AIP Applied Physics Letters

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Citation: Applied Physics Letters **86**, 203504 (2005); doi: 10.1063/1.1929870
View online: http://dx.doi.org/10.1063/1.1929870
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/86/20?ver=pdfcov
Published by the AIP Publishing

Threshold current density of electromigration in eutectic SnPb solder

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(Received 2 December 2004; accepted 5 April 2005; published online 12 May 2005)

Electromigration has emerged as an important reliability issue in the microelectronics packaging industry since the dimension of solder joints has continued to shrink. In this letter, we report a technique that enables the precise measurement of the important parameters of solder electromigration, such as activation energy, critical length, threshold current density, effective charge numbers, and electromigration rate. Patterned Cu/Ti films in a Si trench were employed for eutectic SnPb solder to be reflowed on, and thus solder Blech specimens were fabricated. Atomic force microscope was used to measure the depletion volume caused by electromigration on the cathode end. The threshold current density is estimated to be 8.5×10^3 A/cm^2 at 100 °C, which relates directly to the maximum allowable current that a solder joint can carry without electromigration damage. This technique facilitates the scientifically systematic investigation of electromigration in solders. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1929870]

The rapid growth of microelectronic technology has been based on the constant reduction in cost per transistor, together with increased performance. Along with the trend of miniaturization, electronic packaging of a Si chip that has a very-large-scale-integration of circuits requires a very large number of input/output (I/O) connections on the packaging substrate. Flip chip technology with area array of solder bumps has become the most important packaging technology to achieve high-density packaging. The size of these solder bumps is quite small, with a diameter of about 100 μm or less.[1,2] The design rule for packaging requires that each bump will carry 0.2–0.4 A. Under a high current density, a common cause of failure in interconnects is "electromigration," which is the enhanced diffusion of atoms in the current direction due to electron momentum transfer to a diffusing atom.[3]

From the point of view of device reliability, electromigration in a flip chip solder joint is as significant as that in Al or Cu interconnect line because of the high lattice diffusivity in the solder alloys, together with higher resistivity, lower Young's modulus, and higher effective charge number of the chemical elements in solder alloys than those of Al or Cu.[3–8] It is known that the current density needed to cause a solder joint to fail is about two orders of magnitude less than that to cause an Al or Cu line to fail.[4,6] However, one of the fundamental parameters of electromigration, the critical length of solder joint, has not been measured or estimated.

In general, the atomic flux of electromigration "J_{EM}" in a conductor driven by a constant current density "j" can be expressed as the following:[3]

$$J_{\mathrm{EM}} = CDZ^{*}eE = C\left(\frac{D_0}{kT}\right)\exp\left(-\frac{E_a}{kT}\right)Z^{*}e\rho j,$$

where J_{EM} is the electromigration flux, C is the concentration of atoms per unit volume of the eutectic alloy, D is the effective lattice diffusivity of the solder at testing temperature, Z^* is the effective charge number, E is the electric field, D_0 is the prefactor for the diffusivity, E_a is the activation energy for electromigration, ρ is resistivity of the film, k is the Boltzmann's constant, and T is the absolute temperature. Among these factors, Z^* is the most important parameter in electromigration.

Blech developed a short stripe technique for measuring Z^*, provided that the length of the stripe is longer than a critical length.[4] The "critical length" is defined by the length in which the electromigration flux is balanced by an opposing flux due to the back stress gradient induced by the electromigration. The critical length can be measured from a set of stripes longer than the critical length and tested under a constant current density or from stripes of a given length but tested at various current densities. Electromigration will cause depletion at the cathode end of the stripe. Measuring the depletion length and time, we obtain the draft velocity. Thus, the threshold or critical current density corresponding

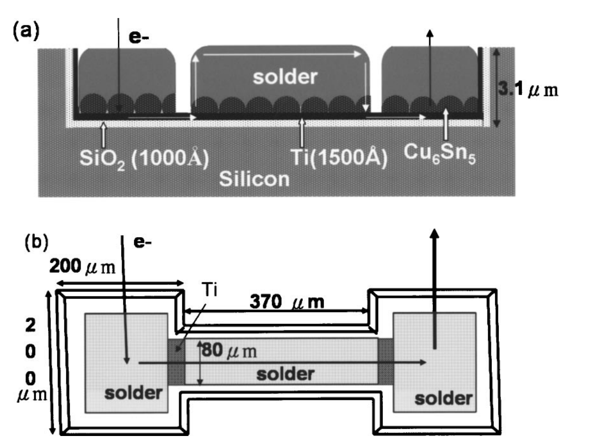

FIG. 1. The schematics of solder Blech specimens. (a) Cross-sectional diagram of the solder strip inside the Si trench. (b) Plan-view diagram of the solder strip on the Cu/Ti metallization layer. The SnPb strip is 370 μm long, 80 μm wide, and approximately 3 μm thick.

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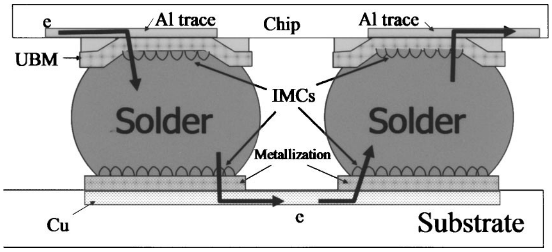

FIG. 2. Schematic structure for a pair of solder bumps, in which the electrons in the Al trace crowd into the left solder bump after passing through the IMC layer, flowing inside the solder bump, and then drift into the Cu line after the passing into another IMC layer.

to the critical length can be obtained by extrapolating to the zero drift velocity.

When solder joints are stressed by a current density of 5×10^3 A/cm^2 and above, electromigration occurs even at room temperature.[5–12] The electromigration rates in Pb-containing solders were measured by applying currents in thin strips of solder lines joined with Cu electrodes. The effective charge number of eutectic SnPb solder was measured to be 33 for a fixed length of V-groove solder lines stressed by 2.8×10^4 A/cm^2 at 150 °C.[8] However, no measurement of electromigration in a Blech stripe of SnPb solder has been done because the evaporation of lead is toxic, so we cannot use deposition methods to fabricate Blech stripes of Pb-based alloys as Al stripes. In this letter, we report a technique to fabricate solder Blech specimens, in which the depletion volume caused by electromigration and the drift velocity can be measured precisely. The electromigration rate for various current densities at 100 °C and the threshold current density of eutectic SnPb solder are reported in this letter.

To fabricate the solder Blech specimens, trenches of about 3.1 μm deep were etched in a (001) Si wafer by deep reactive ion etcher, and an oxide layer of 100 nm was grown on the Si wafer for electric insulation. Then 0.12 μm Ti film was deposited on the oxide surface, followed by 0.4 μm Cu film deposition using e-beam evaporator. Then, photolithography and selective etching were employed to pattern the Cu layer. The wafer was cut into small pieces of about 5 mm $\times$5 mm squares. They were polished to remove the Cu/Ti metallization layer on the top Si surface, leaving the metallization layers in the trench intact.

Afterwards, SnPb solder paste was positioned in the trenches, and they were reflowed at 210 °C for 4 s on a hot plate. Since the molten solder wets only the Cu surface, solder Blech specimens were formed automatically after the reflow. Nevertheless, the shape of the solder became bump-like due to its surface tension during the reflow process. A second polishing was needed to obtain a flat and smooth surface. The Si trench served as a polish stop, since SnPb is known to be very soft. Thus the thickness of the solder strip can be controlled by the polishing. The schematic of the specimen is illustrated in Fig. 1. Figure 1(a) depicts the cross-sectional view of the solder strip inside the Si trench. The thickness of the solder stripe is controlled by the depth of the trench. When electrical currents are applied through the electrode pads, the electron path is indicated by the arrows in the figure. Figure 1(b) depicts the plan view of the specimen. The dimension of the SnPb strip is 370 μm long, 80 μm wide, and 3.1 μm thick. The pads are squares of about 200 μm $\times$200 μm.

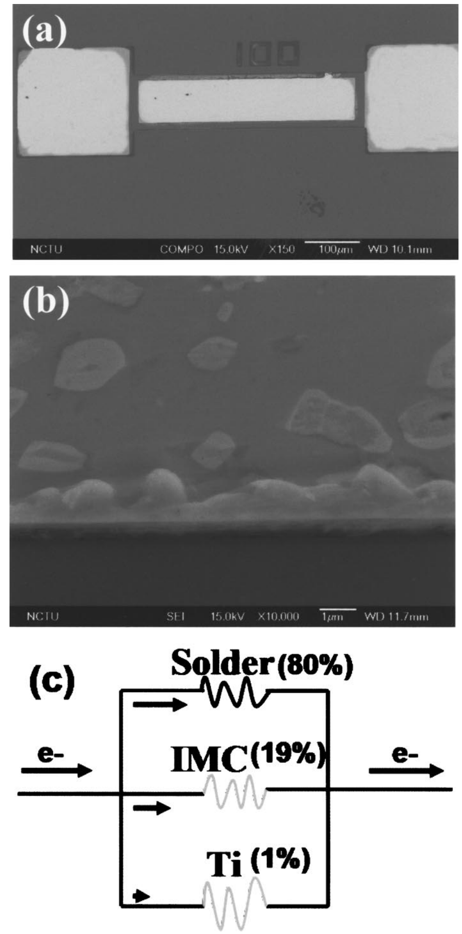

FIG. 3. SEM images for a fabricated Blech specimen. (a) The plan view image, in which the SnPb solder strip and the two pads are labeled. (b) The cross-sectional image of the solder stripe is (a). The average thickness of the IMC layer is 0.6 μm. (c) The effective circuit for the tri-layered Blech structure. Around 80% of the applied current drifted in the solder.

Figure 2 depicts the schematic structure of bump pairs, in which the electrons in the Al trace crowd into a solder bump after passing through the intermetallic compound (IMC) layer, flowing inside the solder bump, and then drift into the Cu line after the passage of another IMC layer. Typically, electromigration failure occurs at the junction of the Al trace and the bump, where current crowding takes place.[2] The path of electrons in the Blech specimen is quite similar to that in the flip chip solder bump. Thus, the measured electromigration rate in the Blech specimen may be close to that in flip chip solder bumps. Furthermore, the Cu metallization layer could be changed to Ni, since Ni is another important metallization film for flip chip solder bumps. The effect of metallization layer and IMC on electromigration can be investigated using these specimens.

To measure threshold current density for SnPb solder, various current densities ranging from 3×10^4 to 1×10^5 A/cm^2 were applied to the specimen by probing the two pads on a probe station with a hot stage at 100 °C. The current densities refer to the average ones drifting in the solder strips. The depletion volume on the cathode end was measured before and after the current stressing. However, due to the softness of the solders, the edge of the solder was not abrupt after the above-noted sample preparation procedures. Therefore, the depletion volume could not be measured accurately by scanning electron microscope (SEM)

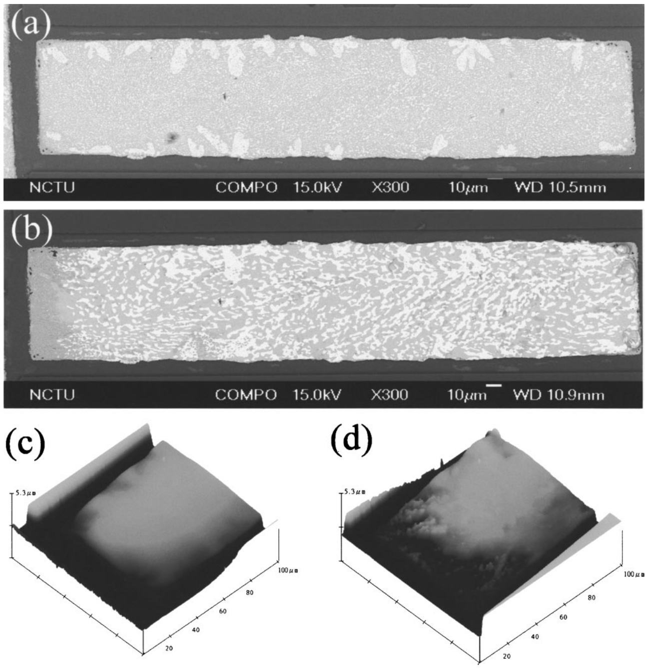

FIG. 4. (a) Plan-view SEM image of a SnPb solder strip before current stressing, in which the brighter region represents the Pb-rich phase and the darker region corresponds to the Sn-rich phase. (b) The solder strip in (a) after the current stressing of 6.9×10^4 A/cm^2 at 100 °C for 34.7 h. (c) AFM image of the cathode end of the solder strip in (a). (d) AFM image of the cathode end of the solder strip in (b).

alone. To overcome this difficulty, atomic force microscope (AFM) was employed to scan the region near the cathode end before and after the stressing, so that the depletion volume could be estimated precisely. The AFM used in this study was DI Nanoscope E.

Figure 3(a) shows the plan-view SEM image for a fabricated Blech specimen, in which the SnPb solder strip and the two pads are labeled. The cross-sectional SEM image of the solder strip is seen in Fig. 3(b). An IMC of Cu_6Sn_5 formed between the SnPb solder and the Cu metallization layer. The thicknesses of the solder, IMC, and remaining metallization were measured to be 2.4, 0.6, and 0.1 μm, respectively. Therefore, when the electrons drift in the solder

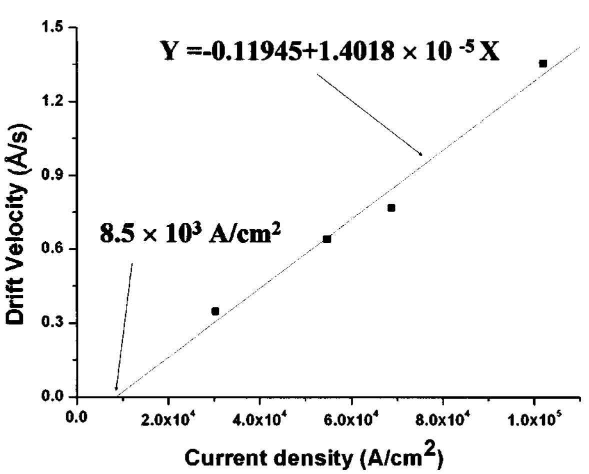

FIG. 5. The measured drift velocity as a function of applied current density at 100 °C. The calculated threshold current density is 8.5×10^3 A/cm^2 by extrapolating to the zero drift velocity.

outside the crowding area, they encounter an effective circuit, as shown in Fig. 3(c). As can be seen, around 80% of the applied current drifts in the solder strip, 19% in the IMC layer, and only 1% in the Ti layer.

Upon current stressing, depletion of solder occurred on the cathode end and extrusion formed on the anode end of the solder strip, as seen in Figs. 4(a) and 4(b). Figure 4(a) shows the plan-view SEM image of another SnPb solder strip before current stressing, in which the brighter region represents the Pb-rich phase and the darker region corresponds to the Sn-rich phase. After the current stressing of 6.9×10^4 A/cm^2 at 100 °C for 34.7 h, its microstructure is shown in Fig. 4(b). Depletion of solder occurred at the cathode end due to electromigration, causing the IMC to be visible from a top view. On the other hand, irregular extrusions of solder were observed on the anode side. To measure the depletion volume for calculating drifting velocity, AFM scanning was performed to obtain three-dimensional surface profiles before and after the current stressing, as seen in Figs. 4(c) and 4(d), respectively. By estimating the volume difference between the two profiles, depletion volume and thus drift velocity were acquired.

Figure 5 shows the measured drift velocity as a function of applied current density at 100 °C. The drift velocity increases when the applied current increases. By extrapolating to the zero drift velocity, the estimated threshold current density is obtained as 8.5×10^3 A/cm^2. This value represents the maximum current density that the solder can carry without electromigration damage at device operation temperature of 100 °C. To verify if this extrapolated value is accurate, another specimen was stressed at the current density of 5×10^3 A/cm^2 at 100 °C for 100 h, and no detectable volume change was found.

In summary, we have successfully developed a technique that can measure precisely the important parameters of solder electromigration. Solder Blech specimens were fabricated on patterned Cu/Ti films in Si trenches. By employing AFM to measure the depletion volume on the cathode end, the electromigration rate can be measured. The threshold current density was estimated to be 8.5×10^3 A/cm^2 at 100 °C.

The authors would like to thank the National Science Council of the R.O.C. for financial support of this study through Grant No. 91-2216-E-009-032.

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