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Characterizing the Interfacial Fracture Toughness for Microelectronic Packaging

Z. Chen, B. Cotterell and W. T. Chen*
Institute of Materials Research and Engineering, 10 Kent Ridge Crescent, Singapore 119260
** Correspondence to: Z. Chen, Institute of Materials Research and Engineering, 10 Kent Ridge Crescent, Singapore 119260.*

In a microelectronic package there are many interfaces where the adhesion between different materials plays an important role in its reliability issue. Take an example in a flipchip package: delamination at the interfaces between underfill/passivation, underfill/substrate, etc. will lead to the speeded breakdown of the interconnection. Proper characterization of interfacial adhesion strength is very important for process control as well as reliability prediction.

From a fracture mechanics point of view, a strained body with defects will break when the rate of change in its potential energy G reaches a critical value G_c (toughness). In this paper both analytical and experimental descriptions are given on the determination of G_c using single cantilever beam (SCB) specimens. A composite beam on an elastic foundation model is employed to interpret the testing results once the modulus of the foundation is known. The modulus of the foundation can be estimated by analytical approach or deduced from the experimental record. The approach described in our paper is generically suitable for many more interfacial toughness determinations.

INTRODUCTION

Packaging plays an important role in the microelectronics industry: sound packaging guarantees the designed life-span of the device. The demand for higher and higher performance at ever lower cost has posed a great challenge to the packaging community to come up with new designs and to employ novel materials. Before applying the new process, one of the major concerns is whether or not the coming products will reach the targeted reliability and yield. Most of the time, it is those numerous interfaces in a package that will fail under the stringent working conditions (temperature, humidity, etc.). Therefore, there is a great demand to understand the interface and to characterize properly the interfacial strength.

The surface science concept of work of adhesion, obtainable from contact angle measurements, had been employed as a measure of the strength of the interface. This is a reversible, molecular-scale thermodynamic description. Although it does give an indication of whether or not the two materials 'like' each other, this parameter does not necessarily produce a quantitative signal of the actual mechanical bonding strength at the interface. The reason for this is that the fracture is a mechanical phenomenon, which will have to take into account any influence from existing defects, non-reversible dislocation motion in metals or crazing in polymers. As observed by Irwin[1] and Orowan,[2] the separation work of engineering materials is a few orders larger than the surface free energy in a bulk material. The same is true for the interfacial fracture. Therefore, the thermodynamic interfacial work of adhesion is negligible compared to the mechanical work of fracture, or fracture toughness. Traditional mechanical adhesion tests, such as stud pull and lap shear, do not correspond well to the strength of the interface because they do not assume defects. To avoid confusion, throughout this paper we will use the term 'work of adhesion' as the thermodynamic measurement and the term 'fracture toughness' as the mechanical measurement of the strength of the interface, respectively.
It is, however, apparent that the surface condition will affect the adhesion and thus the interfacial fracture toughness, even though the thermodynamic work of adhesion may have missed some important factors. There has been some work trying to link the thermodynamic work of adhesion to the fracture toughness, e.g. Refs 3 and 4. However, experimental data seem to suggest that higher work of adhesion does not necessarily lead to higher fracture toughness.[4] The situation has created a need for multidisciplinary studies from surface science, materials science and mechanical engineering. This joint effort is crucial to the fundamental understanding of the mechanical integrity of interfaces. In this paper we will describe a simple way to carry out the mechanical aspect of such an effort.

As has been pointed out by Chen *et al*.,[5] rapid development of the microelectronics industry has pushed the packaging community into expanding their knowledge base for a more fundamental understanding of the packaging problems. Interfacial fracture mechanics has been identified as one of the 'new' tools for microelectronic packaging. Recently there has been development in such a direction.[6,7] The testing methods reported so far have been quite diversified, ranging from three-point bending, four-point bending and mix-mode bending (MMB) to double cantilever beams, etc. In this paper we are aiming to devise a simple plan that enables tests on a real package. The ability to do this will facilitate both the production engineers in their packaging process control and the packaging researchers in their fundamental studies.

EXPERIMENTAL SCHEME

In order to accommodate a real microelectronic package, a single cantilever beam (SCB) scheme was chosen, as shown in Fig. 1. In this fixation, the package (a flipchip in this case) was attached to a steel block on its substrate side and to a cantilever beam on the chip side.

Before the attachment, a crack was introduced at the interface of interest, e.g. between the chip passivation and the underfill. There were many ways to make such a pre-crack, such as spreading weakening agents like Teflon powder, mould release, etc. or vapour depositing a thin solid layer of material of weak adhesion. In our study we wanted to keep the surface chemically intact for surface analysis before and after the test, therefore spreading powders is not considered because this may introduce surface contamination. We have used two methods of pre-cracking: vapour depositing a thin layer of gold (100 Å) on the silicon passivation side; and covering the passivation surface with thin film (5 μm). The packages were then assembled in the usual way. Both the surfaces of the silicon passivation and the FR-4 substrate were not treated.

The test was carried out in an Instron machine with our in-house attaching fixture. The load-displacement curve was recorded for further analysis.

FRACTURE MECHANICS

From a fracture mechanics point of view, a strained body with defects will break when the rate (with respect to defect size) of change in its potential energy G reaches a critical value G_c that depends on the mode mixity. This value is an indication of the structure's ability to resist fracture, which is called fracture toughness. Irwin[8] defined the mathematics to calculate G in an elastically strained body as

$$G = \frac{\mathrm{d}U_{\mathrm{ext}}}{\mathrm{d}A} - \frac{\mathrm{d}\Lambda}{\mathrm{d}A} \qquad (1)$$

where A is the crack area, U_{ext} is the external work and Λ is the internal elastic strain energy. An alternative form of Eqn (1) that is more conveniently linked to experimentally measured data for elastic fracture is the so-called compliance method

$$G = \left.\frac{\mathrm{d}\Lambda}{\mathrm{d}A}\right|_{\mathrm{p}} = \frac{1}{2}P^2\frac{\mathrm{d}C}{\mathrm{d}A} \qquad (2)$$

where P is the load, C is the compliance, which equals δ/P, and δ is the loading-end displacement. This method enables calculation of the potential energy release rate of any geometry from the compliance.

The testing fixation in Fig. 1 can be modelled basically as a beam on elastic foundation (see Fig. 2). We tentatively assume that the beam is uniform throughout the loading point and the back end of the attachment. Besides the compliance from bending the beam, there is an extra source of compliance from materials underneath the crack plane (mainly due to the underfill layer and the substrate), which will be accounted for by the elastic foundation.

Under such a model, the governing equation can be written as

$$\begin{cases} E'I\dfrac{\mathrm{d}^4u(x)}{\mathrm{d}x^4}+ku(x)=0 & \text{for} \quad x\geq 0 \\ E'I\dfrac{\mathrm{d}^4u(x)}{\mathrm{d}x^4}=0 & \text{for} \quad x<0 \end{cases} \tag{3}$$

where u is the deflection of the beam, I is the second moment of area of the beam, k is the modulus of the foundation. E' is Young's modulus E for the plane stress condition, and equals $E/(1 - \nu^2)$ for the plane strain condition, where ν is Poisson's ratio. Here we are treating the beam as having limited length. The boundary conditions are that the shear force and the moment at the back end ($x= c$, where c is the ligament length) are both zero and those at the loading point $x = -a$ are equal to P and zero, respectively. Solving the two equations in Eqn (3) separately and matching the first three derivatives and u at $x = 0$, the end displacement of the beam can be worked

$$\begin{aligned} \delta = u(-a) = \frac{Pa^3}{3E'I}\Bigg[1+\frac{3}{\beta a}\left(\frac{\sinh\beta c\cosh\beta c+\sin\beta c\cos\beta c}{\sinh^2\beta c-\sin^2\beta c}\right) \\ +\frac{3}{\beta^2 a^2}\left(\frac{\sinh^2\beta c+\sin^2\beta c}{\sinh^2\beta c-\sin^2\beta c}\right)+\frac{3}{2\beta^3 a^3} \\ \times\left(\frac{\sinh\beta c\cosh\beta c-\sin\beta c\cos\beta c}{\sinh^2\beta c-\sin^2\beta c}\right)\Bigg] \end{aligned} \tag{4}$$

where $\beta = \sqrt[4]{k/(4E'I)}$, a is the crack size and c is the ligament length. The energy release rate can then be calculated according to Eqn (2) as

$$G = \frac{P^2 a^2}{2BE'I}\left[\left(\frac{\sinh^2 \beta c + \sin^2 \beta c}{\sinh^2 \beta c - \sin^2 \beta c}\right) + \frac{1}{\beta a}\left(\frac{\sinh \beta c \cosh \beta c - \sin \beta c \cos \beta c}{\sinh^2 \beta c - \sin^2 \beta c}\right)\right]^2 \quad (5)$$

where B is the width of the beam, because we use a beam of rectangular cross-section.

Looking at Eqn (5), most of the information needed to calculate *G* either can be measured from the specimen, such as the beam dimensions or crack size, or read directly from the test record, such as the load *P*. The only unknown parameter is *k*: the modulus of the foundation. The value of *k* can be obtained both analytically[9] and experimentally. Analytically, the modulus of the foundation can be estimated by assuming a series of biaxially constrained thin layers. For such a system, *k* is worked out as the combination of a series of foundations

$$k = \frac{1}{\sum_{i=1}^{n} \frac{1}{k_i}} \quad (6)$$

where *ki* is the contribution from the *i*th layer (see the Appendix for detailed calculation and discussion of *k* and *ki*).

Experimentally for a linear elastic fracture test record, the compliance of the test record, C = δ/P, can be obtained easily. The value of *k* will be known by solving the following non-linear equation

$$C = \frac{a^3}{3E'I}\left[1 + \frac{3}{\beta a}\left(\frac{\sinh \beta c \cosh \beta c + \sin \beta c \cos \beta c}{\sinh^2 \beta c - \sin^2 \beta c}\right) + \frac{3}{\beta^2 a^2}\left(\frac{\sinh^2 \beta c + \sin^2 \beta c}{\sinh^2 \beta c - \sin^2 \beta c}\right) + \frac{3}{2\beta^3 a^3}\left(\frac{\sinh \beta c \cosh \beta c - \sin \beta c \cos \beta c}{\sinh^2 \beta c - \sin^2 \beta c}\right)\right] \quad (7)$$

A slight complication in the interpretation of our test, by the model in Fig. 2 and Eqns (5) and (7) derived from it, is that in reality the beam cannot be modelled as uniform thickness throughout. As shown in Fig. 1, the silicon chip is composited with the beam at

one end. Because the adhesive between them is very thin and the joint between the beam and the chip will not break during the test, we have to consider a partially composite beam on an elastic foundation model, as shown in Fig. 3. We define a composite value of E'_cI_c as

$$E'_cI_c = E'_1I_1 + E'_2I_2 \qquad (8)$$

where I_1 and I_2 are the moments of the beams to the neutral axis of the composite beam. Subscripts 1 and 2 refer to the two materials.

All the other assumptions of the new model are the same. Without going into details again, we present the solutions directly. The compliance equation for this fixation is

$$C = \frac{a^3}{3E'_cI_c}\left\{\left[1 + \frac{3}{\beta a}\left(\frac{\sinh\beta c\cosh\beta c + \sin\beta c\cos\beta c}{\sinh^2\beta c - \sin^2\beta c}\right) + \frac{3}{\beta^2a^2}\left(\frac{\sinh^2\beta c + \sin^2\beta c}{\sinh^2\beta c - \sin^2\beta c}\right) + \frac{3}{2\beta^3a^3}\left(\frac{\sinh\beta c\cosh\beta c - \sin\beta c\cos\beta c}{\sinh^2\beta c - \sin^2\beta c}\right)\right] + \left(\frac{a_c}{a}\right)^3\left(\frac{E'_cI_c}{E'I} - 1\right)\right\} \qquad (9)$$

where k is now calculated as $\beta = \sqrt[4]{k/(4E_c'I_c)}$, a_c is the part of the beam that is not composited with the silicon chip and a is the crack size (see Fig. 3). The fracture toughness is in a very similar form

$$G = \frac{P^2a^2}{2BE'_cI_c}\left[\left(\frac{\sinh^2\beta c + \sin^2\beta c}{\sinh^2\beta c - \sin^2\beta c}\right) + \frac{1}{\beta a}\left(\frac{\sinh\beta c\cosh\beta c - \sin\beta c\cos\beta c}{\sinh^2\beta c - \sin^2\beta c}\right)\right]^2 \qquad (10)$$

The only difference is that $E'I$ has been replaced by E'_cI_c. We use Eqns (9) and (10) for our analysis, with an experimentally determined value of k.

RESULTS AND DISCUSSION

We have tested flipchips of size 10 mm × 10 mm × 0.67 mm. The substrate is 0.25 mm thick FR-4 laminate. The gap between them is ~0.1 mm, varying slightly between samples. There have been two major types of fracture path observed: cracking between the chip and the underfill; and delamination within the FR-4 substrate. In the former case, the interfacial toughness value, using a commercially available underfill material, is -30 J m^{-2}. However, when this interface is stronger, the substrate, being a laminate material itself, will delaminate. As has been mentioned before, the surface conditions of the chip and the substrate were not controlled in our experiment. Weak adhesion may happen as a result of surface contamination, residual flux or trapped air during dispensing, etc. Further work is needed to study the effect of surface conditions on the fracture toughness.

We have not studied the effect of mode mixity on the fracture toughness. The testing plan presented here should be able to be adapted to different mode mixity by either varying the combination of thickness of the beam/crack length or simply tilting the whole testing fixture to a certain degree. In the latter case, finite element calculation may be necessary for an accurate result.

We have presented a simple way to test the fracture toughness of interfaces and the related calculation formula. Although experimentally we only demonstrate the application of fracture mechanics to the chip/underfill interface, this approach is generically applicable to other interfaces, as well as to the evaluation of temperature and moisture effects. The latter have become more and more important because plastic packaging is widely used nowadays.

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APPENDIX

The assumption of biaxially constrained thin layers is not unreasonable because in a package the underfill layer and substrate have much larger in-plane dimensions than the thickness and the whole stacks are held tightly by a rigid testing block (see Fig. 1). For a layer of isotropic material such as the underfill, its modulus can be worked out by Hooke's law as[9]

$$k_i = \left(\frac{B}{t_i}\right)\left[\frac{E_i(1-\nu_i)}{(1+\nu_i)(1-2\nu_i)}\right] \qquad (11)$$

where E_i and ν_i are Young's modulus and Poisson's ratio of the material, respectively, and t_i is the thickness of that particular layer. A typical substrate material such as FR-4 is laminated composite and can be described best as orthotrophic; the modulus can be calculated as

$$k_i = \left(\frac{B}{t_i}\right)\left[\frac{E_{2i}(1-\nu_{13i}\nu_{31i})}{(1-\nu_{13i}\nu_{31i}-\nu_{12i}\nu_{21i}-\nu_{23i}\nu_{32i}-2\nu_{12i}\nu_{23i}\nu_{31i})}\right] \qquad (12)$$

where E_{2i} is the Young's modulus in the thickness direction. After working out individual layers, Eqn (6) will be used to calculate *k*.

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Figure 1 The SCB testing plan.

Figure 2 Beam on elastic foundation model.

Figure 3 Composite beam on elastic foundation model.

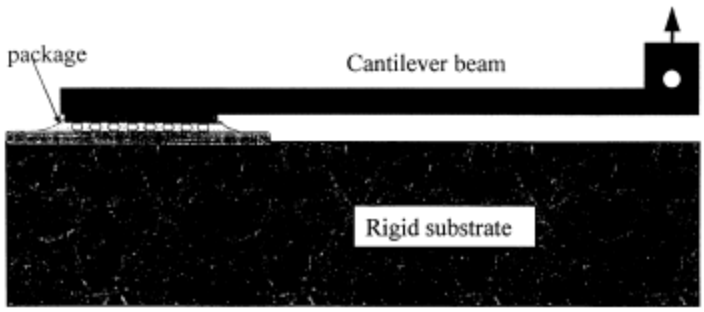

Figure 1

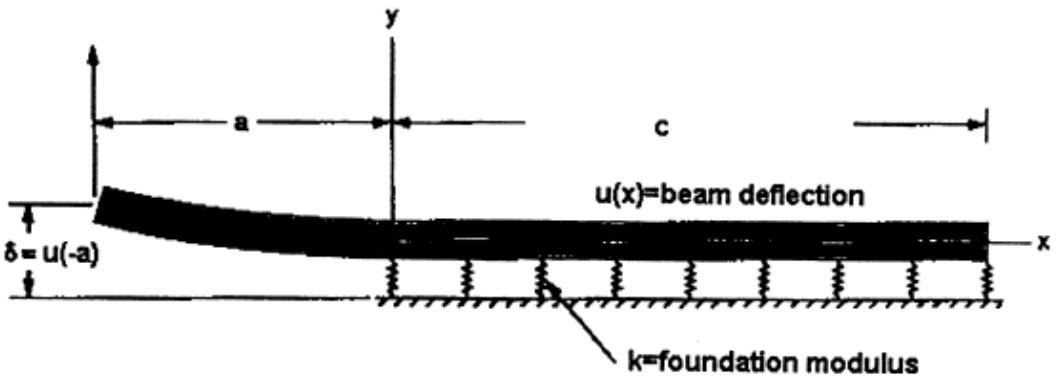

Figure 2

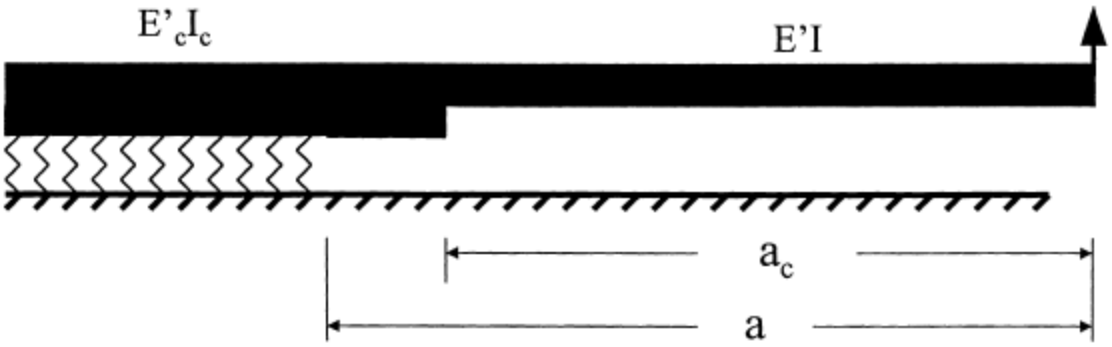

Figure 3