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Tin Whiskers Formation in $Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi$ under Electro-Migration Stressing

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Stress induced by electrical current testing indeed has caused the formation of many whiskers growth in soldering applications. The aim of this investigation is to investigate the electrical current testing to the formation of whiskers. Also the mitigation could be achieved with the additional element of Nickel-Bismuth (Ni–Bi). Characterization of whisker growths are evaluated using the Scanning Electron Microscopy (SEM) on the deposits near anode and cathode areas. Synchrotron micro-XRF were performed on $Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi$ at anode and cathode to accurately observe the distributions of elements in the sample. The obtained results demonstrate that the whisker growths with the effect of current stressing is associated with the intermetallic compound (IMCs) thickness on the anode and cathode areas. Finding shows that by addition of Ni-Bi elements can help to reduce the amount of whiskers form by refining the IMCs formation.

topics: electromigration, tin whiskers, Intermetallic compound, micro-XRF

1. Introduction

Tin whisker growths on the lead-free solder of copper-based conductors is a serious reliability problem in electrical and electronic devices, as well as in aerospace interconnects. The growth of tin whisker can be spontaneous and irreversible process. Some whiskers can grow to several hundred micron in length, which are long enough to cause short circuiting or break off [1]. To overcome this problem, Tin lead (Sn-Pb) solders and plating were used extensively for soldering due to many reasons. Pb is used to mitigate whiskers growth because it has the equiaxed grain structure and inhibit the grain boundary (GB) IMC growth without altering the columnar grain structure [2]. Despite of all its efficacy, due to the Restriction of Hazardous Substances (RoHS) for environmental concerns, the materials containing lead has been banned in electric and electronic interconnects. Recently, researchers have shown an interest in the mitigation process of whiskers formation by microalloying. Particularly, the addition of Zinc (Zn) and Copper (Cu) to pure tin (Sn) has been done, where it shown to has the ability to modify the microstructure of a pure Sn coating [3]. Thus, other approaches such as addition of Argentum (Ag) has been shown effectively to reduce the tendency for whiskers growth by modifying the grain structure to equiaxed grains and by forming fine particles of Ag_3Sn IMC along grain boundaries [4]. Moreover, other researchers also had control the grain orientation to slow the rate of diffusion hence mitigate the whiskers growth. Other than that, the addition of Gallium (Ga) can significantly refine the microstructure of Pb-free solder alloy. Furthermore, it also can refine the intermetallics (IMCs) on the bulk solder and interfacial intermetallics [5].

The electromigration has been studied by many researchers as one of the acceleration tests since current can be one of the dominant factors for whiskers to grow. The advantages of using electromigration are that the applied current density (larger driving force) can be varied and it can also be applied in higher temperature (faster kinetics).

In this study, nickel and bismuth elements were used to mitigate the whiskers formation. The electromigration technique has been used to study the correlation between anode and cathode to the whiskers growth. Therefore, in this study, we investigate the microstructure of different solder alloys on copper substrate that can be correlated to the whiskers formation which may solve the reliability issue.

2. Experiment

2.1. Sample preparation

The $Sn_{0.7}Cu$, $Sn_{0.4}Pb$ and $Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi$ solders was obtained in the form of ingots from Nihon Superior (M) Sdn. Bhd. The raw materials were melted in the solder pot at 350 °C for 1 h by casting method. Stirring was then performed every 1 min during the whole duration of 15 min to obtain homogenized solder alloys. A flat square-shaped copper plate with dimensions of 15 mm ×15 mm size and 1 mm thickness was used as a substrate. The substrates were cleaned using acid cleaning liquid that contain of 5 g (35%) of hydrochloric acid with 95 g of deionized water (1.75%) to remove surface oxides and contaminations.

The dipping process was performed using a hot soldering machine after the cleaning process. Each coupon was hang using a crocodile clip at the dipping machine. The dipping machine is equipped with a direct current (DC) motor with 12 V power supply and 531 rpm speed. The coupon was first covered with flux before dipped in the solder pot containing molten bath for 20 s and blown at a pressure of 300 MPa to get an even thickness. The thickness for each samples were measured at 50–70 μm each. Three coupon were prepared for each solder coating. Then, the samples were cleaned again with acetone for 3 min using ultrasonic cleaner to remove excessive flux.

2.2. Electromigration

The electromigration (EM) test for the dipping sample was performed by applying a direct current to both ends of sample with crocodile clips at the anode and cathode areas. Before the samples undergone electromigration testing, the samples are indented with 9.807 N square-based diamond pyramid with 136° angle between the opposite faces at thevertex of Vickers Hardness Test to force the whiskers growth. Current density of 8.0×10^4 A/cm^2 had been applied to the sample for 14 days at room temperature by applying constant electric current to the solder joint. The testing parameter for dipping and electromigration are presented in Table I.

TABLE I

Testing parameter for dipping and EM test.

Solder alloy	$Sn_{0.7}Cu$, SnPb, $Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi$
substrate	copper
dipping time	20 s
dipping temperature	350 °C–400 °C
coating thickness	50–60 μm
current density	8.0×10^4
current stressing time	14 days

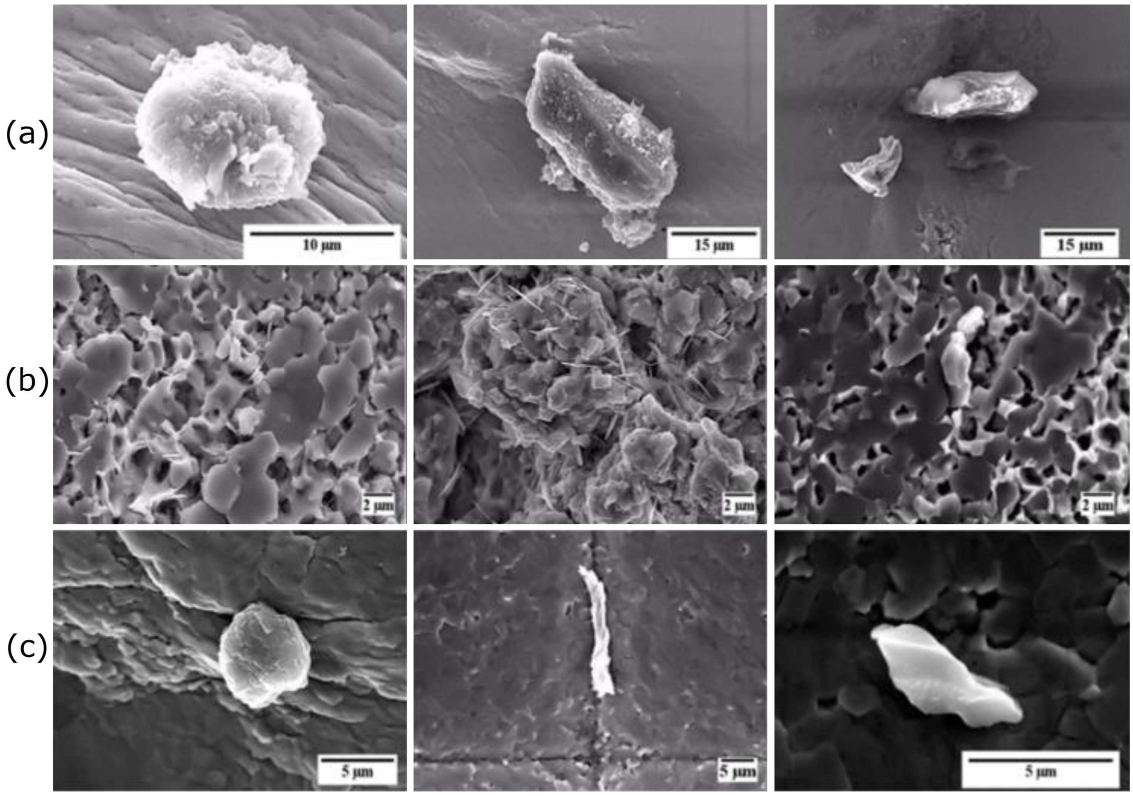

Fig. 1. SEM images after EM tests under current density of 8.0×10^4 A/cm^2 in 14 days from anode to cathode (left to right) (a) $Sn_{0.7}Cu$, (b) Sn-Pb, (c) $Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi$.

2.3. Micro-XRF

Then, the samples were undergone Synchrotron μ-X-Ray Fluorescence testing for elemental analysis. This testing was performed to determine accurate elements that cannot be detected by conventional laboratory works. Two focus areas were anode and cathode with the nominal sample as a reference. The beamline utilizes continuous synchrotron radiation with energy in the range 2 keV to 12 keV with the beam size 30 μm at the sample position using polycapillary as an X-ray optics. The high precision motorized stage provides user to accurately specify any specific areas or point of interests on the sample.

3. Results and Discussions

Scanning electron microscopy (SEM) images of the growth of whiskers after electromigration testing were shown in Fig. 1a–1c. From the observation, the growth of whiskers/hillocks is presented on both cathode and anode sides. This also has happened along the solder matrix alloy where the current is flowing. There are mixed types of whiskers forms on solder alloy. The whiskers also formed mostly from the hole based of the solder matrix.

Other than that, the whiskers form on $\mathrm{Sn_{0.7}Cu}$ are thick and big while the whiskers form on SnPb and $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$ are thin and small. When the electron flows from cathode to anode, all the solder alloy show the reduction of whiskers size in anode. Figure 2 shows the maximum whiskers length measured from SEM. From the observation, it can concluded that the addition of Ni-Bi could reduce the whiskers length however SnPb shows the most shortest length. We believe that, the shortest length of whiskers in SnPb solder is due to the crack and uneven surface of SnPb which facilitate the whiskers to grow [6].

The results of whiskers density had been tabulated on the graph as shown in Fig. 3. From the observation, after 14 days of exposure to the electric current, it can be seen that the higher number of whiskers form on anode side of $\mathrm{Sn_{0.7}Cu}$ solder alloy while the less number of whiskers form on the $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$ solder alloy. This is because the electromigration helps to transport the Cu atoms from the cathode to the anode side which enhances the whiskers growth at the anode side [7]. Other than that, the grain size has been refined and altered from columnar to equaixed grain. The equiaxed grain structure of SnPb and $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$ can reduce the internal stress from Sn coating, thus mitigate whiskers formation of the surface. Figure 4 shows the result for the μ-XRF testing on dipped $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$ solder. From the observation, Cu substrate was consumed along with the IMC growth but slower at the anode side than at the cathode side, suggesting that the IMC at anode dissolves. This resulted in the increment of Cu supply for the IMC growth at the anode. By electromigration, the Cu atoms transported from the cathode to anode side which improves the interfacial IMC growth at the anode [8]. However, the addition of Ni-Bi to the solder inhibits the diffusion of Cu and Sn to the anode due to of the electrical current stressing. The intensity of Bi element at the cathode area has significantly higher compared to the anode area [9]. This can be due to the fact that the transfer of Sn atoms is difficult and the development of IMC layer at the anode side became limited which significantly reduce the whiskers growth [10].

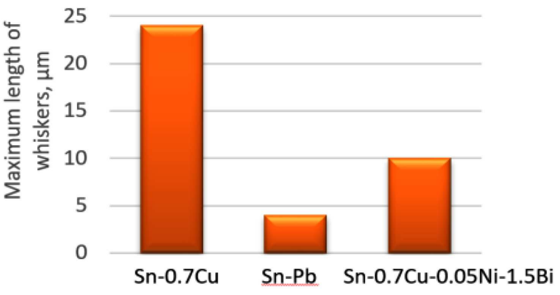

Fig. 2. Maximum length of whiskers after electromigration tests of 8.0×10^4 A/cm^2 current density in 14 days.

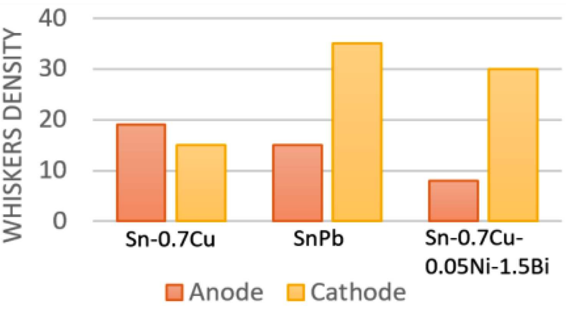

Fig. 3. Whiskers density after electromigration tests of 8.0×10^4 current density in 14 days.

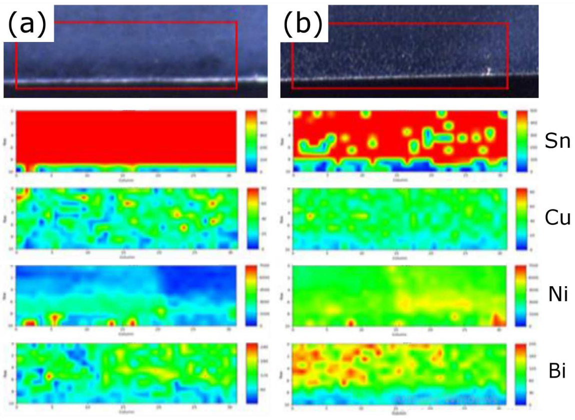

Fig. 4. The μ-XRF elemental analysis of $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$/Cu interface at (a) anode, (b) cathode.

4. Conclusions

As a summary, this paper investigates the relationship of electrical current testing on the tin whiskers formation. Moreover, the results of additional elements of Ni-Bi as the microalloying to the Sn-Cu were systematically presented in this paper. Other results are summarised as below:

- The addition of Ni-Bi to $\mathrm{Sn_{0.7}Cu}$ could reduce the whiskers length however SnPb shows the most shortest length (4 μm).
- $\mathrm{Sn_{0.7}Cu_{0.05}Ni_{1.5}Bi}$ solder shows lowest whisker density on anode (8).
- The formation of whiskers on electrical current stressing shows the least formation of whiskers on cathode while more whiskers formed on anode region.
- Micro-XRF analysis results show that the formation of whiskers has reduced by inhibits the diffusion of Cu and Sn to the anode which then lessen the compressive stress generated by electromigration.

Acknowledgments

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