Copper Ball Bonding Advances for Leading Edge Packaging

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

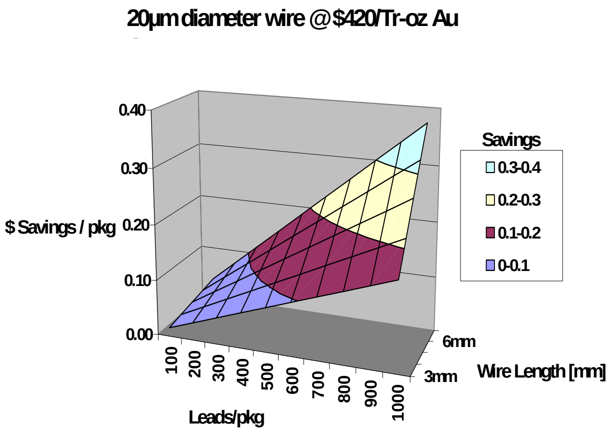
The Graphic Processing Unit (GPU) represents the leading edge in assembly technology, eclipsing the Central Processing Unit (CPU) as the most challenging semiconductor device. This paper will explore ways in which GPUs are advancing the state-of -the–art in assembly with its low cost manufacturing requirements, high number of interconnects (now approaching 1,000 interconnects/device) and demanding electrical requirements. In addition to leading devices in the development of wire bond pitch below 50µm, the GPU has led the development of multi-tiered wire bonded structures. These packaging innovations have enabled the production of the industry's lowest cost, high-density packages, enabled by manufacturing flexibility in the wire bonding process.

Cost Savings

Replacement of gold represents one of the most significant cost savings available in semiconductor packaging. Considering that gold weight is proportional to volume, larger wire diameter, longer wires, and more wires increase the volume, and, therefore, the cost of gold. Figure 1 shows the savings-per-device by substituting copper for gold wire (gold value is based on $420/ Troy-oz (31.1grams). Wire costs can be separated into manufacturing and material costs. Manufacturing costs for gold and copper wire are virtually equivalent. Material costs for gold are substantial while costs for copper are negligible, in comparison. In the current GPU application, potential savings are $0.18/package. For a high-volume consumer device, this savings provides a significant competitive advantage.

Figure 1 Copper Wire Cost Savings

- 63% Savings @ 20µm Diameter

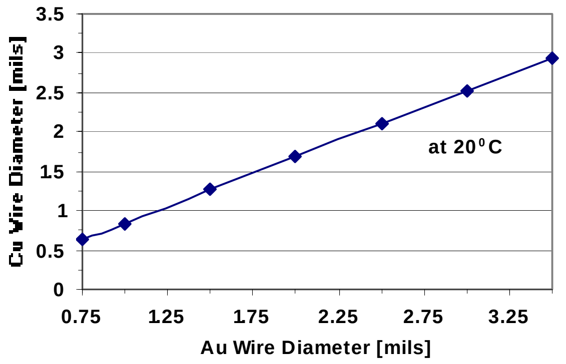


Copper Ball Bonding Status

Copper wire bonding has been accepted and become a high-volume assembly process[1]. It has captured a substantial portion of the low-cost power device market where the significant cost reduction of copper (as much as 90% in materials cost) in larger diameter wire bonding applications provides a large incentive. Now, copper ball bonding is entering the high I/O, fine pitch marketplace where it offers both lower cost and improved performance. Current qualifications include GPU devices requiring high I/O and fine-pitch (20µm wire diameter, <50µm pitch). In this application, copper offers advantages with its better mechanical and electrical properties. Copper has higher strength and stiffness than gold. In addition, it is more conductive, allowing the use of a smaller diameter wire for equivalent conductivity. Figure 2 shows a comparison of the conductance between copper and gold wire as a function of the wire diameter.

Figure 2 Equivalent Conductance

- 29% Higher Conductivity

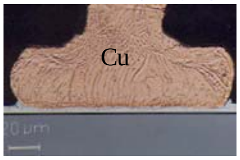


Copper Reliability

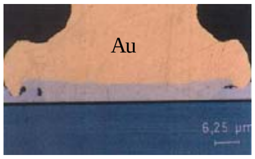
A copper wire-aluminum pad, ball bond is more reliable and has a longer life than a gold-aluminum bond, which is currently the standard for our industry. Numerous studies have demonstrated that the Cu-Al intermetallic has approximately 10x the life expectancy (based on time-temperature to 50% strength degradation) of an equivalent

Figure 3 Intermetallic Reliability

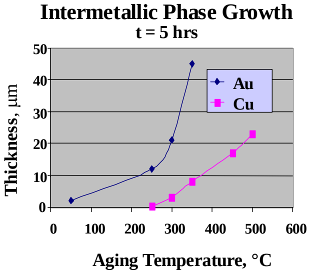
- 10X the life expectancy of Gold



Intermetallic Penetration - AlSi-Cu Bond
(aged 800 hours at 180°C)



Intermetallic Penetration - AlSi-Au Bond
(aged 200 hours at 200°C)



Au-Al bond[2]. In addition, Cu-Al is less 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. Aging studies of fine-pitch Cu-Al ball bonds are currently being conducted.

Figure 3 depicts two metallographic cross-sections of Cu and Au ball bonds after long-term HTS. As shown, the Au bond has consumed the underlying Al bond pad and has begun to show voids. Voids are separations that occur between two of the Au_4Al crystallographic phases[3]. They signify impending failure. Copper, on the other hand, has formed a very thin intermetallic layer. No voids are present and the bond is good. The graph in Figure 3 shows the thickness of intermetallic growth from roll formed samples that have diffused for 500 hours at elevated temperatures. Copper requires higher temperature to initiate diffusion and the diffusion rate is much lower.

Area Array Bonding Trends

Recently, the trend for greater pitch reduction in wire bonding has slowed. This is because multi-tiered, staggered rows of peripheral bond pads have enabled device designers to achieve the I/O requirements of ultra-fine pitch, without requiring the associated smaller diameter wire and manufacturing difficulties. Today, a few production processes have been qualified at 45µm pitch with 20µm wire, but most efforts to push below this level have been postponed. Figure 4 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.

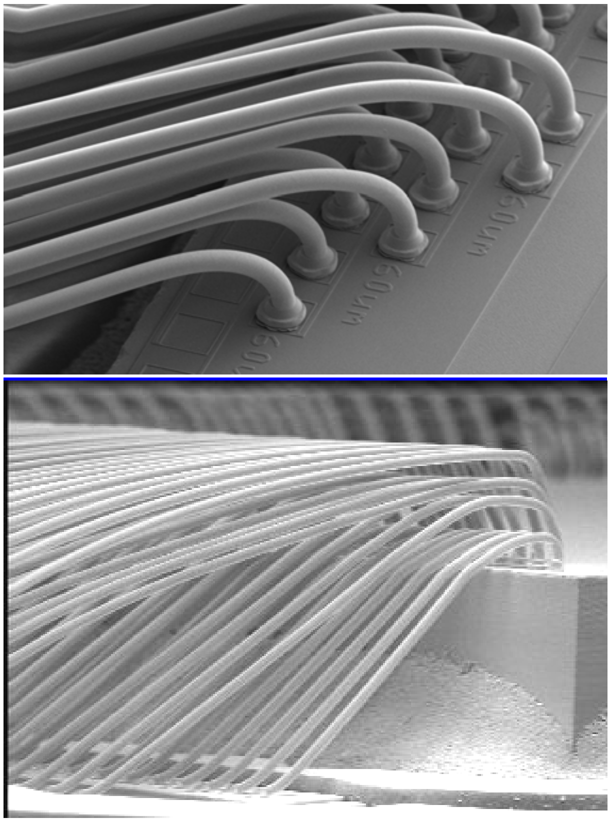
There are two challenges in multi-tiered area array wire bonding: loop height control and package inspection. Copper wire provides the improved loop height control that allows this package to meet maximum loop height requirements. Maximum loop height for the quad-tiered copper device was <375µm, approximately 25% lower than an equivalent gold device. This is 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-cost, high I/O density and excellent electrical performance.

Copper Ball Bonding Process

The formation of high-quality, spherical Free Air Balls (FAB), that are free of oxidation, is a critical process requirement. Oxidized FABs cause defective bonds, failure to stick (NSOP) and craters. Figure 5 shows FABs formed with both N_2 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 N_2. Although forming gas provides the best results and is required for devices with advanced, sensitive bond pad metallization, N_2 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. Specialized Electronic Flame-Off (EFO) hardware is required for copper ball bonding. The hardware provides an oxygen-free environment by shrouding the wire with reducing gas during ball formation.

Figure 4 Tri-tiered and Quad-tiered Copper Ball Bonds

- High I/O with larger wire diameter



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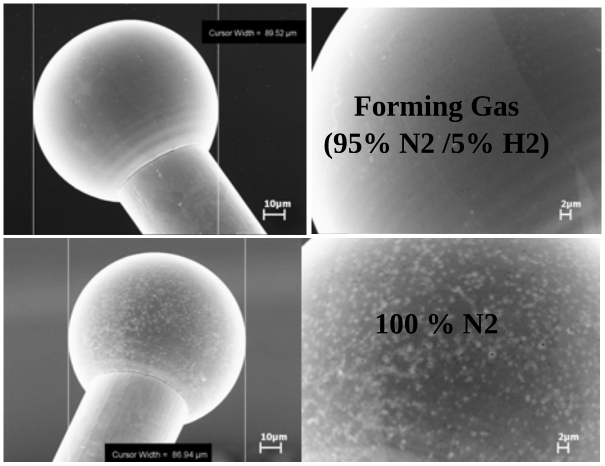

Figure 5. Free Air Ball Examples

- **Forming Gas recommended**

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 modeling to control harmful parasitic ultrasonic resonance modes, provide high-quality welds.

In addition to bonding machine improvements, innovative changes in bonding tools and materials have been introduced to the market. New bonding tool designs, such as the CuPRA™ capillary, offer significant benefits by allowing reduced bond parameters. This eliminates serious cracking and defect problems in sensitive, multi-layered metallization structures that would, otherwise, have presented long-term reliability risks. New copper wire alloys are in development, tailored to provide optimized performance and reduce pad damage in fine-pitch, long-wire applications such as GPUs.

Applications Studies

Application studies and qualifications are currently being conducted on GPUs and other leading-edge devices. GPUs require ultra-fine pitch, thin wire diameter and have advanced multi-layer bond pad structures over active circuitry (Circuit Under Pad, CUP). Qualification of GPU devices is the most challenging activity that the copper process currently faces. Optimization of the bonding process in this ultra-fine pitch application, with 20µm wire diameter and 40µm bonded ball diameter, is challenging, even for a gold bonding process. The use of Design of Experiments techniques (DOEs) is necessary to understand the interplay of all of the variables. Figures 6-8 show data from a DOE, optimizing the ball size, shear strength and pull strength.

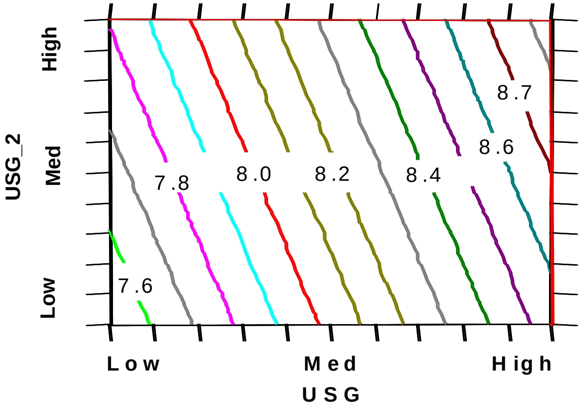

Figure 6 Average Pull Strength

- **Exceeded Specs**
- **Optimum = 8.4 g**

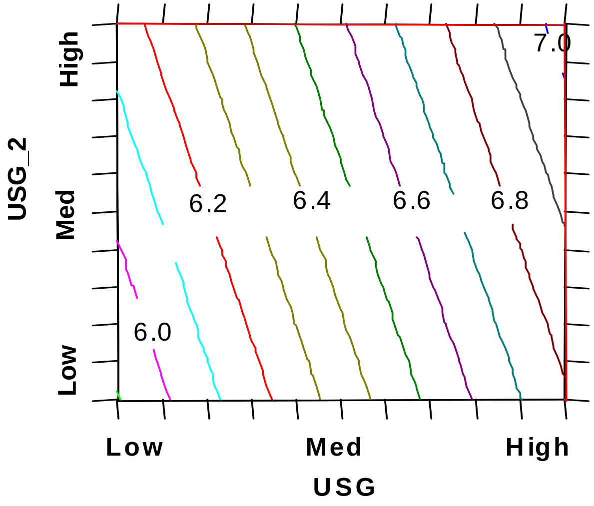

Figure 7 Shear Strength [g/mil^2]

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

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 wire bonding variable. Both ultrasonic power and bond force had significant effects on the bonded ball diameter. In this case,

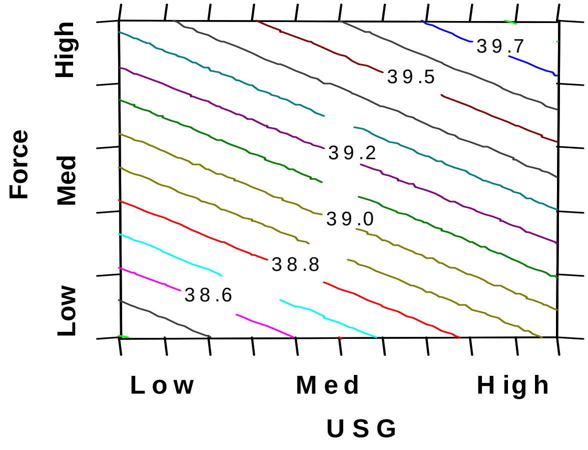

Figure 8 Ball Diameter [µm]

- **Exceeded Specs**
- **Target < 40µm**

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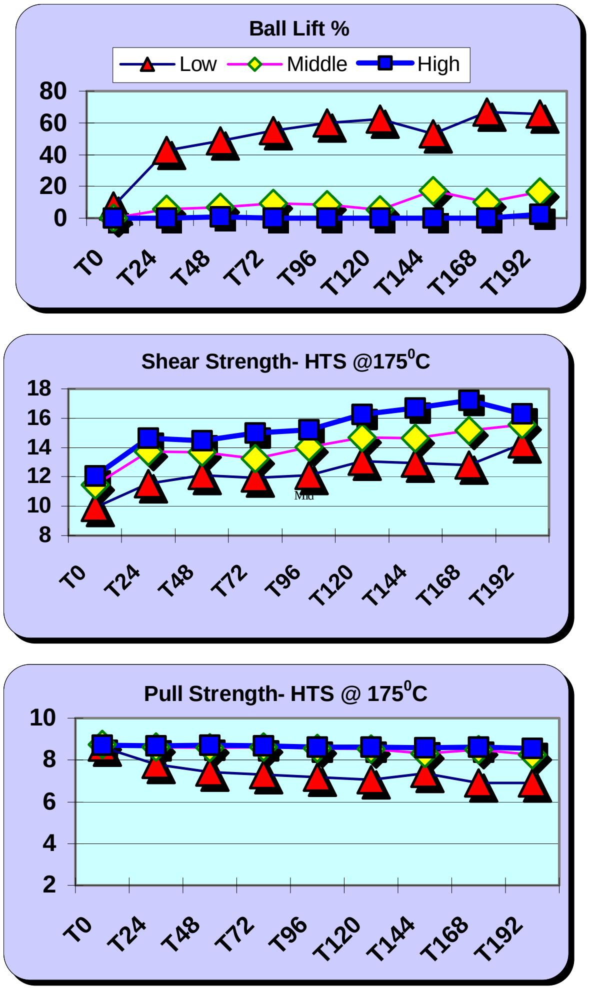
we were able to simultaneously achieve a ball diameter of 39.6 µm (see Figure 8), average pull strength of 8.4g (see Figure 6), shear strength of 6.7g/mil^2 [102 MPa] (see Figure 7), while achieving "no craters" and a defect-free process meeting all specifications.

High temperature storage (aging at 175^0C for 192 hours) is an accelerated test method used to screen before full qualification trials are conducted. Figure 9 provides data from a pre-qualification HTS test on the GPU application[4]. In this application, with multi-layer CUP bond pads, intermetallic quality and integrity are a critical response. Therefore, three levels of parameters (high, medium and low) were tested to determine the final process parameters for a qualification run. The pre-qualification testing demonstrated that only the "high" level parameters met all of the pre-qualification requirements necessary for starting the full qualification.

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

Figure 9. GPU Device Pre-Qualification

- HTS Testing Passed Specs



Conclusions

The level of qualification activity has increased substantially for copper ball bonding. Many semiconductor companies are evaluating and qualifying the process because of its significant advantages. As the infrastructure and volume of qualified products increases, this trend will accelerate. Competitive advantage and reliability will be the significant driving forces. Current efforts require substitution of copper in packages previously designed and optimized for gold wire. However, as packages are initially designed for copper bonding, the benefits will improve packaging reliability.

As copper ball bonding establishes a stronghold in fine pitch packaging, it will grow and, eventually, reach a dominant position. The qualification of GPU, and other fine-pitch advanced devices with CUP bond pads, represents an important milestone in this development. 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 low-cost technology over flip chip interconnection for many high pin-count packages.

Acknowledgements

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References

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