The Emergence of High Volume Copper Ball Bonding

By
Michael Deley, Director, Ball Bonder Marketing
Phone 215-784-6738, Fax 215-784-7588. mdeley@kns.com
And
Lee Levine, Sr. MTS, Advanced Packaging
Phone 215-784-6036, Fax 215-659-7588, llevine@kns.com
Kulicke & Soffa Industries Inc.
2101 Blair Mill Road,
Willow Grove, PA 19090

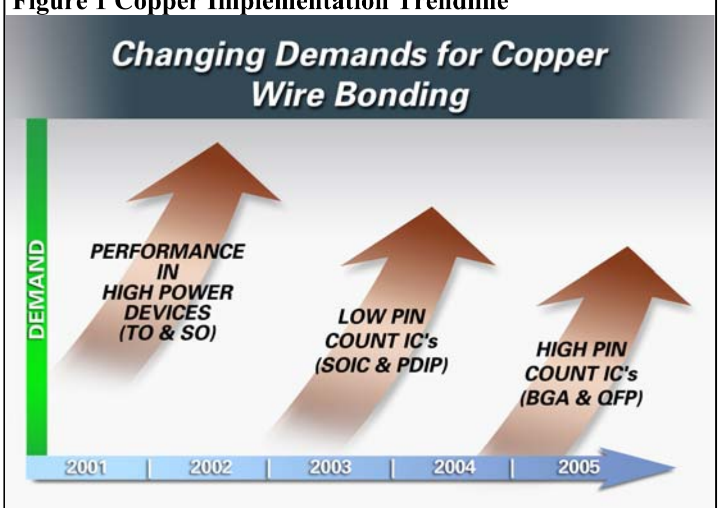
Abstract

Although copper ball bonding currently comprises less than 2% of the total interconnect market, it is entering a high growth stage of development. As demand for copper bonding wire increases, wire costs are decreasing, approaching levels similar to aluminum bonding wire. This fuels further expansion of candidate packages for conversion to copper wire. Presently, copper ball bonding is a fully qualified production process for low I/O and power packages. As manufacturers gain production experience and infrastructure is established, copper ball bonding will present less risk. In the near future, it will expand into midrange I/O packages (SOIC, PDIP) because it offers a large potential savings in packaging costs as well as improved performance and reliability. New improved capabilities in wire bonder technology have enabled high yield, high quality copper ball bonding with lower manufacturing costs by reducing consumption of the inert gas required for spherical ball formation.

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 yield issues and cyclic corporate priorities. While significant cost savings were forecast and described in literature[1,2,3,4], the cost advantages of copper ball bonding were not significant enough to justify development costs, qualification requirements, and reliability concerns. As the market for low cost and high power devices has become extremely competitive, small competitive advantages are now considered very significant. The value of gold in bonding wire presents a significant cost savings opportunity. Copper ball bonding also has improved and matured. Better ball formation and improved bonder dynamics offer new potential to

Figure 1 Copper Implementation Trendline



significantly reduce package costs. Market dynamics dictate that significant cost reductions will emerge swiftly and quickly become the mainstream. This article discusses the advances in Cu wire bonding and presents advantages driving this transition.

Figure 2 Copper's Advantages

Features	Benefits
Lower cost	• Package savings • Competitive advantage
Electrical conductivity Gold 4.55×10^7 Ω-m Copper 5.88×10^7 Ω-m	• Thinner wires for fine pitch packages • Higher current capacity for power packages
Thermal conductivity Gold 31.1kW/m^{2}K^0 Copper 39.5kW/m^{2}K^0	• 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

Benefits

Cost savings are the most significant driving force in semiconductor assembly. In power packaging, where larger diameter wire is required to carry the increased current, the cost of gold represents a large portion of packaging costs.

Gold wire volume increases with the square of the diameter. Doubling the wire diameter increases the gold content by fourfold. With increased manufacturing demand, the price of copper wire in production volumes has fallen. The value of the copper metal in the wire is negligible. Copper wire is now approximately the same price as aluminum bonding wire. A major portion of the cost of gold bonding wire is the value of gold (approximately 85% for 1 mil wire in high volumes).

As copper wire bonding works its way into mass production, higher wire I/O packages will also convert from gold to copper. Current attention is focused on low-medium I/O devices (SOIC, PDIP). As substrate costs continue to fall for higher pin count packages (BGA, QFP), making gold wire a larger portion of the packaging budget, the demand to minimize gold content will accelerate. Figure 1 illustrates these trends and the anticipated timeline for implementation.

Figure 3 Wire Diameter with Equivalent Conductivity

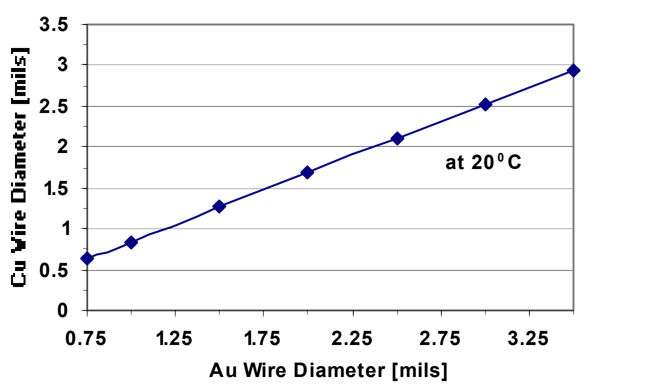
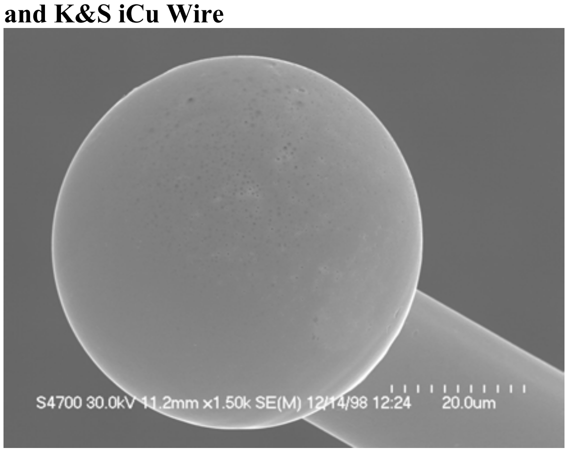


Figure 2 lists the benefits of copper wire bonding. In addition to eliminating the gold requirement, copper possesses greater conductivity than gold, allowing for the use of a smaller diameter wire for equivalent conductivity or, in power limited devices, allowing for higher current-carrying capacity than gold or aluminum for the same wire diameter. Figure 3 provides a graph showing the equivalent copper wire diameter, replacing gold wire with equivalent electrical conductance. Another benefit, increased thermal conductance, enables it to drain more heat from the chip than gold. Copper ball bonding also is a much faster process, providing more than twice the productivity of heavy aluminum wedge bonding.

Mechanically, copper is stronger and stiffer than gold or aluminum. It provides almost double the tensile strength. The weld interface for copper ball bonds is also stronger, providing approximately 30% higher shear strength/area than a comparable fine pitch gold bond. Increased stiffness (Young's Modulus) for copper wire improves looping for very long wires, especially when they are subjected to the forces exerted during the molding process. Mold sway is reduced significantly.

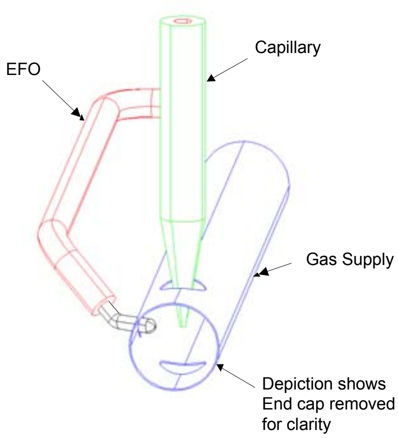
Figure 4 Cu Free Air Ball, K&S Nu-Tek Bonder and K&S iCu Wire



The Bonding Process

Gold is a noble metal, having no oxides. Copper oxidizes quickly when exposed to elevated temperatures and slowly under ambient conditions. The ball bonding process requires the formation of a ball on the tip of the wire (Figure 4). The ball is formed by a spark, discharged from the Electronic Flame-Off (EFO). The spark melts the wire tip, and the surface tension of the molten tip causes a spherical ball formation. Oxidation during formation significantly increases surface tension and results in distorted hard balls, unsuitable for bonding. Figure 4 is a SEM photo of a FAB produced by the Kulicke & Soffa Nu-Tek bonder with Kulicke & Soffa iCu wire. The ball is perfectly spherical and has a clean, bright surface, without signs of oxide scale or blemishes. Controlling and optimizing the formation of the FAB, and developing hardware that robustly produces uniform, defect-free balls is a requirement for process capability.

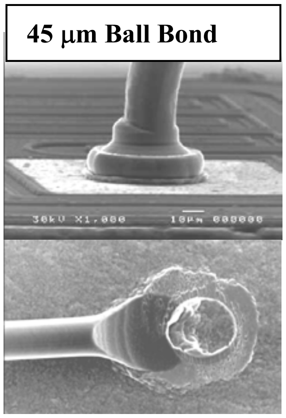
Figure 5 K&S Nu-Tek Microflow Anti-oxide Gas Delivery System Concept



- **Minimum Gas Usage / Costs**
- **Controlled Ball Formation/ Reliability**
- **Upgrade Existing Equipment/ Value**

Figure 5 illustrates the Kulicke & Soffa concept for providing a protective atmosphere during ball formation. Prior to firing the EFO, the capillary tip descends into the gas delivery system where an inert atmosphere shields the wire tip from oxidation. 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 were not only inefficient in gas consumption, (which led to increased costs), but also did not form as high quality balls. Factory grade cryogenic bleed-off Nitrogen, N_2, is adequate for good ball formation. Forming gas (95%

Figure 6 Copper Wire Bonds K&S Nu-Tek Bonder and 0.8 mil iCu Wire



Compared to Gold

30% Higher shear Strength / Area

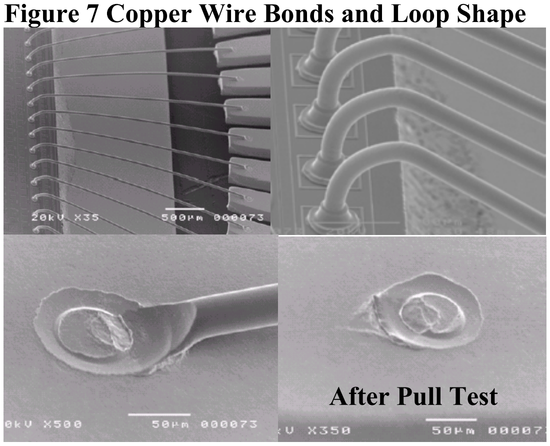
25% Higher Pull Strength

N_2, 5% H_2) offers an additional margin of safety by providing a reducing atmosphere that eliminates any possible oxidation from air currents and turbulence.

As low I/O and high power copper ball bonded devices become more common, the process will expand into the medium I/O range where finer pitch and small ball size are a requirement. Figure 6 is a photo of a 45µm ball bond made with 0.8 mil wire. This size is equivalent to the state-of-the-art usage for existing high volume production gold ball bonding (approximately 55µm pitch). Fine pitch copper ball bonding for medium I/O devices will soon become a reality, with the cost savings, performance and reliability of copper ball bonding driving it into the mainstream.

Figure 7 is a collage of recent copper ball bonding SEM photos. The top two thumbnails show the looping characteristics of copper wire. Because of its increased Young's Modulus, copper is structurally stiffer than gold. In general, it provides better looping with less mold sweep and wire sag for standard loop shapes. Some of the more complex loop shapes used in leading edge, fine-pitch packages i.e. stacked die, multi-tier, CSP loops will require further development. Examples of these loops include some of the BGA looping that requires bends near second bonds that provide additional standoff above ground and power rings on BGA packages. New loop shapes, and development of existing shapes for copper wire, will be developed as the need arises. The bottom two SEM photos in Figure 7 show a second bond and the remnant of a stitch pull test. As the second bond appearance for copper ball bonding is very similar to gold ball bonding, the same visual inspection criteria apply. When optimizing second bond with copper wires, it is important to conduct pull tests with the hook located as close to second bond as possible. Locating the hook in this location focuses the resultant forces on the second bond. When the bond is optimized in this way, the process achieves a better optimum. Subsequent production auditing, with the hook at midpoint (1/3 from the ball for down bond devices), will provide good manufacturing process control.

Figure 7 Copper Wire Bonds and Loop Shape



Reliability

A copper wire-aluminum pad ball bond is more reliable and has longer life than a gold-aluminum bond, which is currently the standard for our industry. Numerous studies have demonstrated that the Cu-Al intermetallic has approximately 10x the life expectancy (based on time-temperature to 50% strength degradation) of an equivalent Au-Al bond[5]. At 110^0C, the estimated time to 50% degradation is $2x10^6$ hours. In addition, Cu-Al is less sensitive to high temperature degradation than Au-Al.

Conclusions

As copper ball bonding establishes a stronghold in the low-cost packaging marketplace, it will migrate into Fine Pitch IC packages and eventually reach a dominant position. In fine pitch packaging, the benefits of cost reduction, improved reliability and better electrical performance are significant advantages. These advantages will continue to maintain wire bonding as the preferred technology over flip chip interconnection for many high pin-count packages.

Bibliography

[1] L. Levine and M. Sheaffer, "Copper Ball Bonding" Semiconductor International, Aug 1986

[2] T. Ellis, L. Levine, R. Wicen and L. Ainouz, "Copper Ball Bonding, An Evolving Process Technology", Proceedings Semicon Singapore, May 9-11, 2000

[3] T. Ellis, L. Levine, and R. Wicen, "Copper, an Emerging Material for Wire Bond Assembly", Solid State Technology, April 2000

[4] M. Sheaffer , L. Levine and B. Schlain, "Optimizing the wire bonding process for copper ball bonding using classic experimental designs," IEEE Transactions CHMT, vol CHMT-10, No3, pp321-326 Sept 1987

[5] J. Onuki, M. Koizumi, I. Araki, "Investigation on the Reliability of Copper Ball Bonds to Aluminum Electrodes", *37th Proceedings ECTC 1987,* pp566-572

[6] S.L. Khoury, D.J. Burkhard, D.P. Galloway, T.A. Scharr , "A Comparison of Copper and Gold Wire Bonding on Integrated Circuit Devices", *40th Proceedings ECTC 1990*, pp768-776