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Characteristics of Sn-2.5Ag flip chip solder joints under thermal shock test conditions †

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Abstract

The interfacial reaction between Cu pad coated with Au/Ni and solder bump of flip chip package, using Sn97.5wt.%-Ag2.5wt%, was studied under thermal shock stress. All joints were subjected to thermal shock test with -65℃/+150℃ temperature range. For the Sn-2.5Ag solder, a scallop-like $(Cu,Ni)_6Sn_5$ intermetallic compound was formed in the solder matrix after 20 cycles of thermal shock. $(Cu,Ni)_6Sn_5$ was detached from the interface as $(Ni,Cu)_3Sn_4$ grew underneath the $(Cu,Ni)_6Sn_5$ IMC(Intermetallic Compound), whereas the elements of Sn, Ni and Cu were moved by interdiffusion at the interface between solder alloy and Cu pad. The composition of the IMCs in the solder joints and elemental distribution across the joint interfaces were quantitatively measured with EPMA (electron probe micro analysis). Finally, it was found that the crack initiation point and its propagation path could be influenced by the thermal shock conditions, two underfills, and their properties.

Keywords: Intermetallic compound; Lead-free solder; Flip chip; Reliability

1. Introduction

The rapid development of electronic devices requires highly integrated and reliable IC packaging systems such as ball grid array (BGA), chip scale package (CSP) and flip chip [1,2]. Flip chip technology involves the direct attachment of silicon chip face down onto printed circuit boards (PCBs) by solder joints. Solder joints are very important elements that provide electrical and mechanical connections between chips and PCBs. Solder bumped flip chip technology has many advantages. The short distance of flip chip interconnection provides quite good electrical performance and also has advantages of high density, high I/Os, low coupling noise, and so on. Flip chip interconnections usually experience a wide range of temperature variations during the service life. The differences in coefficient of thermal expansion (CTE) between a chip and a PCB often lead to solder fatigue. In accelerated temperature cycling (ATC) reliability testing, fatigue failure of material and structures occurs due to the initiation and propagation of fatigue fractures under the action of repeated removal and reversal of applied load [3]. Hence, temperature cycling is an important reliability test to predict fatigue life during development of manufacturing processes and the service conditions [4].

Pb-Sn alloys are the dominant solders used in soldering because of good material properties and low cost, and they have been studied extensively for several decades. However, due to the toxicity of lead in the Sn-Pb system solders, the electronics industry has

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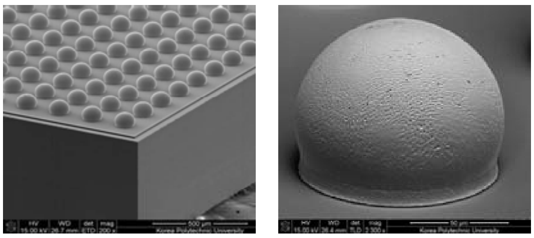
moved to eliminate lead from solder alloys. Among the lead-free solder alloys [5], the Sn-containing binary and ternary alloy solders have been regarded as the most feasible solder alloy for replacing Sn-Pb solders. These lead-free solders are generally Sn-rich solders, which comprise more than 90wt% of Sn. In the case of Sn-rich solders on a Cu substrate, Cu_3Sn and Cu_6Sn_5 intermetallic compounds (IMCs) are formed, and the solder joint reliability is more influenced by the chemical and mechanical properties of Sn compared with that in the case of Sn-Pb solders. The board level reliability is strongly affected by Ag content, especially the bump with Sn-Ag-Cu or Sn-rich (i.e. >90wt%) solders for area array packages such as BGAs and CSPs [6]. Electroplated Sn-3.5Ag solder bumps have been used for flip chip connections, and intermetallic compound formation such as Ag_3Sn in the Sn-Ag solder joints have been found to be one of the main factors to affect reliability [7].

In this paper, the characteristics of Sn-2.5Ag flip chip solder joints were experimentally discussed to examine the microstructure and mechanical properties.

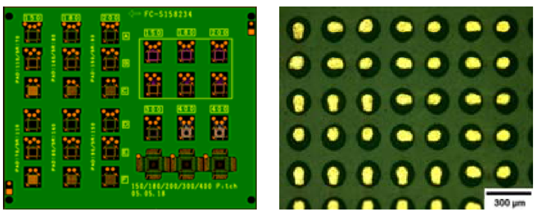
2. Experimental details

Thermal shock testing was performed to investigate the effects of thermal cycling on lead-free (Sn97.5-Ag2.5wt%) flip chip solder bumps.

Fig. 1 shows a 0.2 mm pitch flip chip bump (bump height: 120 μm) with Ti/W under bump metallization



(a)



(b)

Fig. 1. (a) FE-SEM images of a Sn-2.5 Ag solder bump and (b) photographs of the substrate.

(UBM) and electroless Ni immersion gold (ENIG) surface pad finish that were investigated by using Sn-Ag solder.

A schematic diagram for the UBM is shown in Fig. 2. Daisy chained flip chips (5 mm x 5 mm units, 676 I/Os) were used for experiments. The flux used was Alpha 9154Q RMA type and the underfill for the assembly was Henkel Loctite Hysol CUF996-47(underfill 1) and 1050-42(underfill 2).

A separate test board was designed to perform the reliability testing. All pads on the board were non-solder mask defined and their average area, measured by optical microscopy (VHX-100: KEYENCE), was 88.2 x 88.2 μm^2. All boards were of two-sided construction and were made of 1.1 mm thick FR-4 material with OSP surface finish. The solder pads for electronic packages included a metal barrier layer to control the growth of the Cu-Sn intermetallic compounds. In recent years, electroless Ni/immersion Au (ENIG) has been used extensively as a Cu pad coating. The Ni layer is commonly used as barrier layer to Cu diffusion, and it also retards excessive growth of Cu-Sn intermetallic compounds between the solder and the copper. The outermost Au layer provides good wetting and oxidation protection to the underneath layer [8, 9]. Because all the Sn-rich alloys have higher melting point than Sn/Pb eutectic alloy, the reflow temperature is significantly higher when attaching flip chip packages to the substrate, which tends to cause delamination and cracking of packages.

Therefore, reflow soldering was done in a reflow machine which had seven temperature zones to reduce these failures. A number of ATC (accelerated test conditions) are currently used in the industry to evaluate the thermal reliability of solder joints. To evaluate the reliability under thermal shock conditions, the assembled samples were put into the thermal shock test chamber.

Fig. 3 depicts the assembled samples. The thermal shock test was executed according to the JESD22-

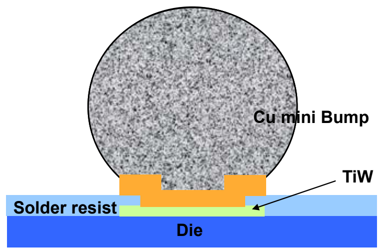
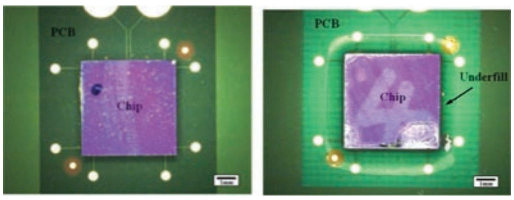


Fig. 2. Schematic diagram of TBGA assembly.

A104C. To emphasize thermomechanical stresses, the condition C (T_s(min)-65℃, T_s(max)+150℃), a short cycle with 15-minite dwell times, and less than 30 second ramp time was chosen as shown in Fig. 4. Testing was done by using an Espec TSE-11-A two-chamber environmental test cabinet. A multi-meter was used to monitor the continuity of electrical signals during the experiment. After completion of the test, cold mount epoxy resin was used to mount samples for mechanical polishing and microstructural observation. Solder was selectively etched with an etching solution consisting of 50 vol.% ortho-nitrophenol 50 vol.% NaOH to reveal the microstructure of the solder joints. The cross-sectioned samples were imaged by a field emission scanning electron microscope (FE-SEM). Element analysis was also done by using energy dispersive X-ray spectroscopy (EDS). Electron probe micro analysis (EPMA) was used for more accurate quantitative analysis.

3. Results and discussion

The flip chip assemblies experienced thermal strain due to CTE mismatch between the flip chip and PCB. To not only improve adhesion force but also release thermal strain at the interface between a Si chip and Cu pads, underfill materials could be used and they



(a) (b)

Fig. 3. Photograph of assembled samples (a) without underfill and (b) with underfill.

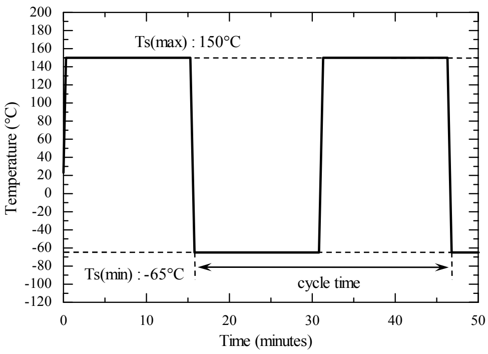


Fig. 4. Temperature profile for thermal shock test.

play the role of relaxing the thermal stresses between the interface and the base materials [2, 10].

Fig. 5 compares the solder joint lifetimes without underfill and with two different underfill materials. Without underfill, the average lifetime of a solder joint was determined to be 15 to 20 thermal shock cycles, while with underfill(1) and underfill(2), the lifetime was much higher: 1,700 and 3,000 cycles, respectively. For underfills, no delamination was detected immediately after a number of thermal shock test cycles. It means underfill materials could play an important role in releasing thermal stress between interface and base materials; besides, life cycles could be affected by kinds of underfills as well as their properties. Generally, the board level reliability with underfill can be improved as the elastic modulus of underfill increases and CTE of underfill closes to the solder joint. With these optimized properties, improvements of the solder joint life time from 5 times to 20 times or even higher have been demonstrated [11, 12]. The chip constraint with underfill is enhanced, thus reducing shear on the solder joints, and the added gluing surface also reduces the tendency of the chip to curl [13]. Therefore, the board level reliability with underfill can be improved by at least these factors.

Fig. 6 illustrates FE-SEM images of solder joints without underfill after 20 cycles and with underfill after 3000 cycles. During thermal shock testing, the flip chip assemblies experienced thermal strain due to CTE mismatch between the flip chip and PCB. The CTE mismatch caused thermomechanical fatigue and creep and microstructural coarsening. Cracks were initiated very close to the solder/IMC interface, and they propagated through the solder interconnect.

The hardness and elastic modulus of the IMCs formed at the interface are known to be higher than those of the SnAgCu solder alloy [14, 15]. Therefore,

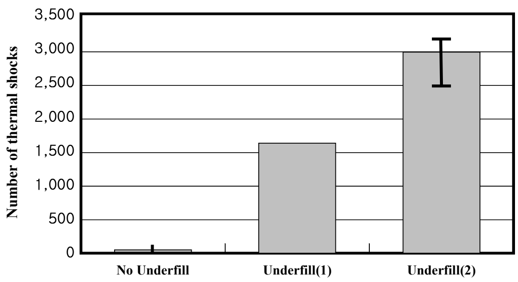


Fig. 5. Summary of average solder joint life times with and without underfill.

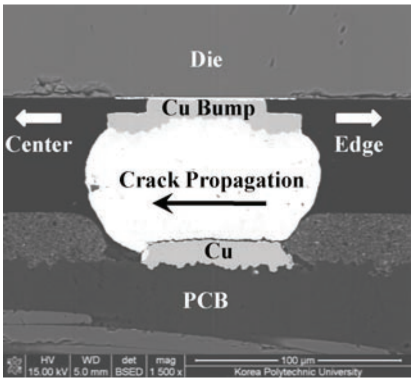
the weakest link in the joint and the location of failure was the solder material. As shown in Fig 6(b), crack initiation could be observed at the edge of the solder joint. In thermal cycling reliability testing, stress concentration usually occurs at the edge (especially at the outermost edge) of the solder joint. The solder joints are sealed hermetically from the environment by underfill material. Therefore, the lifetime of solder joint with underfill can be improved, as the avoidance of oxidation at the crack tip retards crack growth. Also, with an elastic modulus close to that of solder, the underfill forms a quasi-continuum with the solder joints, thus reducing the stress riser associated with the sharp angle made by the joint profile at the chip and substrate interfaces [13].

Figs. 6(a) and 6(b) compare different crack modes between IMCs and pads for joints without underfill and with underfill material.

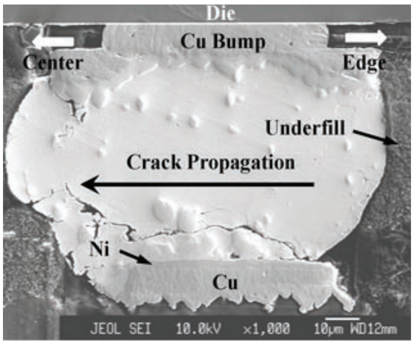
A crack was initiated at the interface between IMCs and Ni layer in both cases, but propagation was along the solder-pad interface when no underfill was used. It might be explained by early failure from the thermal shock test due to harsh condition. The flip chip solder joint undergoes nonisothermal aging during thermal shock testing, and the stress could be relaxed by the formation of an intermetallic compound layer. Hence, the interfacial reaction at the solder bump was analyzed. Figs. 7 and 8 show FE-SEM images of the interfacial reactions between electroplated Ni/Au/Cu pad and Sn-2.5Ag bump after 20 cycles and 3000 thermal shock cycles.

According to earlier researchers [14-16], the topmost Au layer dissolves into the solder immediately during the reflow soldering, forming a randomly distributed $AuSn_4$ compound. The intermetallics formed at the Sn/Cu interface are Cu_6Sn_5 and Cu_3Sn. During reflow, Ni diffused into the liquid Sn-Ag solder and interfacial reactions between Cu and Sn formed the intermetallic compounds $(Cu,Ni)_6Sn_5$ as shown in Figs. 7 and 8 [17, 18].

In addition, the spalling behavior of $(Cu,Ni)_6Sn_5$ and the change of IMCs morphology from a columnar type to a planar type could be observed as shown in



(a)



(b)

Fig. 6. Cross-sectional views of a solder joint (a) without underfill (20 cycles) and (b) with underfill (3000 cycles).

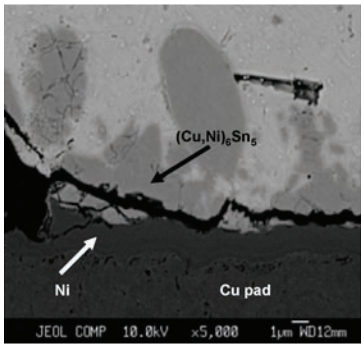


Fig. 7. Cross-sectional view at the solder bump/pad after thermal shock 20 cycles.

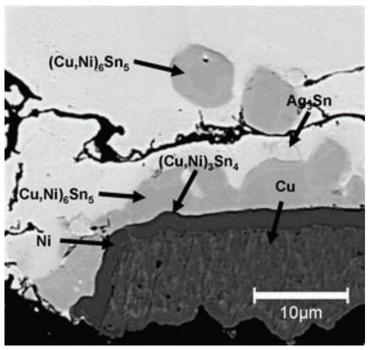


Fig. 8. Cross-sectional view at the solder bump/pad after thermal shock 3000 cycles.

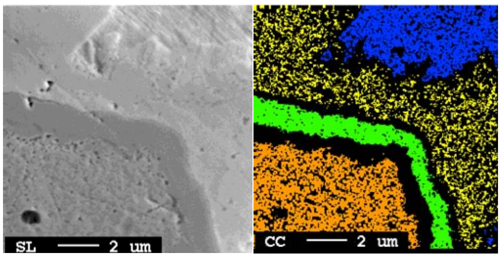


Fig. 9. EPMA element mapping of the Sn-2.5Ag solder joint after thermal shock 20 cycles.

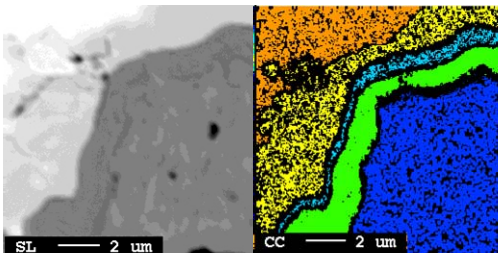


Fig. 10. EPMA element mapping of the Sn-2.5Ag solder joint after thermal shock 3000cycles.

Fig. 8. These spheroid grains, which are driven by lower surface and interfacial energies in conservative ripening, can detach easily from its UBM and migrate into the solder [19]. Because of high cyclic shear stresses and strains induced during thermal cycling, together with the transformation of these spheroids, the $(Cu,Ni)_6Sn_5$ IMC grains were spalled from the interface easily [20]. For more accurate analysis, EPMA was conducted at the solder joint. Fig. 9 and Fig. 10 show EPMA element mapping results of the Sn-2.5Ag solder joint after 20 cycles and 3000 thermal shock cycles, respectively. As shown in the result, the IMCs formed after reflow soldering continue to grow by interdiffusion between the solder and substrate.

In Fig. 10, continued reaction occurred between the Au/Ni/Cu pad and solder during thermal cycling aging. $(Cu,Ni)_6Sn_5$ and Ag_3Sn were formed on the solder side of the interface and $(Ni,Cu)_3Sn_4$ grew between $(Cu,Ni)_6Sn_5$ and the Cu pad. $(Cu,Ni)_6Sn_5$ was detached from the interface as $(Ni,Cu)_3Sn_4$ grew underneath the $(Cu,Ni)_6Sn_5$ IMC. However, after 20 cycles of thermal shock test, the $(Ni,Cu)_3Sn_4$ layer had not grown enough to be observed.

4. Conclusions

The characteristics of Sn-2.5Ag flip chip solder joints were experimentally discussed to examine the microstructure and mechanical properties.

Thermal shock testing was conducted on flip chip solder joints made by using Sn-2.5Ag solder alloy. The Sn-2.5Ag binary solder alloy was reflow soldered onto immersion Au/electroless Ni/Cu pads. The observed failure mode under thermal shock test with underfilled sample was fatigue cracks initiated from the corner of the solder joint at the substrate side. Cracks propagated through the solder bump differently for sample with and without underfill. The different crack mode might be explained by early failure due to the harsh conditions of the thermal shock test. During thermal cycling, continued diffusion and reactions occurred between the Au/Ni/Cu pad and the solder materials. $(Cu,Ni)_6Sn_5$ and Ag_3Sn were formed on the solder side and $(Ni,Cu)_3Sn_4$ grew between $(Cu,Ni)_6Sn_5$ and Cu pad. Spalling behavior of $(Cu,Ni)_6Sn_5$, the columnar morphology of IMCs changed to a planar type, was also observed. Finally, it was found that the crack initiation point and its propagation path could be influenced by thermal shock conditions, two kinds of underfill, and their properties.

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