

Body of Knowledge (BOK) for Copper Wire Bonds

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Executive Summary

Copper wire bonds have replaced gold wire bonds in the majority of commercial semiconductor devices for the latest technology nodes. Although economics has been the driving mechanism to lower semiconductor packaging costs for a savings of about 20% by replacing gold wire bonds with copper, copper also has materials property advantages over gold. When compared to gold, copper has approximately: 25% lower electrical resistivity, 30% higher thermal conductivity, 75% higher tensile strength and 45% higher modulus of elasticity. Copper wire bonds on aluminum bond pads are also more mechanically robust over time and elevated temperature due to the slower intermetallic formation rate – approximately 1/100th that of the gold to aluminum intermetallic formation rate. However, there are significant tradeoffs with copper wire bonding - copper has twice the hardness of gold which results in a narrower bonding manufacturing process window and requires that the semiconductor companies design more mechanically rigid bonding pads to prevent cratering to both the bond pad and underlying chip structure. Furthermore, copper is significantly more prone to corrosion issues. The semiconductor packaging industry has responded to this corrosion concern by creating a palladium coated copper bonding wire, which is more corrosion resistant than pure copper bonding wire. Also, the selection of the device molding compound is critical because use of environmentally friendly green compounds can result in internal CTE (Coefficient of Thermal Expansion) mismatches with the copper wire bonds that can eventually lead to device failures during thermal cycling. Despite the difficult problems associated with the changeover to copper bonding wire, there are billions of copper wire bonded devices delivered annually to customers. It is noteworthy that Texas Instruments announced in October of 2014 that they are shipping microcircuits containing copper wire bonds for safety critical automotive applications. An evaluation of copper wire bond technology for applicability to spaceflight hardware may be warranted along with concurrently compiling a comprehensive understanding of the failure mechanisms involved with copper wire bonded semiconductor devices.

Introduction

The semiconductor industry has been rapidly transitioning to copper wire bonds as a replacement for gold wire bonds for microelectronic interconnections in the commercial semiconductor packaging market. In 2011, George G. Harman¹ (NIST Fellow) stated:

“The wire bonding industry is undergoing a paradigm shift from gold to copper ball bonding due to external world events. This is as significant to our industry as the no-lead mandates (RoHS Directive) were to soldering! With this in mind, The Editors of this Special Issue of Microelectronics Reliability have invited and put together papers covering all aspects/consequences of changing to Cu ball bonding.”

The transition from gold to copper wire bonds is a direct result of the compelling economic materials cost advantage that copper has over gold. On May 11, 2015, the Bloomberg² web site reported during intraday trading that COMEX (Commodity Exchange, Inc.) spot gold was trading for approximately

\$1,189 per ounce and that spot copper for approximately \$2.90 per pound. Thus, as of that date, the materials cost of gold was approximately 6,000 times higher than copper.

In order to understand the materials cost impact of converting from gold wire to copper wire in the actual usage configuration, since the processing cost to manufacture bonding wire is significant, a manufacturer of copper/gold bonding wire was contacted and a wire cost comparison was requested. The manufacturer supplied a quote on 10,000 feet of both 99.99% copper and 99.99% gold bonding wire for three different wire diameters. Based on this quotation, the calculated materials cost savings for switching from gold to copper wire were approximately 12%, 66%, and 85% for 0.0007", 0.001" and 0.002" diameter bonding wire, respectively.

To account for the total costs of bonding wire assembly integration into an actual semiconductor package, Palesko³ and Vardaman reported the following pricing structure for a 31x31 mm sized semiconductor package with 624 IOs assembled with copper wire and the same package assembled with gold bonding wire:

"The total package cost for this design with copper wire is approximately \$2.19 compared to the original \$2.65 with gold wire."

This equates to a cost differential of 46 cents per package unit which is an approximate assembly/packaging cost savings of 20% by switching over from gold to copper wire bonds for the identical package.

To gain a focused perspective on the state of gold to copper bond wire conversion in the semiconductor industry as it existed in 2014, both the latest annual report for Advanced Semiconductor Engineering, Inc. (ASE: the world's largest independent semiconductor packaging and testing company), and the quarterly report for Kulicke & Soffa Industries, Inc. (K&S: the world's largest manufacturer of wire bonders) were examined.

In the ASE⁴ Annual Report 2013, ASE's Letter to Shareholders reported the following:

"Revenue from copper wire bonding reached 65% of revenue from packaging wires as of the fourth quarter of 2013 and the manufacturing process of copper wire bonding began to be used in microcontrollers for automotive electronics and other new markets."

In this report, ASE⁵ also commented on the importance of the gold to copper conversion in the microelectronics assembly process by emphasizing the mutual benefits:

In addition, we intend to promote our copper wire solutions to our customers in addition to gold wire. Gold wire is a significant raw material for us. Gold prices, however, are subject to intense fluctuations and have in the past impacted our profitability. We believe that replacing gold wire in some of our packages with copper wire technology will not only improve our profitability but will also enable us to provide more value to our customers by providing lower cost solutions, which could enhance our competitiveness and market share. We are currently the industry leader in terms of copper wire capacity."

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In the November 6th news release of Kulicke & Soffa Reports Fourth Quarter and Fiscal Year 2014 Results⁶, K&S reported the following bullet:

“83.5% of ball bonder equipment was sold as copper capable.”

In conclusion, the fact that the largest independent market leader in the assembly and packaging sector, ASE, and the largest wire bonder manufacturer, K&S, recently reported copper bonding wire market penetration of 65% and 83.5%, respectively, it appears that the copper bonding wire process has widespread commercial customer acceptance. The next section will examine the technological advantages and disadvantages of both copper and gold bonding wire.

Copper Technology

Z.W. Zhong⁷ noted in Microelectronics Reliability the following reasons why copper has advantages over gold for the latest generation semiconductor devices:

“Copper wires have better electrical and thermal properties than gold wires.”

A comparison of both copper and gold intrinsic material properties is presented in Table 1.

Table 1. Material Properties⁸ of Copper and Gold.

Property	Copper (Cu) (Annealed)	Gold (Au)
Hardness, Vickers	50	25
Tensile Strength, Ultimate (psi)	30,500	17,400
Modulus of Elasticity (ksi)	16,000	11,200
Electrical Resistivity (ohm-cm)	1.70 x 10⁻⁶	2.20 x 10⁻⁶
Thermal Conductivity (BTU- in/hr-ft²-°F)	2670	2090
CTE, linear (um/m-°C) @Temperature 20.0 – 100 °C	16.4	14.4

The copper electrical resistivity is approximately 25% lower than that of gold. In addition, copper has an approximately 30% higher thermal conductivity than that of gold. This combination of copper having a lower electrical resistivity than gold and a higher thermal conductivity would lead one to expect that copper has a higher fusing current than gold. Based on a modified Preece equation in a real world application where the bonding wires are encapsulated in a molding compound, Jitish Shah⁹ provided a “Summary of current values in Amperes for different wire combinations” for copper and gold wires. For 1 mil diameter gold wire, the wire current-carrying capacity results showed a current of 1.12 A, 0.625 A, and 0.435 A for the respective wire lengths of 1 mm, 2 mm, and 3 mm. The same sized copper wire had a current-carrying capacity of 1.475 A, 0.81 A, and 0.56 A for the same wire lengths. Thus, based on these calculated results, copper wire has approximately 30% higher current-carrying capacity than gold.

One of the reasons that gold has been successfully used in thermosonic wire bonding of ball bonds onto aluminum bonding pads on integrated circuits is attributable to its low Vickers hardness of 25. On the other hand, copper with a significantly higher hardness of 50 on the Vickers scale has created challenges to the wire bonding process. In regards to copper’s higher material hardness and also lower corrosion resistance, George G. Harman¹⁰ reported the following:

“It [copper] oxidizes and thus requires an inert atmosphere during “EFO” [Electric Flame-Off] ball formation, it is harder and more crater prone,”

In regards to inert atmospheres and Free Air Ball (FAB) creation, Bernd K. Appelt et al¹¹ stated:

“The first step in wire bonding is the free air ball (FAB) formation. For 4N [i.e. 99.99% purity] Cu wire forming gas (95% nitrogen and 5% hydrogen) were used as a shroud and for PdCu[] wire nitrogen was used. The FAB geometry was tuned to yield a spherical FAB without any surface blemishes.”*

*Note: The use of Palladium Copper (PdCu) will be addressed later in this paper.

The combination of the tensile strength of copper being approximately 75% higher than that of gold and the modulus of elasticity being about 45% higher for copper may result in a more robust wire bond span. However, Serene SH Teh et al¹² published the following narrative.

“Many studies presume copper wires have higher hardness and stiffness than gold wires and further imply better wire sweep performance. However, there is a general lack of experimental data to support this hypothesis.”

Furthermore, Serene SH Teh et al¹³ published the following statement:

“..., wire sweeping resistance of copper wires are strongly dependent on the fabrication processes and heat treatments of the respective wire suppliers. Moreover, it was found that wire sweep percentage was very much influenced by wire locations during transfer molding process.”

Intermetallic Compounds

Intermetallic Compounds (IMCs) are an important reliability consideration when switching from gold to copper wire bonds. Hyoung-Joon Kim et al¹⁴ reported that:

“... slower intermetallic compound (IMC) growth between copper wires and aluminum pads results in lower contact resistance and better reliability in comparison to gold wires and aluminum pads.”

In addition, Hyoung-Joon Kim et al¹⁵ reported that:

“Moreover, the reaction rate of Cu/Al IMC formation is 100 times slower than that of Au/Al IMC formation.”

Similar IMC research by Liangyi Hung et al¹⁶ has provided the following noteworthy statement:

“Because the growth of intermetallic compound between Cu balls bonded on aluminum is very much slower than Au-Al system. Kirkendall void also does not exist in Cu-Al system for longer aging test.”

Liangyi Hung et al¹⁷ final conclusion was:

“In comparison to Gold – Aluminum system, the growth rates of Copper – Aluminum phase are very slow. The resistivity of Cu-Al intermetallic compound has better electrical performance.”

Gold wire bonds on aluminum metallization can result in the creation and growth of intermetallics which have a higher resistance and a tendency to initiate Kirkendall voids with ageing that could result in a wire bond failure.

Furthermore, as a result of analyzing intermetallic formations in both copper and gold wire bonds, S. Murali et al¹⁸ published three conclusions, one of which is as follows:

“Atomic radii of aluminum and gold atoms is nearly equal but copper differs from aluminum atom significantly, which results in a misfit of + 10.5%. This hinders the aluminum atom movements in the copper ball bond. Therefore, complete solid solubility cannot take place, consequently avoiding the formation of copper aluminide.” [Note: Clarification as to origin of the 10.5% number: Per Wikipedia^{®19} reference for atomic radii cited in the “Metallic” column, copper has an atomic radius of 128 picometers (pm), aluminum has an atomic radius of 143 pm, and gold has an atomic radius of 144 pm.]

All the aforementioned IMC research leads one to the conclusion that copper wire bonds are more mechanically robust than gold wire bonds over time.

Copper Corrosion Mitigation – Palladium Coated Copper Bonding Wire

In order to mitigate the risk of copper corrosion, some package assemblers are using palladium coated copper wire instead of pure copper wire. Dominik Stephan et al²⁰ had the following comments including the relative cost of copper wire and palladium coated copper wire:

“Copper wire has been the natural low cost alternative but concerns on corrosion susceptibility and package reliability have driven the industry to look for better alternative wire materials while maintaining substantial materials cost savings. PdCu wire is supposed to close this gap and serves a promising solution for applications that require cost effectiveness (still significant cost savings over gold) and robust bonding performance (closer to that of gold wire).”

Regarding a study on EX1 [Palladium coated copper bonding wire, a patented product of Nippon Steel Materials Co., Ltd. (NSMAT) and its subsidiary Nippon Micrometal Corporation (NMC) who have licensed this technology to others], Tomohiro Uno²¹ reported:

“The extended lifetime and improved bond strength of EX1 yield numerous advantages in operating wires. The improved stitch pull strength contributes to higher packaging yield. In addition, EX1 had wider parameter windows of bond force and ultrasonic vibration in stitch bonding, which leads to robust productivity.”

Tomohiro Uno²² has reported various conclusions after experimentally comparing bonding wire of copper 4N purity to copper bonding wire coated with a thickness of less than 0.2um palladium. Two of these conclusions are presented as follows:

“The stitch pull strength of EX1 was significantly better than that of bare Cu wire even under fresh conditions.”

“Cost-effective and secure gas, pure N₂ is only available for EX1, whereas the bare Cu wires require N₂ + 5%H₂.”

In addition, B.K. Appelt et al²³ has stated:

“Another reason for conceiving the Pd–Cu wire was to improve the HAST [Highly Accelerated Stress Test] performance of Cu wires. As stated earlier, oxidation of the wire itself is clearly retarded significantly. Evidence for a more robust HAST performance is quite limited to date.”

Tomohiro Uno²⁴ performed reliability testing [i. e. PCT (Pressure Cooker Test) and UHAST (Unbiased Highly Accelerated Stress Test)] on EX1 and arrived at nine conclusions of which an important one is provided below:

“1. EX1 produced significantly greater humidity reliability than bare Cu after PCT and UHAST testing.”

In summary, all the aforementioned palladium coated copper bonding wire research leads one to the conclusion that palladium coated copper bonding wires have significant reliability and manufacturing productivity advantages as compared to using pure 4N copper bonding wire.

Bond Pad Construction

Regarding nickel bonding pads, George G. Harman²⁵ has published the following narrative:

“Due to the higher potential of Cu to work-harden during ball bonding, a harder and stiffer bonding surface can help prevent bond pad cratering and other damage that is easily induced during Cu ball bonding for both Cu and Al interconnect materials. Alternative bond pad structures have been proposed and adopted recently, which include the addition of a Ni layer directly over the bond pad interconnect.”

On the same subject of using nickel-based bond pads, Bob Chylak et al²⁶ has reported the following:

“Ni-based bond pads have emerged to solve the pad damage problem. Nickel is about 50% harder than copper and four times harder than aluminum so that it provides greater protection against the higher stress resulting from Cu ball bonding, as well as damage during probe. This is especially beneficial for devices with low-k active circuitry under the bond pad. NiPd, NiPdAu, and or NiAu have demonstrated their great robustness to receive the Cu wire bonding with a huge bonding window without any splash and with excellent reliability.”

Eliminating ball bond splash, which is the movement of aluminum metallization underneath and away from the ball bond, is important because excessive splash can result in electrical shorts whenever the splash bridges to an adjacent bond pad. George G. Harman²⁷ alluded to aluminum splash when he discussed copper wire bonding reliability in the following narrative:

“The bondability of Cu balls to Al pads has proven excellent, and the reliability of bonds to Al pads under high temperature is very good For thin soft Al metallizations (<0.6um) the harder Cu ball may push the Al metallization aside, so the Al pad should be made harder, or a TiW layer put under the pad. This will also reduce any cratering problem due to the Cu-ball hardness (compared to Au balls).”

In order to assure semiconductor bond pad and device structure reliability on low dielectric constant (Low-K) insulating materials, the copper damascene process has been implemented to mitigate the effects of the lower modulus of elasticity that Low-K dielectrics have. Essentially, the copper damascene process consists of incorporating copper trenches underneath the bond pad to provide the requisite bond pad rigidity to allow reliable wire bonding. Regarding the more complex copper damascene process, George G. Harmon²⁸ has provided the following design guidance:

“All copper conductors imbedded in the Lo-k dielectrics must be encased in thin diffusion barriers to prevent copper from drifting/diffusing into the dielectric or the Si, which would change their properties, eventually degrading or destroying the device.”

Product Change Notices

Numerous industrial companies issue Product Change Notices (PCNs) whenever significant changes occur to the product line. During the gold to copper bonding wire transition in the semiconductor packaging industry, a number of semiconductor companies have issued PCNs to document this change. One of these PCNs was issued by Microchip Technology, Inc.²⁹ which qualified palladium coated copper bonding wire in a certain surface mount package. This PCN contained a Qualification Plan that cited the following four JEDEC Standards referenced in the device testing plan:

- 1) HAST test: JESD22-A101C (Steady State Temperature Humidity Bias Life Test).
- 2) Autoclave test: JESD22-A102D (Accelerated Moisture Resistance – Unbiased Autoclave).
- 3) MSL (Moisture Sensitivity Level) Pre-Conditioning: JESD22-A113F (Preconditioning of Nonhermetic Surface Mount Devices Prior to Reliability Testing).
- 4) Bond Shear Test: JESD22-B116A (Wire Bond Shear Test Method).

Problems

In a PCN located at one of their authorized distributor's web site, Micrel³⁰ *"has withdrawn PPCN 130018 to qualify Cu wire bonding at ASE Kunshan, China. Although copper wire bonding was fully qualified at ASE Kunshan by Micrel, initial mass production runs did not meet our in-line quality requirements."* Therefore, one has to be careful about qualifying the copper wire bond process due to difficulties that can occur if the manufacturing process is not robust enough to satisfy quality requirements.

Regarding CTE mismatches between copper wire and low-CTE green mold compounds (GMC), Bart Vandeveld et al³¹ had the following conclusion:

"It was found in reliability experiments that the combination of the switch from Au to Cu wire and the introduction of low-CTE GMC's leads to a reduced life time of the wire bond. This could be a show stopper for the use of copper wire bonds in high reliability applications. The main reason is the mismatch in thermal expansion between the copper wire and the overmold. In the conventional (non green) packages, the CTE of Au wire (14 ppm/°C) matches well with the conventional overmold (13 - 17 ppm/°C). With the double switch, the mismatch increases to near 10 ppm/°C (Cu: 16.5 ppm/°C, GMC: 7-9 ppm/°C). In temperature cycling, the copper wire will be stressed by the GMC. In cycling mode, this will lead to mechanical fatigue cracks."

R. Schueller³² reported the following narrative in the conclusions section:

"The majority of data shows that if a good bond is created with the Cu wire bonding process, then this bond should hold up well over time under typical conditions (an actual improvement in reliability). However, some more recent data shows some concerns with potential wear-out mechanisms such as brittle fracture or galvanic corrosion."

A significant concern to semiconductors packaged with copper wire bonds is the potential for copper corrosion. Peng Su et al³³ performed research by varying pH level and Cl⁻ concentration in the molding compound and arrived at the following conclusion:

“Results from this study suggest that for the purpose of evaluation and selection of key packaging materials such as molding compound, typical testing durations such as those used for component qualification are not sufficient. Extended testing durations are necessary to generate results that can help identify key controlling material properties that have the greatest impact on long-term component reliability. Additionally, as the comparison for Au wire and Cu wire components has shown, packaging materials set that may provide sufficient reliability for Au bond wires can have deteriorated performance for Cu bond wires.”

In regards to the copper wire bond corrosion concerns, B.K. Appelt et al³⁴ has stated:

“The ease of oxidation of Cu remains a concern for the long term durability of Cu wire and bonds under the varying temperature and humidity conditions during the life of the respective components. Further, the ease of corrosion of Cu is another industry concern and has prompted mold compound manufacturers to lower the amount of free ions like chloride and bromide in the compounds.”

Related to the copper corrosion concern is a potential problem³⁵ involving the inventory storage of microcircuits containing copper wire bonds if not stored in an inert atmosphere such as nitrogen. If microcircuits were stored for years to the point that the device termination leads became unsolderable, there may also be a risk of copper bond wire corrosion. In addition, the corrosion risk may be increased if a device lead replating operation was introduced to refurbish the leads back to a solderable condition. Such a replating process could result in a contaminant influx via preexisting or newly formed package cracks into the copper wire bond region; thereby, initiating a copper corrosion mechanism that may result in device failure.

If an expensive semiconductor chip is going to be copper wire bonded, it is even more of a necessity to have a process of sustaining high wire bond yields since Bernd K. Appelt et al³⁶ has indicated that:

“Cu wire bonds are not reworkable and therefore first pass yields are final yields for bonding.”

As a side note for failure analysts, Sarangapani Murali et al³⁷ provide recipes for the acid decapsulation of epoxy molded IC packages with copper wire bonds and stated the following conclusion:

“A mixture of fuming nitric acid and 96% concentrated sulfuric acid can be used to decap the epoxy molded packages without distorting the copper wire bonds and its interfaces (Cu-Al).”

Qualification Testing

Regarding copper bond testing, Preeti Chauhan et al³⁸ had the following noteworthy narrative published in 2013:

“Currently, there are no standardized tests for Cu wire-bonded devices, and it is unknown whether the tests designed for Au wire-bonded devices are sufficient to qualify Cu wire-bonded devices.”

In addition, Preeti Chauhan et al³⁹ had the following recommendations on reliability test selection:

“Reliability tests should be selected based on the failure mechanism under study. Common failure mechanisms in wire bonds and the recommended reliability tests to detect them are as follows: For moisture-related mechanisms, recommended reliability tests include HAST, uHAST, THB, MSL conditioning and reflow, PCT, and autoclave. For corrosion-related mechanisms, recommended reliability tests include HAST, THB, and PCT. For electromigration, recommended reliability tests include bHAST and THB. For electrochemical migration-related mechanisms, recommended reliability tests include THB, HAST, and uHAST. For package-level reliability, recommended reliability tests include PCT, HAST, THB, temperature cycling, thermal shock, and MSL reflow. For fatigue related mechanisms, recommended reliability tests include temperature cycling and thermal shock.”

In 2011, Bernd K. Appelt et al⁴⁰ reported the following reliability conclusion in regards to copper wire bonds:

“Reliability has been demonstrated to exceed 2+ X standard JEDEC testing and is continuing which should be adequate for harsh environmental applications like automotive.”

Automotive Qualification

The Automotive Electronic Council (AEC) has created a copper bond wire qualification document that is numbered AEC – Q006 - Rev- , dated June 8, 2015 and entitled “Qualification Requirements for Components Using Copper (Cu) Wire Interconnections”.

At a Texas Instruments web site dated October 14, 2014, Mahadevan Iyer⁴¹ provided the following information on both TI copper wire bond shipments and TI copper bonding wire usage in automotive devices:

“The majority of our existing analog and CMOS silicon technology nodes have been qualified with copper, and all new technologies and packages are being developed with copper wire bond. Cu wire is at 71 percent of TI’s total wire usage. In fact, since 2008, TI has shipped more than 22 billion units with copper wire bonds from its internal sites.

We are currently shipping about two billion units of copper wire bond technology each quarter. This includes production for key automotive segments such as safety (e.g., anti-lock brake systems, power steering, stability control), infotainment, body and comfort, and powertrain.”

Pros and Cons

A. Pros:

- Copper is an economic alternative to gold wire bonds in commercial device packages.
- Copper bonding wire has lower electrical resistance than gold bonding wire.
- Copper bonding wire has better thermal properties than gold bonding wire.
- Copper bonding wire has a higher current carrying capacity than gold bonding wire.
- Copper has a higher modulus of elasticity than gold resulting in stiffer wire bond loops which may lead to better wire sweep performance during the device molding process.
- Copper-Aluminum intermetallic formation rate is much slower than that of the gold to aluminum intermetallic formation rate which results in better reliability under ageing conditions.

B. Cons

- Copper bonding wire is significantly more prone to corrosion issues than gold bonding wire; therefore, the molding compound pH and molding compound halide concentrations need to be controlled. In addition, delamination of the package needs to be avoided.
- Copper is harder than gold resulting in a smaller manufacturing process window and the need for stronger bond pads.
- Copper bond wires would be difficult to implement on legacy semiconductor devices due to the potential need to redesign bond pads to accommodate the extra copper hardness.
- The copper bonding process requires additional manufacturing process expense since nitrogen is required to obtain a FAB for palladium coated copper bonding wire and a forming gas is required for pure copper bonding wires in order to create a reliable FAB.
- Gold wire bonds have a well-established reliability history over many decades usage whereas widespread copper wire bonds in commercial devices have been implemented only recently on a large scale.
- Copper bonding wire has a limited manufacturing shelf life which could be mitigated by using a more expensive palladium coated copper bonding wire.
- Copper has a greater CTE than gold; therefore, the device designer has to ensure that the copper to molding compound CTE mismatch is minimized to prevent device failures during thermal cycles.
- Copper wire bonds on aluminum metallization are not reworkable.

Alternative – Silver Bonding Wire

Another low cost alternative to gold bonding wire is silver bonding wire. According to E. Jan Vardaman⁴², silver had an approximate 8% market share of bonding wire in 2014. Micrel⁴³ issued a Process/Product Change Notification with number PPCN # 150001 that describes a bonding wire transition from gold to silver for certain device part numbers.

The alloying of silver bonding wire with other elements can increase corrosion resistance and decrease silver migration; however, the presence of the alloying elements can significantly increase electrical resistivity so that the silver bonding wire is not performance competitive with copper based technology.

It is not possible to predict what other elemental alloys the semiconductor process materials engineers may create in the future to compete with copper and silver alloys for the wire bonding market.

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Gaps - Potential Future Work on other areas of Copper Bonding Wire Research

- 1) Attempts to find technical literature on copper wire bonding inside hermetic packages were unsuccessful. It is recommended that NASA monitor the situation carefully so as to be involved in any proposed adoption of copper wire bonds in hermetic packages, especially for MIL (military) QML (Qualified Manufacturer List) devices.
- 2) A specification is needed to define appropriate qualification of copper wire bonded semiconductors for spaceflight hardware. In addition to the electrical and environmental testing requirements in this specification, a mechanical section could be included to define the appropriate visual inspection criteria for copper wire bonds and suitable wire bond pull and bond shear strength requirements.
- 3) A reverse engineering study is needed on one or more automotive grade semiconductors manufactured with copper bond wire interconnects in an epoxy molded package. Research areas: DPAs of devices to learn about bond pad construction and a workmanship assessment of ball bond and stitch bond quality characteristics. A materials identification study of the bonding wire elemental constituents and the specific molding compound that was used including the mold compound properties such as CTE and T_g along with the identification of any foreign contaminants (such as halogens), moisture content, and pH of the mold compound.
- 4) Review data from various reliability qualification tests as cited by Preeti Chauhan et al³⁸. See page 9 of this BOK.

Conclusion

This BOK research revealed how economic cost benefits resulted in copper bond wire adoption in the commercial semiconductor industry and also referenced both the reliability concerns and potential improvement in some applications by using copper bonding wire.

The semiconductor device users for commercial products have already accepted copper wire bonds since billions of annual device shipments are already occurring. Texas Instruments is already shipping semiconductor devices with integral copper wire bond technology to automotive customers for safety critical applications. Due to the difficulties of the copper wire bonding process, it is essential that a semiconductor packager have the right microcircuit bond pad design and the appropriate manufacturing process recipe for the copper wire bond process in order to assure long-term product reliability.

As systems engineers and circuit designers are expected to want to reap the technological benefits of using the latest generation semiconductor devices, which may contain copper wire bonds, it may be justifiable to start researching copper wire bond reliability data for potential device usage in spaceflight hardware applications.

Further work is required to understand the variations in bond quality for devices currently in the commercial marketplace before copper wire bonding is used in parts for spaceflight applications.

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References

- 1) George G. Harman. "Editorial Preface". Microelectronics Reliability 51 (2011) 3. Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel
- 2) Bloomberg web site URL: <http://www.bloomberg.com/markets/commodities/futures/metals> ©2015 Bloomberg L.P. All Rights Reserved. Retrieved on May 11, 2015.
- 3) Chet A. Palesko, E. Jan Vardaman. "Cost Comparison for Flip Chip, Gold Wire Bond, and Copper Wire Bond Packaging". 2010 Electronic Components and Technology Conference. ©2010 IEEE. Page 11.
- 4) Advanced Semiconductor Engineering Inc. Annual Report 2013: Retrieved on May 8, 2015 from web site URL: http://www.aseglobal.com/en/IR/ir_annual.asp
- 5) Ibid.
- 6) "Kulicke & Soffa Reports Fourth Quarter and Fiscal Year 2014 Results". November 6, 2014. Retrieved on May 11, 2015 from web site URL: <http://investor.kns.com/releasedetail.cfm?ReleaseID=880990> Section entitled "Third Quarter Fiscal 2014 Key Product Trends".
- 7) Z.W. Zhong. "Overview of wire bonding using copper wire or insulated wire." Microelectronics Reliability 51 (2011) 4-12. Second sentence in section 3.1 (Benefits of wire bonding using copper wire). Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel
- 8) MatWeb™, LLC database: Web site URL: <http://www.matweb.com> Copyright 1996-2015 by MatWeb, LLC. Retrieved May 11, 2015. In a telephone consultation on May 11, 2015, Dr. Dale O. Kipp (President of MatWeb, LLC.) provided permission to cite the MatWeb™ database.
- 9) Shah, Jitish. "Estimating Bond Wire Current-Carrying Capacity". July/August 2012. Table 2 (Summary of current values in Amperes for different wire combinations). © 2015 Power Systems Corporation. All rights reserved. Retrieved on May 11, 2015 from web site URL: <http://www.powersystemsdesign.com/estimating-bond-wire-current-carrying-capacity>
- 10) George G. Harman. "Wire Bonding in Microelectronics. Third Edition". The McGraw-Hill Companies, Inc. 2010. ©Copyright 2010, 1997, 1989. Page 67.

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.

- 11) Bernd K. Appelt, Andy Tseng and Yi-Shao Lai*. "Copper Wire Bonding Experiences from a Manufacturing Perspective". ASE Group. 1255 E Arques Ave, Sunnyvale, CA USA. *ASE Group, Nantze Export Zone, Kaohsiung, Taiwan. First three sentences in 2nd paragraph in section entitled "Manufacturing Process Development".
- 12) Serene SH Teh, BY Low, CS Foong, CT Siong. "Wire Sweep Characterization of Multi-tier Copper Wire Bonding on Thermally-Enhanced Plastic Ball Grid Array Packages". 34th International Electronic Manufacturing Technology Conference, 2010. Final paragraph of section 1 (Introduction).
- 13) Ibid. Last two sentences in Abstract.
- 14) Hyoung-Joon Kim, Joo Yeon Lee, Kyung-Wook Paik, *Member, IEEE*, Kwang-Won Koh, Jinhee Won, Sihyun Choe, Jin Lee, Jung-Tak Moon, and Yong-Jin Park. "Effects of Cu/Al Intermetallic Compound (IMC) on Copper Wire and Aluminum Pad Bondability". IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES, VOL. 26, NO. 2, JUNE 2003. Page 367.
- 15) Ibid. Page 373.
- 16) Liangyi Hung, Yuwei Lin, Simon Chen, Yupu Wang, C. S. Hsiao. "The Characterization of Intermetallic Growth in Copper and Gold Ball Bonded on Thicker Aluminum". Siliconware Precision Industries Co., Ltd. 2006 7th International Conference on Electronics Packaging Technology. © 2006 IEEE. Second and third sentences in third paragraph of section 1 (Introduction).
- 17) Ibid. Item 4 in section 5 (Conclusion).
- 18) S. Murali, N. Srikanth, Charles J. Vath III. Research and Development Unit, ASM Technology Singapore Pte. Ltd. 2 Yishun Avenue 7, Singapore 768924, Singapore. "An analysis of intermetallics formation of gold and copper ball bonding on thermal aging". Available online at www.sciencedirect.com. © 2003 Elsevier Science Ltd. All rights reserved. www.elsevier.com/locate/matresbu Materials Research Bulletin 38 (2003) 637–646. Page 645.
- 19) Wikipedia[®]: "Atomic radii of the elements (data page)". Retrieved on May 11, 2015 from Wikipedia[®] web site URL: http://en.wikipedia.org/wiki/Atomic_radii_of_the_elements_%28data_page%29
- 20) Dominik Stephan^a, Frank W. Wulff^b, Dr. Eugen Milke^b. "Reliability of Palladium Coated Copper Wire". 2010 12th Electronics Packaging Technology Conference. ^a Heraeus Materials Singapore Pte Ltd Block 5002 Ang Mo Kio Avenue 5, #04-05 TECHPlace II, Singapore 569871. ^b WC Heraeus GmbH Contact Materials Division, Heraeusstrasse 12 -14, 63450 Hanau, Germany. © 2010 IEEE. Page 343.
- 21) Tomhiro Uno. "Enhancing bondability with coated copper bonding wire". Microelectronics Reliability 51 (2011) 88-96. Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel Page 90.
- 22) Ibid. Page 96.
- 23) Bernd K. Appelt^a, Andy Tseng^a, Chun-Hsiung Chen^b, Yi-Shao Lai^b. ^aASE Group, 3590 Peterson Way, Santa Clara CA 95054, USA. ^bASE Group, 26 Chin 3rd Rd., Nantze Export Zone, Kaohsiung 81170, Taiwan. "Fine pitch copper wire bonding in high volume production". Microelectronics Reliability 51 (2011) 13-20. Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel Page 17.
- 24) Tomhiro Uno. "Bond reliability under humid environment for coated copper wire and bare copper wire". Microelectronics Reliability 51 (2011) 148-156. Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel Page 155.
- 25) George G. Harman. "Wire Bonding in Microelectronics. Third Edition". The McGraw-Hill Companies, Inc. 2010. ©Copyright 2010, 1997, 1989. Page 201.

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.

- 26) Bob Chylak^a, Jamin Ling^a, Horst Clauberg^a, and Tom Thieme^b. "Next Generation Nickel-Based Bond Pads Enable Copper Wire Bonding". ^a Kulicke and Soffa Ind. Inc., 1005 Virginia Drive, Fort Washington, PA 19034, USA. ^b Atotech Deutschland GmbH, ErasmustraBe 20, 10553 Berlin, Germany. Third paragraph in Abstract.
- 27) George G. Harman. "Wire Bonding in Microelectronics. Third Edition". The McGraw-Hill Companies, Inc. 2010. ©Copyright 2010, 1997, 1989. Pages 155-156.
- 28) Ibid. Page 356.
- 29) Microchip Technology, Inc.: Product Change Notification – JAON-18NOTK861: "CCB 1539 Initial Notice: Qualification of Supertex HV9803B device family in 8L SOIC (0.150") package using palladium coated copper (PdCu) bond wire at MTAI Assembly site." April 7, 2015. ©Copyright 1998-2014 Microchip Technology Inc. All rights reserved. Retrieved on May 11, 2015 from the Microchip Technology, Inc. web site URL: <http://www.microchip.com/mymicrochip/NotificationDetails.aspx?pcn=JAON-18NOTK861&opennew=n>
- 30) Micrel Process/Product Change Notification: "PPCN #130018 withdrawn". June 2, 2014. ©Copyright 1995-2015, Digi-Key Electronics. All Rights Reserved. Retrieved on May 11, 2015 from the Digi-Key Corporation web site URL: http://www.digikey.com/classic/documentredirector.aspx?doc=http://www.digikey.com/Web%20Export/Supplier%20Content/Micrel_576/PDF/micrel-ppcn130018.pdf&curr=USD
- 31) Bart Vandeveld, Geert Willems. "Early fatigue failures in Copper wire bonds inside packages with low CTE Green Mold Compounds". Imec, Kapeldreef 75, 3001 Leuven, Belgium. First paragraph of "Conclusions".
- 32) Randy Schueller, Ph.D. "Copper Wire Bond Failure Mechanisms". DfR Solutions. Minneapolis, MN. Third and fourth sentences in paragraph entitled "CONCLUSIONS".
- 33) Peng Su (Component Quality and Technology, Cisco Systems, Inc.), Hidetoshi Seki¹, Chen Ping², Shin-ichi Zenbutsu¹ and Shingo Itoh¹ (¹Electronic Device Materials Research Laboratory I, Sumitomo Bakelite Co. Ltd. ²Electronic Device Materials Research Laboratory, Sumitomo Bakelite Singapore Pte. Ltd.), Louie Huang³, Nicholas Liao³, Bill Liu³, Curtis Chen³, Winnie Tai³, and Andy Tseng⁴ (³Advanced Semiconductor Engineering Group, Taiwan, ⁴Advanced Semiconductor Engineering Group, USA). "An Evaluation of Effects of Molding Compound Properties on Reliability of Cu Wire Components". 2011 Electronic Components and Technology Conference. ©2011 IEEE. Pages 368-369.
- 34) Bernd K. Appelt^a, Andy Tseng^a, Chun-Hsiung Chen^b, Yi-Shao Lai^b. ^aASE Group, 3590 Peterson Way, Santa Clara, CA 95054, USA. ^bASE Group, 26 Chin 3rd Rd., Nantze Export Zone, Kaohsiung 81170, Taiwan. "Fine pitch copper wire bonding in high volume production". Microelectronics Reliability 51 (2011) 13-20. Content lists available at ScienceDirect. © 2010 Elsevier Ltd. All rights reserved. Journal homepage: www.elsevier.com/locate/microrel Page 14.
- 35) David M. Peters of The Aerospace Corporation provided this potential problem during a June, 2014 telephone consultation.
- 36) Bernd K. Appelt, Andy Tseng and Yi-Shao Lai*. "Copper Wire Bonding Experiences from a Manufacturing Perspective". ASE Group. 1255 E Arques Ave, Sunnyvale, CA USA. *ASE Group, Nantze Export Zone, Kaohsiung, Taiwan. Third sentence in 9th paragraph in section entitled "Manufacturing Process Development".
- 37) Sarangapani Murali and Narasimalu Srikanth. "Acid Decapsulation of Epoxy Molded IC Packages With Copper Wire Bonds". IEEE Transactions on Electronic Packaging Manufacturing. Vol. 29, No. 3. July 2006. ©2006 IEEE. Page 182.
- 38) Preeti Chauhan,^{1,3} Z.W. Zhong,² and Michael Pecht¹. 1.-CALCE Electronic Products and Systems Center, University of Maryland, College Park, MD 20742, USA. 2.-School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore. 3.-e-mail:

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.

preeti@umd.edu. "Copper Wire Bonding Concerns and Best Practices". Journal of ELECTRONIC MATERIALS, Vol. 42, No. 8, 2013. ©2013 TMS. Page 2429.

- 39) Ibid. Page 2429.
- 40) Bernd K. Appelt, Andy Tseng, Louie Huang*, Scott Chen**. "Is Copper Wire Bonding Ready for Automotive Applications?" 2011 13th Electronics Packaging Technology Conference. ASE Group 1255 E Arques Ave, Sunnyvale, CA 94085. *ASE Group, Nantze Export Zone, Kaohsiung, Taiwan. **ASE Group, Chung-Li, Taiwan. ©2011 IEEE. Page 390.
- 41) Mahadevan Iyer. "Using copper wire bonding in chips for autos". October 14, 2014. ©Copyright 1995-2015 Texas Instruments Incorporated. All rights reserved. Retrieved on May 11, 2015 from Texas Instruments web site URL: http://e2e.ti.com/blogs_/b/behind_the_wheel/archive/2014/10/14/using-copper-wire-bonding-in-chips-for-autos.aspx?DCMP=corp-tms-cuwire-141008&HQS=corp-tms-cuwire-ba-blog
- 42) E. Jan Vardaman. President. TechSearch International, Inc. www.techsearchinc.com "Key Market Growth Areas in Polymers for IC Packaging". © 2014 TechSearch International, Inc. Slide 6.
- 43) Micrel Process/Product Change Notification PPCN # 150001. January 30, 2015. ©Copyright 1995-2015, Digi-Key Electronics. All Rights Reserved. Retrieved on May 11, 2015 from the Digi-Key Corporation web site URL: <http://media.digikey.com/pdf/PCNs/Micrel/PPCN150001.pdf>

Appendix A: Acronyms

AEC Automotive Electronic Council

bHAST Biased Highly Accelerated Stress Test

BOK Body of Knowledge

CTE Coefficient of Thermal Expansion

DPA Destructive Physical Analysis

EFO Electric Flame-Off

FAB Free Air Ball

4N Four Nines, i.e. 0.9999

GMC Green Mold Compound

HAST Highly Accelerated Stress Test

HTS High Temperature Storage

IC Integrated Circuit

IMC Intermetallic Compound

K&S Kulicke & Soffa Industries, Inc.

HTS High Temperature Storage

MSL (Moisture Sensitivity Level)

NIST National Institute for Standards and Technology

N₂ Nitrogen

PCN Product Change Notice

PCT Pressure Cooker Test (Autoclave Test)

T_g Glass Transition Temperature

THB Temperature Humidity Bias Test

TI Texas Instruments

uHAST Unbiased Highly Accelerated Stress Test