Three-dimensional simulation on current-density distribution in flip-chip solder joints under electric current stressing

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Three-dimensional simulations on current-density distribution in solder joints under electric current stressing were carried out by finite element method. Five underbump metallization (UBM) structures were simulated, including Ti/Cr–Cu/Cu thin-film UBM, Al/Ni(V)/Cu thin-film UBM, Cu thick-film UBM, Ni thick-film UBM, and Cu/Ni thick-film UBM. The maximum current density inside the solder occurs in the vicinity of the entrance of the Al trace into the solder joint, while there is no obvious current crowding effect in the substrate side of the joint. The crowding ratio, which is defined as the maximum current density inside the solder divided by the average value in the UBM opening, is as high as 24.7 for the solder with the Ti/Cr–Cu/Cu UBM. However, it decreases to 23.4, 13.5, 8.7, and 7.2 for the rest of the UBM structures, respectively. Solder joints with thick UBMs were found to have a better ability to relieve the current crowding effect. The simulation results are in reasonable agreement with limited published data. The solder joints with higher current crowding ratios have a shorter electromigration failure time. © 2005 American Institute of Physics. [DOI: 10.1063/1.2000667]

I. INTRODUCTION

As the required device density and power of flip-chip packages increase, the electromigration (EM) of solder joints under high current stressing has attracted a lot of attention. The pitch of solder bumps has decreased quickly to meet the high performance requirement, and the contact area of the solder bumps and the diameter of underbump metallization (UBM) have decreased rapidly. On the other hand, the operation current for the bumps keeps increasing, resulting in a dramatic rise of the current density in the solder bump. Currently, each solder joint carries 0.2 A, which will be required to carry higher current in the future. The average current density of the flip-chip joint will reach $1 \times 10^4$ A/cm$^2$. Therefore, electromigration in the flip-chip solder joints has become an important reliability issue.

The distribution of current density inside the flip-chip solder joint is not uniform due to the current transition from the thin on-chip metal line to the solder bump. Current crowding occurs in the solder joint much more seriously than that in Al and Cu interconnects, and it was found to play a critical role in the electromigration failure of the solder joints. Therefore, two-dimensional (2D) simulation on current-density distribution has been performed to explain the current-crowding-induced failure in flip-chip solder joints. Furthermore, the current-density distribution in the solder bump with Cu/Ni(V)/Al thin-film UBM and 5-$\mu$m-thick Cu UBM has been simulated. However, the current-density distribution in the flip-chip solder joints may not be symmetrical in geometry over a specific plane. Thus, a three-dimensional (3D) simulation is needed to provide a deeper understanding of the current-density distribution in the solder joints. In addition, various UBM structures have also been used in the microelectronics industry. However, there is little research done on the current-density distribution in the solder joints with different UBM structures. This study employed the finite element method to simulate the current-density distribution in solder joints with five different UBM structures, including Ti/Cr–Cu/Cu thin-film UBM, Al/Ni(V)/Cu thin-film UBM, Cu thick-film UBM, and Cu/Ni thick-film UBM. This research provides a better understanding on the current-density distribution in the solder joints and the correlation of the current crowding effect to electromigration failure time.

II. SIMULATION

Five popular UBMs were investigated in this study, including two thin-film UBMs and three thick-film UBMs: (a) Ti/0.3-$\mu$m Cr–Cu/0.7-$\mu$m Cu thin-film UBM, (b) Al/0.3-$\mu$m Ni(V)/0.4-$\mu$m Cu thin-film UBM, (c) 5-$\mu$m Ni thick-film UBM, (d) 5-$\mu$m Cu thick-film UBM, and (e) 5-$\mu$m Cu/3-$\mu$m Ni thick-film UBM. The cross-sectional schematic diagram for the whole solder joint is illustrated in Fig. 1(a), and the schematics for the above five UBMs are shown in Figs. 1(b)–1(f), respectively. Compared with the flip-chip structure, each layer in the thin-film UBMs was too thin to be simulated individually, and thus an effective layer was used to represent the trilayer structure. In addition, the intermetallic compound (IMC) formed between the UBM and the solder was also considered in the simulation models. The Cu layers in (a), (b), and (d) were assumed to consume 0.5 $\mu$m, and form 1.4 $\mu$m of Cu$_5$Sn$_5$ IMC. The Ni layers in (c) and (e) were assumed to consume 0.5 $\mu$m, and form 1.0 $\mu$m of Ni$_3$Sn$_4$ IMC. On the substrate side, a Ni$_3$Sn$_4$ IMC of 1 $\mu$m was used in the models for Ni metallization. Layered IMCs were used in this simulation for both
the Cu$_6$Sn$_5$ and Ni$_3$Sn$_4$. In addition, eutectic solder was used in this model. For the UBM consisting of 0.1-μm Ti/0.3-μm Cr–Cu/0.7-μm Cu, an effective layer of 0.6 μm with a resistivity of 13.1 μΩ cm was used in the simulation, whereas for the 0.4-μm Al/0.3-μm Ni(V)/0.4-μm Cu thin-film UBM, a 0.7-μm effective layer with 29.5 μΩ cm was adopted. The resistivities of the materials used in the simulation are listed in Table I.

A 3D finite element model was constructed to simulate the current-density distribution in the flip-chip solder joints, as illustrated in Fig. 2. A simplified UBM structure with the UBM opening of 120 μm in diameter was used. The contact opening in the substrate side was 144 μm in diameter. A current of 0.567 A was applied. The corresponding current density in the Al trace was $1.11 \times 10^6$ A/cm$^2$, and the calculated average current densities were $5.01 \times 10^3$ and $3.48 \times 10^3$ A/cm$^2$ for the contact opening of the chip side and of the substrate side, respectively.

### Table I. The resistivities of the materials used in the simulation models.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Resistivity (μΩ cm)</th>
</tr>
</thead>
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<tr>
<td>Al</td>
<td>4.3</td>
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<tr>
<td>Ti</td>
<td>43.1</td>
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<tr>
<td>Ni(V)</td>
<td>63.2</td>
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<tr>
<td>Cu$_6$Sn$_5$ IMC</td>
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<td>Sn$_6$Pb$_3$</td>
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</tr>
<tr>
<td>Ni$_3$Sn$_4$ IMC</td>
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<tr>
<td>Ni</td>
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<tr>
<td>Cu</td>
<td>1.7</td>
</tr>
<tr>
<td>Cr</td>
<td>12.9</td>
</tr>
</tbody>
</table>

**III. 3D CURRENT-DENSITY DISTRIBUTION IN FLIP-CHIP SOLDER JOINTS**

**A. Ti/Cr–Cu/Cu thin-film UBM**

Figure 3(a) shows the simulated 3D current-density distribution in the solder joint with the Ti/Cr–Cu/Cu thin-film UBM. The majority of the current crowds into the joint in a small volume near the Al trace, causing very high current density up to $3.32 \times 10^5$ A/cm$^2$ in the UBM. Since the current density in the Al trace is as high as $1.11 \times 10^6$ A/cm$^2$, and the resistance of the solder joint is only few milliohms, current crowding occurred at the entrance of the Al trace into the solder joint. However, once the current enters the solder joint, it drifts down vertically toward the substrate (Y-axis direction), and also spreads out laterally at the same time (X-axis and Z-axis directions). Thus, the solder close to the...
The current-density distributions at the six cross sections are shown in Figs. 4(a)–4(f), respectively. Figure 4(a) shows the current-density distribution in the UBM layer, in which the maximum current density reaches $3.32 \times 10^5$ A/cm² near the entrance of the Al trace. However, the current density at the other end of the UBM is only about $1 \times 10^5$ A/cm². Current crowding occurred at the entrance of the Al trace. Figure 4(b) shows current-density distribution in the IMC layer. The distribution behaves similarly to that in the UBM layer. The maximum current density decreased slightly, and its value is $2.58 \times 10^5$ A/cm² near the entrance of the Al trace. The current-density distribution inside the solder near the UBM layer is shown in Fig. 4(c). The maximum current density of $1.24 \times 10^5$ A/cm² occurred at the upper-left corner of the solder joint, which is near the entrance of the Al trace. This small volume of solder experiences about 25 times larger than the average value of this cross section. Therefore, it is the most vulnerable site of the solder joint during current stressing, since the solder has a much lower melting point than the UBM materials and Al. Solder may migrate away much more easily from the volume and form voids at this site. In addition, the gradient of the current density reaches approximately $5.40 \times 10^7$ A/cm³ along the Z-axis direction at this cross section.

The “crowding ratio” is denoted as the local maximum current density divided by the average current density on the UBM opening in this paper. The average current density on the UBM opening is $5.01 \times 10^5$ A/cm² in the simulation models. The crowding ratio inside the Ti/Cr–Cu/Cu UBM is about 66.2, which means that the local current density is 66.2 times larger than the average one on the UBM opening. The maximum current density inside the solder is $1.24 \times 10^5$ A/cm² and the corresponding crowding ratio is 24.7. The current-density distribution at the middle cross-section Y4 is depicted in Fig. 4(d). The maximum current density at the middle cross section is $4.07 \times 10^3$ A/cm² and the corresponding crowding ratio is only 0.8, which is the lowest ratio in the solder joint due to its large cross section.

It is interesting that the current-density distribution at the cross-section Y5 is concave and it features a bowl-like shape, as shown in Fig. 4(e). It means that the current density on the peripheral region is larger than that in the inner region of the solder joint. This is attributed to the smaller diameter of the cross-section Y5, and that the current flowing in the vicinity of the peripheral region above the Y5 plane needs to be crowded into this smaller cross section, leading to the bowl-like current-density distribution. The maximum current density at this cross section is $8.23 \times 10^3$ A/cm² and the corresponding crowding ratio is 1.6. On the contrary, the current-density distribution at the bottom of the solder joint appears convex again, as displayed in Fig. 4(f). The current density in the periphery of the joint is lower than that in the inner region of the cross-section Y6, because the current spreads out owing to a larger cross section after passing the Y5 plane. After passing through the Y5 plane, the current drifts out of the solder joint into the Cu line in the substrate from the left-hand side in the figure. Thus the current density on the left-hand side is higher than that on the rest of the solder. Nevertheless, due to the thick Cu line, the crowding ratio is
as low as 1.2. Consequently, no obvious electromigration damage has ever been found in the substrate side of the solder joint. The maximum current densities and the corresponding crowding ratios for the above five cross sections are listed in Table II.

The effect of current crowding on the electromigration damage in the solder joint has been observed experimentally. When eutectic SnAg solder joints were stressed under the applied current of 0.567 A at 150 °C for 20 h, they did not fail prior to microstructure observation on the chip side. Figure 5(a) shows the microstructure on the cathode/chip side after the current stressing, in which the solder was selectively etched away, and the position of the Al trace was depicted by the white dotted lines. The correspond-
ing simulation on the current-density distribution in the top layer of the SnAg solder is shown in Fig. 5(b). Although the solder used in the electromigration test is different from the SnPb solder, their current crowding behaviors are quite similar. The current flowed from the Al trace, passing through the UBM and the IMC layers, was then drifted into the solder joint. It showed that IMC/UBM dissolved much faster near the entrance of the Al trace into the solder joint, where the current crowding occurred seriously. In addition, the morphology of the damaged region matches with the shape of the high current-density region, which indicates that higher current density caused more serious electromigration in the IMC/UBM layer. It is expected that the solder near this region would be migrated much easier than those in other regions, causing void formation there. Therefore, the current crowding effect plays a critical role on the electromigration failure in solder joints.

**B. Al/Ni(V)/Cu thin-film UBM**

For Al/Ni(V)/Cu thin-film UBM, the distributions of the current density at the six cross sections are quite similar to those in the Ti/Cr–Cu/Cu UBM. The crowding ratios in the UBM and in the IMC layers are 51.5 and 47.1, respectively. However, the maximum current density at the Y3 cross section is $1.17 \times 10^5$ A/cm$^2$, which is slightly lower than that in the Ti/Cr–Cu/Cu UBM. It is speculated that this is mainly due to the resistive Ni(V) layer, which has the resistivity of 63.2 $\mu$Ω cm.$^{12}$ The layer may be able to alleviate the current crowding effect. The current-density distributions in the rest of the cross sections behave in a similar way as those in the Ti/Cr–Cu/Cu UBM. Their maximum values as well as the current crowding ratios are listed in Table II.

**C. 5-μm Ni thick-film UBM**

With the 5-μm-thick Ni UBM, the crowding ratio inside the solder near the entrance of the Al trace reduces to 13.5, as shown in Table II. The corresponding maximum current density in the solder decreases to $6.77 \times 10^4$ A/cm$^2$. At the Y1 cross section near the entrance of the Al trace, the crowding ratio reaches to 79.1, but it descends to 22.5 in the IMC layer, which indicates that the current has been spread out in the Ni layer. Moreover, the crowding ratio inside the solder decreased to 13.5. Hence, the maximum current density in the solder decreases by a factor of 1.8 compared with that in the Ti/Cr–Cu/Cu thin-film UBM. The current crowding behaviors are similar to those in the Ti/Cr–Cu/Cu UBM for the Y4–Y6 cross sections.

**D. 5-μm Cu thick-film UBM**

With the 5-μm-thick Cu UBM, the crowding ratio inside the solder near the entrance of the Al trace reduces further to 8.7, as shown in Table II. Similar to the thick Ni UBM, this Cu UBM also relieves the current crowding effect inside the solder. Moreover, it has a better ability to ease the current crowding effect than the thick Ni UBM. This may be attributed to its lower resistivity. When the current enters from the Al trace, it would encounter less resistance in the Z-axis direction for the Cu UBM. Therefore, the current would spread out more than that in the Ni UBM. The corresponding maximum current density in the solder decreases to $4.37 \times 10^4$ A/cm$^2$ at the Y3 cross section. For the current-density distribution at the Y4–Y6 cross sections, no obvious differences were observed from those in the thick Ni UBM.

**E. 5-μm Cu/3-μm Ni thick-film UBM**

The Cu/Ni thick film appears to be the best UBM structure among the five models for relieving the current crowding effect. Table II summarizes the maximum current density and the corresponding crowding ratio for the UBM. The maximum current density inside the solder is further reduced down to $3.56 \times 10^4$ A/cm$^2$, which is about 3.5 times smaller than that in the Ti/Cr–Cu/Cu thin-film UBM. The crowding

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Y1, UBM layer</th>
<th>Y2, IMC layer</th>
<th>Y3, top layer of solder</th>
<th>Y4, middle layer of solder</th>
<th>Y5, necking layer of solder</th>
<th>Y6, bottom layer of solder</th>
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<tbody>
<tr>
<td>UBM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ti/Cr–Cu/Cu</td>
<td>Max. 3.32 × 10^5</td>
<td>2.58 × 10^5</td>
<td>1.24 × 10^5</td>
<td>4.07 × 10^5</td>
<td>8.23 × 10^5</td>
<td>6.10 × 10^5</td>
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<tr>
<td>Ratio</td>
<td>66.2</td>
<td>51.5</td>
<td>24.7</td>
<td>0.8</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Al/Ni(V)/Cu</td>
<td>Max. 2.58 × 10^5</td>
<td>2.36 × 10^5</td>
<td>1.17 × 10^5</td>
<td>4.07 × 10^5</td>
<td>8231</td>
<td>6.10 × 10^5</td>
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<tr>
<td>Ratio</td>
<td>51.5</td>
<td>47.1</td>
<td>23.4</td>
<td>0.8</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Ni</td>
<td>Max. 3.96 × 10^5</td>
<td>1.13 × 10^5</td>
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<td>3.72 × 10^4</td>
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<td>Ratio</td>
<td>79.1</td>
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<td>13.5</td>
<td>0.7</td>
<td>1.6</td>
<td>1.2</td>
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<tr>
<td>Cu</td>
<td>Max. 6.15 × 10^5</td>
<td>7.53 × 10^4</td>
<td>4.37 × 10^4</td>
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<td>7.2</td>
<td>0.7</td>
<td>1.5</td>
<td>1.2</td>
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</table>
The maximum current densities, which range from 3.56 × 10^4 to 1.24 × 10^5 A/cm^2 inside the solder, always occurred at the entrance of the Al trace into the solder joint for the five UBM structures. Among these five UBM structures, the solder joint with the Ti/Cr–Cu/Cu UBM has the largest current density of 1.24 × 10^5 A/cm^2 inside the solder; while the solder joint with the 5-μm Cu/3-μm Ni UBM has the smallest current density of 3.56 × 10^4 A/cm^2 inside the solder, which is 3.5 times smaller than the largest value. In general, the thicker the UBM is, the less the current crowding effect inside the solder.

Figure 6(b) displays the current-density distributions at the Y4 cross section for the five UBM structures. The maximum current densities at the middle cross section range from 3.25 × 10^3 to 4.07 × 10^3 A/cm^2, which are approximately one order of magnitude lower than the maximum values at the Y3 cross section. The saddle points for the five curves locate almost directly below the positions where the maximum current density took place at the Y3 cross section. The current also spreads out laterally in the solder after passing through about 50 μm of SnPb solder. Yet, solder joints with the thin-film UBM structures still have slightly higher current densities than the ones with thick-film UBMs.

The current-density distributions at the Y5 cross section for the five UBM structures are concave, as shown in Fig. 6(c). The maximum current densities are located on the left-hand side. The maximum current densities at this cross section range from 7.70 × 10^3 to 8.23 × 10^3 A/cm^2. The current-density distributions behave almost the same for the five UBM structures at this cross section, which means that the UBM structure does not affect the current-density distribution below the Y5 plane.

Figure 6(d) displays the current-density distributions at the bottom of the solder for the five UBM structures. Compared with the results in Fig. 6(c), the current density decreases by approximately 25%, owing to a larger diameter at this cross section. The maximum current density varied from 5.90 × 10^3 to 6.10 × 10^3 A/cm^2 for the five UBM structures. Compared to the solder near the chip side, the current crowding is much less serious at the bottom of the solder. This is attributed to the thick conductive layers below the solder. The metallization layer in the substrate consists of 5-μm Ni and 25-μm Cu. Moreover, the cross section of the Cu line is 25 × 80 μm^2, which is 42 times larger than that of the Al trace in the chip side. The current may drift through the IMC and the Ni layers, and keep drifting down and then flow out of the joint from the Cu line, resulting in a much lower maximum current density in the bottom of the solder than that on the chip side.

Figure 7 shows the crowding ratios at different cross sections inside the solder for the five UBM structures. The maximum crowding ratios for the solder occurred at the Y3 cross section, which is the top of the solder joint. They range from 7.2 to 24.7 for the five UBM structures. The joints with thin-film UBM structures have higher crowding ratios. How-
ever, the crowding ratios drop dramatically down to 1.5–2.0 at the middle cross section, and they remain at low values of less than 3 in the substrate side.

IV. DISCUSSION

In general, the maximum current density of the solder joints always occurs at the entrance of the Al trace into the joint for all five cases. For the thin-film UBM structures, the higher the resistivity it has, the lower the current crowding effect. This may be attributed to the fact that the resistive thin UBM may alleviate the current crowding effect. When the current enters from the Al trace, and then flows down toward the solder joint, it encounters this resistive layer first. Therefore, some of the current may drift farther in the 1.5-μm Al metallization layer above the UBM, and then drift down to the solder joint. Thus, thin resistive UBM may be able to relieve the current crowding effect. On the other hand, for thick-film UBM structures, the thick Cu UBM could ease the current crowding effect better than the thick Ni UBM. Since Cu has very low resistivity, it is speculated that the current may be able to drift laterally more easily than that in the Ni UBM.

In the five models, the thickness of the UBM seems to play a crucial role on the maximum current density inside the solder. Figure 8 shows the maximum current density inside the solder as a function of the UBM thickness, showing that the maximum current density decreases approximately linearly as the UBM thickness increases. The main reason why the solder joint with thicker UBM has lower maximum current density is that the thick UBM may keep the solder away from the high current-density region. As shown in Table II, the maximum current density in the UBM layer does not

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**FIG. 6.** The current-density distribution inside the solder along the Z axis for the five UBM structures: (a) at cross-section Y3, (b) at cross-section Y4, (c) at cross-section Y5, and (d) at cross-section Y6.

**FIG. 7.** The crowding ratios inside the solder joint for the five UBM structures at different cross sections.
FIG. 8. The plot of maximum current density inside the solder as a function of the UBM thickness, showing that the maximum current density decreases approximately linearly as the UBM thickness increases.

differ much for the five models. Once the current entered the UBM, it may spread out laterally in the UBM and IMC layers. Thus it decreases more for thicker UBM before the current reaches the solder.

Furthermore, different UBM layers may have an effect on the failure mechanism of electromigration. Nah et al. found that the Cu UBM was migrated into a high-Pb solder to form an IMC, causing voids formed in the Cu layer. As listed in Table II, the maximum current densities in the Cu UBM and in the Cu₆Sn₅ IMC layer were 6.15 × 10⁵ and 7.53 × 10⁴ A/cm², respectively, for the solder joint with 5-μm Cu UBM, while they were 3.96 × 10⁵ and 1.13 × 10⁵ A/cm², respectively, for the solder joint with 5-μm Ni UBM. In addition, compared with Cu, Ni has a higher melting point and lower reaction rate with Sn. Although the electromigration behavior for Ni₃Sn₄, Cu₃Sn, and Cu₆Sn₅ IMCs is not available at this moment, it is expected that the Ni₃Sn₄ IMC has better electromigration resistance due to its higher melting temperature of 794.5 °C. Therefore, it is speculated that voids are susceptible to form in the interface of the Ni₃Sn₄/solder for the solder joint with Ni UBM in the models C and E.

Jang et al. performed an electromigration test on eutectic SnPb solder joints with different UBM structures, including 0.15-μm Cr/0.3-μm Cr–Cu/0.8-μm Cu thin-film UBM, 0.2-μm Ni(V)/0.8-μm Cu thin-film UBM, and 0.2-μm TiW/0.3-μm Cu/5-μm Cu thick-film UBM.¹⁰ They found that the failure times for the three joints were 35, 42, and 68 h, respectively, when stressed by 1.8 A at 140 °C. Although these three solder joints were not identical to our simulation models, they are similar to the three models in Secs. III A, III B, and III D in this paper, respectively. Consequently, according to the simulation results, it is expected that the solder joint with the Ti/Cr–Cu/Cu UBM would have a larger value of maximum current density inside the solder than that with the TiW/Cu/Cu UBM. It is noteworthy that

the dimension of the Al trace, of the UBM opening, and of the joints for the samples of Jang et al. may be different from the ones used in this study. The relative crowding ratios may be slightly different. However, our modeling results supported the above published observations. Consequently, the failure time of the solder joints may highly correlate to the maximum current density inside the solder joints during current stressing, which is reasonable since voids form at the solder or IMC with high current density and then cause an open failure of the joint.¹⁹

V. CONCLUSIONS

The current-density distribution in the SnPb solder joints under current stressing has been simulated by 3D finite element models. The maximum current density always occurs at the entrance of the Al trace into the solder joint for the five UBM structures. It is found that the solder joints with thick-film UBMs have better performance in alleviating the current crowding effect than those with thin-film UBM. The highest crowding ratio reached 24.7 for the solder joint with the Ti/Cr–Cu/Cu UBM, whereas it decreased to 7.2 for the solder joint with thick Ti/Cu/Cu/Ni UBM. The simulation results agree with the experimental electromigration data published by previous researchers. These findings suggest that the failure time of the solder joint is highly related to the maximum current density in the solder joint.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Everett C. C. Yeh for helpful discussions and the National Science Council of Taiwan for the financial support through Grant No. 92-2216-E-009-008. In addition, the assistance on the simulation facility from the National Center for High-performance Computing (NCHC) in Taiwan is highly appreciated.

¹²http://www.flipchips.com