The Effect of Pre-Aging on the Electromigration of Flip-Chip SnAg Solder Joints

Po-Chun Yang, Chien-Chih Kuo, and Chih Chen

The effect of pre-aging on electromigration is investigated in this study using flip-chip SnAg solder joints. The solder joints were pre-aged at 170°C for 1 h, 3 h, 5 h, 10 h, 25 h, and 50 h, and then they were subjected to electromigration tests of 0.9 A at 150°C. It was found that the average failure time increased about three times when the joints were pre-aged for 3 h to 25 h. But it decreased when the joints were overaged. It is proposed that the major contributor to the prolonged failure time may be the densification of the nickel and copper under-bump metallization (UBM) and the solder due to the aging treatment. The pre-aging treatment at 170°C may stabilize the microstructure of the solder. The vacancies in the solder were annihilated during the heat treatment, causing a slower diffusion rate. In addition, the UBM structure became denser after the pre-aging process. Thus, the denser UBM structure may lead to slower consumption rates of the nickel and copper layers, resulting in the enhancement of electromigration resistance.

INTRODUCTION

The flip-chip solder joint has become the most important technology for high-density packaging in the microelectronic industry.[1] As the required performance in microelectronics devices becomes higher, thousands of solder bumps are fabricated into one chip. Thus the size of the joints progressively shrinks, with a diameter of about 100 μm or less. The design rule of packaging requires that each bump is going to carry 0.2 A to 0.4 A, resulting in a current density of approximately 2×10^3 A/cm^2 to 2×10^4 A/cm^2. Therefore, electromigration has become an important reliability issue for flip-chip solder joints.[2]

The previous studies on electromigration of flip-chip solder bumps were mainly focused on eutectic SnPb solders.[3–5] Current crowding effect on the cathode/chip side was proposed to be responsible for the failure at the cathode/chip side of the SnPb bumps.[1,6] Three-dimensional simulation has been carried out to depict the current density distribution in solder bumps and a hot spot was proposed to occur at the region of current crowding.[7,8] The current crowding induced by electromigration still plays a crucial role in the failure of the bumps. Recently, due to environmental concerns, studies have been conducted on the electromigration of lead-free solder bumps.[9–11] Particularly, several approaches have been proposed to relieve the current crowding and Joule heating effect in the joints, hoping to prolong the electromigration lifetime of the joints. The approaches mainly include enlarging the cross section for aluminum traces in the chip end[12] and using thicker under-bump metallizations (UBMs).[13–15] It is reported that thicker UBMs keep the solder away from current-crowded and hot-spot regions and thus may increase the electromigration resistance.[3,14] Solid-state aging may form thicker intermetallic compound (IMC) layers and this may be able to increase the electromigration resistance. However, the effect of pre-aging on the electromigration of flip-chip solder joints is not clear.

How would you…

…describe the overall significance of this paper?

Pre-aging at 170°C was able to increase the electromigration lifetime of flip-chip solder joints, which has not been reported previously.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

The effect of pre-aging on electromigration is investigated in this study of flip-chip SnAg solder joints. It was found that the average failure time increased about three times when the joints were pre-aged at 170°C for 3 to 25 hours.

…describe this work to a layperson?

In high-performance devices such as microprocessors, there are thousands of solder bumps in one chip. It was found that the lifetime of the devices may increase three times when the devices are heated to 170°C for 3 to 25 hours prior to usage of the devices.

In this paper, lead-free eutectic SnAg solder joints were annealed at various conditions to produce various thicknesses of Ni_3Sn_4 IMCs. Then electromigration tests were performed on the joints to examine the effect of the pre-aging on failure time and failure mechanism. It was found that the appropriate amount of pre-aging at 170°C may increase the electromigration resistance.

See the sidebar for experimental details.

RESULTS AND DISCUSSION

By controlling the annealing conditions, solder bumps with various IMC thicknesses can be fabricated. Since electromigration failure occurs in the chip side of the solder joints, the thickness of the Ni_3Sn_4 layer on the substrate end will not be discussed in this paper. The Ni_3Sn_4 layer was 1.96 μm on the chip side before aging. Figure 1a through c show the cross-sectional SEM images for the solder bumps after the solid-state aging at 170°C for 0 h, 5 h, and 50 h. The solders were selectively etched to reveal the morphology of the IMC layers. The IMC was identified as Ni_3Sn_4 for all the samples used in this study using scanning-electron microscopy–energy dispersive spectroscopy (SEM-EDS). The thickness was 1.96 µm, 2.15 µm, and 3.27 µm for the three samples, respectively. The Ni_3Sn_4 thicknesses for all the annealing conditions are shown in Figure 2. The Ni_3Sn_4 IMC layer on the chip end grew thicker as the aging time increased. At the same time, some of the nickel layer was consumed due to the IMC formation. Yet, the copper UBM remained intact after all the annealing conditions.

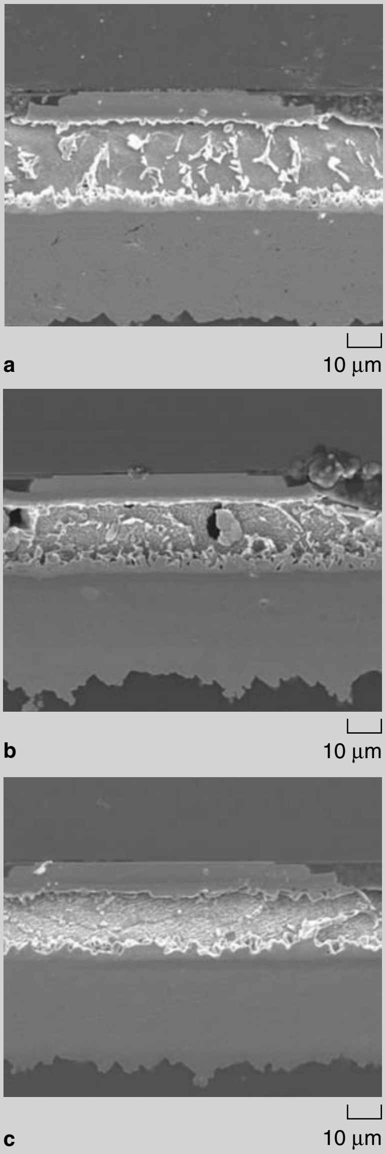

Figure 1. Cross-sectional SEM images showing the microstructure of the pre-aged samples at 170°C for (a) 0 h; (b) 5 h; and (c) 50 h. The sample thickness is 1.96 µm, 2.15 µm, and 3.27 µm, respectively.

To investigate how the pre-aging affects electromigration failure time, the joints were stressed by 0.9 A at 150°C. The failure criteria was defined when the bump resistance of Bump 3 increased 20% of its original value. The mean failure time was obtained by averaging the results of three samples for all the annealing conditions. Figure 3 shows the average failure time as a function of the pre-aging time. The failure time without pre-aging treatment was 103 h, and increased significantly after the pre-aging treatment. With pre-aging of 1 h, the failure time increased to 173 h, and it further increased to 325 h for the samples pre-aged for 3 h. The slight drop in failure time for the samples pre-aged for 5 h may be attributed to sample variation. It reaches a peak value of 331 h for the samples pre-aged for 25 h. The results indicate that the failure time can be prolonged by approximately three times by a simple pre-aging treatment at 170°C for few hours to 25 h. Yet, it decreases to 238 h for the samples pre-aged for 50 h.

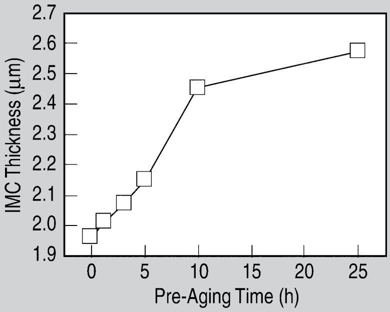

Figure 2. The measured thickness of the Ni_3Sn_4 IMC layer on the chip end as a function of pre-aging time at 170°C. The IMC grew thicker as the annealing time increases.

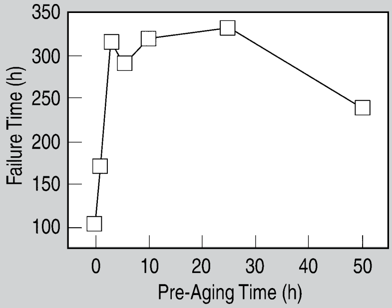

Figure 3. Average electromigration failure time of solder joints as a function of pre-aging time. The failure time increases rapidly with proper pre-aging time. Yet, it decreases for the bumps after the aging for 50 h.

The failure mechanism was examined to investigate the reasons for this interesting observation. Figure 4a through c presents the cross-sectional SEM images on the failure site for the bumps with pre-aging for 0 h, 5 h, and 50 h, respectively. The electron flow entered from the aluminum trace on the left-hand side, as indicated by the arrows. Dissolution of the nickel UBM was observed on the failure sites. Once the nickel UBM was destroyed, the 5 µm copper UBM dissolved quickly into the solder to form $(Cu, Ni)_6Sn_5$ ternary IMCs. Since copper atoms were migrated into the solder by the electron flow, voids accumulated in the contact opening. Both the IMCs and void formations are responsible for the increase in bump resistance.

It is speculated that a thicker Ni_3Sn_4 layer may relieve the current-crowding effect in the flip-chip solder joints. A three-dimensional (3-D) finite-element method was employed to simulate the current-density distributions in the sol-

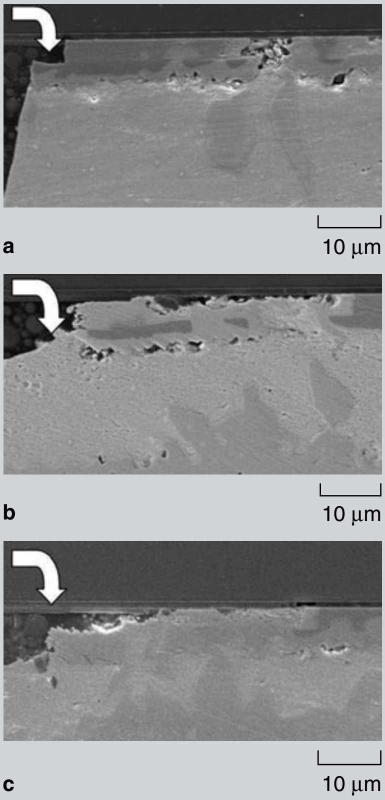

Figure 4. Cross-sectional SEM images showing the microstructure on the failure sites for the samples pre-aged at 170°C for (a) 0 h; (b) 5 h; and (c) 50 h. Dissolution of the nickel and copper UBM was responsible for the electromigration failure.

Table I. The Resistivity of the Materials used in the Simulation Models

Materials	Resistivity at 20°C (μΩ-cm)
Al Trace	3.2
Electroless Ni	70.0
Cu	1.7
Ni	6.2
SnAg Solder	11.5
Ni_3Sn_4	28.5

der joints with the pre-aging for 0 h and 25 h. The dimensions of the two models were identical except the thickness of the IMCs and the remaining nickel layer in the chip and in the substrate ends. The Ni_3Sn_4 layer on the chip side was 1.96 μm and 2.57 μm for the solder bumps with pre-aging for 0 h and 25 h, respectively. The consumption of the nickel UBM was also considered. Layered-type Ni_3Sn_4 IMCs were used in this simulation to avoid difficulty in meshing. The parameters of the materials used in the simulation were tabulated in Table I. The model used was SOLID69 8-node hexahedral coupled field element using ANSYS simulation software developed by ANSYS Inc.

It is surprising that the simulation results indicate that no obvious differences in current density distribution were observed between the two bumps, as presented in Figure 5a and b. Yet, the bump with the pre-aging for 25 h has a slightly lower maximum current density. The value is 21,923 A/cm^2, which is only about 0.4% lower than that of the bump without the pre-aging treatment. The difference in failure time could be estimated using the mean-time-to-failure equation for solder joints, which is typically expressed as[17]

$$\mathrm{MTTF} = A\frac{1}{j^n}\exp\left(\frac{Q}{kT}\right)$$

where A is a constant, j is the current density in amperes per centimeter square, n is a model parameter for current density, Q is the activation energy, k is Boltzmann's constant, and T is the average bump temperature in degrees Kelvin. To estimate the failure time difference due to the variation of current density distribution, the maximum current density and the stressing temperature were adopted for the values of j and T, respectively. In addition, the values of n and Q used are adopted as 0.678 eV and 0.691 eV, respectively.[18] The calculation results indicate that the thicker Ni_3Sn_4 layer can only prolong the failure time less than 1%. Yet, the experimental data show that the mean failure time for the bumps with the pre-aging for 25 h is about 3.2 times that of the non-aged one. Thus, the major reason for the higher electromigration resistance does not come from the change in current density distribution due to the IMC formation.

The major contributor to the prolonged failure time after the proper aging conditions may come from the densification of the UBM and the solder. C.Y. Liu et al. performed electromigration tests in thin solder strips and they found that the electromigration rate of pure tin could be reduced by about 50% when the strips were annealed at 150°C for 48 h.[19] The annealing temperature in this study is 170°C, which is higher than 150°C. Therefore, it is speculated that the pre-aging treatment at 170°C may stabilize the microstructure of the solder. The vacancies in the solder were annihilated during the heat treatment, causing a slower diffusion rate. In addi-

EXPERIMENTAL PROCEDURES

The dimensions of the flip-chip joints used in this study are shown schematically in Figure Aa. The $Sn_{96.5}Ag_{3.5}$ bump has a dimension of 130 μm in width and about 25 μm in height with an under-bump metallization (UBM) opening of 120 μm in diameter. The solder joints consist of eutectic SnAg solder bumps with an electroplated 5 μm-Cu/electroplated 3 μm-Ni UBM. The four bumps are connected together with aluminum trace 2,550 μm long, 100 μm wide, and 1.5 μm thick. The bumps were annealed at 170°C for various durations of time, including 1 h, 3 h, 5 h, 10 h, 25 h, and 50 h.

Kelvin bump probes were adopted to measure the resistance changes during electromigration and they consist of four bumps, which are denoted as bump 1 through bump 4, as shown in Figure Ab. Six copper nodes were fabricated on the substrate side and they are labeled as Nodes n1 though n6. The copper lines on FR5 substrates were 25 μm thick and 100 μm wide. Bump 2 and bump 3 were applied by 0.9 A current at 150°, in which the electron flow goes from the board side to the chip side in bump 2, whereas it is from the chip side to the board side for bump 3. Kelvin probes were employed to monitor the resistance changes for both bumps 2 and 3.[16] Thus the degree of damage can be measured for these two bumps. In this study, we define the electromigration failure as the resistance of the bump 3 increases 20% of its original value. Field-emission scanning-electron microscopy of JEOL 6500 was employed to observe surface microstructure, and energy-dispersive spectroscopy was used to analyze compositions.

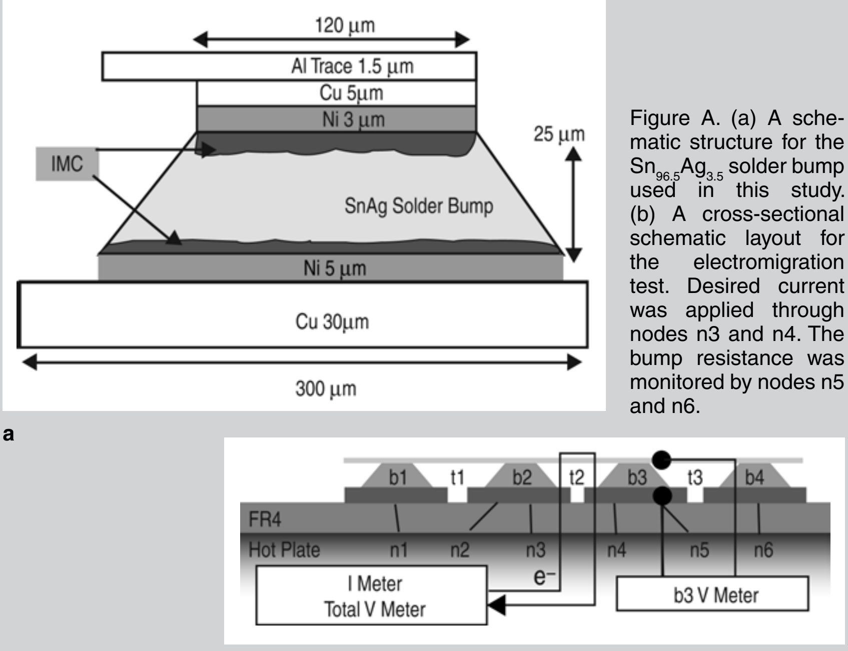

Figure A. (a) A schematic structure for the $Sn_{96.5}Ag_{3.5}$ solder bump used in this study. (b) A cross-sectional schematic layout for the electromigration test. Desired current was applied through nodes n3 and n4. The bump resistance was monitored by nodes n5 and n6.

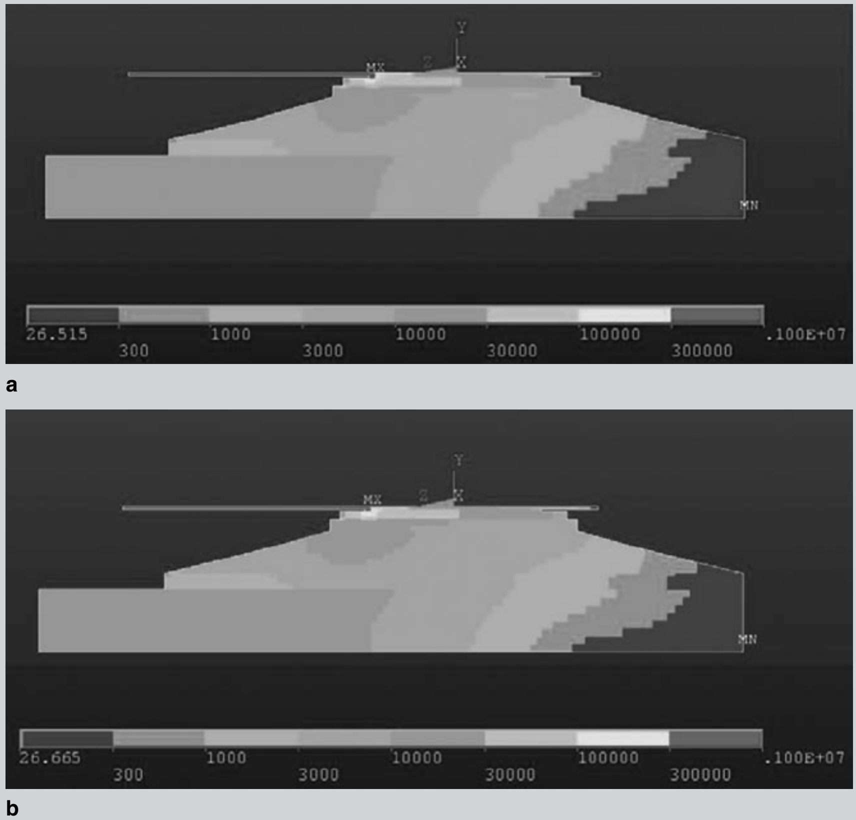

Figure 5. Simulation results showing the current-density distributions for the solder bumps pre-aged at 170°C for (a) 0 h and (b) 25 h. No obvious difference in current distribution was found due to the variation in the thickness of the nickel and the IMC layers.

tion, the UBM structure became denser after the pre-aging process. As mentioned previously, the consumption of the nickel layer plays a crucial role in the electromigration failure. The denser UBM structure may lead to slower consumption rates of the nickel and the copper layers. Thus, proper annealing treatment is able to enhance electromigration resistance by about three times.

On the other hand, over-aging may consume too much of the nickel UBM and result in a shorter failure time. For the solder bump pre-aged for 50 h, as shown in Figure 1c, the remaining nickel UBM was about 2.1 μm after the annealing treatment. Since the nickel layer serves as a diffusion barrier for the copper UBM, the electromigration lifetime may decrease when the nickel UBM becomes too thin. Therefore, the average failure time dropped to 238 h for the solder bumps pre-aged for 50 h.

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Po-Chun Yang is a corporal with the military police of Taiwan, Chien-Chih Kuo is a master student and Chih Chen is a professor in the Department of Materials Science and Engineering at National Chiao Tung University, Hsin-chu 30010, Taiwan, Republic of China. Dr. Chen can be reached at chih@mail.nctu.edu.tw.