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AN INVESTIGATION OF PLASTICITY IN MEMS MATERIALS

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ABSTRACT

We have developed a membrane deflection experiment particularly suitable for the investigation of sub-micron thin films that directly measures actual load and film stretch. The experiment consists of loading a fixed-fixed membrane with a line load that is applied to the middle of the span with a nano-indenter column. A Mirau microscope-interferometer is conveniently aligned with the nano-indenter to directly measure strains. This is accomplished through a specially manufactured wafer containing a window to expose the bottom surface of the membrane. The sample stage incorporates the interferometer to allow continuous monitoring of the membrane deflection during both loading and unloading. As the nanoindenter engages and deflects the sample downward, fringes are formed due to the motion of the bottom surface of the membrane and are acquired through the use of a CCD camera. Digital monochromatic images are obtained and stored at periodic intervals of time to map the strain field.

Through this method, loads and strains are measured directly and independently without the need for mathematical assumptions to obtain the parameters describing material response. Additionally, no restrictions on the material behavior are imposed in the derivation of the model. In fact, inelastic mechanisms including strain gradient plasticity effects can be characterized by this technique.

INTRODUCTION

Thin Films & MEMS: Thin films, thickness of a few microns or less, are applied as components in almost all MEMS devices and frequently serve as essential device functions. The demands placed on thin films in these applications can sometimes subject them to various mechanical conditions, such as; fracture, plasticity, friction and wear, creep, fatigue, etc. Most knowledge of bulk material behavior fails to describe the response in this size regime. Many researchers currently have programs to study such characteristics [1-4]. Frequently, each particular investigation involving MEMS tends to be device dependent and introduces new fundamental questions. Progress in this field has leaned toward providing more specific technological solutions rather than generating a basic understanding of mechanical behavior.

Testing Methodologies: Techniques to study MEMS materials response to mechanical loading are diverse and can be classified in two basic regimes; *static* and *dynamic*. Although both will yield the materials mechanical properties, they accomplish it in completely different manners. Within the *static* group are nanoindentation (in standard DC mode) [5], micro-tensile [6], bending [6-9] and bulge tests [10-12]. Nanoindentation (when the Continuous Stiffness Measurement is used), resonance and fatigue methods [13-15] belong to the *dynamic* group in this observation. When applied to thin films, these methods fail to accurately describe behavior as the scale is reduced to micron and sum-micron dimensions. The high interface-to-volume ratio of thin films enhances interface driven processes that alter the conventional understanding of yielding. Thus, there is a need to establish new testing methodologies that contain no mathematical assumptions and measure material parameters independently.

The equivalent of a tensile test performed on bulk samples is desirable for thin films for several reasons. Loads and strains are measured directly and independently; no mathematical assumptions are needed to obtain the parameters describing the material response. Techniques that use a special fixture to load small tensile samples have been developed, [7-9]. However, stress-strain curves cannot be uniquely determined when the various techniques are compared. This is due in part because complex sensors and actuators for loading are used.

An ideal architecture to achieve this testing scheme involves a freestanding membrane that is fixed at both ends. A line load applied at the middle of the span produces a uniform

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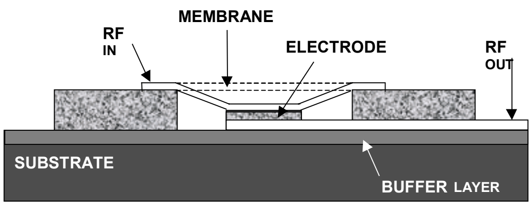
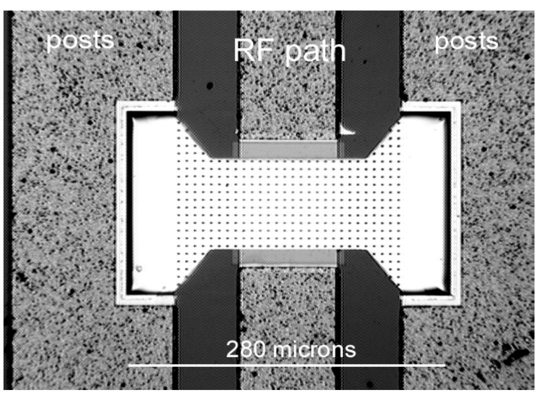
stretch on the two halves of the thin membrane. The test was demonstrated by the investigation of RF (radio frequency) MEMS switches, produced by Raytheon Systems Co.[16-18].

RF MEMS Switches: An RF MEMS switch is a device that uses the electrostatic deflection of a thin film membrane for tuning and switching of RF circuits [19-22]. The idea of applying a MEMS device to these engineering tasks results from a shortcoming of their solid-state counterparts, i.e. current leakage. For this kind of solution, Raytheon Systems Co. developed MEMS switches to operate in tunable filters and oscillators used as varactors (tunable capacitors). The structure of one such MEMS switch is schematically shown in Figure 1. Particulars of the switch can be found elsewhere [16-18].

This paper will focus on developing new methodologies for mechanical testing that solves specific engineering needs as well as increasing the fundamental knowledge of thin film mechanical behavior.



(a)



(b)

Figure 1: (a) Cross section of RF MEMS switch manufactured by Raytheon Systems Co. (b) Top view of the "bow-tie" membrane mounted on posts. It is made of an aluminum alloy and contains a pattern of holes for membrane release during microfabrication.

RESULTS AND DISCUSSION

Membrane Deflection Experiment: We have previously developed a methodology for testing freestanding thin film membranes that involved the combination of a membrane deflection experiment (MDE) with 3-D numerical simulations to identify Young's modulus and residual stress state [16-18]. The MDE test specimen consists of a thin film membrane supported by and fixed to posts at either end such that a gap exists below it (see fig. 1). The experiment makes use of a nanoindenter to apply a line at the center of the membrane (see fig. 2). Pushing the membrane down tests the specimen structural response and provides information on its elastic behavior and residual stress state. In this manner, simple tension of the membrane is achieved except for boundary bending effects.

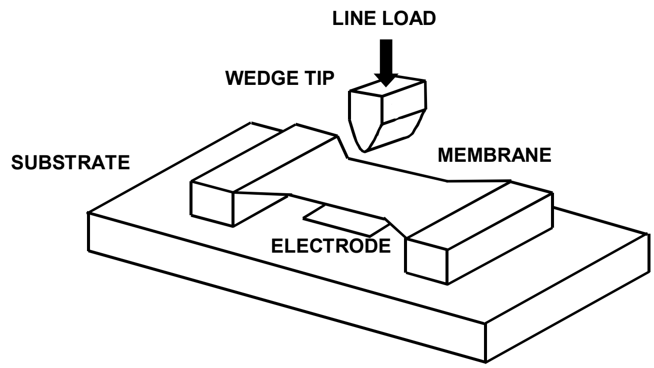


Figure 2. Schematic of the MDE test using a nanoindenter tip.

A critical concern in MDE testing is accounting for the thermal drift and spring constant of the nanoindenter column. Since the column dimension is orders of magnitude larger then the membrane deflection, subtle changes in temperature can significantly affect displacement measurement. To account for these two factors indents are made on either post, see fig. 3. Correction for thermal drift and spring constant can be calculated from the approach segment data before contact is achieved. Other important information is also gained from these indents such as; device tilt, height of the membrane at contact, and middle position in the plane of the film. The load-displacement data can then be adjusted accordingly. An example of adjusted experimental output is given in fig. 3.

In actuality the initial membrane shape varies from switch to switch. This was taken into account using finite element modeling to determine residual stress state. The analysis was conducted using ABAQUS Implicit, version 5.7. All cases were run using flat meshes, curved in x only or doubly curved in xy. The membrane is discretized using 8-noded 2D shell elements with variable sizes in the x-y plane, preserving the membrane geometry, and constant thickness of 300 nm in the z-direction. By this method simulated load-displacement curves of different assumed residual stress states and Young's moduli can be compared with experimental signatures.

One of the main findings from this investigation was that variations in residual stress and membrane elastic properties affected the load-deflection curve in different regimes [16-18]. In fact, changes in initial residual stress significantly affected the load-deflection slope at small values of deflection. By contrast, variations in Young's modulus resulted in changes in load-deflection slope at large displacements. This decoupling allowed the identification of E and So in RF MEMS switches, see [16-18].

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This novel technique has the potential to examine plasticity and failure mechanisms of MEMS films at the nano-scale. However, a few enhancements to the MDE test need to me made to independently measure stress and stretch. This is discussed below.

Integration of Interferometry: Although the above methodology is equivalent to a tensile test performed on a bulk material some modifications can be made. The first improvement is to alter the shape of the membrane to avoid generating boundary bending effects. This is accomplished by tapering the membranes width where it is fixed at the posts and at the center where the line load will be applied, see Fig. 4(a).

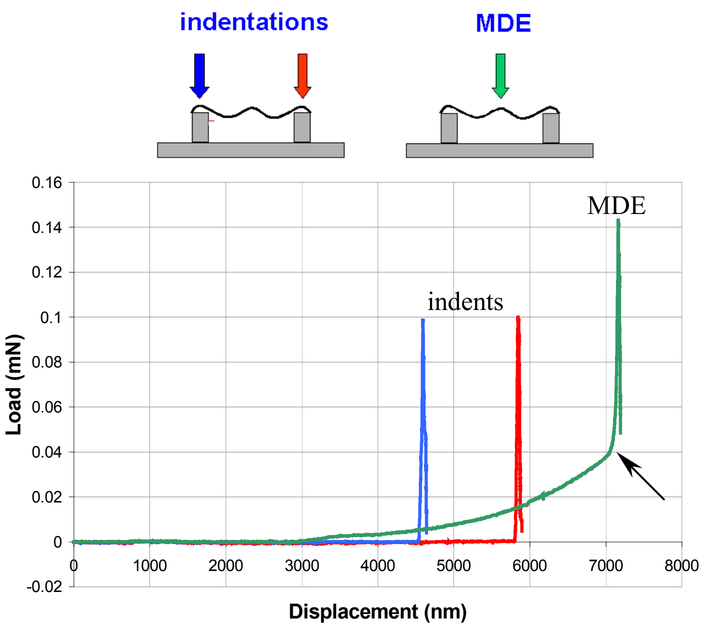

Figure 3. Load-deflection curves of the three steps in the MDE tests. Notice the point of contact with the bottom electrode (arrow) in the MDE step.

A second modification to the MDE methodology is to add apparatus to independently measure stress and strain in order to eliminate the need for mathematical assumptions to obtain parameters that describe the membranes response. By this method, membranes are fabricated such that they span windows etched through the supporting wafer that allow an interferometer, positioned below the specimen, to directly measure and map the strain fields. A schematic cross section of a specimen with a window microfabricated on the back surface of a silicon wafer is shown in Fig. 4(b). The geometry allows the wedge-tip to be pushed down to achieve large membrane deformations, making it possible the study of plasticity and passivation in thin films. Through these windows, scanning white light interferometry (SWLI) is used to scan the bottom surface of the film while the experiment is taking place. In this way, the nanoindenter deflects the sample down, towards the objective, while fringes of the bottom surface are acquired in a CCD camera, see Figure 5.

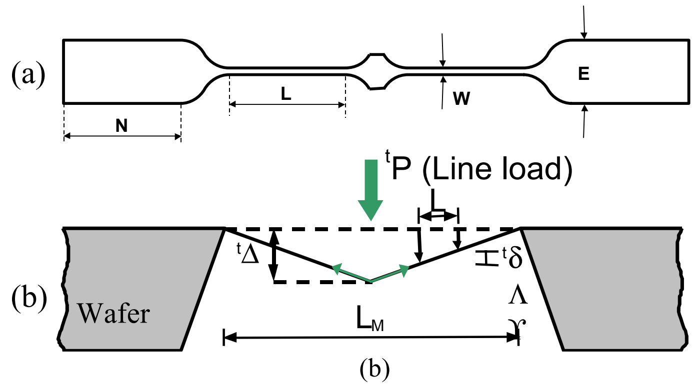

Figure 4. Schematic view of membrane top (a) and side (b).

Turning our attention back to the cross-sectional view of the experiment shown in Figure 4(b), where supra-index t indicates dependence upon time, formulas for stretch and stress can be derived. ^{t}P and ${}^t\Delta$ are obtained from the nano-indenter, while L and ${}^t\delta$ are obtained from the SWLI (Scanning White Light

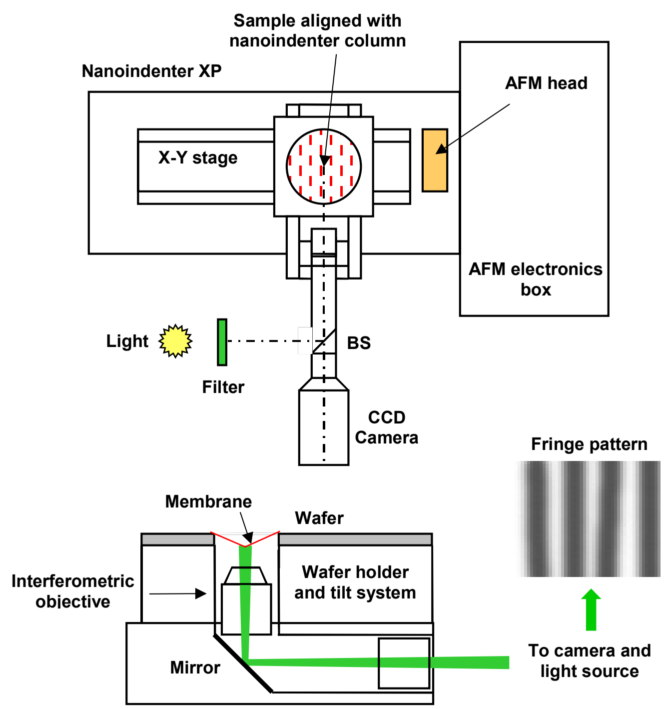

Figure 5. Schematic drawling of combined AFM-Nanoindenter testing rig with integrated Mirau microscope-interferometer.

Interferometer). Software for identifying middle line fringes provides distance L, Fig. 4. Using these data, the stretch and Cauchy stress are computed from:

$$ {}^t\lambda = \frac{\sqrt{L^2+{}^t\delta^2}}{L} \quad ; \quad {}^t\sigma = \frac{{}^t p\,{}^t\Delta}{L_M A_M} $$

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where L is the distance between two consecutive fringes, ${}^t\delta$ is the vertical difference in displacement as the slope increases, ${}^tP$ is the applied load, ${}^t\Delta$ is the vertical displacement at the position of maximum deflection, L_M is the membrane length, and A_M is the membrane cross-sectional area.

It is clear that from these two simple expressions, a σ-λ curve of Cauchy stress σ versus stretch λ can be directly determined. No restrictions on the material behavior are present in the derivation of the model. In fact, inelastic mechanisms including strain gradient plasticity effects and grain morphology can be characterized by this technique.

Another potential of the test is its utilization in characterizing notch and crack tips in small specimens. Fig. 6 shows Au specimens containing notches with 1 µm radius, which were machined using reactive ion etching (RIE). Fracture behavior and failure mechanisms is being investigated in samples subjected to basically uniaxial stress.

The results of our new testing methodology are preliminary and ongoing. Results will be reported in the final manuscript and conference presentation.

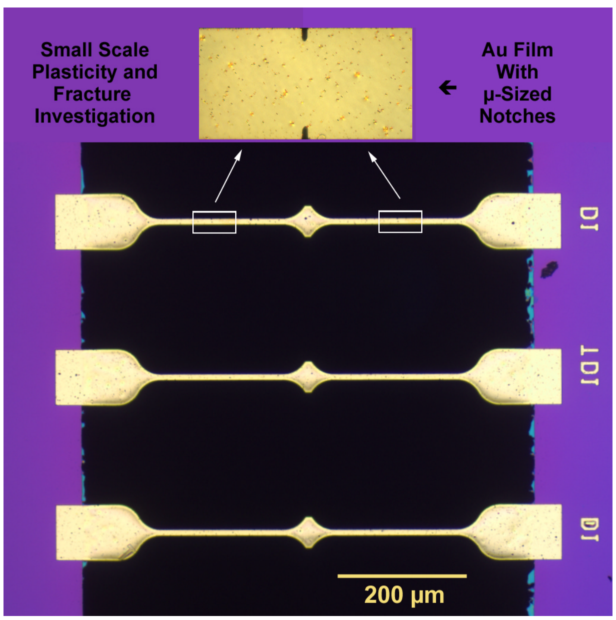

Figure 6. Suspended gold membranes showing µ-sized notches.

CONCLUSIONS

Based on previously conducted membrane deflection experiments it is clear that micron-thick thin films can be tested by direct tension using a properly designed membrane or beam geometry. The equipment involved has shown to possess the sensitivity and control required for such precise measurements. The new idea is to combine our existing MDE methodology with an interferometric station and an AFM to independently measure stress and strain. Results of this new method will be reported in the final manuscript and conference presentation.

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