Copper Ball Bonding for Fine Pitch, High I/O Devices

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Abstract

Copper ball bonding is now a high-volume production process for heavy-wire, low I/O devices. Currently, it is being qualified for finer pitch, high I/O devices including devices with sensitive metallization and Bonds Over Active Circuitry (BOAC). Copper has been shown to provide a more reliable intermetallic bond to Al metallized die than gold wire. However, copper is harder and can damage sensitive die. Advanced wire bonders, with Z-axis controls capable of sensitive contact detection and precisely controlled ultrasonic bonding, are required for the most advanced devices. New developments in bonding tools and wire enable high yield, high reliability processes.

Keywords: Wire bonding, ball bonding, interconnections, fine-pitch, copper ball bonding

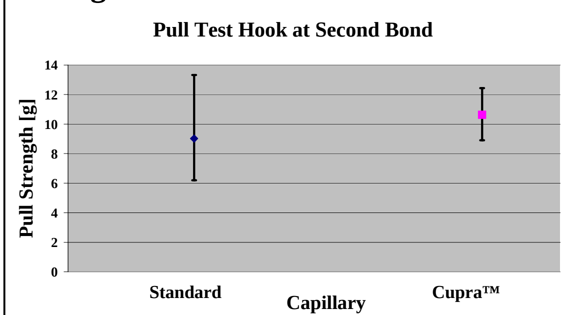
Market Drivers

Copper wire bonding has become a high-volume assembly process for heavy wire, low I/O and power devices[1,2]. It has captured a substantial portion of the market for these device types as copper offers significant cost savings (as much as 90% in materials cost for larger diameter wire bonding applications), over gold, resulting in a greater competitive edge.

Currently, copper ball bonding is entering the high I/O, fine pitch marketplace where it offers both lower costs and improved performance. However, in this market segment, there are additional challenges as device costs and I/O counts are higher. A small decrease in yield can quickly offset gold savings. Therefore, yield generated from copper ball bonding must be as good or better than that of a comparable gold wire bonding process. In addition, qualification and acceptance of higher value devices requires demanding long-term reliability testing. Copper has been shown to withstand extensive reliability testing at larger wire sizes and with larger diameter ball bonds. Demonstration of copper's long-term reliability in fine-pitch, small ball bond applications is ongoing.

Current qualifications include advanced devices requiring high I/O and fine-pitch (20µm wire diameter, <50µm pitch). These are challenging applications for copper wire bonding because they have advanced multi-layer bond pad structures over active circuitry (BOAC). Advanced bonders, with excellent control of their Z axis velocity and position, are required to achieve reliable copper bonds without damage to the sensitive underlying die metallization. Advanced ultrasonic systems, designed using FEM to control harmful parasitic ultrasonic resonance modes, provide high quality welds. Even with the most advanced machine capabilities, optimized die metallization is required to accommodate the increased hardness that is a characteristic of copper.

Figure 1: Second Bond Pull Test



Bonding Tools

In addition to bonding machine improvements, innovative changes in bonding tools and materials have been introduced. New bonding tool designs, such as Kulicke & Soffa's CuPRA™ capillary, offer significant benefits. By allowing reduced bond parameters, the CuPRA helps to eliminate serious cracking and defect problems in sensitive multi-layered metallization structures that would, otherwise, have presented long-term reliability risks.

Capillary tip design features play an important role in the development of high-strength second bonds. Figure 1 shows a comparison of a Standard conventional capillary with a Cupra™ capillary that is specifically designed for copper bonding. Conventional capillaries were developed for Au ball bonding. However, copper has significantly different mechanical and surface properties than gold. Capillaries, therefore, need to be optimized specifically for copper.

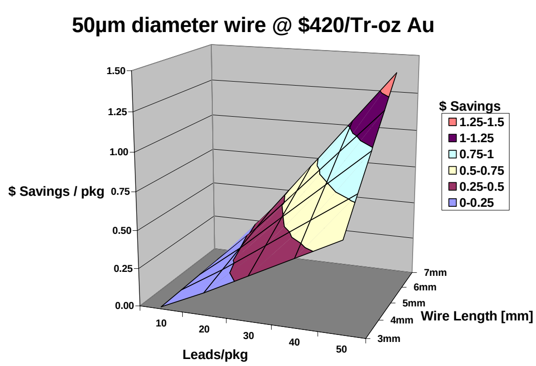
Bonding Wire

Copper is stiffer than gold and has better electrical and mechanical properties. Increased stiffness provides better loop control for long, low loops. Higher tensile strength provides improved mechanical integrity and ease of handling in fine wire applications. New copper wire alloys are in development, tailored to provide optimized performance in fine-pitch, long-wire applications.

The challenge of achieving high yields and high bond reliability in a high I/O device with advanced metallization structures are formidable. Copper is harder than gold. The welding process requires deformation of the copper ball and wire and harder materials require more energy for deformation. Simultaneously, new device structures, incorporating finer lines, low-K dielectrics and BOAC, demand more sensitive bonding conditions. The challenge for copper ball bonding is to resolve the conflicting engineering demands in order to provide lower cost, high reliability devices.

Figure 2: Gold Savings

- **90% Savings at 50μm**

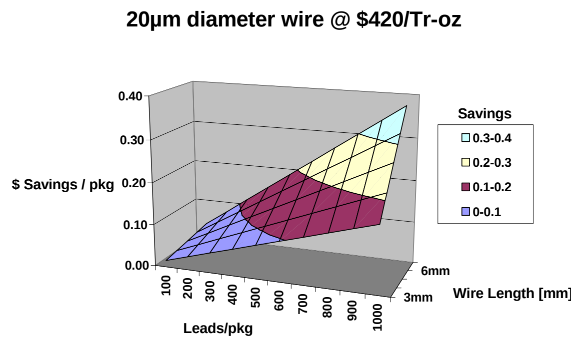


Cost Savings

Replacement of gold represents one of the most significant cost savings available in semiconductor packaging. Considering that gold's weight is proportional to its volume, larger wire diameter, longer wires, and more wires increase the volume, and, therefore, the cost of gold in a package. Figures 2 and 3 shows the savings-per-device by substituting copper for gold wire (gold value is based on $420/ Troy-oz (31.1grams) for both 0.8 and 2 mil, wire respectively. For a 2-mil wire, cost savings is more substantial as over 90% of the gold cost potentially can be saved. For the 0.8-mil wire, the volume is significantly smaller, so more wires would be required to achieve significant savings. Wire costs can be separated into two areas: manufacturing and material. Manufacturing costs for gold and copper wire are essentially equal. Material costs for gold are substantial, while, in comparison, costs for copper are negligible. However, as copper purity increases from 99.99% to 99.999% or 99.9999% its cost increases dramatically, offsetting the potential savings. Fine pitch devices, with high I/O, long wires and high production volumes have very high potential savings.

Figure 3 Gold Savings

- **63% Savings at 20μm**

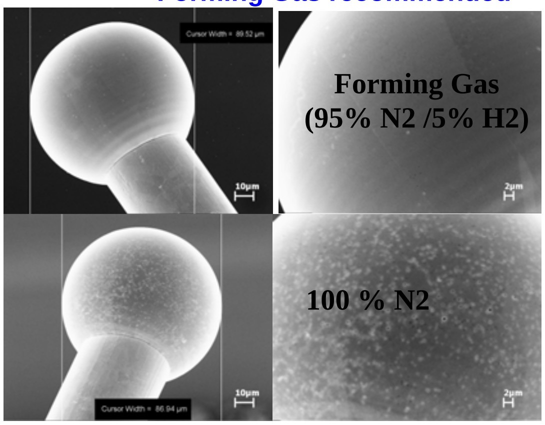


Copper Ball Bonding Process

Specialized Electronic Flame-Off (EFO) hardware is required for copper ball bonding. The hardware provides an oxygen-free environment during ball formation by shrouding the wire with reducing gas. This allows the formation of high-quality, spherical Free Air Balls (FAB) that are oxidation free. Oxidized FABs cause defective bonds, failure to stick (NSOP) and craters. Even small amounts of oxidation are detrimental, making good atmosphere control an essential process capability. Figure 4 shows FABs formed with both N2 and forming gas (95%N2 / 5% H2). The forming gas mixture is reducing (i.e. converts copper oxide back to copper) and provides much better (oxidation-free) surface quality. The result is significantly better bonding. Surface oxidation (speckled appearance) is visible on the FAB formed in N2. Although forming

Figure 4: Free Air Ball Examples

- Forming Gas recommended



gas provides the best results and is required for devices with advanced, sensitive bond pad metallization, N2 can often provide acceptable results with low I/O, large pitch standard devices. Hydrogen levels greater than 5% are flammable (5% is not a flammable mixture) and are not recommended.

Area Array Bonding Trends

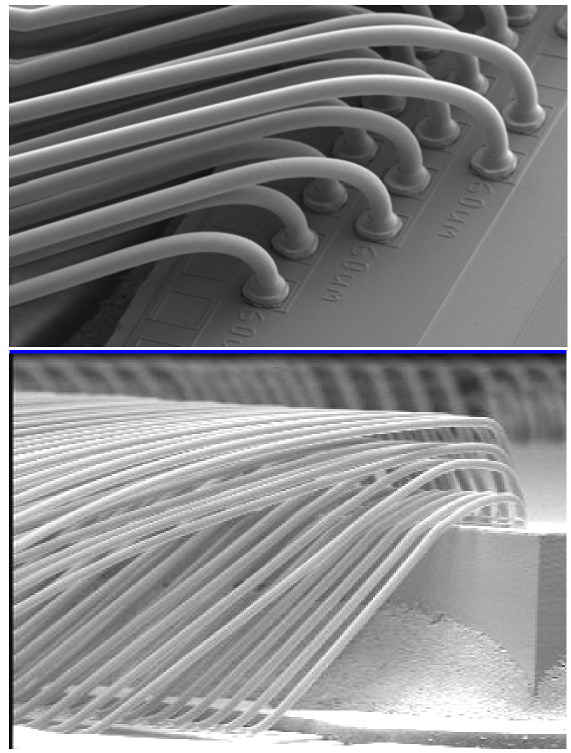
Recently, the trend for greater pitch reduction in wire bonding has slowed. The introduction of multi-tiered, staggered rows of peripheral bond pads has provided an alternate evolutionary path. Device designers can achieve the I/O requirements of ultra-fine pitch, yet maintain the wire diameter and manufacturing capability enjoyed today. Packaging development will follow the most cost effective, reliable path to achieve device design requirements.

Figure 6 depicts SEM photos of quad- and tri-tiered copper ball bonds on K&S test devices. The quad-tiered design enables over 1,000 wires using 25µm diameter wire on a 60µm pitch, functionally equivalent to a single peripheral row 15µm process. The use of 25µm copper wire for this high I/O package provides a significant saving when compared to an equivalent gold wire package.

There are two challenges in multi-tiered area array wire bonding: loop height control and package inspection. Copper wire provides the improved loop height control that allows this package to meet maximum loop height requirements. Maximum loop height for the quad-tiered copper device was <375µm, approximately 25% lower than an equivalent gold device. This height was achieved because copper wire has better looping capabilities than gold wire. Multi-tiered, copper-wired packages bridge the gap between fine-pitch gold wire packages and area array flip chip devices. They provide low-

Figure 5: Tri-tiered and Quad-tiered Copper Ball Bonds

- **High I/O with larger wire diameter**



cost, high I/O density and excellent electrical performance.

Wire bonders with advanced looping algorithms, capable of programmable loop height control, enable grouping and adjustment of each wire tier for accurate loop heights. In addition to good software and control algorithms, bonders need excellent control and resolution of their Z (vertical) axis motions.

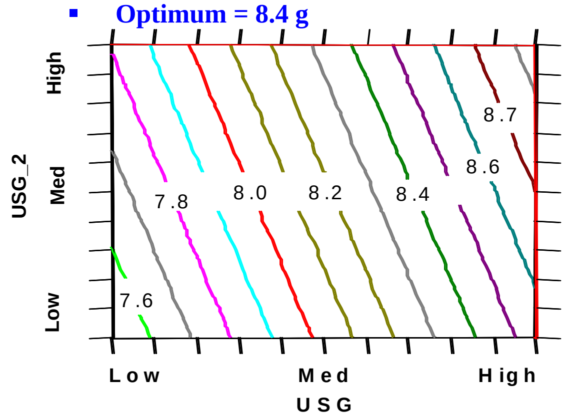
Inspection of loop height for each tier in these packages presents a problem. It is impossible to inspect lower tiers because of the wire density. Lower tiers must be inspected by partially bonding devices and, then, inspecting each tier sequentially. On-bonder encapsulation methods such as No-Sweep™ are highly recommended in dense area-array devices.

Copper Reliability

A copper ball-aluminum pad bond is more reliable and has a longer life than a standard gold ball-aluminum pad bond. 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[3,4]. In addition, Cu-Al is less

Figure 6: Average Pull Strength

- Exceeded Specs
- Optimum = 8.4 g



sensitive to high temperature degradation than Au-Al because the Cu-Al intermetallic grows at a much slower rate and does not produce Kirkendall voids, a significant problem with fine-pitch gold ball bonds[5]. Aging studies of small diameter Cu-Al ball bonds are currently being conducted. Issues regarding reliability of fine pitch copper balls on BGA devices, and with "Green" and halogen containing encapsulation compounds are less well understood and require additional studies.

Applications Studies

Application studies and qualifications are currently being conducted on leading-edge fine-pitch devices. These devices require ultra-fine pitch, thin wire diameter and have advanced multi-layer bond pad structures over active circuitry (Circuit Under Pad, CUP). Qualification is the most challenging

Figure 7: Shear Strength [g/mil^2]

- Exceeded Specs
- Optimum 6.7 g/mil^2 [102 MPa]

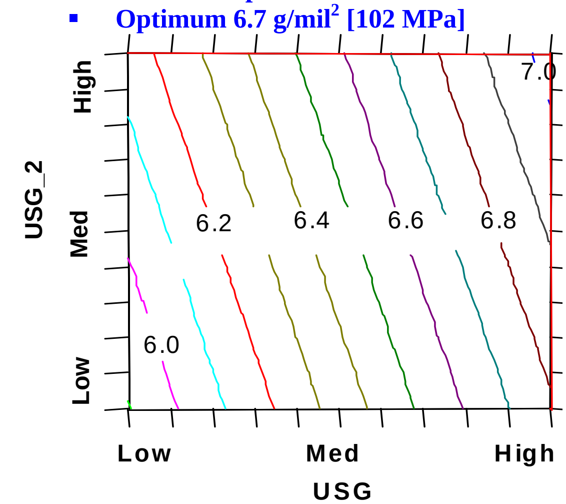
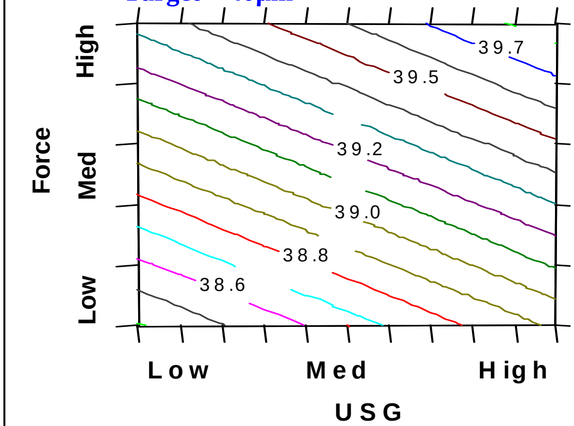


Figure 8: Ball Diameter [µm]

- Exceeded Specs
- Target < 40µm



activity that the copper process currently faces. Optimization of these applications, with 20µm wire diameter and 40µm bonded ball diameter, is challenging, even for a gold bonding process. The use of Design of Experiments techniques is necessary to understand the interplay of all of the variables. Figures 7-9 show data from a DOE, optimizing the ball size, shear strength and pull strength.

Conclusions show that two modes of ultrasonic power had significant effects on shear strength and pull strength. Ultrasonic power (electrical current to the ultrasonic transducer) is proportional to the displacement amplitude of the transducer tip and is the most significant wirebonding variable. Both ultrasonic power and bond force had significant effects on the bonded ball diameter. In this case, we were able to simultaneously achieve a ball diameter of 39.6 µm (see Figure 9), average pull strength of 8.4g (see Figure 7), shear strength of 6.7g/mil^2 [102 MPa] (see Figure 8), while achieving "no craters" and a defect-free process meeting all specifications.

High temperature storage (aging at 175^{0}C for 192 hours) is an accelerated test method used to screen before full qualification trials are conducted.

Although full qualification testing is proceeding well, there are still hurdles to overcome before high I/O devices with copper wire are in fully qualified mass production. As the rewards of cost reduction, high reliability and improved performance are great, the industry will continue qualifying more copper ball bonding products.

Conclusions

As copper ball bonding establishes a stronghold in fine-pitch packaging, it will grow and, eventually, reach a dominant position. 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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