Mechanism of electromigration-induced failure in flip-chip solder joints with a 10-μm-thick Cu under-bump metallization

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The electromigration-induced failure in flip-chip eutectic SnPb solder joints with a 10-μm-thick Cu under-bump metallization (UBM) was studied without the effect of current crowding in the solder region. The current crowding occurred inside the UBM instead of in the solder joint at the current density of 3.0×10^4 A/cm^2 because of the spreading of current in the very thick Cu UBM. In these joints, the failure occurred through a two-stage consumption of the thick Cu UBM in the joint where electrons flowed from the chip to the substrate. In the first stage, the Cu UBM dissolved layer by layer rather uniformly across the entire Cu UBM–solder interface. In the second stage, after half of the Cu UBM was dissolved, an asymmetrical dissolution of Cu UBM took place at the corner where electrons entered from the Al interconnect to the Cu UBM. Experimental observation of dissolution steps of the 10-μm-thick Cu UBM is presented. The transition from the first stage to the second stage has been found to depend on the location of current crowding in the flip-chip joints as the UBM thickness changes during the electromigration test. The current distribution in the flip-chip solder joints as a function of UBM thickness was simulated by three-dimensional finite element analysis. The dissolution rate of Cu UBM in the second stage was faster than that in the first stage. The mechanism of electromigration-induced failure in the flip-chip solder joints with a 10-μm-thick Cu UBM is discussed.

I. INTRODUCTION

Under-bump metallization (UBM) is very important in the flip-chip technology because it acts as a solder wettable layer, diffusion barrier, and adhesion layer.[1] Currently, the most common choices for solder wettable layers are Cu and Au, and the diffusion barrier and adhesion layers are TiW, Ti, Cr, Al, NiV, and Ni. These choices depend not only on a solder bumping process, but also on a balancing of capabilities and costs, as well as the manufacturer's skill and experience. When a trilayer thin film of Cr/Cu/Au is applied as UBM, spalling of Cu–Sn compounds from the Cu–solder interface occurs and results in a weak mechanical solder joint, which is one of the most serious reliability problems because the Sn-based Pb-free solders react very fast with Cu and the amount of Cu is very limited in the thin-film metallization.[2–4] To overcome the spalling problem, a 5-μm-thick electroplated Cu UBM has been integrated into the UBM so that the chemical reaction will not consume all the Cu and no spalling may occur during aging.[5] However, when the joint is subjected to current stressing, current crowding leads to a rapid dissolution of the 5-μm-thick Cu UBM at the corner where electrons entered from Al interconnect to Cu UBM and the joint failed quickly.[6] Due to the demand for high performance and miniaturization in the electronics industry, the problem of electromigration must be overcome; a thicker Cu UBM has been designed to overcome the electromigration-induced failure.[7] Currently, the design rule requires that each flip-chip solder joint of 50 μm in diameter carries 0.2 A, which means that the average current density in such a joint is about 10^4 A/cm^2.[7] The International Technology Roadmap for Semiconductor (ITRS) projections indicated that electromigration is a near-term issue in high current density packages.[8]

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It is conceivable that if a thicker Cu UBM is used, a longer lifetime would be expected. However, the same failure mechanism of the asymmetrical dissolution of Cu UBM and short lifetime have been reported in the literature even for solder joints with a 8.5-μm-thick Cu UBM. When the applied current was increased, the current crowding occurred at the UBM–solder interface and led to fast failure.[9–11] In this paper, the electromigration in a 10-μm-thick Cu UBM under low current density has been studied. While the current crowding area is located initially inside the UBM, electromigration-induced failure still occurs. We observed two-stage UBM consumption in this system during the electromigration test. At the first stage, the 10-μm-thick Cu UBM dissolved rather uniformly at the entire Cu UBM–solder interface. In the second stage, when the Cu became thinner, the asymmetrical dissolution of Cu UBM due to the current crowding effect came back. A three-dimensional (3D) simulation was performed to show the distribution of current density during electromigration testing and to help understand the UBM–solder interfacial reaction when we attempt to avoid current crowding by using very thick Cu UBM.

II. EXPERIMENTAL

A schematic diagram of the sample used for electromigration testing is shown in Fig. 1(a). The Si chip was flipped over and assembled on the organic substrate by using eutectic SnPb solder bumps. The Al pad on the chip was 60 × 60 μm^2, and the lines connecting the pads of two neighboring bumps had a width of 50 μm and thickness of 1 μm. The opening diameter of the dielectric passivation on the chip was 50 μm in diameter. The eutectic SnPb solder bumps on the test chip were electroplated onto the sputtered TiW (0.2 μm)/Cu (0.4 μm)/electroplated Cu (10 μm) UBM. On the organic substrate, the metal trace was Cu (18 μm) and the bond pad metal layers on the Cu trace were electroless Ni (5 μm)/immersion Au (0.01 μm). The opening of the solder mask on the substrate was 120 μm in diameter.

The applied current was 0.6 A, and the average current density at the 50 μm diameter contact opening was 3.0 × 10^4 A/cm^2. During the current stressing, the sample was placed on a hotplate kept at 100 °C in an atmospheric ambient. The resistance change was monitored in situ using a control unit and power supply. To investigate the microstructural change and the failure mode in a solder joint induced by the electromigration tests, a set of solder bumps was cross-sectioned before and after current stressing at various periods of time and examined by field-emission scanning electron microscopy (FE-SEM).

A 3D finite element model was constructed to simulate the structure and current density distribution in the flip-chip solder joint as illustrated in Fig. 2. The model used in this study was SOLID69 8-node hexahedral coupled field element using Ansys simulation software (Ansys Inc., Canonsburg, PA). The dimension of the mesh was 3.8 μm. A detailed description of the simulation can be found elsewhere.[12] The resistivities of the materials used in the simulation are listed in Table I.

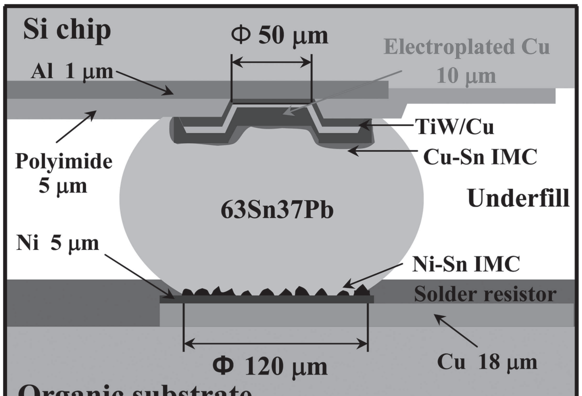

FIG. 1. Schematic diagram of the electromigration test sample.

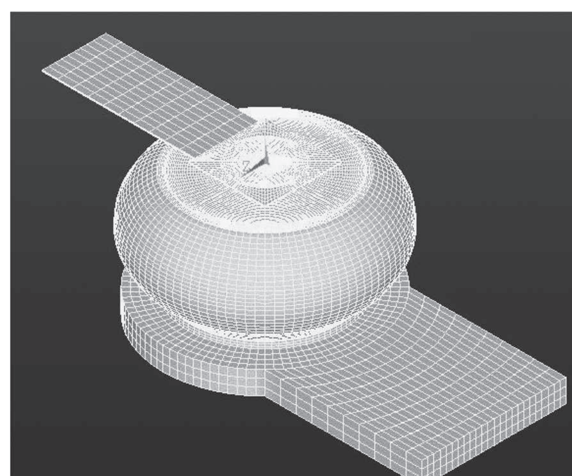

FIG. 2. The 3D finite element model showing the meshes in a solder joint.

TABLE I. The resistivities of the materials used in the simulation models.

Materials	Resistivity (μΩ cm)
Al	4.3
TiW	70
Cu	1.7
Cu_6Sn_5 IMC	17.5
Eutectic SnPb	14.6
Ni_3Sn_4 IMC	28.5
Ni	6.8

III. RESULTS

A. Three-dimensional current density distribution in flip-chip solder joints with a thick Cu UBM

Figure 3(a) shows the simulated 3D current density distribution in the solder joint with 10-μm-thick Cu UBM when the applied current was 0.6 A, and Fig. 3(b) shows the current density distribution at the cross section along the vertical Z-axis in Fig. 3(a). The current density in the Al trace was 1.94×10^6 A/cm^2, and the maximum current density in the Cu UBM was as high as 4.53×10^5 A/cm^2, which occurred near the interface between the Al trace and the Cu UBM. The current crowding region has spread about 3-μm wide and 5-μm deep into Cu. However, there was no serious current crowing at the interface between Cu UBM and solder. The uniform current density in the solder region was 5.0×10^3 A/cm^2, which was much lower than the calculated average value of 3.0×10^4 A/cm^2 at the contact opening as given in the experimental section. Therefore, it is expected that the flip-chip structure with a 10-μm-thick Cu UBM could have avoided the electromigration-induced failure of void formation at the cathode where electrons flowed from the chip to the substrate under 0.6 A current stressing.

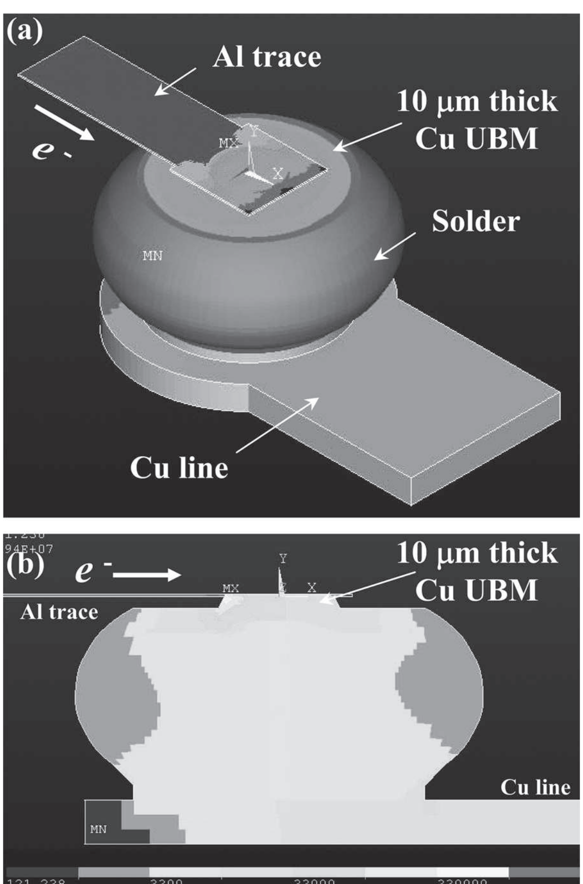

FIG. 3. (a) The 3D current density distribution in the solder joint with a 10-μm-thick Cu UBM. (b) The current density distribution at the Z-axis cross section in (a).

B. Electromigration in flip-chip eutectic SnPb solder joints with a 10 μm thick Cu UBM

Figures 4(a)–4(c) are SEM images of the cross-sectioned flip-chip solder joints before and after current stressing of 138 h at 100 °C with a current density of 3.0×10^4 A/cm^2. Before the current stressing, as shown in Fig. 4(a), the microstructure of solder bump showed a typical lamella structure of eutectic SnPb solder, and a small amount of Cu_6Sn_5 intermetallic compounds (IMCs) was formed under the 10-μm-thick Cu UBM. After the current stressing, the Pb atomic flux and the failure of a flip-chip joint related to the consumption of

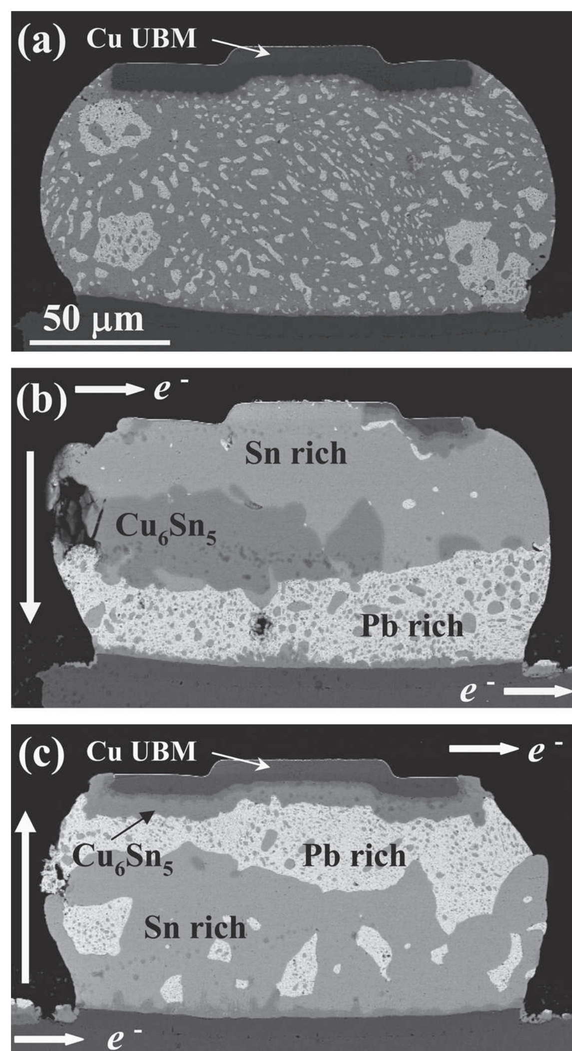

FIG. 4. SEM images of the cross-sectioned surface of flip-chip eutectic SnPb solder joints with 10-μm-thick Cu UBM (a) as received, (b) after downward current stressing for 138 h at 3.0×10^4 A/cm^2 and 100 °C, and (c) after upward current stressing for 138 h at 3.0×10^4 A/cm^2 and 100 °C.

Cu UBM could be recognized in Figs. 4(b) and 4(c). The arrow marked by "e^-" indicates the direction of electron flow. In the bump with electrons flowing from the chip to the substrate, as shown in Fig. 4(b), the Pb atoms migrated toward the substrate side and the Sn atoms diffused back to the chip side. This result was in agreement with previous work on electromigration in composite SnPb solder.[6] The upper region of the solder bump consisted of the dark color (Sn-rich) matrix alone while the lower region was composed of gray particles apparently embedded in the white color (Pb-rich) matrix. In addition, the dissolution of almost all the 10-μm-thick Cu UBM was observed after 138 h in electromigration test. A large amount of Cu_6Sn_5 IMC was found in the middle of the solder bump. In the opposite case when the electrons flowed from the substrate side to the chip side, as shown in Fig. 4(c), the Pb migrated toward the chip and Sn diffused back to the substrate. The upper region of the solder bump consisted of the Pb-rich phase, while the lower region was composed of Sn-rich phase. The layer-type Cu_6Sn_5 IMC formed under the Cu UBM by consuming Cu, and a small amount of Ni_3Sn_4 IMC was observed on the substrate side. Since the reaction rate between Ni and Sn is slower than that between Cu and Sn, the amount of IMC formation on the substrate side in Fig. 4(c) was smaller than that on the chip side in Fig. 4(b), although Sn diffused back to the cathode sides in both cases during electromigration. Comparing the images in Fig. 4, it is clear that the failure occurred due to UBM consumption and voids formation at the cathode of the joint in a downward electron flow case (from the chip to the substrate). The interesting finding in this study is that the final failure mode in flip-chip solder joints with a 10-μm Cu UBM was exactly the same as that of the solder joint with a 5-μm-thick Cu UBM[6] and thin-film UBM[13] where the current crowding occurred in the solder region.

C. Two-stage dissolution of the 10-μm-thick Cu UBM

Figures 5(a)–5(d) show the cross-sectional SEM images of flip-chip solder joints in the case of downward electron flow, from the chip to the substrate, after current stressing for 50, 75, 100, and 120 h, respectively. Electrons entered from the upper left-hand side, went down into the bumps, and exited to the lower right-hand side of solder joints as indicated by the white arrows. Figure 5 shows the sequential changes of the Cu UBM thickness, formation of IMCs, and catastrophic failure at the cathode side during electromigration. Before the current stressing, as shown in Fig. 4(a), the thickness of Cu UBM was 10 μm and a small amount of Cu_6Sn_5 IMC was formed at the Cu–solder interface. After 50 h of current stressing, as shown in Fig. 5(a), the thickness of the Cu_6Sn_5 IMC increased at the whole interface under the Cu UBM, and the layer-type dissolution of Cu UBM was observed. When the current stressing time increased to 75 h as shown in Fig. 5(b), the continuous and uniform decrease of the Cu UBM thickness at the whole interface of Cu UBM–solder increase was clearly observable. However, after 100 h current stressing, nonuniform consumption of the Cu UBM was observed and many large

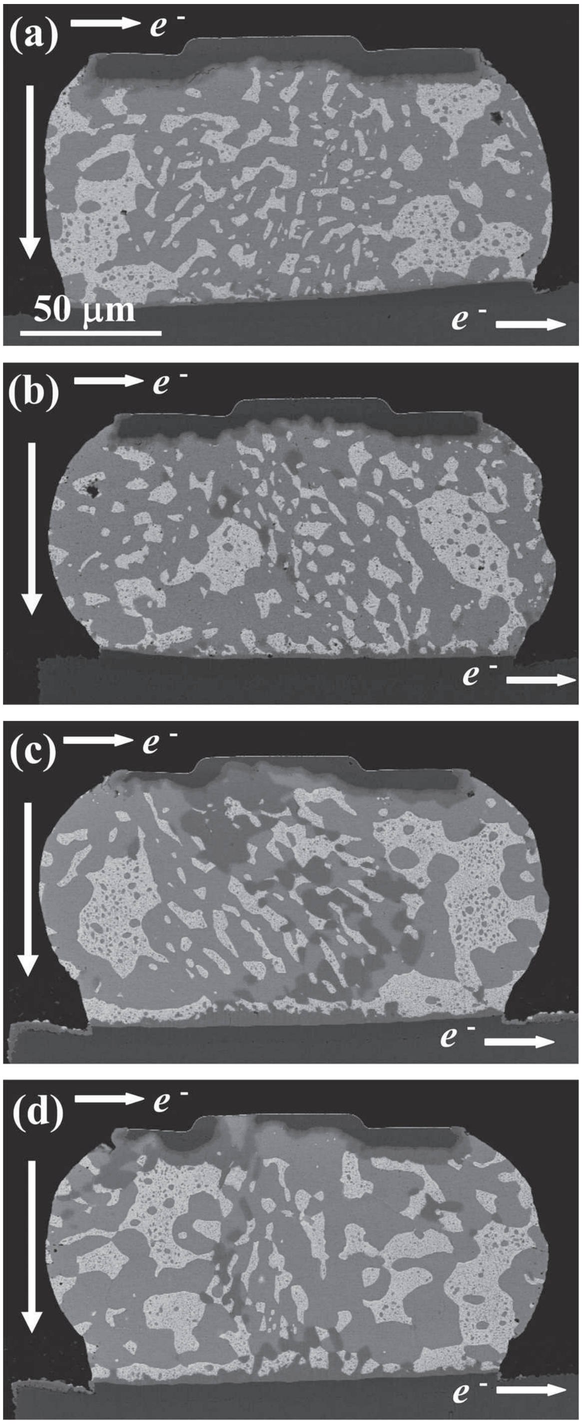

FIG. 5. SEM images of the cross-sectioned surface of flip-chip eutectic SnPb solder joints with a 10-μm-thick Cu UBM tested at 3.0 × 10^4 A/cm^2 and 100 °C after (a) 50 h, (b) 75 h, (c) 100 h, and (d) 120 h.

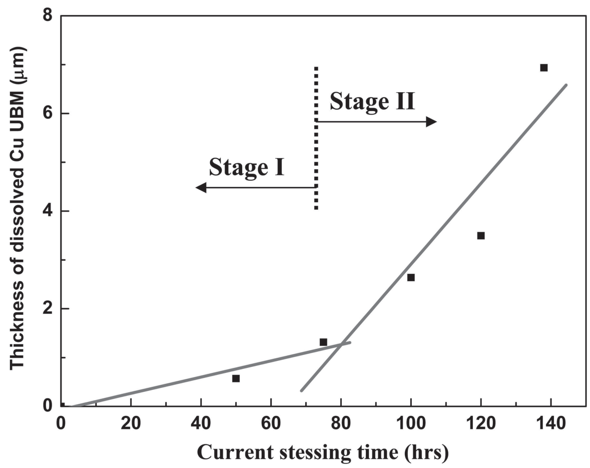

FIG. 6. Thickness of dissolved Cu UBM at various current stressing time.

Cu_6Sn_5 IMCs started to form at the left-hand side corner of the contact window, as shown in Fig. 5(c). After 120 h, there was no more Cu or Cu_6Sn_5 at the left-hand side corner of the solder bump, see Fig. 5(d). The final failure was the consumption of almost all Cu UBM at the cathode interface, as shown in Fig. 4(b). The failure sequence of Figs. 5(c) and 5(d) was similar to the conventional flip-chip solder joints with a 5-μm-thick Cu UBM[6] or with multilayered thin-film UBM.[13] However, the layer-type dissolution of the Cu UBM before 100 h, as shown in Figs. 5(a) and 5(b), was unique in this study. Below, we shall correlate the two-stage consumption of the 10-μm-thick Cu UBM and 3D simulation results of current distribution during electromigration.

Figure 6 shows the dissolution of the Cu UBM as a function of current stressing time. The amount of dissolved Cu UBM was calculated from the images of the cross-sectioned joints in Figs. 4 and 5. At first, the area of the Cu UBM in Figs. 4 and 5 was measured by using computer software of Image-Pro Plus (Media Cybernetics Inc., Silver Spring, MD). The measured Cu UBM area was divided by the length of TiW in each picture, and thus we could obtain the average height of the Cu UBM that remained at each current stressing time. This method gave us reasonable average height of Cu UBM that remained, even though the cross-sectioned images in Figs. 4 and 5 were not the exact center position of flip-chip joints. The thickness of dissolved Cu UBM was obtained from the difference between the average height of Cu UBM after electromigration and that of Cu UBM before electromigration. In Fig. 6, it was observed that the rate of Cu UBM dissolution increased as the current stressing time increased. Especially, there was a big difference in the dissolution rate between stage I of the layered dissolution and stage II of the asymmetric dissolution of Cu UBM. The average dissolution rate in stage

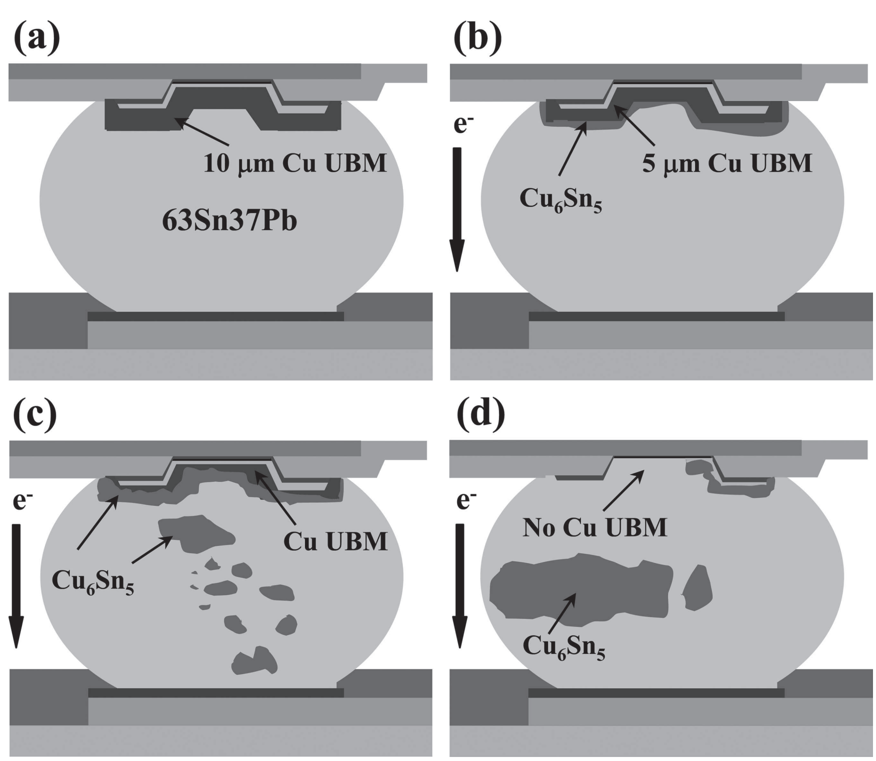

FIG. 7. The failure mechanism of two stages dissolution of a 10-μm-thick Cu UBM in a flip-chip joint. (a) Before current stressing, (b) layered dissolution of Cu UBM at the whole Cu UBM/solder interface, (c) asymmetrical dissolution of Cu UBM by the current crowding effect, and (d) after the final failure.

I was 0.0175 μm/h and that in stage II was 0.0892 μm/h. The origin of this accelerated dissolution in stage II was from the current crowding effect discussed in the next section. The current crowding at the Cu UBM–solder interface enhanced the reaction between Cu and Sn and accelerated the consumption of Cu UBM to form the Cu_6Sn_5 IMC.

IV. DISCUSSION

A possible mechanism for the two-stage dissolution of the 10-μm-thick Cu UBM under low current density, i.e., the current crowding area located inside the UBM is illustrated in Fig. 7. As shown in Fig. 7(a), the flip-chip solder joint had 10-μm-thick Cu UBM before current stressing. In the initial stage of electromigration, since the thickness of Cu UBM was thick enough to contain the current crowding region inside Cu UBM, the current distribution at the entire Cu UBM–solder interface was uniform and resulted in the layer-type dissolution of the Cu UBM, as shown in Fig. 7(b). However, as the thickness of the Cu UBM decreased with increasing time of current stressing, the effect of current crowding on the nonuniform current distribution at the Cu UBM–solder interface increased, especially at the location where the electrons flowed into the solder bump. The current crowding drove Cu atoms from the upper left-hand side corner toward the anode and accelerated the formation of Cu_6Sn_5 IMC at the upper left-hand side corner as shown in Fig. 7(c). The formation of Cu_6Sn_5 IMC was greatly enhanced as the time increased, and finally the dissolution of Cu_6Sn_5 IMC into the solder induced the failure in the flip-chip joint as depicted in Fig. 7(d).

In Fig. 8, the simulated 3D current density distribution in the solder joint with a 5-μm-thick Cu UBM and the current density distribution at the cross section along Z axis were given when the applied current was 0.6 A. The current crowding effect at the Cu UBM–solder interface was clear in Fig. 8(b). The current crowding occurs in the upper left corner of the Cu UBM and has spread to the solder region at the upper left corner interface between Cu UBM and solder. The peak current density was much higher than the average current density inside the flip-chip solder bump, and it could accelerate the Cu_6Sn_5 IMC formation and cause asymmetric Cu UBM consumption as shown in Figs. 5(c) and 5(d). The TiW, which is very thin and bright color above the Cu UBM, does not react with Sn or Cu. The rapid dissolution of the 5-μm-thick Cu UBM due to the current crowding at the corner where electrons entered from Al interconnect to Cu UBM during electromigration test has been reported elsewhere.[6]

It is worth mentioning that for a 5- to 10-μm-thick Cu by itself, no electromigration occurs with a current density of 3.0×10^4 A/cm^2 at 100 °C for 138 h. The failure reported here is mainly due to the Cu–Sn chemical reaction at the cathode. On the basis of the two-step consumption of 10-μm-thick Cu UBM in electromigration, we conclude that the increase of UBM thickness to avoid the current crowding effect is not the solution to reduce electromigration-induced failure. A different packaging paradigm is required to solve the electromigration-induced reliability issue in flip-chip technology.

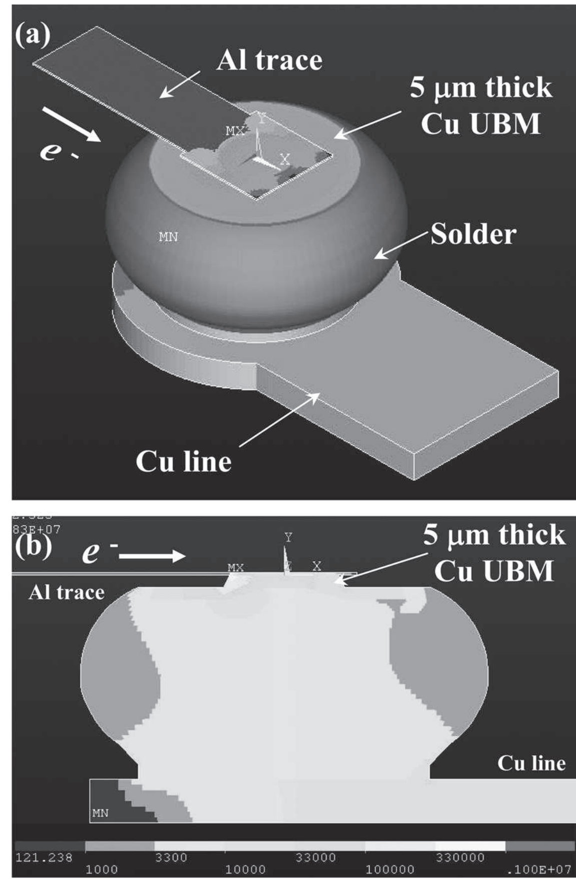

FIG. 8. (a) The 3D current density distribution in the solder joint with a 5-μm-thick Cu UBM. (b) The current density distribution along the cross section of the Z-axis in (a).

V. CONCLUSION

Electromigration of flip-chip solder joints with a 10-μm-thick Cu UBM was investigated at 100 °C with a current density of 3.0×10^4 A/cm^2. The consumption of the thick Cu UBM at the cathode that was the top of the flip-chip joints where electrons flowed from the chip to the substrate induced failure. During the electromigration, a two-stage consumption of the thick Cu occurs with increasing current stressing time. At first, the Cu UBM dissolved layer by layer across the entire Cu UBM–solder interface. After half of the Cu UBM was consumed, the decrease of the Cu UBM thickness had caused the current crowding in the solder region to return and had induced the asymmetrical dissolution and failure of the Cu UBM. The average dissolution rate of Cu UBM in the second stage was faster than that in the first stage. We have confirmed the change of the current crowding region accompanying the change of Cu UBM thickness by 3D simulation of current density distribution.

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