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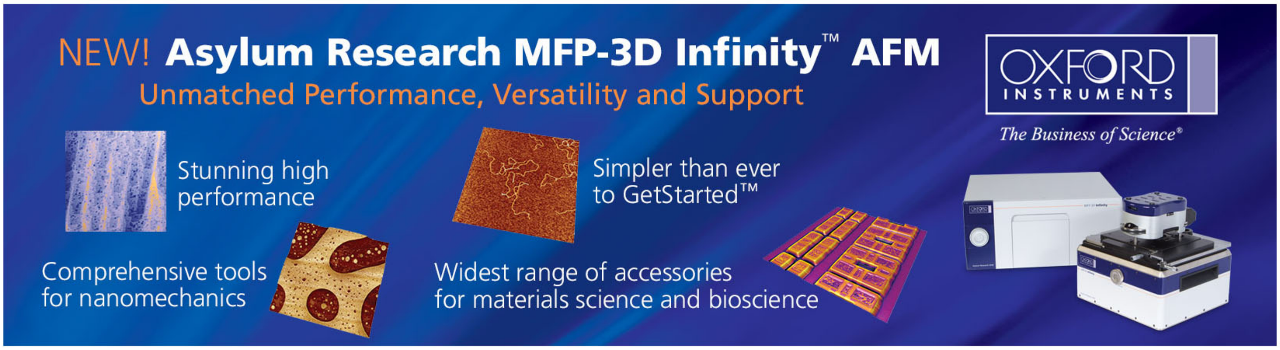

Thermomigration in Pb-free SnAg solder joint under alternating current stressing

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Lead-free solders have been adopted by the microelectronics industry. However, their thermomigration behaviors are unclear. Thermomigration in eutectic SnAg3.5 solder joints was investigated using an alternating current (ac) of 0.57 A at 100 °C. The ac eliminates the electromigration effect and creates a thermal gradient of 2829 °C/cm, facilitating the study of thermomigration. Arrays of tiny markers fabricated by a focused ion beam are employed to measure the thermomigration rate. It is found that Sn atoms migrated toward the hot end. The thermomigration flux and molar heat of transport are measured to be 5.0×10^{12} atoms/cm^2 and 1.36 kJ/mole, respectively. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3089872]

Because of concerns about the environment impact of Pb-containing solders, the electronic packaging industry is in a hurry to replace Pb-containing solders Pb-free solders, most of which have a high Sn content of approximately over 96 wt %.[1] Therefore, the matrix of Pb-free solder joints consists of Sn grains. Additionally, electromigration in flip-chip solder joints has become an important reliability issue in recent years because of the trend toward miniaturization to meet the requirement for improved performance in portable consumer electronics.[2,3] With the use of Pb-free solders, electromigration caused by increased current density is a serious reliability issue that must be considered in flip-chip packaging.[4]

Joule heating in the silicon chip generates a thermal gradient in a flip-chip solder joint. Since Al traces serve as the major source of heat during accelerated electromigration tests, high current stressing also produces a nonuniform temperature distribution, creating a large thermal gradient in a flip-chip solder joint.[5] This thermal gradient has been demonstrated to introduce a component of thermomigration during accelerated electromigration tests.[6,7] In recent years, work has been undertaken to tackle the issue of thermomigration in SnPb solder.[5–10] The temperature gradient causes Pb atoms in Pb-containing solders to move to the cold end on the substrate end and Sn atoms to migrate to the hot end on the Si side. At test temperatures of over 100 °C, Pb atoms appear to be the dominant diffusion species, forming voids on the chip end. However, the effect of thermomigration in Pb-free solders is presently unclear. Although the Sn-rich phase segregates to the hot end for the Pb-containing solders,[7,8] whether Sn migration is caused by the thermomigration of Sn atoms by or the exchanging of positions with the diffusing Pb atoms is unknown. As Pb-free solders are used in the packaging industry, thermomigration in Pb-free solder becomes a critical issue. It may also take place during accelerated electromigration tests.

In this study, tiny markers fabricated by a focused ion beam (FIB) are adopted to monitor the thermomigration of Sn in eutectic SnAg3.5 solder joints. An alternating current (ac) is employed to distinguish electromigration and thermomigration effects. The thermal gradients that are created by current stressing are measured using infrared microscopy. Therefore, the motion of Sn atoms, the thermomigration flux, and the heat of transport can be studied using this approach.

Cross-sectioned solder bumps were employed to facilitate the detection of the movement of markers and the measurement of the thermal gradient inside the solder bumps. A test model, in Fig. 1, was constructed. The solder joints comprise eutectic SnAg3.5 solder bumps with electroplated 5 μm Cu/3 μm Ni under bump metallurgy (UBM). To observe thermomigration *in situ*, solder joints were cross sectioned into halves, polished laterally until the contact openings were exposed, leaving about 50% of the mass of the bump. To prevent electromigration, an ac was adopted for current stressing. The ac generates the same amount of Joule heating but without electromigration. Flip-chip packages were stressed at a temperature of 100 °C on a hot plate. A current of 0.57 A was passed through the bump, producing a nominal current density of 1.01×10^4 cm^2.

Before current stressing, the emissivity of the specimen was calibrated at 100 °C, after which the bump was powered by an ac. The temperature was then measured to map the temperature after the temperature reached a steady state. The

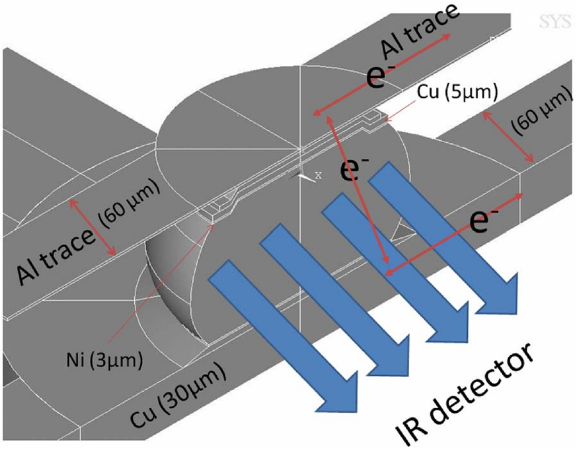

FIG. 1. (Color online) Schematic of bump used in this study.

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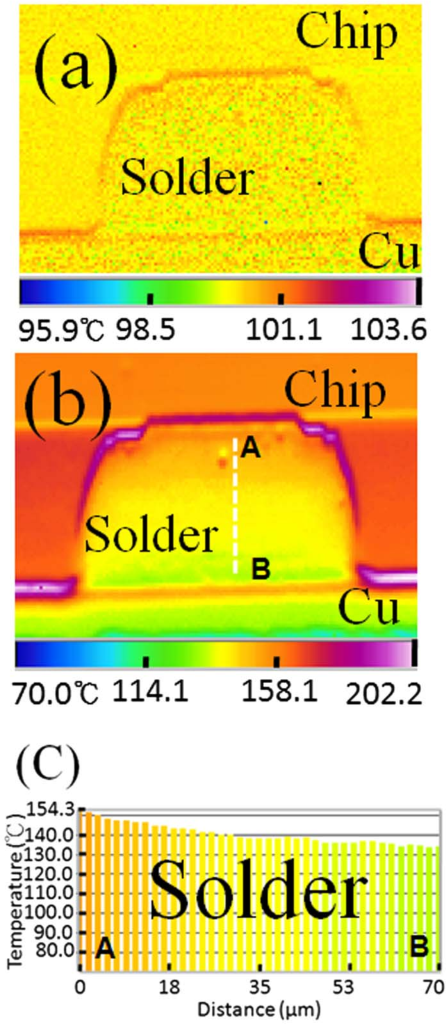

FIG. 2. (Color online) Temperature map of SnAg bump before current stressing, indicating a uniform temperature distribution in solder; (b) temperature map of bump powered by 0.57 A; (c) temperature profile along dashed line in (b); a huge thermal gradient of 2829 °C/cm is generated.

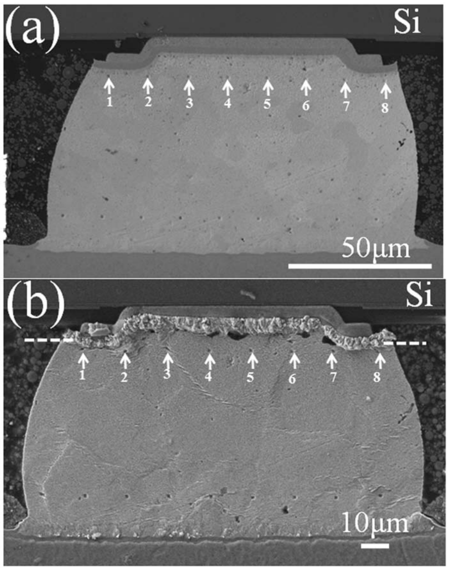

FIG. 3. Cross-sectioned bump with markers before and after thermomigration test at 1.01×10^4 A/cm^2 and 100 °C (a) initially; (b) at 800 h. After the thermomigration test, the markers moved toward the substrate end.

temperatures in the solder joints were mapped by QFI thermal infrared microscopy, with a temperature resolution of 0.1 °C and a spatial resolution of 2 μm. Changes in the maker positions and the surface microstructure were examined by scanning electron microscopy (SEM).

A huge thermal gradient can be established using this technique to study thermomigration. Figure 2(a) presents the temperature distribution in the bump before current stressing. The temperature distribution across the solder bump was then quite uniform. When current stressing commences at 0.57 A, the temperature distribution in the joint changes in response to Joule heating, as shown in Fig. 2(b). The average increase in temperature in the bump due to current stressing was observed to be as high as 40 °C. In the surrounding underfill, the temperature rises to 60.0 °C. The thermal gradient is defined herein as the difference between the average temperatures in the bump near the substrate (T_{subs}) and near the chip (T_{chip}), divided by the bump height, h:$(T_{\text{chip}}-T_{\text{subs}})/\text{h}$. Figure 2(c) shows the temperature profile along the dashed line in Fig. 2(b), where T_{chip} is higher than T_{subs}. The thermal gradient was measured to be 2829 °C/cm.

To measure the heat of transport of Sn and the thermomigration flux under a specific thermal gradient for eutectic SnAg3.5 solder joint, inert holes on the solder surface were utilized as markers. Two rows of 0.1 μm holes are etched using Ga ions from a FIB on to the cross-sectional surface of the joint; one is close to the chip side: and the other is located near the substrate end. Figure 3(a) displays the markers on the cross section of the bump before current stressing. The depth of the markers is approximately 100 nm; they each had an area of about 10^4 nm^2.

After current stressing, thermomigration causes observable mass transport. After 800 h of current stressing, hillocks are present on the chip side, as shown in Fig. 3(b). The hillocks comprised Sn using a SEM energy dispersive spectrum. These hillocks are formed directly by the mass transfer of the solder caused by thermomigration. The fact that $T_{\text{chip}} > T_{\text{subs}}$ gives rise to a thermal gradient between the chip and the substrate side, in which the heat is generated in the Al trace. This thermal gradient causes bottom to top mass diffusion in the joint, driving the mass transfer of Sn toward the hot chip end. Under current stressing, the markers moved to the substrate end because of thermomigration. The bottom edge of the Si chip was used as a fixed reference frame. Figure 3(b) displays an image of the markers after current stressing. The markers moved in the direction opposite the diffusion flux of Sn atoms. This observation suggests that the actual direction of overall diffusion of tin atoms is from the substrate side to the chip side, indicating the influence of the thermomigration under current stressing. This result also reveals that net mass transport proceeded from the cold end to the hot end. Notably, some voids appeared in the chip end after current stressing, as presented in Fig. 3(b). Why the voids form there is unknown. Lu *et al.*[11] reported that Cu and Ni atoms diffuse much more quickly along the *c*-axis than along the *a*- or *b*-axis of the Sn crystals, forming a significant number of voids near the Cu or Ni UBM. Further study is required to verify this assertion.

To analyze the thermomigration behavior of Sn atoms, the thermomigration flux was measured by the movement of markers. The positions of the upper-row markers were measured with respect to the reference frame. The thermomigra-

TABLE I. Measured displacements and thermal gradients at upper-row markers. The reference frame was set at the bottom edge of the Si die.

Marker number	1	2	3	4	5	6	7	8
Marker position before current stressing (μm)	−15.1	−15.1	−15.1	−15.1	−15.2	−15.3	−15.3	−15.3
Marker position after current stressing (μm)	−19.1	−19.1	−19.1	−19.1	−19.1	−19.1	−19.0	−18.5
Marker displacement (μm)	−4.0	−4.0	−4.0	−4.0	−3.9	−3.8	−3.7	−3.2
Thermal gradient (°C/cm)	2971	2829	2829	2829	2700	2229	2143	1571
Calculated Q (kJ/mole)	1.17	1.23	1.23	1.23	1.26	1.48	1.50	1.77

tion flux J in a temperature gradient dT/dx can be written for one-dimensional case:[12]

$$J_{\mathrm{TM}} = \frac{C D_A (Q^*/N)}{\kappa T^2}(-dT/dx), \tag{1}$$

where C represents concentration; $D_A = Do \exp(-Q/kT)$ is the coefficient of self-diffusion; k is Boltzmann's constant; N is Avogadro′s number; dT/dx is the thermal gradient, and T is the temperature. Q^* is a constant, which is the heat of transport.

If the displacement, stressing time, and cross-sectional area of the solder bump are known, the thermomigration flux can be measured. Table I lists the positions of the upper-row markers before and after the current stressing. The markers moved downward to the substrate side. The mean displacement of the markers was 3.8 μm. The atomic flux in thermomigration is given by

$$J_{\mathrm{TM}} = \frac{(A\Delta X)\rho N}{MAt}, \tag{2}$$

where ρ is the density of the SnAg3.5 solder $(7.42\ \mathrm{g/cm^3})$; M is the molecular weight of SnAg3.5 (118.33 g/mole), and t is the stressing time. The mean displacement ΔX can be obtained by measuring the displacements of these markers Thus, the atomic flux associated with thermomigration can be calculated as $5.0 \times 10^{12}\ \mathrm{atoms/cm^2}$.

The experimental atomic flux is substituted into Eq. (1) as is the value of DA published by Sun and Ohring.[13] Table I summarizes the measured displacements and local thermal gradients of all the markers. The average molar heat flux Q^* is determined to be 1.36 kJ/mole.

The results concerning motion of markers close to the substrate end follow the same trend as those close to near the chip end. The markers also moved toward the substrate side. Yet, the average displacement is only 2.2 μm, which is smaller than the value of 3.8 μm obtained from the upper-row markers. This difference may be attributed to the fact that the local temperatures at the two locations are different. As shown in Fig. 2(c), the temperature is 148 and 132 °C at upper row and at lower row, respectively. As shown in Eq. (1), the atomic flux is a function of the temperature. If the published value of the activation energy for self-diffusion of pure tin (11 700 cal/mol) was used,[13] the calculated atomic flux ratio between the upper row and lower row comes to 1.6, assuming no difference in thermal gradient. This calculated ratio is very close to the measured ratio of the marker movement 3.8/2.2=1.7.

The molar heat flux obtained herein seems quite reasonable. Kuz′menko and Golovinskiy[14] studied the diffusion of Sn in a thallium-tin liquid alloy at 450 °C and they obtained a molar heat flux of Sn of approximately 3.58 kJ/mole. In contrast, the testing conditions in this study were ac current stressing of $1.01 \times 10^4\ \mathrm{A/cm^2}$ at 100 °C. However, most importantly, in this investigation, the thermal gradient was directly measured by infrared microscopy, while the temperature gradient used in the work of Kuz′menko and Golovinskiy was assumed. The Sn atomic flux is one order of magnitude smaller than the thermomigration flux in eutectic SnPb,[7–9] which is dominated by Pb migration. Therefore, Pb atoms dominate the thermomigration behavior in eutectic SnPb solder.

In summary, thermomigration in eutectic SnAg3.5 solder joints in the flip-chip configuration was observed at 100 °C under stressing with an ac of 0.57 A. A current of 0.57 A yielded a thermal gradient of 2829 °C/cm. Thermomigration, which is caused directly by the aforementioned thermal gradient, induces the transport of Sn atoms to the hot end of the bump. As a result, hillocks were formed above the chip side. Based on the movements of the markers fabricated on the cross-sectional surface of the bump by FIB, the molar heat of transport of Sn was calculated as 1.36 kJ/mole.

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