**Influence of an Immersion Gold Plating Layer on Reliability of a Lead-Free Solder Joint**

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Electroless Ni/Au plating is often performed on a surface of a Cu pad to improve the wettability of lead-free solders on such a pad. Generally, electroless Au plating is performed by an immersion plating method. Since a substitution reaction of Ni and Au occurs selectively on the surface of a Ni layer in immersion plating, the Au layer does not uniformly form on the Ni layer and microvoids or microcracks easily form at the Ni/Au interface. Such defects induce void formation at the joint interface in soldering, and consequently degrade the reliability of the lead-free solder joint. In this study, the influences of immersion plating time on microvoid formation at the joint interface and the reliability of a solder ball joint with a Sn–3 mass%Ag–0.5 mass%Cu lead-free solder were investigated.

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**Keywords**: lead-free solder, electroless plating, gold plating, Sn–3 mass%Ag–0.5 mass%Copper, joint reliability

1. **Introduction**

Due to the toxic effect of lead on human health, the use of lead-free soldering has become wide spread in the manufacture of many electronic devices.¹ Generally, a lead-free solder has a poor wettability to a copper electrode;²–³ thus, the surface of the copper electrode is finished by electroless Ni/Au plating to improve the wettability of the solder.⁴ In a solder joint using an electroless Ni/Au-plated electrode, interfacial fracture often occurs at the joint interface, thereby degrading joint reliability.⁴–⁸ Interfacial fracture is mainly caused by microvoids formed at the joint interface in soldering.⁷–⁸

Generally, electroless Ni/Au plating is conducted by an immersion plating method.⁹–¹¹ In such a method, a substitution reaction of Ni and Au occurs selectively on the surface of the Ni layer; thus, the Au layer does not uniformly form on the Ni layer. Therefore, microvoids or cracks form at the interface between the Ni and Au layers in the plating process. Such defects induce the formation of microvoids at the joint interface in soldering. In this study, the influence of an immersion Au plating layer on the reliability of a lead-free solder joint was investigated. In particular, the influence of plating time, which is approximately proportional to the thickness of the Au plating layer, on the reliability of the lead-free solder joint was investigated.

2. **Experimental Procedures**

An FR-4 substrate, which has Cu pads with a diameter of 300 µm, was prepared. Electroless Ni plating was performed on the surface of the Cu pad. The thickness of the Ni plating layer was 3 µm, and the composition of the Ni layer was Ni–8 mass%P. Afterward, two types of electroless Ni/Au-plated Cu pad were prepared by conducting immersion Au plating for 10 and 30 min. The thicknesses of the Au layers were 60 and 150 nm for the plating times of 10 and 30 min, respectively. The surface of the Ni/Au layer was observed using scanning electron microscopy (SEM). Moreover, the surface of the Ni layer whose Au layer was removed by etching treatment was also observed using SEM.

A Sn–3 mass%Ag–0.5 mass%Cu lead-free solder ball with a diameter of 350 µm was also prepared to form a solder ball joint. The solder ball joint was formed by reflow soldering with a reflow furnace. The peak temperature and the holding time beyond 220°C in the reflow process was 250°C and 60 s, respectively. A subsequent heat exposure treatment was conducted for the solder ball joint at 150°C for 500 h. Ball shear and ball pull tests were performed before and after the heat exposure treatment. The test speeds of the ball shear and ball pull tests were 15 mm/min and 10 mm/min, respectively. Microstructural observations for the cross sections of the solder ball joints and fracture surfaces after the ball shear and ball pull tests were performed using electron probe X-ray microanalysis (EPMA) and SEM.

3. **Results and Discussion**

3.1 **Surface of plating layer**

Figure 1 shows the surfaces of the electroless plating layers. For the surfaces of the Ni/Au layers, they are relatively smooth and the influence of Au immersion time on the Ni/Au surface is hardly found. On the other hand, the influence of Au immersion time on the surface of the Ni layer is observed on the surfaces of the Ni layers with removed Au layers [refer to Figs. 1(c) and (d)]. Microvoids of submicron size are observed on the surfaces of the Ni layers. With increasing Au immersion time, the number of such microvoids increases and their growth in size is observed. Moreover, microcracks are also observed on the Ni surface subjected to Au immersion treatment for 30 min. Usually, the thin Au layer is dissolved in a molten solder in the soldering process, and a reaction layer forms at the joint interface between the Ni layer and the solder. Thus, microvoids existing in the Ni/Au interface probably cause the void formation at the joint interface in the soldering process.
3.2 Initial microstructure of solder ball joint

Figure 2 shows secondary electron images of the cross sections of the solder ball joints after reflow soldering. In both cases of the Au layers with 60 and 150 nm thicknesses, the Au layers were not observed at the joint interface. The reaction layers formed at the joint interfaces were determined to be ternary Cu–Sn–Ni compounds by EPMA analysis. In the joint with the 60 nm-thick Au layer, the reaction layer grows uniformly at the joint interface. In contrast, an inhomogeneous growth of the reaction layer is observed in the joint with the 150 nm-thick Au layer. Moreover, it is found that the Ni layer is attacked partially in the joint. Such a growth morphology of the reaction layer and the partial attack of the Ni layer easily cause void formation at the joint interface in reflow soldering.

3.3 Ball shear strength

Figure 3 shows the results of ball shear tests. The ball
shear force of the joint using the 60 nm-thick Au layer is approximately 15% larger than that of the joint using the 150 nm-thick Au layer. The ball shear force is relatively stable under the heat exposure conditions investigated.

In this study, fractures occurred in the solder layer beside the joint interface in all the joints. The fractured surfaces observed using SEM are shown in Fig. 4. When the thickness of the Au layer is 60 nm, solder deformation in the shear direction is observed in both joints after soldering and heat exposure treatment at 150°C for 500 h. Compared with the joints using the 60 nm-thick Au layer, many voids are observed in the fractured surfaces of the joint using the 150 nm-thick Au layer. The diameter of such voids ranges from approximately 10 to 30 μm. Since such large voids were not observed in the cross sections of the joints after soldering, the voids are formed in the ball shear test. As described above, void formation occurs easily at the joint interface using the 150 nm-thick Au layer. Because the microvoids exist at the interface between the Ni and Au layers before soldering and the reaction layer does not grow uniformly at the joint interface in soldering. The inhomogeneous growth of the reaction layer prevents the solder from deforming uniformly in the shear direction. Therefore, voids easily coalesce during solder deformation due to potential microvoids at the Ni/Au interface and the inhomogeneous growth morphology of the reaction layer promotes the formation of larger voids.

### 3.4 Ball pull strength

Figure 5 shows the results of ball pull tests. Ball pull forces...
are maximum before heat exposure treatment and they decrease after heat exposure at 150°C for 100 h; afterward, they are stable under the heat exposure conditions investigated. The ball pull force of the joint using the 60 nm-thick Au layer, as well as the ball shear force, is larger than that of the joint using the 150 nm-thick Au layer under the heat exposure conditions investigated.

Figure 6 shows the fractured surfaces after ball pull tests observed using SEM. In the case of the joint using the 60 nm-thick Au layer, fractures occurred at the joint interface after reflow soldering. A similar fracture mode was observed after heat exposure at 150°C for 500 h. Several dimples are observed in the fractured surface shown in Fig. 6(b). Although the relationship between such dimples and the void row that formed at the interfaces of the reaction layers is not clarified, microvoids that formed at the Ni/Au interface in plating seem to promote void formation in soldering. Thus, the ball pull force of the joint with the 150 nm-thick Au layer after reflow soldering [Fig. 6(b)].

Table 1 EPMA quantitative analysis results for each area marked in Fig. 6.

<table>
<thead>
<tr>
<th>Analysis area</th>
<th>Sn (at%)</th>
<th>Ag</th>
<th>Cu</th>
<th>Ni</th>
<th>P</th>
<th>Au</th>
<th>Inference phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>47.8</td>
<td>0.0</td>
<td>33.4</td>
<td>18.8</td>
<td>0.0</td>
<td>0.0</td>
<td>(Cu,Ni)$_6$Sn$_5$</td>
</tr>
<tr>
<td>B</td>
<td>35.3</td>
<td>0.0</td>
<td>23.5</td>
<td>32.2</td>
<td>7.9</td>
<td>1.0</td>
<td>Sn–Ni–P</td>
</tr>
<tr>
<td>C</td>
<td>3.2</td>
<td>0.2</td>
<td>3.0</td>
<td>73.4</td>
<td>20.2</td>
<td>0.0</td>
<td>P-rich phase</td>
</tr>
<tr>
<td>D</td>
<td>42.4</td>
<td>0.1</td>
<td>33.4</td>
<td>23.6</td>
<td>0.1</td>
<td>0.4</td>
<td>(Cu,Ni)$_6$Sn$_5$</td>
</tr>
<tr>
<td>E</td>
<td>31.1</td>
<td>0.0</td>
<td>25.8</td>
<td>35.4</td>
<td>7.5</td>
<td>0.3</td>
<td>Sn–Ni–P</td>
</tr>
<tr>
<td>F</td>
<td>24.5</td>
<td>0.2</td>
<td>23.9</td>
<td>39.0</td>
<td>10.5</td>
<td>1.9</td>
<td>Sn–Ni–P</td>
</tr>
<tr>
<td>G</td>
<td>18.5</td>
<td>0.1</td>
<td>19.1</td>
<td>47.8</td>
<td>13.4</td>
<td>1.0</td>
<td>Sn–Ni–P, P-rich phase</td>
</tr>
</tbody>
</table>

In this study, Ni–Sn–P, (Cu,Ni)$_6$Sn$_5$ and P-rich phases were observed in the fractured surface of the joint with the 60 nm-thick Au layer. Therefore, fractures occurred at the interfaces between reaction layers regardless of whether or not heat exposure treatment was carried out when the thickness of the Au layer was 60 nm. In contrast, fractures occurred in the solder in the case of the joint with the 150 nm-thick Au layer after reflow soldering [Fig. 6(b)]. Several dimples are observed in the fractured surface shown in Fig. 6(b). Although the relationship between such dimples and the void row that formed at the interfaces of the reaction layers is not clarified, microvoids that formed at the Ni/Au interface in plating seem to promote void formation in soldering. Thus, the ball pull force of the joint with the 150 nm-thick Au layer decreases to values lower than that of the joint with the 60 nm-thick Au layer. The interfacial fracture was also observed in the joint with the 150 nm-thick Au layer after heat exposure treatment at 150°C for 500 h. With increasing heat exposure time, the reaction layer grows and simultaneously the growth of voids at the joint interface.

Electron microscopy. They have reported that Ni–Sn–P, Ni$_3$P and (Cu,Ni)$_6$Sn$_5$ form at the joint interface from the Ni–P plating layer to the solder when the thickness of the Au layer is 50 nm. Moreover, it has also been reported that Ni$_3$P, Ni–Sn–P and (Cu,Ni)$_6$Sn$_5$ form at the joint interface on the Ni–P plating layer and voids form in rows at the Ni–Sn–P/ (Cu,Ni)$_6$Sn$_5$ interface when the thickness of the Au layer is 500 nm. Similar void row formation has been reported by Yamamoto et al. They have also reported that void rows form in the electroless plating process.
probably occurs. Therefore, fractures occur easily at the joint interfaces.

In this study, the joint with the 60 nm-thick Au layer is stronger than the joint with the 150 nm-thick Au layer in terms of both ball shear strength and ball pull strength. A similar tendency was obtained in a ball pull test using ball grid array (BGA) solder joints. Moreover, it has been reported that the BGA joint using the electroless Ni/Au-plated Cu pad, which has void rows at the Ni/Au interface, has a degraded impact bend strength. Therefore, it is important to prevent void formation in the Ni/Au interface in the electroless plating process to improve the reliability of the solder joint. When Au plating is conducted by immersion using the substitution reaction of Ni and Au, the thickness of the Au layer should be controlled to be approximately 50 nm in order to prevent void formation at the Ni/Au interface due to the inhomogeneous substitution reaction.

4. Conclusions

The influence of immersion Au plating on the reliability of a solder ball joint with the Sn–3Ag–0.5Cu lead-free solder has been investigated. The following results are obtained.

(1) With increasing Au plating time, the Ni layer develops inhomogeneously and microvoids and microcracks form at the Ni/Au interface.

(2) The solder joint with the 60 nm-thick Au layer is stronger than the joint with the 150 nm-thick Au layer in terms of both ball shear strength and ball pull strength.

(3) In the case of the solder joint with the 150 nm-thick Au layer, many voids are observed in the fractured surface after ball shear and ball pull tests.

REFERENCES