Wire Bond / Ball Shear Application Note

DLI•Novacap•Syfer•Voltronics

Wirebonding

What is wirebonding

Wirebonding is an electrical interconnection technique using thin wire and a combination of heat, pressure and/or ultrasonic energy. Wire bonding is a solid phase welding process, where the two metallic materials (wire and pad surface) are brought into intimate contact. Once the surfaces are in intimate contact, electron sharing or interdiffusion of atoms takes place, resulting in the formation of wirebond. In wirebonding process, bonding force can lead to material deformation, breaking up contamination layer and smoothing out surface asperity, which can be enhanced by the application of ultrasonic energy. Heat can accelerate Interatomic diffusion, thus the bond formation.

Wirebonding processes

Wirebonding process begins by firmly attaching the backside of a chip to a chip carrier using either an organic conductive adhesive or a solder (Die Attach). The wires then are welded using a special bonding tool (capillary or wedge). Depending on bonding agent (heat and ultrasonic energy), the bonding process can be defined to three major processes: thermocompression bonding (T/C), ultrasonic bonding (U/S), and thermosonic bonding (T/S), as shown in Table 1-1.

Table 1-1. Three wirebonding processes

Wirebonding	Pressure	Temperature	Ultrasonic energy	Wire
Thermocompression	High	300-500˚C	No	Au
Ultrasonic	Low	25˚C	Yes	Au, Al
Thermosonic	Low	100-150˚C*	Yes	Au

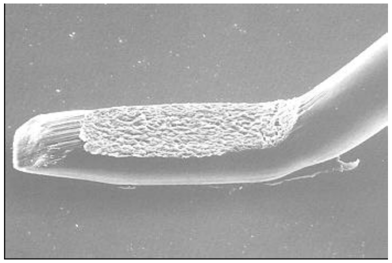
* DLI Thermosonic temperature 100-240˚C

Wirebonding

Wire bond forms

There are two basic forms of wire bond: ball bond and wedge bond, the corresponding bonding technique, bonding tool and materials are listed in Table 1-2. Currently, thermosonic gold ball bonding is the most widely used bonding technique, primarily because it is faster than ultrasonic aluminum bonding. Once the ball bond is made on the device, the wire may be moved in any direction without stress on the wire, which greatly facilitates automatic wire bonding, as the movement need only be in the *x* and *y* directions.

Ball bond



Wedge bond

Table 1-2. Wire bond formation

Wirebond	Bonding technique	Bonding tool	Wire	Pad	Speed
Ball bond	T/C, T/S	Capillary	Au	Al, Au	10 wires/sec (T/S)
Wedge bond	T/S, U/S	Wedge	Au, Al	Al, Au	4 wires/sec

Wirebonding

Wirebond evaluation

Wirebonding evaluation criteria varies depending on the application requirements. Evaluation methods can be found in several published standards, but the most common standard is MIL-STD-883. It lists the following methods:

- Internal visual
- Destructive bond pull test
- Nondestructive bond pull test
- Ball bond shear test
- Constant acceleration
- Random vibration
- Mechanical shock
- Stabilization bake
- Moisture resistance

Typical Failure Mechanisms

Common failures are:

- Cratering or peeling of a wirebond pad
- Wirebond fracture (leading to weak bonds or bond lifts)
- Inconsistent tails (which cause shorting with other bonds or traces on the surrounding circuitry)
- Poor welding (leading to weak bonds)
- Improper positioning on the bond pad (leading to shorts and bad welds)

Common wirebonding related failure mechanisms:

- ***Ball Bond Lifting*** - detachment of the ball bond from the silicon chip; also refers to non-sticking of the ball bond to the bond pad.

  Common causes:
  - Contamination on the bond pad
  - Incorrect wirebond parameter settings
  - Bond pad corrosion
  - Excessive bond pad probing
  - Bond pad metallization/ barrier metallization lifting
  - Cratering

- ***Ball Bond Neck break*** – breakage of the wire at the neck of the Au ball bond.

  Common causes:
  - Incorrect wirebond parameter settings
  - Incorrect wire looping

- ***Cratering*** – Cratering is commonly attributed to “overbonding”, damage appears under the bonding pad. In severe cases, a hole is left in the substrate and a divot is attached to the bonding wire.

  Common causes:
  - Incorrect wirebond parameter settings
  - Excessive bond pad probing

Reprinted from The Nordic Electronics Packaging Guideline: Wire bonding: Introduction of Wirebonding technology

Wirebonding

Like soldering, the wire bonding process is complex and requires a thorough understanding of the metallurgy, thermodynamics, and surface chemistry involved. A characterization of the significant differences between a supplier with superior bonds and suppliers with normal bonding quality was made in an attempt to understand the reasons for differences in bond failure rates. This characterization evaluated the following:

- Shape and size of the ball bond
- Form of the wire loop
- Bond position on bond pad
- Die bonding technique
- Device metallization
- Metallurgical characteristics of the ball bond.

Evaluation showed several interesting facts:

1. The shape of the ball bond, a larger ball diameter provided a significantly larger bond area and a potentially stronger bond.
2. The loop of the bond wires, which is very important in preventing shorting between the bond wire and the edge of the chip.
3. The location of the wire bond on the bond pad is obviously extremely important and the best suppliers maintained very good control on bond positioning.
4. Cross sections of the poorer quality bonds showed a spotty to non-existent intermetallic layer.

Wirebonding

Several methods are employed to evaluate and ensure the integrity of the wire bond process.

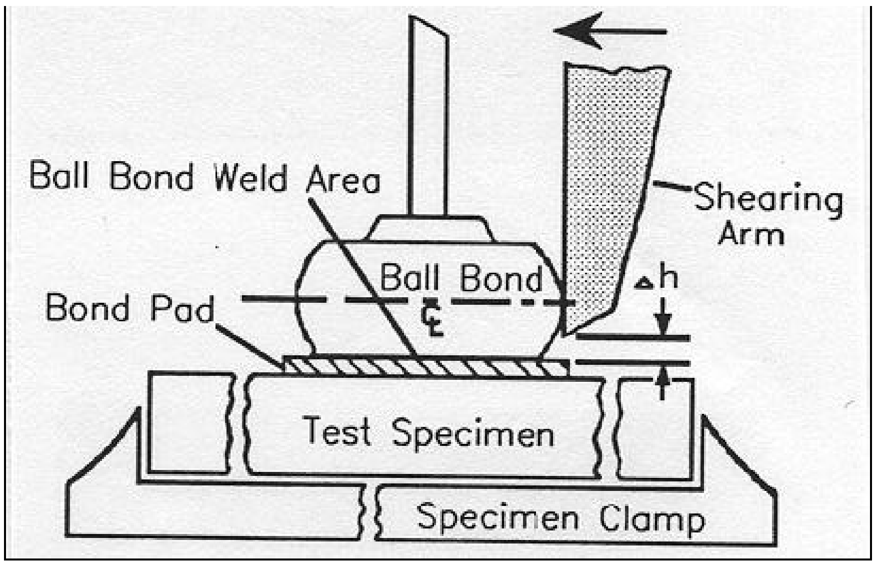
1. Visual Inspection
   Visual techniques are used to ensure the proper ball and wedge bonds have been formed. Visual inspection also verifies the bonds are properly placed with respect to the bond pads & Bond Fingers of the leadframe/substrate.

2. Pull Test
   The wire pull test is used to measure the strength and failure mode of the wire bond. Generally, if the hook is placed at the mid span of the wire, then the test will show the weakest link of the bond. This is typically either the neck of the ball bond (right above the ball) or at the heel of the wedge bond. Pull Test is a destructive test & it's a Statistical Process Control monitor at all of National Semiconductors' Assembly sites.

2. Ball Shear Test
   Ball shear test is another method for evaluating the quality of a ball bond. The bond strength and failure mode are measures of the ball bond quality. Ball Shear Data reflects the intermetalic formation & its coverage of the bonds.

Wirebonding / Ball Shear

The wire pull test (with the limited stress it could apply to the joint) could not provide enough information about the true strength of the bond. Wire pull testing of bonds with a strength of greater than 12 to 15 grams just measure the strength of the bond wire. Cross sectioning has confirmed the effectiveness of ball shear in determining the presence of a uniform intermetallic in the bond.



- Bonds with a uniform intermetallic formation had a stronger bond shear strength than bonds with spotty or non-uniform intermetallic.
- Wire pull testing does not assure that wire bonds are high quality and will be reliable.
- Ball shear testing appears to provide a true indication of bond strength and can be used as a reliable method for developing bond schedules.

Wire bonding

The Ball Bonding Process

Ball bonding is the process in which pads are connected onto a die and leadframe (or substrate) using very fine diameter wire. The basic steps of ball bonding include the formation of: the first bond (normally on the chip), the wire loop, and the second bond (normally on the substrate). The wire-bonding cycle is shown in Figure 1.

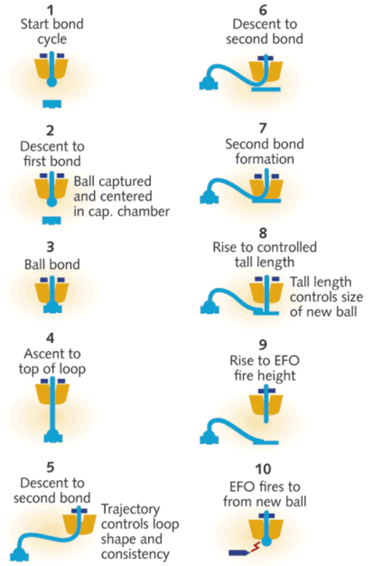


Figure 1. *Ball bonding steps.*

At the beginning of the wire cycle, the bonding tool travels down to the first bond location (Steps 1 and 2). The first bond is achieved by bonding a spherical ball to the pad using thermal and ultrasonic energy (Step 3). The initial bond is also referred to as the ball bond. Looping motions are programmed to meet the package requirement for loop height and shape (Steps 4, 5, and 6).

The second bond consists of a stitch bond that bonds the opposite end of the wire and a tail bond (Step 7). The tail bond is needed to form a wire tail for the next ball formation. After the bonding tool rises to pay out the wire tail, the tail is broken off and the bonding tool rises up to the ball formation height (Steps 8, 9, and 10). The ball formation process is achieved by ionization of the air gap in a process called “electronic flame-off” (EFO). The resulting ball is known as a “free air ball” (FAB).

Wirebonding

Wire Bonding Material

Wire bonding materials used in a ball bonding process mainly include the bonding wire and bonding tool. Ball bonding tools are called capillaries, which are axial-symmetric ceramic tools with vertical feed holes. Figure 2 shows an example of a capillary used in fine-pitch applications. The tool's tip is shaped to give the clearance needed in fine-pitch bonding.

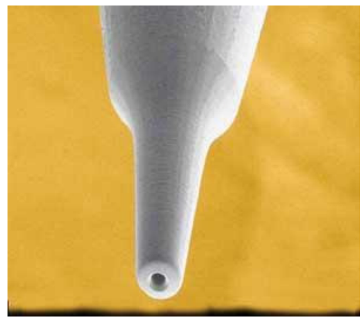


Figure 2. *Wire bonding tools.*

Figure 3 outlines the critical dimensions of a capillary, which include the tip diameter (T), angle of the bottom face (FA), outside radius (OR), hole diameter (H), and chamfer diameter (CD). The tip usually is determined by an application's pitch. FA and OR affect mainly second bond, while the hole and chamfer diameters affect both the first and tail bond formations. These are the most critical dimensions of a capillary.

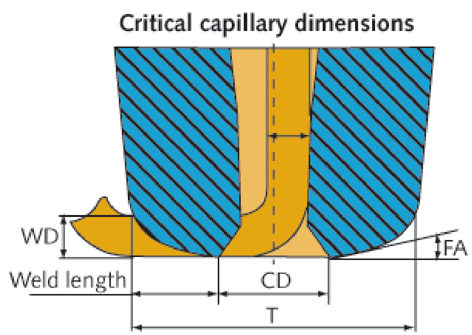


Figure 3. *Critical capillary dimensions.*

Wirebonding

Most bonding wire used in ball bonding is gold (Au) wire of 99.99% purity, which is often referred to as 4Ns wire. Alloy wires (99.99% or less purity) are sometimes used to meet special application requirements, such as high wire strength. Studies have shown that certain dopant (impurity in the wire) can slow Au-Al intermetallic growth. 3Ns and 2Ns wires are sometimes considered to improve device reliability

A special consideration for bonding wire is its heat-affected zone length, which is related to the recrystallization process due to the heat from EFO. The heat-affect zone often weakens the wire. A longer heat-affect zone in the wire often results in higher loop height. Some low-loop applications require high strength and a low heat-affected zone, as shown in Figure 4.

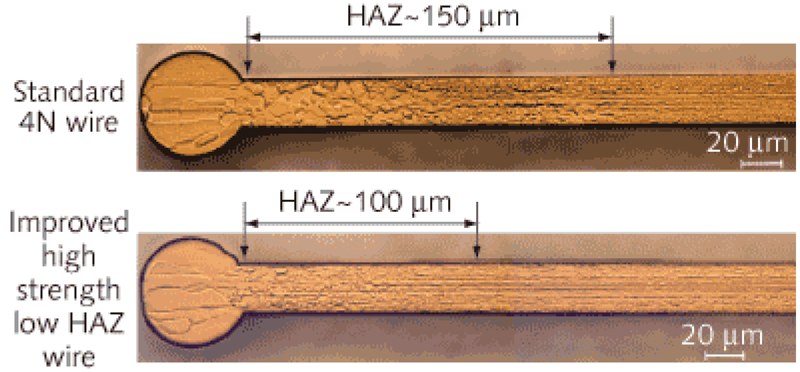


Figure 5. *Forward ball bonding loops in stacked die applications.*

Copper (Cu) wires can be bonded with some modifications to the wire bonder. The modifications mainly consist of using a forming gas environment to prevent Cu oxidation during the free air ball formation. Both Au and Cu bonding are done at an elevated temperature (normally 150˚ to 240˚C, depending on the device). This process is called thermosonic bonding because of the use of heat and ultrasonic energy.

Wirebonding

Wire Bonding Process

The critical steps in the wire bonding process include achieving reliable bonds (first bond, second bond, and tail bonds), maintaining desired loops, and positioning the bonds accurately. Throughput also is an important factor, since it affects the cost of the device.

Achieving desired first and second bonds usually requires optimizing bonding parameters. A design of experiment (DOE) can be done to optimize these parameters, which would include impact force, bonding force, and ultrasonic energy levels. A proper free air ball size normally is determined before starting a first-bond DOE. Looping trajectories are selected according to the application requirements. There are two basic types of loops: forward and reverse. A forward looping process places a ball bond on the die first, then places a stitch bond on the lead, as shown in Figure 1. A reverse ball bonding process, however, places a bump on the die pad first. After the bump is formed, a ball bond is placed on the substrate, followed by a stitch bond on the bump (Figure 5). Low-profile looping requirements have propelled the growing use of reverse ball bonding, which is a slower process than forward bonding.

Figure 5. *Forward ball bonding loops in stacked die applications.*

Leading Wire Bonding Applications

The most advanced wire bonding applications include: ultra-fine pitch (<60-µm pitch), stacked die, and multi-tier applications. These advanced applications often require more process optimization, as well as higher requirements for bonding material and equipment.

Wire bonding

Fine-pitch Applications. Wire bonding fine-pitch capability has been demonstrated in the laboratory at 35-µm inline pitch. For 35-µm pitch ball bonding, 15-µm wire typically is used with a bonded ball diameter of 27 µm.

Fine-pitch applications demand a higher capability of the wire bonder, including better control of the bonding force, ultrasonic energy level, as well as a looping capability of fine wires, which has much less strength and is more inclined to loop sway. A wire bonder that meets the demands of fine pitch should also include high-precision motion and a vision system with submicron accuracy.

Stacked Die Applications. Stacked die applications are one of the fastest-growing trends in the semiconductor industry. The desire for smaller, lighter, and smarter devices is driving this 3-D packaging technology. Stacked die applications present various wire bonding challenges, including low-loop and multi-level wire bonding loop clearance requirements, bonding to overhang unsupported die edges, and loop resistance to wire sweep during molding.

Most wire bonding applications use the typical forward bonding process, because it is faster and more capable of finer pitch than reverse bonding. However, forward ball bonding has a loop height constraint due to the neck area above the ball. Excessive bending above the ball can cause neck cracks, which results in reliability problems. Reverse bonding can achieve loop height lower than 75 µm (Figure 6).

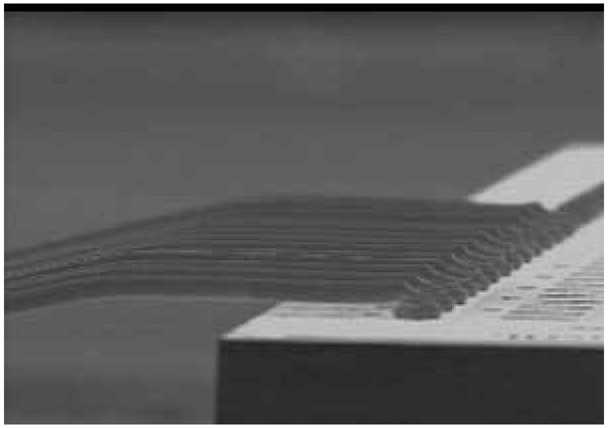


Figure 6. *Reverse ball bonding loops.*

Failure Mechanisms of Wire bonds

Failure Mechanisms of wire bonds

- **Pad cleanliness**
  - Impurities are a major cause of the loss in the bondability and the reliability of wire bonds. 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 105 particles per minute of greater than 0.3 mm 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).

- **Bonding failures / Cratering of a wire bond 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:
    - 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.

Wire bonding

Failure Mechanisms of wire bonds (continued)

- **Wire bond lift off**
  - During bonding, a wire can break at the neck of a wirebond, leading to an electrical open. Thallium, a major source of wire bond neck failures, forms a low-melting eutectic with gold and can be transferred to gold wires from gold-plated lead frames 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 -55oC and 125oC, although bond strength decreases as a function of temperature above 150˚C for gold-aluminum bonds and above 300˚C for gold-copper bonds.
    - **Bond lifting** refers to any of several phenomena in which a wire bond that connects the device to the outside world becomes detached from its position, resulting in loss or degradation of electrical and mechanical connection between that bond and its bonding site.
    - In this context, a bond may be one that attaches to a bond pad of the die (also referred to as the first bond) or one that attaches to a lead or post of the package (also referred to as the second bond). First bonds are usually in the form of gold ball bonds or aluminum wedge bonds, while second bonds are usually gold or aluminum crescent bonds (also known as 'fishtail' bonds).
    - **Ball Bond lifting** or simply **ball lifting**, is the detachment of a ball bond from the bond pad of a semiconductor device. It can be due to a variety of factors. Poor wire bond equipment set-up and bond pad surface contamination are primary causes of ball lifting. Poor set-up includes improper wirebond parameter settings, unstable workpiece holders, and worn-out wirebonding tools. These result in poor initial welding and inadequate intermetallic formation between the bond pad and the ball.
    - Ball lifting can also be due to contaminants on the bond pad, which act as barriers between the ball and the bond pad. Common contaminants that inhibit good bonding include unetched glass, unremoved photoresist, and Si saw dust. Resin bleed-out from the die attach material can also impede good bonding and result in ball lifting. Halides such as Cl on the bond pad can trigger corrosion, which is again another source of ball lifting.

Wire bonding

Failure Mechanisms of wire bonds (continued)

A disturbed or uneven bond pad surface also inhibits bonding. Excessive probe digging results in aluminum heaps and an exposed substrate or barrier metal area, which prevent good intermetallic formation. Silicon nodules on the surface of bond pads can also result in poor ball bonding.

Fig 1. Photo of a lifted ball bond

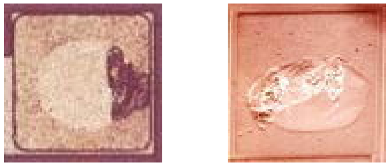


Fig 2. Photos of bond pads w/ contamination that prevented good intermetallics and led to ball lifting

Lifted balls may also result from excessive interdiffusion between the bond pad and ball bond metals. Kirkendall voiding, which is the formation of voids underneath the ball bond due to excessive diffusion of Al from the bond pad to the Au ball bond to form purple plague, is an example of this mechanism. The reflow of thermoplastic die attach material at the bonding temperature also results in ball lifting, because it allows movement of the die during the thermosonic bonding itself.

Cratering, which is considered to be a different failure mechanism, can also manifest as a lifted ball, with the Si underneath the bond pad coming off with the bond. Excessive probing and overbonding are common causes of cratering. Similarly, bond pad peel-off, or the mechanism wherein the bond pad metal peels off from the barrier metal or substrate, can result in ball lifting.

Fig 3. Photo of a bond pad crater

Fig 4. Photo of a bond pad metal peel-off that led to ball lifting

This Application Note includes excerpts from the following:

- *The Nordic Electronics Packaging Guideline: Wire bonding: Introduction of Wirebonding technology*
- *Advanced Packaging July, 2005 Author: Ivy Wei Qin Ph.D.*
- *National Semiconductor, Semiconductor Packaging Assembly Technology, August 1999*
- *Siliconfareast.com: bondlifting*