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Modeling crack propagation for advanced 4-point bending testing of metal–dielectric thin film stacks

K.R. Gadelrab [a,*], M. Chiesa [a], M. Hecker [b], H.-J. Engelmann [b]

[a] Laboratory for Energy and Nano Science (LENS), Masdar Institute, Abu Dhabi 54224, United Arab Emirates
[b] Center for Complex Analysis, GLOBALFOUNDRIES Dresden Module One LLC & Co. KG, Wilschdorfer Landstr. 101, D-01109 Dresden, Germany

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ABSTRACT

For monitoring and improving mechanical properties of BEoL (back-end of line) interconnect structures in microprocessor technology, it is crucial to analyze their adhesion and crack propagation properties. In the present investigation, a camera assisted 4-point bending beam technique has been used to obtain fast and reliable adhesion measurements including locally resolved crack length information. To interpret the obtained crack propagation data, a finite-element modeling approach has been utilized. The combination of local measurement of the crack energy release rate and modeling enables to evaluate measurement curves for both symmetric and asymmetric crack propagation modes and to describe the crack propagation properties of the involved film stacks not attainable in such detail by conventional 4-point bending technique.

1. Introduction

The 4-point bending (4pb) delamination test is widely utilized for studying the interface properties of thin film structures such as semiconductor devices [1,2]. The importance of adhesion analysis as by 4pb has gained weight since the introduction of new materials in the field of semiconductors such as *low-k* and *ultralow-k* dielectrics [1], having a low mechanical stiffness and intrinsically poor adhesion to other materials [3,4]. This test has also been used to study the time dependent debonding of thin film interconnect structures [5] and the dependence of crack velocity on the film thickness [6,7].

A force curve extracted from a 4pb test can provide vital information on the mechanical properties of the test sample; however, the critical strain energy release rate G_c is particularly important to characterize the interface quality of the film stack [5]. Charalambides et al. [8] have provided a closed form solution to G_c as a function of the material properties, sample geometry and the applied load for 4pb conditions, resulting in the case of a sample of a single material and equal thicknesses of the two beams in:

$$G_c = \frac{21P_c^2L^2}{16Eb^2h^3} \quad (1)$$

where P_c denotes the critical load, L the distance between the inner and outer pins, E the effective Young's modulus, b the sample width and h the single beam height (cf. Fig. 1).

For the derivation of Eq. (1), it is assumed that, two cracks are propagating symmetrically along the beam axis within materials or interfaces of G_c values equal for both cracks. These assumptions are too ideal for day to day experiments and in reality are difficult to achieve. Misalignment and shape distortions can result in asymmetric crack growth, at least for stiff

* Corresponding author. Tel.: +971 561073723; fax: +971 26988121.
E-mail address: kgadelrab@masdar.ac.ae (K.R. Gadelrab).

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Nomenclature

b	sample width
c	pre-crack length
g	measured gap in 4-point bending
h	single beam height
l	cantilever length
y	pin displacement
I	moment of inertia
E	effective Young's modulus
L	distance between the inner and outer pins
M	bending moment on a deflected cantilever
G_{I}	energy release rate for mode I
G_{II}	energy release rate for mode II
G_c	critical strain energy release rate
L_i	inner pins separation
P_c	critical load
τ	maximum traction in cohesive zone model
φ	phase angle in mixed mode fracture
δ	cantilever deflection
CZM	cohesive zone modeling
FEM	finite element modeling
BEoL	back-end of line
4pb	4-point bending

specimens [9]. Imperfections in the initiation of the crack and variation of material properties can also result in asymmetric pre-crack growth or crack propagation at different interfaces. It is of interest to utilize a modeling approach to investigate such non-ideal situations and assess the errors that might result in the measured G_c.

Finite element modeling FEM has been utilized to address crack propagation and interface delamination in semiconductor devices [2–4,10,11]. Particularly cohesive zone modeling CZM has proven to be an added value in modeling fractures in different material behaviors [4,12–17]. A CZM describes a gradual degradation in the adhesion between two surfaces along their interface. A traction separation law describes the relation between the bonded surfaces separation and the traction vector acting on them [4]. Therefore, the CZM can be utilized to describe the 4pb experiment especially when the crack propagation path is predefined.

In the present work, we utilize FEM to simulate a conventional 4pb test assuming idealized conditions. After numerical verification, we address the case of asymmetric pre-crack as a common situation in real experiments. Furthermore, we study the case where the crack propagates in one direction only or at two different interfaces. Comparison with data obtained from an advanced 4pb technique including crack length measurements enables to verify the FEM approach and to obtain explanations for experimental observations in the crack propagation plots. We demonstrate that Eq. (1) is applicable to much wider situations. Besides, crack length measurements are an added value to give indications of deviations in the test case.

2. Materials and method

A beam bending test setup has been utilized including measurement of the actual beam displacement, the loading force, and the length of both cracks propagating within the layer stack of a 4pb adhesion test. The crack length measurement was

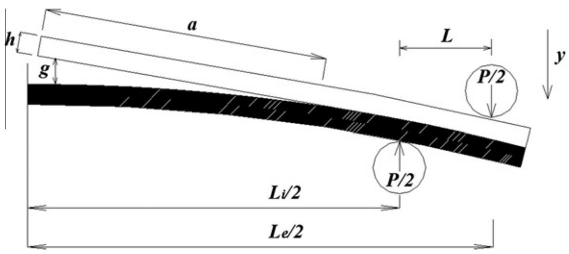

Fig. 1. A schematic representing an idealized 4pb test with the geometric parameters and with the symmetry applied on the left hand side. The gap opening and the crack length are denoted by g and a, respectively.