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Four Point Bending Test for Adhesion Testing of Packaging Structures: A Review

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Abstract: To establish the reliability of a packaging structures, adhesion testing of key interfaces is a critical task. Due to the material mismatch, the interface may be prone to delamination failure due to conditions during the manufacturing of the product or just from the day-to-day use. To assess the reliability of the interface adhesion strength testing can be performed during the design phase of the product. One test method of interest is the four-point bending (4PB) adhesion strength test method. This test method has been implemented in a variety of situations to evaluate the adhesion strength of interfaces in bimaterial structures to the interfaces within thin film multilayer stacks. This article presents a review of the 4PB adhesion strength testing method and key implementations of the technique in regards to semiconductor packaging.

Keywords: four-point bending (4PB), adhesion, thin structures, multi-layers, packaging

1. Introduction

With the advancement of thin-profile designs of semiconductor packages, in-situ reliability assessments early in the design process is a critical challenge. One reliability concern in particular is delamination occurring at key interfaces in packages. To assess the reliability of an interface, adhesion strength testing can be employed to quantitatively characterize the integrity of the interface.

From experimental testing two key reliability parameters are established to characterize the reliability of the interface: the critical interfacial energy release rate, G_c , and the mode mixity, Ψ . The critical interfacial energy release rate is an indication of the adhesion strength and represents the interfaces resistance to delamination, whereas the mode mixity indicates the ratio of shear-to-opening loading the interface is under.

Several conventional adhesion strength test methods that have been applied for adhesion strength testing include double cantilever beam (DCB)¹⁻⁷⁾, four-point bending (4PB) with side cracks testing method⁸⁾, and 4PB with a central notch.^{2, 8-12)} Each technique has distinct advantages and disadvantages.

The DCB technique, where a precrack is placed in a bimaterial sample and loaded in tension, allows for testing in a near mode I condition. As seen in Figure 1, tensile

loading is applied at both ends of the cantilever beam at a constant displacement rate until the precrack propagates along the interface of interest. From the critical load and the precrack length the energy release rate can be assessed from the compliance of the system.¹³⁾ The system can be reset and tested again at a new crack length as seen in Figure 2 for multiple G calculations from a single sample. While this test does allow for multiple data points from a single sample and testing in a near mode I condition, the sample preparation for the precrack and alignment of the loadings is difficult, which adds unwanted uncertainty to this method.

Another adhesion strength testing approach is the four-point bending (4PB) with side cracks method which involves two symmetric side cracks placed on a multilayer

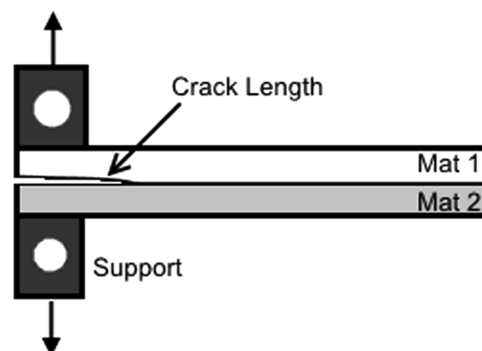


Fig. 1. Schematic of bimaterial double cantilever beam test.

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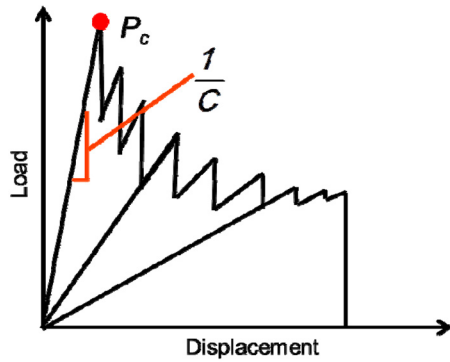


Fig. 2. Schematic of typical load vs. displacement curve in DCB testing.

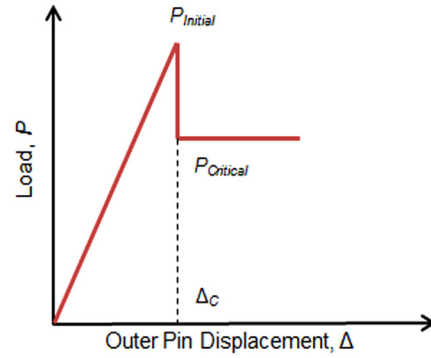


Fig. 5. Schematic of typical load vs. displacement curve in 4PB test method with a vertical center crack.

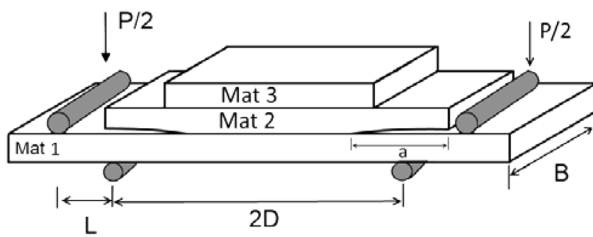


Fig. 3. Schematic of symmetric side crack 4PB testing.

specimen.^{8, 14, 15)} A schematic of this setup is seen in Figure 3. The specimen is aligned in a 4PB fixture and monotonic displacement loading is applied until the cracks delaminate along the interface. Since both crack tips are within the inner loading pins, each side of the crack is subjected to the same constant moment. The displacement continues until both cracks delaminate along the interface of interest at a critical load. From that point the J-integral method^{16, 17)} is applied to evaluate the energy release rate of the interface. A major advantage of testing in 4PB is that the energy release rate can be determined without a crack length measurement. However some disadvantages of testing in this configuration stem from the larger mode mixity at the interface and the difficulty of creating two perfectly symmetric precracks during sample prep which can lead to added uncertainty in testing results.

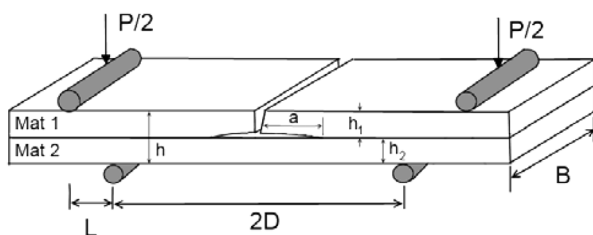


Fig. 4. Schematic of a 4PB setup for a vertical center crack.

The last case considered is a 4PB test method with a central crack. This test method is quite similar to the previous 4PB method except that before testing only a vertical notch is made to the interface of interest in the middle of the bimaterial sample^{2, 9)} (Figure 4). Loading is then applied in a similar manner until the crack initiates along the interface of interest at an initial load, $P_{initial}$. At this moment the load will drop as the crack begins to initiate. The crack then begins to stably propagate along the interface of interest at a critical load, $P_{critical}$, due to the constant moment region between the inner loading pins. This region is known as a steady state region. Figure 5 depicts a typical load vs displacement diagram for this type of testing. Using the critical load from testing the energy release rate can be evaluated from analytical methods. Similar to the previous 4PB testing method this method also has a larger mode mixity due to the nature of 4PB loading, but has the advantage of easier sample preparation and having a crack length independent method to calculate the energy release rate, which greatly reduces uncertainty in measurements.

Among these three techniques, the 4PB test method with a vertical center crack is further investigated in this paper. While each technique mentioned above has its own advantages and disadvantages, crack length independent testing is most attractive due to reduced testing uncertainty, and most practical to implement in reality. Additionally there has been an uptick in recent years of 4PB with center crack applications as opposed to the other testing techniques. Following will be a more in depth description of the 4PB test method with a vertical center crack, implementations of the method for specific problems and interfaces, and finally a look at the particular challenges when extending this test method to evaluate key interfaces in thin multi-layer packaging structures.

2. Four-Point Bending Test with Vertical Center Crack

Several authors have examined different application of 4PB and have helped to extend the technique.^{8-11, 18-20} The four-point bending adhesion strength testing method was initially proposed by Evans and Charalambides^{2, 9} for assessing the adhesion strength of bimaterial interfaces in mixed mode conditions.

A schematic of a typical 4PB specimen can be seen in Figure 4. In this configuration, a bimaterial sample is notched in the center and a predefined crack length, a , was then created by applying clamps to the structure and applying load until the crack advanced to the end of the clamps. The specimen is then placed under a four-point bending loading fixture and outer pin displacement is increased monotonically. Since the precrack has already been established the load increases until the critical load, $P_{critical}$ is reached. At this point the crack will continue to delaminate stably along the interface due to the center of the specimen being under a constant moment condition as in Figure 5. The delamination will continue along the interface at the critical load until the crack reaches the inner loading pins. This critical load can be used to assess the energy release rate, G , of the interface-of-interest analytically by applying beam theory and assuming plane strain conditions⁹:

$$\frac{E_2 G h^3 b^2}{P_{crit}^2 (1-\nu_2^2)} = \frac{3}{2} \left\{ \frac{1}{\left(\frac{h_2}{h}\right)^3} - \frac{\lambda}{\left\{ \left(\frac{h_1}{h}\right)^3 + \lambda \left(\frac{h_2}{h}\right)^3 \right\} + 3\lambda \frac{h_1 h_2}{h^2} \left(\frac{h_1}{h} + \lambda \frac{h_2}{h}\right)} \right\} \quad (1)$$

where

- l = pin spacing,
- E_i = modulus,
- b = width,
- h_i = thickness,
- ν_i = Poisson's ratio, and
- λ = plane strain constant.

Evans and Charalambides detailed the fundamentals of

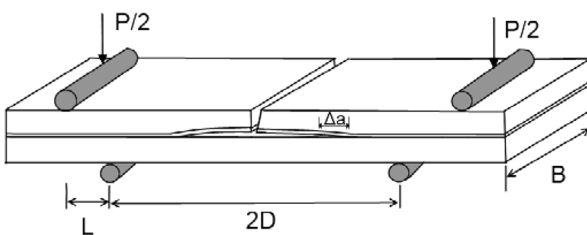


Fig. 6. Schematic of a 4PB setup with a thin film stack sandwiched between two much larger substrates.

this test method and examined how the energy release rate and mode mixity are a function of the crack length, pin spacing, and modulus ratio between the two materials.^{9, 19} The authors then applied this approach to evaluate an ideal interface of aluminum/PMMA materials. For this particular interface the typical adhesion strength results of this interface were on the order of 12 J/m².

3. Implementations of 4PB Test with Vertical Center Crack

Several authors have implemented the 4PB method with a vertical center crack to evaluate the adhesion strength of particular interfaces-of-interest.

3.1. “Essentially Homogeneous” Approach for Thin Film Stacks¹⁰

Later on Dauskardt implemented this approach to evaluate the adhesion strength of a SiO₂/TiN interface in thin film stacks. By sandwiching the thin film stacks between massively large silicon substrates, as seen in Figure 6, an essentially homogeneous structure was assembled and a simplified analytical solution was applied to evaluate the energy release rate from testing¹⁰:

$$G = \frac{21(1-\nu^2)M^2}{4Eb^2h^3} \quad (2)$$

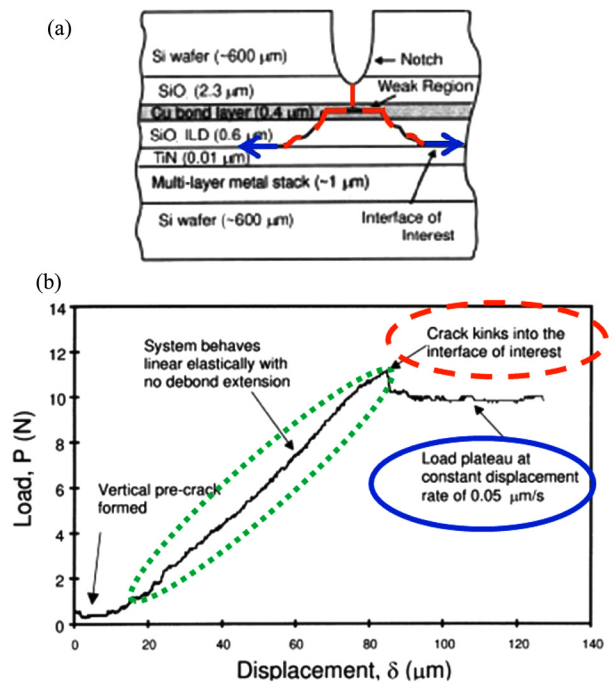


Fig. 7. (a) Thin film stack sandwiched in Dauskardt's implementation, and (b) the load vs. displacement graph for 4PB testing of SiO₂/TiN interface.¹⁰

where M is the critical moment and the material properties of the silicon substrates are used.

A weak intermetallic layer was used in the thin film stack (Figure 7a) to initiate a precrack to the interface of interest during testing. The benefit of this weak intermetallic layer is seen in the load vs. displacement curve in Figure 7b. The displacement is increased monotonically for the duration of the test. Once a critical initial load is reached, the crack propagates from the vertical notch to the weak copper bond layer of the thin film stack and then kinks downward to the interface of interest (depicted with the dashed red line in Figure 7a). As the displacement continues to be increased a load plateau is reached where steady state delamination is occurring at the interface of interest (depicted with the solid blue line in Figure 7a). For the SiO₂/TiN interface tested the energy release rate values were on the order of 10 J/m², representing a relatively weak interface.

3.2. Importance of Precrack¹¹⁾

Another key implementation assessed the importance of using a precrack at the interface of interest.¹¹⁾ Similar to the previous extension, two massive substrates were used to create an essentially homogeneous material (Figure 8). The interface of interest for this case was a CDO/SiN interface in a thin multilayer stack as shown schematically in Figure 9a.

The layers were deposited on one silicon substrate and then a thin epoxy layer was used to sandwich the specimens. The top substrate was then notched close to the interface before testing, but no precrack was created. Upon testing under a constant displacement rate, the load would increase until at an initial load, $P_{initial}$. At this point the crack begins to initiate along the interface-of-interest while being accompanied by a load drop in the system (depicted with the dashed red line in Figure 9). As the outer pin displacement continues to increase the load will reach the critical load, $P_{critical}$. The crack will continue to delaminate stably along the interface due to the center of the specimen being under a constant

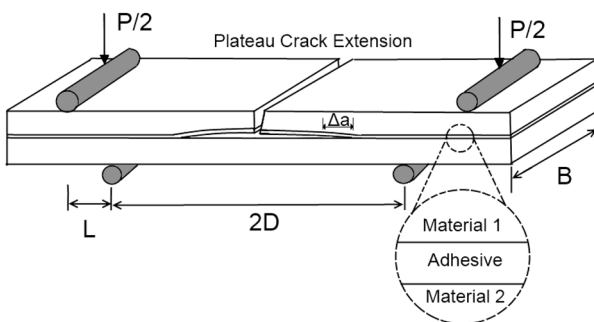


Fig. 8. Schematic of a 4PB setup with a thin adhesive layer between two much larger substrates.

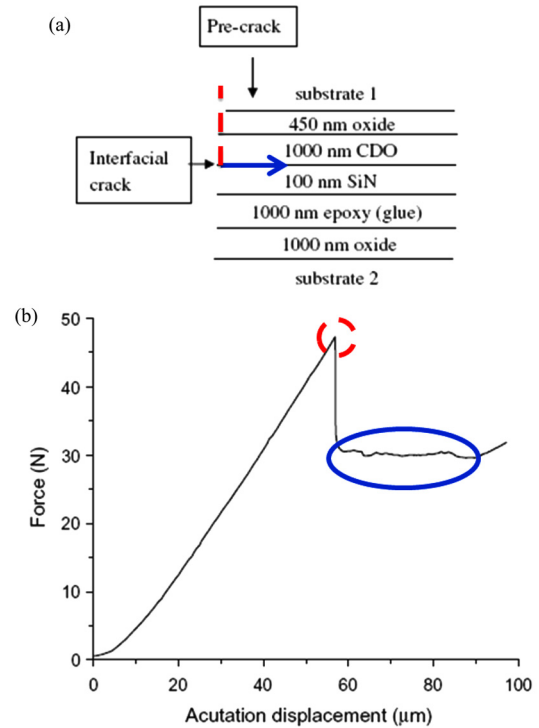


Fig. 9. Second configuration for 4PB testing of CDO/SiN interface (a) schematic of multilayer stack sandwiched between two much larger substrates with epoxy below the interface of interest and (b) typical load vs. displacement curve of 4PB.¹¹⁾

moment condition system (depicted with the solid blue line in Figure 9). The delamination will continue along the interface at the critical load until the crack reaches the inner loading pins. This critical load can then be used to assess the energy release rate of the interface-of-interest.

An interesting takeaway from this work is that when testing without a precrack there will always be a larger load required to initiate the crack before the critical load required for delamination is reached. However, by employing a very thin precrack, it would be possible to eliminate the initial load overshoot which can prove problematic in certain cases. For example, the authors considered two configurations in this experiment: one with the epoxy below the interface-of-interest, and another with the epoxy above (Figure 10a).¹¹⁾

It was found that when testing with the epoxy layer above the interface-of-interest, the load required to initiate the precrack along the interface of interest was so large that instead of the crack arresting after reaching $P_{initial}$, the crack would rapidly propagate all the way to the inner loading pin without establishing a load plateau at the critical load (Figure 10b). This case highlights a particular situation where if a precrack was first created, testing may have been possible. From the first case the evaluation of the energy release rate showed a relatively weak interface of 4 J/m².

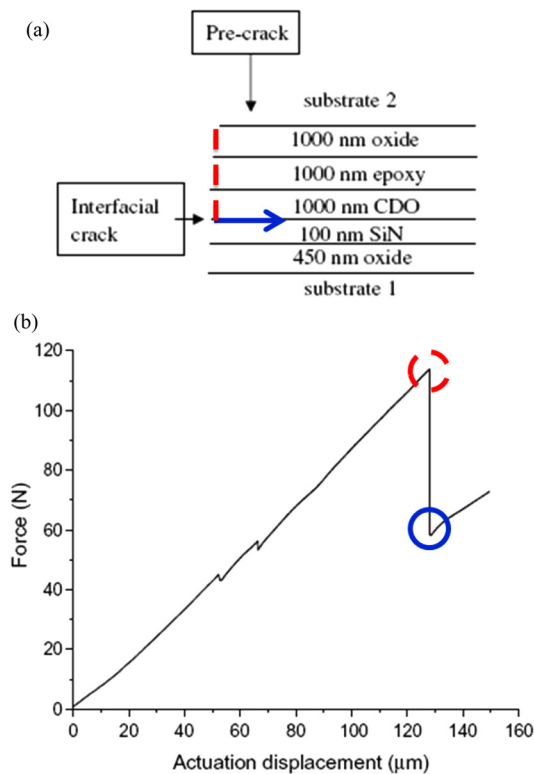


Fig. 10. Second configuration for 4PB testing of CDO/SiN interface (a) schematic of multilayer stack sandwiched between two much larger substrates with epoxy above the interface of interest and (b) typical load vs. displacement curve of 4PB.⁽¹⁾

3.3. Application: Evaluating adhesion strength of bonds in Through Silicon Via (TSV)

One application of this technique is for the copper-copper direct bonds used in through silicon via (TSV) applications.^(20,21) Copper-copper direct bonds are typically cured under high temperature conditions. The authors were interested in evaluating the effect of curing conditions on the adhesion strength between the bonds.

Samples were made by depositing a layer of copper on to two larger silicon wafers (Figure 11) and then cured under various conditions. The samples were then tested (Figure 12) in 4PB and Dauskardt's simplified analytical solution, Equation (2), was applied to assess the adhesion strength. Adhesion strength results were relatively small, $\sim 3 \text{ J/m}^2$ and varied based on the temperature and pressure conditions applied. Adhesion strength increased with bonding temperature and post-bond annealing temperature.

3.4. Application: Evaluating adhesion strength of EMC/Copper bonds

Another interface of interest that has been investigated by several authors with the 4PB method is the interface

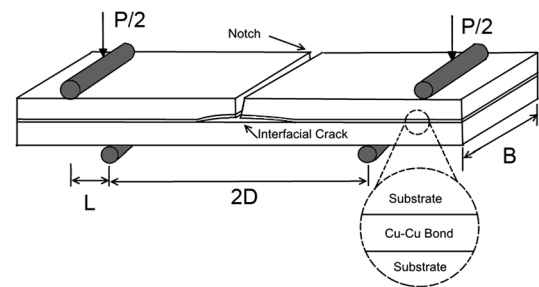


Fig. 11. Schematic of copper-copper bonding samples created on larger silicon substrates.⁽²⁰⁾

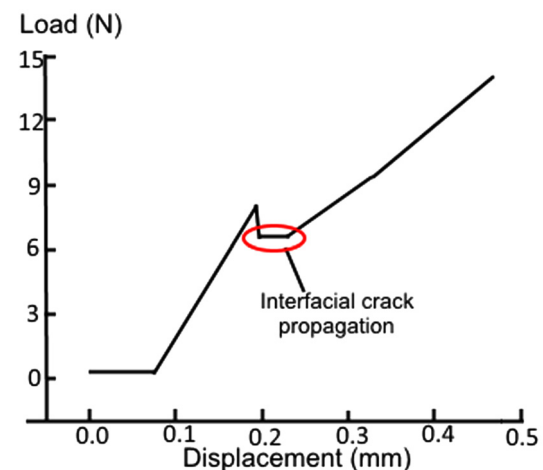


Fig. 12. Load vs. displacement curve for Cu-Cu direct bond 4PB adhesion testing.⁽²⁰⁾

between epoxy molding compound (EMC) and copper leadframe.^(12,22-24) Figure 13 provides an example of the type of package where this interface can be found. Epoxy molding compound is typically employed to protect the critical components and connections of the chip from the outside environment and moisture exposure. However, since the properties of the EMC are subject to change from long term exposure to moisture and temperature conditions, the initial adhesion strength and the adhesion strength degradation over time exposed to these conditions are critical to determine for characterizing the device reliability.

To evaluate this interface authors typically employ a simple bimaterial strip of EMC/copper. After creating the bimaterial strips, a vertical notch is cut in the center of the sample and then 4PB loading is employed. As documented before, the displacement is increased until an initial load is reached where the crack initiates along the interface. The load then drops to a critical plateau load where the crack delaminates in a steady state condition to the end of the inner loading pin.

To evaluate the energy release rate the equations initially

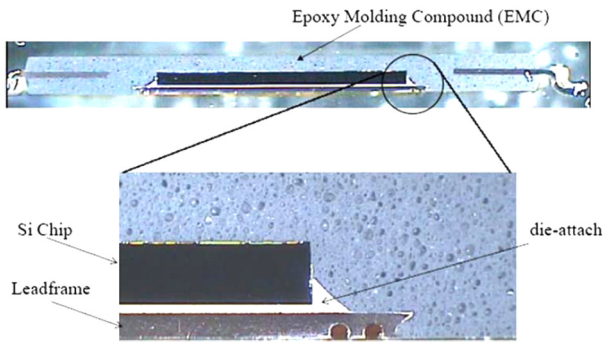


Fig. 13. Cross section image of typical microelectronic package with EMC/copper leadframe interface.¹²⁾

proposed by Charalambides et al.⁹⁾ are employed. For testing performed immediately after sample creation authors have reported energy release rates on the order of 20 J/m^2 . The authors were also able to test after exposing samples to high temperature and humidity conditions and characterized the degradation of the adhesion strength with time.

4. Concluding Remarks

The four-point bending method with a vertical center crack is an effective test method for evaluating the critical interfacial energy release rate for a bimaterial interface in mixed mode loading conditions. Previous implementations in the community have shown the method is very effective when evaluating interfaces with small adhesion strengths in comparison to the adherend materials.

However, difficulties with using this technique are met when extending to the thin multilayer structures that are common in semiconductor packaging systems. Samples are thinner than ever and are multilayered and with non-ignorable volume stiffness of the intermediate layers. Additionally with the advancement of materials engineering the adhesion strength of interfaces of interests are larger than ever. When large adhesion strength interfaces are mixed with low fracture toughness adherends, such as with high filler epoxy molding compounds (EMC) or other brittle layers, crack kinking into the adherend instead of delamination during testing also becomes a concern. Further investigation must be made for evaluating the adhesion strength at critical interfaces in thin-multilayer samples. Additional consideration must be made for the high toughness interfaces where crack kinking out of the interface is a distinct possibility.

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