Thin Film Interface Fracture Properties at Scales Relevant to Microelectronics

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Abstract

Nowadays, one of the trends in microelectronic packaging is to integrate multi-functional systems into one package, resulting in more applications of highly dissimilar materials in the form of laminated thin films or composite structures. As a consequence, the number of interfaces increases. Often, the interface between these dissimilar materials is where the failure is most likely to occur especially when the packaged devices are subjected to the thermo-mechanical loading. Prediction of interface delamination is typically done using the critical energy release rate. However, the critical value is dependent on mode mixity. This paper describes our efforts on interface characterization as a function of mode mixity. A new test setup is designed for mixed mode bending testing. It allows for measuring the stable crack growth as the function of mode mixity. The crack length, necessary for calculation of the energy release rate is measured by means of an optical microscope. Finite element simulation is used to interpret the experimental results and thus to establish the critical energy release rates and mode mixities.

1. Introduction

Most micro-electronic packages are composite structures made up from multiple-materials among which thin film coatings. Generally, the interface between two different materials is a weak link due to imperfect adhesion and stress concentrations. At present, interfacial delamination is one of the major concerns in IC packages (figure 1). Failure of these interfaces induces decreased reliability and performance of such packages. Therefore, adequate knowledge of delamination prediction is desirable.

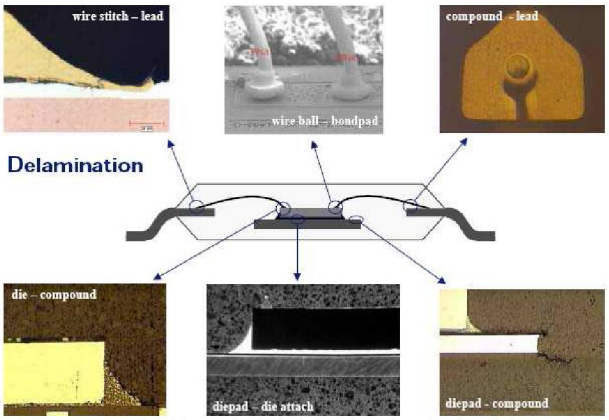

Figure 1. Typical interfacial delamination in lead frame based packages.

Recently, the extension of linear elastic fracture mechanics in homogenous material to bimaterial interface crack problems has become one of the interests. Many researchers have made important contributions on bi-material interface fracture mechanics. However, the analytical solutions are limited to very simplified cases and can not directly be applied to real engineering applications. General speaking, there are two approaches in fracture analysis: the stress intensity approach and the energy approach. The stress intensity approach regards the crack growth when the stress intensity factor exceeds a critical material specific fracture resistance. Comparing to the stress intensity approach, the energy approach is more attractive [1, 2]. It turns out that the crack propagates as a result of the so-called energy release rate exceeding its critical value. The critical value can be obtained experimentally. However, its measurement is complicated due to the fact that adhesion strength is not only temperature and moisture dependent but also stress state (mode mixity) dependent. In this research, a mixed mode bending method [1,5] is proposed, in which generally, interface delamination growth occurs under combined mode I (opening mode) and mode II (shearing mode) conditions. The mode mixity or mode angle is determined by the ratio from mode I to mode II loading. For an isotropic homogeneous material, a mode angle of 0° describes pure mode I, and mode angles of -90° or 90° describe pure mode II loading (shown in figure 2). In general, critical energy release rate is higher under mode II loading than under mode I loading.

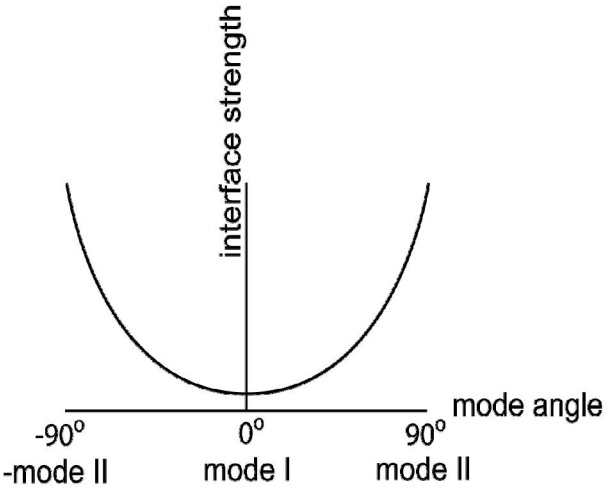

Figure 2. Interface strength versus mode angle.

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2. Theory of interfacial fracture mechanics

For an isotropic homogeneous material, usually a crack propagates along the path where pure mode I occurs. For dissimilar laminated thin films, due to material mismatch, the interface cracks propagate under mixed mode combined condition. This means that mode I, mode II and even mode III (3D case) may coexist together.

Linear elastic fracture mechanics is a theory that describes if and how a crack will grow under given loading conditions when assuming an initial crack with given size and location [3]. It assumes the existence of some detectable cracks and predicts the crack propagation during processing and operational cycles. It applies when the nonlinear deformation of the material is confined to a small region near the crack tip compared to the size of the crack. To predict interface delamination, fracture quantities are needed for comparison to the critical data such as fracture toughness. In general, stress intensity factors (SIF) and energy release rate are used to define the loading state at the crack tip.

A criterion for crack growth can be obtained by regarding the energy balance of the material (1), where U represents the energy per unit of time and volume.

$$U_e = U_i + U_a + U_d + U_k \tag{1}$$

U_e is the total external mechanical energy that is supplied to the material, U_i is the elastic energy that is stored in the material, U_a is the energy dissipated by crack growth, U_d is the energy dissipation caused by other mechanism, and U_k is the change in kinetic energy. It is assumed that U_d is zero, implying that the crack growth is the only cause of energy dissipation. U_k is zero means that crack growth is slow enough for changing in kinetic energy is negligible. The remaining energy balance is know as the Griffith's energy balance (2), which regards energy per unit of newly created fracture surface, or when the material is taken to be constant, per unit of crack length a:

$$\frac{dU_e}{da} - \frac{dU_i}{da} = \frac{dU_a}{da} \tag{2}$$

Dividing the left hand of equation by the material thickness B, it gives the energy release rate (3).

$$G = \frac{1}{B}\left(\frac{dU_e}{da} - \frac{dU_i}{da}\right) \tag{3}$$

The energy release rate G is known as Griffith's energy balance, which regards energy released per unit of newly created fracture surface when the crack grows a unit of length. The criterion from Griffith states that crack growth occurs when the energy release rate exceeds a critical value $G > G_c$. The energy release rate appears to dependent on temperature, moisture and mode mixity so that the criterion for fracture is:

$$G(T, C, \psi) > Gc(T, C, \psi)\ [2] \tag{4}$$

The mode mixity ψ for a homogeneous material is usually defined as the ratio between mode I to mode II loading and is described by the loading stress state at the crack tip (5).

$$\psi = arctg\frac{K_{II}}{K_I} \tag{5}$$

Here, K_I and K_{II} represent intensities of mode I (opening) and mode II (shearing) stress states for a crack in a homogeneous material. K_I characterizes the tendency of remote loads to open the crack, while K_{II} characterizes the shear loading.

For an interface crack, due to the elastic mismatch between two materials, the mode mixity can not be simply described by the equation 5. The opening and shearing stresses at the interface ahead of the crack tip, with a distance of r can be calculated from (6).

$$(\sigma_{22} + i\sigma_{12}) = \frac{K}{\sqrt{2\pi r}} r^{i\varepsilon} \tag{6}$$

Where σ_{12} represents shear stress and σ_{22} represents normal stress. ε is the oscillatory index which is a function of the Young's moduli and the Poisson's ratios. K is the complex stress intensity factor. It is described by:

$$K = K_I + iK_{II} \tag{7}$$

The mode mixity for an interface crack is described by:

$$\psi = \tan^{-1}\left(\frac{\sigma_{12}}{\sigma_{22}}\right) \tag{8}$$

According to the basic solution, stress components along the interface are oscillatory [2, 4] and thus can not well be obtained by numerical solutions. Therefore, often an alternative mode mixity definition is used, where the mode mixity is defined by interface stresses (normal and shear) at a chosen length $\hat{L}$ ahead of the crack tip:

$$\psi = \tan^{-1}\left(\frac{\mathrm{Im}(K\hat{L}^{i\varepsilon})}{\mathrm{Re}(K\hat{L}^{i\varepsilon})}\right) \tag{9}$$

Here the choice of $\hat{L}$ is somewhat arbitrary, but restricted by the dimensions of test samples and the applications within microelectronics.

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3. Design of the MMB setup

Measuring interfacial adhesion strength requires loading a sample consisting of two material layers. To determine the interfacial adhesion strength, various test methods (figure 3) have been used. Such as the double cantilever beam (DCB) test, three point bending (TPB) test, and four point bending (FPB) test etc. Note that using the shown test methods to determine the influence of mode mixity on the interfacial fracture toughness, combining normal and shear stresses on the delamination plane, different thickness ratio of material layers has to be generated. However, it is highly impractical as it requires the development of different types of samples for each mode mixity. Also, even when changing the thickness ratio, none of the shown test methods can cover the full range of mode mixity. Moreover, to determine pure mode I, pure mode II, and mixed mode critical values (G_{Ic}, G_{IIc}, and $G_c(\psi)$, respectively), different types of samples need to be subjected to different loading configurations. These configurations can involve different test variables and analysis procedures that can influence test results in ways that are difficult to predict.

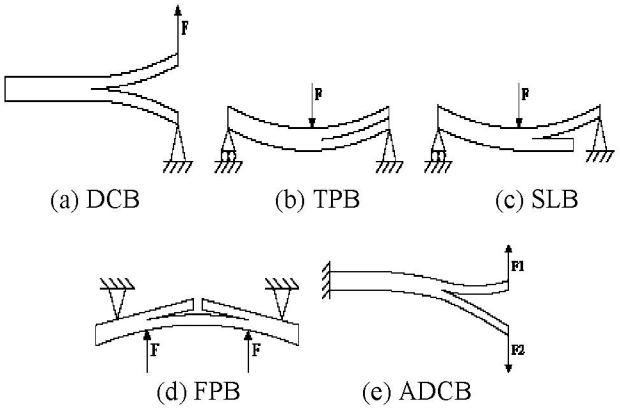

Figure 3. Different test methods for interface strength measurement: (a) Double cantilever beam, (b) Three point bending, (c) Single leg bending, (d) Four point bending, (e) Asymmetric double cantilever beam

The mixed mode bending test method (figure 4), which is used in this research, was first introduced by Reeder and Crews [1990]. This method has been widely used for measuring the interfacial strength experimentally. It provides the stable crack growth over the full range of mode mixities. In their published paper, it had also been proved that the MMB test was rather simple and was believed to offer several advantages over most current mixed mode test methods [5].

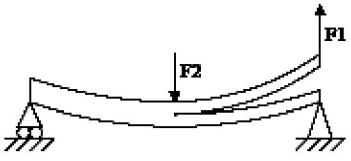

Figure 4. Mixed mode bending (MMB) test method

The test setup is designed and fabricated especially for the mixed mode bending test. It allows transferring two separated loads on a single specimen. A schematic drawing is shown in figure 5.

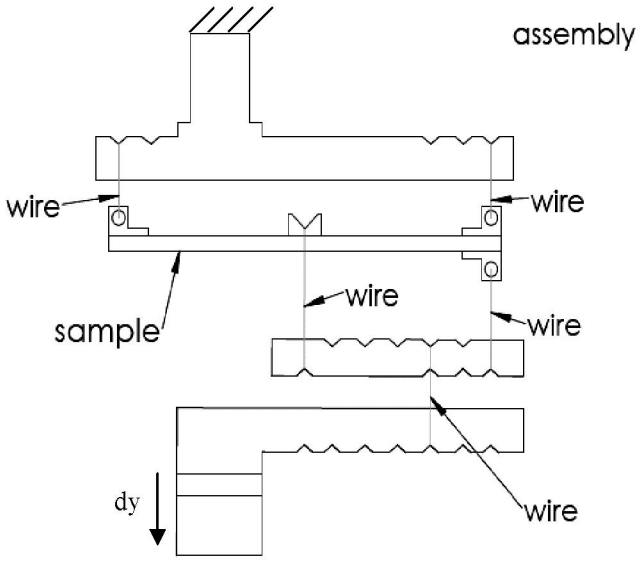

Figure 5. Schematic drawing of the MMB setup

The setup consists of two loading beams and a lever, three attachment hinges, one protecting metal block and several wires. A sample is first glued in between the hinges. The hinges are linked by the wires, and the wires are hitched on the beams and lever. The protecting block is glued on the middle of the sample. This metal block is used to prevent the sample damage and also to prevent wire sliding along the horizontal direction during the experiment. By changing the loading position of the lowest wire, different mode mixities can be controlled. The mode II TPB test occurs when we do not use the lever and directly connect the middle of the sample with the lower loading beam. Mode I DCB test occurs when remove the protecting block, middle beam and left hinge and hitch the lower hinge with wire on the lower beam. The notches on the beams are used to provide the test abilities for different sample length. When attaching a sample in the setup, it seems that the sample is loaded immediately due to the gravity of the middle load transfer beam. However, the weight of this beam is very small. It is not expected that this mass will propagate the initial crack of the sample. The small load of this beam can be simply added to the sample load when interpreting the results of the loading system.

4. Experiment results

In this study, the interface between copper and die attach is investigated. The sample is 28 mm long, 1.2 mm thick and 3 mm wide. It consists of two 5.6 mm thick bonded substrates, two 30 micron thick layers of copper

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and a 20 micron thick layer of glue. A schematic drawing is shown in figure 6.

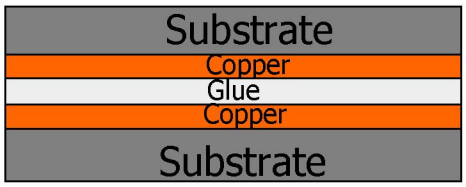

Figure 6. Schematic drawing of test sample

In order to characterize the interface strength more accurately, the test samples are created with identical fabrication processes and materials as used in creating the microelectronic components. The initial pre-stress levels in the test sample are known to play a predominant role in the crack growth behaviour. It is important to note that for large scale samples, high residual stresses may disturb the experiment significantly.

The experiments are performed at room temperature. Firstly, a specially prepared test sample is placed in the load transfer setup. Then, the setup is clamped in a micro tensile tester (actually a sensitive dynamic mechanical analyzer is used), in which various temperature and moisture combinations can be applied. The crack length is monitored and used for calculating the critical energy release rate. It is measured directly using an optical microscope.

Figures 7, 8 and 9 show the force-displacement results from a DCB test, a MMB test (performed at mid loading point), and a TPB test (here the sample is destroyed directly after crack initiation).

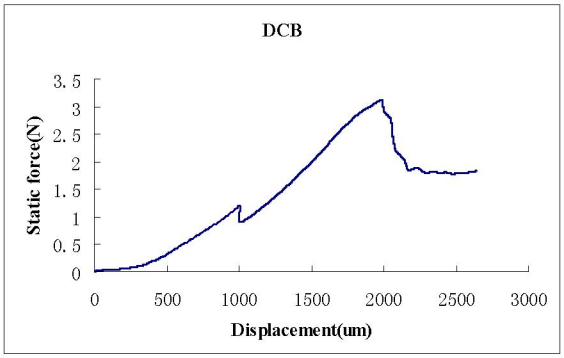

Figure 7. DCB test

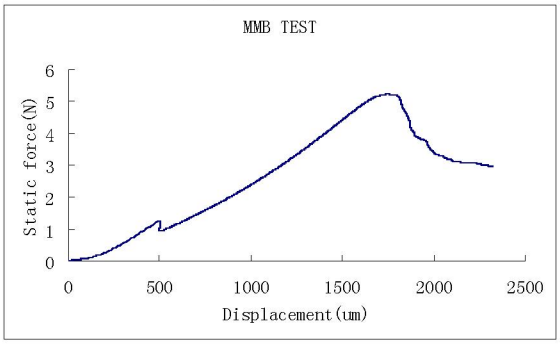

Figure 8. MMB test

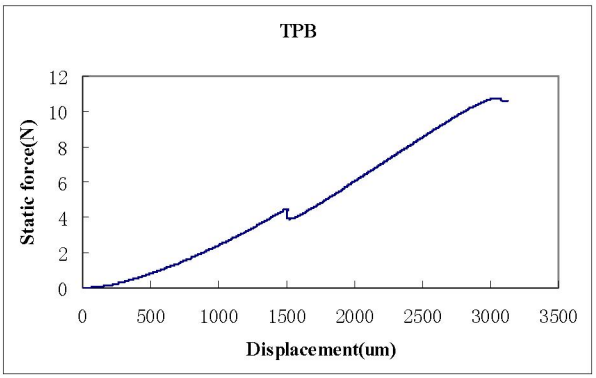

Figure 9. TPB test

Note that in order to speed up the test, at the beginning the system is loaded at high rate. Then, the system stops for 1 minute, and afterwards, it is loaded at low rate continuously. From the test results, initially, the force - displacement curve represents the opening of the pre-crack. When the pre-crack starts to propagate, the force decreases. It is found that the crack growth initially is not stable.

From the graphs, it is found that the tests start with a non-linear response. This is because the test setup consists of wires and these wires provide inelastic deformation. The area under the measured force-displacement curve does not equal the sum of the energy that has been used for a crack growth and the elastic energy stored in the sample. It also contains the energy that is dissipated by the wires. Numerically, it is difficult to include the behaviour of the wires in the finite element simulation. Therefore, the force and crack length relations are measured. A result is shown in figure10.

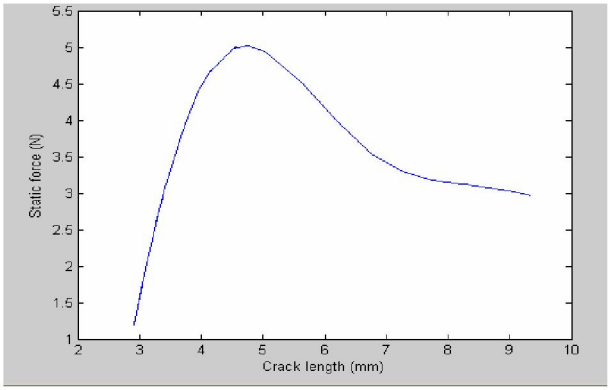

Figure 10. Crack length versus static force

4. Finite element analysis

Experimental data from MMB, DCB, and TPB tests is interpreted through finite element fracture mechanics simulations using a modified *J* integral concept [6]. The model is shown in figure 11. Quarter-point elements were used around the crack tip to capture the stress singularity.

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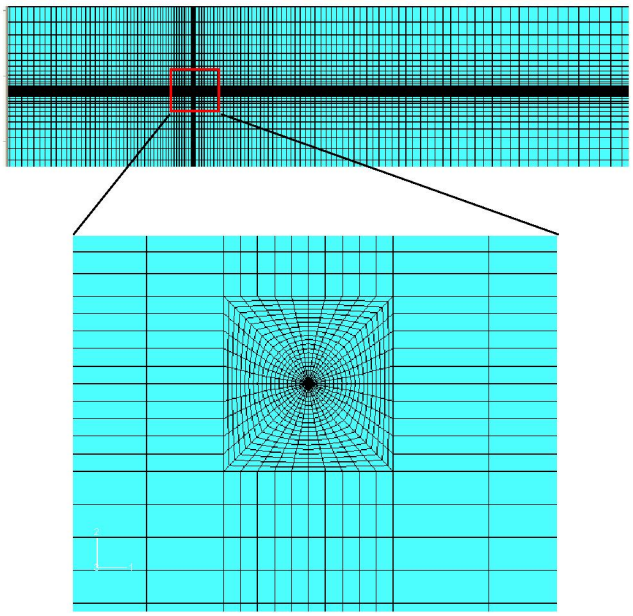

Figure 11. Geometry of 2D FEM model and crack tip mesh

For each crack length the loading is taken from the force-crack length graph. Than a model with the same crack length and loading is used to establish the energy release rate (through J-integral calculation). This established energy release rate is considered as the critical one G_c. The matching mode mixity is calculated with reference length equal to 0.15mm. The result is shown in figure 12.

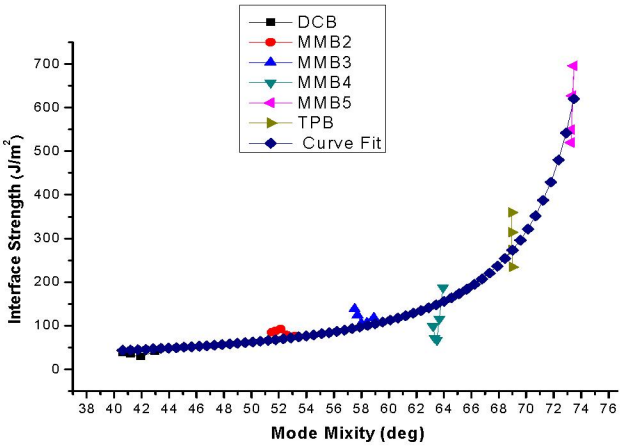

Figure 12. Interface strength versus mode mixity

5. Discussion

The result in figure 12 clearly shows the relationship between interface strength and mode mixity. The interface strength has a minimum mode mixity of 42° (depending on the reference length). One would expect that the minimum interface strength to occur at a mode mixity close to 0°. The definition of mode mixity used to design the test is based on the arbitrarily chosen reference length. In this study, a reference length of 0.15 mm is chosen. Changing the reference length will shift the curve horizontally. According to equation 9, a reference length of 20 micron (thickness of the glue) would result in a horizontal shift to the right of ~10 degree.

It is also found that glue stiffness plays a dominant role in the mode mixity calculation. Low stiffness of glue could also shift the mode mixity curve. Increasing glue stiffness may indeed decrease the mode mixity. Figure 13 shows the glue young's modulus as function of DCB mode mixity. This result proves that the reason caused mode mixity shifts, is actually the effect of non-linear deformations.

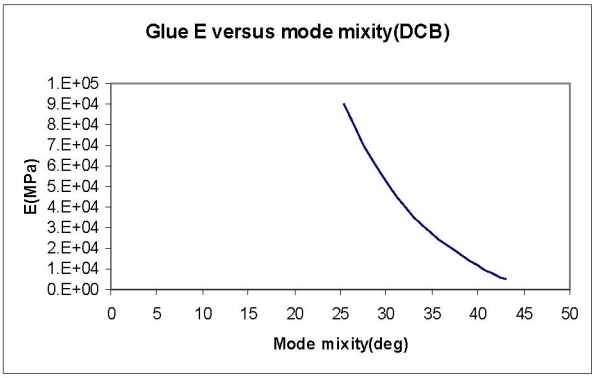

Figure13. Glue Young's modulus versus DCB mode mixity

6. Conclusions

A newly designed mixed mode bending setup has been used to analyze the interface strength of copper and die attach. The force is measured using a DMA test facility as tensile tester and the crack length is obtained using a microscope. The finite element analysis is used to calculate the critical energy release rate and mode mixity. The results are used to determine the critical energy release rate as a function of mode mixity.

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