Joule Heating Effect under Accelerated Electromigration in Flip-chip Solder Joints

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Abstract

This study employs three-dimensional simulation to investigate the Joule heating effect under accelerated electromigration tests in flip-chip solder joints. It was found that the Joule heating effect was very seriously during high current stressing, and a hot spot exists in the solder bump. The hot-spot may play important role in the void formation and thermomigration in solder bumps during electromigration.

Introduction

To meet the miniaturization trend for portable devices, flip chip technology has been adopted for high-density packaging due to its excellent electrical performance and better heat dissipation ability[1]. As the required performance in microelectronics devices becomes higher, the current design rule requires that the current each bump needs to carry is 0.2 A, and it will increase to 0.4 A in the near future. Therefore, electromigration (EM) has become an important reliability issue. During electromigration test, the applied current may be as high as 2.0 A[2-3], and thus Joule heating effect in the solder bumps became very seriously.

Therefore, the temperature in the bumps during EM testing may be much higher than that of the ambient due to Joule heating, and may affect the mean-time-to-failure (MTTF) analysis, as described by Black's equation:[4]

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

where A is constant, j is the current density, n is a model parameter for current density, Q is the activation energy, k is the Boltzmann's constant, and T is the average bump temperature. It is noteworthy that the MTTF decreases exponentially with the stressing temperature. Wu *et al.* conducted electromigration test for SnPb solder bumps,[5] and found that the MTTF decreased from 711 hours to 84 hours when the testing temperature increased from 125 °C to 150 °C at 5.0×10^3 A/cm^2. Therefore, the influence of the stressing temperature on MTTF is significant. However, little research has been done on the Joule heating effect in flip-chip solder joints.

In this study, three-dimensional (3-D) simulation on current and temperature distribution was carried out by finite element analysis to examine the temperature distribution in the solder bumps.

Experimental and Simulation

The dimension of the flip-chip joint used in this study is shown in Figure 1 schematically. The fabrication procedure for the SnPb bumps can be found in our previous publication.[6] A thin film UBM of 0.4-μm Al/0.3-μm Ni(V)/0.4-μm Cu was adopted for the chip side and Ni metallization was used on the substrate side. Eutectic SnPb solder was adopted for the bump materials. The Cu layer in the UBM was assumed to be completely consumed to form 1.4μm Cu_6Sn_5 IMC. Therefore, an effective layer of 0.7 μm UBM with an effective resistivity of 29.54 μΩ·cm was used in the simulation model. On the substrate side, we assumed that 1-μm of Ni_3Sn_4 IMC was formed in the interface of the solder and the Ni metallization. Both Cu_6Sn_5 and Ni_3Sn_4 IMCs were assumed to be the layered-type. The resistivity values of the materials used in this simulation are listed in Table I. The effect of temperature coefficient of resistiviy (TCR) was considered, and the TCR values for the metals are also listed in Table I. Eutectic SnAg solder was adopted.

Table I.

Materials	Thermal conductivity (W/m-°C)	Resistivity (μΩ-cm) at 20°C	TCR 10^{-3} K^{-1}
Silicon	147.00	--	--
Al trace	238.00	2.7	4.2
Electro-less Ni	9.32	70.0	6.8
Cu	403.00	1.7	4.3
Ni	76.00	6.8	6.8
SnAg3.5	33.00	12.3	4.6
BT	0.70	--	--
Underfill	0.55	--	--
PI	0.34	--	--

An infrared (IR) microscope was employed to measure the temperature in the Al trace during current stressing. The procedure for IR measurement can be found in our previous publication.[7] Since the Si is transparent to the IR, the temperatures in the Al trace and the Al pad directly on the solder bumps can measured without damaging the solder joints. Figure 2 shows the radiant IR image of the circuit, in

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which the Al trace and the Al pads on the solder bumps can be seen clearly. In addition, UBM and passivation openings were labeled in the figure. The UBM and passivation openings were 120 μm and 85 μm in diameter, respectively. The Al trace on the chip side was 34 μm wide and 1.5 μm thick. Then we can measure the temperature distribution on the Al trace and the pads under various stressing conditions.

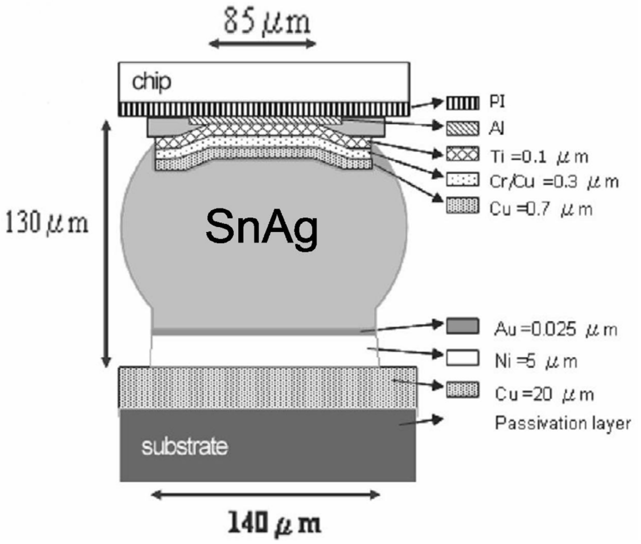

Figure 1. Schematic diagram for the SnAg solder bump used in this study

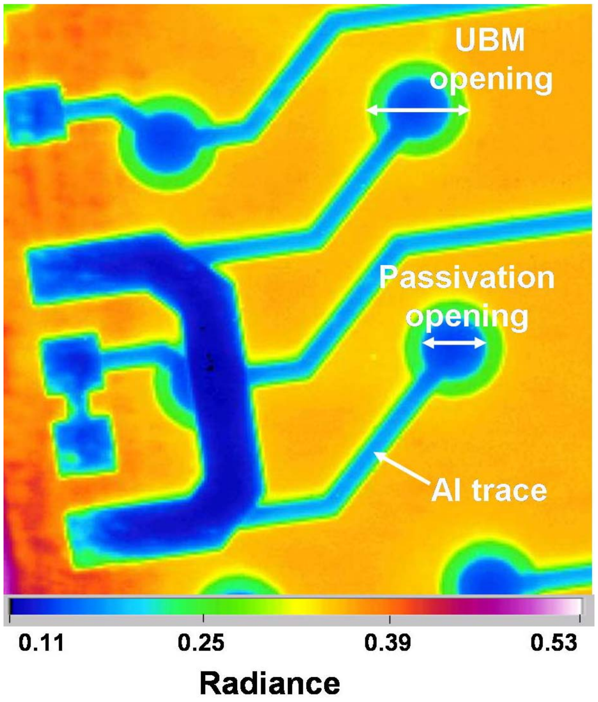

Figure 2. IR image of radiant mode showing the layout of the Al trace.

On the basis of the IR results, a three-dimensional (3-D) simulation was carried out by finite element analysis. The schematic diagram for the package is shown in Figure 3(a). Two solder bumps had electrical current applied through the circuit shown in Figure 2, and the location of the two bumps is indicated by one of the arrows in the figure. 3-D coupled electro- thermal analysis using ANSYS was conducted to predict the steady state temperature distribution. The model used in this study was a SOLID69 8-node hexahedral coupled field element. The whole flip chip package with meshization was illustrated in Figure 3(b). Figure 4 shows the plan and cross-sectional views of the package. The dimension of the Si chip was 7.0 mm × 4.8 mm and the thickness was 290 μm, whereas the dimension of the BT (Bismaleimide Triazine) substrate was 5.4 mm wide, 9.0 mm long, and 380 μm thick. The bottom of the BT substrate was maintained at 70 °C and the convention coefficient was set to 10 W/m^2-°C around the 25°C environment temperature.

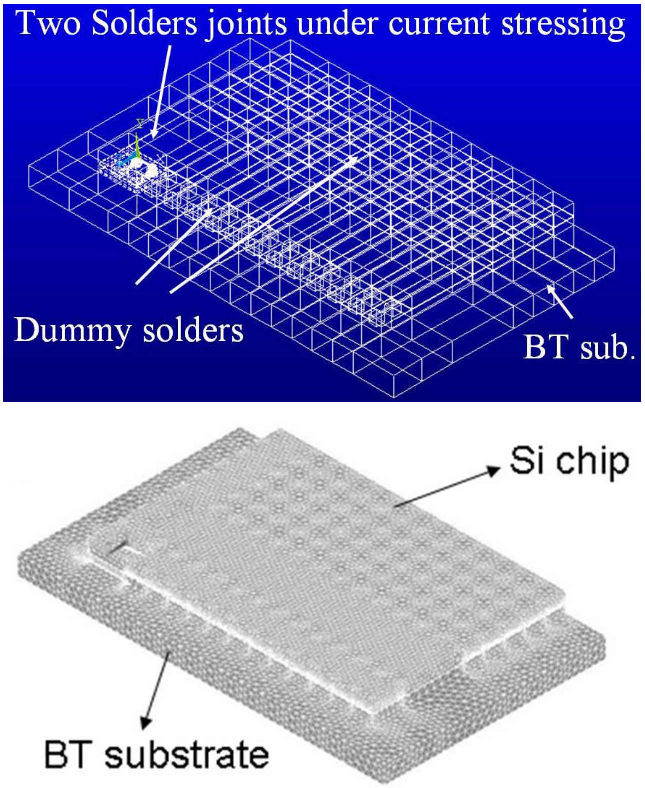

Figure 3. (a) The constructed package for 3-D simulation. (b)The whole flip chip package with meshization

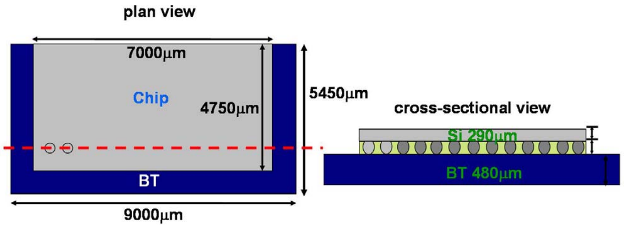

Figure 4. Sample dimension of the whole package for our real sample and for the model constructed for simulation.

Results and Discussion

Joule heating effect

Figure 5 shows temperature distribution on the surface of the Si die when the two solder joints were powered by 0.59A. The values of the temperatures on the four corners were labeled. The temperatures near the two stressed solder joints was about 91 □, whereas it decreased down to about 77 □ on the rest of the three corners. This is because that there was no Joule heating on the three corners. To examine the Joule heating effect on the Al trace, the cross-section along one of solder joints was analyzed. Figure 6 shows temperature distribution on the cross-section along one of the stressed bumps. It is found that the temperature in the Al trace was higher than temperature in the solder bump and in the Si die, and the maximum value reach 147 °C. This is because the Al trace had much smaller cross-section, and thus the current density in the Al trace may reach 1×10^6 A/cm^2, which had much higher local Joule heating. However, the temperature dropped to about 91 °C in the solder bump. This may be due two reasons. First, the current density value in the solder bump was 1-2 order lower in magnitude than that in the Al trace. Second, solder may serve as a heat sink, and some of the heat was dissipated away through BT substrate. Figure 7 shows the temperature distribution in the Si surface right above the solder bump. The temperature drop was only 1°C across the thickness direction of 290 μm. This low thermal gradient in the Si may be mainly attributed to its excellent thermal conductivity of 147 W/m-°C.

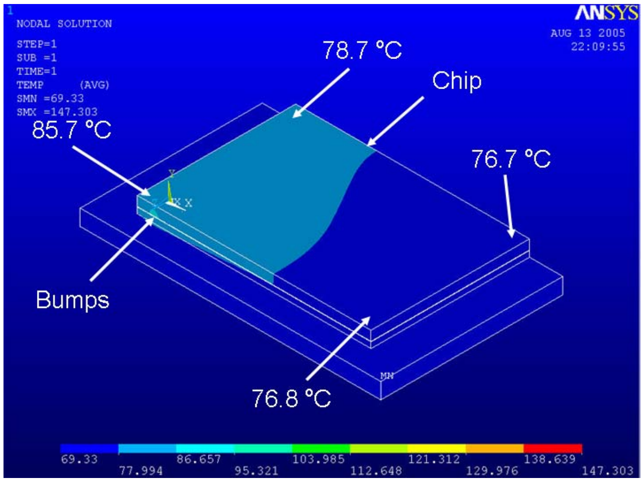

Figure 5. The temperature distribution in the whole package under the current stressing of 0.59 A.

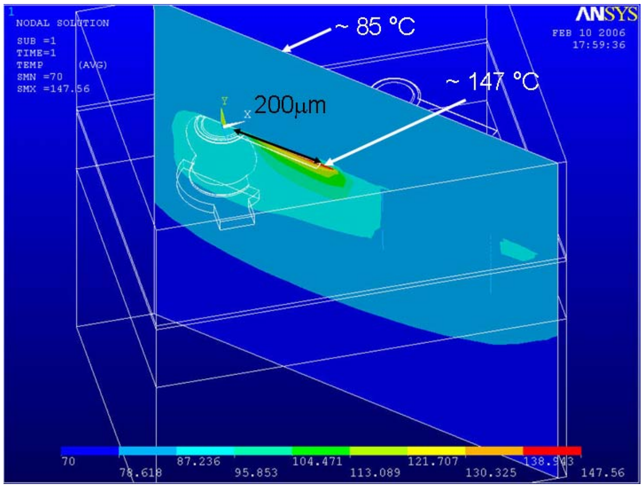

Figure 6. The temperature distribution on one of the cross-section containing Al trace and solder bump.

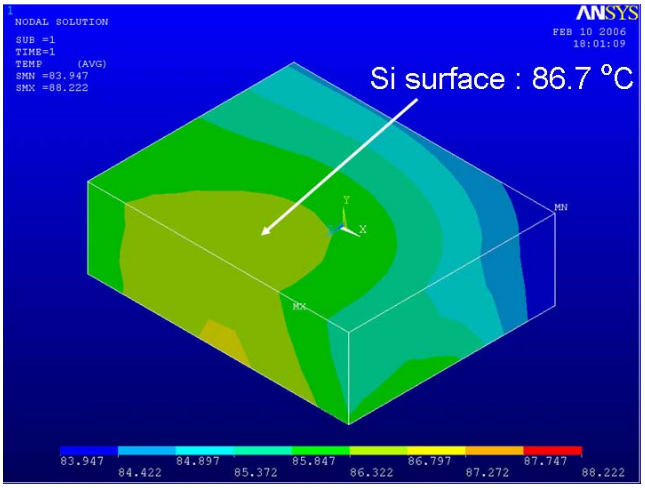

Figure 7. The temperature distribution in Si above the solder joint under the current stressing of 0.59 A.

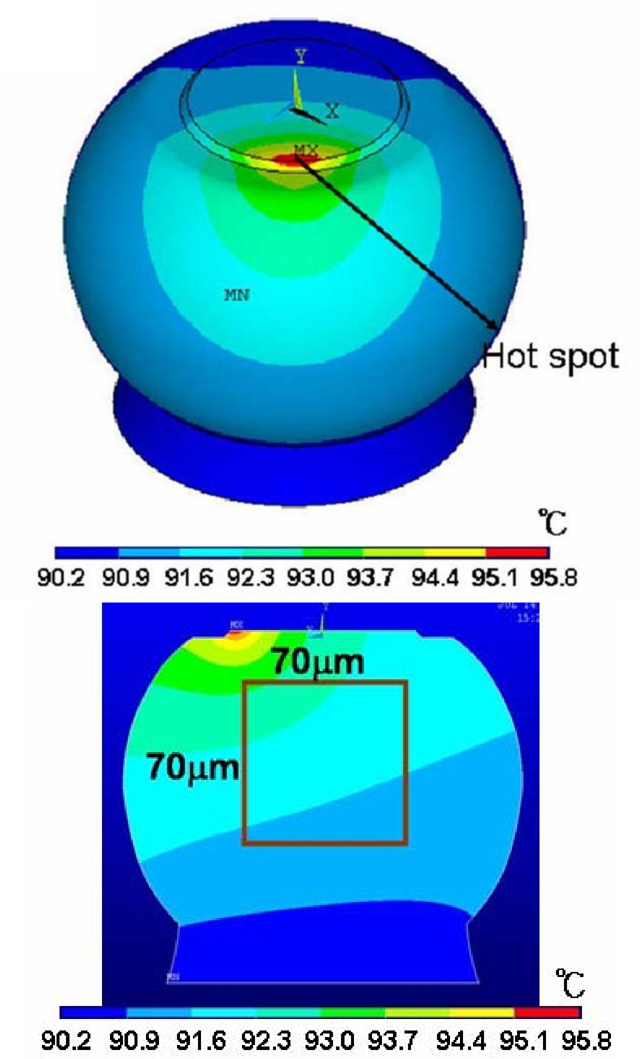

Figure 8. (a) The temperature distribution of a bump. A hot spot exist at the entrance points of the Al trace into the solder at the passivation opening. (b) The temperature distribution in the solder bump. the average temperature in the solder bump was obtained by averaging the temperatures in a square of 70 μm × 70 μm in the center of the solder.

As for the temperature distribution in the solder bump, Figure 8(a) shows the distribution in the solder bump only, in which the Al pad, UBM, IMC layer, and the BT substrate were excluded. It is clear that there is a hot spot near the entrance point of the Al trace, as indicated by the arrow in the figure.[8] Figure 8(b) shows the distribution in the center cross-section of the bump, in which the temperature distribution across the solder bump can be clearly seen. The temperature at the spot was 95.6 °C, which was 4.5 °C higher than the average value in the solder. The average value was obtained by averaging the values in the area of 70×70 μm^2, as labeled in the figure. The occurrence of the hot spot may be mainly attributed to the local Joule heating effect, since there is serious current crowding effect in the hot-spot region.[9] Thermal gradient across the solder joint was built up due to this hot spot, and its value was 260.5 °C/cm when the joints were stressed by 0.59 A. This gradient play important role in the thermomigration in the solder joints.[10-11]

Figure 9 shows the temperature map in the BT substrate directly below the two stressed bumps. The BT substrate under the two solder bumps has higher temperatures. In addition, since BT is a poor heat conductor, there was about 20 °C temperature drop across the thickness direction.

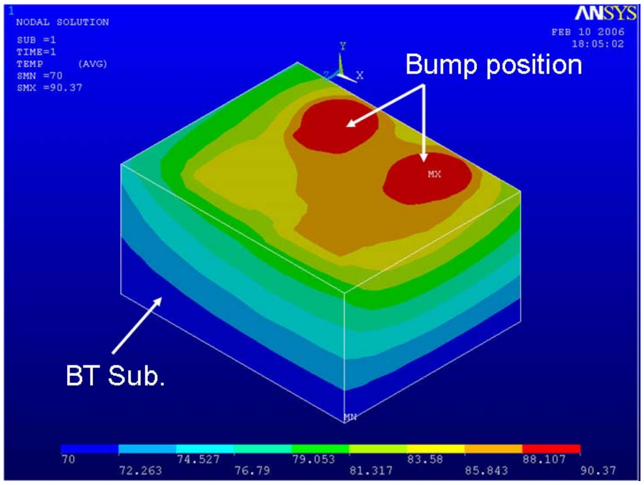

Figure 9. The temperature distribution of BT substrate under current stressing of 0.59 A.

From the above results, it follows that temperature measure on the die surface by a thermal couple may be able to detect the average temperature in the solder bump. In this case, the temperature in the die surface was 86.7 °C, whereas it was 91.1 °C in the solder. However, it can not measure the hot spots in the solder bump and in the Al trace.

The solder in the hot spot was the most vulnerable part in the solder joint, since it may experience much larger electron wind force due to the higher current density and the higher diffusivity owing to the higher temperature. Hence, voids start to form at this spot.[12] Consequently, the hot-spot temperature should be taken into account in Black's equation. Especially, the difference between the hot-spot and the average temperature may be over 10 °C at higher stressing current.[8] We suggest that the temperature term in Black's equation should be modified as the hot-spot temperature. Thus, the MTTF and activation energy could be measured more precisely.

Conclusions

The Joule heating effect in the solder joints has been investigated using a 3-D coupled thermal-electrical simulation. The temperature distribution in joints can be determined thoroughly. A hot spot was found in the vicinity of the entrance point of the Al trace, which is detrimental to the electromigration life time of the solder joints.

Acknowledgments

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References

1. International Technology Roadmap for Semiconductors, Assembly and Packaging Section, Semiconductor Industry Association, San Jose, CA (2003), pp. 4-9
2. K. N. Tu, "Recent advances on electromigration in very-large-scale-integration of interconnects," *J. Appl. Phys.*, 94, 5451 (2003).
3. S. Brandenburg and S. Yeh, *Proceedings of Surface Mount International Conference and Exhibition*, SM198, San Jose, CA, Aug. 23-27, 1998(Edina, MN: SMTA, 1998), p. 337.
4. J. R. Black, "Electromigration-A brief survey and some recent results," *IEEE Trans. Electron Devices* ED-16(4), 338 (1969).
5. J. D. Wu, P. J. Zheng, Kelly Lee, C. T. Chiu, and J.J. Lee, *Proceedings of the 52th Electronic Components and Technology Conference*, IEEE Components, Packaging, and Manufacturing Technology Society, San Diego, 2002, p. 452.
6. T. L. Shao, Y. H. Chen, S. H. Chiu and Chih Chen, "Electromigration Failure Mechanisms for SnAg3.5 Solder Bumps on Ti/Cr-Cu/Cu and Ni(P)/Au Metallization Pads**,** " *Journal of Applied Physics,* Vol. 96, 8, 4518 (2004).
7. T. L. Shao, S. H. Chiu, Chih Chen, D.J. Yao, and C.Y. Hsu, "Thermal Gradient in Solder Joints under Electrical Current Stressing," *Journal of Electronic Materials*, 33 (11): 1350-1354, 2004.
8. S.H Chiu, T.L. Shao, C. Chen, D. J. Yao and C.Y. Hsu, "Infrared microscopy of hot spots induced by Joule heating in flip-chip SnAg solder joints under accelerated electromigration," *Appl. phys. Lett.* 88, 022110(2006)
9. T. L. Shao, Shih-Wei Liang, T.C. Lin, and Chih Chen, "3-D Simulation on Current Density Distribution in Flip Chip Solder Joint under Electrical Current Stressing," *J. Appl. Phys.* **98**, 044509 (2005)
10. Hua Ye, Cemal Basaran, and Douglas Hopkins, "Thermomigration in Pb–Sn solder joints under joule heating during electric current stressing." *Appl. phys. Lett.* 82, 7 (2003).
11. A.T. Huang, A.M. Gusak, K.N. Tu, Y-S Lai. "Thermomigration in SnPb composite flip chip solder joints." *Applied Physics Letters*, in press.
12. J. W. Nah, K. W. Paik, J. O. Suh, and K. N. Tu, "Mechanism of electromigration-induced failure in the 97Pb--3Sn and 37Pb--63Sn composite solder joints," *J. Appl. Phys.* 94, 7560 (2003).