Reliability Study of Underfill/Chip Interface with Multifunctional Micro-Moiré Interferometry System

Zhang Y.L. (a), Shi X. Q. (b), and Zhou W. (c)

(a) School of MPE, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798
(b) Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 6380751
(c) Tel: 65-67906122; Fax: 65-67906122; Email: Ritchie_Zhang@hotmail.com

Abstract

Interface reliability issue has become a major concern in developing flip chip assembly. The CTE mismatch between different material layers may induce severe interface delamination. In this study, multifunctional micro-moiré interferometry (M³I) system was utilized to study the fracture response of flip chip assembly under accelerated thermal cycling (ATC) in the temperature range –40 ºC to 125 ºC. This in-situ measurement provided good interpretation of fracture behavior of delaminated flip chip assembly under ATC test, which was quantified by interfacial fracture mechanics. The results indicated that the assembly with artificial crack was safe according to fracture criteria established in our previous work.

1. Introduction

Flip chip technology is one of major assembly technologies, with which the smallest packaging size can be achieved for desired functionality. Therefore, flip chip technology is expected to have a rapid growth in the industry applications in the next decade. However, large coefficients of thermal expansion (CTE) mismatch between individual materials of flip chip packages can lead to large thermal stress in solder interconnects, and hence reduce the life of package. Epoxy-based underfill materials are, therefore, introduced into flip chip assemblies in order to reinforce the strength of increasingly miniaturized solder interconnects [1,2]. However, the introduction of underfill brings another serious reliability problem of interface delamination in flip chip assembly. It is reported that the solder joint fatigue failure appears shortly after the delamination happens at the interface [3,4]. Therefore, it is most likely that crack may initiate at the underfill/chip interface with the largest CTE mismatch and propagate into the solder joint and further cause the function loss of electronic devices.

Consequently, the reliability issue of interface problem is becoming more and more important in extensive commercialization of flip chip packages. Due to the complex nature of flip chip assembly and complicated environmental loading, considerable limitations and difficulties exist in studying the interface delamination problem in flip chip packages using traditional strength theory. For example, the most common method used in industry is accelerated temperature cycling (ATC) test, which not only takes a long time and considerable resources, but also gives little insight into the failure mechanism and thus less help in the package design. Accordingly, the research emphasis has shifted strongly to damage and fracture mechanics, which offers a fundamental approach to the delamination problems. Briefly, two categories of research work have been carried out. On the one hand, different numerical and experimental methodologies have been developed to characterize the fracture toughness of polymer/inorganic interface [5,6]. The fracture toughness is employed as a criterion for the interface design. On the other hand, many numerical simulations [3,7] and in-situ measurement [8,9,10] have been performed to investigate the reliability of flip chip assembly subject to different mechanical and thermal loadings. However, less experimental investigation has been conducted on the delamination reliability of polymer/inorganic interface, especially under real ATC loading due to lack of in-situ/real-time optical measurement system.

In this study, an integrated multi-functional micro-moiré interferometry (M³I) system was developed to measure the deformation of flip chip assembly under ATC loading. The moiré fringe patterns were recorded with respect to certain temperature intervals and interface mechanics technique is employed to analyze the crack-tip displacement field and further study the fracture behavior of chip and underfill interface. From our previous study [11], it is also found that the effective fracture toughness of the assembly subjected to the ATC loading is lower than that of chip/underfill interface under either mode I tension loading or mode II shearing loading, indicating that the interface is safe during the ATC test. It is therefore concluded that the system can be used as an accurate and effective experimental tool for the investigation of interface delamination reliability problems involved in various electronics packages.

2. Experimental and theoretical backgrounds

2.1 M³I system

In this study, an integrated multi-functional micro-moiré interferometry (M³I) system was developed by combining moiré interferometry (MI) technique with phase shifting, micro-force application and measurement, thermoelectric heating and cooling, ultrasonic humidity excitation, and microscopic imaging techniques. The schematic diagram of M³I system is shown in Fig. 1. The system was used to investigate the interface reliability of flip chip assembly.
Fig. 1 Schematic diagram of M^3I system: 1: computer; 2: driver of phase shifter; 3: microscopic imaging device; 4: phase shifter; 5: moire interferometer; 6: micro-force controller; 7: micro-force amplifier; 8: cooling chiller; 9: micro-force actuator; 10: six-axis adjustment fixture; 11: miniature thermal cycling chamber (or miniature humidity chamber); 12: chamber support; 13: fixing frame; 14: temperature controller; 15: optical table

With this system, two fields of fringe patterns can be obtained to calculate displacements in orthogonal U and V directions

\[
U = \frac{1}{f} N_x \tag{1a}
\]

\[
V = \frac{1}{f} N_y \tag{1b}
\]

where \(f\) is the frequency of virtual reference grating, and \(N_x\) and \(N_y\) are fringe orders in the U and V field respectively. In practice, a virtual reference grating with a frequency of 2400 lines/mm was used, which provided a basic sensitivity of 2.4 fringe/µm displacement; therefore, the corresponding contour interval in the moiré fringe patterns was 417 nm/fringe.

2.2 Interface fracture mechanics

For the interface crack shown in the Fig. 2, Dundurs elastic mismatch parameters \(\alpha\) and \(\beta\) are functions of the elastic properties of the component materials defined as [12]

\[
\alpha = \frac{\mu_1 (\kappa_2 + 1) - \mu_2 (\kappa_1 + 1)}{\mu_1 (\kappa_2 + 1) + \mu_2 (\kappa_1 + 1)} \tag{2a}
\]

\[
\beta = \frac{\mu_1 (\kappa_2 - 1) - \mu_2 (\kappa_1 - 1)}{\mu_1 (\kappa_2 + 1) + \mu_2 (\kappa_1 + 1)} \tag{2b}
\]

where \(\mu_i\) is shear modulus; subscripts 1 and 2 donate specified materials 1 and 2 respectively; and \(\kappa\) given by

\[
\kappa_i = (3 - 4\nu_i)/(1 + \nu_i) \quad \text{for plane stress} \tag{3a}
\]

\[
\kappa'_i = 3 - 4\nu'_i \quad \text{for plane strain} \tag{3b}
\]

where \(\nu_i\) is the Passion’s ratio of materials. Nondimensional constant \(\varepsilon\) is related to the Dundurs parameters \(\alpha\) and \(\beta\), through

\[
\varepsilon = \frac{1}{2\pi} \ln \left( \frac{1 - \beta}{1 + \beta} \right) \tag{4}
\]

The relative crack displacement \(\delta\) at a distance of \(r\) behind the crack tip [13] is

\[
\delta = \delta_x + i\delta_y = \frac{8}{(1 + 2i) \cosh(\pi\varepsilon)} \sqrt{\frac{r}{2\pi E^* L}} \left( \frac{r}{L} \right)^\varepsilon \tag{5}
\]

where \(\delta_x\) and \(\delta_y\) are the crack-tip opening displacements (CTODs) in the X and Y direction, respectively; \(E^*\) is the effective Young’s modulus given by

\[
\frac{2}{E^*} = \frac{1}{E_1} + \frac{1}{E_2} \tag{6}
\]
with \( E = E_i/(1-\nu_i) \) for the plane strain and \( E = E_i \) for plane stress. \( K \) is the complex interfacial stress intensity factor (SIF) defined as

\[
K = K_1 + iK_2
\]  
(7)

By solving Eqs. (2-7), the individual SIF is obtained

\[
\begin{align*}
K_1' &= \left[ A \cos[dn(r/L)] + B \sin[dn(r/L)] \right]/D \\
K_2' &= \left[ B \cos[dn(r/L)] - A \sin[dn(r/L)] \right]/D 
\end{align*}
\]  
(8)

where

\[
\begin{align*}
A &= \delta_x - 2\epsilon \delta_x \\
B &= \delta_x + 2\epsilon \delta_y \\
D &= \frac{8}{E \cosh(\pi \epsilon)} \sqrt{\frac{r}{2\pi}} 
\end{align*}
\]  
(9)

and the phase angle is defined as

\[
\psi = \tan^{-1} \left( \frac{\text{Im}(K_2^\ast)}{\text{Re}(K_1^\ast)} \right)_{\epsilon=0}
\]  
(10)

Based on interface fracture mechanics, it is explicit that the fracture parameters, including strain energy release rate, stress intensity factor and phase angle, can be determined as long as one can obtain the CTODs \( \delta_x \) and \( \delta_y \) behind the crack with respect to a distance \( r \) away from tip.

3. Experimental details

3.1 Materials and specimen preparation

The assembly used in this study consists of three materials, namely, silicon chip, underfill and FR-4. A commercialized epoxy based underfill material supplied by Loctite® was used in this study. The composition of the material was 60% epoxy with 40% silica filling sizing from 1 to 4 \( \mu \)m. The glass transition temperature (\( T_g \)) of underfill was determined to be 105 \( ^\circ \)C using differential scanning calorimeter (DSC).

A specially designed mould, as shown in Fig. 3, was employed to prepare the sandwich sample with desired dimension, i.e. 8 mm\( \times 5 \) mm \( \times 1.8 \) mm, which were length, width and thickness respectively. Accordingly, the thickness of underfill layer was chosen to be 0.5 mm since the underfill layer thickness optimized for critical adhesion will not result in enhanced resistance to progressive debonding under cycling load, which was carried out in this experiment [14]. The pre-crack was made at the chip/underfill interface with length \( a=2.7 \) mm, and the ligament ahead of the crack tip \( w=5.3 \) mm, satisfying \( a, w > H + h + t \), where \( H, h, \) and \( t \) are the thickness of FR-4, silicon wafer and underfill respectively. The selection of these dimensions was to neglect edge effects on loading. Under these situations, a steady state solution was valid and any dependence of the energy release rate on the crack length was eliminated.
A dispenser and a curing oven were employed to prepare the SBN specimen. By following flip-chip packaging process, an optimized curing condition was defined to be 165 °C for 8 min. In order to measure the interface fracture toughness, a pre-crack was prepared on the chip passivation by using a piece of silicon rubber film with a thickness of 20 µm. Due to capillary action, underfill was dispensed into the gap between chip and FR-4. When the specimen was partially cured, the rubber was quickly removed from the specimen and a sharp crack was fabricated. After molding, each specimen was carefully polished with a fine SiC paper to remove excessive underfill and to obtain the desired dimensions.

3.2 Accelerated thermal test (ATC)

Accelerated temperature cycling (ATC) is the most common reliability test method used in industry. In this study, the pre-cracked specimen was put into a miniaturized thermal cycling chamber with temperature controller. The requirement of in-situ measurement was, therefore, achieved to investigate the deformation behavior of delaminated flip chip assembly under a single temperature cycling. According to JESD22-A104-A condition G standard, the temperature range was chosen to be −40 °C to 125 °C. Additionally, the dwell time (for creep), which was kept at temperature extremes, was set to 12 minutes. Each cycle was circulated within 70 minutes, and each temperature range was repeated four cycles. The fringe patterns were recorded at the specific temperature steps, e.g., −40 °C, −25 °C, 0 °C, 25 °C, 50 °C, 75 °C, 100 °C and 125 °C. The schematic diagram for the thermal cycling testing is illustrated in Fig. 4. The platform plotted in the figure shows time for recording fringe pattern images.

3.3 Materials properties

The materials of flip chip assembly, including silicon chip, underfill and FR-4, were modeled as temperature-dependent in fracture toughness calculation. The details are listed in Table 1. The mechanical properties of underfill material with respect to temperature were shown in Fig. 5 [15].

4. Results and discussion

4.1 Moiré fringe patterns under ATC test

The moiré fringe patterns were recorded according to ATC test profiles presented before. The patterns reflected the deformation with respect to different temperature stages and time intervals. As shown in Fig. 6, U and V field of sample deformation under the entire thermal cycling was measured using M3I system. The attention was focused on the crack and its flanks’ deformation behavior in case of thermal loading. CTODs from crack flanks during deformation was used to calculate the relative fracture parameters.
From the fringe patterns, it can be found that the thermal deformations increased with the temperature going high or minus. Because of low CTE and high Young’s modulus, silicon deforms the least compared to the other two materials. It can also be noted that, during heating process, the FR-4/underfill structure behind the crack tip bended down at the low temperature (such as 50 °C and 75 °C). However, the warpage reduced in bending displacement especially when the temperature (125 °C) went higher than glass transition temperature of underfill valued 105 °C. The change of this deformation trend can be observed clearly from fringe patterns of V displacement. When the specimen was cooled down, the structure had an opposite direction bending, whose magnitude increased continuously throughout the entire cooling process. And that when the specimen was cooled down to minus temperature, due to the CTE as well as stiffness mismatch between underfill and FR-4, the warpage of the structure became significant again for the part of coupled underfill and FR-4 component.

At the temperature above $T_g$, the coupling between silicon and FR-4 through underfill material tended to diminish and the assembly was going to a stress-release state. However, note that underfill experienced large inelastic deformation at this state due to large CTE (110 ppm/°C), the large strain would also consequently affect the interfacial reliability.
Fig. 6 Moiré fringe pattern under accelerated temperature cycling test: a) U field at 75 °C during heating up; b) V filed at 75 °C during heating up; c) U field at 100 °C during cooling down; d) V field at 100 °C during cooling down; e) U field at 50 °C during cooling down; f) V field at 50 °C during cooling down; g) U field at –40 °C during cooling down; h) V field at –40 °C during cooling down; i) U field at 0 °C during heating up; j) V field at 0 °C during heating up

4.2 Fracture behavior investigation

In this study, one of linear elastic fracture mechanics (LEFM) named CTOD method was used to investigate the fracture behavior under thermal cycling. The Dundur’s parameters changed as a function of elastic mismatch between chip/underfill since the elastic modules of underfill varied significantly when temperature went up around and even above the $T_g$. The corresponding fracture parameters were changed obviously. CTOD method was basically derived from moiré fringe pattern representing displacement along two crack flanks. Typical CTODs distribution of $\delta_x$ and $\delta_y$ within the temperature cycling was displayed in Fig. 7. It is shown that when the temperature cooled down to room temperature, residual deformation existed along crack flanks, which was generally influenced by the viscoelasticity of underfill. While in minus temperature loading, the time effect was minimized since elasticity behavior is dominant for underfill material.

Fig. 7 CTODs at $r/l=0.3$ throughout the temperature cycling by moiré experiment ($l=0.5 \text{ mm}$)
From the equations (2) to (10), $K_{\text{eff}}$, and $\psi$ with fixed distance $r$ from crack tip can be determined. In this study, a characteristic length $l = \eta_{\text{underfill}}$ valued 0.5 mm was selected as reference length since it is useful for discussing the mixed mode character of bimaterial crack solution, independent of material fracture behavior. The SIFs were calculated according to LEFM method as a function of $r$ distance away from crack tip. Afterwards, extrapolation is needed to obtain real fracture parameters at the crack tip. Under the assumption of linear elastic solution taking no account of plastic zone near the tip, a linear extrapolation was firstly verified to know its feasibility. Fig. 8 showed the CTOD value as well as effective $K$ with respect to the distance $r$ at $-25 \degree C$. The results showed that within $r / l = 0.3 \sim 0.8$, a general linear relation could be used for extrapolation. The consequent $K_{\text{eff}}$ and $\psi$ in the temperature cycling are plotted in Fig. 9. To avoid the coupling character of $K_1$ and $K_2$, $K_{\text{eff}}$, which is related to energy release rate, was introduced in this study.

During the process of heating, the acme of $K_{\text{eff}}$ happened at the temperature between 75 $\degree C$ and 100 $\degree C$ rather than 125 $\degree C$. From the definitions in Eqs. (6) to (10), it is anticipated that change of $E^*$ and consequently $D$ can change $K$ value apart from CTODs. This also implied that both CTE and stiffness mismatch could significantly influence the deformation and corresponding fracture parameters. In particular, when underfill was in the glass transition state, the dramatically deceased Young's modulus of underfill is thought to be the main reason for such peak shift. Similarly, the increase of underfill modulus at minus temperature was helpful to increase the $K$ value although the CTODs were almost same as those at 100 $\degree C$ (see Fig. 7). When the temperature went down, there is residual $K_{\text{eff}}$ generated with the comparison of prevented $K_{\text{eff}}$ during heating up process. This enlargement is aroused by viscoelastic history especially when temperature exceeded glass transition temperature. The shift sign of phase angle during cooling process, as presented in Fig. 9 b), showed alteration of the direction of shear stress inside the specimen.
As aforementioned, $K_{\text{eff}}$ decreased as stress relaxation happened in glass transition state of underfill. However, one cannot determine that the most dangerous stage in the thermal cycling is located at the point with highest $K_{\text{eff}}$, since the interfacial energy release rate varies with the mode mixity at the same time [16]. According to the definition of interfacial fracture extension, the expression can be

$$G = G_c (\psi)$$

$$\psi = \psi + \frac{2n}{L}$$

where $L$ and $\hat{\psi}$ are characteristic length and mode mixity respectively. From Eqs. (11), it can be seen that the critical value of $G_c$ becomes a curve with the function of mode mixity $\Psi$ rather than an independent point. Consequently, referring to the value in Table that was experimented by Suo [17], one can readily know that the smaller phase angle has corresponding smaller $G_c$, since mode I failure is more fatal than mode II. Apart from mode mixity, it is anticipated that temperature-induced moduli change will also decrease the interfacial toughness in case of the fixed phase angle [18]. From our previous study [11], it is also found that the effective fracture toughness of the assembly subject to the ATC loading is lower than that of chip/underfill interface under either mode I tension loading or mode II shearing loading, indicating that the interface is safe during the ATC test. It is therefore concluded that the system can be used as an accurate and effective experimental tool for the investigation of interface delamination reliability problems involved in various electronics packages.

5. Conclusions

In-situ measurement was carried out to investigate the thermal deformation and fracture parameters of delaminated flip-chip package under the $-40$ °C to $125$ °C thermal loading condition using high density laser M3I system.
It indicated that not only CTE mismatch is a main effect to cause internal stress intensity around the crack tip, but also stiffness mismatch plays important role on structure deformation and consequently stress intensity behavior. Therefore, underfill with high Tg and strong adhesion to its adherends is ideal for the encapsulant of solder joints. Since the fracture toughness was calculated with respect to different temperature and time, the fracture critical toughness measurement with various temperatures and phase angles in our previous work proved that the interface is safe during the ATC test for flip chip assembly.

References


