Fluxless plasma bumping of lead-free solders and the reliability effects of under bump metallization thickness

Joon Kwon Moon
LG Electronics Institute, Seoul, Korea

Y. Zhou
Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada, and

Jae Pil Jung
Department of Materials Science and Engineering, University of Seoul, Seoul, Korea

Abstract

Purpose – To investigate fluxless plasma ball bumping and effect of under bump metallization (UBM) thickness on joint properties using lead-free solders.

Design/methodology/approach – A fluxless soldering process was investigated in this study using Ar-10 percent H_2 plasma reflow. Balls made from two lead-free solders (Sn-3.5 weight percent Ag and Sn-3.5 weight percent Ag-0.7 weight percent Cu) were reflowed and, also Sn-37 weight percent Pb as a reference. In particular, the effects of the UBM thickness on the interfacial metallurgical bonding and joint strength were studied. The UBM (Au/Cu/Ni/Al layers) thicknesses were 20 nm/0.3 μm/0.4 μm/0.4 μm and 20 nm/4 μm/4 μm/0.4 μm, respectively.

Findings – The experimental results showed that in the case of a thin UBM the shear strengths of the soldered joints were relatively low (about 19-27 MPa) due to cracks observed along the bond interfaces. The thick UBM improved joint strength to 32-42 MPa as the consumption of the Cu and Ni layers by reaction with the solder was reduced and hence the interfacial cracks were avoided. To provide a benchmark, reflow of the solders in air using flux was also carried out.

Originality/value – This paper provides information about the effect of UBM thickness on joint strength for plasma fluxless soldering to researchers and engineers.

Keywords Soldering, Joining processes, Strength of materials, Organometallic compounds

Paper type Research paper

1. Introduction

Environmental concerns have led to considerable new technology development in the electronics industry, especially within electronics assembly companies, regarding lead-free solders (Harrison *et al.*, 2001; Miric and Grusd, 1998) and fluxless soldering processes (Wassink, 1984; Takyi *et al.*, 1999; Hong *et al.*, 2002a). In general, chemical fluxes are needed to remove oxide layers during soldering. However, flux residues remaining at the soldered joints can cause problems such as corrosion and decreased electrical insulation resistance (Zou *et al.*, 1999; Hunt and Zou, 1999). Thus, much research work has been performed to permit either removal of flux residues after soldering, or to avoid using fluxes in the first place during the manufacturing of electronic products, especially for fine pitched devices or opto-electronics parts. The use of plasma in soldering processes (Takyi *et al.*, 1999; Hong *et al.*, 2002b; Park *et al.*, 2001; Deltschew *et al.*, 2001) is one of the methods available to avoid the use of fluxes. For example, it was found that a pre-soldering treatment using a plasma comprising of a mixture of CH_4 and air in the ratio 10 : 1, helped to eliminate the use of fluxes in the soldering of Sn-Pb alloys (Deltschew *et al.*, 2001). However, it is known that CH_4 is not an ideal plasma gas since it introduces other environmental concerns (Hong *et al.*, 2002b).

In a previous study to develop flux-free soldering processes (Hong *et al.*, 2002b), a plasma gas mixture of Ar + 10 percent H_2, which is environmentally friendly, was found to be effective in removing/reducing surface oxides on Sn-Pb and Sn-Ag solders. The plasma-cleaned solders were then hot-plate reflowed successfully in air without fluxes. However, the joint strength was relatively low compared to that of joints

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0954-0911.htm

Soldering & Surface Mount Technology
17/2 (2005) 3–9

[ISSN 0954-0911]
[DOI 10.1108/09540910510597456]

This study was carried out by the financial support of the University of Seoul, 2004.
Received: 28 May 2004
Revised: 17 January 2005
Accepted: 17 January 2005

made with fluxes, because of the reoxidation of the solder surface between etching and reflow and, more importantly, the reoxidation of the molten solders in air during reflow. It was therefore recommended that the plasma-cleaned flip chip be bonded in an inert atmosphere to prevent the reoxidation of the molten solders (Hong *et al.*, 2002b).

In the present work, Ar + 10 percent H_2 plasma was applied as both a heating and cleaning source in the reflow of solder balls (including Sn-3.5 weight percent Ag and Sn-3.5 weight percent Ag-0.7 weight percent Cu lead-free solders and also Sn-37 weight percent Pb as a reference). It was anticipated that the reflow temperature obtained in plasma soldering would be higher than that for conventional hot air or plate reflow, and this might have some implications for the required under bump metallization (UBM) thickness. For example, Jang *et al.* (2003) observed that excessive reactions (caused by repeating the reflow process five times) resulted in detachment of the intermetallic compounds (IMCs) formed between Sn-37Pb solders and Cr/CrCu/Cu, TiW/CrCu/Cu, or TiW/Cu UBMs, from the substrate, due to the consumption of the Cu layer by reaction with the solder. A minimum UBM thickness, especially the minimum Cu layer thickness, was recommended to avoid this interfacial detachment (Jang *et al.*, 2003). Although the basic concept of fluxless plasma bumping with small solder balls (100 μm in diameter) for Sn3.5Ag alloy was reported recently by the authors (Hong *et al.*, 2004), an investigation for a larger size of solder ball was not carried out. For example, a solder ball 500 μm in diameter may need a thicker UBM than that for smaller solder balls, because the UBM can be exhausted by its reaction with this larger amount of solder under the high temperature plasma. In addition, application of the plasma bumping process to the most promising lead-free solder of Sn-Ag-Cu was not studied previously.

Thus, the objectives of the present work were to study the effects of UBM thickness on the joint development and strength for 500 μm solder balls, and to evaluate the fluxless plasma solderability of the Sn3.5Ag0.7Cu alloy using Ar + 10 percent H_2 plasma.

2. Experimental

The thin and thick UBMs (Au/Cu/Ni/Al), coated on to a Si-wafer, had layer thicknesses of about 20 nm/0.3 μm/0.4 μm/0.4 μm and 20 nm/4 μm/4 μm/0.4 μm, respectively (Figure 1). The UBM layers were deposited by thermal evaporation (for the Al, Cu and Ni layers) and electron-gun evaporation (for the Au layer), but by electroplating for the 4 μm-thick Cu and Ni layers. Bond pad areas on the UBM for solder bumping were 300 μm in diameter, and were defined by a Ti layer to serve as a dam against molten solder.

Solder balls of the three different compositions, but the same diameter (500 μm), were placed onto the UBMs of the test wafer and plasma reflowed into sphere-shaped bumps. Before plasma treatment one side of the solder ball was made flat mechanically to allow it to sit on the Si-wafer. Figure 2 shows a schematic illustration of the plasma soldering process used. A plasma gas mixture consisting of Ar-10vol percent H_2 was selected since it was proved to be effective in removing oxides from solder surfaces in previous studies (Hong *et al.*, 2002b; Park *et al.*, 2001). The pressure in the plasma chamber was 360 mtorr. The flow rates of Ar and H_2 gases were 63 and 7 sccm (standard cubic centimeter per minute), respectively. The plasma reflow equipment used had a RF-type power source and the heating curve for the test wafer at 150 W is shown in Figure 3 (measured using thermocouples). Therefore, a reflow time of 60 s, which was used in this study, would give a peak temperature of 320°C.

As a reference study, hot air reflow using RMA flux was also performed in an IR (infrared) oven on the same types of specimens as used in the plasma reflowing. The oven had a conveyor system with four heating zones. The peak soldering temperatures used were 250°C for Sn3.5Ag and Sn3.5Ag0.7Cu, and 230°C for Sn37Pb, considering their melting points at 221°C, 217°C, and 183°C, respectively. Experimental conditions for the plasma and air reflow are shown in Table I.

Figure 1 Schematic illustration of soldered specimens

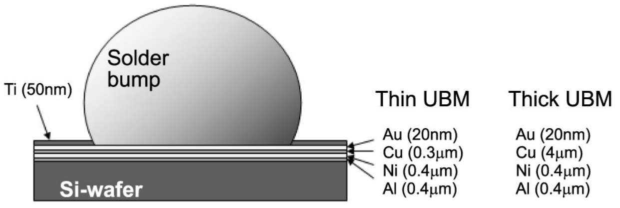


Figure 2 Schematic illustration of plasma soldering process

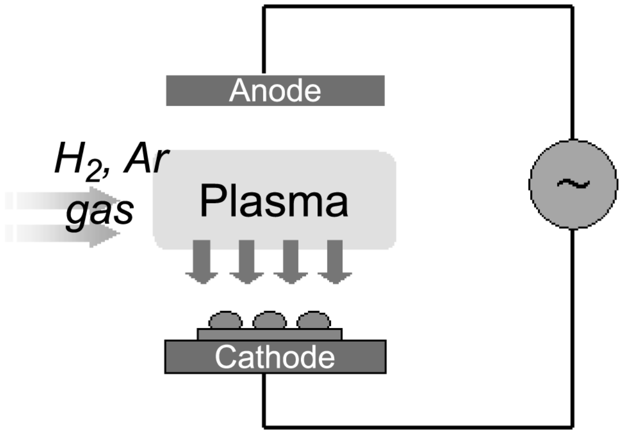


Figure 3 Heating curve for the UBM in an Ar-10 percent H2 plasma at 150 W RF power

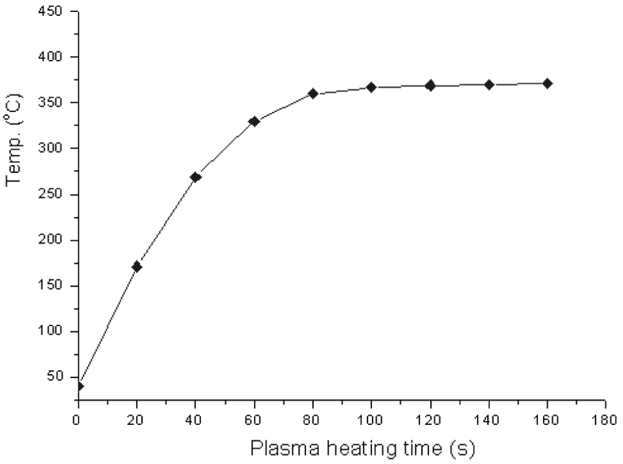


Table I Soldering conditions

	Soldering conditions		
Soldering method	**Sn37Pb**	**Sn3.5Ag**	**Sn3.5Ag0.7Cu**
Hot air reflow (with RMA-flux)	Temperature: 230°C Conveyor speed: 0.6 m/min	Temperature: 250°C Conveyor speed: 0.6 m/min	
Plasma reflow (without flux)	Plasma gas: Ar-10vol percent H_2 RF power: 150 W Dwell time: 60 s		
Times above liquidus	30 s		

The soldered specimens were shear tested using a micro-shear tester with a clearance of 10 μm between the shearing tip and substrate and a shearing speed of 200 μm/s. The soldered area was measured using an image analyzer, and the shear strength was determined from the area and maximum shear force. Each shear strength datum in this work was an average of 20 tests under the same conditions. Both bond interfaces of the joint cross-sections and fractured surfaces of the shear tested specimens were observed using scanning electron microscopy (SEM) with an energy dispersive spectrometer (EDS) for microanalysis.

3. Results and discussion

3.1 Thin UBM

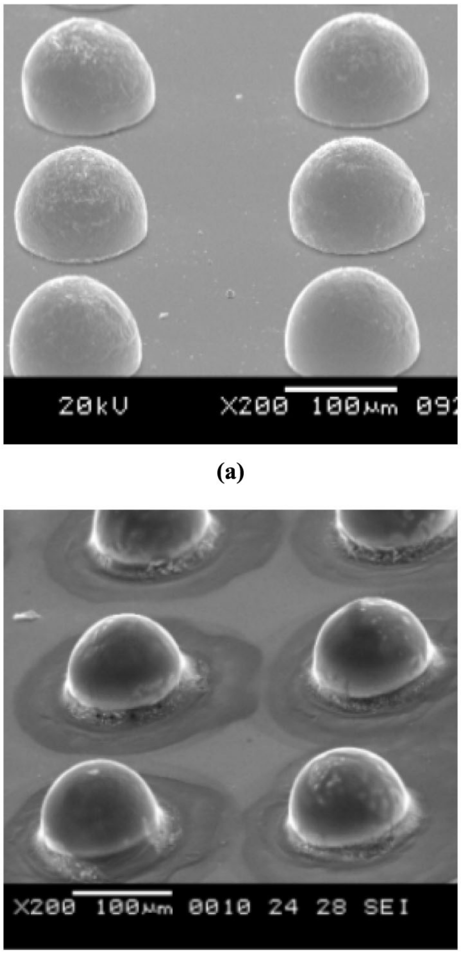
Figure 4 shows the solder balls reflowed by hot air (with flux) and Ar-10 percent H_2 plasma (without flux). The solder balls formed by the plasma reflow were well shaped and clean (Figure 4(a)), while flux residue was clearly visible on the balls reflowed in air (Figure 4(b)).

The bonded solder joints, with Sn37Pb, Sn3.5Ag or Sn3.5Ag0.7Cu on the thin UBM, were then cross-sectioned and the interfaces between the reflowed solder balls and substrates were examined (Figure 5, where the upper three photos are for air reflowed samples and the lower three plasma reflowed).

The air reflowed solder/substrate interfaces showed a sound bond interface without visible defects and including a layer of rod-shaped IMCs produced between the substrate and solder balls, which was clearly visible after etching the solder away. In the case of plasma reflow, however, cracks were observed along the interfaces between the IMCs and remnant metallization layers (Figure 5). The bulk solders in the cross-sections were removed by chemical etching.

An EDS analysis indicated the compositions of the IMCs in the case of air reflow were (in atomic percent) about 47 Sn, 42 Cu, 11 Ni; 65 Sn, 15 Cu, 20 Ni, and 81 Sn, 18 Cu, 0 Ni for Sn37Pb, Sn3.5Ag and Sn3.5Ag0.7Cu, respectively. On the other hand, for plasma reflow, the compositions of the IMCs were about 56 Sn, 8 Cu, 36 Ni; 26 Sn, 0 Cu, 74 Ni, and 74 Sn, 4 Cu, 22 Ni for Sn37Pb, Sn3.5Ag and Sn3.5Ag0.7Cu, respectively. Comparing these results, it is clear that the IMCs produced by the plasma reflow contained much more Ni and less Cu than those produced by the air reflow. This appears to indicate that, in the case of plasma reflow, the Cu layer in the UBM was almost exhausted or dissolved into the molten solder and at least part of the Ni layer (underneath the Cu layer in the UBMs) reacted with the solders to produce these Ni-rich IMCs. This seems reasonable considering the higher processing temperature plasma reflow reached, about 70-90°C higher than that in the hot air reflow at 230-250°C.

Figure 4 Solder balls formed: (a) by Ar-10 percent H_2 plasma reflow without flux; and (b) by hot air reflow with RMA flux



(a)

(b)

The higher temperature in plasma reflow would result in a complete consumption of the thin Cu and Ni layers through excessive dissolution in and reaction with the molten solder.

Figure 6 shows that the joint strengths of plasma-reflowed solder balls were much lower than those of the air reflowed samples. This appears to be due to the different fracture modes in shear testing, as shown by the fracture surfaces on the substrates in Figure 7.

It is clear that the plasma-reflowed solder balls were detached from the substrates, while the air-reflowed ones

Figure 5 Bond interfaces between solders and Si-wafer substrates with thin UBM

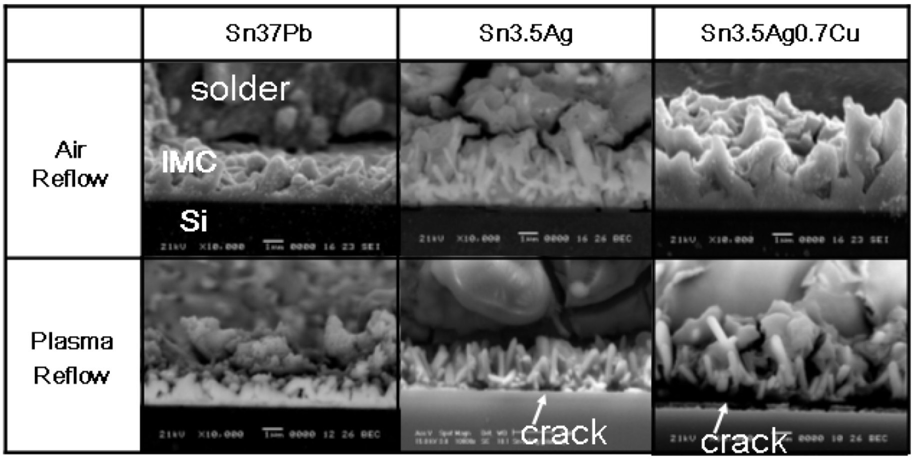


Figure 6 Shear strengths of soldered joints with the thin UBM

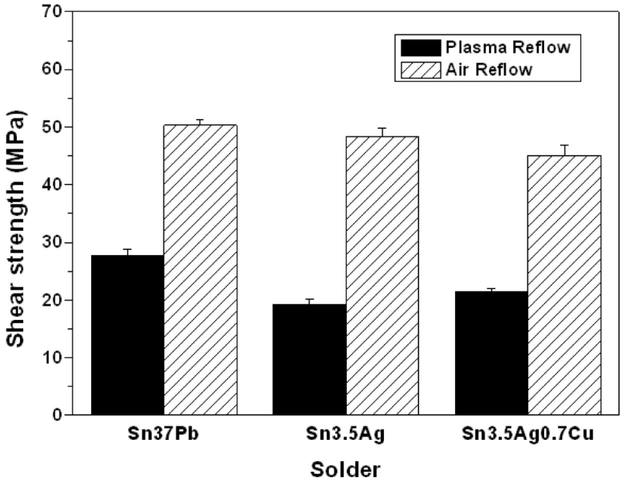
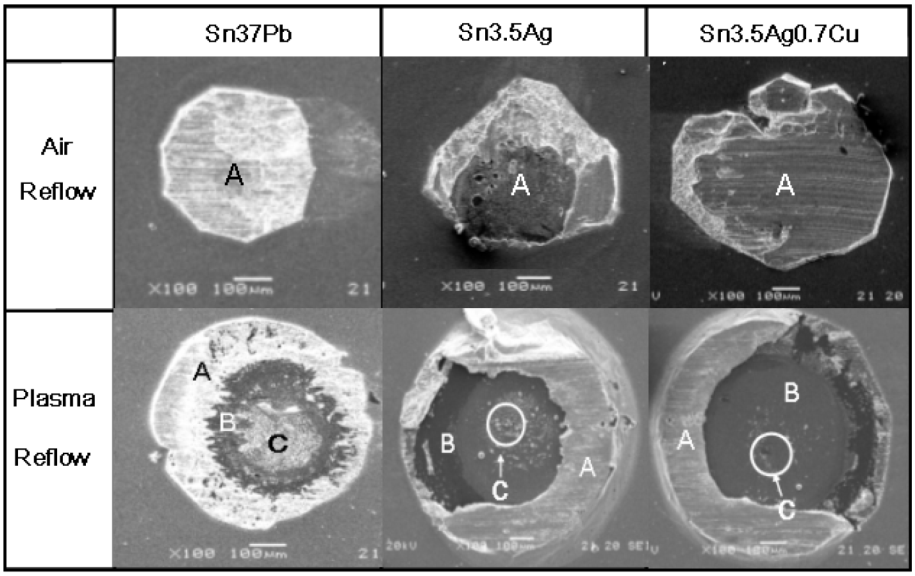


Figure 7 Fractured surfaces of shear-tested specimens with the thin UBM for hot air and plasma-reflowed samples



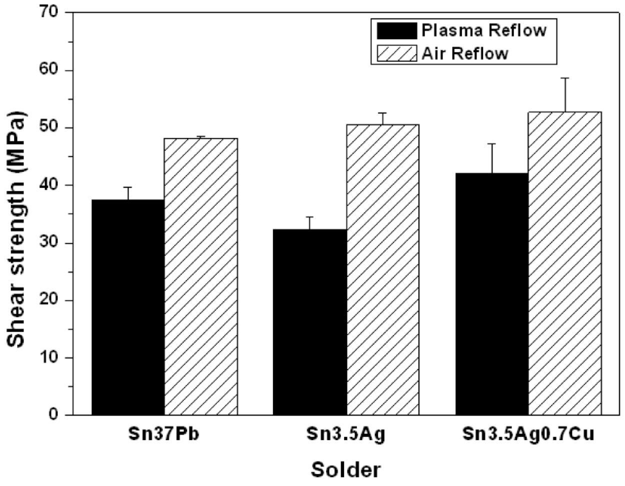
fractured through the solder. A comparison of Figures 5 and 7 implies the weak interfaces between the IMCs and substrates, indicated by the interfacial cracks, may be responsible for the detachment of plasma-reflowed solder balls from the substrates. To confirm this, the fracture surfaces on the substrates in Figure 7 were examined with EDS in detail to locate the fracture positions. On the fracture surfaces, the area marked by “A” was measured to have a composition (in atomic percentages) close to that of the bulk solders, for example 68 Sn and 32 Pb for Sn37Pb, indicating fracture through the solder. The area marked by “C” consists of white, granular spots with composition of about 51 Sn, 2 Cu, 48 Ni; 45 Sn, 2 Cu, 53 Ni, and 52 Sn, 9 Cu, 39 Ni for Sn37Pb, Sn3.5Ag and Sn3.5Ag0.7Cu, respectively, indicating that those were the Ni-rich IMCs observed in Figure 5. These compositions are typical of the $(Ni,Cu)_xSn_y$ IMCs, (which are either $(Ni,Cu)_3Sn_4$ or $(Ni,Cu)_5Sn_6$, depending on process conditions) previously observed at the interfaces between UBMs containing Cu and Ni, and Sn-Cu-(Ag) solders (Shiau *et al.*, 2002; Choi *et al.*, 2002). The area marked by “B” has a composition in atomic percentages of about 73 Si and 27 Al, indicating that the solder detachment occurred between the IMCs and the Al layer on the Si wafers. Therefore, the cracks between the IMCs and the substrates were responsible for the low strength of plasma-reflowed joints compared to air-reflowed joints.

3.2 Thick UBM

To improve the joint strength of plasma-reflowed solder balls, the thicknesses of the Cu and Ni layers were increased by about a factor of 10 to prevent complete consumption of these layers during the reflow process (Figure 1). Figure 8 shows the joint strength of both plasma- and air-reflowed solder balls on the thick UBM.

Comparing Figures 8 and 6 indicates that, while little change was observed in the joint strength of air-reflowed solder balls (46-50 MPa for the thin UBM and 48-52 MPa for the thick UBM), the thick UBM improved the strength of plasma-reflowed solder balls by 1.4-1.9 times (from 19-27 to 32-42 MPa). Meanwhile, the strength for the Sn3.5Ag0.7Cu alloy was close to that for Sn3.5Ag and Sn37Pb.

Figure 8 Shear strengths of soldered joints with the thick UBM



No change was observed in bond interface and fracture mode for air-reflowed solder joints with both thick and thin UBMs. However, interfacial cracks disappeared between the IMCs and substrates (Figure 9) and shear fracturing occurred mostly through the solders (Figure 10) for plasma-reflowed joints with the thick UBM compared to those with thin UBM (Figures 5 and 7).

This demonstrates that the thick UBM is an effective way to prevent interfacial cracks and hence weak solder joints. Compositional analysis by EDS of the IMCs for the plasma reflow from the cross sections (Figure 9) indicated in atomic percentages 52 Sn, 48 Cu and 48 Sn, 52 Cu for Sn37Pb and Sn3.5Ag0.7Cu, respectively. This confirmed that the IMCs only contained Sn and Cu, which indicates that the Cu-layer in the UBM was too thick to be exhausted, and thus the underlying Ni layer did not participate in the formation of IMCs. This in turn resulted in sound metallurgical bonding in the plasma-reflow solder process. In the case of air reflow, even for the thin UBM the interfaces were free of cracks because of the lower soldering temperatures. The detachment of the interfacial IMC from the substrate due to the exhaustion of UBM was also observed by Jang *et al.* (2003) in air reflow of Sn37Pb. Their detachment was caused by excessive temperature exposure due to reflow being repeated five times, and it was suggested that the excessive growth of IMC resulted in the complete exhaustion of the Cu layer in those UBMs. In order to avoid interfacial detachment they recommended a minimum UBM thickness.

However, the joint strength of the plasma-reflowed balls on the thick UBM was still lower than those reflowed in air. This is believed to be caused by the partial interfacial fractures observed in Figure 10 (marked “D”), due to an incomplete action of plasma cleaning on the substrate areas underneath the solder balls. It is therefore recommended that plasma cleaning be used on substrates prior to plasma reflow.

4. Conclusion

The effects of UBM thickness on a fluxless soldering process by plasma reflow were investigated. The thickness of the Au/Cu/Ni/Al layers was 20 nm/0.3 μm/0.4 μm/0.4 μm and 20 nm/4 μm/4 μm/0.4 μm, respectively, for the thin and thick UBM, respectively. The solders investigated included lead-free solder balls, 500 μm in diameter, with compositions of Sn-3.5 weight percent Ag-0.7 weight percent Cu and Sn-3.5 weight percent Ag, and lead-containing Sn-37 weight percent Pb as a reference. The main results can be summarized as follows.

- The thick UBM improved the shear strength of the plasma soldered joints to 32-42 MPa, compared to that of the joints with the thin UBM, which was 19-27 MPa.
- Little change was observed in the joint strength of air-reflowed solder joints (46-50 MPa for the thin UBM and 48-52 MPa for the thick UBM).
- The shear strengths of Sn3.5Ag0.7Cu balls on the thick UBM were similar to those for Sn3.5Ag and Sn37Pb.
- The lower shear strength with the thin UBM in plasma reflow was caused by interfacial cracks produced by

Figure 9 Bond interfaces between solders and Si-wafer substrates for plasma reflow and a thick UBM

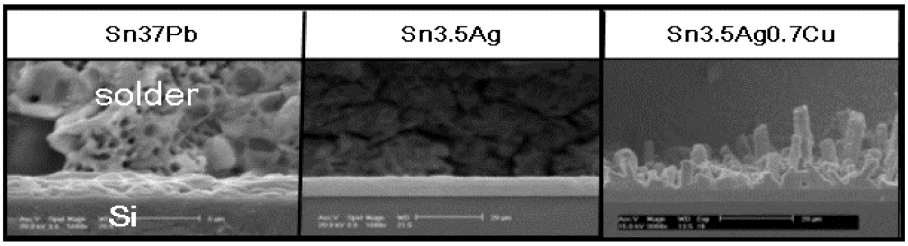
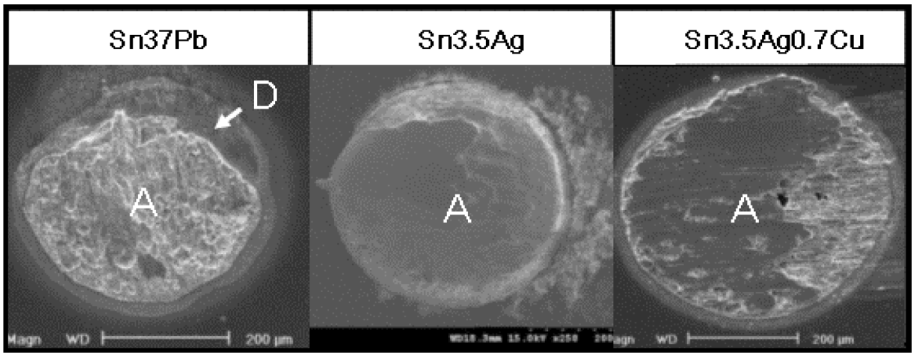


Figure 10 Fracture surface of shear tested specimen for plasma reflow and a thick UBM



complete consumption of the Cu- and Ni-layers. The cracks can be avoided by increasing the UBM thickness.

- The strength of plasma-reflowed joints with the thick UBM, was still lower than that of air-reflowed joints. This is believed to be caused by the incomplete action of plasma cleaning of the substrate surface under the solder balls. Therefore, it is recommended that plasma cleaning be used on substrates before plasma reflow.

References

Choi, W.K., Kang, S.K. and Shih, D.Y. (2002), "A study of the effects of solder volume on the interfacial reactions in solder joints using differential scanning calorimetry technique", *Journal of Electronic Materials*, No. 11, pp. 1283-91.

Deltschew, R., Hirsch, D., Neumann, H., Herzog, T., Wolter, K.J., Nowottnick, M. and Wittke, K. (2001), "Plasma treatment for fluxless soldering", *Surface and Coating Technology*, Vols. 142-144, pp. 803-7.

Harrison, M.R., Vincent, J.H. and Steen, H.A.H. (2001), "Lead-free reflow soldering for electronics assembly", *Soldering & Surface Mount Technology*, Vol. 13 No. 3, pp. 21-38.

Hong, S.M., Kang, C.S. and Jung, J.P. (2002a), "Fluxless Sn-3.5mass%Ag solder bump flip chip bonding by ultra-sonic wave", *Materials Transactions*, Vol. 43 No. 6, pp. 1336-40.

Hong, S.M., Kang, C.S. and Jung, J.P. (2002b), "Flux-free direct chip attachment of solder-bump flip chip by Ar+H_2 plasma treatment", *Journal of Electronic Materials*, Vol. 31 No. 10, pp. 1104-11.

Hong, S.M., Kang, C.S. and Jung, J.P. (2004), "Plasma reflow bumping of Sn-3.5Ag solder for flux-free flip chip package application", *IEEE Transactions on Advanced Packaging*, Vol. 27 No. 1, pp. 90-6.

Hunt, C. and Zou, L. (1999), "The impact of temperature and humidity conditions on surface insulating resistance values for various fluxes", *Soldering & Surface Mount Technology*, Vol. 11 No. 1, pp. 36-43.

Jang, S.Y., Wolf, J., Ehrman, O., Gloor, H., Schreiber, T., Reichl, H. and Paik, K.W. (2003), "CrCu based UBM study with electroplated Pb/63Sn bumps-interfacial reaction and bump shear strength", *IEEE Transactions on Component & Packaging Technology*, Vol. 26 No. 1, pp. 245-54.

Miric, A.Z. and Grusd, A. (1998), "Lead free alloys", *Soldering & Surface Mount Technology*, Vol. 10 No. 1, pp. 19-25.

Park, C.B., Hong, S.M., Jung, J.P., Kang, C.S. and Shin, Y.E. (2001), "A study on the fluxless soldering of Si-wafer/glass substrate using Sn-3.5mass%Ag and Sn-37mass%Pb solder", *Materials Transactions*, Vol. 42 No. 5, pp. 820-4.

Shiau, L.C., Ho, C.E. and Kao, C.R. (2002), "Reactions between Sn-Ag-Cu lead-free solders and Au/Ni surface finish in advanced electronic package", *Soldering & Surface Mount Technology*, Vol. 14 No. 3, pp. 25-9.

Takyi, G., Ekere, N.N. and Philpott, J.D. (1999), "Solderability testing in nitrogen atmosphere of plasma treated HASL finish PCBs for fluxless soldering", *Journal of Electronics Manufacturing*, Vol. 9 No. 3, pp. 233-9.

Wassink, R.J.K. (1984), *Soldering in Electronics*, Electrochemical Pub. Ltd, Port Erin, p. 34.

Zou, L., Dusek, M., Hunt, C.P. and Dunn, B.D. (1999), "An evaluation of the effect of aging on the cleanability of solder flux residues", *Soldering & Surface Mount Technology*, Vol. 11 No. 1, pp. 27-35.

About the authors

Jun Kwon Moon received his BS and MS degrees in 2001 and in 2003, respectively, from the University of Seoul in Materials Science and Engineering. He is currently a Researcher at the LG Electronics Institute, Seoul, Korea. He is working in the fields of electronics packaging and plasma display panels.

Y. Zhou received his PhD degree in 1994 from the University of Toronto, Canada, in metallurgy and materials science. He is currently an Associate Professor of Mechanical Engineering at the University of Waterloo, Canada, where he has been employed since 1998. Since 2003, this has been as a Canada Research Chair in Microjoining. His research interests lie in the areas of laser welding, and microjoining materials and processes including wire bonding, resistance welding, soldering and other joining mechanics.

Jae Pil Jung received his BS and PhD degrees in 1983 and 1992, respectively, from Seoul National University, and his MS degree in 1985 from Korea Advanced Institute of Science and Technology in Materials Science and Engineering. He is currently an Associate Professor of Materials Science and Engineering at the University of Seoul, Korea, where he has been employed since 1996. His research interests lie in the areas of interconnection materials and processes for electronics including soldering, wire bonding and other microjoining processes and the mechanics of electronic packaging.