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Study of the thermal stress in a Pb-free half-bump solder joint under current stressing

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The thermal stress in a Sn3.5Ag1Cu half-bump solder joint under a 3.82×10^8 A/m^2 current stressing was analyzed using a coupled-field simulation. Substantial thermal stress accumulated around the Al-to-solder interface, especially in the Ni+(Ni,Cu)$_3$Sn$_4$ layer, where a maximal stress of 138 MPa was identified. The stress gradient in the Ni layer was about 1.67×10^{13} Pa/m, resulting in a stress migration force of 1.82×10^{-16} N, which is comparable to the electromigration force, 2.82×10^{-16} N. Dissolution of the Ni+(Ni,Cu)$_3$Sn$_4$ layer, void formation with cracks at the anode side, and extrusions at the cathode side were observed. © *2007 American Institute of Physics.*
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Current-induced degradation of solder joint is recently recognized as a potential reliability issue of the flip chip interconnection.[1] Tu and co-workers have characterized the microstructural evolution and mechanical strength of solder joints during various experiments of current stressing. In particular, the current crowding-induced electromigration and thermal gradient-induced thermomigration were identified.[2,3] Ye *et al.* have measured the displacement of solder joints under current stressing and applied an electromigration constitutive model to simulate their deformation.[4] Chiu *et al.* have confirmed a hot spot in the solder joint by the thermal measurement and simulation.[5] However, the thermal stress due to a mismatch of coefficient of thermal expansion and modulus was not considered in the failure analysis of solder joints under current stressing. Although there have been a great many of literatures on the electromigration and thermomigration,[2] so far, no work has been reported on the stress migration in solder joints. With a quantitative investigation of the thermal stress, the individual contribution of stress migration to the physical degradation or failure of solder joints could be clarified. This letter reports a study on the thermal stress distribution in a Pb-free half-bump solder joint under current stressing.

As shown in Fig. 1(a), a flip chip sample was mounted in a cold-setting epoxy resin cylinder and then cross sectioned toward the middle of solder joints. The cylinder was 8000 μm in diameter and 5000 μm in length. The thickness of chip and substrate was 0.635 mm and 1.54 mm, respectively. Figure 1(b) illustrates the configuration of a half-bump solder joint. The bump was made of Sn3.5Ag1Cu with a diameter of 190 μm. The under bump metallization (UBM) opening was 100 μm in diameter. The stand height of solder joint was about 110 μm. The thickness of Ni, (Ni,Cu)$_3$Sn$_4$, and Cu$_6$Sn$_5$ layer was about 1, 3, and 5 μm, respectively. For electrical continuity, Al traces ($660\times100\times2$ μm^3) and Cu traces ($5000\times150\times35$ μm^3) were used on the chip and substrate, respectively, to connect the solder joints.

As illustrated by the hollow arrows in Fig. 1(b), a 1.5 A current was applied to two solder joints [Nos. 9 and 10 solder joint in Fig. 1(a)] at 75 °C for up to 162 h. From time to time, the microstructural evolution of solder joints was monitored using a scanning electron microscope (SEM). For verification of the Joule heating effect, a finite element simulation on the model mentioned above was conducted using the ANSYS software. The ambient temperature was fixed at 75 °C, the thermal convection coefficient was set to be 10 W/m^2 K,[6] other physical parameters were taken from Refs. 7 and 8, and the solder was assumed to follow a viscoplastic behavior in the Anand model.[8] At first, a solid69 element was used for an electrothermal modeling, from which the temperature distribution on the solder joints was obtained. Then, the model was remeshed with a solid visco-108 element for a thermomechanical analysis, during which the thermal result in the first step was imported as an initial load. The thermal stress distribution in the solder joints upon temperature variation was then calculated. The following discussion is based on the No. 9 solder joint.

When 1.5 A is applied, the average current density j in the solder joint is calculated to be 3.82×10^8 A/m^2 based on the area of UBM opening. Under such a high-density current, the temperature of solder joint increases substantially, as

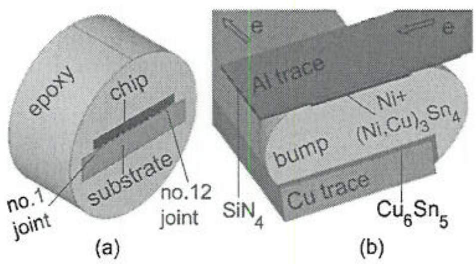

FIG. 1. (Color online) Schematic diagram of the half-bump sample. (a) Cured in the epoxy. (b) A half-bump solder joint.

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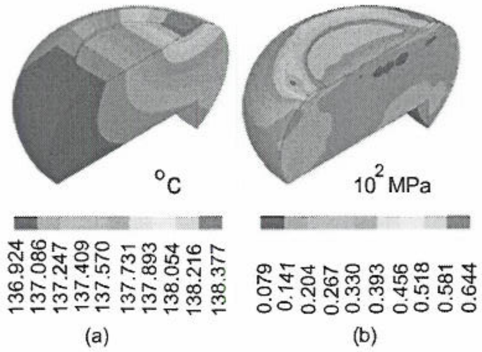

FIG. 2. (Color online) Temperature and thermal stress distribution in the bump. (a) Temperature distribution. (b) Stress distribution.

shown by the contour plot of temperature distribution in Fig. 2(a). The highest temperature is about 138 °C, which is an increase of 63 °C from the ambient temperature (75 °C). Temperature is one of the key factors determining the migration degradation because of the exponential dependence of the atomic diffusivity and apparent activation energy on it. Therefore, the atom transport process will be accelerated and the lifetime will be shortened as the temperature rises. The effective charge of electromigration, Z^*, is generally found to be at the order of 10 for a good conductor.[2] Yeh and Huntington have calculated that the average Z^* for Ni was very large, ranging from −67 at 166 °C to −36 at 203 °C.[9] Here, Z^* were estimated to be −72 at 138 °C according to an extrapolation from Fig. 5 in Ref. 9. Taking the electron charge e of 1.6×10^{-19} C and the resistivity ρ of 6.4×10^{-8} Ω m, the electromigration force F_{em} of Ni atoms is determined by[10]

$$F_{em} = -Z^* e\rho j = 2.82 \times 10^{-16}\ \mathrm{N}. \quad (1)$$

When the joint undergoes a large temperature change (63 °C), substantial stress is built up inside the solder joint. Figure 2(b) shows the distribution of thermal stress in the solder. The high-stress region locates at the top of solder, i.e., around the Al-to-solder interface. In particular, the maximal stress in the $Ni+(Ni,Cu)_3Sn_4$ layer is 138 MPa, as shown in Fig. 3(a). In order to estimate the stress gradient in the $Ni+(Ni,Cu)_3Sn_4$ layer, the variation of stress in direction Y with the distance from the migration-susceptible area, point A in Fig. 3(a), is plotted in Fig. 3(b). The slope shows that the stress gradient in the Ni and $(Ni,Cu)_3Sn_4$ layer is 1.67×10^{13} and 3.56×10^{12} Pa/m, respectively. Since the mechanical stress gradient is generally a driving force for the stress void nucleation and growth due to fast vacancy and/or atomic diffusion, these two layers will be more susceptible to stress migration than any other places in the solder joint.

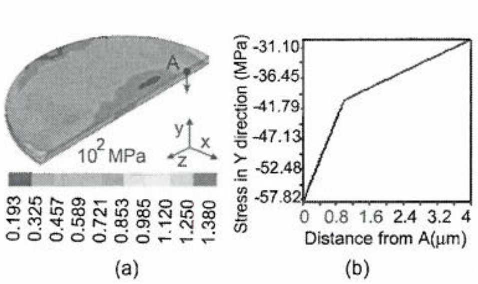

FIG. 3. (Color online) Thermal stress distribution in the $Ni+(Ni,Cu)_3Sn_4$ layer. (a) Stress distribution. (b) Variation of the stress with the distance from point A in direction Y.

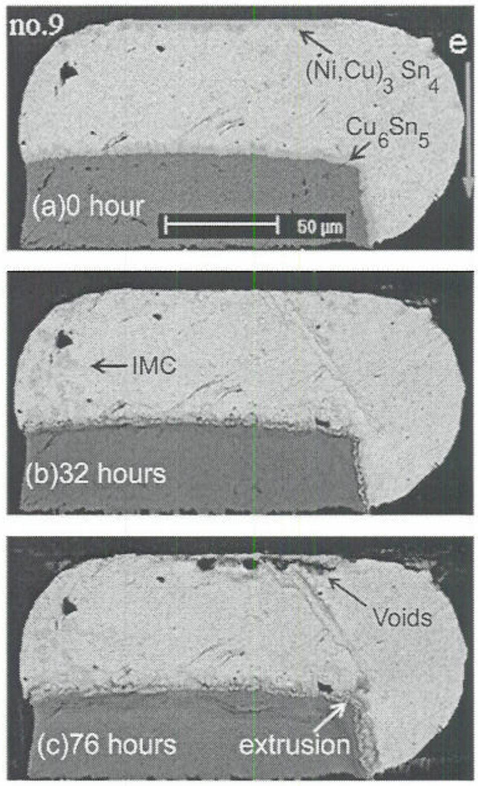

FIG. 4. (Color online) Morphological evolution of the solder joint. (a) 0 h. (b) 32 h. (c) 76 h.

Taking the atomic volume Ω of Ni of 1.09×10^{-29} m^3/atom and the stress gradient $d\sigma/dy$ of 1.67×10^{13} Pa/m, the stress migration force F_{sm} of Ni atoms is determined by[10]

$$F_{sm} = \Omega\frac{d\sigma}{dy} = 1.82 \times 10^{-16}\ \mathrm{N}. \quad (2)$$

F_{sm} is at the same order of F_{em}, which suggests that stress migration could also occur and contribute much to the total migration process. At the initial stage of test, if the stress is not released effectively, stress migration would interact with electromigration by means of enhancing diffusion, void formation, and cracking. As simulated, the local temperature of solder joint is about 138 °C, which in terms of homologous temperature for the solder is too high, but for the $Ni+(Ni,Cu)_3Sn_4$ is too low. Thus, the stress will be released immediately from the solder, but the relaxation process from the $Ni+(Ni,Cu)_3Sn_4$ will require a period of time. Therefore, the stress migration and electromigration have comparable contributions to the degradation of the solder joint by this stage. However, once the stress relaxation is completed, the stress migration will not occur any more.

The modeling results were validated by experimental examinations. With microstructural SEM photos, Fig. 4 tracks the overall morphological evolution of the solder joint with time, where three major evidences of thermal stress were noticed. First, rapid dissolution of original $Ni+(Ni,Cu)_3Sn_4$ layer at the anode side was confirmed within 32 h, as indicated in Fig. 4(b). Under the interaction of electromigration and stress migration, the atoms (Ni and Cu) depart from there and dissolve into the solder quickly. It is interesting to find that some intermetallic compound particles are formed in the bulk solder on the left, which corresponds to the area with relatively larger stress according to the simulation result in Fig. 2(b). Second, fast void growth with obvious cracks was found at the anode side after 76 h. Severe migration-induced destruction occurs due to material depletion when the back diffusion of Sn atoms cannot fully occupy the vacancies. According to the current density and temperature used in the electromigration tests done by other researchers, it takes a few hundreds of hours to form obvious voids.[1–3] Without a highly accelerated effect of stress, continuous mass transport only due to electromigration could not make the void to be about 8 μm in diameter within such a short time (76 h), as shown in Fig. 4(c). Also, the solder is deformed seriously to be crinkled and large cracks are seen inside the solder around the voids, which is a direct indicator of local stress releasing. Third, hillocks are noticeable at the cathode side. It is believed that an enrichment of arriving atoms and substantial internal stress make the surface extrude locally. The squeeze out of whisker can be regarded as another means of stress releasing. It is confirmed that from 76 to 162 h, the rate of void growth and hillock development slows down, which suggests that a complete stress relaxation is achieved through the voiding, cracking, and extruding processes.

In summary, this study shows that the solder joint has a local temperature rise of 63 °C under a 3.82×10^8 A/m^2 current, thereby a significant stress and stress gradient is built around the Al-to-solder interface, especially in the $Ni+(Ni,Cu)_3Sn_4$ layer, where the maximal stress and stress gradient is 138 MPa and 1.67×10^{13} Pa/m, respectively. The driving force of electromigration and stress migration for Ni atoms is 2.82×10^{-16} N and 1.82×10^{-16} N, respectively. Rapid dissolution of the $Ni+(Ni,Cu)_3Sn_4$ layer, fast void formation with cracks at the anode side, and substantial extrusion growth at the cathode side occur, which suggests an accelerated degradation due to the electromigration and stress migration in a high tension condition of current, temperature, and stress.

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