Copper Ball Bonding, An Evolving Process Technology

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Biography:
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has more then 15 years of experience in process engineering. He currently directs operation of K&S' new Advanced Materials Development Lab, and has developed processes for virtually every product manufactured by the company. He has an M.S. Degree in Chemistry, a Ph.D. in Metallurgy, has published more than 60 technical articles and holds 22 U.S. patents.
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Rudy Wicen is currently an Advanced Engineer in the Advanced Materials Development Lab for Kulicke and Soffa. He has 17 years of wire bonding experience and has also served as QC Supervisor and QC Engineer at K&S.
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Abstract:
Several significant transitions currently are 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 cost savings as small as a few cents per device can add up to significant savings. In addition, the continuing trend for devices that are currently pad limited is to further reduce size or form factor, 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 (more functions, higher speed, lower cost/function, smaller size, lower power consumption). 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 Ball Bonding

Bonding copper wire to aluminum pads was previously evaluated as a method for reducing costs[1,2,3]. Ten years ago, gold prices were extremely volatile, reaching a historic peak above $800/troy ounce compared to $260-$325 today. In addition, the technology drivers discussed above – cost and increased circuit density – were not present.

The industry standard package type was the 18-40 lead PDIP with 150-200µm pad pitch and 100-125µm bonded ball diameters. Individual wire lengths were rarely above 3mm. 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 has changed dramatically.

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 of >5mm, the potential savings in direct material cost/package is significant.

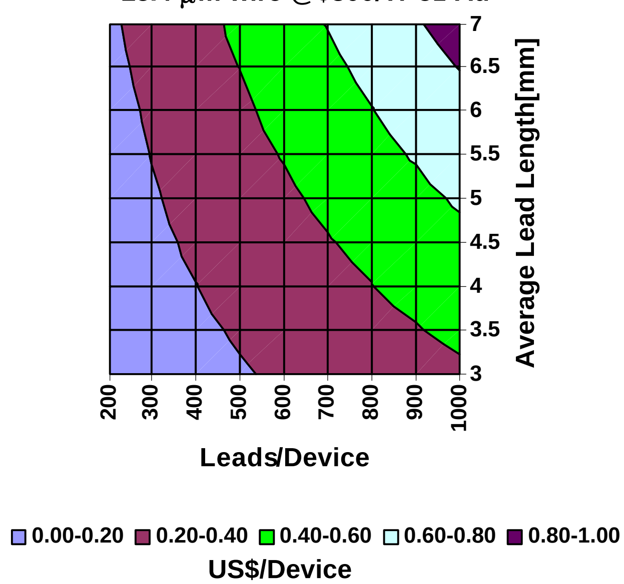


Figure 1. Au Bonding Wire Cost

25.4 µm wire @$300/Tr oz Au

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 0.18µm 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 0.13µm 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 60µm, the diameter of the bonding wire must be reduced to below 25µm[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 <25µm 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.

Copper Bonding Processes

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

Two additional copper processes are under development.

- Gold wire to copper pads, driven by wafer line width, will be available by mid-2000. Enhancements to provide oxidation protection and still achieve high yield, reliable bonding to copper metallization through use of proprietary surface treatments are in advanced development (see OP^2, below).
- Copper ball bonding to copper wafer metallization, the ultimate goal of current development efforts, is expected to enter production by the end of 2001. Pad pitch of 50µm is the goal of current development efforts.

Process enhancements that have been developed to make robust production processes possible include a new captured gas EFO, Oxidation Protection Processes (OP^2), Modulus Reduction Processes (MRP), improvements in capillary materials and new wire alloys.

Captured Gas EFO

Early electric flame-off (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 tube where the gas is captured and there is no turbulence, ensuring that ball quality is excellent and that the process is defect free.The new design does not require a reducing atmosphere, commercial nitrogen, is suitable.

OP^2

Copper and gold ball bonding are typically performed at normal wire bonding temperatures (175-225^{0}C). At this temperature, copper oxidizes rapidly and is not bondable without surface protection. Surface treatments that provide oxidation protection and also provide a high reliability, bondable surface are required.

MRP

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.

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 5-6 grams; with MRP off, the strength was 1-2 grams.

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 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.

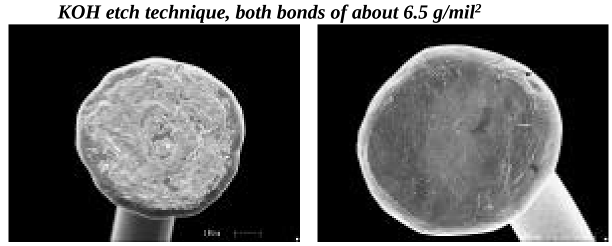
As with gold wire, wire bonding with copper wire requires very high quality surface finish, spooling, and chemistry standards to achieve the high yield, trouble free manufacturing processes that our industry expects. In addition to these requirements copper wire types that are insensitive to oxidation 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

Figure 4. Copper vs. Gold in Intermetallic Phase Coverage

KOH etch technique, both bonds of about 6.5 g/mil²

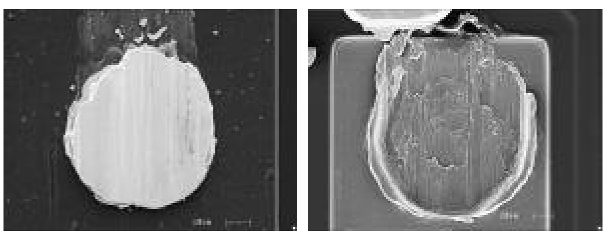


Au ball with intermetallics   Cu ball does not show IPs metallization after initial bonding. While IP is distinctly present and covers the ball bond interface with gold-aluminum, it is not visible with copper-aluminum.

There also are differences in failure mode during shear testing. Figure 5 shows high strength (100MPa [~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 5. Copper vs. Gold in Ball Shear

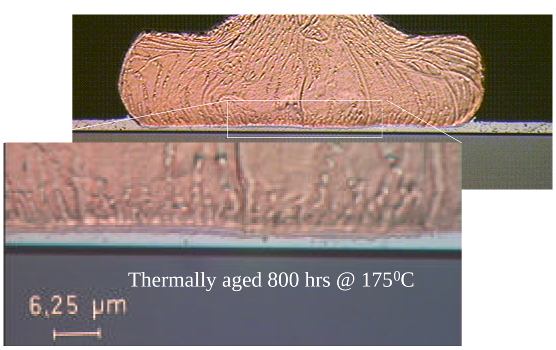
Shear Pattern of good bonds (both bonds about 6.5 g/mil^2)



Au shears within ball   Cu shears Al metallization

Figure 6 shows a cross section of a copper ball bond on an aluminum bond pad after thermal aging at 175^{O}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.

Figure 6. Cu-Al Intermetallic Phase Growth



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 interconnection 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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Figure 2. Relative Stiffness of Bonding Wire

Stiffness and Modulus are Key Parameters for Bonding Wire

Distributed load, w, over span length, L

$$y_{max} = \frac{5wL^4}{6E\pi d^4}$$

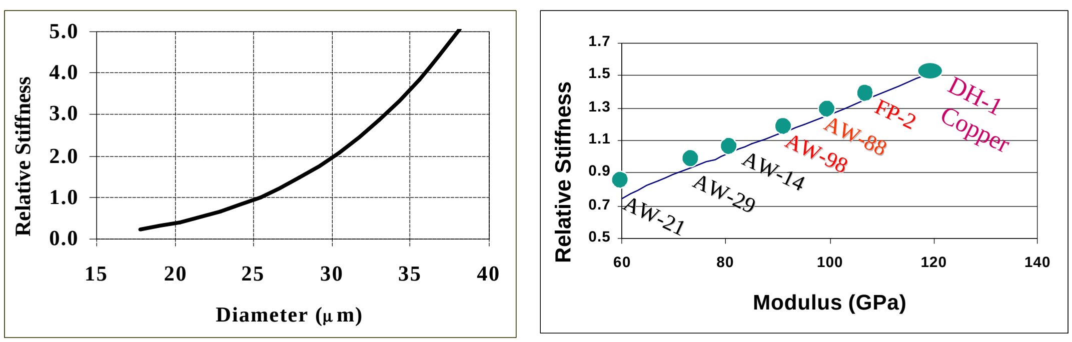

Figure 3. Modulus Reduction Process Effect on Second Bond Quality