# Wire bonding using copper wire

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**Abstract**
**Purpose** – This paper attempts to review recent advances in wire bonding using copper wire.
**Design/methodology/approach** – Dozens of journal and conference articles published recently are reviewed.
**Findings** – The problems/challenges such as wire open and short tail defects, poor bondability for stitch/wedge bonds, oxidation of Cu wire, strain-hardening effects, and stiff wire on weak support structures are briefly analysed. The solutions to the problems and recent findings/developments in wire bonding using copper wire are discussed.
**Research limitations/implications** – Because of page limitation of the paper, only a brief review is conducted. Further reading is needed for more details.
**Originality/value** – This paper attempts to provide introduction to recent developments and the trends in wire bonding using copper wire. With the references provided, readers may explore more deeply by reading the original articles.

**Keywords** Copper, Wires, Joining processes

**Paper type** General review

## 1. Introduction

Integrated circuit (IC) technologies are resulting in the required advances through size reductions following Moore's law (Jackson *et al.*, 2005). Recently, the capacity-doubling period has become three years towards five, with the passing of the lithographic threshold of 10 nm being postponed to 2015 (Eloy and Depeyrot, 2006). Manufacturing of silicon and various substrates also face more new challenges (Shankar and Zhong, 2006; Young *et al.*, 2006; Zhong *et al.*, 2006; Paehler *et al.*, 2007; Schoenfelder *et al.*, 2007). Silicon nanowires may become crucial components for ultra-low power devices (Pott and Ionescu, 2006). Nano-roughness is also very important in nanostructures and nano-devices (Gogolides *et al.*, 2006). Nano-imprinting is a potential patterning technology (Trybula, 2006). Imprint lithography is proposed as a low-cost method for next generation lithography for fabrication of IC chips (Maltabes and Mackay, 2006).

The importance of microelectronics packaging is significantly increasing, as the microelectronics industry moves into the nano-era (Brillouet, 2006). The future's nanometer-scale circuits require advanced packaging technologies to distribute reliable power and signals among microelectronics devices (Kaushik *et al.*, 2006). At the same time, manufacturers should also understand recently-enacted environmental legislation and directives, and study their effects on the microelectronics industry (Ciocci and Pecht, 2006). Intensive research and developments of lead-free products (Arulvanan and Zhong, 2006) are stimulated by a USA Congress bill that has proposed to ban lead from a wide variety of uses (Kamal and Gouda, 2006). Developments of wearable microelectronics devices are also increasing (Whitmarsh, 2005). Today's hand-phones usually include three modern packages: wafer level, leadless and area array packages such as ball-grid-array (BGA) packages (Xie *et al.*, 2002; Tee *et al.*, 2003a; Plieninger *et al.*, 2006).

Advanced packaging technologies continue to be developed to deal with the new challenges for advanced microelectronics devices, driven by the smaller, faster and cheaper demands (Longford, 2005). Although flip chip (Zhong and Goh, 2000; Tee *et al.*, 2003b; Jang *et al.*, 2006), wafer-level packaging (Oberhammer and Stemme, 2005), and tape automated bonding (Kassamakov *et al.*, 2007) technologies are also increasingly employed, wire bonding is the most widely used microelectronics packaging technology in the industry (Zhong *et al.*, 2007a).

In the microelectronics packaging industry, economic improvement is measured in fractions of pennies, and ultimately cost rules. A manager has to consider costs, not only package performance. Wire bonding dominates more than 90 per cent of the packaging market because of its cost effectiveness and flexibility. It has an established huge base of materials, equipment and manpower. A recent study by Yole confirms wire bonding is currently the lowest-cost IC interconnect technology (Lyn and Crockett, 2007).

As the industry moves into a new era, new challenges in wire bonding emerge, such as reduction in wire size, cost and bond pad pitch, emergence of alloyed gold wires and copper wires, increase in I/O numbers, and reliable wire bonding of ultra-fine-pitch low-*k* devices (Viswanath *et al.*, 2005; Kim *et al.*, 2006; Fiori *et al.*, 2007a, b; Viswanath *et al.*, 2007). To deal with these challenges, capillaries must have very small holes and tip diameters with good ultrasonic energy transfer (Zhong and Goh, 2006), and customized designs for multi-tier bonding, stacked-dies wire bonding (Tee *et al.*, 2006), and wire bonding using insulated wire (Zhong, 2008). The wire must have high-tensile strength and a short heat affected zone for low-loop requirements. The surface hardness and roughness of the substrate also become important. Wire bonders must have sufficient bond placement accuracy, *Z*-resolution, bonding speeds, free air ball (FAB) forming consistency and looping algorithms (Goh and Zhong, 2007b).

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**www.emeraldinsight.com/1356-5362.htm**

Microelectronics International
26/1 (2009) 10–16
 [ISSN 1356-5362]
[DOI 10.1108/13565360910923115]

Microelectronics International
Volume 26 · Number 1 · 2009 · 10–16



This paper attempts to review recent advances only in wire bonding using copper wire. Dozens of journal and conference articles published recently are reviewed. The new challenges related to wire bonding using copper wire are briefly analysed, and the solutions to the problems and recent findings/developments are discussed.

## 2. The advantages of wire bonding using copper wire

Wire bonding using copper wire has many advantages over wire bonding using gold wire, which are summarised in Table I.

Gold wire has been the most widely used wire in wire bonding. However, in recent years the price of Au has greatly increased, fueling the demand for high-volume wire bonding using Cu wire, which can lead to significant cost savings due to lower raw material cost (England and Jiang, 2007). Moreover, copper is not subject to sudden price fluctuations in the market (Chen *et al.*, 2006a). The price of copper wire is 10-40 per cent of that of gold wire (Hong *et al.*, 2005; Tian *et al.*, 2005).

Copper wires have better thermal and electrical properties than gold wires. Copper is about 25 per cent more conductive than gold, accounting for better heat dissipation and increased power rating, a main factor to the development of high performance, high power and fine-pitch devices using smaller-diameter copper wire to accommodate smaller pad sizes. Higher electrical conductivity leads to less-heat generation and a higher speed (Tian *et al.*, 2005; Chen *et al.*, 2006a; Ratchev *et al.*, 2006; England and Jiang, 2007).

Copper wires have excellent ball neck strength after the ball formation process (Chen *et al.*, 2006a). The higher stiffness of copper wires is more suitable to fine pitch bonding than that of gold wires (Hong *et al.*, 2005; Tian *et al.*, 2005). Copper wire can be directly bonded on bare Cu lead frames and BGA substrates, saving cost and time because of elimination of the plating process (Goh and Zhong, 2007a).

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/lower loop profiles (Chen *et al.*, 2006a; Ratchev *et al.*, 2006; England and Jiang, 2007). Copper has higher stiffness than gold, leading to better looping control and less wire sagging for fine pitch and ultra-fine pitch wire bonding (Goh and Zhong, 2007a). Using Cu wire for wire bonding can be a solution to the wire short problem caused by small wire sizes, besides other solutions such as using insulated wire (Zhong, 2008) and having varying loop heights (Zhong, 2007; Zhong *et al.*, 2007a).

There is also very little void formation in the Al-Cu system compared with the Al-Au system. The growing speed of the intermetallic compound (IMC) 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 (Hong *et al.*, 2005; Tian *et al.*, 2005; Chen *et al.*, 2006a; England and Jiang, 2007).

## 3. Challenges in wire bonding using copper wire

Although Cu wire has many advantages over Au wire, it has not been widely used like Au wire, because it also brings many new challenges to wire bonding, which are summarised in the second column of Table I.

Copper is easy to be oxidized in air, and therefore copper wire bonders must have additional tools to prevent copper oxidation (Hong *et al.*, 2005). Additional bonding parameters for using forming inert gas need to be optimised (Chen *et al.*, 2006a), and additional cost of forming gas must be considered (Goh and Zhong, 2007a). Although $N_2$ gas can be a suitable option, a forming gas mixture of 95 per cent $N_2$/5 per cent $H_2$ has been shown to be the best choice (England and Jiang, 2007).

Copper wires have much higher hardness and stiffness than gold wires. Copper wire bonding needs more ultrasonic energy and higher bonding force, which can damage the Si substrate, form die cratering (Hong *et al.*, 2005) and induce cracking and peeling of the bonding pad (Tian *et al.*, 2005). A stage temperature of 150-200°C is also needed for bonding copper wire (Chen *et al.*, 2006a). As-drawn copper wire possesses higher strength and hardness, but its lower ductility reduces the reliability of bonding. The lower strength of the annealed wire results in breakage (Hung *et al.*, 2006). There is also a need to investigate the effects of the process parameters on the hardness of Cu FABs (Zhong *et al.*, 2007b), because Cu exhibits a larger strain-hardening effect at a higher strain rate (Bhattacharyya *et al.*, 2005).

**Table I** Advantages of copper wires over gold wires and challenges of wire bonding using copper wires

| Advantages | Challenges |
|---|---|
| **Lower cost** | Easy to be oxidised in air |
| **Better thermal properties** | Additional bonding parameters for using forming inert gas |
| **Better electrical properties** | Needs more ultrasonic energy and higher bonding force, which can damage the Si substrate, form |
| **Excellent ball neck strength** | die cratering and induce cracking and peeling of the bonding pad |
| **Higher stiffness** | Lower strength of annealed wire resulting in breakage |
| **Can be bonded on bare Cu substrates** | High pressure is put on pad structures, which can contain low-*k* materials having very low stiffness |
| **High-loop stability and better looping control** | A larger strain-hardening effect at a higher strain rate |
| **A solution to the wire short problem** | Wire open and short tail defects |
| **Very little void formation in the Al-Cu system** | Poor bondability for stitch/wedge bonds |
| **Low growing speed of IMC** | |

**Sources:** Bhattacharyya *et al.* (2005), Degryse *et al.* (2005), Hong *et al.* (2005), Tian *et al.* (2005) Chen *et al.* (2006a), Hung *et al.* (2006), Kaimori *et al.* (2006b), Ratchev *et al.* (2006), England and Jiang (2007), Goh and Zhong (2007a) and Zhong *et al.* (2007b)

Since copper wire is harder than gold wire, to improve stitch bondability, higher parameter settings have to be used, causing heavy cap marks and potential short tails or wire open. Cu/Au stitch bonds are weak, and thus copper wire bonding has wire open and short tail defects, poor process control, and low stitch pull readings (Goh and Zhong, 2007a). Oxidation of Cu wire leads to poor bondability for stitch bonds (Kaimori *et al.*, 2006b), which can result in increased non-sticking rates. Although many wire suppliers add dopants and anneal Cu wire to lower the hardness, softer Cu wire may help to magnify the tendency of work hardening and cause large variations in stitch pull strength (England and Jiang, 2007).

During wedge bonding of copper wire, two failure modes occur, lifting off of the wedge bond and uncontrolled breakage of copper wire during tail formation, if the wire is not deformed enough during bonding (Tian *et al.*, 2005). Thick oxide can prevent a good wedge bond, which becomes critical when a spool of Cu wire is on the bonding machine for long time periods. The longer it has been removed from its package, the thicker the oxide becomes. A Cu ball is too strong (compared to an Au ball) to be sheared in half after it work-hardens during ball bonding. The Cu-Al interface is the weakest link in the system, and therefore the ball lifts during the shear test (England and Jiang, 2007).

During Cu wire bonding, high pressure is put on bond pad structures, which can contain low-*k* materials having very low stiffness ranging 1-10 GPa, depending on the porosity in low-*k* materials (Degryse *et al.*, 2005). This means future wire bonding will be performed using stiffer wire on a weaker support structure.

## 4. Findings and solutions for wire bonding using copper wire

To deal with the challenges and solve the problems in copper wire bonding in order to fully benefit from its many advantages, research on wire bonding using copper wire is intensively carried out worldwide, resulting in many solutions to the problems and new findings, which are summarised in Table II and briefly discussed in this section.

Investigation of copper wire ball bonding on an Al-metallised silicon substrate found that the solidification proceeded from the ball towards the wire and the orientation of the cell-type fine substructures was irregular due to a rapid solidification of Cu during the electric sparking (Hong *et al.*, 2005). Slip was the major mechanism involved in the overall deformation of polycrystalline copper, although twinning was also found in very limited bonds. The shear force of the ball bonds did not degenerate after 1,500 h at 200°C, and it had some extension of increasing, due to the interface diffusion of the bonds.

Cross section analysis after ultrasonic wedge bonding using copper wire at ambient temperature on Au/Ni/Cu metallization of a PCB finds a continuous interconnection between copper wire and Au/Ni/Cu metallization (Tian *et al.*, 2005). Three common failure modes found are bond break when the bond is deformed excessively, bond lifting off from the metallization surface, and wire break at the bond neck, which is the preferred mode indicating good bonding. Strong copper wire wedge bonds on an Au/Ni plated Cu substrate are obtained by ultrasonic bonding at room temperature, achieved by wear action induced by ultrasonic vibration (Tian *et al.*, 2008). The ultrasonic power enhances deformation of the copper wire because of the ultrasonic softening effect followed by the strain hardening of the copper bond. Higher bonding force and power are needed for the second bond than the first bond to have strong pull force.

Investigation of the annealing effect (at 150-250°C for 1 h) on the mechanical properties of copper wire revealed that with annealing temperatures $>200$°C, copper wire possessed a fully annealed structure, its hardness and tensile strength decreased, and its elongation was raised significantly (Hung *et al.*, 2006). By re-crystallisation, the matrix structure transferred from thin, long grains to equiaxed grains and a few annealed twins. The FAB microstructures of the annealing wire after EFO (electronic-flame-off) were column-like grains, which grew from the heat-affected zone (HAZ) to the Cu ball, and the preferred orientation was (100). Owing to the thermal effect of EFO, the necks of Cu balls underwent re-crystallisation and grain growth was induced. Decreased hardness and strength of the HAZ led to breakage sites of the wires to be in the HAZ near Cu balls.

After annealing, single crystal copper wires were bonded (Chen *et al.*, 2006a) on Au (1-2 $\mu$m thick) and Al (2 $\mu$m thick) surfaces without gas protection. $Cu_3Au$ and AuCu IMCs were found at the Cu/Au interface while $CuAl_2$ was found at the Cu/Al interface. After thermal aging, Kirkendall voids were discovered at the Cu/Au interface. Annealed Cu wires exhibited tensile strength and elongation characteristics comparable to those of Au wires.

Studies of the IMC growth in wire bonds and the Cu-to-Si diffusion behaviour reveal that Au-Al IMC grows much faster than Cu-Al IMC (Zhang *et al.*, 2006, 2007). Cu-to-Si diffusion is faster than Au-to-Si diffusion under the same annealing condition. With a TiW barrier layer adopted, Cu or Au diffusion to Si is decreased. Al pad deformation induces more Cu-to-Si diffusion. Cu-Al IMC is thinner than Au-Al IMC at the bonding interface, which results in better bond strength and smaller electrical resistance.

As one solution to the poor bondability problem due to surface oxidation, electroplating of an oxidation-resistant metal on Cu wire was conceived to prevent surface oxidation (Kaimori *et al.*, 2006a, b). Experiments using $\phi 25\ \mu$m wires with a 0.1 $\mu$m thick oxidation-resistant metal revealed that electroplating of Ag, Au, Ni or Pd on Cu wire increased bond strengths but produced problematic ball shapes except the Pd-plated Cu wire, which could produce the same ball shape as that of Au wire. Pressure cooker, temperature humidity bias and temperature cycling tests confirmed that the Pd-plated Cu wire had excellent reliability and bondability.

As another solution to the poor bondability for stitch bonds due to surface oxidation, a new capillary has been developed with a new surface morphology (Goh and Zhong, 2007a). Bonding experiments using the new capillary were conducted using 70 and 100 $\mu$m bond-pad-pitch BGA devices and 25 $\mu$m copper wire, and satisfactory results were confirmed by ball shear and stitch pull tests.

Through bond integrity testing, it was found that increasing the temperature could enlarge the bondability window and less bonding force could be used (England and Jiang, 2007). Lower ultrasonic power and bonding force could help minimise pad cratering. Cu ball bonds performed better than Au ball bonds in wire pull and ball shear tests. Ball lifts were the shear failure modes, while neck breaks and pad lifts were the wire pull failure modes. The pads occasionally lifted, but this was not detrimental because the pull strength values

**Table II** Solutions for reliable wire bonding using copper wire and findings from investigations of copper wire bonding

| Findings and solutions | References |
|---|---|
| **The bonding position significantly affects the local stress near the bond, and the wire should be bonded at the pad center** | Chen *et al.* (2004) |
| **The stress is large if the pad size is close to the wire ball size** | |
| **Cu and Au bond wires have a work-hardening effect and higher forces are needed to form a Cu bond, leading to higher stresses in the pad structure** | Degryse *et al.* (2004, 2005) |
| **Slip was the major mechanism involved in the overall deformation of polycrystalline copper** | Hong *et al.* (2005) |
| **Higher bonding force and power are needed for the second bond than the first bond to have strong pull force** | Tian *et al.* (2005, 2008) |
| **Decreased hardness and strength of the HAZ led to breakage sites of the wires to be in the HAZ near Cu balls** | Hung *et al.* (2006) |
| **Annealed Cu wires exhibited tensile strength and elongation characteristics comparable to those of Au wires** | Chen *et al.* (2006a) |
| **With a TiW barrier layer adopted, Cu or Au diffusion to Si is decreased** | Zhang *et al.* (2006, 2007) |
| **Cu-Al IMC is thinner than Au-Al IMC at the bonding interface, resulting better bond strength and smaller electrical resistance** | |
| **Pd-plated Cu wire demonstrated excellent reliability and bondability** | Kaimori *et al.* (2006a, b) |
| **A new capillary with a new surface morphology leads to satisfactory results in ball shear and stitch pull tests** | Goh and Zhong (2007a) |
| **Increasing the temperature can enlarge the bondability window and less bonding force can be used** | England and Jiang (2007) |
| **Lower ultrasonic power and bonding force can help minimise pad cratering** | |
| **Plasma cleaning of lead-frames before bonding increases the tail breaking stability significantly** | Lee *et al.* (2007) |
| **Asperity plastic deformation is the most significant factor for good bonding** | Murali *et al.* (2007) |
| **Ultrasonic energy breaks the oxide film and deforms asperities, while the bonding force increases the asperity proximity** | |
| **To have shorter firing time during FAB formation, use a lower contact velocity and provide sufficient inert-gas coverage is recommended for a softer FAB and minimised stress induced during ball bond impact** | Zhong *et al.* (2007b) |
| **Cu/Al IMCs are mainly $Cu_9Al_4$ and $CuAl_2$, with CuAl present in smaller amounts** | Hang *et al.* (2008) |

were not smaller than the neck break values. Mechanical properties of the Cu bonds were superior to those of Au bonds.

A weak tail bond can result in non-uniform tail length and FAB formation. The bonder stops before flaming off the tail, reducing the production throughput, if the tail bond is weak enough to loose before the clamp can close, resulting in the wire being blown out from the capillary. The cleanliness of bonding pads is important for using Cu wire. Plasma cleaning of the lead-frame before bonding increases the tail breaking stability significantly, and an average Cu tail breaking force $>50$ mN is obtained, comparable to that obtained using Au wire (Lee *et al.*, 2007). The standard deviation of the Cu tail breaking force is about two times that obtained using Au wire.

Investigations of Cu wire bonding on metallised and plated materials such as Al, Cu, Ag, Au and Pd find that asperity deformation is the most significant factor for good bonding (Murali *et al.*, 2007). Ultrasonic energy breaks the oxide film and deforms asperities, while the bonding force increases the asperity proximity. The copper bonds are harder than the wire, exhibiting work hardening. Soft Al with lower asperity deformation is easier to be wire bonded than harder surfaces (Ni, W, Mo, Cr, Co, Ta). Good adhesion can be achieved on bare and plated surfaces with surface roughness (Ra) of 0.01-0.15 $\mu$m and 0.02-0.6 $\mu$m, respectively.

Cu FABs with an identical diameter obtained under different EFO firing conditions were bonded and hardness tests were then performed on the cross-section of the bonded balls (Zhong *et al.*, 2007b). The microhardness of bonded Cu balls depends on the EFO parameters, with FABs obtained using higher EFO current being softer. The lower hardness is attributed to the higher maximum temperature during the FAB melting. Higher EFO current results in a higher maximum temperature of the Cu FAB. To achieve a softer FAB and minimise the stress induced during ball bond impact, it is recommended to have shorter firing time during FAB formation, use a lower contact velocity, and provide sufficient inert-gas coverage.

Aging at 250°C is performed to study the Cu/Al IMC growth in Cu ball bonds (Hang *et al.*, 2008). It is found that Cu/Al IMCs are mainly $Cu_9Al_4$ and $CuAl_2$, with CuAl present in smaller amounts. Cu/Al IMCs form at the bond periphery and extend towards the bond centre. Cavities also start to grow from the ball periphery towards the bond centre, and finally form a complete fracture between the upper IMC layer and the ball bottom surface. The IMC growth rate decreases gradually with the increasing aging time and stops when the fracture completes.

Many factors affect the quality of copper wire bonds. Experimental and numerical approaches are mainly adopted to investigate wire bonding using copper wire. Experimental investigations are the basis for technology development and science discovery (Huang *et al.*, 2006). Therefore, as discussed above, bonding and testing experiments are typically conducted to evaluate the performance of wire-bonded devices. Optimal parameters result from proper selection and suitable design of experiments at the earliest stage of process development cycles (Alagumurthi *et al.*, 2006).

On the other hand, numerical investigations are also widely conducted because this approach can save cost, time and manpower for time-consuming experiments and tests. Finite element analysis (FEA) is a useful method to discover facts or investigate processes in a way that no other tool can accomplish (Sun and Zhong, 2002; Luan *et al.*, 2003; Tee *et al.*, 2004; Tee and Zhong, 2004; MacKerle, 2005). There is increasing research on applying FEA to wire-bonded packages (Chen *et al.*, 2006b; Ishiko *et al.*, 2006; Saiki *et al.*, 2006; Fiori *et al.*, 2007a, b; van Driel, 2007; Viswanath *et al.*, 2007; Chen *et al.*, 2008; He *et al.*, 2008), although articles reporting FEA of Cu-wire-bonded packages are still scarce.

FEA of a Cu-to-Cu wire-bond forming process reveals that the bonding position significantly affects the local stress near the bond, and the wire should be bonded at the pad center (Chen *et al.*, 2004). The stress is large if the pad size is close to the wire ball size. The bonding temperature also largely affects the stress. Raman spectroscopy combined with FEA is a helpful tool to investigate bonding stresses and optimize bonding parameters.

The traditional configuration with $SiO_2$ dielectric and Al interconnection layers is being replaced with low-*k* dielectrics and Cu interconnection layers (Degryse *et al.*, 2004). Numerical investigations reveal that the yield stress of the wire bond determines the pressure on the pad structure (Degryse *et al.*, 2005). A stiffer and thicker capping lowers local stresses under the bond edge. Cu and Au bond wires have a work-hardening effect. Higher forces are needed to form a Cu bond, leading to higher stresses in the pad structure. A stiffer capping redistributes the deformation over a larger area, resulting in a smaller local deformation in the metal layer at the bond edge, and the stress peak decreases.

## 5. Conclusions

Wire bonding using copper wire has many advantages over wire bonding using gold wire. However, it also brings many new challenges to wire bonding. To deal with the challenges and solve the problems in copper wire bonding in order to fully benefit from its many advantages, research on wire bonding using copper wire is intensively conducted worldwide, resulting in many new findings and solutions to the problems, which are only briefly introduced in this paper. For the detailed and accurate description of a particular solution or finding, readers may closely read the published original paper with detailed figures and explanations. Articles reporting numerical investigations including FEA of Cu wire bonds are still scarce. More such reports are expected in the future.

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