Effect of pinhole Au/Ni/Cu substrate on self-alignment of advanced packages


Department of Electronic Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

Received 10 September 1999; received in revised form 22 December 1999; accepted 7 January 2000

Abstract

The self-alignment of advanced packages (µBGA) on both non-pinhole and pinhole Au/Ni/Cu pads has been discussed. It is found that a slight reduction of self-alignment of the packages using pinhole pads occurs. Rutherford backscattering spectrometer (RBS) results suggest that this reduction should not be attributed to the oxide formation of the surface or interface layer in the Au/Ni/Cu pads. The solder wetting experiments show that slow spreading of molten solder on pinhole pads may result in a reduction of effective board pad surface area that can be wetted. This will reduce the restoring force of the solder joints, and thus causing a less better self-alignment of the packages using pinhole pads. Oxidation of nickel at the exposed area and Au/Ni interface is observed to occur by direct exposure of substrate pads through pinholes during aging. The solder wetting of the aged pads has been described. For flux reflow soldering, the aging of the pads seems to have no serious effect on the self-alignment of the package. However, it is found from the peel-off test that a few solder joints of the samples after reflow have weak adhesion strength at the solder and aged pinhole pad interface. The mechanism for this weak adhesion strength has been proposed. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Pinhole Au/Ni/Cu substrate; Self-alignment; Advanced packages (µBGA)

1. Introduction

Trends in portable electronics industry are packages that are as thin, small and lightweight as possible [1]. Flip chip and chip scale packages (CSP) such as µBGA are the most advanced technologies that have gained popularity in a wide variety of portable electronics applications. Because the size and the pitch of the solder bumps in those advanced packages are very small, high pick-and-place accuracy compared with older surface mount technology standards is necessary. Any misalignment may cause assembly defects such as poor solder joints, resulting in considerable reliability issues where the failure of one joint can make an entire product cease to operate. It is known that slightly misaligned parts (less than 50% off the pad centre) will automatically self-align during reflow for ball grid array (BGA) and similar packages [2,3]. The understanding of the self-alignment for the advanced packages becomes crucial to achieve highly reliable electronics products.

Besides, in computer and communication applications, the precious metallic thin films such as gold (Au) have been used extensively as protective layers in electronic packaging technology because of their excellent conductivity, wettability and corrosion resistance. Theoretically, protection is enhanced by increasing the thickness of the Au layer. However, too thick an Au layer will increase the plating and manufacturing costs. More importantly, too thick an Au layer forms intermetallics with tin, which embrittles solder joints [4,5]. To minimize plating costs and to limit the formation of Au–Sn intermetallics, it is desirable to find the mini-
imum gold thickness which will protect the substrate during storage and soldering. It is also found that electroplates of gold that are too thin contain pinholes on top of the substrate. Au plates less than 0.5 μm in thickness have traditionally been considered too porous to provide effective protection [6,7]. It is because pinholes may cause oxidation of the pads. Pinholes either allow oxidation of the exposed pad area or provide a diffusionless path for oxygen delivery to the gold–substrate interface. Oxide formation as a result does affect the solder wetting.

For the sake of manufacturing high reliable and good performance electronics products using advanced packages, it is necessary to understand which mechanisms of oxidation are factors to limit the wettability and how it affects and relates to the self-alignment of the packages. Yet, a precise correspondence between the pinhole on the substrate, wettability of solder and the self-alignment of the advanced packages has not been studied. Therefore, in this paper, we will examine the wetting of eutectic lead tin solder on Au/Ni/Cu substrates in which both the pinhole and non-pinhole substrates are considered.

2. Experimentation

2.1. Au/Ni/Cu test board pad measurements

The test board for assembling the μBGA packages is composed of FR4. There are two categories of test board pads. Both are copper (Cu) plated with nickel (Ni) but with different thickness of thin layer of gold (Au) flash on top. The thinner one has pinholes in the Au layer on top of the Ni layer. Parts of the pinhole Au/Ni/Cu pads are aged at 200°C in air for 1 h. The surface morphology of both the raw and aged Au/Ni/Cu pads was inspected by using Philips XL 40 scanning electron microscope (SEM). The thickness of the top Au layer on Ni was measured by using Rutherford backscattering spectrometer (RBS) and the surface oxide or interface oxide in the Au/Ni/Cu pads was detected by using oxygen resonance with a 3.04 MeV He$^+_{2}$ ion beam. We also determine the time dependence of radius of the molten solder cap on the Au/Ni/Cu pads by using a wetting dynamic setup [8].

2.2. Mounting of μBGA packages

Both the raw and aged Au/Ni/Cu test boards are mounted with the dummy Tessera’s μBGA packages in which the bump size and pitch are, respectively, 0.35 and 0.75 mm, and the solder bump material used is eutectic 63Sn/37Pb. Before mounting the μBGA packages onto the test board, CLEANLINE™ LR721H2 BGA no-clean flux is dispensed onto the test board pads. Following the application of flux, the μBGA samples are mounted onto the test boards by a high-precision, high-speed flexible mounter (CASIO YCM-5500V). We make use of the high accuracy of the mounting machine to control the misalignment of the μBGA samples on the board pads. Before reflow, the mounted samples are inspected to ensure the correct misalignment by using a SOFTEX real time X-ray inspection system. A five-zone reflow gas-forced-convection oven (BTU VIP-70N) is used to reflow the mounted samples in a compressed air environment. The time-resolved temperature during reflow between the component and the test board is measured using a wireless profiler (Super M.O.L.E, E31-900-45/10). After the assembly process, the samples are inspected by the X-ray inspection system again. Additionally, electrical tests, peel-off tests, shear tests, cross-sectioning, and optical microscopic analysis are performed.
3. Results and discussion

3.1. Pinhole versus non-pinhole substrates

Fig. 1 shows the SEM pictures of (a) non-pinhole and (b) pinhole Au/Ni/Cu pads. From the energy dispersive X-ray spectrum (EDX), it is seen that the pinholes on the pads do not contain any Au element. This means that the Ni layer at the pinhole region is exposed to the environment and thus there may be some possibility to form oxide at the pinhole region. Fig. 2 shows the RBS results of (a) non-pinhole and (b) pinhole Au/Ni/Cu pads. The dotted lines in the figure represent the fitting results for determination of unknown parameters such as layer thickness, oxide, and composition, etc. The gold thickness of non-pinhole and pinhole Au/Ni/Cu pads is determined to be 842 and 152 Å, respectively. However, the RBS results show that there is no surface oxide and interface oxide in these raw Au/Ni/Cu pads.

Fig. 3 shows the optical micrographs of cross-sections of solder joints using (a) non-pinhole board pad and (b) pinhole board pad after reflowing the µBGA packages for 30 s. The initial misalignment of the µBGA packages for the figure is 0.20 mm. The self-alignment of the µBGA package shown in Fig. 3(a) is very good and the µBGA package is almost aligned to the centre of the non-pinhole board pad even though the initial misalignment was larger than 50% off the pad centre. However, in Fig. 3(b), it can be seen that the self-alignment is inferior using the pinhole Au/Ni/Cu pad. Closer inspection reveals that the solder has not wetted the pad properly. From the RBS results, it is found that a slight reduction of self-alignment of the µBGA packages on using the pinhole pads should not be attributed to the oxide formation at the surface or interface layer in Au/Ni/Cu pads. In order to interpret the above observation, a solder wetting dynamic experiment on the Au/Ni/Cu pads has been performed, which permits direct measurement of the radius of the molten solder cap as a function of time. Fig. 4 shows the plot of radius of the molten solder cap against time for both the non-pinhole pad and pinhole pad. The temperature used in this wetting dynamic experiment is set to be 240°C. Fig. 4 indicates that the spreading of molten solder on non-pinhole pad is faster than that on pinhole pad. Wenzel [9] claimed that a surface that wets
Fig. 4. Plot of radius of the molten solder cap against time for both the non-pinhole pad and pinhole pad.

Fig. 5. Schematic diagram of the cross section of a mounted μBGA sample.

Fig. 6. SEM pictures of aged (a) type A and (b) type B Au/Ni/Cu pads.

For the aged pinhole Au/Ni/Cu board pads, two types of samples are studied. Fig. 6 shows the SEM pictures of aged (a) type A and (b) type B Au/Ni/Cu pads. For the same magnification in Fig. 6, it can be seen that the pinholes in type A pads are denser than that in type B pads. However, type A contains only

3.2. Aged pinhole substrates

For the aged pinhole Au/Ni/Cu board pads, two types of samples are studied. Fig. 6 shows the SEM pictures of aged (a) type A and (b) type B Au/Ni/Cu pads. For the same magnification in Fig. 6, it can be seen that the pinholes in type A pads are denser than that in type B pads. However, type A contains only

(contact angle < 90°) when smooth will wet even better when rough. Therefore, the reason for different degree of spreading in Fig. 4 may be attributed to the different surface roughness between non-pinhole and pinhole pads, see Fig. 1. Moreover, it is expected [10] that the spreading of molten solder will be much slower for both types of pads as the temperature is decreased down to the reflow temperature range, e.g. 183–200°C. At temperatures above 183°C during the reflow of μBGA package, the molten solder will spread over the Au/Ni/Cu board pad and the package will then self-align to the desired position. Because the spreading of molten solder on pinhole pads is much slower, the effective board pad surface area that can be wetted by the molten solder may be smaller. That is, the molten solder may not wet the whole area of the pinhole pad due to the slow spreading of solder. Thus, the restoring force for the solder joints using pinhole pads will be reduced due to the smaller board pad surface area that can be wetted by the molten solder. As a result, the change of equilibrium condition results in less better self-alignment of the package using pinhole pad.

In addition, some of the mounted μBGA samples after reflow were put into a tensile tester to perform the peel-off test and shear test. In order to have a clear explanation, the schematic diagram of the cross section of a mounted μBGA sample is shown in Fig. 5. From the peel-off test, it is found that the fracture surface always occurs at the interface of polyimide film and Cu die pad for all the samples using either non-pinhole or pinhole board pads. The maximum load to peel-off the samples is ~ 0.03 kN. This low peel-off strength is attributed to the weak peel-off adhesion strength between the polyimide film and Cu die pad [11]. From the shear test, it is found that the fracture surface can occur at either polyimide film and Cu die pad interface, Cu die pad and solder interface, or solder and Au/Ni/Cu board pad interface. The maximum load to shear off the samples using either non-pinhole or pinhole board pads is found to be in the range of 0.12–0.18 kN.
small pinholes with size below 1 μm. Type B contains both big pinholes with size varying from 3 to 8 μm and small pinholes with size below 1 μm. In fact, aging will accelerate the oxide formation of exposed pad area and Au/Ni interface via pinholes. In addition, aging will also thermally activate the interdiffusion among gold, nickel and even oxygen. This means that oxidation may result from either oxygen diffusing through gold to the Au/Ni interface or from nickel diffusion through gold to the free surface. Fig. 7 shows the RBS results of (a) type A and (b) type B pinhole Au/Ni/Cu pads. The fitting results of RBS for type A and type B aged pinhole samples are shown in Table 1. RBS results show that both types of aged Au/Ni/Cu samples contain oxygen.

The fitting results of RBS for type A and type B aged pinhole samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Equivalence gold thickness (Å)</th>
<th>Layer thickness (1 × 10^{15} \text{ at. cm}^{-2})^a</th>
<th>Elemental ratio$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Layer 1, Ni: Au: O</td>
<td>Layer 2, Ni: Au: O</td>
</tr>
<tr>
<td>Type A</td>
<td>83</td>
<td>35:80</td>
<td>0.10:0.83:0.07</td>
</tr>
<tr>
<td>Type B</td>
<td>95</td>
<td>50:50</td>
<td>0.07:0.72:0.21</td>
</tr>
</tbody>
</table>

$^a$ Layer 1:layer 2.
$^b$ Ni:Au:O in atomic number ratio, sum = 1.
Fig. 8. SEM pictures of aged (a) type A and (b) type B Au: Ni: Cu samples after solder wetting experiments at 190°C for 5 min.

\[ \gamma_S - \gamma_{SL} = \gamma \cos \theta_e \]  

(2)

where \( \theta_e \) is contact angle, and \( \gamma_S, \gamma_{SL}, \gamma \) are the solid, solid–liquid, and liquid surface tensions, respectively. For different solid surfaces, \( \alpha \) and \( \beta \), one can construct area fraction weighted average solid–liquid energy [14]:

\[ \gamma_{SL} = (1 - s)\gamma_{\alpha SL} + s\gamma_{\beta SL} \]  

(3)

where \( s \) is the area fraction of \( \beta \) solid, \( \gamma_{\alpha SL} \) and \( \gamma_{\beta SL} \) are the \( \alpha \) solid–liquid and \( \beta \) solid–liquid surface tensions, respectively. Using Eqs. (2) and (3), one can obtain a simple estimate of the effective contact angle \( \theta_e \) [14]:

\[ \cos \theta_e = (1 - s)\cos \theta_{e,\alpha} + s \cos \theta_{e,\beta} \]  

(4)

where \( \theta_{e,\alpha} \) and \( \theta_{e,\beta} \) are the contact angle due to \( \alpha \) and \( \beta \) surfaces, respectively. If the \( \alpha \) surface is Au/Ni and the \( \beta \) surface is Ni oxide, we have

\[ \cos \theta_e = (1 - s)\cos \theta_{e,\text{Au:Ni}} + s \cos \theta_{e,\text{oxide}} \]  

(5)

where \( \theta_{e,\text{Au:Ni}} \) and \( \theta_{e,\text{oxide}} \) are the contact angle due to Au/Ni surface and poorly wettable Ni oxide patches. Eq. (5) here shows that the smaller the area fraction of the poorly wettable Ni oxide patches, the smaller the effective contact angle \( \theta_e \). This theoretical finding qualitatively agrees with our experimental results shown above. In addition, we found that the effective contact angle of the solder droplet without using flux is larger than that using flux in the wetting dynamic experiment. It is because the action of flux will impose a time dependence that reduces the area fraction of the poorly wettable nickel oxide patches. Thus the effective contact angle will decrease with time due to the action of flux according to Eq. (5).

Fig. 10 shows X-ray pictures of the μBGA package using (a) type A and (b) type B aged pinhole Au/Ni/Cu pads before and after reflow using no clean flux. The initial misalignment of the μBGA packages for the figure is \( \approx 0.20 \) mm. The self-alignment of the μBGA package shown in Fig. 10 is still quite good and the μBGA packages are nearly aligned to the centre of both types of aged pinhole board pad. However, it is found that the μBGA package using aged pinhole pads cannot self-align itself if the fluxless solder reflow is used. This means that the aging of the Au/Ni/Cu board pads seems to have no detrimental effect on the self-alignment of the μBGA package for flux soldering but does have serious effect on the self-alignment of the μBGA package for fluxless soldering.

Fig. 9. SEM pictures of cross section of aged (a) type A and (b) type B Au/Ni/Cu samples after solder wetting experiments.
Fig. 10. X-ray pictures of the μBGA package using (a) type A and (b) type B aged pinhole Au/Ni/Cu pads before and after reflow using no clean flux.

(a) Type A Au/Ni/Cu Pad

(i) Before reflow

(ii) After reflow

(b) Type B Au/Ni/Cu Pad

(i) Before reflow

(ii) After reflow

Fig. 11. SEM picture of one of the type A aged board pad after peel-off test.

From the peel-off test of the samples using flux soldering reflow, it is found that most of the fracture surface occur at the interface of polyimide film and Cu die pad but ~5% of fracture surfaces occur at the solder and Au/Ni/Cu board pad interface for all the samples using either type A or type B aged pinhole board pads. This means that a few solder joints have weak adhesion strength at the solder and Au/Ni/Cu board pad interface. Fig. 11 shows the SEM picture of one of the type A aged board pad after peel-off test. It is shown that there are solder-rich regions and non-solder regions on the fracture surface of the board pad. The solder-rich region contains solder that has wetted the aged pad. The non-solder region does not contain any solder on the pad surface and this implies that the solder may not have wetted the surface of Au/Ni/Cu pad. We found that all the fractures at the solder and Au/Ni/Cu board pad interface for both type A and type B pads show similar surface morphology like Fig. 11. In order to interpret the peel-off test results, a schematic diagram is shown in Fig. 12. Fig. 12(a) shows the misalignment of the μBGA package on the aged Au/Ni/Cu board pads. Due to the random distribution of the pinholes and the small size of the pads, it is found that some of the aged pads contain less nickel oxide patches. Upon the action of flux, some of the aged pads become wettable (W) but a few of the aged pads are still poorly or non-wettable (NW). In Fig. 12(b), during the reflow, the molten solder will spread over the wettable Au/Ni/Cu board pads but cannot spread and wet the non-wettable pads. However, the package is still self-aligned itself due to the restoring force of the wettable solder joints. This means that the non-wettable solder joints are pulled towards the centre position due to the entire self-alignment of the package even though the restoring force of those joints is weak. Fig. 12(c) shows that after self-alignment, the wettable pads will form good joints with the solder but only part of the pad area on the non-wettable pads will react with solder thus forming a weak solder joint. As a result, the weak joint on the non-wettable pads will easily be fractured during the peel-off test which is shown in Fig. 12(d).

Fig. 12. Schematic diagram to interpret the peel-off test results of μBGA package using aged Au/Ni/Cu pads.
4. Conclusion

The self-alignment of the μBGA package on the non-pinhole pads is very good even though the initial misalignment was greater than 50% off the pad centre. However, the self-alignment is inferior using the pinhole Au/Ni/Cu pad. From the RBS results, it is found that a slight reduction of self-alignment of the μBGA packages using pinhole pads should not be attributed to the oxide formation on the surface or interface layer in Au/Ni/Cu pads. The solder wetting experiments show that the spreading of molten solder on pinhole pads is slow and this may be due to the less surface roughness of the pinhole pads. The slow spreading of molten solder may result in reduction of effective board pad surface area that can be wetted; thus causing the reduction of restoring force of the solder joints. This will attribute to less better self-alignment of the packages using pinhole pads.

The aging of the pinhole pads causes oxide to be formed at the Ni exposed area and Au/Ni interface. It is found that the larger the area fraction of pinholes in the Au/Ni/Cu pads, the larger the area fraction of nickel oxide will be in the pads, and thus the larger the effective contact angle of the solder droplet will have. For the fluxless reflow soldering, the μBGA package using aged pinhole pads cannot self-align itself due to the poorly or non-wettable oxide in the Au/Ni/Cu substrate pads. For the flux reflow soldering, the aging of the pads seems to have no serious effect on the self-alignment of the package. However, it is found from the peel-off test that a few solder joints of the samples after reflow have weak adhesion strength at the solder and aged pinhole pad interface. The reason is that upon the action of flux, few of the aged pads are still poorly or non-wettable, thus resulting in weak solder joint formation after reflow.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Direct Allocation grants (7100016) and the strategic Research Grants (7000955) of the City University of Hong Kong and the Research Grants Council of Hong Kong. The authors are grateful to Dr W.Y. Cheung from Advanced Surface and Materials Analysis Centre of the Chinese University of Hong Kong, for RBS measurements.

References