COPPER WIRE BOND FAILURE MECHANISMS

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ABSTRACT

Wire bonding a die to a package has traditionally been performed using either aluminum or gold wire. Gold wire provides the ability to use a ball and stitch process. This technique provides more control over loop height and bond placement. The drawback has been the increasing cost of the gold wire. Lower cost Al wire has been used for wedge-wedge bonds but these are not as versatile for complex package assembly. The use of copper wire for ball-stitch bonding has been proposed and recently implemented in high volume to solve the cost issues with gold. As one would expect, bonding with copper is not as forgiving as with gold mainly due to oxide growth and hardness differences. This paper will examine the common failure mechanisms that one might experience when implementing this new technology.

Keywords
Cu Wire Bonding, Failure Mechanisms, Failure Modes, Defects, Process Control

INTRODUCTION

With the cost of gold having risen from $350 to over $1600 an ounce in the past several years, it is easy to understand the attractiveness for finding an alternative to gold wire for interconnecting a die to the package substrate. Aluminum wire is often used in wedge bonding, however, it is not practical for use in fine pitch ball bonding since Al oxidizes too readily during the spark formation of the ball. The industry has selected copper as the best alternative to gold. Cu does oxidize during a ball formation, but this can be kept to an acceptable level using forming gas (95%N and 5%H_2). Figure 1 shows a machine modification that enables ball formation with copper wire.

If copper were an easy drop-in replacement for gold the industry would have made the change long ago. Unfortunately copper has a few mechanical property differences that make it more difficult to use as a wire bond material. Cu has a higher Young's Modulus (13.6 vs. 8.8 N/m^2), thus it is harder than gold and, more significantly, copper work hardens much more rapidly than gold. This means that during the compression of the ball in the bonding operation, the copper ball becomes much harder while the gold remains soft and deforms more easily. A thin layer of oxide on the copper also makes bonding more challenging, especially on the stitch side of the bond. However, there are some positive attributes of copper as well. Cu actually has lower electrical resistivity than Au (1.7 vs 2.3 µohmcm) so electrical performance is slightly better. Cu has better thermal conductivity (394 vs. 293 W/mK), which allows it to more efficiently dissipate heat within a package. Additionally, Cu forms intermetallics with an Al bond pad more slowly than does gold, so data shows it to be more stable over time.

Let's examine the cost advantages of Cu wire. As with most manufacturing operations, material cost is only a small component of the overall production cost. In fact the wire cost itself is a sum of the cost to produce the wire and the material cost. Therefore, greater savings with copper wire is achieved when the wire has larger diameter (doubling the wire diameter actually increases the volume fourfold). An example of wire cost vs. diameter is shown in Figure 2. The cost to produce an IC package must take into account the cost of the wire plus the overall throughput and the cost of labor and other materials. Ramos performed an analysis of

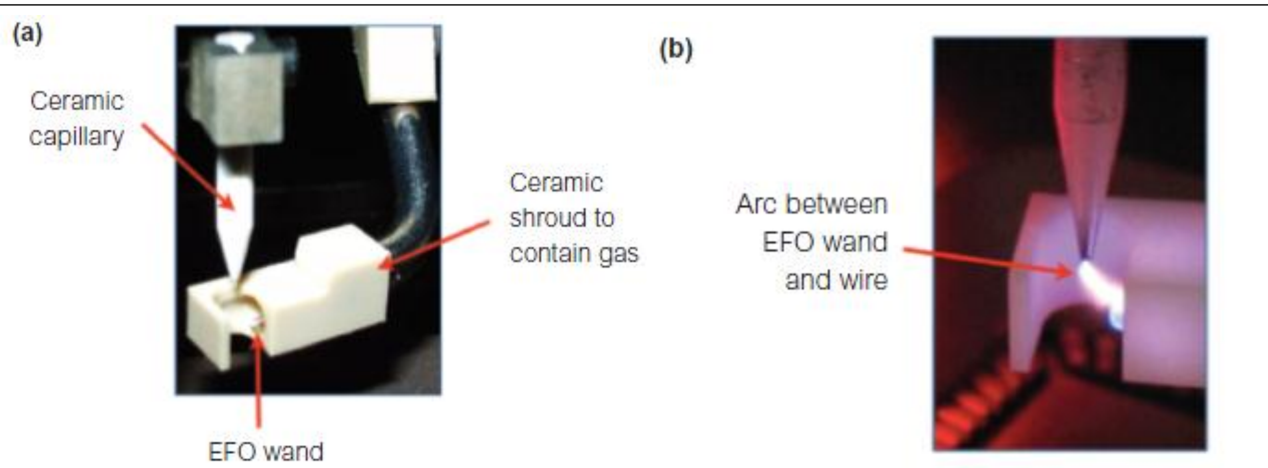


Figure 1. A common addition to a wire bonder to enable Cu ball formation in a forming gas.[1]

producing a quad flat pack no-lead package with 85 wires (a lower cost package) with Cu wires vs. gold. He assumed slower throughput that added 10% to the manufacturing cost and a wire cost savings of 85%. Figure 3 shows the results of this analysis.

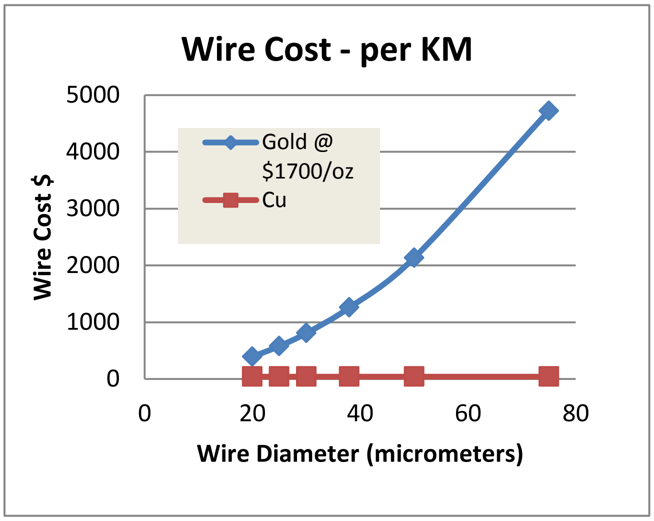


Figure 2. Cost savings for Cu wire compared to gold

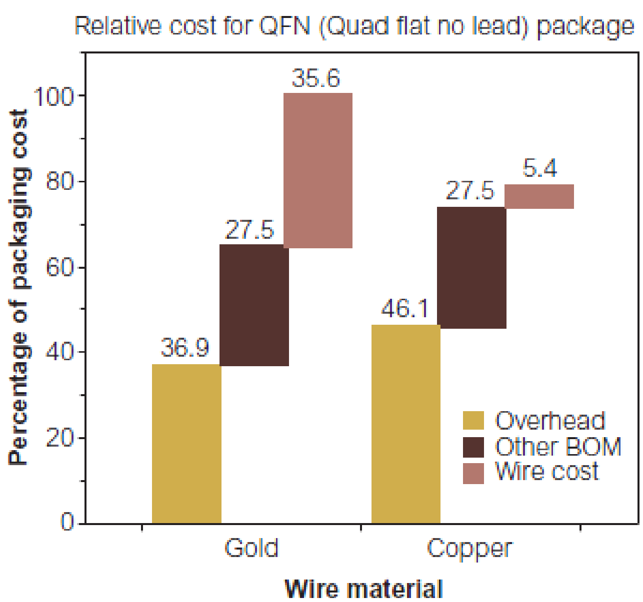


Figure 3. Comparative cost of assembling an 85 lead QFN package with gold and copper wires.[1]

So one can see that as the price differential between gold and copper become large, a sizeable overall cost savings can be attained even with a slower throughput due to the limitations of copper. Due to this overall manufacturing cost savings, copper wire bonding has exploded over the past few years. Adoption began with power devices that used large diameter wire and has migrated to even fine pitch devices with 80µm wire. For example, the package assembler STATS ChipPAC claims to have shipped over 100 million Cu wire bonded devices at the end of 2010 and the rate was growing 75% each year. A telling quote from the press release says the following,

> "Originally used for low leadcount power devices, copper wire use has now expanded into mid- and high-end Input/Output (I/O) packaging, both leadframe and laminate substrate based, and has been proven on advanced wafer fabrication nodes and fine pitch devices"[2]

STATS is only one of many package assembly subcontractors who has been converting product to Cu wire bonding. The chart in Figure 4 was produced in 2009 and shows the rapid growth in volume of Cu wire bonded products. K&S, a leading supplier of wire bond machines, has stated that the number of fine pitch machines capable of bonding Cu wire had increased from 5% of the installed base in early 2009 to almost 25% by the end of 2010.[3]

Many system OEMs do not even realize they are using this new technology in their products. As with most new technology, Cu wire bonding was first introduced in cheap throwaway products that make up an enormous volume of the electronics market. Such products are the most cost sensitive and lowest risk. However, the reliability of such products is not often tracked. The concern is when the new technology migrates into the higher value markets and the products have been in the field for over a year. That's when it can get interesting for reliability engineers. So in preparation, one needs to know how copper wire bonds fail and how to properly analyze them compared to gold.

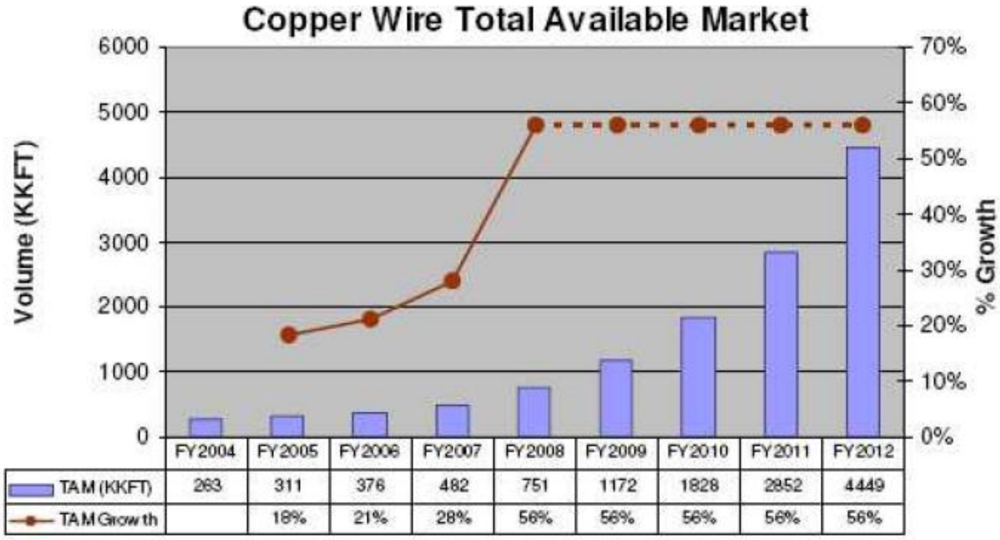
FAILURE MECHAMISMS

When one thinks of failure mechanisms it is sometimes helpful to separate those that occur as a result of poor quality (product not being built correctly) and those that occur due to natural wear-out during the course of the product life (built correctly but eventually breaks anyway).

With Cu wire bonding the most significant concern is a poor quality bond being made, since the process window is made considerably smaller due to the less favorable properties of copper. Studies have shown that the most prevalent defects are ball lift, IC damage, and second bond lift. The following sections will discuss common causes and critical variables responsible for these types of manufacturing defects. Then wear-out mechanisms will be addressed.

Aluminum Splash

Because of the higher hardness of copper, the process of pressing the ball onto the surface while vibrating will cause actual displacement of the Al on the bond pad. The softer Al will be forced out to the side, as shown in Figure 5. The harder the copper or the higher the bonding energy the more Al is moved to the edges of the ball. This leaves less Al on which the copper can bond. It also puts more stress on the underlying silicon or passivation layer, which can lead to



	FY2004	FY2005	FY2006	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012
TAM (KKFT)	263	311	376	482	751	1172	1828	2852	4449
TAM Growth		18%	21%	28%	56%	56%	56%	56%	56%

Figure 4. Growth in Cu Wire Bond Market[1]

cratering (to be discussed next). Higher purity copper (softer wire) will help reduce the Al splash and minimizing the oxidation of the ball and improving the cleanliness of the bond pad will reduce the ultrasonic energy required for a strong bond (thus less splash). For example it has been found that use of forming gas will result in a much cleaner ball surface than if simple N2 is used.[4] Some amount of Al splash is acceptable, however it is important that enough Al remains to form a bond and that the remaining Al is not consumed to form intermetallic after long term aging.

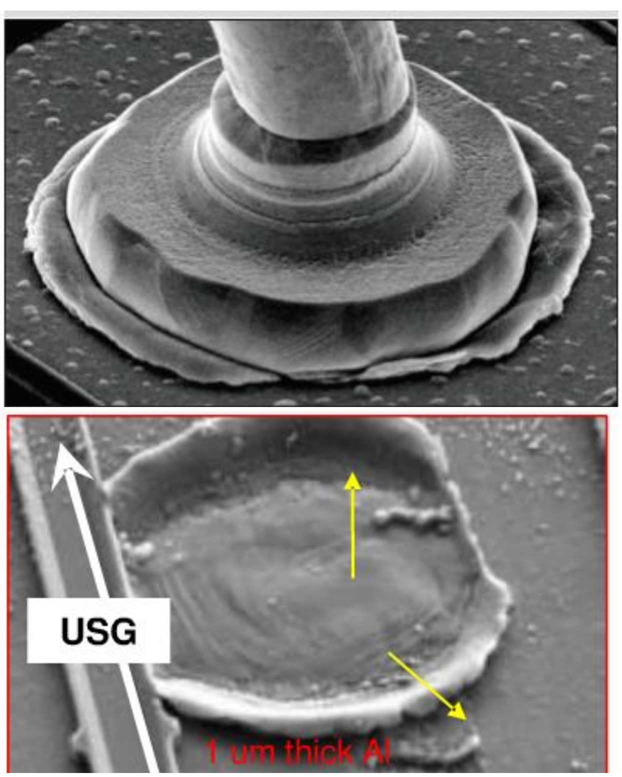


Figure 5. An example of Al splash.

Cratering

When the passivation layer or the silicon beneath the Al bond pad fractures it is called cratering. This type of defect is caused by too much ultrasonic energy being transferred to the Si and has become a more significant issue with Cu wire bonding. A small chip out type defect as shown in Figure 6, does not always cause an actual functional failure since active circuitry does not typically lie beneath the bond pads. However, it can cause weakness of the overall bond interface and can fail early in the field due to thermal cycle stress. It is important to perform bond pull and shear testing as part of the process optimization and to inspect the die surface and record the type of failure that is occurring. Interfacial fractures should not show signs of cratering. Thicker Al on the die pad can also being used to minimize cratering. The Al layer was purposefully rather thin for Au bonding to reduce the growth of thick Au-Al intermetallic, however, the Al-Cu intermetallic grows very slowly so the Al layer can presumably be made thicker without causing a reliability concern.

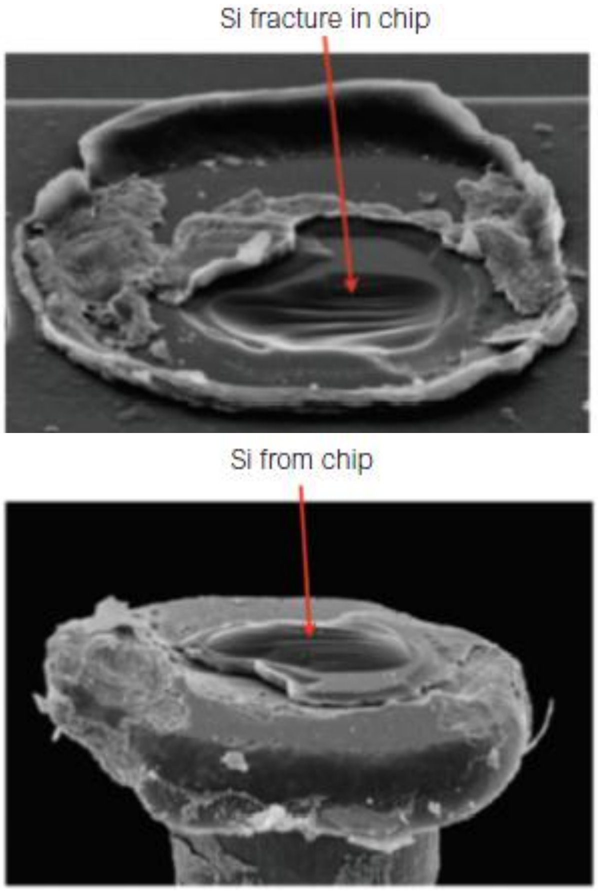


Figure 6. An example of cratering due to Cu wire bonding.

Inadequate Bond Strength – Ball Bond

The process window is considerably smaller with copper due to its higher hardness and oxidation tendencies. We have seen what happens when too much ultrasonic energy is used (splash and cratering) to create the bond. If too little energy is used, the risk is a bond with inadquate bonding area that can fail early in the field. To consistently hit a tight process window one needs a thorough optimization process that ensures bond parameters near optimum are found. Following this, one needs to ensure that all the critical variables are well controlled during manufacturing. One must not overlooks factors such as capillary wear-out, oxidation of the copper wire, contamination of the substrate bond pads, thickness of the Al on the die, or anything else that could interupt the formation of a strong bond. Excellent equipment and quality control systems are critical to achieve consistent bonds in the high volume manufacturing environment.

Consistent and solid support under the bond pad is also required for transfer of the thermosonic energy to the bond surface. This scrubbing energy is what allows the displacement of surface oxides and films that then allows metal-to-metal welding. Gold wire that has no oxide and is softer will allow bonding to a less rigid pad, however, copper is much less forgiving. For example with a QFN package, the gold plated bond pads on which the second bond is placed, are supported by tape (see Figure 7). Cu wire bonding to these is difficult since the lead can move during the bonding operation. Additionally, it can be difficult to transfer heat to these bond pads.

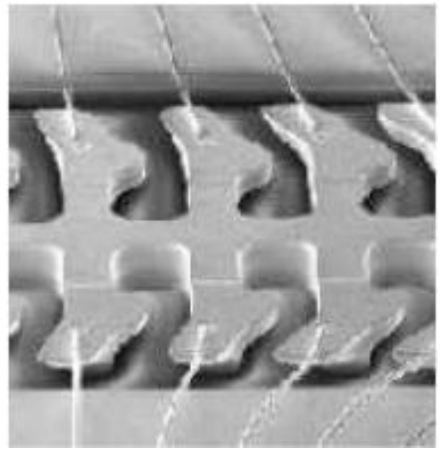


Figure 7. Bonding to a QFN lead can be difficult with copper, since the leads are not well supported.[5]

The industry is looking to move more three dimensional in order to achieve higher densities. In some cases this involves die stacking in very creative ways. Often times the IC device being wire bonded to is cantilevered and unsupported. Gold wire is better able to adapt to such changes while a significant amount of optimization work is required for Cu wire (and sometimes is simply not practical). The resulting failure mechanism if not performed correctly is poorly stuck bonds (insufficient weld area) or if bond pressure is too high, die fracture can occur.

Second Bond Strength

A ball bond machine used for fine pitch bonding creates two types of bonds. The first is the ball bond that was described previously. The second bond (or stitch bond) is created when the capillary crushes the wire against the bond surface. Oxidation of the copper wire becomes a greater concern with the second bond because the oxide has had longer to form on the wire surface (unlike the freshly molten ball). Additionally, this oxide layer must be broken through with less plastic deformation of the copper and the bonding area is smaller than the ball bond. There are a number of modifications that have been implemented to overcome a weak copper stitch bond. Some bond machines come with a Stitch Bond Enhancement (SBE) feature that includes programmable table displacement cycles, directions, amplitude and bond force/power.[6] These have proven to be effective, as shown in Figure 8.

Some have turned to softer copper and larger amplitude motions of the capillary (in a circular motion in some cases). These motions move fresh oxide-free copper to the bond interface. Developments have also been made to roughen the surface of the capillary. The rougher surface bites into the copper wire and better transmits the ultrasonic energy. Others have implemented Pd coated copper wire that eliminates the oxidation concerns. This triples the cost of the copper wire but some reports show a 50% improvement in bond strength.[7] One downside of Pd however, is that it intermixes with the copper during the formation of the ball which results in a harder ball, and an exacerbation of the previously discussed challenges with the ball bond.

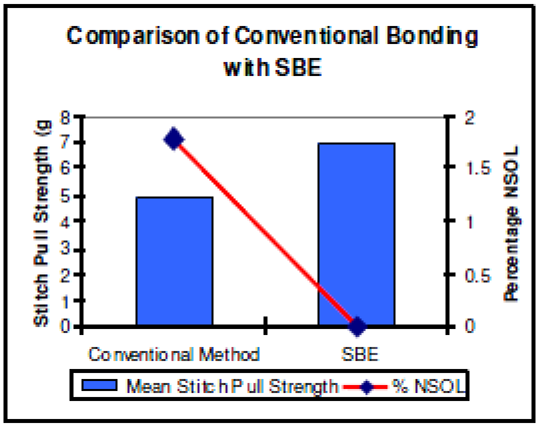


Figure 8. Results of using a stitch bond enhancement feature on a wire bond machine. Non-stick-on-lead failures were elminated.

WEAR-OUT MECHANISMS

In the event that the Cu bonds have been made properly and of adequate strength, the next concern is how well they survive in the expected user environment. This potential risk of wear-out is perhaps the biggest area of concern for OEM's in most non-consumer environments (medical, enterprise, telecom, industrial, automotive, etc.). While wearout is relatively rare in the ranking of all time failure mechanisms, the monetary risk can be enormous (think Pinto). Wearout of wire bonds, in the classic sense, tends to be driven by exposure to elevated temperature, elevated temperature and elevated humidity, and temperature cycling.

A good understanding of the life and wear-out mechanisms is needed. Typical component level reliability testing involves thermal cycling (-65/150°C) for 500 cycles, high temperature storage at 150°C for 1000 hours, and a pressure cooker test (130°C/85%RH for 96 hours at voltage bias).

In typical Au to Al bonding, the long term failures commonly occur due to the formation of Kirkendall voids as the intermetallic grows thicker at elevated temperature. One can therefore measure intermetallic thickness with the Au-Al system and gain a good understanding of the expected life. At temperatures approaching 300°C purple plague forms (a specific type of Al-Au intermetallic).

However, with Cu bonding to Al the intermetallic growth rate is much slower and the formation of Kirkendall voids is not a real concern. Figure 9 shows measurements of IMC growth for Au and Cu at 175°C.[8] The growth rate is of Cu IMC is about 1/5 that of gold. Figure 10 shows cross section examples of IMC thickness under high temperature exposure conditions. As one might expect, the slower growth of intermetallic results in more stable bond strength over time at elevated temperature. Figure 11 shows shear strength of Au and Cu ball bonds made on Al bond pads after aging at various temperatures and times.[9] Interestingly the strength loss differences are not nearly as pronounced as the IMC growth rates. At temperatures of 120°C or below Cu and Au are very similar in strength loss.

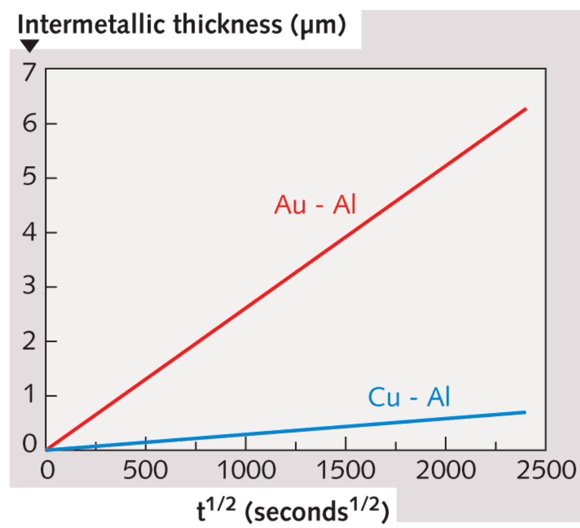
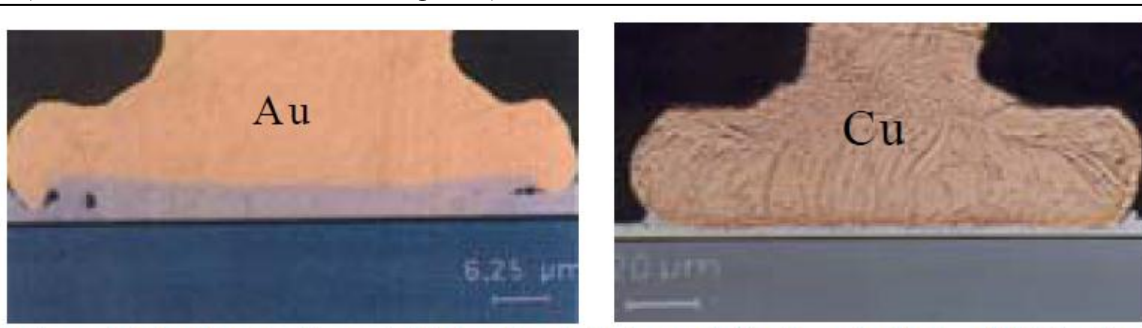


Figure 9. Growth of intermetallic thickness vs. time at 175°C.[10]



Intermetallic Penetration - AlSi-Au Bond (aged 200 hours at 200°C)

Intermetallic Penetration - AlSi-Cu Bond (aged 800 hours at 180°C)

Figure 10. A comparison of intermetallic growth rate with Au and Cu ball bonds on Al.[1]

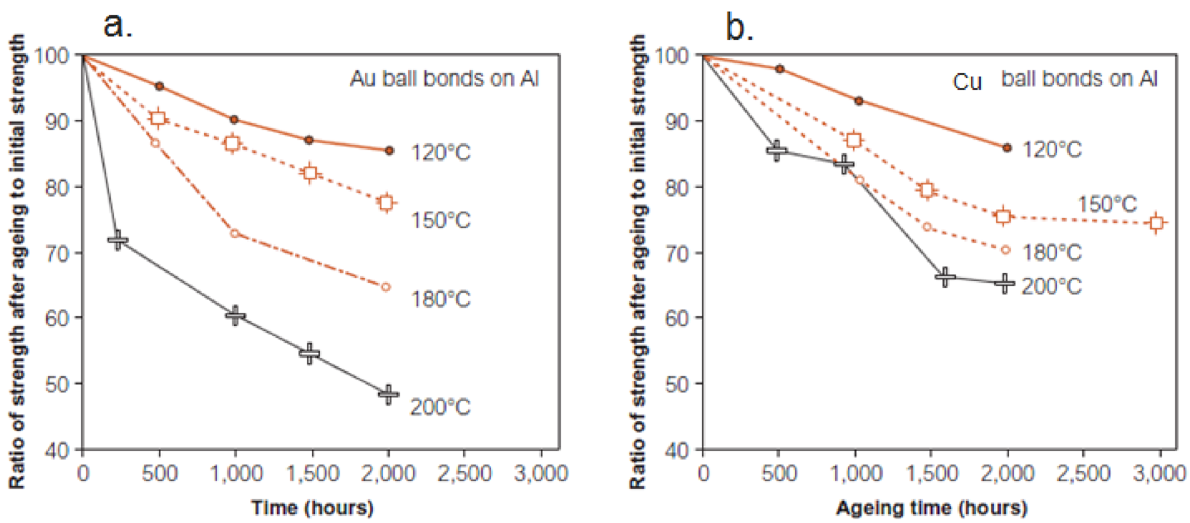


Figure 11. Shear strength of Au and Cu ball bonds on Al bond pads after aging. At temperatures of <120°C they are similar after 2000 hours.[9]

More recent studies have shown some surprising results that occur when Cu wire or Pd coated Cu wire is aged at 200°C. It was found that Pd coated wire performed better over time (see Figure 12)[11]. Most concerning was the discovery that after 500 hours of aging, the shear failure mode changed from fracture within the copper to a brittle crack along the IMC. Figure 13 shows such results. This newly discovered and concern actually highlights a common problem among component manufacturers and New Technology: the assumption that standard testing and standard acceleration factors (such as Peck's Law) are relevant for New Technology (hint: it usually isn't).

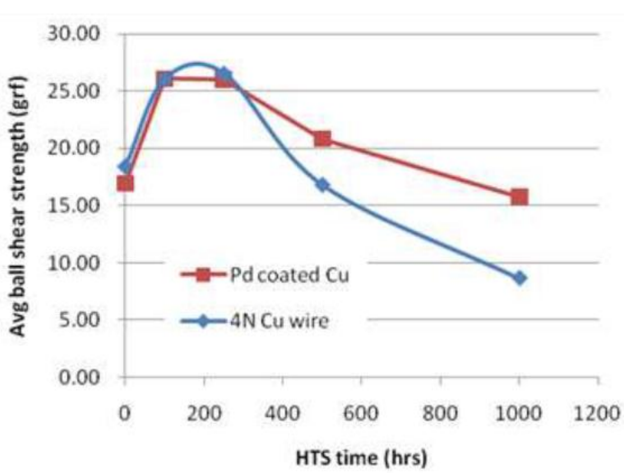
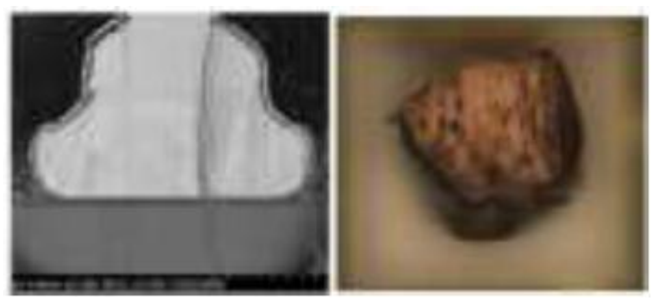
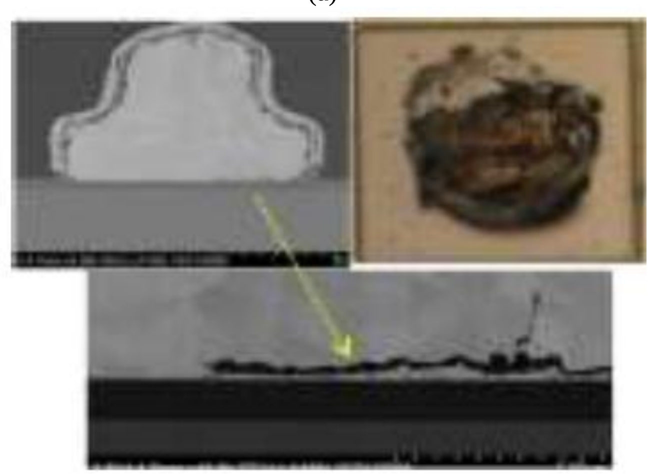


Figure 12. Shear strength of ball bonds after aging at 200°C.



(a)



(b)

Figure 13. A change is fracture mode is observed from (a) 250 hours of aging at 200°C to (b) 500 hours of aging.[11]

Temperature Cycling

Wire bonds do not typically fail due to temperature cycling. When not encapsulated, the loop height of the wire provides compliance that easily absorbs any expansion mismatch. When encapsulated, the mold compound protects the wires and distributes the stress evenly along the length of the wire. If the die to overmold interface delaminates due to say popcorning, then expansion mismatch stress can concentrate on the ball bond interface. Should such an event occur, one would actually expect the Cu to perform better than the Au due to its higher ductility – unless of course the IMC structure in Cu is such that brittle failure occurs.

Temperature/Humidity Conditions

Even after large scale introduction of Cu wire bonding, the industry is learning about new and unexpected failure mechanisms. Perhaps the most worrisome is the susceptibility to oxidation/corrosion when exposed to autoclave conditions (130°C/85%RH plus bias).[12,13] This weakness was validated at the Fraunhofer Institute where they found early failures in T/H testing and determined it was due to galvanic corrosion of the copper oxides between the intermetallic and Cu bond wire.[14] Figure 14 shows an example of the weakened and fractured interface between the Cu and the Al. Analysis showed the presence of Cl as a corrosion activator and high oxidation of the Al near the edges of the Cu ball. The primary IMCs that form in a Cu-Al bond is $CuAl_2$ and CuAl, however, this study also revealed a Cu_9Al_4 phase that formed presumably during predconditioning at 260°C. This Cu rich phase was highly susceptible to galvanic corrosion, acting as the sacrificial anode; leading to delamination.

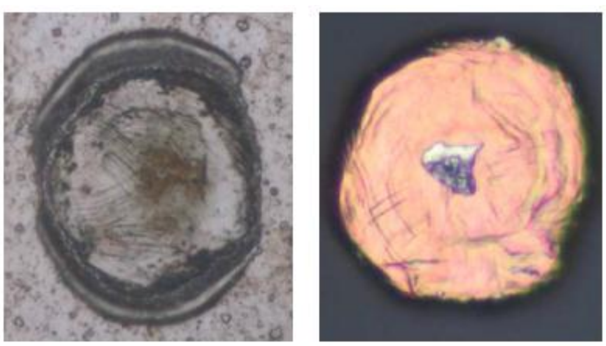


Figure 14. A weak interface revealed by ball shear after autoclave testing.

Additionally, under voltage bias testing (T/H/B) the copper can migrate and cause shorting between pads on the device. The prevalence depends on the type of mold compound used, as noted by H. Clauberg (see Figure 15). In this failure mechanism, the Pd coating can actually help prevent the copper from migrating. The bottom line is that encapsulants and molding compounds should be carefully selected with Cu wire bonding. They should resist moisture absorption and be free of Chlorine, that is, contain fire retardants specifically designed to eliminate copper corrosion.

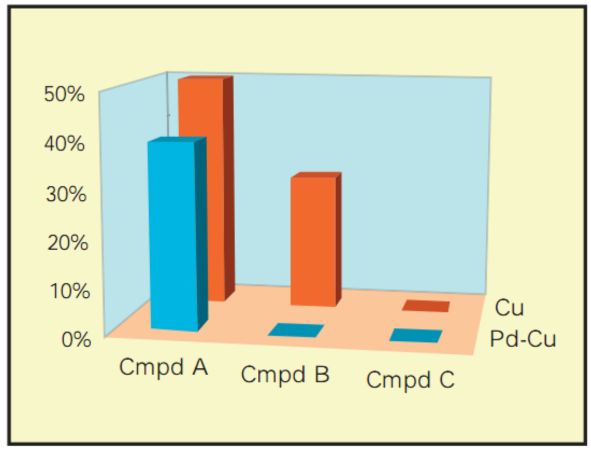


Figure 15. Failure rates after 336 hours biased HAST test for three mold compound formulations with 0.8 mil Cu wire on Al pads (5V bias, 130°C, 85% RH). [15]

Wire Sweep

The higher modulus and work hardening rate actually work in favor of Cu with regards to preventing wire sweep. However, if wires are nearly touching and voids exist in the compound between them, metal migration could be more prevalent with copper wire compared to gold.

FAILURE ANALYSIS

An additional challenge with Cu wire bonding is how to observe failures if you are a failure analyst tasked with decapsulating an overmolded package. With traditional gold wire bonding, the gold would withstand the harsh chemicals used to dissolve the compounds. Cu will simply be dissolved using these chemicals and all evidence destroyed. A number of recipes exist and the right one will depend upon the encapsulant material. The following recipe is a good place to start:

- Use 20% fuming sulfuric acid
- Use about a 3:1 or 5:2 ratio of nitric to sulfuric acid
- Use a low temperature (from 17°C to 25°C)
- Be patient (this could take awhile)
- Consider pre-decapsulation material removal, such as laser ablation or mechanical milling, to speed up the process

DISCUSSION

Wire bonding with gold has produced many challenges over the years, with non-optimized processes causing expensive defects and field failures. The industry responded with major improvements in the areas of process optimization, equipment control, and measuring methods. These advancements are being heavily leveraged with the transition to Cu wire bonding, since this change has significantly reduced the process window (in a similar way as occurred with the transition to Pb-free assembly).

Finding optimal values for variables such as cleanliness of the bond pads, ultrasonic energy, force, and temperature are now even more important. With Cu wire, one must also be concerned with added variables such as the age of the copper wire, softness or purity of the wire, thickness of the Al bond pad, mix and flow rate of forming gas, and the composition of the overmold compound. A company making this transition would be wise to invest a portion of the newfound cost savings to ensure these variables are optimized and controlled. This could mean the addition of an on-going reliability test procedure, where a sampling of product is subjected to reliability testing to ensure product is stable over time. OEMs should be aware of the challenges and ensure suppliers are following best practices when auditing factories

With any major change, one can count on different and unexpected failure mechanisms to reveal themselves after products have been in the field for a few years. The expectation with Cu wire bonding is that improved performance is found with high temperature exposure. However, we should not grow complacent since some have found the tendency for oxidation/corrosion of the wire bond if put into a high humidity environment with the wrong encapsulant material. Cu migration can also be a concern if gaps or voids exist between wires. With hundreds of millions of Cu wire bonded devices being put into service, failure engineers should keep their antennas up and watch for any issues and communicate them to the industry if they are found.

CONCLUSIONS

Cu wire has been adopted and moved to high volume production rather quickly over the past few years due to the cost savings. Many end users may not even realize they have this new technology in their products. 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. These need to be better understood. Most would agree that the largest challenge with Cu wire bonding is in adequately controlling the bond parameters to the levels needed to achieve good bonds in high volume production. Six sigma practices should be employed to maintain control of parameters such as, Al bond pad thickness and cleanliness, copper wire softness, purity, age, forming gas flow, spark control, and of course all the bonding parameters. The failure mechanisms described in this paper provide guidance on where to look in the event that failures occur with this new material set.

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