**Mechanical Implications of High Current Densities in Flip-chip Solder Joints**

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**ABSTRACT:** We studied the electromigration damage to flip-chip solder joints of eutectic Sn/Pb under current stressing at room temperature with a current density of $1.3 \times 10^4$ A/cm$^2$. The height of the solder joints was 100 $\mu$m. The mass accumulation near the anode side and the void nucleation near the cathode were observed during current stressing. In the preliminary experiment, the surface marker movement technique was used to measure the atomic flux driven by electromigration and to calculate the product of effective charge number and diffusivity ($DZ^*$) of the solder. Subsequent experiments revealed that the presence of thermomigration due to joule heating makes the extraction of the product of effective charge number and diffusivity erroneous when using marker movement technique.

**KEY WORDS:** solder joint, reliability, electromigration, phase coarsening, thermomigration.

**INTRODUCTION**

The trend in flip-chip and ball grid array (BGA) packaging is to increase I/O count. This trend drives the interconnecting solder joints to be smaller in size and, thus, they have a higher current density. The current densities further increase as chip voltage decreases and as the absolute current level increases. There is also a similar drive in flip-chip power semiconductors and evolving system-on-package power processors to increase the current densities (Liu et al. 1999; Paulasto-Krockel and Hauck, 2001). A physical limit to increasing current density in both microelectronics and power electronics is electromigration. Electromigration of interconnecting metal lines is the major source of failure in ICs, but it is seldom recognized as a reliability concern for solder joints. Most of the published literature on electromigration focuses on thin, pure metal lines,
and there is little published on present day solder interconnects (Brandenburg and Yeh, 1998; Lee and Tu, 2001; Lee et al., 2001; Liu et al., 1999, 2000).

This work covers the electromigration damage to eutectic Sn/Pb flip-chip solder joints under current stressing at room temperature ambient $1.3 \times 10^4 \text{A/cm}^2$. The test flip-chip modules were produced in an industrial lab to obtain consistent interconnects representative of high volume commercial manufacturing. The test module has a dummy silicon die with only an aluminum (Al) conductor trace on it. The silicon die is attached to a FR4 printed circuit board (PCB) through eutectic Pb37/Sn63 solder joints. The copper plates on the PCB provide the wetting surface and the electric connection to the solder joints. The under bump metallization (UBM) on the silicon die side is electroless nickel (Ni). The voids between the solder joints are filled with underfill between the silicon die and PCB substrate. The thickness of the Al trace is about 1 μm and the width is about 150 μm. The diameter of the solder joint is around 140–150 μm and the height is about 100 μm. The test module was cross-sectioned and finely polished towards the center of the solder joints before current stressing. On each module, two solder joints were tested. The solder joints on each test module is configured in such a way that current always flows from the copper trace through solder joint A into the Al trace on the silicon die and then flows through solder joint B out to another copper trace. Figure 1(a) shows the schematic cross section of the test module and the direction of current flow in the experiments.

In the preliminary experiment, only solder joint A was measured. However, by measuring both solder joints A and B on the test module in the subsequent experiments, interesting results were revealed. Mass accumulation near the anode and void nucleation near the cathode were observed during current stressing in Module #1. We used surface marker movement to measure the atomic flux driven by electromigration and to calculate the product of effective charge number and diffusivity ($D \times Z^*$)
of the solder. Subsequent experiments revealed that thermomigration due to joule heating makes the extraction of the product of effective charge number and the diffusivity results flawed. Pb phase coarsening was also observed during the experiment.

ELECTROMIGRATION RESULTS

The eutectic Sn/Pb solder joints on Module #1 were cross-sectioned and polished for direct observation of electromigration. A schematic cross-section of the solder joint and an SEM secondary image of the cross section are shown in Figure 1. The specimen was cross-sectioned and polished to the center of the solder joint using 240, 600, and 1200-grit silicon carbide abrasive paper. The joint was subjected to current stressing with 1 A DC at room temperature, yielding an average current density through the solder joint of $1.3 \times 10^4 \text{A/cm}^2$ based on its diameter. We removed the test module for scanning electron microscopy (SEM) analysis after 3, 6, 14.5, and 37.5 h of stressing. A nano-indentation experiment was performed on the solder joints of Module #1 after 37.5 h of stressing.

Figure 2 shows the SEM backscattered images of the cross-sectioned surface of the solder joint for 0, 6, 14.5, and 37.5 h of current stressing. SEM secondary images of the joint after 37.5 h of stressing are shown in Figure 3 at several magnifications. The SEM backscattered image gives more information about elemental composition, whereas the secondary image gives more topographic information (Goldstern et al., 1992).

The direction of electron flow is from the Ni UBM on the silicon die side to the Cu plate on the Printed Circuit Board side. The mass accumulation on the anode side and the void nucleation on the cathode side can be seen in Figures 2 and 3. The surface of the cross-sectioned solder joint became very rough due to electromigration after 37.5 h. Large depression areas formed on the cathode side and large voids formed near the Ni UBM side. This indicates large amounts of mass depletion in the region. Hillocks formed near the Cu plate region due to mass accumulation. Hillocks and crystalline formation were clearly shown in the anode region in Figure 3(a). Figure 3(c) clearly shows both voids and cracks near the cathode region.

ANALYSIS OF ELECTROMIGRATION THROUGH MARKER DISPLACEMENT

In order to measure the atomic flux in the solder joint due to current stressing, inert particles on the sectioned solder surface were used as markers. The markers were SiC particles left on the surface during polishing. The Cu plate–solder interface was chosen as the fixed point of
Figure 2. SEM backscattered image of solder joint on Module #1 for: (a) initial; (b) 6 h; (c) 14.5 h; and (d) 37.5 h.
reference. This method was reported by Lee et al. (2001) in their electromigration experiment.

The markers’ positions and their movements are shown in Figures 4 and 5. All the markers moved to the cathode side, which is the opposite direction of the electromigration flux. We calculated the marker movement...
by measuring the change in marker position with respect to the reference frame on the SEM backscatter images after 6, 14.5 and 37.5 h of current stressing. The average movement of the markers, shown as a dashed line in Figure 6, indicates a near linear dependence on current stressing time. This observation is consistent with Lee and Tu’s (2001) observations.

**CALCULATION OF $D \times Z^*$ IN SOLDER JOINT**

The atomic flux due to electromigration can be calculated from the marker movement, stressing time, and cross-sectional area of solder at the initial marker position (Tu et al., 1992) as follows:

$$J_{\text{atom}} = \frac{V_{\text{EM}}}{\Omega \cdot A \cdot t} = C \frac{D}{kT} Z^* e \cdot \xi$$  \hspace{1cm} (1)
where \( V_{EM} \) is the volume of solder moved by electromigration (cm\(^3\)), \( \Omega \) is the average atomic volume of the solder (cm\(^3\)/atom), \( A \) is the cross-sectional area at the initial marker position (cm\(^2\)), \( t \) is the time of current stressing (s), \( C \) is the number of atoms per unit volume, (atoms/cm\(^3\)) (assumed to be \( 1/\Omega \) in a unary system), \( D \) is the diffusivity, (cm\(^2\)/s), \( k = 8.617 \times 10^{-5} \text{eV/K} \) (Boltzman’s constant), \( T \) is the temperature in Kelvin. \( Z^* \) is the effective charge number, \( e \) is the electron charge, \( \xi \) is the electrical field, (V/cm).

The volume of solder moved by electromigration \( (V_{EM}) \) is calculated using the average marker movements (Lee and Tu 2001; Lee et al., 2001). In this experiment, \( V_{EM} \) is calculated to be \( 4.51 \times 10^{-8} \text{ cm}^3 \) after 37.5 h of current stressing. The cross-sectional area of the solder joint at the initial marker position is \( 7.697 \times 10^{-5} \text{ cm}^2 \). The average marker movement is \( 6.078 \text{ mm} \). The electrical field is calculated with a eutectic Sn/Pb solder resistivity of \( 15 \mu \Omega \cdot \text{cm} \) at room temperature and the current density is calculated from the measured current and the cross-sectional area of solder joint at the initial marker position. In this experiment, the stressing current is 1 A so that the current density is \( 1.3 \times 10^4 \text{ A/cm}^2 \) and the electrical field \( \xi = \rho j = 15 \times 10^{-6} \times 1.3 \times 10^4 = 0.195 \text{ V/cm} \).

The value of \( D \times Z^* \) is thus computed and compared to that found by Lee et al. (2001) and Lee and Tu (2001), as shown in Table 1.
FURTHER DISCUSSION ON ANALYSIS OF MARKER MOVEMENT

The use of marker movements to derive the effective charge number in the previous section is based on the assumption that electromigration is the only driving force for the diffusion in solder joint during current stressing. Therefore, Equation (1) can be used to extract the effective charge number. However, we found that this was not the case in our subsequent electromigration experiments. Thermomigration due to the thermal gradient (which is caused by joule heating) within the flip-chip solder joint is significant and may be a leading cause of diffusion (Ye et al., 2003a,b). In our subsequent experiment, the microstructural evolutions of solder joints A and B of a test module are measured during current stressing. The temperature on the silicon die is measured with a fine-tipped thermocouple thermometer (OMEGA® HH-602). The measurement indicated that the temperature on silicon die (100–150°C) was much higher than ambient temperature. This conflicts with the initial assumption that it was close to the ambient temperature (Lee et al., 2001).

In a typical flip-chip module, the cross-section area of the metal trace on the silicon die is much smaller than that of the solder joint. Therefore, the primary heat source is the metal traces which contribute to most of the electric resistance of the module. The joule heating during current stressing maintains a thermal gradient within the solder joint. This is verified by the three-dimensional coupled thermal-electrical finite element simulation of the real structure of the flip-chip test module (Ye et al., 2003a,b). The temperature of the simulation is in agreement with the temperature measured on the silicon die and indicates that a temperature gradient as high as 1500°C/cm may be maintained within the solder joint. The temperature on Si die–solder interface is much higher than that on solder–copper plate interface (Ye et al., 2003a,b). This thermal gradient is well beyond the reported thermal gradient needed to trigger thermomigration in solder joint (Roush and Jaspal, 1982).

Figures 7 and 8 show marker movement versus stressing time on the cross-sections of solder joints A and B from test module #4. The electron flow direction is different in these two solder joints. As discussed in previous section, if electromigration is the only driving force for diffusion, the marker movement is expected to be in the direction opposite to the electron flow as indicated by the arrows in these two figures. Figure 7 shows that the marker movement in solder joint A of Module #4 agrees with this expectation and confirms that the direction of diffusion is from cathode to anode. On the contrary, Figure 8 shows that the marker movement in solder joint B of Module #4 is opposite to the expected direction, indicating that the overall
diffusion is from anode to cathode (from the hotter silicon die side to the cooler copper plate side). This observation suggests that the overall diffusion is the combination of electromigration (from cathode to anode) and thermomigration (from hotter to cooler) and that thermomigration is actually taking the leading role. In the case of solder joint A in Module #4 and Module #1, thermomigration actually assisted electromigration. The atomic flux due to electromigration and thermomigration in the absence of stress gradient and concentration gradient is (Huntington, 1972):

$$J_{\text{atom}} = \frac{DC}{kT} Z^* e p j - \frac{DC}{kT^2} Q^* \nabla T$$

where $Q^*$ is the heat of transport, the isothermal heat transmitted by the moving atom in the act of jumping, less its intrinsic enthalpy. It is clear that in the presence of thermomigration, Equation (1) cannot be used to extract effective charge number. Therefore, although marker movement can be used
to estimate the atomic flux in solder joint during current stressing, it cannot be used to extract information on the effective charge number. This finding explains the discrepancy in effective charge number between our results and those in the literature. The magnitude of thermomigration is related to the thermal gradient within the solder joint, which is dependent on the testing ambient temperature and the thermal management of the test module.

CONCLUSIONS

The main goal of this project was to identify the mechanism of electromigration damage in microelectronics solder joints. Eutectic Sn/Pb flip-chip solder joints were studied under electrical current stressing at ambient room temperature. Mass accumulations near the anode and void nucleation near the cathode were observed during current stressing. Surface marker movement was used to measure the atomic flux driven by electromigration and to calculate the product of effective charge number and diffusivity ($D \times Z^*$) of the solder at room temperature. Experiments revealed that thermomigration due to joule heating makes the extraction of the $D \times Z^*$ erroneous when using the marker movement technique. In order to obtain $D \times Z^*$ with the marker movement technique, advanced thermal management must be applied to ensure that the temperature gradient within the solder joint is small enough and thermomigration is negligible compared to electromigration.

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