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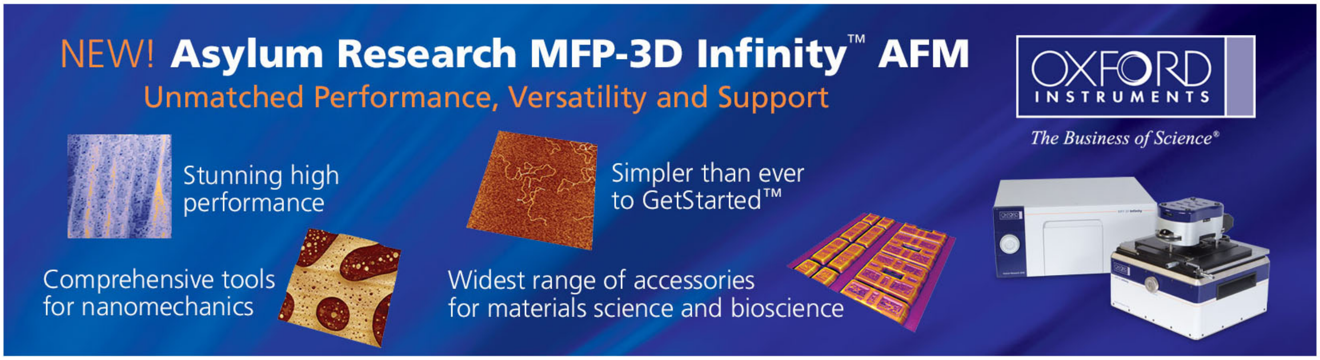

APPLIED PHYSICS LETTERS **88**, 172108 (2006)

# Effect of Al-trace dimension on Joule heating and current crowding in flip-chip solder joints under accelerated electromigration

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Three-dimensional thermoelectrical simulation was conducted to investigate the influence of Al-trace dimension on Joule heating and current crowding in flip-chip solder joints. It is found that the dimension of the Al-trace effects significantly on the Joule heating, and thus directly determines the mean time to failure (MTTF). Simulated at a stressing current of 0.6 A at 70 °C, we estimate that the MTTF of the joints with Al traces in 100 $\mu$m width was 6.1 times longer than that of joints with Al traces in 34 $\mu$m width. Lower current crowding effect and reduced hot-spot temperature are responsible for the improved MTTF. © *2006 American Institute of Physics*.
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To meet the relentless drive for miniaturization of portable devices, flip-chip technology has been adopted for high-density packaging due to its excellent electrical characteristic and superior heat dissipation capability. As the required performance in microelectronics devices becomes higher, the design rule indicates that in each bump the operation current is expected to attain a value of 0.2 A, with further increase to 0.4 A likely in the near future.[1] Loading with such a high current at the confined space of the solder bump, electromigration inevitably becomes a critical reliability issue.[2] In addition, during accelerated electromigration test, the applied current may reach 2.0 A,[3] rendering substantial Joule heating in the solder bumps.[4] The total length of the Al trace is typically few hundreds to few thousands micrometers, which corresponds to a resistance of approximately few hundreds milliohms or few ohms. In contrast, the resistances of the solder bumps and the Cu trace in the substrate are relatively low, typically in the order of few or tens of milliohms. Therefore, the primary contributor for Joule heating in the solder joints is the Al trace.[4] As a result, the temperature in the bumps during accelerated testing is likely to be much higher than that of the ambient because of the Joule heating. The other critical issue is the current crowding effect in the solder bumps. The line-to-bump geometry is believed to render undesirable current crowding behavior, resulting in elevated current density in the solder regime than the average current density.[5] These two issues play substantial roles in the mean-time-to-failure (MTTF) analysis, as delineated by Black's equation,[6]

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

where $A$ is a constant, $j$ is the current density, $n$ is a model parameter for current density, $Q$ is the activation energy, $k$ is the Boltzmann constant, and $T$ is the average bump temperature. It follows that the MTTF decreases exponentially with increasing bump temperature. Wu *et al.*[7] conducted a series of electromigration tests for SnPb solder bumps, and observed that the MTTF decreased from 711 to 84 h as the testing temperature was raised from 125 to 150 °C at a current density of $5.0\times10^3$ A/cm$^2$. In addition, the MTTF decreased from 277 to 84 h as the current density was doubled from $2.5\times10^3$ to $5.0\times10^3$ A/cm$^2$ at 150 °C. Predicted by Black's equation and validated experimentally by Wu *et al.*, the stressing temperature and the current density both play substantial role in determining the observed MTTF.

Several intrinsic material characteristics contribute to the Joule heating and current crowding effects. They include the dimension of Al trace, the thickness of under bump metallization (UBM), the UBM materials, the solder materials, as well as the dimension of passivation.[8] Among them, the dimension of Al trace is believed to be the critical one. However, no systematic studies have been initiated to elucidate the effect of Al-trace dimension in Joule heating and current crowding of the solder joints during electromigration. This is because the solder joints are completely encapsulated by Si die, underfill, and underlying substrate. Hence, it is somewhat difficult to analyze the temperature fluctuation and the current density inside the solder joints. To overcome this problem, in this study we used a three-dimensional thermoelectrical simulation to identify the temperature and the current density inside the solder bumps. This study offers a better insight on the effect of Al-trace dimension in the Joule heating and current crowding during accelerated electromigration of solder joints.

To proceed our simulation, four models with identical structure of solder bumps and Cu lines but with different dimensions of Al trace were constructed. Shown in Fig. 1(a) is a standard model, which includes two SnPb solder bumps connected by an Al trace of 1840 $\mu$m in length, 34 $\mu$m in width, and 1.5 $\mu$m in thickness. For the second model, as shown in Fig. 1(b), the width of the Al trace was increased to 100 $\mu$m with the remaining structure unchanged. Figure 1(c) exhibits the third model, in which the thickness of the Al trace was adjusted to 4.4 $\mu$m with the remaining dimension identical to those of the first model. It is noted that the second and the third model had the same cross-sectional area of Al trace. For the fourth model, as depicted in Fig. 1(d), a shorter Al trace which is 670 $\mu$m less than the standard model was used while the remaining features identical to those in the first model. The dimension of the Si chip was

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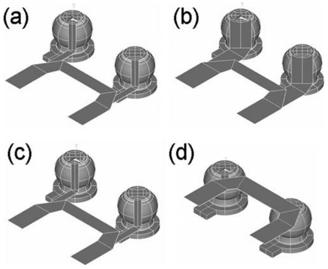

FIG. 1. The four models constructed in this study. (a) The first model with a 34-$\mu m$-wide, 1.5-$\mu$m-thick, and 1848-$\mu$m-long Al trace. (b) The second model with a wider Al trace of 100 $\mu$m. (c) The third model with a thick Al trace of 4.4 $\mu$m. (d) The fourth model with a shorter Al trace of 1178 $\mu$m.

$7.0\times4.8$ mm$^2$ with its thickness of 290 $\mu$m. The dimension of the bismaleimide triazine (BT) substrate was 5.4 mm in width, 9.0 mm in length, and 480 $\mu$m in thickness. The bottom of the BT substrate was maintained at 70 °C and the convection coefficient was set to be 10 W/m$^2$ °C in a 25 °C ambient temperature. The intrinsic parameters of materials used in this simulation can be found in our previous publication.[9] Constant currents, ranging from 0.1 to 0.6 A, were applied through the two Cu lines on the BT substrate.

The current crowding effect can be relieved to some extent by increasing the width or the thickness of the Al trace. In this letter, we designate the crowding ratio to be the maximum current density inside the solder bump divided by the average current density in the UBM opening, which was obtained assuming the current spreads uniformly on the UBM opening. The crowding ratio indicates the degree of nonbalance in the current distribution in the solder bump. It is realized that the current crowding would accelerate the damage caused by electromigration because of the enhanced wind force in the current crowding region. Figures 2(a)–2(d) demonstrate the cross-sectional views for the current density distribution of the four models as they were stressed at 0.6 A. As shown, the local current density inside the solder bump near the entrance of the Al trace was reduced substantially in the second and the third model. The crowding ratio for the first model reached a value of 19.8. When the cross section of the Al trace was increased by 2.9 times, the crowding ratios were reduced down to 12.0 and 11.7 for the second and the third model, respectively. Since the geometry of the Al trace near the solder bump was not varied for the fourth model, the distribution of current remained the same as the first model. From our simulation, we conclude that increasing the cross section of the Al trace directly reduced the crowding ratio.

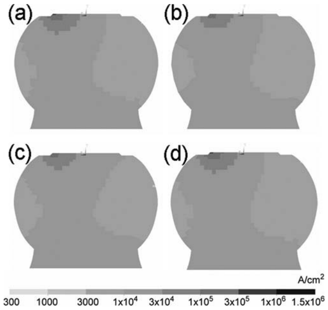

FIG. 2. The cross-sectional views for the current-density distribution in the solder bump when they were stressed by 0.6 A. (a) The first model. (b) The second model. (c) The third model. (d) The fourth model.

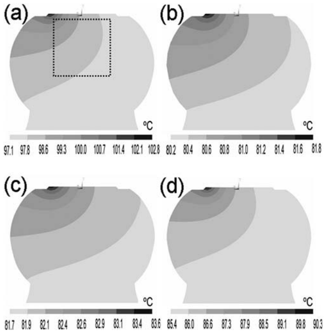

FIG. 3. The cross-sectional views for the temperature distribution in the solder bumps when they were applied by 0.6 A at 70 °C. (a) The first model. (b) The second model. (c) The third model. (d) The fourth model.

Furthermore, the dimension of the Al trace exerts significant effect on Joule heating of the solder bumps. Figures 3(a)–3(d) illustrate the temperature distributions in the center cross sections for the four models when they experience a stress current of 0.6 A at 70 °C. A hot spot inside the solder bump was observed near the entrance point of the Al trace into the solder bump just beneath the passivation opening. The mean temperature was obtained by averaging the node temperatures in a $70\times70$ $\mu$m$^2$ area, as shown in Fig. 3(a). The temperatures in the hot spot were 102.8, 81.7, 83.6, and 90.3 °C for the four models, respectively, whereas the average temperatures were 97.9, 80.6, 82.0, and 86.1 °C, respectively. It can be seen that the Joule heating effect was greatly reduced when the cross section of the Al trace was increased. Figures 4(a) and 4(b) show the hot-spot and average temperatures as a function of the applied current up to 0.6 A. Also, the trend for lower stressing current behaves the same with smaller magnitude in temperature difference as that stressed by 0.6 A. Due to the hot spot, a thermal gradient was built up across the solder bump. The thermal gradient was derived from the temperature difference between the hot-spot and the average temperature of the solder close to the BT side, divided by the bump height. It can be observed that the second model exhibits the lowest thermal gradient among the four models.

In general, the Al trace is considered to be the primary Joule heating source during accelerated electromigration test as its cross-section area is typically one to two orders of magnitude less than that of the solder bump and the Cu line. Under the same applied current, the Joule heating power is proportional to the total resistance of the stressing circuit. The resistance of the Al trace for the first model was 1331 m$\Omega$, whereas it decreased to 530, 551, 532 m$\Omega$ for the rest of the three models, respectively. Therefore, the Joule heating effect was less significant for the stressing circuit configuration with smaller total resistance. In addition, for the third and fourth models, the total resistance and the cross section for heat dissipation were almost identical, yet there is still 6.7 °C difference in hot-spot temperature. Since the average current density in the Al trace for the fourth model was about three times larger than that for the third model, the local Joule heat power, which is proportional to the square of the local current density, is likely to be responsible for the temperature difference in these two models.

Furthermore, the effect of Al-trace dimension on the MTTF could be estimated using Eq. (1). For the same solder joint with different dimensions of the Al traces under the

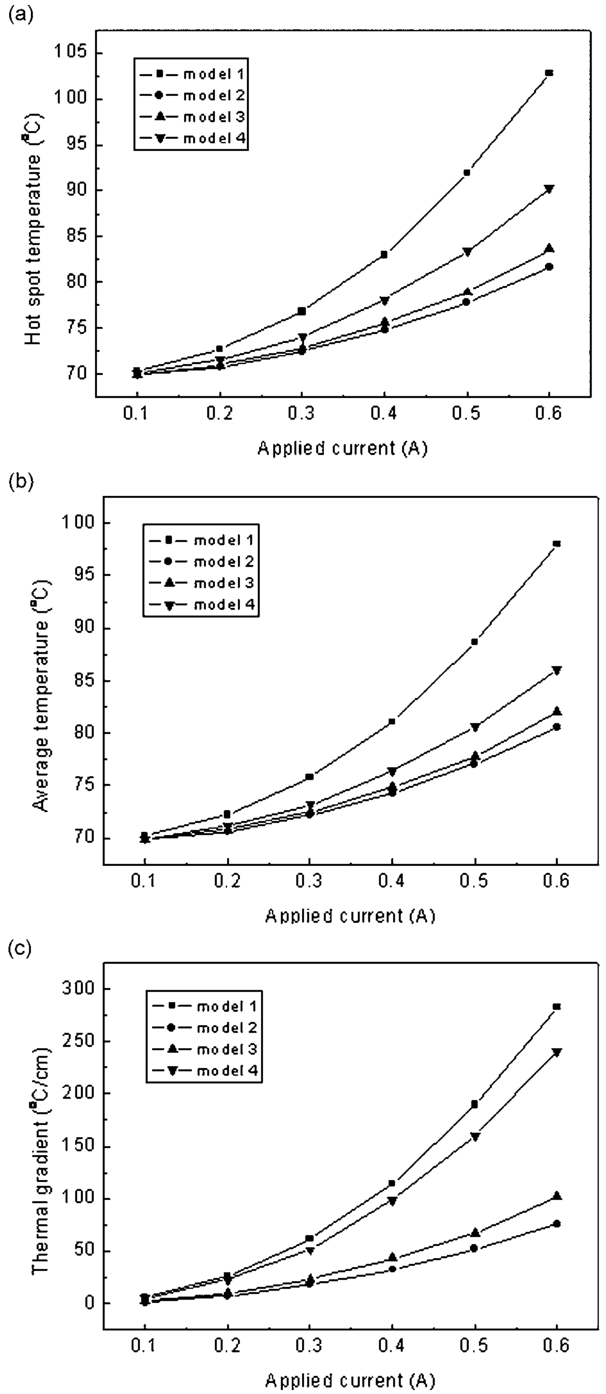

FIG. 4. (a) The hot-spot temperature. (b) The average temperature. (c) The thermal gradient in the solder bump as a function of applied current up to 0.6 A at 70 °C for the four models.

same stressing conditions, the activation energy $Q$ and the constant $A$ are kept identical for the four models. Choi *et al.* proposed that the term $j^{-n}$ in the equation needs to be revised to $(cj)^{-n}$ in order to include the high current crowding effect in the solder joints. In addition, the temperature factor is modified to $(T+\Delta T)$ to account for considerable Joule heating effect during the accelerated electromigration test. Brandenburg and Yeh found that $n$ is equal to 1.8 for the eutectic solder joints when the average current density is employed, and the activation energy they measured was 0.5 eV for the SnPb solder with Al/Ni(V)/Cu UBM.[10] Since voids typically form near the entrance point of the Al trace where the solder experiences the maximum current density and the hot-spot temperature, we propose that the $(cj)$ term to be taken as the maximum current density and the hot-spot temperature should be adopted for the $(T+\Delta T)$ term. For the solder joint in the standard model, the maximum current density reached $1.05\times10^5$ A/cm$^2$ and the hot-spot temperature was 102.8 °C. For the solder joint with Al trace in 100 $\mu$m width, the maximum current density was $6.39\times10^4$ A/cm$^2$ and the hot-spot temperature was reduced down to 81.7 °C. The MTTF would be 6.1 times longer than that of the standard model under 0.6 A at 70 °C, in which the relief of current crowding contributed about 2.5 times, and the decrease in Joule heating contributed approximately 2.5 times on the lifetime increase. For the joint with Al trace in 4.4 $\mu$m thickness, the maximum current density decreased to $6.20\times10^4$ A/cm$^2$ and the hot-spot temperature was reduced to 83.6 °C. The estimated MTTF would be 5.9 times longer than that of the standard. For the fourth model, the MTTF is about 1.7 times longer than that of the standard model, mainly due to lower Joule heating effect. It is noteworthy that the Joule heating effect could be further reduced if the length of the Al trace is further decreased, but the current crowding effect remains the same when only the length is changed. The above estimation demonstrates that the solder joints with wider or thicker Al traces could significantly increase the electromigration resistance. In addition, it also indicates that the Joule heating effect needs to be taken into account during the accelerated electromigration test. Otherwise, the MTTF may be underestimated.

In conclusion, the dimension of the Al trace plays a crucial role in the Joule heating effect during accelerated electromigration test since the Al trace is the dominant heating source. The solder joints with wider or thicker Al trace would render reduced current crowding and Joule heating effects. Therefore, the electromigration lifetime would be extended significantly for the solder joints with wider or thicker Al traces under the same stressing conditions.

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