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Electromigration-induced Bi-rich whisker growth in Cu/Sn–58Bi/Cu solder joints

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Abstract Effect of current stressing on whisker growth in Cu/Sn–58Bi/Cu solder joints was investigated with current densities of 5×10^3 and 10^4 A/cm^2 in oven at different temperatures. Two types of whiskers, columnar-type and filament-type, were observed on the solder film propagating along the surface of the Cu substrate and at the cathode interface, respectively, accompanied with many hillocks formation. Typically, these whiskers were 5–15 μm in length and 0.06–2 μm in diameter. EDX revealed that these whiskers and hillocks were mixtures of Sn and Bi rather than single crystal. It should be noted that the sprouted whiskers would not grow any more even if the current-stressing time increased again when the solder joint was stressed under lower current density. Nevertheless, when the current density was up to 10^4 A/cm^2, the whiskers would melt along with the increasing current-stressing time. Results indicated that the compressive stress generated by precipitation of Cu_6Sn_5 intermetallics provides a driving force for whisker growth on the solder film, and the Joule heating accumulation should be responsible for whisker growth at the cathode interface.

Introduction

The pursuit of better performance in microelectronic devices has led to a significant increase in current density and Joule heating in solder joints. Therefore, electromigration (EM) inevitably becomes one of the most crucial reliability issues in electronic packaging. EM is considered as an accelerated diffusing phenomenon driven by electron force. Metal atoms diffuse along the direction of electron flux, which results in the voids or cracks formation at the cathode side and hillocks formation at the anode side [1–3]. In the development of Pb-free solders, whisker growth is regarded as another important reliability issue. It is known that the whiskers on solder joints can grow up to lengths of a few hundred microns, and that these whiskers possess a good electrical conductivity which results in short circuiting or interference with other devices [4, 5].

However, few studies about whisker growth in lead-free solders induced by electromigration have been reported before. In other words, the relationship between electromigration and whisker growth has not been known exactly. Lin et al. [6] studied the effect of electric current on the tin whisker growth on Sn stripes in ovens at different temperature and different current density. It was found that the stress induced by the electric current caused Sn-whiskers formation. Results showed that a higher current density would cause more Sn whiskers to form and 50 °C was regarded as the most favorable temperature for the Sn-whiskers formation. Yuki Fukuda et al. [7] investigated an eight-month design-of-experiment assessment of whisker growth on bright and matte tin-plated copper. Whiskers were observed to grow both at the anode and cathode. It was proved that electrical current could increase the standard deviation of the length distribution and generate longer whiskers. Chi-Chang Hu et al. [8] found the anomalous growth of Bi–Sn extrusions from tin-enriched alloys induced by post-plating annealing in N_2 between 145 and 260 °C for 10 min. What was their opinion was that annealing resulting in thermal expansion of Sn grains was believed to squeeze the Bi–Sn alloys to form whisker-like extrusions.

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Sn–Bi lead-free solder is a simple eutectic system with a eutectic composition of 42 wt% Sn and 58 wt% Bi that melts at 138 °C. Sn has almost no solubility in Bi. It has been considered as one of the most promising lead-free products as a substitute for conventional SnPb solders in recent years. Its low melting point makes it widely used in some special situation for soldering [9, 10]. As one of the most excellent lead-free solders, its reliability issues are being drawn much more attention. In this study, Cu/Sn–58Bi/Cu solder joints were stressed with different current density and different temperature. The advantage of using electromigration to study whisker growth is that not only we can vary the applied current density, but also we can use higher temperatures.

Experimental

Sample preparation

The preparation procedure of the Cu/Sn–58Bi/Cu solder joint concludes five steps: alloy smelting, solder balls production, soldering, inlaying and polishing. So first of all, pure Sn and Bi metal particles with purity of 99.9 wt% were used as raw materials. Sn and Bi metal particles were weighed accurately according to the mix percentage and then put into an Al_2O_3 ceramic crucible, and meanwhile eutectic salt (KCl + LiCl) with weight ratio of 1.3:1 was used to cover the surface of the particles to prevent oxidation during smelting. The crucibles were placed in an induction furnace at 550 °C for about 20 min. The molten alloy was then held on for about 40 min and mechanically stirred every 10 min with a glass rod to promote uniformity of the solder alloy [11, 12]. The molten solder was finally chill cast into a rod ingot in a mold. Solder balls were made of solder alloy with uniform droplet spraying equipment in our laboratory. Solder balls were placed between two copper wires with 500 lm in diameter and placed on a hot plate fixed in the soldering platform designed and built by ourselves. The specific soldering procedure was described in detail in our previous study [13, 14]. For consideration of easy observation, the Cu/Sn–58Bi/Cu solder joints were mounted with epoxy resin. Grinding machine was applied to reduce the dimension of the samples, followed by grid sandpapers, and finely polished with Al2O3 suspension. Microstructural and compositional analysis was examined by an S-3400N scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDX) system.

Electromigration test

The samples were connected with a DC power supply to provide a constant current flow varying from 5 to 10 A and put into a furnace. The temperature range was from room temperature to 100 °C. Unlike the line-to-bump structure, the current density distributes more uniformly in this end-to-end structure. The current crowding happens at the electron entry and exit region can be eliminated in our experiment. However, the Joule heating effect will be obvious if applying such a high current flow. In order to remove this adverse influence, a heat dissipation device was employed in our test structure. A thermocouple was attached on the surface of the solder joint to detect the temperature fluctuation. Figure 1 shows the schematic drawing of the electromigration test. The average current density was calculated by dividing the current value by the virtual cross sectional area which the electrons passed.

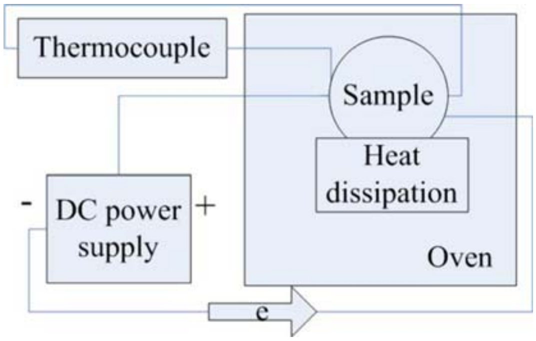


Fig. 1 Schematic drawing of the electromigration test

Results and discussion

Figure 2 shows the low- and high-magnified SEM-BSE morphologies of the typical Cu/Sn–58Bi/Cu solder joint before current stressing. A clear two-phase microstructure, the bright white Bi-rich phase, and the dark gray Sn-rich phase, is uniformly distributed in the solder matrix. EDX analysis revealed that a continuous thin Cu_6Sn_5 layer was formed at the solder/substrate interface. During the electromigration test process, two types of whiskers, filament-type and columnar-type, were observed at the cathode side and the anode side, respectively.

The columnar-type whisker growth on the Cu substrate

During the current stressing test, as long as the solder matrix propagated along the Cu substrate to form a thin solder film, where the whiskers would grow. Figure 3 shows the microstructural morphology of the Sn–58Bi solder joint with current density of 5×10^3 A/cm^2 at 80 °C after current stressing for 310 and 535 h, respectively. We can see that the solder matrix became uneven after a long-time current stressing. A number of whiskers and hillocks were distributed randomly on the thin-film layer covering on the anodic

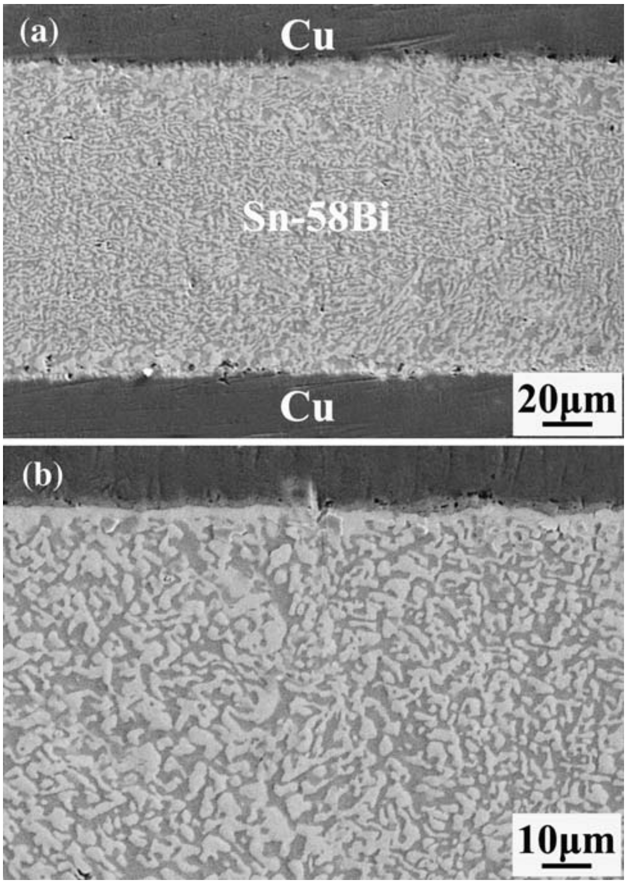
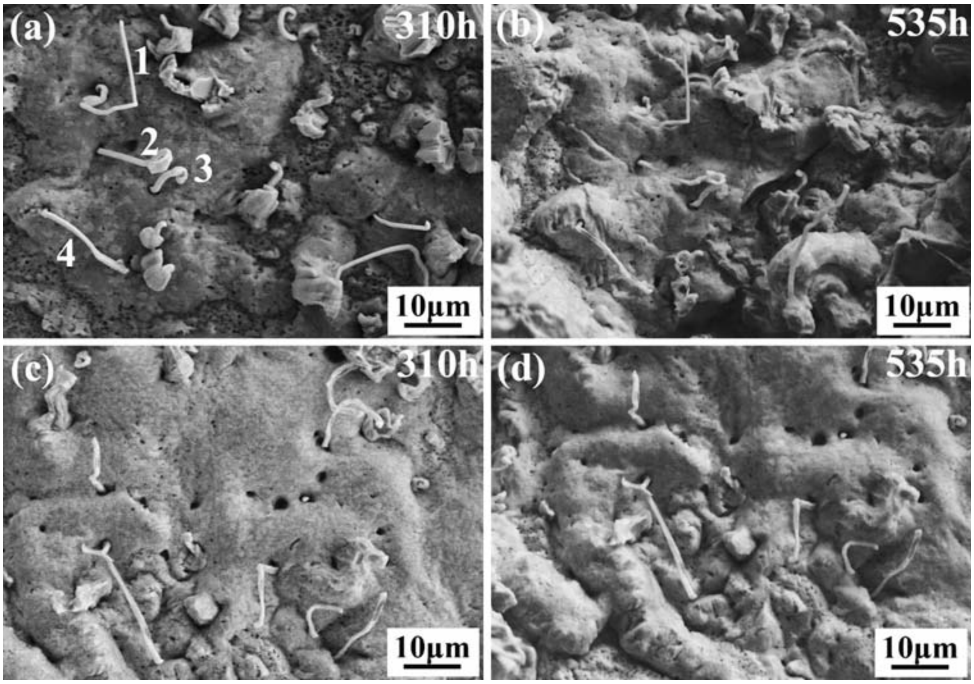


Fig. 2 SEM-BSE images of the Cu/Sn–58Bi/Cu solder joint before current stressing. **a** Low-magnified SEM-BSE image; **b** enlarged SEM-BSE image

Cu substrate. These whiskers were typically columnar in appearance, with the size of about 1 μm in diameter and 5–20 μm in length. In normal, these columnar-type whiskers were grown with the kink angle of 45 or 90 °C. To look for subtle difference, the whisker lengths were measured with Image J software and then analyzed statistically. As we all know that the whisker length reported is the maximum length of the whisker. In the case of a bent or kinked whisker, the maximum length is the sum of the individual segments. The longest whisker in this case was about 36 μm in length but only less than 0.6 μm in diameter. What was interesting was that whiskers in Fig. 3a, c had the similar morphology as that of in Fig. 3b, d. Most of the whiskers remained their size, which was to say that they stopped growing when the stressing time increased. However, there were still few morphological changes in some whiskers. For example, the orientation of whisker 1 slightly deflected to the right; whisker 2 became longer and thinner; whisker 3 became larger; and the root of whisker 4 turned longer. It also proved that whisker growth was from the root not from the top as reported by many investigators. It was worth mentioning that the whisker surfaces were not smooth any more with increasing stressing time, but ragged. Additionally, the thin-film layer on the Cu substrate became rather rugged. The most commonly observed whiskers also presented columnar-type, with hooked or curled appearance. The whiskers were less than 20 μm in length and 1 μm in diameter. What was important to note was that the very beginning of the initiation of the whiskers was from micro-voids surface.

Fig. 3 Microstructural morphology of the Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C after current stressing for 310 and 535 h, respectively. **a**, **c** Whisker morphologies after current stressing for 310 h; **b**, **d** whisker morphologies after current stressing for 535 h



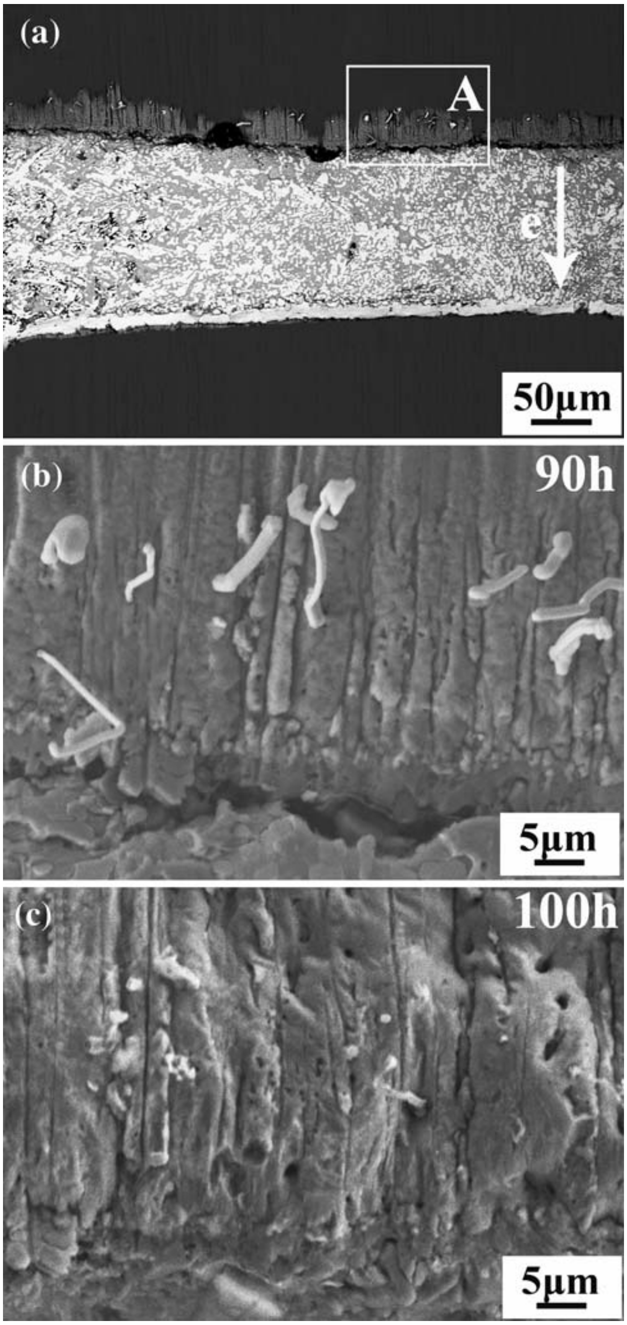


Fig. 4 Microstructural morphology of the Sn–58Bi solder joint with current density of 10^4 A/cm^2 after current stressing for 90 and 100 h, respectively. **a** Low-magnified SEM-BSE image for 90 h; **b** enlarged whisker morphologies of region A in Fig. 5a for 90 h; **c** enlarged whisker morphologies for 100 h

Figure 4 shows the microstructural morphology of the Sn–58Bi solder joint with current density of 10^4 A/cm^2 after current stressing for 90 and 100 h, respectively. Figure 4b, c is the enlarged image of region A in Fig. 4a. Columnar-type whiskers were observed at the cathode side as could be clearly seen in Fig. 4a, b when the current-stressing time increased to 90 h. However, when the current-stressing time increased to 100 h, the whiskers melted and disappeared as shown in Fig. 4c.

Table 1 EDX compositional results of region I–VI in Fig. 5

	I	II	III	IV	V	VI
Bi	15.31	–	94.89	62.94	95.24	89.67
Sn	48.46	36.72	5.11	37.06	4.76	10.33
Cu	36.23	63.28	–	–	–	–

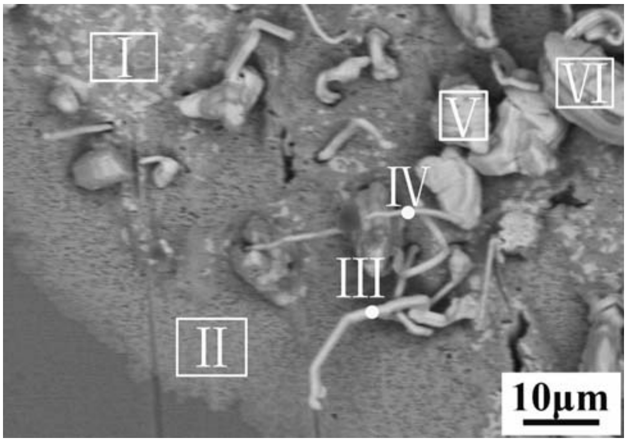


Fig. 5 Microstructural morphology of the Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C after current stressing for 310 h

To ascertain the composition of the whiskers and hillocks, EDX compositional analysis was applied. Table 1 showed the compositional analysis results of regionI–VI in Fig. 5. As could be analyzed from Fig. 5 and Table 1, these whiskers and hillocks were composed of not only Sn but also Bi according to the compositional results. Region I was the local area of the thin film which was also composed of Bi and Sn. However, in region II, only Sn and Cu were detected. Presumedly, intermetallic compounds were formed in this region or only pure Sn on the Cu substrate. It could not be judged unless further evidence to confirm.

Based on the above observation, we can draw some conclusions. Whiskers were observed on the anodic Cu substrate or the cathodic Cu substrate with the current densities of 5 × 10^3 and 10^4 A/cm^2. They were typically columnar-type and with the size of about 1 μm in diameter and 5–20 μm in length. Furthermore, these columnar-type whiskers were grown with the kink angle of 45 or 90 °C. It is very interesting to find out that the whiskers were the mixtures of Sn and Bi rather than single Sn. In order to explore the mechanism of whisker and hillock formation, the solder film formed on the Cu substrate was slightly polished to see the interior microstructure. Figure 6 shows the interior microstructure of the solder film after polishing. A great many IMC precipitates with dark color were

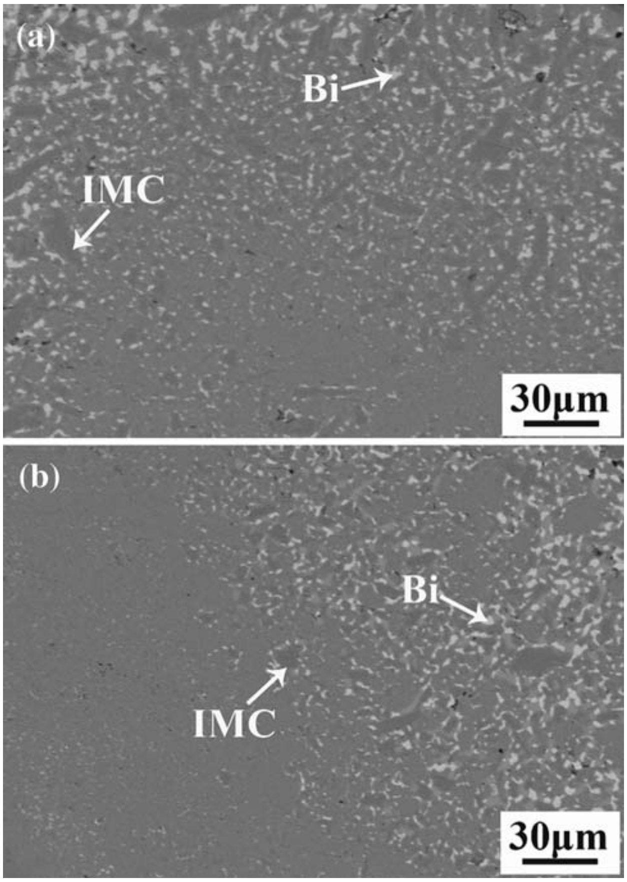


Fig. 6 Microstructure of the solder film after polishing

observed on the Cu substrate surface. EDX results indicated that these IMC precipitates were Cu_6Sn_5. Moreover, many Bi phases aggregated around the Cu_6Sn_5 interfaces. From the images in Fig. 6 presented here, it was logical to speculate that the Cu_6Sn_5 precipitates had been attributed to the driving force for the whiskers growth.

It has often been proposed that the driving force for the whisker growth is the relief of internal compressive stress in the Sn layer plated on a substrate [1, 15]. Lee et al. [16] found that the as-deposited Sn film on a Cu plate possessed a tensile stress, which transformed with the formation of Cu_6Sn_5 intermetallics at the Sn/Cu interface to a compressive stress level. The growth of whiskers caused the release of such a compressive stress. For the Cu/Sn thin-film interfacial reaction at room temperature, Tu [17] has also shown that a biaxial compressive stress is produced in the Sn film accompanying the Cu_6Sn_5 formation that drives the Sn whiskers to grow. Further analysis suggested that whiskers sprouted from weaker spots on the Sn surface where the oxide layer had broken, and the whisker roots became localized stress-relief centers [18]. In this electromigration test, Cu_6Sn_5 precipitates were found in the solder film formed on the Cu substrate which took on the main driving force for the whiskers growth. The results are greatly in accordance with other investigations. Several mechanisms of whisker growth have been proposed, but are not universally accepted. By general consensus, compressive stress is recognized as the main driving force for whisker growth and a break of the protective oxide on the surface. Hence, based on the above results, the whole process of the whiskers formation can be described as follows: first of all, solder melting occurred due to the current stressing and Joule heating production. Solder matrix began to diffuse toward the Cu substrate induced by electromigration force and formed a thin solder film on the Cu substrate. The area of the solder film would become larger when current-stressing time increased. In the mean time, Sn in the solder film reacted with Cu to form IMC precipitates. Thus, compressive stress was built due to the volume increase which squeezed out the whiskers. It had been proposed that melting failure in solder interconnects under current stressing was a time-dependent phenomenon [19]. When stressing time increased, much more Joule heating was produced by high current flow. Diffusion of the metal atoms from the cathode to the anode was accelerated owning to the combined effect of electromigration force and Joule heating. Accordingly, voids or cracks were easily formed at the cathode interface. The effective contact area was decreased, which led to serious local current crowding. Meanwhile, the Joule heating was also enhanced. Therefore, under such synthetic effects, and for the low melting point of the Sn–58Bi solder matrix, solder melting was finally induced. Inevitably, diffusion of the solder matrix toward the Cu substrate was triggered to form a solder-film layer. Cu diffused rapidly into the thin film reacting with Sn to form Cu_6Sn_5 IMC precipitates [20]. Therefore, it is the Cu_6Sn_5 IMC volume increase for the combined Cu and Sn atoms which establishes a compressive stress within the entire intermetallic region. Figure 7 shows the schematic drawing of the whisker growth on the Cu substrate.

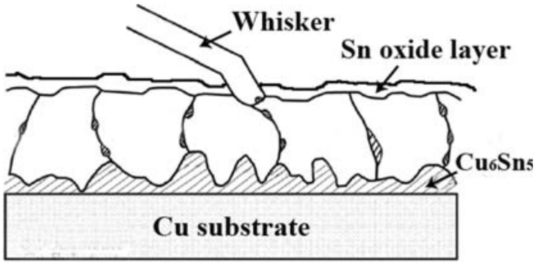


Fig. 7 Schematic drawing of the whisker growth on the Cu substrate

The filament-type whisker growth at the cathode region

Figure 8 shows the local SEM images of the Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C after current stressing for 540 h at the cathode interface. After such a long current-stressing time, a deep and wide crack was formed at the cathode interface where Whiskers were found in this region. It should be noted that these whiskers were not columnar-type any more, but typically filament-type in appearance, with the size of about 0.06 μm in diameter and about 5 μm in length. Figure 9 shows the local SEM images of another Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C after current stressing for 540 h at the cathode interface. Surprisingly, whiskers were found not in the crack formation region, but in the solder matrix. The reason for the filament-type whisker growth should be responsible for the Joule heating accumulation. As we all know that Joule heating accumulation would occur at the solder depletion which could induce the thermal stress production. Therefore, the thermal stress-gradient was built in the local region. To relief the stress gradient, whiskers were squeezed out of the solder matrix to make the system stable.

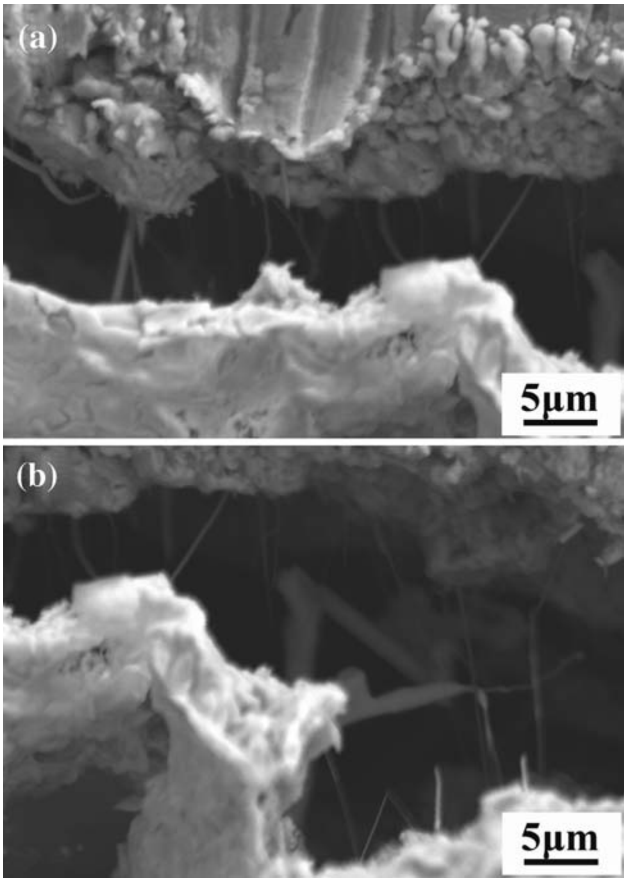


Fig. 8 Whisker morphologies of the Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C at the cathode interface after current stressing for 540 h

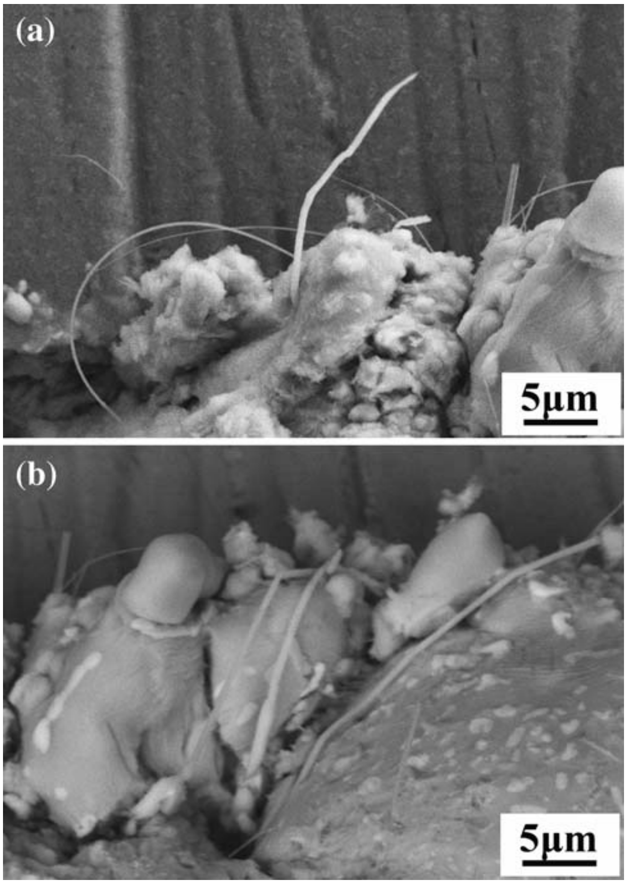


Fig. 9 Whisker morphologies of the Sn–58Bi solder joint with current density of 5 × 10^3 A/cm^2 at 80 °C after current stressing for 540 h

Any stressed system, if possible, will adopt whisker formation as the preferred stress-relief mechanism. Such a compressive stress produced the driving force for the migration of Bi and Sn atoms to the root of the whiskers to feed their growth. Since most Sn atoms had reacted with Cu, many Bi atoms were remained to become the main substance of the whiskers [21, 22]. However, the whisker formation was a very complicated process, which was controlled by many factors. Another main contributing factor should be the Sn-oxide layer formation on the solder film. As can be seen in Figs. 3 and 4, the solder matrixes had been oxidized seriously. As the stress increased with time, the thin oxide layer may rupture at the weaker points. Once the oxide layer had ruptured, whiskers may be extruded in a continuous fashion through the oxide layer as a means of relaxing compressive stresses.

Although the electrical current was continuously applied to the solder joints, most of the observed whiskers seemed to stop growing. The cease of whisker growth implied that the driving force of a compressive stress-gradient for whisker growth was eventually reduced to an inactive level. Tu also pointed out that in addition to stress relaxation, another ingredient was required for continued whisker growth: constant stress generation [17]. In this study, there was not enough high compressive stress generation to develop whiskers growth. Whisker formation is a very interesting phenomenon, and further study is needed to assess the whisker growth time/growth rate and so on. It is still a complicated issue which was worth studying in the future.

Conclusion

In summary, electromigration tests were conducted with current densities of 5×10^3 and 10^4 A/cm^2 in oven at different temperatures in Cu/Sn–58Bi/Cu solder joints. Two types of whiskers, columnar-type and filament-type, were found in the solder joints accompanied with many hillocks formation. EDX revealed that these whiskers and hillocks were mixtures of Sn and Bi rather than single crystal. It should be noted that the sprouted whiskers ceased to grow any more even if the current-stressing time increased. Nevertheless, when the current density was up to 10^4 A/cm^2, the whiskers would melt in the end when the current-stressing time increased. Results indicated that the compressive stress generated by precipitation of Cu_6Sn_5 intermetallics provides a driving force for whisker growth on the solder film, and the Joule heating accumulation should be responsible for whisker growth at the cathode interface.

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