ADVANCED PACKAGING'S
Step by Step

step 4

Wire bonding, a low-temperature welding process, continues to dominate semiconductor interconnection. New technologies, such as copper wire and wafer metallization, promise increased flexibility and performance.

Wire bonding

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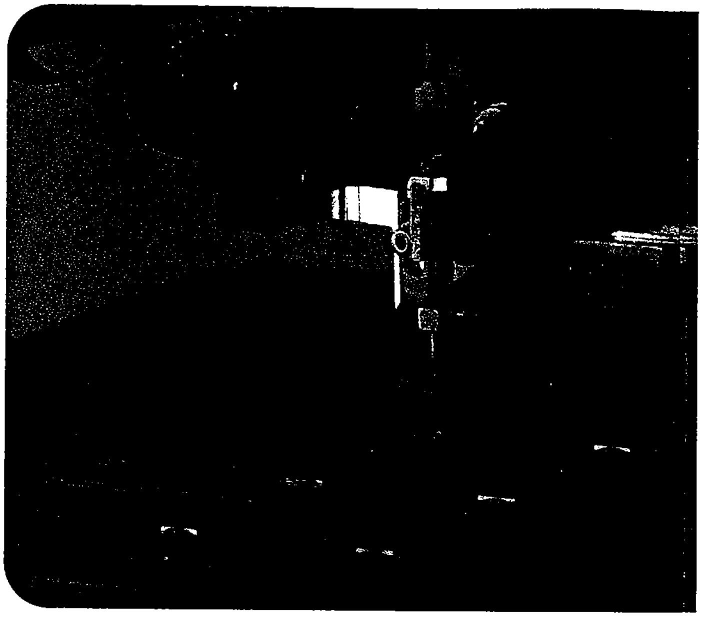

Wire bonding continues to dominate semiconductor interconnection, accounting for more than 90 percent of all leads assembled to packages in 1999. The worldwide lead count for integrated circuit (IC) interconnections is expected to double to more than 9 trillion by 2003.[1]

There are currently two wire-bonding techniques: gold ball bonding, which lays claim to more than 95 percent of the total wire bonded lead count, and gold or aluminum wedge bonding. Applications involving copper ball and wedge bonding are expected to increase as copper wafer metallization becomes more prevalent during the next two years.[2]

The Ultrasonic Bonding Mechanism

In the simplest terms, wire bonding is a low-temperature welding process. Ultrasonic energy, applied through a bonding tool (called a capillary or wedge), increases the dislocation density of the wire and bond site, lowering flow stress and the modulus of elasticity while increasing the rate of diffusion. This allows the material to deform easily at much lower stress than would otherwise be required.[3]

As material flow occurs, microscopic slip planes shear across each other. At the surface, this slipping provides new surfaces that are metallurgically clean. Because these clean surfaces on the bond site and wire are in contact, they diffusion weld to each other. Table 1 lists the stages of ultrasonic welding. Higher ultrasonic frequencies increase the strain rate and enable the material to transfer energy from the bonding tool tip through the wire or ball to the bond interface more efficiently.

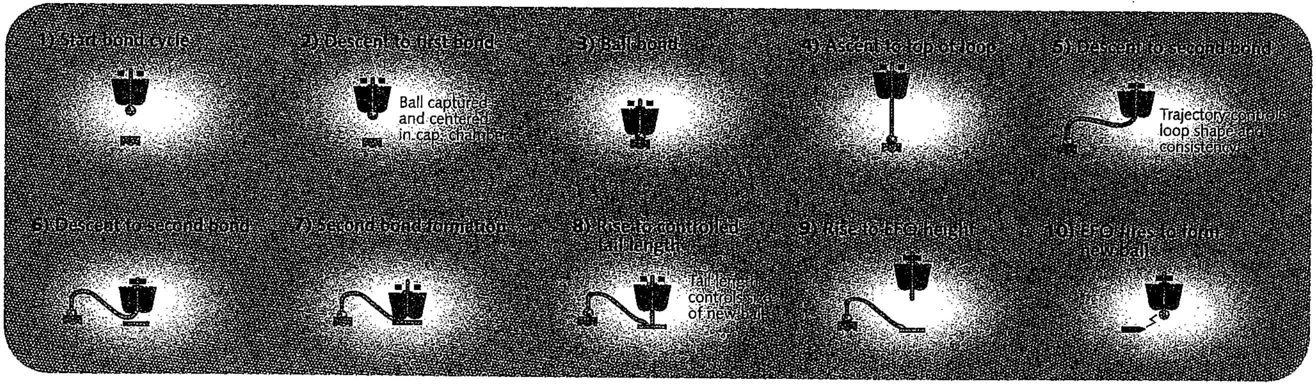

Figure 1. Schematic of the wire, substrate, bonding capillary tip cross section and wire clamps through the important stages of forming a ball bond.

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Wire-bonding Equipment

Modern high-speed, automatic wire-bonding equipment has been continuously developed and refined to meet never-ending requirements for small complex devices for computers, electronics, wireless communications and other products. As a result, pad pitches (the distance between the centers of the pads to which the wires are attached) for leading edge devices have decreased from 100 µm just a few years ago to 60 µm and below today. Concurrently, the number of leads per device has increased to as many as 1,000.

Exponential increases in research and development for wire bonders, bonding tools and bonding wire have been required to keep pace with these demanding requirements. In addition, integration of equipment, tools and materials has become critical to the development of robust mass production processes.[3] Table 2 describes the current state-of-the-art capabilities available in automatic ball and wedge bonders.

Ball Bonding Steps

An advantage of ball bonding is that the round cross-section of the capillary enables bending the wire at any angle radiating from the ball, enabling wire placement at any angle with only X-Y motions. The ball bonding process consists of creation of a first (ball) bond on a pad on the die, followed by a second (wedge) bond on the corresponding package lead to form the electrical circuit between the chip and carrier. It can be broken down into the following ten steps, all of which occur in as little as 80 milliseconds.

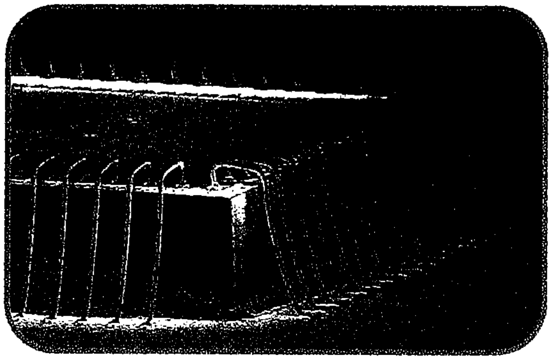

Figure 2. CSP loops created by a ball bonder. Special bends are formed that provide this shape with the second bonds close to the die edge.

Before bonding a package, the bonder's vision system identifies two previously "taught" regions in the pattern of circuitry (eye points) on the top surface of the die. Once the pattern recognition system (PRS) locates the two eye points, the bonder is able to transform the bond locations that were originally taught, correcting them for placement variation in each device. For fine pitch bonding, lead locations are also corrected based on scanning the leads and locating them using the bonder's video lead locator (VLL).

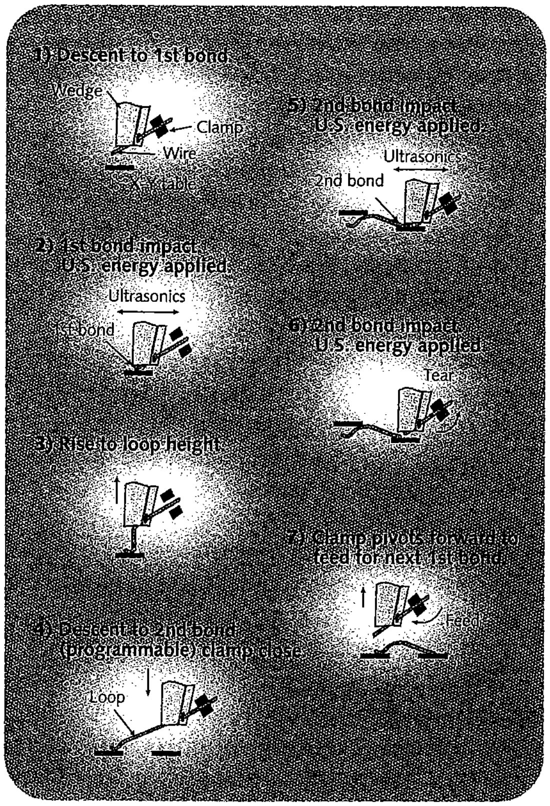

Figure 3. Schematic of 7-step wedge bonding process.

1. The process begins with the capillary and a ball at the end of the wire at reset height. The wire clamps are open, and an air tensioner applies force to seat and center the ball in the conical chamfer of the capillary.

2. The capillary descends to first bond. There are two components to this motion: a high-speed portion and then, close to the work surface, a slower, controlled-velocity descent during which the bonder "senses" contact with the surface. It is not unusual for the height of die or substrate to vary by several mils; therefore, a wire bonder must be capable of sensing touchdown for each bond and cannot rely on previous height data.

3. During creation of the ball bond, ultrasonic energy changes the material properties of the ball and bond pad, allowing easy deformation and bonding.

4. The capillary ascends to the top of the wire loop. Die position variation can change the lengths of each wire within a package. The wire bonder recalculates and adjusts the length of wire required by each loop in the package before it is bonded. During the ascent to top of loop, the required wire length is metered out precisely. At top of loop, the wire clamps close so that no additional wire can enter the loop.

5. During the trajectory, precisely calculated motion algorithms, both on the ascent to top of loop and in descent toward second bond, enable the wire bonder to produce some of the special shapes required by many of today's advanced packages. They include the "worked" loop shape, chip scale package (CSP) loop and ball grid array (BGA) loop.

6. As the bondhead descends, wire protruding from the capillary contacts the surface first. As the capillary continues downward, the wire rolls upward, lifting and shaping the loop near second bond.

7. Two welds are made during second bond formation. First, the capillary face forms and welds a crescent (fishtailed) shape, attaching the wire to the lead. Second, the inner chamfer of the capillary welds the tip of the wire still within the capillary to the substrate (the "tail bond"), providing the attachment that will allow the proper length of wire to be metered for the next ball.

8. With the wire clamps open, the capillary rises from the substrate to the correct height, pulling wire through the capillary to meter the ball volume; this height provides a cylindrical volume of wire equal to the volume required for the programmed ball size for the next first bond. If the tail bond is not welded securely, this volume will either be incorrect or the electronic flame off (EFO) wand will fail to fire. Either case will result in a machine stoppage for a short tail defect.

9. With the wire clamps closed, the bond head ascends toward the EFO fire position, tearing the tail bond from the substrate. The correct volume of wire for formation of a new free air ball (FAB) protrudes from the capillary tip.

10. The EFO fires, melting the wire to form a new FAB for the next bond. EFO wand polarity is negative for modern wire bonders. Negative wands provide better ball size control and longer capillary life because ion flow is away from the ball (capillary) and toward the wand.

Figure 4. 50 μm wedge bond.

Factors in Fine-pitch Ball Bonding

Fine-pitch ball bonding requires more control of all equipment and materials than conventional bonding. Because the bond pads are smaller and closer together, smaller balls are required.

To achieve the required FAB size and then successfully bond these small balls, the equipment must be capable of fine-pitch processing. Some of the required features include a precision EFO, high accuracy Z axis (bondhead motion) controls, high accuracy X and Y axes (delivering 0.1 μm table resolution), and high-resolution dual magnification optics and PRS. Wire-bonder software is capable of precise loop shape control and repeatability, as well as providing the speed and productivity required for high-volume assembly (Figure 2).

Ultra-fine-pitch bonding processes (less than 60 μm pad pitch) require wire thinner than the standard 25 μm diameter, necessitating the use of alternate wire alloys, or copper wire, featuring improved strength to reduce breakage and stiffness to prevent wire sweep during the subsequent molding operation. Precise control of capillary dimensions and tolerances are also becoming critical. These adaptations allow for stable, robust, repeatable processes.

Wedge Bonding Steps

Wedge bonding has always demonstrated leading-edge pad pitch capability, because a full-strength wedge bond can be formed by deforming the wire only 25 to 30 percent beyond its original diameter. By comparison, ball bond deformation results in a bond diameter 60 to 80 percent larger than the original wire. Because the bond is smaller, finer wedge bond pad pitch can be achieved than what is possible with equivalent ball bonds. In addition, for very fine pitch devices, wedge bond device yields are often higher than equivalent ball bonded packages (Figure 4).

New wedge bonding capabilities, such as rotary bondhead motion (theta axis) and advanced loop shapes, have offered increased versatility. These new features enable interconnection of normally configured, inline orthogonal bond pads with radial fan out of the wire, including complex loop shapes, for BGA and CSP applications. Figure 3 shows the steps in a typical wedge bonding process.

1. The bonding tool (wedge), wire and wire clamps descend toward first bond. The wedge has an angled hole through which wire is fed. Clamps are closed during descent to prevent wire from pulling back through the wedge.

2. During first bond formation, ultrasonic energy and bond force are applied by the tool, deforming the wire and welding it to the pad on the die. Aluminum and copper wire are normally bonded at room temperature with wedges made from tungsten carbide. Gold wire is typically bonded at 125 to 150°C with wedges made from titanium carbide.

3. During the rise to the top of loop motion, wire must pay-out through the wedge without damage through the open wire clamps. Wedge polish and funnel shape are critically important to enable smooth pay-out. As the tool begins to wear, surface buildup of wire and contamination results in higher friction and surface damage to the bottom surface of the wire, eventually resulting in bond degradation. Most tools fail as a

Table 1. Stages of bonding

	Frequency	
Stage	60KHz	120KHz
0	Deformation resulting in strain hardening	High strain rate hardening with slight deformation
1	Slip	
2	Couple formation with ultrasonic enhanced diffusion	
3	Bond area increase	

result of buildup and contamination, rather than wear or erosion.

4. The motion control systems and software position the tool over the second bond site, and the wire clamps close as descent begins. As with ball bonding, software algorithms provide special loop trajectories for BGA and radial lead fan-outs.

5. Ultrasonic energy is applied during second bond formation. The back radius of the bonding tool has a significant effect on the location at which the wire will subsequently separate. A sharp radius will provide better control of the fracture location but may cause surface cracks at the heel of first bond, resulting in reduced pull strength. A large radius may not have as good fracture control, resulting in tail length variation at second bond, but better first bond appearance. New linear groove wedges provide the best surface appearance and have good tail length control.

6. Ultrasonic energy application continues as the wire clamps swing back, fracturing the wire at the heel of second bond.

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7. The wire clamps pivot forward, pushing wire back through the hole in the wedge. Bonders are available with several feed angles from low (30°) through high (90°). Each option requires correct clamp setup and a wedge with the correct angle. Low angles offer better wire feed performance, but cannot readily access deep packages, because the wire clamps for low angle setups are closer to the substrate and may interfere with the package. As the wire clamps are adjusted for higher feed angles, there are less interference problems, but wire feed is more difficult and defects because of lost wires are more likely. Special deep access wedge bonders with 60° or 90° feed angles require special options.

Table 2. Wire bonding equipment capabilities

Process	Travel	Speed (wires/sec)	Pitch (μm@ 3 sigma mass production)	Typical applications
Ball	IC (2 x 2.5 in.)	12	60	Ball grid array quad flat package thin small outline package
	Large area (16 x 13 in.)	8	70	Multi-chip modules, hybrids, chip on board wafer level bumping
Wedge	IC (2.5 x 2.5 in.)	6	50	Ball grid array multi-chip modules, devices requiring aluminum wire
	Large area (16 x 13 in.)	6	60	Multi-chip modules, hybrids, chip on board

Factors in Fine-pitch Wedge Bonding

Achieving fine-pitch wedge bonding requires equipment capabilities similar to ball bonding, except an EFO is not used. The same high-resolution vision and PRS capabilities and precise X, Y, Z and theta motions are needed to achieve accuracy and repeatability in bond placement, loop shape control and bond quality, without sacrificing speed and productivity. Ultrasonic frequency of 120kHz is commonly employed for fine-pitch wedge bonding. This higher frequency can achieve full strength bonds at lower temperatures with less deformation (25 to 30 percent of wire diameter) than lower frequency (60kHz) bonders.

Wedges with special narrow ground tips that will not damage adjacent wires have been developed for fine-pitch wedge bonding. Consistent, high-quality wire is required for trouble-free automatic operation. Copper wire is a good alternative to gold or aluminum wire because of its better strength and stiffness.

In conclusion, integrated ball and wedge bonding processes promise to keep pace with increasing device complexity for many years to come. Use of designed experiment methods to optimize specific processes enables engineers to establish stable, robust limits for each environment.

Technology Outlook

The capability to control all process elements and download′ the process "recipes" to multiple wire bonders in production environments is available today. New technologies, including copper wire and wafer metallization, are under development to allow manufacturers to continue achieving milestones in cost per lead, pad pitch and electrical performance, expanding and extending wire bonding's role as the dominant interconnect technology. **AP**

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