The Microelectronic Wire Bond: Past, Present, and Future

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Abstract

Since its very inception, the microelectronic wire bond has been the dominate form of first-level interconnection (chip to package or substrate). Wire bonds account for over 80% of first-level chip interconnections made by the microelectronic industry each year. Wire bonding is reliable, flexible, and low cost when compared to other forms of first-level interconnections. In this article a brief discussion of wire bonding is presented along with bond formation fundamentals. Aspects of wire bond reliability will be explored in conjunction with methods of wire bond testing. Particular attention is given to fine pitch bonding, bonding to stacked die, higher frequency bonding, ball bonding with copper wire, and advanced bond testing methods.

Key Words: Wire Bond, Wire Bonding, Ball Bonding, Wedge Bonding, Fine Pitch Wire bonding

Introduction

Wire bonding is the dominant form of first-level chip interconnection method. It is estimated that about 10 trillion wire bonds are made annually. This staggering number of wire bonds accounts for over 80 percent of all first-level interconnects (chip to package or chip to board) produced in the world. Wire bonding is reliable, flexible, and low cost when compared to flip chip and other forms of first-level interconnection.

Wire bonded interconnects are usually applied to perimeter bonding pads on integrated circuits (ICs). Perimeter pads are located over non-active regions of the chip, thus preventing any damage to the IC, due to forces associated with the bonding process. Similar damage concerns give rise to the requirement that the first bond of the wire bonded interconnect be placed on the chip or IC and the second bond be formed on the package or substrate. Using modern wire bonding machines, under precise computer control, researchers and some manufacturers have demonstrated bonding over active regions, as well as reverse bonding (first bond on substrate or package and second bond on the chip) without causing any chip damage or reliability concerns. This reverse bonding or reverse loop as termed by some manufacturers has been especially useful in chip stacking.

Since the invention of the transistor [1], semiconductor device technology has had unparalleled growth in all aspects ranging from device density and complexity to market applications. In fact, IC technology has followed a path (Moore's Law) of doubling its complexity (measured by the number of devices per chip), approximately every eighteen months to two years since its birth [2].

Today, ICs routinely have I/O numbers in the hundreds with some chip types exceeding the 1000 mark (application specific integrated circuits (ASICs), microprocessors, etc.) A few devices even have higher I/O numbers, typically around 1500. Future ICs will have I/O requirements in the multiple thousands. A typical system will still, however, contain a wide variety of chip types - ranging from memory with I/O counts less than one hundred to special-purpose microprocessors, random logic, and ASICs with I/O numbers in the thousands. For high I/O numbers, wire bonding is somewhat limited because wire bonds are typically confined to perimeter bonding pads. Even with fine pitch and staggered bonding pads in multiple rows (up to 4 or 5) wire bonding will be limited to a range of 10 to 20

I/O per mm^2. Flip chip [3] assemblies because they use the entire chip (not just its perimeter) can easily support 100 to 200 I/O per mm^2. This increased density coupled with ease of repair and high frequency performance has allowed flip chipping to become the second major form of first level interconnect (despite its cost and lack of flexibility) with over a 15% market share [4].

Wire Bond Types

The three major techniques [4] for wire bonding are: thermo-compression, ultrasonic, and thermo-sonic bonding. Thermo-compression and thermo-sonic bonding methods produce a ball-wedge (first bond-second bond) type bond, where the wedge (tail, crescent, or second) bond lies on an arc about the first bond or ball bond. Ultrasonic bonding (wedge bonding) produces a symmetric wedge-wedge (first bond-second bond) style bond. In ultrasonic bonding, the second bond must lie along the center line of the first.

A thermo-compression bond (or weld) requires two metal surfaces (e.g. bonding wire and pad metallization) to be in intimate contact during a controlled time, temperature, and pressure (or force) cycle. Interfacial bonding temperatures reach the300-400^{o}C [5] temperature range. The bonding cycle, exclusive of bond positioning, takes a fraction of a second. The required heat for weld formation is applied by either a heated capillary (the bonding tool through which the wire feeds) or by mounting the substrate and/or package on a heated stage (column). With stage heat, the die and package combination must come into thermal equilibrium with the stage, which can take seconds to minutes depending upon mass. Because of the high stage temperatures (>300^{o}C) involved in thermo-compression bonding, die attachment is usually limited to the gold-silicon eutectic or certain metal alloy and glass materials. Also, long durations on heated stages can cause reliability problems with previously placed wire bonds [4]. Most modern thermo-compression bonders use a combination of both capillary and stage heat. The capillary is made of ceramic, ruby, tungsten carbide, or other refractory material. Special capillary shapes are needed for fine-pitch and deep access applications.

There are five major steps in the ball bonding process: (1) ball formation; (2) ball attachment to IC or substrate pad (first bond); (3) traverse to second bond location; (4) wire attachment to package or board pad (second bond); and (5) wire separation. The initial ball formation step is accomplished by cutting the wire end as it extends through the capillary with an electronic discharge (electronic flame off). Once cut, the ends of the wire ball up due to surface tension and capillary action. Heat, time, and pressure (force) are the major factors controlling the formation of thermo-compression bonds. Typically, the forces used in thermo-compression bonding are higher than in thermo-sonic ball bonding, resulting in a much more flattened ball. It should be noted also that fine pitch thermo-sonic ball bonding produces very flat, minimal diameter and height balls.

Gold wire is used in most thermo-compression wire bonding processes because it is easily deformed under pressure at elevated temperature and is very resistant to oxide growth that can inhibit proper ball formation. Aluminum wire, because of its rapid oxide growth, has difficulty in forming properly shaped balls on standard bonding machines. Successful aluminum wire ball bonds have been formed using an inert atmosphere around the bonding head to minimize oxide formation. Copper and other materials (e.g., palladium and platinum) have also been ball-bonded in both thermo-compression and thermo-sonic applications. Also, wedge style thermo-compression bonding with many different wire materials has been performed

Ultrasonic bonding (or wedge bonding) is a lower-temperature process in which the source of energy for the metal welding is ultrasonic energy produced by a transducer vibrating the bonding tool (wedge) in the frequency range of 20 to 300 kHz. The most common frequency is 60 kHz although higher frequency ultrasonic energy sources are in use or being considered for difficult bonding situations. The ultrasonic process has been described previously [4]. In ultrasonic bonding, the wedge tip vibrates parallel to the bonding pad. Ultrasonic bonds are typically formed with aluminum or aluminum alloy wire on either aluminum or gold pads. Gold wire ultrasonic bonding has been performed with both round wire and flat ribbon, although it is not widely used because of cost. Ribbon, because of its rectangular cross section, provides a lower inductance interconnect (compared to a round wire of equivalent cross-sectional area) useful in radio frequency and microwave circuit applications. In special applications, copper and palladium have been bonded by the ultrasonic process. The major advantages of ultrasonic bonding (over ball bonding methods) are reduced or no applied stage heat (allowing the use of organic die attach and substrate materials) and bonding at finer pitches (because of the elongated, narrow shape of the bond). Automated wedge or ultrasonic bonders are typically slower than ball bonders due to the requirement that the second bond must be in-line with the first bond; i.e., follow the centerline of the wedge. Thus, either the entire package (substrate) or the bonding head must be rotated to bond in different directions. This slows down the bonding process when compared to ball bonding, which can place the second bond anywhere on a circle surrounding the first bond with only a transversal movement of the head (or stage).

In **thermo-sonic wire bonding**, ultrasonic energy is combined with the ball bonding capillary technique employed in thermo-compression bonding. The thermo-sonic bonding is similar to the thermo-compression bonding, except the capillary heat is reduced or eliminated and the stage temperatures are typically 150^oC or less. To generate the required interfacial heat for welding, short bursts (tens of milliseconds) of ultrasonic energy are applied to the capillary when the wire and the pad are in contact. The forces in thermo-sonic bonding are typically much less than those encountered in thermo-compression bonding, thus allowing bonding over delicate or force sensitive regions. Since the stage temperature is 150^oC or less, the ICs can be attached with epoxy or other organic adhesives without fear of degradation. Because the temperatures are lower, there is also significantly less risk of uncontrolled inter-metallic growth. Thermo-sonic wire bonding is conducted primarily with gold wire, but aluminum, copper and palladium wires have been used successfully. As the metallization on high performance ICs migrates from aluminum alloys to copper, there is a growing increase in the use of copper wire bonds. In a recent survey of chip manufacturers and IC packaging firms about 40% said they use some copper in their product line. No one used it exclusively, but over 70% said they are considering it for new products.

Machine Optimization

The most straight forward way to optimize a bonding machine is to do a fractional factorial experimental design. Typically, the machine parameters of interest include the ultrasonic energy (P), the substrate temperature (T), and the duration of the ultrasonic energy or dwell time (D). The bonding force is usually not considered (once an initial value is picked for the geometry and materials at hand) since it is typically held constant for a given chip, substrate, hybrid, or module configuration. The force is usually set to a level that promotes long capillary lifetime, thus eliminating the need to change capillaries during an experimental set. Details of the optimization process have been presented by several authors [6].

Bonding Wire

The major wire materials used to form wire bonds are gold (pure and alloys), aluminum (pure), aluminum with 1% silicon, aluminum with magnesium, and, more recently, copper. Gold has been the dominant material used for ball bonding, while aluminum and its alloys predominate in ultrasonic bonding. Pure gold (containing less than 10ppm of impurities) is used in most bonding situations. A beryllium additive is used to stabilize the wire and to tailor some of its mechanical properties. The gold wire used for stud bumping (single ended ball bonds) is not as pure, with a significant amount of palladium (~ 1%). Aluminum with 1% silicon wire matches the common semiconductor device metallization and offers improved strength and stiffness over pure aluminum in small diameter applications. Pure aluminum is used in most large-wire applications, while aluminum with magnesium is used in cases where the interconnection is subject to conditions of low-cycle fatigue or on-off power cycling. Properties of bonding wire and potential storage issue have been given previously [4].

Today more copper wire is being used in ball bonding processes. Copper wire has a high electrical conductivity and because of its strength, it resists wire sweep during the injection molding and/or encapsulation processes. Since copper rapidly oxidizes in air, the ball formation process must be done in an inert atmosphere requiring significant bonding machine modifications. Copper has a higher shear modulus than gold (48GPa versus 26GPa) and Cu balls are significantly harder than gold balls, thus creating the potential for damage (such as crater formation) to delicate chips and substrates in the bonding process. Several changes to bonding machine operation have been developed to mitigate the copper hardness problem including increased stage and capillary heat, reduced ultrasonic energy and a rapid first bond touchdown (to keep the ball hot and hence softer).

Bonding to copper pads, unless protected by a gold flash, requires significantly more ultrasonic energy due to the formation of copper oxides. In a similar vein, copper ball bonds made to conventional aluminum alloy pads seems to be viable without major parameter change. Copper-aluminum inter-metallic compounds exist ($CuAl_2$ and CuAl) and some studies have indicated rapid increases in joint resistance during thermal aging. Most studies report the reliability of the copper-aluminum system to be equal to that of the gold-aluminum system.

Cleaning

In order to make high quality, reliable wire bonds, the bonding pads must be clean. Many techniques have been tried over the years, but of all the methods, UV-ozone and oxygen plasma have proven to be the most effective in removing organic contamination [7]. They are also effective against certain inorganic materials that form either a volatile oxide or, if not volatile, one that can be easily removed. Because of the strong oxidizing environments present in O_2 plasma and UV-ozone reactors, metals such as silver, copper, and nickel may oxidize, and thus reduce the ability to form strong wire bonds.

Wire Bond Testing

There are three major wire bond tests in use today: 1) the destructive wire bond pull test (DPT), 2) the non-destructive wire bond pull test (NDPT), and 3) the ball bond shear test. The destructive wire bond pull test is the most widely accepted technique for the evaluation and control of both the wire bond's strength and the associated setup of bonding machine parameters. Since it is destructive, it can only be used on a lot sample basis.

Because of limitations [4] in the DPT, two additional wire bond tests (NDPT and ball shear) were developed. The 100% NDPT provides a degree of confidence that each bond is strong (at least to the nondestructive preset force limit). The NDPT has been shown to have a beneficial effect in eliminating potentially ultra low strength outliers in the pull test distribution of microelectronic wire bonds. Figure 1 is an illustration of a test performed with gold-metallization on ceramic using two identical thermo-sonic wire-bond sample populations. One group had the NDPT applied post bonding and the other did not. Both populations were aged for 240 hours at 125°C. Results showed that the NDPT, which eliminated some low strength bonds prior to burn-in, kept the resulting aged distribution from having catastrophically low strength outliers.

The ball-shear test can be used to investigate not only the ball-bonding pad interfaces, but also the influence of both pre- and post-bonding factors. Table 1 summarizes the areas of application for both the wire bond pull test and the ball-bond shear test. Figure 2 illustrates the improvement that can be achieved in the strength of the ball-bond pad interface by using the ball shear test (instead of the wire bond pull test) to optimize the bonding machine parameters [4].

Unfortunately, as device features shrink and wire bonds become increasingly close together, the mechanical testing methods described above become hard to implement. A new method for wire bond testing has been developed to address these mechanical test limitations [8]. The technique uses a laser to generate an ultrasonic pulse which is passed through the bond interface and detected nearby. The ultrasonic wave travels through the ball or wedge bond and the bond interface onto the surface of the IC. The ultrasonic wave on the surface of the integrated circuit is detected by a laser interferometer that measures changes in the surface height. This laser technique has several potential advantages over the standard mechanical tests including: non-contact, non-destructive, and high speed. The potential exists to integrate the laser detection system with an automatic wire bonder for real-time bond assessment.

Reliability

Wire bonds can have reliability detractors if proper precautions and controls are not exercised. Some of the typical problems include: mechanical wire fatigue due to conditions of thermal or power cycling; interactions both chemical and mechanical with encapsulation during molding and after cure; corrosion induced by the die attach material, the atmosphere, and/or process-related contamination; and wire structural changes due to bonding parameters, such as uncontrolled grain growth associated with the heat-affected zone. Of all the issues two particular ones deserve further discussion: inter-metallic compounds and craters.

Inter-metallic compounds. Aluminum-gold inter-metallic formation occurs naturally during the bonding process and contributes significantly to the strength and integrity of the gold-aluminum interface. Inter-metallic compounds (in particular, $AuAl_2$ or purple plague and Au_5Al_2 or white plague) are generally brittle; and, under conditions of vibration or flexing may break due to metal fatigue or stress cracking, resulting in bond failure [9].

At elevated temperatures, aluminum rapidly diffuses into the gold forming the $AuAl_2$ phase, leaving behind Kirkendall voids [9] at the aluminum-$AuAl_2$ interface. Voiding has also been observed at gold-Au_5Al_2 interfaces. Excessive inter-metallic growth can lead to the coalescence of voids, which can lead to a bond crack or lift and an open circuit. Impurities in the bonding wire, on the pad metallization, or at the wire-bond-pad interface have been shown to cause rapid inter-metallic growth and Kirkendall voiding [9]. The deleterious effects of inter-metallic formation can be controlled if the time of exposure to high temperature is minimized and if proper materials, cleaning, and bonding procedures are used.

Craters. Craters can be a significant problem associated with the bonding and subsequent shearing of ball bonds from silicon integrated circuits. Inter-metallic formation, induced stress, metallization thickness, bonding parameters, and underlying dielectric layers have all been noted to have an effect on crater formation [10].

Results from experimental studies [10] indicated that the stronger the bond, the less likely the substrate was to crater when ball shear tested. This is equivalent to stating that the larger the weld (a flatter bond), the less likely that craters will occur. Once again, this is consistent with the results from finite element modeling and previous data indicating that the manufacture of larger, more robust bonds is less likely to cause craters [10].

Design (Wire Spacing, Loop Height)

Historically, ball bonding standards required relatively large balls compared to the wire diameter (≥ 2.5 times the wire diameter (D)) yielding effective bond areas five to six times greater than the wire cross-sectional area. Today ball bonds are small nail heads (See Figure 3) with sizes down to approximately 25μm in diameter (for 15μm diameter wire). Thus, the typical modern ball diameter standard requires the "ball" to be about 1.2 to 1.5 D. Such diameters yield effective bond cross-sectional areas (wire to pad) of about 1.5 to 2 times that of the wire and thus the bond should still be robust enough to avoid ball lifts under pull testing.

In the ultrasonic bonders, the historical deformation of the bond foot was 1.5 times the wire diameter. Today that deformation is down to about 1.1 to 1.2 D in fine pitch applications (See figure 4). Thus, for the same wire diameter wedge-wedge bonds can be placed closer together provided the required bond wire geometry (height, length, first bond-second bond location, etc.) can be accomplished with the ultrasonic bonders in line step,

Today's packaging environment is creating new geometrical challenges for wire bonding. Not only are we seeing multi-tiered pad arrangements but also the requirement for low profile bonds necessitated by the wide spread deployment of stacked packages. Stacking requires special wire bond profiles and low loop height. As die thickness decreases the spacing between the loops of the different tier wire bonds must decrease proportionally to avoid wire shorts between the different wiring layers. The top layer loop also must remain low (less than a die thickness) to avoid wire exposure during molding.

Some situations even require reverse bonding (i.e. the ball is on the package substrate and the tail bond is on the die). In a reverse bonding process a stud bump is placed on the chip contact pad. This bump provides elevation above the chip and acts as a force distributor for the stitch bonding process to come. Next the chip is wire bonded with the ball bond placed on the substrate and the tail bond placed on the bumped chip bonding pad. Loop height with reverse bonding can be less than 75μm. Over hanging thin die (thickness down to 50μm) require special bonding techniques die to die flexure (bending) upon application of bonding force. The use of delayed application of ultrasonic energy after capillary touchdown is a must.

Fine Pitch

Fine pitch ball and wedge bonding is continuing to evolve rapidly. While most ball-bonded products are still in a pitch range of 80μm to 100μm and above, pitches in the 60μm to 80μm range are in volume production, while pitches of 50μm and below have been used on a limited scale. Such bonds must be made with bottleneck or stepped-neck capillaries to avoid damaging adjacent wires. Today most bonding machines are limited to minimum pitches between 35μm and 70μm. The bond is quite different from a traditional ball bond. It is quite low, almost nail head-like with a "ball" diameter in the range of 1.2-1.5 D (See Figure 3). The low height of the nail head (typically 5 to 15μm) makes the fine pitch ball bond difficult to shear. Most fine pitch ball bonds are still done with 25μm diameter gold wire, although 15μm to 20μm diameter wire is gaining popularity. Wire diameters less than 25μm are subject to greater damage in handling and molding operations.

Wedge bonding leads the fine pitch parade. Wedge bonds at pitches of 40μm have been demonstrated (See Figure 4) using 10μm diameter gold wire. Wedge bonds at 60μm and above are made in high volume production using 25μm diameter gold or aluminum wires. To achieve such fine pitches, the wedge bonds typically have low deformation (≤ 1.2 D). Narrow, cutaway wedge tools are necessary to prevent adjacent wire damage during bonding.

Higher Frequency Bonding

Most of the world's current wire-bonding machines have ultrasonic generators and transducers that operate at 60 kHz. The choice of 60 kHz was made several decades ago based on transducer size and its stability during the bonding operation. Other frequencies from 25 to 300 kHz have been used to attach wires. Higher frequencies produce better welds at lower temperatures in shorter bonding times (dwell times). Higher frequency wire bonding also improves bonding to pads on soft polymer layers such as Teflon®, unreinforced polyimide, and flex-circuits. Results from a direct experimental comparison between 60 kHz and 100 kHz bonding are shown in Table 2. In these experiments three pad metallization types were used: pure aluminum, aluminum plus 1% silicon, and pure gold.

Shear test data with gold metallization on ceramic substrates showed that an optimized 100 kHz system produced much stronger bonds than the 60 kHz system (See Table 2). When the data was analyzed for the Al + 1% Si metallization (on oxidized silicon), the 60 kHz bonds appeared somewhat stronger (statistically significant). Similar results were observed on thermo-sonic ball bonds attached to an integrated circuit chip (Al + 1% Si metallization), on which both the ball shear test and the wire bond pull test gave a small edge to the 60 kHz system. Independent of frequency, the difference in ball bond shear strengths between metallization types, was relatively large and highly significant. Bonds on gold were always stronger than bonds on Al + 1% Si metallization.
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Table 2 also shows results for both 60 and 100 kHz bonded samples under conditions of thermal aging (120 hrs at 150°C). Again, large and significant differences were observed in the shear strengths between the metallization types with bonds to gold being much stronger than bonds on Al + 1% Si metallization. These results are consistent regardless of the bonding frequency. After aging, the shear strength of the bonds on gold, at both frequencies, remained essentially unchanged. On the Al +1% Si metallization the strength of the bonds increased significantly for both frequencies. Again, 100 kHz bonding produced stronger bonds on gold metallization, while 60 kHz bonding appeared to have a slight edge on Al + 1% Si.

Extreme Temperature Environments

Wire bonding has proven to be a useful interconnection for ICs and other devices operating over a wide range of temperatures. In fact, with careful selection of materials, wire bonded interconnections can be used in packaging chips and other electronic components and devices from below -200°C to over +500°C. Such temperature extremes are found in many current and future applications including: deep space, oil and geothermal wells, rocket and jet engines, and at some locations in and on the engines of automobiles. Single metal systems, such as gold-gold or aluminum-aluminum, have been shown to be more reliable at high temperatures. In fact, gold-gold interface strength has been shown to increase with both time and temperature [11].

Over the years, high temperature testing has shown that the gold-gold interface holds up well at temperatures above 200°C. Benoit, et al. [12], reported excellent results when heating gold-gold systems to 350°C for 300 hours. Recent experiments were conducted by this author to determine the high temperature limits of the gold-gold bonding system [4]. Thermally aged samples (gold wire bonds on gold pads with both bare silicon and oxidized silicon substrates) on both substrate types show consistent and expected wire bond pull test and shear test results up to 350°C. At 400°C the wires on the bare silicon substrate displayed an anomalous gold migration effect [4] and the test on silicon was terminated. Continued testing of the samples on SiO_2 produced consistent results to at least 500°C. At 550°C the samples began experiencing metal lifts and the tests were terminated. Gold-gold bonds above 550°C on SiO_2 are believed possible with changes to adhesion layer materials and/or thicknesses.

While the author has not investigated the aluminum-aluminum bonding situation personally, there is considerable evidence in the literature [13] that this interface would also be robust at elevated temperatures. Given aluminum's melting point of 660°C (compared to gold at 1060°C), it should be recognized that its upper temperature use limit would be more restricted than that of gold. Aluminum-aluminum interfaces remained strong under testing for 300 hours at 350°C [13].

Summary

Wire bonding continues to be the dominant form of first-level chip connection. Over 80% of the worlds chip production is wire bonded. Because of its sheer volume, flexibility, and low cost, it will continue to dominate chip interconnect for decades to come. Wire bonding is accomplished by three basic techniques using a variety of wire and pad metallurgies. Wire bonding is robust and, on rigid substrates, has been shown to be extremely reliable. Bonding to softer substrates, small pads, unconventional metallurgies and stacked components has presented challenges. With appropriate care and understanding of the processes, the wire bonded interconnect, even under these challenging conditions, can be performed reliably with high yield. Wire bonding is continually improving through advancements in automation, refinement of welding kinetics, improvements in wire and pad metallurgies, improved cleaning methods, and a better and wider spread understanding of wire bonding science. Work at extreme temperatures has begun and, at least, the gold wire-gold pad interface appears viable over a 700ºC ΔT (-200ºC to +500ºC).

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Table 1: A comparison of areas of applicability between the wire bond pull test (ASTM Standard Test Method F458-84), and the ball bond shear test (ASTM Standard Test Method F1269-89).

Area of Applicability	Wirebond Pull Test	Ball Bond Shear Test
Module geometry	Yes	No
Wirebond geometry	Yes	No
Wire quality, defects, etc.	Yes	No[a]
Second Bond	Yes[b]	No
Bonding machine set-up, optimization, etc.	No[c]	Yes
Process development	No[c]	Yes
Substrate, bonding pad quality	No[c]	Yes

[a] Sensitivity to contamination, insensitive to mechanical defects
[b] Extremely dependent on geometry
[c] Insensitive unless the effect is catastrophic

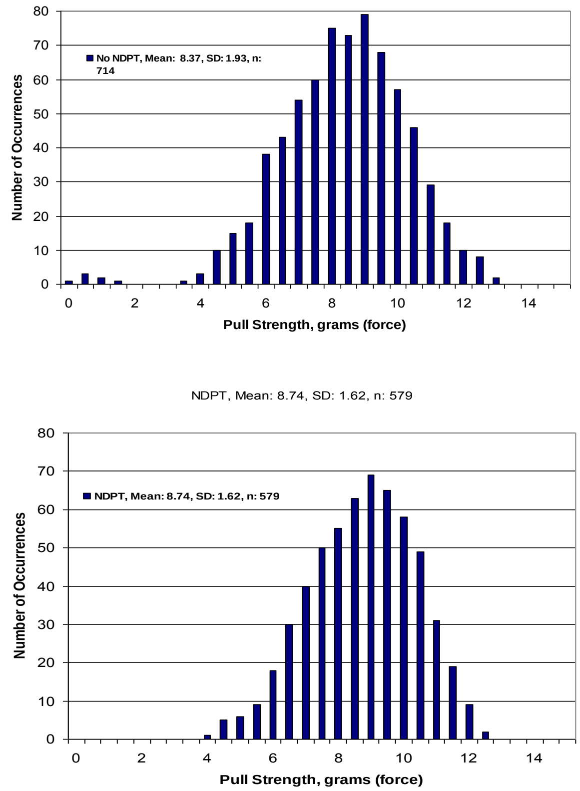

Figure 1: Wire Bond pull strength histograms for 25 µm diameter thermo-sonically bonded gold wire on gold thin-film metallization on highly polished alumina ceramic. Top Histogram: after burn-in without NDPT, Bottom Histogram : after burn-in with NDPT applied post bonding. NDPT limit was 3 grams (force).

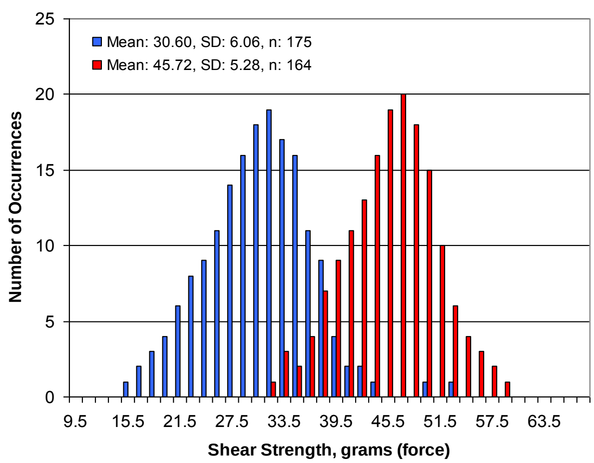

Figure 2: Histograms of gold thermo-sonic ball bond shear strengths for bonds placed on aluminum metallization (over silicon). Histogram A (left or blue bars) are the shear test results after the bonding machine was set up using the wire-bond pull test. Histogram B (right or red bars) are the shear test results after the bonding machine was optimized using the ball shear test.

Table 2: Gold Thermo-sonic Wire Bond Shear Strength (grams(force)) for 60kHz versus 100kHz on Various Substrates and Under Thermal Aging (120 hours at 150°C).

Metal (Substrate)	**60kHz**	**100kHz**	**ΔX_1[a]**
Au (Ceramic)	68.4±3.7	84.8±6.5	**16.4**
Al+1%Si (Silicon)	54.0±3.2	50.6±2.9	**3.4**
ΔX_2[b]	**14.4**	**34.2**	
Au (Silicon) Initial	81.4±4.6	97.4±3.7	**16.0**
Au (Silicon) Aged	82.1±3.3	96.4±4.6	**14.3**
ΔX_3[c]	**0.7**	**1.0**	
Al+1%Si (Silicon) Initial	47.0±3.7	46.5±4.3	**0.5**
Al+1%Si (Silicon) Aged	57.8±3.3	56.1±4.1	**1.7**
ΔX_4[d]	**10.8**	**9.6**	

[a]ΔX_1 = 60kHz-100kHz mean difference
[b]ΔX_2 = Gold-Aluminum mean difference
[c]ΔX_3 = Gold Initial-Gold Aged mean difference
[d]ΔX_4 = Al+1%Si Initial-Al+1%Si Aged mean difference

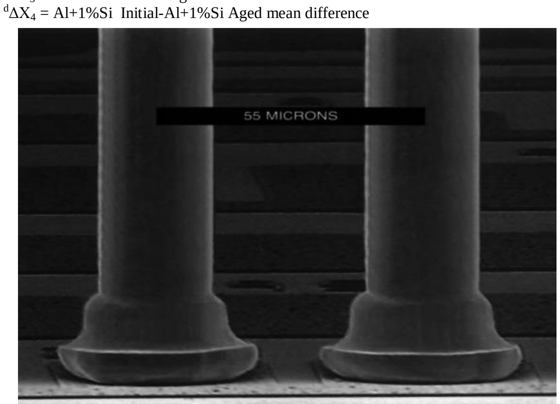

Figure 3: Scanning electron photomicrograph of ultrafine pitch (55µm) thermo-sonic ball bonding. The bonds were made on a K&S Model 8020 automatic ball bonder using 23µm (0.9 mil) diameter gold alloy wire. Pad metallization was Al + 1% Si + 2% Cu on SiO_2 with nominal 1µm thickness. (Photomicrograph courtesy of L. Levine, K&S).

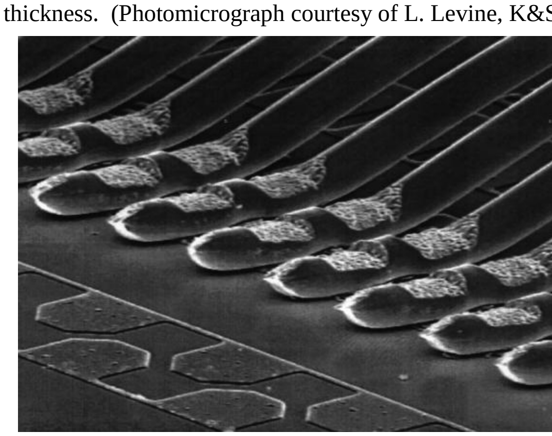

Figure 4: Scanning electron photomicrograph of ultrafine pitch (40µm) wedge bonds. The bonds were made on a K&S Model 8060 automatic wedge bonder using 20µm (0.8 mil) diameter gold alloy wire. Pad metallization was Al + 1% Si + 2% Cu on SiO2 with nominal 1µm thickness. (Photomicrograph courtesy of L. Levine, K&S).