Thermomigration in Eutectic Tin-Lead Flip Chip Solder Joints

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Abstract
The thermomigration of eutectic tin-lead flip chip solder joints under ambient temperatures of 20 °C, 100 °C and 150 °C was investigated in terms of microstructural evolution. No significant thermomigration occurred after 100 h at 20 °C and at 100 °C. Only microstructural coarsening was observed in solder joints for these cases. However, Pb thermomigration and phase segregation were observed in solder joints after only 50 h at 150 °C. Measurements showed that the temperature difference between the chip side and the substrate side reached 8.1 °C (a temperature gradient of about 2700 °C/cm across the solder joints) at an ambient temperature of 150 °C. It is believed that Pb atoms migrated from the chip side (the hot side) to the substrate side (the cold side) under a temperature gradient of 2700 °C/cm.

1. Introduction
With the trend towards higher integration and further miniaturization in the microelectronics industry, the cross sectional area of conductive lines on the chip has been decreased significantly. Due to different electrical resistances and thermal dissipations of individual parts within the flip chip interconnection structure, it is possible that the heat accumulated at the chip side is larger than that at the substrate side. This will inevitably lead to a considerable temperature gradient across the solder joints, which can provide a driving force for atomic diffusion to trigger thermomigration. In our previous studies [1], we established the presence of this temperature gradient by observing the melted solder near the chip side. Other research work concerning Joule heating also verified this by finite element simulation [2]. Recently, hot spots near the entrances of Al traces in the solder joints have been detected by a thermal infrared microscope [3], which provides further support for the existence of a temperature gradient across solder joints.

Being a complex mass migration process, thermomigration, of which the driving force comes from the energy transported by the moving atoms and the interactions with the usual heat carriers in the lattice [4], has become a new reliability concern for flip chip solder joints. Roush and Jaspal [5] ever reported both Pb and In moved under a temperature gradient in lead-indium solder alloys. Van Gurp and co-workers [6] observed fast thermomigration in In and In alloy films and found that atoms migrated from the hot to the cold areas. The latest reports about thermomigration in solder joints include [7,8,9]. Basaran and co-workers [7] reported that thermomigration in flip chip solder joints may assist or counter electromigration with microstructural observations and marker measurements, and their simulation predicted a temperature gradient of 1500 °C/cm across solder joints. Chen’s group [8] also proposed that a temperature gradient of 365 °C/cm was one of the possible reasons for anode failure in their experiments. However, the individual contribution of thermomigration to the failure of solder joints was not investigated in these papers. Recently, Tu’s group observed obvious thermomigration in tin-lead composite solder joints [9] and wires [10], whereas the microstructural evolution such as phase separation in eutectic tin-lead solder joints under thermomigration was not characterized.

As thermomigration might play an important role in the solder joints of microelectronic devices, this investigation is intended to study thermomigration phenomena in eutectic tin-lead solder joints under Joule heating in terms of microstructural analysis.

2. Experimental
The samples used in this study were flip chip test chip kits, including dummy chips (from Flip Chip International) and laminate boards (PB08-250×250, from Practical Components Incorporation). The chip size was 6 mm×6 mm with a thickness of 0.635 mm. The Al traces on the chip had a width of 105 μm and a thickness of about 2 μm. The under bump metallization (UBM) layer was composed of a thin film of Al/Ni/Cu, and the via in the passivation layer for this UBM had a diameter of 102 μm. There were four rows of 12 solder bumps along each side of the chip with a pitch of 457 μm. The solder bump material was eutectic tin-lead, and the bump diameter was about 190 μm. The test substrate was a high temperature FR4 board with a thickness of 0.84 mm. The copper pad connected to the flip chip had a width of about 152 μm and a thickness of 35 μm, which was covered with a thin 2 μm nickel-plated layer. A solder assist layer of organic solderability preservation coating was placed on the bond pad area. Both chips and substrates were daisy-chained for electrical continuity.

The flip chip was attached to the substrate using flip chip bonding technology by a KarlSuss FCM Flip-Chip bonder. The bonded samples were then reflowed using a five-zone air convection oven (BTU VIP-70 N). In the temperature profile, the peak temperature was 230 °C and the time above liquidus was about 60 s. Figure 1 shows a typical bonded sample prepared for testing.

Figure 2 is a sketch of flip chip solder joints used for this study. Two pairs of solder joints (joint 5, 6, 7 and 8) were powered with a current of 1.8 A at different ambient temperatures of 20 °C, 100 °C and 150 °C. The applied constant current of 1.8 A corresponds to an average current density, defined by dividing the applied current by the area of the passivation via, of about 2.2×10^4 A/cm². A MC-810 model (Tabai Espec Corp.) chamber and a LHT4/30 type (Carbolite) oven were utilized to realize the stable and...
uniform ambient temperatures of 100 °C and 150 °C. The temperature difference between the chip side and the substrate side under the current stressing and different ambient temperatures was inspected with a M.O.L.E. thermal profiler by contact temperature measurement. Two micro-thermocouples, with a temperature measurement resolution of 0.1 °C, were directly attached on top of the chip surface and the copper trace surface near the powered joints, as shown in Figure 3. An additional ten minutes was needed for thermal stabilization and equilibrium of test samples after the current was applied at a certain ambient temperature.

Figure 1 Flip chip sample used in this study (The arrowed region shows the area which is given as an expanded sketch in Figure 2).

Figure 2 Sketch of solder joints with four solder joints (joint 5 to 8) under current stressing.

Figure 3 Temperature measurement of chip surface using thermocouples.

Only un-powered solder joints such as joint 4 and 9 (see Figure 2) were investigated for thermomigration study. After an experiment, the samples were ground and polished with a great deal of care for cross-sectional observations. These cross sections were examined under an optical microscope and with a scanning electron microscope (SEM, Philips XL40 FEG) separately. In addition, the local compositions were analyzed using energy dispersive X-ray (EDX).

3. Results and Discussions

A current of 1.8 A was applied to the middle four solder joints (joint 5, 6, 7 and 8) at 20 °C, 100 °C and 150 °C. The local temperatures on top of the chip surface and the copper trace surface near the powered joints were inspected and compared. As shown in Table I, the temperature difference between the two surfaces increased with the ambient temperature in this test structure, and it reached 8.1 °C at an ambient temperature of 150 °C. It should be mentioned that the temperature measurement was not accurate because of the contact resistance between the thermocouples and the surfaces, and the actual temperature gradient was likely to be larger than the measured value because the top of solder joints was covered by the chip. However, our measurements provide an important reference that the effect of Joule heating was significant for these test structures, and the temperature gradient across the powered solder joints may approach 2700 °C/cm (8.1 °C/30 μm ≈ 2700 °C/cm). Moreover, owing to good thermal conductivity of silicon chip, this temperature gradient was formed across the adjacent un-powered solder joints. Also, the electrical resistance of the Al traces, solder joints and copper conductors in this test structure were calculated to be approximately 121 mΩ, 1.636 mΩ and 1.942 mΩ, respectively. These values represent their relative contributions to the Joule heating. It is clear that the thin Al trace is the primary heat source because of its higher Joule heating effect. Hence, it is believed that a certain temperature gradient existed in the un-powered solder joints such as joint 4 and 9.

Table I Temperature measurement results at different ambient temperatures when four solder joints were powered with 1.8 A current

<table>
<thead>
<tr>
<th>Ambient temperature (°C)</th>
<th>20</th>
<th>100</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip temperature (°C)</td>
<td>43.1</td>
<td>122.2</td>
<td>172.9</td>
</tr>
<tr>
<td>Copper trace temperature (°C)</td>
<td>39.6</td>
<td>116.3</td>
<td>164.8</td>
</tr>
<tr>
<td>Temperature difference between the chip side and the substrate side (°C)</td>
<td>3.5</td>
<td>5.9</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Figure 4(a) and 4(b) illustrate the original microstructure of solder joints before the experiments (as-reflowed). Fine scale Pb rich phase particles (light regions) are uniformly dispersed in the Sn rich matrix (dark regions). These two regions are α-Pb and β-Sn phases, respectively.

For samples treated at 150 °C, cross sectioning was performed when powered joint pairs failed after 50 h of current stressing. However, for samples at 20 °C and at 100 °C, no joint pair was found to fail even after 100 h. Cross sections of these samples whose stressing was conducted up to 100 h were also prepared for comparison.

Figure 5 shows an SEM image of the cross section of un-powered solder joint after 100 h at 20 °C. No thermomigration phenomena could be detected. However, phase coarsening was observed after 100 h as compared with the original microstructure in Figure 4. This can be explained as phase coarsening as a result of the temperature
rise, of which the thermodynamic basis is a combination of the driving force for grain coarsening and the Thomson-Freundlich solubility relationship [11]. Moreover, phase separation can be accelerated considerably when the homologous temperatures are high. Therefore, more substantial coarsening of un-powered solder joints was observed at 100 °C after 100 h, as shown in Figure 6. However, thermomigration phenomena were still not apparent. This is similar to the study by Chiang’s group [12]. They noticed that the thermomigration of un-powered solder joints was not clear despite a microstructural change when tin-lead solder joints were stressed at a current density of 2.01×10⁵ A/cm² at 100 °C.

Obvious Pb thermomigration was detected at 150 °C after 50 h, as illustrated in Figure 7(a) and 7(b). The Pb rich phase separated from the Sn rich phase completely and accumulated at the bottom of solder joints. It is believed that Pb migrated to the substrate side (the cold side) under the temperature gradient across the un-powered solder joints since no current was applied to them. This was also supported by the EDX analysis. The result is in reasonable agreement with those of thermomigration in tin-lead composite flip chip solder joints reported by Tu’s group [9]. They found that Pb moved to the cold side and Sn to the hot side under an estimated temperature gradient of above 1000 °C/cm at 150 °C. For other un-powered solder joints (from joint 1 to 3 and joint 10 to 12), the thermomigration was not apparent except for a large amount of phase coarsening, as shown in Figure 8(a) and 8(b).
An appropriate explanation for the above is as follows. At a lower ambient temperature, the diffusion of atoms was not fast enough to cause a significant migration within a short time. More importantly, the temperature differences between the chip side and the substrate side at 20 °C and 100 °C were small. Likewise, at 150 °C, the temperature gradients across the solder joints (from joint 1 to 3 and joint 10 to 12) were not high enough due to the increasing distances from the powered solder joints, i.e., the source of heating. This is why no noticeable thermomigration in those solder joints was found under these conditions. In contrast, at 150 °C there existed a larger temperature gradient across the solder joint 4 and 9 which were nearest to the heat source. Since the flow of atoms is from the hot side to the cold side if there is a temperature gradient [5,6,7,9,10], it is supposed that Pb and Sn atoms all migrated from the hot side to the cold side under this temperature gradient. However, Pb atoms are the dominant diffusion species in the eutectic tin-lead solder above 120 °C [13,14,15]. Therefore, Sn atoms migrated slowly and replenished the vacancies due to the depletion of Pb atoms. Macroscopically, the Pb-rich phase migrated to one side and the Sn-rich phase was pushed towards the opposite side. This gives a reasonable explanation to the fact that the effect of thermomigration was apparently visible in these solder joints at 150 °C.

On the other hand, it is noticeable that a few fine Pb grains are still dispersed in the tin-matrix near the hot end, and Sn grains are dispersed in the lead-matrix near the cold end in Figure 7(b). This is due to dual-phase precipitation. According to the tin-lead phase diagram [16], dual-phase precipitation is expected to occur when single-phase Pb or single-phase Sn are cooled down from around 180 °C.

Now, the contribution of thermomigration to the failure of solder joints should be considered here. We make a simple estimation for the contributions by driving forces of thermomigration and electromigration with reference to [9]. Taking the atom diameter (d) as 3×10^-8 cm [9] and a temperature gradient (g) of 2700 °C/cm, the thermal energy change by the driving force of thermomigration is calculated to be:

\[ \Delta \omega_{tm} = 3k\Delta T = 3kdg \]
\[ = 3 \times 1.38 \times 10^{-23} \times 3 \times 10^{-8} \times 2700 \quad (1) \]
\[ = 3.35 \times 10^{-27} \text{Joule} \]

In contrast, taking an effective charge number (Z*) of 10 [17], a resistivity (\( \rho \)) of 10×10^8 Ω m [17], and the current density (j) of 2.2×10^6 A/m², the energy change by the force of electromigration is estimated to be:

\[ \Delta \omega_{em} = Z^* ejd \]
\[ = 10 \times 1.602 \times 10^{-19} \times 10 \times 10^{-8} \times 2.2 \times 10^6 \times 3 \times 10^{-10} \quad (2) \]
\[ = 1.06 \times 10^{-26} \text{Joule} \]

The ratio of \( \Delta \omega_{tm} \) to \( \Delta \omega_{em} \) is then:

\[ \frac{\Delta \omega_{tm}}{\Delta \omega_{em}} = 3.35 \times 10^{-27} \quad (3) \]

Consequently, mass flux due to the thermomigration driving force cannot be ignored completely, and the equation for mass flux is described as follows:

\[ J_{maxflux} = J_{em} + J_{\sigma} + J_{tm} \quad (4) \]

where \( J_{em} \) is the flux due to the electron wind force, \( J_{\sigma} \) is the flux due to the hydrostatic stress gradient, and \( J_{tm} \) is the flux due to the thermomigration. Furthermore, similar to that in an Al interconnection [18,19], the combined effect of electromigration and thermomigration in flip chip solder joints should be another important reliability concern.

4. Conclusions

We present results on thermomigration in eutectic tin-lead solder joints at different ambient temperatures of 20 °C, 100 °C and 150 °C. For the case of 20 °C, phase coarsening was observed in the un-powered joints after 100 h. However, no thermomigration could be detected. For the case of 100 °C, more dramatic microstructural coarsening was observed after 100 h, but thermomigration was still not evident. For the case of 150 °C, obvious Pb thermomigration was observed after only 50 h.

The driving force of thermomigration mainly comes from the temperature gradient across the un-powered solder joints. Temperature measurements showed the existence of a temperature difference of about 8.1 °C between the chip side and the substrate side (temperature gradient of about 2700 °C/cm across solder joints) at 150 °C. At an ambient temperature of 150 °C Pb and Sn atoms obtain sufficient diffusion energy and migrate from the hot side to the cold
side, and the migration of Pb can be observed because of its faster diffusion rate in eutectic tin-lead solders. In contrast, Pb migration at 20 °C and at 100 °C could not be observed due to the smaller temperature gradients and lower ambient temperature.

The energy change by the driving force of thermomigration is estimated to be about $3.35 \times 10^{-27}$ Joule compared to that of electromigration ($1.06 \times 10^{-26}$ Joule). The atomic flux due to thermomigration should be considered in the total mass flux since thermomigration plays an important role in the reliability of solder joints in microelectronic devices.

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