

Thermomigration in Pb–Sn solder joints under joule heating during electric current stressing

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Electromigration of solder joint under high dc current density is known as a reliability concern for the future high-density flip chip packaging and power packaging. Biased mass diffusion within solder joint from cathode to anode under high dc current density is observed in these experiments. In this letter, the experiments on flip chip solder joints under dc current stressing are conducted and thermomigration due to the thermal gradient in the solder joint caused by joule heating is reported. A three-dimensional coupled electric thermal finite-element (FE) simulation of a realistic flip chip module shows the existence of thermal gradient in the solder joint which is high enough to trigger thermomigration. © 2003 American Institute of Physics. [DOI: 10.1063/1.1554775]

The electromigration of solder joint under high current density is of reliability concern for the future high-density flip chip packaging and power packaging.^{1,2} Voids nucleation near cathode side and hillock developing near anode side during current stressing indicates a biased mass diffusion from cathode to anode which is referred to as electromigration. During current stressing, heat is also generated due to joule heating. In a typical flip chip module, the cross section area of the metal trace on the silicon dies is much smaller than that of the solder joint. Thus, the primary heat source is the metal trace which contributes to the most of the electric resistance of the module. The joule heating during current stressing may maintain a thermal gradient in the solder joint. Thermal migration is reported in Pb–In solder alloy at a thermal gradient of 1200 °C/cm by Roush *et al.*³ In this letter, a three-dimensional coupled thermal electrical finite-element (FE) simulation on a realistic flip chip module is performed, and the result shows that a thermal gradient greater than Roush's reported value is possible in the solder joint. A series of experiments of flip chip solder joints under high current stressing are studied in this letter. The measured temperature on the silicon die agrees with that from the FE simulation. In some cases, void nucleation is observed near anode side in some solder joints which can not be explained by electromigration. In these cases, anode side is also the hotter side (silicon die side). The authors believe thermomigration (in the opposite direction of electromigration) is dominant in these cases.

The test module used in the experiments has a dummy silicon die with only Al conduct trace on it. The silicon die is attached on a FR4 printed circuit board (PCB) through eutectic Pb/Sn solder joints. The copper plates on the PCB provide the wetting surface and electric connection to the solder joints. The solder joints are encapsulated in the under-fill between the silicon die and PCB. The thickness of the Al trace is about 1 μm and the width is about 150 μm. The solder joint has a diameter about 150 μm and height of 100 μm. The test module was cross sectioned and finely polished

to the center of the solder joints before current stressing. On each module, two solder joints were tested. The solder joints on each test module are named in such a way that current always flows from copper plate through solder A into the Al trace on silicon die and then flow through solder B out to the copper plate. Figure 1 shows the schematic cross section of the test module and the direction of current flow in the experiments. During the course of current stressing, the test modules were taken off circuit for scanning electron microscopy (SEM) analysis and sometimes for nanoindentation tests.

Figures 2 and 3 show the secondary SEM images of solder A and solder B from the same test module after 16 h of 1 A current stressing. The calculated current density in the solders is about 1.3×10^4 A/cm². Severe voids nucleation is observed on solder A near Si die side (which is also cathode) as expected since the direction of electromigration is from cathode to anode. Hillock is observed near Cu plate side or anode side on solder A. Voids nucleation is also observed on solder B near Si die side which is anode side. Although the voids nucleation on solder B near Si die side is much less severe compared to that on solder A, electromigration alone cannot explain this observation. If electromigration were the only driving process in microstructure evolution of solder during current stressing, voids nucleation should be expected to start near cathode side, e.g., Cu plate side for solder B, which was not the case. Similar observations were found on several other test modules. There has to be another process operative during the current stressing.

We think this process is thermomigration. Since the Al trace on the Si die contributes to the most of the electric

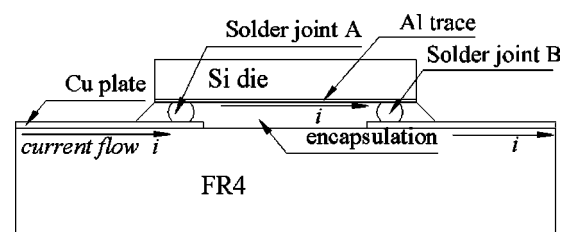


FIG. 1. Schematic cross section of the test module.

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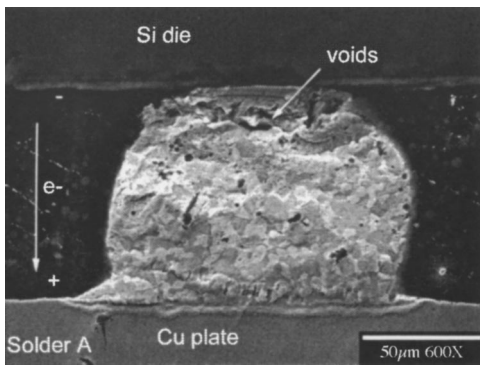


FIG. 2. Secondary SEM of solder A on one module after 16 h 1 A stressing.

resistance, most of the joule heating is generated in Al, which makes the silicon die side very hot. During the experiments, the temperature on top of the silicon die measured by a thermal couple ranged from 40–200 °C for different modules under different current stressing level. Thus, it is reasonable to assume that there is a temperature gradient maintained in the solder joint during current stressing. This assumption is verified by a three-dimensional coupled thermal electrical FE simulation of the test module as will be reported in the next section. Thermomigration would start in the solder joint with the existence of the thermal gradient. Roush *et al.*³ observed the thermomigration of Pb/In solder alloy at a thermal gradient of 1200 °C/cm and reported that both In and Pb move in the direction of the thermal gradient. Van Gorp *et al.*⁴ reported fast thermomigration in In and In alloy films and found material is transported from hot to cold areas. Thermomigration in pure Pb has been observed by Johns *et al.*⁵ over the temperature range 322–202 °C. They reported that in all circumstances flow of material was from hot to cold. In our experiments, thermomigration in eutectic Pb/Sn solder is from hot side (Si die side) to cold side (Cu plate side), which agrees with aforementioned reports. Thermomigration may assist electromigration if the hot side coincides with cathode side as in solder A or it may counter electromigration if hot side coincides with anode side as in solder B. If thermomigration outbalances electromigration in the overall diffusion process during current stressing in the latter case, voids nucleation would be found near anode side as is the case in Fig. 3. Thermomigration can also explain the observation that much more severe voids nucleation near Si die side in solder A than in solder B. This conclusion suggests that thermomigration may not be omitted in the elec-

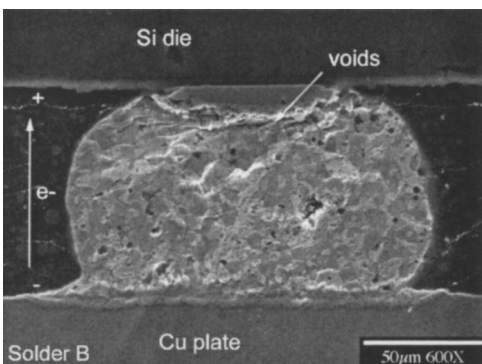


FIG. 3. Secondary SEM of solder B on one module after 16 h 1 A stressing.

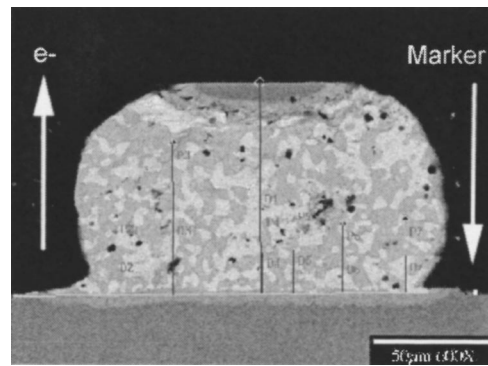


FIG. 4. Marker measurement on solder B.

tromigration analysis of flip chip solder joint when joule heating from Si die is not negligible.

Besides the observation of void nucleation near anode side in solder B, inert marker movements also suggest mass flow in the opposite direction of electromigration on solder B on some test modules. SiC particles left on the surface during polishing can be used as inert marker to measure the atomic motion in solder joint.² Figure 4 shows the measurement of marker movement on solder B on the same test module as shown in Figs. 2 and 3. Inert marker is expected to move in the opposite direction of electromigration² as shown in Fig. 4, or from Si die side to Cu plate side as in solder B. Figure 5 shows the marker movement versus stressing time, which indicates markers actually moved in the same direction of electromigration (as indicated by the negative values). This observation suggests that the actual overall diffusion direction is from Si die side (hot side and anode side) to Cu plate side, indicating the influence of thermomigration during current stressing. The measured marker movement on solder A of the same test module shows the mass diffusion from Si die side (hot side and cathode side) to Cu plate side but with a higher value since thermomigration assisted electromigration in solder A.

A three-dimensional coupled thermal electrical FE simulation of the real structure of flip chip test module is conducted to determine the temperature distribution on the solder joint. Since in the experiment the module was cross sectioned through the center of the solder joint, only cross sectioned module is modeled in the simulation. Due to the

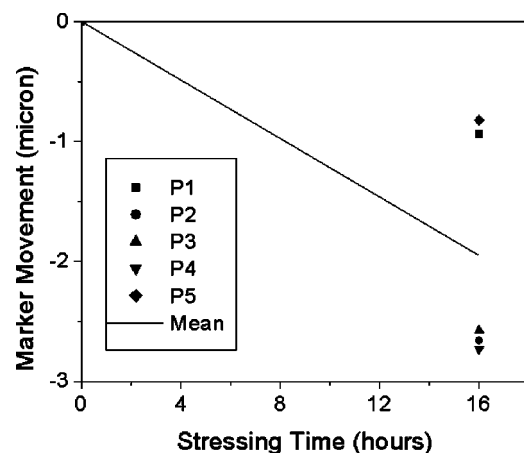


FIG. 5. Marker movement vs stressing time on solder B.

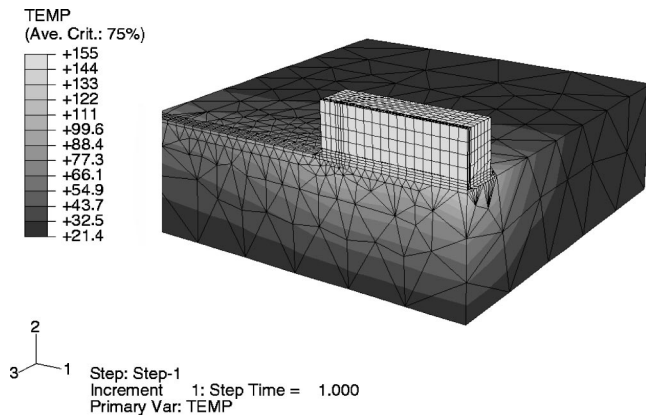


FIG. 6. Temperature distribution on the module.

symmetric geometric structure of the module, only half of the module is modeled. Joule heating by the conducting of electric current is the only thermal loading in the model. The thermal boundary condition is that the temperature on the far end surface of the PCB is fixed at room temperature, 23 °C. The thermal radiation is considered for all the external surface of the module and an emissivity of 0.7 is assumed. The electric potential is fixed to be 0 at one end of the Al trace and a concentrated current load is applied at the other end of Cu plate. The material properties used in the simulation is taken from Pecht *et al.*⁶ The temperature distribution for the case of 1 A current loading is shown in Fig. 6. The Al trace and Si die has the highest temperature of 150 °C, which agrees with the measured temperature in the test. The tem-

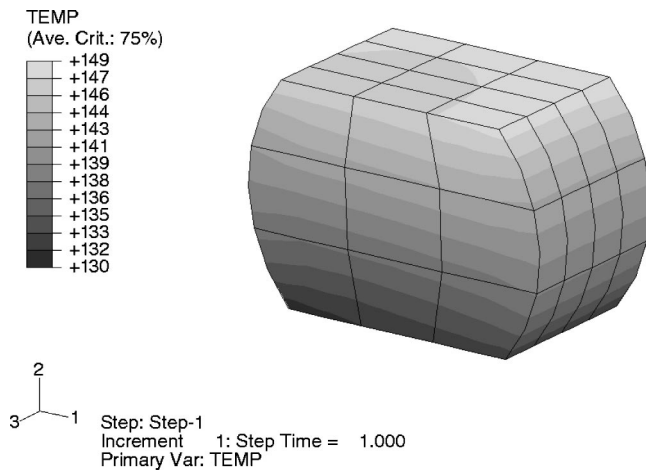


FIG. 7. Temperature distribution on the solder.

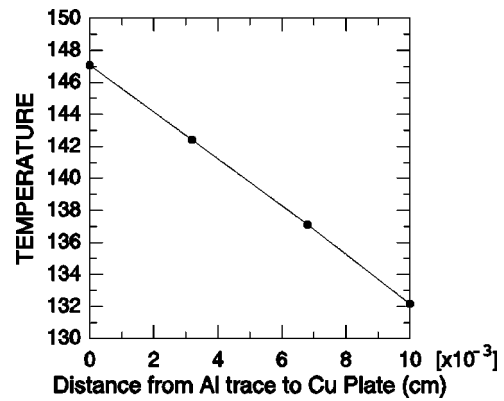


FIG. 8. Temperature distribution along the vertical line across the solder.

perature distribution on the solder joint alone is shown in Fig. 7. Figure 8 shows temperature gradient through a vertical line across the solder joint. A thermal gradient of 1500 °C/cm is predicted in the simulation which exceeds the thermal gradient reported by Roush. The real temperature gradient in the solder joint may not be exactly 1500 °C/cm due to the discrepancy between the simulation model and real module. This simulation just verifies the existence of a great thermal gradient in solder joint to trigger thermomigration during current stressing.

Thermomigration of flip chip solder joints under current stressing is reported in this letter. The authors believe that the joule heating from the silicon die maintains a great thermal gradient within the solder joint, which triggers thermomigration. An FE simulation result supports the existence of the thermal gradient. Thermomigration may assist or counter electromigration depending on the direction of thermal gradient and electric field. Besides electromigration, thermomigration is also a reliability concern for flip chip solder joint under high current stressing.

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