a], Jun Li[a], Meijiang Song[a], Varughese Mathew[b]. Copper wire bond pad/IMC interfacial crack layer study during HTSL (high temperature storage life) test”. 2016 IEEE 18th Electronics Packaging Technology Conference (EPTC). 978-1-5090-4369-9/16 © 2016 IEEE. Page 797.
a. NXP Semiconductor, Inc. Tianjin China, 300385.
b. NXP Semiconductor, Austin, TX 78735 USA.

36. Ibid. Pages 798-799.

37. Varughese Mathew and Sheila Chopin. “High Temperature Reliability of Copper Wire - Bonded Packages Encapsulated with Mold Compounds Containing Sulfur Compounds”. Proceedings – 2014 47th International Symposium on Microelectronics, IMAPS 2014. © 2014 IMAPS – International Microelectronics Assembly and Packaging Society. All Rights Reserved.

38. Lee Levine. “Wire Bonding”. Electronic Device Failure Analysis, February 2016, Volume 18, Issue 1. EDFAAO (2016) 1:22-28. 1537-0755 ©ASM International®. edfas.org Page 22.

39. Hao-Wen Hsueh, Fei-Yi Hung, and Truan-Sheng Lui. “A study on electromigration-inducing intergranular fracture of fine silver alloy wires”. Department of Materials Science and Engineering, National Cheng Kung University, Tainan 70101, Taiwan. Applied Physics Letters 110, 031902 (2017). Published by AIP Publishing. http://dx.doi.org/10.1063/1.4974154. Copyright © 2018 AIP Publishing LLC. 0003-6951/2017/110(3)/031902/4 P. 031902-3.

40. Subramani Manoharan, Chandradip Patel, Patrick McCluskey. “Advancements in Silver Wire Bonding”. CALCE, University of Maryland. Proceedings of the Conferences on Packaging and Integration of Electronic and Photonic Microsystems (INTERPACK). August 29-September 1, 2017. San Francisco, California, USA. IPACK2017 -74286. Copyright © 2017 by ASME. P. 7.

41. Sarangapani Murali, B. Senthilkumar, Loke Chee Keong, Ei Phyu Phyu Theint and IT Kang. “Basics of Thermosonic Bonding of Fine Alloyed Ag Wires”. 978-1-5090-4369-9/16 ©2016 IEEE. 2016 IEEE 18th Electronics Packaging Technology Conference (EPTC). Page 240. Innovation, Heraeus Materials. Singapore Pte. Ltd., Ang Mo Kio Ave 5, TECHplaceII, Blk 5002#04-07, Singapore-569871.

42. Jiaqing Xi[1], Norbe Mendoza[1], Kevin Chen[1], Thomas Yang[1], Edward Reyes[1], Steve Bezuk[1], Juln Lin[2], Shenggin Ke[2], and Eason Chen[2]. “Evaluation of Ag Wire Reliability on Fine Pitch Wire Bonding”. 2015 Electronic Components & Technology Conference. 978-1-4799-8609-5/15 © 2015 IEEE. Page 1395.
[1]Qualcomm Technologies, Inc. 5775 Morehouse Drive, San Diego, CA 92121.
[2]Siliconware Precision Industries Co. Ltd.

43. NASA Electronic Parts and Packaging (NEPP) Program. 2017 Electronics Technology Workshop at the NASA Goddard Space Flight Center. June 26-29, 2017. https://nepp.nasa.gov/workshops/etw2017/talks.cfm

44. Muhammad Akbar, Chance Hunter. “Copper (Cu) wire bond test methodology development for microcircuit, hybrid and semiconductor devices”. Engineering Practice Study. Final Report. Study Project 5962-2017-002. September 20, 2017. Study Conducted by DLA Land and Maritime Document Standardization Division (VA). Approved for public release; distribution is unlimited. https://landandmaritimeapps.dla.mil/Downloads/MilSpec/Docs/5962EPStudies/prf38535CuWireBond.pdf

45. Ken Rispoli, Aaron Lecomte (Presenter), Aaron DerMarderosian. “Assessment of Copper Bond Wire for Use in Long Term Military Applications”. Raytheon Integrated Defense Systems. eTPCR: IDS-11029. 05/10/2017 Copyright © 2017 Raytheon Company. All rights reserved. Approved for Public Release. Page 16. ewh.ieee.org/r1/boston/rl/files/boston_rs_meeting_may17.pdf

Addendum A. 2017 NEPP Workshop at NASA Goddard Space Flight Center

Integra Technologies, LLC.

Sultan Ali Lilani[A] of Integra Technologies, LLC cited the following capabilities for:

"*Failure mode analysis & understanding of physics behind potential Cu wire failures*":

- *IMC failure mode analysis*
- *Bond wire/pad splash phenomenon*
- *Break mode understanding*
- *Implications of pad lifting*
- *Hidden micro-crack damages*
- *Die cracks & corrosion*

A. Sultan Ali Lilani. "Integra Technologies Update". Integra Technologies, LLC. NEPP Workshop at NASA Goddard June 26-29, 2017. Page 27. https://nepp.nasa.gov/workshops/etw2017/talks.cfm Internet Explorer - Select link on "Integra Technologies, LLC".

Appendix A: Acronyms

AEC Automotive Electronic Council

AFPC Gold Flash Palladium Coated Copper Wire

Ag Silver

Al aluminum

APC Au-Pd Copper Wire

Au Gold

AuPCC Gold Flash Palladium Coated Copper Wire

BGA Ball Grid Array

BOK Body of Knowledge

BPO Bond Pad Opening

BPT Bond Pull Test

BSPA Average Ball Shear per Squashed Ball Area

Cl^- Chlorine ion

CSAM C-Mode Scanning Acoustic Microscopy

CTE Coefficient of Thermal Expansion

Cu Copper

°C Degrees Centigrade

DCT Dynamic Current Tensile Test

DPA Destructive Physical Analysis

DRQFN Dual Row Quad Flat No Lead

EFO Electric Flame-Off

EDX Energy Dispersive X-Ray Spectroscopy

FAB Free Air Ball

HAST Highly Accelerated Stress Test

HAZ Heat Affected Zone

HTS High Temperature Storage

HTSL High Temperature Storage Lifetime

IC Integrated Circuit

JEDEC Joint Electron Device Engineering Council

IMC Intermetallic Compound

Low-k Dielectric Constant Smaller than Silicon Dioxide

MIL Military Specification

MSL (Moisture Sensitivity Level)

NEPP NASA Electronic Parts and Packaging Program

Ni Nickel

NIST National Institute for Standards and Technology

nm Nanometer

PCC Palladium Coated Copper Wire

Pd Palladium

PCN Product Change Notice

PED Plastic Encapsulated Devices

PEM Plastic Encapsulated Microcircuits

pH Numeric Scale that Specifies the Acidity or Basicity

RF Radio Frequency

SAC Solder (Sn-Ag-Cu)

SEM Scanning Electron Microscope

SO Small Outline Semiconductor Package

TC Thermal Cycling

TEM Transmission Electron Microscopy

THB Temperature Humidity Bias Test

TI Texas Instruments

um micron ($1X10^{-6}$ meters)