Fine Pitch Cu Wire Bonding – As Good As Gold

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Abstract

Fine pitch wire bonding has traditionally been the domain of gold wires. The significant increase in gold commodity prices has driven a continuous reduction in wire diameters to minimize the impact of the raw materials cost of the wire. This has reached a point now where copper wires are beginning to displace gold wires despite the technical challenges associated with copper wires. The basic challenges like propensity for oxidation, hardness and propensity for corrosion can be managed with the appropriate investment in tooling and infrastructure. Doubts are persisting about yield and reliability. With a very methodical approach to developing the process controls, it can be demonstrated that yields are as good as those for gold despite the fact that copper bonds are not reworkable. Likewise, the typical JEDEC reliability tests can be full filled. Here, an extensive effort has been placed on extended JEDEC testing to demonstrate that with good process control and proper materials choices, test durations of more than 2x can be passed. This excellent performance demonstrates that copper wire bonding can be as good as or better than gold wire bonding.

Introduction

Wire bonding was developed as the first interconnection method over 40 years ago and still is the dominant technique for chip to substrate interconnection with a penetration rate of about 90%. While some have predicted the end of wire bonding due to interconnect density limitations, equipment and wire manufacturers as well as assemblers have been able to advance their technology and delayed the wholesale conversion to flip chip bonding. Gold wire bonding has been demonstrated down to < 40 µ bond pad pitches and wire diameters of 0.5 mils. Multi-tier bonding has been demonstrated up to four tiers which is the equivalent of peripheral flip chip bonding but at much greater pitch density. Copper (Cu) wire bonding also has a long history of more than 20 years but had been limited to high power applications with wire diameters of > 2 mils. Therefore, many of the technical challenges associated with Cu wire like hardness, propensity for oxidation and corrosion have been experienced and mastered. The Cu bonded dice were also designed and built with Cu wire bonding in mind i.e. die pad structure and metal thickness were optimized accordingly.

Fine pitch Cu wire bonding or fine diameter Cu wire bonding had not been seriously considered as long as Au commodity prices were in the low 100s dollar range. Now that commodity prices have surpassed USD 1,200 and appear to stay at these levels (Fig. 1), the continuous drive for cost reduction is demanding its toll from wire bonding. The expected cost reduction is more than can be achieved by reducing Au wire diameters except for the finest diameters of =< 0.6 mils.

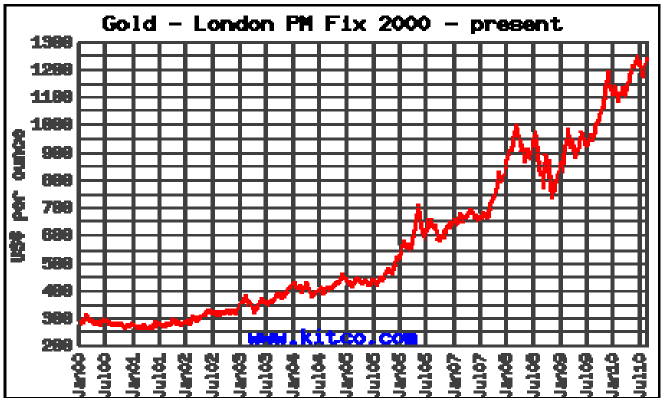


Fig. 1: Gold commodity price evolution over the past ten years

The previously mentioned technical challenges have been exacerbated by the advancement of wafer nodes. The development of low dielectric constant (lowK) wafer dielectrics have resulted in mechanically brittle dice. Every new wafer node is based on lowerK dielectrics and hence ever more fragile dice. This has been difficult already for Au wire bonding and has lead to the development of more robust pad stack structures. Another challenge has been set forth by bonding over active die area (circuit under pad, CUP) which required further enhancement of pad structures. Some relief was gained from the introduction of Cu metal in the wafers which is more robust than the prior aluminum (Al) die wiring. However, the typical pad finish is Al which is softer than Cu and always leads to some degree of Al splash on impact of the Cu ball.

To date, all dice are designed and built for eventual Au wire bond assembly. Even Cu wafers have an Al pad finish except for a few products which employ different finishes like nickel/gold or nickel/palladium/gold. Here, the focus will be on dice with Al pads or Al pad finishes. The bonding parameters and reliability performance differ greatly between the different finishes.

Literature Review

Though Cu wire bonding received great attention only recently, its engineering feasibility studies have been going on for over twenty five years. Key engineering and reliability issues of Cu wire bonding have also been pointed out long ago [1-5]. To overcome Cu oxidation during electronic flame off (EFO) that leads to a free air ball (FAB) of an undesired appearance, forming gas typically composed of 95% N_2 and 5% H_2 was proposed [3] and widely adopted. The H_2 in the forming gas provides additional thermal energy to melt Cu during EFO [6-8], and may convert Cu oxide back to Cu [9]. In response to the increased hardness of the Cu FAB, soft Cu wires with high Cu purity or dopants were sought [10] to soften the wires. However, wire hardness may have little connection with the recrystallized FAB hardness [11]. The key factor may actually be the work hardening that occurs during the actual bond formation. Initial studies to characterize this phenomenon have been performed already [11]. On the other hand, the Al pad can be doped with Si and/or Cu (e.g., [2, 3, 5, 12]) to resist impact and ultrasonic loadings during Cu wire bonding

The most distinguishable feature of Cu wire bonding compared to conventional Au wire bonding, however, is the spotty and small coverage as well as slow growth of Cu-Al IMCs [1, 3, 13 - 22]. Yet, slow Cu-Al IMC growth is considered an advantage in enhancing reliability of Cu wire bonding [1, 3, 9, 10, 12, 16, 21The strong bondability right upon bonding despite the limited IMC coverage on the Cu-Al interface has attracted intensive investigations; as a result several hypotheses on the bonding mechanism have been proposed [14-16, 20, 23]. Owing to the ease of oxidation of Cu, long-term durability of Cu wire bonding under varying temperature and humidity conditions have become an essential issue in the industry. However, the reliability data, in particular for fine pitch Cu wire bonding, is so limited and dispersive such that, for instance, whether the ionic impurity in the mold compound leads to the corrosion of Cu wires [4, 8, 24] is still in dispute [1, 15, 25]. Pd-coated Cu wire [8, 26] was developed following the demand of enhancing long-term reliability of Cu wire bonding and shelf life. A recent update on Cu wire bonding reliability in a manufacturing environment can be found at [29].

Manufacturing Process Development

For the purpose of this discussion, fine diameter Cu wires refers to wire diameters below 1.2 mils. In fact, the majority of the experiences described here is based on 0.8 mils diameter wire, either 4N Cu wire from Heraeus or 1X Palladium coated Cu wire from Nippon Steel. The wire bonders were KnS models Maxum Ultra and Maxum Plus as well as lately Iconn. All wire bonders are equipped with inert gas EFO kits for Cu or CuPd wires. A proprietary capillary design was used and substrates and dice are customer specified with nodes ranging from 180 to 45 nm.

The first step in wire bonding is the free air ball (FAB) formation. For 4N Cu wire forming gas (95% nitrogen and 5% hydrogen) was used as a shroud and for PdCu wire nitrogen was used. The FAB geometry was tuned to yield a spherical FAB without any surface blemishes. This is achieved as usual by optimizing sparc current and duration as well as the gas flow. The spherical ball shape is a good indicator that an 'oxide-free' ball has been formed. This first step is actually one of the easier steps in the process. Examples of good and poor FABs are shown if Fig. 2.

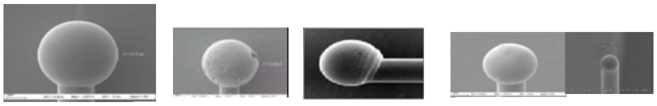

Good FAB Void Asymmetry Unstable FAB

Fig. 2: Examples of good, spherical and unoptimized free air balls.

The second step is the actual bond formation on the die pad. The process of tuning the bonding parameters is essentially the same as for Au wires. Albeit considerably more adjustments are required to ensure that no pad cratering or die cracking occurs due to the more aggressive conditions required to achieve a strong bond. The bond parameter optimization typically follows the standard procedure design of experiment (DOE) as for Au albeit the process window turns out to be considerably smaller than for Au. The boundary conditions are that Al splash, which is usually quite pronounced, must be contained within the bond pad opening (BPO) as shown in Fig. 3. Further, the residual Al thickness has been selected to be 100 nm minimum. It has been shown separately, that this thickness typically survives JEDEC TCT of more than 1000 hrs.

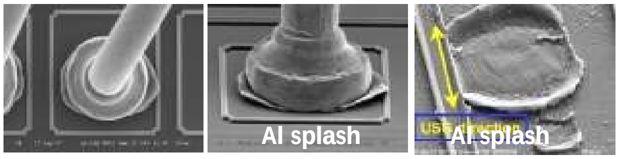


Fig. 3: Examples of Al splash which is contained within the bond pad opening.

While the exact bonding parameters are dependent on the particular devices and considered proprietary, the bond attributes are open and defined as specified (some parameters are listed in Table 1). The wire pull and ball shear strength at time zero are considerable higher than for corresponding Au wires although the AlCu intermetallic compounds is very thin. Part of the process optimization is to obtain adequate IMC coverage. During process devlopment this IMC growth is tracked throughout the entire assembly process and at times through reliability testing. In general, the observations in above literature have been confirmed: initial IMC is very thin and difficult to detect and IMC growth is very slow, more than an order of magnitude slower than Au.

Table 1: Some typical Cu wire bond specifications

Specification	Wire pull (gf)	Ball shear (gf)	Ball thickness (µm)
18 µm (0.7 mil)	3	8	10 +/- 3
20 µm (0.8 mil)	4	10	11 +/- 3
23 µm (0.9 mil)	6	12	13 +/- 3
25 µm (1.0 mil)	8	15	15 +/- 3

Bonded ball thickness as well as diameter is measures of the forces applied during bonding as well as the extent of work hardening that has taken place. It can be determined from the same cross-section to measure the residual pad thickness. In Fig. 4 several slices through the same ball have been taken to determine the uniformity of ball height / thickness and pad thickness. It can be seen that relatively good uniformity can be achieved with proper optimization.

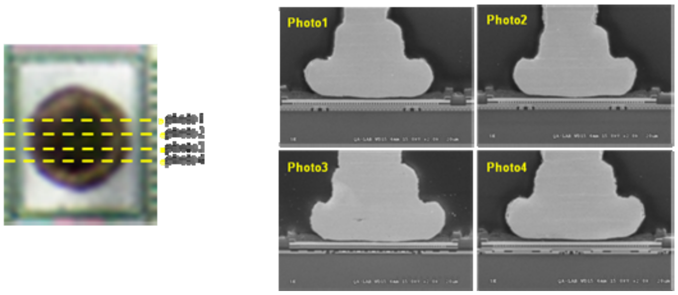


Fig. 4: Cross-section of a Cu wire bond to various depths to ascertain the uniformity of bond and ball

Fig.4 also yields the residual Al thickness under the ball. It is controlled to exceed 100 nm. That was deemed sufficient given the slow IMC growth rate for AlCu IMC during typical JEDEC reliability testing and operating life.

Pad cracking and cratering are typically analyzed visually after etching off the ball and Al pad [1, 27, 28]. A great new tool to provide more detailed information is focused ion beam (FIB) microscopy. FIB can provide high resolution pictures of pad structures and whether any deformation or defects have been induced during bonding (see Fig. 5). FIB does not lend itself to in-line process control or monitoring due to analysis time and expense and is therefore used primarily during the development phase of a project.

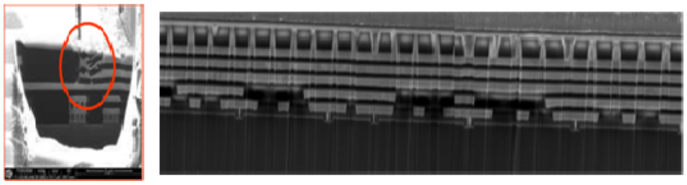


Fig. 5: FIB spectra of pad stacks: pad damage (left) and no cracking (right)

Looping of the stitch bond has not presented any difficulties albeit the most aggressive loops are not yet in production. Especially with latest generation bonders and the additional control parameters available, the challenges of very low loop heights and particular shapes should be minimized. 50 µ loops have been qualified at this stage of the program. The seond bond or stitch bond has not been any challenge to date. No changes in substrate or substrate surface finish has been required either to obtain strong bonds as reflected in the wire pull values. This applies to lead frames as well as organic substrates. Bond shapes are equivalent to Au. The second bond certainly benefits from an inert gas shroud by minimizing oxidation of the wire even though the temperature is between ambient and substrate temperature. In a high volume naufacturing environment, the shelf / floor life of the wire is not really an issue as the rate of consumption is a fraction thereof. But manufacturing floor management is simpler with a wire of long shelf life like PdCu wire.

Lastly, die, wire bonds and substrate are encapsulated via molding. The mold process and pre-mold plasmas do not require any change other than the usual optimizations of plasma. Concerns have been raised about the reliability of standard mold compounds due to the propensity of oxidation and corrosion of Cu. Corrosion is a known phenomenon also for Au wire on Al pads. The corrosion mechanisms are essentially the same for Au/Al IMC and Cu/Al IMC. Typically two IMCs are formed during bonding which grow at different rates during the entire packaging and subsequent operational life of the package. One of the IMCs is (more) vulnerable to the attack by halogen ions in th epresence of moisture. The Al is attacked and converted into Al oxide while the halogen ion is reformed. The corrosion therefore continues until the weak IMC is consumed. The end result is a crack between the Al oxide and the Cu or other IMC. After decapsulation this appears as a lifted ball with Al oxide on the pad.

Extensive efforts have therefore been undertaken to reduce the amount of halogen ions in the mold compounds. This is an effort that has started long ago for Au and is being continued vigorously for Cu. The mold compound suppliers have an extensive repertoire of actions to minimize the effective amount of halogen ions in the mold compound. Apart from screening resins for intial low halogen content, additives act as ion trappers and buffer the pH as well as modify the glass transition temperature. The chemistries involved are of course proprietary.

There are of course other potential sources for halogen ions: substrate, wafer, die attach compound and the operating environment with operators figuring highly. Substrates and wafers need to be cleaned appropriately to ensure cleanliness with aqueous washes and or plasma. Die attch compounds need to meet low halogen specifications which appears to be accomplished easily. Operator training and clean room practices must met high standards of cleanliness.

Therefore, as a general practice of wire bonding and especially for Cu wire bonding, strict manufacturing floor management is key for successful high volume manufacturing. This entails strict clean room management, decidcated tools and operators, as well as strict adherence to hold times between operations to minimize oxidation and surface contamination. Cu wire bonds are not reworkable and therefore first pass yields are final yields for bonding. With such a rigorous methodology it is possible to achieve yields equivalent to Au and machine stop rates of less than the traditional Au floor. Of course the learning can be reapplied to the Au floor and improve its perfromance.

Based on above learning experiences for package types: SO, QFP, QFN and BGA as well as dice from virtually all wafer foundries, a rigorous methodology for the evaluation and qualification of new devices has been devised. It is a three step procedure (see Fig. 6 for the applicable flow diagram) where bondability of a die is established with a base set of parameters in phase one. In phase two the bond parameters are optimized and the bond attributes are characterized. In some cases, short loop reliability tests are being performed. Finally in phase three, the actual qualification hardware is being built and tested with the usual JEDEC tests as specified by the application environment. If the new die has some novel attributes like pad stack, metal thickness, etc., additional characterization loops and tests may be performed to ensure the reliability of the package.

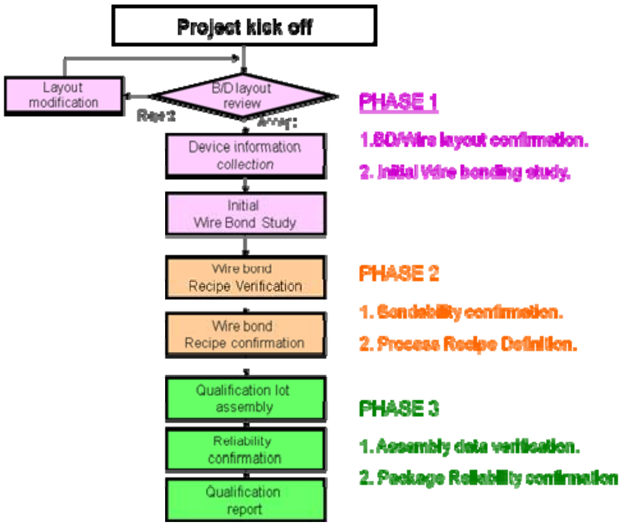


Fig. 6: Flow diagram of the three phase evaluation and qualificaton which is used for Cu wire bonding of new dice.

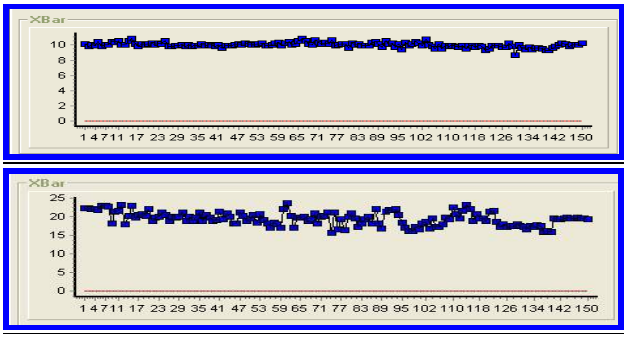
Reliability and Performance of Cu Wire Bonding

To demonstrate the reliability of above Cu wire bond process, extended reliability testing has been performed on a number of devices. It has been demonstrated that more than 2x of standard JEDEC life can be achieved as shown in Table 3. These reliability data are collected as part of the monthly reliability production monitoring across different package types and dice from different wafer nodes / foundries.

Table 1: Extended reliability testing of selected packages – number cycles / hours passed for dice from different wafer nodes and foundries.

Package Type	Body Size	PCT	TCT	HAST	HTST	THT
		hrs	cycles	hrs	hrs	hrs
QFN	8 x 8		2,000	200	2,000	2,000
aQFN	6 x 6		2,000	200	2,000	2,000
aQFN	11.5 x 11.5	168	500 *		500 *	
LQFP	10 x 10	336 F	1,000			
LQFP	14 x 14	264	1,500 F			
LQFP	20 x 20	336	2,000	192	2,000	
TQFP	14 x 14		2,000	400 F	2,000	2,000
TFBGA	9 x 9		3,500 *	144 F		
TFBGA	12 x 12		3,000 *	192	2,000	
* test in progress		F failed at this read-out				

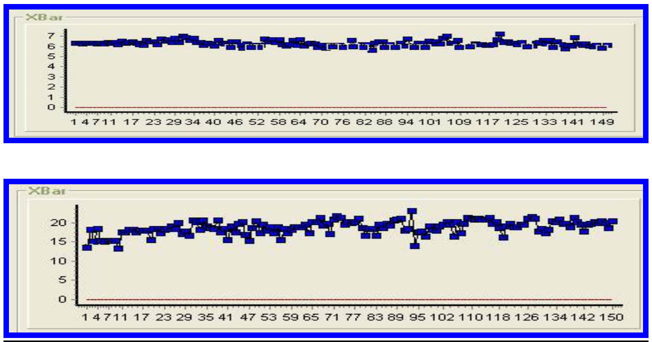
Typical results for wire pull and for ball shear are shown in Fig. 7 and 8 for a lead frame package and BGA package respectively. Pull strength are noticeably higher than for corresponding Au wires. This is observed at time zero despite the fact that there is only spotty IMC observed. The typical failure mode is neck break. Ball shear results likewise exhibit a strong bond. Yield has been worked up to be equivalent to Au wire bonding.



Ball size: Max.=42 um. min = 38 um. average = 40 um. Cpk = 5.33
Ball thickness: Max.=13 um. min = 9 um. average = 10.5um. Cpk = 1.31
Loop height : Max.=148um. min = 124um. average =131.6um. Cpk = 4.83
No cratering

Fig. 7: Cu wire monitoring data for a 28×28 mm LQFP with 20 µm diameter wire

As demonstrated by above data, Cu wire bonding reliability is equal or better tan for Au wire. All the potential advantages of Cu wire have not yet been utilized. E.g. it is anticipated that wire length for the same diameter can be extended due to the higher stiffness of Cu which results in less wire sweep and sag. Those design rules will be developed in the future.



Ball size: Max.=43 um. min = 37 um. average = 40 um. Cpk = 4.66.
Ball thickness: Max.=14 um. min = 9 um. average = 11.2um. Cpk = 1.04
Loop height : Max.=150 um. min = 122um. average = 131.6um. Cpk= 3.95
Cratering: None

Fig. 8: Cu wire monitoring data for a 12×12 mm TFBGA with 264 I/O and 20 µm diameter wire

Conclusions

Cu wire bonding for fine wire diameters has been developed for implementation in manufacturing. Currently the process is used for both Cu and PdCu wire in very high volume operations and is close to 25% conversion from Au to Cu at the time of this writing. The success is based on the development of the base bonding parameters and on a rigorous methodology for qualification of new devices. Strict management of the manufacturing floor is a key ingredient to this performance. The yields for Cu wire bonding are equivalent to Au after meticulous improvements. It is anticipated that the conversion rate from Au to Cu will continue at a rapid pace, motivated by the high market prices for Au.

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