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Copper Wire Bonding Concerns and Best Practices

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Copper wire bonding of microelectronic parts has developed as a means to cut the costs of using the more mature technology of gold wire bonding. However, with this new technology, changes in the bonding processes as well as bonding metallurgy can affect product reliability. This paper discusses the challenges associated with copper wire bonding and the solutions that the industry has been implementing. The paper also provides information to enable customers to conduct qualification and reliability tests on microelectronic packages to facilitate adoption in their target applications.

Key words: Wire bonding, copper, gold, oxidation, corrosion, humidity

INTRODUCTION

Wire bonds form the primary interconnects between an integrated circuit chip and the metal lead frame in semiconductor packaging. They are generally considered a more cost-effective and flexible interconnect technology than flip-chip interconnects. Gold (Au) wire has been used for wire bonding in the electronics industry for more than 55 years because of its mechanical and electrical properties, high reliability, and ease of assembly. However, due to the increasingly high cost of Au, alternative wire bonding materials have been considered. Copper (Cu) is the most preferred alternative material for wire bonding because of its lower cost, higher mechanical strength, lower electrical resistance, slower intermetallic growth on aluminum (Al) pads, and higher thermal conductivity compared with Au.

Cu wire bonding has been investigated for more than 25 years.[1–4] Replacing Au wire with Cu wire in the wire bonding process presents many challenges. Cu wire bonds have the limitations of high oxidation rate, high hardness, and susceptibility to corrosion. Process and equipment changes are needed for conversion to Cu wire bonding, requiring new process optimizations and parameter adjustments for ball bond and stitch bond formation, and to achieve the looping profiles. To address Cu oxidation, bonding is carried out in an inert environment, e.g., in forming gas (95% N_2/5% H_2). In most cases, wire manufacturers adopt palladium-coated Cu (PdCu) wire, which is more resistant to oxidation than bare Cu, does not require forming gas, and has better second bond reliability. However, PdCu wires have the known challenges of higher hardness than bare Cu wires average hardness of (90 HV versus 85 HV),[5] higher melting point, as well as higher cost than bare Cu wires.[6]

Due to the high hardness of Cu, a relatively high bonding force (20% to 25% higher than for Au for the same ball height) is required to bond the Cu wire to bare Al pads, as compared with Au on Al pads.[7,12] The high bonding force makes Cu wire bonding unsuitable for fragile structures, and causes Al splash and possible damage to underlying circuitry. Since Al splash is considered unavoidable, the industry is currently using thinner Cu wires than Au to account for the splash. The industry is also exploring harder surface finishes, including Ni-based finishes (NiAu and NiPdAu). These finishes can address the high hardness, high yield strength, and required high bonding force in Cu wire bonding, since Ni is several times harder than both Al and Cu. However, Ni-based pad finishes are difficult to implement and significantly reduce the capillary lifetime (from 1 to 2 million bonds per capillary on Al pads, to 100 k to 200 k bonds per

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capillary for Ni-based pads[12]) due to the high hardness of Ni. Cu has more stringent requirements for the molding compound in molded packages than Au, due to its sensitivity to corrosion due to the pH and chlorine (Cl) content[8,9] and is susceptible to corrosion from the chemicals during deprocessing.[10,34] Currently, there are no standardized tests for Cu wire-bonded devices, and it still needs to be determined whether the tests designed for Au wire-bonded devices are sufficient to qualify Cu wire-bonded devices. The current units per hour (UPH) value for Cu is up to 30% lower than in Au wire bonding due to the lower capillary mean time between assists (MTBA) than that for Au wire bonding.[11,12]

Continued research and process optimization to address these challenges need to be conducted to develop reliable and cost-effective Cu wire-bonded parts. The industry is moving towards using Cu, but there are many companies still unprepared to implement Cu wire bonding because of the cost, equipment, and skillset involved. The initial investment for Cu wire bonding machines and process development and qualification is high. Furthermore, companies need to understand the equipment and process changes, new bonding metallurgies, yield, and throughput before putting Cu wire-bonded parts into high-volume manufacture. Companies looking to adopt Cu wire-bonded devices have to obtain or develop a database of reliability test data and establish the reliability of Cu and PdCu wires. Companies should conduct independent in-house testing of Cu wire-bonded parts to ensure that the parts meet their target applications. Cu wire bonding technology also needs to be developed for newer applications, including ultrafine-pitch, low-*k*, and extra-low-*k* (ELK) devices, stacked dies, and other applications in optoelectronics and light-emitting diodes (LEDs). Cu is currently only used in high-volume consumer devices including toys, televisions, and cellphones. The development of Cu wire-bonded devices for automotive and military applications needs to wait until Cu wire bonding technology is qualified for these applications. Before approval, long-term data under common reliability tests, including temperature cycling and high-temperature storage (HTS), must be obtained.

FROM Au TO Cu WIRE BONDING

This section discusses the motivation for the adoption of Cu wire bonding technology in the semiconductor industry. The rising cost of Au, better mechanical and electrical properties, and better interfacial reliability of Cu with Al pads are the primary reasons for the transition from Au to Cu.

Au Prices

Au wire has been the most common means to bond the Al pads on semiconductor chips to lead frames, and it is acceptable in terms of manufacturing and reliability. However, the price of Au has been steadily increasing, raising doubts over its continued use for wire bonding. Cu wire bonding has been widely accepted as a less expensive alternative to Au.[13] The semiconductor industry has seen a dramatic increase in the use of Cu for wire bonding applications. K&S reported that, by the end of 2010, the installed base of Cu-wire-capable bonders rose to 25%, up from $<5\%$ at the beginning of 2009.[14] As seen in Fig. 1[15] (based on internal estimates of Micromechanics Ltd.), the 5-year projection for the installed base of bonding machines shows that the installed base for Cu wire bonding machines is expected to rise steadily up to 2015.

Better Properties and Interfacial Reliability with Al

Bare Cu and palladium (Pd)-coated Cu wires are the two forms of Cu wire currently in use in the industry. A comparison of the mechanical properties of wire metallurgies reveals that both PdCu and bare Cu wire are harder than Au wire, which provides higher tensile strength, low electrical resistance, and higher thermal conductivity.[5] Cu wire has higher tensile strength (290 MPa versus 240 MPa) and Young's modulus (120 GPa versus 80 GPa),[5] higher electrical conductivity[16,17] (5.88×10^7 Ωm versus 4.55×10^7 Ωm),[18] slower intermetallic compound (IMC) growth (with an Al pad),[16–20] and higher thermal conductivity (394 W/m·K versus 311 W/m·K[7]) than conventional Au wire. The better electrical and thermal conductivity of Cu enable use of smaller-diameter wire for equivalent current carrying or thermal conductivity. This makes Cu wire a better option for high-power applications. Lower IMC thickness at the Cu–Al interface as compared with the Au–Al system leads to lower heat generation, lower electrical contact resistance (7.0×10^{-6} Ω cm to 8.0×10^{-6} Ω cm versus 37.5×10^{-6} Ω cm),[21] and better reliability as compared with the Au–Al interface.[17,22–27]

Since Cu wires conduct heat faster and better than Au, they allow for a shorter heat-affected zone (HAZ). As very high currents and temperatures are reached during electronic flame-off (EFO) firing, the heat generated during free air ball (FAB) formation

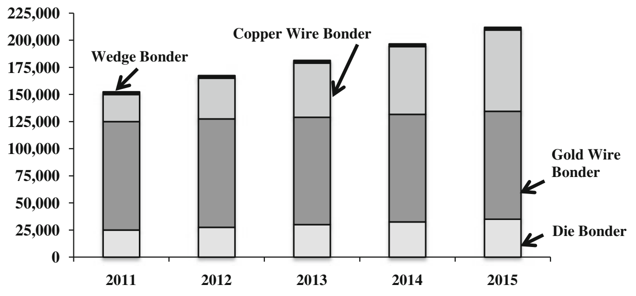


Fig. 1. Installed base of bonding machines from 2011 to 2015.

will promote grain growth along the wire. It is well known that grain growth is undesirable for wire bond reliability.[159] Better thermal conductivity can reduce grain growth and shorten the HAZ, resulting in improved looping performance, especially in ultralow loop applications that demand stricter requirements at the wire neck area.[29] Cu also has higher tensile strength and is stiffer and harder than Au, resulting in higher shear strength[26,27,30,31] and pull strength.[26,31] Cu has been reported to have better wire sweep performance during molding and encapsulation of fine-pitch devices.[32] Teh et al.[33] reported the wire sweep performance of Cu to be dependent on the fabrication processes and heat treatments as well as the wire location during the transfer molding process. Cu can help to achieve longer/lower loop profiles, and it provides better looping control, including less wire sagging as compared with Au wire bonding.[33,34] Cu wire bonding also allows longer wire lengths and smaller wire diameters in the same package,[34] thereby providing more flexibility in the wire bonding process as compared with Au.

IMC formation at the wire bond–pad interface is desirable to form a good metallurgical bond. However, excessive IMC thickness can be detrimental to wire bond strength under high-strain-rate testing because IMCs are inherently brittle and have a propensity for voiding. Cu is generally bonded to bare Al, bare Au, or NiAu-based finishes. The Cu–Al system involves the formation of multiple IMC phases, namely $CuAl_2$, CuAl, Cu_4Al_3, Cu_3Al_2, and Cu_9Al_4. Cu–Al IMCs have lower electrical resistivity and lower heat generation than Au–Al IMCs.[17] The larger size difference between Al and Cu and their lower electronegativity will restrict the solubility of Al in Cu, thus forming thin IMCs.[23] Various studies have shown that Cu–Al IMC growth is much slower than Au–Al IMC growth.[17,22–27] Kirkendall voiding has also been widely observed in Au–Al IMCs,[35–37] but is very sparse in Cu–Al IMCs[38,39] at 150°C. For Cu–Al bonds, only a few voids nucleate and grow adjacent to the alumina after high-temperature annealing, and are usually only tens of nanometers in diameter even after annealing at 250°C for 25 h.

CURRENT MARKET ADOPTION OF Cu WIRE BONDING

Several semiconductor companies, including Amkor and Texas Instruments (TI), have adopted Cu wire bonding technology in their assembly lines. TI announced in May 2012 that it shipped around 6.5 billion units of Cu wire-bonded technology in its analog, embedded processing, and wireless products. TI also reported that all seven of its assembly and test sites are running Cu wire bonding production across a wide range of package types, including quad flat no lead (QFN) packages, ball grid array (BGA) packages including new fine pitch ball grid array and plastic ball grid array, package-on-packages, quad flat packages (QFPs), thin quad flat packages, thin shrink small outline packages, small outline integrated circuit (SOIC) packages, and plastic dual inline packages.[40] Altera has projected that by 2015 all wire-bonded packages will be converted from Au to Cu wire.[41] Advanced Semiconductor Engineering reported that sales from Cu bonding grew 39% sequentially to US $325 million in the second quarter of 2012, from 24% in the first quarter of 2011.[41] Siliconware Precision Industries reported that sales generated from Cu wire bonding accounted for 53% of the company's overall wire bonding revenues in the second quarter of 2012, from 50% by the end of 2011, up from 30% at the end of the second quarter of 2011. The proportion is set to climb further to 55% in the third quarter and to 60% by the end of 2012.[41,42]

Heraeus, Amkor, Altera, Carsem, Freescale, Infineon, and several Japanese companies have also undertaken Cu wire bonding projects at their respective facilities. Other companies are considering adoption of Cu wire bonding and are assessing the total cost of conversion to Cu. Companies are developing Cu wire bonding for 45-μm-pitch, low-k and ELK device dielectrics, and optoelectronics and LEDs. Conversion to Cu wire for three-dimensional (3-D) packaging and stacked dies has also been investigated and is ready for production.[43]

Concerns with Cu Wire Bonding

The conversion to Cu wire bonding is currently facing several technical challenges. The bonding process has to be optimized, parameter adjustments for first and second bond formation and looping profiles are needed, and the process window needs to be widened. Cu is harder than both Al and Au, thus presenting the risk of damage to the underlying pad and dielectrics. Another concern with Cu wire is its propensity to oxidize, which requires additional processing/tools or Pd coating to prevent oxidation. This section discusses these challenges to the adoption of Cu wire bonding.

Cu HARDNESS: Al SPLASH AND PAD CRATERING

The wire bonding industry has been using Al bond pads because they are inexpensive and easily wirebondable. It has been reported that a Cu–Al bond is more reliable and has a longer life than an Au–Al bond. Additionally, Cu–Al intermetallics grow at a slower rate than Au–Al intermetallics and have a lower tendency to form Kirkendall voids at the ball bond–pad interface.[22–24] However, the high stiffness of Cu introduces difficulties during bonding to Al or Au surfaces. Pure Cu is about twice as hard as pure Au[28] and is also more susceptible to work hardening.[45] A higher bonding force (20% to 25% higher than for Au[7]) is required because of the higher hardness and greater work hardening.[12] The deformation associated with wire bonding can increase the hardness of Cu by a half. Thus, Cu wire bonding can result in up to 30% higher pad stress than Au wire bonding.[30] This can cause pad peeling and dielectric cracking,[46] and soft Al can also smear off during bonding along the ultrasonic direction, causing Al splash (Fig. 2).[47]

High-performance devices are increasingly relying on low-k [dielectric constant (k) < 3[48]] materials under the bond pads to improve the capacitance, device speed, and signal integrity in Cu interconnects.[48,49] Since low-k materials are soft and have low mechanical stiffness, Cu wire bonding poses the concern of damage to the circuitry under pad (CUP). Recently, ultralow-k materials have been used in the semiconductor industry; production of these materials is achieved by incorporating porosity into existing low-k materials, which increases the risk of pad damage. While a high bonding force risks pad and CUP damage, a low force will lead to non-stick-on-pad. Bond over active (BOA) technology is another development for miniaturization of semiconductor devices. It enables the use of the "keep-out zone" underneath the bond pad by moving the devices, electrostatic discharge (ESD) circuitry, and power and ground buses underneath the bond pads. The implementation of fine-pitch, low-k, and BOA technology in wire bonding has led to several new metal-lift failure modes, which are observed under ball shear and wire pull testing.[50]

The use of ultrasonic energy in bonding lowers the bonding force by softening the FAB. Ultrasonic energy increases the dislocation density, thereby lowering the flow stress. A decrease in flow stress results in softer wires and hence lowers the wire deformation required for bonding. Ultrasonic energy breaks the surface oxidation of the FAB to improve the interfacial adhesion between the FAB and bond pad.[51,151] The ultrasonic generator (USG) current increases the bonded ball diameter (BBD), ball shear force, and shear force per unit area, and decreases the ball height.[52,53] The shear force per unit area represents how well the microweld has been formed between the Cu ball and the Al bond pad on an integrated circuit (IC) chip. Since the shear force per unit area is directly proportional to the USG current, too high an USG current can also cause cratering on the Al bond pad of the IC chip. As a result of the application of ultrasonic energy during bonding, shear forces add to the already applied normal bonding force. Such shear stress can be transmitted through the bond pad metallization to the brittle, easily fractured dielectrics underneath, leading to pad peeling and bond failure. Since the ultrasonic energy is applied in the horizontal direction without a vertical bonding force in the area, the contact at peripheral areas is weak. The ultrasonic energy can cause an initial crack in the ball periphery, which can then propagate under high-temperature storage as well as in corrosive environments, decreasing the bond reliability.[54] Hence, an optimum USG current should be determined to achieve good Cu ball bonds.

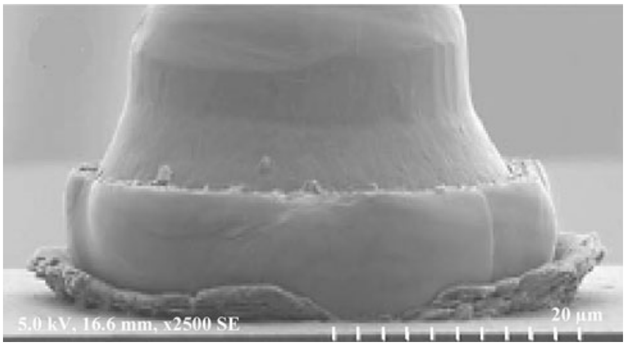


Fig. 2. A Cu bond on an Al pad showing Al splash.

Al splash or Al bond pad squeeze is observed in Cu wire bonding because of the lower flow stress of Al as compared with Cu.[51] Although Cu wire bonds can achieve higher shear strength values than Au (12 g/mil^2 versus 8 g/mil^2), the amount of Al splash increases linearly with the shear per unit area.[6] Therefore, the shear strength must be limited by the minimum Al thickness under the bond pad (remnant Al). The remnant Al under Cu bonds is less than that under Au bonds owing to the higher Al splash.[55] The remnant Al is required to maintain bond reliability, since thin remnant Al can be completely consumed by the Cu–Al IMC, leading to bond failure.[56,57]

Process-Related Concerns

Cu wire bonding process optimization is essential for bonding process stability and portability of machines and materials. Process optimization defines a process parameter window for first and second bond quality. The main requirements for FAB formation are consistency of the FAB and tight tolerance for FAB size and FAB crystal structure.[58,160] It has been reported that FABs with high anisotropy exhibit lower flow stress as compared with FABs with directionality in the crystal structure. Because of the lower flow stress, a lower bonding force is required, which results in lower Al splash.[59]

The higher bonding force required for Cu wire bonding than for Au bonding risks damaging the pad and underlying circuitry, as well as shorting the adjacent metallization area by USG displacement due to metal damage of the pad material. For fine- and ultrafine-pitch devices, the requirements for ball placement accuracy are stricter than for low-pitch devices.[60] In terms of yield and MTBA requirements, Cu wire bonding must be conducted for at least an hour without assists. The main concerns with Cu wire bonding processes are discussed below.

FAB formation requires the generation of high voltage across the electric flame-off (EFO) gap, causing a high-current spark to discharge and melt the tail of the Cu wire to form a spherical ball. Oxidation must be avoided in order to obtain a symmetrical FAB without deviation in size.[51] Cu oxidation during ball formation inhibits the formation of a spherical ball, which in turn affects the reliability of the first bond. Under high-temperature and high-humidity environments, Cu oxidation at the interface of the Cu–Al bonding region causes cracks and weakens the Cu–Al bonding. Cu oxidation typically starts at the wire region and then spreads to the upper bonded area and then to the bonding interface with time. Cu oxidation also causes corrosion cracks. Since Cu oxidizes quickly, Cu FABs need to be formed in an inert gas environment. Oxidation can also occur if the cover (inert) gas flow rate is not sufficiently high to provide an inert atmosphere for FAB formation.[61,103] On the other hand, if the flow rate is higher than the optimized level, the formed FABs are pointed. It has been reported that use of single-crystal Cu wires eliminates the need for cover gas during bonding.[62] Requiring inert gas, such as forming gas, to address the oxidation problem adds complications to the bonding process and results in a narrow process window.

Cu wire bonding requires modification of the capillary material and design to lower the ultrasonic energy to achieve the same ball size control as in Au wire bonding.[63–65] During second bond formation, higher ultrasonic energy is needed to deform Cu wire, leading to work hardening of the section of the wire where the second bond and wire tail meet. The work-hardened area can snap easily, creating a no-tail or missing-tail condition and causing the bonder to fail its automatic bonding sequence. This in turn reduces the time between bonding failures, known as the MTBA. A low MTBA leads to lower machine uptime and productivity, increasing production costs.

Capillary-related failures reduce the MTBA. The capillary lifetime is reduced (from 4 to 2 million touchdowns) from Au to Cu wire bonding due to faster wear-out. For Au, capillary lifetime reduction is typically caused by cap clogging, build-up, and dopants in the Au. For Cu, capillary wear-out is the main reason for the reduction of the capillary lifetime. The smooth capillary finish typically associated with Au wire bonding does not work with Cu, since it results in wire slippage during bonding and reduced grip between the wire and the capillary.

Fine Pitch/Low-*k* Dielectrics/Overhang Die/Ball Stitch on Ball

Cu wire bonding has already been adopted in high-volume manufacturing (HVM) for low-pin-count, heavy wire packages.[18,67] Bonding at ultrafine pitch and on low-*k* wafers requires modifications of the bonding tools and manufacturing process. The adoption of Cu wire bonding for fine-pitch and low-*k* devices is currently underway with many fine-pitch devices already in production.[6,7,19,27,30,34,46,48,49,56,65,66,68–85]

Chylak[66] discussed the challenges for converting to high-pin-count (>200) Cu wire-bonded devices. The challenges for fine-pitch bonding are similar to the ones for low pin count, including the propensity of Cu to oxidize, the higher hardness of Cu as compared with Au, the requirement for a higher bonding force for Cu than Au, and the sensitivity to corrosion. Cu wire bonding needs to be developed for specialized bonding applications including bond stitch on ball (BSOB) and reverse bonding, and bonding on stacked and overhang dies.

BSOB is performed in extremely low-profile ($<50\ \mu$m) wire bonding applications. The process consists of a two-step cycle, where first a stud ball bump is formed in the bond pad, then reverse bonding is carried out. In reverse bonding, the ball bond is bonded into the lead frame and stitched on top of the ball bump. BSOB with Cu is more challenging than normal Cu bonding due to the multiple bonding impacts on the bond pad.[86] The use of Cu wire induces higher stress in the pad and underlying circuitry due to its high hardness and the strain-hardening effect. Reverse bonding is also an issue with Cu wire bonding because it is difficult to break the wire cleanly due to the higher elongation of Cu (12%) than Au (4%).[87]

Cu bonding on thin overhang dies introduces additional bending and twisting during the bonding process due to the higher bonding force.[88] Li et al.[89] reported that Cu overhang bonding to an Al pad (1.0 μm thick) on a silicon (Si) die leads to greater impact, rebound, and deflection, resulting in low shear strength of the bond as compared with that in the supported die. Additionally, the reduction of the natural frequencies of the stacked die due to the increase in overhang length poses the risk of resonance. Lin et al.[90] reported that, if the die structure has large vibration at ultrasonic frequency, this would reduce the ball shear and wire pull strengths of the wire bonds.

Mold Compound Composition/Chemical Deprocessing

The requirements for mold compound composition are stricter for Cu wire-bonded parts than for Au wire-bonded parts since Cu is highly prone to corrosion by the mold compound.[10,18] Studies on the molding reliability of Cu wire-bonded parts have revealed that Cu wire requires more stringent pH and Cl level control[8–10,91] than that for Au wire bonding. Corrosion from halide ions is observed in Cu–Al IMCs, wherein alumina is formed.[27,91,92] The halogen ions re-form, leading to continuation of the reaction to form alumina until all the IMCs are consumed, leading to an electrical open. Mold compound suppliers therefore aim to minimize the halogen content in the mold compound.[27] Highly accelerated temperature and humidity tests are conducted to determine the effect of mold compound on the reliability of Cu wire bonds.

During the chemical deprocessing or decapping of Cu wire-bonded parts, care must be taken to minimize the possibility of chemical attack on the Cu wire. Deprocessing is usually done with fuming nitric acid or sulfuric acid to remove the mold compound and inspect the wire bonds. These acids cannot be used for Cu wire-bonded parts since they readily attack Cu wire.[10,34] Severe damage occurs in Cu wire bonds during the mold compound removal process, including reduction in wire diameter. This deprocessed package is not suitable for wire bond (shear and pull) strength testing since the reduction in wire diameter will affect the pull and shear strengths.

Other Concerns

Apart from the concerns listed above, there are other concerns, related to Cu wire bonding for second and tail bonds, yield, requalification expenses, lack of standardized test methods, and Cu wire bonding capability in the industry. Cu wire bonding has lower yield than Au wire bonding. In general, there is a drop of about 10% to 30% in UPH as compared with the Au wire process.[93] The reduction in UPH is due to the longer bonding time required in bonding with Cu wire. The additional time is required because the first bond is formed slowly to avoid pad damage, and more time is required to form the stitch bond. The stability and quality of the second bond is the key requirement of a wire bond cycle,[88] since it contributes more to the UPH reduction than the first bond, affecting the MTBA and yield of the bond process. Another roadblock to Cu wire adoption is the requalification expense. Since the Cu wire bonding process is relatively new, the requalification expenses for the process and wire-bonded parts are high. Electronic companies are still calculating the total cost of conversion to Cu, which also includes the cost of requalification. Solutions to improve yield and qualify Cu need to be developed.

The lack of standard testing methods and reliability data also poses a challenge to the adoption of Cu wire bonding. Owing to the fast-paced transition to Cu, reliability and qualification tests have not been verified for Cu wire bonding, and the industry has adopted the same test methods for Cu as for Au. The wire bonding industry is still working to establish their reliability. A database of reliability and qualification test data has to be established before Cu wire bonding can be widely adopted, especially for automotive and critical applications such as military and aerospace.

The initial cost of the transition to Cu wire bonding is high due to the investments in equipment, process, and material changes required for Cu wire bonding. Additionally, the Cu wire bonding equipment, process, and materials have to be optimized to achieve portability between machines and materials. With the exception of a few big wire bonding companies, the rest of the industry does not have the required funds for the transition to Cu wire bonding to achieve high throughput and yield.

Solutions for Cu Wire Bonding

This section presents industry solutions for Cu wire bonding. Bonding process optimization, the bond metallurgies of the different bond–pad interfaces, and PdCu wires are discussed.

Bonding Process Optimization

The requirements for achieving high-quality first and second joints are optimized process parameters, an optimal bonding environment, a contamination-free surface, and low maintenance of the bonding tool. The bonding process needs to be optimized, and parameter adjustments for power, prebleed energy, ultrasonic generator current, electric flame-off current, force, and temperature have to be made. The optimum power should be determined to achieve good bond quality, and the optimum USG current should be established to achieve a uniform ball bond, as the ball deformed diameter and ball shear force increase with an increase in USG current.

Process optimization is essential for bonding process stability.[94] The process optimization approach followed by Kulicke and Soffa Industries (K&S), a leading semiconductor equipment design and manufacturing company, is described as follows: a model-based response-driven approach is adopted, where a numerical model is derived from extensive process testing. The bonding parameters are scaled mainly for larger ball diameters. The pitch model for Cu wire bonding is developed by setting the target ball diameter and bonder accuracy, taking Al splash into account. The wire size is then chosen; the Cu wire diameter is 0.1 mil thinner than Au for the same pitch to allow for Al splash. Cu wire bonding currently has a narrow process window (Fig. 3). Table I presents an example of the optimized wire, bonded ball, and capillary dimensions chosen by K&S for Cu wire bonding.

The process window for Cu wire bonding is narrower than that for Au wire bonding.[27] A good process window for Cu wire bonding can be achieved by design of experiments (DOE) for the bonding process.[95] The bond parameter optimization aims at carrying out bonding with no pad cratering or cracking, and also 100% ball bond containment within the pad, which is lower than the surrounding metal. Tight capillary control coupled with bond force, bond power, and FAB hardness control is required to reduce the variation in ball size and facilitate HVM. Another part of the process optimization is to obtain the desired IMC coverage.[8,130] To maintain the yield, the pad metallization should be cleaned using plasma cleaning to prevent ingression of foreign particles into the die or substrate prior to bonding.

Researchers have adopted several methods for process optimization of Cu wire bonding such as Taguchi methods,[96] the Six Sigma define–measure–analyze–improve–control (DMAIC) methodology,[97] the orthogonal response surface methodology (RSM),[80,98,99,120] and statistical DOE.[99] Su et al.[96] demonstrated the application of Taguchi methods for process optimization and demonstrated an increase in yield from 98.5% to 99.3%, saving US $700,000. Lin et al.[97] used the Six Sigma DMAIC methodology to optimize the material, machine, and bonding parameters. They developed a new bonding method of flattening the bonded ball and applying gentle ultrasonic operation. They also reported that the capillary design and surface roughness helped to improve the wire bond response. Wire coupling with optimum electrical firing parameters and air cushioning can help to achieve robust and oxidation-free FABs.

Researchers[98,99] have conducted statistical DOE and RSM on common bonding process parameters, such as the contact velocity (C/V), bond power, bond force, USG current, and bonding time, to determine the significant factors affecting the process. Jiang et al.[98] investigated the process window development for Cu wire bonding based on contact velocity (C/V), initial force, bond force, USG current, and bonding time. The DOE was carried out based on the above input factors; the response factors were wire pull strength, ball shear strength, and cratering performance on bond pads. The DOE study adopted a half fractional DOE with the five input factors to look for "significant factors" affecting the experimental model. Based on the results, three significant factors were chosen for advanced DOE with RSM to obtain the final optimum parameter range. Wong et al.[99] conducted a DOE to optimize the process parameter window to achieve a ball bond with targeted BBD, bonded ball height (BBH), wire pull, and ball shear strength. The DOE was conducted on bond power, bond force, and bond time to determine the "significant parameters" affecting the process parameter window. The response surface comprised BBDs, BBH, and wire pull and ball shear strengths. After the initial screening, full factorial design to determine the interactions between the two significant parameters, bond power and bond force, was conducted. The RSM matrix was used to determine and model the optimum region. Based on the study, bond power was found to be the critical factor in reducing the BBD.

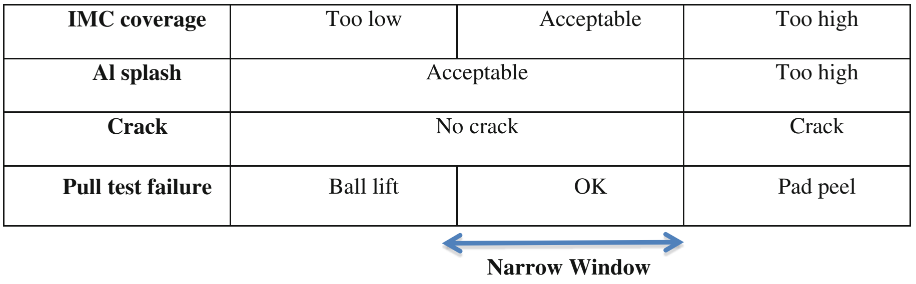
In addition to bonding parameter optimization, process control for Cu wire bonding manufacturing conditions needs to be conducted. Chin et al.[71] conducted a wire floor life control study to determine the usable life of Cu wire after unpacking it from a wire supplier's seal with inert gas. The capillary touchdown limit for 47 μm bond pad pitch with 20 μm wire size was determined. They reported that capillary degradation started at 200 k touchdowns, and the build up at the capillary sidewall at 300 k touchdowns was the major contributing factor to the short-tail conditions. Lastly, staging on a heater block was studied to determine the reliability and manufacturability due to substrate outgassing during wire bond heating. The die-bonded unit was staged on top of the wire bonder heater block for 0 min, 15 min, and 30 min to simulate possible scenarios where a unit is left on a wire bonder heater unit after the machine has stopped. They reported that substrate outgassing did not affect the manufacturability. The wire pull and ball shear strengths showed reduction after 15 min of staging, but showed an improvement after 30 min of staging. The improvement was attributed to interfacial IMC growth due to the 30 min of heating at 170°C. Other researchers[100] have also proposed heat treatment to enhance intermetallic growth, thereby improving the Cu–Al adhesion after bonding.

Process optimization can help to improve the bond reliability of specialized die structures such as

Table I. Optimized wire, bonded ball, and capillary dimensions

Wire Diameter (μm)	Cap Hole (μm)	Cap Chamfer Diameter (CD) (μm)	Min. BBD (μm)
15 (0.6 mil)	19–20	23–25	27
20 (0.8 mil)[a]	24–28[a]	28–35.5[a]	36[a]

[a] Common wire diameter



IMC coverage	Too low	Acceptable	Too high
Al splash	Acceptable		Too high
Crack	No crack		Crack
Pull test failure	Ball lift	OK	Pad peel

Fig. 3. Process window for Cu wire bonding.

overhang dies.[88,89] Kumar et al.[88] demonstrated the process characterizations of different overhang die configurations wherein a process was developed for consistent ball shape, remnant Al underneath the bonded ball, and looping across the overhang area. Li et al.[89] demonstrated an approach to significantly reduce the bonding impact on the die by increasing the thickness of the Al pad from 1 μm to 2.8 μm. The microhardness of the bond pad structure decreased by three times, leading to a reduction in the impact and rebound force. The shear strength of Cu wire overhang showed an improvement in the shear strength.

Optimization of EFO Parameters and Looping Profile

The EFO parameters, such as EFO current, FAB diameter, FAB hardness, EFO gap length, spark angle, and cover gas flow rate, have to be optimized for Cu wire bonding.[20,52,61,102–104]

Eu et al.[72] discussed the development of Cu wire bonding technology for ultrafine-pitch, ultralow-*k* wafer technology with bond over active (BOA) bond pads on a BGA package. They demonstrated a modified Cu bonding process with reduced ball size (30 μm) and a wire diameter of 18 μm. The bond placement accuracy was maintained at ±2 μm. They reported that cover gas played an important role in reducing Al splash. They also reported that ultrafine-pitch Cu wire bonding on ultralow-*k* wafer technology could be achieved through careful optimization of the bonding and manufacturing process.

FAB requirements include ball size repeatability [relative standard deviation (standard deviation/average diameter) $<$ 1% to 1.5%], ball-to-wire offset for bonded ball concentricity, and no malformed (e.g., pointed or oxidized) balls.[12] During the solidification and cooling of FABs, a substantial amount of heat is lost by conduction up the wire, and the heat loss is proportional to the cross-sectional area of the wire. An increase in the EFO current coupled with a decrease in the EFO time results in a high FAB temperature and thermal gradient across the FAB and the unmelted wire. The resulting FAB has a higher residual stress, dislocation density, and therefore hardness.[161] In general, the ratio of the FAB diameter to the wire diameter should be between 1.6 and 3, depending on the wire diameter, EFO current, and firing time.[12] A higher EFO current leads to better ball size repeatability but a lower number of concentric balls. The optimal settings for the EFO gap depend on the flow head design. A higher gap provides better ball concentricity. The cover gas flow rate also affects the formed ball[60,61] in that a low rate results in oxidized balls, whereas a high rate results in pointed balls. Based on the wire diameter and type of EFO current, the gas flow rate should be optimized.

For PdCu wires, a larger-diameter wire typically has a thicker Pd layer compared with wires of smaller diameter. As the wire diameter gets smaller, the Pd–Cu solid-solution protective layer on the bonded ball becomes thinner. Therefore, there is a higher tendency for smaller wires to have more exposed Cu regions on the bonded balls than larger wires.[105] To ensure protection of first bonds against highly accelerated stress testing (HAST) and pressure cooker testing (PCT), the Pd in PdCu wire has to be distributed over the entire surface of the FABs, forming a protective shield against corrosive attack by halogen ions in molding compounds. Various PdCu wires may have different Pd layer thicknesses over the Cu cores. FABs of different PdCu wires behave differently under the same EFO conditions. Unlike bare Au and bare Cu wires, the FAB formation in PdCu wire has to be optimized individually and is not interchangeable among different PdCu wires. If the EFO parameters are not optimized, dimple FABs and/or inconsistent FABs will be formed.[106] The nonuniform distribution of Pd in the first bonds and the voids associated with Pd-rich phases may contribute to an increase of resistivity and temperature, influencing the formation of IMCs. Also, the Cu ball bond is harder in Pd-rich regions.[107]

Oxidation Prevention Technology

Oxidation of Cu is prevented in two ways: use of an inert gas (nitrogen or forming gas) during bonding, and use of an oxidation prevention coating on the Cu wire.[108–110] Use of N_2 as the cover/shielding gas has resulted in defective FABs. Since forming gas contains 5% H_2 (95% N_2/5% H_2), it has better anti-oxidation properties than N_2 and is the cover gas for Cu wire bonding. The main purpose of injecting forming gas is to form an inert gas shroud around the Cu tail and the FAB to prevent oxidation prior to bonding. Use of H_2 has the twofold purpose of helping to melt the Cu as well as acting as a reducing agent to reduce the Cu oxide back to Cu.[51]

Use of oxidation-resistant coatings is another way to address the problem of Cu oxidation. Al-coated Cu wires for room-temperature wedge–wedge bonding have been shown to suppress oxidation, and to have better pull strength, better metallic contact formation, and better storage capabilities than bare Cu wires.[111] Al-coated wire is suited for room-temperature bonding on low-temperature cofired ceramics with silver and Au metallization.

Among the oxidation prevention coatings (Au, Ag, Pd, and Ni), Pd coating on Cu has shown sufficient potential to replace Au wire for its excellent bondability and reliability at a relatively low cost.[112–118] Pd is a seminoble metal with similarities to both Ag and Pt. PdCu is oxidation free, and Pd has good adhesion to Cu wire and higher tensile strength than bare Cu wire when bonded on Al pads. Table II presents a comparison of Au, Cu, and PdCu wires as reported by K&S.

The stitch pull strength of PdCu wire is more than 50% higher than bare Cu.[115] PdCu wire on an Al bond pad has also been demonstrated to perform better than bare Cu in high-humidity conditions, such as in highly accelerated stress testing (HAST) and pressure cooker testing (PCT),[114,119] as well as HTS testing.[119] The robustness of the second bond leads to an improved C_{pk} (process capability index).

Since PdCu wire has a larger diameter than bare Cu wire, the FAB diameter for PdCu wire needs to be smaller than for bare Cu wire. Because of the Pd layer on the Cu wire, there is always a layer of Pd or a Pd-rich phase that protects the bonded ball from corrosive attack. The use of Pd may also ease the stringent molding compound requirement. Pd prevents the formation of CuO and can form a bond with N_2 without requiring forming gas. A comparison of N_2 and forming gas for PdCu wire (0.6 mil) suggests that forming gas is superior to N_2 since it is not sensitive to changes in EFO (FAB diameter relative standard deviation: 0.94; ball-to-wire offset: 0.53 μm).[12] Comparisons of bare Cu and PdCu wire have shown that, at a higher EFO current, an FAB with bare Cu wire has higher hardness caused by having smaller grains. Varying the EFO current in PdCu wire causes the hardness of the wire to vary due to the different distributions of the PdCu alloy in the FAB.[44]

Although Pd coating prevents oxidation of Cu, it introduces new challenges for wire bonding. It is about two times more expensive than bare Cu[6] and has a higher melting point than Cu.[6] The industry is thus looking to optimize the Pd thickness to achieve cost reduction; for example, K&S decreased the Pd thickness from 0.2 μm to 0.1 μm. PdCu is harder than pure Cu and hence increases the risk of pad cracking and damage to the CUP.

Solutions for Al Splash, Pad Cratering, and Surface Contamination

Pad cratering can be prevented by optimization of bond pad metallization, pad thickness and structure, and bonding parameters.[30,120] Researchers have adopted several approaches to reduce pad damage, such as increasing the bond pad hardness by doping the bond pads with Si or Cu,[24] using softer Cu wire,[30,121] along with optimized bond force and ultrasonic power,[30,31,46,121] using harder metallization finishes,[10,28,81,122] and using more robust under pad structures.

One of the ways to reduce the ultrasonic bond stresses is to select a softer Cu wire or reduce the ultrasound level.[30,46,83,121] Shah et al.[30,46] demonstrated that adopting a softer Cu wire resulted in a 5% reduction in ultrasonic force. Also, a reduction in the ultrasound level caused the ultrasonic force to be reduced by 9%. It has been reported that, by using softer wire along with optimized force and ultrasonic power, 39% lower pad stress than with Au wire can be achieved.[30] Shah et al.[46] also reported that, by using 7% to 9% lower ultrasound level, the pad stress can be reduced by 42%. England et al.[26] proposed optimization of the bonding force, and the ultrasonic parameters were optimized at bonding temperatures of 150°C and 175°C. They reported that the increased temperatures resulted in a reduction of the bonding force, which in turn can help minimize the occurrence of pad cratering.

Another solution is to modify the chip design for Cu wire bonding. The main factors in chip design are robust under pad structure and optimal Al pad thickness.[123,124] Special under pad support structures need to be designed for Cu wire bonding to protect the low-k polymers encased in brittle diffusion barriers.[77] Qiang et al.[124] recommended using an Al layer thicker than 8000 Å to prevent damage to the pad structure. For Al thickness below 8000 Å, the under pad structure and the via distribution need to be optimized to prevent damage to the pad structure. England et al.[123] conducted a study on the influence of barrier layer structure and composition on the presence of pad cratering. They reported that use of titanium nitride (TiN) as the barrier layer resulted in high occurrence of cratering. Pad cratering was absent in Ti and titanium tungsten barrier metals, as well as in the configuration of TiN on top of Ti. Periasamy et al.[125] developed hybrid structures with bottom 2–4 Cu-low-k stacks and top 2 Cu/SiO_2 stacks. This structure can address the problems of bond pad peeling, bond pad sinking, low ball shear, and damage to underlying circuitry.

The performance and reliability of the Cu wire bonding process can be improved by understanding of the microstructural and mechanical properties of

Table II. Bonding wire comparison: Au, Cu, and PdCu

	Au	Cu	PdCu
Cost	High	Low	Low (higher than Cu)
Cover gas	No need	Forming gas	Forming gas or N_2
FAB hardness	Compatible with Al	~40% harder than Au	~10% harder than Cu
1st bond process	Good process window	Narrower than Au	Same or slightly narrower than Cu
2nd bond process	Same	Same	Same
Portability requirement	Moderate	High	High
Reliability	Good	Good, more stringent mold compound	Same or slightly better than Cu

FABs and the Cu–Al interface. Researchers have proposed several methods such as nanoindentation and atomic force microscopy to measure and characterize the hardness of the FAB and the bonding wire.[107,126,141] Xiangquan et al.[126] characterized the tensile properties of Cu wire before and after the EFO process by conducting pull tests. The hardening constant in the Hall–Petch equation, which determines the localized stress in the pad, was obtained. The measured material properties provided the inputs for an finite-element analysis (FEA) model to characterize the dynamic response of Cu wire bonding on the Al pad.[49,127,128]

The pad thickness needs to be optimized as well. A pad that is too thin cannot protect the CUP, whereas a thicker pad can have more Al splash and has more risk of passivation cracks and pad shorts. Lastly, examination of damage occurring during wafer probing should also be carried out, since probing might crack the dielectric layer under the pad. A few unbonded devices should always be etched to see whether cracks are present.

The industry is exploring options to protect underlying structures, such as harder pad metallization. Ni-based finishes are gaining popularity for Cu wire bonding. Nickel is about 50% harder than Cu and four times harder than Al, so it provides greater protection against the higher stress resulting from Cu ball bonding, as well as damage during probing. This is especially beneficial for devices with low-*k* active circuitry under the bond pad.[10,28,81,122] Ni-based finishes have the advantages of high reliability, high bonding load, protection of fragile structures, compatibility between probing and bonding, and compatibility with Au and Cu wire bonding. Typically, a layer of Ni 1 μm to 3 μm thick is deposited on either the Al or Cu base metallization as the surface finish.

A Ni layer by itself is not easily wire bondable because it forms a layer of surface oxide, which is hard and unbreakable. Therefore, a thin noble layer of Au and/or Pd is required on top of the Ni for more robust manufacturability, bondability, and reliability. Typical thicknesses are 0.03 μm Au, 0.1 μm to 0.3 μm Pd, and 1 μm to 3 μm Ni.[122] Au provides an excellent bondable surface, but it is an expensive metal. Therefore, owing to cost considerations, the electronics industry is considering options such as a Pd layer between the nickel and Au or pure Pd. The use of Pd thins down the Au layer and improves the corrosion resistance of the nickel layer. The diffusion of Ni, Cu, or Au into Pd is slow; therefore, it provides highly reliable bond–pad interfaces. NiPdAu pad metallization can be applied on both the existing pads and the Cu conductors in semiconductor dies. The finish for laminate pads should be determined based on the operating environment, reliability, and cost analysis. Bare Cu wire bonding on NiAu laminate pad finish has been used in the industry due to its good reliability performance. Due to the prohibitive cost of Au, electroless nickel–electroless palladium–immersion gold (ENEPIG) finish is also gaining momentum as an alternate finish for bare Cu bonding. However, the application of Ni-based finishes is difficult, and the industry is struggling to develop plating processes for these finishes. Capillary lifetime is another issue with Cu wire bonding, especially for Ni-based finishes. Ni and Pd are hard, so it is difficult to bond onto them. The yield reduces from 1 to 2 million bonds per capillary on Al pads to 100 k to 200 k bonds per capillary for Ni-based pads. Cu wire can also be bonded on NiPdAu-Ag-plated and roughened NiPdAu-Ag-plated lead surfaces, although Wu-Hu et al.[129] reported that packages with NiPdAu-Ag-plated lead frames showed delamination at the top of the die paddle after stress testing, while packages with roughened NiPdAu-Ag-plated lead frames showed positive results after stress testing.

Al splash can be reduced using several methods. First, high-purity Cu wires can be used. Srikanth et al.[59] reported that higher-purity wires have lower flow stress than lower-purity wires due to their having fewer grains. Because of the lower flow stress, a lower bonding force is required, which results in a lower Al splash. Second, a modified capillary design can reduce Al splash by allowing a lower ultrasonic power than the original design. Third, the ball size can be reduced relative to Au to allow for splash. For many processes, shear and area show a direct correlation. To allow for splash, the ball size must be reduced, which in turn reduces the size of Cu wires required.[56,80] In general, for a given pitch, Cu wires are made thinner than Au wires. A special process, such as ProCu developed by K&S,[130] is required for Cu to reduce the splash while still maintaining the shear per unit area. Finally, the Cu wire ball and pad can be made to rub against each other in a direction intersecting the ultrasonic wave application direction, minimizing Al splash.[131]

Wire bond bondability and quality depend on the quality of the bond pad surface. The presence of contamination on the bond surface affects the formation of high-quality bonds and, hence, bond strength. Plasma cleaning has been found to remove organic contaminants from the surface of the bond pad.[132] Plasma cleaning used in conjunction with optimized wet and dry cleaning processes cleans the surface before bonding. The primary gases used for the plasma are oxygen, hydrogen, and argon.

Loop height in stacked die packages, especially for ultrafine-pitch applications, must be optimized. To avoid electrical shorting between different loop layers in stacked packages, the loop height must not be greater than the die thickness.[133] Compared with Au, Cu requires extra shaping to make the desired loop shapes. Cu wire is less prone to wire sway and has better mold sweep properties. Hence, the process parameters for looping are different. Since the tail bond affects the MTBA, it is necessary to obtain a balanced process and form a tail bond without affecting the looping. It has been reported that, with proper parameter optimization, the average loop height of Cu wire can be comparable to that of Au wire and was reported to be 56.7 μm.[134]

Choice of Mold Compound and Improved Deprocessing Scheme

Cu corrosion by halides in the mold compound can be prevented by the choice of mold compound.[8,27,91,92] Mold compound suppliers aim to minimize the halogen content in their mold compounds by screening the resins for low halogen content, adding additives as ion trappers,[135] buffering the pH (buffer solutions are used to maintain the pH at a near-constant value), and modifying the glass-transition temperature.[27] Abe et al.[135] developed a new ion trapper through chemical model simulation, which was shown to pass 336 h at 130°C/85% relative humidity (RH)/5 V with bare Cu wire. The Pd layer in the PdCu wires acted as a barrier layer for Cl^- penetration, potentially behaving as a Cl^- catcher. "Green" mold compounds and substrates are materials that do not include bromine (Br) or antimony, both of which have been identified as being environmentally hazardous. Green mold compound and green substrate (both with low halide content) with optimized wire bonding parameters improve the reliability performance of Cu wire bonds, thus helping to minimize and mitigate Cu ball bond corrosion under unbiased highly accelerated stress test or temperature humidity bias reliability tests.[92] Seki et al.[91] reported that HAST reliability (140°C, 85% RH, and 20 V for 480 h) for Cu wire-bonded devices can be improved by combining a pH buffer and epoxy with low Cl ion level. Additionally, some flame retardants (FRs) have a negative impact on HAST properties. Use of Al hydroxide and green epoxy molding compound (EMC) without flame retardants resulted in good HAST performance, whereas the HAST performance of EMC with magnesium hydroxide [$Mg(OH)_2$] was inferior to those of EMCs with Al hydroxide [$Al(OH)_3$], owing to the high pH of $Mg(OH)_2$.[91]

The deprocessing recipe should be optimized for Cu wire-bonded packages to prevent damage to the Cu wire. Murali et al.[136] recommended a mixture of fuming nitric acid and 96% concentrated sulfuric acid for decapping the epoxy encapsulation in Cu wire-bonded packages. Other techniques of decapsulation are laser ablation and plasma etching,[137] and each of these techniques have their inherent advantages and disadvantages. Tang et al.[137] provided a review of these techniques. Laser ablation employs a laser beam to ablate the mold compound and create a uniform opening in the plastic packages. However, the laser can cause damage to the die and thus is recommended as a pre-decapsulation method. Plasma decapsulation has the advantage of high etching sensitivity, but is slow in removing the silica fillers in the mold compound. This in turn reduces the etching rate. Plasma ions may also cause damage to the IC package. Tang et al.[137–139] demonstrated decapsulation of Cu wire-bonded plastic packages by using atmospheric-pressure microwave-induced plasma (MIP). This has several advantages: the etching rate is at least ten times higher than the conventional plasma etching, localized etching, and localized heating; hence, damage to the IC is prevented, potential electrical damage caused by radiofrequency (RF) field is reduced, and the vacuum system is eliminated since MIP operates at atmospheric pressure.

Second Bond

Formation of a good second bond is a challenge with Cu wire bonding due to the tendency of Cu to oxidize. PdCu wires and special capillaries have been developed to mitigate these differences. The morphology of the pad surface finish affects the pad hardness, wherein a pad with coarse-grained structure is softer than a pad with fine-grained structure. Variation in the pad surface morphology will result in variation in the pad hardness and hence the pad deformation. Vath et al.[140] demonstrated the effect of morphology of nickel-based bond pads on the pad hardness. Hard pads such as Ni-based pads are difficult to bond to and cause fast wear of the capillary tool. PdCu wire is adopted because of the robustness in the second bond. The stitch pull strength of PdCu wire is more than 50% higher than for bare Cu.[115] Table III[112] presents a bond strength and defective second bond ratio comparison of Au, Cu, and PdCu wires. The PdCu wires have a higher first and second bond strength than bare Cu wires and zero defective second bonds.[112] PdCu also works better at higher USG current levels than Cu wire. It should be noted, however, that due to the higher hardness and rigidity of PdCu over Cu, a higher bonding force is needed for PdCu wires, which could increase the risk of Al splash and pad damage. Hence, careful optimization of bonding parameters is needed for PdCu wires.

Another modification for second bond formation in Cu wire bonding is the use of granular surface tools to minimize wire slippage during bonding and improve gripping between the wire and the capillary.[63,64,81] For improved capillary design, considerations such as surface morphology, physical dimensions, and the bonding process window need to be taken into account in engineering

Table III. Bond strength and defective second bond ratio comparison

	Au	Cu	PdCu
First bond strength (g)	26.1	21.9	35.9
Second bond strength (g)	5.4	2.6	7.5
Defective second bond ratio (ppm)	0	7933	0

evaluations.[84] Goh et al.[63–65] proposed a new capillary design with enhanced capillary tip surface texture, a larger inner chamfer, a larger chamfer diameter, and a smaller chamfer angle for improved bondability (Fig. 4).[63] The modified design led to smaller-sized ball bonds, resulting in higher reliability under high-temperature storage testing.

The granular capillaries used in Cu wire bonding wear out quickly compared with the polished capillaries used in Au wire bonding. Chin et al.[71] studied the capillary touchdown limit for 47 μm bond pad pitch with 20 μm wire size. It was found that, at 200 k touchdowns, the capillary started wearing out. At 300 k touchdowns, the buildup at the capillary wall resulted in stoppages due to short tail lengths. Therefore, it was recommended that the capillary life of Cu wire should be controlled at the maximum of 300 k touchdowns to avoid stoppages.

The bonding force must be optimized for second bonds. Adhesive tape is attached to the bottom of the lead frame to provide mechanical support to the lead frame structure and to prevent mold flash. However, the tape, in combination with the high bonding force, contributes to the high deflection of the lead during the wire bonding process. Thus, poor joint quality and non-stick-on-lead problems occur, whereas too little force does not clean the surfaces sufficiently and results in low stitch strengths. Additionally, plasma cleaning, typically argon plasma cleaning, is performed on all substrates within a few hours of wire bonding.

The formation of stitch bonds on QFN packages is a challenge for Cu wire bonding. Ultrasonic energy cannot be used for the stitch processes on QFN packages due to the resonant condition of the lead beams that causes wire fatigue and breakage. Thermocompression scrub is used instead, with a combination of force and low-frequency X–Y table scrubbing. For Cu wire bonding on preplated lead frames, the low strength of second bonds, which is related to the cold forming of Cu wire, is a challenge. Bing et al.[142] conducted vacuum heat treatment of samples at 200°C for 10 min, followed by wire pull tests and microstructure observations. Deformed grains in the second bonds went through a recovery process, resulting in the bonding strength of the second bonds exceeding the Cu wire strength.

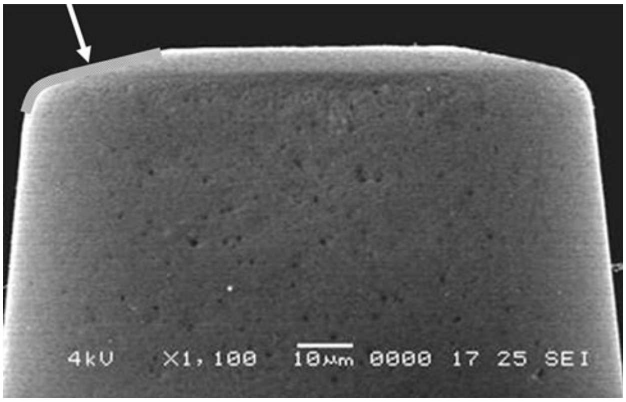


Fig. 4. Modified capillary design (the modified portion is shown by the curved line).

Cu wire bonding has low UPH because of the longer bonding time for the formation of first and second bonds, compared with Au wire bonding, due to the high hardness of Cu as well as due to the low interfacial IMC (Cu–Al) formation rate. Mechanical limitations such as heat profile delays, mechanical motion delays, and bonding delays introduce additional delays in the bonding time. Process and bonding time optimization need to be carried out to improve the UPH. Low MTBA is mainly caused due to the nonsticking and short tail. Appelt et al.[143,144] reported successful implementation of fine-pitch Cu wire bonding in HVM, with quality and yield equal to those of Au wire bonding. Those Cu wire-bonded parts exceeded the standard Joint Electronic Device Engineering Councils (JEDEC) reliability testing specifications by two times.

Cu WIRE BONDING METROLOGY AND RELIABILITY TESTS

Due to the lack of standardized tests and industrial metrologies for Cu wire bonding, companies such as K&S are adopting their own metrologies and target specifications, as listed in Table IV. In general, there are lower target specifications for the second bond.

Propensity for oxidation, high hardness, and strain hardening are concerns for the quality and robustness of first, second, and tail bonds* in Cu wire bonding.[104,145] Hence, bonding process optimization has to be conducted in order to meet the process capability index (C_{pk}) requirement and achieve a wide process window. The lower and upper ends of the process window are defined by the occurrence of ball lifts and pad peeling/metal lift, respectively. Variations in wire diameter should be examined, since the break load is proportional to the cross-sectional area of the wire. A greater break load causes more peels and lifts. The most common tests to establish the strength of first and second bonds, as well as tail bonds, are the shear and pull tests. Shear and pull tests are performed at time zero and on aged specimens (e.g., aged at 175°C for 168 h). Usually, the failure data for the shear tests directed parallel and perpendicular to the USG

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*The second bond is formed by the application of bonding force and USG energy by deformation of the wire between the capillary and the lead finger or substrate. Tail formation is the last step in the bonding process and is a necessary step to continue the bonding process. The tail bond is formed by the upward movement of the capillary, the wire clamp being opened until the desired tail length is achieved, after which the clamp is closed. The tail bond formed between the wire tail and the lead finger or substrate is then broken. The FAB is formed on the wire tail, and the bonding process continues.

direction follow a bimodal distribution. A needle pull test ("tweezer test") is carried out on the wedge side of a wire using tweezers after the ball bond is sheared, to determine the strength of the wedge bond.

To assess Al splash, the amount of pad material displaced and ball placement accuracy are measured by visual inspection. In order to pass reliability tests, a sufficient level of remnant Al is required; the preferable thickness is almost half or more than half of the original thickness of the Al pad.[57] Appelt et al.[27] reported the required remnant Al thickness to be a minimum of 100 nm.

Etching is carried out to remove the ball and inspect for pad damage. The thickness of the remnant Al and IMC coverage are then measured.[6] Contrary to the practice for Au wire bonding where Al is etched to look for IMCs, IMC coverage for Cu is examined by etching the ball away and looking for IMCs on the pad. Typically, high-temperature aging is carried out before ball etching to accelerate IMC growth. After etching, the IMC coverage is examined by conducting IMC measurement. The percent of IMC is given by the IMC area divided by the contact area.[130] The IMC area is given by subtracting the nonmetallic area from the contact area. The thickness and uniformity of the remnant Al can also be examined after etching the ball away.

Reliability tests, such as the HTS test and PCT, are conducted by the industry to evaluate wire bond performance. In HTS, storage temperatures range from 150°C to 250°C, depending on the operating conditions. High-temperature applications with temperatures above 200°C require a storage temperature of 250°C to accelerate IMC growth and produce interfacial failure mechanisms, whereas tests for consumer electronics are conducted at temperatures of 150°C to 200°C. Molded packages require reliability tests including temperature cycling, temperature humidity, PCT, and biased HAST (bHAST) to assess performance against moisture, electrical parametric shift, and electromigration. Temperature cycling evaluates the reliability implications of flexure resulting from differences in the thermal expansion of packaging materials. The failure mechanisms include flexure failure of the wire at the heel, bond pad–substrate shear failure, and wire–substrate shear failure.[146] For PdCu wire, additional failure analysis should be carried out to analyze the presence of Pd in the joint, as the interfacial presence of Pd could be the cause of early failures in reliability testing. Reliability tests should be followed by inspection tests, such as optical inspection to analyze bond damage, pull strength and shear tests to analyze bond strength, and electrical tests to assess parametric shifts.

Table IV. Target specifications (first bond)

Wire pull	No pad lift, peeling
Shear area	7.5 g/mil^2 to 9.5 g/mil^2
Cross-section	Uniform thickness of Al: nonuniform thickness correlates to peels in the bake test
IMC coverage	80% or more
Height/diameter ratio	Below 20%
Al splash	Al splash should not overlap the passivation layer
Dielectric cracking	No cracking

Since Cu is reactive with the mold compound, reliability tests for Cu wire-bonded parts can be divided into molded and unmolded reliability tests. Table V[12] presents the common reliability tests for molded parts. These tests were originally designed for Au wire-bonded parts and have not yet been qualified for Cu wire-bonded parts. The most common tests conducted by the industry are indicated.

A molded bake test is carried out to assess the HTS life of molded wire-bonded parts. The test could be biased (application of voltage) or unbiased. Researchers have assessed the reliability of molded Cu wire-bonded parts under bHAST and uHAST.[8,9] bHAST is the severest test due to the applied voltage, whereas uHAST is the mildest of the wet bake tests. The companies reported that low pH and Cl levels are the most important factors for the best HAST reliability. They also reported that Al_4Cu_9 IMCs are attacked by corrosion in molded HAST tests. PdCu wire was found to be less sensitive to corrosive components in the mold compound than bare Cu. It was also found that Cu oxidation during storage after bonding and before molding had no effect. EFO current had very little effect on the HAST reliability of PdCu.

An unmolded bake test (UBT) is a high-temperature aging test conducted on unmolded Cu wire bonds to accelerate IMC growth. Currently, no standards exist for these tests, and companies choose the test conditions, based on the application requirements; For example, K&S conducts aging at 175°C for 24 h to 192 h in an air or nitrogen environment. A pull test at the die edge or above the ball is usually conducted for 5 or 10 wires per side, and then peels and lifts are counted. The most important requirement for passing UBT is uniform Al thickness under test. Researchers[16,38,39,101,117,147–150,152] have also conducted high-temperature aging tests in the temperature range of 150°C to 340°C for up to 3000 h to evaluate the long-term impact of aging on the wire pull strength and ball shear strength.

An electromigration test is another test conducted on wire bonds. In the past, failure mechanisms related to electromigration have been reported for Au–Al systems. Since the resistivity of Cu–Al IMCs is lower than that of Au–Al IMCs, the Cu–Al system has different reliability under electrical current loads. Current knowledge of the effects of electromigration on Cu wire bonding is limited. It is also important to study the effects of the reversal of current to understand the growth behavior of IMCs during the usage life of electronics.

Bonds formed by Cu wire on Au pads have passed qualification tests, including HTS (150°C) and temperature cycling (1000 cycles: −40°C to 125°C),[153] with pull strength and shear strength values above the target specifications (pull strength >3 gf and shear strength >8 gf).[153] Cu and PdCu wires have also been compared under HTS tests.[115] First bond comparisons of Cu and PdCu wires on Al pads for unaged (as-bonded) samples indicate that PdCu wire has higher pull strength than Cu wire. However, the bond strength for PdCu wire degrades after just 24 h at 175°C, also leading to a higher rate of pad peeling failure. The cause of the bond pull strength degradation is segregation of Pd near the interface after extended aging at high temperatures.[115] A study of second bonds of Cu and PdCu wires on a BGA substrate revealed that the stitch pull strengths are similar for each wire type, but PdCu shows 50% higher tail pull strength than Cu bonds.[115] Cu wire-bonded packages have been qualified against temperature cycling testing, and the Cu wire bonds passed the different temperature cycling test regimes, including −50°C to 150°C, −40°C to 125°C, and −65°C to 150°C for up to 1000 cycles.[8,153–155]

The reliability of Cu wire bonds in a high-humidity environment is a major concern in replacing Au wires.[114] Researchers[156,157] have reported that PdCu wires are more reliable than bare Cu wires. The bond–pad interface for bare Cu wire showed continuous cracking due to corrosion, whereas for PdCu wire, no cracking was observed. The lifetimes for the PdCu wire and the bare Cu in a PCT (121°C/100% RH) were over 800 h and 250 h, respectively. Corrosion-induced deterioration was the failure cause for bare Cu wires, and the corrosion was a chemical reaction of Cu–Al IMCs and halogens (Cl, Br) from the molding resins. The PdCu wire has better bond reliability since Pd inhibits diffusion and IMC formation at the bond interface.[114]

Recommendations

The semiconductor industry needs to be acquainted with the process changes, new metallurgies, and reliability of the wire bond and pad combinations in Cu wire bonding technology. Recent advancements in Cu wire bonding, including bare Cu and PdCu wires on different pad materials and finishes, and major concerns with Cu wire bonding technology need to be assessed. Inspection, bond characterization, qualification, and reliability tests on devices with Cu wire bonding need to be carried out.

To facilitate the transition to Cu wire bonding, wire bonding companies need to develop both short- and long-term goals. Short-term goals include carrying out further optimization of the bonding process to increase the stability of the bonding process, improve production portability, and achieve a wider process window. The gap in UPH between Au and Cu wire bonding needs to be closed, and pad cratering and Al splash must be reduced. Stable stand-off stitch bond/reverse bonding processes and production processes for Cu wire bonding need to be developed, and 45-μm-pitch Cu production needs to be attained. The long-term goals focus on research and development, such as producing 40-μm-pitch Cu; closing the gap in portability between Au and Cu; designing Cu-friendly packages, more robust wafers, and better substrates; and selecting the best pad finish.

Companies looking to adopt wire-bonded parts need to obtain package-level reliability and qualification test data from the part manufacturers for the common reliability tests: PCT, HAST, THB, temperature cycling, thermal shock, and moisture sensitivity level (MSL) reflow. The part manufacturers need to provide a comparison of Cu wire-bonded devices and Au wire-bonded devices to assess their reliability.

This section presents recommendations for the bonding process, inspection, bond characterization, qualification, and reliability tests.

Table V. Molded reliability tests

Tests	JEDEC Conditions	Comments
HTS[a]	150°C/1000 h	
Temperature cycling[a]	Cycles −55°C to 125°C: 1000 cycles	
THB	85°C/85% RH/voltage: 1000 h	+5 V
bHAST	130°C/85% RH/voltage: 96 to 100 h	Typically +5 V, often runs longer, up to 336 h
uHAST[a]	130°C/85% RH: 96 h	Often runs longer, up to 336 h
TH	85°C/85% RH: 1000 h, no voltage	
PCT	121°C/98% RH/2 atm, no voltage	

[a] The most common tests conducted by the industry

Bonding Process

The Cu bonding process faces challenges due to the oxidation and hardness of Cu. An inert atmosphere, typically forming gas, is required to prevent Cu oxidation.[123] Cu oxidation can also be addressed by coating the Cu wire with an oxidation-resistant coating such as Pd. Pd can form uniformly shaped FABs with nitrogen instead of forming gas,[44] has better bondability on lead surfaces, and is resistant to oxidation and corrosion. However, PdCu wire is about 2.5 times more expensive than bare Cu wire. In PdCu wires, Pd distributions should be analyzed in the wire, the FAB, the bonded ball, and the bond–pad interface using scanning electron microscopy and energy-dispersive spectroscopy.

The high bonding force involved in Cu bonding, if using an Al pad, can also cause Al splash, which is an undesirable feature that can result in package failure. Currently, Al splash is unavoidable and the wire diameter is reduced to account for splash. The Cu wire bonding process must be further optimized to minimize Al splash. Another option is the use of Ni-based pad finishes such as NiAu or NiPdAu instead of bare Al pads, which have been shown to minimize pad damage during bonding. At present, Ni-based pad finishes are difficult to implement and reduce the capillary lifetime. Further research is recommended to facilitate the implementation of Ni-based finishes for Cu wire bonding. Another solution to the pad damage problem is to modify the chip design and use an optimal Al pad thickness to achieve a robust under pad structure.

The formation of a good second bond is another challenge due to the formation of a thin oxidation layer on the Cu wire surface, and the wire slippage and capillary wear. PdCu wires and granular capillaries have been developed to mitigate these differences, but granular capillaries wear out faster than polished capillaries. Currently, Cu wire bonding has a narrow process window. Further process optimization and parameter adjustments should be conducted as well. The second bond reliability and capillary design should be improved to increase the MTBA and improve the yield and throughput.

Pad contamination can directly influence bond strength, hence proper cleaning procedures and surface preparation need to be carried out prior to bonding. Plasma cleaning, used in conjunction with optimized wet and dry cleaning processes, can help to remove organic contaminants from the pad surface. The effects of plasma on bonding strength should be investigated. Primary plasma gases for removing contamination, oxygen and argon, should be used with an optimal combination of plasma parameters, such as plasma time, gas mixture, power, flow rate, and operation sequence, to achieve optimal bond strength. The effectiveness of plasma cleaning can be analyzed using a contact-angle measurement system.

Inspection, Reliability, Qualification, and Failure Analysis

Using inspection, qualification and reliability tests, and failure analysis, the common defects arising from Cu bonding should be identified and avoided. First, the bond strength should be characterized and the wire bond metallization combinations should be qualified under common strength, inspection and reliability tests such as pull tests, shear tests, visual inspection, corrosion testing, and HTS for a variety of package types. Three common failure modes observed during pull testing are interfacial breaking from the metallization, wire break at the neck, and bond break. Wire break at the neck is the preferred break during the pull strength test. A break of the wire indicates a strong bond between the wire and the metallization. The typical target specification for 0.8-mil Cu wire for the minimum pull strength is 3 gf, whereas the typical target specification for the minimum shear strength is 8 gf.[153] Second, data on the ball size, the bonding frequencies, and cratering, if any, should be collected. Third, during failure analysis, the location of Pd should be investigated, since the presence of Pd decreases the reliability of PdCu wires. It is essential to consider the bonding conditions to minimize Pd diffusion into the Cu ball to achieve higher reliability.

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.

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. Extensive test data need to be collected for the common reliability tests described above. Reliability monitoring should be conducted using contact resistance measurement techniques and electrical resistance change techniques. The design of reliability tests should take the operating conditions and applications into account. For high-frequency applications, reliability tests should involve measuring electrical parametric shifts using a network analyzer. The effects of wire parameters, such as diameter, length, and number of wires, should be taken into account.

Microstructure and IMC Characterization

Microstructural characterization must be considered to understand the reliability of wire bonds. The interfacial IMCs formed under the new interface materials should be extensively studied under HTS and temperature cycling tests. Metallographic examinations should be conducted to detect voiding, if any, and the mechanical and electrical properties of the IMCs, such as hardness and resistivity, should be documented. Shear and pull tests should be conducted on aged specimens to determine if interfacial IMCs play a role in wire bond failure. To analyze IMC formation in the Cu–Al system, an aging temperature of 200°C to 300°C should be used. The Cu–Al system involves the formation of multiple IMC phases, namely $CuAl_2$, CuAl, Cu_4Al_3, Cu_3Al_2, and Cu_9Al_4.[21] Na et al.[158] derived a Cu–Al IMC growth model to predict the IMC thickness at a given temperature and aging time using the Arrhenius model and experimental data. The growth equation was given as $X^2 = t \times 1.641 \times 10^{-10} \times e^{\frac{-5385.3}{T}}$, where X is the IMC thickness (in μm) at time t (in seconds), and T is the temperature (in Kelvin).

According to the binary Cu–Au phase diagram, there are three IMC phases—Cu_3Au, CuAu, and $CuAu_3$—that occur when the temperature is above 200°C, with the Cu_3Au IMC layer being visible first. Therefore, for Cu–Au IMC analysis, an aging temperature of 250°C is recommended for analyzing Cu–Au IMC phases. The IMC coverage for Cu is examined by etching the ball away and looking for IMCs on the pad. Typically, aging is carried out at high temperature before etching to accelerate IMC growth. After etching, the IMC coverage is examined by carrying out the IMC measurement. The percentage of IMC is given by the IMC area divided by the bond–pad contact area. Typically, the acceptable IMC coverage is 80% or more.[130]

CONCLUSIONS

The increasing cost of Au, higher electrical and thermal conductivity of Cu, and better interfacial reliability of Cu compared with Au have led to the industry transition to Cu wire bonding. Many companies are adopting Cu wire bonding technology into their assembly and test sites and are running Cu wire bonding production across a wide range of package types. However, there are a few challenges which need to be overcome to facilitate the widespread adoption of Cu wire bonding in automotive, military, and aerospace applications. The main concerns are Cu's hardness, propensity to oxidize, and susceptibility to corrosion. At present, Cu wire bonding on fragile structures is a challenge due to the higher bonding force requirement than that for Au. To address Cu oxidation, bonding is typically carried out in an inert environment. Another approach is to adopt PdCu wire, which is more resistant to oxidation than bare Cu wire, can form uniformly shaped FABs with nitrogen instead of forming gas, has better bondability than bare Cu on lead surfaces, and is also resistant to corrosion.

Al splash is unavoidable, but thinner Cu wires with a smaller FAB diameter are utilized to allow for splash. The industry is also exploring Ni-based finishes to address the problem of Al splash. Ni-based bond pads, including NiAu and NiPdAu, address the concerns of high hardness, high yield strength, and high bonding force in Cu wire bonding. However, Ni-based pad finishes are difficult to implement and reduce the capillary lifetime. Another solution to pad damage is to modify the chip design for Cu wire bonding to obtain a robust under pad structure and to use an optimal Al pad thickness.

Cu bonding requires granular capillary finish to prevent slippage between the capillary and bond pad and improve the grip between the wire and the capillary. However, this reduces the capillary MTBA and lifetime due to faster wear (especially during second bond formation). Process optimization and parameter adjustments for ball bond formation, stitch bond formation, and the looping profile are needed as well. 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. Cu wire bonding also results in low units per hour values (20% to 30% lower compared with Au wire bonding). Cu has more stringent requirements for the mold compound in molded packages than Au due to the sensitivity of Cu to pH and Cl content. Continued research into Cu wire bonding is necessary to address these challenges and to increase the yield, throughput, and stability of the process.

Due to the lack of standardized tests and metrologies for Cu wire bonding, companies are adopting their own metrologies and target specifications. Bond inspections can be nondestructive or destructive, depending on the requirements, and are conducted prior to and after bonding. Nondestructive tests provide information about the electrical and quality requirements of the joint, and destructive tests provide information on the long-term performance and package robustness. Pads are checked for the contamination level, oxide formation, and plating chemistry. Reliability tests, including HTS and PCT, are conducted to evaluate wire bond performance. Molded packages require reliability tests including temperature cycling, PCTs, and bHAST to assess the performance under moisture, electrical parametric shift, and electromigration. A database of reliability and qualification test data should be established before Cu wire bonding can be widely adopted, especially for automotive and critical applications such as military and aerospace.

The industry is rapidly moving towards using Cu, but many companies are still unprepared to implement Cu wire bonding because of the cost, equipment, and skillset involved in developing Cu bonding processes. The initial investment for Cu wire bonding machines, and process development and qualification is high. Furthermore, companies need to understand the equipment and process changes, new bonding metallurgies, yield, and throughput in order to adopt Cu wire bonding technology. Companies should conduct independent in-house testing of Cu wire-bonded parts to ensure that the parts meet their target applications.

Cu wire bonding technology has already been adopted in HVM for low-pin-count and heavy wire packages. Cu is used in high-volume consumer devices including toys, TVs, and cellphones, a market which makes up ~90% of world interconnect production. However, for products and systems with high reliability or long-term reliability requirements, or where the conditions of use are harsh, special care must be taken, since there is not a sufficient amount of test data and field-use history to provide adequate assurance of use. Therefore, before carrying out HVM of Cu wire-bonded parts for newer applications, including ultrafine-pitch, low-*k*, and extra-low-*k* device dielectrics, stacked dies, optoelectronics, and LED applications, the reliability of Cu wire-bonded parts in these applications needs to be established.

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