Highly Reliable Solder ACFs FOB (Flex-on-Board) Interconnection Using Ultrasonic Bonding

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(Received March 19, 2015: Corrected March 25, 2015: Accepted March 27, 2015)

Abstract: In this study, in order to improve the reliability of ACF interconnections, solder ACF joints were investigated in terms of solder joint morphology and solder wetting areas, and evaluated the electrical properties of Flex-on-Board (FOB) interconnections. Solder ACF joints with the ultrasonic bonding method showed excellent solder wetting by broken solder oxide layers on solder surfaces compared with solder joints with remaining solder oxide layer bonded by the conventional thermo-compression (TC) bonding method. When higher target temperature was used, Sn58Bi solder joints showed concave shape due to lower degree of cure of resin at solder MP by higher heating rate. ACFs with epoxy resins and SAC305 solders showed lower degree of resin cure at solder MP due to the slow curing rate resulting in concave shaped solder joints. In terms of solder wetting area, solder ACFs with 25-32 µm diameters and 30-40 wt% showed highest wetted solder areas. Solder ACF joints with the concave shape and the highest wetting area showed lower contact resistances and higher reliability in PCT results than conventional ACF joints. These results indicate that solder morphologies and wetting areas of solder ACF joints can be controlled by adjustment of bonding conditions and material properties of solder and polymer resin to improve reliability of ACF joints.

Keywords: Anisotropic conductive film (ACF), Ultrasonic bonding, Solder ball, FOB interconnection, Reliability of electronic packaging

1. Introduction

Anisotropic conductive film (ACF) is a film-type interconnection adhesive material which consists of polymer adhesive resins and randomly dispersed conductive particles. Electrical interconnection is made by the mechanical trapping of conductive balls between two metal electrodes. ACF interconnection has several advantages such as fast bonding time, low bonding temperature, fine-pitch capability, and cost effectiveness.1,2 However, hygroscopic expansion of ACF polymer resin in high temperature and humidity environment may cause expansion of polymer resin, resulting in unstable electrical problems due to the poor contact of trapped conductive balls.3

In order to solve such reliability problems of conventional ACFs, solder ACFs which consist of solder balls instead of conductive metal particles have been introduced. Solder balls in solder ACFs can form solder metallurgical alloy joints at the metal electrodes and show excellent electrical properties compared with conventional metal conductive balls at a harsh environment.4

However, in the solder ACF bonding, the solder oxide layer on solder ball surfaces can prohibit the solder wetting. Therefore, during the bonding process, it was found the ultrasonic vibration can break the solder oxide layer resulting in excellent solder joining. In addition, unlike conventional ACFs where its bonding temperature are purely determined by the curing properties of polymer resin, the bonding temperature for solder ACFs should be determined by considering both curing properties of polymer resin and the melting point of solder, because the wetted solder morphologies on the metal electrodes needs to be achieved. Moreover, high ratio of wetted solder area on a metal electrode is needed for lower solder joint resistances and better reliability.

In this study, solder ACF joints were demonstrated using an ultrasonic bonding method. Solder joint morphologies were investigated at various bonding temperatures, solder types and polymer resin types. In addition, wetted solder areas were observed depending on various solder ball sizes...
and contents. Electrical properties of solder ACF joints were also evaluated in terms of joint contact resistances and reliability compared with conventional ACF joints.

2. Experiments

2.1. Materials preparation

In this study, acrylic resins were used for fast curing. And slow curing epoxy resins were also used to compare solder morphologies depending on the resin type. Two types of solders were used with different solder MP. One is Sn58Bi solder which has the solder MP of 138°C. The other is SAC305 with the solder MP of 217°C. The solder balls were prepared in various sizes of 5-15 μm, 25-32 μm, and 38-45 μm, and the contents of solder balls were selected as 10 wt%, 20 wt%, 30 wt% and 40 wt%. In all cases, 5 wt% of 8 μm diameter Ni particles were added inside solder ACFs as a spacer to maintain a uniform gap between FOB metal electrodes.

The test vehicles were a 1-mm-thick FR-4 printed circuit board (PCB) and a 25-μm-thick polyimide based Flexible PCB (FPC) which had 300 μm and 500 μm pitch Cu patterns with electroless nickel immersion gold (ENIG) metal finish, as shown in Fig. 1.

2.2. ACF bonding process

In this study, an ultrasonic bonding method was used to obtain stable solder metallurgical joint formation. By this bonding method, solder oxide layers of molten solder can be broken by ultrasonic vibration resulting in good wetting of solder balls in ACFs with metal electrodes. Fig. 2 shows the experimental set up of the ultrasonic bonding method. In the ultrasonic bonding process, the bonding pressures were applied simultaneously with 40 kHz ultrasonic vibration and the ACF temperature was controlled by controlling ultrasonic amplitude up to 12 μm.5) ACF joints were bonded with bonding temperature of 200°C and 250°C with bonding pressure of 2 MPa and bonding time of 9 seconds were used. In order to compare reliability of solder ACFs, conventional ACF joints were also bonded at 200°C and 2 MPa with same bonding time.

2.3. Observation of soldering behaviors

The effects of ultrasonic vibration on solder oxide layer removal were investigated using a transmission electron spectroscopy (TEM) analysis. The presence of solder oxide layers after heating at higher temperature than solder melting point (M.P) was observed using 400 μm diameter solder balls without resins. One of solders was heated without ultrasonic vibration on the hot plate and then, the surface was observed. The other solder was heated with ultrasonic vibration applied during the heating.

Cross sectional analysis was used by a Scanning Electron Microscope (SEM) to observe solder morphologies. In the Sn58Bi solders, there were two phases, a Sn rich phase and a Bi rich phase. After solders were wetted on the electrodes, Au can be diffused from ENIG finish on Cu pads to Sn rich phases in Solders. As another method to quantify the degree of solder ball wetting, the contents of Au ele-
ments in Sn rich phase of wetted solders were also measured using an energy dispersive spectrometer (EDS) by spot analysis. Stress concentration region was also investigated. Stress concentration in solder ACF joints is related with lengths and radius of curvature at the stress concentration region of solder joints as shown in Fig. 3.6)

Amount of solder balls on electrodes was investigated depending on the solder ball size and contents. In order to compare the effect of wetted solder areas with specific values, the cover ratio, wetted solder areas per a whole electrode area was calculated. The FPCs were peeled from PCBs after FOB bonding, and then cured epoxy resin was removed by an acetone solvent. And the wetted solder areas and the whole electrode area of PCBs were measured by image processing software.

2.4. Electrical test & Pressure cooker test (PCT)
To evaluate electrical properties of ACF joints, contact resistances of ACF joints were measured. Fig. 4 shows the 4-point probe method used for single ACF joint contact resistance measurement. For the reliability evaluation of the solder ACF joints, PCT tests were performed at 121°C, 2 atm and 100%RH, and the joint contact resistances were observed during the tests.

3. Results and Discussion

3.1. Demonstration of solder ACF joints using an ultrasonic bonding

Fig. 5 shows the effects of ultrasonic vibration on the solder oxide layers after solders were heated above the solder melting temperature and then cooled. As shown in Fig. 5(a), when a solder was melted without ultrasonic vibration, continuous 10 nm thick solder oxide layer remained on the surface of the solder. However, when ultrasonic vibration was applied after solder melting, non-continuous solder oxide layer was observed as shown in Fig. 5(b) because ultrasonic vibration broke the oxide layer of the molten solder ball. The results mean that ultrasonic vibration is needed for the solder ACF bonding to make wetted solder ACF joints by breaking solder oxide layers.

Fig. 6 shows the solder ACF joints depending on the bonding methods. Solder ACF joints bonded with conventional TC bonding without ultrasonic vibration showed almost non-wetted solders as shown in Fig. 6(a), because solder oxide layer remained between the solder balls and
electrodes at the TC bonding. However, when ultrasonic vibration was applied during bonding process, solders were completely wetted on the ENIG electrodes as shown in Fig. 6(b), because solder oxide layer was completely broken by ultrasonic vibration as explained by the Fig. 5(b). The results indicate that solder balls can be completely wetted on the electrodes by the ultrasonic vibration applied to the molted solder ball.

In EDS analysis, Au contents diffused from ENIG finish of electrodes to solder balls were measured depending on the two bonding methods as shown in Fig. 7. The Au contents of solder balls bonded with ultrasonic bonding was about 12 atomic%, which was about three times higher than those bonded with the TC bonding without ultrasonic vibration. These results confirm that excellent solder wetting was achieved at the ultrasonic bonding method.

3.2. Investigation of solder joint morphologies depending on the bonding temperatures, solder ball types and resin types

3.2.1. Bonding temperature effects

Fig. 8 shows Sn58Bi solder ACF joints bonded at 200°C and 250°C bonding temperatures. The joints bonded at 200°C showed a convex shaped solder, and the solder joints bonded at 250°C showed a concave shape. The result is related to the degree of cure of polymer resin at the solder MP. Fig. 9 shows the ACF temperatures measured during the bonding process and degree of cure of resin at the time when ACF temperature reached at the solder MP. The degree of cure of the polymer resin was measured by Fourier Transform Infrared Spectroscopy (FTIR). The resin around solder at 250°C bonding temperature showed 13% degree of cure. On the other hand, the resin with 200°C bonding temperature showed two times higher degree of cure of resin because ACF temperature with higher bonding temperature reached to solder MP in shorter time. Therefore, the solder joints showed large spreading at the lower degree of resin cure bonded at 250°C temperature. The solder morphologies are related to the stress concentrations as shown in Equation (1) and Fig. 3.

$$\sigma_m = \sigma_0 \left( \frac{a}{\rho t} \right)^{1/2}$$

(1)

$\sigma_m$: Maximum stress surrounding a stress concentration region
$\sigma_0$: Nominal applied tensile stress
$a$: Length of stress concentration region
$\rho t$: Radius of curvature of stress concentration region

These results represent that larger stress could be concentrated at solder joints bonded with the bonding temperature of 200°C compared with those of 250°C due to the smaller radius of curvature of stress concentration region represented at the Equation (1) and Fig. 3. In the equation of stress concentration commonly used, geometry factor consists of length of stress concentration region ($a$) and radius of curvature of the dented region in solder joints ($\rho t$) as shown in Equation (1).

3.2.2. Solder ball types effect

Fig. 10 showed the solder ACF joints with various solder ball types. Bonded at 250°C bonding temperature and 2
MPa bonding pressure. Sn58Bi solder ACF joints showed a concave shape at 250°C bonding temperature as shown in Fig. 10(a). On the other hand, SAC305 solder ACF joints showed a convex shape in Fig. 10(b). It is due to the difference of degree of cure of resin at the solder MP. During bonding process, ACF temperature reached to the MP of Sn58Bi solder within 0.5 second. On the other hand, the ACF temperature reached to the MP of SAC305 within 3 seconds as shown in Fig. 11. Therefore, the degree of cure of resin at the MP of SAC305 solder was about 6 times higher than that at the MP of Sn58Bi solder.

3.2.3. Resin types effect

Fig. 12 represented solder joints depending on the polymer resin types. The joints were bonded with bonding temperature of 250°C using SAC305 solder. Solder joints bonded with an acrylic resin showed a convex shaped solder joint. On the other hand, solder joints bonded with an epoxy resin showed a concave shape because of the slow curing rate of epoxy resin. As shown in Fig. 13, curing onset temperature of epoxy resin is about 20°C higher than that of the acrylic resin. Therefore, the degree of cure of the epoxy resin at the MP of SAC305 was 28% which is more than two times lower than that of the acrylic resin. Because of this reason, the solder joints with the epoxy resin showed a concave shape.

3.3. Investigation of wetted solder areas depending on the solder ball size and contents

The images of wetted solder areas after peeling FPCBs were shown in Fig. 14. In this experiment, the epoxy resins were used. Solder ACF joints with 5-15 μm solder balls size show the smallest and well dispersed wetted solder areas, and solder ACFs with 38-45 μm solder balls size show the largest wetted and agglomerated solder areas. However, solder ACF joints of 25-32 μm solder balls show the best numbers of solder joints and wetted solder areas. Fig. 15 shows the cover ratio of wetted solder areas per a whole metal electrode area as a function of solder ball sizes and contents. Because solder balls in small sizes would flow out of metal electrodes with resin during bonding, 5-15 μm solder ACFs show the lowest cover ratio of wetted solder areas. 25-32 μm solder ACFs show the largest values and 38-45 μm solder ACFs show medians. In the case of 25-32 μm solder ACFs, as the solder ball content increased from 10 wt% to 30 wt%, cover ratios of wetted solder areas also increased, and then from 30 wt% to 40 wt% become saturated. According to the results, extra solder ball would flow out along with the resin, but did not make a contribution to the solder joint when the solder ball content was above 30 wt%. In terms of the cover ratio of

![Fig. 10. Solder ACF joint morphologies with (a) Sn58Bi solders and (b) SAC305 solders at 250°C bonding temperature and 2 MPa bonding pressure.](image1)

![Fig. 11. Actual ACF temperature during the ultrasonic bonding process and the degree of cure of resin at the solder MP depending on two solder types.](image2)

![Fig. 12. Solder ACF joints bonded with (a) acrylic resin and (b) epoxy resin.](image3)

![Fig. 13. DSC analysis depending on the acrylic and epoxy resins.](image4)
wetted solder areas and the saturate effect, ACFs at 25-32 μm sizes of above 30 wt% solder ball content are best candidates for 300-μm-pitch FOB assembly.

Fig. 14. Microscope observation of wetted solder areas as a function of solder ball sizes and contents.

Fig. 15. Cover ratio of wetted solder areas as a function of solder ball sizes and contents.

Fig. 16. Contact resistances of conventional ACFs and solder ACFs.

3.4. Evaluation of joint properties of solder ACFs compared with conventional ACFs

Fig. 17. Contact resistances after PCT tests of (a) conventional ACF joints and (b) solder ACF joints.

Fig. 16 showed contact resistances of a single solder ACF joint. In this experiment, the joints were bonded at 2 MPa and 250°C. The ACFs with epoxy resins and 23-32
solders with 30 wt% contents were used. As shown in the Fig. 16, solder ACF joints showed about 1 mOhm lower than that of conventional ACF joints because of that is the solder ACF joints form metallurgical alloy between electrodes and solders compared with conventional ACFs which showed physical contacts between Ni particles and electrodes.

The joint contact resistances after PCT tests were shown in Fig. 17. Contact resistances of conventional ACF joints increased after 48 hours as shown in Fig. 17(a). And after 120 hours, some joints showed open failures due to poor physical contact of metal conductive particles by hygroscopic expansion of polymer resins. On the other hand, solder joints showed no open failures after 120 hours of PCT tests due to metallurgical joint between solders and electrodes.

4. Conclusions

In this study, solder ACF joints with ultrasonic bonding were demonstrated in FOB assembly. Solder ACF joints with conventional TC bonding showed partially wetted solders on electrodes by remaining solder oxide layers. However, joints bonded with ultrasonic vibration showed excellent solder wetting due to the broken solder oxide layers. It was found that solder joint morphologies and wetted solder areas affect solder joint reliabilities were investigated. In the investigation of solder morphologies, Sn58Bi solder joints bonded at 250°C bonding temperature showed a concave shape resulting in lower stress concentration compared with solder joints bonded at 200°C bonding temperature which showed a convex shape, because lower degree of resin cure at solder MP was obtained at 250°C bonding temperature than that at 200°C bonding temperature. However, in case of SAC305 with acrylic resins, solder joints showed convex shape despite of 250°C bonding temperature due to longer time to reach the solder MP by higher solder MP. In the epoxy resins, SAC305 showed concave shaped solder joints because of lower degree of cure of resin at the solder MP by slow curing rate of resins. In terms of wetted solder areas, the highest wetting areas were shown with 25-32 μm diameter solders and 30-40 wt%. Solder ACF joints with a concave shape and the highest wetting area showed lower contact resistances and higher reliability of ACF joints compared with joints with conventional ACFs. As a summary, excellent PCT reliability results were achieved with solder ACF joints compared with conventional ACF joints.

References