Bondability & Solderability of Neutral Electroless Gold

by J.L. Fang

Ordinary immersion gold (IG) plating solution can corrode electroless nickel (EN) deposits. This results in the formation of an immersion gold deposit, a residue of phosphorus in the electroless nickel deposit (Ni-P) and the formation of black pad in the interface between the electroless nickel and immersion gold deposits. The black pad will cause solder joint failure. By increasing the time and therefore the thickness of the immersion gold deposit, the adhesion of the gold deposit and the wire bonding ability will clearly be decreased. In this work, we studied the conditions and mechanism of formation of the black pad and subsequent solder joint failure. Two coating systems, involving neutral electroless gold were found to solve the problem of black pad in the electroless nickel/immersion gold finishing of printed circuit boards and are described herein.

With the increasing complexity and densification of electronic equipment, microcircuit designs have become more complicated and parts with electrically isolated tracks and bonding pads continue to proliferate. Today's complex printed circuit boards (PCB) demand increased functionality in the final surface finishing processes. The manufacturing process must not only be able to produce finer lines, smaller holes and flatter pads; it must also provide a final surface finish which is bondable, solderable and provides a long-lived low contact resistance.[1]

The bondable gold plating process in current use is an electrolytic soft gold process. Unfortunately, it cannot be used where a board has non-contactable circuits. Further, the thickness of the gold deposit is dependent on the current density distribution, which is not necessarily uniform over the entire area of the circuit board.

Electroless nickel, followed by an immersion gold can be used with aluminum wire bonding, but it cannot be used with gold wire bonding. Normal immersion gold solutions are acidic and can corrode the electroless nickel, creating a "black pad" problem at the interface between the electroless nickel and the immersion gold. Any attempt to compensate for this condition by increasing the thickness of the immersion gold will reduce the adhesion of the gold deposit and reduce the ability to successfully wire bond.[2]

An electroless nickel/palladium/gold process can be used on the non-contactable circuit patterns in the board. Although the wire bondability characteristics are very good, the solderability is poor.

Electroless gold plating has found success in a variety of applications because of its ability to plate parts in discreet and isolated areas. Under like conditions, the current distribution characteristics of similar electroplating processes make them difficult or impossible to use.[3] We have found that a neutral electroless gold solution provides a deposit which not only has excellent bondability and solderability, but also produces no "black pad" condition at the electroless nickel/gold interface. Therefore, a neutral electroless gold is suitable for the manufacturing of chips-on-board (COB), ball grid arrays (BGA), multi-chip modules (MCM) and chip scale packages (CSP).

Recently, a large number of studies have dealt with autocatalytic electroless gold plating, based on either cyanide[4,5] or cyanide-free[6,7] chemistries. This work deals with a study of the bondability and solderability of deposits from a neutral electroless gold solution using potassium gold cyanide ($KAu(CN)_2$) as the gold salt.

Experimental

Bonding Tests

An ASM Assembly Automation thermosonic bonding machine, Model AB306B, was used in the bonding tests. The bonding test is configured, as shown in Fig. 1.

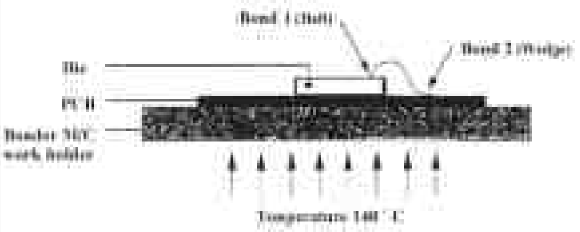

Fig. 1—Schematic layout of failure modes in the gold wire bondability test.

Table 1
SEM Analyses in Cross Section for "Black Band" Formation & Corrosion for Various EN/Gold Combinations

Method*	Black Band	Corrosion
EN/IG (pH 4.0, 12 min)	Serious	Serious
EN/IG (pH 4.5, 12 min)	Yes	Yes
EN/EG-1 (pH 7.0, 12 min)	No	No
EN/EG-1 (pH 7.0, 12 min) plus EG-2 (pH 6.7, 12 min)	No	No

* EN: Electroless nickel; IG: Immersion Gold; EG: Electroless Gold

One end of the gold wire is bonded to a gold ball, at left. The other end is bonded to the gold pad under test at the right. The bonding parameters for the gold ball bond were time, 45 ms; power setting, 55 and force, 55 g. For the wedge bond, the conditions were time 35 ms; power setting, 180 and force, 115 g. The power setting refers to the arbitrary dial setting for ultrasonic power on the bonding machine, which ranges from 0 to 255. The operating temperature was 140ºC. The diameter of the gold wire was 32 µm (1.25 mil). During the test, the gold wire is pulled with increasing force until failure occurs. If the wire breaks at any point, the bond is satisfactory. If separation occurs at the gold pad, however, the result is indicative of failure.

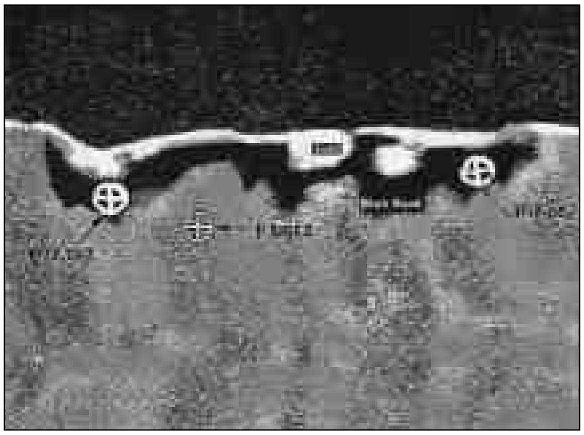

Fig. 2—”Black band” defect.

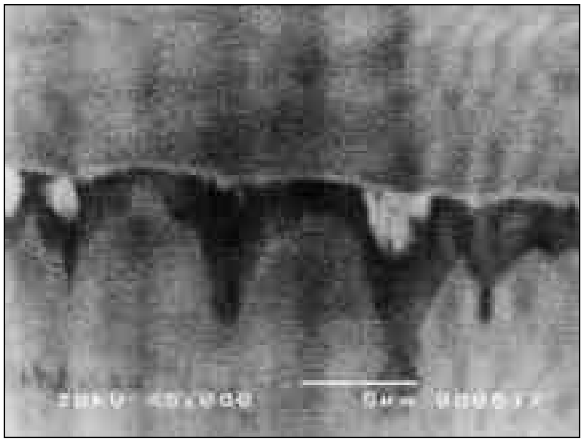

Fig. 3—”Black tooth” defect.

Solderability Testing

A Millice solder ball shear test machine, model DAGE-BT 2400PC, was used for solderability testing. The ball shearing test used a shearing arm positioned adjacent to a solder ball, 0.5 mm in diameter. The ball was soldered by conventional reflow methods onto the gold pad being tested. The shearing arm was used to apply an increasing lateral shear force on the solder ball to the point of fracture. This test was performed manually.

SEM & EDX Analysis

A JOEL scanning electron microscope, model JSM-5310LV, was used in our scanning electron microscopy (SEM) and electron diffraction (EDX) analyses. The “black band” and other phenomena were observed in sample cross-sections in the SEM. The relative elemental composition was determined by EDX.

Results & Discussion

Black Band Formation with Immersion Gold Over Electroless Nickel

When an electroless nickel-plated board is immersed in a weakly acidic immersion gold solution, the immersion gold deposit forms on the electroless nickel surface. When we peeled off the immersion gold layer, we found a black nickel deposit at the interface. Below that layer, the deposit still retained its normal bright gray color. If the black nickel defect were found in a discreet layer at the surface, which

Table 2
Comparison of Solderability for Various PCB Gold Pad Finishes

Finish Type*	EN/IG	EN/EP/IG	Electrolytic Ni/Au	EN/EG-1/EG-2
Thickness of each metallic layer, µm	4.57 / 0.10	4.57 / 0.76 / 0.25	12.70 / 0.76	7.62 / 0.013 / 0.64
Avg. shear force, g	858	530	1370	1093
Failure mode	1	1	2	1

* EN: Electroless nickel; EP: Electroless palladium; IG: Immersion Gold; EG: Electroless Gold

Table 3
Comparison of Gold Wire Bondability for Various PCB Gold Pad Finishes

Finish Type*	EN/IG	EN/EP/IG	Electrolytic Ni/ Au	EN/EG-1/EG-2
Thickness of each metallic layer, µm	4.55 / 0.11	5.26 / 0.76 / 0.09	9.30 / 0.76	7.06 / 0.013 / 0.73
Avg. pull force, g	11.0	11.6	12.2	11.7
Failure: Gold ball	8	0	0	0
Failure: Wire near gold ball	0	2	2	2
Failure: Center of wire	32	58	58	58
Failure: Wire near pad	0	0	0	0
Failure: Gold pad	2	0	0	0
Bondability	Poor	Good	Good	Good

* EN: Electroless nickel; EP: Electroless palladium; IG: Immersion Gold; EG: Electroless Gold

could be peeled away with tape as shown in Fig. 2, the condition was called “black pad.” In some cases, the black deposit defect branched deeper into the electroless nickel layer and could not be so easily removed, as shown in Fig. 3. This condition was called “black teeth.”

By the nature of the process, electroless nickel is a nickel-phosphorus alloy. Depending on the solution composition, the deposit may contain the intermetallic compound Ni_2P. The deposit can be corroded when immersed in the weakly acidic immersion gold solution:

$$Ni_2P + 4[Au(CN)_2]^- \rightarrow 4Au + P + 2[Ni(CN)_4]^=$$

The result is the formation of the gold deposit, the nickel complexing ion $[Ni(CN)_4]$= and a phosphorus residue on the electroless nickel layer. The phosphorus residue will blacken the electroless nickel. Electroless nickel can be similarly blackened if immersed in other corrosive solutions, such as a microetching solution composed of sodium persulfate and sulfuric acid. Our EDX analysis showed that that Ni-P was dissolved, leaving phosphorus on the surface. The surface nickel content decreased from 78.8% to 48.4%, while the phosphorus content increased from 8.56% to 13.14%.

Influence of “Black Pad” on Solderability & Bondability

During the soldering process, phosphorus in the blackened nickel does not migrate into the gold layer. When this blackened nickel is present in significant amounts, the area of wetting will be greatly reduced and a weak solder joint will result. On the other hand, because both the purity and thickness of the immersion gold are relatively low, the bondability of the electroless nickel/immersion gold layers is rather poor. As a result, it is only usable for aluminum wire bonding, and not for gold wire bonding.

Effect of Immersion Gold Solution pH on Electroless Nickel Corrosion

Non-electrolytic gold plating can be achieved by two means: 1) immersion gold (IG) or 2) electroless gold (EG). Immersion gold involves a direct displacement reaction between gold ions in solution and the electroless nickel (EN) deposit:

$$Ni_2P + 4[Au(CN)_2]^- \rightarrow 4Au + P + 2[Ni(CN)_4]^=$$

As noted earlier, the result of the displacement reaction is the deposition of gold and the dissolution of nickel. As a result, phosphorus is left as a residue on the surface of the electroless nickel deposit, producing the “black band” at the nickel/gold interface. On the other hand, electroless gold plating deposits by chemical reduction, according to the reaction:

$$2[Au(CN)_2]^- + H_2PO_2^- + H_2O \rightarrow 2Au + H_2PO_3^- + 4CN^- + H_2 \uparrow$$

The electroless reaction results in the deposition of gold and the oxidation of hypophosphite. There is no corrosion of the electroless nickel or formation of a phosphorus residue. The gold deposit is formed through the reduction of $[Au(CN)_2]$- by hypophosphite.

We examined cross sections by scanning electron microscopy for a number of immersion and electroless gold depositions on electroless nickel. The results are shown in Table 1.

The results in the table show that the “black band” or “black pad” problem is primarily dependent on the pH value of the gold solution. Lower values of pH leads to more rapid corrosion and formation of the “black band.” The use of a neutral electroless gold, either as a single or duplex process results in no observable corrosion or “black band” formation. With the neutral electroless gold process, solder failure is non-existent.

Solderability

Table 2 shows the results of ball shear testing done to compare the solderability of gold pads produced by various coating methods. Failure mode “1” refers to separation from the gold pad. Failure mode “2” refers to fracture within the solder ball itself. The results show that the solder joints on electrolytic soft gold plating have the highest shear force, exceeding 1300 g. The electroless nickel and duplex electroless gold system also showed good strength, with an average shear force exceeding 1000 g. The industry standard is a minimum of 800 g for solder joints.

Gold Wire Bondability

Table 3 summarizes the gold wire bondability test results. It can be seen that a conventional electroless nickel/immersion gold deposit system cannot be used for gold wire bonding. There were two failures at the pad, and eight failures at the gold ball itself. The bondability of the electroless nickel with duplex electroless gold was similar to that for the electrolytic nickel/gold and electroless nickel/electroless palladium/immersion gold systems. We attribute this to the low hardness of the second electroless gold layer (98 VHN_{25g}).

Effect of Electroless Gold Thickness on Bondability

Gold wire bonding tests were performed with various thicknesses of electroless gold. The results are shown in Table 4. Good gold wire bondability is achieved at electroless gold thicknesses above 0.25 µm. For comparison, the normal thickness of electrolytic sift gold in this application ranges from 0.64 to 0.76 µm.

Conclusions

1. When neutral electroless gold is used in place of immersion gold, it can prevent the corrosion of electroless nickel and

Table 4
Effect of Electroless Gold Thickness on Bondability

Total gold thickness, µm	Average pull force, g	Failure mode	Bondability
0.2	14.21	Wire, pad	Poor
0.25	15.06	Within wire	Good
0.33	14.77	Within wire	Good
0.40	13.89	Within wire	Good
0.45	13.89	Within wire	Good
0.50	13.34	Within wire	Good
0.55	13.55	Within wire	Good
0.68	14.29	Within wire	Good

prevent the occurrence of "black pad" between the gold and electroless nickel deposit.

2. Thicknesses of 0.25 to 0.50 µm of neutral electroless gold can achieve both good solderability and gold wire bondability. It is therefore a good alternate to conventional electrolytic soft gold.

3. Electrolytic soft gold is limited to surfaces where electrical connection through the printed circuit board is possible, posing a severe limitation on board design. Neutral electroless gold does not have this limitation.

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