1 Introduction

Flip chip assembly using anisotropic conductive adhesives/films (ACAs/Fs) has gained much popularity because of low temperature processing, low cost capability and green interconnection technology [1–3].

One of the most important issues whether this interconnection technology is suitable to be used for flip chip application is thermal cycling reliability. Adhesive flip chip assemblies are typically manufactured by bonding at an elevated (curing) temperature and subsequently cooling down to a low temperature. Because thermo-mechanical 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. So 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. Coefficient of thermal expansion (CTE) mismatch between chips and substrates causes large thermal stresses/strains and warpage of the ACF packages during thermal cycling test as shown in Fig. 1. Interconnection fatigue and interface delamination can occur during thermal cycling test. Therefore the investigation of relationship between thermal deformation and assembly reliability of an anisotropic conductive adhesive bonded assembly during thermal cycling test is practically important.

In this study, we investigated the thermal deformation of adhesive bonded flip chip on-board package with various ACF materials using in situ high sensitivity moiré interferometry in order to understand the effect of ACF materials on the thermal deformation, thermal cycling reliability, and delamination susceptibility of ACF flip chip assemblies.

2 Experimental Procedure

2.1 Sample Description. 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 bump size was 80 to 90 μm in diameter and the bump pitch was 800 μm. Three ACFs with difference in coefficient of thermal expansion (CTE) and modulus were prepared with 0, 10, and 30% by weight silica fillers of 0.8 μm diameter. These ACFs were denoted as ACF-A, ACF-B, and ACF-C. The materials properties of three ACFs are listed in Table 1.

ACF flip chip assemblies were prepared by processes of ACF placement on substrate, chip alignment to substrate, and thermodression bonding at 180°C for 20 s by pressure of 5 to 6 kgf/cm². The thickness of adhesive layer was about 50 μm after flip chip bonding.

2.2 High Resolution Moiré Interferometry. Moiré interferometry is a whole-field optical interference technique with high resolution and high sensitivity for measuring the strain fields [4]. Recently, this technique has been successfully applied to measure the thermal-mechanical deformation of electronic packages for the study of package reliability [4–6]. A widely used moiré interferometer in electronic package analysis is the portable engineering moiré interferometer from Photomechanics. In moiré interferometry, gratings on deformed specimen interfere with the reference grating to produce the moiré fringe pattern. The resulting fringe pattern can be used to measure displacement fields, strain fields, and thermal deformation of the bonded packages.
which are, respectively, defined as in-plane displacements in orthogonal $x$ and $y$ directions. The displacements can then 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 $\mu$m per fringe order. When the strains are required, they can be derived from the displacement fields by the relationships for small engineering strains

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

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

The test package was first sectioned and polished to the cross section of interest. 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 ultralow expansion grating mold and high temperature curing epoxy (F253, TRA-BOND) were used for this experiment. The deformation at this temperature was taken as a reference deformation state. The moiré experiment was performed at room temperature ($\sim$25°C) hence providing a thermal loading of $-75^\circ$C.

### 2.3 Scanning Acoustic Microscopy

The package was immersed in water, and a sonic transducer emitting sound wave pulses was scanned over the surface by a highly accurate translation stage. Sound energy is reflected by internal interfaces in the package and detected by the same sonic transducer. The depth at which the reflection occurs is the interface between solid materials and air, for example, at a void or delamination. An image is built up from the scan by gating the reflection signal from the transducer to cover the layer or layers of interest in the package. Because total reflection of the sound pulse occurs at the interface between solid materials and air, voids and delaminations usually cause the largest reflected signal, and hence appear as white color within the image. In this work, a transducer frequency of 230 MHz was used to monitor both the chip to ACF layer and the ACF layer to board interfaces.

### 2.4 Thermal Cycling Analysis

To investigate the interconnect reliability of ACF flip chip, thermal cycling tests between $-40^\circ$C and 125°C were performed. Initial resistance was measured using a four-point probe method and after each cycle interval. The effective dwell time was 15 min at both low and high temperature. The number of electrically failed joints is dependent on the failure criteria. The different failure criteria were defined to analyze the thermal cycling reliability. Failure was defined as the point of time when the initial interconnect resistance exceeded the resistance value with respect to different failure definition. It was assumed that single joint failure follows a Weibull distribution. To distinguish individual joint reliability of ACF flip chip with different bump positions, with various distances from neutral point, it is necessary that all of bumps in a chip should be classified with the distances from chip center. Accordingly, the bump distance from chip center will be represented by DNP.

### 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 (Seiko Instruments TMA/SS 6100) equipped with thermal analysis software over a temperature range from 30°C to 180°C with a heating rate of 5°C/min. N$_2$ gas was continuously purged into the sample tube. Figure 2(a) shows the trimethylaluminium curves of three ACF materials studied. Around these inflection points, there were shifts to higher thermal expansion coefficients due to changes in molecular free volume. The CTE values were calculated at the linear section of thermal expansion versus temperature ranged from 50°C to 80°C. Thermal expansion coefficients below inflection points were summarized in Table 1. Figure 2(b) shows the temperature dependence of storage modulus for all ACFs studied. The storage modulus of ACF materials decreased as the temperature increased. In particular, storage modulus significantly decreased near the glass transition region. It is the well-known effect of the storage modulus drop of nearly two orders of magnitude above the glass transition temperature. Elastic modulus exhibited a significant decrease as ACF materials changed from a hard-glassy material to a soft-rubbery one. ACF materials properties were summarized in Table 1.

#### 3.2 Moiré Deformation Analysis

The fringe patterns for ACF assemblies resulting from the CTE mismatches between Si chip and FR4 board were measured by a moiré interferometry. The $U$ and $V$ displacement fields of the assembly, induced by the bithermal loading, are shown in Fig. 3. A number of qualitative observations can be made from Fig. 3:

- $U$ and $V$ fields regarding Si chip show that the contraction of the Si chip is very small as indicated by low fringe density. It is because the Si material has extremely low CTE and high Young’s modulus. $U$ and $V$ fields regarding FR4 board shows that 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.
- The horizontal ($x$) displacement distributions along the ACF layers were observed in $U$ fields. This demonstrates that the thermal mismatch between the die and board induces the shear displacement.
- The $V$ fields display that the fringe density becomes higher toward the chip corner. This pattern explains the bending warpage behavior. In the $V$ fields, a few fringes within the ACF layer were

### Table 1 Candidate ACFs properties

<table>
<thead>
<tr>
<th>CTE ($\text{ppm/}^\circ$C)</th>
<th>Modulus (GPa)</th>
<th>$T_g$ ($^\circ$C)</th>
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<tbody>
<tr>
<td>ACF-A</td>
<td>67.1</td>
<td>1.8</td>
</tr>
<tr>
<td>ACF-B</td>
<td>55.9</td>
<td>2.5</td>
</tr>
<tr>
<td>ACF-C</td>
<td>40.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

1 Calculated in the range from 50°C to 80°C.
2 Room temperature storage modulus.
3 Estimated from the tan $\delta$ peak in DMA.
observed along the vertical direction. It means that the ACF materials were contracted along the thickness direction.

The right-bottom and left-bottom chip corner areas have the highest shear strain, which can be seen from the large displacement gradient along the y direction in the U field. Figure 4 depicts the shear strain distributions along three ACF layers obtained from Eq. (2). Figure 4 illustrates this point more dramatically, wherein the maximum shear strain is at the die edge position where the distance from the neutral point (DNP) is maximum. Within the DNP of 5 mm, shear strain in ACF layer was almost negligible as shown in Fig. 4. From moiré results, it is expected that the outermost ACF joint on a chip will be significantly suffered from the thermal fatigue caused by CTE mismatch between a chip and a board. Therefore, the outermost ACF joint is the one very likely to fail first. In the viewpoint of structural design, to improve thermal cycling lifetime, the interconnect bump should be designed to be located inside the critical region near the chip corner as shown in Fig. 4. It was also observed that the shear strain of ACF-C was roughly half of that of ACF-A.

The warpage of the package can be evaluated according to the relative deformation between the middle point and corner point at the top surface from the V field fringe pattern. Figure 5 shows the warpage distributions along the distance from chip center obtained from the Eq. (1). As shown in Fig. 5, the warpage increases as the ACF material has higher stiffness from ACF-A to ACF-C. Therefore, for the same thermal loading condition, ACF-C is the most deflected structure. For this case, it was found that the bending displacement was about 18 μm. Moiré deformation analysis results reveal that the high CTE and low modulus ACF (ACF-A) resulted in small warpage and high shear strain in the ACF assembly, while the low CTE and high modulus ACF (ACF-C) resulted in large warpage and low shear strain in the assembly. That is, the high modulus ACF (ACF-C) increases the stiffness of the assembly, which leads to a larger warpage but smaller shear strain. Another reason for the decreased shear strain is the low CTE property of ACF-C. In other words, the reduced thermal deformation of low CTE ACF is contributing to a reduced shear deformation at ACF layer.
3.3 Thermal Cycling Lifetime and Delamination. Thermal cycling reliability of adhesive flip chip is practically dependent on the dimensional and thermo-mechanical properties of three components: chips, substrates, and ACFs. These properties are closely related to the thermal deformation of flip chip structure. To investigate the effect of thermal deformation depending on ACF properties on a thermal cycling reliability, thermal cycling tests and Weibull analysis were performed.

The number of electrically failed joints is dependent on the failure criteria. Figure 6 shows the two Weibull reliability plots based on the different failure criteria, respectively. Table 2 summarizes the thermal cycling lifetime depending on the failure criteria and failure rate. The cumulative failure rate ($F$) does not correspond to the Weibull function value. The Weibull function values are related to the CDF by $-\ln(1-F)$. It was seen that ACF material properties, which were closely associated with thermal deformations in ACF layer, noticeably affected the mean lifetimes of ACF assemblies. For both failure criteria of $\Delta R > 50 \, \text{m}\Omega$ and failure rate of 40 percent, ACF-B and ACF-C assemblies showed 18% and 34% in Weibull life versus ACF-A assembly, respectively. It means that, although the assembly deformation has large warpage characteristics, the failure mode in ACF joint is still shear strain dominated. The shear strain of the corner joint was substantially reduced by low CTE and high modulus ACF, and the thermal cycling lifetime increased due to the reduced shear strain. From moiré results, it is expected that the outermost ACF joint on a chip will significantly suffer from the thermal fatigue caused by CTE mismatch between a chip and a board. Figure 7 shows the dependence of the number of thermal cycles ($\sim 40^\circ\text{C} \text{ to } 125^\circ\text{C}$) to failure on bump locations of flip chip assembly using ACF-A material. As shown in Fig. 7, the mean lifetimes were strongly dependent on the distance from the chip center (DNP). In particular, it was found that the mean thermal cycles to failure significantly decreased near the chip corner.

C-scanning acoustic microscopy (SAM) images of ACF flip chip packages were given in Fig. 8 to demonstrate the delamination pattern after reliability test. The white color in the chip side indicates delamination or debonding. Before thermal cycling, flip chip assembly did not show any delamination over the entire chip.

**Table 2** Thermal cycling lifetimes estimated from the Weibull reliability plot

<table>
<thead>
<tr>
<th>Failure criteria</th>
<th>Cycles in 10% failure</th>
<th>Cycles in 40% failure</th>
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<tr>
<td></td>
<td>ACF-A</td>
<td>ACF-B</td>
</tr>
<tr>
<td>$\Delta R &gt; 50 , \text{m}\Omega$</td>
<td>1765</td>
<td>2083</td>
</tr>
<tr>
<td>$\Delta R &gt; 100 , \text{m}\Omega$</td>
<td>2197</td>
<td>2757</td>
</tr>
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area. However, following 6200 cycles, the assemblies showed severe corner delamination between ACFs and chip as shown in the SAM images. It was seen that the delamination was initiated from the edge of silicon die and then evolved to the inner area of the assemblies. The ACF/chip interface is more prone to delamination than ACF/substrate interface. Interestingly, delamination patterns were different with various ACFs properties. As shown in Fig. 8, high CTE and low modulus ACF (ACF-A) assembly exhibited more significant delamination than low CTE and high modulus ACF (ACF-C) assembly. Accordingly, it is observed that during thermal cycling testing, driving force for a delamination increases as the ACF CTE increases and modulus decreases. C-SAM images clearly reveal that flip chip assemblies using low CTE and high modulus ACF are less prone to delamination failures, due to the reduced shear strain. This effect is analogous to the effect of underfill properties on a flip chip reliability [7].

Experimental results reveal that thermal cycling fatigue and delamination failure of ACF flip chip assembly are dominated by thermally induced shear strain damage of adhesive layer. Accordingly, the reduced shear strain of adhesive layer by modification of ACF properties can lead to less fatigue and delamination failure under thermal cycling testing.

4 Conclusions

The effects of ACF materials on thermal strain and susceptibility to delamination in an ACF flip chip on board were studied. Results indicate that optimum ACF properties can enhance ACF package reliability, and ACF properties have a significant role in overall reliability during thermal cycling testing. An ACF with low CTE and high modulus can reduce the thermally induced shear strain in ACF layer, and thus can increase the overall thermal cycling lifetime of ACF joint compared with high CTE and low modulus ACF. It was also observed that low CTE and high modulus ACFs are less susceptible to delamination failures at free edges during thermal cycling testing. It is due to the reduced shear strain and lower interfacial stress that resulted from lower CTE and higher modulus properties of ACF.

Acknowledgment

This work was supported by the Center for Electronic Packaging Materials of Korea Science and Engineering Foundation.

References