An Update on High Volume Copper Ball Bonding

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Abstract

Copper ball bonding is now becoming a high-volume semiconductor assembly process. Well established in the high-power (large wire diameter) market, copper ball bonding is beginning to make inroads in the low pin- count IC market (fine wire diameter). In addition to offering significant cost advantages, copper provides higher electrical and thermal conductivity, higher strength and stiffness, and better intermetallic reliability than comparable gold ball bonds. As these benefits are demonstrated through its increased manufacturing use, copper ball bonding will migrate into higher I/O, more demanding, fine pitch product lines. Cost savings achievable with copper ball bonding are substantial and represent a major cost improvement for our highly competitive industry. As the challenges are resolved and implemented, copper ball bonding will provide the competitive edge that extends wire bonding as the low cost packaging solution.

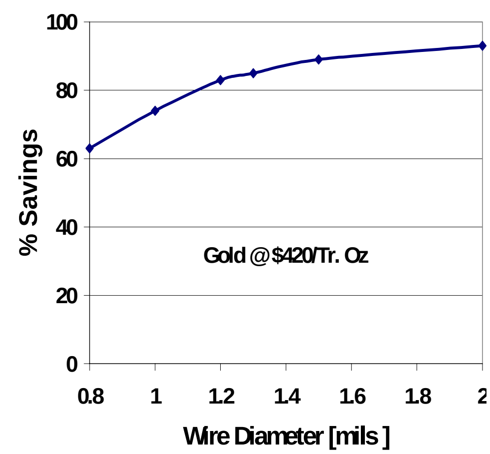
Introduction

Although copper ball bonding development programs were conducted by virtually every major semiconductor manufacturer during the late 1980s and early 1990s, copper ball bonding failed to enter high volume IC manufacturing due to process difficulties and corporate priorities. While significant cost savings were forecasted and described in literature[1,2,3,4], development costs, qualification requirements, and reliability concerns offset the advantages. In addition, the high yield and established reliability of the gold ball bonding process proved a significant entry barrier to copper ball bonding, which still needed to meet or exceed the capability of the gold process. Since then, the copper ball bonding process has improved and matured. Although it still represents only a small percent of total interconnections worldwide, it has entered high-volume production in several market segments.

The market for low-cost and high-power devices has become extremely competitive, making the large cost advantages of copper a very significant factor affecting profitability. Market dynamics dictate that cost reductions emerge swiftly and quickly become the mainstream.

Currently, copper ball bonding specifications must meet or exceed comparable gold ball bonding specifications. As companies complete process capability studies and develop historical data, they will establish new specifications reflecting copper's benefits.

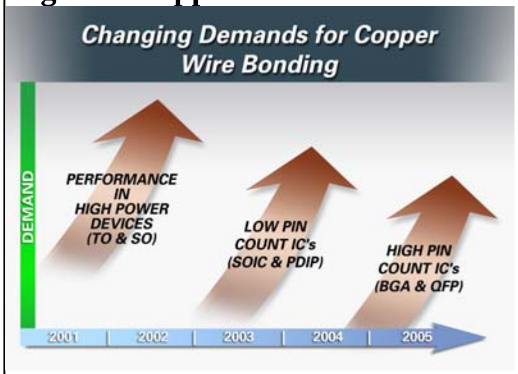
Figure 1 Copper vs Gold Wire Savings



Copper's Advantages

In power packaging, where larger diameter wire is required to carry the electrical load, the cost of gold wire represents a significant portion of packaging costs. Gold value comprises the largest portion of wire cost. Figure 1 compares the cost of gold and copper wire. Doubling the wire diameter from 1 to 2 mils increases gold content by fourfold and, hence, increases package cost. For packages with larger

Figure 2 Copper Trendline



diameters, copper wire would provide a significant cost advantage, saving more than 90% of the cost of gold wire. Although other package types do not require large diameter wire, potential cost savings are still large because new fine-pitch packages may require as many as 1,000 wires, with wire lengths as long as 6 mm. A fine-pitch, QFP or BGA package may require more than 5 meters of wire. Gold wire replacement, therefore, represents a significant cost savings for all package types.

Power packaging is the first major product where copper wire has been introduced in high-volume. Other product lines are not far behind. Figure 2 shows the implementation timeline for copper ball bonding. As noted in the diagram, copper ball bonding has established a stronghold in the low-cost and power packaging marketplace and has already begun to migrate into SOIC, PDIP packages. Currently, subcontractors are evaluating its use in QFP and BGAs. In the higher leadcount packages, including BGAs and QFPs, substrate costs have been reduced to levels where wire now represents a larger portion of the packaging budget. The demand for a gold replacement will drive copper's development as the dominant interconnection material.

Figure 3 Copper's Advantages

Features	Benefits
Lower cost	• Package savings • Competitive advantage
Electrical conductivity Gold 4.55x10^{7} Ω-m Copper 5.88x10^{7} Ω-m	• Thinner wires for fine pitch packages • Higher current capacity for power packages
Thermal conductivity Gold 31.1kW/m^{2}K Copper 39.5kW/m^{2}K	• Improved heat transfer efficiency
Mechanical Properties	• Higher tensile strength • Increased ductility • Stronger Heat Affected Zone (HAZ) • Stiffer, improved looping • Reduced molding sway
Slow Intermetallic Growth	• High mechanical stability • Long-term reliability • Less resistance drift/time

In addition to cost savings, copper has other important mechanical and electrical advantages. Figure 3 provides a summary of copper wire features and benefits. Copper is mechanically and electrically superior to both gold and aluminum, the other metals commonly used in wire bonding. It is also stronger (>50%) and stiffer (≈30%) than these metals, providing better tensile strength and loop formation. Copper also has greater conductivity (≈30%) than gold, allowing the use of a smaller diameter wire for equivalent conductivity.

Figure 4 Equivalent Conductance

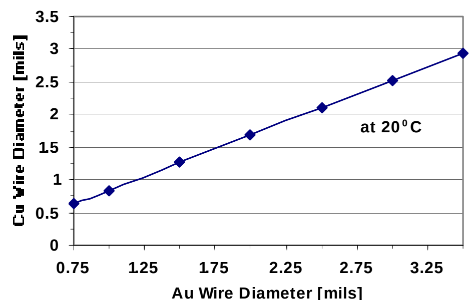


Figure 4 shows the diameter of a copper wire having equivalent conductance to a gold wire. Copper's better electrical conductivity has two important aspects. First, in power devices, where large diameter wires are required, it is advantageous to replace large diameter gold wire with a smaller diameter copper wire because of its higher conductivity. Second, in fine pitch packages, where current-carrying capacity becomes compromised as wire diameter decreases, copper wire with higher conductance, carries a heavier load for improved electrical performance equivalent to a larger diameter gold wire.

Copper does have two significant disadvantages: corrosion and hardness. Gold is a noble metal, with no known oxides and excellent chemical resistance. In contrast, copper corrodes and reacts readily. Therefore, it must be protected by the package encapsulation to provide reliable interconnections. Although several papers have shown less harmful effects from halide flame retardants in molding compounds with copper than with gold packages, correct selection and qualification testing of molding compounds is essential to achieving a reliable copper wire bonded package[5].

New, more sensitive processes such as Bonding Over Active Circuits (BOAC) and over multi-layered, low-K dielectric metallization stacks present a difficult bonding challenge for the harder copper ball. Combined efforts with machine, process and device changes and optimization will be required to overcome these challenges.

Ultra-fine pitch devices that require small ball-bonds (small bond pad size) and small capillary tip diameter (less second bond size) also challenge the bonding process. The development of high-yield, high-reliability copper ball bonding with 45µm pitch BOAC devices is currently underway.

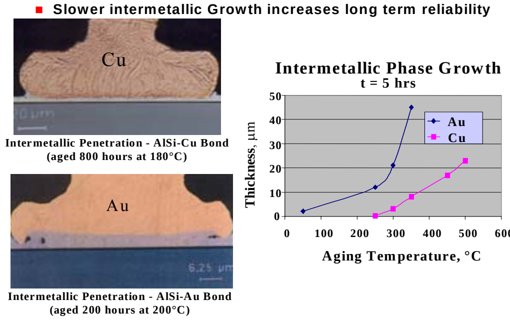
Bond Reliability

Both copper-aluminum and gold-aluminum bonds form an intermetallic weld. In an intermetallic weld, the initial bond formation is based on interfacial mating. Subsequently, diffusion controls the growth of intermetallic compounds. Copper-aluminum intermetallics form much slower and at a higher temperature than gold-aluminum intermetallics. Slower intermetallic growth provides better reliability and a longer life for Cu-Al bonds[6]. Numerous studies have demonstrated that the Cu-Al intermetallic has approximately 10x the life of an equivalent Au-Al bond, based on time-temperature to 50% strength degradation.

Figure 5 shows a metallurgical cross-section of thermally aged Au-Al and Cu-Al ball bonds. Intermetallic growth thickness measurements for diffusion couple coupons (not bonds) are also shown. The graph and photos show that Cu-Al has significantly slower growth, especially at temperatures below 200^{0}C.

Figure 5 Intermetallic Cross-Section

- Slower intermetallic Growth increases long term reliability



Because of the slow, high temperature growth rate, the Cu-Al intermetallic is less sensitive to high temperature degradation than Au-Al. With today's devices operating at hotter temperatures, the benefits of slower intermetallic growth, no Kirkendall voiding, higher strength, and better electrical and thermal conductance combine to provide the best solution for ultra-fine pitch, high-reliability wire bonding.

Figure 6 Intermetallic Appearance

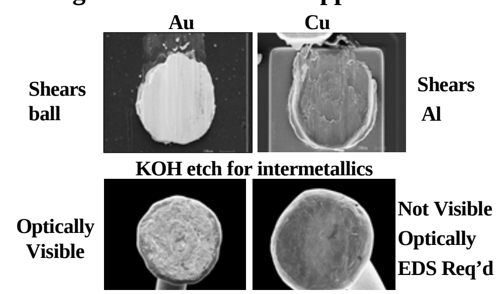
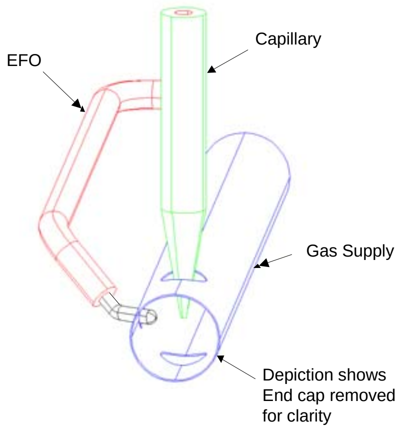


Figure 6 shows photos of shear tested ball bonds for both Cu and Au. The two materials normally fail by different modes. Copper balls normally shear within the aluminum bond pad; copper is stronger than aluminum. Gold balls normally shear within the gold ball; aluminum is stronger than gold. When each bond type is etched with potassium hydroxide (KOH) to release the ball, and the bottom interface of the ball is inspected, they also have different appearances. Gold ball bonds visually present a uniform coverage of gold-aluminum intermetallic. Copper ball bonds do not visibly show any intermetallic. However, under closer inspection with SEM and EDS, the presence of Cu-Al is detectable. Normal modes and acceptance specifications need to reflect the material under test.

Bonder

Most current copper ball bonding applications do not require the most advanced fine-pitch wire bonders needed for today's ultra-fine pitch packages. Instead, copper ball bonding applications can be run on many of the recent generation wire bonders with some modifications. Upgrade kits that retrofit many existing machine models are, therefore, being introduced into the market. This strategy enables low-entry costs and strategically positions copper for high-growth, high-volume products.

Figure 7 K&S Nu-Tek Microflow Anti-oxide Gas Delivery System Concept



- **Minimum Gas Usage = Lower Costs**
- **Controlled Ball Formation = Improved Reliability**
- **Upgrade Existing Equipment = Increased Value**

Figure 7 illustrates the gas-feed EFO system that enables production of oxide–free copper balls. Oxide-free copper balls are an essential requirement for high-yield, high-reliability bonding. By forming the ball totally within the closed environment of the gas delivery system, a perfect ball is formed with minimum gas usage. Earlier mechanisms that relied on high flow volumes to flood the area around the ball not only consumed gas inefficiently, but also increased costs and but did not form perfect balls.

Tools and Materials

Capillaries and wire for copper ball bonding are also developing at a rapid pace. New wire alloys (DHF and iCu are examples) have already been introduced that demonstrate longer shelf life, without degradation of ball formation when exposed to ambient conditions on the wire bonder. Capillary designs (such as the CuPRA), with optimized features for long life under the aggressive conditions of copper ball bonding, are being qualified.

Bundled solutions, jointly optimizing equipment, capillaries and wire to produce the best product, provide a more robust process solution. Joint application development projects, with equipment, materials, tools and device

Figure 8 Customer Confirmation

- **Collaboration with Amkor Technology**
- **4 Magazines, 65280 Wires**
- **2mil DHF wire, CuPRA capillary**
- **Bonding metrics PASS**

2.0 mil DHF Cu on K&S Test Vehicle				
	Plasma		non-Plasma	
Process Requirement	Actual Mag 1	Actual Mag 2	Actual Mag 3	Actual Mag 4
Bonded Ball Size (µm)				
Max	110.55	108.55	107.35	106.55
Min	101.75	100.35	100.35	100.55
Average	104.8	102.9	102.75	103.76
Stdev	1.89	1.77	1.51	1.6
Ball Height (µm)				
Max	38.4	36	32.8	34.8
Min	32.2	30.8	27.2	29.2
Average	34.96	33.26	29.67	31.37
Ball Shear (grams)				
Max	143.95	149.35	114.58	123.4
Min	111.92	100.69	75.8	87.36
Average	128.16	126.94	95.92	104.12
Cpk @LSL 40 grams	3.38	2.88	2.34	2.82
Shear per Unit Area (gms/mil^2)	9.57	9.85	7.45	7.92
Top Loop Pulls				
Max	54.37	54.66	54.64	56.05
Min	48.42	47.54	46.12	52.49
Average	52.22	52.03	51.92	54.19
Stdev	1.4	1.36	1.56	0.86
Cpk @LSL 25 grams	6.5	6.6	5.8	11.3

manufacturers forming cooperative teams can achieve better results more quickly than independent development efforts. Most transition plans do not include wafer FAB changes to bond pad metallization in order to accommodate the harder copper ball. Therefore wire and process changes are required to compensate.

Application Studies

Customer application studies are being conducted at a number of OEMS, assembly subcontractors and IDMs. The transition from Au to Cu will require package re-qualification including high temperature storage and thermal cycle reliability testing. Because of the slower growth intermetallic bond between Cu and Al initial reliability test results have generally been positive.

Figure 8 shows the results of a confirmation, which was run in collaboration with Kulicke & Soffa, and Amkor Technology. The run was performed using the K&S Copper Kit, the K&S QFP test vehicle, 2.0mil DHF wire and the CuPRA capillary. Four magazines were run, two (2) with plasma cleaning and two (2) without. While plasma cleaning provided a significant increase in shear strength for this package, both conditions produced acceptable results. Standard specifications, acceptable for gold ball bonding with the same size wire, were easily exceeded.

Figure 9 Customer Application

- **2.0 mil DHF wire, CuPRA Capillary**
- **In Collaboration with Amkor Technology**

Ball Diameter [µm]	Average	105.47
	St Dev	2.88
	Max	99.55
	Min	110.55
Ball Height [µm]	Average	39.57
	St Dev	2.43
	Max	34.8
	Min	43.6
Pull Strength [g]	Average	49.44
	St Dev	7.32
	Max	37.4
	Min	64.8
	LSL	8
	Cpk	1.9
Shear Strength [g]	Average	123.2
	St Dev	12.2
	Max	95.1
	Min	146.5
	LSL	40
	Cpk	2.27
Shear /UA [MPa]		138.4
Shear /UA [g/mil^2]		9.11

Figure 9 is a different customer application study using 2.0mil DHF wire and the CuPRA capillary. Conducted again in collaboration with Kulicke & Soffa and Amkor Technology, it produced excellent results. Wire bond yield in this study was 99.79%, an acceptable level for this stage of work. Production yield targets, equivalent to gold, are the goal. Shear strength/UA was 138 MPa (9.11 g/mil^2), well above the 87 MPa target typically set for gold. The two photos show the excellent control of looping and ball shape. Copper, because of its higher stiffness and lower density, supports better looping than gold and doesn't have the sagging that must be controlled with gold wires.

Figure 10 K&S Application Results
1.3 mil Wire

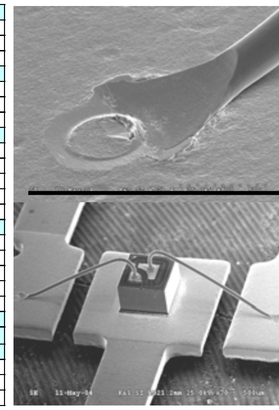
Bonder	K&S 8028-PPS+ Cu Kit	
Wire Diameter	1.3 mil wire	
	Results	Spec
Ball Size	65	65
Ball Ht	16	<20
Ball Shear	64	>25
Cpk @ LSL 25g	2.61	>1.67
Wire Pull	18.6	>6
Cpk @ LSL 6g	2.4	>1.67

Good ball formation

Figure 10 shows the results of an application study using 1.3mil wire, an 8028-PPS ball bonder and a copper ball bonding upgrade kit. Results show that ball formation and size control are on target and bond strength is excellent,

Figure 11 Customer Application
1.0 mil iCu Wire, CuPRA capillary

Ball Diameter [µm]	Average	59.4
	St Dev	2.1
	Max	65
	Min	54.1
Ball Height [µm]	Average	10.3
	St Dev	0.8
	Max	13
	Min	8.5
Pull Strength [g]	Average	10.7
	St Dev	0.8
	Max	12.6
	Min	9.7
	LSL	6
	Cpk	1.67
Shear Strength [g]	Average	34.9
	St Dev	2.8
	Max	39.2
	Min	34.9
	LSL	20
	Cpk	1.78
Shear /UA [MPa]		123.4
Shear /UA [g/mil^2]		8.1
Loop Height [µm]	Average	147
	St Dev	2.9
	Max	154
	Min	139

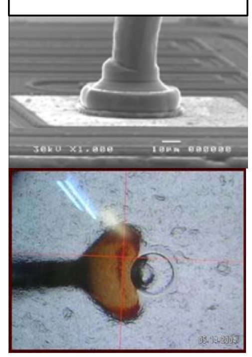


meeting all target specifications. Customer specifications vary widely, reflecting the rapidly changing industry experience.

Figure 11 shows an application with a 1.0mil wire used on a K&S Nu-Tek bonder. The devices are low-cost SOT-23. Although, there were only two (2) wires per device, the application represents very high-volume production. Results show that both looping and strength requirements exceeded standards. Cost savings that copper provides in this fine wire (1.0mil), low I/O device are very large because of the high production volume. Copper provides a competitive advantage in this case, where margins were very low and competition was fierce.

Figure 12 Copper Wire Bonds

45 µm Ball Bond



- **0.8 mil iCu wire**
- **CuPRA Cap**

Compared to Gold

30% Higher shear Strength / Area

25% Higher Pull Strength

Figure 12 represents a fine-wire application with a 0.8mil wire used on a Nutek bonder. This application required a 45µm ball diameter for 60µm pitch bonding. Shear strength was 30% higher than gold, and pull strength was 25%

higher. High magnification photos of the ball and wedge bonds are shown. Development of copper wire bonding for ultra-fine pitch (< 50μm pitch) applications is proceeding. Here, the reliability improvements, provided by copper's slow intermetallic growth and increased conductance, provide the incentive for development.

Conclusions

Copper ball bonding provides significant cost improvements, improved electrical and mechanical performance, and better bond reliability than conventional gold ball bonding. It has already been implemented in power and low pin-count packages. As volumes increase and industry experience matures, it will migrate into finer pitch packaging, providing a low cost alternative to flip chip packaging for many high pin-count packages. Capability demonstrations of fine-pitch feasibility have already been performed at trade shows, where fine-pitch quad-tier devices with over 1,200 wires were shown. Bonding pre-qualification studies with ultra-fine (45 μm) pitch BOAC devices and 20μm diameter wire are in early stages.

Acknowledgements

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