Enhancing Fine Pitch, High I/O Devices with Copper Ball Bonding

Inderjit Singh, Sr. Assembly/Packaging Engineer
Phone 408-486-8194, Fax 408-486-8694, isingh@nvidia.com
*n*Vidia Corporation
2701 San Tomas Expressway
Santa Clara, CA 95050

J.Y. On, Mgr Technology Center
Phone +886.7.361.7131 ext 713409,Fax +886.7.361.3094, jy_on@aseglobal.com
ASE Group Kaohsiung
26, Chin 3rd Rd., Nantze Export Processing Zone
Kaohsiung, Taiwan 811, R.O.C

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 GPU's are advancing the state-of-the-art in assembly with their lowest cost manufacturing requirements, high number of interconnects (now approaching 1000 interconnects/device) and demanding electrical requirements. The use of copper ball bonding in ultra-fine pitch applications such as GPUs is a new and challenging development.

Background

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, supported by the manufacturing flexibility of the wire bonding process. Figure 1 shows SEM images of tri-tiered and quad-tiered copper ball bonds. Both packages are bonded at 60µm pitch using 25µm wire. The quad-tiered device has over 1200 wires without sacrificing the mechanical and electrical properties of the larger diameter wire. A single peripheral row requires a smaller diameter wire with lower mechanical and electrical properties (for equivalent I/Os). In addition, the single row requires increased die size for equivalent interconnections. Maximum loop height for the quad-tiered copper package is 375µm. Because copper is stiffer, it has better looping properties than gold. This allows a lower height for the four-layered copper package than if it was bonded using gold wire.

Figure 1 Tri-tiered and Quad-tiered Copper Ball Bonds

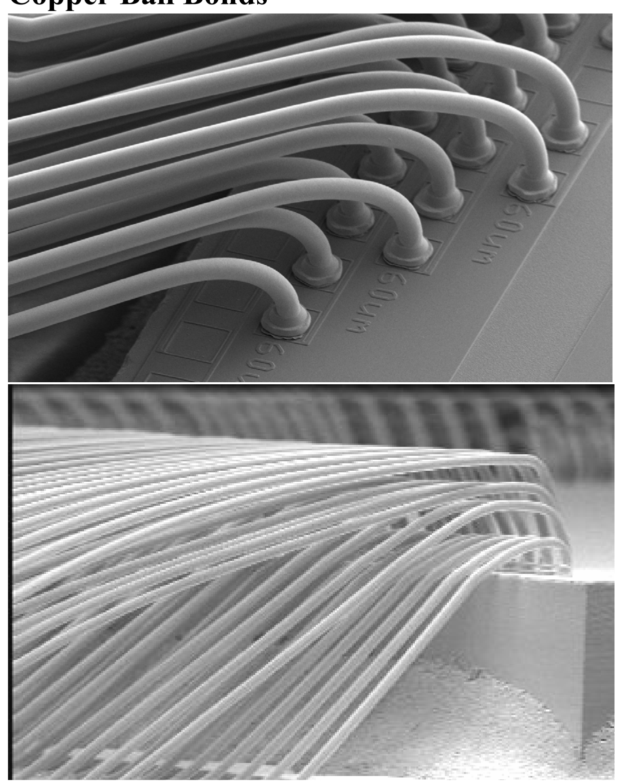


Figure 2. A Comparison of Copper and Gold wire/Materials Properties

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

Copper Bonding Process

Figure 2 is table comparing gold and copper materials/wire properties. Copper has better properties with the exception of corrosion resistance and hardness. Gold is a noble metal and is unsurpassed in corrosion resistance and copper is also harder than gold.

Copper wire bonding has been accepted by the industry and has become a high-volume assembly process. It has captured a substantial portion of the low-cost power device market, where the significant cost reduction of copper (as much as 90% reduction in wire cost[1]) provides a competitive advantage. Figure 3 shows copper's cost advantage, as the wire diameter increases copper's advantage gets larger. For packages with many wires copper has a strong advantage even when the wire diameter is small, because the length of wire in the package is larger. For the GPU application discussed in this paper savings exceed $0.17/device.

Now, copper ball bonding is entering the high I/O, fine pitch marketplace where it offers both lower cost and improved performance. Copper has better mechanical and electrical properties, higher strength, stiffness and has more conductance than gold. These properties allow the use of a smaller diameter wire for equivalent conductivity. Higher strength and stiffness improve mechanical reliability during molding and assembly.

Formation of high quality, spherical Free Air Balls (FAB) that are free of oxidation are a critical requirement of the process. Oxidized FAB cause defective bonds, failure to stick (NSOP) and craters. Figure 4 shows Free Air Balls (FAB) formed with both N_2 and forming gas (95%N_2 / 5% H_2). The forming gas mixture is reducing (i.e. converts copper oxide back to copper) and provides much better (oxidation free)

Figure 3. Cost Advantage of Copper Wire

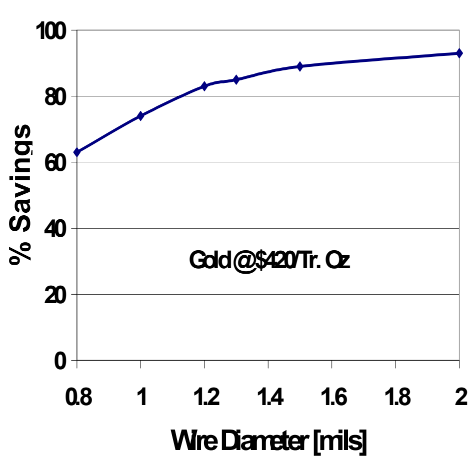


Figure 4. Free Air Balls made with N_2 and Forming Gas (95%N_2 / 5% H_2)

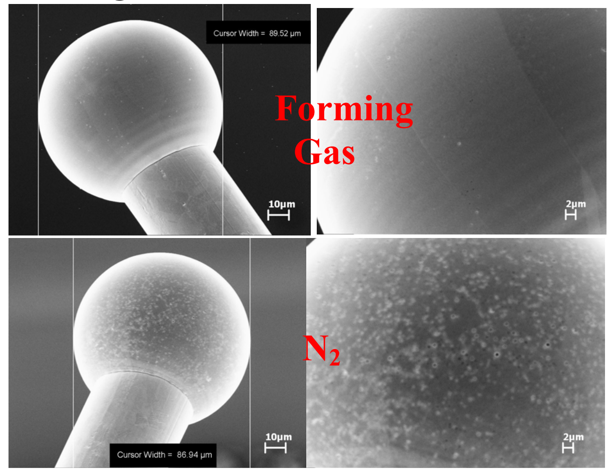
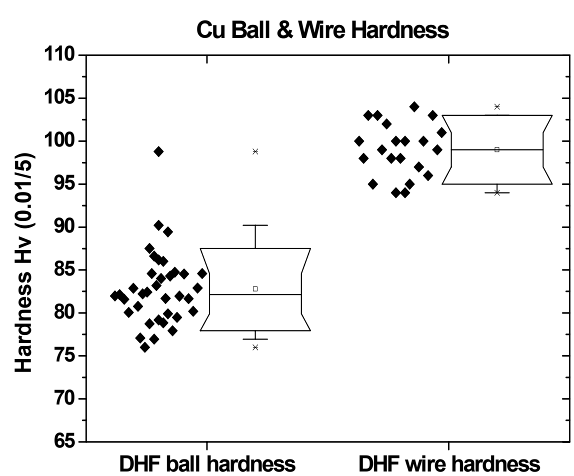


Figure 5. Vickers micro-hardness of copper Free Air Balls and wire



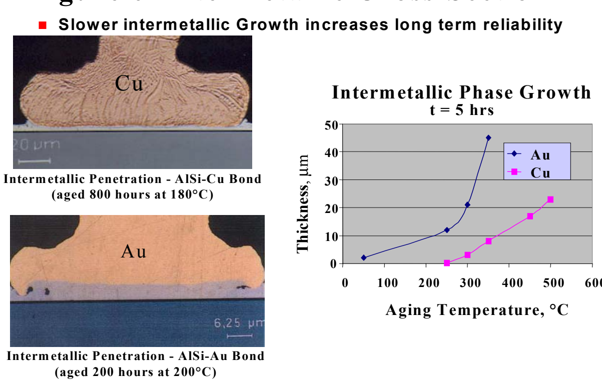
surface quality. The result is, significantly better bonding. Surface oxidation (speckled appearance) is visible on the FAB formed in N_2. Although forming gas provides the best results and is required for devices with advanced, sensitive bond pad metallization, N2 can often provide acceptable results 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. 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

Yield Issues

The predicted savings associated with copper ball bonding are significant, but if device yield is not as good as gold ball bonding, the savings will not materialize. Gold has been the high-volume wire bonding material of record for over 40 years. The gold bonding process has a record that is exemplary. In high-volume production, it is not unusual to achieve device defect rates of <200ppm and associated wire defect rates of <1ppm. Copper must equal gold's yield and reliability to compete.

Copper is harder than gold. Hardness is a mechanical property that measures resistance to deformation when a load is applied. Figure 5 shows Vickers hardness measurements of copper free air ball cross sections. Typically, copper is 20-30% harder than equivalent gold balls. As the industry moves to multi-layered bond pads with low-K dielectric layers, the additional hardness of copper presents a challenge to process development. Traditional methods, such as the use of thicker bond pad metallization, harder bond pad metallizations, or higher-frequency ultrasonics, are being tested. The use of hard, frangible layers, coated directly on copper die metallization has already been tested[2] and may be a future solution.

Figure 6 Intermetallic Cross-Section



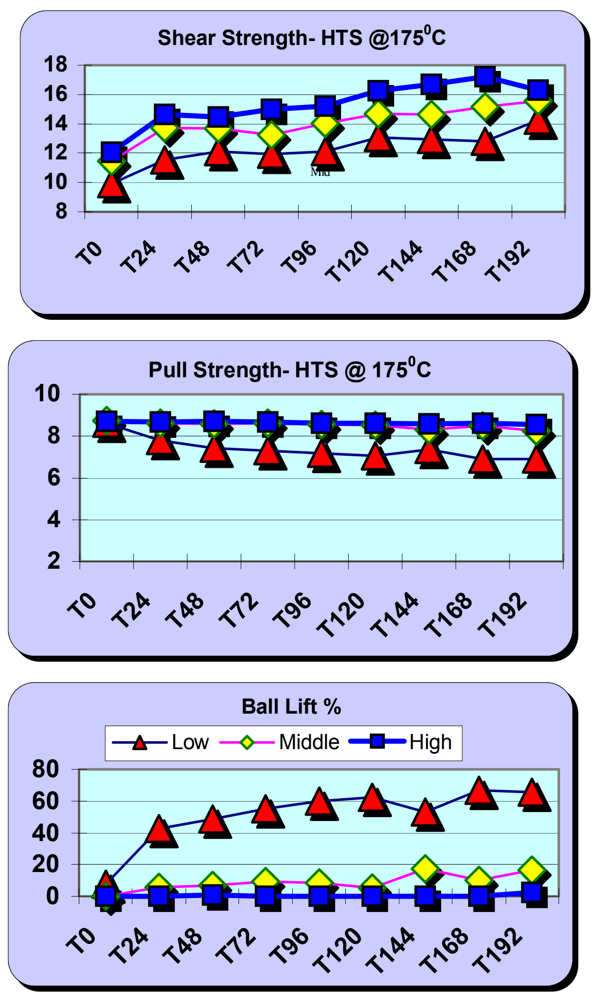
Copper Reliability

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 Au-Al bond[3]. 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. Figure 6 shows intermetallic cross-sections after HTS for Cu and Au ball bonds. Cu-Al intermetallic is very difficult to see without EDAX techniques because it is very thin and grows very slowly. Au-Al intermetallic grows quickly and consumes the entire Al bond pad under the ball. In it's final stages of development the Au-Al intermetallic undergoes a transformation from the Au_5Al_2 phase to the Au_4Al. Within the 4:1 phase there are two crystallographic forms- cubic and rhombohedral. Voiding occurs between the two forms. When voiding reaches a significant proportion of the cross section failure occurs[4]. Copper has not demonstrated this failure mechanism.

GPU Application Studies

Application studies and qualifications are currently being conducted on GPUs and other leading-edge devices. GPUs are a challenging application for copper wire bonding because they require ultra-fine pitch bonding, thin wire diameter and have advanced multi-layer bond pad structures that are more sensitive and require advanced bonding capabilities. Currently, a GPU device is in advanced qualification studies. In the configuration under test, this device required 745 wires

Figure 7. Pre-Qualification HTS Testing



at an in-line pitch of 48µm. Targeted bonded ball diameter was 39µm using 20µm diameter wire. Bonded shear strength for the optimized process exceeded 89 MPa (5.9 g/mil^2).

Cooperative development projects and joint ventures between end-users, subcontractors, and equipment/materials suppliers have benefited this type of application. As each member has a real interest in advancing development, they can jointly resolve problems and develop processes and equipment more efficiently than individually. We believe that focused partnering enables better development.

HTS testing is an important benchmark for ultra-fine pitch wire bonds. It is not unusual for ultra-fine pitch gold ball bonds to fail HTS at 175^{0}C for 192 hours if they are not properly optimized and if wire alloy constituents are not selected for their HTS properties[4]. Copper grows intermetallic at a significantly slower rate than gold, and requires higher temperatures for diffusion. Therefore, copper is capable of better HTS behavior than gold. Figure 7 shows results from pre-qualification HTS testing. DOEs were run to establish response surfaces for the bond parameters and test responses. From the response surface experiments, three levels were chosen representing high, medium, and low responses. All three levels met minimum initial shear and pull strength requirements. The three levels, then, were used to generate samples for pre-qualification HTS testing. Good HTS results are indicative of good, long-term reliability test results and are used as a preliminary screen before qualification testing. In this case, although shear strength increased for all three levels, pull strength decreased and lifts (separation between the copper ball and the aluminum metallization during destructive pull testing) increased significantly for the lower level samples. Qualification studies are proceeding with high level samples. Controlling and maintaining an optimized process requires good infrastructure and process skills. The best assembly subcontractors have the process knowledge and skills that come from the use of DOEs and statistical methods for process development and qualification.

In this application, bond peels (separation between the barrier metal layer and the underlying dielectric layer during pull testing) are a critical failure mode. Process optimization, DOEs, materials evaluations, (Cu wire) EFO ball formation optimization, capillary and materials optimizations were all required to find a suitable process window that provided good results.

Copper Bond Testing

Etching and subsequent inspection of bond pads and underlying structures for damage (cratering, oxide cracks etc) is a common requirement for wirebonds. Copper bonds require different etch procedures than gold. The best procedure is to first remove the copper balls and wire with nitric acid. Wire bonds must be removed before the bond pad is etched, otherwise etching will undercut the pad leaving the ball on a thin pedestal of residual bond pad. As this pedestal is dissolved the residual stress will nucleate a crack that is an artifact. Etching the ball first with nitric acid will not attack the Al bond pad and will eliminate possible artifacts. Etching the Al bond pad in a two step process with Aqua Regia will reveal the first dielectric layer. Optical Inspection should be at 400-500X.

Decapping of molded copper ball bonded parts has not been resolved. Normal decapping methods involve mold compound carburetion with hot fuming nitric acid or hot sulphuric acid. They will decompose the molding compound but not attack the gold wire. Both, however, readily attack copper and are not good methods. Other possible methods, plasma, laser etc are either costly or very time consuming.

X-ray inspection of copper ball bonds does not work and is therefore an issue. Gold bonds are visible because the high density of gold appears bright against the copper background in a BGA package. Copper wires are not visible against the copper background of the package.

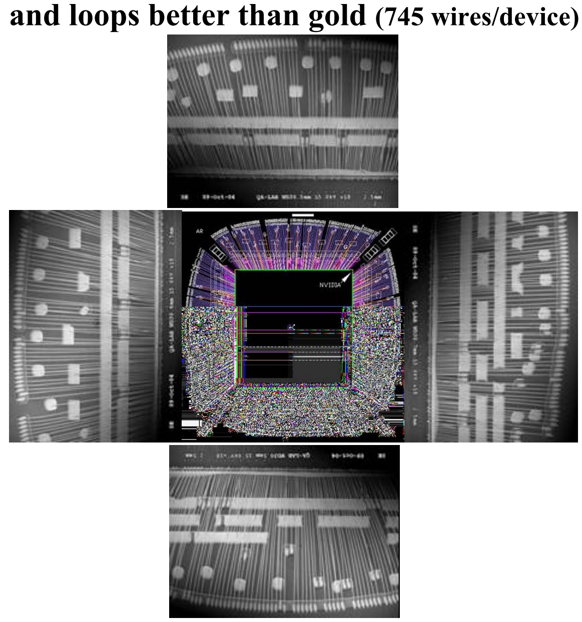
Equipment

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. The newer generation bonders have more Z encoder resolution and software improvements that allow better, more sensitive control of their Z axis. These enhancements provide better precision, sensitivity and speed. Ultrasonic systems, driven by piezo-electric crystals, can have displacement modes other than the desirable Y axis mode. Advanced ultrasonic systems, designed using FEM modeling to control harmful parasitic ultrasonic resonance modes, provide higher quality welds with better repeatability.

Bonding Tools

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

Figure 8 Copper Looping. Copper is stiffer and loops better than gold (745 wires/device)



reliability risks. The CuPRA™ design also reduces friction between the bore of the capillary and the wire, allowing the use of larger wire than standard designs at the same pitch. Larger wire diameter is stiffer (stiffness is the fourth power of diameter so a small change in wire diameter has a large effect on stiffness) and has better loop control. In addition, copper has a higher Modulus of Elasticity than gold, providing additional stiffness. Figure 8 depicts a drawing of the device and SEM photos of the wire looping from four sides of the die. Optimization of looping for a complex device such as this is very critical to high-yield manufacturing and takes both good process development and equipment capability.

Copper Wire

New copper wire alloys are in development, tailored to provide optimized performance in fine-pitch, long-wire applications such as GPUs The new alloys must maintain the mechanical and electrical properties yet also improve bondability on sensitive multi-layer and low-K metallizations.

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.

Although these results are very promising and we are moving into qualification there are still many challenges ahead before copper ball bonding becomes a fully qualified manufacturing process. Gold ball bonding still represents the standard of excellence and meeting that standard is a formidable challenge for the future.

Acknowledgments

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