Electroless Ni-P/Pd/Au Plating for Semiconductor Package Substrates

By Kiyoshi Hasegawa, Akio Takahashi, Takaaki Noudou & Akishi Nakaso*

Since portable electronic equipment has become popular, BGAs (ball grid arrays) are increasingly used for semiconductor packages mounted on high-density printed circuit boards. Semiconductor chips and package substrates are connected by gold wire bonding in most BGAs. These package substrates and motherboards are connected by solder balls. To satisfy the reliability required for these connections, gold plating is applied to the terminals on both sides of the package substrate. Electroless gold plating has an advantage in the higher-density package substrates. However, as the reliability of the conventional electroless Ni-P/Au plating was not sufficient, we have developed a new electroless Ni-P/Pd/Au plated coating which ensures adequate reliability.

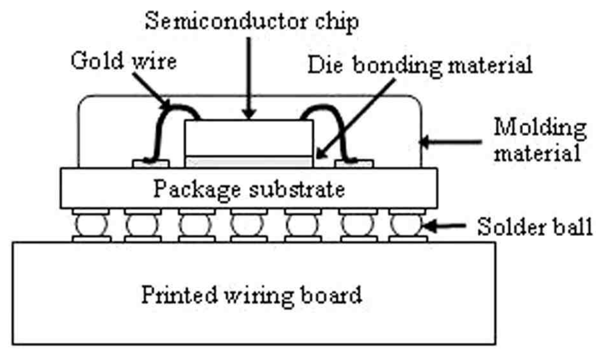

Figure 1—Structure of the electronics package (Wire bonding type).

As portable electronics have become popular, CSPs (chip-size packages) and BGAs (ball grid arrays) are increasingly used for semiconductor packages mounted on high-density printed circuit boards. As shown in Fig. 1, semiconductor chips and package substrates are connected by gold wire bonding in most CSPs and BGAs. Printed circuit boards and package substrates are connected by solder balls. In order to satisfy the reliability required for these connections, gold plating is applied to the terminal surfaces on both sides of the package substrate. Conventionally, the mature technology of electrolytic gold plating has long been used for the surface finishing of package substrates. Today, electroless gold plating technology, which uses no leads for electrolytic plating, is becoming the focus of interest as the circuit integration on the substrate consistently advances.[1-6]

Electroless gold plating technology, however, has some technical problems. The most immediate issue is related to wire bonding, *i.e.,* the process of connecting semiconductor chips and package substrates with gold wire by thermal-ultrasonic bonding. The thermal history during the process of semiconductor packaging will decrease the strength of the wire bonding by deforming the plated surface. Another problem is concerned with the reliability of the solder ball joint. Solder balls connect the CSP and the BGA when they are mounted on the printed circuit board. The solder ball connection has less connection area than exists with the conventional method, in which the metal leads of Thin Small-Outline Packages (TSOP) and Quad Flat Packs (QFP) are connected by soldering. Also, there is no stress alleviation by the leads. Recently, the solder joint reliability of the CSP and BGA has been examined in several studies.[7-13] Many reports have been issued concerning the relationship between the surface finish of solder ball pads and the solder joint reliability.[14-20] The electroless gold plating was insufficient in terms of solder ball joint reliability as well as wire bonding after heat treatment.

Nuts & Bolts: What This Paper Means to You

Ball grid arrays are increasingly used for semiconductor packages on high-density printed circuit boards and are connected by gold wire bonding. These package substrates and motherboards are connected by solder balls. Reliability is a question and the authors have investigated the use of electroless gold plating and a palladium diffusion barrier layer to enhance that reliability.

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In this work, we studied the causes of the low wire bonding strength after heat treatment and the possibility of improving the strength. We also looked into the causes of low connection strength of solder balls and possible processes for improvement. Our findings indicate that the low wire bonding strength arose from contamination of the gold plated surface by the diffusion of nickel plated under the gold. In addition, we found that the low connection strength of solder balls was caused by the formation of a corrosion layer between the gold and the nickel. This paper discusses a newly developed multi-layer coating system consisting of electroless nickel, palladium and gold as an improved process.

Experimental

Sample preparation for wire bonding studies.

The test substrate for the wire bonding study consisted of an epoxy resin impregnated glass-fabric laminated board cladded with 35 μm (1.38 mil) thick copper foil. It was etched using a test pattern, and then subjected to acid degreasing, activation, electroless nickel plating, immersion gold plating and electroless gold plating in that order.

Production processing of test samples for solder joint reliability studies

After the test pattern was etched on the surface of the test substrate, solder resist was formed around the ball pads to cover the surface. The ball pads had a diameter of 0.6 mm (23.6 mil) each. Test substrates were then treated with one of the four different types of surface finish: (a) Cu / organic solderability preservative (OSP), (b) electrolytic nickel / electrolytic gold plating, (c) electroless nickel / immersion gold / electroless gold plating and (d) electroless nickel / electroless palladium / immersion gold / electroless gold to produce test sample substrates for solder ball shear testing.

Evaluation of wire bonding reliability

Wire bonding was performed** under the following conditions: gold wire diameter, 28 μm (1.1 mil); plate temperature, 150°C (302°F); load, 100 g (0.22 lb.) and ultrasonic output, 120 PLS (partial least squares) for 20 msec. The pull strength of the wire was measured with an all-purpose bond tester.***

Evaluation of solder ball joint reliability

Eutectic solder balls were bonded to a plated test substrate after applying flux, and were then loaded in a nitrogen reflow furnace at maximum temperature range of 220 to 250°C (428 to 482°F) to be subject to a ball shear test. The shear strength was measured with the all-purpose bond tester. The fracture mode was also checked and evaluated by observing the fracture of the solder balls with an optical microscope.

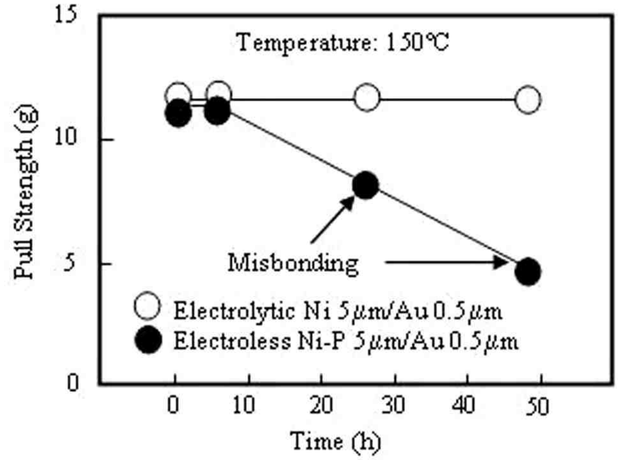

Figure 2—Wire bonding reliability of gold plating.

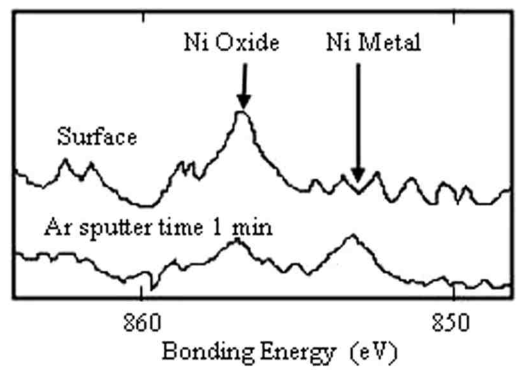

Figure 3—XPS results for electroless plated gold after heat treatment for 50 hr at 150°C (302°F).

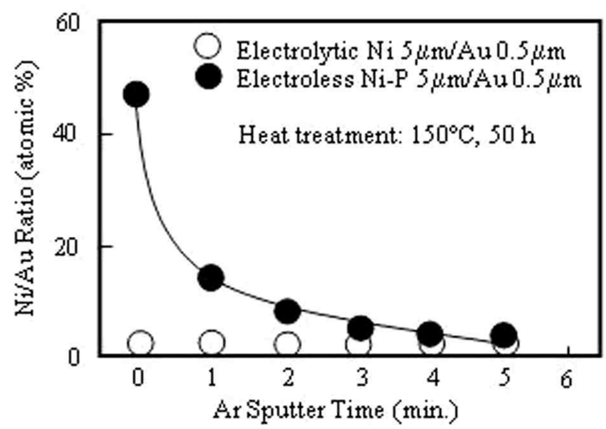

Figure 4—XPS results for both plated golds after heat treatment.

Results & discussion

Wire bonding reliability of gold plating

Degradation of the wire bonding strength by heat treatment. Figure 2 shows the relation between the heat treatment time at 150°C (302°F) and the pull strength of the wire bonding. The electroless gold was not inferior to the electrolytic gold until subjected to 3 hr of heat treatment. Thereafter, the pull strength for the electroless gold gradually decreased and bond failure occurred after 10 hr. On the other hand, the electrolytic gold retained constant pull strength up to 50 hr. It was clear, therefore, that it was important to determine the cause of the decrease.

The electroless gold surface after heat treatment was examined by X-ray photoelectron spectroscopy (XPS). The results are shown in Fig. 3. It was observed that the nickel underplate diffused to the gold plated surface to form nickel oxide. In addition, to get the depth profile of nickel in the gold layer, the argon-sputtered surface was analyzed by XPS. Figure 4 indicates that the nickel oxide was concentrated on the surface of the gold. The distribution of nickel on the gold surface was also observed by Auger

**Shinkawa UTC 230 BI wire bonding machine, Shinkawa Ltd., Tokyo, Japan.
***Dage 2400PC Series Wire Pull Tester, Dage Precision Industries, Fremont, CA.

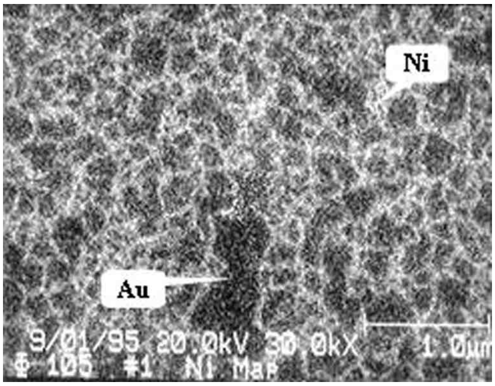

Figure 5—AES results for the nickel distribution on the gold plated surface.

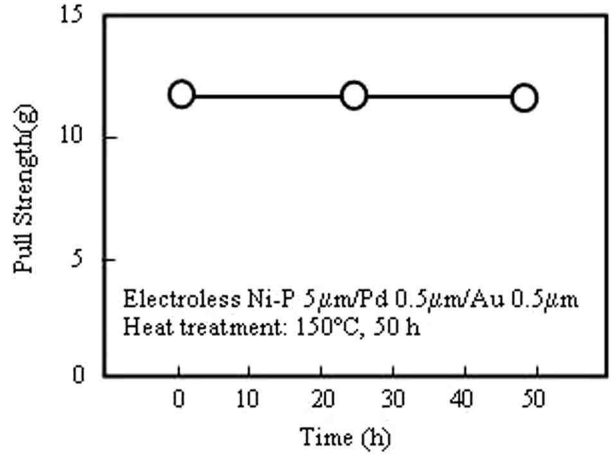

Figure 7—Wire bonding reliability of electroless Ni-P/Pd/Au.

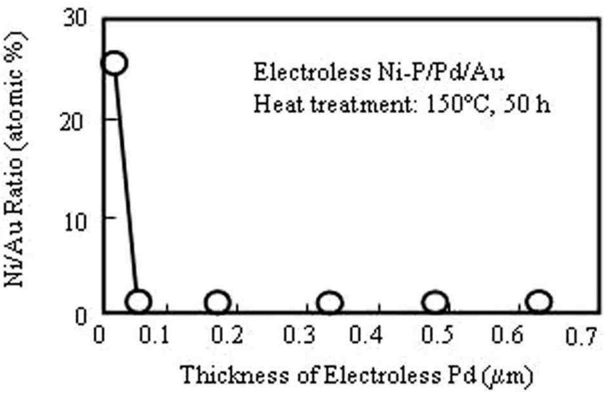

Figure 6—Thermal diffusion barrier effects of electroless Pd as evaluated by XPS analysis.

electron spectroscopy (AES). The result is shown in Fig. 5, which suggests that nickel diffusion occurred through the grain boundaries of the gold layer. From these findings, we concluded that the pull strength decrease was caused by the diffusion of the nickel underplate through the grain boundaries to the surface of the gold layer during heat treatment. The accumulation of diffused nickel apparently interfered with the gold wire bonding produced by thermal-ultrasonic operation.

Improvement in pull strength of wire bonding after heat treatment. We have studied two methods to control the formation of nickel oxide on the gold plated surface. The first method was to increase the thickness of the electroless gold layer. Although this method was effective, the main disadvantage was the increased cost in proportion to the thickness. The second method was to form an electroless plated layer, which resists oxidation, as an intermediate barrier layer to suppress nickel diffusion.

Selection of the electroless plated intermediate layer. We performed a comparative study of different materials for use as an intermediate barrier layer using oxidation-reduction potential as the reference index, since oxidation was proved to play a key role in the nickel diffusion to the gold surface. We selected an electroless palladium coating, which is difficult to oxidize, as the bonding layer.[21,22]

The Ni/Au ratio was measured by XPS by varying the thickness of the intermediate palladium layer of the Ni-P/Pd/Au plating. As shown in Fig. 6, the nickel diffusion was drastically decreased when the thickness of the electroless palladium plating as barrier metal was 0.05 μm (2.0 μ-in.) or greater.

Wire bonding reliability of electroless Ni-P/Pd/Au. The terminal surface was first plated with 5 μm (197 μ-in.) of electroless nickel. Then, a 0.5-μm (19.7-μ-in.) electroless intermediate palladium layer was added, followed by a 0.5-μm (19.7-μ-in.) electroless gold layer. The samples were heat-treated at 150°C (302°F) for 50 hr. The pull strength was then measured to determine the reliability of the wire bonding. It was confirmed that a high level of wire bonding pull strength could be attained with the electroless Ni-P/Pd/Au multilayer system, even after heat treatment, as shown in Fig. 7. The wire bonding reliability of the electroless Ni-P/Pd/Au multilayer was as good as that of the electrolytic Ni/Au system.[23,24]

Reducing the thickness of electroless plated gold layer. The relation between the thickness of the gold plated layer and the reliability of the wire bonding was studied to optimize the electroless Ni-P/Pd/Au layers. The wire bonding reliability, with 0.05 μm (2.0 μ-in.) of electroless gold was maintained during heat treatment, as long as the 5-μm (197-μ-in.) electroless nickel layer was covered with 0.5-μm (19.7 μ-in.) of electroless palladium. Therefore, the thickness of the gold layer could be thinner than that for the conventional electrolytic Ni-P/Au plating, thus proportionally reducing plating costs.

Solder ball joint reliability

Solder ball shear strength and fracture mode. Figure 8(a) shows the solder ball shear testing method. Pressure was applied to the solder ball by moving a shear tool at a constant speed to the point of fracture of the bonded portion of the solder ball. If part of the solder remained on the substrate, as shown in Fig. 8(b), separation occurred within the solder, and the fracture mode was considered acceptable. If fracture occurred at the interface between the solder and the plating, as shown in Fig. 8(c), the fracture mode was considered to be defective. In Fig. 8(c), interfacial fracture occurred because the bond between the solder and the coating was weaker than the solder itself. The ratio of the number of solder ball fractures to the total number of tests was called the solder ball fracture rate (%). This was used as an index of reliability of the solder ball joint.

High-speed shear test. Different shear speeds have been used by different manufacturers for the shear test to evaluate the reliability of the solder ball joint. The shear speeds range from 1 to 20 mm/min (0.04 to 0.79 in./min). To create a situation which is closer to the impact caused by dropping, a high-speed shear test (20 mm/min or more) was developed.

Surface finish process applied to the ball pad. Four processes were examined to be applied to the ball pad. A proprietary organic solderability preservative (OSP) (preflux) was used as a protective organic compound, and the metal connecting with the solder was copper. The connecting metal was nickel in the case of both electrolytic gold plating and the two types of electroless gold

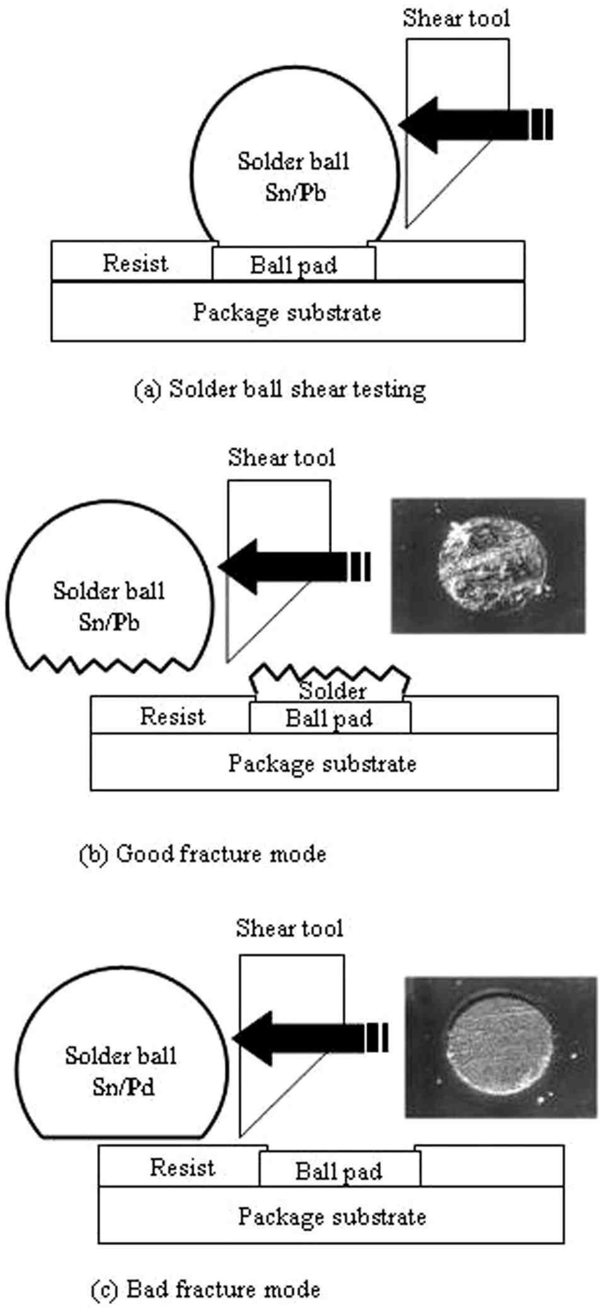

Figure 8—Solder ball shear testing and fracture modes.

plating. Gold and palladium were dissolved in the solder. The electroless Ni-P/Pd/Au plating process was developed by Hitachi Chemical.[23,24]

Surface finish and solder-ball joint reliability. The ball shear tests were conducted by mounting the solder ball on the test substrate made by each surface finish technique. The results are shown in Fig. 9. When the shear speed was less than 10 mm/min (0.39 in./min), the rate of solder ball fracture was independent of the surface finish applied. However, when the shear speed was greater than 10 mm/min (0.39 in./min), the rate was dependent on the applied surface finish. The electroless Ni-P/Pd/Au multilayer coating performed equally to the OSP-treated copper and electrolytic Ni/Au coatings, which means the plating was satisfactory. In the case of electroless Ni-P/Au plating however, when the shear speed was 100 mm/min (3.9 in./min) or greater, the solder ball fracture rate decreased to about 70%.

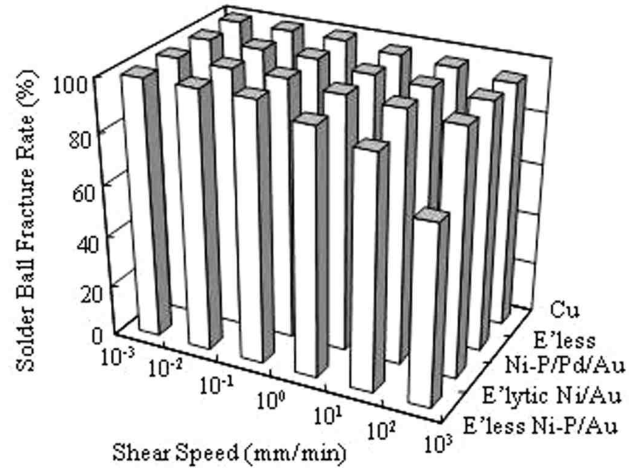

Figure 9—Relationship between the type of surface finish and fracture mode.

Observation of interfacial fracture by SEM. It was confirmed that the reliability of the solder ball joint was lower for electroless Ni/Au plating than for the other surface finishes. Many reports have been issued concerning the causes for this.[7-13] We noted that the reliability might depend on the electroless palladium plating. Based on this new result, we tried to clarify the cause of the decreased reliability for the electroless Ni-P/Au plating.

In the high-speed shear testing, interfacial fractures occurred only with electroless Ni-P/Au coatings. The fractured interfacial surface was observed by scanning electron microscopy (SEM). The result is shown in Fig. 10. It can be seen that the original electroless Ni-P plating surface exhibited microscopic cracks at the plating grain boundary.

Electroless Ni-P surface after gold dissolution. The gold film produced in the electroless Ni-P/Au plating process was dissolved in a selective stripping solution to clarify the process by which cracks were formed at the interface. A proprietary gold stripping solution was used for this purpose. The exposed electroless Ni-P surface was then observed by SEM. Figure 11 shows the results. There was intergranular corrosion residue consisting of nickel oxide in the electroless Ni-P coating. This corrosion must have been formed during the immersion gold plating. On the other hand, we used the SEM to observe the electroless Ni-P surface after the gold and palladium were dissolved from the electroless Ni-P/Pd/Au multilayer coating. This surface was similar to that of the electroless Ni surface immediately after plating. There was no corrosion under the electroless palladium.

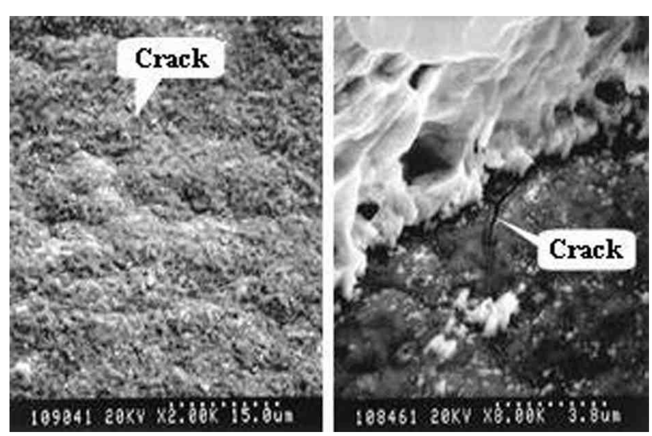

Figure 10—SEM photos of interfacial fracture.

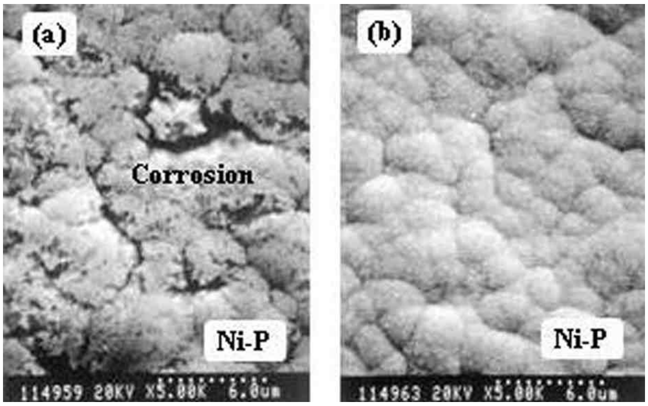

Figure 11—Ni-P Surface after the dissolution of Au or Pd: (a) Electroless Ni-P/Au; (b) Electroless Ni-P/Pd/Au.

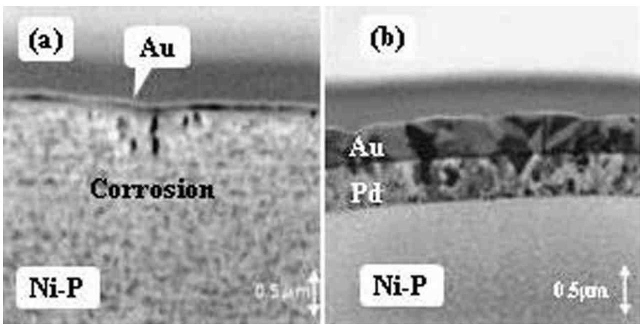

Figure 12—FIB-SIM photos of the cross-section of electroless gold: (a) Electroless Ni-P/Au; b) Electroless Ni-P/Pd/Au.

FIB/SIM observation of electroless gold. The result shown in the previous section was obtained by SEM. Information concerning the intergranular corrosion into the coating depth was desirable. Therefore, the cross-section of the electroless gold layer was analyzed with a focused ion beam (FIB) and observed with scanning ion-beam microscopy (SIM). Figure 12 shows the results. For the electroless Ni-P/Au system, we observed local pitting dissolution in the electroless Ni-P at the interface with the immersion gold layer. This corresponded to the formation of corrosion residue shown in the previous section. We assumed that this corrosion caused the local pitting into the deposit. In the cross-section of the electroless Ni-P/Pd/Au layer, there was no local pitting at the interface between the electroless palladium and the electroless Ni-P. This also corresponded to the results shown in the previous section. Further, there was no local pitting at the interface between the electroless gold and the electroless palladium.

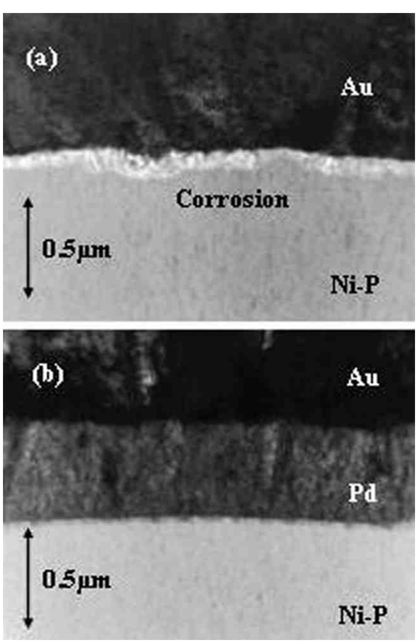

Figure 13—TEM photos of the cross-section of electroless gold: (a) Electroless Ni-P/Au; (b) Electroless Ni-P/Pd/Au.

TEM study of the electroless gold. When the cross-section was observed with FIB/SIM, we noticed local dissolution of the electroless Ni-P plating layer caused by the immersion gold plating reaction. We then more closely observed the cross-section of the electroless gold plating layer by increasing the magnification using transmission electron microscopy (TEM). The results are shown in Fig. 13. In Fig. 13(a), the surface of the electroless Ni-P was dissolved evenly and minutely by the immersion gold plating. Also, a few large local dissolution pits were observed. On the other hand, in Fig. 13(b), there were no white corrosion layers observed at the interface between the electroless palladium and the electroless Ni-P. Further, we observed no white corrosion at the electroless gold / palladium interface.

Electrical potential change in the immersion gold and electroless palladium reactions. As a result of the work reported in the previous sections, we assumed that the difference in the reaction between the immersion gold plating and the electroless palladium plating on the electroless Ni-P coating surface affected the joint reliability. We then measured the electric potential change in each plating reaction on the electroless Ni-P coating. The results are shown in Fig. 14. The chemical reactions are given as:

$$Ni + 2Au^{+} \rightarrow Ni^{+2} + 2Au \quad (1)$$

$$Pd^{+2} + 2e^{D} \rightarrow Pd \quad (2)$$

As a result, we found that the electroless Ni-P/immersion Au appeared to be covered with gold, but the electric potential of the immersion gold plating reaction was close to that of nickel. Thus, we surmised that the immersion gold plating reaction was a combination of nickel dissolution and gold deposition and that the nickel dissolution was dominant. We also found that the electri-

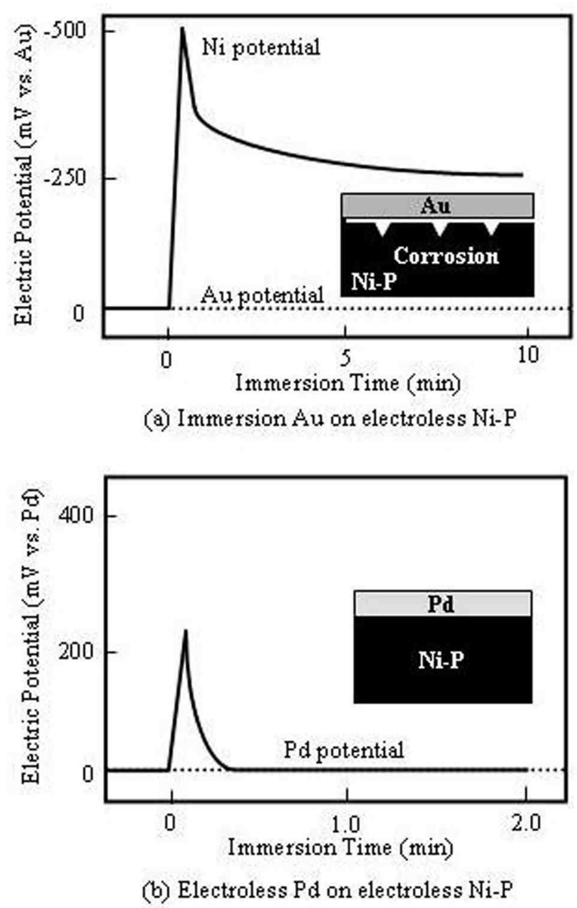

Figure 14—Changes in electric potential for each surface finish process.

cal potential of the electroless palladium became equal to that of the palladium electrical potential within 30 sec of the start of the deposition process, and that nickel dissolution did not occur. We assumed, therefore, that palladium was autocatalytically deposited on the nickel during the electroless palladium reaction and that the electroless Ni-P plating surface was instantaneously covered with palladium.[25]

Summary

Our study on the wire bonding reliability after heat treatment and on the solder ball joint reliability, which was undertaken in the course of our research on electroless gold plating for package substrates such as CSPs or BGAs, has disclosed the following.

Wire bonding reliability of electroless gold plating

We found that in the electroless gold plating process the nickel underplate diffused through the coating and over the surface of the gold coating by heat treatment and was converted to nickel oxide. This interfered with the bonding between gold wire and the gold coating and decreased the bond strength. We also found that applying a palladium barrier layer between the nickel underplate and the gold coating will acted as a diffusion barrier to prevent nickel diffusion. We concluded that the wire-bonding strength of the multilayer Ni-P/Pd/Au coating after heat treatment was equivalent to that of the conventional electrolytic gold coating.

Solder-ball joint reliability of the electroless gold plating

We examined the relationship between the type of gold plating and the reliability of the solder ball joint. The reliability of the solder ball joint for an electroless Ni-P/Pd/Au multilayer coating was be better than that of a conventional electroless Ni-P/Au coating, and equivalent to those for OSP and electrolytic Ni/Au coating systems. The low reliability observed with electroless Ni-P/Au was related to minute pits formed in electroless Ni-P, which were caused by nickel dissolution resulting from the replacement reaction of immersion gold.

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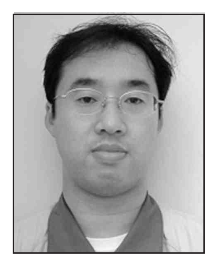

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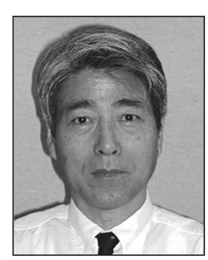

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