Deformation mechanism and its effect on electrical conductivity of ACF flip chip package under thermal cycling condition: An experimental study

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Abstract

In this study, experimental works are performed to investigate the deformation mechanism and electrical reliability of the anisotropic conductive adhesive film (ACF) joint subjected to temperature cycling for flip chip on organic board (FOCB) assemblies. This paper presents some dominant deformation parameters governing the electrical degradation in an ACF joint between a chip and a substrate when flip chip assembly is heated and cooled. The deformation mechanism of ACF flip chip assemblies during the temperature cycling are investigated using in situ high sensitivity moiré interferometry. A four-point probe method is conducted to measure the real-time contact resistance of ACF joint subjected to the cyclic temperature variation. As the temperature increases below \( T_g \) of ACF, the bending displacement of assembly decreases linearly. At the temperature higher than \( T_g \) of ACF, there is no further change in bending behavior and in-plane deformations of a chip and a substrate become approximately free thermal expansion. It is because that soft-rubbery ACF at the temperature above \( T_g \) cannot provide the mechanical coupling between a chip and a substrate. The effect of bump location on the temperature dependent contact resistance is evident. A characteristic hysteresis in bending curves is observed and discussed. The contact resistance of the corner bumps increases with increasing temperature at a higher rate when compared to that of the middle. Failure analysis is performed to examine the ACF interconnections before and after thermal cycling test. The results indicate that during the thermal loading, the shear deformation is more detrimental to the electrical degradation of ACF joints than normal strain.

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1. Introduction

Flip chip assembly using anisotropic conductive adhesives/films (ACAs/Fs) has gained much popularity because of low temperature processing, fine pitch inter-

connection, low cost capability and green interconnection technology [1–3].

A key issue in long term reliability of ACF joints is joint failure during the thermal cycling. Adhesive flip chip assemblies are typically manufactured by bonding at an elevated (curing) temperature and subsequently cooling down to a low temperature. Because thermomechanical properties of bonded materials are different, thermally induced stresses and strains, caused by the
thermal contraction mismatch of these materials, arise at low temperature conditions. These thermal stresses and strains are one of the most serious of reliability problems for electronic packaging and can lead to mechanical and functional failure in adhesive flip chip assemblies during the thermal cycling testing. CTE and stiffness mismatch between a chip and a substrate cause large thermal stresses/strains and warp of the ACF packages during the thermal cycling test, resulting in the electrical degradation of ACF joint. Therefore the investigation of relationship between deformation mechanism and electrical reliability of an anisotropic conductive adhesive bonded assembly during the thermal cycling test is practically important to attain the high reliable ACF package [4,5]. However, the whole deformation history of adhesively bonded flip chip package over the temperature cycle was not clearly understood and the critical deformation mechanisms at the temperature extremes were not clarified.

Moiré interferometry is a whole-field optical interference technique with high resolution and high sensitivity for measuring the strain fields [6]. Recently, this technique has been successfully applied to measure the thermal-mechanical deformation of electronic packages for the study of package reliability [6–8]. A widely used moiré interferometer in electronic package analysis is the portable engineering moiré interferometer (PEMI) from photomechanics.

The objective of this paper is to study the temperature-dependent deformation mechanism of ACF package assembly subjected to thermal cycling condition and to clarify the critical factor affecting the electrical performance of ACF package.

2. Experimental procedures

2.1. Sample description

Fig. 1 shows the schematic drawing of the global structure of the IC chip to substrate packaging based on the anisotropic conductive film and local bonding structure around the bump/pad region. The dimension of the silicon chip with daisy-chain structure was 14.7 mm × 8.5 mm × 0.7 mm. Gold bumps were formed on pads of test chip. The bumps were 80–90 µm in diameter and 20 µm in height. The 1.2 mm thick FR4 substrate had an 18 µm thick copper conductor and a 10 µm thick Ni/Au surface finish. It had a conductor track of 120 µm diameter and a 70 µm wide routing line to measurement point.

The anisotropic conductive film used was made of thermosetting epoxy type containing Ni/Au plated polymer spheres with a mean particle size of 5 µm. ACF flip chip assemblies were prepared by processes of ACF pre-bonding on substrate, chip alignment to substrate, and thermo-compression bonding at 180 °C for 20 s by bonding pressure of 100 MPa/bump. The thickness of adhesive layer was about 50 µm after flip chip bonding.

2.2. Thermo-mechanical and dynamic mechanical analysis

The thermal analyzer (Seiko Instruments TMA/SS 6100) with a heating rate of 5 °C/min was used to measure the thermo-mechanical and dynamic mechanical properties of polymeric films. N2 gas was continuously purged into the sample tube. Thermal expansion character of the samples was measured on a thermo-mechanical analyzer (TMA). The analyzer was operated in a tension mode, and rectangular samples (3.0 mm wide × 15.4 mm long × 0.05 mm thick) were used. For the thermo-mechanical analysis, dimensional change of the specimen was continuously monitored with heating rate of 5 °C/min. A constant force was applied to the sample to keep it flat and stable. In dynamic mechanical analyzer (DMA), rectangular samples were fastened vertically between the grips and a sinusoidal tensile stress was applied to the specimen.

2.3. High resolution moiré interferometry

In moiré interferometry, gratings on deformed specimen interfere with the reference grating to produce the moiré fringe pattern. The resulting fringe patterns generate contour maps of U and V displacement fields, which are respectively defined as in-plane displacements in orthogonal x and y directions. The displacements then can be determined from fringe orders by the following relationships:

\[ U = \frac{1}{f} N_x, \quad V = \frac{1}{f} N_y, \]

where \( f \) is the frequency of the virtual reference grating, and \( N_x \) and \( N_y \) are fringe orders in the U and V field moiré patterns, respectively. A virtual reference grating with a frequency \( f \) of 2400 lines/mm is used, which provides a sensitivity of 0.417 µm per fringe order. When the strains are required, they can be decided from the

Fig. 1. Schematic global structure of the IC chip to substrate bonding using anisotropic conductive film and local bonding structure around the bump/pad region.
displacement fields by the relationships for small engineering strains.

\[
\varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial x} \right], \quad \varepsilon_y = \frac{\partial V}{\partial y} = \frac{1}{f} \left[ \frac{\partial N_y}{\partial y} \right],
\]

\[
\gamma_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial y} + \frac{\partial N_y}{\partial x} \right].
\]

(2)

Fig. 2(a) shows a schematic drawing of the specimen preparation for the moiré experiment. The test package was first sectioned and polished to the cross-section of interest. The depth of cross-section surface of interest is practically close to the die edge. A very thin layer of epoxy adhesive was used to adhere a fringe grating on the cross-section of the specimen at the temperature of 100°C. The ultra low expansion (ULE) grating mold and high temperature curing epoxy (F253, TRABOND) were used for this experiment. The epoxy was cured during 2 h at the elevated temperature of 100°C. The deformation at this temperature was taken as a reference deformation state. When the specimen was cooled, its thermal deformation was imbedded in the specimen grating. The moiré experiment was performed at room temperature (~25°C) hence providing a thermal loading of ~75°C.

The same specimen was subjected to the thermal cycling and in situ moiré measurement was performed during the thermal cycling. Fig. 2(b) shows the schematic drawing of the thermal chamber for the moiré experiment and the temperature profile used in the thermal cycling. To simulate an accelerated thermal cycling (ATC) condition, thermal chamber with heating and cooling was implemented with moiré interferometry. The conduction heating and cooling scheme using thermoelectric (Peltier) modules were applied to the chamber. The fringe patterns were recorded by a CCD camera system or a large format camera system as a function of temperature and time in a controlled environment. The specimen was kept at the room temperature for about one week before the thermal cycling. Maximum and minimum temperature of the thermal cycle was 125°C and 25°C in Fig. 2(b). Step heating and cooling were performed to investigate the moiré fringes during the temperature cycling. The heating and the cooling rate was approximately 7°C/min and a dwell time of 5 min was used at all the measurement temperatures, which resulted in about 69 min per cycle.

2.4. Continuous contact resistance monitoring

Fig. 3 shows a schematic circuitry view to measure the contact resistance using four point probe measurement. By using the circuit design for electrical measurement,
contact resistance can be calculated as $V/I$. The thermal chamber with the conduction heating and cooling scheme using thermoelectric (Peltier) modules was used to monitor the temperature dependent contact resistance. Stable temperature can be achieved with $1^\circ C$ maximum variation through the closed loop control of thermal chamber. With changing environmental temperature, a real time contact resistance was continuously recorded. The measured middle and corner bumps are located in which the distances from neutral chip center are 0.25 mm and 5.75 mm, respectively.

3. Results and discussion

3.1. Thermo-mechanical characterization of ACF materials

Thermo-mechanical properties such as glass transition temperature, CTE and modulus were experimentally determined by thermal analyzer equipped with thermal analysis software over a temperature range from 30 $^\circ C$ to 180 $^\circ C$ with a heating rate of 5 $^\circ C$/min. Many repetitions of the measurement confirmed that material properties measured by TMA and DMA were experimentally reproducible with a variation of less than 10%. Fig. 4(a) shows the dimensional changes of ACF material studied. Around the inflection point of the TMA curve, there was a shift to higher thermal expansion coefficients due to changes in molecular free volume. During multiple expansion measurements on a same sample, the TMA curves on second and third measurements were different from the TMA curve of as-cured ACF sample. The CTE values were calculated at the linear section of thermal expansion versus temperature ranged from 50 $^\circ C$ to 80 $^\circ C$ and summarized in Table 1. As shown in the above Fig. 4(a), after second thermal exposure, elongation changes were nearly reversible on heating and cooling. Fig. 4(b) shows the temperature dependence of storage modulus. The storage modulus of ACF materials decreased as the temperature increased. In particular, the storage modulus significantly decreased near the glass transition region. It is the well-known effect of the significant modulus drop due to the change from a hard-glassy material to a soft-rubbery one above glass transition region. Interestingly, the glass transition temperature in DMA curve was shifted to a higher temperature on the second mea-

![Fig. 3. Schematic circuitry view of four point probe method to measure the contact resistance measurement of single bump.](image)

![Fig. 4. (a) Dimensional changes and (b) modulus changes of cured ACFs as a function of temperature.](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Comparison of CTE and modulus as a function of measurement cycles</th>
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<tr>
<td>Measurement sequence</td>
<td>CTE below $T_g$ (ppm/K)</td>
</tr>
<tr>
<td>1st</td>
<td>66.4 ± 3.4$^a$</td>
</tr>
<tr>
<td>2nd</td>
<td>52.8 ± 2.2$^a$</td>
</tr>
<tr>
<td>3rd</td>
<td>50.2 ± 2.8$^a$</td>
</tr>
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$^a$ Measured (TMA).

$^b$ Measured (DMA).
measurement and did not change regardless of further measurement. Moreover, the storage modulus of ACFs exposed to high temperature became higher than that of as-cured ACF. There are a few points of interest worth mentioning. It is known that an internal stress and a frozen-in excess free volume are built into the cured epoxy resin, which should lead to a different thermal expansion behavior. Moreover, the frozen-in excess free volume and internal stress are relaxed by high temperature exposure above its $T_g$ and is not restored to the as-cured state. The different thermal expansion behavior between initial and second measurement is attributed to the relaxation of the excess free volume and internal stress built in polymeric ACF. During the subsequent thermal history, polymeric materials did not show the significant difference in the dimensional change. Most important fact from the standpoint of thermo-mechanical deformation is that these sudden changes in materials properties have a great influence on the deformation mechanism of package.

3.2. Deformation characteristics during the thermal loading

The original deformation fields ($U$ and $V$ fields) at room temperature before the room temperature storage and the thermal cycling, induced by the bi-thermal loading, are shown in Fig. 5. After the specimen was cooled by 75 $^\circ$C, all of the components contracted in both the $x$- and $y$-directions. The deformations of the Si chip are very small (indicated by low fringe density), because silicon material has low CTE and high Young’s modulus. In the printed circuit board, the $y$-direction contraction is much greater than the $x$-direction contraction (shown by the higher fringe gradient in the $V$ field fringe pattern) because of the anisotropic CTE property of the board. To confirm the effect of the cross-sectioning for moiré experiment on the initial strain condition, out-of-plane deformation can be used. Twyman/Green interferometry can measure the out-of-plane deformation on the die surface without a cross-sectioned damage. Out-of-plane deformation along the die edge measured by Twyman/Green interferometry was equal to that measured by moiré interferometry. Therefore, it seems that the sectioning and polishing does not affect the strain condition. The $V$ field pattern in Fig. 5(b) indicated that near the end of the chip, the original vertical displacement of the chip was about 15 $\mu$m in the downward direction.

3.2.1. Local deformation of assembly

The measured moiré fringes represent the total displacements, which include the free thermal contraction or expansion part of displacement and the stress-induced part of displacement [6]. In terms of strain, the total strain obtained from the moiré fringes is

$$\varepsilon^T = \varepsilon^e + \varepsilon^a + \alpha \Delta T,$$

where $\varepsilon^T$ is a total strain, $\varepsilon^e$ is the stress-induced part of the strain, $\varepsilon^a$ is the free thermal contraction or expansion part of strain, $\alpha$ is a coefficient of thermal expansion (CTE) of the material, and $\Delta T$ is a temperature change in the thermal loading.

Fig. 6 shows the displacement fields of the right half of the specimen corresponding to the temperature profile in Fig. 2(b). The $x$-axis strains ($e_x$) at rightmost die corner were determined by Eq. (2) using the fringe orders ($N_x$) of $U$ displacement fields. Fig. 7(b) shows the change of strain ($e_x$) as a function of temperature at different vertical positions marked in Fig. 7(a). In the temperature range from RT to 80 $^\circ$C of Fig. 7(b), the change of strains with temperature for silicon top surface (position A) and PCB bottom surface (position D) yielded slopes of 2.0 ppm/$^\circ$C and 13.5 ppm/$^\circ$C. Interestingly, these CTE values are analogous to the reported CTE values of silicon (≈2.8 ppm/$^\circ$C) and FR4 (≈13–17 ppm/$^\circ$C) materials. This indicates that the amount of stress-induced part of strains ($\varepsilon^a$) is negligible near the free surface. In the meanwhile, the strain behaviors at position B and C (the vicinity of adhesive) below 100 $^\circ$C were greatly different from those at position A and D. It means that cured ACF material gives a remarkable constraint on its adjacent contacting surfaces. As the package temperature exceeded 100 $^\circ$C, strain at position C asymptotically approached to strain behavior for the PCB free expansion (at position D). That is, at temperature above $T_g$ of ACF, the deformation of organic substrate is not constrained by silicon chip, because ACF with rubbery characteristics above $T_g$ cannot provide the mechanical coupling between a chip and a substrate.

![Fig. 5. Moiré fringes of the ACF flip chip assembly, induced by bi-thermal loading of $\Delta T = -75$ $^\circ$C: (a) $U$ field and (b) $V$ field patterns.](image)
3.2.2. Global deformation of assembly

Relative vertical displacements with respect to neutral point were determined by Eq. (1) using the fringe orders \( N_r \). Fig. 8 shows the maximum bending displacements of the chip during the temperature cycling. The specimen was kept at the room temperature for 7 days before the thermal cycling. So, the bending displacement of the chip induced by bi-thermal loading
(about 15 μm) is reduced up to 13 μm, which means the relaxation behavior of the assembly at room temperature. The capital letters in Fig. 8(b) represent the temperature cycling sequence. As the temperature increased, the bending displacement changed linearly. As the temperature increased further, which will be discussed below, silicon chip exhibited an upward bending behavior upon an initial heating cycle from 80 °C to 120 °C. During further thermal loading, chip bending was shifted to lower curve and followed the curve in Fig. 8. The amount of upward bending displacement observed on an initial heating cycle was equal to that of bending displacement relaxed at room temperature. It means that the nonlinear behavior due to the relaxation of the assembly at room temperature causes the upward chip bending at initial heating cycle.

There was a characteristic hysteresis in bending curves as illustrated in Fig. 8. The bending behavior of package is affected by the thermal and mechanical properties of assembly components including chip, substrate, and adhesive materials. In particular, polymeric adhesive material greatly affects the bending characteristics of assembly. As mentioned above, the excess free volume and internal stress built in cured ACF after subsequent curing and cooling processes is relaxed by high temperature exposure above its $T_g$ and is not restored to the as-cured state. In this view of the free volume change in ACF, such an irreversible relaxation phenomenon ultimately altered the ACF material properties in Fig. 4. Meanwhile, both CTE and modulus properties of the ACF material were reversible after the second measurement. Accordingly, the large amount of warpage hysteresis is attributed to the change of ACF properties due to the excess free volume and internal stress of the as-cured ACF. No other transitions were observed after first temperature cycle. That is, the reversible warpage curves after the first temperature cycle indicate that the warpage exhibit the elastic behavior.

The temperature dependent deformation mechanism of adhesive flip chip package was schematically illustrated in Fig. 9. The initial heat cycle resulted in the decrease of overall warpage. In the neighborhood of ACF $T_g$, the mechanical coupling between a chip and an organic substrate was significantly reduced and the assembly exhibited the zero bending displacement. At temperatures higher than $T_g$, there was no further change in bending behavior, and then in-plane deformations of chip and organic substrate became...
approximately free thermal expansion. It means that at the temperature exposure above $T_g$, a chip and a substrate expand with the inherent CTE of each component in $x$–$y$ direction. Consequently, significant shear induced by the free thermal expansion of each component is entirely taken by the flip chip joint. Most important from the standpoint of thermo-mechanical deformation is that at temperature higher than $T_g$ of ACF, the critical factor in the ACF joint damage is shear deformation.

### 3.3. Contact resistance monitoring during the subsequent thermal cycling

The average contact resistance value was about 4–5 mΩ just after flip chip assembly. Fig. 10 describes the temperature-dependent contact resistance of interconnects located at the middle ($x_{\text{bump}} = 0.25 \text{ mm}$) and corner ($x_{\text{bump}} = 5.75 \text{ mm}$) of silicon chip, which was assembled on an FR4 substrate. As shown in Fig. 10, the middle bumps were found to have no resistance increase over the entire temperature range. The contact resistance of the corner bump increased with increasing temperature at a higher rate when compared to that of the middle bump. It may be conjecturable that under the thermal loading not only shear deformation resulting from a CTE mismatch in $x$–$y$ direction are important, but also the normal expansion in $z$-direction is of importance. Normal stress $\sigma_z$ acting on ACF layer between two bumps may play an important role to maintain electric connection. At the room temperature, $\sigma_z$ is large contraction stress, but it decreases when temperature increases. Small contraction stress may induce the increase of electric resistance and result in electric disconnection in the worst case. In viewpoint of thermo-mechanical deformation, the middle bumps on a chip experience only the normal deformation along the $z$-direction, while the corner bumps experience the significant shear deformation developed in $x$–$y$ directions. Accordingly, contact resistance behaviors indicate that the shear deformation, which is dependent upon the distance from neutral point of package, is more detrimental to the electrical degradation of ACF interconnection than normal deformation. At higher temperature, the effect of bump location on the contact resistance was more
evident in Fig. 10. In particular, corner bumps exhibited the significant resistance increase at higher temperature than 150 °C. The local and global deformation results from moiré analysis clearly revealed that at high temperature above $T_g$ of ACF, the shear deformation of corner bumps is significantly larger than normal deformation. Accordingly, a distinctive variation of contact resistance with the distance from chip center reveals that high temperature degradation is mainly due to the shear deformation.

At temperatures between 100 °C and 125 °C during the first heating cycle, anomalous increase of contact resistance was also observed. Bending behaviors of the chip top surface and PCB bottom surface calculated from V field fringes in the first heating cycle was shown in Fig. 11. As shown in Fig. 11, during the first heating cycle between 100 °C and 120 °C, chip and substrate had upward and downward bending behaviors, respectively. That is, each component expressed opposite bending characteristics. This anomalous bending behavior explains the bulged shape of contact resistance behavior. After the first thermal cycling, the anomalous bending was permanently disappeared, and both chip and substrate had the equivalent downward bending behavior. Moreover, during further thermal cycles, the bulged shape of contact resistance curve was not observed around 110 °C. In addition, during the first heating and cooling cycles, the contact resistance exhibited the reversible change. Only one thermal cycle practically does not damage the ACF interconnections. As the number of thermal cycle increase, joint damages (cracking of coating layer and Au bump recess formation in

![Image](image_url)

**Fig. 11.** The anomalous bending behavior of the chip (positive) and substrate (negative) between 100 °C and 125 °C of the first heating cycle.

A surprising finding of our study was that sliding traces were clearly observed on the contact surface of substrate pad after exposure to thermal cycling. Fig. 12 shows SEM images revealing the sliding traces on a substrate metal pad after 6000 thermal cycles between −55 °C (15 min) and 150 °C (15 min). In viewpoint of tribology, the moving traces on a substrate pad is attributed to the sliding contact of “hills” of rough surfaces of a metal bump (Au) and a substrate pad (Cu/Ni/Au). After several thermal cycles, no severe

![Image](image_url)

**Fig. 12.** SEM micrograph showing the sliding traces after temperature cycling.
damage may be observed in the ACF joint. However, after 6000 thermal cycles, sliding traces on contact surfaces were obviously observed. The direction of sliding traces was strongly dependent upon the interconnect positions on a chip. In particular, the moving traces on a substrate pad located at the chip corner in Fig. 12 exhibited oblique line in the same direction with a diagonal of chip. It reveals that the ACF joints in adhesively bonded flip chip are prone to the resulting shear due to difference in thermal expansion between the chip and organic substrate in the presence of cyclic temperature variations. Fig. 13 shows the SEM images of ACF interconnection before and after thermal cycling. In Fig. 13(a), as-bonded interconnection had no damage in the joint structure. After thermal cycling, the coating layer of conductive particles in Fig. 13(b) was severely cracked down or damaged around the bump to particle contact edge. In particular, it was observed that the left and right interfaces between the conductive particle and Au bump were mechanically worn out by the bump to particle shear sliding, resulting in the reduction of contact area. Both sliding traces on a substrate pad and the recess formation at the left and right interfaces of the Au bump to conductive particle contact manifestly support the deformation and electrical degradation mechanisms mentioned above.

4. Conclusions

Deformation mechanism and its effect on electrical interconnections of ACF flip chip package subjected to thermal cycling were experimentally studied. At temperatures higher than $T_g$, there was no change in bending behavior, and both a chip and an organic substrate expanded with the inherent CTE of each component in $x$–$y$ direction. It means that the deformation of organic substrate was not constrained by silicon chip, because ACF with rubbery characteristics above $T_g$ could not provide the mechanical coupling between a chip and a substrate. A significant hysteresis was also observed in bending behaviors between initial heating cycle and second heating cycle. However, during further thermal cycling, the amount of bending hysteresis became almost negligible when compared with that of initial hysteresis. The large amount of warpage hysteresis upon an initial temperature cycling is attributed to the change of ACF properties by relaxation of the excess free volume and internal stress of the cured ACF. The contact resistance of the middle bump was found to have no noticeable change during the thermal cycling. However, the corner bump exhibited the significant resistance increase at high temperature loading. The sliding traces on the contact pad, cracking of the coating layer, and recess formation at edges of the bump to particle interface were observed after severe thermal cycles. The primary cause for electrical degradation is therefore from the resulting shear due to difference in thermal expansion between the chip and organic board in the presence of cyclic temperature variations.

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References


