Bonding to the Chip Face

‘Wire bonding’ is used throughout the microelectronics industry for interconnecting dice, substrates and output pins. Fine wires, generally of aluminium or gold 18–50µm in diameter, are attached using pressure and ultrasonic energy to form metallurgical bonds. Devices bonded with gold wire generally need additional thermal energy, and the bonding process is referred to as ‘thermosonic’ rather than ‘ultrasonic’.

Although many alternative joining methods have been devised, the development of automated, high speed, high throughput equipment has maintained the position of wire bonding as the principal interconnect process.

There are two main bond geometries:

- **Wedge** bonding, most commonly used with aluminium wire, which has a stitch bond at both ends
- **Ball** bonding, generally used with gold wire, where a ball bond is formed at one end and a ‘fish tail’ bond at the other, the capillary cutting through the wire to produce a single ‘tail-less’ bond.

Wedge bonds

Stitch bonds are formed at both ends of the interconnect by a combination of pressure and vibration. An ultrasonic transducer and ‘horn’ are designed to translate electrical energy into tool movement along the horn axis. As this energy softens the wire, freshly exposed metal in the wire comes in contact with the freshly exposed metal on the pad and a metallurgical bond is formed. The bonding dwell time is typically 20ms for an automatic bonder.

In Figure 1, which is an SEM photograph of a typical ultrasonic wedge bond, distortion of the wire is visible, but there is no evidence of a weld ‘fillet’. This contrasts with soldering operations.

Figure 1: SEM photograph of an aluminum ultrasonic wedge bond formed on an IC bond pad

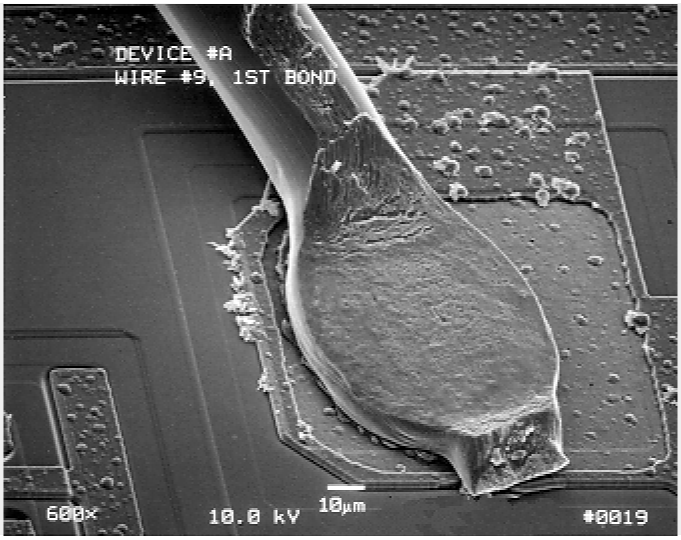
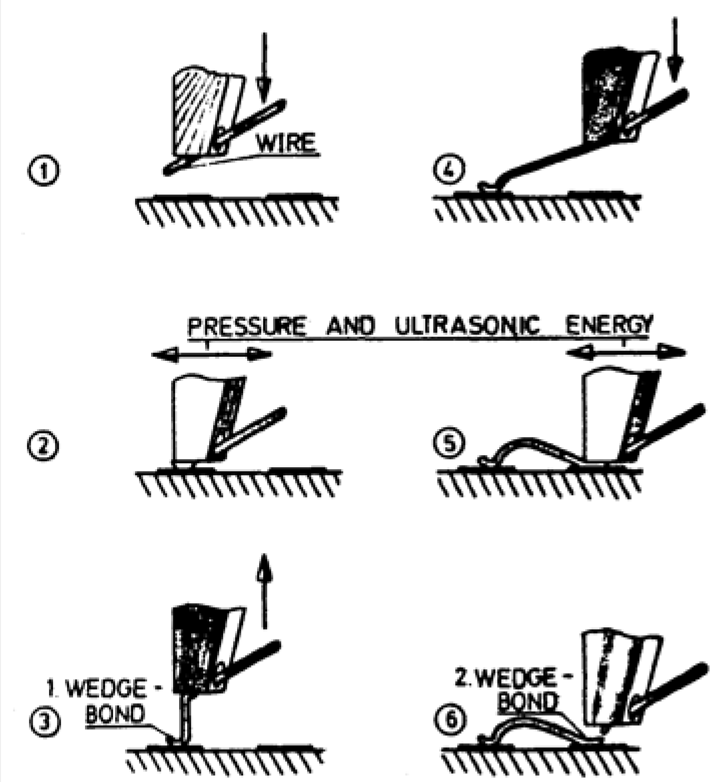


Figure 2: The sequence of forming an ultrasonic wedge bond



The operation starts by threading the wire through the bonding tool, known as the 'wedge', ensuring that the wire is directly underneath the foot of the wedge and projects slightly in front of the toe. The repetitive bonding cycle (Figure 2) has three parts:

> **First bond** . The wedge is moved directly above the target pad, and then lowered. Clamps behind the wedge grip the wire. When the wire is sensed as having touched the bond pad, ultrasonic energy is transmitted to the wedge. The foot of the wedge, which may be grooved, presses the wire and ensures that the energy is dissipated at the wedge-pad interface. The profile and finish of the wedge, and the energy and pressure applied, control the deformation of the wire.
>
> **Looping** . The wire clamps are released, and the wedge is raised and simultaneously moved backwards towards the second bond target pad, creating a wire loop without stressing the first bond.
>
> **Second bond** . The wedge is lowered, using ultrasonic energy and pressure to deform the wire and form the second bond. The wire clamps then grip the wire and are moved backwards so that the wire breaks at the heel of the wedge. The tool is then raised and the wire clamps moved forward so that a short length of wire again projects in front of the tool.

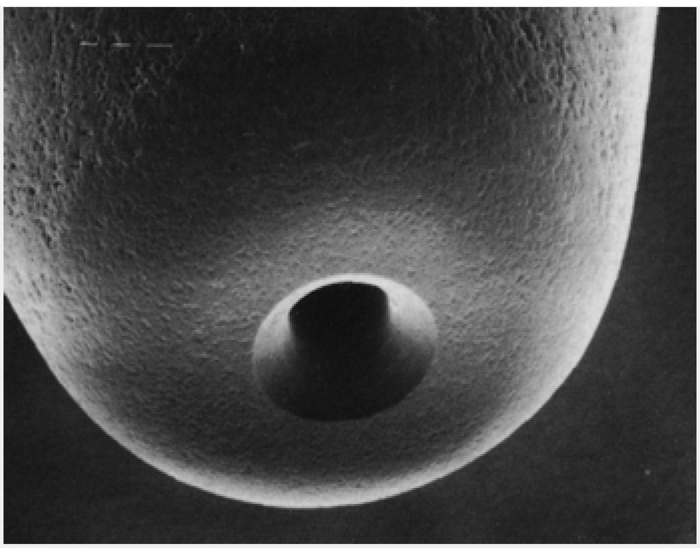
The wedge must be moved directly *backwards*, and not at an angle to the wire, to avoid applying a detrimental torsional shear force to the first bond and to ensure that the wire remains under the tool so that a second bond can be made,. It is necessary therefore, *before* making the first bond, to bring the points to be joined in line with the tool movement. This can be accomplished by moving either the work or the bonding head.

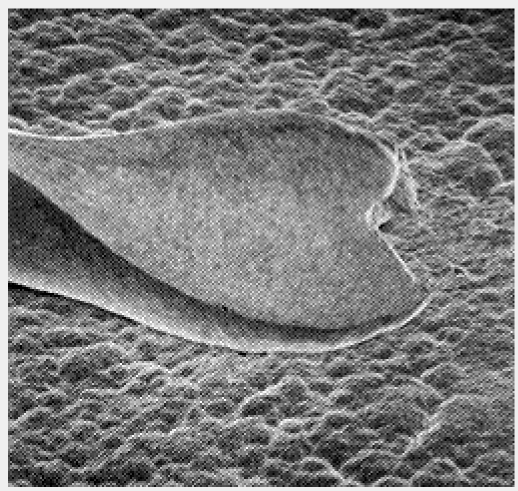
Ball bonding

Ball bonding uses the same friction welding principle as wedge bonding, with an ultrasonic horn which produces a rapid translational movement of the tool. The differences are that:

- The wire is located centrally in a tubular tool known as a ‘capillary’: Figure 3 shows the tip of a capillary viewed from underneath.
- Because the tool has a circular cross-section, a ‘fish tail’ (Figure 4) rather than a wedge bond is produced at the other end of the wire.
- Additional thermal energy is needed, and ball bonders normally heat both die and lead-frame.

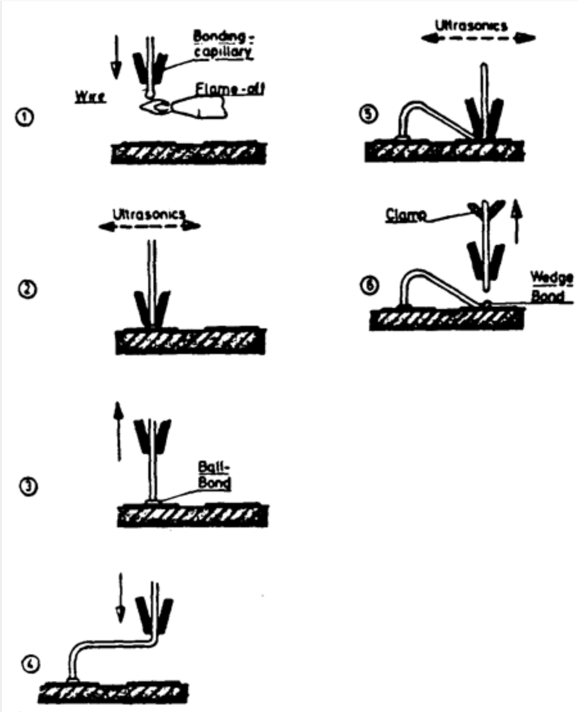
Figure 3 (left): View of a capillary from the underside
Figure 4 (right): A fishtail bond

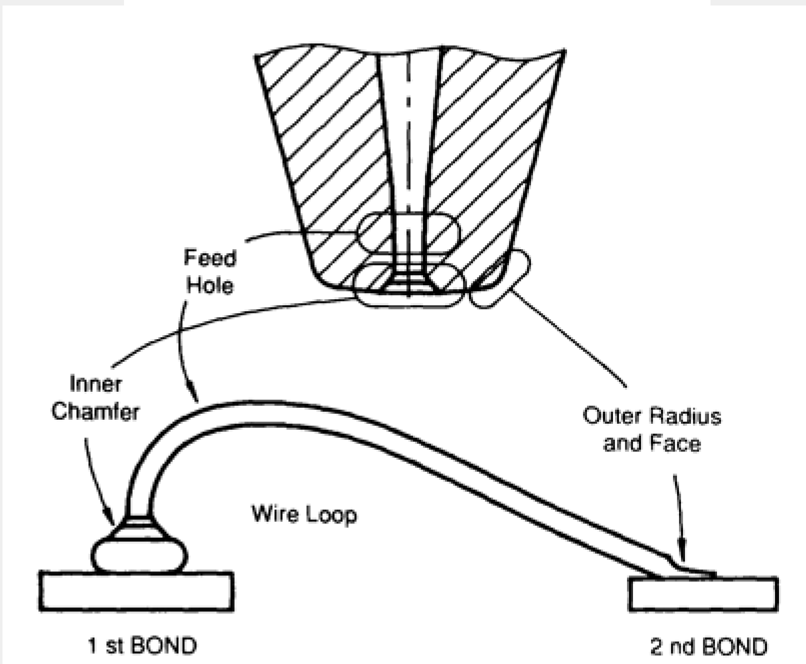




The operation starts by threading the wire through the bonding tool and forming a ball by melting the protruding wire end (Figure 5). The diameter of the ball is usually just over twice that of the wire from which it was made. This process is known as ‘flame-off’ because early machines used a small hydrogen flame for this function: the task is now carried out by capacitance discharge, referred to as Electronic Flame-Off (EFO).

Figure 5: The ball bonding sequence
Inset shows the function of the capillary





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The repetitive bonding cycle has four parts:

First bond . The capillary is moved directly above the target pad, and then lowered. This pulls the ball into the chamfer at the end of the capillary, centring it and tensioning the wire.

When the ball is sensed as having touched the bond pad, ultrasonic energy is transmitted to the capillary. The inside surface of the capillary grips the ball and ensures that the energy is dissipated at the ball-pad interface. The inner profile and finish of the capillary, and the energy and pressure applied, control the shape of the ball after bonding. A typical bonding time is 20ms with 80gm-force applied.

Looping . The capillary is raised and then moved towards the second bond target pad, leaving wire in a loop. In order to control the shape of this loop and optimise the strength of the bond without stressing the wire, automatic machines employ complex tool trajectories. For this reason, a bonding sequence with loop control may take a total of 200ms.

In a typical machine, the capillary is raised to the 'kink height' and then moved in the *opposite* direction to the target pad, bending the short length of wire immediately above the ball slightly away from the target. Then the capillary rises to 'loop height', and moves towards the target bond pad. This action straightens the portion of the wire above the 'neck', without breaking it.

Second bond . The capillary is lowered, using ultrasonic energy and pressure to deform the wire and form the second bond. The capillary rises to leave a 'tail' of wire exposed beneath the capillary. Clamps close and hold the wire and the clamps and capillary are moved upwards together so that the wire breaks at its thinnest and weakest point, where the sharp edge of the capillary has cut into the wire.

A key factor in controlling the shape and quality of the second bond is the outside profile of the tip. Bonding time is as for the first bond, but at higher pressure (around twice the force applied).

Forming a new ball . The capillary rises to 're-set height', when an electronic flame-off moves close to the tail and an electrical discharge melts the protruding end of the wire. The EFO retracts, and the melted section of wire solidifies to form a new ball. The diameter of the ball is a function of the tail length and the EFO energy, and this requires tight control of the critical parameters of voltage, current and time.

During ball formation, the wire is melted and then rapidly solidified. As a result of this annealing process, the structure and hence the properties of the balled wire are different from the original wire, and the weakest part of the bond is the section just above the ball.

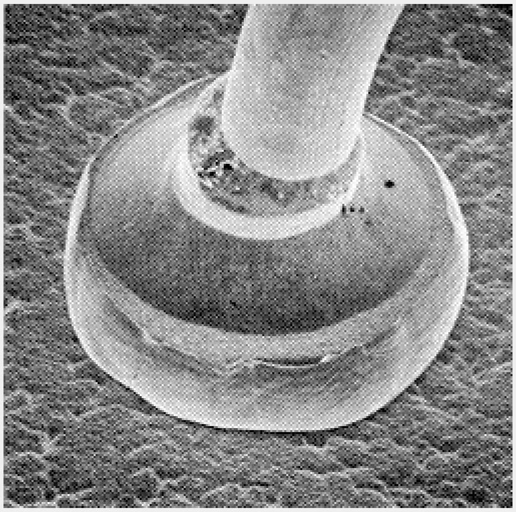
Ball bonding experiments have been carried with both copper and aluminium, but their use has been limited by the properties of the oxide coating on these materials. Compared with gold, a higher level of energy is required to produce a ball, and an inert atmosphere has to be used to reduce oxidation during ball formation.

Bond assessment

Visual inspection is an effective way of assessing the quality of the wire bonding process. Cracked heels, tearing at the wedge, misplaced wires, inconsistent wire placement, balls not centred on the wire ('golf-clubbing'), or excessive necking above the ball are indicators of a process which is not in control. Some examples are shown in:

- Figure 6 shows an acceptable gold ball bond: Figure 7 shows a badly formed gold ball which indicates that the process is not running properly.
- Figure 8 shows a correctly formed aluminium wedge bond, whereas Figure 9 shows cracks at the heel of the wedge

Figure 6 (left) : A satisfactory gold ball
Figure 7 (right) : SEM photo of a deformed gold ball bond, caused by excessive EFO power



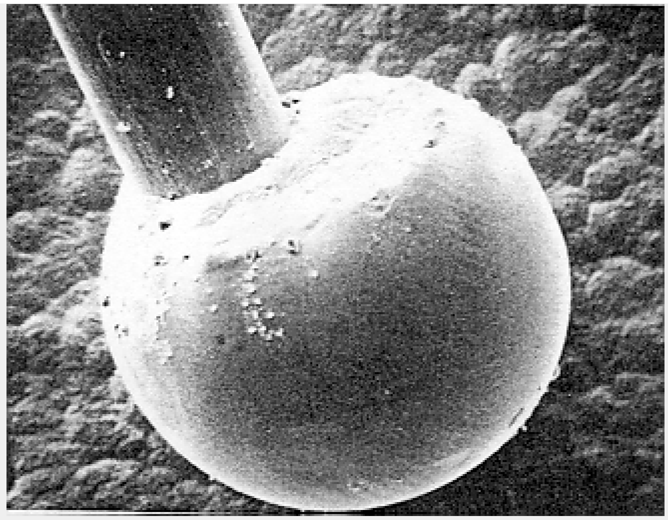
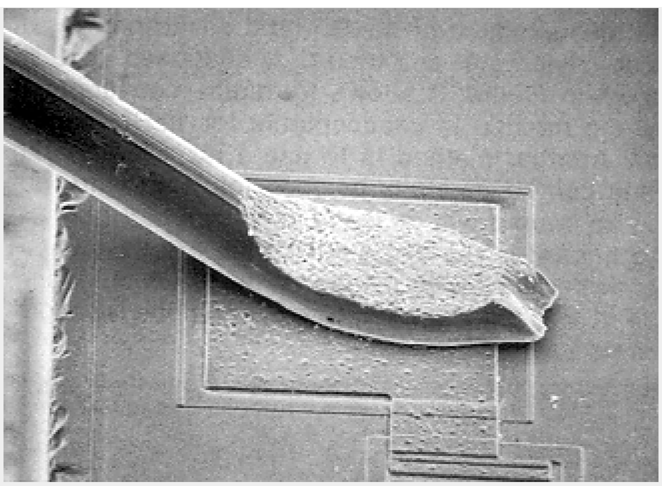
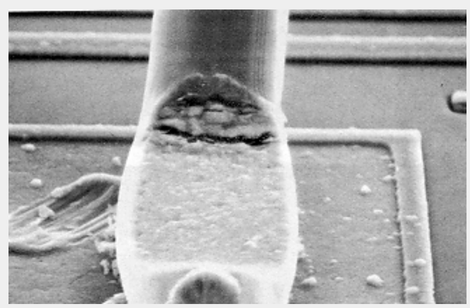


Figure 8 (left) : An acceptable aluminum wedge bond
Figure 9 (right) : A wedge bond which shows a small crack at the heel



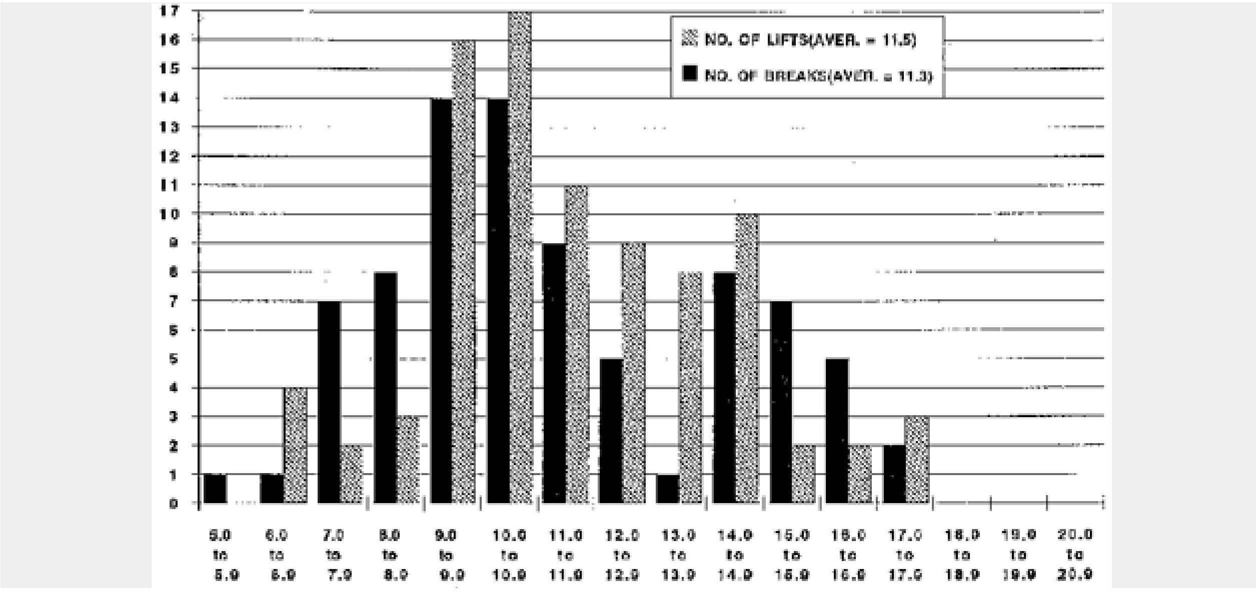


The **bond pull test** is the destructive test method most widely used as an off-line tool to monitor the bonding process. A small hook is placed in the centre of the wire span and pulled in a direction normal to the bonding plane. The wire is pulled until the bond fails and the value of the pull force recorded – a 1µm diameter gold wire would typically break with 6–8 gm-force applied.

When recording bond test results, failures should always be categorised by where they occur (e.g. above ball, in loop, at tail) and whether the fault is a wire break or a bond lift. This gives important additional information on the likely source of any problems.

Figure 10 contains actual breaking strength data collected from a K&S Model 4123 automatic aluminium wedge bonder using 32µm wire, showing the distribution of two different failure modes (wire lifts and wire breaks).

Figure 10: Production breaking strength data from an automatic aluminum wedge bonding process



Note the distinction made between wire lifts and wire breaks

A standard test procedure is defined in MIL-STD-883, Method 2011. In using this test to verify production set-ups, check out new batches of wire, or when the process parameters are changed, it is important that sample bonds are truly representative of the production process. Sample averages and range would typically be charted on $\overline{X}$ and R charts with adverse trends used to initiate corrective action such as replacement of defective bonding tools.

There are a number of important variables of the bond pull test that must be considered. For example, both the position in which the hook is placed during testing and the wire elongation affect the pull strength result.

Non-destructive pull testing (MIL-STD-883, Method 2023) may be carried out as a screen to reveal weak or marginal bonds whilst avoiding damage to acceptable bonds. Since 100% testing is costly and time consuming, its use is confined to low volume parts for high-reliability applications.

The test has to be carried out at a consistent position on each bond, and with a consistent steady pull rate, and comparisons between different bonds have to take into account that the measured bond strength is a function of the loop geometry. The maximum pull force applied is set below the -3 s limit of the expected bond strength distribution, the intention being to weed out the ‘no bonds’ with almost zero bond strength.

The damage remaining in the wire after test has been found to be negligible and generally will be annealed during device temperature screens. However, even at this low level, the wire loop will be distorted after pulling.

Ball shear testing is used to assess the integrity of the gold ball-to-bond pad interface. A hardened tool moves parallel to the bonded surface and shears the bond. Shear values typically range from 40 to 80 gm-force for a 25µm gold wire. This test is useful not only in setting up ball bond parameters, but also in detecting cratering and testing the adherence of die metallisation.

Incorrect or misleading shear test values can result from incorrect positioning of the tool, for example, if it drags along the surface. Special precautions are needed when shearing gold ball bonds on gold surfaces as the surfaces may become friction welded to each other.

Factors affecting the bond

The key parameters of the wire bonding process which affect bond quality are:

- The accuracy of placement of the bond wire and the form of the bond.
- The physical parameters of the bonding process
- The metallurgy of the wire.
- The materials, morphology and surface cleanliness of the bond pad metallisation.
- Any ageing or degradation of wire and bond pad.

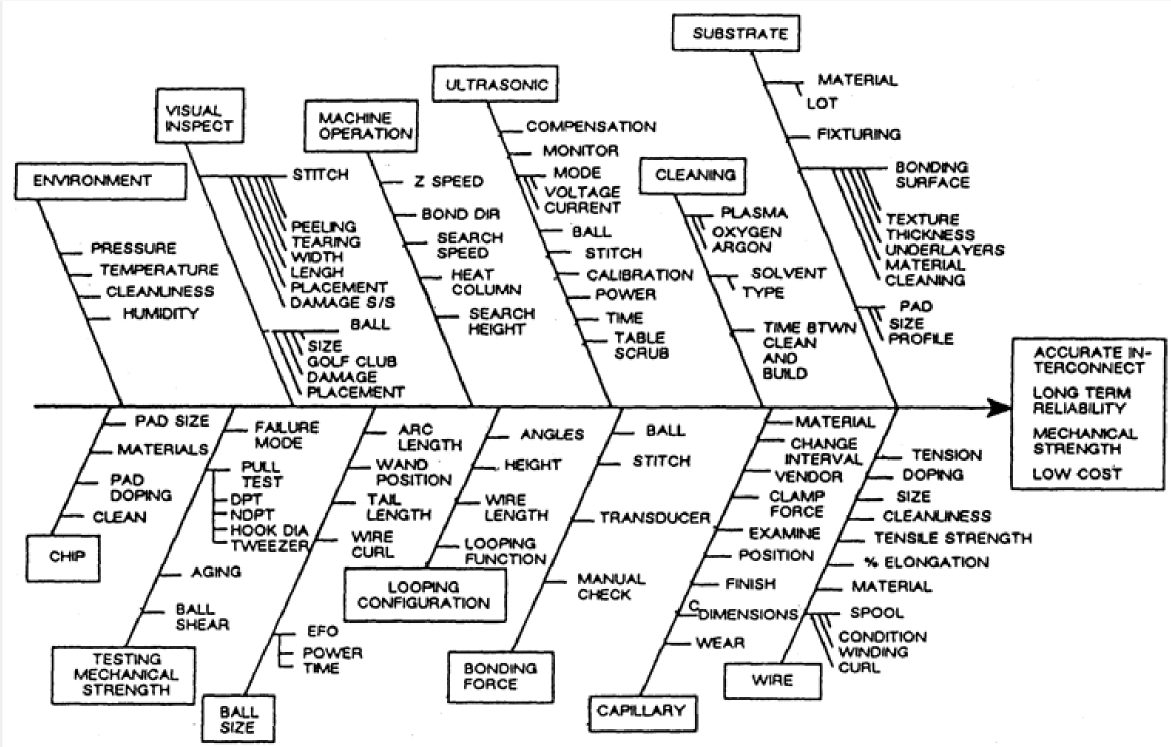
Table 1 is a more complete list of the many parameters that affect yield, reliability and the cost of the wire bonding process. Each needs to be optimised for the intended application. The parameters interact, and a useful way to visualise the important factors in the wire bonding process is a cause and effect diagram such as that in Figure 11.

Table 1: Factors affecting joint quality

materials	wire	material	alloying; purity; additives
		diameter	
		as drawn vs. annealed	
		hardness	ultimate tensile strength; percent elongation
		lot to lot variations	
		storage conditions	
	bonded surface	cleanliness	even small amounts of contamination adversely affect both bondability and reliability
		pre-cleaning methods	plasma; solvent
		freedom from defects	

		surface condition	
Capillary or wedge	force applied		
	ultrasonic	frequency	
		power	
		resonant system	
	time		
	tool	size and shape	
		material	trend to ceramic
		surface finish	
		cleanliness	
		wear	
	stage temperature		150–200°C is typical for thermosonic bonding
Machine	bond positioning		pattern recognition
	wire loop		bond geometry, take off angle, loop height
	freedom from vibration		
	rigidity		

Figure 11: Thermosonic wire bond cause and effect diagram



from Eisenberg 1990

One analysis of thermosonic ball bonding found that pull strength could be optimised by reducing the bonding time, increasing the bonding force and increasing the bonding temperature. Of these parameters, the effect of the substrate temperature was most marked. However, the results and the optimum conditions might well have been different given differences in the surfaces or bond wire specifications: care has to be taken with the experimental design!

Generally the measure of bond quality adopted is the pull strength. Rather than look just at minimum or mean values, the analysis of pull strength data should arguably concentrate on the *standard deviation* of the sample. Reducing this decreases the possibility of process errors resulting from the machine/tool interaction.

Bonding wires

The choice of bonding wire specification will reflect many factors, in particular compatibility with the overall packaging process used and the quality requirements of the market.

Materials used

Although there are exceptions:

- **gold** wire is generally selected for moulded plastic packages, and for hybrids and MCM packages, where the substrate pads are typically also of gold;
- **aluminium** wire is used for devices in ceramic hermetic packages, and for high pin count applications, where the closer packing ability of wedge bonding may be an advantage.

Compared with gold, aluminium has a stable and lower material cost, is more resistant to radiation hardening, and is a better metallurgical match to the aluminium metallisation generally used for bond pads on semiconductor die. However, there are good reasons for continuing to prefer gold for volume plastic package applications which include:

- A concern that aluminium wire may **corrode** when embedded in a non-hermetic encapsulant.
- The greater design and manufacturing **flexibility** of the ball bonding process. Bonds can be made in any direction, there is easier access to the interior of crowded packages, and wire loops with better characteristics can be made in configurations where the first and second bonds are at different heights.
- This is particularly true where wire bonders equipped with real time process control are used.
- There are difficulties in ball bonding materials other than gold, the ready growth of an oxide coating on aluminium presenting a particular challenge.
- The generally higher process **throughput** of gold ball bonding.

Work has also been carried out using copper and palladium wires. Although its electrical conductivity is lower than gold or aluminium, palladium is claimed to show particular promise for high-volume non-critical applications, as it has high strength at both low and high temperatures, deforms precisely, and allows small, regular balls to be formed without needing an inert atmosphere.

The wire-forming process

The starting point is high purity material, for example, 99.999% ('5N') purity gold, which is melted in high vacuum to ensure homogeneity and correct properties. The resulting cast bar is drawn through a series of dies of reducing diameter to produce bonding wires which are typically 18µm to 75µm diameter for small-signal devices and ICs. Because of the fragility of the wire, both for manufacture and in bonding, the smaller sizes require many more stages of drawing (30+ stages from 25µm to 18µm) and are generally reserved for specialist applications such as microwave devices.

The gold wire used in bonding is normally doped with small (~50ppm) amounts of beryllium to optimise the yield characteristics. For low-power devices, 'aluminium' wire is most frequently an alloy containing 1% of silicon (less commonly magnesium). This makes it easier to draw, gives higher pull-test strengths, and improves the match between the hardness of the wire and the bond pad material. However, for high current devices,. pure aluminium is generally preferred to alloy wire as it is softer and needs lower bond forces.

For alloy wires, one of the most important characteristics is homogeneity, and microscopic checks of the alloy structure of finished batches are routinely performed.

Processing of all wires has to be carried out in conditions which give a clean surface and smooth finish, in order to ensure that the wire will 'de-reel' from the spool without snagging. The wire is normally provided on 2 inch diameter spools, the earlier small spools tending to feed wire with an intrinsic twist.

Wire diameter

The choice of wire diameter depends little on cost, but mostly on compatibility with the process and the current rating: the current carrying capability is determined by the wire cross-section and, to a lesser extent, the bond length. For example, a 25µm diameter wire 10mm long has a fusing current of 500mA, but this figure increases to 1A for a more typical bond 2mm long.

Multiple wires are used both for current handling and to guarantee dynamic speed: in production this is generally more convenient than using different wire diameters on the same assembly, although manufacturers of low-volume hybrid circuits allow this.

The most usual wire diameters are 28, 30 and 33µm; 25µm wire is also used, but tends to be confined to consumer electronics. For power devices, 125µm and 250µm are commonly used, and 500µm represents a practical top limit – for higher currents, ribbon connections are chosen.

Wire parameters

The suitability of wire for bonding is determined by its:

- Elongation (%)
- Breaking strength (gm.force)
- State of anneal (stress relieved or fully annealed)

These affect both the quality of the bond and the looping characteristics of the wire. The choice is influenced by the wire diameter, and the optimal parameters are different for wedge and ball bonding.

Annealing is a important operation as aluminium wire in particular work-hardens during the drawing operation. By using annealed wire, the variation in bond strength is reduced and the process becomes less sensitive to thermal effects.

Once the correct specification for the application has been established, it is usual to carry out sample usability tests on batches of bonding wire. The check is that a bond with the correct form is created at every attempt, and an adequate bond strength is achieved.

Wedges and capillaries

Materials

Most tools used are now made from fine-grained ceramic, replacing the earlier tungsten carbide (occasionally titanium carbide). This conversion to ceramic happened first with ball-bonding capillaries, because tungsten carbide tools tend to stick to gold wire, but has extended to bonding wedges. The enhanced surface texture of the ceramic gives optimum coupling to the wire, with efficient ultrasonic energy transfer and the reported benefits of:

- Increased bond adhesion and pull test results
- Ability to bond at lower temperature and reduced ultrasonic power
- Extended tool life

- Improved bond definition
- Improved production yields

Mechanical design

For wedges:

- The face angle of the bond affects the shape and strength of the second bond and the style of termination. Angles between 0° and 8° are most common, with the former used for soft materials, to ensure a wide bond area, and the latter for optimum strength on hard surfaces.
- The feed hole angle is normally 45°, but 52° and 60° variants (so-called 'deep access' or 'vertical feed' bonding wedges) may be preferred to maintain maximum looping and tail control in applications where tool access is difficult. Here there are substantial differences between the bonding requirements of a lead-frame and a pre-manufactured package.

For capillaries:

- The external cone angle is normally 30°, but alternatives (a smaller angle or a relieved tip) are used where there is limited access to the first bond position (e.g. with fine pitch parts) or the second bond is close to the package wall.
- Requirements of the tip are that the chamfer and hole should be highly polished to minimise drag resistance, the chamfer angle selected to centre the ball (90° is usually more effective than 120°), and using a matt finished outer surface with the correct radius to form a reliable second bond.

The ultrasonic system

The bonding performance depends critically on the tuning, in order to ensure the correct direction and amplitude of tip movement, so most equipment has Phase-Locked Loop auto-tuning.

In the past, bonders have standardised on 60 kHz transducers. Given the trend to reducing the pitch between bond pads, a higher frequency transducer has been tried, and shown to produce wedge bonds with up to 25% smaller squash width, whilst maintaining reliability.

Bonding at 120kHz also seems to drive ultrasonic energy into the bond interface faster than 60 kHz systems, with the benefits of:

- Reducing metal 'splash' (bond pad metal which is squeezed out from under the pad during bonding).
- Reducing the bond time from 20ms to 10ms per bond (20ms/wire), which increases machine throughput by around 10%.
- Reducing damage to the heel of the bond, resulting in higher pull strength.

- Decreasing the sensitivity of the bond width and wire pull strength to changes in first bond force.

Practical bonders

With manual machines, the operator aims the tool using a spotlight; automatic machines use a pattern recognition system to locate specific area on die and lead-frame.

Early bonders had static heads, which moved in a controlled manner only in the Z-axis, the movement between first and second bonds and between bonds being carried out by moving the work-piece in X and Y. For wedge bonding, where the second bond must lie directly behind the first so that the wire stays beneath the tool tip, the 'stage' was also able to rotate, and a preliminary action was to move the work-piece so that the points to be joined by the bond were aligned with the Y-axis of the machine.

In most advanced automatic machines, all the movements for each bond take place on the head, and there is no need to orientate the wire bond direction. The only stage movement is to index the lead-frame. This makes it easier to provide heat for thermosonic bonding, current pactice being to heat both chip and lead-frame, but not the ultrasonic capillary.

A major design task is to create frictionless bonding heads, usually on air bearings, where X, Y and Z axis motion is precisely synchronised, and wire loop parameters such as the loop height and step back can be set. The cycle time is determined more by the mechanical movement than by the time taken for each bond, and a cycle time of 120–130ms per lead (8 leads/second) is achievable.

Bonding down onto devices in packages requires a greater range of Z movement, and another of the design aspects of a ball bonder is the clearance between the electronic flame-off wand and the transducer, for applications where there is a large difference in bond height between first and second bonds.

Bonding problems

There are a number of sources of **positional erro**r:

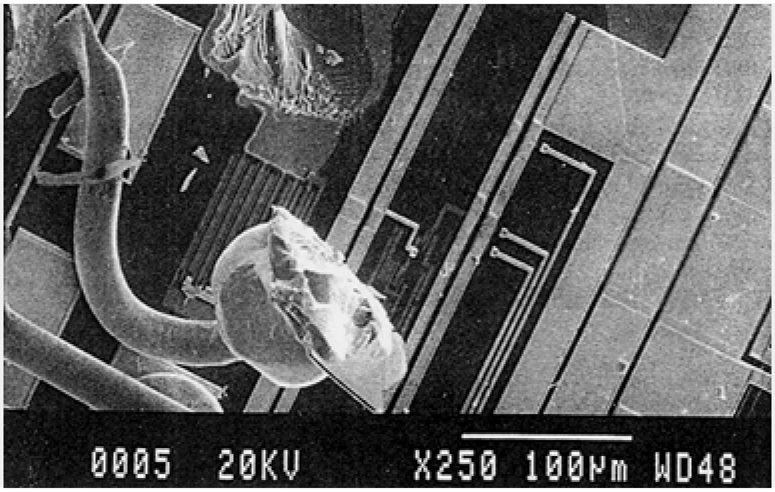
- Variations introduced during the 'teaching' of a bonding program, where the taught bond location is off-centre to the pad.
- Variation in bond tool location about the target (machine repeatability).
- Variation of the centre of the bonded ball in relation to the centre line of the capillary ('concentricity')
- Variations in bond compression and in the shape of the bond, which are functions of the bonder parameters.

The first of these results in bias, whereas the others will be spread randomly about the mean.

For many years, failures at gold bonds to aluminium pads due to '**purple plague'** monopolised the attention of process engineers. The term was applied because of the purple appearance of one of the phases ($AuAl_2$) of the gold/aluminium system that develops at the wire bond interface under certain conditions. Although this intermetallic compound is brittle, the failures are usually caused by the associated Kirkendall voids that develop as the metals diffuse one into another.

Cratering describes a wide range of mechanical damage to the semiconductor material underlying the bond pad. This can result in total mechanical bond failure, where fragments of pad and die material on the underside of the wire are apparent by visual or SEM inspection. Less severe damage may only be apparent as anomalous electrical test results which occur only under specific conditions of temperature and bias. Here it will be necessary to etch back the bond pad metal and inspect the underlying die for cracks or 'shell-outs'. Figure 12 shows a picture of a lifted ball bond and the corresponding crater on the bond pad of the semiconductor die.

Figure 12: SEM photomicrograph of cratering of a bond pad area with the silicon fragment attached to the ball bond



Cratering is caused by a combination of:

- excessive bonding force or ultrasonic energy ('over-bonding')
- thin metallisation on die bond pads
- too hard a grade of bonding wire

Some applications will be more prone than others to cratering: for example, the incidence of cratering varies with wafer material, polysilicon and gallium arsenide being more susceptible, and 'hard-to-bond' die may combine thin metallisation with the need to increase the bonding energy. It is important to use proper experimental design techniques to devise a robust process with a minimum incidence of cratering.

Cracks in aluminium wire bonds can be caused by the motion of the bond head after the first wedge bond is formed. The tool may rise too high or come off at an angle that overworks the wire and causes a crack to form. However, minor cracks sometimes will anneal during subsequent heat treating and pose no real danger.

Contamination problems are usually first encountered during wire bond pull testing as 'lifts'. Lower bonding yields may be caused by contamination from plating impurities or thin layers of organic contamination on the bonded surface, halogens especially degrading bondability. Such organic contamination, can originate from small particles of human debris or manufacturing residues from photo-resist, cleaning solvents, and the outgassing of epoxy products.

Contamination may also cause early thermal stress failure during burn-in and in the field. Plating contaminants such as thallium or hydrogen bubbles in the plated surface can cause Kirkendall-like voiding as well as bondability problems.

Effective wire bonding is primarily a matter of awareness and good process control. Table 2 was developed from the point of view of an engineer auditing a sub-contract activity, and suggests that there five levels of 'maturity' in wire bonding, which carry corresponding levels of risk to the user. A similar TQM table could be developed for the other processes involved in component packaging.

Table 2: Levels of maturity progression	
Level 1 Neglect	Wire bonding process not well understood. Yields low or not known. Fundamental process controls not in place. Bond test equipment not available. Capillaries/wedge condition not monitored. No scheduled preventative maintenance. Wire stored in uncontrolled environment with no shelf life controls. Bonding operation performed in uncontrolled environment, with parts left uncovered. Bonding stations not equipped with ESD precautions. **High risk** : Uniformity from lot to lot may be very poor and bond test data may not relate to product purchased. Customer should institute lot sampling/rejection. Do not use parts in mission or life critical applications unless non-destructive testing is done by a reputable source.
Level 2 Awareness	Wire bonding process has been flow-charted and technicians/engineers understand the critical points in the process. There is at least a minimum understanding of bond metallurgy and the mechanics of the process. Wire bond schedules have been developed and are used. Sample bond pulls performed before production bonding. Bond defect data collected and fed back to engineers responsible. Main failure mechanisms and problems known. Operators receive some on-the-job training. Documented work instructions and equipment manuals are used.
Level 3 Implementation	Wire bonding process under control and process data routinely collected. Management understands the importance of bonding to clean surfaces: equipment in place to clean before bonding. Bond test equipment available. Bonding operation performed in a certified Class 100,000 cleanroom. Parts stored in enclosed dry nitrogen environments. Wire bonding design rules are followed e.g loop heights, layouts pad dimensions. Good manufacturing discipline is evident. Master machine/part/wire bond software programs are controlled and easily identified. The yields are known.
Level 4 Sustaining	Evidence that wire bond device yields are at 99.99%. SPC charting techniques in place and used by trained operators and process engineers. Trends and out of control conditions are easily identified and corrective action is taken on the process prior to shipping bad product. A comprehensive operator training and certification program is in place. The wire bonders are routinely cleaned and maintained on a regular basis.
Level 5 Improving	The wire bonding process is designed to achieve maximum yields at the lowest possible cost. Controlled experiments are routinely run to optimize and improve the process. New device set up times are minimized. Automated real time process control and defect data reporting used extensively to monitor and improve the process. Wire bond failures at subsequent process steps are investigated and analyzed. Failure analysis results are documented and the information shared to prevent reoccurrence. Every aspect of the wire bonding process is understood and controlled.

	Very low risk Bond defect rates below 1 ppm. Bonds should not be tested. Handling damage would increase the defect rate above the as-delivered value.

Design rules

Figure 13 and Table 3 show some of the considerations involved in trying to set design rules for assembly. However, these indicate conservative practice, design rules being more for the convenience of subcontractors than an indication of the limits.

Figure 13: Some of the considerations involved in trying to set design rules for assembly

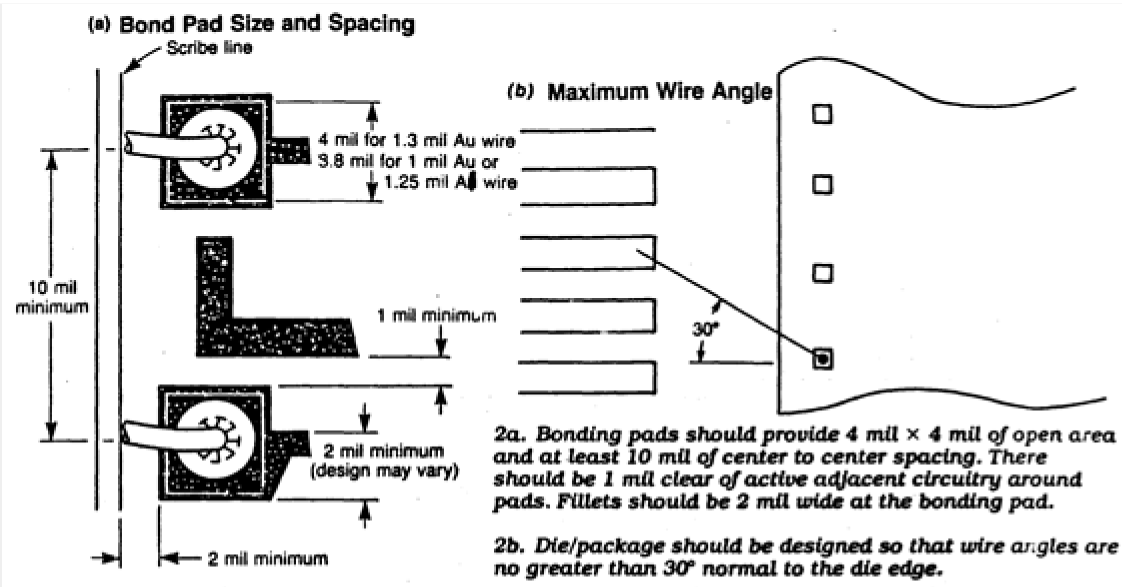


Table 3: Some suggested parameters for bond-wire design

Wire diameter/type	Package type	Min. length	Max. length
33µm gold	plastic	1.3mm	2.5mm
33µm gold	ceramic	1.0mm	3.2mm
25µm gold	ceramic	1.0mm	2.5mm
33µm aluminium	ceramic	1.0mm	3.2mm

In particular the suggested maximum wire angle of 30° makes life difficult for the designer. The risks being guarded against are of the wire shorting to the die edge and of adjacent wires shorting together. A tighter design can be produced by considering a 3D view of the assembly, and allowing for some mould sweep. Ideally, Design For

Manufacture should take into account the likely die size and required package in determining both the appropriate lead-frame and the optimised lead pad positions.

The continuing trend towards reducing chip size, increasing device functionality and pin count, requires bond pads which are both smaller and closer together.

- **Pad size** is a function of the accuracy of the exit metal and the pad design. For gold wire, pad width would normally be a minimum of three times the wire diameter, in line with the dimensions of the ball after it has been squashed during bonding. In order to reduce the width, control of both ball size and deformation needs to be tightened.

- The limit is influenced by the way that the metallisation exits the pad, in view of the military requirement that a bond may not obscure the lead-in, a situation which can be made easier by a tapered exit.

- **Pad spacing** is determined by the accuracy of bond placement and by the size of the bonding tip. A number of modifications have been proposed to reduce the width of both wedges and capillaries, by removing metal from areas above the actual tip.

Close pitches can result in two types of defect:

- Bonds where part of the bond is off the bond pad.

- Bonds where either the bond tool or the bond wire makes contact with a previously made bond - a ‘collision’.

Both are undesirable, because they reduce yield and may affect the reliability of the process. Practical experience is that the first of these types is generally the more important, because if bonds shift they normally shift by an equal amount, whilst maintaining correct relative centres.

A ball bond has a wider footprint than a wedge bond. Thermo-compression of 28µm diameter wire produces a ball bond of 80–90µm diameter, compared with a wedge less than 60µm wide. Minimum standard bond pitches are therefore 120µm and 90µm, respectively, although modified tools can reduce this somewhat.

Figure 14 shows some examples of tools which have been modified to allow closer pitch bonding, and Figure 15 the results of using such tools in combination with modified machine settings to reduce bond deformation.

Figure 14: Bottleneck capillary and side-relief wedge, to allow tools close to previously bonded wires

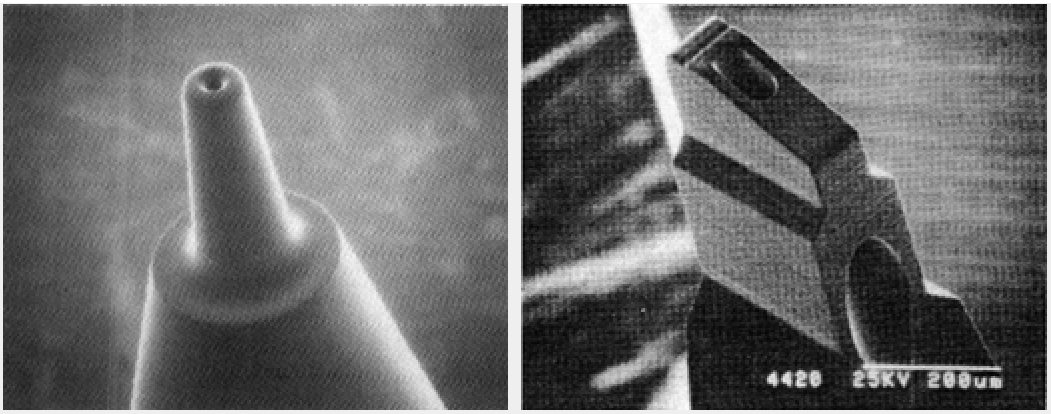
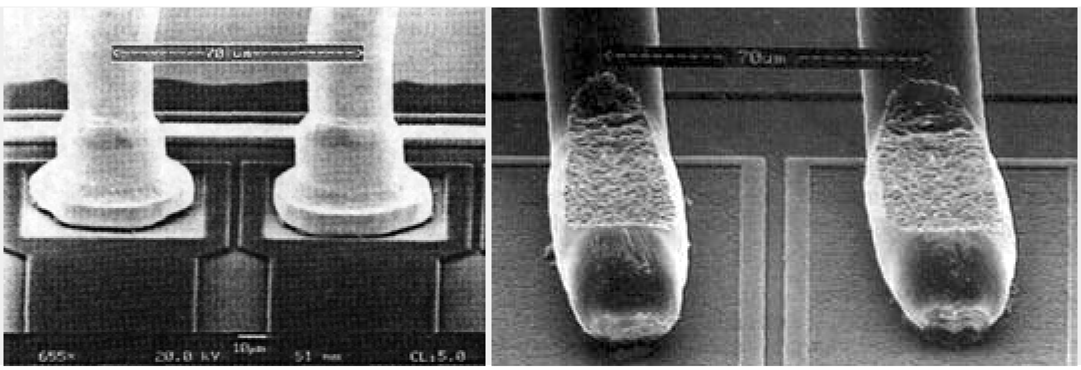


Figure 15: The 1998 bench-marks for fine-pitch bonding, 70µm ball bonding (with greatly reduced ball size and bond squash) 60µm wedge bonding (high--frequency ultrasonics for minimum squash-out)



For tighter pitches, is is possible to stagger the bonds, using two rows of pads on the die, although this requires multiple loop heights to reach inner pads (Figure 16). As lead count increases and die area decreases, the bond finger pitch will reach the manufacturing limits of the lead-frame. In order to get round these problems, a bonding interposer may become necessary. Alternatively, one can consider bonding over the active circuit, although this brings its own problems (Figure 17).

Figure 16: Staggered bonds to reduce effective lead pitch

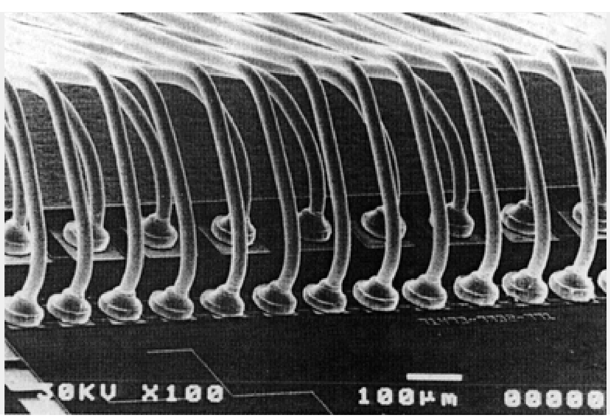


Figure 17: Bonding over the active area

There would be benefit in being able to bond over the active area, as this

- allows larger bond pads with a wider pitch, particularly for area arrays
- reduces the silicon area needed, and hence its cost.

Many attempts to wire bond over active circuits failed because of damage to brittle thin film dielectrics and electrical failures caused by capacitor decoupling between the bond pads and the underlying active circuitry. Cracks in the passivation or inter-level dielectric can be caused by impact forces during wire bonding, and shear stresses exerted on ball bonds by plastic encapsulation during temperature cycling have resulted in device failures. Cracked passivation has even been observed from the thermal mismatch between silicon nitride passivation and silver in flip chip reflow bonding, where no impact force is exerted.

Texas Instruments developed a process which uses a separate layer of metallisation for bond pad and buses. A stress buffer layer of polyimide is applied between the inorganic passivation and this top metal layer.

The polyimide type was selected with compromise mechanical characteristics, requiring a modulus high enough to allow sufficient transfer of ultrasonic energy for effective bonding, yet low enough to provide acceptable stress buffering.

Polyimide thickness was again a compromise: increasing the thickness reduced bond strength, but for reliable bonding the polyimide must be thick enough to planarise the chip. Acceptable bond strength and intermetallics with no underlying dielectric damage were found for between polyimide layers 3–6µm thick.

It proved not possible to bond to a pad containing many vias. This was thought to be because the irregular nature of the pad surface concentrated the energy transfer from the ultrasonic bond head to just a few regions in the bond pad, causing insufficient intermetallic to form, and resulting in weak or non-existent bonds.

Source : http://www.ami.ac.uk/courses/topics/0268_wb/index.html