



Fast phase transformation due to electromigration of 18 μm microbumps in three-dimensional integrated-circuit integration

Y.W. Chang^a, Chih Chen^{a,*}, T.C. Chang^b, C.J. Zhan^b, J.Y. Juang^b, Annie T. Huang^c

^a Department of Materials Science and Engineering, National Chiao Tung University, Hsin-chu 30010, Taiwan, ROC

^b Introduction of Electronics & Optoelectronics Research Laboratories, Industrial Technology Research Institute, Hsinchu, 31040 Taiwan, ROC

^c Research Center for Applied Sciences, Academia Sinica, Taipei, 11529, Taiwan

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ABSTRACT

The electromigration behavior was investigated in 18- μm SnAg microbumps at 150 °C. The monitored resistance increase abruptly soon after the current stressing of $4.6 \times 10^4 \text{ A/cm}^2$ was applied but the resistance rose much slower after a certain period of time. The formation of the high-resistivity Ni_3Sn_4 intermetallic compounds (IMCs) was responsible for the abrupt resistance increase in the beginning of the current stressing. The whole solder joint was transformed into an IMC joint. Because IMC has a higher electromigration resistance than the solder, a much slower increase in resistance was resulted after the solder joint was transformed into IMCs.

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Three-dimensional integrated circuit (3D-IC) has emerged as a critical technology to offer higher performance than traditional flip-chip technology [1,2] with 3D-IC technology, dissimilar Si devices can be stacked vertically with much shorter interconnection lengths. Among different methods, microbumps with a diameter of approximately 20 μm have been adopted as the interconnections between chips, which have the height of about 1/5 and the contact area only 1/25 of a flip-chip joint. Therefore, current density may reach 10^4 A/cm^2 in microbumps, and electromigration (EM) can be a very important reliability issue. In addition, the decrease in bump height to approximately 20 μm makes the volume of a microbump two orders of magnitude less than that of a flip-chip solder joint. Electromigration behavior is expected to be quite different from flip-chip solder joints. However, there are few studies addressing this issue and the failure mechanism is not clear [3,4].

In this study, we performed EM tests on 18 μm microbumps and use Kelvin probe to in-situ monitor the resistance change during EM test. We found that the resistance was increased rapidly in the beginning of the current stressing, but slowed down after a certain stressing time. Microstructure analysis indicated that the microbump was transformed completely into an intermetallic (IMC) joint at this stage. Electromigration failure was investigated and possible failure mechanism was proposed.

Microbumps of SnAg2.5 with Cu/Ni under-bump-metallization (UBM) were selected for EM tests. The UBM was consisted of 100-nm-thick Ti adhesion layer, 300-nm-thick Cu seed layer, 5- μm -

thick electroplated Cu and 3- μm -thick electroplated Ni layer on both Si chip and Si interposer sides as shown schematically in Fig. 1(a). The diameter of the microbump is 18 μm and the pitch is 60 μm . On the Si chip side, SnAg2.5 solder was electroplated on the Ni UBM, and the chip was bonded to a Si interposer by thermo-compression at 280 °C. Fig. 1(b) shows that the fabricated microbump has a solder height of 6.2 μm , and the Ni_3Sn_4 IMC of about 1.0 μm thickness was formed on both the top and the bottom interfaces. Yet the total thickness of the UBM layers is approximately 19 μm , thus, the volume of the UBM is larger than that of the solder. This difference between a traditional flip chip solder joint and a microbump is expected to affect EM behavior in the microbump significantly.

A Kelvin bump structure was designed in the EM layout to monitor the resistance change of a single microbump during EM tests [5]. A current of 0.12 A, or a nominal current density of $4.6 \times 10^4 \text{ A/cm}^2$, was applied to a pair of microbumps placed on a 150 °C hot plate. After the resistance reached a certain value, the current stressing was terminated and the samples were polished for microstructure analysis using a scanning electron microscope (SEM). Compositional analysis was performed by energy dispersive spectroscopy (EDS).

The transformation of a solder joint into an IMC joint may occur in the very early stage of EM, resulting in an abrupt resistance increase. Fig. 2(a) shows the typical resistance change measured by a Kelvin probe located on the opposite end of the current-feeding Al line. The measured resistance is lower than the real value but this layout can detect the subtle microstructure changes in the joint [6]. The resistance was increased abruptly upon current stressing of 0.12 A at 150 °C. As soon as the measured resistance was increased

* Corresponding author.

E-mail address: chih@mail.nctu.edu.tw (C. Chen).

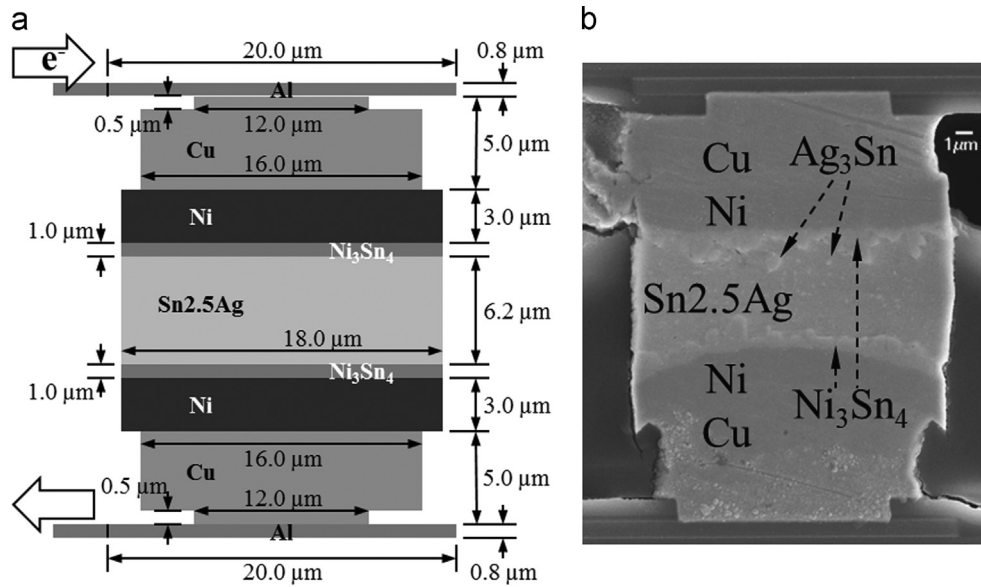


Fig. 1. (a) The schematic drawing on the dimension of the microbump used in this study and (b) cross-sectional SEM image of an as-fabricated microbump.

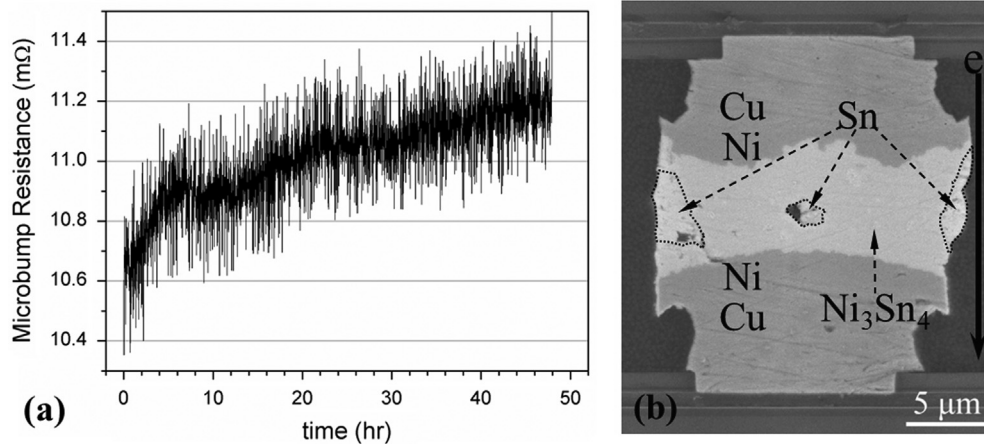


Fig. 2. (a) The monitored resistance of the microbump stressed by 0.12 A at 150 °C up to 47.9 h and (b) cross-sectional SEM image after the current stressing condition in (a) with an upward electron flow.

by 5% from its original value, the test was terminated for microstructure analysis. Fig. 2(b) presents the cross-sectional SEM image of the microstructure for the microbump with an upward electron flow. It is surprising that the whole joint was almost transformed into an IMC joint within 47.9 h. No voids are observed at this stage. Therefore, the resistance increase is mainly attributed to the IMC formation. Upward electron flow caused the dissolution of the bottom Ni UBM and Ni₃Sn₄ IMCs formation. Compositions of the IMCs joint were labeled in Fig. 2(b). Most of the solder had reacted with the Ni to form Ni₃Sn₄ IMCs and only some residual Sn was found in the solder. The microbump with a downward electron flow had similar results except that the top Ni UBM was consumed instead of the bottom Ni UBM.

It is intriguing that the measured resistance was increased rapidly at the very early stage of electromigration and slowed down gradually as the current stressing continued. Fig. 3 presents the monitored resistances as a function of stressing time for a pair of microbumps with opposite current directions. Their resistances were increased by approximately 20% from their original values before the current stressing was terminated at 350 h. The measured initial resistances were 113.5 mΩ and 115.5 mΩ. As shown in Fig. 1(b), the UBM structure is consisted of 5 μm-Cu/3 μm-Ni on both the chip and the interposer side. Therefore, both microbumps may have similar

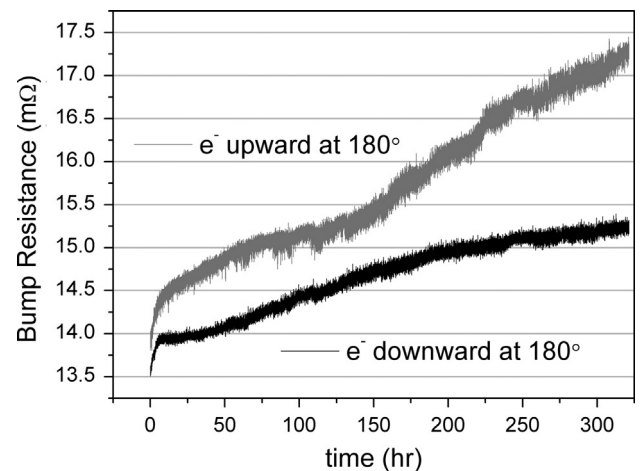


Fig. 3. The measured resistances as function of stressing time for a pair of microbumps stressed by 0.12 A for 350 h with opposite current directions. Their resistances increased approximately 20% of their original values.

electromigration damage. Fig. 4(a) and (b) shows the cross-sectional SEM images for the two microbumps stressed at 0.12 A at 150 °C for

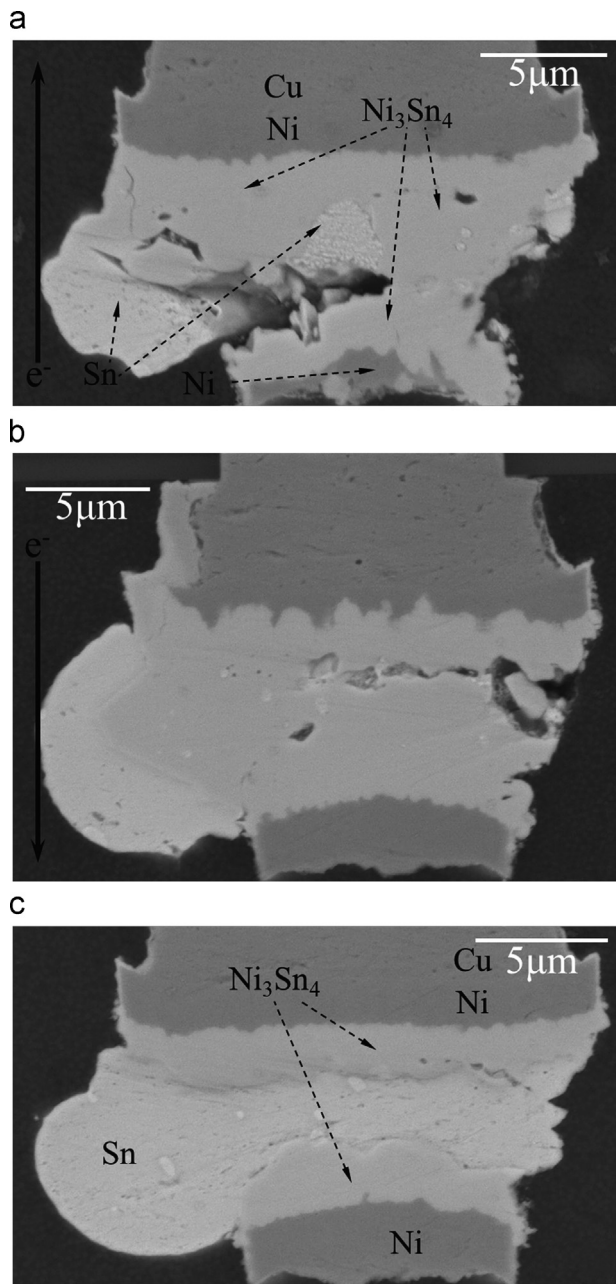


Fig. 4. Cross-sectional SEM images for the microbump stressed at 0.12 A at 150 °C for 350 h (a) with an upward electron flow and (b) with a downward electron flow; (c) cross-sectional SEM images for the microbump without current stressing but with similar thermal history with the microbumps in (a) and (b).

350 h with opposite electron flow. It is interesting that all the SnAg solders have transformed into Cu–Ni–Sn IMCs in both microbumps. In addition, both microbumps had serious EM damages, and some solders were slightly extruded from these bumps. For the microbump with an upward electron flow as shown in Fig. 4(a), the Ni UBM and part of Cu UBM on the bottom side were dissolved into the solder layer to form Cu–Ni–Sn IMCs, and a large void was formed near the original Cu/Ni interface. For the microbump with a downward electron flow as shown in Fig. 4(b), the joint also almost became an IMC joint, and some voids formed at the original upper Ni/ solder interface. As a comparison, Fig. 4(c) shows the cross-sectional SEM image of the microbump without current stressing but with the same thermal history. With a distance of 60 μm from the stressed bump shown in Fig. 4(a), this microbump showed that the thickness of the interfacial IMCs has merely increased from 1.0 μm to 2.1 μm

after thermal annealing. Therefore, the failure of the microbump is mainly attributed due to EM.

In general, Ni reacts with Sn at a very slow rate even in a liquid-state reaction [7]. However, the formation of the Ni_3Sn_4 IMCs appears very fast under current stressing of 0.12 A at 150 °C. This current produces a nominal current density of $4.6 \times 10^4 \text{ A/cm}^2$ in the microbump. As shown in Figs. 2(a) and 3, no incubation time was observed. When Sn reacts with Ni to form Ni_3Sn_4 , the resistance was increased immediately upon current stressing because the resistivity of the Ni_3Sn_4 , $28.0 \mu\Omega\text{-cm}$, is much higher than Sn ($14.0 \mu\Omega\text{-cm}$) and Ni ($6.8 \mu\Omega\text{-cm}$). The IMC formation has a large effect on resistance change. On the other hand, no such effect has been observed in a traditional flip-chip bump. This is due to the reason that the bump height of a typical solder bump is approximately 70–100 μm, and solder serves as the major constitute. When few-micron thick IMCs are formed at the interfaces, no obvious changes in resistance can be detected. On the contrary, the thickness of the solder layer is only several microns in a microbump, and current-assisted interfacial reactions can transform all the solder into IMCs. Therefore, the IMC formation has a big effect on the resistance increase in microbumps. It is expected that the Ni–Sn or Cu–Ni–Sn IMCs have better EM resistance [8] because the IMCs has a higher melting temperature than the SnAg solder [9]. Therefore, the resistance was increased at a much slower rate after the IMCs formation.

In summary, EM behavior has been investigated in 18 μm microbumps with Cu/Ni UBMs that were current stressed by $4.6 \times 10^4 \text{ A/cm}^2$ at 150 °C. The EM behavior is quite different from that of flip-chip bumps. The resistance of a microbump was increased rapidly upon current stressing due to the formation of Ni_3Sn_4 IMCs. Because IMCs have higher EM resistance than SnAg solder, the resistance increase was much slower after the formation of the Ni_3Sn_4 IMCs. The EM failure took place by void formation at the interface of the original Ni/Cu UBM due to fast diffusion of the Cu into the Ni_3Sn_4 IMCs, or at the original Ni/ solder interface, due to flux divergence.

Acknowledgments

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