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Copper: Emerging material for wire bond assembly

OVERVIEW Copper is being re-evaluated as a material for wire bonding because of the emergence of copper metallization on wafers. This work describes the current status of copper wire bonding, including the need for special processes to address the metallurgical challenges created by the new systems.

A close-up of the copper wire bonding process on the Kulicke & Soffa model 8028 ball bonder.

Today the semiconductor industry is in the midst of a significant structural and architectural transition. Three strong trends are driving changes in interconnection technology. These drivers and the solutions that are evolving are shown in the table.

The first driver, cost, has always been a major concern. Now, with wire lengths >5mm and lead counts moving above 400, the gold value for the wire is being driven above $0.20/package, and wire cost is a bigger consideration than ever. Device manufacturers are viewing the potential savings more intensely as annual gold wire costs increase. Copper wire bonding reduces these costs by replacing gold. In addition, copper is a better interconnect material than gold because of its physical properties.

The second driver, shrinking wafer line dimensions, is a result of the need for increased density and higher functionality (more functions, higher speed, lower cost/function, smaller size, lower power consumption, etc.), which in turn creates the need for finer-pitch, higher-lead-count packages with smaller bond pads and smaller bonds. Copper metallization reduces electromigration, which allows production of finer linewidths than Al without sacrificing reliability. Finer linewidths are required to increase device density.

Robust, stable, wire-bonding processes capable of making reliable interconnections to these new copper-metallized wafers are evolving. The appropriate metallurgy (summarized in the table) depends on the requirements of the particular application.

The third driver, device speed, builds on the first two. Copper wafer metallization provides faster chips because of the low propagation delay of copper interconnect. Copper-metallized wafers bonded with copper wire provide a low-cost, high-speed,

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monometallic system. In general, monometallic systems have better long-term reliability than intermetallic systems [1]. New packaging designs for high-speed devices, encompassing short copper wires bonded to copper bond pads on <50µm pitch, will continue to compete favorably with flip chip for the high-end packaging market.

Because the bond pitch in quad flat pack and ball grid array packages has not been decreasing as fast as the bond pad pitch on the device, longer wire bonds are needed to provide the fan-out required to connect the bond pads on the chip to the leads on the package (Fig. 1). Longer, thinner wires have greater propagation delay (slower speed), and they are harder to mold without significant yield reductions due to "wire sweep." In addition, copper wire has an advantage over gold wire because it is twice as strong and 30% stiffer for the same diameter. Stronger, stiffer wire is easier to handle and has higher device yield, especially at wire diameters below 25µm.

Not all IC manufacturers will require the three interconnection solutions listed in the table, but virtually all will adopt at least one of them. In any case, copper has different properties from gold, and complete process optimization, encompassing the wire bonder, bonding tools, and bonding wire, will be needed.

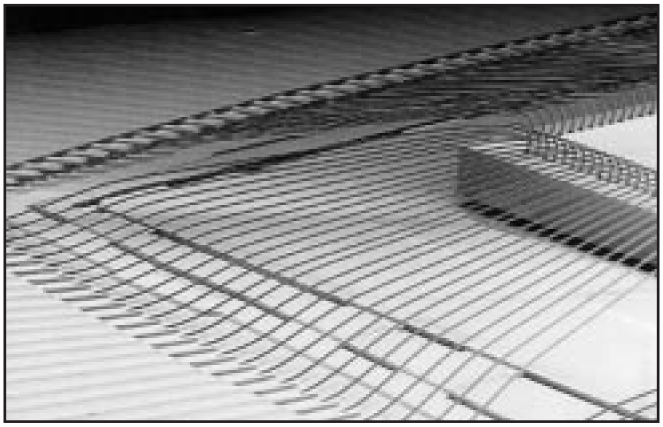

Figure 1. Wire fan-out and length are increasing today because IC bond pad pitch is decreasing faster than package bond pad pitch.

Copper wire to aluminum wafer metallization

Ball bonding of copper wire to aluminum-metallized wafers was evaluated as a method for reducing costs 10 years ago [2–4]. The primary motivation for this effort was the extreme volatility of gold prices at that time, which reached a historic peak above $800/troy ounce, compared to $260–$325 today. The industry standard package type was the 18–40 lead plastic dual in-line package with 150–200µm pad pitch and 100–125µm-bonded ball diameters. Individual wire lengths rarely exceeded 3mm. Therefore, much less gold was being used/package compared to today, so the price of gold was actually not as strong a factor. Compared to Au ball bonding, the industry standard for high yield and high reliability, the Cu ball-bonding process was less robust and the obstacles outweighed the benefits.

Today the parameters in the cost equation have changed. Fine-pitch advanced packages have as many as 500 leads and the wire lengths approach 5mm. The gold value in the wire for a package like this exceeds $0.20, and the potential savings found by replacing the gold are larger. Process enhancements such as a new captured gas electronic flame-off (EFO), oxidation protection processes (OP^2), modulus reduction processes (MRP), improved capillary materials, and new wire alloys all combine to provide a stable, robust, manufacturing process environment. Several subcontractors and captive manufacturers are qualifying copper ball-bonding processes. Figure 2 shows first and second bonds in a Cu ball-bonding process (produced in the Kulicke & Soffa Advanced Materials Development Lab).

Ultrafine-pitch ball bonding is a technology that is finding its way into real products now. As pitch is reduced below 60µm, the diameter of the bonding wire must be reduced to below 25µm [5]. Smaller-diameter wire has lower strength and less stiffness (mechanical resistance to deflection by a force), resulting in more handling difficulties and molding-related defects due to wire sweep [6]. The use of copper wire, with twice the strength and up to 40% higher stiffness than gold wire, alleviates some of the assembly difficulties with <25µm-diameter Au wire. Figure 3

Product drivers and resulting metallurgies for IC interconnection

Driver	Wire	Wafer top metal	Time frame
Cost reduction	Cu	Al	Now
Wafer linewidth	Au	Cu	Mid-2000
Device speed	Cu	Cu	End of 2000

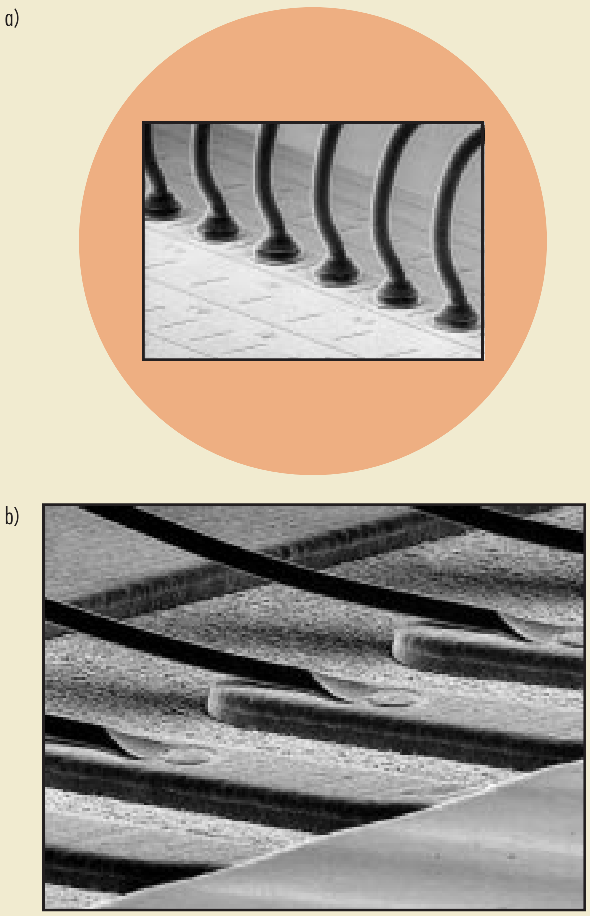

Figure 2. Results of a Cu ball-bonding process: a) first bonds on the IC and b) second bonds on the package

compares relative gold, aluminum, and copper wire strength and stiffness, with 25µm (1 mil) gold wire as a reference.

Finite element modeling of copper ball bonding

Finite element modeling (FEM) of the bonding process has provided new insights into the effects of materials and tool geometry. Comparisons of stress patterns during gold and copper ball deformation reveal that higher levels will be generated in the underlying bond pad during copper ball bonding. Higher stress may result in bond defects, such as cratering and metal lift (delamination between layers in multilayer bond pad structures), that would not occur with gold.

Figure 4 shows a stress map of a gold and copper ball bond. In this mathematical model, more force was required to deform the copper ball to the same height as the gold ball. The copper bond also has a higher stress level, shown by the dark area within the bond pad at the outer edge of the ball. Additionally, extrusion of the pad metallization is significantly higher, and the bond pad is substantially thinner at the center of the ball. The conclusion is that copper's hardness (significantly higher than gold's) requires higher flow stress for deformation. All previous bonding processes considered only bond parameters and adjusted them to achieve equivalent deformation. FEM demonstrates that a new MRP is required to achieve high yields and reliability. Using proprietary ultrasonics, MRP has been shown to increase the peel strength of copper bonds by several grams. Reliability testing of copper ball bonds to aluminum bond pads has been documented [7–9]. Two of the significant outcomes of those studies were: 1) encapsulants with fire retardants designed to eliminate copper corrosion are required, and 2) a protective atmosphere surrounding the wire is also needed as the bonder's EFO unit fires during ball formation.

Gold wire to copper wafer metallization

As pad pitches decrease below 55µm, gold ball bonding could represent the entry-level process for interconnection to copper metallization for many devices because of its wide infrastructure. Gold is a noble metal and does not need a protective atmosphere for ball formation. However, unprotected copper wafer metallization oxidizes readily at normal process temperatures. Special cleaning and protective surface treatments, OP^2, are required to protect the copper from oxidation during the assembly process, including dicing, die attach, thermal cure, and wire bonding.

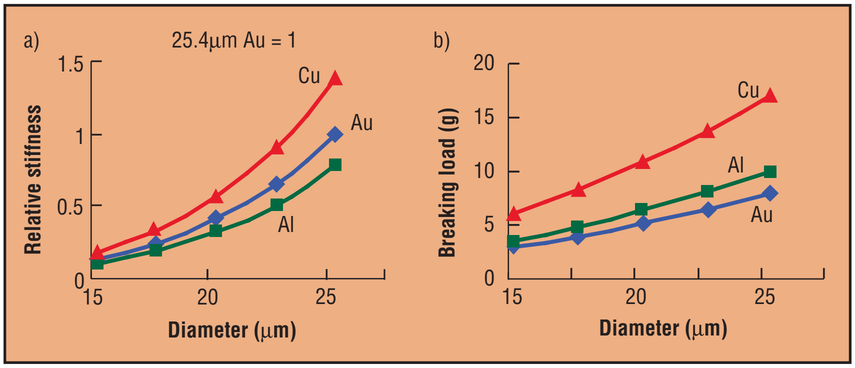

Figure 3. a) Relative stiffness and b) strength of gold, aluminum, and copper wire.

Experiments have shown that the shear strength and ball shape are at the same quality level for gold ball bonds on protected copper metallization as for gold ball bonds on standard aluminum metallization. The diffusion rate for gold-copper is significantly lower than for gold-aluminum, and there is less differential diffusion between species (Au→Cu vs. Cu→Au). This contributes to higher reliability than benchmark Au-Al systems, because there will be less intermetallic formation and less chance of voiding.

Copper wire to copper wafer metallization

Device speed will be the primary driver of copper-to-copper processes. Wedge-bonding processes are already available, and ball-bonding processes should follow by the end of this year.

Wedge bonding has always been at the leading edge in fine-pitch bonding because wedge bonds are narrower than ball bonds. High-frequency ultrasonics enable development of a full-strength wedge bond with a deformation width only 20–30% larger than the wire diameter. In comparison, the ball bond diameter is 50–60% larger than the wire, because the process requires first ball formation and then deformation. In addition, copper wedge bonding is a room temperature process, whereas ball bonding requires an elevated temperature to aid bond formation. Elevated temperatures accelerate oxidation, which can impede bonding. Figure 5 shows copper wedge bonds on copper-metallized mirror die. A primary drawback of wedge bonding is that it is slower than ball bonding, because the additional axis of motion required to rotate the bond head decreases the speed. However, newer wedge bonders have made significant progress in productivity and accuracy, now achieving mass production speeds of up to 6 wires/sec and pitch capability of 50µm.

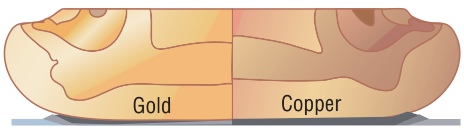

Figure 4. Finite element-modeling output showing stress contours for gold vs. copper ball bonding.

Copper ball bonding to copper wafer metallization is the object of current development efforts. Concurrent development of equipment, materials, and bonding tools will result in a more robust process than individual efforts can achieve. Work so far has identified the requirement for an OP^2, MRP, and captured gas EFO to ensure high-yield, stable, bonding conditions.

Capillary design considerations for bonding to copper wafer metallization are not entirely 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 and the targeted size of the bond [10], and capillary design for copper ball bonding must also meet the same size constraints. However, optimized surface coatings and ceramic materials may be necessary to meet life expectancy requirements because of the additional hardness of copper wire and because of the adhesion of copper to the face of the capillary. Special tool geometries may also be required to further improve the second bond and reduce short tail defects. Recommended bonding wedges for copper wire are tungsten carbide (WC) with a linear cross-groove tip and the smallest (sharpest) possible back radius for proper wire termination. The effect of the cross-groove is shown in Fig. 5.

Wire bonding requires wire with very-high-quality surface finish, spooling, and chemistry standards to achieve the high-yield, trouble-free, manufacturing processes that our industry expects. Copper alloys that meet these requirements have been developed [11].

THE TENACIOUSNESS OF WIRE

The challenge of continued cost containment

The challenge of constant pitch reduction has led to predictions that the move from wire-bonding to flip chip will occur over the next few years. However, wire-bonding technology has constantly surprised the industry by pushing the physical abilities of the equipment further and further. In the past, copper wire had been used to bond low-input/output discrete devices, a result achieved by shrouding with an inert or reducing atmosphere. In the case of plastic ICs, however, concerns about corrosion have been a barrier to acceptance. The next challenge—the replacement of aluminum with copper on the wafer—represents an even bigger hurdle. To keep the cost down, it will be imperative that no additional bondable layers on the copper (such as aluminum) be required.

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Conclusion

Although cost and device speed will play important roles, ultrafine pitch will be the ultimate driver that will force wire diameter reductions and move copper wire bonding into the mainstream. Three alternative wire-bonding solutions have been presented for the emerging copper marketplace. Copper ball bonding to conventional aluminum bond pads reduces costs and provides stronger, stiffer wire for high-yield, fine-pitch packages. Successful copper ball-bonding processes are currently being implemented. Gold ball bonding to copper bond pads will be facilitated by OP^2 and MRP. Processes should be qualified by the middle of this year. Copper wedge and ball bonding directly to copper wafer metallization will provide the finest pitch solutions for totally copper packages. Ball-bonding process qualifications are expected by the end of this year. ■

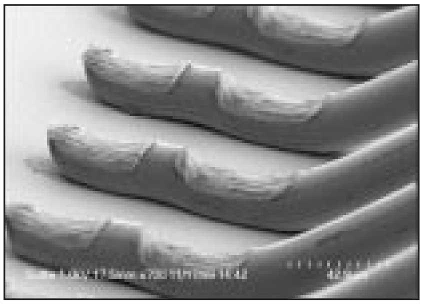

Figure 5. Wedge-bonded copper wires reflect the cross-groove in the tip of the bonding tool that is designed to increase the coupling between the ultrasonic transducer and the wire.

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