

## Thermomigration in flip-chip SnPb solder joints under alternating current stressing

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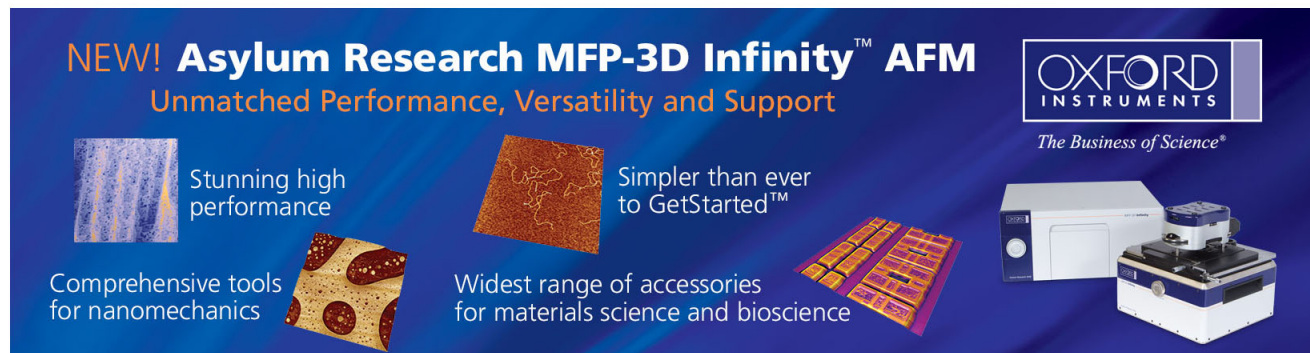
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## Thermomigration in flip-chip SnPb solder joints under alternating current stressing

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Thermomigration in flip-chip solder joints is investigated using alternating currents and infrared microscopy to decouple it from electromigration effect. It is found that the thermal gradient in solder bump can be as high as 2143 °C/cm when  $9.2 \times 10^4$  A/cm<sup>2</sup> was applied at 100 °C. Markers fabricated by focus ion beam are employed to measure the thermomigration rate. The thermomigration flux is measured to be  $3.3 \times 10^{13}$  at./cm<sup>2</sup>. With the known thermal gradient, the molar heat of 26.8 kJ/mole has been obtained for the transport of Pb. © 2007 American Institute of Physics. [DOI: 10.1063/1.2721136]

Electromigration in flip-chip solder joints has attracted a lot of attention in recent years due to the miniaturization trend in high-performance devices.<sup>1</sup> As the current density in solder bump continues to increase, the electromigration becomes an inevitable reliability issue in solder joints. During electromigration test, thermomigration also occurs under severe stressing conditions.<sup>2-4</sup> Since Al traces act as the major Joule heating source,<sup>5,6</sup> the solder close to the chip is hotter than that near the substrate, creating a thermal gradient across the solder bump, thus driving the motion of Sn and Pb atoms. Ye *et al.* performed a simulation and reported that the thermal gradient in the solder joint may be as high as 1500 °C/cm when applied by 1 A.<sup>2</sup> Huang *et al.* found that Sn atoms move to the hot end,<sup>3</sup> while the Pb atoms diffuse to the cold end. They estimated that the thermal gradient needed for thermomigration to occur during electromigration is 1000 °C/cm. Chuang and Liu created a thermal gradient of up to 1000 °C/cm in a Cu/SnPb/Cu sandwich structure, and the heat of transport was measured to be 22.16 kJ/mole.<sup>4</sup> However, there are no experimental data to verify if such a large thermal gradient exists in real flip-chip solder bumps.

In this study, infrared microscopy was employed to measure the thermal gradient directly in cross-sectioned solder joints. An alternating current (ac) was applied to the joint to decouple the thermomigration from electromigration effect, since there is no electromigration effect under ac stressing. However, the ac produces the same amount of Joule heating as the direct current dose. In addition, markers indented by focused ion beam (FIB) were employed to measure the thermomigration flux in this experiment. Thus, the molar heat of transport can be obtained.

Infrared microscopy was employed to measure the thermal gradient in the cross sections of solder bumps under different stressing currents. The experimental setup is shown in Fig. 1. The diameter of the eutectic SnPb solder joint was 130 μm. It had a height of 70 μm and an under-bump-metallization (UBM) opening of 120 μm in diameter on the chip side. The UBM was electroplated with Ni and Cu. The original dimension of the Al traces on the chip side was

100 μm wide and 1.5 μm thick, while the dimension of the Cu lines on FR5 substrates was 25 μm thick and 100 μm wide. The pitch in the solder bumps was 1 mm.

To observe the thermomigration *in situ*, the bumps were polished laterally to approximate their centers. After being polished, the widths of the Al traces and the Cu lines also decreased accordingly. Current stressing was carried out at a temperature of 100 °C on a hot plate. A constant ac of 0.55 A with a frequency of 45 Hz was passed through two bumps, producing a nominal current density of  $9.2 \times 10^4$  A/cm<sup>2</sup> in the bumps.

Prior to current stressing, the emissivity of the specimen was calibrated at 100 °C. After the calibration, the bumps were powered by an alternating current. The temperature was then measured to record the temperature distribution (map) after reaching a steady state. The temperatures in the solder joints were mapped by Quantum Focus Instruments thermal infrared microscopy, which has a temperature resolution of 0.1 °C and a spatial resolution of 2 μm. The changes in surface microstructure were examined using a scanning electron microscope (SEM).

The thermal gradient can exceed 2000 °C/cm at a higher current density in real flip-chip solder joints. The temperature distribution in the bump before current stressing is shown in Fig. 2(a). The temperature in the solder bump is quite uniform except for the left and right edges of the bump.

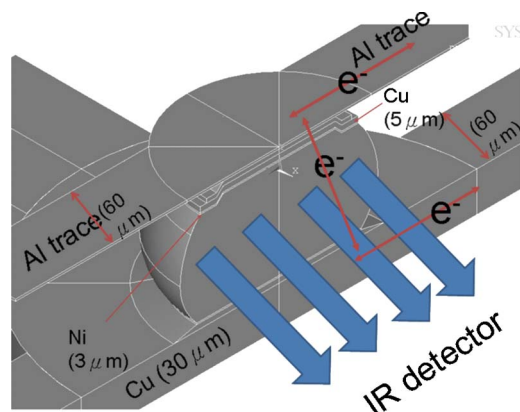


FIG. 1. (Color online) Schematic diagram of the experimental setup used in this study.

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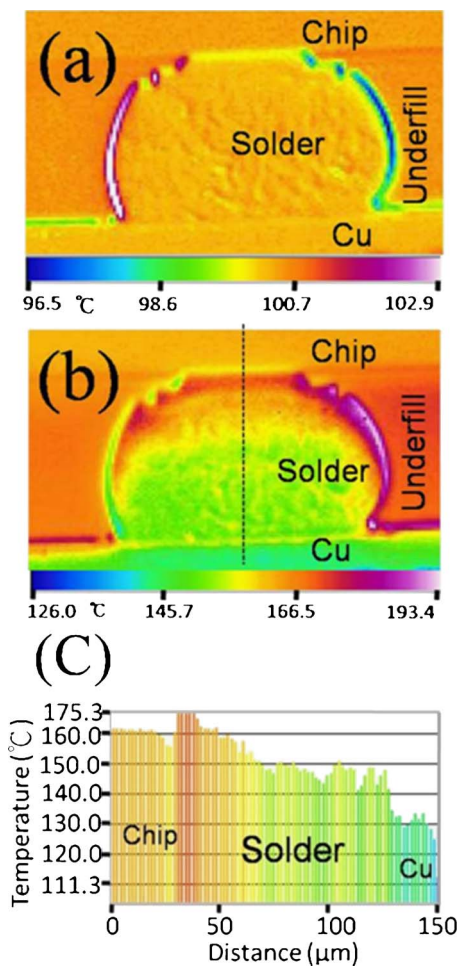


FIG. 2. (Color online) (a) Temperature distribution of the bump before current stressing, showing a uniform temperature distribution in solder; (b) temperature distribution in the bump powered by 0.55 A, which corresponds to a current density of  $9.2 \times 10^4$  A/cm<sup>2</sup>; and (c) temperature profile along the dashed line in (b). The thermal gradient was calculated to be 2571 °C/cm.

The temperatures on the two edges may not be correct since the image was taken at a long exposure time of 15 s and the sample may vibrate during the time span. When the joint was powered by 0.55 A, the temperature increased nonuniformly, as shown in Fig. 2(b). The average temperature increases in the bump because the current stressing was as high as 55.6 °C. The solder near the chip end was hotter since the major Joule heating source was the Al traces on the chip side, which created a thermal gradient across the bump. The thermal gradient is defined here as the difference between average temperature near the substrate end in the bump and that near the chip end in the bump divided by the height of the bump, i.e.,  $(T_{\text{chip}} - T_{\text{sub}})/h$ . The temperatures near the chip and substrate ends were obtained by averaging the values in the white rectangles in Fig. 2(a). Figure 2(c) shows the temperature profile along the dashed line in Fig. 2(b), in which the average temperature in the chip end is 16.0 °C higher than that in the substrate end. The thermal gradient was calculated to be 2143 °C/cm.

The measured temperature gradients in the bump for various stressing conditions are shown in Fig. 3. The temperature gradients increase as the stressing currents increase. The joints may fail instantly when the applied current exceeds 0.6 A. The temperature gradient was as high as

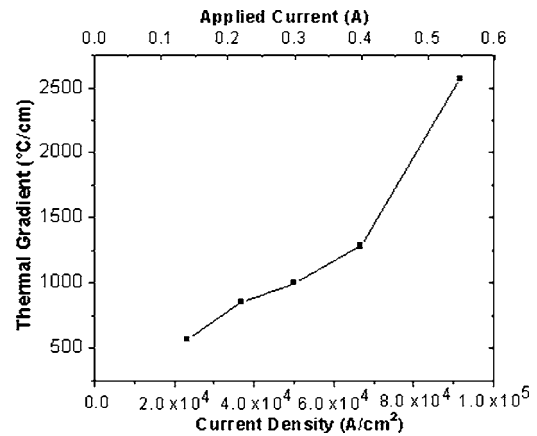


FIG. 3. Measured temperature increases in the bump as a function of applied current and current densities.

2143 °C/cm when powered by 0.55 A but only 571 °C/cm when powered by 0.14 A. The current density required to create a thermal gradient of 1000 °C/cm was about  $5 \times 10^4$  A/cm<sup>2</sup>.

Thermomigration behavior becomes severe when the bumps were subjected to a high thermal gradient of 2571 °C/cm. Figure 4(a) shows the backscattered SEM image for the bump before applying the alternating current. After applying 0.55 A at 100 °C for 108 h, thermomigration damage was observed, as illustrated in Fig. 4(b). Some of the solders near the chip side have migrated to the substrate side. In addition, phase separation was found. The Pb-rich phase migrated toward the substrate, which was the cold end. These results are in agreement with those reported by Huang *et al.*<sup>3</sup> As shown in Fig. 2(b), the average temperature in the bump during current stressing was as high as 155 °C, Pb atoms are the dominant diffusion species. Therefore, more Pb atoms are migrated to the substrate side than the flux of Sn atoms migrating in the opposite direction. Therefore, depletion was observed on the chip side. The other bump that experienced current stressing also exhibited similar behavior, thus it was not shown in this letter.

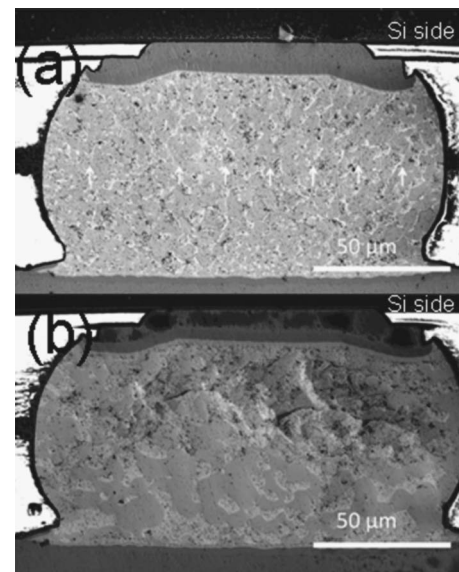


FIG. 4. Backscattered SEM images for the bump: (a) before current stressing and (b) after ac stressing by 0.55 A at 100 °C for 108 h. Thermomigration damage occurred obviously.



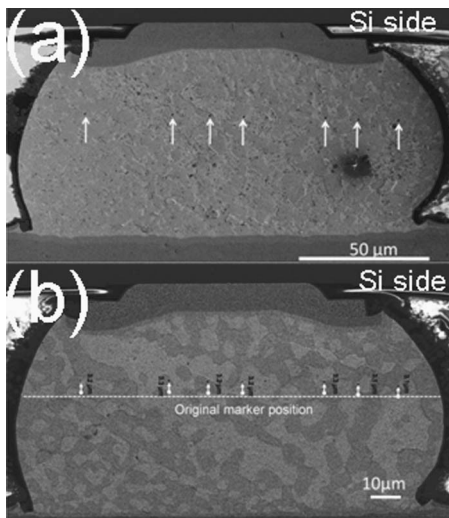


FIG. 5. SEM images for the bump with seven markers: (a) before current stressing and (b) after current stressing by 0.55 A at 100 °C for 108 h. All the markers moved upwards after ac stressing.

To measure the thermomigration flux under a specific thermal gradient, seven 0.1  $\mu\text{m}$  holes were etched by Ga ions in a FIB on the surface of another bump.

The depth of the hole was about 200 nm. The holes were used as markers during thermomigration. Figures 5(a) and 5(b) show SEM images for the bump with the markers before and after current stressing, respectively. The thermal gradient was measured to be 2143 °C/cm for this bump under the stressing of 0.55 A. The seven markers all moved upwards by a distance of 3.2  $\mu\text{m}$  after current stressing for 96 h, as the Pb atoms moved downwards. The original marker positions were indicated in Fig. 5(b).

By measuring the average displacement of the markers  $\Delta X$ , the thermomigration  $J_{\text{TM}}$  can be obtained using the following equation.

$$J_{\text{TM}} = \frac{(A\Delta X)\rho N}{MA t}, \quad (1)$$

where  $\rho$  is the density of SnPb (8.11 g/cm<sup>3</sup>),  $M$  is the atomic weight of SnPb (136.39 g/mole),  $A$  is the cross-sectional

area, and  $t$  is the stressing time. The average displacement was measured to be 3.2  $\mu\text{m}$ . Thus, thermomigration flux was calculated to be  $3.3 \times 10^{13}$  at./cm<sup>2</sup>. In addition, the thermomigration flux for the one-dimensional case under a thermal gradient  $dT/dx$  can be expressed as<sup>5,7</sup>

$$J_{\text{TM}} = \frac{nD_A(Q^*/N)}{kT^2} \left( \frac{dT}{dx} \right), \quad (2)$$

where  $n$  is the atomic density,  $D_A$  is the coefficient of self-diffusion,  $k$  is Boltzmann's constant,  $N$  is Avogadro's number,  $dT/dx$  is the thermal gradient, and  $T$  is the temperature.  $Q^*$  is a constant, which is called the heat of transport. With the  $D_A$  data published by Gupta *et al.*,<sup>8</sup> the molar heat flux  $Q^*$  can be determined to be 26.8 kJ/mole. Compared with the value reported by Chuang and Liu, the value obtained in this study was slightly larger. Their testing conditions were 80–110 °C on eutectic SnPb alloy, and the value they obtained was about 22.16 kJ/mole.

In summary, by using alternating currents, the thermomigration effect can be investigated independently. A very large thermal gradient exceeding 2143 °C/cm can be detected at a high current density with the aid of an infrared microscope. Pb atoms were found to diffuse to the cold end under a current stressing of 0.55 A. From the displacement of markers, the thermomigration flux can be measured to be  $3.3 \times 10^{13}$  at./cm<sup>2</sup>. With the measured flux and thermal gradient, the molar heat of transport of Pb has been calculated to be 26.8 kJ/mole.

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