

# WHITE RING DEFECT FORMATION IN LEAD-FREE WAFER LEVEL PACKAGING

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## ABSTRACT

FlipChip (FC) and Wafer Level Packaging (WLP) are two of the fastest growing segments in the integrated circuit (IC) packaging industry. The practice of incorporating FC or bump technology in devices is experiencing significant growth, due to the improvement it provides in power and ground distribution, with the attendant reduction in simultaneous switching noise, (SSN). The demand for WLPs is increasing due to their small form factor and the increased demand for portable products.

Both FC and WLP technologies impose significant new demands related to the materials used for permanent dielectric layers and photoresists for fabrication processes. Cleaning chemistry must be designed to remove highly cross-linked films such as photoresists and fluxes; but keep the solder bump, exposed metals, under-bump metallization (UBM), and dielectrics undamaged. Device reliability and performance rely heavily on the proper working of all these components. *In situ* or discrete analytical procedures are required for testing the reliability of the materials used.

Typical quality assurance and control procedures for fabrication monitor the appearance (surface condition, shape) of the solder bumps. Wafer or device inspections are commonly performed by optical microscopy, and indicate if the device is free of photoresist after cleaning, and whether or not metal remains after etching.

The focus of this paper is defect formation during lead-free wafer level packaging. The defect type that the talk will concentrate on is referred to as the 'white ring' defect. It is found at the base of electroplated bumps and first becomes visible to the line operator in the bumping process after the thick photoresist is removed.

Key words: wafer bumping, defects, photoresist removal

## BACKGROUND

A typical packaging process to produce solder connections could include the following steps: (1) application of a passivation layer, (2) deposition of UBM materials for adhesion promotion and to deter migration, (3) deposition of an electroplating seed layer, (4) application of a laminated photoresist which is exposed and developed to generate the bump placement mold, (5) solder electroplating, followed by (6) photoresist removal and (7) inspection. Although in many fabrication facilities, many of these processes are

performed by separate and distinct process groups, defect formation can occur many steps prior to detection. As an example, in the overall process defined above, the wafer surface is not visible for inspection between the steps of photoresist application and photoresist removal.

Historically, common defects include "photoresist lifting", ("resist lifting", or "photo lifting") in the PCB board industry and "photoresist delamination" in the semiconductor industry.<sup>1</sup> This defect has resulted in foot plating and in more extreme cases, metal films being deposited in areas which would otherwise have undergone seed layer removal *via* an etch process.

In the case of plating lead free solders, (for example, SnAg,) the metal that is deposited outside of the foot plating area is white in color and has been referred to as the 'white ring'. This ring is visible to the line operator only after the thick photoresist is removed.

Other causes of the white ring have been examined including redeposition of photoresist, and local mixing of electroplating solution and photoresist removal products. The results will be discussed briefly, but our results indicate that they are not the cause of the white ring.

The delamination and underplating results reported here have been shown to occur during electroplating of eutectic solders when the photoresist processing has not been optimized. In this instance, the excess metal deposit is blue in color and referred to in the industry as "blue film".

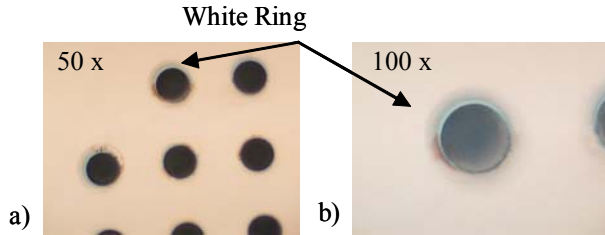
## EXPERIMENTAL PROCEDURES

Testing was carried out on test samples that were composed of a Ti/W adhesion layer, a Cu seed layer, patterned thick photoresist [thickness = 80  $\mu\text{m}$ , bump diameter  $\sim$  100  $\mu\text{m}$ , space  $\sim$  300  $\mu\text{m}$ ], a Ni stud layer, and a lead free [Sn<sub>93</sub>Ag<sub>7</sub>] electroplated solder bump. Samples were cleaned with Dynastrip™7000 at 97 °C for 40 minutes. Samples were examined using a Hitachi 3000N Scanning Electron Microscope (SEM), a PV7743 energy dispersive x-ray analysis (EDX) detector from Ametek, and a Physical Electronics model PHI 660 scanning Auger microprobe with a LaB<sub>6</sub> cathode scanning electron gun operated at 10 keV. The base pressure was 3.4  $\times$  10<sup>-10</sup> Torr. The parameters used in the depth profile analysis were 3 keV, with 70

$\mu\text{A}/\text{cm}^2$  Ar+ plasma. The etch rate was calibrated using  $\text{SiO}_2/\text{Si}$  and found to be 37 nm/min.

### RESULTS OF TESTING

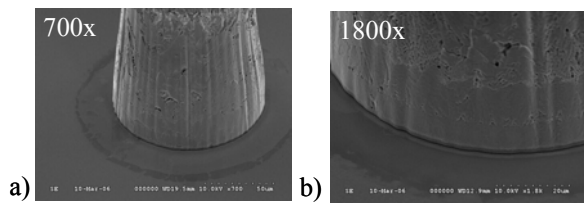
Test samples were cleaned and then examined for resist removal. Figure 1 shows optical images of the bumps, including the area described as the ‘white ring’.



**Figure 1.** Optical microscope images of the white ring.

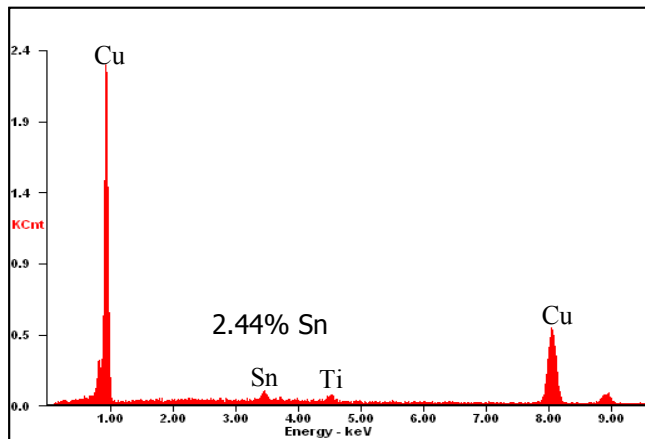
The white ring is characterized by a metal layer which extends out beyond the typical distance of the foot plate. In the images in Figure 1, the ring appears to have a white color.

Figure 2 shows SEM images of the ring.



**Figure 2.** SEM images of a typical bump showing the formation of the metal ring.

The images show that the metal film propagates outward from the bump, over the copper field metal.



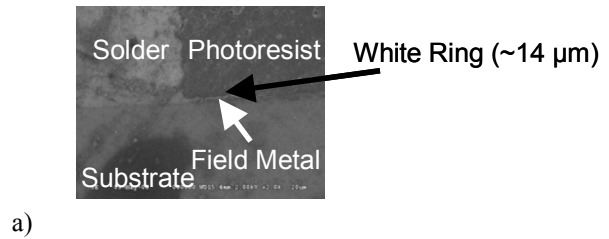
**Figure 3.** EDX spectrum of the white ring at 15 kV.

The EDX spectrum was obtained for a sample on the white ring and is shown in Figure 3. The copper and titanium are due to the field metal while the tin is due to the white ring. If the composition of the ring is tin, the only sources of tin are from the electroplated bump, of which it is the major

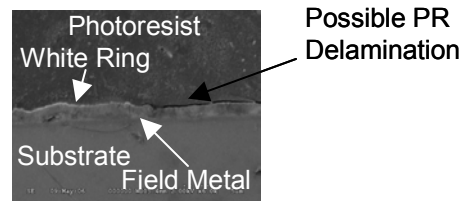
component, or from uptake of tin ions into the photoresist during electroplating.

One drawback to this technique is that the sampling size of the beam in EDX is large enough (up to 3  $\mu\text{m}$ ) that analyses at areas close to the bump may have contributions from the solder bump. As a result, further data were collected to ensure that they were representative.

To further confirm the results, we obtained cross-sectional SEM images of samples prior to photoresist removal, (Figure 4). Samples were visualized after sputter deposition of approximately 10  $\text{\AA}$  of Pd metal.



(a)

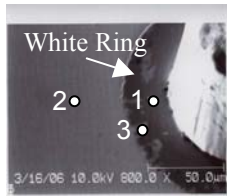


(b)

**Figure 4.** SEM micrographs of the electroplated metal underneath the photoresist (PR). (a) 2000x magnification (b) 6000x magnification.

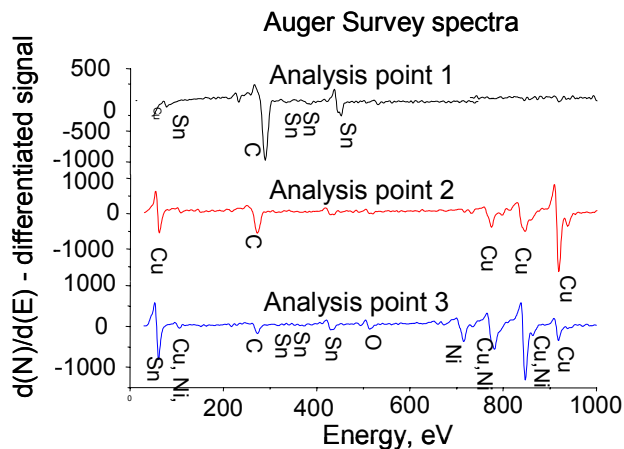
In Figure 4, it may be seen that there is metal deposition underneath the photoresist. In Figure 4 (a), the solder bump, substrate, field metal and photoresist can be seen. The ‘white ring’ is the lighter colored film (due to the heavier element, Sn) on top of the seed layer (Cu) and under the resist. In Figure 4 (b), the higher magnification image shows the ‘white ring’ film on top of the field metal. These results are consistent with delamination of photoresist, allowing further electroplating under the resist. It is important to note, however, that the additional delamination in Figure 4(b) may be due to sample preparation.

Further analysis of the cleaned sample was performed using Auger Electron Spectroscopy. Figure 5 shows an image indicating where the data were obtained for comparison. Analysis area (1) is located on the white ring, (2) on the copper field metal, and (3) on the margin of the white ring. Spot sizes for the analyses were 0.5  $\mu\text{m}$ . Auger spectroscopy is a very suitable surface technique for resolving compositional information at areas near the solder bump since the analysis spot size is small and the depth of penetration (4 – 50  $\text{\AA}$ ) is very low.



**Figure 5.** Analysis areas for Auger Spectroscopy.

The survey scans shown in Figure 6 identify all the elements in the sample. The carbon present is adventitious carbon, which is always found in Auger samples, despite the analysis being carried out under high vacuum. The size of each peak in the scan is proportional to the amount of the element that is present in the sample, provided that there is no peak overlap. In this case, the peak at 50 eV cannot be considered diagnostic for tin, copper, or nickel, due to the fact that they all overlap in this region. However, Auger is sensitive to these elements at other binding energies [Sn, ~425 eV; Ag, ~350 eV; Ni, 850 eV; Cu, 920 eV] that do not overlap and these peaks can be used to identify these elements.



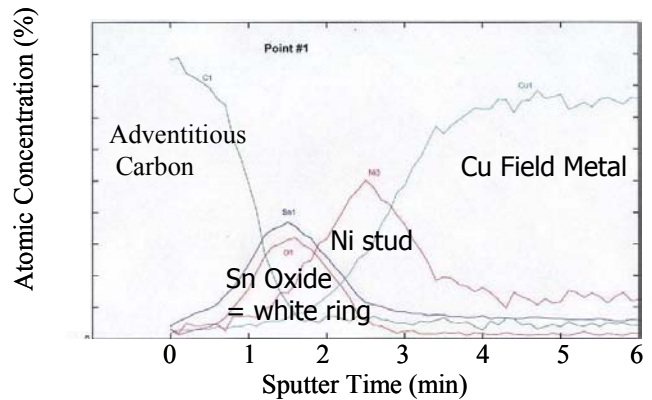
**Figure 6.** Survey scans of points of analysis.

Since this is a tin-silver lead-free electroplated bump ( $\text{Sn}_{93}\text{Ag}_7$ ), it was expected that silver would be present in the white ring deposit. The Auger Spectroscopy handbook of reference spectra<sup>ii</sup> shows that Auger spectroscopy is very sensitive to silver and gives the binding energy for the diagnostic peak as 350 eV. However, none of the spectra of the white ring had a peak in the 350 eV region, indicating that silver was not present in the deposit. On review of the metal composition of the electroplating solution, the ratio of tin salt to silver salt was 100:1, meaning that the electroplating solution was very tin rich. Comparison of the standard reduction potentials for tin ( $E^\circ = -0.136 \text{ V}$ ) and silver ( $E^\circ = +0.799 \text{ V}$ ) indicated that tin should electroplate preferentially. Because solution is trapped under the laminated photoresist, mass transport effects in the electroplating solution become dominant in determining the composition of the deposit. The trapped solution experiences a different potential and changes in ion concentration from that of the bulk solution, which affect

the alloy composition. In this case, the electroplating conditions are changed so much that no silver is electroplated and the deposit is composed of tin only.

As shown in Figure 6, the white ring is composed mainly of tin. Analysis point 2 shows the expected peaks for the copper field metal. Analysis point 3 shows the expected contributions from the copper field metal due to the thinness of the film in this area, as well as contributions from the film itself (tin). An interesting thing to note is that there are contributions from nickel as well which indicates that the delamination occurred in the process step prior to the deposition of the lead-free solder, during the nickel stud deposition.

To further clarify the film components, a depth profile using Auger spectroscopy was recorded on the area of the white ring, (analysis area 1), in Figure 5. The depth profile is shown in Figure 7.



**Figure 7.** Depth profile through the white ring, the Ni stud and the Cu field metal.

The depth profile (Figure 7) confirms that the photoresist delamination and electroplating started with the nickel stud electroplating step. When it was complete and the sample was electroplated with the lead-free solder (Sn/Ag), the tin deposited on the nickel stud underneath the photoresist. It is believed that the oxidation of the tin was in subsequent processing steps, however, this is still under investigation.

## SUMMARY AND CONCLUSIONS

Wafer level packaging relies critically on each process step being carried out successfully to ensure the greatest first pass yield. Formation of white rings is a common phenomenon that may be prevented with a robust photoresist process. The advent of white ring adds significantly to the cost of ownership, especially since the wafer being processed is complete and has the full value added from the front end fabrication facility.

Characterization of success or failure of each process step can be difficult when the wafer surface is not visible to the line operator. Once the thick photoresist is removed, after

the solder bumps have been electroplated, defects in resist removal or in previous steps can be viewed for the first time. Use of surface sensitive tools such as SEM and Auger spectroscopy can aid in determining at which step a defect was made.

In the present paper, we have shown that the phenomenon known as “white ring” in lead-free electroplated bumping applications, is caused by photoresist delamination and underplating. Cross-sectional SEM images show that the the ring was present prior to photoresist removal, and Auger spectroscopy results indicate that the resist delamination occurs prior to the nickel stud deposition.

#### **ACKNOWLEDGEMENTS**

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#### **REFERENCES**

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<sup>i</sup> Kietz, K., Circuitree, Tech Talk, “Fine Lines in High Yield (Part LXVIII)”, May 1, 2001. Web publication.

<sup>ii</sup> Childs, K. D., Carlson, B. A., LaVanier, L. A., Moulder, J. F., Paul, D. F., Stickle, W. F., Watson, D. G., *Handbook of Auger Electron Spectroscopy, Third Edition*, Physical Electronics, Inc., 1995.