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Blocking hillock and whisker growth by intermetallic compound formation in Sn-0.7Cu flip chip solder joints under electromigration

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Mass extrusion occurs in electromigration at the anode in cross-sectioned Sn-0.7Cu flip-chip solder joints. In a pair of joints, the hillock squeezed out at the anode on the board side is more serious than the whisker grown at the anode on the chip side. The difference of mass extrusion has been found to be affected by the amount of intermetallic compound (IMC) formation in the solder bump. It is found that when a large amount of Cu–Sn IMCs form in the grain boundaries of Sn grains, small hillocks are extruded on the anode end. It is proposed that the excessive IMC formation may be able to block the diffusion path of Sn atoms, so the growth of both the Sn whiskers and hillocks are retarded. © *2010 American Institute of Physics*. [doi:10.1063/1.3410796]

I. INTRODUCTION

Electromigration in flip-chip solder joints has become a major reliability issue in recent years because of the miniaturization trend to meet the demand of higher performance in portable consumer electronics. Many studies have investigated high current density induced electromigration failure in flip chip solder joints.[1–3] Typical failure in flip chip solder joints with thin-film under-bump-metallization (UBM) involves pancake-type void formation and propagation adjacent to the UBM in the cathode. In particular, when Cu UBM is adopted, serious UBM dissolution and formation of huge amounts of intermetallic compounds (IMCs) under electromigration have also been found.[4,5] Recently, another kind of failure has been discovered namely whisker growth in anodes.[6] The unique line-to-bump structure of flip chip solder joints causes the current crowding effect,[7] which leads to the development of the stress concentration and stress potential gradient needed for whisker growth.

Spontaneous Sn whisker growth is an important concern in high reliability devices such as satellites.[8,9] To understand whisker growth, we need to accelerate the growth. Electromigration can achieve this goal by using Blech test structures of pure Sn stripes.[10] However, finding a way to reduce and prevent whisker growth is the important issue that has attracted the widest interest. In this study, electromigration in Pb-free solder bumps was conducted to observe whisker and hillock growth in an anode. We found that the accompanied IMCs in the anode served as diffusion barriers to block the diffusion of Sn and to slow down the whisker and hillock growth. The effectiveness of the barrier depends on the amount of IMC formation at the anode, which in turn depends on the supply of Cu from the cathode.

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II. EXPERIMENTAL

The test vehicle which was employed in the electromigration study was a $13 \times 10 \times 0.56\ \mathrm{mm}^3$ flip chip package, which has a $3.5 \times 0.5 \times 0.73\ \mathrm{mm}^3$ Si chip interconnected to the substrate by an array of Pb-free solder joints. The pitch between adjacent solder joints is 270 μm. Figure 1 is a schematic diagram of the cross-sectional view of a flip chip joint. The UBM on the chip side is a tri-layer thin film of Ti/Ni(V)/Cu. The thickness of the Cu thin film is 0.5 μm. The diameter of the UBM opening and passivation opening were 110 μm and 85 μm, respectively. Printing solder of Sn-0.7Cu alloy was used on the chip side. The substrate metallization on the Cu bond-pad features solder-on-pad (SOP) surface treatment, i.e., with printed Sn-3.0Ag-0.5Cu pre-solder on the Cu bond-pad surface. The Cu bond-pad has a thickness of 15 μm, which is much thicker than the Cu thin film UBM on the chip side. The printing solder and the SOP were reflowed together to become Pb-free bumps. Since Cu acted as the adhesion layer on both sides of the solder joint, the Cu_6Sn_5 IMCs formed on both sides of the solder bumps during the reflow.

The sample was cut and polished to the center of the solder joints. One pair of the flip chip solder joints was stressed by a current density of $1.3 \times 10^4\ \mathrm{A/cm}^2$ on a hot-

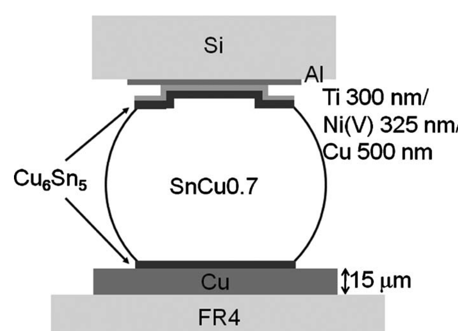

FIG. 1. Cross-sectional schematic drawing of the solder joint.

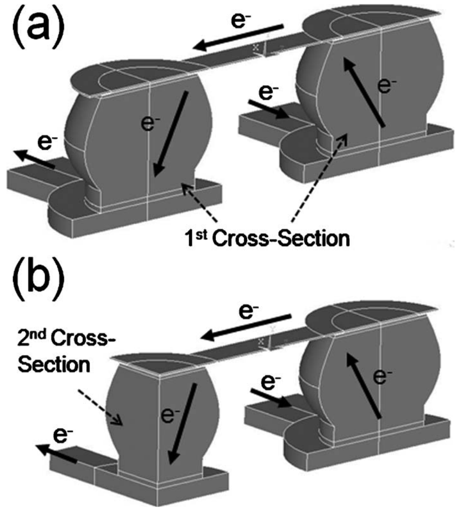

FIG. 2. Three-dimensional diagram for the solder joints with the direction of electron flow (a) After first cross section. (b) After second cross section.

plate maintained at 100 °C. Figure 2(a) depicts the three-dimensional view of the pair. The cut surface is denoted as the first cross-sectional surface for *in situ* observation in electromigration, and the arrows indicate the direction of electron flow. The electrons enter the right bump from the substrate side at the bottom and exit the bump at the upper-left corner. They drift in the Al trace and then enter the left bump on from the upper-right corner. The chip side of the right-hand-side bump is the anode end and current crowding occurs at its upper left corner. In the left-hand-side bump, the anode end locates at the bottom, which is near the Cu bondpad. To facilitate the observation of the microstructure and IMC formation in the matrix of the solder joint, the sample was cross-sectioned a second time as illustrated in Fig. 2(b) after electromigration tests. Both the bumps were cross-sectioned after current stressing. Then an ion channeling images were taken using a focused ion beam (FIB) and secondary SEM images were employed to investigate the surfaces morphology and phase distribution of the second cross sections.

III. RESULTS AND DISCUSSION

Figures 3(a)–3(c) show the evolution of surface morphology in the first cross section of the left-hand side bump for the as-prepared, after 150 h, and after 1632 h of current stressing, respectively. The electron flows went downward (from the chip side to the substrate side). As shown in Fig. 3(b), a hillock was extruded near the anode end on the substrate side. As stressing time increased, voids formed and propagated at the cathode end of the bump, as illustrated in Fig. 3(c). The direction of the electron flow is labeled in the figure. Moreover, hillock grew extensively and almost occupied the entire bottom of the solder bump, as depicted in the enlarged figure in Fig. 3(d).

In the solder joint on the right-hand side with an upward electron flow (from the substrate side to the chip side), smaller hillocks were observed at the anode. Figures 4(a)–4(c) show the morphology changes in the first cross section of the as-prepared solder bump, after 150 h, and after

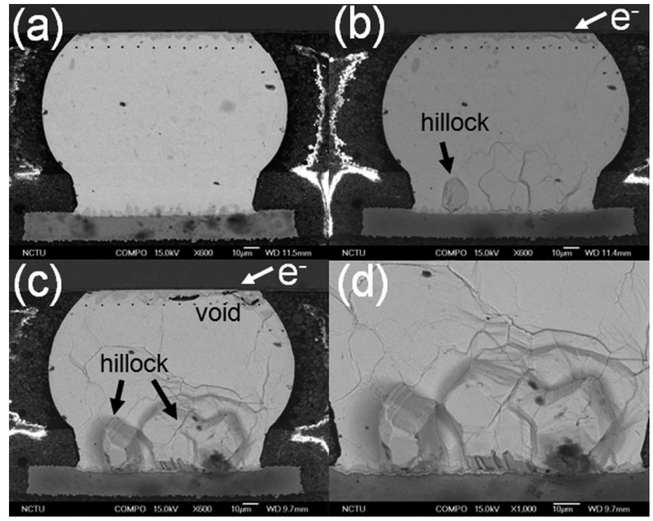

FIG. 3. Cross-sectional SEM images for the solder joint with downward electron flow before and after the current stressing. (a) Before current stressing, (b) after 150 h, (c) after 1632 h of current stressing, and (d) higher magnification of the sample in (c) to show a clear image of the hillock at the substrate side.

1632 h of current stressing, respectively. By comparing Fig. 4(a) with Fig. 3(a), the phase distribution in the as-prepared state was almost the same before current stressing. After the current stressing for 150 h, a large amount of IMCs was formed in the cathode near the Si chip side but no hillock formed, as highlighted by the circle in Fig. 4(b). After stressing for 1632 h, as shown in Fig. 4(c), the formation of IMCs became more obvious than that in Fig. 4(b). This is because there was a thick UBM in the substrate side. The electrons migrated the Cu atoms into the solder during current stressing. Yet, it is interesting that only one small whisker was extruded, as shown in the enlarged image in Fig. 4(d). The hillock locates in the upper left corner of solder bump where the electrons leave the solder and enter the Al trace in the chip side.

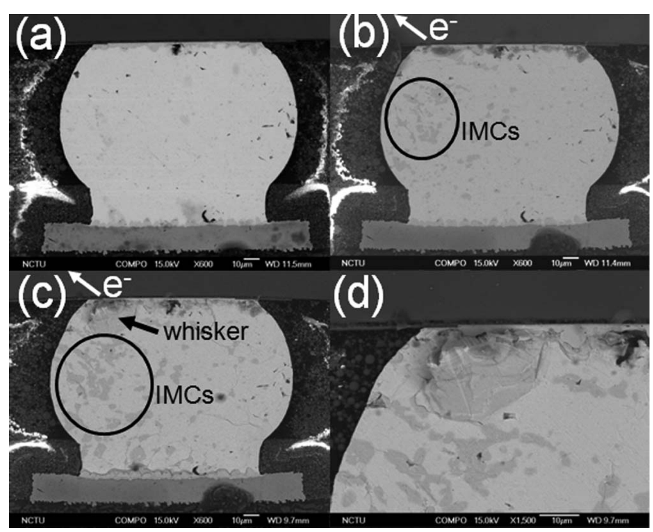

FIG. 4. Cross-sectional SEM images for the solder joint with upward electron flow before and after the current stressing. (a) Before current stressing, (b) after 150 h, (c) after 1632 h of current stressing, and (d) higher magnification of the sample in (c) to show a clear image of the whisker at the chip side.

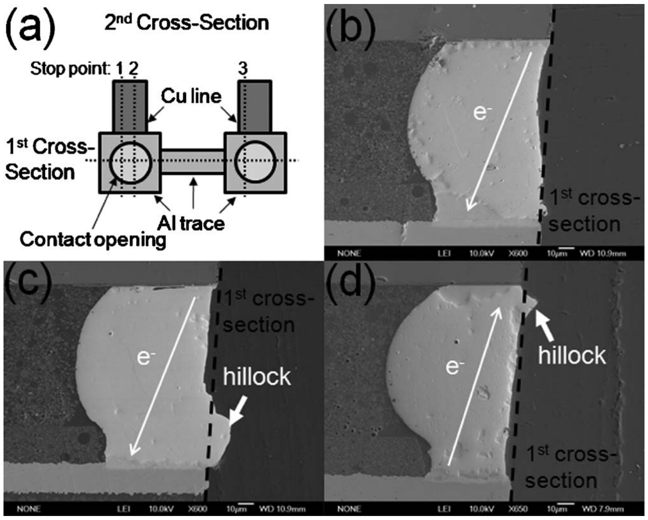

FIG. 5. (a) Plan-view schematic diagram of the test sample showing the positions where the second cross sections were made: (b) SEM image at stop point 1 in (a); (c) SEM image at stop point 2 in (a); (d) SEM image at stop point 3 in (a).

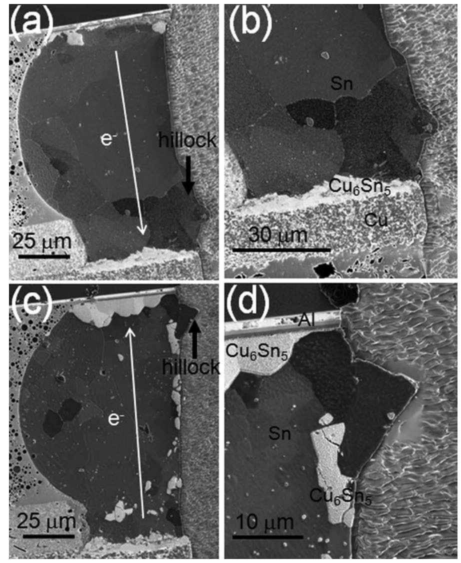

FIG. 6. FIB images for the second cross section of the solder joint after current stressing for 632 h. (a) At stop point 2 in Fig. 5(a). The electron flow went upward in this solder bump; (b) higher magnification of (a) to show the distribution of grains and IMCs close to the substrate side; (c) at stop point 3 in Fig. 5(a). The electrons drifted upward in this solder bump; (d) higher magnification of the sample in (c) to show the IMCs formation blocking the Sn diffusion path for whisker growth in the anode end.

However, from the images of the first cross section, the volume of the voids in Fig. 3(c) is quite small as compared with the volume of the hillocks. The SEM images for the second cross sections were taken at three polished positions as marked in Fig. 5(a). For the same specimen, the solder joints were polished to the first cross section and SEM and FIB images were taken. Then it was polished again to the second cross section and it was observed by SEM and FIB. Figures 5(b) and 5(c) depicts the SEM images for the second cross sections of the first and second positions in Fig. 5(a), in which electrons drifted downward. The dotted lines in the figures indicate the surface of first cross section. It is found that the surface sank in the cathode end of the solder bump. Therefore, the volume or mass is conserved. The mass of the hillocks is from both the voids and the depletion of the free surface of the solder joint. The thickness of the hillocks is about 10 to 20 μm for the solder with downward electron flow. To observe the second cross section for the other bump, the specimen in Fig. 5(c) was polished again to the third position in Fig. 5(a). Figure 5(d) shows SEM image for the right bump with an upward electron flow for 1632 h. It is interesting that the bump with an upward electron flow shows smaller hillocks and dimpling than the other solder bump in Fig. 5(c).

To investigate the grain structure and IMC distribution in the solder joints, FIB ion images were used to analyze the second cross sections. Due to the ion channeling effect, the contrast of Sn grains looks darker than that of IMCs since IMC has less ion channeling, as shown in Fig. 6. Figures 6(a) and 6(b) show the second cross section of the bump in Fig. 5(c) with a downward electron flow. The hillock is the closest Sn grain to the substrate to be extruded out. There is no IMC between the hillock and the matrix of the solder. Next to the hillock, there are two columnar-type of Sn grains along the electron flow, they were dimpled and the Sn atoms were driven to grow the hillock by electromigration, as illustrated in Fig. 6(b).

When the electron flow went upward as in the bump, Sn and large amount of Cu were driven from the bond-pad to the anode and a large amount of IMC was formed there, as shown in Fig. 6(c). It is an FIB image for the sample in Fig. 5(d). It is found that the IMC grains were distributed along the surface of the first cross section and some of them accumulated at the chip end. The high magnification image in Fig. 6(d) reveals that the Cu_6Sn_5 IMCs became a diffusion barrier and blocked the Sn supply to the hillock grain.

It is known that in electromigration the driving force of hillock growth is to relieve the compressive stress that occurs due to IMC formation and the accumulation of Sn atoms at the anode. The following model is proposed to explain the observed results. Figure 7(a) represents the schematic drawing for the grain structure of solder bump with electron flow from the chip end to the substrate end. The Sn grains close to the chip side are depleted by electromigration and the Sn grain closest to the substrate side is extruded. Since the Cu metallization is only 500 nm, thus only few Cu atoms can be driven into solder by electromigration. On the other hand, for the bump with electron flow from substrate end to the chip end, electromigration drives both Sn and Cu to the anode. Because the thickness of the Cu pad on the substrate end is as thickness as 15 μm. Therefore, vast amount of Cu atoms are migrated by electromigration into solder bump by electromigration. A lot of Cu–Sn IMCs are formed in the grain boundaries of Sn grains and on the cross-sectioned surface. These IMCs may block the diffusion of Sn and thus the hillock formation is much less in this bump, as illustrated in Fig. 7(b). In Figs. 4(b) and 6(c), with a thick Cu bond-pad, a large amount of Cu atoms were driven from the substrate side to form IMCs in the solder and on the chip side. A

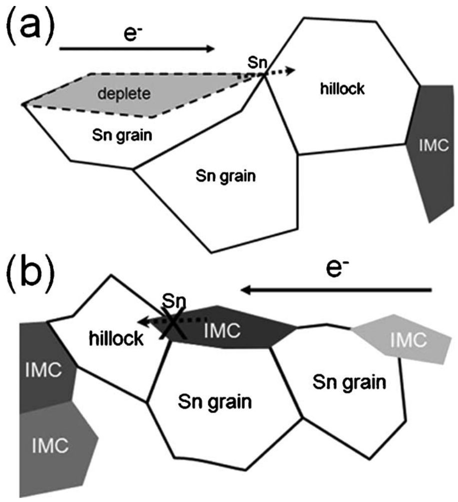

FIG. 7. (a) Schematic drawing showing the mechanism for the whisker growth due to electromigration in the bump with electron flow from the chip end to the substrate end. A big hillock is formed in the anode end. (b) Schematic drawing showing the IMC formation in the Sn grain boundaries. The IMCs may block the diffusion path of Sn atoms to retard the hillock and whisker growth in the bump with electron flow from the substrate end to the chip end.

typical case is shown in Fig. 6(d), where the IMC at the root of the hillock has become a diffusion barrier and hinders the growth of hillock.

In addition the blocking effect of IMC, the difference of the temperature at the chip and the substrate side may also affect the hillock and whisker growth rate. We found that if the hotplate temperature increased to 150 °C, the hillock growth at the substrate side was not as significant as that at 100 °C. Since 150 °C is a high homologous temperature (0.86 T_m) for Sn, Sn will have a lower mechanical strength and significant creep will take place under stress. Therefore, the mechanical stress can be relaxed more quickly so the driving force of hillock or whisker growth is reduced.[11]

On diffusion of Cu, it has been reported recently that due to anisotropic effect, the diffusivity of Cu in Sn along the c-axis is three to four orders of magnitude faster than the diffusivity along the a-axis or b-axis. Copper interstitial diffusivity along the c-axis is 500 times faster than that along the a-axis or b-axis of Sn crystals at 25 °C,[12] and the diffusivity of Ni along the c-axis is $\sim 7\times10^4$ times than that at right angles (a-axis or b-axis) at 120 °C.[13] Hence, the orientation of the Sn grains in the solder joint matrix may have a profound effect on the diffusion of Cu from the cathode to the anode.[14] The interaction among the anisotropic effect, current crowding, and the supply of Cu from the cathode to the anode requires more study. In the present case, since the grain size in the solder joint matrix is about 20 μm, there were about 5 grains in the solder joint between the cathode and the anode, the change in orientation between grains may also have effect on the Cu diffusion.

In addition to the formation of IMCs, the change in the stress state in the joint may also have a large effect on the whisker formation. During current stressing, both electron wind force and electromigration-induced back stress may affect the motion of atoms in the joint.[15] Because the current distribution in the top solder is different from that in the bottom solder,[7] the electron wind force is different for the two bumps in Fig. 2(a), resulting in different back stress in these two locations. Yet, how the wind force and stress affect the growth of whiskers/hillocks is not clear. More study is needed to clarify it. In addition, thermal stress may have influence on the stress state. Wu *et al.*[16] reported that the high-stress region locates at the top of solder, i.e., around the Al-to-solder interface. However, more whiskers/hillocks were found at the bottom of the solder joints in this study. This implies that the thermal stress may not serve the main reason for the formation of whiskers/hillocks.

IV. CONCLUSIONS

Hillock and whisker growth occurs at the anode in cross-sectioned Sn-0.7Cu flip-chip solder joints stressed by a current density of 1.3×10^4 A/cm^2 on a hotplate maintained at 100 °C. It is found that when a large amount of Cu–Sn IMCs are presented in the solder joints, the growth of Sn hillocks at the anode is retarded. It is proposed that IMC formation may become a diffusion barrier to block the supply of Sn in the growth of hillocks and whiskers. It is effective if the supply of Cu is sufficient. Cross-sectional FIB images support this assumption.

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