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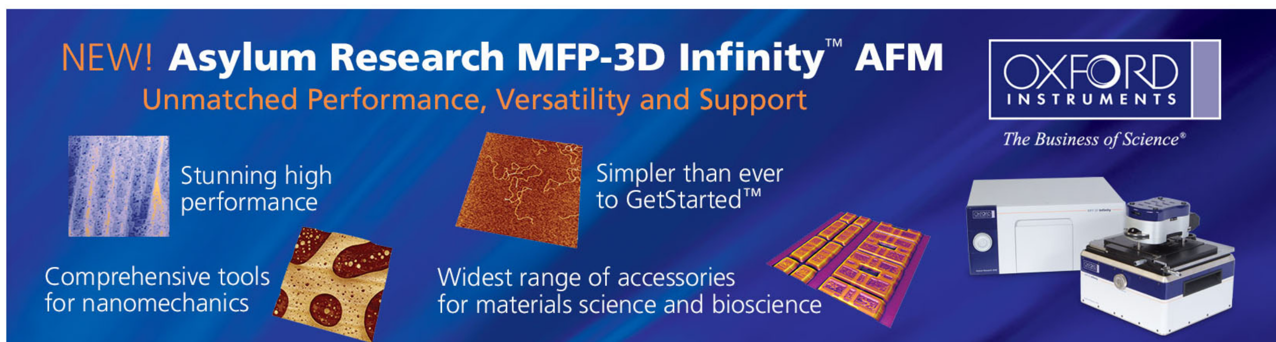

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APPLIED PHYSICS LETTERS **93**, 122103 (2008)

Failure induced by thermomigration of interstitial Cu in Pb-free flip chip solder joints

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Failure induced by thermomigration in Pb-free SnAg flip chip solder joints has been investigated by electromigration tests under 9.7×10^3 A/cm^2 at 150 °C. The fast interstitial diffusion of Cu atoms from underbump metallization into Sn matrix caused void formation at the passivation opening on the chip side. The Cu diffusion was driven by a large thermal gradient and led to void formation even in the neighboring unpowered bumps. When the thermal gradient is above 400 °C/cm, theoretical calculation indicates that the thermomigration force is greater than the electromigration force at 9.7×10^3 A/cm^2 stressing. © *2008 American Institute of Physics*.
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Electromigration in flip chip solder joints has become a major reliability issue in recent years because of the miniaturization trend to meet the demand of higher performance in portable consumer electronics.[1] Much research has been conducted to provide scientific understanding of this reliability issue.[2–8] Serious current crowding effect has played a crucial role in the failure mechanism in electromigration,[3,9] causing void formation near the thin-film underbump metallizations[10] (UBMs) or enhancing dissolution of metallization of the thick-film UBM in flip chip solder joints.[11,12]

Moreover, thermomigration accompanies electromigration.[4,5,13] The Joule heating of the Al interconnect on the chip side builds up a large temperature gradient across the solder joints. For Pb-containing solder, Pb atoms move to the cold end on the substrate side and the net effect is void formation on the chip side. However, failure induced by thermomigration in Pb-free flip chip solder joints has not been reported yet.

In this letter, electromigration and thermomigration in eutectic SnAg solder joints with Cu UBMs are reported. It is found that thermomigration of Cu dominates the failure mechanism. The fast Cu interstitial diffusion[14] from Cu UBM into Sn-based solder matrix left supersaturated vacancies to form voids below the UBM on the chip side. The large thermal gradient has caused the migration of Cu atoms and the formation of Cu_6Sn_5 intermetallic compounds (IMCs) to the cold end, and the Cu atoms also served as the dominant diffusion species in electromigration. An independent study on thermomigration was performed to verify the results. Theoretical calculation was conducted to support the observed phenomena.

To study electromigration and thermomigration simultaneously, a special layout of four solder joints was adopted, as illustrated in Fig. 1(a). On the chip side, an Al trace connects the four bumps together. Its dimensions are 2550 μm long, 100 μm wide, and 1.5 μm thick. The four bumps were denoted as bump 1 through bump 4. The solder joints consists of eutectic SnAg solder bumps with electroplated 5 μm thick Cu as UBM on the chip side. The bump dimensions are 130 μm wide and 70 μm high with a UBM opening of 120 μm in diameter. On the substrate side, six Cu nodes were fabricated and they are labeled as nodes N1–N6. The dimensions of the Cu lines on the FR5 substrate are 25 μm thick and 100 μm wide.

To facilitate the observation of electromigration and thermomigration, the joints were polished laterally and approximately to their centers, as shown in Fig. 1(b). After the polishing, the widths of the Al traces and the Cu lines also decreased accordingly. Electric currents were applied only through nodes N3 and N4, as shown in Fig. 1(b). Therefore, bumps 1 and 4 did not have current passing through, so did the Al line connecting bumps 1 and 2 and that connecting bumps 3 and 4. Yet, the four bumps have experienced almost the same Joule heating because the Al line and the Si die possess excellent heat conduction. The applied current was 0.55 A at 150 °C on a hot plate, which corresponds to an average current density of 9.7×10^3 A/cm^2 in the UBM opening. Kelvin probes were employed to monitor the resistance changes in both bumps 2 and 3;[15] thus the degree of damage as a function of time can be measured for these two bumps.

The temperature distribution in the solder bump during the current stressing was measured by a QFI infrared (IR) microscope, which has 0.1 °C temperature resolution and 2 μm spatial resolution. The thermal gradient is 1143, 1643, 1857, and 1143 °C/cm for bumps 1, 2, 3, and 4, respectively, under stressing at 0.55 A and 150 °C.

We found that voids formed in the chip end of the solder joint for all the four bumps after the current stressing for 76 h. The current was terminated when the resistance of bump 3 reached three times its original value. In bump 3, the void formed in the cathode end (the chip side) because of electromigration. However, we observed that serious damage due to void formation also occurred in the anode end (the chip side) of bump 2. Its resistance also increased up to two times the original value. According to the thermomigration results on Pb-containing solder,[4,5,13] Pb atoms moved to the cold end on the substrate side; thus Kirkendall voids formed on the chip side. It was also found that Sn atoms migrated to the hot

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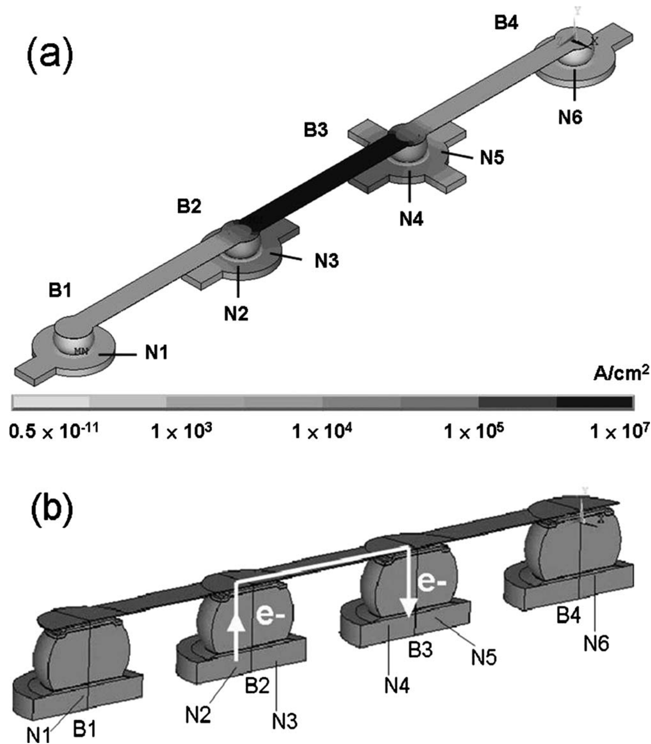

FIG. 1. Schematic diagram of the experimental setup used in this study. (a) The layout before the bumps was polished. The distribution of current density was also shown in the figure. (b) Schematic drawing of the samples after polishing.

end on the chip side.[5] For the Pb-free solder in this study, it might be expected that Sn atoms would migrate to the hot end on the chip side since Sn has a positive value of heat transport number.[16] Thus we expect void formation at the cold end on the substrate. Thus, the voids in the chip side for bump 2 cannot be accredited to the thermomigration of Sn in the solder.

Instead, we propose that thermomigration of Cu atom dominates the failure mechanism in this study. The scanning electron microscopy (SEM) images for bumps 1–4 support this assumption, as illustrated in Figs. 2(a)–2(d). We note that only thermomigration has taken place in bumps 1–4. Because the thermal gradients were slightly smaller than those in bumps 2 and 3, smaller voids occurred in them. Furthermore, the voids replaced the original position of the Cu_6Sn_5 IMCs or that between the Cu UBM and the IMC. In contrast, in the SnPb solder, the thermomigration voids accumulate below the IMC.[4,5,13] Therefore we propose that the damage was due to the Cu migration from the hot end to the cold end.

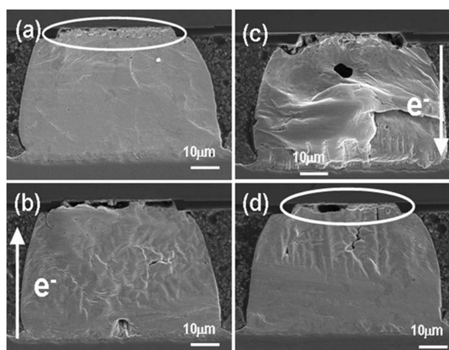

FIG. 2. Cross-sectional SEM images showing the microstructure changes of unpowered bump 1 and bump 4 after current stressing at 9×10^4 A/cm^2 at 150 °C for 76 h. (a) Bump 1. (b) Bump 2. (c) Bump 3. (d) Bump 4. Voids formed in all the four bumps.

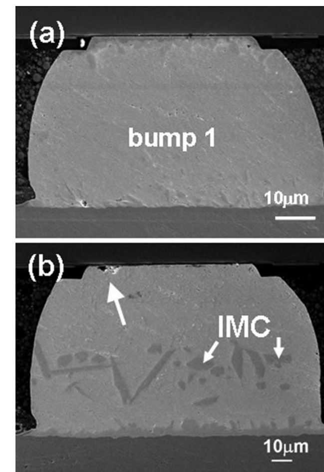

FIG. 3. Cross-sectional SEM images representing the microstructure for the un-powered bump 1 in Cu UBM system before and after current stressing in bumps 2 and 3 at 0.55 A at 150 °C for 60 h (a) before and (b) after the current stressing.

The Cu interstitial diffusion in Sn matrix is extremely fast[14] especially driven by a large thermal gradient. Based on Huntington's[17] results, Cu atom has the tendency to move to the cold end in thermomigration. When Cu dissolves interstitially in Sn, the original substitutional site of the Cu atom would be replaced by a vacancy. When the vacancies become supersaturated, the nucleation and growth of void can occur. Although there should be a net vacancy flux form the chip side to the substrate side since the vacancy concentration should be greater at the chip side, the diffusion rate of vacancies is much less than that of the interstitials. In turn the Sn flux in exchange with the vacancy flux is less, too. Thus vacancy supersaturation and void formation tend to occur below the Cu UBM.

Furthermore, a higher Cu solubility in Pb-free solders may also facilitate the thermomigration of Cu and the formation of Cu–Sn IMCs. It was reported that the solubility of Cu in eutectic SnPb at 220 °C is 0.18 wt. %, whereas it reaches 1.54 wt. % in Pb-free solders at 260 °C.[18]

Another evidence that lends support to Cu diffusion can be illustrated in Figs. 3(a) and 3(b). Figure 3(a) represented the cross-sectional view of bump 1 before current stressing, and Fig. 3(b) was the view after 60 h stressing when the resistance of bump 3 reached to 2.3 times its original value. While bump 1 was unpowered, the damage is clear near the upper left-hand corner, as indicated by the left arrow in Fig. 3(b). In addition, from the backscattered SEM image shown in Fig. 3(b), the IMC has formed toward the substrate side and the Cu UBM has dissolved almost completely into solder. This can be accredited to the thermomigration of Cu atoms by fast interstitial diffusion and reaction with Sn atoms to form IMC inside the solder bump.

Since the electromigration force in bump 2 also pushed the Cu atoms to the chip side, the void formation in the chip side infers that the thermomigration force overwhelmed the electromigration force. To verify this point, theoretic calculations are performed below. The electromigration force is represented as[19]

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$$F = Z^* eE = Z^* e\rho j, \tag{1}$$

where Z^* is the effective charge number of ions, ρ is the resistivity, j is the electric current density, and E is the electrical field. If we assume that the driving force is independent of the mechanism of diffusion, we take the effective charge number of Cu to be 6.4,[20] resistivity as $1.67 \times 10^{-8}\ \Omega$ m, and the current density in the current crowding region as $9.7 \times 10^3\ \mathrm{A/cm^2}$. The force is 1.66×10^{-18} N and the work done by the force in an atomic jump distance of 3×10^{-8} cm is 4.98×10^{-28} J. On the other hand, in thermomigration, the driving force is[21]

$$F = -\frac{Q^*}{T}\left(\frac{\partial T}{\partial x}\right), \tag{2}$$

where Q^* is heat of transport. With a thermal gradient temperature difference across an atomic jump as $\Delta T/\Delta x$, the thermal energy change would be $3k\Delta T$. When the thermomigration force balances the electromigration force, we have $3k\Delta T = 4.98 \times 10^{-28}$ J, which yields $\Delta T = 1.2 \times 10^{-5}$ K across an atomic jump. Therefore, the critical thermal gradient is 400 °C/cm. In other words, when the thermal gradient is greater than 400 °C/cm, thermomigration force on Cu atoms would be bigger than that of electromigration force. Our IR thermal gradient measurement agrees with this calculation. So voids form in the chip/anode side for bump 2.

Additionally, when we performed isothermal annealing of the flip chip solder joints at 165 °C for 90 h, by taking into account the higher temperature due to Joule heating, we found no void formation, but the Cu_6Sn_5 IMCs grew thicker below the UBM, yet they did not migrate to the substrate side. Also when we have changed the Cu UBM to Ni UBM, no obvious change was observed after 160 h under the same current stressing condition. So what is shown in Figs. 2 and 3 is unique to the Cu UBM in thermomigration. Regarding thermal migration of Ag_3Sn IMCs, it is not clear so far and more studies are needed to verify whether they move under a thermal gradient.

In summary, thermomigration in Pb-free SnAg solder joints with Cu UBM has been investigated during electromigration tests under $9 \times 10^3\ \mathrm{A/cm^2}$ at 150 °C. Void formation was observed in the powered bumps, regardless the direction of the current flow, as well as in the unpowered bumps. We propose that the fast interstitial diffusion of Cu from the Cu UBM into Sn solder left behind supersaturated vacancies for void formation. The driving force of the Cu diffusion is the large thermal gradient accredited to Joule heating across the solder bumps. A critical thermal gradient of approximately 400 °C/cm was found, above which thermomigration force would be bigger than the electromigration force tested in the present study.

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