Comparison of solder ball shear strengths for various nickel platings on the bond pads of a PBGA substrate

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Keywords
Product reliability, Soldering, Shear strength, Semiconductor technology

Abstract
This paper presents an experimental study to assess the reliability of solder ball attachment to the bond pads of PBGA substrates for various plating schemes. The basic structure of the under bump metallisation is Cu/Ni/Au. Three different kinds of electroless plating solutions are used to deposit the Ni layer, namely, Ni-B, Ni-P (5 per cent), and Ni-P (10 per cent). Also, conventional electrolytic Ni/Au plating is performed to provide a benchmark. After solder ball attachment, mechanical tests are conducted to characterize the ball shear strength for comparison. Furthermore, some specimens are subjected to multiple reflows to investigate the thermal aging effect.

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Abstract
The plastic ball grid array (PBGA) package has attracted substantial attention since its first appearance in the electronics industry in the late 1980s. Recent technology trends show that PBGAs will dominate the market for packages with pin counts from > 208 to 420 in the next decade. Owing to the tremendous mass production volumes expected, the cost and the reliability of PBGAs are the main issues for the electronics manufacturing industry (Lau, 1995).

One of the features of PBGA packages is that they are surface mount technology (SMT) compatible. For surface mounted components (SMC), the solder joints are not only the means for passage of electrical signals, power, and ground, but also the mechanical support to hold the module in position on the printed circuit board (PCB). Since the solder volume and the stand-off height are rather small, the solder joint reliability of SMCs is always a concern to the packaging engineers (Lau and Pao, 1997).

Currently, the standard package configuration for PBGAs is to attach eutectic Pb/Sn solder balls to the bond pads on the bottom side of a BT substrate. The surface finishing metallisation on the solder bond pads is Ni/Au deposited by electroless plating. However, since this process requires routing traces to connect all of the bond pads together, a considerable amount of space is wasted on the BT substrate (which leads to a higher production cost). In order to avoid this deficiency, an electroless Ni/Au plating process is desired for the fabrication of PBGA substrates. However, the conventional electroless Ni plating solutions available in the industry usually contain a relatively high concentration (9-10 per cent) of phosphorus (P) that would reduce the solder joint reliability (Bradley and Banerji, 1996; Martyak and McCaskie, 1996). As a result, the electroless Ni/Au plating process is still not yet adopted by the packaging industry for manufacturing PBGA substrates. In order to reduce or to eliminate the phosphorus, two other types of electroless plating solutions may be considered. One is a Ni-P solution with a low phosphorus-content (5 per cent), and the other is a Nickel-Boron (Ni-B) solution. However, the effects on solder joint reliability due to these alternative electroless Ni plating solutions are not available in the literature.

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Specimen preparation
The objective of this study is to investigate the effect of various UBM plating schemes on the reliability of PBGA solder joints. The mechanical ball shear tests were employed as a means to evaluate the reliability. During the course of this study, many PBGA substrates were fabricated. The specimens were BT laminates with one surface fully covered with a layer of Cu. The solder bond pads were defined by the solder mask opening with a diameter of 0.5 mm. On the top of bond pads two more layers of metallisation (Ni/Au) were deposited using various plating schemes as shown in Table I. The detailed processing parameters for Ni plating are given in Table II (Fang et al., 1992; Parker, 1987). After surface finishing, the thicknesses of corresponding metal layers are listed in Table I. The cross-section of a typical Cu/Ni/Au metallisation structure is shown in Figure 1.

Once the UBM was prepared, the conventional PBGA ball placement process was performed to attach solder balls to the bond pads on the substrate. The diameter of the solder balls used in the present study was 0.76 mm (30 mil) and the solder material was 63Sn/37Pb. After dispensing a flux paste (Alphametals WS609) onto the bond pads, the solder balls were manually placed onto the pads and reflowed using the...
temperature profile given in Figure 2. A typical cross-section micrograph of an attached solder ball is shown in Figure 7.

### Ball shear tests and experimental results

In this study, mechanical shear tests were employed to characterize the strength of solder ball attachment to the bond pads of PBGA substrates. Such ball shear strength measurements are considered to be an index for solder joint reliability. The ball shear tests were performed using a Dage S4000 machine. A schematic diagram of the testing configuration is presented in Figure 4. The ram speed was 100 μm/s and the gap between the ram tip and the base plane was 50 μm. After each run, the value of peak shear force was recorded. In order to investigate the effect of thermal aging, some specimens were subjected to multiple reflows (1-time, 5-time, 10-time reflows) using the same temperature profile shown in Figure 2.

From the experimental results shown in Table III and Figure 5, it is found that the electroless Ni/Au plating leads to the highest ball shear strength. Among the UBMs with electroless plating, Ni-B gives the best results. Furthermore, the fact that Ni-P (5 per cent) is better than Ni-P (10 per cent) indicates that phosphorus (P) is an undesirable element.

On the other hand, for most cases under investigation, the testing results reveal that multiple reflows may slightly reduce the solder ball shear strength. However, the magnitudes of these reductions are not very significant.

### Scanning electron microscopy and failure analysis

In view of the fact that P usually causes the embrittlement of metals, the experimental results obtained from mechanical ball shear tests seem to be reasonable. In order to further understand the failure mechanism in the present specimens, a series of cross-sections followed by SEM were performed. The SEM micrographs are presented in Figures 6-8.

Figure 6 shows typical cross-section pictures after ball shear tests. It is found that, for all cases under investigation, the fracture surface cuts through the solder ball. However, for UBMs with electroless Ni/Au plating and electroless Ni-B plating, there is a relatively large portion of solder remaining on the bond pad. Besides, it can be seen that the fracture surfaces associated with electroless Ni-P (both 5 and 10 per cent) plated UBMs are rather flat. From the SEM micrographs shown in Figure 7, it is observed that the fracture surfaces are associated with electroless Ni-P, showing a.kink while the fracture surfaces associated with electroless Ni-B plating, there is a relatively large portion of solder remaining on the bond pad. Besides, it can be seen that the fracture surfaces associated with electroless Ni-P (both 5 and 10 per cent) plated UBMs are rather flat. The top-view pictures presented in Figure 7 show similar features and the close-up micrographs in Figure 8 again confirm the aforementioned phenomenon. It is believed that these observed characteristics in the failure mechanisms contribute to the variations in solder ball shear strength.

For the UBMs having a lower ball shear strength, it is suspected that there should be some evidence of metal...
enbrittlement on the surfaces. In order to verify this, energy
dispersive X-ray spectroscopy (EDX) was performed on the
fracture surfaces shown in Figure 8. The corresponding
spectrums are presented in Figure 9. It is identified that, for
UBMs with electroless Ni-P (both 5 and 10 per cent), the
fracture surfaces contain a small amount of P. In the
literature, it is well known that P may cause enbrittlement in
metals, e.g. Tai et al. (2002). Therefore, the inspection
results by SEM and EDX seem to give a qualitative
explanation for the differences in ball shear strength.
However, more rigorous failure analyses are required in
order to obtain quantitative correlations between all of the
experimental data.

Concluding remarks
An experimental study is presented in this paper to assess
the effect of various UBM plating schemes on the
reliability of solder ball attachment to the bond pads of a
PBGA substrate. Three different kinds of electroless

<table>
<thead>
<tr>
<th>Plating scheme</th>
<th>No. of reflow</th>
<th>No. of samples</th>
<th>Strength (mean, g)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolytic</td>
<td>1</td>
<td>24</td>
<td>1,905</td>
<td>58</td>
</tr>
<tr>
<td>Ni/Au</td>
<td>5</td>
<td>21</td>
<td>1,962</td>
<td>77</td>
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<tr>
<td></td>
<td>10</td>
<td>30</td>
<td>1,863</td>
<td>65</td>
</tr>
<tr>
<td>Electroless</td>
<td>1</td>
<td>30</td>
<td>1,790</td>
<td>74</td>
</tr>
<tr>
<td>Ni-B + Imm. Au</td>
<td>5</td>
<td>30</td>
<td>1,727</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>30</td>
<td>1,588</td>
<td>93</td>
</tr>
<tr>
<td>Electroless Ni-P</td>
<td>1</td>
<td>30</td>
<td>1,658</td>
<td>52</td>
</tr>
<tr>
<td>(5 per cent) +</td>
<td>5</td>
<td>30</td>
<td>1,540</td>
<td>89</td>
</tr>
<tr>
<td>Imm. Au</td>
<td>10</td>
<td>30</td>
<td>1,448</td>
<td>103</td>
</tr>
<tr>
<td>Electroless Ni-P</td>
<td>1</td>
<td>30</td>
<td>1,331</td>
<td>47</td>
</tr>
<tr>
<td>(10 per cent) +</td>
<td>5</td>
<td>30</td>
<td>1,222</td>
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</tr>
<tr>
<td>Imm. Au</td>
<td>10</td>
<td>29</td>
<td>1,155</td>
<td>59</td>
</tr>
</tbody>
</table>
Comparison of ball shear testing results

Figure 5

Cross-section micrographs after ball shear tests

Figure 6

Comparison of solder ball shear strengths for various nickel platings on the bond pads of a PBGA substrate

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16/2 [2004] 21–26

(a) Electrolytic Ni/Au
(b) Electroless Ni-B
(c) Electroless Ni-P (5%)
(d) Electroless Ni-P (10%)
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**Figure 7**
Top view micrographs after ball shear tests

![Micrographs](image1)

(a) Electrolytic Ni/Au  
(b) Electroless Ni-B

(c) Electroless Ni-P (5%)  
(d) Electroless Ni-P (10%)

**Figure 8**
Close-up view micrographs after ball shear tests

![Micrographs](image2)

(a) Electrolytic Ni/Au  
(b) Electroless Ni-B

(c) Electroless Ni-P (5%)  
(d) Electroless Ni-P (10%)
plating solutions, namely, Ni-B, Ni-P (5 per cent), and Ni-P (10 per cent), were used to deposit the Ni layer. The surface was finished with immersion Au to prevent oxidation and to improve the solder wettability. Also, conventional electrolytic Ni/Au plating was performed for use as a benchmark. After solder ball attachment, mechanical tests were conducted to characterize the ball shear strength for comparison. Furthermore, some specimens were subjected to multiple reflows to investigate the thermal aging effect.

The testing results indicate that, compared to the electroless Ni-P plating, the electroless Ni-B plating may lead to a better solder ball shear strength. However, the conventional electrolytic Ni/Au plating still gives the highest ball shear strength. For most cases under investigation, multiple reflows seemed to decrease the solder ball shear strength slightly. However, the amount of reduction was not very significant. In addition to the ball shear tests, SEM and EDX were performed to inspect the cross-sections and the fracture surfaces of the tested specimens. From the failure analyses, certain characteristics in failure mechanism were identified.

Figure 9
Typical EDX spectrums for the fracture surfaces after a single reflow

(a) Electrolytic Ni/Au

(b) Electroless Ni-B

(c) Electrolytic Ni-P (5%)

(d) Electroless Ni-P (10%)

References