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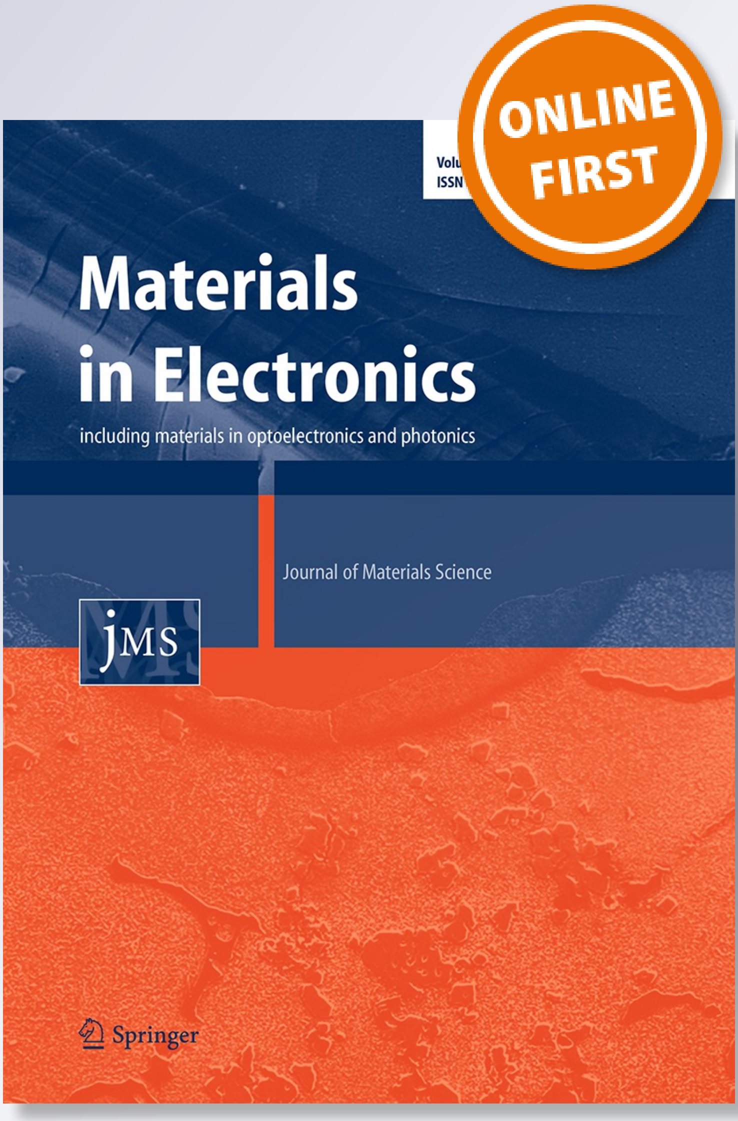

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REVIEW

Evolutions of bonding wires used in semiconductor electronics: perspective over 25 years

Chong Leong Gan · U. Hashim

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Abstract The objective of this review is to study the evolution and key findings and critical technical challenges, solutions and future trend of bonding wires used in semiconductor electronics. Evolutions of bonding wires from Au to Cu and till the most recent silver (Ag) wire (perspective over 25 years packaging technology) have been discussed in this paper. The reliability performances of Au wire bonding, technical barriers of Cu wire bonding and corrosion mechanisms of Cu ball bonds are analyzed and covered. We focus on the influence of a variety of factors that have been reported recently, including reliability performance, wear out reliability performance that determine the selection of bonding wires to reach for developing high reliability of bonded devices. In the end of this review, the evolutions and future trends of bonding wires are compared and illustrated, which have marked effect based on the materials properties as well as reliability of wire types.

1 Introduction

The most important invention of the electronics industry is, arguably the transistor, which earned John Bardeen, Walter Brattain, and William Shockley the 1956 Nobel Prize in Physics. Wirebonding is equally important and is the heart of first level die-to-substrate interconnects technology in semiconductor packaging. Gold (Au) and Copper (Cu) wirebonding have been invented more than 25-year-old technology and continually sustained in semiconductor electronic packaging. This paper reviews and discusses the key finding and critical technical challenges, solutions and future trend of bonding wires used in semiconductor electronics. Evolutions of bonding wires from Au to Cu and till the most recent silver (Ag) wire (overview of perspective over 25 years packaging technology) have been discussed in this paper.

2 Gold wirebonding (1990s till current)

Gold wirebonding is the first wire alloy been introduced and deployed in semiconductor packaging. However, owing to the increasing packaging cost due to rising price of gold, IC suppliers start to look at lower cost alternative wire alloy such as Cu wire. Breach et al. [1–3] reported gold can be as reliable as copper wire in High Temperature Storage test (HTST) but copper is facing problems in more challenging stress tests such as temperature cycling (TC) and Pressure cooker test (PCT) that is driving the evaluation of Pd-coated Cu wires. There is no doubt that copper can and should replace gold wherever viable but the main driving force to do so, at present, is cost reduction [1]. Zulkifli et al. [4] reviewed the methods that have been introduced to determine the bonding mechanisms of gold wire bonding. Each of the techniques that have been introduced leads to different explanations for the Au wire bonding mechanism.

Au wirebonding is identified as primary packaging option in high power light emitting diode (LED) packaging since 1990s. Au wirebonding with low-alloyed Au wire has been introduced in semiconductor packaging with higher

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mechanical strength and more robust HTSL reliability performance. These gold alloys usually contain up to 1 % alloying elements, in some cases up to 5 %. The most important alloying elements are the precious metals Ag, Pd, Pt, and also Cu. Other elements are also used, but preferably at lower concentrations to minimize the danger of corrosion. Simons et al. [5] studied reliability tests after long-term temperature exposure indicate higher shear strength values for the low alloyed wire compared to pure Au wire (as shown in Fig. 1a, b).

Ag wire possesses similar mechanical properties with Au wire but Ag is more superior in terms of electrical and thermal conductivity. When compared to Cu, Ag is similar in conductivity, but softer in terms of mechanical properties [6]. However, Au wirebonding is still the mainstream in semiconductor industry. Au wire is noble and more stable than other wire alloys such as Ag and Cu wirebonding. However, extra argon shielding will enhance the bondability of Au wirebonding onto Al bondpad [6]. Semiconductor industry usually deploys plasma cleaning prior to bonding step to increase the Au or Cu wirebonding. This is one of the alternatives in bondability enhancement. Au ball bond tough is more corrosive resistant however it will undergo AuAl intermetallic oxidation if left unmolded and exposed to 175 °C HTST test for long duration [7]. Breach et al. [8] reported the Au ball bond oxidation and corrosion mechanism which is different from Cu ball bond.

Initial Au ball bond started at the peripheral areas of the contact area situated along the direction of ultrasonic vibration. Those areas extended inwards with an increase in ultrasonic power [9]. This explains why the IMC is thicker at the peripheral of Au ball bond. DeLucca et al. [10] investigated the interface between the thin and thick IMC is observed as the location where greater voiding/low-density interface development takes place, as opposed to the Au/IMC interface. The AuAl IMC intermetallic growth kinetic is studied and reported with activation energy of [11]. The same AuAl intermetallic compound Au_8Al_3 and Au_4Al are found on 2 N and 4 N Au wires [12].

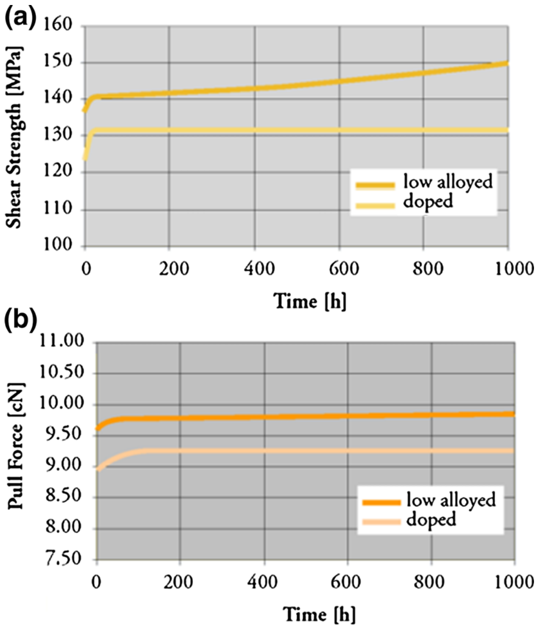

Fig. 1 Reliability tests of gold wire bonds after temperature exposure at 150 °C (Fig. 1a); pull test, hook near ball bond (Fig. 1b) [4]

Au wire is a softer material than Cu and Ag wires. Hence, the breaking mode after wire pull or shear tests are a bit different for Au compared to other wire alloys. Soft gold balls are typically sheared by the tool, leaving a lower section of the ball bonded to the aluminum metallization. In contrast, copper balls do not undergo appreciable plastic deformation and are sheared completely away from the bond pad [12–14]. For both Cu and Au wires, the larger the tensile strength of the wire the larger the maximum pull force and displacement. Murali et al. [14] found the gold ball bond fails predominantly along aluminum metallization close to gold aluminide. However, the copper ball bond fracture occurs deeper into the aluminum bond pad. The mode is entirely different for the aged gold ball bond where the gold fracture is above the intermetallic layer. Gold wire is well-deployed in rigid and flexible substrates [15] and LED packaging [16]. Xu [17] characterized oxidation in bulk Au IMCs can be occurred at two types of bulk gold aluminides, $AuAl_2$ and Au_4Al, using thermogravimetry. Initial results on bulk materials show that appreciable amounts of oxidation can occur in these intermetallics. Blish [18] studied the E_{aa} of Au–Al IMC formation at grow laterally (Al-rich phases) in a Fickian fashion with an activation energy of 1.0 eV, but vertical IMC thickness (Au-rich phases) grows functionally as a power law on time with a sub-Fickian exponent of 1/4, which is substantially smaller than what would be expected for bulk lattice diffusion (0.50).

3 Cu wirebonding (after 1995 till current)

Cu wirebonding is the first alternate wirebonding option adopted other than Au wirebonding in semiconductor packaging. The great interest of deploying Cu wirebonding is mainly driven by lower cost, higher electrical conductivity and tool readiness at this moment. Cu wirebonding has been widely adopted in recent nano electronic packaging due to its conductivity properties and cost effectiveness [19]. There are several advantages of Cu wire versus conventional Au wire in nanoscale semiconductor packaging. Copper wires have excellent ball neck strength after the ball formation process [20]. High stiffness and high-loop stability of Cu wire result in better wire sweep performance during molding or encapsulation for fine pitch devices, and can help to achieve longer or lower loop profiles [20–22]. Copper has higher stiffness than gold, leading to better looping control and less wire sagging for fine pitch and ultra-fine pitch wire bonding [23]. The rate of intermetallic (IMC) growth between Cu and Al is much lower than that between Au and Al, resulting in less heat generation, lower electrical contact resistance, better reliability and better device performance compared to Au/Al bonds The higher stiffness of copper wires is more suitable to fine pitch bonding than that of gold wires [24].

There are several challenges to Cu wirebonding, though. Copper can be easily oxidized in air, and therefore copper wire bonders must have additional mitigation techniques to prevent copper oxidation Although N_2 gas can be a suitable option, a forming gas mixture of 95 % N_2/5 % H_2 has been shown to be the general choice [25]. Appelt et al. [25] investigated the key process design rules in Cu wirebonding in nanoscale packaging. These rules are a starting point for a rigorous methodology that was implemented for the qualification of each new device for all three major package families: quad-flat package (QFP), quad-flat no-lead (QFN) and ball grid array (BGA). This iterative approach confirms initial bondability in phase 1 on the actual device. In phase 2 the bonding recipe is optimized for the specific device, and, if the device is outside the experience data base, some preliminary JEDEC type reliability testing is performed. Copper wire bonding needs more ultrasonic energy and higher bonding force, which can damage the Si substrate, initiate die cratering, and induce cracking and peeling of the bonding pad [26]. Oxidation of Cu wire can also lead to poor bondability for stitch bonds, which can result in increased non-sticking rates.

However, the lower corrosion resistance of Cu wire especially in biased or unbiased highly accelerated humidity and temperature stress test (HAST) has drawn the technical concerns from semiconductor industry [27]. Cu ball bond with harder material properties cannot deployed with the same Au ball bonding parameters. Excessive first Cu ball bonding on Al bondpad will induced silicon cratering during bonding or post reliability stresses such as PCT. Key Cu wirebonding process developments and ongoing reliability monitoring have been laid out extensively to address those technical barriers to replace Au wirebonding in semiconductor packaging [28, 29].

Many previous research works have been carried out to understand the Cu ball bond corrosion mechanisms under higher humidity conditions such as biased HAST (HAST) or unbiased HAST test. The primary source of corrosion is the moisture content and the presence of halide element, Cl^- content in packaging material [28, 29]. Xu et al. [30–32] conducted detailed characterization of CuAl IMC growth under aging test, oxidized CuAl IMC and microvoiding in Cu ball bond. PH level of molding compound chemistry (pH level) and halogen content of substrate (in ppm) will affect the HTST and biased HAST reliability performance of Cu wire. Peng et al. [33, 34] reported pH level of around 5.5 and low halogen content ($\sim$ 10 ppm) produce the best HTST and biased HAST reliability performance with Cu wirebonding. Hence, higher corrosive resistant Cu based alloy is highly desired to replace the existing bare Cu alloy in semiconductor packaging. There most recent improved version of Cu alloy include the Pd-coated Cu wire where a thin Pd is coated onto the wall of bare Cu wire and has been evaluated extensively in Cu wirebonding.

4 Key challenges and solutions of Cu wirebonding

There are various advantages and challenges associated with the Cu wirebonding. Notably, higher bonding duration and bonding temperature will produce Cu ball bond strength but we need to control the bonding parameters during Cu wirebonding. Cu wirebonding key challenges include moisture reliability, IMD (Intermetal microcracking) or pad cratering and control of Chloride content in molding compounds [32]. Various engineering studies have been carried out in order to resolve the challenges with coated Cu wirebonding in microelectronic packaging. The summary our comments and views on some of the reported technical solutions are as tabulated in Table 1 for Cu wirebonding.

5 Cu wirebonding performance

5.1 Cu wire reliability studies and hurdles

Liu et al. [46] investigated that “Al splash” or squeeze out must be controlled with the bond pad opening, as shown in Fig. 2a and b [46]. The remnant Al of bond pad must also remain a certain thickness in order to ensure the bonding reliability. If the remnant Al layer of bond pad is too thin, it could be completely consumed by Cu/Al IMC. Due to the poor adhesion between IMC and SiO_2, ball lifts or microcracks readily happen in a pull test.

Studies of the effect of wire purity on copper wire bonding showed that higher purity copper wires have larger grain size in FABs and smaller flow stress, requiring a smaller force to deform the squashed ball which resulted in less Al squeeze. Figure 3a, b reveal the typical cross-section of Cu ball bond with and without Al splash on different bondpad metallization. [47].

Table 1 Solutions and our views of reliable wire bonding with Cu wire

Previous research findings and challenges on Cu wirebonding	References	Comments and views
1. The bonding position significantly affects the local stress near the bond, and the wire should be bonded at the pad center	[33]	This requires accuracy in ball bond placement and could be achieved with latest high-end Cu wire bonder to ensure ball bond placement
2. Decreased hardness and strength of the HAZ lead to breakage sites of the wires to be in the HAZ near Cu balls	[34]	This is a low level challenge since proper setting of EFO flame off parameters at wire bonder and wire looping profile will mitigate wire neck break or tight wire issue with Cu wire
3. Cu wire is vulnerable to corrosion. Pd-plated Cu wire demonstrated excellent reliability and bondability	[35, 36]	Agree. Recent industrial and academic data reveals higher moisture reliability margin with Pd-coated Cu wirebonding
4. New capillary with a new surface morphology leads to satisfactory results in ball shear and stitch pull tests	[37, 38]	Improved morphologies of capillary's profile will increase second bond strength. However further optimization needs to be carried out to improve short-tail stoppages especially with bare Cu wire
5. Use a lower contact velocity and provide sufficient inert-gas coverage is recommended for a well formation of Pd-coated Cu FAB and minimize stress induced during ball bond impact	[39]	Some findings shows effect of contact and constant velocity will increase first ball bond strength with Cu wire. Stress relief could be achieved with optimized first ball bond parameter and bondpad structure. Sufficient supply of N_2 will ensure proper formation of Cu FAB
6. Cu/Al IMCs are mainly Cu_9Al_4 and $CuAl_2$, with CuAl present in smaller amounts	[39, 40]	Agree to the findings. Extra baking step after wirebonding will improve its first ball bond integrity
7. Wire open and short tail defects. Needs to use Pd-coated Cu wire to improve short-tail issue and increase its moisture reliability	[41]	This is well-known solution and challenge with bare Cu wirebonding
8. Cu wire is stiffer and caused pad crater or pad peeling with excessive bonding. First ball bond parameter should optimized to minimized silicon cratering at bondpad	[42–44]	This is well-known solution and challenge with bare Cu wirebonding. Other solution proposed include to introduce dummy microvias beneath Al bondpad metallization to stabilized or strengthen the bondpad structure and mitigate bondpad crater defect
9. Cu/Al IMCs are thinner than conventional Au/Al IMCs	[45]	Thinner IMCs of Cu/Al would results in lower first ball bond strength and will reduce its moisture reliability. However this behavior helps in HTSL long term reliability compare to Au/Al IMC system

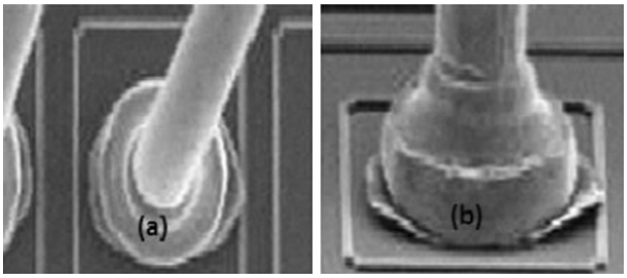

Fig. 2 **a**, **b** Examples of Al splash within the bondpad opening [46]

Onuki et al. [47, 48] attempted rather early in the history of copper bonding in 1990 to understand the effects of copper ball hardness on bond pad damage and looked at effects of wire purity and ball formation parameters on the softness of copper balls. Wulff et al. [49] showed by measuring Vickers hardness of bonded balls that gold and copper ball bonds can work harden and that copper does so more than gold. Intermetallic phases that were observed in

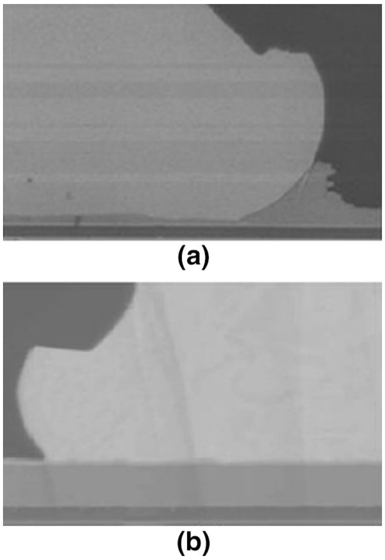

Fig. 3 Al splash/squeeze with Cu wire: **a** Al Pad, **b** Ni–Pd–Au plated Al pad [47]

this paper for copper wire were CuAl and $CuAl_2$, but not all compounds occurred at each ageing temperature (and other research has demonstrated other intermetallic as well). Onuki reported that for both wire types (gold and Cu wire), strength loss was due to separation within intermetallic phases despite the much slower intermetallic growth rate for copper. For devices encapsulated in epoxy molding compound, more degradation was found with gold wire than copper.

A study by Khoury et al. [50] compare Au and Cu bonding wires on Al, Al-Cu and Al–Si-Cu bond pad metallization of unspecified thickness. Bond pad compositions were not given. Specimens were assembled and electrically tested and different batches subjected to high temperature storage at 145 °C, PCT at 121 °C, 2 atm, isothermal ageing at 85 °C at 85 % RH and temperature cycling from −65 °C to 150 °C. The reliability data indicated that copper wire bonding is at least equivalent to that of conventional gold wire bonding. The results of this paper show that a copper ball bond assembly process can be developed for mass production which will equal and potentially surpass the performance and reliability of the present gold ball bond assembly process.

Another key study in 1995 by Nguyen et al. [51] reached much the same conclusions as the previously described studies, i.e. that copper is at least as reliable as gold and that copper could become dominant. Tan et al. [45] in 2002, which described silicon cratering as a major hurdle to overcome, and like previous studies, concluded that the higher ultrasound needed to bond copper balls causes more cratering and that harder bond pads could help in eliminating cratering. Tan [26, 27] al described PCT experiments on un-molded copper ball bonds bonded at 350 °C and observed high shear forces with time and a drastic reduction of shear force due to corrosion and formation of copper and aluminium oxides. Murali et al. [52] studied FAB hardness and cratering in 25, 50 and 75 μm copper wires in 2003 published similar data in 2004. Both papers draw essentially the same conclusion that FABs harden significantly during the copper bonding process. Other papers by Murali et al. [52] compared intermetallic growth in gold and copper ball bonds and concluded that after 2 days ageing at 175 °C there was little intermetallic growth in the copper ball bond.

In 2003, Kim et al. [53] annealed copper ball bonds at 150, 250 and 350 °C and measured intermetallic thickness without a gold control annealed under identical conditions. Kim et al. [53] investigated the effects of IMC formation on the copper wire bondability on Al pad, ball shear tests were performed on annealed samples. For as-bonded samples, ball shear strength ranged about 240–260 gf, and ball shear strength changed as a function of annealing times. For annealed samples, the ball shear breaking mode is found at IMC layer or Cu wire itself. The IMC growth and the diffusion rate of aluminum and copper (due to the annealing step) have a large impact on the failure mode observed. Examination of etched specimens of copper ball bonds in Fig. 4 reveals that in addition to bulk interdiffusion, ageing at higher temperature caused Cu–Al intermetallic growth along grain boundaries.

With new interest in copper wire bonding over the past several years there has been extensive evaluation of copper wire in industry. HTST generally demonstrates that although gold wire intermetallic growth is much more rapid than copper wire, gold ball bonds can be generally as reliable as copper. For that reason, copper wire appears capable of replacing gold in low-end as well as advanced packages. However, over the past few years some problems have emerged. In some cases, copper ball bonds can fail TC and PCT. There are few published studies regarding this phenomenon but it is a real problem faced by industry. The problem is serious enough that it is stalling the widespread adoption of copper and sweeping replacement of gold in all applications. Thinning of Al bondpad metallization after wirebonding may result in stress gradients and potential for crack formation at the ball periphery during TC tests whereas it is possible that stresses in the ball and between the ball and bond pad anneal out during HTST. One of the first published studies regarding this problem was by Kaimori et al. [54], which compared encapsulated 25 μm diameter copper and gold wire and proposed a solution in the form of Pd-coated copper wire.

More recently, Vath et al. [55] performed HTST tests with Pd coated copper, 4 N gold and copper wire, concluding that Pd coated wire gave the best performance, followed by 4 N gold with bare copper wire in third place. Industry feedback is that currently, performance is somewhat improved relative to copper but there are insufficient data from which to draw clear and reliable conclusions.

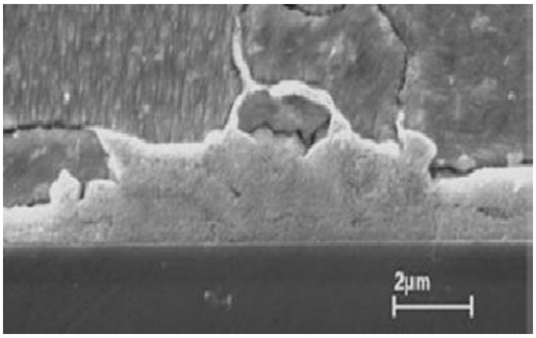

Fig. 4 Cu–Al intermetallic growth reported by Kim et al. [53]

5.2 Cu ball bond failure mechanisms

5.2.1 *Cu–Al IMC corrosion under high humidity (Unbiased HAST, biased HAST, THB Tests)*

It has been a challenge to ensure Cu ball bond integrity in nanoelectronic packaging through various reliability stress tests. One of the most critical stress is high humidity UHAST and biased HAST tests [56]. Griffin et al. [57] identified Cu_9Al_4 intermetallic phase oxidizes under biased HAST conditions. Systematic failures due to catalyst in mold compound. Bias is required for this failure mode to activate the catalyst (which possibly contains Cl^- content) in molding compound used in packaging. Positively biased pins collect anions and initiate oxidation whereby ground pins or negatively biased pins remain intact, Cu_9Al_4 phase oxidizes randomly without systematic bias effect. Random failures occurred in autoclave, biased HAST and temperature humidity bias test (THB), occurring on positively biased, negatively biased or grounded pins, demonstrate that in some cases, bias is not required as a catalyst already exists on a bond pad prior to or after wire-bonding, but prior to encapsulation with a "good" mold compound.

Breach et al. [58] hypothesized the possible reactions resulting in formation of aluminium oxide that might occur with gold and copper ball bonds are given in Eqs. 1 and 2. It is highly possible that hydrogen gas is released as a product of Au and Cu ball bond hydrolysis (as shown in Eqs. 1–4)

$$2Au_4Al + 3H_2O \rightarrow Al_2O_3 + 8Au + 3H_2 \quad (1)$$

$$Cu_9Al_4 + 6H_2O \rightarrow 2(Al_2O_3) + 9Cu + 6H_2 \quad (2)$$

Possible reactions resulting in formation of aluminium tri-hydroxide that might occur with gold and copper ball bonds are given in Eqs. 3 and 4.

$$Au_4Al + 3H_2O \rightarrow \left(Al(OH)_3\right) + 4Au + 3H_2 \quad (3)$$

$$Cu_9Al_4 + 12H_2O \rightarrow 4\left(Al(OH)_3\right) + 9Cu + 6H_2 \quad (4)$$

It appears that such reactions generate more hydrogen in the case of selective oxidation of Cu–Al intermetallics than with Au–Al intermetallics. However, this does not necessarily mean that copper aluminides will degrade more due to hydrogen because nothing is known about the susceptibility of Cu–Al and Au–Al intermetallics to hydrogen embrittlement. It can only be suggested that if these reactions occur. Intermetallic degradation of gold and copper ball bonds on aluminum metallization under moist conditions has been observed. In both cases aluminum oxide is present on weak areas of bond pads. A possible root cause of this phenomenon is internal oxidation that is a process of selective oxidation of aluminum with in situ precipitation of gold or copper. This may explain recent results that show precipitation of copper and the presence of an aluminum oxide in degraded copper ball bonds [59].

Another Cu–Al IMC corrosion failure mechanism was proposed by S. Peng [59, 60] whereby the Cl^- contents (in ppm level) and pH level exists in molding compound will affect the biased HAST reliability performance. Considering the high level of Cl^- (100 pm) in the molding compound used for the evaluation, plus the fact that this ball bond is part of the positively biased daisy chain, it is likely that Cl^- ions are driven to locations near the ball bonds by the electrical bias, and the lower pH content in molding compound would creates an acidic environment that accelerates the corrosion of the IMC layers. The missing of Cu_9Al_4 layer suggests it is corroded fastest compared with other nearby materials. The exact reason for this difference in corrosion rate is not yet well understood, but we can hypothesize the electro-chemical reaction at the interface formulated as in Eq. 5 below:

$$\begin{aligned} &Cu_9Al_4 + 6HCl + 3O_2 + nH_2O \\ &\rightarrow 2AlCl_3 + 2Al(OH)_3 + 9Cu + nH_2O \end{aligned} \quad (5)$$

When the pH level in the molding compound is sufficiently low, the Cu_9Al_4 layer can be selectively etched by the acidic environment, which in turn creates a self-propagating crack between Cu and the $CuAl_2$ IMC layer [60].

For the HTS test, within the testing duration used in this study, the variations in molding compound did not generate failures for any of the experimental cells. Microstructure analysis performed on some of the experimental cells show the Cu–Al IMC growth rate is significantly less than that for Au–Al IMCs. As this is mostly a 'dry' environment, the lower pH levels and increased Cl^- content do not have significant impact on the failure process. These results also indicate that the HTS test is not a sensitive or effective test method for molding compound evaluation or selection. All failures observed in this study are located within the positively biased daisy chains. This observation suggests the electrical potential may help drive the negatively charged Cl^- to these regions, further increase the acidity of the environment near the ball bonds. The corrosive environment appears to accelerate the corrosion of one of the IMC layers (Cu_9Al_4) the most and the consumption of these layers generates cracks at the interface that eventually lead to open failures. [59, 60].

Low and Inderjith [61] reported for the mold compound contained high level of Chlorine, Cl^-. The Cl ions are driven to locations near the ball bonds by the electrical bias, forming an acidic environment that accelerates the corrosion of the IMC layers. Mold compound has low pH level. The electro-chemical reaction at the interface formulated when the pH level in the molding compound is sufficiently low, the Cu_9Al_4 layer can be selectively etched by the acidic environment, which in turn creates a self-propagating crack between Cu and the $CuAl_2$ IMC layer. Due diligence in bill of material selection and optimized wire bond are key to success in reliability. It is found that the key Cu process design rules should include using mold compound with pH 5–7, $Cl^- < 20$ ppm, use Pd-coated Cu wire, minimize the occurrence of Al splash in order to produce flatter ball bond (within bond pads).

Uno et al. [62–66] revealed the Continuous cracking was formed at the bond interface for bare Cu wire, although there was no cracking for Pd-coated Cu wire. The cracking was a cause of failure for Cu/Al bonds in PCT aging. There were mixture products of Al oxide, Cl, and metal Cu formed at the bond interface for bare Cu wire with green resin. Corrosion-induced deterioration would be a root cause of failure for bare Cu wire. The corrosion products for bare Cu wire with conventional resin were Al oxide, Cu oxide, Br, and metal Cu. Pd was condensed at the bond interface for Pd-coated Cu wire after aging. The Pd-enriched layers formed were composed of Cu–Al–Pd compound and Cu–Pd solid solution. The Pd-enriched layers were helpful for improving the bond reliability under a humid environment by controlling diffusion and specific IMC formation. For green molding compound (in which contains <20 ppm Cl^-), the possible mechanism of the bond failure can be proposed as the following sequence of reactions. It is presumed here that the predominant Cu–Al IMC before corrosion would be Cu_9Al_4 phase and the reactants included Cu–Al IMC, Cl with reaction products of Al_2O_3 and Cu [66]. Detailed chemical reactions as shown in Eqs. 6–10.

$$9Cu + 4\ Al \rightarrow Cu_9Al_4(\text{IMC formation}) \tag{6}$$

$$Cu_9Al_4 + 12Cl^- \rightarrow 4AlCl_3 + Cu + 9Cu + 12\ e^-(Cl^-\text{attack}) \tag{7}$$

$$H_2O + 1/2\ O_2 + 2\ e^- \rightarrow 2OH^-(\text{acidic}) \tag{8}$$

$$AlCl_3 + 3OH^- \rightarrow Al_2O_3 + 3HCl + 3e^-(\text{Hydrolysis}) \tag{9}$$

$$Cu_9Al_4 + 5Al \rightarrow 9CuAl(\text{IMC transformation}) \tag{10}$$

Non-green molding compound which contains Br- was detected at the interface after failure. Br attacks Cu–Al IMC instead of Cl- in green resin, and the reactants included Cu–Al IMC, Br with reaction product of Al_2O_3, Cu_2O, and Cu [66]. There is a possibility that two types of bromide such as $AlBr_3$ and CuBr would be formed as intermediates and immediately transformed into Al oxide and Cu oxide. The oxide formation can be expressed in Eqs. 11 and 12.

$$2\ Al^{3+} + 3OH^- \rightarrow Al_2O_3 + 3H_2O \tag{11}$$

$$2Cu^+ + 2OH^- \rightarrow Cu_2O + H_2O \tag{12}$$

Another CuAl corrosion failure mechanism under high humidity was proposed by T. K. Lee et al. [67, 68] which shows there is a native oxide that exists on Al bondpads prior to Cu wirebonding. Upon Cu ball bonding on Al_2O_3 the Al_2O_3 is not perfect. It was hypothesized that $Al(OH)_3$ was formed and galvanic and pitting corrosion occurred with the presence of chloride halides from sodium chloride solutions. They soaked the Cu bonded unit in different concentration of sodium chloride solutions to understand and simulate the effects of Cl^- on Cu ball bond on Al bondpads. The detailed chemical reactions govern the attack of aluminium pad by chloride ions are described by Eqs. 13–15 below:

$$4Al(OH)_3 + 4Cl^- \rightarrow Al(OH)_2Cl + 4\ OH^- \ (\text{dissolution of native oxide layer}) \tag{13}$$

$$Al + 4Cl^- - 3\ e- \rightarrow [AlCl_4]^- \ (\text{dissolution of Al base metal by Cl} - \text{ions}) \tag{14}$$

$$[AlCl_4]^- + 3H_2O \rightarrow Al(OH)_3 + 3H^+ + 4Cl^- \ (\text{hydrolysis of dissolved metal ions}) \tag{15}$$

Yu et al. [69] conducted a study on copper wire bonding samples were aged at 205 °C in air from 0 to 2000 h. It was found that the bonding of a Cu wire and an Al pad formed Cu_9Al_4, CuAl, and $CuAl_2$ intermetallic compounds, and an initial crack was formed by the ultrasonic squeeze effect during thermosonic wire bonding. The cracks grew towards the ball bond center with an increase in the aging time, and the Cl ions diffused through the crack into the ball center. This diffusion caused a corrosion reaction between the Cl ions and the Cu–Al intermetallic phases, which in turn caused copper wire bonding damage. Gan et al. [70–72] studied the wearout reliability of Cu wirebond in 110 nm technology, and the failure mechanisms of Cu ball bond wet Corrosion under unbiased HAST test can be described in Eqs. (16–19) as follows:

$$Cu + O_2 \rightarrow 2CuO(\text{Cu oxide layer} - \text{Dry metal oxidation}) \tag{16}$$

$$CuO + H_2O \rightarrow Cu(OH)_2 \ (\text{Wet corrosion and hydrolysis of Cu oxide under UHAST}) \tag{17}$$

$$Cu_9Al_4 + 4O_2 + H_2O \rightarrow 4Al + 9CuO + H_2 \ (\text{Oxidation of CuAl IMC} - \text{in humid air environment}) \tag{18}$$

$$2CuAl_2 + 1/2\,O_2 + H_2O \rightarrow 4Al + 2CuO + H_2(\text{Oxidation of CuAl IMC} - \text{in humid air environment}) \tag{19}$$

The Cu ball bond opens post UHAST test were mainly induced by Cl^- content in mold compound. Figure 5 illustrates typical Cu ball bond failure mechanism. The initial formation of CuAl IMC beneath Cu ball bond is dominated by Cu_9Al_4 and $CuAl_2$.

Hydrolysis of IMC and $AlCl_3$ (intermediate product) under moisture environment forms Aluminium (III) oxide which is a resistive layer and Cl- is usually found at corroded ball bond. Cl^- element also has been found and Eqs. 20–22 indicate the hydrolysis of Cu_9Al_4 into Al_2O_3 and out gassing. It is believed the out gassing of hydrogen gas induce the interfacial Cu–Al IMC microcracks. [70, 71]

$$Cu_9Al_4 + 6H_2O \rightarrow 2(Al_2O_3) + 6H_2 + 9Cu \tag{20}$$

$$\begin{gathered} CuAl_2 + 3H_2O \rightarrow Al_2O_3 + Cu + 3H_2 \\ \text{(out gassing which causing IMC cracks)} \end{gathered} \tag{21}$$

$$2AlCl_3 + 3H_2O \rightarrow Al_2O_3 + 6\ HCl(\text{acidic}) \tag{22}$$

In summary, there are few key differences for Cu–Al corrosion comparing moist environment (biased HAST/THB or Unbiased HAST) and dry environment (HTST) tests. In general, most of the researchers discovered Al_2O_3 and $Al(OH)_3$ as the corrosion products as a results of Cu–Al IMC corrosion in moisture environment. Not much chemical equations developed for dry environments (HTST). Micro-cracking was initiated from edge of Cu ball bonds and propagate to center of ball bond in both environments. CuAl IMC interface micro-cracking is normally found as a result of outgassing during corrosion or stress relief of CuAl IMC oxide formation after hydrolysis or IMC oxidation. PH level and Chloride content (ppm) in molding compound dominant the corrosion rate in moist environment but not in dry environment. Hence, moisture reliability tests (biased HAST/THB or Unbiased HAST) are the most effective and suitable ongoing reliability monitoring methods for Cu wirebonding. No major difference in term of moist environment corrosion mechanisms between bare Cu and Pd-coated Cu ball bonds since the trace Pd element would be dissolved during Cu-Pd-Al IMC formation. It is believed the presence of Pd in Pd-coated Cu wire will improve bond reliability under a humid environment by controlling diffusion and specific IMC formation.

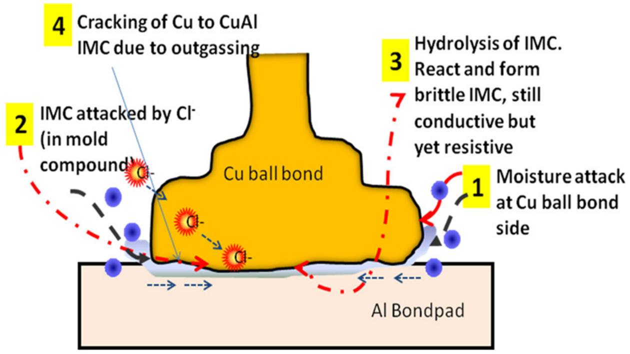

Fig. 5 Typical Cu ball bond failure mechanism. [70]

5.3 Wearout reliability studies on Au and Cu ball bonds (after 2010s)

Both industry and academic researchers are working very hard in understanding the Cu wire reliability in nanoscale semiconductor packaging. Various works have been conducted to understand its IMC growth, hypothesize its failure mechanisms, point out key challenges and technical barriers, and make recommendations for reliability enhancements. Kim et al. [73] suggested that to resolve the low reliability performance of Cu wire, it is necessary to reduce the chance of a corrosion reaction by obtaining good initial bonding conditions. Sufficient IMC thickness of the Cu wire and Al pad and optimum alloy design of the bonding wire are needed to reduce the corrosion rate. In addition, it is important to use a low humidity adsorption material for the epoxy molding compounds (EMC) or substrate. To increase the speed of IMC formation, some doping elements having relatively rapid diffusion rates can be considered; other dopants, such as Pd barrier to block corrosion provide another option. One of the methods for maximized Pd effect is the use of PCC wire. The reliability performance of PCC wire is relatively more stable than bare. When Pd is distributed on the ball surface rather than into the ball, a reliability advantage occurs. Gan et al. [74–78] suggest to use green mold compound and low halogen substrate for BGA laminate packaging, use of Pd-coated Cu wire to increase UHAST reliability margin, control the assembly staging time (less than 3 days for bare Cu wire), keep unwrapped bare Cu wire spool in N_2 cabinet for a maximum of 7 days, deploy optimized bonding parameters to prevent underneath IMD cracking, and ensure the Cu ball bond response of shear to around 8.5 g/mil square). Finally, recommendations are made to implement periodic Cu wire bond reliability monitors and conduct in-depth wearout reliability studies of Cu wire bonding to estimate the reliability margin of Cu ball bonds. Wearout reliability studies on Cu and Au wires are rarely found. C. L. Gan et al. [79–82] investigated the wearout reliability performance of two wires used in flash fineline BGA package. Weibull plots for two wire legs have been used to calculate the survival hours and cycles at 0.10 % failure rate & its characteristic life. The bond reliability of Cu and Au wires are compared in the reliability testing of unbiased HAST (UHAST), biased HAST (HAST) and component level temperature cycling. The lifetimes for two wire types in extended reliability stresses are calculated respectively.

Apparent activation energy (E_{aa}) for both Au and Cu wires are derived based on HTST wear out reliability data points.

There are limited reliability characterization and assessment conducted on ball bond especially on wearout reliability region. Wearout reliability of a product is defined as the staged whereby a product or part's reliability would give way at its weakest interconnect or link in a system. It is important information to extrapolate and predict the lifetime based on 99.9 % probability of survival. The values obtained for E_{aa} (in eV) of AuAl IMC formation (1.04 eV), while E_{aa} of CuAl IMC interdiffusion (1.18 eV). It clearly indicates that Au atoms diffuse at least 5 times faster than PdCu atoms in Al metallization of the 110 nm flash device tested [79–83]. Au ball bonds show superior UHAST package reliability performance with higher mean-time-to failure hours (t_{50}) and characteristics life ($t_{63.2}$) in UHAST reliability plot (fitted to Weibull distribution) compared to Cu ball bond but not in TC stress regardless of EMC (Epoxy Mold Compound) effect (Table 2).

6 Silver wirebonding (after 2010s)

Silver has been recently evaluated and proposed as another alternative to replace gold wirebonding. There are few researchers have studied and evaluated the feasibility of deploying silver alloy as an alternative of bonding wire to be used in semiconductor packaging. Among the research works, Long et al. [84] started to evaluate the Ag ball bond onto Au bondpad by using joint time—frequency analysis, the instantaneous characteristics of the bonding process can be observed completely and clearly. The input or output ultrasonic energy versus time—frequency in a bonding process, including the shift of frequency, harmonic components, and amplitude of corresponding energy, varies along with the change of temperature. It is concluded that temperature not only affects the bonding strength, but it also affects the ultrasonic energy of the transducer system. Chen et al., [85] reported hardness measurements on Ag wire and FAB as tabulated in Table 3. However, in the FAB state the expected hardness was observed; for example a much lower hardness for Ag wire compared to Cu and similar to Au. Ag wire outperforms Au and Cu in terms of inter-metallic dielectric (IMD) microcracking, as the deformation of the underlying structure when using Ag wire is comparable to Au and much smaller than Cu wire. This allows improved bonding on bond pads coving active areas on devices with a less complex metallization stack.

Cho et al. [86] studied the effects of % Pd content in Ag alloy which helped in improving the Pressure Cooker Test (PCT) reliability. The life time in PCT increased with increasing Pd concentration in the Ag wire: Ag-3 %Pd wire > Ag-1 %Pd wire > Ag wire. Cho proposed the Ag–Al interface microcracking occurred as a result of interface corrosion. Wu et al. [87] concluded between Ag-alloy and PdCu wires, PdCu showed higher wire pull strength but more variation at 150 h in 175 °C of HTSL. Ag-alloy wire had a higher variation of wire pull than that of PdCu wire after being baking at 175 °C for 300 h, mainly due to the occurrence of some ball lifts. Although higher variability of the ball shear of Ag-alloy wire during baking was observed, increasing shear strength of Ag- alloy wire during baking was also achieved. This is mainly due to the addition of Pd in the Ag-alloy (Ag-Pd-Au) plays a critical role in improving of the IMC quality during the baking. In terms of stitch pull, Ag-alloy wire shows consistent performance up to all the 300 h of baking while degradation of pull strength for PdCu wire was observed during the baking.

Kai et al. [88] conducted reliability studies on 2 N Ag wire and Ag–Au–Pd alloy wire. His findings reveal Ag–Au–Pd wire could get better FAB geometry during EFO process & higher intermetallic compound coverage performance because of the Au and Pd doping provides better oxidation resistance. In his study, 2 N Ag has serious asymmetry phenomenon. Ag–Au–Pd alloy wire could get better FAB geometry during EFO process, especially inserted into protective shield gas. It means that Au & Pd can support better oxidation resistance. Hence, better FAB formation will give first ball bond compression during wirebonding which would result in higher IMC coverage.

Table 2 Summary of E_{aa} (activation energies) of associated failure mechanisms comparing Au and Cu ball bonds used in semiconductor device [79–83]

Ball bond type	HTSL aging test conditions (°C)	E_{aa} (eV)	Failure mechanism	Reference
Au	N/A	1.00–1.26	Kirkendall void	[83]
Cu	N/A	0.75	CuAl corrosion	[83]
Cu	150, 175, 200	0.70	CuAl microcrack	[83]
Cu	150, 175, 200	0.91	CuAl microcrack	[79–82]
Au	150, 175, 200	1.00	Kirkendall void	

Table 3 Nano-indentation results for FAB [85]

FAB	Modulus (GPa)	Hardness (GPa)
Au	103.09	1.49
Ag	94.90	0.52
Cu	103.67	1.72

Both 2 N Ag wire and Ag–Au–Pd alloy wire passed preconditioning level 3, HAST 96 h, TCT 1000 cycles and HTSL 1000 h.

Chuang et al. [89, 90] proposed another candidate of Ag alloy consists of Au-8Ag-3Pd which is pretty different from the single Ag or Ag–Au–Pd alloys. Through a unique drawing and annealing processes, an innovative Ag-8Au-3Pd bonding wire containing a large amount of annealing twins can be produced. Annealing twin is a process whereby are the result of a change in crystal system during cooling as one form becomes unstable and the crystal structure must re-organize or transform into another more stable form. During aging at 600 °C for various time periods, the grain size of this annealing-twinned Ag-8Au-3Pd wire remains almost unchanged, while apparent grain growth can be observed in a conventional Ag-8Au-3Pd wire produced for comparison. Annealing twins have an advantageous effect on retaining the thermal stability of the grain structure and mechanical properties of the bonding wire at elevated temperature, which is useful for development of a highly reliable wire-bonding material. It is obvious that in this Ag alloy wire, the alloying effect has dominated the beneficial effect of annealing twins on the lattice defects term. With extended aging time, the percentage of twinned grains in this annealing-twinned alloy wire rises to a maximal value of about 65 % and then remains almost constant. An attractive benefit can also be obtained in this annealing-twinned Ag-8Au-3Pd bonding wire, i.e., that both the tensile strength and elongation increase simultaneously with aging time. The results show that annealing twins have an advantageous effect on retaining the thermal stability of the grain structure and mechanical properties of the bonding wire at elevated temperature, which is useful for development of a highly reliable wire-bonding material [90]. Kumar et al. [91] laid out the list of benefits of Ag wirebonding in semiconductor packaging compared to conventional Au wirebonding and Cu wirebonding (as tabulated in Table 4).

7 Evolution and future of wire alloys in semiconductor electronics

The evolutions of bonding wires used for past 25 years can be summarized in Table 5. Au wire is introduced in early of 1980s and still exists till current due to its noble in nature. Cu wire starts to emerge in mid of 1990s however wasn't deployed in large scale manufacturing due to its vulnerability to wire corrosion and oxidation properties. There are different Cu wire alloys been introduced since 2010s such as Pd-coated Cu wire, Pd-doped Cu wire and bare Cu wire depends on its applications and humidity reliability performance. Ag wire emerges since 2010s and widely introduced on chip-scale packages (CSP) and LED semiconductor packaging.

In general, Cu wire is not an ultimate bonding wire solution in semiconductor packaging. Cu wirebonding is more suitable to be deployed in low pin-count semiconductor packaging, RF device packaging, flash memory packaging or high power devices or Micro-electromechanical system (MEMS) which utilize larger diameter of bonding wire with lower IO counts. The various considerations such as its long term extended reliability performance and bondpad cratering challenges still pose a show stopper for full sweep of copper wirebonding in semiconductor packaging. Undeniably, the improved N_2 kit (which is installed on wire bonder) will improve the wirebonding process with an inert environment since Cu wire is vulnerable to corrosion and oxidation in production floor. Recently, some researchers investigated Ag wire (either bare Ag or Ag wire coated with Palladium) which will be the next candidate of wire alloy to replace conventional Au and Cu wirebonding. Ag wire requires minor process parameter tweaking and similar bonding parameters to Au wirebonding [91, 92]. Ag wirebonding shows higher PCT (Pressure Cooker Test) reliability results with increasing doping of Pd percentage in bare Ag wire. Bare Ag or Pd-coated Ag wire will be one of the next options of wire alloy for semiconductor packaging but it needs further reliability assessment, electrical characterization and AgAl IMC studies. However, Au wirebonding is the preferably packaging option by industry in lower pin count microelectronics packaging while Cu wirebonding is adopted for higher IO counts due to cost constraint such as Field Programmable Gate Array (FPGA) packaging. Ag wirebonding is discovered recently and some LED manufacturers started to deploy Ag wirebonding in LED semiconductor packaging. There is not a clear bonding wire deployment based on market segments at this moment as Au wirebonding will be still kept as backup of Cu wirebonding in high volume manufacturing.

8 Future works and conclusions

Cu wire implementation is becoming more common and will dominate the next few years of nanoscale semiconductor packaging industry. However, Au wire still showing

Table 4 Benefits of Ag wirebonding [91]

Benefits of Ag wire bonding	Likely to DfM manufacturability
Higher throughput: this invokes a lower manufacturing cost of Ag wire, especially die-to-die product	Most likely
Shorter setting time for wire bonding parameter: the workability included the wire bond parameter optimization procedure, IMC formation check, Al splash control, pad crack control, cross-section check, confirmation run, etc., Ag alloy wire is much shorter than Cu wire	Most likely
Regular bonder can be used if compared to Cu wire requires high-end bonder for more precise parameter output on bonding power, force and time. Ag alloy wire can adopt regular bonder. Only additional forming gas conversion kit needs to be equipped	Most likely
Outstanding bias-HAST performance Compared to Cu wire, Ag alloy wire passes longer life time with real die and apple-to-apple comparison	Likely
Longer material shelf-life of Ag wire if compared to Cu wire	Likely

Table 5 Evolutions of bonding wires in semiconductor packaging

Bonding wire	Applications	Reference
Au wire (with dopants)	ICs, RF, LED, FPGA, memory packaging	[92]
Bare Cu wire	ICs, RF, FPGA, memory packaging	[28, 96, 99]
Pd-coated Cu wire	ICs, RF, RFPGA, memory packaging	[93, 94, 97, 98]
Pd-doped Cu wire	In research stage	[75]
Ag wire (Au–Pd–Ag alloy)	ICs, LED packaging	[95]
Au-coated Ag wire	In research stage	Not applicable

its dominance over lower pin count device packaging such as in LED and RF device packaging. The unique properties and advantages of bare Cu wire and Pd-coated Cu wire have already fulfilled their promises in the burgeoning new fields of semiconductor device packaging. The reliability improvement of bare Cu wire can be achieved with Pd-coated Cu wire under high humidity stress tests and dry oxidation environments based on most of the recent engineering studies. Cu wire will be continuously developed to replace Au wire in higher pin counts of semiconductor packages but transition is predicted to be less on power device based packages. Future engineering works should be focused on knowledge-based reliability testing and prediction to understand the initial failure point in semiconductor device packaging. Wearout reliability concept would be used in this type of reliability studies. Future works should be carried out on the continual deployment of Pd-coated Cu, Pd-doped Cu or Ag wire bonding in nanoscale device packaging especially for low power devices especially in LED and RF packaging.

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