A Study on the Optimization of Anisotropic Conductive Films for Sn-3Ag-0.5Cu-Based Flex-on-Board Application at a 250 °C Bonding Temperature

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Abstract—Although cationic epoxy was optimized for low-melting SnBi58 solder joints with the lowest coefficient of thermal expansion (CTE) in terms of reliability, cationic epoxy also showed a faster curing property than any other types of adhesives. In fact, solder joint shapes at 250 °C bonding are very different from those shapes at 200 °C bonding. In this paper, four adhesive film types were investigated in terms of Sn-3Ag-0.5Cu solder ACF joint shapes on the electrical performances and reliability in a pressure cooker test (PCT). Thermal stability of adhesive films was tested to be first. Resin curing speeds were measured in a 250 °C isothermal mode differential scanning calorimetry, resin viscosities were checked by a parallel-plate rheometer, and adhesive thermomechanical properties, such as modulus and CTE, were characterized. Then, four different types of ACF resins containing the same weight percentages of Sn-3Ag-0.5Cu solders were assembled by the same thermocompression bonding parameter (250 °C 10s 2MPa on bump) on a 500-µm-pitch flex-on-board (FOB) application, and different solder joint morphologies were verified. Various bonded solder ACF joints were compared in terms of solder wetting areas, electrical performances by a four-point-probe method, and the reliability of PCT (121 °C 100% humidity 2atm) for 120 h. This paper aims at optimizing the best adhesive film candidate for SAC305 solder joints of FOB application.

Index Terms—Anisotropic conductive film, high reliability, Sn-3Ag-0.5Cu solder, thermal compression bonding.

I. INTRODUCTION

Anisotropic conductive films (ACFs), which generally consist of thermosetting polymer adhesives and conductive particles, are well-known interconnection materials that have been used to provide the electrical path in the z-direction but insulation in the xy-directions for display applications, such as flex-on-board (FOB), flex-on-flex (FOF), flex-on-glass, chip-on-board, chip-on-flex, and chip-on-glass, due to environment-friendly, low-temperature process, ultrathin assembly, and fine-pitch capability [1]–[5].

There is a trend from assembly industries to use ACF-based FOB and FOF applications to replace conventional socket connectors at various applications [6]. In this regard, solder ACFs, micrometer-size solder particles added to conventional ACFs, are as an excellent solution to generate solder metallurgical joints, resulting in a lower electrical contact resistance and higher current handling capability and better reliability performance [7]–[10]. Therefore, solder metallurgical joint is an essential ACF material to replace the conventional physical contact-based joint using nickel metal balls or metal-coated core polymer balls for FOB and FOF applications.

Solder oxide layer prevents the solder wettability and reliability [11]. To effectively remove the solder oxide layer, it was previously reported that a novel flux function material was added to solder ACFs, using a thermocompression (TC) bonding method in our research group [12]. The effects of thermal swelling and hydroswelling of polymer resins on the reliability performance of the flux function material added Sn58Bi solder ACF joints at 200 °C bonded FOB applications were reported earlier [13]. However, Sn58Bi solder alloy
Fig. 2. Schematic of FOB interconnection using solder ACF joints.

Fig. 3. Schematic of resin flow by bonding pressures and spacer effect of solder joints before melting.

Fig. 4. In situ temperature of SAC305 ACF joints during TC bonding.

Fig. 5. Schematics of ACF thermal decomposition on the joint dimension using a TMA.

Fig. 6. Schematic of solder wetting areas on metal electrodes.

Fig. 7. Contact resistance measurements for solder ACF joints. (a) Four-point probe method. (b) Measured pad areas.

particles with a low-melting temperature (138 °C) may not be a common solder material at assembly’s industries [14]. Therefore, it is necessary to investigate resin properties at a higher bonding temperature for Sn-3Ag-0.5Cu (SAC305) solder ACF joints (melting point 221 °C).

In order to bond SAC305 solder particles, 250 °C ACF joint temperature is needed [15]. Compared with SnBi58 solder...
ACF bonding at 200 °C, thermal decomposition of adhesive films may not be issued. However, thermal stability of adhesive films needs to be concerned for SAC305 solder ACF bonding at 250 °C. Despite that, curing speeds of adhesive resin at 250 °C bonding become significantly higher, and SAC305 solder ACF joint shape at 250 °C bonding will be very different from those at 200 °C bonding.

Although cationic epoxy was optimized for low-melting SnBi58 solder ACF joints with a lowest coefficient of thermal expansion (CTE) in reliability [13], cationic epoxy also showed a faster curing property than any other types of adhesives. Therefore, convex-shaped solder joints at 250 °C bonded cationic epoxy-based adhesives may be a concern for ACF joints reliability. Referring to recent reports, convex solder ACF joints showed worse reliability performances than those of concave solder ACF joints due to poor handling capability to thermal stress from polymer resins and crack formation [14]. However, there has been no literature on reporting either resin properties or solder joint shapes more greatly determining joint reliability so far.

In this paper, the effects of adhesive films types on Sn-3Ag-0.5Cu solder ACF joint shapes on the electrical performances and reliability were investigated for highly reliable flex-on-board assembly. Thermal stability of resins was tested to be first. Resin curing speeds were measured in a 250 °C isothermal mode differential scanning calorimetry (DSC), resin viscosities were checked by a parallel-plate rheometer, and CTE were measured by a thermomechanical analyzer (TMA). Then, four different types of ACF resins containing the same weight percentages of Sn-3Ag-0.5Cu solders were assembled by the same TC bonding parameter (250 °C 10 s 2 MPa on bump) on a 500-μm-pitch FOB application and different solder joint morphologies were formed. Various bonded solder ACF joints were tested in terms of solder wetting areas, electrical performances by a four-point-probe method, and the reliability of pressure cooker test (PCT) (121 °C 100% humidity 2atm) for 120 h. After this paper, the prospective adhesive resin candidate will be selected out for 250 °C bonded FOB SAC305 solder ACF joints, and future research development for solder ACF joints reliability will be decided.

II. EXPERIMENTS

A. Specimen Preparation

Fig. 1 shows a test vehicle in this paper by using a 1000-μm-thick printed circuit board (PCB) and a 60-μm-thick polyimide-based flexible printed circuit (FPC). During a TC bonding, heat conduction is theoretically from top to bottom through this path: hot-bar/FPC/ACF joint/PCB/room temperature metal substrate, but hot bar required setting temperature below 400 °C for longer machine lifetime. Hence, PCB is designed as thick as possible for heat prevention, and FPC is designed as thin as possible for higher ACF joint temperature even at lower hot-bar temperature. For metal electrodes, 500-μm-pitch Cu patterns were treated by electroless nickel immersion gold (ENIG) finish on both PCBs and FPCs sizes. Fig. 2 shows a schematic of bonded FOB interconnection using solder ACF joints.

The 50-μm-thick solder ACFs contained four different kinds of thermosetting polymer resins such as acrylic and epoxies and 30 wt% of 25–32-μm diameter SAC305 solder particles [15]. What is more, 2 wt% flux function additive was added into four typical adhesive resins to remove the solder oxide.

B. Thermocompression Bonding

TC bonding processes were: 1) solder ACFs were prelaminated onto the designed bonding areas of PCB;
2) the electrodes of PCB and FPC were aligned by a vision system; and 3) a rubber interposer was covered on the top of aligned FOB test vehicles to keep uniform pressures on ACF joints and also to prevent resin materials contaminating the bonding tool.

Bonding parameters were fixed at 250 °C for 10 s and 1 MPa. In addition, the bonding pressure was calculated by the bonding force (57N) and the whole bonding areas (3 × 19 mm²). Because the electrode pads are half the amount of total bonding areas, 2 MPa is exactly on the bump. Fig. 3 shows a schematic of resin flow by bonding pressures and solder gap size effect before solder melting. Before temperature reaches solder melting points, solder particles were as a rigid 25–32-µm spacer.

Fig. 4 shows the in situ temperatures of solder ACF joints measured by a K-type thermocouple every 0.1 s during the 250 °C TC bonding. The temperature quickly reached to the SAC305 solder melting temperature of 221 °C at 1.5 s and gradually reached at 250 °C peak temperature.

C. Thermal Stability Analysis

A thermal gravity analysis was used for thermal stability of adhesive resins as a function of temperatures. The uncured adhesive resins were tested at a 100% nitrogen atmosphere by a 10 °C/min temperature heating rates from 30 °C up to 400 °C. The residual weights of adhesive resins during heating were measured.

In addition to confirm whether the thermal decomposition of acrylic resin is related with the TC bonding pressures, a novel experiment by a thermomechanical analysis (TMA) is done in Fig. 5. In this test, the temperature was gradually increased as a 5 °C/min from 30 °C to 250 °C, and the initial ACF thickness was 500 µm. ACF was covered by two ultralow thermal expansion Si substrates, and the TMA sensor tip was initially compressed on their surface by 100-, 300-, and 500-mN forces, and then the tip was released up at 250 °C. As a result, the thermal decomposition on the influence of joint dimension can be detected. The dimensional change ratio was calculated by the following equation [16]:

Dimensional change (%) = \[ \frac{\text{final thickness(µm)} - \text{original thickness(µm)}}{\text{original thickness (µm)}} \] .

D. Resin Curing Speeds and Viscosity

A DSC was performed at 250 °C isothermal mode to measure the curing speeds of four polymer resins. The prepared samples were 20-mg weight for each DSC measurement. In DSC chamber, the target 250 °C temperature was setting, and sample was heated by around 30 °C/s until the target temperature and keeping an isothermal temperature. Resin viscosity was measured at a constant 5 °C/min heating speed between 30 °C and 250 °C under 1000 Pa and 1-Hz frequency rotational sheer stress.

E. Thermomechanical Properties

Thermomechanical properties of four adhesives, especially for storage modulus and CTE, were measured using a TMA. A cured adhesive film with dimension of 10 mm length, 2.5 mm width, and 50 µm thickness was measured by a constant tensile strain force of 50 mN with a temperature heating rate of 5 °C/min from 30 °C to 200 °C. Except 50 mN tensile force, storage modulus was tested by adding 0.1-Hz 10-mN sinusoidal load, and CTE was without the additional force. The dimensional changes of the prepared adhesive film can be recorded, and the thermal expansion ratio can be obtained by dimensional changes divided by the initial 10-mm length.
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Fig. 10. Curing speeds of four adhesive resins in a 250 °C isothermal DSC mode.

F. Joint Morphologies and Solder Wetting Areas

Solder ACF joint morphologies, such as gap sizes and solder joint shapes, were observed by scanning electron microscopy (SEM) cross-sectional images. Resin delamination and solder joint crack were also checked to examine resin interconnection on an ENIG metal surface. Solder wetting areas were also observed by an optical microscope after peeling FPC substrates.

The wetting of the solder is most likely caused by the surface tension of the solder to the pad. Wetted solder areas per a whole electrode area in the following equation were calculated:

\[
\text{Cover ratio of wetted solder} = \frac{\text{wetted solder area}}{\text{electrode area}}.
\]

1) The FPCs were peeled from bonded FOB; 2) cured epoxy resins were mechanically and chemically removed by acetone and cleaning; and 3) the wetted solder areas and the whole electrode area of PCBs were measured by an image processing software, as in the schematic in Fig. 6.

G. Joint Resistance

Solder ACF joint contact resistance was measured by a four-point probe method, as shown in Fig. 7(a). The designed and measured joint areas are 0.32 mm² in Fig. 7(b). The 25 channels were measured for each type of solder ACF joints.

H. Reliability Test and Failure Analysis

A PCT was used to evaluate SAC305 solder ACF joints reliability using various resin adhesive types at 121 °C, 2 atm, 100% humidity for 120 h. Contact resistance changes of SAC305 solder ACF joints were measured for every 24 h, and the solder joint morphologies were also observed before and after the PCT test for failure analysis.

III. RESULTS AND DISCUSSION

A. Thermal Stability of Polymer Resins

Fig. 8 shows the weight loss of four uncured fresh polymer resins as a function of temperature from 30 °C to 400 °C. Although 95.7% weight was the lowest value for acrylic resins at 250 °C, thermal stabilities of four resins were good for 250 °C assembly. As temperature increased to 150 °C, the weight loss of ACFs was from the evaporation of residual solvent in the fresh polymer resins. However, acrylic-based resins showed a higher weight loss rate above 200 °C, which is due to evaporation of some small molecules.

Corresponding to the acrylic void in Fig. 13(a), the TMA measurement for the joint dimension by acrylic decomposition was done. Fig. 9 shows acrylic decomposition occurred at 220 °C, and the acrylic void in Fig. 13(a) was not caused by TC bonding pressures. It was found the dimension change by acrylic decomposition at 220 °C was decreased by increasing the bonding pressures. However, this decomposition is only related with the high temperature over 220 °C. The other three adhesives were not checked because there was less losing weight in Fig. 8 and void-free joint in Fig. 13(b)–(d).

B. Resin Curing Speeds and Viscosities

In Fig. 10, four fresh resins were cured in the temperature heating process in an isothermal mode of 250 °C. The acrylic resin has an earlier but much lower exothermic curing, which indicates lower amount of polymer cross linking. The cationic cured epoxy has a very sharp and high exothermic curing around 175 °C, suggesting that the adhesive has a faster curing. However, both the epoxy and the functional epoxy have delayed and lower exothermic behaviors than those of the cationic epoxy, which means a slower curing speed. In addition, acrylic resin had experienced a thermal decomposition behavior from 200 °C. However, except for acrylic resin, three types of epoxies were completely cured at 221 °C without any severe thermal decomposition behavior.

Fig. 11 illustrates viscosities of four fresh resins as a function of temperatures. Cationic epoxy showed much higher viscosity than other three types of resins over 200 °C because it had two steps of curing reactions: the first and main exothermic reaction of cationic epoxy groups from room temperature to 150 °C; the second curing reaction for further conversion of epoxy groups is from 200 °C to 250 °C [17].

C. Resin Modulus and CTE

Thermomechanical properties of four polymer resins are illustrated in Fig. 12, such as resin storage modulus and CTEs.
There is a clear trend of thermomechanical properties. Cation epoxy > functional epoxy > epoxy > acrylic. Despite a faster curing speeds in Fig. 10 and a higher viscosity over 200 °C in Fig. 14, cationic epoxy also showed a higher $T_g$ (glass transition temperature) and modulus. Thermomechanical property of acrylic resin was poor due to smaller exothermic curing in Fig. 8 and low cross-linking of polymerization reaction.

**D. Solder Joint Morphologies and Wetting Areas**

Fig. 13 shows cross-sectional images of SAC305 solder ACF joints as function of various resin types after bonding. Delamination was observed at acrylic resins, presumably due to small molecule decomposition over 200 °C in Fig. 9(a). It was found that convex solder joint shape was shown at cationic epoxy joints and concave solder joint shapes at other resin joints in Fig. 13.

The shape of the solder on ENIG pad interface is most likely a result of whether the adhesive has reached its gel-point or not, before the solder is melted. The cationic cured epoxy has a very sharp and a high exothermic behavior around 175 °C in Fig. 10, suggesting that the adhesive has a fast curing and therefore cures before the solder melts as shown in Fig. 15. Before solder melting, solder was in a solid state as a function as a 25–32-μm joint spacer in Fig. 3. Solder melting was very rapid and reached a uniform temperature through all solder joint. On the moment of solder melting, solder transitioned into a liquid state and was immediately buried by cured resins. In this regard, acrylic resin on the heated (top) side has cured before the solder has melted. However, due to the very low thermal diffusivity of the thick resin in Fig. 14, there is no
time to wet the bottom surface before the resin is cured. Both the epoxy and the functional epoxy have delayed and lower exothermic behavior than the cationic epoxy, and therefore likely also a slower curing process.

Fig. 16 shows SAC305 solder wetting morphologies on ENIG surface after bonding and peeling PFC substrates. Solder wetting is stopped by using cationic epoxy due to high viscosity at solder melting points, and solder cannot form concave shape to extend wetting areas on metal electrode surfaces. In other three adhesive resins, SAC305 solder joints can wet freely on ENIG surface because of low viscosity at solder melting points.

Fig. 17 shows cover ratios of SAC305 solder wetting areas on whole ENIG metal electrode surfaces. In cases of three resins with low viscosities at SAC305 solder melting point, it showed over 40% covered areas by solder joints. However, cationic epoxy-based solder ACF joints showed half-mount of solder wetting areas by 21.6% due to its convex solder shapes and high viscosity property stopping solder wetting.

E. Contact Resistance

Contact resistance is a way to predict solder ACF interconnection properties after bonding process. Low and excellent stable electrical resistance is needed for solder ACF joints. Joint resistances of SAC305 solder ACFs joints per electrode pad and per mm² electrode pad areas are shown in Fig. 18(a) and (b), respectively. Acrylic-based solder ACF joints showed the largest average resistance of 37.3 mΩ per mm² electrode pad areas and a larger range of tolerance than other polymer resins ACF joints due to damaged solder joint morphology shown in Fig. 13(a). The concave solder joint shape showed 18.1–18.4 mΩ per mm² pad areas; on the other hand, the convex solder joint shape showed around double amount values of 35.1 mΩ per mm² pad areas.

F. Reliability and Failure Analysis

According to the thermomechanical properties of four polymer resins in Fig. 10, CTE mismatch with SAC305 solder joints (21ppm/°C) was reduced in...
Fig. 19. PCT reliability performance of various SAC305 solder ACF joints. The order: cationic epoxy < multifunctional epoxy < conventional epoxy < acrylic resin. Fig. 19 shows the reliability performance of various SAC305 solder ACF joints during five days of PCT evaluation in terms of joint contact resistance. Despite convex solder joint shapes at faster curing cationic epoxies, there is no resistance changing due to an ultralow CTE of cationic adhesive. 20/25 open failures were observed after one day of the PCT test for acrylic-based SAC305 ACF joints. Although concave solder joint shapes were at low curing epoxy and function epoxy-based resins, solder ACF joint reliability was reduced due to poor resin thermomechanical properties. As a summary, resin thermomechanical properties played a more important role in solder ACF joint reliability than the concave solder joint shape. For next step optimization, ultralow CTE is the new research direction for solder ACF applications.

Fig. 20. SEM images of SAC305 ACF joints after five days of PCT. (a) Acrylic base, (b) epoxy, (c) functional epoxy, and (d) cationic epoxy.

Fig. 21. Magnified SEM images of SAC305 ACF joints after five days of PCT. (a) Acrylic base, (b) epoxy, (c) functional epoxy, and (d) cationic epoxy.
Fig. 20 shows the observation of solder joint cracks after five days of PCT. To be more specific, solder cracks were found at solder joints near the solder/metal electrode interface regardless of resin types at the Sn4Ni3 intermetallic compound (IMC) layer in Fig. 21 [18]. Crack gap size indicates how much amount of the stress generated from polymer resin to crack SAC305 solder joints. It was found that crack gap size decreased from acrylic, epoxy, multifunctional epoxy to cationic epoxy resins, due to different CTE mismatches. Cationic epoxy-based solder ACF joint showed the minor cracks and the most stable resistance due to smallest CTE mismatch with solder, despite its convex solder shape.

IV. CONCLUSION

In this paper, effects of resin properties and Sn-3Ag-0.5Cu solder ACF joint shapes on the electrical performances and reliability were compared at 250 °C FOB bonding. By using the same bonding conditions, four solder ACF joints were formed. Cationic epoxy showed a convex solder joint shape, causing lower electrical performances of 35.1 mΩ/mm² per electrode areas due to faster curing speeds and lower solder wetting areas. Conventional concave solder ACF joint showed around 18.1 mΩ/mm² electrical performances, but showed a worse reliability performance in five days of PCT due to larger CTE than cationic epoxy. After five days of PCT reliability test, solder cracks were found at SAC305 solder joints near the solder/metal electrode interface at the Sn4Ni3 IMC layer, and crack gap sizes decreased from acrylic, epoxy, multifunctional epoxy, and cationic epoxy resins due to smaller CTE mismatch. As a summary, resin thermomechanical properties played a more important role in solder ACF joint reliability than the concave solder joint shape. For the next-step optimization, ultralow CTE is the new research direction for solder ACF applications.

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