Microstructure and Property of Sn–37Pb Solder Bumps in Ø0.6 mm Ball during Thermal Shock

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Sn37Pb solder bumps with Ø0.6mm ball were used to conduct thermal shock test, microstructure and property of solder bumps were investigated. The experimental results have shown that the shear strength of solder bumps was 62.89 MPa after reflow, then dropped to between 47.31 MPa and 50.86 MPa with increasing of thermal shock cycles, but finally reached to 61.96 MPa at 2000 cycles again. Interfacial IMCs were typical scallop-type and loose in the solder bumps, but were serrated and become smoother and compact after thermal shock with 1500 cycles. The IMCs thickness of solder bumps was about 1.80~3.05 µm, but the composition of IMCs was Cu₆Sn₅ whether thermal shock or not. 1/25 of solder bumps at 200~1000 cycles, 2/25 of solder bumps at 1500 cycles and 3/25 of solder bumps at 2000 cycles were failure respectively. Obvious tearing crack and fiber tissue was observed in the solder bumps of as-received, and then became large after thermal shock, but dimples of solder bumps deepened after thermal shock at 2000 cycles. [doi:10.2320/matertrans.M2018289]

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1. Introduction

BGA components appeared in the 1990s as the product of advanced high density packaging technology.¹⁾ The size of these BGA components was growing and the number of component leads was following this trend. The higher the number of component lead, the greater the probability of failure.²⁾ Sn–Pb solder has been used for assembling electronics for >50 years due to its good soldering properties.³⁾ With continuous concerning on the toxic of element Pb, Pb-free solder was gradually used to replace traditional Sn–Pb solder.⁴⁾ However, during the transition period from Sn–Pb to Pb-free solder, mixing of Sn–Pb and Pb-free was inevitable occurred in certain products, and in China where Sn–Pb solder was still used extensively in certain areas especially. Correspondingly, understanding reliability of Sn–Pb solder joints was very important, and further studies were needed.

The impact reliability of solder joints has been one of the critical concerns due to the failure of joints in portable electronic products under thermal shock.^{5–9)} Board level test method and component level test method were used to evaluate the impact strength of solder joints under high strain rate condition.^{10,11)} Compared with the board level test method, the impact shear test for the single solder bump was more convenient and economical, and was actively pursued by the industries.^{12–14)} Solder joints provided the mechanical and electrical interconnect between the package and the board in the electronic devices, they were susceptible to failures during thermal shock, but we were probably focusing a lot on Pb-free solder joints and neglecting Sn–Pb solder joints.^{14–16)}

In this study, thermal shock test between –40°C and 125°C was conducted on Sn–37Pb solder bumps in the BGA

package to investigate microstructural evolution and growth mechanism of interfacial IMCs (intermetallic compound) layer. The effects of thermal shock on the mechanical property and fracture behavior of Sn–37Pb solder bumps were discussed.

2. Experimental

The surface of copper coated FR4 board was prepared as shown in Fig. 1. There had 25 pads in each printed circuit board (PCB) which thickness was 1.653 mm. Pad with size of 0.45 mm spaced at approximately 1 mm centers, the thickness of copper plating was 41.2~41.7 µm and the solder mask was 19.6 µm. The resistance of solder bumps was measured by copper wire from the bonding pads at the back in Fig. 2.

10 vol% HCl was smeared on the surface of PCB, and then distilled water and ethanol used to wash and remove residues, finally reoccupied cold wind blow. 25 BGA solder balls of Sn–37Pb with Ø0.6 mm were placed on the pad coated by paste flux, reflow control system of T200N+ was used to determine the reflow profile as shown in Fig. 3. After cooled

Fig. 1 Size of PCB and distribution of pad.

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Fig. 2 Copper wire from the bonding pads at the back.

Fig. 3 Reflow profile and solder bumps.

Fig. 4 Shear directions (the direction of the arrow).

to below 100°C, PCB was washed with cleaning agent and blow-dried.

The resistance of solder bumps was measured by milliohmmmeter with VC480C+ at first, and then thermal shocked with the temperature profile ranged from -55°C to 125°C with 10 min dwell times respectively. The resistance of solder bumps was reexamined using VC480C+ after 200~2000 cycles respectively. The shear strength was performed at room temperature by using a PTR-1102 bond strength tester with shear direction as shown in Fig. 4, and the average shear strength of each parameter was taken from 25 solder bumps.

After sanding and polishing, the specimens were etched in a solution of mixed acids of 3 vol% HNO_3 + 2 vol%

Fig. 5 The morphology of solder bumps at different thermal shock cycles. ((a) solder ball, (b)(g) 0, (c)(h) 200, (d)(i) 500, (e)(j) 1000, (f)(k) 1500, (l) 2000).

HCl + 95 vol% alcohol for 2 s. SEM (ZEISS SUPRA55 scanning electron microscope) was utilized for analysing the interfacial microstructures. The thickness of the interfacial IMCs layer was measured by using Image-pro plus software.

3. Results and Discussion

3.1 Effect of thermal shock cycles on the morphology of solder bumps

As you can see from Fig. 5(a)–(f), Sn-37Pb solder ball composed of Pb-rich phase (α) and Sn-rich phase (β), the distribution was even. Chunks Pb-rich phase (α) were turn out after reflow, most of chunks Pb-rich phase were long shapes after thermal shock, but some were dendrites from the SEM microscopy. At the same time, there were many voids in the solder bumps of as-received in Fig. 5(g), but the number of visible voids increased after thermal shock with 200 and 500 cycles in Fig. 5(h)–(i), and then voids decreased at 1000 cycles in Fig. 5(j). White region was Pb-rich phase and dark region was Sn-rich matrix in the SEM, Pb-rich

Fig. 6 The morphology (a)(b)(c)(d)(e)(f), the thickness (g) and EDX (h) of interfacial IMCs at different thermal shock cycles ((a) 0, (b) 200, (c) 500, (d) 1000, (e) 1500, (f) 2000).

phase (as blips in picture) were short and small in the solder bumps of as-received except chunks Pb-rich phase as mentioned above. Pb-rich phase were coarsened with the increase of thermal shock cycles, but Pb-rich phase became spindly after 2000 cycles.

3.2 Effect of thermal shock cycles on interfacial IMCs of solder bumps

The morphology and thickness of interfacial IMCs at different thermal shock cycles can be seen from Fig. 6. Interfacial IMCs were typical scallop-type and loose in the solder bumps, but IMCs were serrated and become smoother

Fig. 7 Resistance (a) and shear strength (b) of solder bumps at different thermal shock cycles.

and compact after thermal shock with 1500 cycles. The IMCs thickness of solder bumps was $1.80\ \mu\text{m}$ after reflow, was about $2.58\sim 3.05\ \mu\text{m}$ after thermal shock. Kirkendall voids were only observed at the interface between the Cu and IMCs at 1000 cycles and 1500 cycles.

Interfacial IMCs ended in coarsening of Pb-rich phase which occurred near the interface, and covered on the intermetallic interface. This phenomenon was related to the growth of the intermetallic layer at thermal shock. For the growth of the Cu/Sn intermetallic, Sn was consumed from the bulk solder, causing enrichment of Pb close to the interface. The self-diffusion rate of Sn was lower than the boundary diffusion of Pb, an isolation zone of Pb was formed due to the Pb-rich phase skewing on the soldering interface which will hinder the further overgrowth of the IMC layer.^{17–22)}

There were only a platform in the EDX of interfacial IMCs at different thermal shock cycles. The atomic ratio of Sn/Cu both was about 68.1/31.9 after thermal shock with 1500 cycles in Fig. 6(h), the composition of IMCs was Cu_6Sn_5 in Sn/Cu joint by Sn–Cu phase diagram.

3.3 Effect of thermal shock cycles on resistance and shear strength of solder bumps

Resistance change of solder bumps before and after thermal shock were 0.32, 0.79 and 1.56, 2.21 and 2.41 mΩ at 200, 500 and 1000, 1500 and 2000 cycles respectively in Fig. 7(a). The largest of resistance change in all solder bumps were 25.7%, 20.4% and 23.9%, 40.7% and 27.3% respectively. Based on the statistics data, 1/25 of solder bumps at 200~1000 cycles, 2/25 of solder bumps at 1500 cycles and 3/25 of solder bumps at 2000 cycles were failure respectively because the change ratio of resistance was above 20% by IPC/JEDEC-9704A. The variances of resistance were 1.24, 0.95 and 0.85, 3.71 and 3.41 at 200~2000 cycles respectively, so our test results were valid and reliable.

Resistivity of Cu_6Sn_5 and Cu_3Sn were 17.5 and $8.92\ \mu\Omega\cdot\text{cm}$ respectively.¹⁷⁾ Obviously, the resistance of solder bumps increased significantly with the increasing of thickness of IMC layer. At the same time, the resistance of solder bumps increased at first and then decreased at different thermal shock cycles due to changes in number and size of voids. However, the size of $\alpha\text{-Pb}$ phase and $\beta\text{-Sn}$ phase also increased at first and then decreased with increasing of thermal shock cycles, the grain boundary area will reduce

Fig. 8 Fracture morphology of joint at different thermal shock cycles. ((a) 0, (b) 200, (c) 500, (d) 1000, (e) 1500, (f) 2000).

with increasing of grain size which was conducive to reducing the interconnect resistance.

The mean value of shear strength of 25 solder bumps was 62.89 MPa in the solder bumps of as-received in Fig. 7(b), then dropped to between 47.31 MPa and 50.86 MPa with the increase of thermal shock cycles, the sharpest contraction at 200 cycles was 24.77%. Finally the shear strength reached to 61.96 MPa at 2000 cycles. With the increase of thermal shock cycles, Pb-rich phase was coarsened and voids increased at first, Pb-rich phase refined and voids decreased secondly. Coarser $\alpha\text{-Pb}$ and voids made the solders more prone to breakage. However, finer $\alpha\text{-Pb}$ can improve the shear strength of solder bumps, for example the solder bumps at 0 and 2000 cycles.

Fracture occurred mainly in solders, the shear fractures of solder bumps were showed in Fig. 8. The fracture presented the parabolic dimple, and its orientation was the same with the shear orientation. Obvious tearing crack and fiber tissue

was observed in the solder bumps of as-received. Tearing crack became large after thermal shock, but dimples of solder bumps deepened after thermal shock with 2000 cycles.

4. Conclusions

- (1) With the increase of thermal shock cycles, Pb-rich phase was coarsened and the voids increased at first, Pb-rich phase refined and voids decreased secondly. The shear strength of solder bumps was 62.89 MPa after reflow, then dropped to between 47.31 MPa and 50.86 MPa with the increase of thermal shock cycles, but reached to 61.96 MPa at 2000 cycles again.
- (2) Interfacial IMCs were typical scallop-type and loose in the solder bumps, but were serrated and become smoother and compact after thermal shock with 1500 cycles. Kirkendall voids were only observed at the interface at 1000 cycles and 1500 cycles. The IMCs thickness of solder bumps of as-received was 1.80 μm , and was about 2.58~3.05 μm after thermal shock, but the composition of IMCs was Cu_6Sn_5 whether thermal shock or not.
- (3) 1/25 of solder bumps at 200~1000 cycles, 2/25 of solder bumps at 1500 cycles and 3/25 of solder bumps at 2000 cycles were failure respectively. Obvious tearing crack and fiber tissue was observed in the solder bumps of as-received. Tearing crack became thick after thermal shock, but dimples of solder bumps deepened after thermal shock with 2000 cycles.

Acknowledgments

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