铜球焊接正在进入开发的高速增长阶段。随着对铜焊接线需求的增长，铜线成本正在下降。这促进了转换到铜线的候选封装的进一步扩大。目前，铜球焊接已成为低输入输出组件和电源封装的完全合格的生产程序。在不远的将来，这种生产程序将扩大到中等范围的输入输出封装，因为这种程序既提供封装成本的节约，又提供改善的性能和可靠性。在铜线焊接技术方面的改进通过降低球体成形所需惰性气体的消耗，使高产量、高质量的铜球焊接同较低的制造成本相结合。

The Emergence of High-Volume Copper Ball Bonding

Michael Deley and Lee Levine

As copper ball bonding establishes a stronghold in low-cost packaging, it will eventually migrate to and dominate fine-pitch ICs.

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 integrated circuit (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.

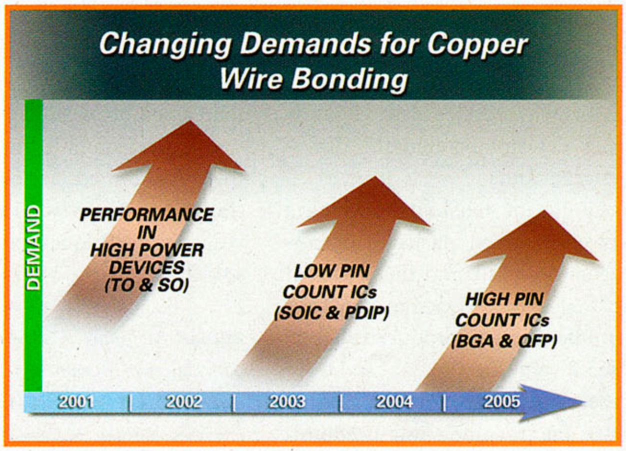

FIGURE 1: Copper implementation trendline.

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 significantly reduce package costs. Market dynamics dictate that significant cost reductions will emerge swiftly and quickly become the mainstream.

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. 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 such as small outline integrated circuits (SOICs). As substrate costs continue to fall for

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 $31.1 kW/m^2K^0$ Copper $39.5 kW/m^2K^0$	• 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

TABLE 1: Copper's advantages.

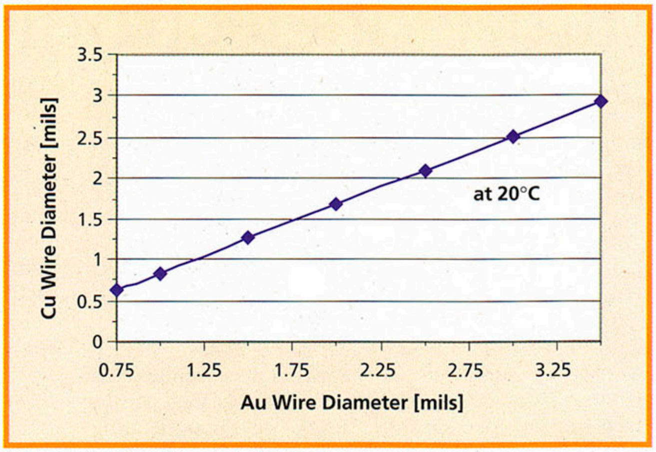

FIGURE 2: Wire diameter with equivalent conductivity.

higher pin count packages such as ball grid arrays (BGAs) and quad flat packs (QFPs), 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.

Table 1 lists the benefits of copper wire bonding. In addition to eliminating the gold requirement, copper possesses greater conductivity than gold. This property allows for the use of a smaller diameter wire for equivalent conductivity or, in power-limited devices, allows for higher current-carrying capacity than gold or aluminum for the same wire diameter.

Figure 2 shows the equivalent copper wire diameter, replacing gold wire with equivalent electrical conductance. Another benefit, increased thermal conductance, enables copper wire 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.

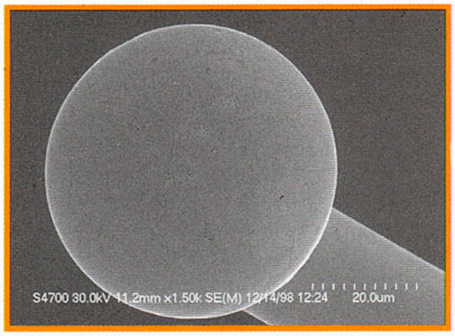

FIGURE 3: Copper-free air ball.

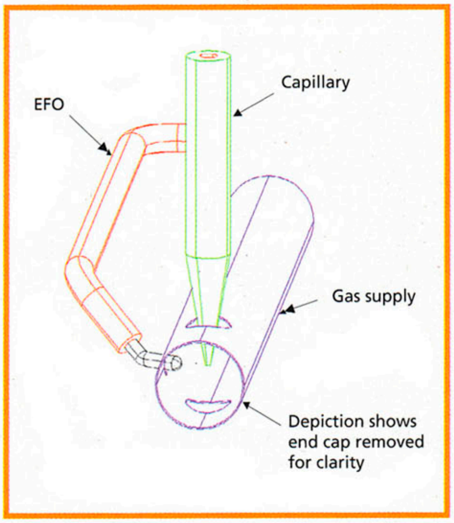

FIGURE 4: A microflow, anti-oxide gas delivery system.

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 3). 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 3 is a scanning electron micrograph (SEM) photo of a FAB produced by a bonder with copper 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 are requirements for process capability.

Figure 4 illustrates a 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

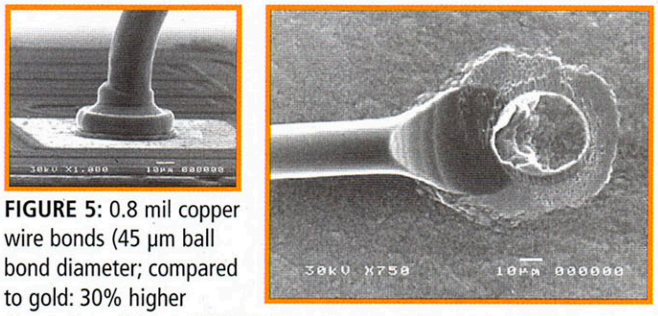

FIGURE 5: 0.8 mil copper wire bonds (45 µm ball bond diameter; compared to gold: 30% higher shear strength/area; 25% higher pull strength).

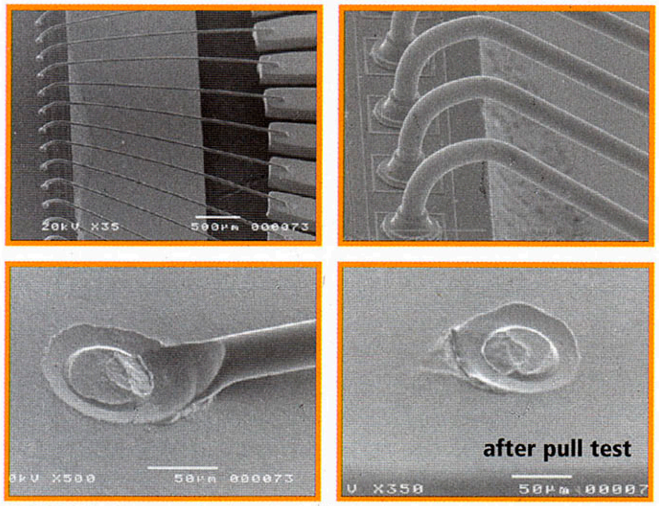

FIGURE 6: Copper wire bonds and loop shape.

good ball formation. Forming gas (95% 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 5 is a photo of a 45 µm 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 55 µm 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 6 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, such as stacked die, multi-tier and chip-scale package (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 6 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 the second bond with copper wires, conduct pull tests with the hook located as close to the 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 or one-third from the ball for down bond devices, will provide good manufacturing process control.

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 copper-aluminum intermetallic has approximately 10 times the life expectancy, based on time-temperature to 50% strength degradation, of an equivalent gold-aluminum bond.[5] At 110^0C, the estimated time to 50% degradation is $2\text{x}10^6$ hours. In addition, copper-aluminum is less sensitive to high temperature degradation than gold-aluminum.

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. ■

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