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Retarding the electromigration effects to the eutectic SnBi solder joints by micro-sized Ni-particles reinforcement approach

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ABSTRACT

Electromigration (EM) has become one of the reliability concerns to the electronic solder joint due to its increasing capacity to bear the high current density (10^4 A/cm^2). Although the failure induced by EM can trigger a large void across the entire cathode interface, no effective solutions are presented throughout years of effort on this problem. Here, the composite solder joints are addressed to demonstrate their potential roles on solving the EM issue in the eutectic SnBi solder joints. Micro-sized Ni particles were selected to intentionally add into the solder matrix due to their extensive application as a barrier layer in the under-bump-metallization (UBM) of flip chip solder joints. The ultimate results illustrated that the Ni particles can react with Sn to form the cluster-type Sn–Ni intermetallic compounds (IMCs) inside the solder matrix after the first reflow. Accordingly, the phase segregation of Sn and Bi was significantly inhibited during the current stressing, demonstrating the Sn–Ni IMCs can act as the obstacles to obstruct the movement of dominant diffusion entity (Bi atoms/ions) along the phase boundaries.

1. Introduction

In the configuration of flip chip solder joints, under-bump-metallization (UBM) layer is considered as a key component, because not only it can improve the wettability between the substrates and solder alloy during the reflow process, but also it acts as a diffusion barrier to inhibit the Sn–Cu reactions during the long-term aging [1–3]. However, with the continuous scale down of flip chip solder joints, the current density at each single joint is significantly increased as higher as 10^4 A/cm^2 [4]. Accordingly, electromigration (EM) induced fast dissolution of UBM layer at the cathode interface arose extensive attention from scientists and engineers, and many studies on this problem have been carried out since the late years of twenty century. Their results demonstrated that the current crowding effect was the main contribution to the initiation and propagation of voids where the electron flowed into the solder joints [5–10]. In other words, the current crowding can mess up the clear understanding of EM problems by redistributing the current densities in flip chip solder joints. Therefore, in recent years, people from different research groups began to develop one-dimensional (1D) solder joints which ensured the straight movement of electron. In addition, they also investigated the microstructure evolution and mechanical properties of 1D solder joints with Ni substrate under high current density [11–13]. Ho and co-workers found the electrical force can obstruct the movement of Cu atoms when the electron flow was directed away from the Ni-side [11]. Chen and co-workers reported that solder/Ni interface had better microtensile toughness comparing with solder/Cu after EM [12]. Gu and Chan, found the migration rate of Bi atoms can be enormously slowed down when the electron heading to Ni substrate [13]. Generally speaking, Ni processes the potential effect to retard the preferred migration of metal atoms/ions in 1D solder joints during the current stressing. As a matter of fact, micron or nano-sized Ni particle is one of the common metallic reinforcements that can be introduced to the conventional lead-free solder pastes by mechanical mixing. The corresponding Ni-particles reinforced composite solder joints exhibited excellent mechanical properties, i.e., improved creep-resistance [14–16], increased shear strength [17], and enhanced thermal–mechanical–fatigue resistance [18,19]. The basic mechanism of the composite approach is that Ni particles exhibiting at the grain boundaries in the solder matrix can retard the sliding or decohesion between two neighboring Sn grains. Therefore, instead of depositing the Ni as a thin barrier layer at the interface, we can directly add them into the solder matrix with the morphology of micron-sized particles. Currently, the aim of this study is to investigate the role of Ni-particles reinforcement on the microstructure evolution of eutectic SnBi solder joints during the current stressing.

The benefit of employing eutectic SnBi solder alloy as an objective material to study the EM behavior is due to its typical lamella microstructure after the first reflow. Normally, after days of current

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stressing, the Sn-rich phase and Bi-rich phase tend to segregate against each other. Therefore, the retarding effect on EM can be evaluated through the measurement of the accumulative layer of Bi-rich phase at the anode interface. Apparently, the thinner Bi-rich layer, the better EM resistance. The mechanical properties are not carried out in this study because of the limitation of current employed 1D solder joints.

2. Experimental

The composite solder was prepared by adding 15 vol.% Ni reinforcement particles with ∼6 μm length in diameter into the eutectic SnBi solder paste. The composite solder was mechanically mixed up to 15 min. To achieve the uniform distribution of the reinforcement particles in paste matrix, at least 15 min was used for mixing. The solder joints with a Cu/Solder/Cu sandwich structure were fabricated to conduct the EM study. Two copper wires (diameter: 500 μm) were first placed into a soldering die with U-grooves, one of which was connected to an X–Y–Z translation stage so that the Cu wires can be well aligned with a controlled gap dimension. The solder thickness can be precisely controlled through a spiral micrometer equipped in such X–Y–Z translation stage. Then, a 5-mg solder paste was placed into the gap between the two copper wires. Finally, the die with specimen was heated up to 179 °C (40 °C higher than melting point of Sn–58Bi) and then cooled down to room temperature rapidly by a ventilating fan. The procedure for fabricating the conventional solder joints is the same as that of composite solder joints.

After solder joints were fabricated, it was then cold mounted in the epoxy resin. In order to reach the current density to a high level (10^4 A/cm^2), half dimension of the specimen was ground and polished off to reach a dimension with a cross-sectional area of 1×10^{-3} cm^2. A current of 10 A was continuously applied to the specimen, the current density of which being 10^4 A/cm^2. More detailed information about the joints preparation can be found in our previous publications [20–22]. Both non-composite and composite SnBi solder joints were kept under the same ambient temperature (25 ± 2 °C) during the current stressing test. Temperature rise at the solder region induced by Joule heating was measured through a temperature recorder equipped with a K-type thermocouple. After 45 min of current stressing, the temperature remained constant at 53 ± 2 °C of the solder region, and the temperature difference was less than 2 °C between the non-composite and composite SnBi solder joints.

Scanning electron microscopy (SEM) was used to observe the microstructural evolution of the solder joints. An energy-dispersive X-ray (EDX) spectrum was used to analyze the composition of the detected regions. The area of different phases in the solder joints was evaluated by the ImageJ™ software, the usage of which can also be found in our pervious publications [20–22].

3. Results

3.1. Initial microstructure

The initial microstructure of eutectic SnBi solder alloy is directly related to temperature-time profile of the solder in the reflow process while it is in the liquid state. As reported by Chen et al., the initial microstructure in terms of the Bi phase size can affect the migrating rate of dominant entity under the electron wind force [7]. Large phase boundary can effectively restrict the accumulation thickness of Bi phase at the anode interface. It should be noted that the large phase boundary in their works was obtained by the long term of isothermal aging at high temperature. However, by employing the slow cooling rate in the soldering process, similar result can be achieved as well. In order to accelerate the EM process, the rapid cooling rate was guaranteed during the soldering process by

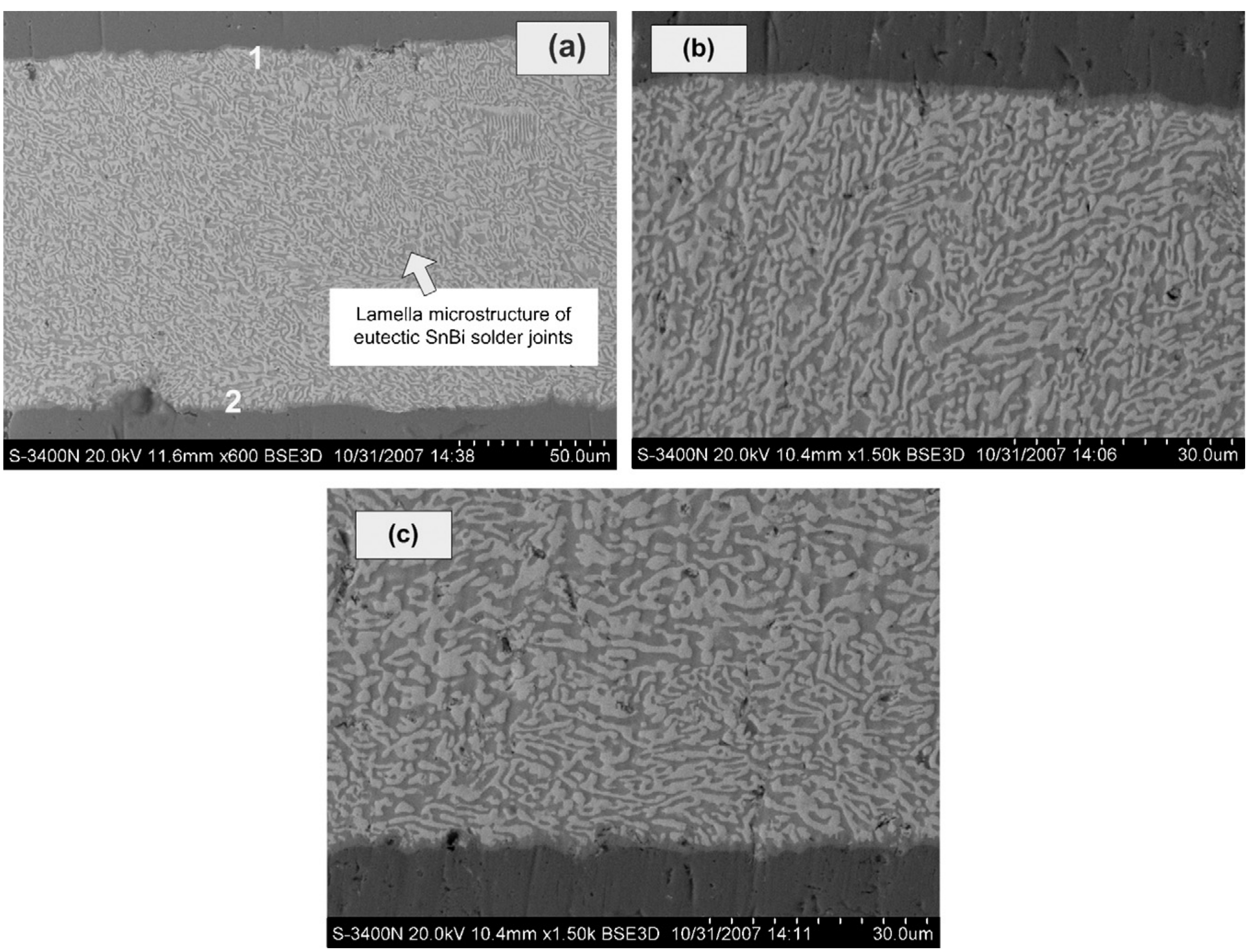

Fig. 1. As-reflowed microstructure of non-composite eutectic SnBi solder joint: (a) full view of the solder joint; (b) enlarged micrograph of region 1 from (a); (c) enlarged micrographs of region 2 from (a).

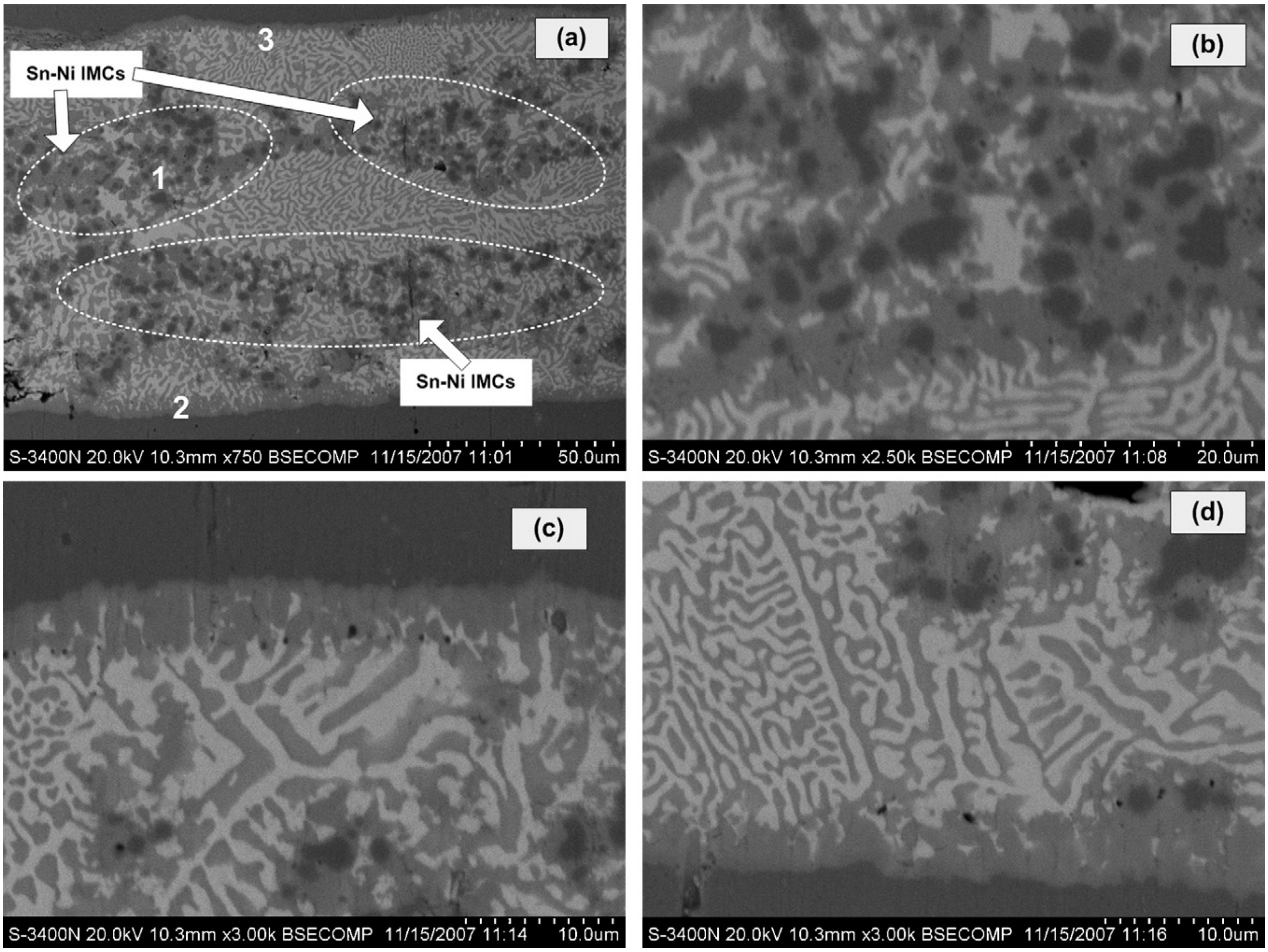

Fig. 2. As-reflowed microstructure of Ni-particles reinforced composite solder joint: (a) full view of the solder joint; (b) enlarged micrograph of region 1 from (a); (c) enlarged micrograph of region 2 from (a); (d) enlarged micrograph of region 3 from (a).

a mechanical fan in our study. Accordingly, the initial microstructure, specifically the phase size of Bi, was significantly decreased. The average size of Bi phase can reach to 11 μm^2. In addition, oval-shape Sn-rich phase is out of detection during the SEM observation, as shown in Fig. 1(a). Fig. 1(b) and (c) are the enlarged SEM images at the interfaces, two distinct structures are visible in the back scattering electron (BSE)-mode images. A more or less continuous grey area which is the Sn-rich phase, inside of which is found a number of island-shaped white area which is the Bi-rich phase.

The microstructure of as-reflowed Ni-composite solder joints are shown in Fig. 2(a) and (b). A cluster of blocky-shape intermetallic compounds (IMCs) with core of Ni particles can be found inside the solder matrix. The chemical composition of these IMCs is identified as $(Ni_{1-x}Cu_x)_3Sn_4$ by the EDX analysis. It is impossible to obtain the accurate atomic ratio among these elements by EDX. Because this technique only reflects the near-surface composition, other advanced techniques, i.e. transmission electron microscopy (TEM) and X-ray diffraction (XRD), should be assisted to identify the composition and structure of these IMCs, but which are out of the discussions in this work. Although Ni_7Sn_2Bi, NiBi, and $NiBi_3$ IMCs were reported in the Sn–Ni–Bi system elsewhere [23], Bi was out of detection from the Sn–Ni IMCs in the composite solder joints due to the rapid cooling rate in the soldering process. Without slow cooling rate plus sufficient cooling time, the equilibrium phases of Ni_7Sn_2Bi, NiBi, and $NiBi_3$ cannot be obtained in the Sn–Bi–Ni ternary system. Fig. 2(c) and (d) are enlarged SEM images of the interfaces showed in Fig. 2(a). Unlike the non-composite solder joints that only include the Sn–Cu interfacial IMCs, the Ni-composite one contains two kinds of interfacial IMCs which are Cu_6Sn_5 and $(Ni_{1-x}Cu_x)_6Sn_5$ based on the point detection from EDX analysis. However, the contrast between Cu_6Sn_5 and $(Cu, Ni)_6Sn_5$ is very poor from the SEM observation due to the similar chemical compositions. Additionally, the thickness of interfacial IMCs in the Ni-composite solder joints can reach to 4 μm, while that of non-composite one is less than 1 μm. In the non-composite solder joints, only Sn and Cu can react with each other during the reflow process to form the Sn–Cu IMCs at the interface, but in the Ni-composite solder joints, the Ni can diffuse to the interfaces to react with Sn and Cu to form the Sn–Ni–Cu IMCs. Therefore, the interfacial IMCs layer is little thicker in the composite solder joints than that in non-composite one.

3.2. Microstructure evolution in the solder matrix

As for the non-composite solder joints, Bi phase presented the visible changes after 24 h of current stressing. As illustrated in Fig. 3(a), a continuous Bi layer can be observed along the anode interface, the thickness of which is 3 μm, on the other hand, localized voids were initiated along the cathode interface. When the current stressing time increased to 133 h, the lamella microstructure of eutectic SnBi was replaced by the segregated phases, in which the white area is Bi phase and the grey area is the Sn phase, as shown in Fig. 3(b). It is worth to note that the Cu substrate at the anode side still connected with Bi phase via the interfacial IMCs,

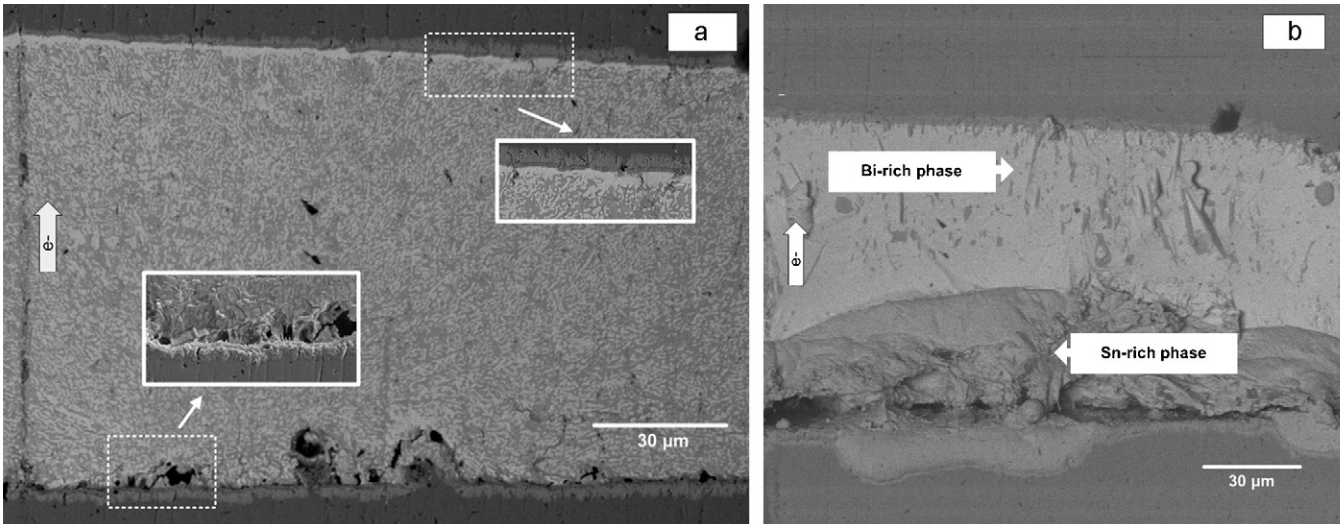

Fig. 3. SEM micrographs of the non-composite solder joint subjected to different current stressing time: (a) accumulation of Bi-rich phases at anode interface after 24 h of current stressing, (b) phase segregation after 120 h of current stressing.

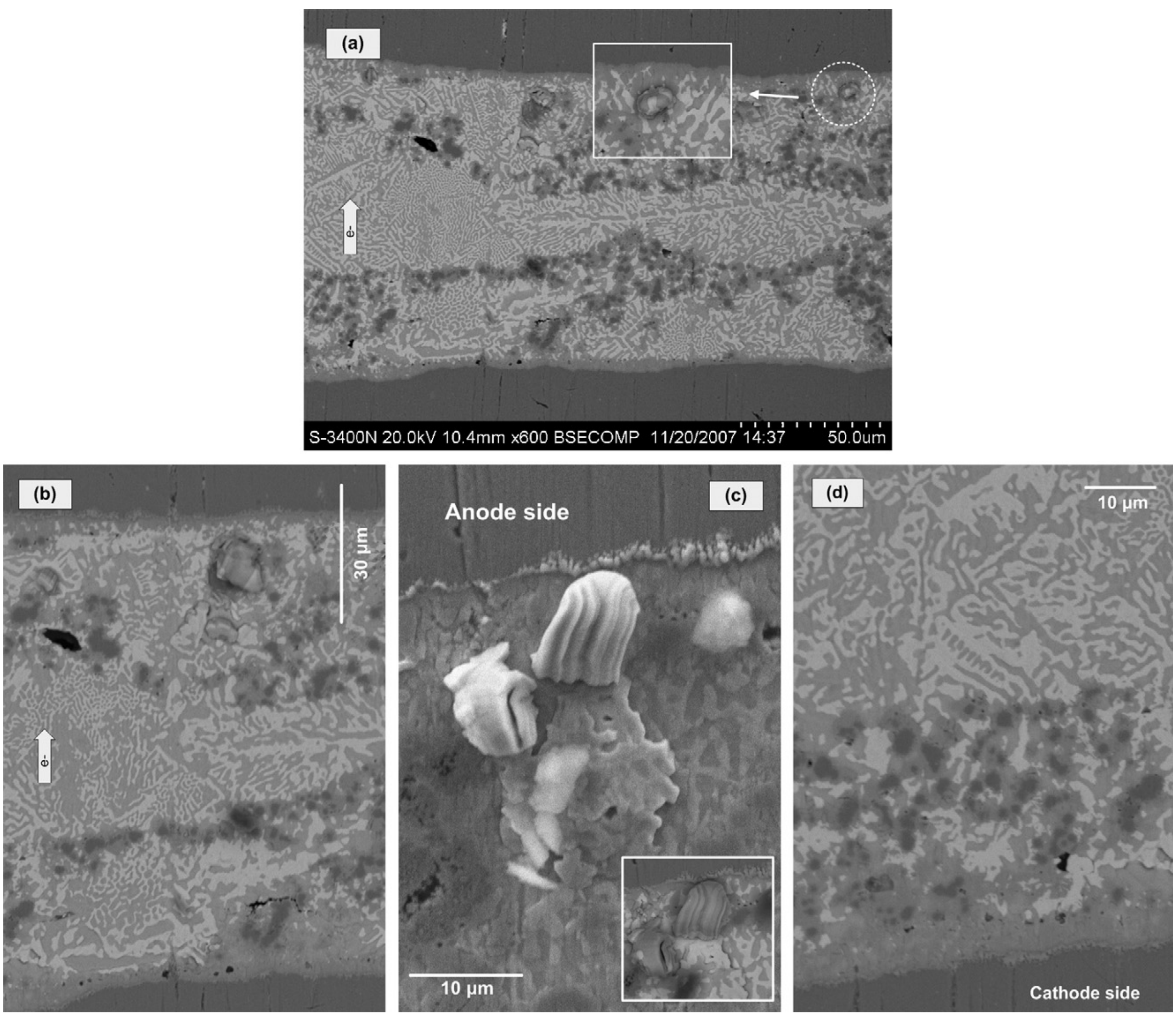

Fig. 4. SEM micrographs of the composite solder joint subjected to different current stressing times. (a) 24 h, (b) 133 h, (c) enlarged view near the anode interface from (b), and (d) enlarged view near the cathode interface from (b).

suggesting that the Cu can not react with Bi to form any IMCs and Bi can act as a barrier layer to inhibit the further reaction between Sn and Cu. Hence, the thickness of interfacial Sn–Cu IMCs at the anode interface remained the constant. Although the separation between Sn phase and Cu substrate can be observed at the cathode interface, the entire solder joint was not under the failure status. It believed that with the resumed current stressing for several extended days, the open circuit can finally occur at the cathode interface. Although it is generally believed that the thinner the initial interfacial IMCs layer, the better the mechanical performance, such belief cannot be simply employed as a solution to improve the EM resistance. Because the cathode interface of Cu substrate and solder matrix at the cathode side of the non-composite solder joints was almost disconnected by the mass depletion under the high current density, but for the Ni-composite solder joints, even after the same period of current stressing time, the cathode interface was still connected through the interfacial IMCs layer, demonstrating the Ni can enhance the EM resistance of interfacial IMCs. Therefore, the initial thickness of the interfacial IMCs layer had no direct influence on the EM resistance, but rather the chemical composition of which can be identified as a crucial factor to determine it.

With presence of the Ni-particles reinforcement inside the solder matrix, the EM-induced microstructure changes were not as severe as that of the non-composite solder joints. No continuous Bi layer was formed after 24 h of current stressing in the Ni-composite solder joints, as shown in Fig. 4(a), only a small sized hillock was formed at the anode interface. Even after 133 h of current stressing, no significant phase segregation occurred inside the solder matrix, but Bi phase tended to coarsen than before. In addition, progressive coarsening of the microstructure, resulting form current stressing, can be found in Fig. 4(b). It is worth to note here that eutectic SnBi and SnPb shared the same lamella microstructure after the first reflow, but the EM-induced progressive coarsening was total different with each other. Unlike the results provided by Lee et al., who found the coarsening of Pb-rich phase in the SnPb solder joints was more significant in the region near the anode with a gradual decrease from the anode to cathode [24]. Our result demonstrates that the coarsened Bi phase tends to appear at both sides of anode and cathode, while the fine Bi phase can be found in the middle of the solder matrix. As illustrated in Fig. 4(c), a hillock that locates at the anode interface had the striation marks on its surface and the grey color demonstrated its chemical composition was Sn, such finding indicated the squeezing effect from the interior solder alloy was due to the soft nature of Sn. Besides, it is interesting to find the well bonding between the solder and Cu substrate at the cathode interface, as shown in Fig. 4(d).

4. Discussion

Sufficient evidence has been accumulated to conclude that diffusion is more rapid along grain boundaries than in the interiors of crystals. Because of the rapid movements of atoms on free surfaces, surface diffusion plays an important role in a large number of metallurgical phenomena. However, grain-boundary is of more immediate concern because, in the average metallic specimen, the grain-boundary area is many times larger than the surface area. Furthermore, grain boundaries form a network that passes through the entire specimen [25]. As for binary Sn–Bi system, the phase-boundary has been approved to be the fast diffusion channel for the movement of Bi atoms/ions [8,21,26,27]. Accordingly, the finer the Bi phases in lamella microstructure, the greater the phase boundaries in number. Therefore, it is easier for Bi atoms/ions to migrate towards the anode side without any difficulties in the non-composite solder joints. As illustrated in Fig. 5, many pencil-type Cu_6Sn_5 IMCs were found inside the Bi phase near the anode side, demonstrating the Cu_6Sn_5 IMCs were sensitive to the high current density as well, and they can also be propelled by the electron wind force with a higher velocity than that of Sn phase. It is interesting to see these embedded Cu_6Sn_5 IMCs were almost paralleling to the electron flow. As reported by Chen and Huang, the plate-type Ag_3Sn IMCs that normal to the electron flow can obstruct the continuous movement of Bi phase [28]. However, it should be pointed out that the orientation-preferred IMCs inside the solder matrix are difficult to achieve by the conventional reflow process. As for the Ni-composite solder joints, as shown in Fig. 6, the cluster of Ni-particles reinforcement can act as a rigid wall to obstruct the movement of Bi atoms/ions. Moreover, the Ni-particles, with blocky-shaped Sn–Ni IMCs surrounded, are not sensitive to the high current density. As shown in Fig. 7(a)–(c), the sizes of current stressed Ni-particles are comparable to that of Ni-particles without current stressing. The average area of Sn–Ni IMCs increases from 4.4 μm^2 without current stressing to 6.6 μm^2 after 133 h of current stressing, demonstrat-

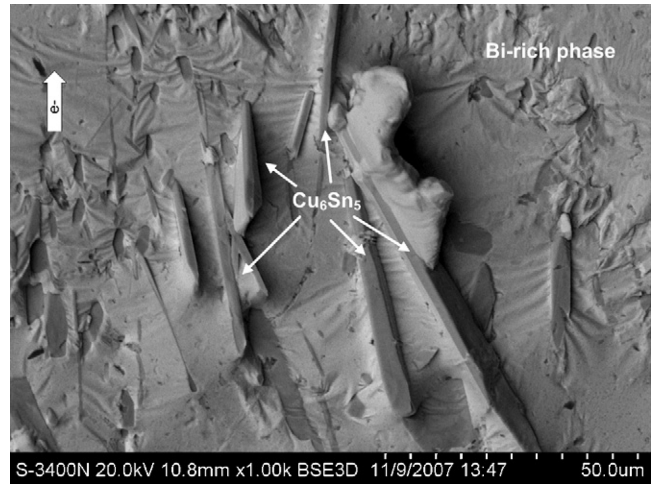

Fig. 5. The pencil-typed Sn–Cu IMCs inside the Bi phase in the non-composite solder joints.

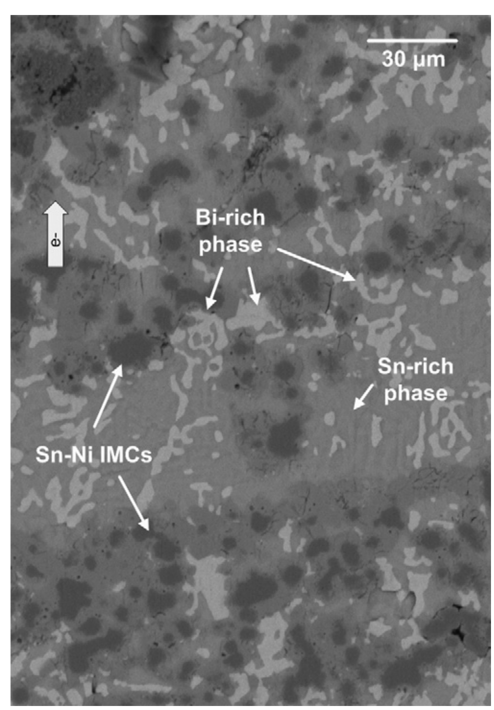

Fig. 6. The cluster of Sn–Ni IMCs inside the solder matrix in the Ni-composite solder joints.

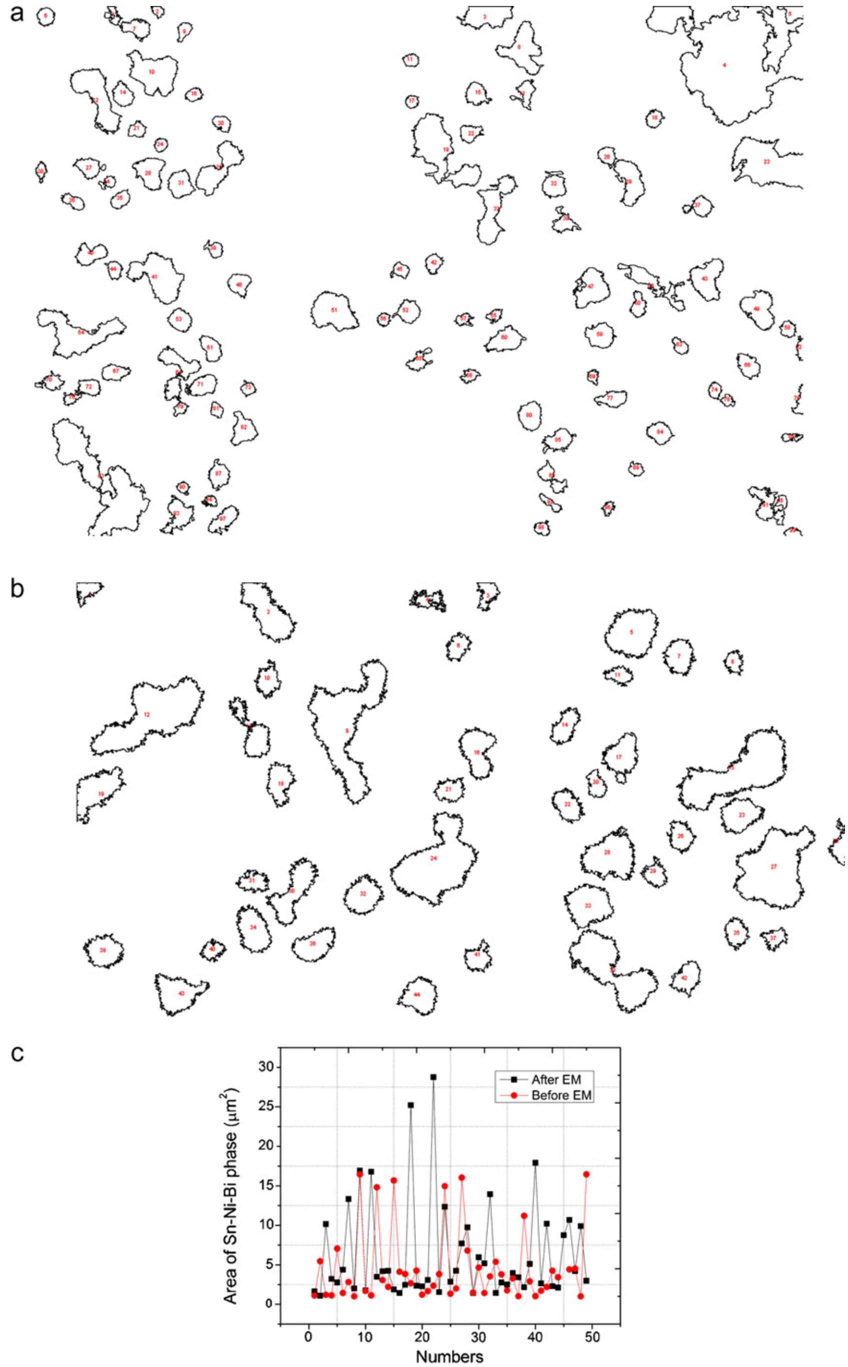

Fig. 7. Profiles and sizes distribution of Ni particles: (a) profile of Sn–Ni IMCs before EM; (b) profile of Sn–Ni IMCs after EM; (c) sizes distribution of Sn–Ni IMCs.

ing the activation energy to prompt the coarsening of Sn–Ni IMCs is much higher than that of Bi-rich phase. The current results illustrate that with moderate ambient temperature EM-induced phase segregation can be solved by the micro-sized Ni particles composite approach.

5. Conclusions

A novel microstructure design by adding the Ni-particles reinforcement into the eutectic SnBi solder joints is developed to retard the phase segregation in binary solder alloy under a high current density (10^4 A/cm^2). Based on the microstructure evolution of eutectic SnBi solder joints during the current stressing, Bi atoms/ions are identified as the dominant diffusion entities which can move easily along the boundaries of Sn phase. Furthermore, total phase segregation of Sn and Bi can occur after long hours of current stressing. Comparing with the non-composite solder joints, Ni particles can act as obstacles to obstruct the fast diffusion channel along the phase boundaries in the eutectic SnBi system. Accordingly, the mean velocity of Bi atoms/ions propelled by the electron wind flow is significantly decreased. Therefore, it is believed that the composite approach can be one of the ultimate solutions to the EM issue in the electronic solder joints.

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