Copper Wire BONDING

by Timothy W. Ellis, Ph.D., Lee Levine, Rudy Wicen, and Larbi Ainouz

Several significant transitions are currently impacting interconnection technology.

The continuing emphasis on reducing manufacturing costs is driving the development of low-cost packaging for fine-pitch, high I/O devices. Cost pressure is intense, and savings as small as a few cents per device can add up to significant reductions.

In addition, the continuing trend is to further reduce size or form factor of devices that are pad limited, resulting in finer pitch interconnections with longer wires.

Finally, the transition from aluminum to copper wafer metallization is beginning. Copper metallization allows finer line widths with higher circuit density. Developing robust, fine-pitch copper wire bonding processes to assemble these new copper devices requires complete process optimization, encompassing the wire bonder, bonding tools, and bonding wire.

Copper Wire Bonding

Bonding copper wire to aluminum pads was previously evaluated as a method for reducing costs.[1-3] Ten years ago, gold prices were extremely volatile, reaching a historic peak above $800/troy ounce compared to $260 to $325 today. In addition, the technology drivers discussed previously—cost and increased circuit density—were not present.

The industry standard package type was the 18 to 40 lead plastic dual in-line package (PDIP) with 150- to 200-µm pad pitch and 100- to 125-µm bonded ball diameters. Individual wire lengths were rarely above 3 mm. Although copper wire bonding was extensively evaluated at major semiconductor manufacturers and many of the long-term reliability issues were resolved, the stability and robustness of the manufacturing process was not good enough to provide the promised advantages. Compared to gold ball bonding—the industry standard for high yield and high reliability—the process was less robust, and yields were unstable. This situation is changing.

Cost Reduction

Figure 1 shows the cost of gold bonding wire within a semiconductor package as a function of wire length and number of leads. With today's leading-edge devices having >500 leads and wire lengths >5 mm, the potential savings in direct material cost/package is significant.

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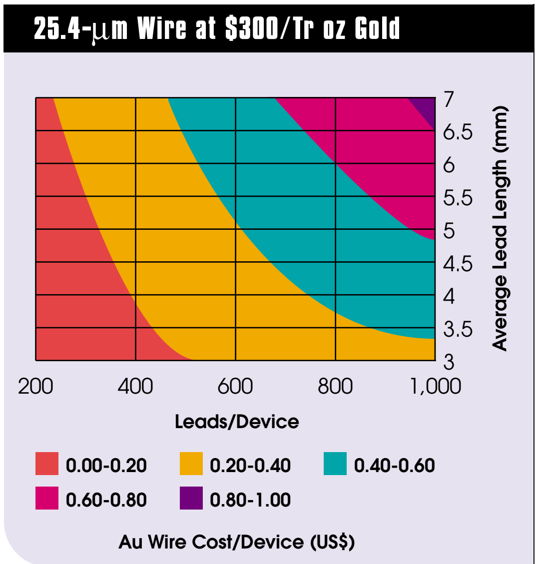

Figure 1. Gold bonding wire cost.

Ultra-Fine Pitch

Ultra-fine pitch is being driven by size/form factor reduction and finer line widths. We are currently at a node defined by 0.18-µm lines with wafer metallization in transition from aluminum to copper. Variants of the copper metallization and intermediate solutions are currently prevalent. By the next node, 2003, we can expect to see leading edge devices with lines of 0.13-µm width and below. The wafer metallization will still have multiple aluminum and copper variants.

Ultra-fine pad pitch will be a requirement for these devices, because higher densification is the focus of copper wafer development, the leading edge technology. As pitch is reduced below 60 µm, the diameter of the bonding wire must be reduced to below 25 µm.[4] Smaller wire diameter has lower breaking load and less stiffness (mechanical resistance to deflection by a force), resulting in more handling difficulties and molding related defects due to wire sweep.[5]

The use of copper wire, with twice the strength and up to 40% higher stiffness than gold wire, can alleviate some of the assembly problems caused by <25-µm diameter gold wire. Figure 2 compares gold and copper wire strength and relative stiffness, using AFW 1 mil AW-14 gold wire as a reference.

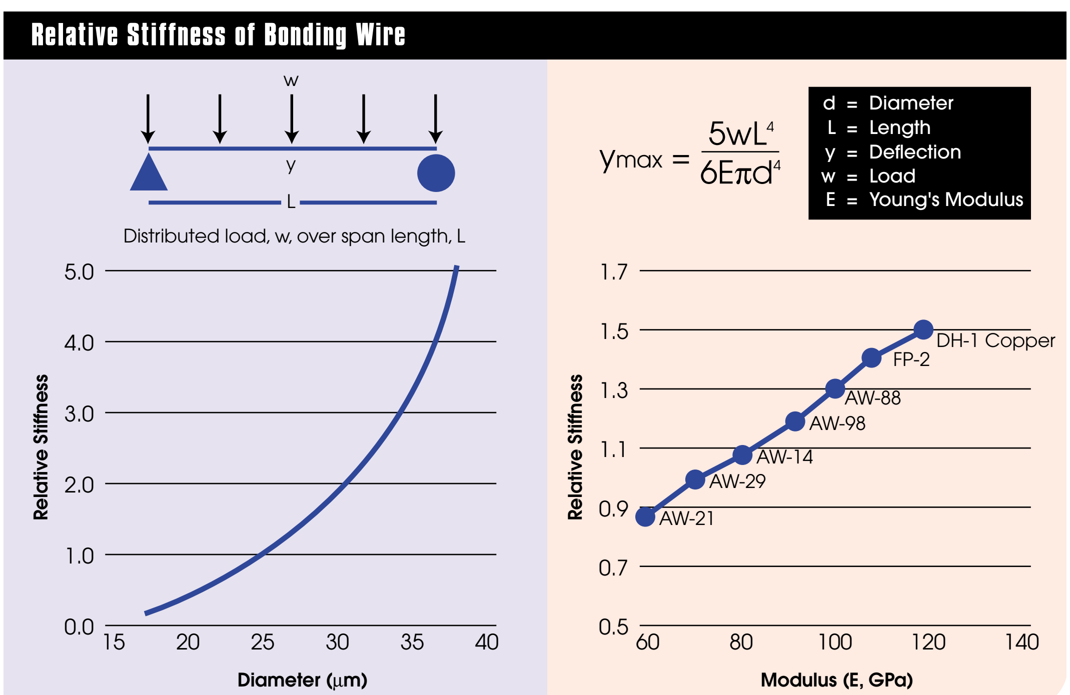

Figure 2. Stiffness and modulus are key parameters for bonding wire.

Copper Bonding Processes

As a result of several process enhancements, the copper wire ball bonding process promises to offer the stability required for a production semiconductor assembly process.

Two additional copper processes are under development.

1. Gold wire to copper pads, driven by wafer line width, will be available by the end of 2000. Enhancements to provide oxidation protection and still achieve high yield and reliable bonding to copper metallization through use of proprietary surface treatments are in advanced development (see "Oxidation Prevention Process").

2. Copper wire bonding to copper wafer metallization, the ultimate goal of current development efforts, is expected to enter production by the end of 2001.

Process enhancements that are being developed to make robust production processes possible include a new captured gas early electric flame-off (EFO), oxidation prevention process (OP^2), modulus reduction process (MRP), improvements in capillary materials, and new wire alloys.

Captured Gas EFO

EFO designs for copper wire bonding included gas flow to provide a reducing atmosphere for ball formation. These designs were sensitive to turbulence, which often resulted in deformed, oxidized balls. Oxidized balls are significantly harder than balls without oxidized surfaces and do not bond.

New EFO designs fire within a patent pending tube in which the gas is captured and there is no turbulence, ensuring that ball quality is excellent and that the process is defect free. The new designs do not require a reducing atmosphere—commercial nitrogen is suitable and therefore reduces costs.

Oxidation Prevention Process

Copper and gold ball bonding are typically performed at normal wire bonding temperatures (175°C-225°C). At these temperatures, copper oxidizes rapidly and is not bondable without surface protection. Surface treatments that provide oxidation protection and a reliable, bondable surface are required.

Modulus Reduction Process

Finite element modeling of copper ball bonding has provided additional process insight. Although the harder, stiffer material properties of thinner copper wire provide looping and molding benefits during the assembly of ultra-fine pitch packages with conventionally bonded wires, these material properties challenge the ultrasonic bonding process. Harder, stiffer ball and wire properties can result in bond defects, such as cratering and bond failure, at both the ball (first) and wedge (second) bonds.

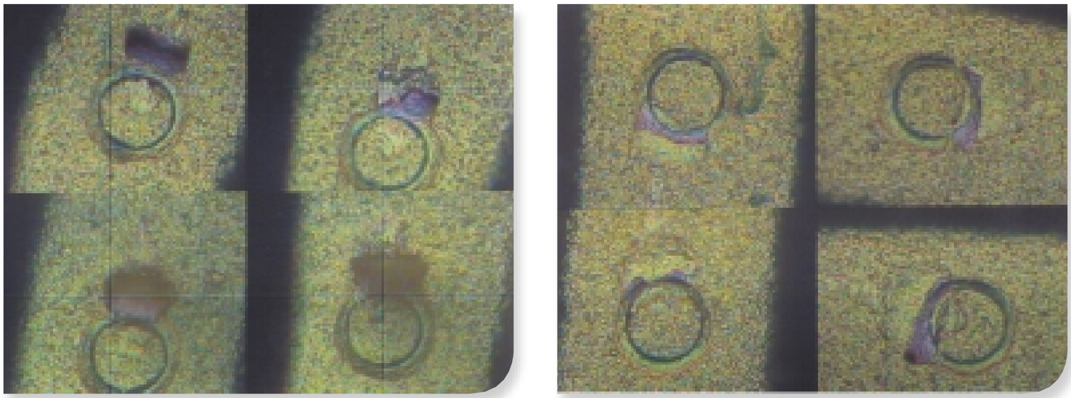

Figure 3. Modulus reduction process effect on second bond quality. (Left) MRP on; (right) MRP off.

Early efforts relied on ultra-high-purity copper (99.999% and 99.9999% purity) to maintain low hardness (all impurities increase a material's hardness). New approaches, incorporating proprietary bonding and wire manufacturing processes, have resulted in the ability to lower the modulus and improve the bond quality without demanding the high-purity materials previously required.

Figure 3 shows second bonds after pull testing with MRP on and off. MRP provides a significant improvement in the strength and failure mode of copper ball bonds produced with small tip diameter, fine-pitch capillaries. With MRP on, the peel strength of the bonds shown was 5 to 6 g; with MRP off, the strength was 1 to 2 g.

Capillaries and Materials

Capillary design considerations for gold ball bonding to copper wafer metallization are the same as for standard gold ball bonding to aluminum metallization. Critical capillary dimensions can be specified based on the size constraints of the package.[6] Capillary design for copper ball bonding must meet

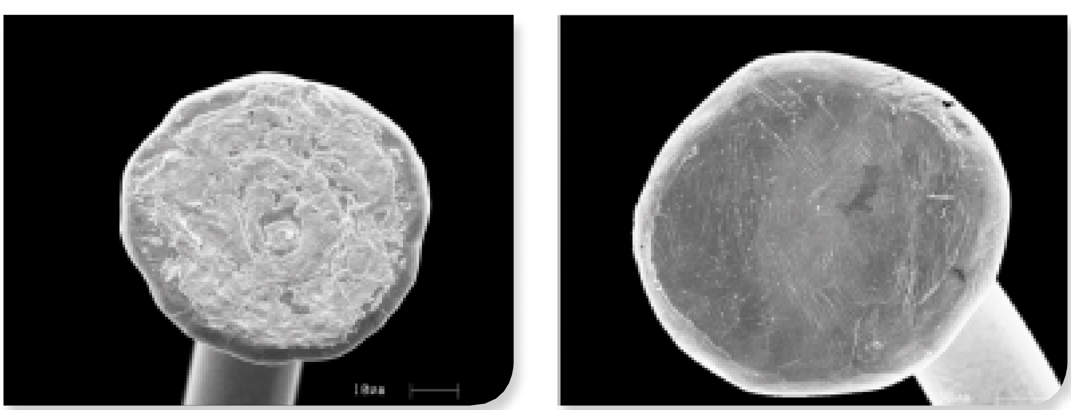

Figure 4. Copper vs. gold in IP cover. Potassium hydroxide etch technique (both bonds about 6.5 g/mil^2). (Left) gold ball with IPs; (right) copper ball does not show IPs.

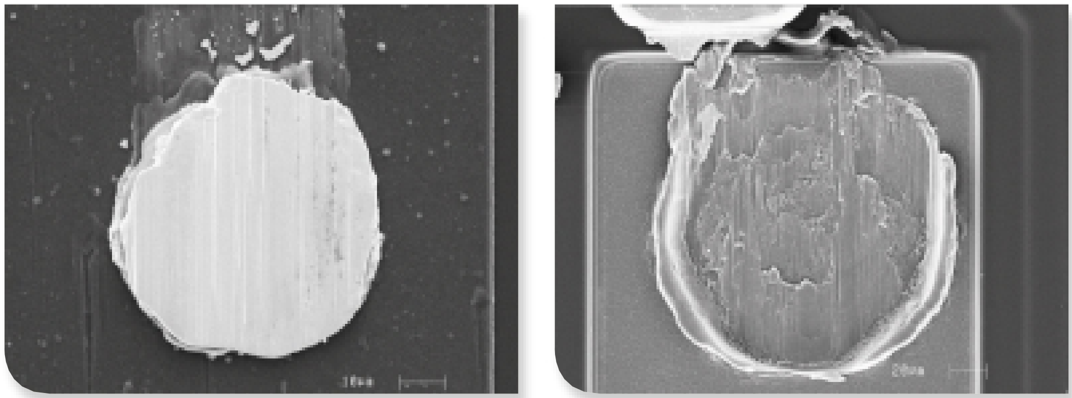

Figure 5. Copper vs. gold in ball shear. Shear pattern of good bonds (both bonds about 6.5 g/mil^2). (Left) gold shears within ball; (right) copper shears aluminum metallization.

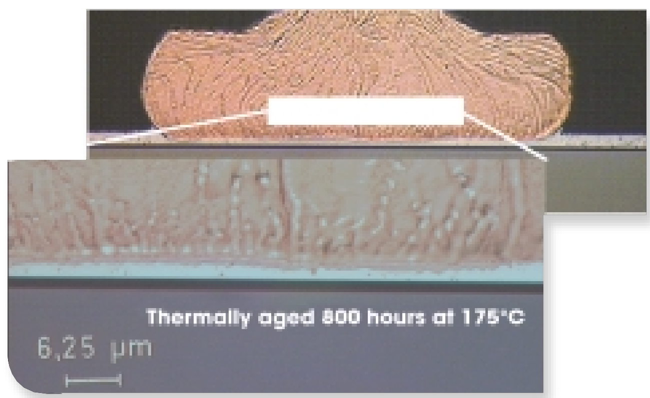

Figure 6. Copper-aluminum IP growth.

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these size constraints, but optimized surface treatments and ceramic materials may be necessary to meet life expectancy requirements because of the additional hardness of copper wire.

As with gold wire, wire bonding with copper wire requires very high-quality surface finish, spooling, and chemistry standards to achieve the high-yield, trouble-free manufacturing processes that the industry expects. In addition, copper wire types that are insensitive to oxidation are under development and soon should be commercially available.[7]

Copper Bonding Reliability

Intermetallic phase (IP) growth is significantly lower with copper bonding than with gold.[8,9] Figure 4 shows a comparison of good gold and copper ball bonds on aluminum metallization after initial bonding. While IP is distinctly present and covers the ball bond interface with gold-aluminum, it is not visible with copper-aluminum.

There also are differences in failure mode during shear testing. Figure 5 shows high-strength (100 MPa (~6.5 g/mil^2)) bonds after shear testing. For the gold-aluminum bond, the shear surface is within the ball, through the gold. Because copper has significantly higher strength than either gold or aluminum, the shear surface of a good copper ball bond is through the aluminum bond pad. The copper ball and intermetallic layer are both significantly stronger than the aluminum pad.

Figure 6 shows a cross section of a copper ball bond on an aluminum bond pad after thermal aging at 175°C for 800 hours. Intermetallic growth is visible. No signs of Kirkendall voids or other reliability risks are present. The fine grain structure of the copper ball is significantly different from the columnar grain structure of a gold ball.

Reliability testing of copper ball bonds to aluminum bond pads has been well documented.[10] Encapsulants with fire retardants designed to eliminate copper corrosion are required.

Conclusion

The introduction of copper wafer metallization will drive the development of robust, high-reliability, low-cost interconnect solutions. Gold and copper ball and wedge bonding will best enable realization of these benefits. New high-density, fine-pitch copper wire bonded packages with performance approaching that of flip chips will continue to make wire bonding a viable interconnection process for future fine-pitch packaging requirements.

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