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Adhesion of arbitrary-shaped thin-film microstructures

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Abstract

We develop, implement in a finite element environment, and experimentally validate an approach to model adhesion of a class of arbitrary-shaped thin-film microstructures commonly used in microsystems technology. The modeling approach adopts principles of three-dimensional linear elastic fracture mechanics and extends them to thin-film plate-like microstructures. A companion experimental effort is carried out to measure adhesion energy of polysilicon microcantilevers using interferometry, and then to study the adhesion behavior of a suite of circular and square plates. The finite element approach is validated by comparison with relevant analytical results. It is then applied to the circular and square plate microstructures and good agreement between measurements and predictions is obtained.

1. Introduction

Thin-film microstructures used in microelectromechanical systems (MEMS) present several challenging reliability-related issues on account of their micron-scale dimensions. Many devices consist of compliant beam- or plate-like microstructures that are in close proximity (on the order of microns) to a substrate or other structural parts. If structures come into contact, either intentionally (for example the electrostatic actuation of a switch) or unintentionally (for example, when subjected to a mechanical shock), short-range adhesive forces can pin them together if they cannot be overcome by the elastic restoring forces of the deformed microstructures. This phenomenon, often called stiction, depends on the structural response of the microstructure, as well as on the nature of the adhesive forces between the contacting surfaces. The former is a function of the geometry of the device, the separation distance between the microstructure and substrate (or other microstructure), and the elastic properties of the microstructure. The presence of residual stresses and/or stress gradients can also have significant effects on structural response. Adhesion typically occurs during release of a MEMS device, or during the post-release use of the device. During the release process, MEMS devices are often subjected to a wet etching process to free the microstructure from the sacrificial layers. This subjects the free-standing device to capillary forces which can draw the device into contact with the underlying substrate. After the etchant dries, the device may remain adhered, even in a relatively clean and dry environment due to van der Waal's forces acting across the interface, or due to contaminants collecting at the interface and forming a solid bridge [1]. While the development of critical point drying has significantly reduced adhesion problems resulting from release [2], adhesion in operational environments still poses a significant reliability challenge [3]. In this case various adhesion mechanisms have been identified, the differences being the nature of the adhesive forces [4,5]. Examples include capillary forces due to high humidity levels [2], van der Waal's forces [3,6], or electrostatic forces due to trapped charges or applied voltages.

The most common way to characterize adhesion between two micromachined surfaces is by the adhesion energy of the interface [7–10]. The adhesion energy is the thermodynamic work of adhesion required to separate a unit area of two surfaces that form the interface [11]; it provides no direct information regarding the details of the

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actual adhesive traction-separation relation. This definition, though, lends itself nicely to energy balance formulations that connect adhesion energy to the elastic strain energy stored in a deformed, adhered structure. Perhaps the simplest way to estimate the adhesion energy of an interface between micromachined surfaces is by coupling measurements of adhered cantilever beams with solutions that relate adhesion energy to adhered cantilever geometry and material properties. Analytical solutions can be derived using an energy balance approach [8], or equivalently an approach based on the ideas of linear elastic fracture mechanics [10]. More detailed models have been developed that consider additional effects such as the anchor compliance and residual stress gradients [12]. In the energy-balance approach, the boundary between adhered and unadhered regions emerges from the solution. When the geometry is simple so that the boundary, which we refer to as the adhesion front, is essentially a one-dimensional curve (a straight line for a beam or a circular line for a circular plate), the approach is quite useful. For example, the analysis of cantilever adhesion can be readily extended to more general microstructures, such as doubly clamped beams and circular plates suspended around the periphery [8,13]. The extension to more complex geometries where the adhesion front is a two-dimensional curve is difficult because the shape of the curve is not known ahead of time. To this end, Mastrangelo and Hsu [8,9] developed estimates of the adhered area of arbitrary-shaped plates by determining outer and inner circular bounds on the adhesion front. Tezuka et al. [14] analyzed the adhesion of arbitrary-shaped plates by parameterizing the unknown shape of the adhesion front with a spline function, then finding the shape that satisfied the energy balance using an optimization procedure. The use of this approach for arbitrary geometries is difficult because it is necessary to parameterize the anticipated adhesion front in a sufficiently general manner so to permit arbitrary shapes to develop.

An alternative approach to the energy balance is to appeal to the ideas of linear elastic fracture mechanics. de Boer and Michalske [15] noted that one can model an adhered cantilever as a cracked structure: the crack length is the length of the unadhered region of the beam. The readily calculated energy release rate of fracture mechanics is then equal to the adhesion energy at the equilibrium crack length, which can be measured, for example, by interferometry [10]. At this point the equivalence of the fracture mechanics and the overall energy balance approaches may seem to be no more than formulational elegance, although there are some significant differences that will be discussed later. The most attractive difference, though, comes in the ease in which the fracture mechanics approach can be applied to more complex geometries. A well-developed framework exists for arbitrary-shaped adhesion fronts (crack fronts in fracture mechanics terminology); the shape of the adhesion front is that in which the energy release rate evaluated locally along the front equals the adhesion energy. Furthermore, computational strategies have been developed to calculate the energy release rate locally in a finite element setting [16–18]. As such, it appears that building on fracture mechanics ideas is more attractive than overall energy balance approaches for modeling adhesion in thin-film microstructures of arbitrary geometry. We note that an alternative approach would be to model the adhesion process directly with a traction-separation relation prescribed between the structure and substrate. While our approach can easily facilitate this, we do not consider it further in this work.

The exploration of this idea is the key objective of this work: we develop an approach to model adhesion in a robust, computationally efficient finite element environment, and demonstrate its capability via a companion experimental study. The modeling approach adopts the principles of three-dimensional linear elastic fracture mechanics (LEFM), but builds significantly on them by the extension to thin-film plate-like microstructures which are modeled by plate elements, rather than continuum elements, in the finite element setting. In this regard it builds on previous efforts in modeling delamination of composite plates [17,19–21]. In Section 2, we describe the modeling approach and its implementation in a finite element program. In Section 3, we then describe our companion experimental efforts which consist of using polysilicon cantilever test structures to determine the adhesion energy, and then measuring adhered shapes of circular and square plates. In Section 4, we compare these measurements to predictions using our approach and the measured adhesion energy, focusing not only on the strengths of the approach but also on some unresolved issues and weaknesses.

2. Modeling approach

We model the adhered film/substrate system as two plates that are adhered along some region and free along the remainder; an example is shown in the interferometric image shown in Fig. 1. The boundary between the adhered

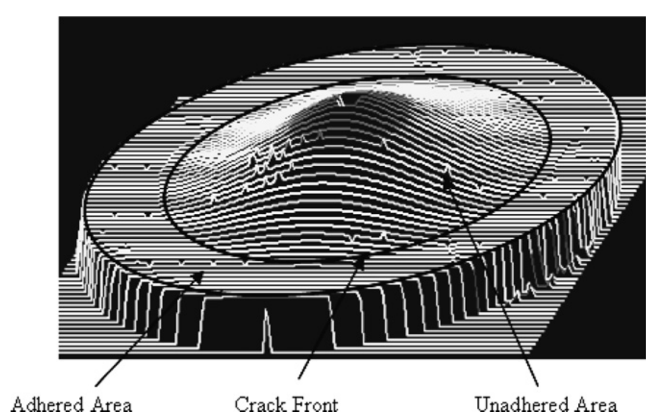

Fig. 1. Interferometric image of a circular microstructure suspended by an anchor at the center and adhered around the periphery to the underlying substrate. Clearly marked are the adhered area, nonadhered area and the "crack front".