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Electromigration-induced cracks in Cu/$Sn_{3.5}$Ag/Cu solder reaction couple at room temperature*

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Abstract: Electromigration (EM) behavior of Cu/$Sn_{3.5}$Ag/Cu solder reaction couple was investigated with a high current density of 5×10^3 A/cm^2 at room temperature. One dimensional structure, copper wire/solder ball/copper wire SRC was designed and fabricated to dissipate the Joule heating induced by the current flow. In addition, thermomigration effect was excluded due to the symmetrical structure of the SRC. The experimental results indicated that micro-cracks initially appeared near the cathode interface between solder matrix and copper substrate after 474 h current stressing. With current stressing time increased, the cracks propagated and extended along the cathode interface. It should be noted that the continuous Cu_6Sn_5 intermetallic compounds (IMCs) layer both at the anode and at the cathode remained their sizes. Interestingly, tiny cracks appeared at the root of some long column-type Cu_6Sn_5 at the cathode interface due to the thermal stress.

Key words: electromigration; cracks; intermetallic compounds; thermal stress
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1. Introduction

Electromigration (EM) has been testified to be one of the major causes leading to failures in flip-chip solder joints. EM in flip-chip solder joints will become a serious reliability concern when the current density reaches 10^4 A/cm^2, which is considered as the threshold value to induce EM[1−3]. However, the threshold current density of 10^3 A/cm^2 or lower is mentioned in some other literature[4−6]. Voids and cracks will appear and propagate along the interface near the cathode which maybe leads to the final open failure due to the dual effect of thermomigration and electromigraton. Some metal atoms will migrate and accumulate towards the anode, leading to the pile-ups or hillocks formation near the anode interface[7−10]. All of these defects can seriously degrade the solder joints' reliability.

Theoretical and experimental results have been reported on SnAg lead-free solder, but few are on eutectic SnAg solder under room temperature condition. In this study, electromigration of eutectic SnAg solder induced cracks is investigated at room temperature. Cu/$Sn_{3.5}$Ag/Cu solder reaction couple (SRC, all the following word of SRC stands for solder reaction couple) is fabricated at the soldering platform designed and constructed by ourselves. The process is terminated at 474 and 950 h, and the microstructural evolution is observed and analyzed with scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX).

2. Experiment

In order to complete the Cu/$Sn_{3.5}$Ag/Cu SRC for EM, a set of assembled soldering platform was applied which was very convenient and effective. The particular soldering procedure completely followed our previous work[11,12]. The schematic diagram of the as-reflowed SRC is shown in Fig.1.

When the DC power supply was turned on, the temperature of the SRC increased due to the Joule heating induced by such a high current flow (5.3 A). According to the detection of the thermocouple, the surface temperature increased rapidly at the beginning. However, half an hour later, it approached to a stable value approximately at 40 °C. In order to have an even temperature distribution, a heat dissipation device as shown in Fig. 2 was employed in our work that could effectively dissipate the Joule heating. It was composed of three metal blocks fixed by screws. The SRC was sticked to the groove of the metal block surface. Therefore, Joule heating could be dissipated away by the device. Considering no mechanical force was applied at the horizontal direction, no subsidiary stresses would affect the experimental result. The surface temperature of the SRC mounted on heat dissipation device was merely 28 °C. Figure 3 shows the temperature profile for EM with and without heat dissipation device. Before performing EM test, the sample was treated metallographically by grinding with sandpaper. Basically, the purpose of the treatment was to reduce the dimension of the solder joint, so as to have a higher current density pass

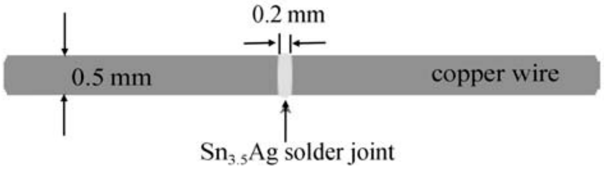

Fig. 1. Schematic diagram of as-soldered Cu/$Sn_{3.5}$Ag/Cu solder reaction couple.

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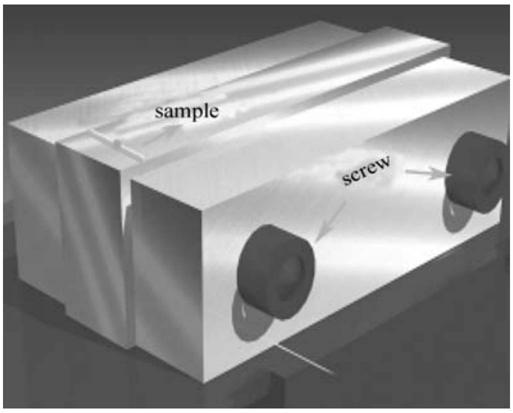

Fig. 2. Three-dimensional drawing of heat dissipation device.

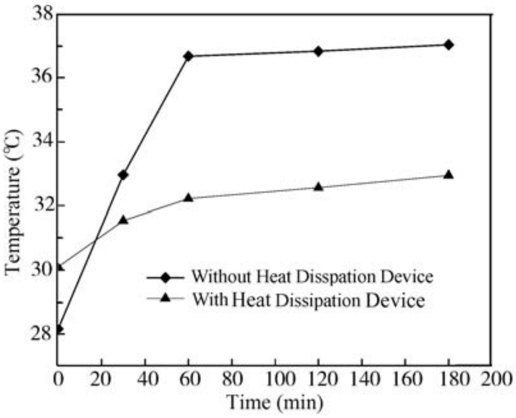

Fig. 3. Temperature profile for soldering with and without heat dissipation device.

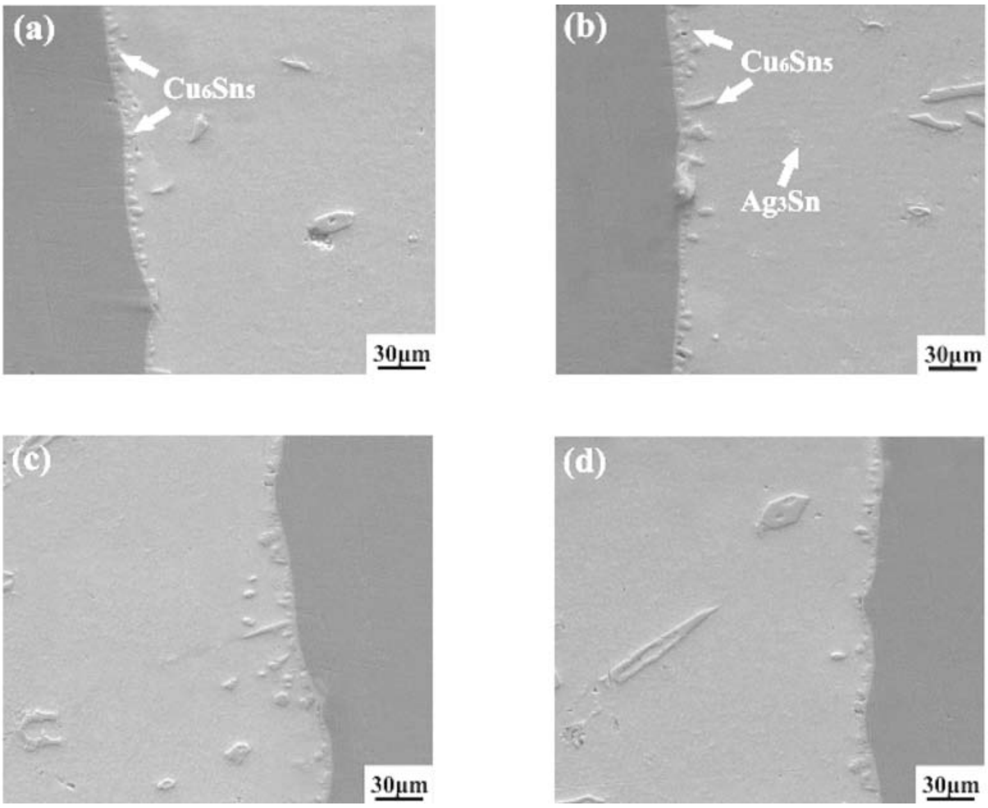

Fig. 4. SEM images of as-soldered $Sn_{3.5}Ag$ solder matrix before current stressing: (a), (b) At the anode; (c), (d) At the cathode.

through the solder joint. After grinding, more than half of the solder joint was removed. The sample was further fine polished with Al_2O_3 suspension to expose the interior microstructure.

By using geometric calculation, the contact area (S) between eutectic SnAg solder matrix and copper wires was about 0.98×10^{-3} cm^2. The current density (J) calculated by dividing the current value (I) by the contact area where electrons passed through was about 5×10^3 A/cm^2.

3. Results and discussion

SEM images of cross section of the solder matrix before current stressing are presented in Fig. 4. Figures 4(a), 4(b) show the morphological pattern at the anode, and Figures 4(c), 4(d) show the morphological pattern at the cathode respectively.

It should be noted that the interface between the solder matrix and the reaction layer is not straight but is undulating. This in turn suggests that the dissolution is not entirely uniform during the soldering process. As can be see from the images that a continuous Cu_6Sn_5 intermetallic compounds (IMC) layer is distributed along the interface between copper substrate and solder matrix at both anode and cathode. The reason for this can be that Cu reactions with liquid Sn, Cu_6Sn_5 is the first phase to form at Cu/Sn interface during soldering. Therefore it is expected that the formation mechanism is controlled by the dissolution of Cu to the molten Sn followed by chemical reaction[8, 9]. Furthermore, some typical scallop-type Cu_6Sn_5 and granule-type Ag_3Sn are also found inside the solder matrix as denoted by white arrows.

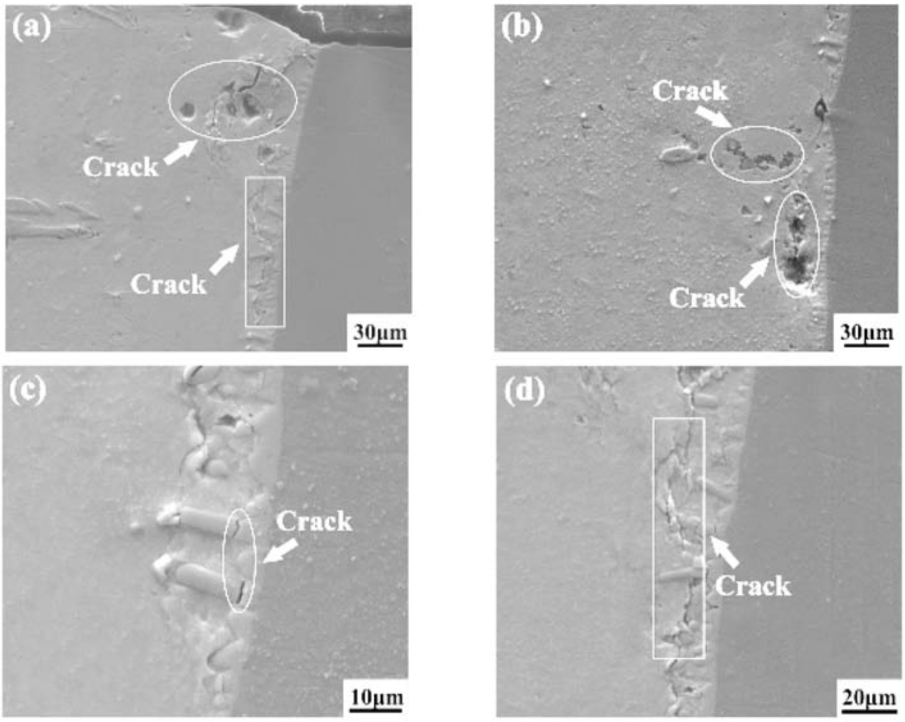

Fig. 5. SEM images of $Sn_{3.5}Ag$ solder matrix after current stressing for 474 h at the cathode.

3.1. Microstructural evolution of $Sn_{3.5}Ag$ solder matrix after current stressing

The whole EM process was conducted for two durations. After 474 and 950 h current stressing respectively, electric circuit was temporarily cut off to observe the microstructural changes at both the cathode and the anode. Figure 5 show the SEM images of cross section of $Sn_{3.5}Ag$ solder matrix after 474 h current stressing at the cathode. It can be clearly seen from the images that some microstructural evolutions merely happened at the cathode. However, there was no obvious microstructural changes occurred at the anode. A few scattered micro-cracks randomly distributed at the cathode interface most of which existed in some local regions between Cu_6Sn_5 layer and $Sn_{3.5}Ag$ solder matrix. Basically, the surface of the whole solder matrix maintained planar except the cathode region where exhibited uneven morphology due to thermal stress caused by current stressing. Interestingly, tiny cracks appeared at the root of some long column-type Cu_6Sn_5 at the cathode interface, which seemed to be related to the current crowding as illustrated in Fig. 5(c).

Figure 6 show the SEM images of $Sn_{3.5}Ag$ solder matrix after 950 h current stressing. It should be noted that cracks near the cathode tended to propagate along the Cu_6Sn_5 IMCs/solder interface because of the harder and brittle nature of the IMCs. Moreover stress is easily concentrated around the IMCs and therefore could induce some defects around the IMCs. Furthermore, surface depression occurred in some local region near the cathode as could be seen in Figs. 6(c), 6(d). However, still no obvious changes happened at the anode. The "polarity effect" of Cu_6Sn_5 growth as referred in previous study was not clearly found throughout the whole EM process. Presumably it was the result of low temperature condition and high melting point of eutectic SnAg solder.

3.2. Effect of current stressing on crack formation and propagation

Based on the observations given above it is suggested that crack formation and propagation is mainly caused by current stressing. In this study, Joule heating was reduced for the application of heat dissipation device. Therefore current stressing should take on the prime driving force to induce the crack formation and propagation at the initial period[3, 4]. Considering the structure of the SRC, the structure of $Sn_{3.5}Ag$ solder is more complicated than the copper substrate which concludes many ingredients such as Sn, Ag, Cu_6Sn_5, and Ag_3Sn and so on. According to general knowledge, electric current flows through the SRC from the anode to the cathode, but electrons are in the contrary direction. As electrons enter the $Sn_{3.5}Ag$ solder matrix from the copper substrate at the cathode interface, their original movement route will be affected because of the different ingredient characteristic. The "electron wind force" is produced by electrons crowding to exchange the momentum with other atoms. Metal atoms are pushed forward to migrate away owing to the electron wind force. Hence, local tensile stress comes into being near the interface leading to the voids and cracks formation after a long time stressing.

When the current stressing time increased, Joule heating effect became noteworthy because current flow induced Joule heating quantity is proportional to square current and current stressing time. The Joule heating quantity can be expressed as $Q = I^2Rt$, where Q is the Joule heating quantity, I is the current, R is the resistance, and t is the stressing time. The Joule heating quantity increases with increasing time. This Joule heating mostly occur at the electron entry in solder joint and

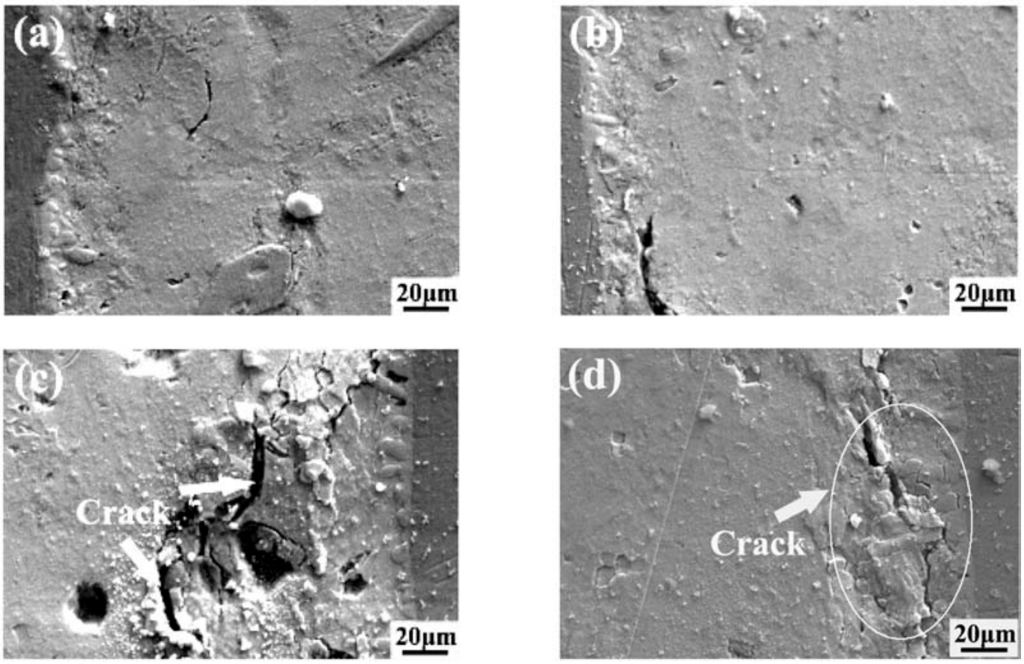

Fig. 6. SEM images of $Sn_{3.5}Ag$ solder matrix after current stressing for 950 h: (a), (b) At the anode; (c), (d) At the cathode.

accelerate electromigration phenomenon and induce local temperature gradient between solder joint and copper substrate. Joule heating induced higher temperature is enough to accelerate the electromigration phenomenon because electromigration is function of temperature and current density. Interfacial voids formed at the cathode after a long time current stressing. The initiation of the interfacial cracks at this location is due to the current crowding around this position. The interfacial crack had propagated along the Cu_6Sn_5/solder interface with increasing time due to the thermal stress during *in situ* electromigration test[9, 10].

It is worth noticing that the Cu_6Sn_5 exhibited a better EM resistance than the $Sn_{3.5}Ag$ solder most of which remained intact after a long time current stressing. However, tiny cracks also appeared at the root of some long column-type Cu_6Sn_5 at the cathode interface due to the thermal stress as could be clearly seen in Fig. 5(c). Presumably because of the comparative larger contact area, thermal stress and current crowding might be more prominent that result in the rupture at the root of the Cu_6Sn_5.

4. Summary

EM behaviors of $Cu/Sn_{3.5}Ag/Cu$ SRC with high current density of 5×10^3 A/cm^2 at room temperature were investigated. Micro-cracks initially appeared at the cathode interface after 474 h current stressing. Cracks grew up and propagated when the stressing time increased. However, there was no obvious microstructural changes occurred at the anode. Tiny cracks also appeared at the root of some long column-type Cu_6Sn_5 at the cathode interface due to the thermal stress.

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