Advances in Wire Bonding Technology for Different Bonding Wire Material

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Abstract
With all the advances in 2.5D and 3D packaging, wire bonding is still the most popular interconnect technology and the workhorse of the industry. Wire bonding technology has been the lower cost solution comparing to flip chip. Wire bonding package cost is much reduced with the introduction of Copper wire bonding. Technology development and innovation in wire bonding provides new packaging solutions that improves performance and reduces cost. This paper reviews the recent innovations in ball bonding technology to provide optimized ball bonding solutions targeted for different bonding wire material. It examines the different challenges for the alternative wire types including Cu wire, Pd coated, and AuPd coated Cu wire and Ag Alloy wire. We will discuss key development in ball bonding equipment, process and material to overcome the challenges and provide robust low cost solutions. The advantages of each wire type are outlined, and guidelines to select the right bonding wire type per application requirements are provided.

Key words
Wire Bonding, Copper Wire Bonding, Silver Wire Bonding, Cost Reduction, Reliability.

I. Introduction
The key driver for semiconductor packaging is to reducing cost while providing even better functionality. The two main interconnect methods are wire bonding and flip chip. Wire bonding has been the more popular method due to its low cost, flexibility and large installed base. The main reason to select Flip Chip over wire bonding is package performance such as the bandwidth of the device. Material cost often contributes to over half of the packaging cost. In recent years, transition to Cu wire bonding has brought significant cost reduction for wire bonded devices. Cu wire bonding is almost always cheaper than Flip Chip [1]. For wire bonded devices, a large portion of cost is the wire cost. Table 1 shows packaging cost comparison between Au wire bonding, Cu wire bonding and Flip Chip for a 500 I/O package with 2-Layer substrate. It shows that more than 33% of the packaging cost is coming from wire in the case of Au wire bonding. By using Cu wire bonding, we can reduce the packaging cost by 20%. Table 1 also shows Cu wire bonding is significantly cheaper than Flip Chip.

Table 1: Packaging Cost Comparison 500 I/O CSP Package with 2-Layer Substrate (source Prismark)

	Au Wire Bonding	Cu Wire Bonding	Flip Chip
Wire	$0.28	$0.07	-
Wire Bonding	$0.20	$0.24	-
Bumping	-	-	$0.15
Underfill	-	-	$0.10
Other Package	$0.08	$0.08	$0.20
Substrate	$0.30	$0.30	$0.35
Total	**$0.86**	**$0.69**	**$0.80**

Figure 1 shows the wire consumption over the last few years and the projection for the next few years. Combination of Cu and Pd coated Cu wire have overtaken Au wire as the most popular wire used for semiconductor packaging. Currently, about 30% of the packages are using Pd coated Cu wire and another 15% are using Bare Cu wire (without any coating). AuPdCu wire is considered as a derivative of PdCu wire. The difference is that a thin layer of Au flash is added on top of the Pd coating. AuPdCu wire has shown better 2nd bond in some studies. Ag wire is another low cost wire that can be used to replace Au wire in applications that have trouble transition to Cu wire. To further reduce the cost of device, more applications can switch to Cu wire bonding or Ag wire bonding. This paper will compare the different wire types in cost, performance and reliability, discuss the technology advances that support the low cost wire transition, and make recommendation for wire selection.

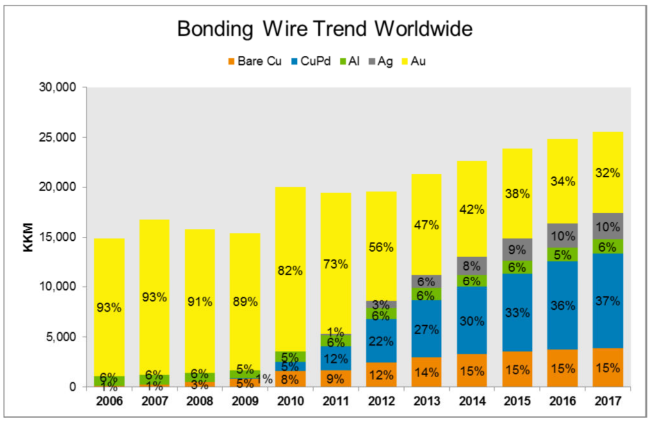


Figure 1. Bonding wire trend over time. (Source: Heraeus Materials).

II. Wire Type Comparison

To select the best wire type for an application, a few key factors should be considered including wire cost, electrical performance of the wire, bondability of 1st and 2nd bond, looping performance, yield, production assist rate and device reliability. Figure 2 shows wire cost comparison. Au wire cost is about 10 times of Cu wire. Pd coated Cu wire is around 50% more expensive than Bare Cu wire. Ag wire is about twice as much as Bare Cu wire. Almost all of the Au wire cost comes from the raw material; manufacturing cost is a very small percentage. On the contrary, the cost of material for Cu wire is a small percentage of the total wire cost; manufacturing cost contributes to a large percentage. The Cu wire manufacturing cost includes the cost of wire drawing dies, the cost of plating in the case of Pd coated Cu wire. Ag wire is more expensive than Cu wire but still offer 80% cost reduction compared to Au wire. Due to the reliability problem with high purity Ag wire, Ag wire used for wire bonding is alloyed. Majority of the Ag wire used today contains between 88% to 95% of Ag. The balance is usually precious metals such as Au and Pd. The low Ag content wire such as 88% Ag wire is call low Ag alloy, the high Ag content wire such as 95% is called high Ag alloy wire. High Ag alloy wire is cheaper, however, the reliability of high Ag wire is still not proven.

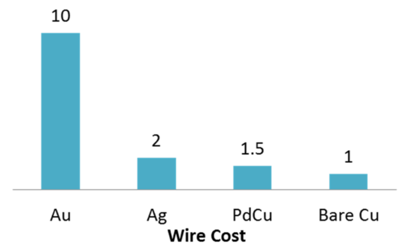


Figure 2. Relative cost for different type of wires (based on 25um diameter wire, source Heraeus and Tanaka). High Ag alloy is used in the comparison. Low Ag alloy wire is more expensive.

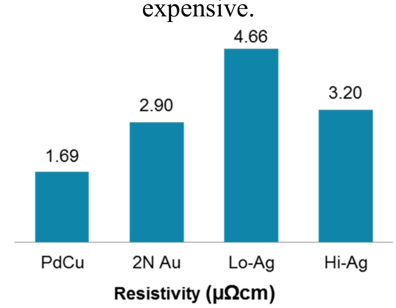


Figure 3. Resistivity comparison for different type of wires.

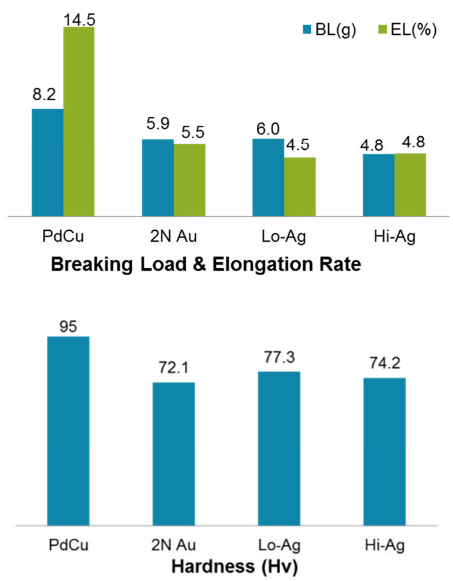


Figure 4. Wire break load, elongation and hardness comparison.

Figure 3 and 4 shows the electrical and mechanical characteristics of the wires. Cu wire has the lowest resistivity, therefore has the best electrical performance. Ag wire has the worst electrical performance especially with the low Ag alloy. Cu wire is stronger than Au and Ag wire. It provides better looping performance for tall loop and long wire span applications. For example, Cu wire is the wire of choice for high pin count multi-tier looping devices. The higher mechanical strength gives Cu wire better looping performance with less wire sway and less loop profile variation than Au and Ag wire (see Figure 5).

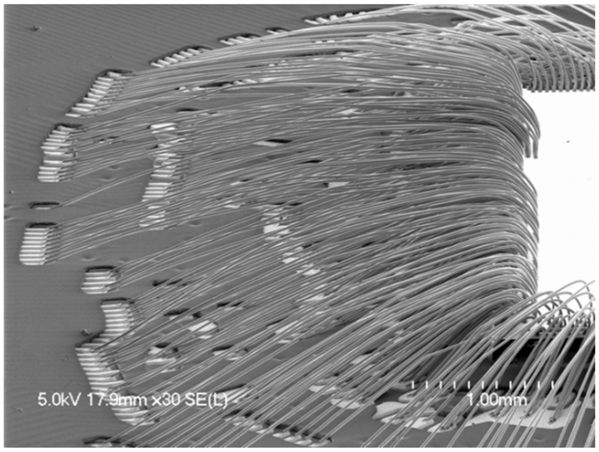


Figure 5. High I/O count, multi-tier application using Cu wire bonding to achieve good wire looping performance. In this example, There are 4 pad tiers on the die. Loop height ranges from 75um for the outer pad, shorter wires to 400um for the inner pad, longer wires.

The higher mechanical strength and hardness have its drawbacks. If not optimized, Cu wire bonding can cause device damage such as pad crack, pad peeling and Al splash as shown in Figure 6. Ag wire has similar issues, may be to a lesser extent. Besides the higher hardness of the wire, the work hardening effect of Cu and Ag also play a role. As the free air ball is deformed, the strain hardening effect causes the hardness of the deformed ball to increase; this further acerbates the pad damage.

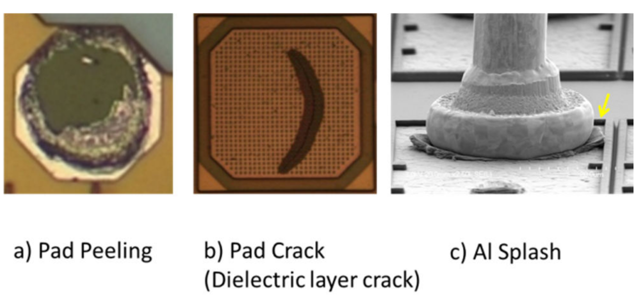


Figure 6. Example of pad damage caused by Cu and Ag wire bonding process. Cu wire was used in a) and b), Ag wire was used in c).

There are additional challenges for bare Cu wire. Bare Cu wire has a thin oxidation layer on the surface. Forming robust 2nd bond can be a challenge for some applications.

Another factor for consideration is reliability performance. Au wire has been used in the semiconductor industry for a long time. Its reliability is well proven. Cu wire is prone to corrosion. A lot of development has been done in wire, molding compound and manufacturing process to improve the molded reliability for Cu wire under humid conditions. Pd coated Cu wire, Pd doped alloy Cu wire [2, 3, 4], green molding compound with low halogen content and ion trappers [2, 5, 6] all showed significant improvement for Cu wire bonding reliability. Fine pitch Cu wire bonding reliability is proven in manufacturing process [7]. Good reliability results are also obtained in Ag alloy wire [8] although there is much less HVM and reliability data with Ag alloy comparing to Cu wire.

If an application can be done with Cu wire with good yield and throughput, Cu wire should be chosen. However, some applications are harder to transition to Cu wire. NAND Memory is one area that has not adopted Cu wire bonding due to a few challenges. One of the challenges is that the bond pads on memory devices are thin, usually only 0.6 um. These thin pads coupled with low K dielectrics makes Cu wire bonding more difficult. Memory devices are often stacked vertically. In this wire bonding configuration, the bond pads are stringed together using Stand-off Stitch Bonding (SSB). There are often multiple bonds made on one pad compounding the pad damage (Figure 7a). Sometimes, the device is un-supported in an 'overhang' configuration (Figure 7b). These configurations are particularly challenging for Cu wire bonding, where Ag wire bonding may be a good alternative.

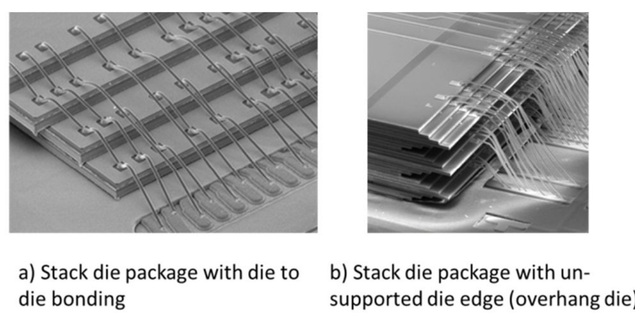


Figure 7. Multi-stack memory device examples.

To realize the cost saving of switching to Cu and Ag wire, bonding issues (such as shown in Figure 6) need to be resolved. Recent development in wire bonding equipment and process has dramatically improved Cu and Ag wire bonding capability. On the wire bonder hardware side, better cover gas delivery system has been developed to achieve lower oxygen level in an expanded area. During the ball formation process, Cu ball is easily oxidized and makes it un-bondable. When the Cu ball is better protected from oxidation, it is easier to bond with, resulting in shorter bond time, higher bond strength and less pad damage [9].

There are also big improvements on the wire bonding process technology with the introduction of optimized Cu processes in the form of model driven, 'Response Based' processes. Cu processes are much more complicated than Au wire process with more complex parameter optimization and narrower process window. Numerical models were developed and implemented with simplified 'Response Based' inputs such as desired bonded ball diameter. The ProCu™ process for first bond and the ProStitch Plus™ process for second bond are such processes that have demonstrated improvements in yield and throughput [9][10]. In the next session, we will review the wire comparison results and the improvements made using these new processes optimized for Cu and Ag wire bonding.

III. Technology advances enabling low cost wire

A. 1st bond Wire Comparison and Process Improvement

The first bond process starts with free air ball (FAB) formation. To compare wires, the ability to form good free air ball should be studied. Unlike Au wire, both Cu and Ag wire need oxygen free environment to form FAB that can be bonded later. Even slightly oxidized Cu or Ag FAB could cause severe pad damage and low bondability such as ball lift. Providing an oxidation free zone is one of the key requirements for Cu wire bonders. Many years of design innovation has led to advanced cover gas delivery system that can limit the oxygen content to less than 1% around the FAB. Typically, either N_2 or forming gas (95% N_2+5% H_2) is used as cover gas to prevent oxidation. Although slightly more expensive, forming gas is preferred due to the presence of H_2, an oxidation reducing agent.

Au ball bonding to Al pads is relatively straightforward – the optimal USG is set to maximize ball shear while still meets ball size specification. On the other hand, Cu ball bonding to Al pads is challenging due to pad damage associated with high shear. The conventional Au wire optimization for maximal shear does not work with Cu wire bonding. While maximal ball shear is main quality criteria for Au ball bond, there are many requirements for a robust Cu ball bonding process. A typical Cu process window is limited by low IMC and ball lift on the low end and pad peeling, Al splash, and crack at the high end. In addition, a flat ball/pad interface with good contact area and acceptable Al remains is desired. Thus, a Cu ball bond process development typically requires careful process design and optimization of a far more number of process parameter settings, which can often be tedious and time consuming. K&S has done extensive R&D to develop Cu optimized ProCu™ processes. The ProCu5 process is the latest ProCu™ process that simplifies Cu ball bonding process development and provides higher IMC, lower splash and effectively eliminates crack.

The complexity of Ag wire process development is somewhere between Au and Cu. Since Ag alloy wire is harder than the Al pad, most of the process issues encountered with Cu wire, e.g. Al splash, pad peeling and dielectric crack, are also encountered with Ag wire. To simplify Ag wire process optimization and improve process capability, we have developed a response based ProAg™ process, which follows the same design principles and has a similar look and feel of ProCu™ process, and with algorithm tuned to Ag wire properties.

Next, a comparison of 1st bond processes made with Au, Ag, and Cu wires is presented. Ball bonding processes are developed using three types of wire – 2N Au (99%), Ag alloy (94.5% Ag) and AuPdCu wire. 0.8 mil (20um) diameter wires are used to make a bonded ball with 44±2 µm diameter and 11±2 µm height, yielding a target shear/area of at least 6.5 g/mil^2 and IMC% of at least 85% average with 80% minimum. The Al Splash need to be lower than 48um. The processes are optimized on K&S IConn ProCu Plus automatic bonder.

A total of four processes are optimized. For Au ball bonding, a simple thermosonic process is used. For Cu wire, a ProCu5 process is used to develop a robust ball bonding process. For Ag wire, two types of processes are optimized: (i) a classic process similar to Au ball bonding; and (ii) the new response based ProAg process. Table 2 below shows the summary of bonding results obtained with these four processes. Figure 8 shows SEM, X-section and IMC images obtained using these four processes. For the process window, the low end is determined by shear and IMC% meeting specification, and the high end is defined by Al splash and ball diameter results.

Table 2: Summary of ball bond process responses obtained with Au, Ag, and Cu wires

Wire Type	Au	Ag	Ag	AuPdCu
Process Type	Classic	Classic	ProAg	ProCu5
USG Current [mA]	65	90	90	90
Ball Dia. [µm]	43.6	44.0	44.5	44.1
Ball Height [µm]	10.3	10.3	11.1	10.5
Al Splash Y [µm]	-	49.0	46.4	46.8
Ball Shear [g]	16.5	19.7	16.5	19.0
Shear/Area [g/mil^2]	7.1	8.4	6.9	8.0
IMC%	>85%	88%	90%	94%
Ball Lift	0%	0%	0%	0%
Pad Peel	0%	0%	0%	0%
Process Window	~30%	0%	~30%	~30%

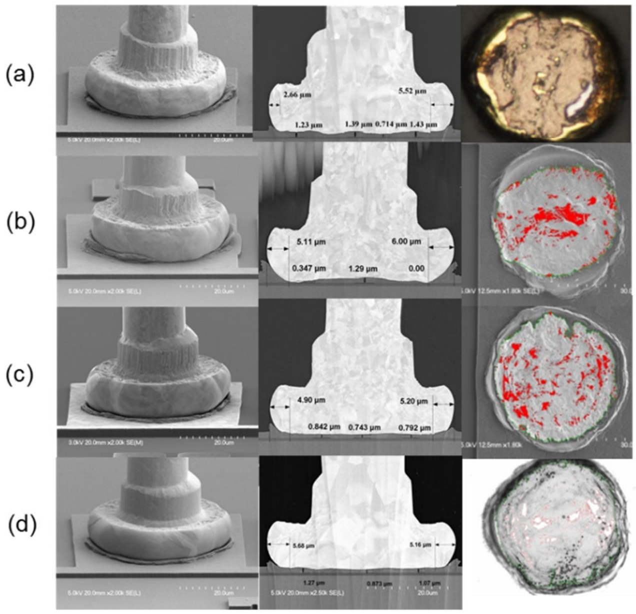


Figure 8. Bonded ball, X-section and IMC images of (a) Au ball bond, (b) Ag ball bond using Classic process, (c) Ag ball bond using ProAg process, and (d) Cu ball bond using ProCu process. For Au wire, IMC is measured on the bottom of the ball. For Cu and Ag wire, IMC is measured on the Al pad after etching.

The results demonstrate that a classic single segment thermosonic process can be easily optimized for the Au ball bonding process with an effective USG process window of at least 30%. All process responses including the bonded ball size and shape, ball shear, IMC% and interface are all found to be within the defined specifications.

In contrast to Au ball bonding, the classic single segment process does not work with Ag ball bonding due to excessive Y-splash. No process window for IMC to splash is found. The bonded ball X-section shows a concave ("crying") interface with depleted Al remains at regions directly below the capillary chamfer (CD). This may cause stress concentrations at these points, which may lead to failure, e.g. pad peeling or dielectric crack. This study demonstrates that from a ball bond optimization perspective, Ag alloy wire has similar challenges and requirements as Cu wire.

By using ProAg process for Ag alloy wire and ProCu5 process for Cu wire, robust processes with wide (~30%) ultrasonic current window for IMC to splash are obtained. Uniform, flat ball/pad interface (Figure 8) is obtained with good shear/area. One useful way of comparing the different types of processes is by looking at the Al Splash vs. IMC% plot as shown in Figure 9. High IMC% is an indicator of good welding. Using higher USG increases weld strength and IMC%. However, it also increases Al splash. The goal is to get high IMC% and low splash. The splash vs. IMC curve for Ag ball bonding using classic process is very linear. Consequently, IMC% cannot be increased without keeping the splash within specified safe level. In contrast, with ProAg and ProCu5 processes, there is a much bigger window where the IMC% increases significantly without a corresponding big increase in splash and there is a big process window meeting the IMC% and Al splash requirements.

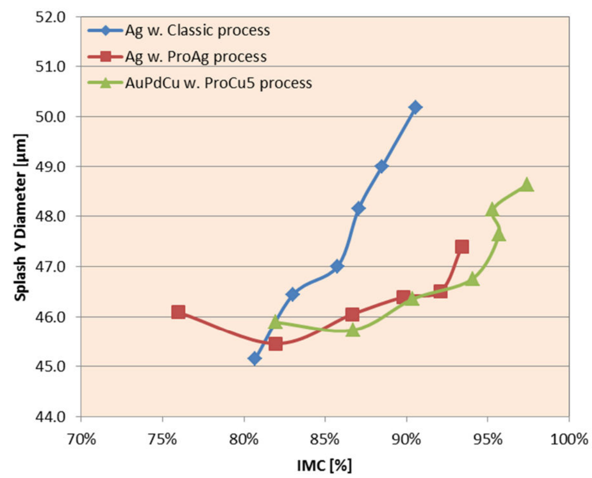


Figure 9. Al Splash vs IMC% curve for different processes.

This example shows that with the advanced processes optimized for Cu and Ag wire, Cu and Ag wire can achieve same bonding window and robust process as Au wire. By programming desired responses such as Target Ball Diameter, the process optimization is also as easy as an Au wire. These advanced processes can help transition more applications to low cost wires with shorter learning curve and more desirable outcome.

B. 2nd Bond Wire Comparison and Process Improvement

Bare Cu wire was first introduced when Cu wire bonding was developed. Bare Cu wire are still being used for a lot of application due to its lowest wire cost, but the 2nd bond bondability is a concern when bonding on challenging lead frames, such as roughened pre-plated lead frame (PPF). The relatively low 2nd bond bondability of bare Cu wire is due to the thin Cu oxide layer on its surface. Pd or AuPd coated Cu wire has no Cu oxide layer, so it has better 2nd bond bondability than bare Cu wire. A comparison study between 0.7mil AuPd coated Cu wire, Au wire and Ag alloy wire (94.5% Ag) were performed. The device is K&S Intech BGA, and the capillary is K&S ACSPro AP662126LX0024. The process is a simple thermosonic process. As shown in Figures 10, all 3 wires tested in this study have large NSOL-SHTL USG window. Au wire and Ag alloy wire can be bonded at as low as 10mA USG while

AuPdCu wire requires at least 40mA USG to have no NSOL. One cause is that AuPdCu is harder than Au and Ag alloy wire, so it requires more USG energy to deform the wire. The same trend is seen in Cu remain. Cu remain is an important 2nd bond response, which is an indicator of stitch strength. In this test, AuPdCu wire requires 70mA USG to have good Cu remain (Figure 11), which is higher than the USG required for Au wire (30mA) and Ag wires (50mA). The combined NSOL-SHTL and Cu remain USG window for AuPdCu wire, Au wire and Ag alloy wire are 50mA, 100mA, and 70mA, respectively. It is noteworthy that 50mA USG window for AuPdCu wire is large, which is good enough for mass manufacturing.

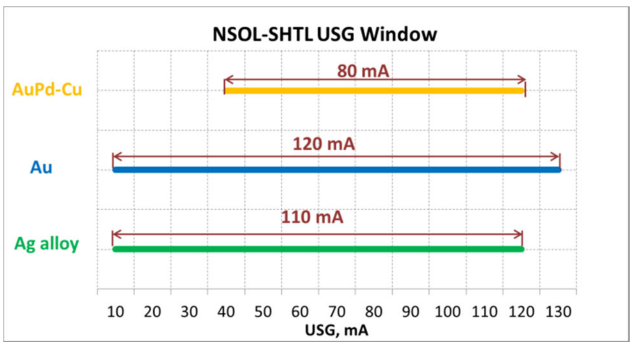


Figure 10. NSOL-SHTL USG window comparison between Au wire, AuPdCu wire and Ag alloy wire.

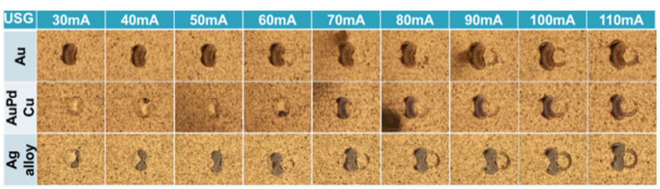


Figure 11. Cu remain USG window comparison between Au wire, AuPdCu wire and Ag alloy wire.

The stitch strength and tail strength are good for all 3 wires tested (Figures 12-13). AuPd-Cu wire has higher stitch and tail strength than Au and Ag alloy wires when USG current is larger than 70mA, due to its higher wire break load.

As mentioned earlier that bare Cu wire has worse 2nd bond bondability than PdCu, Ag alloy and Au wire, due to the thin Cu oxide layer on its surface. In general, bare Cu wire is bondable on less challenging substrate, such as Au coated BGA, and Ag coated leadframe. However bare Cu wire bonding on PPF (usually Au-Pd-Ni leadframe), especially roughened PPF, is challenging. To enable bare Cu wire bonding on those challenging applications, we have developed a new response based 2nd bond feature - ProStitch PLUS. An application example is a 0.8mil bare Cu wire bonding on PPF QFN (Table 3). As a reference, we started this application with the traditional ProStitch process. However, the 2nd bond responses with ProStitch cannot pass specifications, with very low stitch pull strength and no Cu remain. ProStitch PLUS enables bare Cu wire for this application with much better 2nd bond responses, with high stitch strength and good Cu remain.

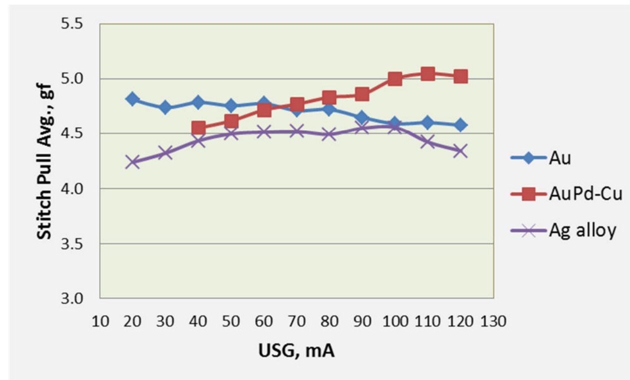


Figure 12. Stitch pull average vs. USG.

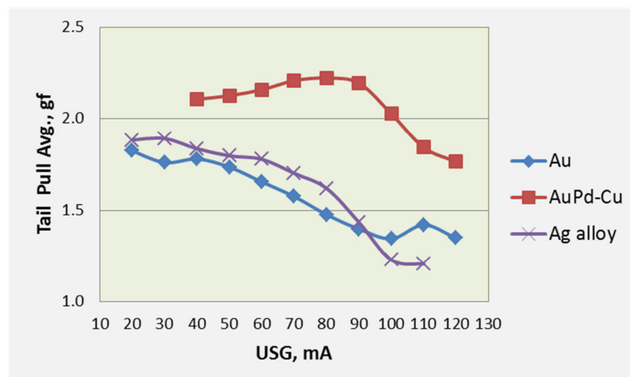
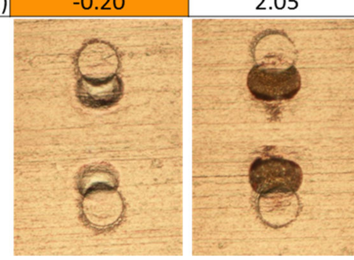


Figure 13. Tail pull average vs. USG.

Table 3: 2nd bond comparison for ProStitch and ProStitch PLUS with 0.8 mil bare Cu wire

	ProStitch	ProStitch PLUS
NSOL/SHTL	None	None
Peel	None	None
Cu remain	Many 0%	>50%
Avg Stitch Pull, [gf]	2.19	5.10
Min Stitch Pull, [gf]	1.35	4.08
Stitch Pull Stdev	0.50	0.42
Cpk (lsl=2.5)	-0.20	2.05



IV. Conclusion

Semiconductor packaging cost can be dramatically reduced by using low cost wire such as Cu wire, PdCu wire and Ag alloy wire. Cu wire bonding is especially suitable for high pin count complex looping application and QFN type low cost packages. Ag wire alloy can be considered for memory devices with thin pad and multi-stack dies. With the most advanced wire bonders and processes optimized for Cu and Ag wire bonding, our experience has shown that majority of the applications using Au wire today can be converted to Cu or Ag wire.

Acknowledgment

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