Reliability and failure analysis of fine copper wire bonds encapsulated with commercial epoxy molding compound

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Abstract

The small outline transistor (SOT) devices which were interconnected with 20 μm copper bonding wire and encapsulated with commercial epoxy molding compound (EMC) have been used in a series of reliability tests which including the thermal shock test, the electrical service life test, and the isothermal ter-diffusion, IMC growth, and heat generation is cyclic and continuous throughout the life of the electronic device. The effects of Cu/Al IMC on the reliability of Cu/Al bond were well investigated [7,9–12]. Cu9Al4, CuAl, and CuAl2 were the possible IMC phases at the Cu/Al bonds if the aging temperature was at the range of 150–300 °C. With the evolution the IMCs, the cracks would occurred between the IMC layers and the Cu bond. However, only the thick copper wires (more than 30 μm in diameter) were used in their studies. The reliability information of fine copper wire bonding is lacking up to now. Onuki et al. [9] has also investigated the influence of the Br– and Cl– on the reliability of Cu/Al bonds. In their study, they put the Cu/Al bonds with the resin powder which contained high concentration of Br– and Cl– together during isothermal aging. It was found that the influence from Br– and Cl– on the reliability of Cu/Al bonds were negligible. Temperature cycling, operating life and pressure temperature humidity under bias (PTHB) have been performed on the Cu/Al bonds and Au/Al bonds [15]. The testing results have confirmed that Cu/Al bonds had much better reliability than Au/Al bonds. However, no detail information about the IMC formation or crack evolution at the bonding interface was involved.

1. Introduction

Copper wire bonding, as its low-cost, excellent mechanical, and electrical characteristics, has been used in many high-speed, power management devices and fine-pitch applications [1–3]. Some literatures [4–12] have reported the reliability information of the Cu/Al bonds at different testing conditions. However, there is only limited reliability information about the fine copper wire bonding with commercial EMC encapsulation. It was reported that thermal decomposition of epoxy molding compound resulted in generation of halogens or halogen-containing molecules cleaved from the epoxy resin or flame retardant and their diffusion reaction with Au/Al bonds. Corrosive reaction of the halogen molecules with Au/Al IMCs would weaken the bonds mechanically [13,14]. As Au is an inert metal, normally Au wire and Au bond will not react with the halogens or halogen-containing molecules. Compared with Au, Cu is more active. Hence, Cu wire and Cu bond have great possibility to react with the halogen molecules. Unfortunately, the report on this issue is very limited.

Another reliability issue is the growth of Cu/Al intermetallic compound (IMC) at the interface between the copper ball and the aluminum pad. Some degree of IMC formation is believed to be necessary to meet the strength requirement of bonds. However, as the IMCs always having high electrical resistances, the bonds with more IMCs will generate more heat at the bonding interface during operation and then generate more IMCs as a consequence. The process of inter-diffusion, IMC growth, and heat generation is cyclic and continuous throughout the life of the electronic device. The effects of Cu/Al IMC on the reliability of Cu/Al bond were well investigated [7,9–12]. Cu9Al4, CuAl, and CuAl2 were the possible IMC phases at the Cu/Al bonds if the aging temperature was at the range of 150–300 °C. With the evolution the IMCs, the cracks would occurred between the IMC layers and the Cu bond. However, only the thick copper wires (more than 30 μm in diameter) were used in their studies. The reliability information of fine copper wire bonding is lacking up to now. Onuki et al. [9] has also investigated the influence of the Br– and Cl– on the reliability of Cu/Al bonds. In their study, they put the Cu/Al bonds with the resin powder which contained high concentration of Br– and Cl– together during isothermal aging. It was found that the influence from Br– and Cl– on the reliability of Cu/Al bonds were negligible. Temperature cycling, operating life and pressure temperature humidity under bias (PTHB) have been performed on the Cu/Al bonds and Au/Al bonds [15]. The testing results have confirmed that Cu/Al bonds had much better reliability than Au/Al bonds. However, no detail information about the IMC formation or crack evolution at the bonding interface was involved.

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In this study, the IMC formation and cracks evolution process at the Cu/Al bonds which were made with 20 μm fine copper bonding wire and encapsulated with commercial EMC were investigated with thermal shock test, electrical service life test, and isothermal...
aging test, respectively. The failure analysis was also carried out to investigate the reaction between Sb (which was released from EMC at high temperature) and Cu bonds and Cu wires during high temperature isothermal aging process.

2. Experimental

The SOT device with fine copper wire bonding interconnection was encapsulated with a popular commercial EMC, as schematically shown in Fig. 1. The 20 µm (0.8 mil) diameter copper wire of 99.99 wt.% purity, with an elongation range of 7–13% and a break load range of 6–10 gf was used for the wire bonding process. The copper balls were bonded on the Al metallization pad with a thickness of 3 µm and the wedge bonds were bonded on the Ag lead-frame fingers using an ASM Eagle 60 wire bonder. The ball bonding were performed with a ultrasonic power of 65 mA, a bonding force of 30 gf for 6 ms with a substrate temperature of 220°C. The wedge bonds were preformed with a ultrasonic power of 85 mA, a bonding force of 50 gf for 10 ms. To prevent oxidation during the Cu FAB formation, 95% N₂ + 5% H₂ shielding gas was maintained at a flow rate of 0.6 l/min. The used EMC which contains small amounts (tens of ppm) of Sb₂O₃ and other bromides (act as the flame retardants) was used for the electronic encapsulation.

The SOT devices passed electrical function test were carried out the thermal shock test in a Espec TSG-71L thermal shock chamber. To meet the service specification required by a customer, the temperature range was set to be –50 to 150°C. The ramp rate was 20 °C/min and the dwell times at each extreme temperature were 10 min. The duration for each cycle was 0.5 h.

Electrical service life tests were also performed on the SOT devices. The rated power for SOT device was 150 mW and the reverse breakdown voltage was 50 V. The operation voltage used in the electrical service life test was selected to be 70% of the reverse breakdown voltage, 35 V. The operation power was 1.2 times of the rated power, 180 mW. In other word, the expected operation current would be 180 mW/35 V = 5.1 mA. When the detected operation current was less than 80% of the expected value, the device was judged to be failed. The test equipment was an ELEC-V multifunction burn-in system.

The isothermal aging test for the SOT devices were carried out at different temperatures of 150°C, 175°C, and 200°C up to 25 days, respectively, and at 250°C up to 49 h. The aged SOT devices were cooled down in air and then were mounted in epoxy resin. For metallographic inspection, the samples were first ground with various grits of SiC papers and then polished with 3 µm and 1 µm grit diamond pastes and fine polished with 0.5 µm diamond suspension. HITACHI S-4700 SEM with an energy dispersive X-ray spectroscopy (EDX) was used to identify the IMC phases.

3. Results and discussion

3.1. Thermal shock test

After up to 1500 cycles thermal shock test, all the SOT devices have passed the electrical operation examination, which means all the tested Cu bonds still have acceptable reliable bonding with Al pads. Fig. 2 showed the SEM pictures of the cross-sectional Cu/Al bonds after thermal shock test with different test cycles. All the Cu/Al bonds had tight bonding interfaces and no visible crack or void

![SEM pictures of Cu/Al bond cross-section after electrical service life test with: (a) 500 h, (b) 800 h, and (c) 1000 h.](attachment:image.png)
was observed in the bonding interface. Isolated IMC spots were found in the Cu/Al interface, as shown in Fig. 2a–d. It was reported [6,10–12] that there was no visible IMC formed in the as-bonded Cu/Al bonds. Hence, the isolated IMC spots were supposed to be formed during the thermal shock test. With an elevated temperature, the inter-diffusion between Cu and Al was accelerated and then small amount of IMCs started to be formed in the bond periphery. The IMCs formation at Cu/Al bonds was well dependent on the time and the temperature [7]. However, with a rapid alternating temperature, the elapsed time of the Cu/Al bonds at a relative high temperature during the thermal shock test was too short to form more IMCs. As a consequence, no layered IMCs was formed between Cu bond and Al metallization pad. As there was only a few brittle IMCs formed in the bonding interface, the stress arose from the environmental temperature change was limited and the Cu/Al interface kept its interface continuity. It was also indicated that low Cu/Al IMCs growth rate would bring high thermal shock resistance. Compared to the Au/Al bonds, Cu/Al bonds were believed to have higher thermal stability.

3.2. Electrical service life test

After up to 1000 h electrical service life test, all the SOT devices have passed the electrical operation examination. Fig. 3 showed the SEM pictures of the cross-sectional Cu/Al bonds after electrical service life test with different operation times. After 500 h electrical operation, the isolated IMC spots started to occur at the Cu/Al bonds interface. With more operation time, more IMC spots formed. When the electrical operation time was up to 1000 h, the

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Fig. 4. SEM pictures of Cu/Al bond cross-sections at 150 °C: (a) 1 day, (b) 4 days, (c) 9 days, (d) 16 days, and (e) 25 days.
sizes of the IMC spots were about 0.5 μm. No layered IMC was observed.

The electronic device will generate heat during operation. The generated heat will be beneficial for the inter-diffusion of Cu/Al and the Cu/Al IMCs growth rate will be accelerated as a consequence. Fortunately, the Cu/Al IMCs growth was relative slow during operation, as indicated in Fig. 3. Low IMC growth brings low contact electrical resistance at the bond interface and less heat will be generated there. Such a positive process cycle will prevent the degradation in electrical performances and extend the device service life.

3.3. Isothermal aging test

3.3.1. 150 °C and 175 °C isothermal aging

The growth behaviors of Cu/Al IMCs aged at 150 °C and 175 °C were similar, as shown in Figs. 4 and 5. Compared that at 150 °C, the IMCs growth rate at 175 °C was higher.

At both aging temperatures, the Cu/Al inter-diffusion was insufficient to form obvious IMCs at the early stages, as shown in Figs. 4a and b and 5a. With longer aging time, more inter-diffusion was accumulated and displayed with a form of IMC formation. As discussed in previous study [10], the bonding tool with a capillary structure brought a special deformation behavior at the Cu/Al bonding interface. The deformation at the bond periphery was more severe than that at the bond center even the optimized bonding parameters were used. The interfacial reaction was apt to happen at the intimate contacted regions priorly [10], the isolated Cu/Al IMC spots occurred at the bond periphery firstly, as shown in Figs. 4c and 5b. The sizes of the IMC spots were less than 1 μm when the aging times were 9 days at 150 °C and 4 days at 175 °C. With the extension of aging time, more new IMC spots formed at different areas and the previous formed IMC spots continued to grow up. The new formed and the grown up IMC spots started to connect with each other, as shown in Figs. 4d and 5c. At 150 °C, even the aging time was up to 25 days, there was no obvious IMC formed at the bond center, as shown in Fig 4e. Therefore, a IMC ring instead of a IMC layer was formed at the Cu bond bottom. At 175 °C, when the aging time was more than 16 days, new IMC spots with the sizes of more than 1 μm were formed at the bond center, as shown in Fig. 5d. After 25 days aging, a consecutive IMC layer was formed at the bonding interface. The layered IMC thickness at the bond periphery was about 1 μm.

3.3.2. 200 °C isothermal aging

Fig. 6 showed the SEM pictures of cross-sectional Cu/Al bonds after different aging times at 200 °C. After 1 day aging, the consec-

![Fig. 5. SEM pictures of Cu/Al bond cross-sections at 175 °C: (a) 1 day, (b) 4 days, (c) 9 days, (d) 16 days, and (e) 25 days.](image-url)
utive IMC layers were formed in the bonding interface. Judging from the different colors, the layered IMCs contained two different IMC layers, which including a thinner layer close to the Cu bond and a thicker one close to the Al pad, as shown in Fig. 6a. The thicknesses of the IMC layers were not uniform as the IMC growth was uneven at different areas. After 4 days aging, three IMC layers were formed, as shown in Fig. 6b. No crack or void was found between the IMC layers and the Cu bond. When the aging time was up to 9 days, a consecutive crack was formed between the IMC layers and the Cu bond. As a result, the Cu bond departed from Al pad and the electrical connection between them was broken completely, as shown in Fig. 6c. Due to the interruption of Cu atomic diffusion admittance, the IMCs gradually transformed to be a single IMC phase as more Al atomics diffused into the IMC layers with enough aging time, as shown in Fig. 6e.

Considering the Cu/Al bond structure and the research results from [7,10], the IMCs in Fig. 6b would be Cu9Al4, CuAl, and CuAl2, respectively (from Cu side to Al side). The final IMC phase which was shown in Fig. 6e would be CuAl2. The EDX analysis has confirmed that the Cu/Al atomic ratio of this IMC phase was 31.5:67.5, which was consistent with the study of [12]. Before the final single IMC phase was formed, there would have more than two IMC phases (but less than three phases) at the interface, as shown in Fig. 6c and d.

Among these three Cu/Al IMCs mentioned above, CuAl2 requires the lowest effective heat of formation (−6.08 kJ/mol/at.) [12] and

![Fig. 6. SEM pictures of Cu/Al bond cross-sections at 200 °C: (a) 1 day, (b) 4 days, (c) 9 days, (d) 16 days, and (e) 25 days.](image-url)
can even form in the as-bonded Cu/Al bond [16]. With more input energy, CuAl would be the second IMC phase as its effective heat of formation is $-5.27$ kJ/mol/at. [12] which is a little bit higher than that of CuAl$_2$ but higher than that of Cu$_9$Al$_4$ ($-3.25$ kJ/mol/at.) [12]. After the formation of CuAl$_2$ and CuAl, the third IMC phase, Cu$_9$Al$_4$, would form in the Cu/Al interface. However, when a crack was formed between the Cu bond and the upper IMC layer, the Cu atomic diffusion admittance was interrupted suddenly. The formed IMCs, CuAl and Cu$_9$Al$_4$, would react with the Al atoms which from the residual Al pad and gradually transformed to be CuAl$_2$.

3.3.3. 250 °C isothermal aging

Fig. 7 showed the SEM pictures of cross-sectional Cu/Al bonds at 250 °C with relative short aging times. With such a high aging temperature, the Cu/Al IMCs quickly formed at the bonding interface even the aging time was only 1 h, as shown in Fig. 7a. When the aging time was up to 4 h, the layered IMCs were formed and the

![Fig. 7. SEM pictures of Cu/Al bond cross-sections at 250 °C: (a) 1 h, (b) 4 h, and (c) 9 h.](image)

![Fig. 8. Reactions between EMC and Cu wire at 250 °C: (a) 16 h, (b) 25 h, (c) 36 h, and (d) 49 h.](image)
The thickness of IMC layers was about 0.5 μm, as shown in Fig. 7b. When the aging time was up to 9 h, Kirkendall voids occurred and the consecutive crack was formed. The thickness of IMC layer was about 1 μm.

When the aging time was more than 9 h, in addition to the Cu bond having been separated from Al pad completely, the elements in EMC started to react with copper wire as well. As shown in Fig. 8a, after 16 h aging, Cu wire was wrapped with a white layer which had a thickness of about 300 nm. With more aging time, the white layer became thick. When the aging time was 25 h, the thickness of the white layer was more than 1 μm. Meantime, the elements from EMC started to react with the inner Cu wire, as shown in Fig. 8b. EDX analysis results suggested that the white layer was composed of Cu and Sb elements. The Sb element was believed to be from the Sb2O3 in EMC. With 36 h aging, the reaction between the inner Cu wire and Sb became more violent. More and more Sb/Cu compound was formed in the Cu wire and occupied the Cu element position. The volume change caused by the formation of new substance severely destroyed the original Cu wire structure. The corroded Cu wire crashed into some pieces, as shown in Fig. 8c. With 49 h aging, Cu wire was completely crashed into pieces. Lots of IMC blocks were formed in Cu wire, as shown in Fig. 8d. EDX analysis showed that the atomic percentage of Sb in the white IMC block was 22–23% [the other element in the IMC block was Cu]. According to the binary phase diagram [17], the possible Cu/Sb IMCs were Cu₄Sb, Cu₃Sb, Cu₁₀Sb₃, and Cu₂Sb. Hence, the white IMC phase was supposed to be Cu₃Sb. The white layer on the wire surface had the same Cu/Sb atomic ratio as that of the white IMC blocks and was believed to be Cu₃Sb as well.

Similar phenomenon has occurred in the Cu bonds, as shown in Fig. 9. After 25 h aging, a white IMC layer has wrapped the Cu bond. Lots of obvious cracks formed between the white layer and the Cu bond, as shown in Fig. 9a. With more aging time, the IMC grew up into the Cu bond. The peripheral structure of the Cu bond became loose. Lots of micro voids were formed on the Cu bond periphery where was involved in the diffusion reaction process, as shown in Fig. 9b. After 49 h aging, Cu bond has been severely corroded. A large amount of IMC was formed in the Cu bond periphery, as shown in Fig. 9c. During cross-sectional sample preparation process, the brittle IMC could be easily broken under the mechanical effect from the grinding tool. Hence, Cu bonds had a great possibility to detach from the sample mounts during grinding process. According to EDX analysis, the main IMC phase in the Cu bond was Cu₃Sb.

The diffusion reaction between EMC and the Cu wire or the Cu bond was not observed when the aging temperature was below 200 °C even with 25 days thermal aging. The possible reason was that the minor elements in EMC, such as Sb, could be significantly decomposed and then reacted with Cu wire and Cu bonds under a temperature of more than 200 °C. It was supposed that there was a threshold temperature which was between 200 and 250 °C for the Sb₂O₃ decomposition in this case. Further study on the mechanism for the minor elements decomposition from EMC is required.

4. Conclusions

In this study, the thermal shock test, the electrical service life test, and the isothermal aging test were performed on the SOT devices which were made with fine copper wire bonding technology and with commercial EMC encapsulation.

After 1500 cycles thermal shock test, no electrical failure was happened. Only some isolated IMC spots were found at the bonding interface during the thermal shock test. No void or crack was observed even after 1500 cycles thermal shock test. It was indicated that Cu/Al bonds had high thermal shock resistance.

The isolated IMC spots were occurred at the Cu/Al bonds interface after 500 h electrical operation, when the electrical operation time was up to 1000 h, the sizes of the IMC spots were about 0.5 μm. No layered IMC was observed during the electrical operation test.

During the isothermal aging test, the IMCs were formed at the bonding interface when the aging temperature was between 150 °C and 250 °C. Micro cracks and Kirkendall voids could be observed if the aging temperature was high enough or the aging time was long enough. When the aging temperature was 250 °C, the minor element, Sb, which was released from EMC, has reacted with the Cu wire and the Cu bond surface. Cu₃Sb was the main product...
of the diffusion reaction. With more aging time, the Cu wire and the Cu bond would keep reacting with Sb until they were crashed into pieces completely.

Acknowledgments

This work has been supported by the National Science Foundation of China (Grant No. 50705021). Authors are grateful to Yuejing High Technology Co., LTD, Guangdong, China, for the financial support and the help of experimental equipments.

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