Wafer Level Mechanical Testing of Al Films at High and Low Temperature

H. D. Espinosa and B. C. Prorok Department of Mechanical Engineering, Northwestern University 2145 Sheridan Road, Evanston, IL 60208-3111, USA

ABSTRACT

There has been growing interest to develop a reliable and repeatable method for investigating the mechanical properties of thin films and MEMS materials. In this study, the mechanical response of suspended thin film Al membranes are examined by the Membrane Deflection Experiment (MDE) and nanoindentation. The MDE tests were conducted at temperatures of 2, 27, and 60°C in order to ascertain differences in the membrane response with temperature. The MDE tests were found to yield E, σ_r , and σ_y for the membranes while the film thickness and roughness obstructed interpretation of the nanoindentation data.

INTRODUCTION

Thin films are widely employed as components of MEMS devices. Their mechanical properties frequently govern the functional aspects of the device and therefore directly influence its reliability. Determining the mechanical properties is essential in designing commercially viable MEMS devices. These devices will likely have to operate under differing temperature regimes and thus, mechanical properties must be determined as a function of temperature.

Nanoindentation is a means to determine Young's modulus, E, and hardness, H, at small scales specimens [1-4]. However, when film thickness becomes small, < 1 μ m, the indenter can only probe to depths of about 100 nm before substrate effects begin to influence the results [3,5-7]. Another aspect to consider is the surface roughness of the film. Typically, the indenter must probe to a depth of approximately 10 times the surface roughness to ensure that the indenter contact area is nominal [7,8]. For the case of a 1 μ m thick film, roughness must be < 10 nm. In many thin film materials, these conditions are difficult or even impossible to achieve.

A novel wafer level mechanical testing scheme involving the deflection of suspended thin film membranes was developed by Espinosa et al. [9-12]. The procedure involves applying a line-load, with a nanoindenter, at the center of the spanning membrane to measure its mechanical response. This method will be used to determine E, σ_r , and σ_y at temperatures of 2, 27, and 60°C. The method and results will be compared with that of nanoindentation on the same material.

EXPERIMENTAL PROCEDURE

Specially designed thin film AI specimens, used in the design of RF-Switches [9,12] were microfabricated in collaboration with Raytheon Company. A specimen shape was chosen to allow testing with the Membrane Deflection Experiment (MDE) and to subject the specimens gauged region to *pure tension* [10-11]. A schematic of the specimen geometry is shown in Fig. 1 and the corresponding dimensions for 4 differently sized specimens are listed in Table 1. The membrane is supported by two posts, such that they are suspended approximately 4 μ m above the substrate. Specific dimensions were chosen in order to achieve plasticity at maximum deflection.

The MDE test is a method for testing the mechanical response of freestanding thin film specimens. The procedure involves applying a line-load, with a nanoindenter, to the center of the spanning membrane. Load is applied and the membrane is deflected downwards until it makes contact with the substrate. The result is direct tension in the gauged regions of the membrane with load and deflection being measured independently, see Fig. 2.



Fig. 1. Schematic representation of the aluminum membrane geometry.

Table 1. Dimensions of Suspended Membranes

Sample	L (µm)	r (µm)	W (µm)	$W_L \left(\mu m \right)$
1	100	10	10	10
2	100	10	20	10
3	50	5	10	5
4	50	5	5	5



Fig. 2. Schematic side view of the Membrane Deflection Experiment for the AI specimen architecture showing maximum deflection.

The data directly obtained from the MDE test must then be reduced [9-12] to arrive at a stress-strain signature for the membrane. The load in the plane of the membrane is found as a component of the vertical nanoindenter load by the following equation:

$$\tan \boldsymbol{q} = \frac{\boldsymbol{D}}{L_M} \quad \text{and} \quad P_M = \frac{P_V}{2\sin \boldsymbol{q}},\tag{1}$$

where (from Fig. 2) θ is the angle of rotation, Δ is the displacement, L_M is the membrane half-length, P_M is the load in the plane of the membrane, and P_V is the load measured by the nanoindenter. Once P_M is obtained, the stress, $\sigma(t)$, can be computed from:

$$\boldsymbol{s}(t) = \frac{P_M}{A},\tag{2}$$

where A is the cross-sectional area of the membrane in the gauge region. The cross-sectional area dimensions were measured using an Atomic Force Microscope (AFM). The displacement from the nanoindenter, Δ , is used to determine an overall strain, $\varepsilon(t)$, through the following equation:

$$\boldsymbol{e}(t) = \frac{\mathbf{D}L_M}{L_M} = \frac{\sqrt{\mathbf{D} + L_M^2}}{L_M} - 1, \qquad (3)$$

A second type of test structure was fabricated and can be described as a thin film nanoindentation pad. The pad was designed to be 100x100 μ m in area and is deposited simultaneously with the membranes in the microfabrication process. These structures were designed to compare results of the MDE tests with nanoindentation. Tests were conducted using continuous stiffness with instrumented data reduction procedure.

MDE tests were performed at temperatures of 2, 27, and 60°C. This was accomplished with the Thermatron unit at MTS Corporation that is capable of modest in-situ temperature testing. The membrane and nanoindentation pad thickness, including surface roughness, was measured through Atomic Force Microscopy (AFM).



Fig. 3. Optical image showing the specially microfabricated specimens. The nanoindentation pad is the square near the top and the 4 different membrane geometries are located at the bottom.

RESULTS AND DISCUSSION

Fig. 3 shows an optical microscopy image of the fabricated specimens. The membranes are seen at the bottom of the image and are labeled 1-4 as in Table 1. The square in the top middle of the image is the Al nanoindentation pad. Based upon aspect ratios and quality of shape, membrane 1 was chosen for MDE testing.

Highly accurate measurements of the membrane dimensions are needed in order to reliably calculate the stress-strain data. Membrane gauge width, w, and membrane half-length, L_M , were measured with a high-precision translation stage with a resolution of 1 μ m. Film thickness was measured with Atomic Force Microscopy (AFM). Fig. 4. shows an AFM s can of the nanoindentation pad. Pad thickness was found to be 351 nm and scans of the membrane where it attaches to the post revealed nearly identical thickness.

Surface characteristics were also measured by AFM. Fig. 5 is a 3-D profile of the nanoindentation pad surface. Grain size at the surface was found to be approximately 300 nm. Surface roughness was also evaluated and is shown in Fig 6. An RMS value of 26.5 nm was measured. This value, along with the thickness of the pad indicates that nanoindentation may not yield fruitful results. First of all, the indenter must probe at least 265 nm into the film to eliminate roughness effects. In contrast, the film thickness is only 350 nm signifying that the Indenter will begin experiencing substrate effects near a depth of 35 nm. Thus, no regime exists where neither influence is present.

Results of the MDE tests are shown in Fig. 7. The loaddeflection signatures of three membranes tested at 2, 27, and 60°C are compared. The curves show the development of load with deflection for each temperature with the point of contact with the substrate signified by the vertical transition in load. The first apparent difference is that the lower the temperature the larger the supported load. This can be attributed to the state of residual stress present in the film. Using room temperature (27°C) as a starting point, a relative picture of the residual stress state can be envisioned. When considering a decrease in temperature the difference in thermal expansion between AI (α =23x10⁻⁶/°K)



Fig. 4. AFM scan showing the thickness of the nanoindentation pad. The top graph is a side view profile from which the thickness can be extracted. The bottom left image is the top-side view of the film edge on the substrate.



Fig. 5. 3-D AFM profile of the grain structure of the thin-film Al membrane.

and the Si substrate (α =2.5x10⁻⁶/°K) indicates that the Al will tend to shrink a lot more than the Si substrate resulting in a tensioning of the Al. The opposite is true when increasing temperature above 27°C. This results in more expansion of the Al and the possibility of the Al membrane sagging downward. This is indeed the case for the 60°C specimen as shown in Fig. 7. The contact point with the substrate occurs at a displacement of approximately 3200 nm, nearly 800 nm less than the 27 and 60°C tests.

Using Equations (2) and (3) stress and strain can be calculated. Curves for the three temperatures are shown in Fig. 8. Several key mechanical properties can be obtained from this plot. Young's modulus is nearly identical for all three membranes, 73 GPa, which is close to that reported in the literature, 70 GPa [13]. By extrapolating the linear elastic region to zero displacement the residual stress state is found. These values are 107 MPa for 2°C, 59 MPa for 27°C and 28 MPa for 60°C.

Deviation from linear elastic behavior defines the yield stress. Note that the 0.2% offset (ε =0.002) usually employed to define this property in bulk specimens, is well into the



Fig. 7. Load-displacement curves for AI membranes at 2, 27, and 60°C. Zero displacement is chosen as the contact point.



Cursor: fixed Zoos: 2:1 Cen line: Off Offset: Of

Fig. 6. Roughness analysis of the thin film AI membrane obtained by AFM.

plastic regime for the 2°C specimen and cannot be defined for the others. Values of yield stress for each temperature was found to be 150 MPa for 2°C, 100 MPa for 27°C and 60 MPa for 60°C. It is interesting to note that the transition from elastic to plastic behavior occurs at the same state of strain, namely ϵ =0.0005.

Fig. 9. is a plot of Young's modulus versus displacement into the surface for nanoindentation on the Al pad at 27°C. Nine indents in total were made with all exhibiting nearly identical signatures. As mentioned earlier, the film thickness and surface roughness of the nanoindentation pad result in specimen conditions not conducive to obtaining reliable nanoindentation data. This appears to be the case with the nanoindentation data acquired on the pad. Modulus values at low displacement depths yield rather low values.

As displacement increases modulus increases abruptly to around 60 GPa and then begins to climb in a more consistent manner. The expected value of 70 GPa [13] is quickly passed by and the data appears to approach a value of 130 GPa, the modulus of the (100) Si substrate [13]. No point in the curve can be identified where the data flattens



Fig. 8. Calculated stress-strain signatures for AI membranes at temperatures of 2, 27, and 60°C.



Fig. 9. Plot of Young's modulus versus displacement into the surface for nanoindentation on the Al pad.

out to define a consistent modulus reading. Therefore, the characteristics of the nanoindentation pad render it useless for nanoindentation studies. Clearly, the Membrane Deflection Experiment is a more suited method to obtaining mechanical property data on submicron films. It also has the added bonus of yielding both residual and yield stress of the material.

CONCLUSIONS

Nanoindentation and Membrane Deflection Experiments were used to determine the properties of a submicron Al film used in the design of RF MEMS switches. Results indicated that the MDE test was more suited to test films of this size. Characteristics of the film such as its 350 nm thickness and surface roughness of 26 nm rendered it un-testable by nanoindentation due to effects of the substrate at large indentation depths and uncertainty in indenter/film contact area at small depths due to surface roughness.

The MDE test revealed that the Young's modulus of the film remained relatively constant in the temperature regime of 2-60°C. The state of residual stress was found to vary greatly from 107 MPa for 2°C, 59 MPa for 27°C and 28 MPa for 60°C. This was attributed to differences in thermal expansion coefficient between the Al film and Si substrate. Yield stress also varied greatly with temperature, 150 MPa for 2°C, 100 MPa for 27°C and 60 MPa for 60°C.

Future work will involve increasing the testing temperature regime and performing numerical simulations to match the experimental data.

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