

COPPER WIRE BONDING ON PURE PALLADIUM SURFACE FINISHES – ELIMINATING THE GOLD COST FROM THE ELECTRONIC PACKAGE

Mustafa Özkök, chemical engineer
Atotech Deutschland GmbH, Berlin, Germany
mustafa.oezkoek@atotech.com

Hugh Roberts, chemical engineer.
Atotech USA Inc., Rock Hill, USA
hugh.roberts@atotech.com

Horst Clauberg, Senior Scientist.
Kulicke and Soffa Industries, Inc.
hclauberg@kns.com

ABSTRACT

During the past two years, fine pitch copper wire bonding has finally entered high volume production. It is estimated that nearly 15% of all wire bonders used in production are now equipped for copper wire bonding. Most of these are used exclusively for copper wire bonding. In terms of pitch, copper wire is only barely lagging behind the most advanced gold applications. The most commonly used copper wire is 20µm in diameter and 18µm copper wire is entering final qualification. Evaluations with even finer wire are underway.

Although some technical challenges remain, many years of research have now resolved most of the problems associated with copper wire bonding and attention is beginning to shift from merely ensuring reliable manufacturing processes to optimizing processes for efficiency and throughput. The most advanced wire bonders now have pre-configured processes specifically designed for copper. In addition to throughput optimization, further cost reductions are being sought. Among these is the desire to eliminate the high-cost gold not just from the wire, but also from the substrate.

On the substrate side the electronics packaging industry still works with electrolytic nickel / electrolytic (soft) gold (Ni/Au) for copper wire bond applications. This surface finish works with copper wire bonding but includes some disadvantages, such as:

- Thick expensive Au layers of 0.1 to 0.4µm
- Electrically connected pads (bussing for the plating) which require added space on the substrate.
- Pd-coated copper wire often delivers better results on gold covered finishes, but is two to three times more expensive as pure copper wire.

Furthermore electrolytic Ni/Au was not chosen as a result of in-depth investigations for the most effective surface finish. The selection was made because it was the surface finish with the highest distribution in the market for wire bond packages.

This paper is offering the results of a two company joint work regarding an alternative copper wire bondable surface finish for substrates mainly with palladium as the final copper wire bondable layer. This offers further cost reduction possibilities. Furthermore, copper palladium intermetallics are regarded as very reliable.

Key words: ENEPIG, ENEP, wire bonding, gold wire bonding, copper wire bonding

SCOPE

This joint project (between Atotech Deutschland GmbH and Kulicke & Soffa) was initiated with three primary objectives in mind:

1. To screen all available surface finishes to determine their suitability for copper wire bonding
2. To determine a process window for copper wire bonding on the surface finishes that passed the first feasibility screening
3. To compare the copper wire bonding capability with that of the copper-palladium wire on selected finishes.
4. Pull test of stitch wire bonds over different temperature aging conditions.

In order to compare the results to a copper wire bondable reference, the surface finish of electrolytic Ni/Au (Soft gold) was selected. This finish is already proven in production to be copper wire bondable. This paper focuses on the test results of the Electroless Surface Finishes, there will be another paper where the results of the electrolytic surface finishes will be discussed.

EXPERIMENTAL

| Parameter | Value/description |
|-----------------------------------|--|
| Cu-wire | 20µm diameter Heraeus Maxsoft copper |
| Wire bonder | Kulicke and Soffa IConn ^{PS} wire bonder equipped with the latest accessory kit for Cu wire bonding |
| Bonding tool | K&S CuPRAplus TM tool (PN CU-FF-1099-P37, hole 1.0 mil, chamfer diameter 1.25mil, face angle 11°, inner chamfer angle 60°) with a granular surface finish. The surface finish of the bonding tool causes a slight granular structure on the copper wedge, as shown in Figure 1. This granular impression on the wedge enhances the bond adhesion of the copper wedge. |
| Cover gas | forming gas (5/95 H ₂ /N ₂) |
| Bond temperature | 165°C |
| Plasma treatment prior to bonding | Devices were cleaned in a March plasma cleaner for 5 min with Ar gas |

Bonding windows were found by varying the ultrasonic bonding energy while maintaining all other parameter fixed in a simple thermosonic bonding process. The data in tables 1 and 4 were obtained by this simple bonding process. This simple thermosonic process was supplemented with a few microns of linear skid for the data in tables 3 and 4. For each ultrasonic energy value, 20 X-direction and 20 Y-direction wires were bonded. Results were averaged over the two directions.

It should be noted that more complex bonding process would likely result in stronger bonds, but the aim of this work was to compare surface finishes by the most straight-forward method. Fully optimized process would likely be different for each of the surface finishes. Also, no attempt was made to equalize the bonding results for X- and Y-direction wires by applying separate bonding parameters to each direction.

Wires were pull tested on a Dage 4000 with the hook placement 1/4 of the wire length from the stitch bond.

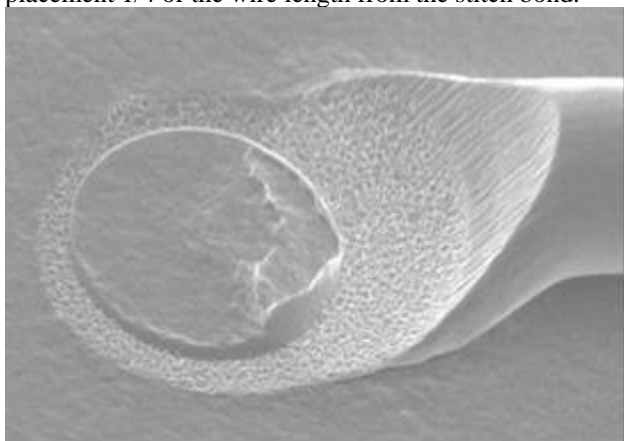


Figure 1: Cu-wedge with granular structure for advanced copper wire bonding

TEST RESULTS: SCREENING OF COPPER WIRE BONDABLE SURFACE FINISHES

A total of 21 different Atotech surface finishes were screened for copper wire bonding capability.

Immediately, it was determined that seven of the surface finishes did not appear to be bondable with pure Cu wire.

The surface finishes which failed in this first step were:

- Organic solderability preservative (OSP)
- Immersion Sn
- Electrolytic Ni/Sn
- Electrolytic Ni/Sn/Au
- Electroless Ni/immersion Au (ENIG)
- Electrolytic white bronze
- Electrolytic Ni/PdNi.

The OSP finish was discussed in the past as a copper wire bondable finish, but the test results show clearly that a copper wire bond could not be achieved. The OSP under the high temperature in the copper wire bonder begins to decompose and copper oxidation occurs on the substrate surface, which then prevents wire bonding.

In the first screening the surface finishes which showed limited potential for Cu-wire bonding with pure copper wire were:

- Electroless Ni / electroless Pd / immersion Au (ENEPIG) with a palladium layer co-deposited – with phosphorus (Pd-P)
- ENEPIG with a pure Pd layer
- Electrolytic Ni/Pd
- Electrolytic Pd/Au
- Electroless Ni / electroless Pd (ENEP) with Pd-P

Again it should be noted that more complex bonding processes could likely improve on these results

The surface finishes with the most potential for copper wire bonding were:

- ENEP (Electroless Nickel, Electroless Palladium with pure Palladium)
- Electroless pure Pd over Cu
- Electrolytic Ni/Pd/Au

Also, the reference surface finish, electrolytic Ni/Au with soft gold was found to be fully copper wire bondable.

TEST RESULTS: COPPER WIRE BOND WINDOW OF THE POTENTIAL SURFACE FINISHES

The ENEPIG surface finishes with different thickness variations were screened for copper wire bonding capability. Surprisingly, the surface finish of ENEPIG (proven for Au wire bonding) did not perform so well with pure Cu wire in all tested thickness variations (see Table 1, Sample Number 1-10). Also, different settings of ultrasonic energy (USG) did not help to improve the pure Cu wire bond on the ENEPIG finish.

As expected, the reference electrolytic Ni/soft gold samples performed well under different USG settings.(Table 1, Sample 11). Electrolytic Ni/soft gold also delivers good results in both the x- and y-direction of copper wire bonding (Table 2 and 3, Sample Numer A,F).

Electroplated silver (Table 1, Sample Numer 13) also shows potential for copper wire bonding. However, silver is known to be less corrosion resistant [1] therefore, this finish was already phased out by several OEMs and packaging companies by 2008. In addition, because of current distribution during plating with the process has limitations when it comes to plating the same metal thickness on different pad sizes. Therefore, we did not focus any further attention on this finish.

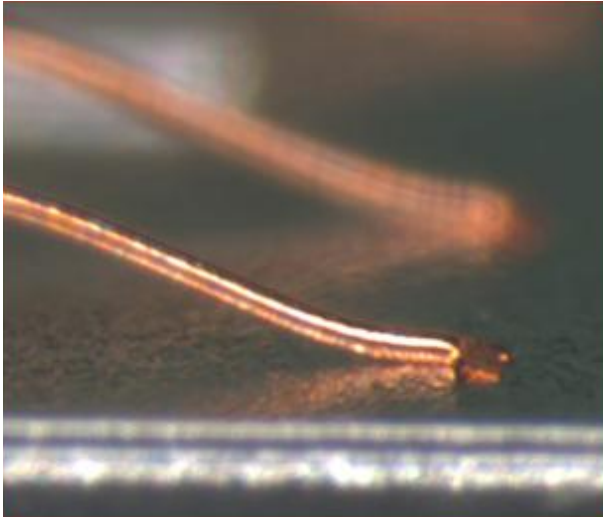


Figure 2: Cu wire bonding on ENEP with pure palladium

ENEP with pure Pd also performed very well in this test with a very good wire bonding window (Table 2 and 3, Sample Number G, H). This surface finish was evaluated as a potential copper wire bondable surface finish for the future. Its pull strengths are comparable to electrolytic Ni/Soft gold with pure copper wire manufactured at much lower material cost..

ENEP with Pd-P (4-6 wt %) offers a smaller process window compared to ENEP with pure Pd. Furthermore the variations of ultrasonic energy show inconsistent pull test results (Table 2 and 3, Sample Number G, H).

Excellent copper wire bond results were achieved with pure copper wire on electroless pure palladium over copper. (Table 1 and 3; Sample Number 12 and Table 2, 3; Sample Number L). Also this finish was identified as a surface finish for the future with excellent Cu-wire bonding capability in x and y direction with pure Cu wire.

TEST RESULTS: COPPER WIRE BOND WINDOW WITH PALLADIUM COATED CU-WIRE

In this investigation, it was unexpected to find that bare Cu-wire did not perform well on ENEPIG surface finishes. However, these results change when using Pd-coated Cu wire.

Electrolytic Ni/soft gold also shows very good results whith this type of wire (Table 4 Sample 3). ENEPIG is copper wire bondable with this type of wire, but the pull test results show lower values compared to electrolytic plated Ni/soft gold. With respect to

electrolytic Ni/soft gold, the thicker gold is supposed to be the reason for the better results and an increasing of the Au thickness on ENEPIG to a similar level might improve results.

ENEP with pure Pd and electroless pure Pd over copper both either exhibit a narrower process window or offer even no bonding capability with Pd-coated Cu wire.

The test results with the Pd-coated copper wire shows clearly that the wire bonding characteristics of the wire are completely different compared to a pure copper wire. The pure copper wire attaches well on pure Pd layers, whereas Pd-coated wire types attach better on thicker Au Layers. This can be seen by comparing the results of Table 1,2,3 with those of Table 4.

COST COMPARISION OF DIFFERENT WIRE AND FINISH COMBINATIONS.

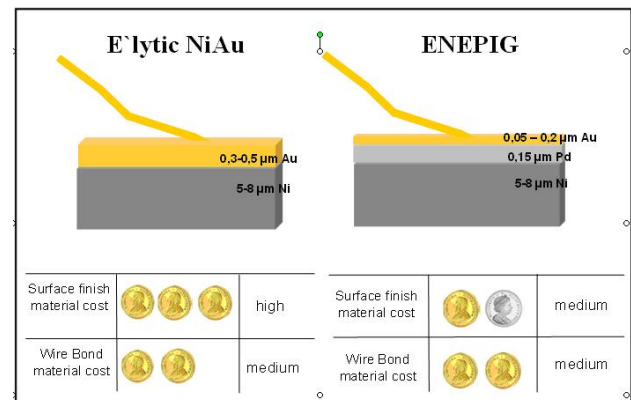


Figure 3: Au wire bonding on ENEPIG and electrolytic Ni/Au

Gold wire bonding on electrolytic Ni/soft gold has been a standard for many years, but the high cost of gold forced the packaging industry to consider ENEPIG finishes as a Au-wire bonding finish alternative. ENEPIG first became established in the packaging industry in 2006 and its use continues. Further cost reduction is possible by using electroless pure Pd in ENEPIG finishes, allowing a reduction in the Pd thickness to 0.05 µm or less [2].

| Average Pull Strength - Cu wire | | | | | Plating Process | Ultrasonic Energy (mA) | | | | | | | |
|---------------------------------|---------|---------|---------|----------|------------------------------|------------------------|------|------|-----|-----|-----|-----|-----|
| Sample | Ni [µm] | Pd [µm] | Au [µm] | Ag [µm] | | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 |
| 1 | 7 | 0.05 | 0.05 | | ENEPIG (pure Pd) | 2.6 | NSOL | NSOL | 2.7 | 2.5 | 2.5 | 3.0 | 2.8 |
| 2 | 7 | 0.15 | 0.05 | | | NSOL | NSOL | 2.4 | 2.6 | 3.2 | 4.0 | 3.8 | 3.7 |
| 3 | 7 | 0.15 | 0.1 | | | NSOL | NSOL | 1.6 | 2.3 | 3.0 | 2.8 | 3.1 | 4.0 |
| 4 | 7 | 0.25 | 0.05 | | | NSOL | NSOL | 2.0 | 2.8 | 3.2 | 3.5 | 3.5 | 4.2 |
| 5 | 7 | 0.35 | 0.05 | | | NSOL | NSOL | 1.3 | 1.8 | 2.1 | 2.3 | 2.8 | 3.1 |
| 6 | 7 | 0.05 | 0.05 | | ENEPIG (Pd-P) | NSOL | NSOL | NSOL | 2.4 | 2.2 | 3.0 | 3.0 | 3.1 |
| 7 | 7 | 0.15 | 0.05 | | | NSOL | NSOL | 1.8 | 3.2 | 3.1 | 3.3 | 3.4 | 3.2 |
| 8 | 7 | 0.15 | 0.1 | | | NSOL | NSOL | NSOL | 1.4 | 1.5 | 2.6 | 3.1 | 2.4 |
| 9 | 7 | 0.25 | 0.05 | | | NSOL | 2.5 | 2.4 | 2.7 | 2.8 | 3.9 | 3.7 | 3.9 |
| 10 | 7 | 0.35 | 0.05 | | | NSOL | NSOL | 2.3 | 2.9 | 3.5 | 3.9 | 3.8 | 4.9 |
| 11 | 7 | - | 0.3 | | Electroplated Ni/Au Softgold | 6.3 | 6.0 | 5.9 | 5.5 | 5.6 | 5.6 | 5.8 | 5.9 |
| 12 | | 0.3 | | | E'less pure Pd over Cu | NSOL | NSOL | 7.0 | 6.4 | 6.5 | 5.7 | 5.6 | 5.3 |
| 13 | 7 | | | 1,0 -1,5 | Electroplated Silver | 4.4 | 4.7 | 4.6 | 4.5 | 4.5 | 4.9 | 4.9 | 5.1 |

Table 1. First Test round results: average pull strength with pure Cu wire

Average Pull Strength (g) - Y Wires

| Sample | Plating | | | | | Cell: USG: | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|--------|----------------------------|-----|------|------|-----|------------|------|------|------|------|------|------|------|------|---|
| | Process | Ni | Pd | Au | 110 | | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | |
| A (Y) | Electrolytic Ni/soft Au | 5,4 | - | 0,11 | | 5,18 | 5,71 | 6,72 | 7,00 | 7,00 | 7,33 | 7,65 | 7,75 | 7,14 | |
| F (Y) | Electrolytic Ni/soft Au | 7,2 | - | 0,31 | | 5,91 | 6,03 | 6,97 | 7,12 | 6,82 | 7,70 | 8,20 | 8,17 | 8,18 | |
| G (Y) | ENEP (pure Pd) | 7 | 0,15 | - | | 7,27 | 6,58 | 6,67 | 6,54 | 6,26 | 6,17 | 6,87 | 7,44 | 7,66 | |
| H (Y) | | 7 | 0,3 | - | | 7,04 | 6,70 | 6,64 | 6,56 | 6,94 | 6,69 | 6,39 | 6,94 | 7,38 | |
| I (Y) | ENEP | 8,1 | 0,1 | - | | NA | 6,25 | 6,02 | 5,64 | 6,22 | 6,46 | 6,97 | 6,82 | 7,33 | |
| J (Y) | (PdP) | 7,5 | 0,3 | - | | NA | 6,23 | 6,04 | 5,84 | 5,35 | 6,08 | 5,96 | 5,66 | 6,35 | |
| K (Y) | Palladium Phosphor over Cu | - | 0,2 | - | | NA | 8,11 | 7,90 | 7,72 | 7,08 | 7,64 | 7,77 | 7,66 | 7,43 | |
| L (Y) | pure Palladium over Cu | - | 0,2 | - | | 8,45 | 7,97 | 7,49 | 7,53 | 7,04 | 6,72 | 6,52 | 6,84 | 7,17 | |

Table 2. Second Test round results: average pull strength in y direction with pure Cu wire

Average Pull Strength (g) - X Wires

| Sample | Plating | | | | | Cell: USG: | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|--------|----------------------------|-----|------|------|-----|------------|------|------|------|------|------|------|------|------|---|
| | Process | Ni | Pd | Au | 110 | | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | |
| A (X) | Electrolytic Ni/soft Au | 5,4 | - | 0,11 | | 4,28 | 3,44 | 4,57 | 5,02 | 5,04 | 5,39 | 5,20 | 5,78 | 5,75 | |
| F (X) | Electrolytic Ni/soft Au | 7,2 | - | 0,31 | | 6,20 | 6,31 | 6,61 | 6,28 | 6,15 | 6,70 | 6,64 | 6,74 | NA | |
| G (X) | ENEP (pure Pd) | 7,5 | 0,12 | - | | 5,17 | 7,72 | 7,26 | 7,10 | 6,61 | 5,95 | 4,83 | 5,03 | 4,64 | |
| H (X) | | 8 | 0,34 | - | | 5,24 | 7,54 | 7,02 | 6,40 | 6,46 | 5,97 | 5,01 | 5,27 | 4,58 | |
| I (X) | ENEP | 8,1 | 0,1 | - | | NA | NA | 7,05 | 6,02 | 6,09 | 5,57 | 5,27 | 4,71 | 3,96 | |
| J (X) | (PdP) | 7,5 | 0,3 | - | | NA | 8,14 | 6,39 | 6,07 | NA | 4,96 | 4,38 | NA | 4,05 | |
| K (X) | Palladium Phosphor over Cu | - | 0,2 | - | | NA | NA | 8,13 | 8,16 | 7,55 | 6,62 | 5,82 | 5,58 | 4,96 | |
| L (X) | pure Palladium over Cu | - | 0,2 | - | | NA | 8,70 | 8,53 | 7,39 | 7,44 | 6,73 | 5,27 | 4,95 | 4,28 | |

Table 3. Second Test round results: average pull strength in x direction with pure Cu wire

| Average Pull Strength - Pd-Cu wire | | | | | Plating Process | Ultrasonic Energy (mA) | | | | | |
|------------------------------------|---------|---------|---------|----------|------------------------------|------------------------|------|------|------|------|------|
| Sample | Ni [µm] | Pd [µm] | Au [µm] | Ag [µm] | | 70 | 80 | 90 | 110 | 130 | 140 |
| 4 | 7 | 0.25 | 0.05 | | ENEPIG (pure Pd) | 4.29 | 4.39 | 4.55 | 4.89 | 4.34 | 4.44 |
| 9 | 7 | 0.25 | 0.05 | | ENEPIG (Pd-P) | NSOL | 4.71 | 4.32 | 4.80 | 5.27 | 5.29 |
| 11 | 7 | - | 0.3 | | Electroplated Ni/Au Softgold | 7.96 | 8.39 | 7.90 | 7.56 | 7.37 | 7.72 |
| 13 | 7 | 0.15 | | | ENEP (pure Pd) | NSOL | NSOL | 3.27 | 4.11 | 4.66 | 4.29 |
| 14 | 7 | 0.3 | | | ENEP (pure Pd) | NSOL | NSOL | NSOL | 2.62 | 3.14 | 3.48 |
| 12 | | 0.3 | | | E'less pure Pd over Cu | NSOL | NSOL | NSOL | NSOL | NSOL | NSOL |
| 13 | 7 | | | 1,0 -1,5 | Electroplated Silver | 6.92 | 6.00 | 6.35 | 5.56 | 5.69 | 5.76 |

Table 4. Third Test round results: average pull strength with Pd coated Cu-wire

Legend:

| | | |
|---|------------------------------------|-------------------------------|
| NSOL or pull avg < 3g Wedge or Ball lift off | 3g < pull avg < 4.0g Wire break | Pull avg > 4.0g Wire break |
|---|------------------------------------|-------------------------------|

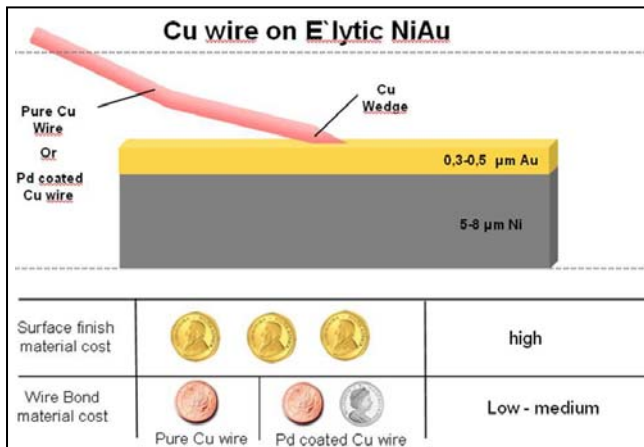


Figure 4: Cu wire bonding on electrolytic Ni/Au

Copper wire bonding on electrolytic Ni/soft gold was established in mass production in 2010. However, the high gold cost of the surface finish still remains in the electronic package. Furthermore, the Pd-coated copper wire is two to three times more expensive compared to pure Cu wire.

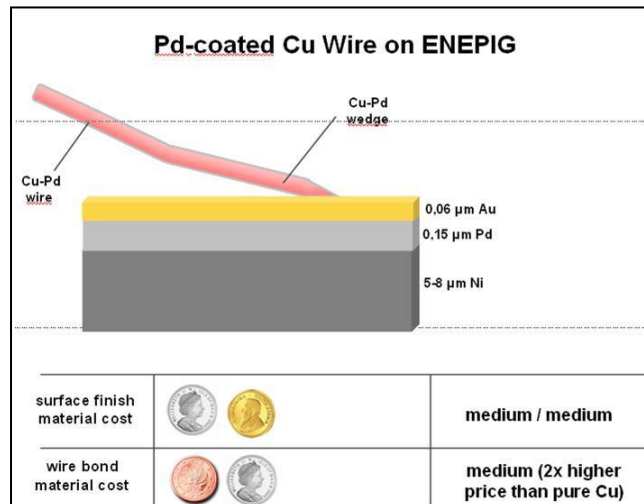


Figure 5: Pd coated Cu wire bonding on ENEPIG

Pure copper wire bonding on ENEPIG is more difficult and generally requires more complex, substantially slower bonding processes. Therefore, Pd-coated Cu is often preferred to achieve acceptable results. However, the results in this investigation show that this combination delivers worse results compared to electrolytic Ni/soft gold. Further increases of Au thickness in ENEPIG might bring similar results but at a higher cost level. Furthermore, the palladium coated Cu wire is harder which does bring further challenges for the ball bond on the Al pad.

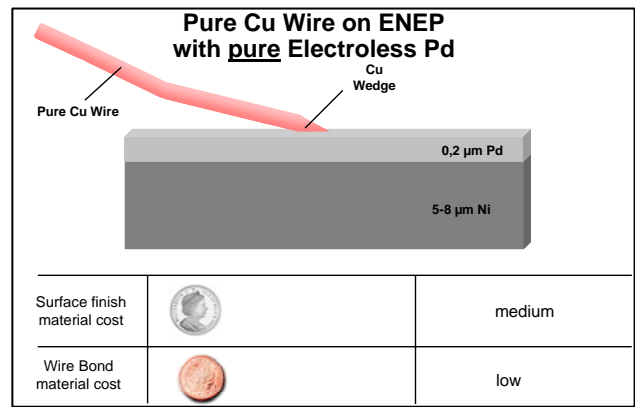


Figure 6: Pure Cu wire bonding on ENEP with pure Pd

This investigation has shown that ENEP with pure Pd achieves pure copper wire bonding pull test results similar to those for electrolytic Ni/soft gold. As such, the electronics industry has an opportunity to (1) eliminate the Au costs from the surface finish and (2) utilize the pure copper wire, which performs well and is only half the cost of Pd-coated wire. Furthermore, if a barrier (i.e. nickel) is needed to prevent the consumption of underlying copper during soldering, the ENEP finish with pure Pd is the most cost-effective solution.

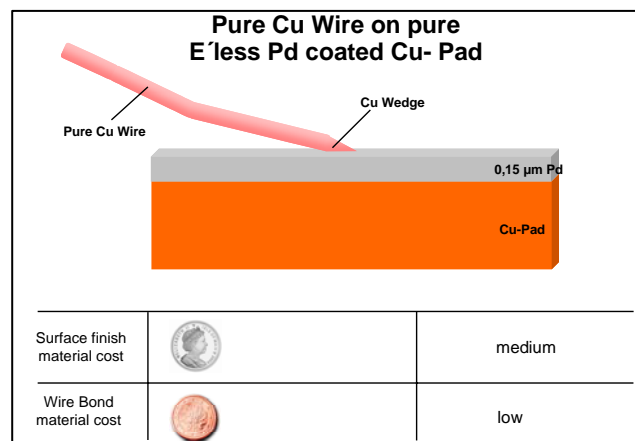


Figure 7: Pure Cu wire on pure electroless Pd on Cu-pad

Electroless pure Pd deposited directly on the copper pad is also very well suited for wire bonding with the pure Cu wire. The results are even better in comparison to pure Cu wire on electrolytic Ni/soft gold, as performed in this investigation. If no nickel barrier is needed (to stop the diffusion of copper into the solder) this surface finish is an alternative with excellent Cu-wire bonding results with pure Cu wire..

SUMMARY

A large variety of surface finishes were investigated to identify cost-effective surface finishes that are functionally suitable for Cu-wire bonding. When using pure Cu wire for bonding, two surface finishes were determined to be cost-effective alternatives to the standard process of electrolytic Ni/soft gold, namely:

- Electroless nickel / electroless palladium (ENEP) with a pure Pd deposit.
- Electroless pure Pd directly over copper

These two surface finishes have the potential to eliminate the Au cost from the electronic package, thus enabling lower manufacturing cost, without sacrificing performance or reliability.

FURTHER OUTLOOK

The Cu wire bonding performance of ENEP and electroless pure Pd over copper was determined in this study. There are further aspects currently being investigated that will be the topic of the next study, including:

1. Intermetallic growth between Cu wires bonded on different surface finishes
2. Study of the Pd-Au interconnection between the Cu-Pd wire and the pure Cu wire with Palladium covered finishes
3. Effect of temperature aging on performance
4. Pull test of stitch wire bonds over different temperature aging conditions.

Initial results from these latest investigations also appear very promising. Furthermore, studies have already been performed on the 1st bond from the semiconductor side [3,4,5], which already show very good results for ENEP with pure Pd in terms of its reliability with pure Cu wire ball bonds over high-temperature storage testing.

REFERENCES:

- [1] "Resistance of Common PWB Surface Finishes Against Corrosion in Harsh Environments" Mustafa Özkök, Mario Gensicke, Hugh Roberts, Joe McGurran, Guenter Heinz, SMTA 2010 Florida Orlando
- [2] "The benefits of ENEPIG with pure Pd for Gold wire bonding" Mustafa Oezkoek, Gustavo Ramos, Dieter Metzger, Hugh Roberts
- [3] „Nickel-Palladium Bond Pads for Copper and Gold Wire Bonding“ Horst Clauberg, Asaf Hashmonai, Tom Thieme, Jamin Ling and Bob Chylak
- [4] „Next Generation Nickel-Based Bond Pads Enable Copper Wire Bonding“ Bob Chylak, Jamin Ling, Horst Clauberg, and Tom Thieme
- [5] „Nickel-Palladium Bond Pads for Copper Wire Bonding “ Horst Clauberg, Petra Backus and Bob Chylak