Electromigration Studies of Flip Chip Sn95/Sb5 Solder Bumps on Cr/Cr-Cu/Cu Under-Bump Metallization

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The electromigration-induced failure of Sn95/Sb5 flip chip solder bumps was investigated. The failure of the joints was found at the cathode/chip side after current stressing with a density of 1×10^4 A/cm^2 at 150°C for 13 sec. The growth of intermetallic compounds (IMCs) was observed at the anode side after current stressing. Voids were found near the current crowding area in the cathode/chip side, and the $(Cu,Ni)_6Sn_5$ IMC at the cathode/chip end was transformed into the Sn phase. The failure mechanism for Sn95/Sb5 flip chip solder joint is proposed in this paper.

Key words: Electromigration, lead-free solder, Sn95/Sb5, flip chip, failure, intermetallic compound

INTRODUCTION

Since the input/output pin count for flip chip products has drastically increased recently, the bump pitch and the diameter of under-bump metallization (UBM) have been forced to decrease. Due to the small contact area of solder bumps, the electromigration of the solder bump has become an important issue. Microvoid formation may be a result of the mass transfer in the electromigration process at high current density. The voids decrease the contact area, and consequently increase the local current density and local resistance. A positive feedback cycle forms and leads to the catastrophic failure of the solder joint. Therefore, it is necessary to investigate the electromigration of flip chip solder bumps. Increasing awareness of the impact of electronics materials on environment and health has recently caused a high demand for lead-free products in IC packages. Previous studies[1–8] on electromigration of flip chip solder bumps focused mainly on solder bumps composed of SnPb, SnAg, and SnAgCu. Lead-free solder of Sn95/Sb5 with low a particle property was used to avoid the soft error of memory IC flip chip packages. There are some aerospace applications of the electronic flip chip packages using Sn95/Sb5 solder material for its stable material properties in high-temperature environments.[9] However, little research has been done on the electromigration of solder bumps composed of SnSb. The purpose of this study is to investigate the electromigration of SnSb flip chip solder bumps. The present study examines the current crowding effect, failure of flip chip joints, and the changes in microstructure resulting from electromigration. This research may lead to a better understanding of electromigration damage and the failure mechanism of SnSb flip chip solder bumps.

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EXPERIMENTAL TECHNIQUE

The flip chip package of Sn95/Sb5 solder bump was prepared as described below. The chip size was 9.5 mm × 6.0 mm with a 105-μm UBM diameter. The UBM consisted of 0.7-μm Cu, 0.3-μm Cr-Cu, and 0.1-μm Ti. Sn95/Sb5 solder paste was printed and deposited on the UBM pad of the wafer. The wafer was reflowed in a nitrogen atmosphere oven with a 280°C peak temperature[10–12] and remained above the liquidus temperature for approximately 60 sec. By sawing the wafer, individual bumped die samples were created. Figure 1a depicts the schematic structure of a bumped die.

The bumped die was first mounted on a BT substrate to form a flip chip, in which Sn95/Sb5 solder paste was printed through a metal stencil onto the metallization pads. The flip chip sample was then reflowed for the second time in a nitrogen atmosphere oven with a 280°C peak temperature for approximately 60 sec. The flip chip joints were formed after the second reflow. Finally, the flip chip package was underfilled. The schematic diagram of the flip chip sample is shown in Fig. 1(b). In this paper, the right bump will be referred to as Bump 1, in which the electron flow goes from the board side to the chip side; and the middle bump will be referred to as Bump 2, in which the electrons migrate from the chip side to the board side. The direction of the electron flow for the electromigration is described in Fig. 2.

Two kinds of samples were used to observe the microstructure evolution at various stages of the current stressing. The first sample, which was a previously cross-sectioned and polished flip chip package, was stressed with a current density of $2 \times 10^4 A/cm^2$ at 150°C. The remaining cross-sectioned area on the chip side was measured against the cross-sectional UBM length. The current applied to this bump was 0.18 A, which corresponded to a current density of 2×10^4 A/cm^2. The second sample, which was an entire flip chip package without cross sectioning, was stressed with a current density of 1×10^4 A/cm^2 at 150°C. In this package, the contact opening is 85 μm in diameter on the chip side and 150 μm in diameter for the pad on the board side. A current of 0.567 A was applied in the bump pair, which was equivalent to a current density of 1×10^4 A/cm^2. Therefore, the current density on the chip side was about 3 times larger than that of the board side. The thermal couple was attached to the chip surface of the sample and the temperature was maintained at 150°C. When electrical failure occurred, solder bumps of the flip chip package were cross-sectioned. The current stressing of both flip chip package samples was performed on a hot plate. Microstructure observation and composition analysis were performed using a JEOL 6500 field emission scanning electron microscope (SEM) and energy dispersive x-ray (EDX) (Japan Electron Optics Ltd., Tokyo). The Sb concentration is difficult to determine, because the signals of Sb and Sn were too close to be distinguished from one another.

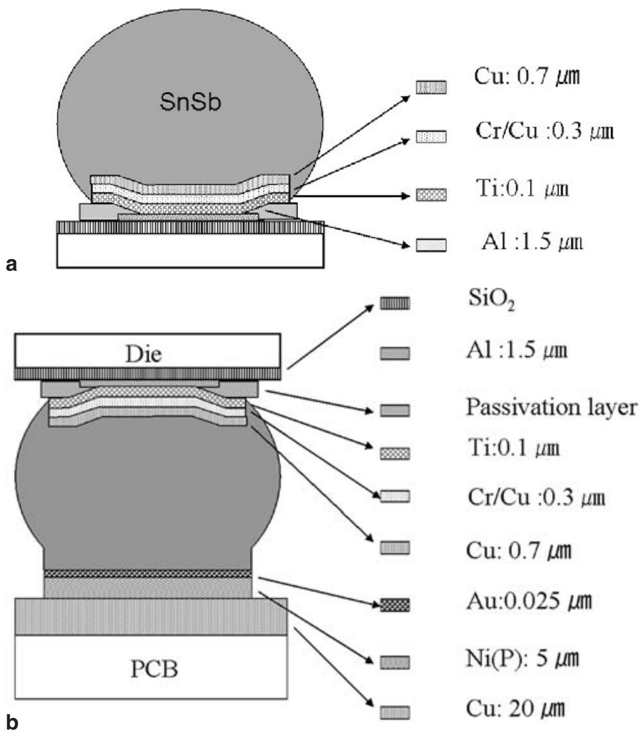

Fig. 1. The schematic diagram: (a) cross section of a bumped die and (b) cross section of a flip chip package.

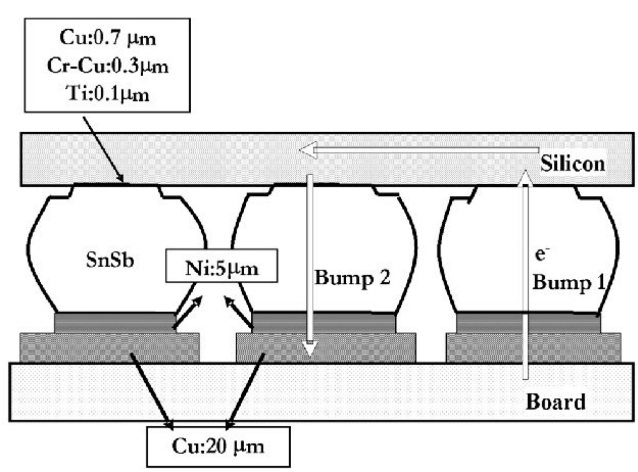

Fig. 2. The schematic diagram of electron flow for the electromigration experiment.

RESULTS AND DISCUSSION

Figure 3a shows the SnSb bump structure of Bump 2 before current stressing. Some voids formed inherently during the reflow process and these inherent voids were of larger size and were generally of circular appearance. On the chip side, the $(Cu,Ni)_6Sn_5$ compound (IMC) formed between UBM and SnSb solder, as shown in Fig. 3b, while the IMC near the board side was identified to be $(Ni,Cu)_3Sn_4$, as seen in Fig. 3c. Figure 4a shows the microstructure of Bump 2 after 2×10^4 A/cm^2 current stressing for 110 h at 150°C, in which the chip side was the cathode and the board side was the anode. Voids were found near the upper-right corner of the bump, as indicated by Arrow 1 in Fig. 4a. The location at which voids formed after current stressing is the current crowding area. For this package, electron flow enters the bump from the right-back corner of the UBM, as indicated by Arrow 2 in Fig. 3a. Similar current crowding has also been reported in SnPb and SnAg flip chip bumps.[5,6]

Before current stressing, the $(Ni,Cu)_3Sn_4$ compound and Ni_3P layer were found in the board side, as shown in Fig. 3c. It is intriguing to note that $(Cu,Ni)_6Sn_5$ replaced $(Ni,Cu)_3Sn_4$ after the current stressing, as indicated by the arrow in Fig. 4(c). The thickness of the Ni-Cu-Sn compound increased on the board side, which was the anode. The Ni-Cu-Sn compound was squeezed out at the anode. Furthermore, $(Cu,Ni)_6Sn_5$ on the chip side was replaced by

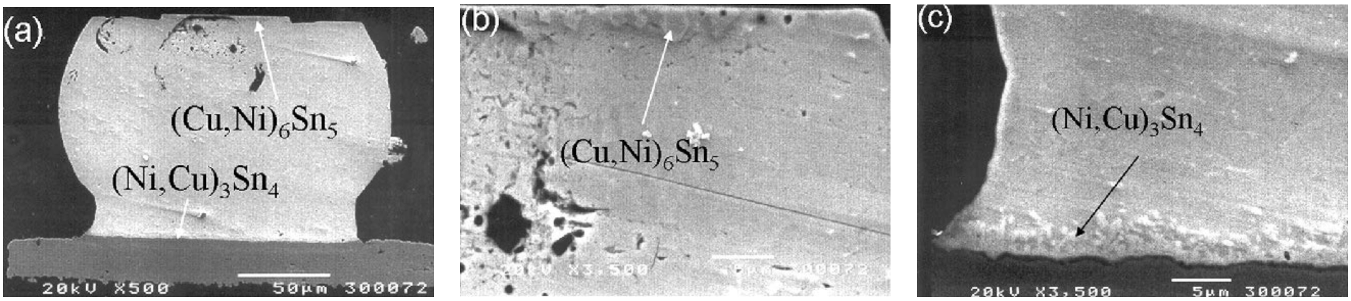

Fig. 3. The cross-sectional SEM images of Bump 2 before current stressing: (a) complete cross section, (b) chip side, and (c) board side.

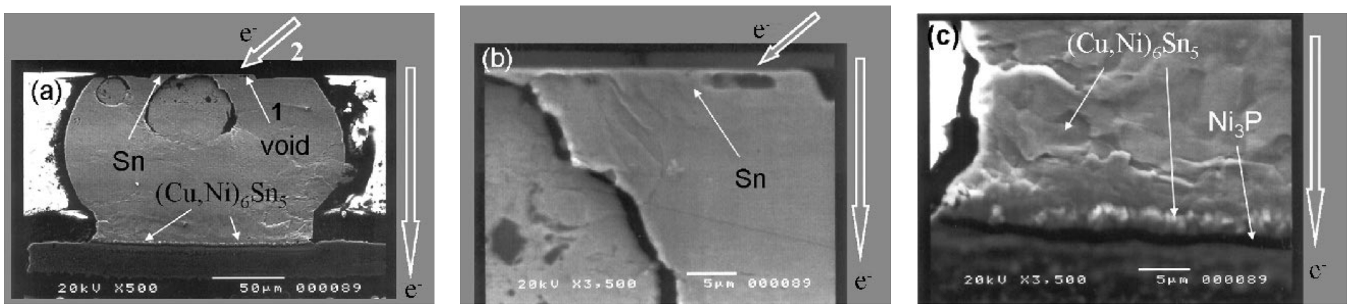

Fig. 4. The cross-sectional SEM images of Bump 2 after current stressing with current density 2 × 10^4 A/cm^2 at 150°C: (a) complete cross section, (b) chip side, and (c) board side.

Table I. Composition of IMC at Bump 1

	The Anode/Chip Side (Cr/Cr-Cu/Ti)		The Cathode/Board Side (Cu/Ni-P/Au)	
	Before Current Stressing	After Current Stressing	Before Current Stressing	After Current Stressing
Ni	20.7 at.%	32.5 at.%	30.7 at.%	31.7 at.%
Cu	31.8 at.%	8.6 at.%	14.0 at.%	8.8 at.%
Sn	47.5 at.%	58.9 at.%	55.3 at.%	59.5 at.%

Table II. Composition of IMC at Bump 2

	The Cathode/Chip Side (Cr/Cr-Cu/Ti)		The Anode/Board Side (Cu/Ni-P/Au)	
	Before Current Stressing	After Current Stressing	Before Current Stressing	After Current Stressing
Ni	22.0 at.%	Not detected	31.3 at.%	29.0 at.%
Cu	30.3 at.%	Not detected	8.0 at.%	19.7 at.%
Sn	47.7 at.%	>99.0 at.%	60.7 at.%	51.3 at.%

Sn after the current stressing, as indicated by the arrow in Fig. 4(b). The movement of Cu and Ni atoms due to electromigration may explain these findings.

Before the current stressing, Ni-Cu-Sn IMC formed on the cathode (the chip side Cr/Cr-Cu/Cu UBM), and its composition was determined to be Ni (22.0%): Cu (30.3%): Sn (47.7%) by EDX. Tables I and II summarize the composition evolution of IMC for the samples. After the current stressing, the signals of Ni and Cu could not be detected by EDX on the cathode and the atomic ratio of Sn increased to 98%. This indicates that the electron flow drives the Ni and Cu atoms in the (Cu,Ni)$_6$Sn$_5$ IMC away from the cathode. In contrast, (Cu,Ni)$_6$Sn$_5$ compound formed near the anode and Ni$_3$P layers were also observed on the board side after the current stressing, as shown in the Fig. 4c. The Sb atoms in the bump were undetectable in this system due to signal positions overlapping with those of Sn atoms; thus, the effect of electromigration upon Sb atoms was unclear.

To investigate the polarity effect, Fig. 5a shows the SnSb bump structure of Bump 1 before current stressing. A large void formed inherently during the reflow process near the chip side. Intermetallic com-

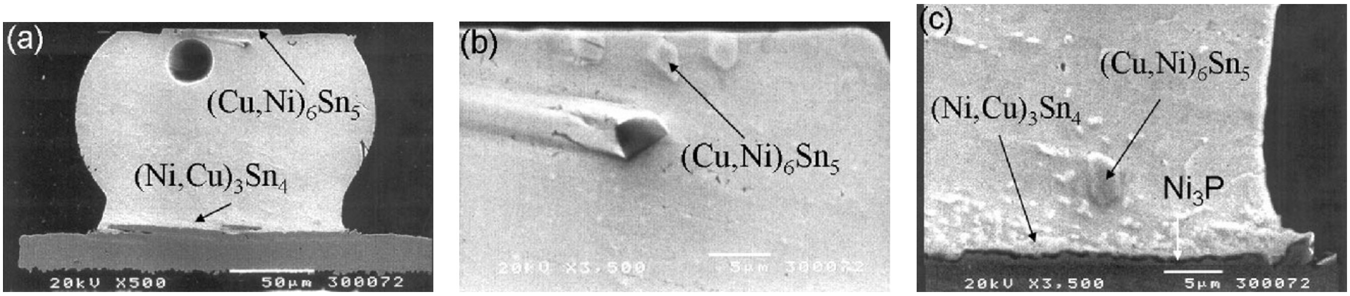

Fig. 5. The cross-sectional SEM images of Bump 1 before current stressing: (a) complete cross section, (b) chip side, and (c) board side .

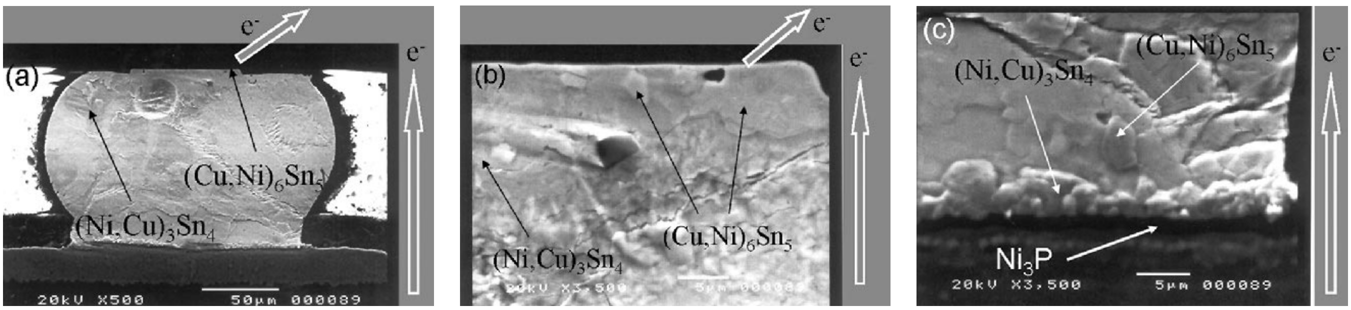

Fig. 6. The cross-sectional SEM images of Bump 1 after current stressing with current density of 2×10^4 A/cm^2 at 150°C: (a) complete cross section, (b) chip side, and (c) board side.

pound of $(Cu,Ni)_6Sn_5$ formed near the chip side, as seen in Fig. 5b. Nevertheless, the IMC near the board side was $(Ni,Cu)_3Sn_4$, as shown in Fig. 5c. The SEM image of Bump 1 after 2×10^4 A/cm^2 current stressing for 110 h at 150°C is shown in Fig. 6a. The void, which originally formed inherently during the reflow process, disappeared after current stressing, as shown in Fig. 6a.

Before current stressing, the $(Ni,Cu)_3Sn_4$ compound was found on the board side. It is interesting to note that the thickness of the Ni-Cu-Sn compound increased on the cathode side after current stressing, as shown in Fig. 6c. Furthermore, $(Cu,Ni)_6Sn_5$ IMC formed near the upper-right corner of the bump, as indicated by Arrow 1 in Fig. 6b. The location at which $(Cu,Ni)_6Sn_5$ IMC formed after current stressing is the current crowding area. For this package, electron flow exits the bump from the right-back corner of the UBM, indicated by Arrow 2 in Fig. 6b. These results suggest that the current density is not uniform inside the solder joint and the electromigration effect is stronger in the current crowding region. At the same time, the $(Ni,Cu)_3Sn_4$ compound formed near the anode and within the solder matrix of the bump, as shown in Fig. 6a. It is likely that the Ni atoms were pushed toward the anode, resulting in the formation of the $(Cu,Ni)_6Sn_5$ IMC and $(Ni,Cu)_3Sn_4$ IMC.

Figure 7 shows the cross-sectional SEM images of the solder joints of the entire flip chip package after stressing at 150°C without current passing through it. Figure 8a shows the microstructure of Bump 1 for the entire flip chip package after 1×10^4 A/cm^2 current stressing for 13 h at 150°C, in which the

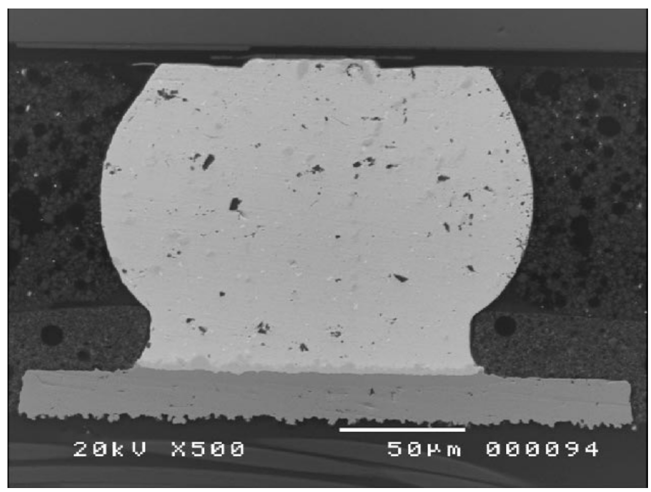

Fig. 7. The cross-sectional SEM images of the entire flip chip package at 150°C without current density.

chip side was the anode and the board side was the cathode. The $(Ni,Cu)_3Sn_4$ IMC is obviously clustered near the upper-right corner of the bump, as indicated by Arrow 1 in Fig. 8a. The location at which IMC was formed after current stressing is the current crowding area. For Bump 1, electron flow exits the bump from the right-back corner of the UBM, as indicated by Arrow 2 in Fig. 8a. Thus, it may be stated that the formation of IMC is strongly related to the current crowding effect. Fig. 8b shows the microstructure of Bump 2 for the entire flip chip package after 1×10^4 A/cm^2 current stressing for 13 h at 150°C, in which the chip side was the cathode and the board side was the anode.

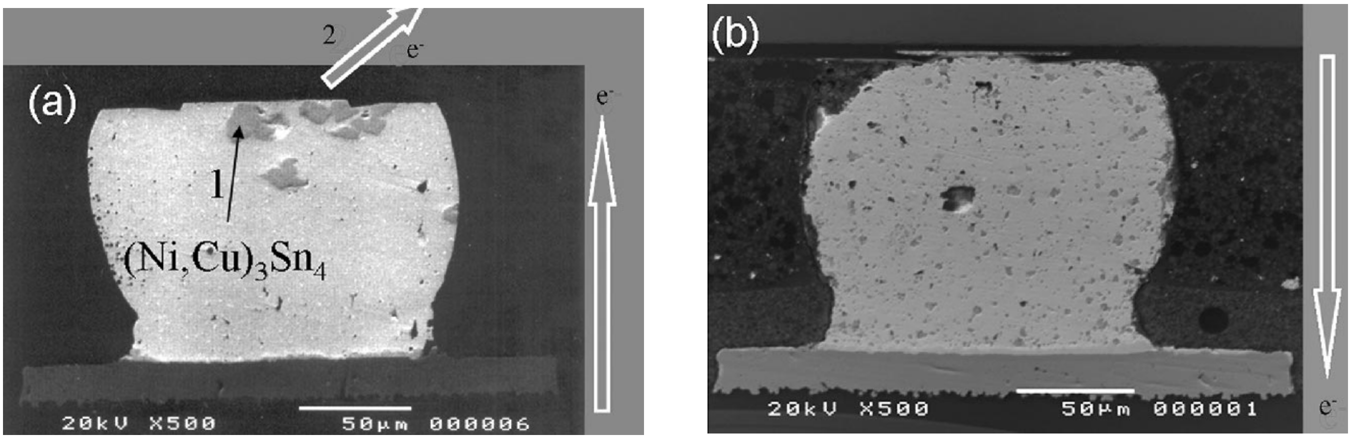

Fig. 8. The cross-sectional SEM images of the entire flip chip package after current stressing with current density of 1×10^4 A/cm^2 at 150°C: (a) Bump 1 and (b) Bump 2.

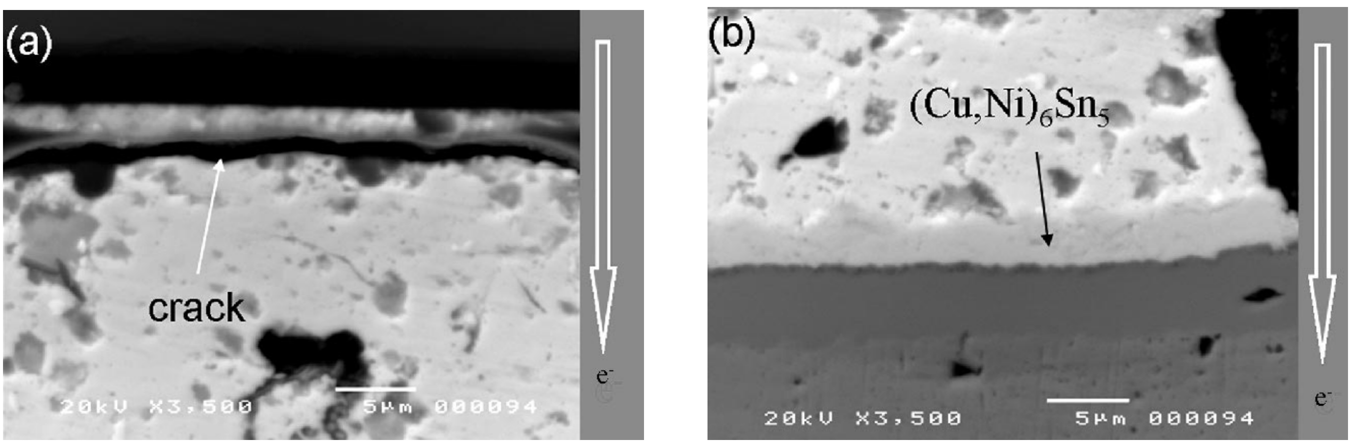

Fig. 9. The enlarged cross-sectional SEM images of the entire flip chip package after current stressing with current density of 1×10^4 A/cm^2 at 150°C: (a) the cathode/chip side and (b) the anode/board side.

The solder joint failure was observed for the entire flip chip package stressed with current density of 1×10^4 A/cm^2 for 13 h at 150°C. Figure 8b shows that the failure was located at the interface of the solder and chip side Cr/Cr-Cu/Cu UBM, where the chip side was the cathode. The crack was clearly seen from the enlarged cross-sectional SEM image in Fig. 9a. However, there was no crack found on the board side, as shown in the Figs. 8b and 9b, where the board side was the anode. It is speculated that the major reason for the package failure is the higher current density at the chip side. In this package, the current density on the chip side is about 3 times larger than that on the board side. However, no solder joint failure was found in the previously cross-sectioned and polished flip chip package sample. There was a free surface for the solder bump of the cross-sectioned flip chip package, whereas the solder bump of the entire flip chip package was surrounded by the underfill. The practical temperatures of the solder bump for the cross-sectioned flip chip package sample and the entire flip chip package sample were different, even under the same controlled temperature on the hotplate. It appears that the electromigration behavior was influenced by the free surface effect and the practical temperature.

CONCLUSIONS

The effect of electromigration on the Sn95/Sb5 solder joints of the flip chip package was examined with the current density of 2×10^4 A/cm^2 and 1×10^4 A/cm^2 at 150°C. The formation of Ni-Cu-Sn IMC at the anode was observed due to the atomic flux driven by electromigration in the Sn95/Sb5 solder joints. The location of the IMC was found in the crowding region and highly related to the practical distribution of current density. The growth of Ni-Cu-Sn IMC was verified at the anode. The thickness of Ni-Cu-Sn IMC increased with current stressing and the IMC was squeezed out as hillocks at the anode. The composition of the Ni-Cu-Sn compound on the cathode changed to high-concentration Sn. One possible explanation is that the electron flux exerted driving force on the Ni and Cu atoms, which pushed Ni and Cu from cathode to anode. The IMC composition change on the Cr/Cr-Cu/Cu UBM may lead to the decrease of the bonding strength between Cr/Cr-Cu/Cu UBM and SnSb solder. The voids were discovered on the cathode (chip side) after current stressing. A series of continuous voids may merge into cracks, which will cause the failure of the solder joint. The failure of the solder joint was observed for the complete flip chip package with the current stressing of current density 1×10^4 A/cm^2 for 13 h at 150°C. The failure was located on the interface of SnSb solder and chip side Cr/Cr-Cu/Cu UBM, where the chip side was the cathode. These findings suggest that electromigration on thin film UBM raises an important reliability issue[13,14] for the SnSb solder joints. The practical temperature of solder bumps at the current stressing needs to be further investigated.

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REFERENCES

1. J.D. Wu, P.J. Zheng, Kelly Lee, C.T. Chiu, and J.J. Lee, *2002 Electronic Components and Technology Conf.*, p. 452.
2. W.J. Choi, E.C.C. Yeh, and K.N. Tu, *2002 Electronic Components and Technology Conf.*, p.1201.
3. Se-Young Jang, Wolf J., Woon-Seong Kwon, and Kyung-Wook Paik, *2002 Electronic Components and Technology Conf.*, p. 1213.
4. T.Y. Lee, K.N. Tu, and D.R. Frear, *J. Appl. Phys.* 90, 4502 (2001).
5. T.Y. Lee, K.N. Tu, S.M. Kuo, and D.R. Frear, *J. Appl. Phys.* 89, 3189 (2001).
6. A. Christou, *Electromigration & Electronic Device Degradation* (New York: John Wiley & Sons, Inc., 1994).
7. J.P. Dekker, P. Gumbsch, E. Arzt, and A. Lodder, *Phys. Rev. B* 59, 11 (1999).
8. Q.T. Huynh, C.Y Liu, Chih Chen, and K.N. Tu, *J. Appl. Phys.* 89, 4332 (2001).
9. *2001 International Technology Roadmap for Semiconducors, Assembly and Package*, p. 3.
10. D.R. Lide, *Handbook of Chemistry and Physics*, 2nd ed. (Boca Raton, FL: CRC Press, 1992).
11. R.J. Fields, S.R. Low III, and G.K. Lucey, *Met. Sci. Joining* 165 (1992).
12. R.J.K. Wassink, *Soldering in Electronics*, 2nd ed. (Ayr, Scotland: Electrochemical Publication Ltd., 1989).
13. C.Y. Liu, C. Chen, C.N. Liao, and K.N. Tu, *Appl. Phys. Lett.* 75, 58 (1999).
14. S. Brandenburg and S. Yeh, *Proc. Surface Mount Int. Conf. Exhib.* (Edina, MN: SMTA, 1998), p. 337.