FINAL PROJECT ME495 LAB (TEAM 2)

Testing of MEMS Materials Using Thermal Actuation, AFM Image Correlation and Capacitance Measurement

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ABSTRACT

An in-situ microtensile testing methodology is designed and instrumented in this project. The 4 microns wide, 2 microns thick, and 10 microns long polysilicon thin film is integrated in a MEMS testing device. The specimen is actuated via a thermal slanted-beam actuator and the force is measured via a parallel plate capacitance sensor. The actuator, specimen, and the load sensor are aligned in the same axis so that the specimen is under pure tension. A new method is established to measure the strain of the specimen which uses an AFM tip to scan the specimen surface while loading. DIC method is used to analysis the image of the undeformed and deformed specimens to get the strain of the specimen under load. When a voltage of 5V is applied to the actuator the measured strain of the specimen is 0.019861±0.0008179 with an accuracy of 4.11%. The load measurement is not performed due to lacking of equipment and time but this is feasible in the future. The technique has the following advantages: stress and strain can be determined at the same time, the experiment is easy to perform, and the results are accurate.
INTRODUCTION

Thin films are customarily employed in microelectronic components and MEMS devices. Their properties frequently allow essential device functions and therefore accurate identification of these properties is key to the development of new technologies [1-4]. The reliability of MEMS devices is a major issue and it can only be addressed by direct measurements on small specimens with dimensions on the same order of magnitude as the fabricated micro-devices. Unfortunately, most of our knowledge in these areas is based on bulk material behavior, which many times fails to describe material response in this size regime. This is the case due primarily to surface and interface effects, limited number of grains in a given volume, and the role played by the manufacturing process. This last feature is very important in view that specimen surfaces are the result of the process employed to remove material. For instance dry and wet etching lead to differences in surface roughness. Likewise, different chemicals utilized as etchings as well as process parameters, such as temperature and time, contribute to produce surfaces with well-defined features and defects, e.g., striations. Many researchers are currently investigating the mechanical response of thin films, e.g., Yuan and Sharpe, 1999-2002, Chasiotis and Knauss, and Espinosa et al., 1999-2002. Various techniques have been developed in the past to address the issues of mechanical integrity and evaluation of the elastic properties of polysilicon. Methods such as load-deflection, beam bending, tensile and nanoindentation tests or resonant frequency measurements of microcantilever beams have provided a span of values for the elastic constants. Of the aforementioned techniques, tensile tests 5-12 are less vulnerable to geometry-induced errors and the measurements are easier to interpret from an error analysis point of view. The design and implementation of the tensile test apparatus can be complicated but the data interpretation is effortless and accurate.

Sharpe et al., 1999, 2001, and 2002, have performed Microsample tension tests to study the mechanical properties of SiC and Polysilicon [5-7]. The specimens are manufactured by surface micromachining with one-end remains attached to the silicon wafer. The gage section and the grip end of the specimen are released by etching away the underlying sacrificial layer. The nominal dimensions of the gauge sections are 6 and 20 microns wide, 250 and 1000 microns long, and 1.5, 2, and 3.5 microns thick. An electrostatic probe is attached to the grip end and the specimen is pulled by a piezoelectric translation stage. Force is measured with a 100-gram load cell and overall system displacement is measured with a capacitance probe. The strain is measured directly on the specimen via laser interferometry. Young’s modulus is extracted from the force-displacement record by comparing the records of specimens of different lengths so that to eliminate the need to know the system stiffness. The measured fracture strengths of polysilicon are quite different: 1.56±0.25 GPa for the Cronos materials, 2.85±0.40 GPa for Sandia’s, and 2.04±0.30 GPa for the SMI polysilicon. The fracture strengths of SiC were 1.2±0.5 for CWRU materials and 0.49±0.2 for MIT’s.

Chasiotis and Knauss, 2000 and 2001, performed tensile tests, using a sample geometry and loading stage similar to the one used by Sharpe and co-workers, to investigate the mechanical strength of polysilicon films [8, 9]. The “bone-shaped” tensile micro-
specimens were designed with test section dimensions of length=400, width=50, thickness=2 microns, attached to a silicon substrate. The displacements are imposed to the specimen via an inchworm actuator that is powered by a system of a personal computer and a dedicated controller. The controller provides a measurement of the system displacement with an accuracy of 4 nm for every single step of the actuator. The induced load is measured by a miniature tension/compression load cell with an accuracy of $10^{-4}$N and maximum capacity of 0.5N. The local deformation is monitored directly on the specimen surface by means of AFM digital image correlation. They measured the fracture strength as $1.3 \pm 0.1$ GPa which was less than the results measured by Sharpe.

In this project tensile test has been performed with a “bone-shaped” micro-specimen integrated with a MEMS testing device fabricated using MUMP’s. The displacements are imposed to the specimen via a thermal actuator and measured via a parallel capacitance sensor. The strain of the specimen can be measured directly with sub-nanometer resolution by an AFM. This method is capable of measuring strains locally on the surface of the specimen.

**EXPERIMENTAL TEMODOLGY**

*Device Design:* The polysilicon specimen is integrated along with MEMS testing device using MUMP’s standard as illustrated in figure1. The device has three components: thermal actuator, specimen, and the load sensor. The thermal actuator is an array of slanted beams. The force provided by the actuators can be calculated as function 1:

$$F = \frac{F_T \cos \theta}{\cos \theta} = \frac{E A \alpha \Delta T \cos \theta}{\cos \theta} \quad (1)$$

**Figure 1.** Schematic showing the MEMS tensile testing device.
Where $\theta$ is the angle between the slanted beam and the horizontal direction, $A$ is the cross section of the slanted beam. $\alpha$ is the thermal expansion coefficient of polysilicon, and $\Delta T$ is the temperature derivation. Assuming $\Delta T = 300$ °C for an applied voltage $V = 10$ Volts [10]. With $E = 170$ GPa, $A = 16 \times 10^{-12}$ m$^2$, $\alpha = 2.33 \times 10^{-6}$/K, $\theta = 60^\circ$, the force due to thermal expansion for each beam is 0.95 mN. In this design, 10 pairs of slanted beams are used. So the maximum load can be applied is 9.5 mN.

The load sensor is comprised of parallel capacitors. The basic physical principle behind this load sensor (as well as many others), is that of a simple mass spring system. Springs (within their linear region) are governed by Hook’s law, specifically, $F = K_L \times X$. Because the load sensor is suspended by four folded beams the stiffness of the sensor can be calculated as:

$$K_L = EA/L = Ebh/L = 160 \times 10^3 \text{ N/m} \quad (2)$$

where $E = 170$ GPa (Young's modulus of polysilicon), $L = 50$ µm (length of the bulk block), $b = 23.5$ µm (width), $h = 2$ µm (height). The mass spring system used in this device is depicted in Figure 2. The mass is a bar of silicon, and the spring system is implemented by the 4 tethers which attach to each corner of the mass. It responds to accelerations that occur in line with the length of the mass. When a load is applied, the mass moves with respect to the anchored ends of the tethers.

![Figure 2. Mass-spring system used in load sensor.](image)

To measure the displacement of the bar we need to measure the differential of the parallel-plate capacitance. The principle is based upon differential parallel-plate capacitance measurement. The parallel plate capacitor can vary with vertical motion of a central movable plate, modifying the gap. Motion of the movable plate in the indicated direction increases one capacitance and correspondingly decreases the other.

Differential capacitors have the virtue of cancelling many effects to first order, providing a signal that is zero at the balance point. From a system point of view, a differential
capacitor accomplishes linearization about the balance point. Consider the parallel plate capacitor, which is shown in Figure 3, a voltage \( +V_0 \) is applied to one plate and a voltage \( -V_0 \) is applied to the other. The sensing voltage is

\[
\frac{V_{\text{sense}}}{V_0} = \frac{\Delta C}{C_0}
\]

(3)

Since the plate areas are equal, this equation is simplified as

\[
\frac{V_{\text{sense}}}{V_0} = \frac{X_L}{d} + o\left(\frac{X_L}{d}\right)^3
\]

(4)

where \( X_L \) is the motion of central plate, and \( d \) is the original gap.

\[
C_1 = C_0 + \Delta C \quad C_2 = C_0 - \Delta C
\]

Figure 3. (a) A schematic of parallel plate capacitor, (b) A typical circuit use of a differential capacitor.

Hence the sensing voltage is proportional to \( x \), but only for small values of displacement. Assuming \( d=10 \mu m \) and \( V_0=5 \) V the sensitivity of the load sensor is 0.32 N/V. To measure the load smaller than 1 mN we need voltmeter having a sensitivity of 0.1 mV.

The total device can be looked as a Lumped model as shown in Figure 4:

\[
K_T \quad K_S \quad K_L
\]

Governing Equations:

\[
X_S = X_T - X_L
\]

\[
K_S X_S = K_L X_L
\]

\[
K_T X_T = F - K_S X_S
\]

Figure 4. The Lumped model and the governing equations.
Deformation of the Specimen
Displacement of the Load Sensor
Displacement of the Thermal Actuator
Stiffness of the Specimen
Stiffness of the Load Sensor
Stiffness of the Thermal Actuator
Failure force generated by the Thermal Actuator

The specimen stiffness is:
\[ K_S = \frac{EA}{L} = \frac{Ebh}{L} = 136 \times 10^3 \text{ N/m} \]  (5)
where \( b = 4 \, \mu\text{m} \) (width of the specimen), \( h = 2 \, \mu\text{m} \) (height), \( L = 10 \, \mu\text{m} \) (length)

The stiffness of each slanted beam of the thermal actuator
\[ K_T = K_B \cos^2 \theta + K_E \sin^2 \theta = 2.27 \times 10^3 \text{ N/m} \]  (6)
where bending stiffness \( K_B = 6.45 \, \text{N/m} \), extension stiffness \( K_E = 9.07 \times 10^3 \, \text{N/m} \) due to the dimensions of the beams, \( L = 300 \, \mu\text{m} \), \( b = 8 \, \mu\text{m} \), and \( h = 2 \, \mu\text{m} \), and \( \theta = 60^\circ \) (the angle between the beams and the truss).

If a voltage of 10 V is applied to the actuator so that \( \Delta T = 300 \, ^\circ\text{C} \) the displacements of the thermal actuator, specimen, and load sensors are computed as: \( X_T = 160 \, \text{nm} \), \( X_S = 86 \, \text{nm} \), and \( X_L = 74 \, \text{nm} \)

**Instrumentation for Microtensile Testing:** An important aspect of the design process of the experimental apparatus for MEMS testing is the inherent dependence of the specimen geometry on the test device layout. The test method needs to be optimized taking into account the combination of optimum specimen and apparatus design.

Experimenting with small specimens demands the test device to be designed so that it simultaneously addresses several important issues, as:

1. Specimen mounting,
2. Facilitation of the necessary electrical connections,
3. Positioning accommodation under the AFM.

**Specimen Design and Characterization:** Tensile, “bone-shaped” specimens were designed with test section dimensions of \((L \times W \times D) = 10 \times 4 \times 2 \, \text{microns} \) (Figure 5). The specimens were designed for the Multi-User MEMS Processes (MUMPs) at Cronos.

The surface roughness was characterized via AFM (Atomic Force Microscope). The AFM image shows the specimen has a very smooth surface during microfabrication and the grain size is only \(~0.5 \, \text{microns} \).
Figure 5. Optical image of the microtensile specimen and the MEMS testing device.

Figure 6. AFM image shows the surface roughness and grain size of the specimen.
MICROTENSILE TESTS-RESULTS

The specimens were gently attached before testing to avoid the beam from being in contact with the substrate due to adhesion [11, 12].

Before we perform the experiments we should first address that there is a drifting between the system and the AFM. The drifting can be induced by the poor mounting of the device, the vibrating of the suspended beams, and other noises from the environment. To eliminate the results of the shifting and minimize the measuring error we need to characterize the system error by scanning the same area at zero loading. Figure 7 is two AFM images (tapping mode) of the same location on the surface of the specimen. The scanning area is 5x5 µm² and the scanning rate is 2 Hz. It is very hard to find the difference of the two images by naked eyes. However, displacement can be analysis by DIC (Digital Image Correlation) method (Figure 8). After the DIC analysis the displacement of the system can be easily characterized. We analysis the image at different size scale: 10x10 µm² (a)(d), 5x5 µm² (b)(e), and 2x2 µm² (c)(f). The strains on x-x direction and y-y direction were determined. From the DIC analysis we can find the initial drifting on both x and y axis. The DIC results are illustrated in Table 1, we can see that the strain in x direction is approximately 0.536% and the strain in y direction is approximately -0.509%. The results show that the AFM tip is drifting at a fixed rate and the movement of the tip can be estimated.

Figure 7. Two AFM images of the undeformed specimen surface. The images are scanned at the same location with a frequency of 2 Hz.
Figure 8. The DIC analysis of the displacement between two scans.
Table 1. DIC analysis of $\varepsilon_{xx}$ and $\varepsilon_{yy}$ at the same location but different scanning area.

<table>
<thead>
<tr>
<th></th>
<th>10 µm x 10 µm</th>
<th>5 µm x 5 µm</th>
<th>2 µm x 2 µm</th>
<th>Avg (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{xx}$ Max.</td>
<td>0.0082266</td>
<td>0.0153208</td>
<td>0.0052433</td>
<td>0.0536%</td>
</tr>
<tr>
<td></td>
<td>-0.00718457</td>
<td>-0.0141811</td>
<td>-0.0042058</td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td>0.000521</td>
<td>0.000569</td>
<td>0.000518</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{yy}$ Max.</td>
<td>-0.0203293</td>
<td>-0.0266018</td>
<td>0.00033872</td>
<td>-5.09%</td>
</tr>
<tr>
<td>Min.</td>
<td>-0.0765621</td>
<td>-0.0751549</td>
<td>-0.106988</td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td>-0.0484</td>
<td>-0.0509</td>
<td>-0.0533</td>
<td></td>
</tr>
</tbody>
</table>

The strains of the surface of the specimen are currently measured using AFM records of deformed and undeformed specimen configurations. This is the final development stage of the described method. Figure 9 illustrates two AFM records of a deforming specimen. The first picture is the monitored area before the induced deformation i.e. at 0 N load while the second figure is captured during the deformation step of 5 V actuation voltages applied in the horizontal direction of the figures shown. Because the width of the specimen is only 4 microns we scanned an area of 2 µm in width and 5 µm in width of the specimen surface. The strains of both x-x direction and y-y direction are obtained as Figure 9 shows. The strains of undeformed specimen and deformed specimen are compared. According to Figure 9, $\varepsilon_{0x}$ (strain of undeformed specimen at x direction) is equal to $(0.025088-0.024469)/2 = 0.035\%$ (a); $\varepsilon_{0y}$ (strain of undeformed specimen at y direction) is equal to $(-0.0293253-0.063183)/2 = -4.63\%$ (b); $\varepsilon_{1x}$ (strain of deformed specimen at x direction) is equal to $(0.0118725-0.00167882)/2 = 0.51\%$ (c); and $\varepsilon_{1y}$ (strain of deformed specimen at y direction) is equal to $(-0.1107334+0.0216046)/2 = -4.59\%$ (d).

Now the strain of the deformed specimen can be calculated as:

$\varepsilon_x = \varepsilon_{1x} - \varepsilon_{0x} = 0.51\% - 0.035\% = 0.475\%$

$\varepsilon_y = \varepsilon_{1y} - \varepsilon_{0y} = -4.63\% - (-4.59\%) = -0.04\% \approx 0$

If there is no noise or drifting the absolute strain of the specimen in y direction should be zero. However, the measured $\varepsilon_y$ is $-0.04\%$ which means the error of the strain measurement is approximately $-0.04\%$. The error of the strain in x direction should be at the same order. So $\varepsilon_x$ can be estimated as $\varepsilon_x = (0.475\pm0.04)\%$. The relative error of the strain measurement can be calculated as:

$\varepsilon = 0.04/0.475 \approx 8.42\%$
Figure 9. DIC results of strain analysis on both undeformed and deformed specimen. The four images are at the same location. X is the direction of the load.
CONCLUSION AND DISCUSSION

In this project an *in-situ* MEMS testing methodology is established to do microtensile testing of polysilicon thin film. The load can be measured using the integrated parallel plate capacitance sensor. However, lacking of equipment and time we are unable to measure the force. This can be done in the future to verify the feasibility of the testing methodology.

The absence of surface developed charges makes the use of a probe microscope possible in the regime of small interaction forces between the film and the AFM probe. Although there is an initial drifting of the AFM image at zero load the strain of the specimen can be compensated by subtract the measured strain by the initial shifting. After calibration the strain can be accurate measured with a relative error of 4.11%. The future work will be conducting measurements at various voltages (loads) to find the sensitivity of the strain measurement. FEM analysis is used to compare the experimental result with the computation results. Figure 10 show the FEM analysis of the testing device, the strain of the specimen is 4.036% which is very similar to the experiment results 4.75%. The simulation verified that the experimental methodology is feasible.

![Figure 10. The FEM analysis results of the device using ANSYS software.](image)
This technique is less vulnerable to geometry-induced errors and the measurements are easier to interpret from an error analysis point of view. The design and implementation of the tensile test apparatus can be complicated but the data interpretation is effortless and accurate.

REFERENCE:

8. Page: 14
11. Page: 14