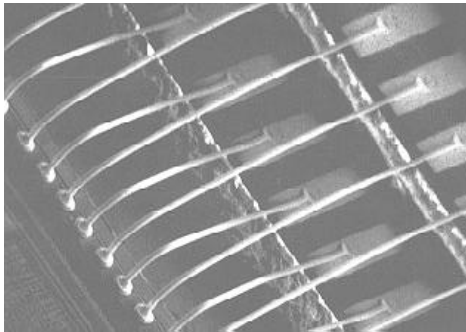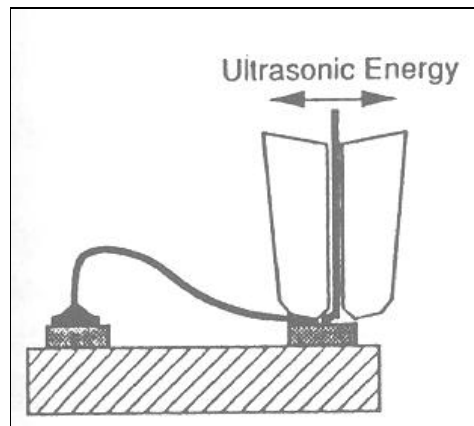# Chapter A: Wire Bonding

2 Level 2. Conclusions and guideline

2.1 Wirebonding techniques

There are two basic wirebonding techniques that are used in thermocompression (T/C), thermosonic (T/S) or ultrasonic (U/S) bonding process: ball bonding and wedge bonding. Approximately 93% of all semiconductor packages are manufactured using ball bonding method, while wedge bonding is used to produce about 5% of all assembled packages.

2.1.1 Ball bonding

In this technique, wire is passed through a hollow capillary, and an electronic-flame-off system (EFO) is used to melt a small portion of the wire extending beneath the capillary. The surface tension of the molten metal from a spherical shape, or ball, as the wire material solidifies. The ball is pressed to the bonding pad on the die with sufficient force to cause plastic deformation and atomic interdiffusion of the wire and the underlying metallization, which ensure the intimate contact between the two metal surfaces and form the first bond (ball bond). The capillary is then raised and repositioned over the second bond site on the substrate, a precisely shaped wire connection called a wire loop is thus created as the wire goes. Deforming the wire against the bonding pad makes the second bond (wedge bond or stitch bond), having a crescent or fishtail shape made by the imprint of the capillary's outer geometry. Then the wire clamp is closed, and the capillary ascends once again, breaking the wire just above the wedge, an exact wire length is left for EFO to form a new ball to begin bonding the next wire. Ball bonding is generally used in thermocompression (T/C) or thermosonic bonding (T/S) process. This technique requires a high 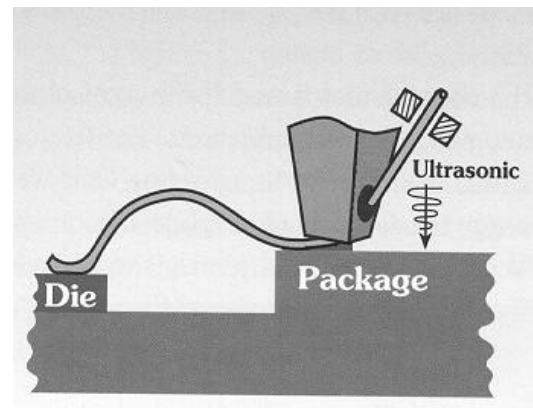temperature raging from 100°C to 500°C depending on bonding process. Heat is generated during the manufacturing process either by a heated capillary feeding the wire or by a heated pedestal on which the assembly is placed or by both depending on the bonding purpose and materials. Relatively small gold wire (< 75 μm) is mostly used in this technique because of its easy deformation under pressure at elevated temperature, its resistance to oxide formation, and its ball formability during a flame-off or electronic discharge cutting process. Ball bonding is generally used in application where the pad pitch is greater than 100 μm. However, the application of the pitches with 50 μm has been reported.

2.1.2 Wedge bonding

Wedge bonding is named based on the shape of its bonding tool. In this technique, the wire is fed at an angle usually 30-60° from the horizontal bonding surface through a hole in the back of a bonding wedge. Normally, forward bonding is preferred, i.e. the first bond is made to the die and the second is made to the substrate. The reason is that it can be far less susceptible to edge shorts between the wire and die. By descending the wedge onto the IC bond pad, the wire is pinned against the pad surface and an U/S or T/S bond is performed. Next, the wedge rises and executes a motion to create a desired loop shape. At the second bond location, the wedge descends, making a second bond. During the loop formation, the movement of the axis of the bonding wedge feed hole must be aligned with the center line of the first bond, so that the wire can be fed freely through the hole in the wedge. Several methods can be used to end the wire after the second bond. For small wires (<75 μm), clamps can be used to break the wire while machine bonding force is maintained on the second bond (clamp tear), or
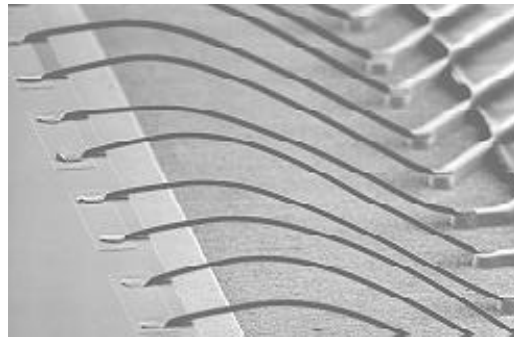
the clamps remains stationary and the bonding tool raises off the second bond to tear the wire (table tear). The clamp tear process offers a slightly higher yield and reliability than the table tear process due to the force maintained on the second bond during the clamp tear motion. The clamp tear process also offers a light speed advantage over the table tear process due to fewer required table motions. However, the table tear process, with a higher wire feed angle capability and stationary clamp, has the potential to provide slightly more clearance from package obstructions such as a bond shelf or pin grid. For large bonding wires (>75 μm), other methods can be used such as a cutting blade or the placement of the wire into a channel in the wedge for wire termination. As the wedge ascends, the clamped wire is fed under it to begin bonding the next wire.

Wedge bonding technique can be used for both aluminum wire and gold wire bonding applications. The principle difference between the two processes is that the aluminum wire is bonded in an ultrasonic bonding process at room temperature, whereas gold wire wedge bonding is performed through a thermosonic bonding process with heating up to 150°C. A considerable advantage of the wedge bonding is that it can be designed and manufactured to very small dimensions, down to 50 μm pitch. However, factors based on machine rotational movements make the overall speed of the process less than thermosonic ball bonding. Aluminum ultrasonic bonding is the most common wedge bonding process because of the low cost and the low working temperature. The main advantage for gold wire wedge bonding is the possibility to avoid the need of hermetic packaging after bonding due to the inert properties of the gold. In addition, a wedge bond will give a smaller footprint than a ball bond, which specially benefits the microwave devices with small pads that require a gold wire junction.

2.2 Wires and typical metallurgical systems

Gold and aluminum are the commonly used wire materials, in addition, copper and silver have also been used. Bonding these wires to different pad materials produces different metallurgical systems.

2.2.1 Wires usually used in wirebonding

Gold wire

Gold wire is used extensively for thermocompression bonding and thermosonic bonding. In producing the gold bonding wires, surface finish and surface cleanliness are the critical issues to ensure the formation of a strong bond and to prevent clogging of bonding capillaries. Pure gold can usually be drawn to produce an adequate breaking strength (ultimate tensile strength of the wire) and proper elongation (ratio of the increase in wire length at rupture to the initial wire length given as a percentage) for use as bond wire. Ultrapure gold is very soft, therefore small amounts of impurities such as 5-10 ppm by weight of Be or 30-100 ppm by weight of Cu are added to make the gold wire workable. Be-doped wire is stronger than Cu-doped wire by about 10-20% under most conditions, thus advantageous for automated thermosonic bonding where high-speed capillary movements generate higher stresses than in slow or manual bonders.

Aluminum wire

Pure aluminum is typically too soft to be drawn into a fine wire. Therefore, aluminum is often alloyed with 1% Si or 1% Mg to provide a strengthening mechanism. At room temperature, 1% silicon exceeds the solubility of silicon in aluminum by a factor of 50, which leads to silicon precipitation. The number and the size of the silicon precipitates are dependent on the cooling rate from higher temperatures. Slower cooling rates result in more precipitation and large nonuniform silicon nodules, while faster cooling rates do not allow sufficient time for silicon precipitation resulting is uniformly dispersed nodules. Silicon grain size can affect wire ductility, the second phase can become a potential nucleation site for fatigue cracks.

Aluminum alloyed with 1% magnesium can be drawn into a fine wire that exhibits a breaking strength similar to that of Al-1% Si. The Al-1% Mg alloy wire bonds satisfactorily and is superior to Al-1% Si in resistance to fatigue failure and to degradation of ultimate strength after exposure to elevated temperatures. These advantages of Al-1% Mg wire occur because the equilibrium solid solubility of Mg in Al is about 2% by weight, and thus at 0.5-1% Mg concentration there is no tendency towards second-phase segregation as is the case with Al-1% Si.

Recently, copper-ball bonding to IC metallization has received considerable attention primarily because of their economy and their resistance to sweep (tendency of the wire to move in the plane perpendicular to its length) during plastic encapsulation. The major problem for this system is the bondability. Copper is harder than gold and aluminum, which can lead to cratering or pushing the metallization aside. Therefore a harder metallization is required. In addition, the ball bonding must be performed in an inert atmosphere as copper oxidizes readily.

2.2.2   Metallurgical systems

In wirebonding process, different pad metallizations are used, depending to the production requirements. Therefore, different metallurgical systems can be formed with different reliability behaviours. The typical metallurgical systems are:

Au-Au system

Gold wire bonded to a gold bond pad is extremely reliable because the bond is not subject to interface corrosion, intermetallic formation, or other bond-degrading conditions. Even a poorly welded gold-gold bond will increase in strength with time and temperature. Gold wire welds best with heat although cold ultrasonic Au-Au wire bonds can be made. Either thermocompression or thermosonic bonds are easily and reliably made. Thermocompression bondability, however, is strongly affected by surface contamination.

Au-Al system

Au-Al welding system is the most commonly used in wirebonding process. However, this bonding system can easily lead to formation of Au-Al intermetallic compounds and associated Kirkendall voids. The formation can be accelerated with the temperature and time of the operational life. There are five intermetallic compounds that are all colored: Au_5Al_2 (tan), Au_4Al (tan), Au_2Al (metallic gray), $AuAl$ (white), and $AuAl_2$ (deep purple). $AuAl_2$ can initially form in the interface between gold and aluminum during bonding process even at room temperature and could transform to other Au-Al compounds depending on the temperature, time and bonding configurations. Therefore, this system often presents a problem in reliability of the bonds.

Au-Cu system

Bonding gold wires to bare copper lead frames can cause the formation of three ductile intermetallic phases (Cu_3Au, $AuCu$, and Au_3Cu) with overall activation energies of 0.8 to 1 eV. The formation of these intermetallic compounds can decrease the bond strength at higher temperatures (200-325°C) as a result of Kirkendall voiding. The degradation is apparently dependent on the microstructure, weld quality, and impurity content of the copper. Cleanliness of the bonding surface is extremely important to ensure good bondability and reliability in Cu-Au systems. In addition, if polymer material is used for die attach, the polymer must be cured in an inert atmosphere to prevent oxidation.

Au-Ag system

The Au-Ag wire bond-system is very reliable for very long times at high temperatures. This bond system does not form intermetallic compounds and does not exhibit interface corrosion. Gold-wire bonds to silver-plated lead frames have been successfully used in high production for many years. Bondability problems can be caused by contaminants like sulfur. Thermosonic Au-Ag bonding is usually performed at high temperature (approximately 250°C) which dissociates thin silver-sulfide films thus increases bondability of silver.

Al-Al system

The aluminum- aluminum wire bond system is extremely reliable because it is not prone to intermetallic formation and corrosion. Aluminum wire on aluminum metallization weds best ultrasonically, although a thermocompression bond can be produced by high deformation.

Al-Ag system

Aluminum wire bonded to a silver-plated lead frame is often used in thick-film hybrids (usually in alloy form with Pt or Pd). The Ag-Al phase diagram is very complex, with many intermetallic phases. Kirkendall voids can occur in this metal system, but typically at temperatures higher than the operating range of the microcircuits. In practice, Ag-Al bonds are seldom used because of their tendency to degrade due to

interdiffusion and to oxidize in the presence of humidity. Chlorine is the main driving element of the corrosion process. Aluminum wires with large diameters are routinely bonded to Pd-Ag thick-film metallization in automotive hybrids. However, the bonding surface must be prepared by washing with solvents, followed by careful resistivity-monitored cleaning in deionized water. Then the hybrids are covered with a silicone gel for further protection.

<u>Al-Ni system</u>

Al-Ni bonds using large diameter, >75 μm, aluminum wires are less prone to Kirkendall voiding and galvanic corrosion, thus more reliable than Al-Ag or Al-Au bonds under various environments. This system has been used in high production on power devices and high-temperature applications such as aircraft turbine blades for over fifteen years. In most cases, the nickel is deposited from electroless boride or sulfamate solutions, which results in reliable bonds. However, phosphide electroless nickel solutions that co-deposit more than 6 or 8% of phosphorous can result in both reliability and bondability problems. The main difficulty encountered when bonding to nickel plating is bondability rather than reliability due to nickel surface oxidation. Thus, packages should be bonded soon after they are Ni-plated, protected in an inert atmosphere, or chemically cleaned before bonding. Changing bonding machine schedules, such as impacting the tool-wire-plating with the ultrasonic energy applied, can improve bondability to slightly oxidized nickel surfaces. Various surface preparation techniques (such as sandblasting) are sometimes applied before or after Ni plating to increase bondability.

<u>Cu-Al system</u>

Copper wire can be bonded to both gold and aluminum substrate. Au-Cu system has been discussed before. For Cu-Al system, there exist five intermetallic compounds favoring the copper-rich side. Thus, there is the possibility of various intermetallic failures similar to those of Au-Al system. However, intermetallic growth in Cu-Al bonds is slower than in Au-Al bonds. The intermetallic growth in Cu-Al bonds does not result in Kirkendall voiding bur lowers the shear strength at 150-200°C due to the growth of a brittle CuAl$_2$ phase. In the temperature range 300-500°C, bond strength significantly decreases with the increase of the total intermetallic thickness. The rate of Cu-Al intermetallic formation relies on the ambient atmosphere composition. For example, the copper-aluminum bond system is adequately reliable as long as some oxygen is present in the package because Cu oxide prevents or inhibits the growth of void-like grooves under the bond. However, the presence of Cl contamination and water can cause corrosion of the aluminum metallization containing copper-aluminum intermetallics.

## 2.3   **Boding equipment**

2.3.1   Wirebonder

Although other connection technologies have gained popularity, wirebonding technique can still maintain its competitive position owing to the massive equipment infrastructure of wirebonding. The bonding equipment is continuously improved by increasing bonding rates, decreasing bond pad pitch, and increasing operation stability. Now, speeds of 4 wires/sec for wedge bonding and 10 wires/second for ball bonding are common, high strength and low variability are achieved and maintained. Many types of analytical equipment are used to monitor wirebonder performance. The bonding location can be accurately determined by vision and positioning systems of the equipment. Fully automated equipment has been manufactured, which is available to measure the impedance of the bonding tool in free air and as the bond is formed. These impedance measurements can be used to maximize the performance of the ultrasonic system and to troubleshoot the system. Another wirebonding equipment feature beneficial to manufacturing is the capability to change quickly from one product to another with minimal tooling and software changes. Software programs for a wide variety of products can be written by the user and stored on disk. A product change can be made in as little as 20 minutes.

2.3.2   Bonding tools

<u>Wedge</u>

Wedge bonding is performed using a wedge-shaped bonding tool. The wire in wedge bonding is addressed at an angle (30° to 60°) through the rear of the wedge. Low angle wire feed style gives best placement control and tail consistency under the bond foot. High angle is only used when absolutely necessary due to high package walls or other tall devices in the bonding vicinity. In the case of high angle wire feed, tail control is less consistent due to the steep feed angle and the action of the clamps. This gives the system a limitation on its access for pads close to deep walled packages. Foot profile of the wedge can be either flat or concave. Most of the automatic aluminum wire applications use concave foot to reduce wire positioning errors. The flat foot is used mainly with gold wire, or with aluminum wire, to obtain extremely short bonds. Recently, a groove foot has been designed for gold wire wedge bonding to improve the wedge-to-wire gripping. The material used for the wedge is dependent on the bonding wire material. For aluminum wire, the wedge is usually made of tungsten carbide or ceramic. The ceramic wedges are relatively new and give improved quality and tool life, however the price is high. For gold wire, the material used is titanium carbide as the gold leaches out the cobalt binder in the tungsten carbide wedge. Tungsten may be used but its life will be greatly reduced. The parameters of the wedge can greatly affect the wirebond characteristics. For the first bond, pull strength is affected by back radius (BR), bond location is influenced by hole size (H), tail length is controlled by feed angle, hole shape and surface quality. The main wedge parameters that affect looping are hole size and shape, as well as feed angle. For the second bond, pull strength is defined mainly by front radius (FR) and bond length, and tail consistency is affected by back radius (BR).
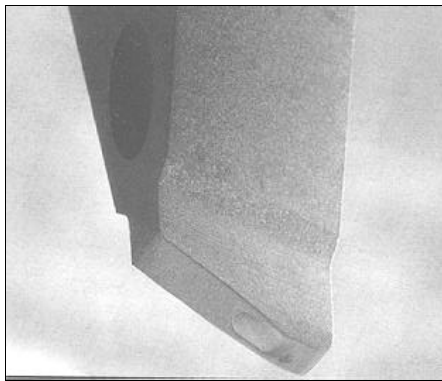

Wedge for Al wire wedge bonding
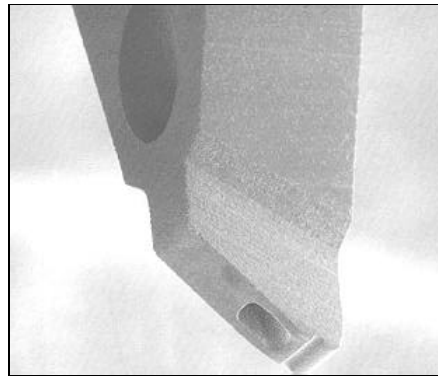
Wedge for Au wire sedge bonding

Capillary

Capillary is used for ball bonding. It can be made from ceramic, tungsten or ruby materials. The most common material for capillaries is high density fine grain alumina ceramic because of its high wear resistance, high oxidation resistance and easy cleaning. A polish finish produces a shiny bond, used when there is good bondability, whereas a matte finish produces a textured stitch bond, which is used when there is less than good bondability. The capillaries are typically 1.585 mm in diameter and 11.1 mm long. They have a large entry hole at the top and then the hole tapers down to a small hole diameter typically between 38-50 μm, depending upon the wire diameter used and the application. At the exit of the small hole, there is normally an inside chamfer (IC) or inside radius (IR). The inside chamfer is designed to seat the ball in the tool and to provide good downward force. A 120° chamfer is designed for poor bondable surfaces by providing more downward force. The disadvantage is that it puts more drag on the wire. A 90° chamfer is designed for easily bondable surfaces giving equal downward and holding forces. There is relatively little drag. The double inside chamfer capillary was introduced to combine the qualities of the 90° and 120° tools. Recently, 70° chamfer is also used for special small ball, fine pitch applications.
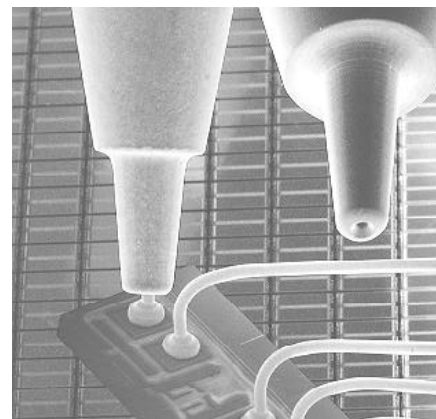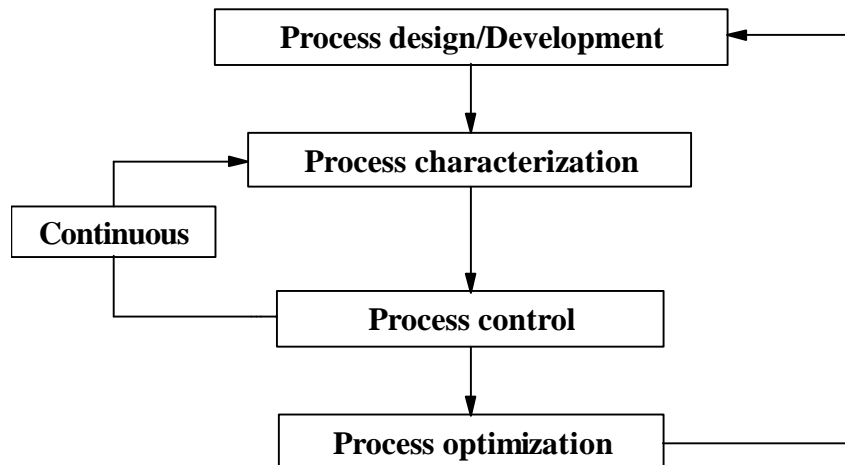

Capillary for ball bonding

2.4 Wirebonding guideline

2.4.1 Process optimization

To develop and improve a production, the key stages generally include initial process design and development, process characterization, process control, as well as process optimization. These stages form a continuous loop between characterization and control, with periodic optimization and development, as shown in the following procedure diagram.

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        ┌─────────────────────────────────┐◄──────────┐
        │    Process design/Development    │           │
        └─────────────────────────────────┘           │
                         │                             │
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        ┌─────────────────────────────────┐           │
   ┌───►│    Process characterization      │           │
   │    └─────────────────────────────────┘           │
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   │            │     Process control       │          │
   └────────────└─────────────────────────┘           │
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                ┌─────────────────────────┐            │
                │   Process optimization   │───────────┘
                └─────────────────────────┘
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Typical wire bond process development flowchart

In the initial stages of the process, process capabilities should be known to set achievable goals. The related information can be obtained from laboratory studies, published literature, as well as from industry and equipment vendor experiences. The second stage (process characterization) is to collect and categorize the data on wirebonding failures such as bond off center, bond not sticking on die, wire breaking and so on. Process control (the third stage) is important for a successful process. To achieve a stable performance, the operating variables such as bond program parameters, machine setup and operation procedures, bonding tool installation, wire pull procedures and product change must be minimized and strict regulation of the existing variables must be established. Consistency across the process, such as in the training of operators also must be established. If the previous stages of process development are in place, process optimization can be performed. Once a process is operating in a production environment, statistical process control (SPC) can be applied to such items as wire pull to monitor the process and to minimize process drift.

2.4.2 Wirebonding design

A good wirebond design can prevent the potential failure mechanisms of wire flexure fatigue, wire-bond-pad shear fatigue, bond-pad-substrate shear fatigue, interdiffusion and Kirkendall voiding, corrosion, dendritic growth, electrical noise, vibration fatigue, resistance change, and bond pad cratering. The inputs for the design process include:

- Chip technology, chip material and thickness.
- Bond pad material, pitch, length, width, and thickness.
- Clock frequency; output high and low voltages.
- Maximum allowable interconnect resistance per unit length.
- Designed-for output capacitive load.
- Transistor conduction channel resistance.
- Maximum allowable interconnect inductance; and mission profile loads.

The process of geometry design of wirebonded interconnects is divided into the design of wire diameter and wire aspect ratio. The minimum allowable wire diameter is based on maximum allowable resistance per unit length. The bond pad dimensions including the length, width, and pitch are used to calculate the maximum for interconnections.

Bonded material selection

Bonded materials include wire and pad metallization. To obtain a good bond, the electrical and mechanical characteristics of the bonded materials must be taken into account. Wire selection includes:

- wire material
- wire diameter
- wire aspect ration from the allowable ranges isolated.

Critical wire material properties include electrical conductivity, shear strength, tensile strength (yield and ultimate), elastic modulus, Poisson's ratio, hardness, and coefficient of thermal expansion. Pad material must be selected to match the wire used. The pad material properties include:

- Conductivity.
- Bondability.
- Activity to form intermetallic phases and Kirkendall voids.
- Hardness.
- Corrosion resistance.
- Coefficient of thermal expansion.

The design is then subjected to a series of checks using physics of failure models to ensure adherence to mission profile requirements. The following is the important points for bonded material selection:

- The wire material must be highly electrically conductive metal so that the signal integrity coming from the on-chip circuitry cannot be deteriorated.
- The wire diameter should not exceed 1/4 of the pad size in case of ball bonds and 1/3 of the pad size in case of wedge bonds. The wirebond size should not exceed 3/4 of the pad size.
- Shear strength and coefficient of thermal expansion of the wire and the bond pad materials are critical material properties. Yield strength, ultimate tensile strength, and endurance limit of the wire should be greater than the stresses produced in the wire during temperature cycling.
- The bonded materials should have interdiffusion constants such that they permit formation of a strong bond while at the same time preventing the formation of excess intermetallics during the expected operational life.
  - Gold-copper bonds should not be used for high-temperature applications.
  - Gold wirebonded to gold is very reliable.
  - Gold bonded to silver is very reliable for very long times at high temperatures.
  - Silver-aluminum bond systems should be used with caution.
  - Silver in bond systems should be used with extreme caution.
  - Aluminum wires bonded to nickel coatings are reliable under various environments.
  - Aluminum wire bonded to aluminum metallization is extremely reliable.
  - Copper wires are preferable during plastic encapsulation because of their economy and their resistance to sweep.
  - Nickel, copper, and chromium should be used with caution on bonding surfaces.
- The bond pad material should be free of impurities to ensure good bondability, Plating bath parameters for depositing the bonding surfaces should be controlled to prevent gas entrapments in the films.
- Wire and bond pad hardness should be reasonably matched. If the wire is harder than the bond pad, it inhibits cratering by absorbing the energy from the bonding process. A wire softer than the bond pad, on the other hand, would readily transmit the energy from the bonding process to the substrate the best bonds are formed when the hardness of the wire and pad were reasonably matched.

Bond design

In bond design, the electrical and mechanical performance of a wire bonded package or module can be optimized if the package designer understands the capabilities and limitations of the wire bond process.

a)   Ball bonding

- Ball size is approximately 2 to 3 times the wire diameter, 1.5 times for small ball applications with fine pitches, and 3 to 4 times for large bond pad application.
- Bond size should not exceed 3/4 of the pad size, about 2.5 to 5 times the wire diameter, depending on the geometry and moving direction of capillary during bonding.

- Loop heights of 150 μm are now common, but very depending on the wire diameter and applications.
- Loop length should be less than 100 times the wire diameter. However, in some cases, high I/Os for instance, wire lengths have to increase to more than 5 mm. The wirebonder must suspend the length of wire between the die and lead frame without vertical sagging or horizontal swaying.

b)   Wedge bonding

- A high-strength wedge bond is possible even the bond is only 2-3 μm wider than wire diameter.
- Pad length must support the long dimension of the wedge bond as well as the tail.
- The pad's long axis should be oriented along the intended wire path.
- Bond pitch must be designed to maintain consistent distance between wires.

Cleaning

To ensure bondability and reliability of wirebond, one of the critical conditions is that the bonding surface must be free of any contaminants. Therefore cleaning is an important work before bonding. The method usually adapted is molecular cleaning method, plasma or UV-ozone cleaning method.

a)   Plasma cleaning

Plasma cleaning technique employs a high power radio-frequency (RF) source to convert gas used into plasma, the high velocity gas ions bombard the bonding surface and sputter off contaminants from bonding surface by combining the contamination molecules, or physically breaking apart the contamination molecules. In most cases, the gas ionized is oxygen, argon, nitrogen, 80%Ar+20%O_2, or 80%O_2+20%Ar. In addition, O_2/N_2 plasma is also used, which can effectively remove epoxy thermal outgas material from bond pads. The optimum results depend not only upon the gas and RF power, but also upon the fixturing, as well as the specific material being cleaned.

b)   Ultraviolet-ozone cleaning

An UV-ozone cleaner is designed to emit significant amounts of radiation of 1849 Å and 2537 Å wavelengths. The organic contaminants are removed with ultraviolet-ozone as follows. The 1849 Å UV energy can break up the O_2 molecule into atomic oxygen (O+O) which combines with other O_2 molecules to form ozone, O_3. Ozone may break up again into atomic oxygen and O_2 with 2537 Å UV. Any water present may also be broken into the OH^- free radical. All of these (OH, O_3, and O) can react with hydrocarbon to form CO_2 + H_2O which leave the bonding surface as a gas. The strong 2537 Å UV may additionally break the chemical bonds of the hydrocarbon, accelerating the oxidation process.

Although both UV-ozone and plasma cleaning method can be used to remove organic contamination from bonding pads, their effectiveness is strongly dependent on the specific contaminant. For example, bondability of the thick-film gold can not be improved by oxygen plasma, possibly due to the oxidation of the bonded elements, such as copper. The best results are obtained with oxygen free argon plasma or solvent cleaning method. In addition, some contaminants, such as Cl^- and F^- may not be removed by any of these cleaning methods because they can become chemically bound. Thus, various solvent techniques including solution, vapor-phase fluorocarbons, ionographic, and DI water, in some cases, are used.

Bonding parameters

Bonding parameters are extremely important because they control the bonding yield and reliability directly. The key variables for wire bonding include:

- Bonding force and pressure uniformity
- Bonding temperature
- Bonding time
- Ultrasonic frequency and power

The optimum conditions are controlled by wire type, pad metallization, and device configurations. Therefore, for every kind of product, a serious of bonding tests has to be performed by varying bonding parameters to draw out the optimum bonding conditions. Evaluation of bond pull strength is used to help the definition. In the evaluation, three sets of curves of bond pull strength versus power, time, or clamping force can be obtained by varying one of these parameters while holding the other two constant at their optimum. Each curve is similar to, and can be related to, the curve of bond pull strength versus wire deformed width. As each parameter is increased, the bond grows stronger in lift off strength. At the same time, due to wire deformation, the transition from the wire into the bond becomes weaker. The failure mode changes from bond failure (lift off) to wire breakage failure. Maximum pull strength is at the intersection of the two failure modes. Lowest reproducibility is within the lift off failure mode and within the breakage failure mode after the deformed width exceeds two times the wire diameter. Highest reproducibility is within the breakage failure mode, directly after, but less than the maximum pull strength. This is the optimum bonding region which, while not at maximum pull strength, produces maximum reproducibility consistent with high bond strength.

Bond pull strength vs. Deformation width or ultrasonic power.
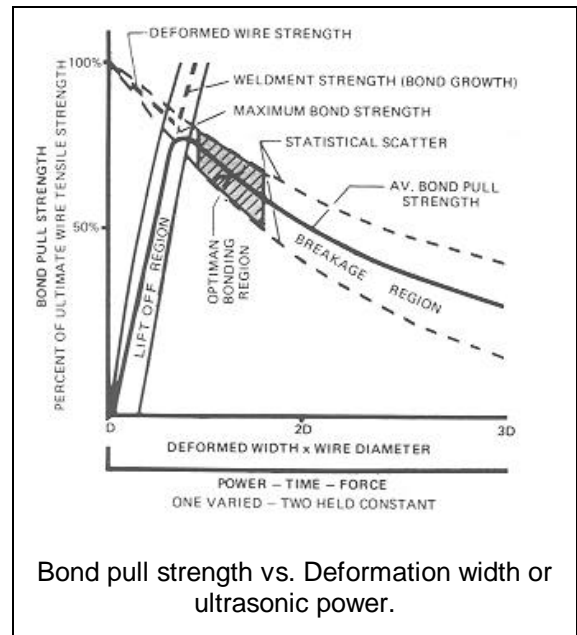
2.4.3   Bond evaluation

After bonding, the wirebond can be evaluated with visual method and mechanical testing, depending on the requirements and the situation that may arise from previous experiences with a particular package or mechanical techniques. Visual method uses optical microscope, scanning electron microscope (SEM), and other analytical instruments to find the undesired bonds. Mechanical testing is employed for the evaluation of bond strength. The wirebond evaluation methods are listed in MIL-STD-833. They include:

- Internal visual (Method 2010; Test condition A and B)
- Delay measurements (Method 3003)
- Destructive bond pull test (Method 2011)
- Nondestructive bond pull test (Method 2023)
- Ball bond shear test
- Constant acceleration (Method 2001; Test condition E)
- Random vibration (Method 2026)
- Mechanical shock (Method 2002)
- Stabilization bake (Method 1008)
- Moisture resistance (Method 1004)

Internal visual (Method 2010: Test condition A and B)

This method is used to check the internal materials, construction, and workmanship of microcircuits in compliance with requirements of the applications. This screen precipitates defects such as improper bond geometries, including deformed ball bonds, small or large ball bonds, golfball bonds, necked ball bonds, ball off the bond pad; deformed wedge bonds with excessive deformation at the heel, or where the bond has damaged the surrounding passivation or semiconductor device circuitry; bonds with excessive large tails touching adjacent bond pads or surrounding metallization; excessive intermetallics; and visible corrosion. Such defects may show up in operational life in the form of interfacial de-adhesion failures, craters, flexure failures in temperature cycling, vibration fatigue failures, electrical shorts, electrical noise, electrical leakage, dendritic growth, or corrosion in presence of contaminants. The test is performed prior to encapsulation to find and eliminate devices with an internal defect, which could lead to device failure in normal application. According to MIL-STD-883 the following defects are not acceptable:

- Voids in the bonding pad or fillet area reduce the metallization path width connecting the bond to the interconnecting metallization to less than 75% of the narrowest entering metallization stripe width.

- Gold ball bonds on the die or package post wherein the ball bond diameter is less than 2 times or greater than 5 times the wire diameter.
- Gold ball bonds where the wire exit is not completely within the periphery of the ball.
- Gold ball bonds where the wire center exit is not within the boundaries of bonding pad.
- Intermetallic formation around the periphery of any gold ball bond.
- Ultrasonic wedge bonds on the die or package post that are less than 1.2 times or more than 3 times the wire diameter in width, or are less than 1.5 times or more than 5 times the wire diameter in length.
- Thermocompression wedge bonds that are less than 1.5 times or more 3 times the wire diameter in width, or are less than 1.5 times or are more 5 times the wire diameter in length.
- Crescent bonds on the die or the package post that are less than 1.2 times or more than 5 times the wire diameter in width, or less than 0.5 times or more than 3 times the wire diameter in length.
- Crescent bonds where the bond impression does not cover the entire width of the wire.
- Bonds where less than 75% of the bond is within the unglassivated bond pad area.
- Wirebond tails that extend or make contact with any unglassivated metallization.
- Wirebond tails that extend more than two wire diameters in length.
- Any wire that comes closer than two wire diameters to unglassivated die area, or the package lid.
- Nicks, bends, cuts crimps, scoring, or neckdown that reduces the wire diameter by more than 25%.

Delay measurements (Method 3003)

This method is to measure the propagation delay of microelectronic devices. The wirebond interconnect should not degrade the pristine waveform coming from the on-die circuitry. Electrical noise in the output, signal distortion, and false triggering can be the result of the defects in the form of increased bond resistance due to improper bonding or precipitation of impurities such as Si (as in Al-1% Si wires) due to improper bonding temperature.

Destructive bond pull test (Method 2011)

Destructive pull test, i.e. bond pull strength test, is the primary method to evaluate the bond strength by hooking and pulling the bonded wire until failure occurs. The purpose of this test is to examine the bond strength and to certify the proper setup of the bonding machine parameters. The results are important evidences for evaluating bonding quality and reliability, as well as understanding bond failure mechanisms including flexure failures, interfacial de-adhesion, cratering, and shear fatigue at bonded interfaces during temperature cycling. Pull strength is strongly dependent upon the geometrical configuration of the pulling test. For absolute values of tensile strength, the pull test should be normalized. The force in each wire with the pull force at hook (F) is represented by

$$F_1 = \frac{F\cos(\theta_2 - \phi)}{\sin(\theta_1 + \theta_2)}$$

$$F_2 = \frac{F\cos(\theta_1 + \phi)}{\sin(\theta_1 + \theta_2)}$$

where ϕ is the pull angle, which is positive when the pull direction is deviated from the bond 1. F_1 is the component of force acting along the wire at the bond 1, F_2 along the wire at the bond 2. θ_1 and θ_2 are the wire angles of the two bonds, which can be easily achieved, based on the hook attachment position, and the hook heights from the two bonds. If both the bonds are at the same level and the hook is applied at the center, the forces can be represented as
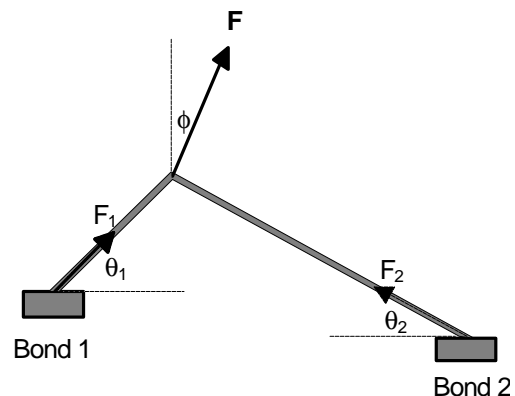
$$F_1 = F_2 = \frac{F}{2\sin\theta}$$

When the both angles are 30°, the pull force is equal to the breakload. The failure during pull test may occur at one of the five positions in the wirebond structure:

A. Lift off first bond
B. Wire break at transition first bond
C. Wire break mid span

D. Wire break at transition second bond
E. Lift off second bond

When properly pulled, the bond should fail at B or D. If failures occur at A, C, or E, then the bonding parameters, metallization, bonding machine, bonding tool, hook, has to be reviewed.

Nondestructive bond pull test (Method 2023)

This test is a variation of the destructive pull test in that the maximum force applied to the bond loop is limited to a predetermined value. It is usually used to detect unacceptable wirebonds while avoiding damage to acceptable wirebonds. The nondestructive pull test force is specified for a given wire diameter and metallurgy. Typical values for 25 μm diameter wire are 2 gf for aluminum and 2.4 gf for gold. Various in-house specifications have ranged from 0.8 gf to 3 gf for the same wire size. However, the specific values do not allow the bonds having different geometries. In addition, the metallurgical characteristics of the wire should also be taken into account.

Shear test

Pull tests are suitable for most applications, however it fails in determining the true strength of ball bonds. The reason is that the ball bonds have a large interfacial welded area in the order of 6-10 times cross-section area of the wire, and the pull test often causes the bonded wire to break at a weak point for instance at the transition above the ball. Thus, little information about the ball bond strength is obtained unless its welded area is less than 10% of its interfacial area. Therefore, to determine the ball bond strength, a shear test is necessary. Also, the shear test is helpful to discover cratering problems not normally uncovered by pull testing.

This test is performed using a shear tool to push off ball bond with a sufficient force. However, cares must be taken to prevent incorrect and misleading data. The factors to influence the test include:

- The improper vertical positioning of the tool, which should approach from 2.5 to 5 μm above the substrate for normally deformed balls and no higher than 13 μm for large, high balls. Otherwise the tool could drag on the substrate.
- Cleanliness of shear tool.
- Friction rewelding for the gold ball on gold metallization during testing.
- Thick-film can cause shear tool to drag across the thick-film surface because they are themselves higher than the vertical position of the tool above the substrate. Even if the positioning of the tool is correct, shear tests made on bonds welded to thick films will yield lower values than expected if the metallization adheres poorly to the substrate.
- Void-free intermetallic compounds formed in Au-Al bonds can trigger exceptionally high shear test values.

The shear test is used mostly for ball bonds, it is not particularly useful for evaluating wedge bonds made from small-diameter wire. The reason is that pull test is very sensitive to the weakening of the bond heel, which increases with wire deformation, whereas shear test is completely independent of the condition of the heel and sensitive to the actual amount of welded area. Thus shear test has a contrary result to pull test. However, large aluminum wedge bonds, such as are used in power devices, can be successfully evaluated with a shear tester.

Temperature cycling (Method 0101; Test Condition C)

The purpose of this test is to determine the electrical performance of wirebond interconnects to exposure to the temperatures alternatively changed. The failure mechanisms addressed by the test include flexure failure of the wire at the heel, bond pad-substrate shear failure, wire-substrate shear failure. Susceptibility to these failure mechanisms may be actuated by excessive neckdown at the heel or excessive embrittlement of the wire during bonding, or poor bond shear strength resulting from surface roughness and the presence of contaminants.

Constant acceleration (Method 2001; Test Condition E)

This test is to find defects such as improper interconnect material for applications subjected to high accelerations of the order of 10000 g loading. Improper hardness of the wire material, or improper stiffness of the wirebond structure in a high-acceleration application such as cannon-launched devices which can result in plastic collapse of the wirebond at high acceleration levels. The failures will be in the form of plastically deformed wires, resulting in shorts to adjacent wirebonds. Constant acceleration test should be

used with caution because high stress levels used in the screen may introduce residual stress, potentially leading to failure in operational life. Sometimes the results of the constant-acceleration test can be more conveniently achieved by subjecting the components to mechanical shock, which is an easier process.

Random vibration (Method 2026)

In this test, wirebond device is rigidly fastened on a vibration platform, and subjected to random frequencies and intensities of vibration. The random vibration aims at detecting the suitability of wirebond interconnects to vibrational loads in operational life. The wirebond interconnects with cracks and brittle intermetallics will fail as a result of thermomechanical fatigue in temperature cycle or vibration. The failures during this screen will be interfacial de-adhesion and delamination failures at the bonded interfaces in wirebonded interconnections.

Mechanical shock (Method 2002)

This test is to certify the suitability of the wirebond geometries and materials for use in electronic equipment that may be subjected to moderately severe shocks as a result of suddenly applied forces or abrupt changes in motion produced by rough handing, transportation, or field operation. Shocks of this type may disturb operating characteristics or cause damage resulting from excessive vibration, particularly if the shock pulses are repetitive.

Moisture resistance

The moisture resistance test is performed to evaluate in an accelerated manner the resistance of the packages to deteriorative effects of high humidity and heat. The failure mechanism addressed by this test is corrosion of the wirebonded assembly. The test certifies the corrosion resistance of the materials in a high-humidity environment.

Stabilization bake (Method 1008)

This test aims at determining the effect on microelectronic devices of storage at high temperatures without electrical stress. These defects may be shown in the form of increased bond resistance, electrical noise, and shear fatigue of the bond in temperature cycling due to increased brittleness of the bonded interface as a result of excessive intermetallic formation. The logic in the approach is that if a bond will not fail under a particular stress level, it will last reasonably long. Some of the correlation results from various investigators are listed in Table 2-1.

Table 2-1. Stabilization bake results.

Time (hours)	Temperature (^{o}C)	Life estimate criteria	Reference
1	390	If the bond is strong after the specified thermal stress, it is acceptable.	Horsting
3000	150	If the bond passes MIL-STD-833, Method 2011, after the specified treatment, it is acceptable.	Ebel
1	300	The bond is acceptable if after the thermal treatment, it has a pull strength of 1 gf for 1 mil wire Au or Al, 0.5 gf for < 1 mil Au or Al wires.	MIL-STD-883 (Method 5008)

2.5   Failure mechanisms of wirebonds

2.5.1   Failure shooting

- A major advantage of wire bonding for microelectronic interconnection is its solid base of reliability from bond strength studies to time and temperature design factors. Many factors, however, may degrade yield and reliability of the wirebonds. Failure shooting can be carried out using a "fishbone diameter" to isolate the errors in wirebonding process . It is then possible to focus problem-solving effort on fewer aspects of the process.

Fishbone diagram
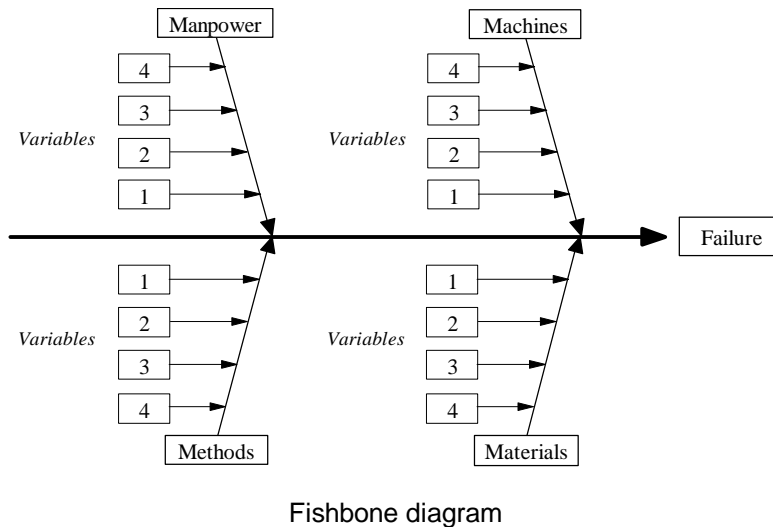
2.5.2   Pad cleanliness

Impurities are a major cause of the loss in the bondability and the reliability of wirebonds. The contaminants that have been found to degrade bonds are shown as following:

- Halogens: plasma etching, epoxy outgassing (dry processing), silox etch, photoresist stripper, solvents (TCA, TCE, chloro-fluro's).
- Contaminants from plating: thallium, brighteners, lead, iron, chromium, copper, nickel, hydrogen.
- Sulfur: packing containers, ambient air, cardboard & paper, rubber bands.
- Miscellaneous organic contaminants: epoxy outgassing, photoresist, general ambient air (poor storage), spittle.
- Others that cause corrosion or inhibit bonding: sodium, chromium, phosphorous, bismuth, cadmium, moisture, glass, vapox, nitride, carbon, silver, copper, tin.

There are many human sources of contamination, such as small particles of skin, hair, sweat, spittle, and mucus. These may arrive at the device surface by talking, coughing, sneezing yawning, head shaking, scratching, etc. A person sitting motionless generates about 10^5 particles per minute of greater than 0.3 μm diameter and up to 50 times more particles while moving. A fully suited person, walking in a class 100 clean room, will distribute 50000 particles in that same period of time. Other sources of contamination may enter the air from drinking water (Cl and Br) or from dry cleaned clothes (tetrachloroethylene).

2.5.3   Bonding failures

Cratering of a wirebond pad

Cratering, typically occurring in ultrasonic bonding, is defined as damage to the semiconductor glass or other layers that lie under the bonding pad metallization. The damage may be in the form of a recognizable divot but more commonly takes the form of invisible structural damage. This damage can degrade the device characteristics and is often is taken for electrical damage. Main causes of cratering are the following:

- High ultrasonic energy can cause stacking faults to occur in the silicon lattice.
- Too high or too low bond force can induce cratering in wedge bonds.
- Excessive tool-to-substrate impact velocity does not induce cratering in silicon but does on weaker crystals such as gallium arsenide.
- Too small a ball can make the hard bonding tool contact the metallization.
- Heavy probing may lead to chip damage under the influence of the applied ultrasonics.
- 1-3 micro thick pads receive minimal damage, < 0.6 micro thick pads are susceptible.
- Best bonds are made when the pad and wire hardness are matched this is also the optimum condition for minimum cratering.

- Harder wire can cause silicon craters during aluminum ultrasonic bonding.

<u>Wire-bond fracture and lift-off</u>

The heel of the bond is already overworked (weakened) during ultrasonic welding, and flex forward and backward is often sufficient to form a crack. Metallurgical crack formation is a critical issue for wirebonding process. The crack often forms in the heel of the first bond of aluminum wedge bonding and the second bond (wedge) of gold ball bonding. The cracks can also form in the heel of a ball bond, due to excessive flexing of the wire during loop formation. One or more of the following reasons can cause cracks:

- Using a sharp heeled bonding tool
- Operator motion of the micropositioner (if a manual bonder is used)
- Bonding machine vibration just before or during bonding tool lift-up from the first bond.
- Excessive bond deformation.
- Too steep an ascent to loop height
- Rapid-tool movement after first bond.
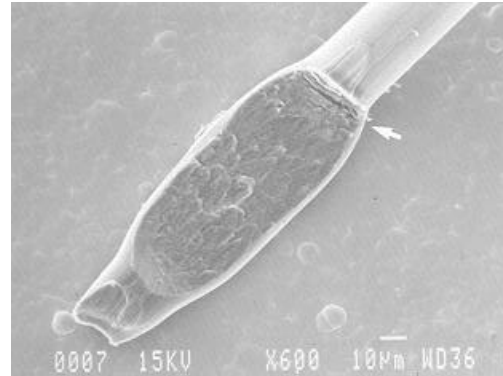
High loops can lead to greater tool motion and an increased probability of heel cracking. The cracks can be enhanced when the second bond is significantly lower than the first, typical of reverse bonding, since the wire is bend backwards more than if bonds are on the same level. Heel cracking can reduce pull strengths by up to 50% and can also lead to premature cycling failures.

<u>Inconsistent tails</u>

This is the most common problem encountered in wedge bonding and one of the most difficult to cure as it can be caused by any of the things listed below.

- Dirty wire path
- Incorrect wire feed angle
- Partially blocked wedge
- Dirty wire clamps
- Incorrect clamp gap
- Incorrect clamp force
- Faulty feed/tear mechanism
- Incorrect wire tension

Too short a tail means that the force on the resulting first bond is distributed over a much smaller area leading to excessive deformation. Too long a tail may lead to shorting between pads.

<u>Peeling bond</u>

Peeling occurs when the bond instead of breaking cleanly at the heel when pulled either partially of fully lifts from the bond surface. Peeling is usually caused by incorrect parameter selection or tool quality degradation. It is a good early warning signal for bond failures and is used as part of statistical real time process control procedures.

2.5.4   Reliability failures

<u>Intermetallic formation</u>

An intermetallic phase is composed of two or more metallic elements. The intermetallic reactions occurring in a wirebond with the time and temperature can result in mechanical and electrical failures of the wirebond. The major reason is attributed to the formation of Kirkendall voids with growth of the intermetallic phases at elevated temperatures. Kirkendall voiding around the periphery can result in a bond mechanically strong but having a high electrical resistance. Kirkendall voiding beneath the bond can cause the bond to fail as a result of mechanical weakness. Intermetallic compounds form in wirebonding process, even possible at room temperature, while Kirkendall voids typically require high temperatures, 1 hour at 300-400°C for Au-Al system, or very long times. Such temperatures and times are seldom reached during modern bonding or modern device and systems packaging. Thus, it is rare that well-made bonds on integrated circuits actually fail due to the formation of intermetallic compounds.
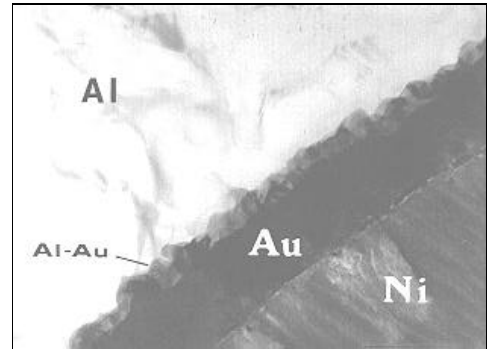
Al-Au intermetallic phase formed after wirebonding at room temperature.

Kirkendall voids are formed by piling up and condensing of the vacancies in the wire bonded structure. There are two sources for the vacancies. The first is the vacancies in the original metal lattices. However, in normal case, these vacancies are not enough to cause serious problems. The second source results from unbalanced diffusion of atoms into and out a same region. Kirkendall voiding can be enhanced by different thermal expansion efficiencies of the components in the wirebond structure and the impurities on bonding surface an in surface metallization. At high temperatures, thermal stress can be produced by the different thermal expansions, thus inducing the formation of microcracks. On subsequent aging, these microcracks can serve as sinks for excess vacancies, until they enlarge to appear as Kirkendall voids. Due to the lower solubility of impurities (surface oxides and contaminants) in intermetallic phases, these impurities can be swept ahead of the intermetallic diffusion front, and precipitated there, acting as sinks for vacancies produced by the diffusion reaction and resulting in Kirkendall-like voids.

Wire flexure fatigue

Wirebond interconnects can fail as a result of metallurgical cracks in the heel. The sharp metallurgical microcracks can propagate through the wire and cause failure during device operating life when temperature changes cause the wire to expand and contract. Flexure of the wire in bonding process can produce stress reversal at the heel of the bond in wedge bonds and stitch bonds, and causes eventual fatigue failure of the wire. In addition, the failures can occur under temperature cycling due to repeated wire flexing resulting from different coefficients of thermal expansion between the bonded wire and the header as the device heated up and cooled down. The maximum flexure and therefore the failure occurs at the thinned bond heels. Concerning with the fatigue, it was found:

- Aluminum ultrasonic bonds were more reliable under temperature cycling conditions than aluminum thermocompression bonds.
- Aluminum wire with 0.1% magnesium was superior to that of the commonly used aluminum-1% silicon alloy.
- Loop height should be at least 25% of the bond-to-bond spacing to minimize the bond flexure.

Wirebond lift-off

During bonding, a wire can break at the neck of a wirebond, leading to an electrical open. Thallium, a major source of wirebond neck failures, forms a low-melting eutectic with gold and can transferred to gold wires from gold-plated leadframes during crescent-bond break-off. Thallium diffuses rapidly during bond formation and concentrates over grain boundaries above the neck of the ball, where it forms a eutectic. During plastic encapsulation or temperature cycling, the neck breaks and the device fails. Ball-bond fracture causes bond lift-off. The fracture can be flow of encapsulant during molding. The latter, also known as wire wash, happens only sporadically; when it does, however, it signals a molding compound that has expired or been improperly conditioned. Generally, bond strength is more a function of temperature cycling than of steady-state temperatures between -55°C and 125°C, although bond strength decreases as a function of temperature above 150°C for gold-aluminum bonds and above 300°C for gold-copper bonds.

Wirebond and bond-pad corrosion

Corrosion can open one end or both ends of the wire completely, permitting the wire to move within the package volume and causing electrical short circuits. The corrosion occurs in the presence of moisture and contaminants. For example, the presence of chlorine or bromine at bonding place can cause the formation of chlorides or bromides, leading to bond corrosion. Bond corrosion increases the electrical resistance of the wirebond interconnect until the device becomes nonfunctional. In most cases, the molding compound exerts a compressive force on the die surface and the adjacent wirebonds, and interconnection problems are not revealed until expensive corrosion has occurred.

Leadframes corrosion

Leadframe corrosion can be caused when high residual stresses and high surface contamination are induced by surface plating (Ni for example) to protect the base metal (usually alloy 42 or copper) from corrosion. During assembly and handling, the lead fingers are bent; cracks can develop and expose any corrodible surface to the external environment. Stress-corrosion-induced cracking can also occur, especially in alloy 42 leads. In the presence of moisture and contaminants, corrosion can be initiated by cracks or voids in the plating. The rate of galvanic corrosion can be high, because the lead finish is often a cathodic metal with respect to the lead base material. The most sensitive area is at the interface between the molding compound and the leadframe.

Metal migration

Metal dendrite growth from the wire bond pads of an integrated circuit is one of the failure mechanisms. This is essentially an electrolytic process that metal ions from the anode region migrates to the cathodic areas, governed by availability of metal, presence of condensed water and ionic species, and the existence of a voltage differential. The metal migration phenomenon leads to an increase in leakage current between the bridged regions or causes a short if complete bridging forms (migrative resistance shorts, MGRS). Silver migration has been most widely reported. In addition, depending on environmental conditions, many other metals like Pb, Sn, Ni, Au, and Cu have been found to undergo migration. Being a time-dependent phenomenon, this is a wearout mechanism.

Vibration fatigue

Vibration forces are seldom severe enough to cause metallurgical fatigue or other bond damage. However, large components of assembled systems can fail before such forces are sufficient to damage the bonds. The minimum frequency that might induce resonance and thus damage wirebonds is in the range 3-5 kHz for gold bonds and 10 kHz for most aluminum wirebond geometries. In general, the wirebond failure due to vibration fatigue occurs during ultrasonic cleaning, therefore, the ultrasonic cleaners with resonant frequencies ranging 20-100 kHz are recommended.

Wire sweep

Wire sweep usually denotes visible wire deformation, typically a lateral movement in the direction of the compound flow through the cavity. Reliability concerns with sweep include device shorting and current leakage. Shorting can be from wire to wire, from wire to lead finger, or from wire to die edge. Failure can be immediate or may not show up until the package experiences stress excursions. Wire sweep can occur from any one of a number of causes: high resin viscosity, high flow velocity, unbalanced flows in the cavities, void transport, late packing, and filler collision.

Electrical noise

Electrical leakage failure is the result of poor insulation from the Si substrate, due to the lack of a multilayer oxide (MLO) layer underneath the bond pad. Bonds with no visible evidence of damage or mechanical weakness may have intermittent electrical leakage, especially in devices with an MLO-free bond pad. Failure analysis of these leakage failures should show that there were no cracks on pads using the same bonding conditions.