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Relieving Hot-Spot Temperature and Current Crowding Effects During Electromigration in Solder Bumps by Using Cu Columns

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Solder joints with Cu columns appear to be one of the best structures to resist electromigration. Three-dimensional thermoelectrical analysis was employed to simulate the current density and temperature distributions for eutectic SnPb solder bumps with 0.5, 5, 25, 50, and 100 μm Cu under bump metallization (UBM). It was found that the hot spots and current crowding effects in the solder were reduced significantly when the Cu thickness was over 50 μm, whereas the overall Joule heating effect remained almost unchanged. The mechanism by which the Cu column is effective in relieving the hot spot and current crowding effects is to keep the solder away from the heat source and crowding region. Simulated at a current of 0.6 A and 70°C, the estimated mean time to failure of the joints with a 50-μm-thick Cu column was 6.7 times longer than that of joints with a 0.5-μm-thick Cu UBM.

Key words: Electromigration, flip-chip solder joints, Joule heating

INTRODUCTION

The flip–chip solder joint has become the most important technology for high-performance packaging in the microelectronic industry.[1] With each generation, the diameter of the solder bumps continues to decrease,[2] while the current that each bump carries continues to increase, resulting in a current density of approximately 2×10^3 to 2×10^4 A/cm^2. Therefore, electromigration has become a critical reliability issue for flip–chip solder joints.[3,4] Due to the special line-to-bump geometry of flip–chip solder joints, substantial current crowding occurs at the entrance point of the Al trace into the bump.[5,6] In addition, considerable Joule heating takes place and a hot spot exists in the solder joints when stressed at high currents.[7] Current crowding and the hot spot play crucial roles in joint failures. Previous modeling results and experimental data have shown that solder joints with thin-film under bump metallization (UBM) exhibit a serious current crowding effect in the solder.[8,9] The maximum current density inside the solder with Al/Ni(V)/Cu thin-film UBM may be 22.2 times larger than the average value and the temperature difference between the hot spot and the solder reached 9.4°C when a current of 0.8 A was imposed on the solder joint at 70°C.[7] Under such high-current drive, solder material near the entrance point may migrate away and void formation may follow.[10] Therefore, elimination of the current crowding and hot spot issues is an urgent subject.

Moreover, thick Cu electroplated up to 80 μm has been adopted for the UBM of Pb-free solders for better metallurgical reliability and electrical conductivity.[11] This may be the best solder joint structure to resist electromigration. However, the exact current density and temperature distribution in flip–chip solder joints with thick Cu columns during electromigration is not clear. In particular, the Joule heating effect plays a very important role in solder electromigration.[7] However, little research has been done on their thermal characteristics. Because the mean time to failure decreases as the testing temperature increases, the Joule heating effect in solder joints deserves more investigation. They are likely to demonstrate better capability in relieving current crowding and hot-spot concerns. In this paper, we employ a three-dimensional (3-D) finite-element method to simulate the current

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density and temperature distributions in solder joints with 0.5, 5, 25, 50, and 100 μm Cu UBMs. A potential mechanism for relieving the current crowding and hot-spot issues under thick Cu UBM is proposed. The effects of current crowding and Joule heating on mean time to failure are also discussed. This simulation work provides a deeper understanding of the current density and temperature distributions in solder joints with thick Cu UBMs.

EXPERIMENTAL

The cross-sectional schematic models for the solder joints with 0.5 μm and 100 μm Cu UBM are shown in Fig. 1a and b, respectively. For all the models in this study, the joint height was kept at 150 μm. Thus, for joints with a thicker UBM, the height of the solder bump was reduced correspondingly. A simplified UBM structure with an opening 120 μm in diameter was used. The contact opening on the substrate side was 144 μm in diameter. The Al traces were 34 μm wide and 1.5 μm thick, whereas the Cu lines on the substrate side were 80 μm wide and 25 μm thick. The intermetallic compound (IMC) formed between the UBM and the solder was also considered in the simulation models. 0.5 μm of electroplated Cu was assumed to react and form a layer of 1.4 μm Cu_6Sn_5 IMC. Similarly, 0.5 μm of electroless deposited Ni is assumed to react and form 1.0 μm of Ni_3Sn_4 IMC. Layered-type IMCs were used in this simulation for both Cu_6Sn_5 and Ni_3Sn_4 to avoid meshing difficulty. In addition, eutectic solder was used in our model. The parameters of the materials used in the simulation can be found in our previous publication.[7] The model used in this study was based on SOLID69 eight-node hexahedral coupled-field elements using ANSYS simulation software developed by ANSYS Inc. USA.

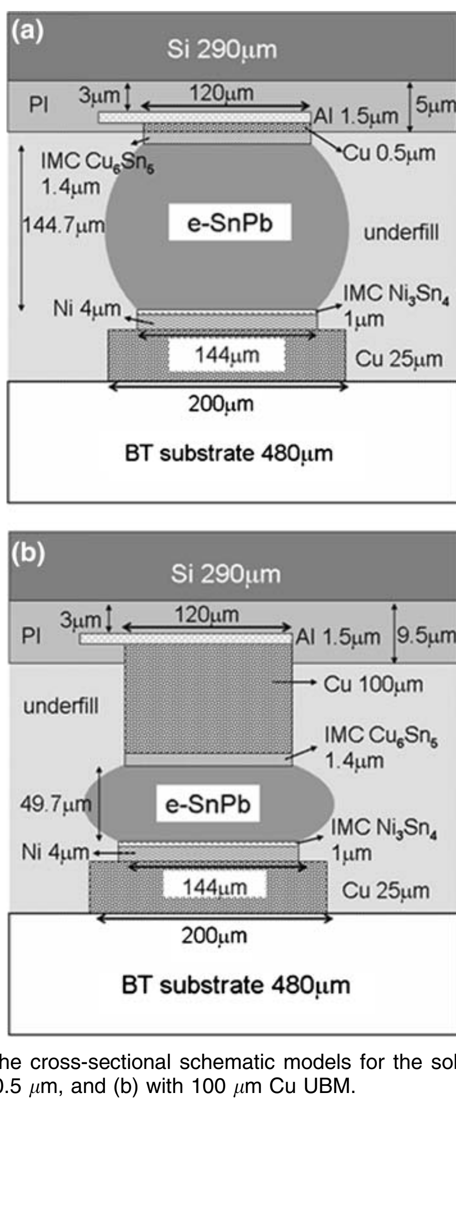

Fig. 1. The cross-sectional schematic models for the solder joints: (a) with 0.5 μm, and (b) with 100 μm Cu UBM.

RESULTS AND DISCUSSION

With a thicker Cu UBM, a more-uniform distribution of current density was obtained in the solder bump. Figure 2a–e shows the current density distribution in the solder joints with 0.5, 5, 25, 50, and 100 μm Cu UBMs, respectively, when a current of 0.6 A was applied. It can be seen that the current crowding effect still occurs in the thick Cu UBM near the entrance of the Al trace into the solder joint. However, as the thickness of the Cu UBM increases, the solder is kept away from the crowding region. When the Cu UBM is thicker than 50 μm, the current crowding occurs mostly in the Cu UBM, and the maximum current density in the solder dramatically decreases. The crowding ratio in this paper is calculated as the maximum current density in the solder divided by the average value in the UBM opening, which is 5.01×10^3 A/cm^2. It is 19.0, 9.6, 2.9, 1.7, and 1.6 for the solder joints with 0.5, 5, 25, 50, and 100 μm Cu UBMs, respectively. We conclude that thick Cu UBM results in a uniform current density distribution and reduced maximum current density. In short, the current flow spreads out and becomes more uniform before reaching the solder bump with a thicker Cu UBM.

In addition, thick Cu UBM can relieve the hot-spot issue in solder bumps. Figure 3a and b shows the Joule heating effect in the Al trace for solder joints with 0.5 μm and 100 μm Cu UBMs, respectively. It was found that the overall Joule heating effect in the stressing circuit did not reduce when the 0.5 μm Cu UBM was replaced by the 100 μm UBM. The total resistance of the circuit was about 1330 mΩ, while the resistance decrease due to the thicker Cu column was only in the milliohm range. Thus, both models have almost the same overall Joule heating effect in the Al trace. Nevertheless, the Joule heating effect in the solder bump was quite different. Figure 4a–e shows tile views for the temperature distribution in the solder joints with 0.5, 5, 25, 50, and 100 μm Cu UBMs, respectively, when a current of 0.6 A was applied. To obtain a

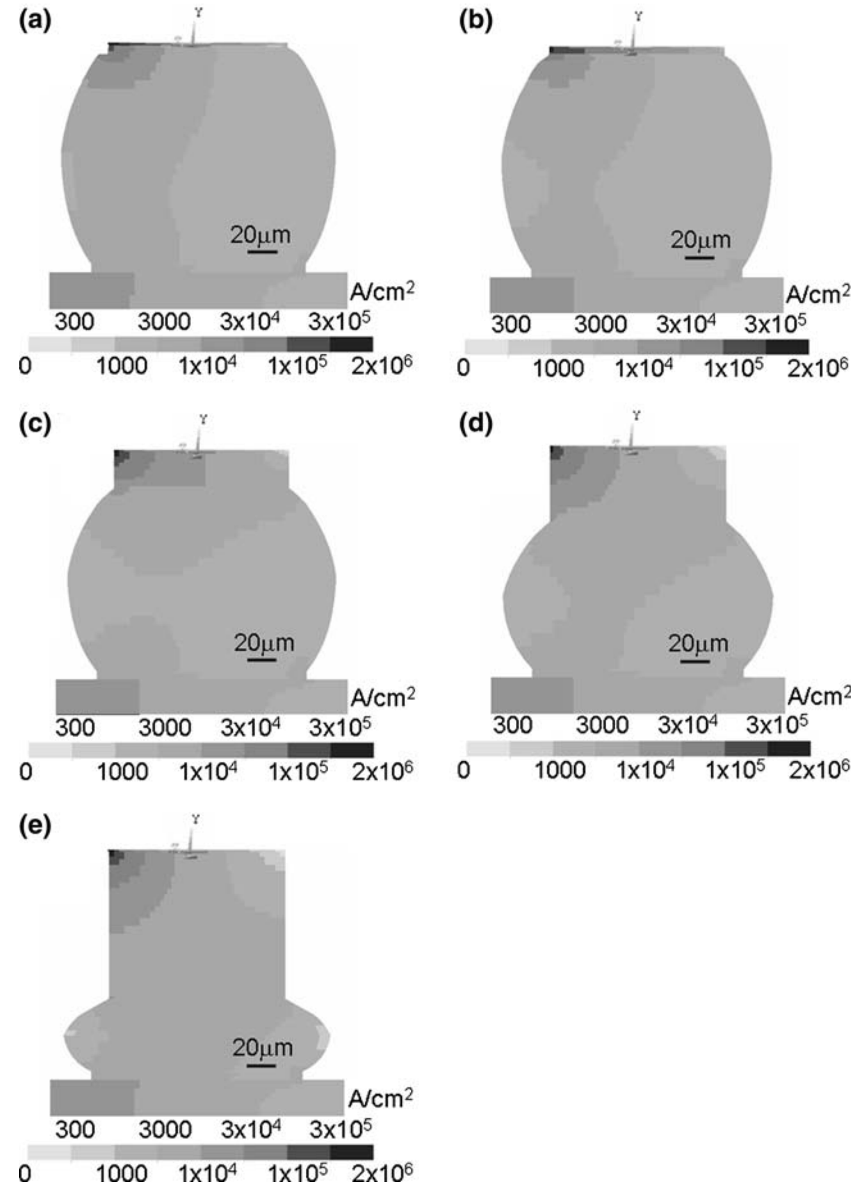

Fig. 2. Current–density distribution in the solder joints with (a) 0.5 μm, (b) 5 μm, (c) 25 μm, (d) 50 μm, and (e) 100 μm Cu UBMs when a current of 0.6 A was applied.

clear view of the hot spot, the Cu UBMs are not shown in these figures. The top surfaces of these bumps represent the solder connecting to the Cu UBMs. Hot spots exist in the solder joints with thin Cu UBMs. However, it is found that, with a Cu UBM greater than 50 μm, the hot spot was almost completely eliminated. Figure 5a–e shows the corresponding cross-sectional views for the temperature distribution. It is clear that the hot spot was almost eliminated for the solder joints with 50 μm and 100 μm Cu column. The temperature difference between the hot spot and the average values is 4.5, 2.5, 0.7, 0.3, and 0.1°C for the solder joints with 0.5, 5, 25, 50, and 100 μm Cu UBMs, respectively, when a current of 0.6 A was applied. The difference between the hot spot and the average temperature increased as the applied current increased. Figure 6a–c shows the hot spot and average temperatures as a function of the applied current up to 0.6 A for the solder joint with 25, 50, and 100 μm Cu columns. No obvious hot spot was found for Cu columns thicker than 50 μm.

Although a thick Cu UBM can relieve the hot spot, the overall Joule heating remains unchanged even for the solder joint with the 100-μm Cu UBM. Figure 7a depicts the hot-spot temperature as a function of applied current for the five models. Compared with the solder joint with the 0.5 μm Cu UBM, the 100 μm Cu can reduce the hot-spot temperature by 5.0°C. However, the overall Joule heating effect did not change much, as illustrated in Fig. 7b. It can be observed that the average

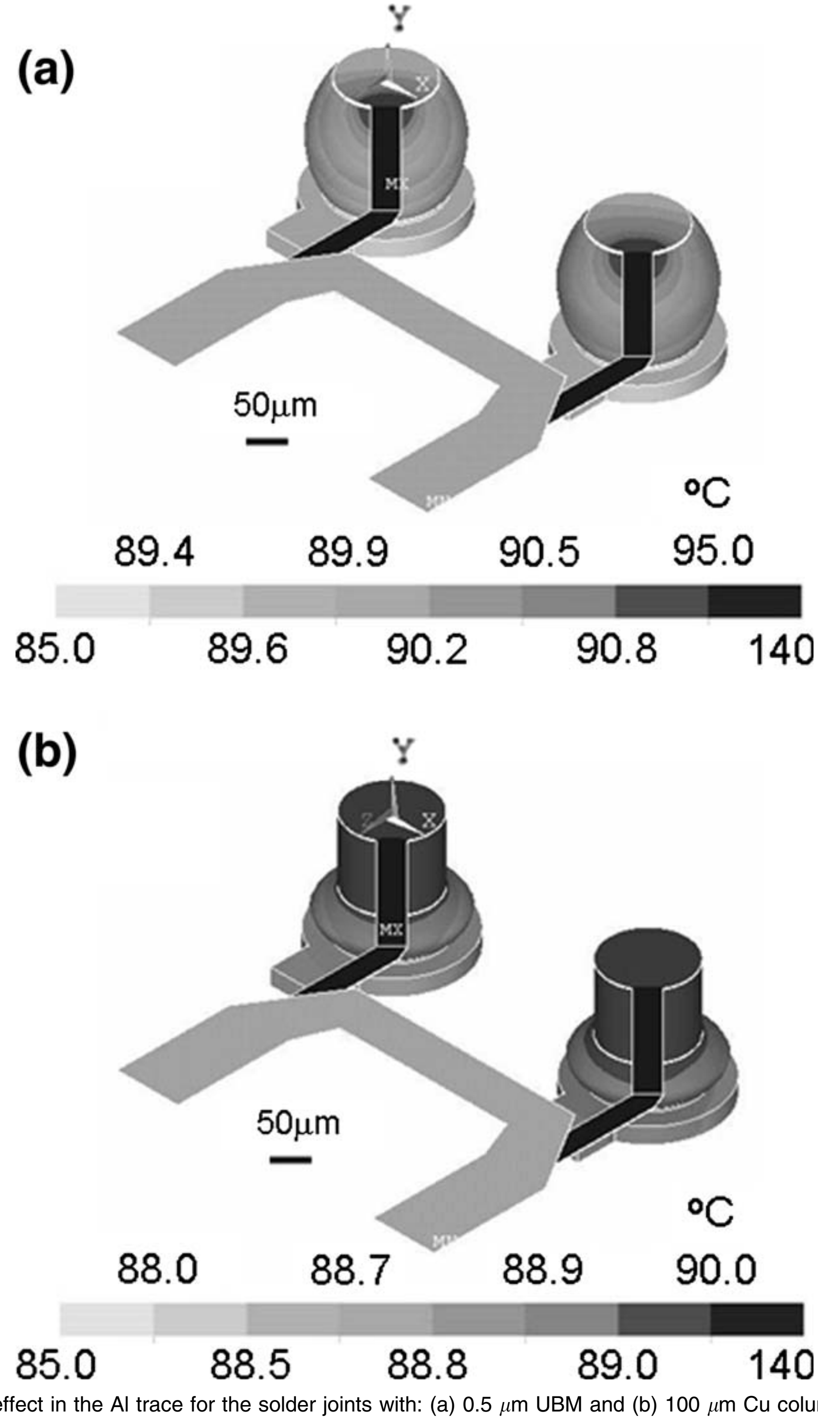

Fig. 3. The Joule heating effect in the Al trace for the solder joints with: (a) 0.5 μm UBM and (b) 100 μm Cu column.

temperature in the solder does not decrease significantly even when the Cu UBM was as thick as 100 μm. This insensitivity to the Cu UBM thickness is because the primary heating source is the Al trace. In these simulation models, the total resistance for the stressing circuit is about 1330 mΩ. The bump resistances are 6.1, 4.4, 3.3, 3.1, and 2.7 mΩ for the five models. Therefore, the reductions in bump resistance due to the thicker Cu UBMs are negligible compared to the total resistance. Although the solder was kept away from the heating source for the 100 μm Cu column, Cu is a superb heat conductor, which is expected to facilitate heat conduction. Thus, the average temperatures in the solder for the five models were quite similar. Furthermore, with thicker Cu UBMs, the thermal gradient is reduced considerably. The thermal gradient in this study is determined by the temperature difference between the top and bottom of the solder divided by the height of the solder bump. As shown in

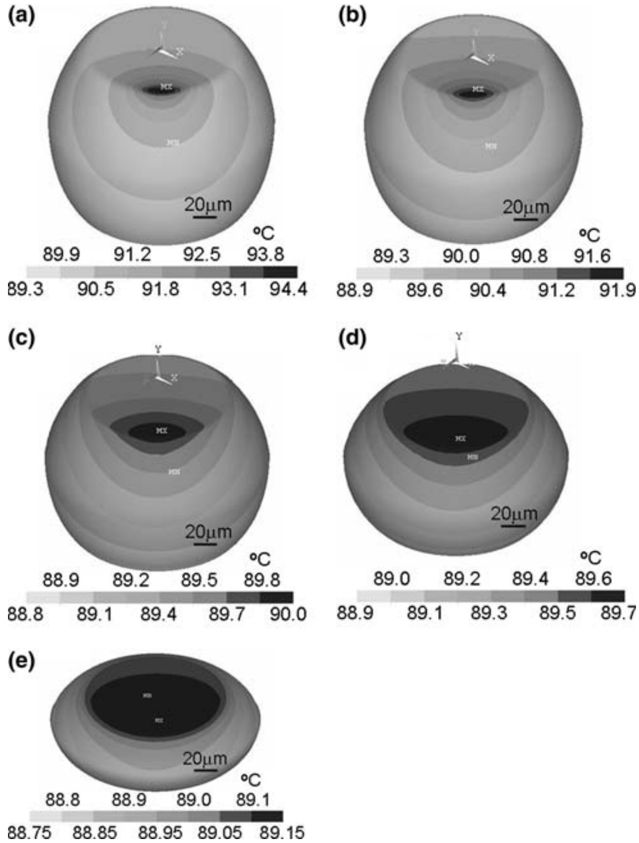

Fig. 4. The temperature distribution in the solder bump with (a) 0.5 μm, (b) 5 μm, (c) 25 μm, (d) 50 μm, and (e) 100 μm Cu UBM when a current of 0.6 A was applied. Only solder bumps are shown.

Fig. 8, the gradient is reduced from 400°C/cm to 60°C/cm when the Cu UBM is increased from 0.5 μm to 100 μm. Thus, thermomigration in the solder would be inhibited with thicker Cu UBM.[12]

The elimination of the hot spot for solder joints with thick Cu UBM may be attributed to the absence of serious current crowding since there is no serious local Joule heating for these joints. The Joule heating power can be expressed as

$$P = j^2 \rho V \tag{1}$$

where P = heating power, j = current density, ρ = resistivity. The local Joule heating power is proportional to the square of the local current density. For the above five models, the overall Joule heating were quite close. Yet, the crowding ratios for the five models are 19.0, 9.6, 2.9, 1.7, and 1.6. It is expected that the local Joule heating power in the hot spot for the bump with the 100 μm Cu column will be 140 times less than that of the bump with a 0.5 μm Cu UBM. Therefore, the hot-spot issue could be relieved significantly in solder bumps with thick Cu columns due to the reduced current crowding effect. Compared with the results published by Chen et al.[13] and Wang et al.,[14] the Cu column can effectively reduce the current crowding effect and Joule heating effect. They observed the highest consumption rate in the current crowding region, which was also a hot spot. Therefore, with the Cu column, the electromigration resistance could be increased.

Furthermore, the effect of the thickness of the Cu UBM on the mean time to failure (MTTF) could be estimated using the equation for solder joints, which is typically expressed as[15]

$$\mathrm{MTTF} = A\frac{1}{j^n}\exp\left(\frac{Q}{kT}\right) \tag{2}$$

where A = constant that contains a factor involving the cross-sectional area of the joint, j = current density in amperes per centimeter square, n = model parameter for current density, Q = activation energy, k = Boltzmann's constant, and T = average bump temperature in Kelvin. It is noteworthy that this equation has proven to be valid for Al and Cu interconnects, but that revision is required for application to solder joints.[6,7] Herein, the maximum current density and the hot-spot temperature were adopted for the values of j and T, respectively, to estimate the MTTF as voids form in the high-current-density and hot-spot regions. In addition, the values of n and Q used were 0.678 and 0.691 eV, respectively, for SnPb solder with a Ti/Ni(V)/Cu UBM structure.[16] Table I summarizes the maximum current density, hot-spot temperature, and the ratio of the estimated MTTF for the five models considered. Compared with the solder joint with 0.5 μm Cu UBM, the MTTF for the solder joints with 5, 25, 50, and 100 μm Cu UBM exhibit a longer electromigration lifetime by 1.8, 4.6, 6.7, and 7.3 times, respectively. Therefore, solder joints with thicker Cu UBMs are likely to demonstrate better electromigration resistance due to lesser current crowding effect and lower hot-spot temperature. In addition, when the Cu thickness is increased from 50 μm to 100 μm, there is no obvious increase in the MTTF since there were negligible current crowding Joule heating effects when the Cu UBM was thicker than 50 μm. Consequently, further thickening in Cu UBM is not expected to render longer electromigration lifetime.

CONCLUSIONS

The current density and temperature distributions in flip–chip solder joints with several thicknesses of Cu UBM have been simulated by the finite-element method. It was found that joints with a thicker Cu UBM exhibited a lower maximum current density and hot-spot temperature, and that current crowding as well as local Joule heating effects are almost eliminated when the Cu UBM was thicker than 50 μm. With more-uniform current and temperature distributions, the MTTF of solder joints are extended. The lower current crowding effect and reduced hot-spot temperature are responsible for the improved MTTF. In addition,

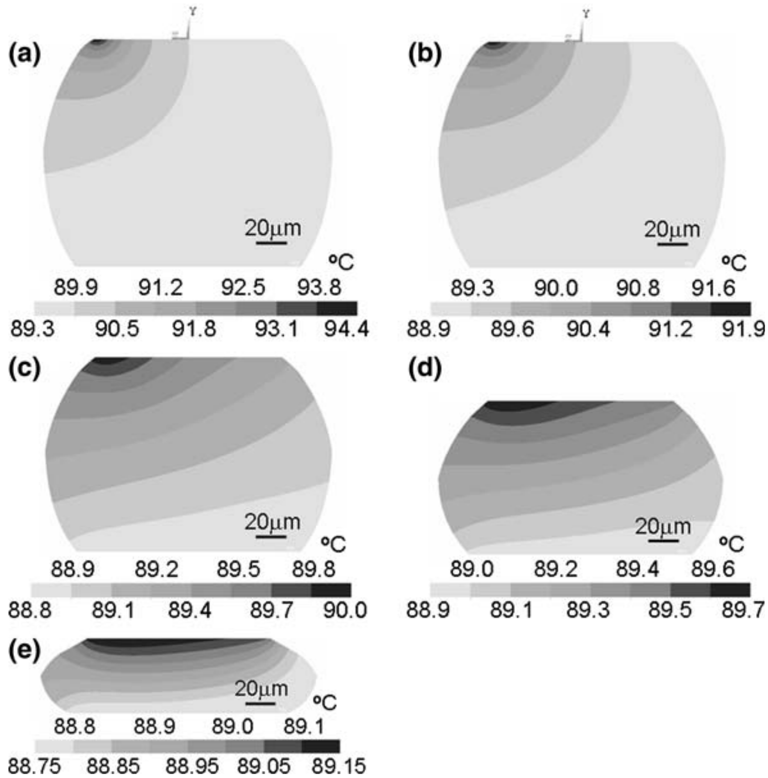

Fig. 5. Cross-sectional view of the temperature distribution in the solder bump with (a) 0.5 μm, (b) 5 μm, (c) 25 μm, (d) 50 μm, and (e) 100 μm Cu UBM when a current of 0.6 A was applied. Only solder bumps are shown.

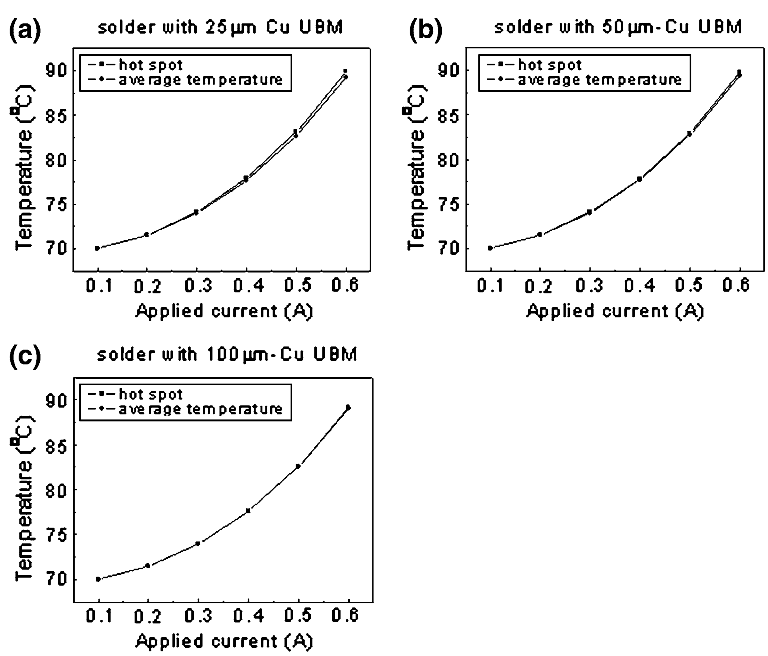

Fig. 6. Hot spot and average temperatures as a function of applied current up to 0.6 A for solder joints with (a) 25 μm, (b) 50 μm, and (c) 100 μm Cu columns. The hot spot was almost eliminated completely when the Cu column was thicker than 50 μm.

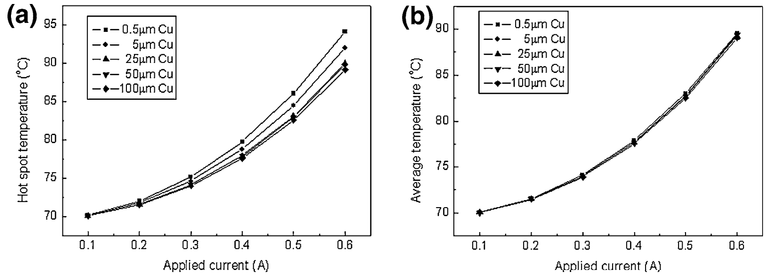

Fig. 7. (a) Hot-spot temperature as a function of the applied current for the five models. The hot-spot temperature decreases as the thickness of the Cu UBM increased. (b) Average temperature in solder as a function of the applied current for the five models. No obvious increase in average temperature when the thickness of the Cu UBM was increased.

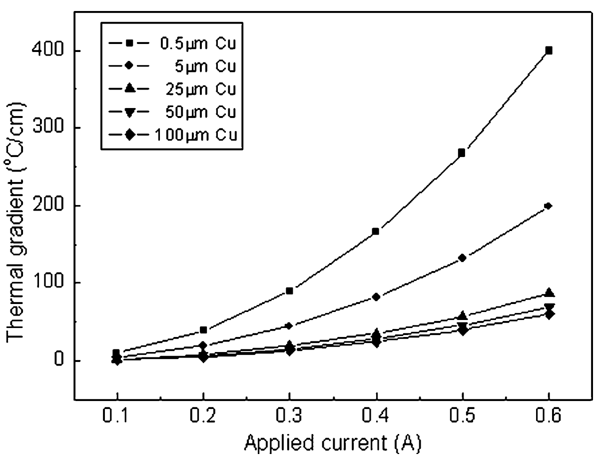

Fig. 8. Thermal gradient as a function of applied current. Thick Cu UBM can effectively reduce the thermal gradient.

with a thicker Cu UBM, thermal migration would be minimized due to the uniform temperature distribution in the solder.

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Table I. The Maximum Current Density, Hot-Spot Temperature, and Estimated MTTF for the Five Models Modeled

Cu UBM Thickness (μm)	Maximum Current Density (A/cm^2)	Hot-Spot Temperature (°C)	MTTF Ratio
0.5	1.01×10^5	94.1	1
5	5.10×10^4	91.9	1.8
25	1.52×10^4	90.0	4.6
50	9.06×10^3	89.7	6.7
100	8.44×10^3	89.1	7.3

REFERENCES

1. Glenn R. Blackwell, *The Electronic Packaging Handbook* (CRC Press in cooperation with IEEE Press, 2000).
2. International Technology Roadmap for Semiconductors, Assembly and Packaging Section, Semiconductor Industry Association, San Jose, CA (2003), pp. 4–9.
3. K.N. Tu, *J. Appl. Phys.* 94, 5451 (2003).
4. C.Y. Liu, C. Chen, C.N. Liao, and K.N. Tu, *Appl. Phys. Lett.* 75, 58 (1999).
5. E.C.C. Yeh, W.J. Choi, and K.N. Tu, *Appl. Phys. Lett.* 80, 4 (2002).
6. W.J. Choi, E.C.C. Yeh, and K.N. Tu, *J. Appl. Phys.* 94, 5665 (2003).
7. S.H. Chiu, T.L. Shao, C. Chen, D.J. Yao, and C.Y. Hsu, *Appl. Phys. Lett.* 88, 022110 (2006).
8. T.L. Shao, Y.H. Chen, S.H. Chiu, and C. Chen, *J. Appl. Phys.* 96(8), 4518 (2004).
9. S.W. Liang, T.L. Shao, C. Chen, E.C.C. Yeh, and K.N. Tu, *J. Mater. Res.* 21(1), 137 (2006).
10. J.W. Nah, K.W. Paik, J.O. Suh, and K.N. Tu, *J. Appl. Phys.* 94, 7560 (2003).
11. J.W. Nah, J.O. Suh, K.N. Tu, S.W. Yoon, C.T. Chong, V. Kripesh, B.R. Su, and C. Chen, in *Proceedings of the 56th Electronic Components and Technology Conference*, IEEE Components, Packaging, and Manufacturing Technology Society, San Diego, CA, 657 (2006).
12. A.T. Huang, A.M. Gusak, K.N. Tu, Y.-S. Lai, *Appl. Phys. Lett.* 88(14), Art. No. 141911 (2006).
13. S.W. Chen, S.K. Lin, and J.M. Jao, *Mater. Trans. JIM* 45(3), 661 (2004).
14. C.H. Wang and S.W. Chen, *J. Chinese Institute Chem. Eng.* 37(2), 185 (2006).
15. J.R. Black, *IEEE Trans. Electron. Dev.* ED-16(4), 338 (1969).
16. Y.-S. Lai, K.-M. Chen, C.-W. Lee, C.-L. Kao, Y.-H. Shao, in *Proceedings of 7th Electronic Packaging Technology Conference*, IEEE Components, Packaging, and Manufacturing Technology Society, Singapore, 786 (2005).