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High Current Density induced Damage Mechanisms in Electronic Solder Joints: A State-of-the-Art Review

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Abstract:

High current density induced damages such as Electromigration in the on-chip interconnection /metallization of Al or Cu has been the subject of intense study over the last 40 years. Recently, because of the increasing trend of miniaturization of the electronic packaging that encloses the chip, electromigration as well as other high current density induced damages are becoming a growing concern for off-chip interconnection where low melting point solder joints are commonly used. Before long, a huge number of publications have been explored on the electromigration issue of solder joints. However, a wide spectrum of findings might confuse electronic companies/designers. Thus, a review of the high current induced damages in solder joints is timely right this moment. We have selected 6 major phenomena to review in this paper. They are i. Electromigration (mass transfer due electron bombardment), ii. Thermomigration (mass transfer due to thermal gradient), iii. Enhanced Intermetallic Compound Growth, iv. Enhanced Current Crowding, v. Enhanced Under Bump Metallisation Dissolution and vi. High Joule heating and vii. Solder Melting. The damage mechanisms under high current stressing in the tiny solder joint, mentioned in the review article, are significant roadblocks to further miniaturization of electronics. Without through understanding of these failure mechanisms by experiments coupled with mathematical modeling work, further miniaturization in electronics will be jeopardized.

Introduction:

To cope with the miniaturization trends of electronic products, electronic packaging is shrinking dramatically over the last few years while functionality is increasing on the other hand. These two divergence scenarios, pose a reliability threat in the designing of the off-chip interconnect of the electronic packaging. It demands a reduced cross-section of the conductive wire and the solder interconnect while on the other hand, is subjected to conduct higher density of electrical currents [1-2].

Since solder alloys operate within a narrow temperature window, it is more sensitive to failure compared with thin-film metallization of Al or Cu in side the chip. From the literature survey of most of the works published so far as well as our own experimental and modeling study, it is believed that carrying an electromigration study for solder joints is much more difficult than that for the thin-film metallization of Al or Cu. It is also believed that contribution from electromigration is insignificant to some extent compared with the damages arising from the competition of Joule heating and heat dissipation within the system plus current crowding, under bump metallization dissolution, high volume fraction of intermetallic compounds, melting etc. Here, we are going to discuss 7 typical cases of damage mechanics to provide a brief idea of solder joints under high current stressing.

I. Electromigration:

In a simple form, the atomic flux can be describe by the following equation of diffusion in the presence of a driving force, F [3-6] ,

$$J = \frac{DC \ \vec{F}}{kT} \qquad \text{......................(1)}$$

Where, J is the mass transport, D is the thermally activated diffusion coefficient, C is the concentration of diffusing atoms, k is the Boltzmann's constant and T is the absolute temperature.

For electromigration,

$$\vec{F} = Z^{*} e\rho \ \vec{j} \qquad \text{......................(2)}$$

where, Z* is dimensionless quantity that can be regarded as the nominal valence of the diffusing ions in the metal, e is the electronic charge, ρ is the electrical resistivity, and j is the applied current density.

However, empirical equations resulting from the observed behavior of thin film conductor do not confirm direct dependency of applied current density, j. In fact, J. R. Black [7] from Motorola, who carried out the early comprehensive experimental study of electromigration failure, co-related median time to failure to the 2 nd power of j. Later, to make it more generalize, the power exponent 'n' of j was introduced – thus, the empirical equation is as follows:

$$t_{50} = Aj^{-n} \exp(\frac{E_a}{kT}) \qquad \text{..................(3)}$$

where, A is a materials and process-dependent constant and E_a is the activation energy for the diffusion processes that dominate over the temperature range of interest.

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Nevertheless, there is not any comprehensive work elsewhere to validate this equation for Solder joint failure. Yet, where failure is induced by void and hillocks, such as for pure Sn strip, we can fairly use Black's equation to find MTF. In deed, typical void-hillock typed failure was reported for Sn strip in ref [8] (see Figure 1).

To compare electromigration phenomena in Sn or Sn-based alloy conductor with the case of Al or Cu conductor , it is easier to discuss 'critical product' [9],

$$j\Delta x = \frac{\Delta \sigma_n \Omega}{Z^* e \rho} \quad \text{...........(4)}$$

where, σ is hydrostatic stress in the metal and Ω is atomic volume. If we replace Δσ by YΔε, where Y is Young's modulus and Δε is the elastic limit, we see in Equation (4) that the "critical product" is directly proportional to Young's modulus and strain, while inversely proportional to resistivity, and effective charge number of the interconnect material.

To compare the value of "critical product" among Cu, Al, and Sn or Sn-based alloys, we note that Sn or Sn-based alloys has a resistivity that is one order of magnitude larger than those of Al and Cu. The Young's modulus of Sn or Sn-based alloys (30 Gpa) is a factor of two to four smaller that those of Al (69 Gpa) and Cu (110 Gpa). The effective charge number of Sn or Sn-based alloys (Z* of lattice diffusion) is about one order of magnitude larger than those of Al (Z* of grain boundary diffusion) and Cu (Z* of surface diffusion). Therefore, if we keep Δx constant for comparison, we find that the current density needed to cause electromigration in Sn or Sn-based alloys solder is two orders of magnitude smaller than that needed for Al and Cu interconnect [3]. This is the major reason why electromigration in solder joint is a serious issue. Furthermore, following 6 cases also accelerates failure in Sn or Sn-based solder joints.

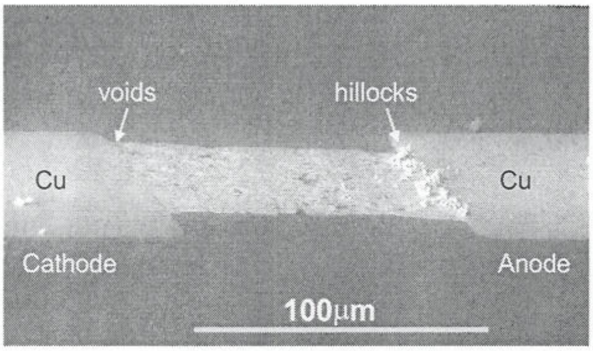


Figure 1. Tilt SEM view of a thin stripe of pure Sn after current stressing at 105A/cm2 of 80 hours at ambient temperature. Hillocks of Sn were observed at the anode side [8].

II. Thermomigration:

Because of the trends of smaller chip size and greater functionality, joule heating from the silicon die experiences a higher temperature than the board side that results in a high thermal gradient across the chip to substrate interconnect. Thus, along with electromigration, thermomigration is also an issue for the solder joint.

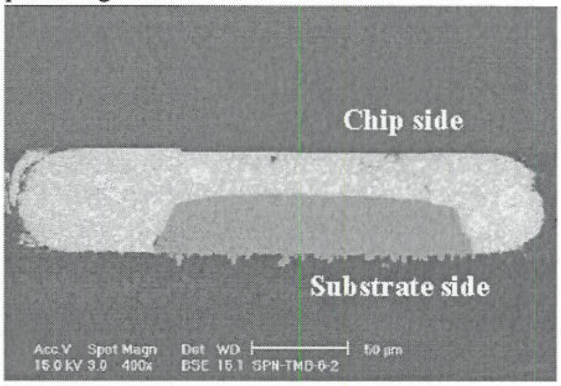
Thermomigration is an accelerated mass transport phenomena in metal from hot zone to cold zone. The mass flux due to thermomigration can be expressed similarly as for electromigration

$$J_{ther} = \frac{DC}{kT} \cdot Q^* \cdot \frac{1}{T} \cdot \left(\frac{dT}{dx}\right) \quad \text{....................(5)}$$

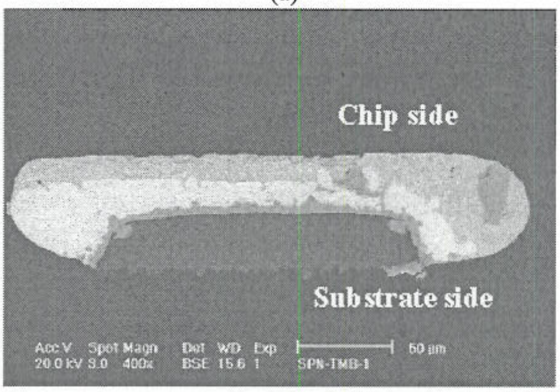
where dT/dx is the temperature gradient, and Q* is constant related to activation energy and comparable to Z* (effective charge number).

Thermomigration in Pb-In solder alloy, In and In alloys and Pb has been observed under a high thermal gradient such 1000 °C/cm [10]. It has only recently been reported that thermomigration in flip-chip solder joints may assist or counter electromigration depending on the direction of the thermal gradient and the electric field [11]. Hue et al., found thermomigration in eutectic Pb/Sn solder from hot side (Si die side) to cold side (Substrate side). Tu's group observed obvious thermomigration in tin-lead composite solder joints [12].

We observed thermomigration and phase segregation in solder joints at 150 °C after only 50 h of experiments as illustrated in Figure 2 [13]. It is believed that Pb migrated to the substrate side (the cold side) under the temperature gradient. The result is in reasonable agreement with those of thermomigration in tin-lead composite flip chip solder joints reported by Tu's group [9]. They found that Pb moved to the cold side and Sn to the hot side under an estimated temperature gradient of above 1000 °C/cm at 150 °C.



(a)



(b)

Figure 2. SEM micrographs of (a) as-reflowed original microstructure of solder joints, (b) thermomigration after 50 h at 150 °C [13].

From our own experiments, we believe that conducting thermomigration experiments is a tedious task for solder joints. This is why much experimental data are not yet available in public domain to realize the extent of thermomigration for solder joints.

III. Enhanced Intermetallic Compound Growth:

Intermetallic compounds (IMCs) formation at the solder/UBM interfaces is essential for good metallurgical bonds. However, the growth of IMCs during field service influences the strength and the mechanical failure of solder joints. In particular, the IMC volume fraction in a tiny solder joint is relatively higher. Such a high volume fraction of IMC in the solder joint introduces new failure mechanism both at the solder interface and in the bulk joint.

Without electric current, the driving force of IMC formation is the chemical potential difference between two contact materials. At a high current density (above 10^2 A/cm^2), the momentum transfer from electrons to atoms can play a significant role in IMC formation. If we add driving force of eletromigration with the chemical potential for nominal compositional gradient, total driving force along the x coordinate (considering electron flow and compositional gradient are acting in the x-direction) can be expressed as follows:

$$\vec{F} = Z^{*} e\rho \vec{j} + \frac{\partial \ln C}{\partial x}$$

Thus, the total flux

$$J_{total} = \frac{DC}{kT}\left[Z^{*} e\rho\vec{j} + kT\frac{\partial \ln C}{\partial x}\right]$$

Chen and co-workers [14-16] have studied the IMC formation in several diffusion couples such as Al/Ni, Sn/Ni, Sn/Ag and Sn/Cu, with a d.c. current density of 10^2-10^3 A/cm^2. They observed the directional effect of electric current on the IMC thickness in Sn/Ni and Sn/Ag couples at a current density of $5x10^2$ A/cm^2. Figure 3 shows thicker IMC at one side of Sn-Ag couple.

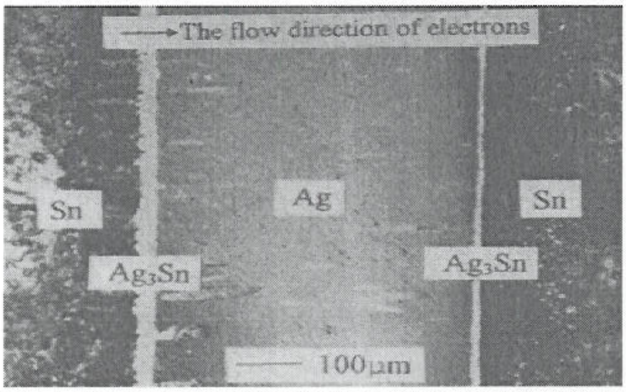


Figure 3. Micrographs of the Sn/Ag couple reacted with the passage of $5A/mm^2$ at 140°C for 20 days [16].

However, the electromigration effect on IMC formation becomes insignificant at higher temperature. It is believed that at higher temperature near melting point of Sn, the contribution from the chemical potential gradient on the interfacial reaction rate is much stronger compared with the electromigration force.

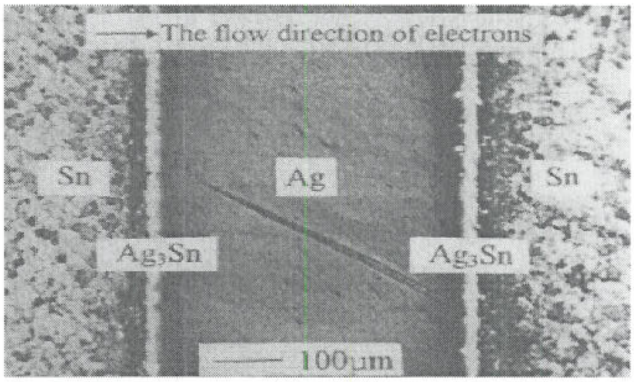


Figure 4. Micrographs of the Sn/Ag couple reacted with the passage of $5A/mm^2$ for 15 days at 200°C [16].

IV. Enhanced Current Crowding:

Current crowding occurs at the contact interface between the solder ball and the metal pad/UBM. It was found for a flip-chip solder joint that the high current density due to current crowding is about one order of magnitude higher than the average current density in the joint (see Figure 5). This current crowding exerts a much greater driving force for electromigration and also generates local Joule heating interfacial reactions [17-18].

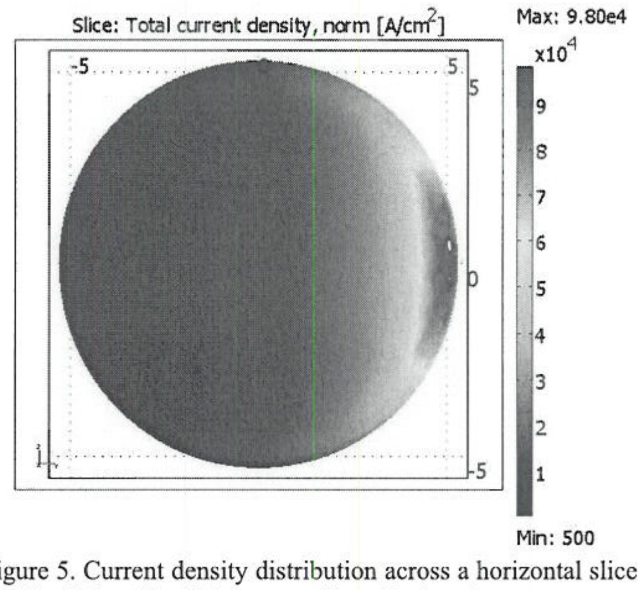


Figure 5. Current density distribution across a horizontal slice of Flip Chip solder joint near solder-chip interface.

It is claimed that voids nucleates from the current crowding spot and propagated through the interface of solder with pad metallization (see Figure 6). Nevertheless, void nucleation was reported to occur in the low current density region for Al metallization. Voids were also found to be distributed throughout the IMC to solder interface (see Figure 7).

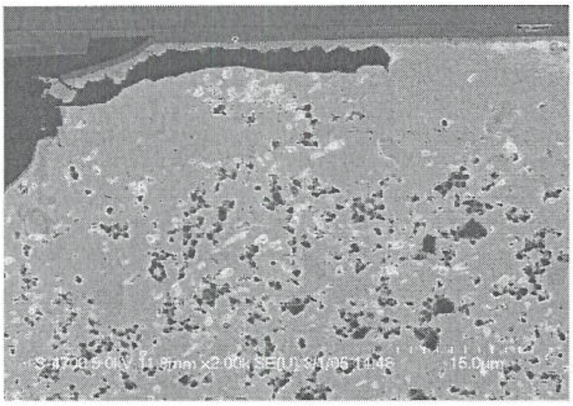


Figure 6. SEM image of void formation in flip chip 95.5Sn–4.0Ag–0.5Cu solder bump. [19]

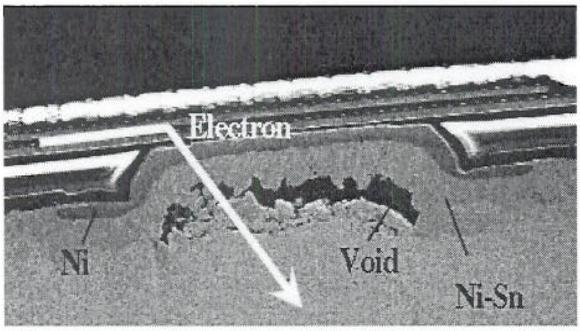


Figure 7. Typical SEM micrographs showing voids at the IMC /solder interface during electromigration test of a solder joint.[20]

3D FEA simulations for relieving the current crowding effect in solder joints under current stressing were carried out by Liang et al.[21-24] Three possible approaches were examined in this study, including varying the size of the passivation opening, increasing the thickness of Cu underbump metallization (UBM), and adopting or inserting a thin highly resistive UBM layer. From their simulation work they reported that the current crowding effect in the solder bump could be relieved with the thick Cu UBM or with the highly resistive UBM. While utilization of highly resistive UBM is an impractical solution, utilization of thicker UBM needs further study in terms of UBM dissolution and subsequent microstructural effect.

In addition, current crowding induced localized UBM dissolution was found to be much severe which is discussed in the next section.

V. UBM dissolution:

Decreasing solder joint size obviously reduces the thickness of UBM in the solder joint, if we keep traditional UBM design of solder interface. Unfortunately, high current density and/or current crowding accelerates dissolution of UBM. Figure 8 shows cross-sectional SEM images of a μBGA solder joint with and without current stressing. In the upper part of the image shown in Figure 8(a), the thick Cu UBM is symmetrical / uniform before current stressing. After 10^3 A/cm^2 of current stressing at 150°C for 30 min, the joint has been opened. From Figure 8(b), it is clear that only the upper right corner of the Cu UBM has been dissolved and replaced by solder. Electrons entered into the joint from the upper right corner. Clearly, it shows the localized current stressing effect.

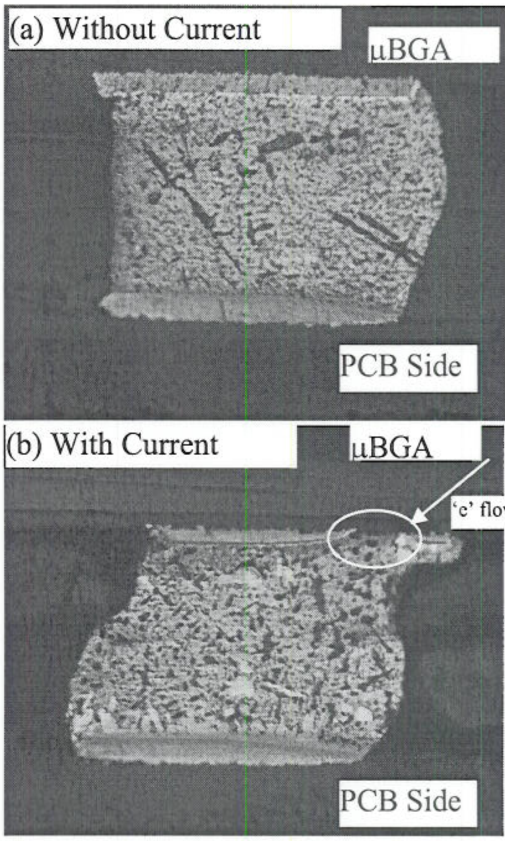


Figure 8. Cross-sectional SEM micropgraphs of the μBGA solder joint.

An interesting dissolution phenomenon of Cu bonding pad and near-by conductor under high current stressing was reported by Hu at el. They reported progressive dish-shaped Cu UBM dissolution starting from the point where Cu conductor met the Cu UBM. Figure 9displays a set of their scanning electron microscopic (SEM) images at several different stages. Figure 9(a) shows the cross-section of the joint before the test. Their samples was made of a very thick (14 μm) Cu UBM at the upper interface.

The electron flow was coming from the upper left-hand interconnect and entered the bump at the upper-left corner. Figure 9(b), (c) and (d) are images of the cross-section of the solder joint after 15, 45, and 90 min, respectively, powered at 1.25 amp at 125°C. The left-hand side of the Cu UBM disappeared gradually and was replaced by solder. Correspondingly, more and more Cu_6Sn_5 intermetallic compound was formed inside the solder bump. The asymmetrical dissolution of the Cu UBM is clearly due to the fact that the electron current entered the solder bump from the upper-left corner so current crowding occurred there. Dissolved Cu conductors seen in Figure c and d, were backfilled with the solder. The part of the conducting trace that was backfilled with solder had a much higher tendency to fail than the original Cu conducting trace since Joule heating in the solder conductor is much higher because of higher resistance in solder.

It is true that dissolution of Cu is much higher than other typical UBM such as Ni, Ni(P). However, there is not yet any comparative study of high current induced dissolution rate for those UBM systems.

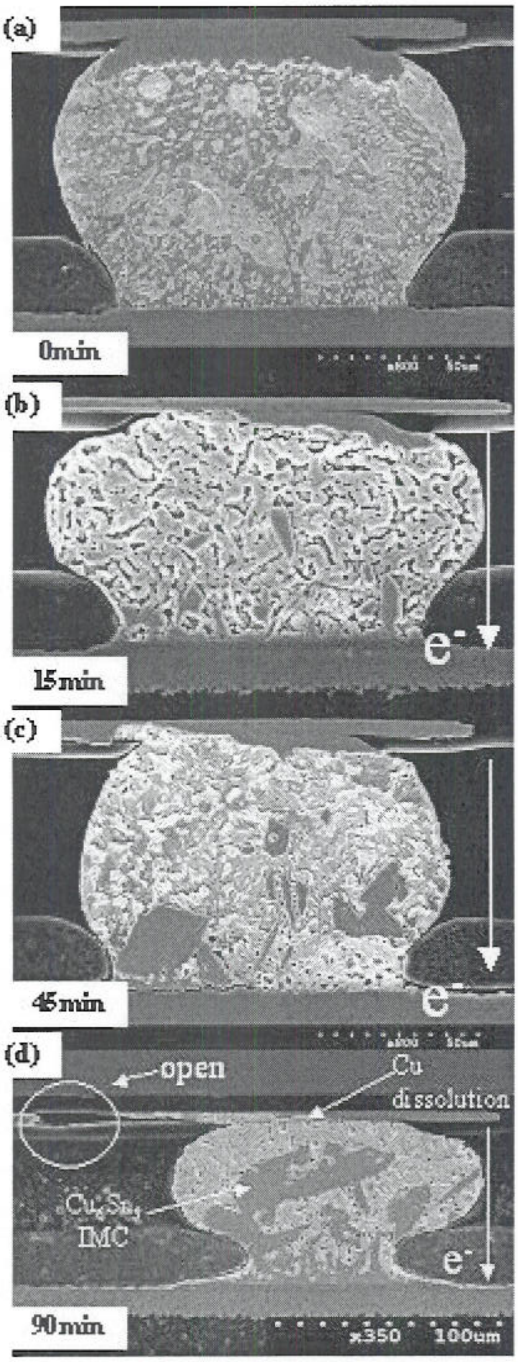


Figure 9. Cross-sectional SEM images of asymmetrical dissolution of a thick Cu UBM 125°C with an applied current of 1.2 A. (a) 0 min, (b) 15 min, (c) 45 min, and (d) 90 min. The electron current entered the bump from the upper-left corner. As the solder replaced the Cu at the upper-left corner, more and more intermetallic Cu_6Sn_5 formed inside the solder bump near the anode. [25]

VI. Joule heating:

A typical accelerated electromigration test sample that is composed of solder joint sandwiched between the thin Al metallization of Si chip, and Cu trace of polymer substrate, it was found that thin Al metallization contributes much for joule heating. Figure 10 shows the simulated Joule heating (Resistive heating) distribution in the Al trace, Cu conductor and in the solder joints when stressed by 1 A. Similar results were also revealed by experimental as well as numerical simulation by other investigators [26].

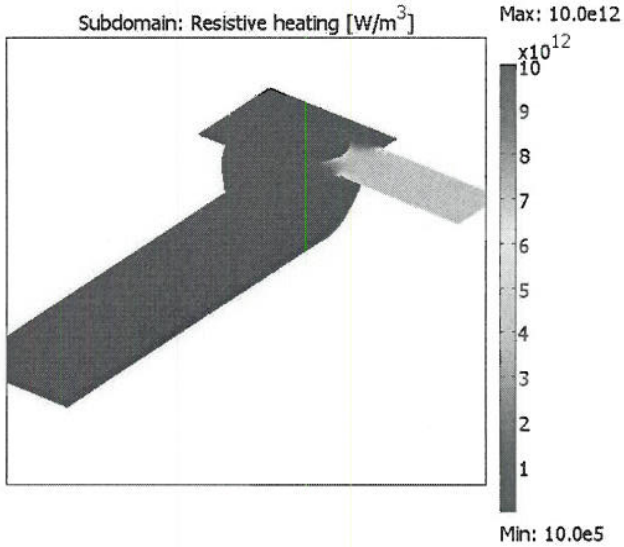


Figure 10. Simulated Joule heating (Resistive heating) distribution in the Al trace, Cu conductor and in the solder joints when stressed by 1 A

Because of current crowding at the interfaces, Joule heating is much higher as can be seen from the simulation. Since Joule heating is proportional to the square of current density, the current crowding effect leads to a local temperature rise that in turn accelerates the void nucleation and growth. The whole process continues till the void is large enough to break the line.

Solder joint near the trace receive higher temperature due to the resistive heating from Al metallization. Such Joule heating induced temperature raise certainly change the experimental pre-set-parameters and thus mislead the result [27-28].

VII. Observation of melting phenomena in solder joints:

Along with the research report of substantial temperature raise during conduction of electromigration experiments, melting of the solder joints have also been reported [28-29]. During the current stressing, when the Joule heating exceeds the heat dissipation, the temperature of the thin Cu trace/Al metalization on the component side may exceed the melting point of the solder alloys. A temperature of 200°C does not produce any change of phase in the Cu conductor, however, at this temperature the eutectic Sn-Pb solder alloy melts down. We understood localized melting near high temperature metalization in a Flip Chip solder joint sample after revealing microstructure shown in Figure 11.

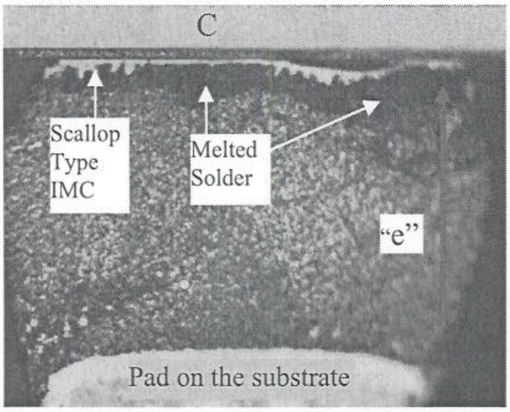


Figure 11. Cross-sectional micrographs after the effect of high current density.

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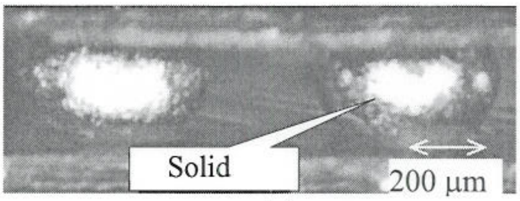
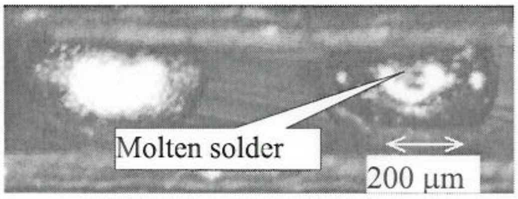


(a)



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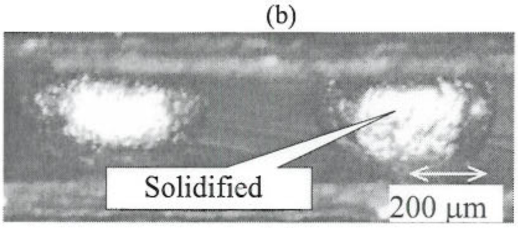

(c)

Figure 12. Stereomicrographs to show cyclic melting and solidification phenomena of a solder joint under 1.2 A current stressing [28].

A special set-up was prepared to observe the *in-situ* melting phenomena at the solder interfaces.[28] Figure 12 shows an *in-situ* melting phenomenon under a high current stressing. The right-hand side solder ball was in electrical connection to see/compare with the left side solder joint which was not under high current stressing. After applying 1.2A current, fusion of that solder ball was observed under a stereomicroscope that was revealed through the rapid change in the color and curvature of the solder ball (see Figure 12 b). Later, the solder ball was seen to re-solidify. Figure 12 (c) shows the solidified solder which depicts metallic lustre by solid state reflection. Liquification of the solder ball was seen again just like the case shown in Figure 12 (b). This happened cyclically. Waves of phase transition were seen to move to and fro from one side to the other side. The liquid phase was seen to nucleate where the Cu trace on the component side met with the solder joint (which can be termed a 'hot spot' of the solder joint) and extended down from the component side to the board side. Solidification again started to proceed from the board side.

Conclusion:

Electromigration is a complex phenomenon even in homogeneous, time-invariant systems such as aluminum or copper. The multicomponent system of common solders and their time-dependant properties offer new challenges for investigation and opportunities for creative solutions. During an electromigration test of a thin Al strip on a Si substrate, Joule heating is not a problem because the heat dissipates quickly. However, for the BGA/FC solder joints, when they are connected in a package, heat dissipation would be less than the contribution from Joule heating and thus, there is a chance to rise the temperature. As solder is the low-melting point component in the interconnection, it is very sensitive to temperature. Rapid dissolution of the Cu UBM demonstrates the occurrence of the melting phenomena of a solder joint. Even when melting does not occur, the temperature might be raised to an unpredictable range depending on the ease of heat dissipation of a particular arrangement. It would be worthwhile to measure the real-time temperature of a solder interface to report and/or understand the electromigration phenomena in a solder joint. Until a real temperature distribution in the solder interface and in the bulk of the solder bump has been obtained, it is impossible to generalize the electromigration behavior in a solder joint.

Acknowledgments

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