Fine Pitch Cu Wire Bonding Capability – Process Optimization and Reliability Study

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Abstract
Wire bonding has been around for over 70 years and it is still growing. The most recent advances in wire bonding are the wide proliferation of fine pitch Cu wire bonded applications and the development of fine pitch Cu capability extending to the newest technology nodes. Around 2008, fine pitch Cu wire bonding started to take off driven by the skyrocketing Au price. Since then, Cu wire bonding capability has improved dramatically so that today's advanced technology devices such as 28nm and 20nm nodes are being bonded with Cu wire including Pd coated and AuPd coated Cu wire. It turns out that not only is Cu wire cheaper, but it is more suitable for high I/O counts, and fine pitch advanced node applications due to its better electrical and mechanical properties.

This paper examines the most advanced Cu wire bonding capability using a Cu optimized process called ProCu™ process. 40um pitch and 35um pitch capability are demonstrated using this new ProCu process. Process responses such as process bonding windows, intermetallic coverage (IMC), and free air ball size control are studied in detail. The ProCu process achieved fine pitch capability for 40um as a robust production process and it also shows that 35um pitch with 13um (0.5mil) wire is a possibility using the latest technology.

The JEDEC Reliability test has been a challenge for Cu wire bonding especially for fine pitch applications. As part of this paper, we also examined reliability aspects of fine pitch Cu wire bonding. TEM analysis was used to understand the major factors that affect Cu wire bonding reliability.

Key words
Cu Wire Bonding, Fine Pitch, Reliability, Advanced Node Device Bonding, Molding Compound, TEM

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I. Introduction
There have been many technology advances throughout the history of wire bonding. Speed and pitch capability are the key measures for wire bonding technology advances. Over the last 20 years, the Au wire bonding pitch capability has improved dramatically from over 100 um pitch to 35um pitch. The drive for fine pitch capability is a result of increasing integration and functionality of new wafer technology nodes that have followed the well-known Moore's law. On the other hand, the industry continues the drive for cheaper products. For the wire bonding equipment, the result is the increasing throughput and the introduction of Cu wire bonding for fine pitch applications. For the 25um diameter wire, the cost of Cu wire and Pd coated Cu wire is less than one tenth the cost of Au wire. In a cost comparison of Au wire bonding, Cu wire bonding and Flip Chip, Au wire bonding becomes more expensive than flip chip for devices with 1024 I/Os and more. If Cu wire is used, the cost is cheaper with wire bonding than flip chip for packages up to 2000 I/O count [1].

Other benefits of Cu wire include better electrical conductivity and mechanical strength. The higher electrical property improves package performance. The higher mechanical strength enables wire bonding high density complex looping devices as in the case of high I/O count advanced node devices. An example is shown in Figure 1.

One of the challenges for Cu wire bonding is the reliability test especially the HAST test due to the corrosion characteristics of the Cu-Al intermetallic. Understanding the reliability requirement of fine pitch Cu wire bonded devices is important. Extensive research and development provided excellent solutions in molding compound [2,3], bonding wire [4,5] and optimized wire bonding process [6,7] . One of such process the ProCu™ process that is developed to enable fine pitch Cu wire bonding with higher reliability and also higher throughput. In this paper, ProCu

process is used to demonstrate fine pitch capability and reliability of Cu wire bonding process.

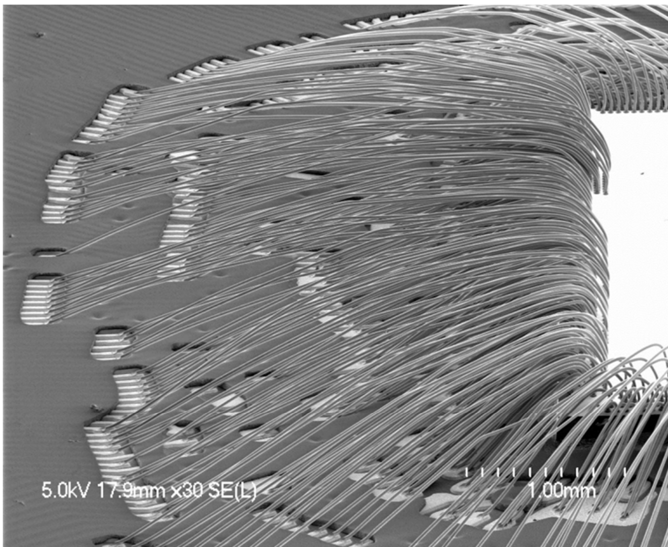

Figure 1. Fine pitch, high density advanced node wire bonded device with PdCu wire

II. Fine Pitch Cu wire bonding study

A. 40um pitch 15um diameter PdCu wire bonding study

The pitch capability of Cu and Au wire at present time is around 40um. In Au wire, 18um diameter (0.7 mil) is used in the 40um process. Bigger diameter wire was used in Au than Cu since there is no Al splash concern in Au wire bonding and bonded ball can be bigger than Cu wire. On the other hand, 0.6mil Au wire is harder to handle and has poor looping performance. To our best knowledge, there is limited production for 40um pitch Au wire production. The leading edge Cu wire bonding production capability is also 40 um pitch but with 15um diameter wire [8]. The bond pad opening is around 35um. 40um pitch process is studied in this paper. The process was developed on ProCu Plus bonder using ProCu5 process in the process lab. The wire is 15um AuPd coated Cu wire (Tanaka CLR-1A). The capillary used is K&S ACSPro capillary AP501822LX0023 with hole diameter of 18um, chamfer diameter (CD) of 22um and tip diameter of 50um. Test device is K&S test die with 1.4um Al thickness on BGA substrate. The spec is ball diameter of 27um, minimal IMC% >80% and average IMC% > 85%, Al splash <34um to meet the requirement of a 40 um pitch process. 27um ball diameter is set as the input for the ProCu5 process. A range of BSA settings are tested and showed good results that met all target spec. BSA is the Bond Strength Adjust parameter in ProCu process, it adjusts the USG level of the bonding stage.

Table1: Process window test for BSA range

BSA% (USG)	Shear/ Area (gr/mil^2)	Ball Dia (um)	Ball Height (um)	IMC (%)	
				Avg	Min
Spec	>7	27 ± 1.5	7.5 ± 1.5	>85%	>80%
60%	8.7	27.3	7.0	92%	85%
66%	8.9	27.5	6.9	92%	86%
72%	10.4	27.4	6.8	95%	89%

Table1 shows the bonding results for ball size, shear and IMC%. For the 3 BSA settings tested, the results met spec. For Cu wire bonding, it is important to have a good process window not a single point process to ensure process robustness when running production on many wire bonders. Besides meeting the ball size and bond strength spec, it is also important to control Al splash to avoid pad damage and bond short. The Al splash measurement met the 34um target spec. Figure 2 shows the IMC coverage and ball cross section at the center cell BSA setting. It shows high IMC%, small amount Al splash (shown as the dark area), round shape contact area and flat cross section area indicating a good process.

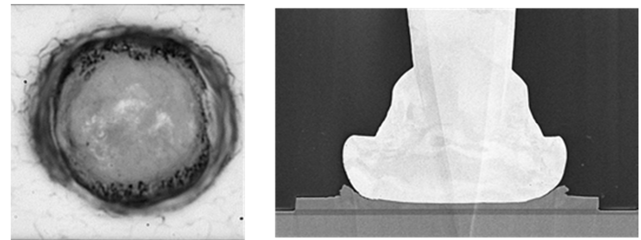

Figure 2. IMC and cross section for BSA=66%.

Next, we verified the results across 5 production machines. Portable results are achieved across all machines meeting all wire bonding specifications. This shows the leading edge wire bonding technology is fully capable to support 28nm and 20nm wire bonding, that may requires 40um pitch capability, in high volume production.

Table 2 Multiple machine 15um wire process test

MC #	Area (gr/mil^2)	Dia (um)	Height (um)	IMC (%)	
				Avg	Min
Spec	>7	27 ± 1.5	7.5 ± 1.5	>85%	>80%
MC#1	8.7	27.2	6.8	92%	88%
MC#2	9.3	27.7	7.0	90%	86%
MC#3	8.0	28.0	8.3	90%	84%
MC#4	7.9	27.4	7.4	94%	90%
MC#5	8.6	27.3	7.0	90%	86%
Avg	8.5	27.5	7.3	91%	87%
Min	7.9	27.2	6.8	90%	84%
Max	9.3	28.0	8.3	94%	90%

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B. 35um pitch 13um diameter PdCu wire bonding study

To understand the fine pitch capability of the latest Cu wire bonding equipment and process, we also studied 13um diameter wire and a 35um pitch process. The wire is AuPd coated Cu wire (Tanaka CLR-1A). The capillary used is a prototype K&S ACSPro capillary with hole diameter of 15um, chamfer diameter (CD) of 19um and tip diameter of 45um. The test device is the same as in the 40um pitch study. The spec is target ball diameter of 24um, minimal IMC% >80% and average IMC% > 85%, Al splash <30um to meet the requirement of a 35um pitch process.

First, we studied the free air ball formation of 13um wire. With the latest cover gas system, we are able to form repeatable and round free air ball. Table 3 and Figure 3 show the free air ball diameter measurement for this process and pictures of the free air ball.

Table 3: SEM measurement of free air ball diameter and actual wire diameter

	FAB (µm)	Wire Dia (µm)
Average	**20.8**	**13.2**
Stdev	0.23	0.25
Max	21.1	13.4
Min	20.5	12.6
Range	0.6	0.8

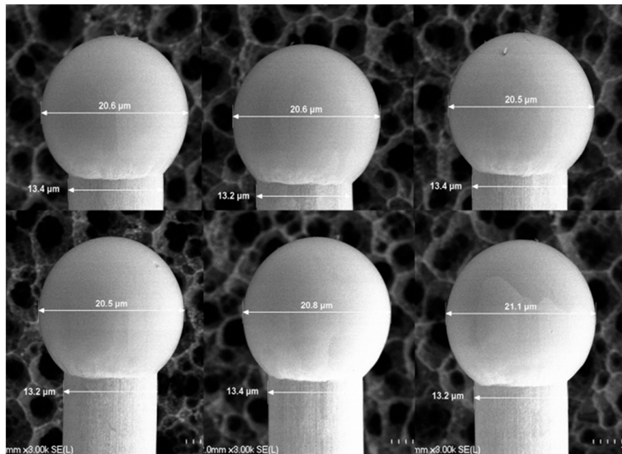

Figure 3. SEM pictures of formed free air ball for 13um wire.

Next we examine the 1st bond process with the 13um wire. 24um ball diameter is set for the ProCu5 process. The bonding results were shown in Table 4, with the 1st bond bonded ball, cross section and IMC image shown in Figure 4. A range of BSA settings were tested and showed good results that met all target spec. This process shows a good process window. The process is robust enough for production on multiple machines. However, both the wire and the capillary are still produced as prototypes. The solutions need to be matured to be ready for production.

Table4: Process window test for BSA range for 13um wire with 24um bonded ball.

BSA% (USG)	Shear/ Area (gr/mil^2)	Ball Dia (um)	Ball Height (um)	IMC (%)	
				Avg	Min
Spec	>7	24 ± 1	6 ± 1	>85%	>80%
60%	8.3	24.3	6.3	91%	85%
65%	8.8	24.3	6.2	94%	88%
70%	9.7	24.1	6.1	96%	92%
75%	10.0	24.3	6.0	98%	96%

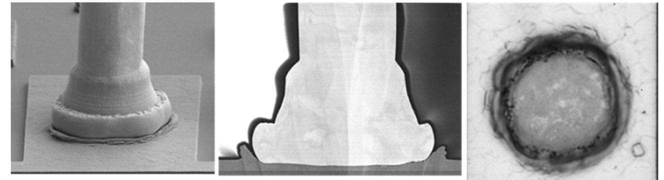

Figure 4. Bonded ball, cross section and IMC image for 13um wire, 35um pitch process.

A quick 2nd bond and looping test was also performed for the 13um wire process. Pull tests were used to evaluate the bond strength. The use of Cu optimized capillary with granular surface helps create strong 2nd bond for the fine wire process. Both the 1st bond and 2nd bond pull test passed the spec and the looping performance is acceptable.

Table 5: Pull test results for the 13um wire process.

Pull Test	1st bond Pull (g)	2nd Bond Pull (g)
Spec	>2	>2
Average	**3.8**	**2.7**
Stdev	0.25	0.22
Max	4.2	3.0
Min	3.1	2.3
Range	1.1	0.7

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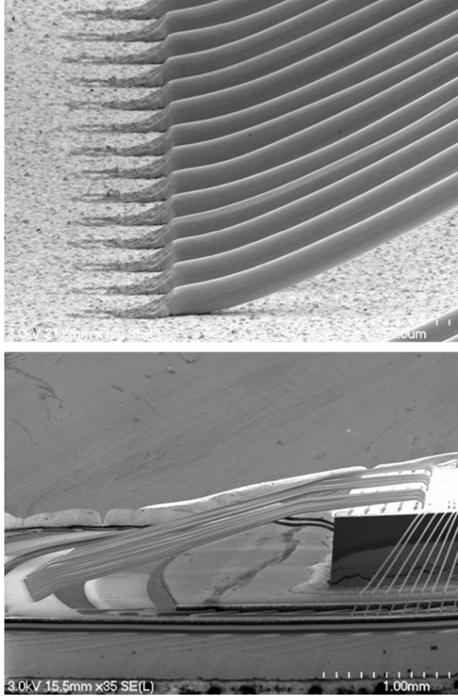

Figure 5. 2nd bond and looping pictures.

C. Molded Reliability Study of 15um Wire Process

In previous sessions, we showed that wire bonding is capable of 40um and 35um pitch process with Cu wire, more specifically, AuPd coated Cu wire. In this session, we will take a look of device reliability for these fine pitch applications. Biased HAST testing is one of the most challenging reliability tests for Cu wire bonded packages. Biased HAST test was performed for up to 336 hours. The biased HAST condition is 130°C, 85% humidity and ±5V biasing voltage. Previous reliability study by the authors identified one of the key factors in achieving good wire bonding reliability outcome is the wire type [9,10]. AuPd coated Cu wire (AuPdCu) wire showed much better performance than Bare Cu wire, Pd doped Cu wire has performance between AuPdCu and bare Cu wire [10]. For the fine pitch Cu wire application we used in our study, we chose the AuPd coated wire. In this study, 3 different molding compounds are used. First is a medium grade molding compound, 2nd is a higher grade molding compound with low Chlorine ppm level, the last one is an even better grade molding compound with low Chlorine and new ion trapper for better reliability. The test results are shown in Table 6. The results show that there is failure starting at 96 hrs for the medium grade molding compound (EMC), there is no failures for the two better grade molding compounds. Besides optimized wire bonding process and equipment, selecting the correct bonding wire and molding compound is also important in pass reliability test for fine pitch applications.

Table 6. Reliability results for 15um wire, 40um process.

EMC Grade	24Hr	96Hr	168Hr	336Hr
Medium	0%	8%	16%	34%
Low Cl	0%	0%	0%	0%
Low Cl + New Ion Trapper	0%	0%	0%	0%

D. TEM Failure Analysis

To understand the failure mechanism, we analyzed samples with three different wire types including Bare Cu wire, Pd-doped Cu wire and AuPd coated Cu wire. Medium grade molding compound was used. These samples were from a previous study [10] where 18um (0.7 mil) wire was used instead of the 15um and 13um wire used in this study. More detailed information on this test can be found in [10]. Table 7 shows the results of this test. AuPdCu wire has the best results with no failures at 168 hrs. Pd Doped Cu wire passed 96 hr but failed 168hr for the medium and high settings of BSA while bare Cu has the worst results. Transmission Electron Microscopy (TEM) combined with Energy Dispersive X-ray Spectrometry (EDX) was performed to examine wire bond's nano-scale interfacial structure and its evolution during HAST so as to understand its failure mechanism. TEM samples were prepared using a dual beam focused ion beam from. As molded (prior to HAST), HAST 96 hours and HAST 336 hours were studied.

Table 7. Reliability results for different wire types and different USG levels. 18um wire is used in this test.

Wire Type	BSA [%]	24 Hr	48 Hr	96 Hr	168 Hr	336 Hr
AuPdCu	Low	0%	0%	0%	0%	9%
AuPdCu	Med	0%	0%	0%	0%	5%
AuPdCu	High	0%	0%	0%	0%	13%
Bare Cu	Low	0%	3%	13%	28%	28%
Bare Cu	Med	0%	0%	3%	12%	20%
Bare Cu	High	0%	0%	3%	12%	38%
Pd Doped	Low	0%	8%	11%	23%	30%
Pd Doped	Med	0%	0%	0%	13%	28%
Pd Doped	High	0%	0%	0%	16%	25%

As shown in Figs. 6(a), (b) and (c), approximate 100-nm-thick IMCs (Cu_9Al_4 near Cu ball and $CuAl_2$ next to Al pad) are formed in the as-molded stage (prior to HAST). There is no significantly difference in interfacial structure between bare Cu, Pd-doped Cu and AuPd-Cu wires. However, EDX confirmed that there is 0.5~2.0wt.% Pd at bond interface on Pd-doped wire bond, 1.0~3.0 wt.% Pd and ~0.5wt% Au on AuPd Cu wire, and no Pd or Au on bare Cu wire bond.

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After 96hr HAST, bare Cu wire bonds failed HAST test. As shown in Fig 6 (a'), IMCs are corroded and a continuous gap is formed between Cu and Al in bare Cu wire bonds. Pd-doped Cu wire has better reliability than bare Cu wire and it passed 96hr HAST. The interface of Pd-doped Cu wire bonds (Fig. 6b') shows that voids have been formed, but they are discontinuous. AuPd-Cu wire has shown the best HAST reliability. There is no voids or gap at AuPd-Cu wire bonds (Fig. 6c') after 96 HAST, instead, a layer of aluminum oxide was formed between Cu and $CuAl_2$, as a result of Cu_9Al_4 corrosion reaction. EDX detected that there is 1.0~5.0wt.% Pd at interface of Pd-doped wire bond, and 1.0~13.0 wt.% Pd and ~0.5wt% Au at interface of AuPd Cu wire bonds. The Pd concentration at interface is higher after 96hr HAST than prior to HAST. The mechanism that AuPd-Cu wire bond and Pd-doped wire bond have better reliability is the appearance of Pd (and Au for AuPd-Cu wire) at the bond interface. It is known that Cu-rich IMC, e.g. Cu_9Al4, is corrosion sensitive. The formation of (Pd, Au, Cu)-Al IMC in AuPd-Cu wire bond, and (Pd, Cu)-Al IMC in Pd-doped Cu wire bond, but not Cu_9Al_4, improves corrosion resistance. AuPd-Cu wire has highest Pd and Au concentration, so it has best reliability property, while there is no Pd or Au on bare Cu wire bond, so it shows poorest reliability among three wire types in this test.

After 336hr HAST, both bare Cu wire bond and Pd-doped Cu wire bond failed because both have formed continuous gaps. The corrosion is also obvious in AuPd-Cu wire bond, and void/gap is formed. However, such gap is discontinuous and not throughout the whole bond interface, so it has not yet failed. EDX detected that there is 1.0~5.0wt.% Pd at bond interface on Pd-doped wire bond, and 3.0~15.0 wt.% Pd and ~0.5wt% Au on AuPd Cu wire bond.

This TEM study together with our previous studies [9] generates below general corrosion sequence and mechanism during reliability test for bare Cu, Pd-doped Cu, and Pd (or AuPd)-coated Cu wires. The presence of Pd and Au and lower content of Cl [9] can slow down the corrosion reaction, so improve reliability.

(1) In the as-bonded state, 20-30nm-thick $CuAl_2$ is formed between Cu and Al (Fig. 7a).

(2) In the as-molded state, approximate 100-nm-thick IMCs (Cu_9Al_4 near Cu ball and $CuAl_2$ next to Al pad) are formed (Fig. 7b).

(3) First stage of reliability test: Cu_9Al_4 is corroded and an aluminum oxide layer is formed between Cu and Al. Corrosion is only at the bond edge and $CuAl_2$ is not corroded at this stage (Fig. 7c). AuPd-Cu wire bond after 96-hr HAST is at this stage.

(4) Second stage of reliability test: corrosion continues and voids are formed, but it still passes reliability test (Fig. 7d). AuPd-Cu wire bond after 336-hr HAST and Pd-doped Cu wire bond after 96-hr HAST are at this stage.

(5) Third stage of reliability test: a continuous gap throughout the whole interface is formed and it fails reliability test (Fig. 7e). Pd-doped Cu wire after 336-hr HAST and bare Cu wire bond after 96-hr HAST are at this stage.

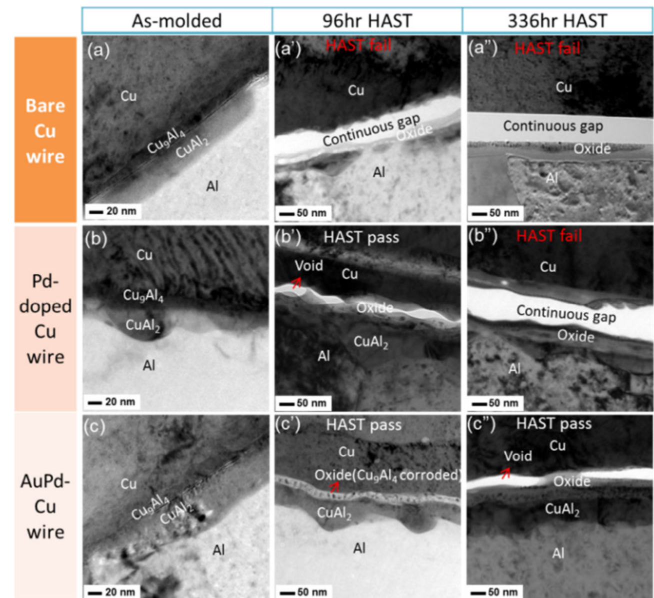

Fig. 6 TEM showing corrosion evolution in the as-molded state, 96hr HAST and 336hr HAST: (a, a', a'') bare Cu wire bond; (b, b') Pd-doped Cu wire bond; and (c, c') AuPd-Cu wire bonds. Bare Cu wire bond failed 96hr HAST, Pd-doped Cu wire passed 96hr but failed 336 hr, while AuPd-Cu wire passed 336hr.

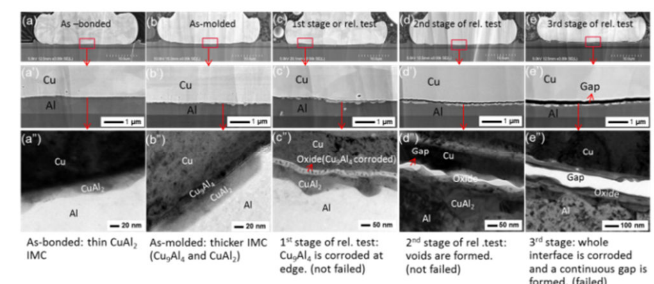

Fig. 7 General interfacial evolution and corrosion sequence in a Cu wire bond: (a, a', a'') as-bonded state: 20-30nm-thick $CuAl_2$; (b, b', b'') as-molded state: approximate 100-nm-thick IMCs (Cu_9Al_4 and $CuAl_2$); (c, c', c') first stage of reliability test: Cu_9Al_4 is corroded and an aluminum oxide layer is formed; (d, d', d'') second stage of reliability test: voids are formed, but still passes reliability test; (e, e', e'') third stage of reliability test: a continuous gap throughout the whole interface is formed and it fails reliability test.

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III. Conclusion

We demonstrated 40um and 35um pitch capability in our work and showed the critical factors in passing reliability for fine pitch applications. These factors include the use of the latest Cu wire bonding equipment, process and material, understanding the process window and set the optimal parameters, choose the wire and molding compound that give the best reliability outcome. Wire bonding has improved significantly over its technology life. The proliferation of Cu wire bonding technology is allowing advanced packages to continue to be wire bonded at a lower cost than flip chip.

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