A Novel Experimental Technique for Testing Thin Films and MEMS Materials

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ABSTRACT

We have developed a novel μ-scale membrane deflection experiment particularly suited for the investigation of sub-micron thin films and MEMS materials. The experiment consists of loading a fixed-fixed membrane with a line load that is applied to the middle of the span with a nanoindenter column. A Mirau microscope-interferometer is positioned below the membrane to observe its response to loading. This is accomplished through a specially micromachined 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 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 necessary parameters for 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 material 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 by as *static* or *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. Conventional understanding of yielding does not apply at this scale because of the increased role that interface driven processes play. Thus, there is a need to establish novel testing methodologies that contain no mathematical assumptions and measure material parameters directly and 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 for data acquisition.

An ideal architecture to achieve a direct tensile testing scheme involves a freestanding membrane that is fixed at both ends. A line load applied at the middle of the span would produce a uniform stretch on the two halves of the thin membrane. We have demonstrated this testing scheme by the investigation of RF (radio frequency) MEMS switches, produced by Raytheon Systems Co.[16-18]. In this method we made use of a nanoindenter to apply a line load at the center of the membrane. 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.

The critical concern in this Membrane Deflection Experiment (MDE) was accounting for the thermal drift and spring constant of the nanoindenter column. Since the column dimension is orders of magnitude larger then the membrane

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deflection, subtle changes in temperature can significantly affect displacement measurement. To account for these two factors we made indents on either post supporting the membrane. Corrections for thermal drift and spring constant are calculated from the approach segment data before contact with the posts. 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. We use a similar testing methodology here although the specimen geometry and wafer are modified.

EXPERIMENTAL PROCEDURE

Specimen Design: A particular specimen geometry was chosen for the membranes to eliminate boundary bending effects. The geometry resembles a typical dog-bone tensile specimen but with tapered regions where the membrane is fixed to the wafer and at the center where the line load is applied. A schematic drawing and optical image of the specimens are shown in Fig. 1.

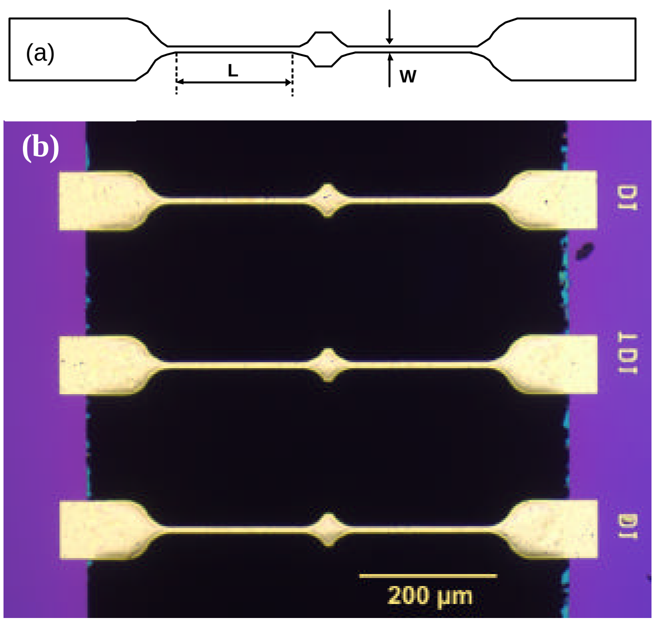

Fig. 1. (a) Schematic view of the membrane specimens where L = 200 µm and w = 20 µm and (b) optical image of microfabricated membrane specimens.

The samples were microfabricated on <111> Si wafers with double-sided polishing. The process is shown schematically in Fig. 2 and can be sumerized as follows; (a) Deposition of Si_3N_4 on both sides of wafer, (b) Deposition of Au on the top surface beginning with a thin layer of Ti for bonding. Definition of Au specimens is achieved by photolithography and lift-off. Wet etching of Si_3N_4 on the bottom side using a Teflon chuck with o-ring to protect the top side, (c) Wet etching of Si to open window and then dry etching of Si_3N_4 to release the membrane.

Experimental Set-Up: The previously mentioned MDE methodology was modified in order to eliminate the need for mathematical assumptions to obtain parameters that describe the membranes response. This was accomplished through addition of a Mirau microscope interferometer to independently measure and map the strain fields. The interferometer is positioned directly below the membrane and views the deflection through the specially fabricated windows in the wafer, Fig 3.

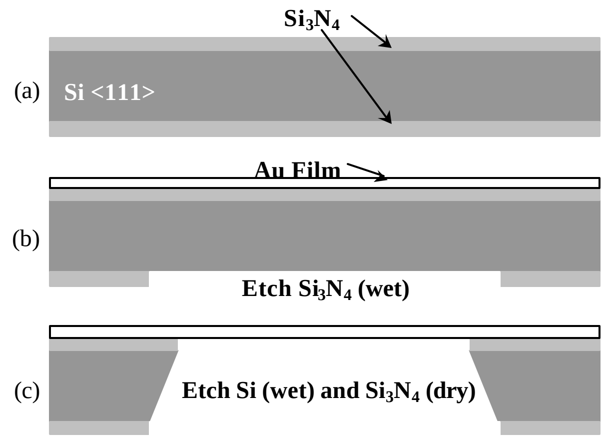

Fig. 2. Summary of microfabrication process for obtaining free standing membranes with bottom view windows.

A schematic of the experimental set-up is shown in Fig. 4. A combined Nanoindenter and Atomic Force Microscope (AFM) apparatus is utilized to apply a line load to the center of the membrane. The typical experimental procedure can be described in three steps. The first step is to locate and characterize the membrane geometry by means of the optical and scanning capabilities of the AFM/Nanoindenter apparatus. Once the profile and surface geometry are stored, the wafer is moved to the test position to begin the second step. The station has an x-y stage for mounting the wafer with the samples. The stage can carry the wafer from the AFM head to the nanoindenter without removing the sample. The resolution achieved in this operation is less than 1 µm.

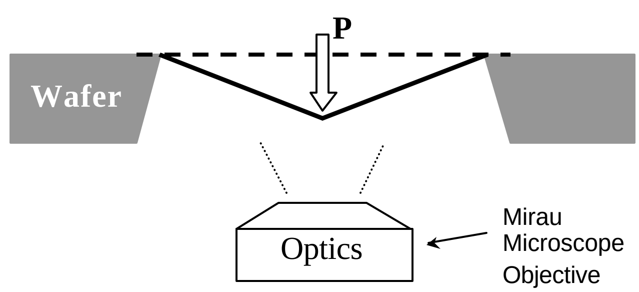

Fig. 3. Cross-sectional schematic view of the of the new MDE test.

The second step is the membrane deflection experiment (MDE) itself. Parameters are set and a drift test is executed. Once the test criterion is reached, the membrane is loaded. Simultaneously, the aligned interferometric station is focused on the back surface of the film. The camera is then set to acquire digital images within a desired period of time. Force and displacement data are stored in the Nanoindenter controller PC, and strain mapping is calculated from the stored monochromatic images. Prior to a new set of pictures being taken, the focus on the surface is updated to correct for the out-of-plane motion that is due to the downward displacement of the membrane.

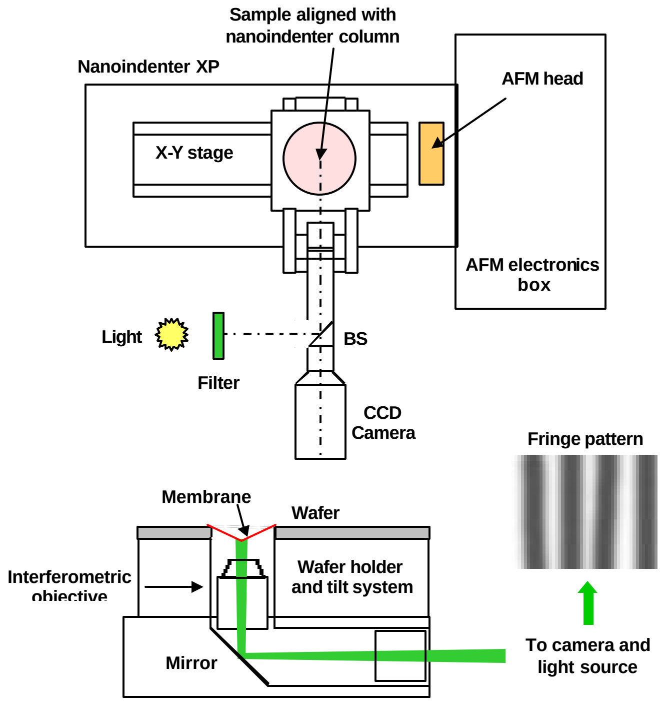

Fig. 4. Schematic drawling of combined AFM/Nanoindenter testing rig with integrated Mirau microscope-interferometer.

The third step of the experiment is data analysis. Using the distance measured between fringes (δ) obtained from the interferometer and load (P) and deflection (Δ) obtained from the nanoindenter measurements, the stretch (${}^{t}\lambda$) and Cauchy stress (${}^{t}\sigma$) are computed from;

$$ {}^{t}l = \frac{\sqrt{d^2 + l^2}}{d} \qquad {}^{t}s = \frac{P}{A_m 2\sin(q)} \qquad (1) $$

where λ is the wavelength of monochromatic light (514 nm), A_m is the membrane cross-sectional area and L_m is distance from the center of the membrane to the edge of the window. It should be noted that the load in the membrane must be derived as a component of the vertical nanoindenter load, i.e. P/2sin(θ) in Fig. 5a.

It is clear from the two simple expressions in equation (1) that a curve of Cauchy stress, ${}^{t}\sigma$, versus strain, $\varepsilon = {}^{t}\lambda$-1, can be directly determined. 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.

Fringe Development and Measurement: The distance between the fringes (δ) was measured from digital images acquired during the test. Values were found by averaging over several fringes at a time. A fringe develops when the reflected beam is out of phase with the reference beam by λ, the wavelength of monochromatic light used. This occurs for a change in vertical distance of λ. Fig. 5b shows the geometrical relationship between δ and the angle of membrane deflection.

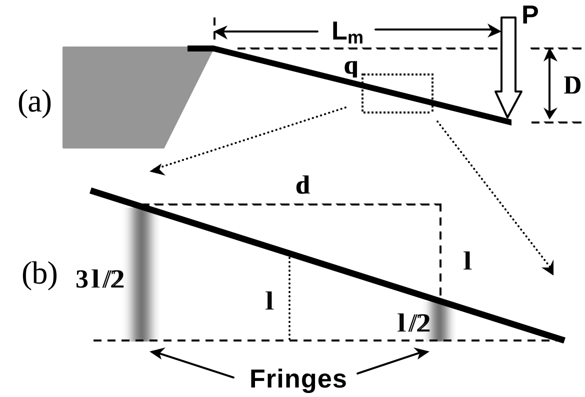

Fig. 5. Schematic drawings of (a) loading relationships between membrane and indenter and (b) relationship between fringe spacing and λ of monochromatic light.

RESULTS AND DISCUSSION

Fringe Analysis: Fig. 6 shows optical images of fringe development at periodic intervals during the membrane deflection test. The interferometer was positioned under the left arm of the membrane. The first frame was taken at 0 seconds and shows that the interferometer was exactly aligned with the membrane surface. As time progresses fringes uniformly developed along the membrane and became progressively closer as deflection increased. The rate of deflection was 100 nm/s and thus the frames show deflections of 5, 10, 15, 20, and 25 µm. The curvature of each fringe is due to curvature of the membrane surface.

Stress-Strain Analysis: A plot of the Cauchy stress and strain for a membrane of dimensions 0.5 µm thick and 20 µm wide is given in Fig. 7. Experimental signatures for maximum deflections of 33 µm (O) and 53 µm (■) Are shown. Both signatures match well and undergo plastic deformation in the region of 45 MPa. In the elastic region the slope, elastic modulus, is 35.4 GPa. This is considerably lower then the bulk value of 79 GPa and literature values for nanocrystalline Au of 55 GPa [19].

CONCLUSIONS

The MDE test results showed that micron-thick films can be tested by direct tension using a properly designed membrane or beam geometry. The equipment involved was also shown to possess the sensitivity and control required for such precise measurements. Our future work will involve testing Au films of various thickness and cross-sectional

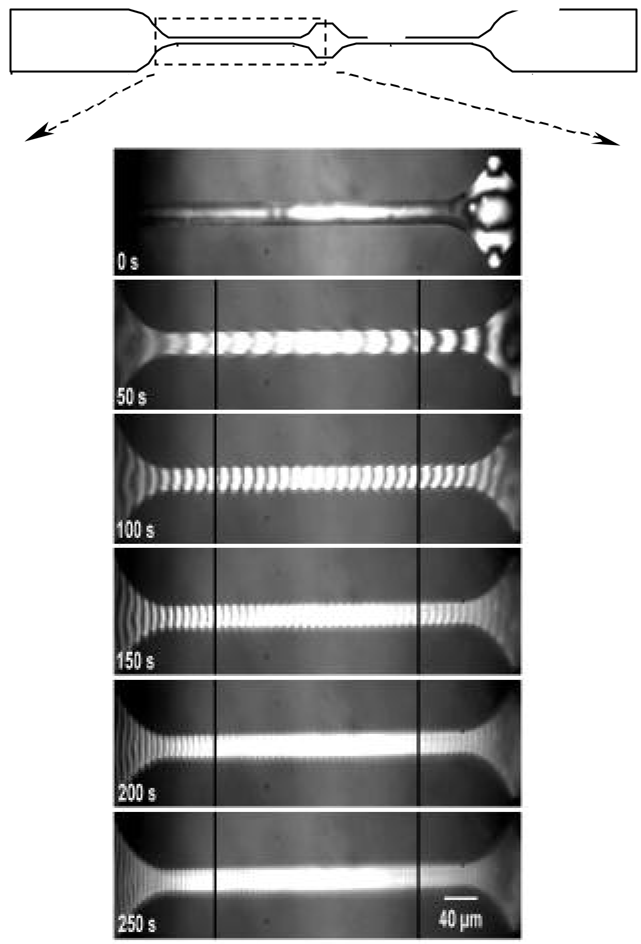

Fig. 6. Digital frames acquired by the interferometer showing fringe development at periodic time intervals.

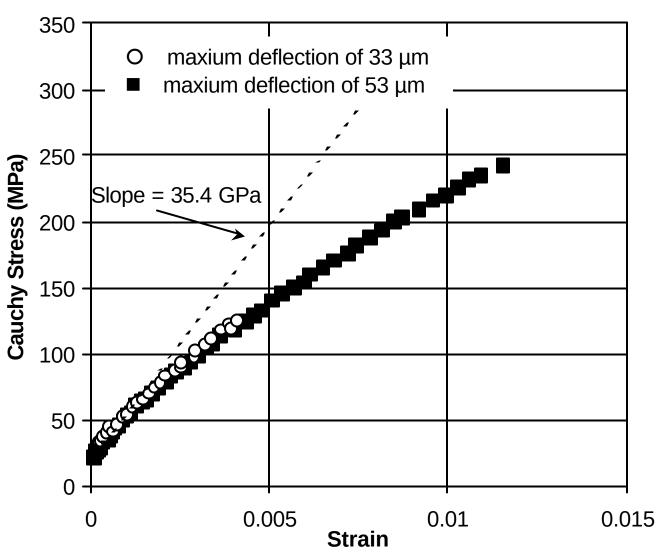

Fig. 7. Cauchy stress vs. strain for an Au membrane 0.5 by 20 μm cross-section. Modulus was found to be 35.4 GPa.

areas as well as other materials including membranes with oxide layers, simulating passivation. Investigations will also be performed to study plasticity and fracture at this scale.

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