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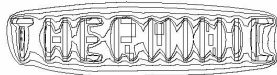
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The Characteristics of Electromigration And Thermomigration in Flip Chip Solder Joints

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Abstract-Electromigration and thermomigration behaviors of eutectic tin-lead solder joints were studied above 100 °C with the currents ranging from 1.6 A to 2.0 A. The local temperature of the chip was deducted according to temperature coefficient of resistance. Also, this temperature was inspected by a thermal infrared mapping technique. It is suggested that the heat accumulation within first-level solder interconnections was highly related to the current density. During the electromigration process, Pb migration was apparently visible because of its faster diffusivity. Meanwhile, voids were initiated at the entry location of the electron flow due to the current crowding effect. Numerical simulation also predicted a local current density of above 10^5 A/cm² within the solder joint. In the thermomigration process, the transport of Pb was detected owing to the thermal gradient across the solder joint. Voids also occurred at the contact window due to accelerated atomic diffusion. In addition, the effect of electromigration and thermomigration on the mechanical behavior of the solder joint was examined through shearing tests.

I. INTRODUCTION

As the current per unit area of the solder joint increases, electromigration (EM) of solder, is becoming a more limiting factor for the application of high current density packages. EM-related issues, such as microstructural evolution, Joule heating, and mechanical degradation have been widely regarded since 1998 [1]. By numerical simulation and experimental work, Chiang *et al.* have demonstrated that the current crowding occurred in solder joints, which could enhance the local atomic flux along with the electron flow and expedite the migration damage [2]. Actually, the crowding region could produce more Joule heating which was considered to be an important factor for the EM-induced failure. Chiu *et al.* have confirmed this local over-heating by inspecting the hot spot using thermal infrared microscopy [3]. In addition, mechanical behavior of solder joints after the EM process has been evaluated. Nah *et al.* have found that the mode of shearing failure changed after EM, and believed that the failure was mostly attributed to the large growth of brittle Sn-based intermetallic compounds (IMCs) at the cathode interface [4]. Ren *et al.* have observed the ductile-to-brittle transition owing to the effect of EM, and proposed that the accumulation of vacancies at the cathode side resulted in the mechanical degradation [5].

More recently, thermomigration (TM) has been proposed as a new significant reliability concern for flip chip solder joints in advanced microelectronic packages. This migration is triggered by a certain thermal gradient across solder joints, which is more evident because of the dramatic Joule heating accumulated at the chip side due to decreased cross sectional area of conductive lines on the chip. Nowadays, the investigation on this area has attracted great attentions from researchers. The individual contribution of TM to the failure of solder joints has been clarified by Tu *et al.* [6]. They found that Pb atoms moved to the cold side and Sn to the hot side in tin-lead composite solder joints. Also, we have observed a redistribution of Sn and Pb-rich phases, during which Pb atoms moved to the cold side in eutectic tin-lead solder joints at 150 °C [7]. In addition, a thermal gradient above 1000 °C/cm across these solder joints has been predicted by numerical simulation in our team [8]. The latest research by Hsiao and Chen has verified the existence of large thermal gradient across solder joints using a thermal infrared mapping technique, which provided a further support to validate the numerical simulation results [9]. However, less work on the combined effect of TM and mechanical stress has been reported.

According to 2006 International Technology Roadmap for Semiconductors (ITRS), EM and thermal dissipation are two of great challenges need to be regarded for the assembly and packaging scheme [10]. Materials changes together with thermal/mechanical reliability modeling should be addressed for the EM concern. Also, Joule heating induced TM damage could be minimized by the substantial heat dissipation through the solder joint. Hence, the current carrying capability of solder/ under bump metallization (UBM) and the thermal dissipation of first-level solder interconnections should be considered based on the EM and TM limitation in the design rule. New solder/UBM with improved current density capabilities and higher operating temperature is required. And it is necessary to obtain the real temperature of the solder joint instead of the mold surface to fulfill the requirement of thermal design for the module system. For the mechanical characteristic, it should be mentioned that the high strain rate fracture failure is as important as the low cycle fatigue failure, which has been of major concern in the past years. As a result, this study is intended to investigate the

characteristics of EM and TM of eutectic tin-lead solder joints, in terms of Joule heating, microstructural variation and shearing behavior.

II. EXPERIMENT

The samples used in this study were the dummy test kits of flip chip package. 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 UBM layer was a thin film of Al/Ni/Cu, and the opening of 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. The pitch and bump diameter was about 457 μm and 190 μm, respectively. The test substrate was a FR4 board with a thickness of 0.84 mm. The copper pad connected to the flip chip had a width of 152 μm and a thickness of 35 μm. Moreover, to confine the dramatic growth of IMCs on the substrate side, the copper pad was electro-plated with a thin nickel layer of about 2 μm. Both chips and substrates were daisy-chained for electrical continuity. The flip chip was attached to the substrate using a flip-chip bonder, and then was reflowed using a five-zone air convection oven. In the temperature profile, the peak was 215 °C, and the time above liquidous of eutectic tin-lead solder was about 70 s. Fig. 1 shows a typical bonded sample prepared for this study.

Fig. 2 is a sketch of flip chip solder joints with the current direction. Two pairs of solder joints (joint 5, 6, 7 and 8) were powered with the currents ranging from 1.6 A to 2.0 A at different ambient temperatures from 100 °C to 135 °C, which were used to explore the EM effect. The average current density in the solder joint was defined as dividing the applied current by the area of the passivation opening. Un-powered solder joints, especially the closest ones (joint 4 and 9) to the stressed, were investigated for TM study since no current was applied to them.

Both EM and TM experiments were conducted in an oven, which was utilized to realize a stable and uniform ambient temperature ranging from 20 to 140 °C. Real temperature in the Al trace under current stressing was deduced by a temperature coefficient of resistance (TCR) method. For TCR calculation, a precision current source and a digital multimeter were used to accurately obtain the resistance values of the solder interconnection. Four-probe measurement was taken to remove the effect of test wires. Also, an infrared camera with a sensitivity of 0.02 °C and an accuracy of ± 1 °C, was applied to monitor the temperature around the powered solder joints at a given temperature on a hot plate. Thermal infrared images of the samples were recorded for comparison.

After the experiments, the mechanical behavior of solder joints was evaluated using shearing test with a shearing speed of 1 mm/min. The fracture surfaces and the cross sectional microstructures of solder joints were then examined by a

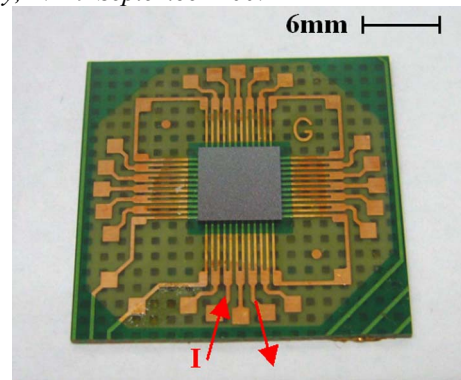


Fig. 1. Flip chip module used in this study (The red arrow shows the current direction.)

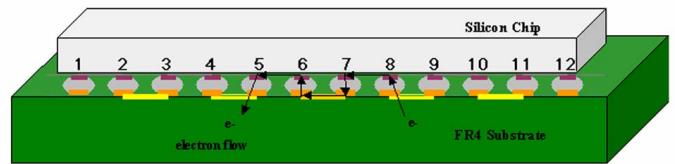


Fig. 2. Sketch of solder joints with four solder joints (joint 5 to 8) under current stressing.

scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) system.

III. RESULTS AND DISCUSSION

The electrical resistance of the aluminum traces, solder joints and copper conductors under stressing were calculated to be about 201.2 mΩ, 1.6 mΩ and 13.0 mΩ, respectively. It is apparent that the Al trace is the primary heat source because of its larger resistance. Also, as the temperature coefficient of resistance of Al, eutectic solder and Cu is of the same order of magnitude, the resistance increase of the Al trace mostly contributes to the resistance variation of the first-level solder interconnection. Hence, the real temperature in the Al trace can be deduced by TCR method. This method is an effective non-contact technique for the determination of temperature, and it was applied by other researchers to obtain the real temperature in the solder joint [2].

The calculation of TCR is typically expressed as

$$TCR = \left(\frac{R - R_0}{R_0} \right) \left(\frac{1}{T - T_0} \right) = \frac{\Delta R}{R_0} \frac{1}{\Delta T} \quad (1)$$

where T_0 is the reference temperature, T is the real temperature, R_0 is the resistance at T_0 , R is the resistance at T , ΔR is the resistance variation, and ΔT is the temperature rise.

Fig. 3 shows the TCR measurement results by the four-probe method. The ratio of the resistance variation to the room temperature resistance ($\Delta R/R_0$) almost increased linearly over the temperature rise (ΔT). The TCR actually equals the slope of $\Delta R/R_0$ vs ΔT . After curve fitting, the linear

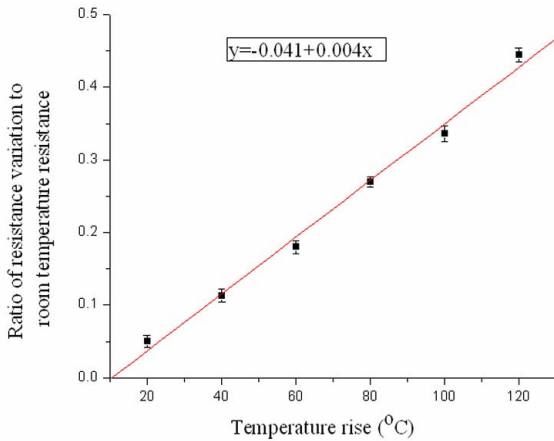


Fig. 3. TCR measurement results of the first-level solder interconnection (Four-probe method with the test current 100 mA).

regression equation was then

$$y = -0.041 + 0.004x \quad (2)$$

where y and x represents $\Delta R/R_0$ and ΔT , respectively. The TCR of the Al trace was estimated to be $0.004 \text{ }^\circ\text{C}^{-1}$, which is approximately in agreement with the empirical value. By substituting the measured resistance into (1), the real temperature in the Al trace can be obtained. Furthermore, since the Al trace is closely attached to the silicon chip with a large thermal conductivity, the real temperature at the chip side can be monitored *in situ* in this way. Table I lists the calculated temperature of the chip under the experiments with different currents and ambient temperatures.

In addition, the local temperatures near the powered solder joints were detected by the infrared camera at different ambient temperatures, as shown in Table I. Compared to the deduced temperatures from the TCR method, they exhibited a similar tendency that the temperature increased sharply with the applied current. Therefore, heat accumulation in the interconnection was closely related to the current stressing. For the 1.6 A case, the temperature rise due to Joule heating

was from 3.8 to 13.9 °C. However, for the 2.0 A case, the temperature rise reached as high as 41.4 °C. In particular, when the 2.0 A current was applied at 135 °C, the real temperature in the chip was approximately 182.5 °C, even approaching the melting point of eutectic tin-lead solder.

Fig. 4 (a) and (b) illustrate the typical EM phenomenon of tin-lead solder joints under a 1.6 A current (average current density $j = 2.0 \times 10^4 \text{ A/cm}^2$) after 100 h at 100 °C. Pb migration along with the electron flow was apparently visible in powered solder joint 7 and 8. Fig. 4 (c) and (d) show the detailed microstructures with a high magnification. Pb atoms migrated towards the substrate side in joint 7. By contrast, Pb atoms had a tendency to migrate to the chip side in joint 8. Generally, most Pb atoms migrated in the direction of electron flow, which agrees well with the findings by other researchers [1,11]. Fig. 4 also illustrates a typical tilting effect of the current during the EM process [12,13]. In joint 7, it is evident that Pb-rich phase migrated towards and accumulated at the substrate side along with the entry direction of electron flow. Moreover, with the consumption of UBM, voids were primarily generated from the entry location of electron flow because of flux divergence at the current crowding region. With prolonged time, these voids would spread across the contact area and hence cause the final interconnection failure. Finite element modeling and numerical simulation were also carried out to understand the characteristics of EM. The current density distribution of flip chip test structure applied with a 1.6 A current is shown in Fig. 5. The current density in most parts of the solder joint reached above 10^4 A/cm^2 , which was sufficient to trigger atomic diffusion for the EM process. The phenomenon of current crowding was also significant. The current density at the entry location was predicted to be $7 \times 10^5 \text{ A/cm}^2$, at least one order of magnitude larger than the average one. This gives a reasonable explanation for the

TABLE I

MEASURED RESISTANCE, CALCULATED TEMPERATURES, AND MEASURED TEMPERATURES UNDER THE TEST CONDITIONS OF CURRENTS AND TEMPERATURES

Ambient temperature (°C)	Current (A)	Measured resistance (Ω)	Calculated chip temperature (°C)	Measured temperature around the chip (°C)
20	1.6	0.191	33.8	35.8
	1.8	0.204	51.8	49.9
	2.0	0.211	61.4	59.2
100	1.6	0.249	113.9	110.0
	1.8	0.263	133.2	118.0
	2.0	0.281	158.1	147.3
135	1.6	0.267	138.8	142.0
	1.8	0.280	156.7	150.4
	2.0	0.298	182.5	171.8

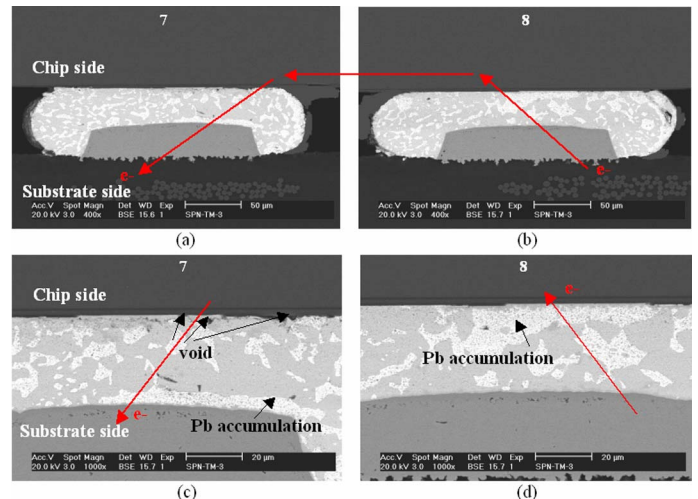


Fig. 4. (a) SEM micrograph of EM in the powered solder joint 7, and (b) joint 8 under the current density of $2.0 \times 10^4 \text{ A/cm}^2$ after 100 h at 100 °C, (c) local magnified micrograph of solder joint 7, and (d) joint 8.

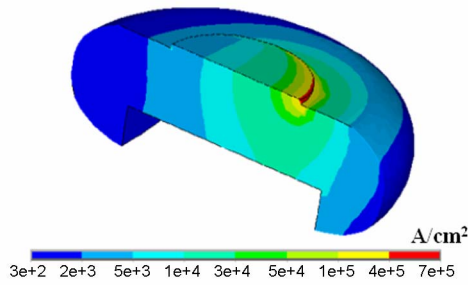


Fig. 5. Current density distribution of the solder joint stressed with a 1.6 A current.

unique tilting effect occurred in the solder joints. In addition, the high current density may enhance local Joule heating and result in a temperature gradient across the solder joint, which may also initiate atomic migration for the TM.

Fig. 6 (a) and (b) illustrate the typical TM phenomenon of tin-lead solder joints under a certain temperature gradient after 100 h. In this case, a 2.0 A current was applied to two pairs of solder joints at 135 °C. Obvious TM of Pb was detected in the neighboring un-powered solder joints (joint 4 and 9). Fig. 6 (c) and (d) show the local magnified micrographs of these solder joints. The Pb-rich phase was separated from the Sn-rich phase and accumulated at the bottom of solder joints. It is believed that Pb atoms migrated to the substrate side (the cold side) under the temperature gradient across the un-powered solder joints since there was no current flow inside. This result reasonably agrees with those of TM study of tin-lead solder joints, which can be explained for that Sn atoms migrated slowly and replenished the vacancies due to the departure of Pb atoms under a temperature gradient, since Pb atoms are the dominant diffusion species in the eutectic tin-lead solder above 100 °C

[6,14,15]. Numerical simulation in our previous studies also supported the existence of a thermal gradient across the un-powered solder joint [8]. The other important reason for TM of Pb is the high temperature within the solder joint. According to Table I, in this TM experiment, the chip temperature reached about 182.5 °C, approaching the melting point of eutectic tin-lead solder. Recent studies have found the similar phenomenon that TM was likely to occur near the eutectic temperature of the solder [9]. This is concerned with an accelerated diffusion at high temperature or an entropy generation during the TM process [16]. Likewise, voids were detected at the contact area of high temperature side after TM. It was the driving force due to temperature gradient, instead of electron flow, that accelerated the atomic diffusion starting from the high temperature region.

In addition, shearing test was performed to evaluate the mechanical characteristics of solder joints. Fig. 7 illustrates the typical fractograph of the solder joint on the chip side (as-reflowed), in which a large deformation with big dimples was visible on the ductile plastic fracture. However, the fracture manner turned to a brittle rupture over the EM and TM experiments. As shown in Fig. 8, after experiencing the current density of 2.5×10^4 A/cm² after 100 h at 135 °C, the fracture of the solder joint on the chip side (cathode side) exhibited a brittle morphology, which was agreeable with the results of the previous studies [1,17]. Also, Fig. 9 illustrates a typical shearing fracture of the un-powered solder joint (neighboring to the solder joints stressed with the 2 A current after 100 h at 135 °C) on the chip side, which was primarily characterized as a brittle behavior. According to the equation of atomic fluxes, atoms migrated from the high temperature side to low temperature side by the thermal gradient force, and hence a reversed flux of vacancies moved to the high temperature side. Consequently, it caused vacancy accumulation and void formation at the interface of the solder and UBM [5]. Meanwhile, large stress was easily built and accumulated around the voids due to thermal mismatch [17]. It is believed that void formation and stress accumulation caused by the TM effect were the main reasons why the high temperature side showed a weaker mechanical property during the shearing test.

IV. CONCLUSION

It is worthwhile to measure the real-time temperature of first-level solder interconnections to fulfill the requirement of thermal design, since thermal dissipation has become a critical factor of reliability concern in high current density packages. In this study, the temperature of the Al trace was deduced by the TCR method ($TCR_{Al} \approx 0.004$ °C⁻¹), and hence the real temperature at the chip side was monitored *in situ*. Also, the local temperature near the powered solder joints was detected by the infrared camera at different ambient temperatures. Both methods indicated that the temperature dramatically increased with the current through solder joints.

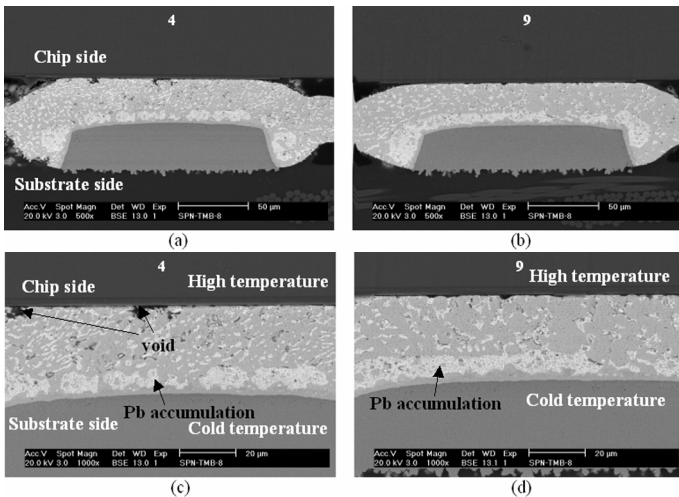


Fig. 6. (a) SEM micrograph of TM in the un-powered solder joint 4, and (b) joint 9 neighboring to solder joints under the 2 A current stressing after 100 h at 135 °C, (c) local magnified micrograph of solder joint 4, and (d) joint 9.

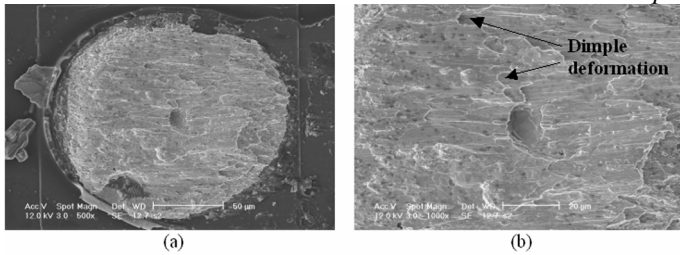


Fig. 7. (a) Typical fractograph of the solder joint on the chip side (as-reflowed), (b) local magnified micrograph.

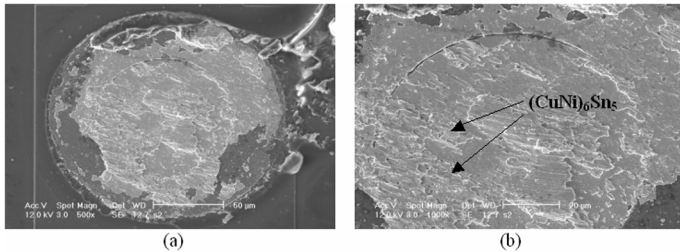


Fig. 8. (a) Typical fractograph of the solder joint on the chip side (powered with the current density of 2.5×10^4 A/cm² after 100 h at 135 °C), (b) local magnified micrograph.

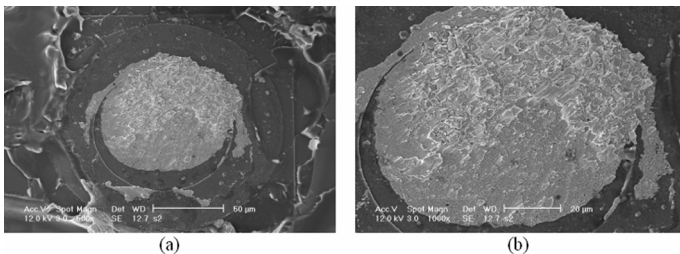


Fig. 9. (a) Typical fractograph of the un-powered solder joint on the chip side (neighboring to the solder joints under the 2 A current stressing after 100 h at 135 °C), (b) local magnified micrograph.

It is suggested that the temperature approximately reached the melting point of eutectic tin-lead solder when a 2.0 A current was applied at 135 °C.

The typical EM and TM behaviors of eutectic tin-lead solder joints were studied sufficiently. In the process of EM and TM, Pb atoms were the dominant species due to their faster diffusivity. For EM, atoms migrated along with the electron flow and phase separation was expected to occur. The effect of current crowding was evident. Numerical simulation also predicted the local current density of 7×10^5 A/cm² within the solder joint. Hence, voids were primarily initiated at the entry location of the electron flow due to flux divergence. Joule heating accelerated the EM progress and enhanced the EM damage during this process. For TM, atoms moved under the thermal gradient, and Sn-rich phase migrated slowly then replenished the vacancies due to the departure of Pb-rich phase. Voids were also detected at the contact area due to accelerated atomic diffusion. Joule heating induced dramatic temperature rise at the chip side led to the formation of the thermal gradient across the solder joints.

Additionally, the effect of EM and TM on the mechanical shearing behavior of solder joints was examined. It is apparent that the ductility of solder joints turned worse over EM and TM experiments.

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