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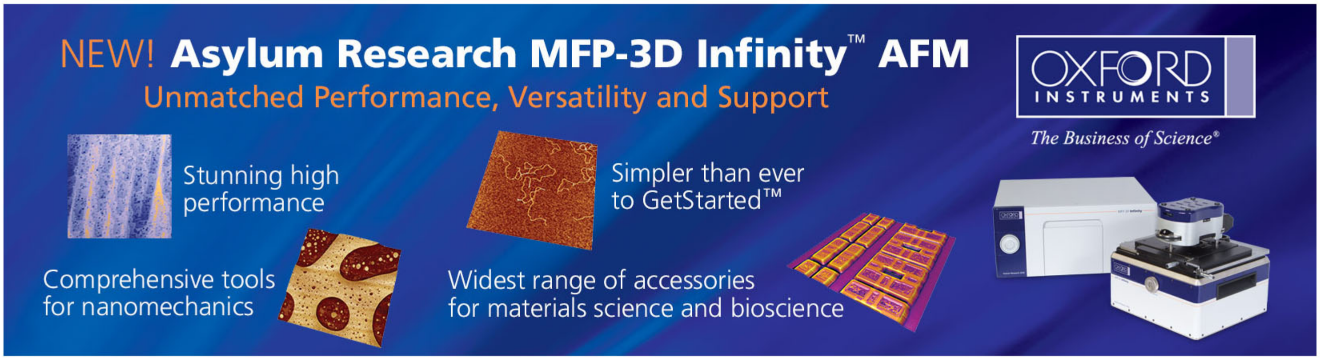

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Effect of Al-trace degradation on Joule heating during electromigration in flip-chip solder joints

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This study investigates the mechanism for the abrupt increase in temperature at later stages of electromigration in flip-chip solder joints. It is found that electromigration also occurs in Al traces when stressed by 0.6 A at 100 °C. Three-dimensional thermoelectrical simulation by finite element analysis was carried out to simulate the temperature distribution in solder joints with and without degradation of the Al trace. It is found that the degradation of the Al trace has substantial effect on the Joule heating of solder joints. This model can explain the serious Joule heating effect in the later stages of electromigration. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2644061]

As the required performance of microelectronic devices increases, the current that each solder bump needs to carry continues to increase.[1] In addition, the miniaturization trend in portable microelectronic products drives the shrinkage of the dimension of solder bumps, resulting in a dramatic increase in current density in solder joints. Therefore, electromigration has become an important reliability issue for flip-chip solder joints.[2]

Several studies investigated the failure mechanism in flip-chip solder joints during electromigration test, and it is frequently reported that there is a dramatic increase in temperature at later stages of electromigration test, causing the melting of solder bumps.[3–6] Melting may happen in the whole solder bump or in the solder adjacent to the Al trace. Tsai *et al.* explained that the solder melted because of two reasons: one is the increase in resistance due to void formation and the other is the local current crowding effect.[5] Huang *et al.* proposed that the void formation due to electromigration would block the heat dissipation of solder joints and thus temperature increases as the voids are formed.[6] Yet, in our previous study, the simulation results show that the temperature increases only by a few °C due to void formation and propagation, even when the voids deplete 95% of the under-bump-metallization (UBM) opening.[7] The experimental observation of solder melting reveals that Joule heating occurs seriously in later stages of electromigration. However, the mechanism of this serious Joule heating remains unclear.

In this study, we investigated the electromigration behavior at 0.6 A at 100 °C and found that the solder melted upon failure. Infrared (IR) microscopy was employed to examine the Al trace, and it is found that the Al trace became open after failure. The total resistance of the stressing circuit was monitored. Three-dimensional (3D) thermoelectrical simulation by finite element analysis was carried out to simulate the temperature increase due to degradation of the Al trace, and the model can explain the serious Joule heating effect in later stages of electromigration.

The solder joints used were eutectic SnPb solder with a 0.7 μm Cu/0.3 μm Cr–Cu/0.1 μm Ti UBM. The passivation and UBM openings were 85 and 120 μm in diameter, respectively. The Al trace on the chip side was 34 μm wide and 1.5 μm thick. The Cu line on the bismaleimide triazine (BT) substrate was 80 μm wide and 25 μm thick. The dimension of the Si die was 7.0×4.8 mm^2 and its thickness was 290 μm, whereas the dimension of the BT substrate was 5.4 mm wide, 9.0 mm long, and 480 μm thick. The chip side was placed on a hot plate, which was maintained at 100 °C, and the current applied was 0.6 A, which corresponded to a current density of 5.3×10^3 A/cm^2 in the UBM opening. The current was terminated by a computer program when the resistance of the stressing circuit exceeded 9999 Ω. The failure time was 25 h under this stressing condition.

Infrared microscopy was employed to measure the temperature distribution and modify the simulation boundary conditions in our previous study.[8] In this study, the infrared microscopy was utilized to examine whether there was any damage in the Al trace, since Si is transparent to infrared. Scanning electron microscopy (SEM) was adopted to inspect the microstructure of the solder joints. According to the experimental results, we modified the resistance of the Al trace. 3D thermoelectric simulation was performed to investigate the effect of Al trace degradation on the Joule heating of the solder joints.

To one's surprise, open failure occurred in the Al trace instead of inside solder bumps under this stressing condition. Figure 1(a) shows IR radiant image before current stressing at 100 °C. The radiance of Al was smaller than that of the underfill. Thus, it appeared brighter in the image. The Al trace can be clearly seen and the two solder joints subjected to current stressing were labeled as bump 1 and bump 2. The two bumps were directly below the circular Al pads. After stressed by 0.6 A at 100 °C for 25 h, the Al trace near bump 2 shows a discontinuous image, as indicated by the solid arrow in Fig. 1(b). The direction of the electron flow was also indicated by the dashed arrows in the figure. The Al trace might become open there. In the bump pairs in Fig. 1, the failure happened on the anode of the Al trace. Nevertheless, the failure may also occur on the cathode end of the Al trace in other cases.

The solder bumps melted after failure, as shown in the cross-sectional SEM images in Figs. 2(a) and 2(b). The bumps were polished to approximate the center area. Dam-

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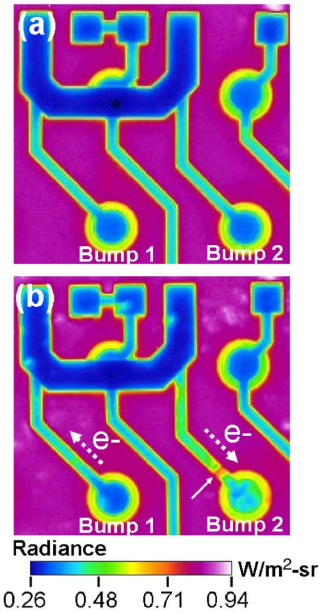

FIG. 1. (Color online) Plan-view radiance-mode IR images of the Al trace (a) before current stressing and (b) after stressing for 25 h. Open failure was found to be at the Al trace near bump 2.

age was found in bump 2, where electrons drifted from the chip side to the substrate side. In addition, the Pb-rich phase in both bumps became finely dispersed. This microstructure change indicated that both solder bumps melted completely upon failure, i.e., the temperature was over 183 °C. This melting behavior demonstrated that serious Joule heating occurred before failure.

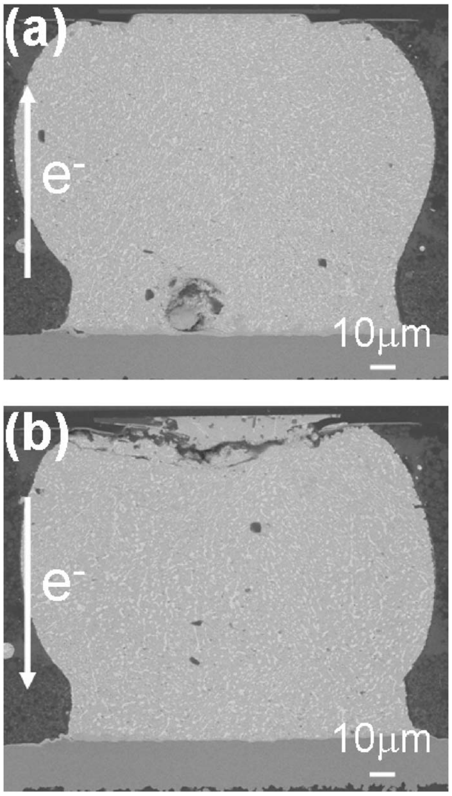

FIG. 2. Cross-sectional SEM images of the solder bumps after open failure for (a) bump 1 and (b) bump 2. Melting behavior occurred in both bumps, and electromigration damage was observed on the chip side of bump 2.

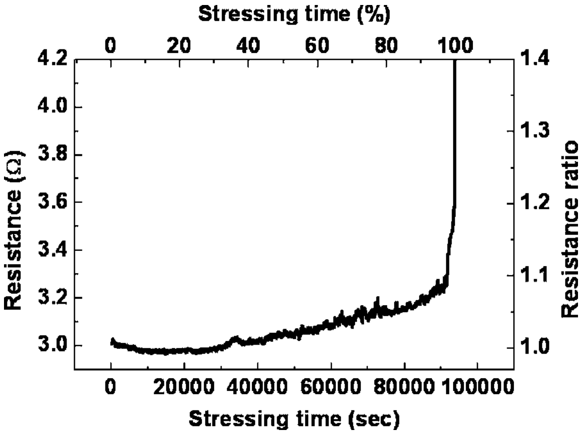

FIG. 3. Measured resistance of the stressing circuit as a function of stressing time. Abrupt increase in resistance took place at later stages of electromigration.

To investigate the mechanism of the abrupt rise in temperature before failure, the change in resistance of the whole stressing circuit was also monitored during the electromigration test, as shown in Fig. 3. The initial total resistance was 3.0 Ω, which also included the resistance of the Al trace on the Si chip, Cu lines on the BT substrate, and the external Cu lines added for current stressing. The theoretic resistance for the Al trace was about 1.5 Ω before current stressing. As stressing time increased, the total resistance increased slowly to 3.2 Ω at 91 500 s, which was about 90% of the failure time. The temperature rose abruptly after 91 500 s, and it increased over 4.2 Ω upon failure. Since the Al trace was found to be open after failure, it is speculated that electromigration damage also occurred in the Al trace, and the degradation of the Al trace may be responsible for the abrupt rise in temperature.

To verify if the increase in resistance of the Al trace can have substantial influence on Joule heating effect, 3D thermoelectric simulations were carried out with and without considering the increase in resistance in the Al trace. Figure 4(a) shows the changes in hot-spot temperature in solder due to void formation when stressed at 0.6 A at 100 °C without considering the damage in the Al trace. The hot-spot temperature was 137.5 °C, which means that the Joule heating effect increased the temperature in the solder bump by 37.5 °C. The hot-spot temperature decreased in the beginning as the voids grew and it increased at later stages. Nevertheless, the increase in temperature was only less than 5 °C even though the voids depleted about 95% of the UBM opening, because the increase in bump resistance was less than 100 mΩ. These results are consistent with our previous findings even under a different stressing condition.[7] As a result, void formation and propagation cannot explain the dramatic rise in temperature in solder at later stages.

It is worth mentioning that the maximum temperature in the Al trace was as high as 217 °C at the initial stage of electromigration. Furthermore, the corresponding current density in the Al trace was as high as 1.2×10^6 A/cm^2. Therefore, electromigration in Al could occur under this stressing condition.[1,9] On the other hand, the current density was only 3.0×10^4 A/cm^2 and the temperature was about 130 °C. Thus, electromigration would not initiate in the Cu lines in the BT substrate.[10,11] In addition, the stressing circuit outside the package had even larger cross section than that of

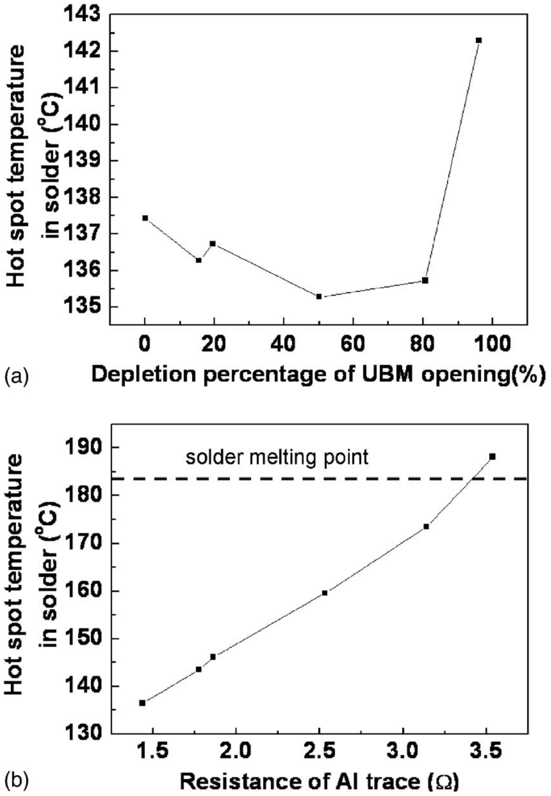

FIG. 4. (a) Hot-spot temperature in the solder bump as a function of the depletion percentage of UBM opening due to void formation. (b) The hot-spot temperature in the solder bump as a function of the resistance of Al trace. Formation of voids was not considered in these results.

the Cu line. Thus, damage may not occur in the external circuit. Consequently, it is reasonable to assume that the huge increase in resistance of 1.2 Ω at later stages of electromigration is mainly attributed to the electromigration damage of the Al trace. Thus, the resistance of the Al trace was increased accordingly by adjusting the Al resistivity in the simulation model. Figure 4(b) shows the hot-spot temperature in the solder bump as a function of the resistance of the Al trace without considering void formation, and it is found that the temperature increased significantly as the resistance of the Al trace increased. In particular, the temperature exceeded the melting point of solder when the resistance of the Al trace increased from 1.5 to 3.5 Ω. On the other hand, the maximum temperature in the Al trace also increased from 217 °C to about 390 °C when the resistance of the Al trace increased from 1.5 to 3.5 Ω, which also accelerated the electromigration in the Al trace.

There exists a discrepancy in the change in resistance required for the temperature in solder to exceed 183 °C in the experimental observation and simulation results. In the experiments, an increase in resistance of approximately 1.2 Ω was detected upon failure as seen in Fig. 3 and the solder melted after failure. However, in the simulation model, it required an increase in resistance of about 2.0 Ω to do so. This discrepancy may be attributed to the fact that the resistance right before failure was not recorded. In Fig. 3, the last point of resistance was 4.2 Ω and it jumped to above 9999 Ω for the next point, which was not shown. The time span between the two points was 10 s, which implies that the resistance may exceed 4.2 Ω, i.e., the increase in resistance right before failure could be larger than 1.2 Ω.

Aluminum electromigration may occur quite often during the accelerated electromigration of flip-chip solder joints. The width of the Al trace was only 34 μm for the samples used in this study. Typically, it is 100 μm wide and 1.5 μm thick, and the stressing currents range from 0.5 to 2.0 A. The current density in the Al trace reaches 8×10^5 A/cm^2 with the applied current of 1.2 A. As for the stressing temperature, the ambient temperature may be elevated to 150 °C or higher, especially for Pb-free solders. Thus, the real temperature in the Al trace may exceed 200 °C easily if the Joule heating effect is considered. In fact, we also observed similar results for the Al trace of 100 μm wide and 1.5 μm thick when stressed by 0.75 A or higher. The above results indicate that electromigration in the Al trace cannot be ignored during the electromigration test of solder joints, and testing conditions should be chosen with caution to avoid it.

In summary, the mechanism of dramatic Joule heating effect at later stages of electromigration in flip-chip solder joints has been studied using IR microscopy and 3D thermo-electrical simulation. It is found that electromigration also occurred in the Al trace under stringent stressing conditions, resulting in a resistance increase in the Al trace. Since the major heating source in the stressing circuit is the Al trace, degradation of the Al trace caused serious Joule heating at later stages of electromigration. This model can explain the observed abrupt rise in temperature in the solder bumps before failure.

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