MEMORANDUM
MEMS LAB #1

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #1: Characterization of Heat Actuator
Date: 7/19/2013

On July 18, 2013, we, members of group B1, conducted the experiment "Characterization of Heat Actuator" in the Micro-Nano Devices and Systems (MiNDS) laboratory to study the deflection of a heat actuator.

To complete this lab, we used Micromanipulator 7000 Probe station with 350 and 250 manipulators with probe holders and probe tips with a point radius of 10um shown in Figure 1. The probe tips were placed on the pads of the heat actuator and were connected to the Pragmatic Instruments 2414A Arbitrary Waveform Generator shown in Figure 2b. This arbitrary waveform generator (AWG) was connected to an E-Machines computer, shown in Figure 2a, by GPIB, which allowed us to apply electrical signals to the thermal actuator. We used a Cohu Color CCD camera connected to a Dell Computer, shown in Figure 3, to observe the deflection of the heat actuator. This computer allowed us to take picture of the heat actuator before and after applying a voltage, which started at 1V to 10V. Two digital multimeters were used to measure the voltage and current applied (seen in Figure 2a). The deflection of the heat actuator can be calculated based on the tick mark from the ruler on the pictures of the heat actuator (Figure 5 a-j). We took picture of the stationary heat actuator (Figure 4) without voltage applied and compared it to others pictures taken as voltage is increased by 1V at a time until it reaches 10V. This way we can see the deflection.

The reason why a heat actuator will deflect is due to its design. When a voltage is applied to the pads of the heat actuator, the hot arm get hotter than the cold arm due to its width. The hot arm is narrower than the cold arm, creating high resistance to the flowing current that causes the voltage to drop. This makes the hot arm to dissipate the power through heat, which create an increasing temperature. The increasing temperature in the hot arm creates thermal expansion. The thermal expansion causes a stress that makes the heat actuator to deflect towards the cold arm. The cold arm has less resistance allowing current to flow smoothly, thus, the cold arm is at a lower temperature compared to the hot arm. In the end of the cold arm, there is a thin part called the flexure, which is a weak link in the cold arm that allows the heat actuator to bend.

We changed the current wave to Wav #7 and set the amplitude to 4V, 8V, and 6V and for each amplitude we varied the frequencies to 10Hz, 25 Hz, 50 Hz, 500 Hz, 1kHz, 5kHz, and 10kHz. We observed that as the amplitude or voltage increases, the deflection increases. Also as the frequency increases, so does the oscillation or vibration. For example, when the amplitude is set to 4V and frequency at 10Hz, we can see it deflects and return to its rest position after a while. When set at 4V and 500Hz, we can see the approximately the same amount of deflection as before, but the heat actuator would go back to its rest position and deflects again faster, it toggles. This tells us that the heat actuator allows us to control how much deflection and oscillation we want to input into it, which is very useful if we need to make a small switch that need to be trigger at a precise distance and timing [1].

The result of the current through the heat actuator should increase proportionally to the voltage if resistance is held constant. However, this is not what we see in Graph 1. The reason is because as voltage is increased, current flows through the heat actuator changing the temperature, this changes the resistance too[2]. Thus, this makes the graph looks quadratic instead of linear. In Graph 3, the highest deflection is 6um when power is at 47.58mW which occurs at 10V. According to the power equation (P = VI), we can infer that the force applied to the heat actuator increases quadratically with respect to the voltage applied (shown in Graph 2). And also, there is also a curve that seems like a dquadratic relationship between power and deflection seen in Graph 3 because the deflection of the heat actuator is displacing with an angle, so as power increases, the heat actuator displace more. As we see when frequency is changed, the heat actuator toggles, which tell that it is a circular motion.

In conclusion, in this experiment we have learnt to characterize a heat actuator. We know what role a voltage plays and how by inputting a frequency can change the behavior in a thermal actuator.

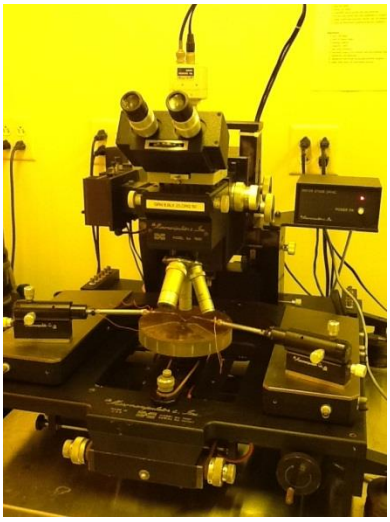


Figure 1. Micromanipulator 7000 Probe Station with micromanipulator 350 and 250 with probe holders and probe tips with a point radius of 10um.

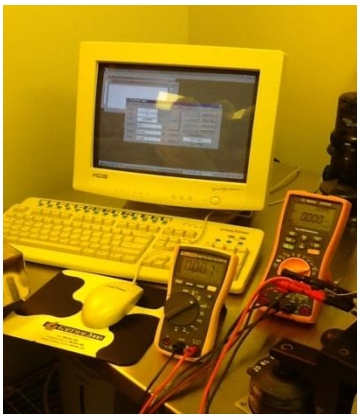


Figure 2 (a). The E-Machine computer used to supply the voltage. Two digital multimeter read the voltage and current supplied through the heat actuator.

Figure 2 (b). Pragmatic Instruments 2414A Arbitrary Waveform Generator is the power supply that applies the voltage to the heat actuator and is connected to the E-Machine computer.

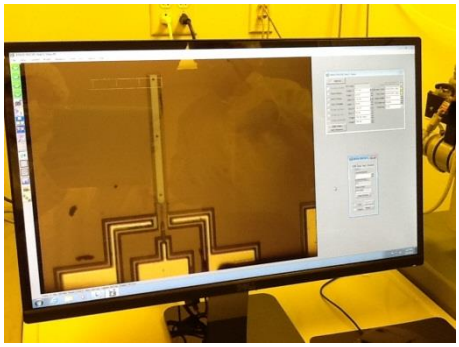


Figure 3. The Dell computer shows the heat actuator and allows us to take picture of the heat actuator.

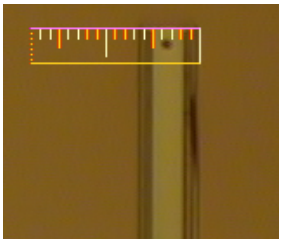


Figure 4. Heat actuator at rest without deflection – No voltage applied.

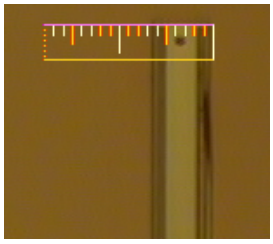


Figure 5 (a). Voltage = 1V

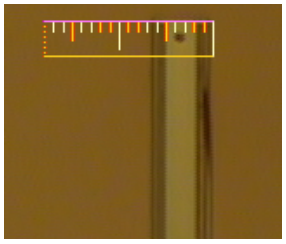


Figure 5 (b). Voltage = 2V

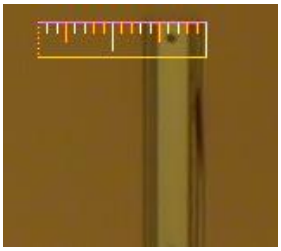


Figure 5 (c). Voltage = 3V

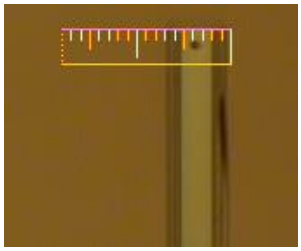


Figure 5 (d). Voltage = 4V

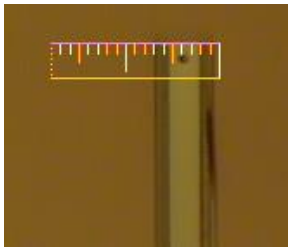


Figure 5 (e). Voltage = 5V

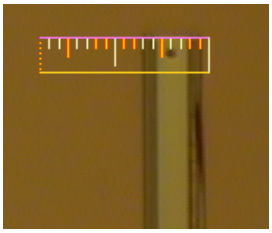


Figure 5 (f). Voltage = 6V

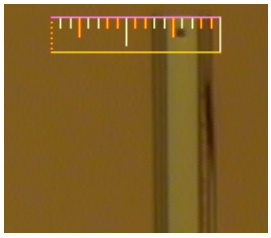


Figure 5 (g). Voltage = 7V

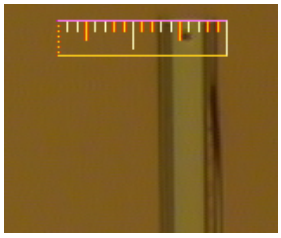


Figure 5 (h). Voltage = 8V

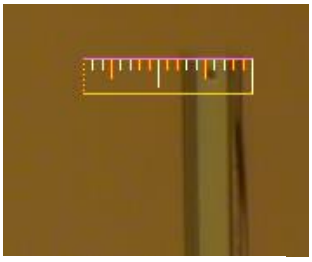


Figure 5 (i). Voltage = 9V

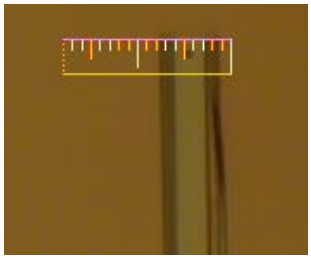
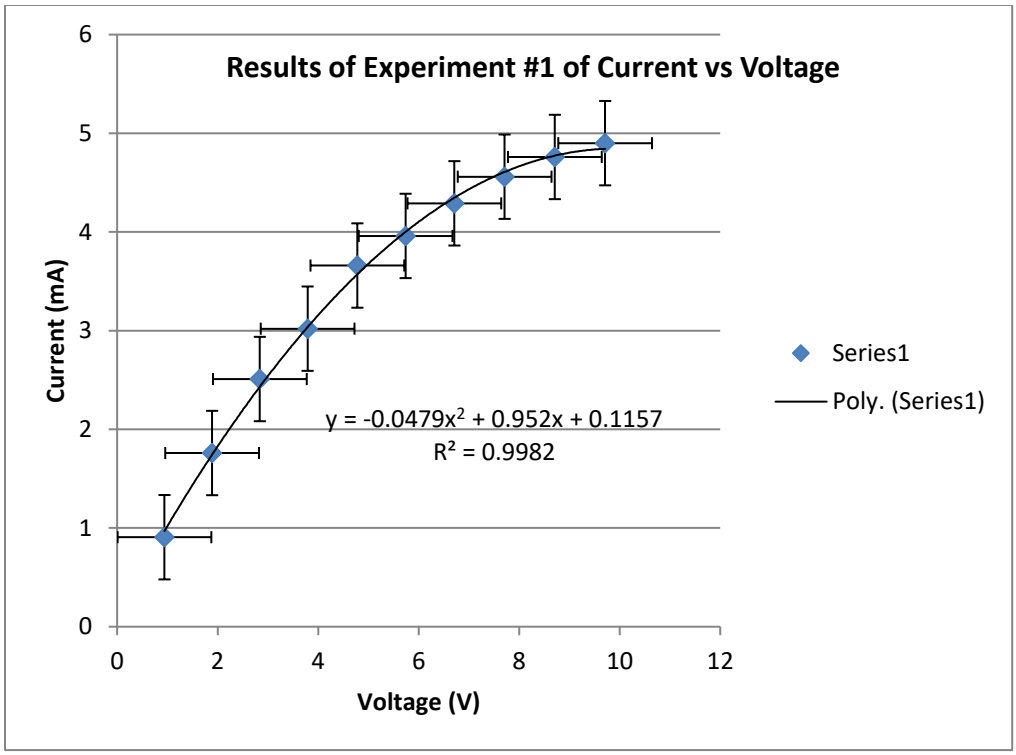


Figure 5 (j). Voltage = 10V

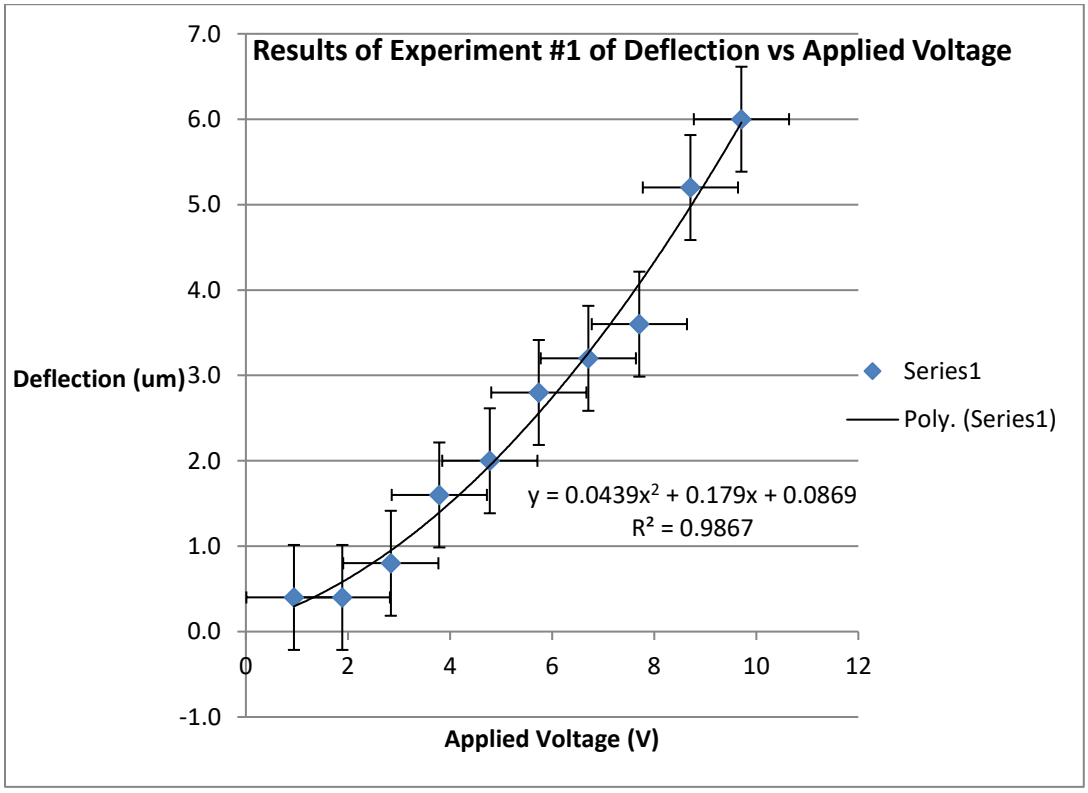
Figure 5. These are the pictures with a voltage applied on the heat actuator. The magnification is 8x and the zoom is 1x. One tick mark from the ruler is 4um.

Table 1. The voltage and current with their uncertainty are read from the multimeters. The power and its error were calculated using voltage and current. The deflection and its uncertainty were measured.

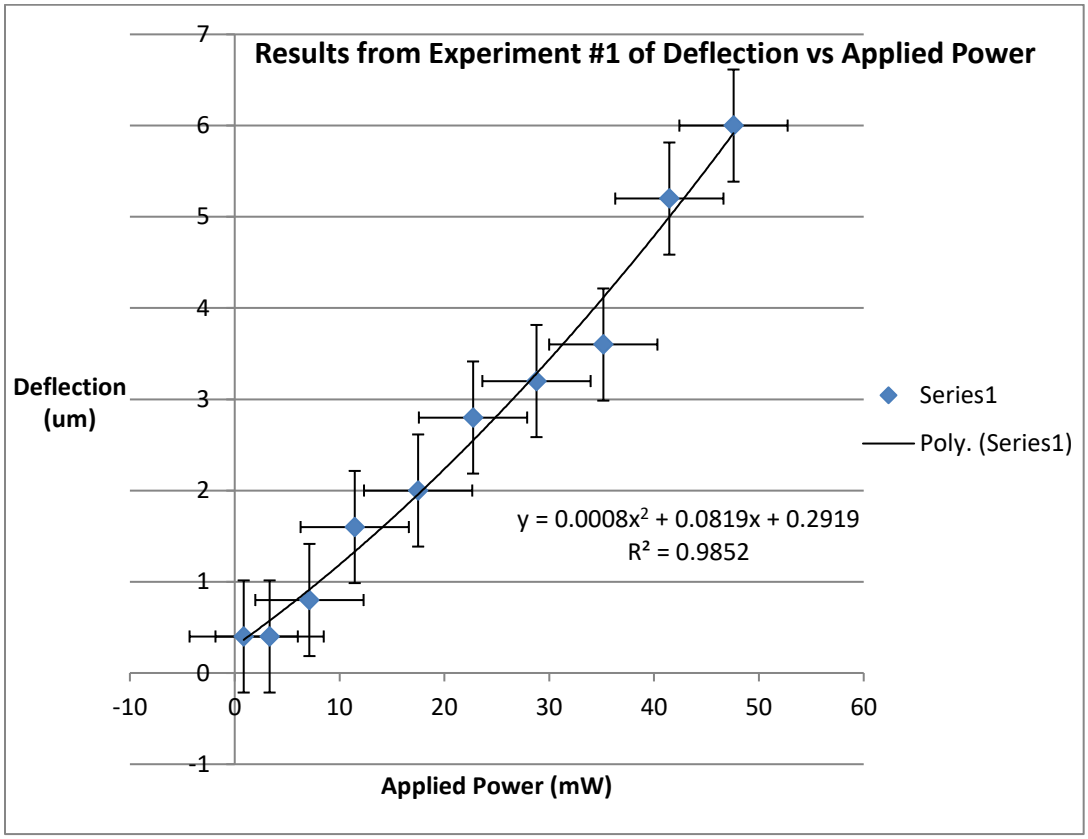
Voltage (V)	Actual Voltage (V)	± Uncertainty (V)	Current (mA)	± Uncertainty (mA)	Power (mW)	± Uncertainty (mW)	Deflection (µm)	± Uncertainty (µm)
1	0.942	0.01	0.91	0.02	0.85	0.02	0.4	0.08
2	1.89	0.01	1.76	0.02	3.33	0.04	0.4	0.08
3	2.84	0.01	2.51	0.02	7.13	0.06	0.8	0.08
4	3.79	0.01	3.02	0.02	11.45	0.08	1.6	0.08
5	4.78	0.01	3.66	0.02	17.49	0.10	2.0	0.08
6	5.74	0.01	3.96	0.02	22.73	0.12	2.8	0.08
7	6.71	0.01	4.29	0.02	28.79	0.14	3.2	0.08
8	7.71	0.01	4.56	0.02	35.16	0.16	3.6	0.08
9	8.71	0.01	4.76	0.02	41.46	0.18	5.2	0.08
10	9.71	0.01	4.90	0.02	47.58	0.20	6.0	0.08



Graph 1. Graph of the results of experiment #1 of current vs. voltage. We can see that as voltage is applied higher, current increases, but it is not linear as Ohm's law states because there is a change in temperature, thus, a change in resistance. This is due to not letting the heat actuator cools down between trials, so the temperature is varied.



Graph 2. Graph of the results of experiment #1 of Deflection vs. Applied Voltage. This graph shows a nonlinear relationship between deflection and the applied voltage. As we can see, as more voltage is applied, more displacement would be seen. However, after the recommended maximum voltage of 10V, the heat actuator starts to deteriorate slowly.



Graph 3. This graph shows the quadratic relationship between deflection and applied power since the deflection of the heat actuator is circular because it has an angle of deflection.

Calculation

Power: P= V*I, where P is power (mW), V is voltage (V), and I is current (mA).
Example: P = 0.942 V * 0.91 mA = 0.85mW

Where P is the power, V is the voltage applied, and I is the current.

Error Propagation of Power: $\delta P = \sqrt{(I \cdot \delta V)^2 + (V \cdot \delta I)^2}$

Example: $\delta P = \sqrt{(0.91 \cdot 0.01)^2 + (0.942 \cdot 0.02)^2}$ = 0.02mW

Where δP is the uncertainty of power, I is the current, V is the voltage, δV is the uncertainty of voltage and δI is the uncertainty of current.

Reference

[1] Carol Livermore, course materials for 6.777J / 2.372J Design and Fabrication of Microelectromechanical Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [20 July 2013].
[2]Ohm's Law, Nonlinear conduction, http://www.allaboutcircuits.com/vol_1/chpt_2/6.html, (22 July 2013)

MEMORANDUM
MEMS LAB #2

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #2: Wet Oxidation of Silicon Wafer
Date: 7/23/2013

On July 23, 2013, we, members of group B1, conducted the experiment "Wet Oxidation of Silicon Wafer" in the Micro-Nano Devices and Systems (MiNDS) laboratory to grow and measure a thin film of SiO_2 by wet oxidation process after performing an RCA clean, which remove contaminants from the surface of the wafer.

To complete this lab, we performed an RCA clean first by dipping the p-type (111) Si wafer (seen in Figure 1) into a solution of NH_4OH, H_2O_2, H_2O in the hot plate at 70°C for 10min (seen in Figure 2) . Then, we rinsed the wafer with DI water and spun dry (seen in Figure 3), and then immersed the wafer into a solution of HCl, H_2O_2, and water in a petri dish heated to 80°C for another 10min (seen in figure 4). Then, we rinsed the wafer in DI water and spin dry the wafer again. By doing an RCA clean, we can remove the organic, inorganic, ionic, and metallic contamination from the surface of the wafer.

After performing the RCA clean, we started the procedure for wet oxidation. The furnace was set first to a 250°C. After reaching that temperature, it was then increased to a 1000°C, shown in Figure 5. Nitrogen gas flowed to the furnace to ensure uniform step oxidation as shown in Figure 6. This was done at a flow rate of 10 (~0.566 L/min). After the furnace reached a 1000°C (Figure 7), we closed the knob of the nitrogen gas and opened the knob of the oxygen gas (Figure 8). The O_2 gas made the water, which was heated by the water bubbler to about 95°C – 98°C. The wafer was placed in the quartz wafer boat, shown in Figure 9, and was introduced slowly into the furnace with the push rod, shown in Figure 10. The wafer was left in the furnace for 60min for the oxidation to complete.

For measuring the thickness of the oxide layer, we used the Filmetrics F20 thin film measurement system, seen in Figure 11. We took 10 measurements shown in table 1, 5 at the center of the wafer and 5 around the edge, and example can be seen in Figure 12. We average the 10 measurements and took the standard deviation and got 358.46 ± 0.39 nm by using Eq. 1.1-1.2 (Table 1). We also applied Deal-Grove model to calculate the oxide layer using Equation 2, and it resulted in a thickness of 450nm, which is approximately 92nm off from our measurements (Table 2). We also found the thickness of the oxide by using a color chart, we thought that the color of the wafer was close to a green to green yellow color, which according to the color chart it is 350nm (shown in Table 2). The thickness of the initial Si wafer was assumed as 500 μm after RCA clean. The thickness of the silicon after oxidation is 500.20 ± μm , this is by adding the thickness of oxide layer grown on top of the initial wafer thickness, which can be seen in Eq. 3.2 (seen in Table 2).

The measured value from the Filmetrics F20 thin film measurement system is close to the color chart value, but the value from the Deal-Grove model is far off. This might be due to Boltzmann's Distribution since it shows that the temperature-dependence diffusion is exponential.

The Deal-Grove model can estimate the thickness of oxide, but it is not always accurate as seen in our calculation compared with the measured one, which makes it not the best method. This inaccuracy is due to the parameters, which can be varied. The color chart is not very accurate to estimate the thickness of the oxide because of the selection of colors available, it is hard to tell if the color is a blue green, green, light green, yellow green, etc. Using the Filmetrics F20 thin film measurement system gave us the best accurate values with little uncertainty, which makes it the best method if accuracy matters.

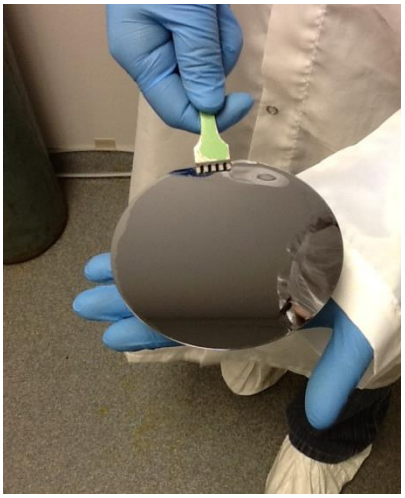


Figure 1. Due to the shape of the flat part, we can tell that we obtained a p-type (111) Si wafer.

Figure 2. A solution of NH4OH, H2O2, and H2O was placed into a petri dish and heated to 70°C. The wafer was immersed in the solution for 10min to removes organic dirt.

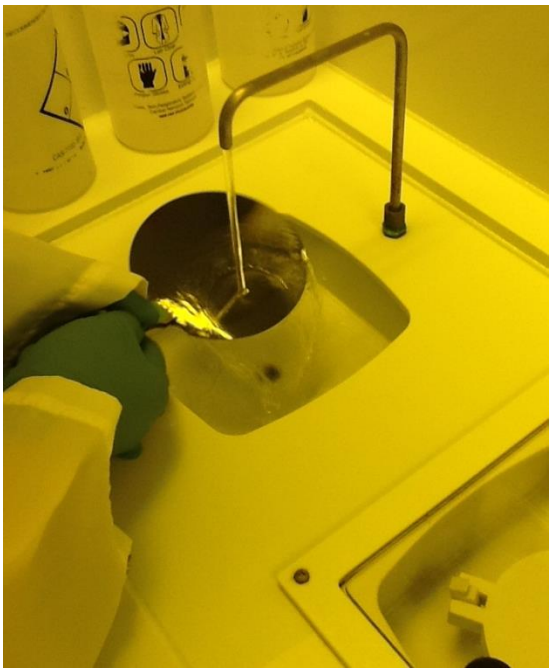


Figure 3. The wafer was rinsed with DI water and spin dry.

Figure 4. A solution of HCl, H2O2, and H2O was put into a petri dish and heated to 80°C. The Si wafer was immersed in the solution for another 10min. This removes the metal ions from the surface of the wafer.

Figure 5. The furnace was ramped to 250°C.

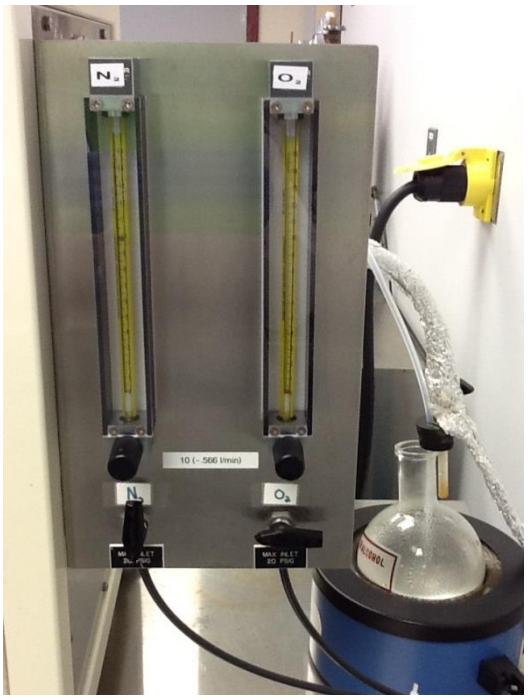


Figure 6. Nitrogen gas was allowed to flow into the furnace to ensure uniform step oxidation. Flow rate read from rotameter: 10 (~.566 L/min).

Figure 7. The furnace reached 1000°C after a while.

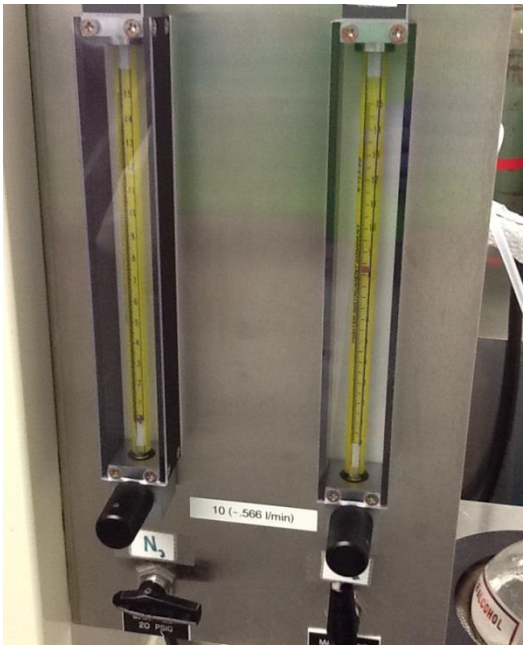


Figure 8. We closed the knob of the nitrogen and opened the oxygen one. The rotameter was reading 8 for the oxygen flow rate.

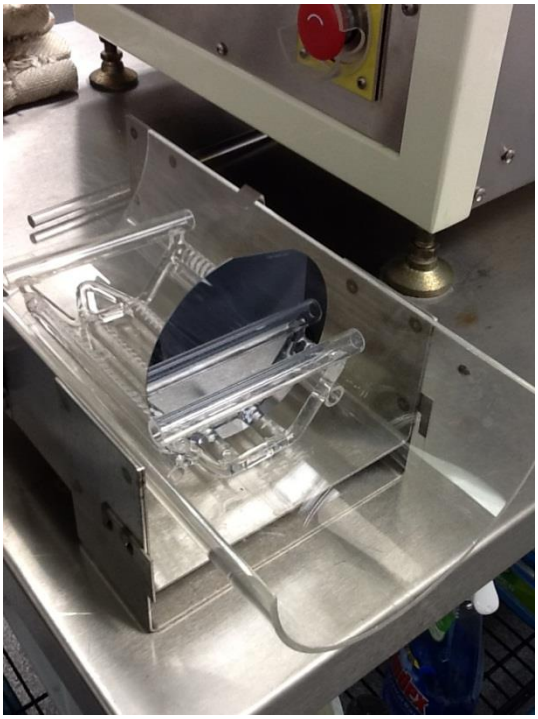


Figure 9. After the RCA clean, the Si wafer was placed on the quartz wafer boat ready to be introduced into the furnace.

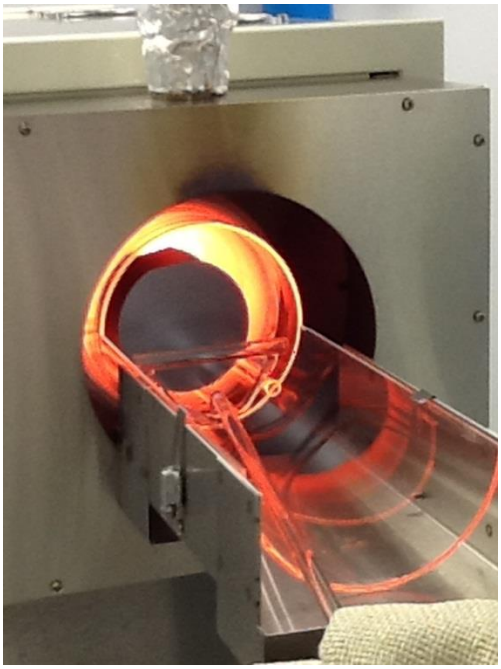


Figure 10. Once the furnace was ready, we introduced the Si wafer into the furnace very slowly and carefully with the push rod.

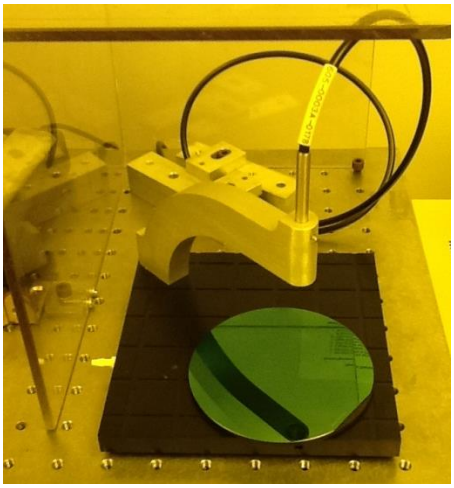


Figure 11. Filmetrics F20 thin film measurement system. It is used to measure the thickness of the oxide layer.

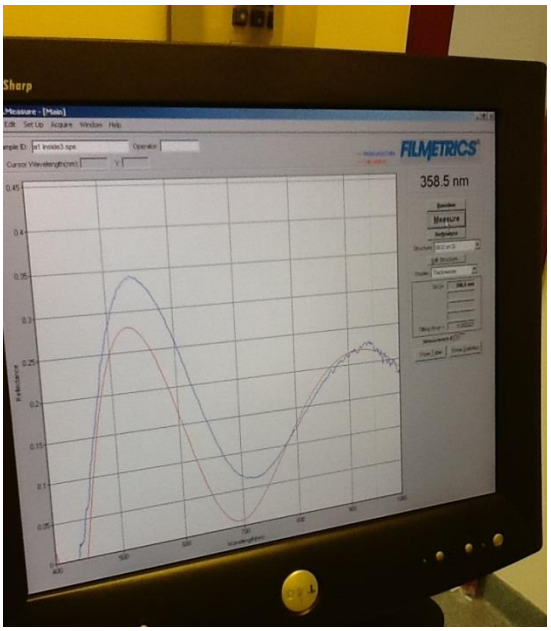


Figure 12. One of the measurement taken with the Filmetrics F20 thin film measurement system.

Table 1. The 10 measurements we took using the Filmetrics F20 thin film measurement system. We average the measurements value and calculated the standard deviation.

Measurement	Film Thickness (nm)	Uncertainty (nm)
1	358.6	0.14
2	358.5	0.04
3	358.5	0.04
4	358	-0.46
5	358.5	0.04
6	358.5	0.04
7	358.5	0.04
8	357.7	-0.76
9	359.3	0.84
10	358.5	0.04
Average Oxide Thickness (nm)	358.46	
Standard Deviation (nm)	0.390384426	
Standard Error (nm)	0.123	

Table 2. All calculations are shown in the calculation section.

Deal Grove Model (nm)	450
Color Chart Thickness(nm)	350
Wafer initial thickness (µm)	500
Wafer consumed (nm)	161.307
Wafer consumed Uncertainty (nm)	0.0553
Wafer thickness after oxidation (µm)	500.197153
Wafer thickness after oxidation Uncertainty (µm)	0.06765

Calculation

Average:

$$p = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$$ **(Equation 1.1)**

Where p is the average, n is the number of values, x is the value.

$$p = \frac{1}{10} \cdot (358.6 + 358.5 + 358.5 + 358 + 358.5 + 358.5 + 358.5 + 357.7 + 359.3 + 358.5)$$

$p = 358.4600000$ nm (grown oxide)

Standard Deviation:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - p)^2} \qquad \textbf{(Equation 1.2)}$$

Where σ is the standard deviation, N is the number of measurements, x is the value of a measurement and p is the average of the measurements.

Example of Standard Deviation:

$$\sigma = \left(\frac{1}{10}\cdot\left((358.6-358.46)^2 + (358.5-358.46)^2 + (358.5-358.46)^2 + (358-358.46)^2 + (358.5-358.46)^2 + (358.5-358.46)^2 + (358.5-358.46)^2 + (357.7-358.46)^2 + (359.3-358.46)^2 + (358.5-358.46)^2\right)\right)^{1/2}$$

$$\sigma = 0.3903844259$$

Standard Error:

$$SD_x = \frac{\sigma}{\sqrt{n}} \qquad \textbf{(Equation 1.3)}$$

Where SD_x is the standard error, the σ is the standard deviation, and n is the number of values.

Example of Standard Error:

$$SD_x = \frac{0.390}{\sqrt{10}}$$

$$SD_x = 0.1233288287$$

Deal-Grove model:

$$Z(t) := \frac{A}{2}\left[-1 + \sqrt{\frac{4B}{A^2}\cdot t + 1}\right] \qquad \textbf{(Equation 2)}$$

Where Z(t) is the thickness of the SiO2 layer with respect to time, t is the time, A and B are a constant dependent on Boltzmann's constant, concentration of oxygen at the surface, molar mass of SiO2, and coefficient of diffusion for the silicon, and they are represented in μm and in μm^2/hour respectively.

Example of Deal-Grove model calculation:

For the constants A and B values, we obtained the data for Wet Oxidation at 1000C for a (111) Si wafer from the book Introductory MEMS by Dr. Adams and Layton[1].

$$Z = \frac{0.252}{2}\cdot\left(-1 + \sqrt{\frac{4\cdot 0.316}{0.252^2} + 1}\right)$$

$$Z = 0.4500867991$$

Wafer Thickness

Wafer consumed (W)= Z * 0.45 = 358.46*0.45 = 161.31nm **(Equation 3.1)**

Wafer final thickness = 500 + Z*0.55 = 500 + 358.46*0.55=500.20 **(Equation 3.2)**

Where Z is the thickness of the average oxide layer.

Uncertainty of wafer

$$U = \frac{SD_x}{p} \cdot W$$ **(Equation 4)**

Where U is the uncertainty, SD is the standard error, p is the average, and W is the wafer consumed thickness.

Example of uncertainty

$$U = \frac{0.123}{358.46} \cdot 161.31$$

$$U = 0.05535102941 \text{ nm}$$

Reference

[1] Adams, Th. M., Layton, R.A. (2010). *Introductory MEMS: Fabrication and Applications*: Springer

MEMORANDUM
MEMS LAB #3

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #3: Photolithography of Sacrificial Layer
Date: 7/30/2013

On July 26, 2013, we, members of group B1, conducted the experiment "Photolithography of Sacrificial Layer" in the Micro-Nano Devices and Systems (MiNDS) laboratory to practice the process for obtaining a sacrificial layer of photoresist on a silicon wafer and measure a the thickness of the resist using the Filmetrics system.

To complete this lab, we picked up our clean oxidized wafer (Seen in Figure 1) and prebaked at 96°C for a minute to remove excess moisture from the wafer (Shown in Figure 2). Then, we put the wafer on the center of vacuum chuck of the spinner (seen in Figure 3.1-3). Then we poured Shipley Microposit 1800 positive photoresist onto the center of the wafer, closed the lid and started the spinner. The spinner was set to 7500rpm for 90seconds. After that, we performed a soft bake to remove excess solvent from the photoresist at 96°C for one minute. We then placed the wafer on the Suss mask aligner, as shown in Figure 5.1, and exposed the wafer with mask 7 (Figure 5.2) for 4 seconds. Then, we performed a post-exposure bake on the hotplate for another minute at 96°C and then we developed the photoresist using Shipley Microposit 351 developer dilute with DI water in a ratio of 1:3 (Shown in Figure 7). Finally, we performed a post bake at 95°C for 3 minutes on hot plate to harden resist.

The clean oxidized wafer looks like green in the beginning as seen in Figure 1. After spinning the photoresist on the wafer, it is coated with a layer that looked pink (Figure 4). After exposing, the pattern was still not clear shown on the wafer (Figure6). Then, we developed, and it was easier to see the pattern on the wafer, seen in Figure 8.

We placed the wafer under the micromanipulator (Figure 8) and took some measurement of the undercut in one of the alignment marks seen in Figure 9.1-9.2. Then, we took measurement of resist on SiO_2 using the Filmetrics system seen in Figure 10. An example of the measurement taken from the Filmetrics F20 system is seen in Figure 11. Table 1 and Table 2 show the measurement from the Filmetrics and the measurement of the undercut. The etching is mostly isotropic, that is why there is the undercut, and it is a little anisotropic too.

In conclusion, in this experiment, we learned how to do make a layer a photoresist on the silicon wafer and how to transfer a pattern onto the wafer. We also measured the thickness of the resist on the SiO_2.

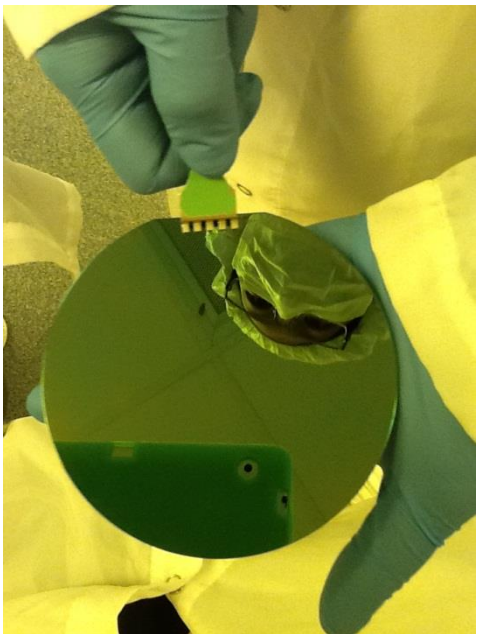


Figure 1. Clean oxidized wafer from previous experiment of oxidation.

Figure 2. Wafer heated for one minute on the hotplate at 96°C

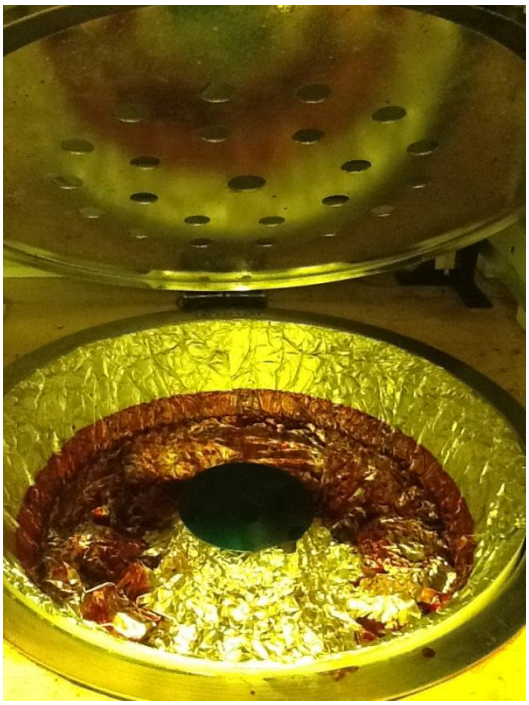


Figure 3.1. The Spinner with lid open.

Figure 3.2. The spinner with lid closed.

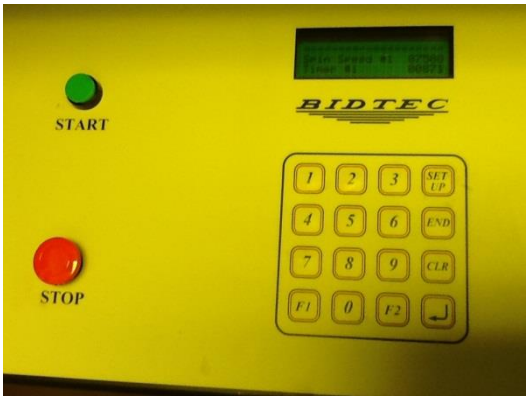


Figure 3.3. The spinner control electronics. Here is where the spinning cycle is controlled.

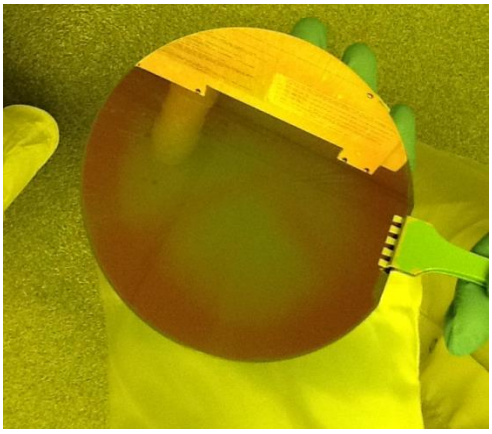


Figure 4. Wafer after spinning photoresist on it.

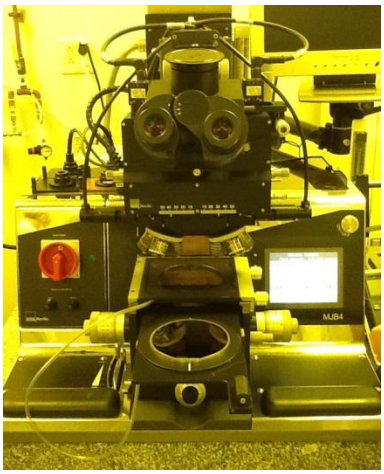


Figure 5.1. Suss Microtec mask aligner.

Figure 5.2. Mask #7 containing the pattern that we want to transfer onto the

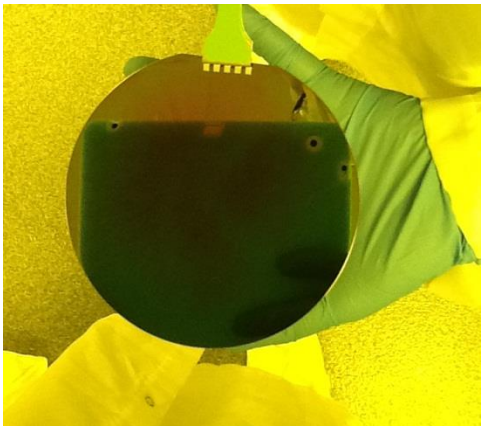


Figure 6. Wafer after exposing, before developing.

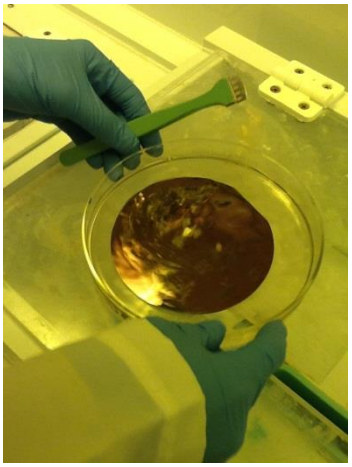


Figure 7.Developing the wafer.

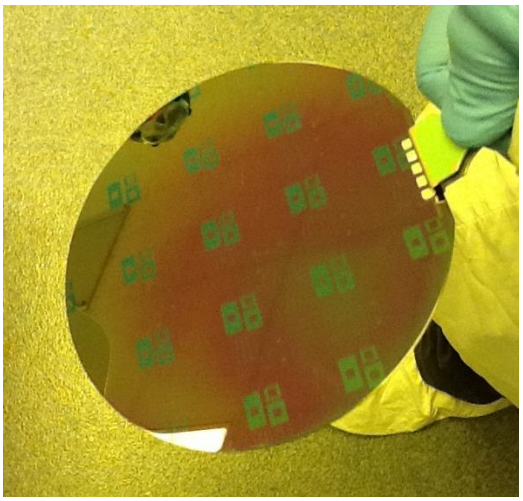


Figure 8. Result of photolithography. We can see the pattern on the wafer.

Figure 8. Wafer under the Micromanipulator.

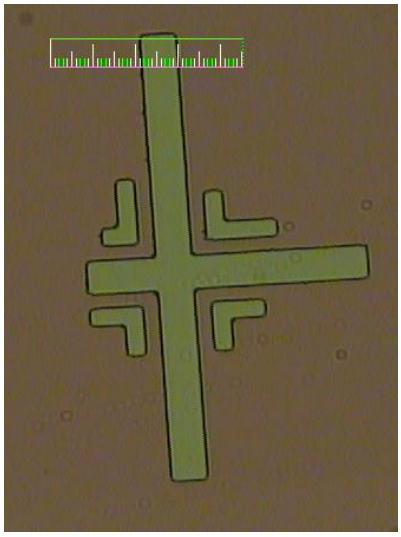


Figure 9.1. Using 10X-2X objective and zoom; each tick mark is 1.25um.

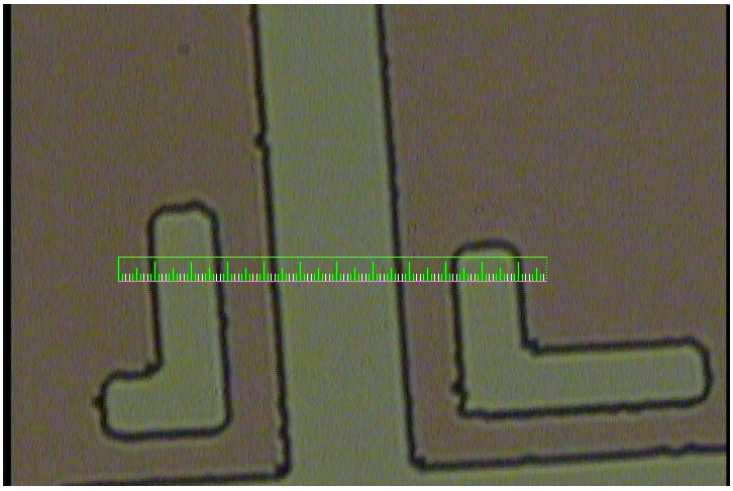


Figure 9.2. Using 20X-2X objective and zoom; each tick mark is 0.62um.

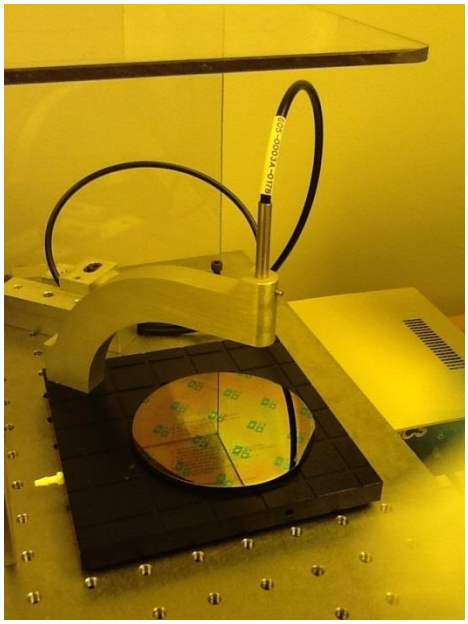


Figure 10. Filmetrics system used to measure the thickness of resist on SiO2.

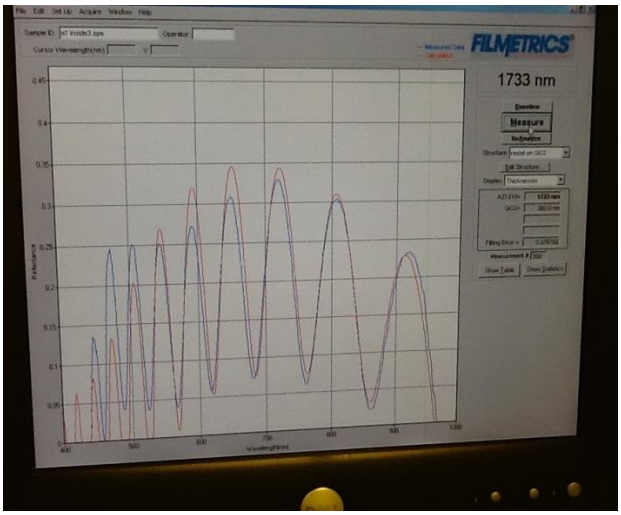


Figure 11. Example of measurement taken from the Filmetrics system.

Table 1. We took 10 measurements using the Filmetrics system. The measurement is in nanometer, and the uncertainty is from the Filmetrics system. We also took the average film thickness, the standard deviation and the standard error of the mean (uncertainty). The range of the thickness of the resist seems wide because part of the wafer has devices.

Measurement	Resist on SiO2 (nm)	Uncertainty(nm)
1	1767	0.5
2	1766	0.5
3	1772	0.5
4	1749	0.5
5	1773	0.5
6	1751	0.5
7	1758	0.5
8	1772	0.5
9	1767	0.5
10	1768	0.5
Average Film Thickness (nm)	1764.3	
Standard Deviation of Film Thickness (nm)	8.7	
Uncertainty of Film Thickness (nm)	2.7	

Table 2. The measurement of the undercut was measured with the tick mark shown on the pictures taken from the micromanipulator connected to a CCD camera. Example of the images can be seen in Figure 9.1 and 9.2.

Undercut Reading	Undercut width (um)	Uncertainty(um)
1	1.55	0.3
2	1.375	0.2
3	1.86	0.3
Average of Undercut width (um)	1.60	
Standard Deviation of undercut (um)	0.26	
Uncertainty of undercut (um)	0.15	

Calculation

Average:

$$p = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$$ **(Equation 1.1)**

Where p is the average, n is the number of values, x is the value.

Example of calculation:
P = 1.55 + 1.375 + 1.86 / 3 = 1.60um

Standard Deviation:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - p)^2}$$ **(Equation 1.2)**

Where σ is the standard deviation, N is the number of measurements, x is the value of a measurement and p is the average of the measurements.

Example of calculation:

$$\sigma := \sqrt{\frac{\left(0.05^2 + 0.225^2 + 0.26^2\right)}{\mathrm{sqrt}(3)}}$$ =0.26um

Standard Error (Uncertainty):

$$SD_x = \frac{\sigma}{\sqrt{n}}$$ **(Equation 1.3)**

Where SD_x is the standard error, the σ is the standard deviation, and n is the number of values.
Example of calculation:

$$SD_x = \frac{0.26}{\sqrt{3}}$$ = 0.15um

MEMORANDUM
MEMS LAB #4

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #4: Depositing Metal Actuators with Electron-Beam Evaporation
Date: 8/5/2013

On July 31, 2013, we, members of group B1, conducted the experiment "Deposition Metal Actuators with Electron-Beam Evaporation" in the Micro-Nano Devices and Systems (MiNDS) laboratory to learn how to deposit a 2um layer of aluminum on the Si Wafer with the Electron beam evaporation system (Physical Vapor Deposition). We also learned how the sputtering machine is used to deposit 50nm of aluminum onto another wafer.

In order to complete this lab, the wafer was heated for 30min at 130°C, and then was placed in the wafer holder in the e-beam system (Figure 1). We then placed the wafer holder into the vacuum chamber in the e-beam system PVD75 (Figure 2). Inside the vacuum chamber, we also have a carbon container also called crucible holding the aluminum pellets (Figure 3 a-b), which is a low density and low melting point metal. The electron beam evaporation is limited to low density and low melting point metal because if the metal is of high melting point, the machine will need more energy to evaporate the target and thus it will also evaporate the crucible which will contaminate the layer we are trying to deposit. Also, if we use a high density metal, when it is evaporated, many atoms will be released which will interfere with each other. We then turned the roughing vacuum (Figure 4) to pump down the pressure. Then we turned on the high vacuum pump. Once the vacuum reached the desired state of 5E-5 torr (Figure 5), we started depositing the film, which can be seen in Figure 6. The deposition was set to a rate of 20 Angstroms per second (Figure 7) to get a 2um layer of Aluminum on the wafer. While depositing, the thickness of the aluminum can be measured using the crystal oscillator inside the PVD75 (Figure 8). It works by measuring the frequency of the crystal depending on the mass. When the deposition is finished, we took the wafer out of the machine after it has done depressurizing the chamber. The resulting wafer with the 2um of aluminum is shown in Figure 9.

We put the wafer in the four-point probe (Figure 10) and input a current to get the voltage which can be seen in Figure 11. This is used to estimate the thickness of the layer by calculating the resistivity of the wafer using Equation 2 and its uncertainty using Equation 3. In our experiment, we were able to get three measurements by inputting a current of 966 ± 0.5 uA, which are 0.005 ± 0.0005 mV, 0.005 ± 0.0005 mV, and 0.003 ± 0.0005 mV. Then we calculated the average of the voltages and the standard deviation to get 0.00433 ± 0.000115 mV (Eq. 1.1 and Eq. 1.2). Using Equation 2 and Equation 3, we calculated that the thickness of the layer is 2.50 ± 0.29 um. This result is close to the value set in e-beam evaporation system of 2um. It may be off by 0.50um because the pressure in the chamber was around 5E-5, which may have allowed certain particles to still be in the chamber making the detection using the crystal monitor not so accurate.

We also observed how to use the sputtering machine (Figure 12) to achieve a 50nm layer of aluminum onto another wafer which has a tape in the center to let us see the difference in layer later on (Figure 13). The wafer was placed into the small chamber seen in Figure 14. Then we waited for the small chamber to get the same pressure as the main chamber and then we pushed the wafer in and aligned it so that the wafer is facing where the plasma is going to be as seen in Figure 15. After this has been done, we allowed the argon to flow into the machine and thus a plasma was created (Figure 16). Once the deposition is done, we waited for the chamber to depressurize, and then we crabbed the wafer to move it back from the main chamber to the small chamber and took out the wafer from there. The resulting wafer can be seen in Figure 17.

In conclusion, we observed how the two methods of physical vapor deposition work. We were able to observe how the PVD75, the electron beam evaporation system, is used to deposit a layer of 2um of aluminum onto the wafer and we were also able to observe how the sputtering system is used to deposit a 50nm of aluminum onto another wafer. We also estimated the thickness of the layer of aluminum with the formula from equation 2 and compared the differences between the theoretical and the experimental value.

Figure 1. Electron Beam Evaporation System – Physical Vapor Deposition – PVD75.

Figure 2. Wafer is put inside evaporation system, which is seen here.

Figure 3 (a) . Aluminum pellets used as the source.

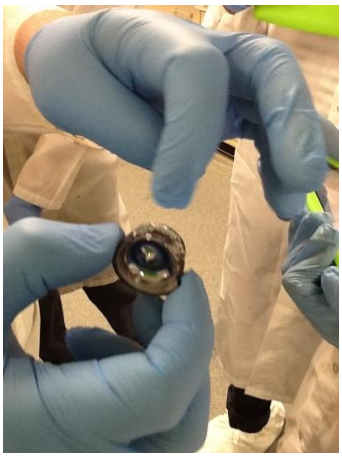


Figure 3 (b) . Aluminum pellets used as the source.

Figure 4. The roughing pump is located in the lower left corner of the PVD75 machine.

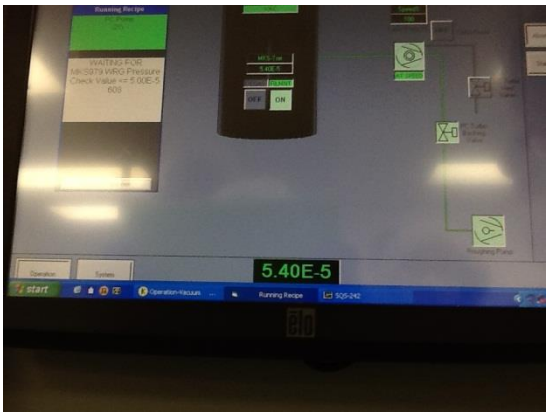


Figure 5. Our targeting pressure was set to 5E-5.

Figure 6. The beam started to evaporate the aluminum pellets.

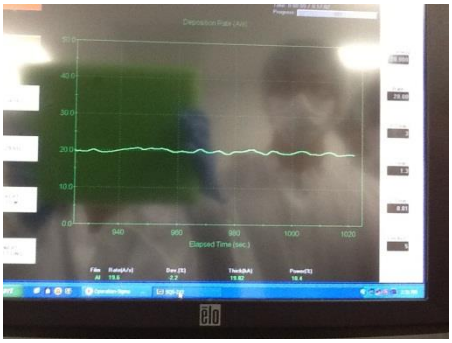


Figure 7. Deposition was done at a rate of 20 Angstroms per second.

Figure 8. Crystal monitor – Crystal Oscillator used to measure the thickness of the depositing layer.

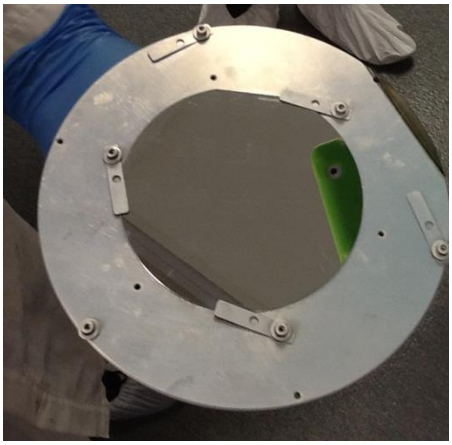


Figure 9. Result of deposition physical vapor deposition of 2um layer of aluminum with the e-beam evaporation system.

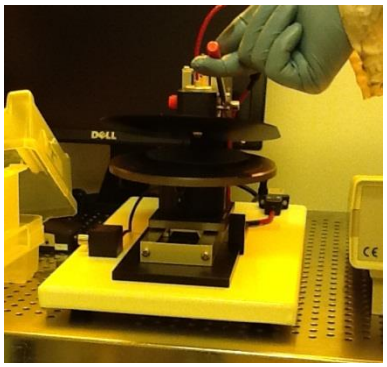


Figure 10. Four-point probe used to measure the voltage of the wafer by inputting a current.

Figure 11. Input current of 966uA. The voltage read was 0.05mV.

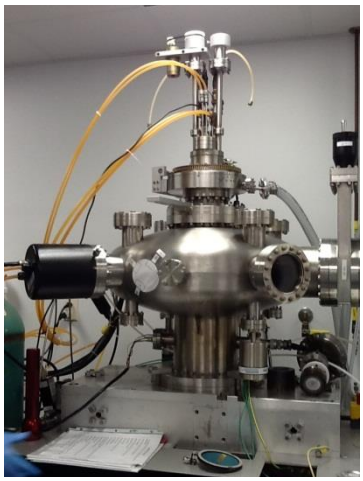


Figure 12. Sputtering system with wafer taped at the center.

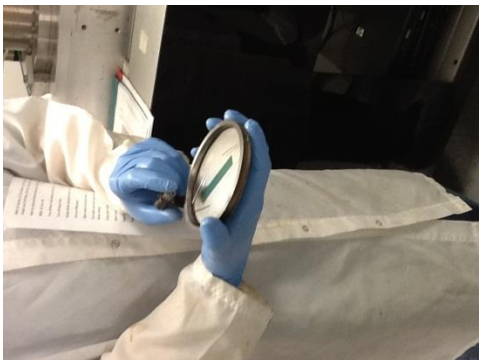


Figure 13. Result of wafer from previous lab, the two layers can be seen because of the tape.

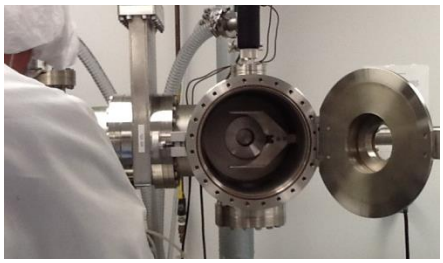


Figure 14. Small chamber in the sputtering machine where the wafer is put into.

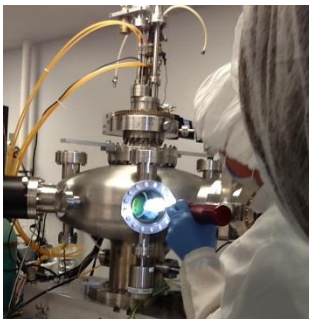


Figure 15. Wafer aligned facing the gun.

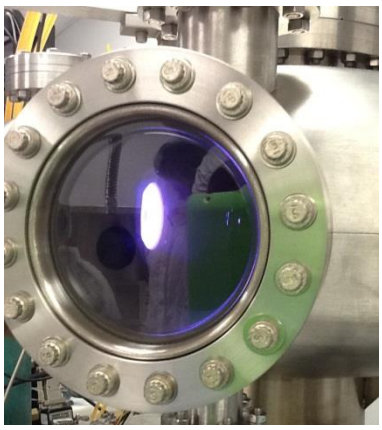


Figure 16. Plasma inside the sputtering machine created when Argon started to flow into the chamber.

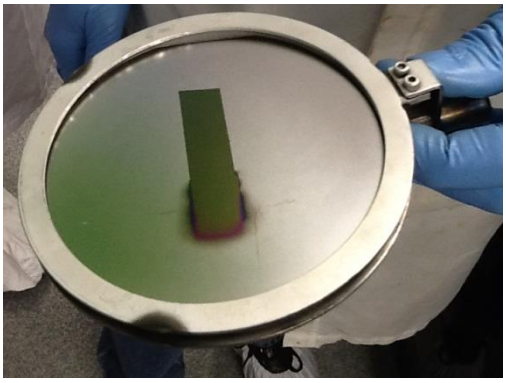


Figure 17. Resulting wafer from sputtering. A layer of 50nm of aluminum was achieved.

Calculation

Average:

$$p = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad \textbf{(Equation 1.1)}$$

Where p is the average, n is the number of values, x is the value.

Standard Deviation:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - p)^2} \qquad \textbf{(Equation 1.2)}$$

Where σ is the standard deviation, N is the number of measurements, x is the value of a measurement and p is the average of the measurements.

Thickness of Layer:

$$t = C\left(\frac{\ln(2)}{\pi}\right)\rho\left(\frac{I}{V}\right) \qquad \textbf{(Equation 2)}$$

Where C is the calibration constant, ρ is the resistivity, I the current, V the voltage and t the thickness of the layer.

The resistivity ρ of Al is 2.82E-8 $\Omega \cdot m$ and the Calibration constant is 1.8.

Sample calculation:

t= $1.8 \cdot \left(\frac{\ln(2)}{\mathrm{Pi}}\right) \cdot 2.82 \cdot 10^{-8} \cdot \left(\frac{966 \cdot 10^{-6}}{4.33 \cdot 10^{-6}}\right)$ = 2.50um

Uncertainty of Thickness of Layer:

$$\sigma_t = \sqrt{\left(\frac{C\rho ln(2)}{\mathrm{Pi}} \cdot \frac{1}{V} \cdot \delta I\right)^2 + \left(\frac{C\rho ln(2)}{\mathrm{Pi}} \cdot \frac{I}{V^2} \cdot \delta V\right)^2} \qquad \textbf{(Equation 3)}$$

Sample calculation:

$$\sigma_t = \left(\left(\frac{1.8 \cdot 2.82 \cdot 10^{-8} \cdot \ln(2)}{\mathrm{Pi}} \cdot \frac{1}{4.33 \cdot 10^{-5}} \cdot 0.5 \cdot 10^{-6}\right)^2 + \left(\frac{1.8 \cdot 2.82 \cdot 10^{-8} \ln(2)}{\mathrm{Pi}} \cdot \frac{9660 \cdot 10^{-6}}{\left(4.33 \cdot 10^{-5}\right)^2} \cdot 0.005 \cdot 10^{-3}\right)^2\right)^{1/2}$$

= 0.29um

MEMORANDUM
MEMS LAB #5

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #5: Wet Chemical Etching of Aluminium
Date: 8/7/2013

On August 5, 2013, we, members of group B1, conducted the experiment "Wet Chemical Etching of Aluminum" in the Micro-Nano Devices and Systems (MiNDS) laboratory to perform a PAN etch to etch the aluminum layer.

In order to complete this lab, we took our wafer seen in Figure 1 and heated it up at 94C for a minute (Figure 2). Then we put the wafer in the spinner seen in Figure 3 and applied photoresist on the center of the wafer and spun. Then we put the wafer on the mask aligner (Figure 4) and aligned the mask mark (Figure 5). Then we exposed the wafer for 4 seconds (Figure 6) using mask #10. The wafer after exposure can be seen in Figure 7. After that, we heated the wafer for another minute at 95C and then we developed (Figure 8). Wafer after developing can be seen in Figure 9. The next step was to put the wafer on the hot plate for another 3 minutes at 95C as seen in Figure 10. After the heating, we did a PAN etch (80% H_3PO_4, 5% $HC_2H_3O_2$, 5% HNO_3,10% DI plus equal amount of DI water to dilute to half strength) at 80C to etch the aluminum from the wafer shown in Figure 11. We stopped when we saw that the aluminum is etched away and the silicon dioxide was exposed as shown in Figure 12. Finally, we rinsed the wafer and took some measurement of the heat actuator using the micromanipulator seen in Figure14. Example of measurements can be seen in Figure 15 (a) and 15 (b). The resulting wafer can be seen in Figure 13.

During the Pan etch the aluminum was completely gone from the surface of the wafer after 7 minutes and 11 seconds of being immersed. To calculate the theoretical etch rate of aluminum, we need the following information: it's stated that the etch rate of Aluminum in PAN medium is typically on the order of 600nm/min at 40C. As we are using a diluted etch it will take twice as long. And we need to add an additional 10% to the calculated time as an approximate deviation. Assuming that the aluminum layer is exactly 2um thick, we will need to immerse the wafer into the PAN medium for 7 minutes and 33 seconds. This calculation can be seen in Equation 1. Comparing the actual answer with the theoretical answer, the actual time of 7.11 minutes is 22 seconds faster than the theoretical calculation.

Measurement of the undercut was 4.2 ± 0.018 um. The data can be seen in Table 1. For the measurement of the parts of a heat actuator see Table 2.

In conclusion, we learned how to estimate the etching rate of aluminum depending on the thickness of the layer. We also practice photolithography again in this lab. Now, we also know the dimensions of our heat actuator.

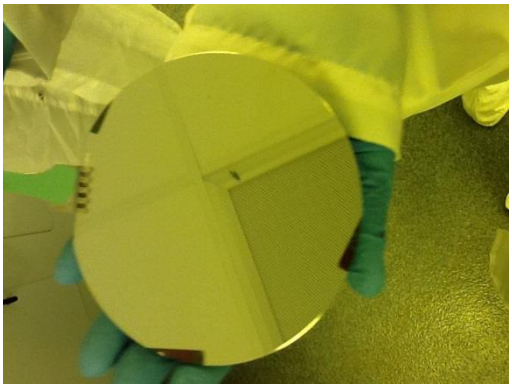


Figure 1. Initial wafer with 2um of Aluminum layer deposited on it.

Figure 2. Wafer is heated at 94C for a minute.

Figure 3. Wafer is put in the spinner. Photoresist is applied by spinning.

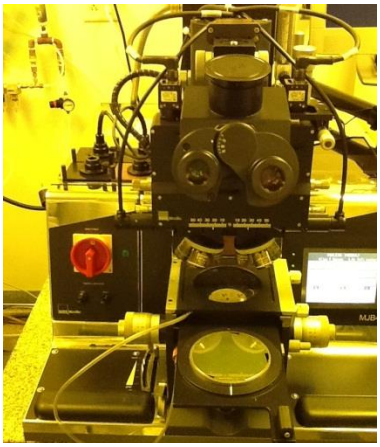


Figure 4. Wafer is put into the mask aligner.

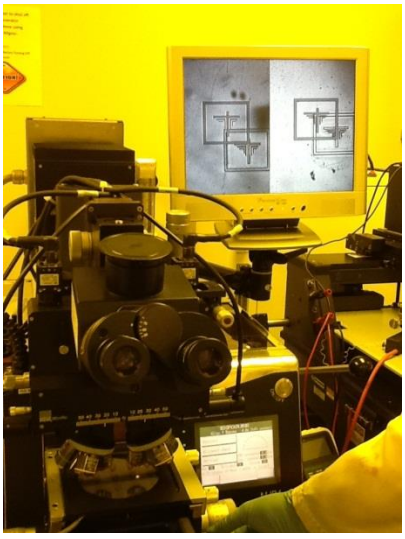


Figure 5. Aligning the mask mark on the wafer.

Figure 6. Wafer is exposed for 4 second with mask #10.

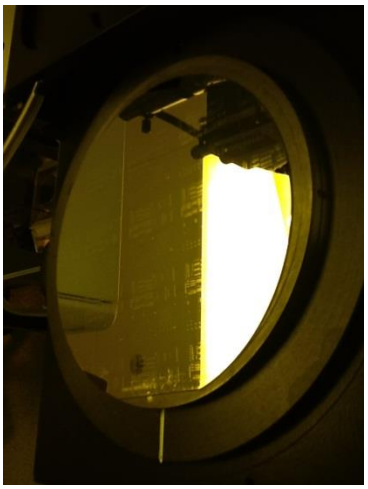


Figure 7. Wafer with pattern on it after exposure.

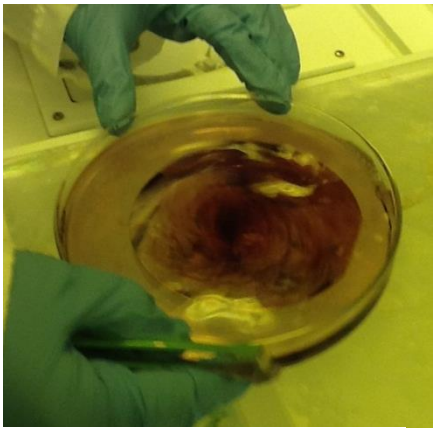


Figure 7. Developing wafer.

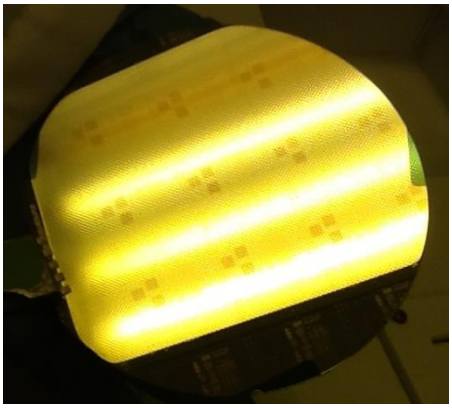


Figure 9. Wafer after developing.

Figure 10. Heating the wafer for 3minutes after develop.

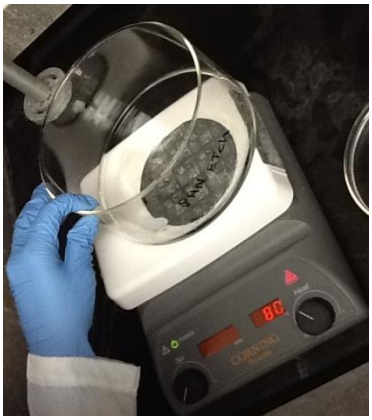


Figure 11. Pan Etch at 80 C.

Figure 12. Aluminum starting to come off the wafer.

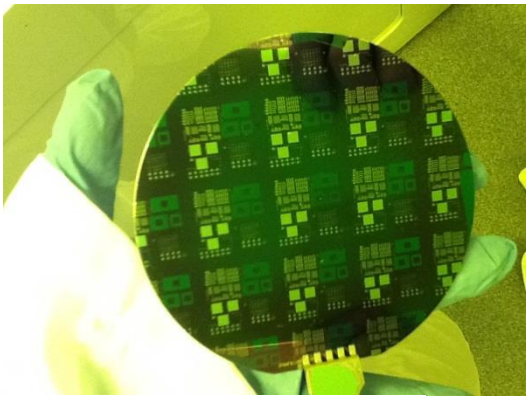


Figure 13. Resulting wafer after PAN etch.

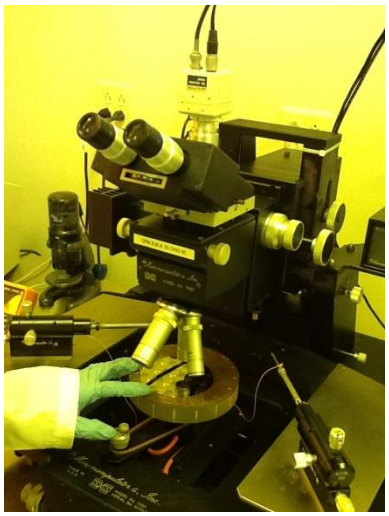


Figure 14. Using the CCD camera connected to micromanipulator to take measurement.

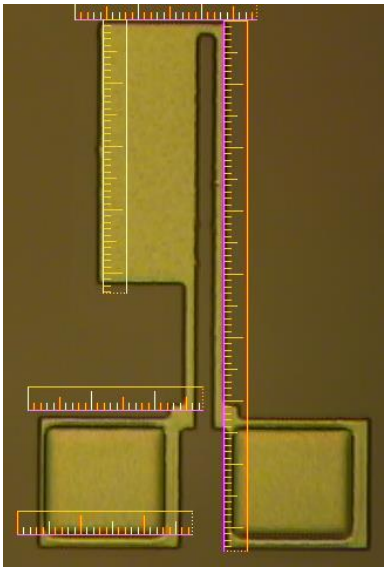


Figure15 (a). Example of Measurement of a small heat actuator.

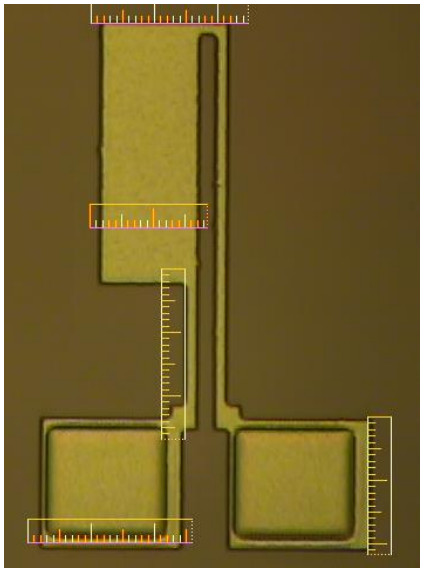


Figure 15 (b). Another example of measurement of the small heat actuator.

Table 1. Undercut measurement are measured from the pictures taken from the micromanipulator. Each tick is 4um. Using objective 8x and zoom 1x.

undercut reading	undercut width (um)	uncertainty (um)
1	4.2	0.3
2	4.3	0.3
3	4.1	0.3
4	4.1	0.3
5	4.3	0.3
average of undercut width (um)	4.2	
standard deviation of undercut	0.090	
uncertainty of undercut (um)	0.018	

Table 2. Dimensions of a heat actuator from our wafer. Each tick mark is 4um, which is taken from picture 15 (a-b). Uncertainty from measurement.

	length(um)	uncertainty (um)	width(um)	uncertainty (um)
right pad	90.0	1.2	90.0	1.2
left pad	90.0	1.2	90.0	1.2
hot arm	240.8	1.2	12.4	1.2
cold arm	180.8	1.2	68.4	1.2
flexture	68.4	1.2	12.8	1.2

Calculation

Etch Rate:

$$\frac{1\ \text{min}}{0.6\,um} = \frac{x}{2\,um} \qquad \textbf{(Equation 1)}$$

$$x = \frac{2}{0.6} = 3.33\ \text{min}$$

$$3.33 \cdot 2 + 0.1(3.33 \cdot 2) = 7.33\ \text{min}$$

Average:

$$p = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad \textbf{(Equation 2.1)}$$

Where p is the average, n is the number of values, x is the value.

Standard Deviation:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - p)^2} \qquad \textbf{(Equation 2.2)}$$

Where σ is the standard deviation, N is the number of measurements, x is the value of a measurement and p is the average of the measurements.

Standard Error (Uncertainty):

$$SD_x = \frac{\sigma}{\sqrt{n}} \qquad \textbf{(Equation 2.3)}$$

Where SD_x is the standard error, the σ is the standard deviation, and n is the number of values.

MEMORANDUM
MEMS LAB #6

To: Dr. McInerney
From: Group B1: GyoungSun Min(SUNNY), KyoungAe Huh(Karen), Elena Chong
Subject: Lab Report #6: Plasma Ash Release
Date: 8/8/2013

On August 8, 2013, we, members of group B1, conducted the experiment "Plasma Ash Release" in the Micro-Nano Devices and Systems (MiNDS) laboratory to remove a photoresist mask and sacrificial layer using an Oxygen Plasma Asher. Also, to characterize the heat actuator by observing the deflection depending on the power applied to it.

In order to complete this lab, our wafer was put in the oxygen plasma asher in order to etch away the photoresist layer. If the photoresist is underneath the aluminum, the plasma would etch it away. In Figure 2, we can see the plasma from the Oxygen Plasma Asher machine, which is basically ion from oxygen. The wafer was in the machine for four and a half hour with pressure at 1956mTorr, Oxygen flowing at 241SCCM, and Argon flowing at 11SCCM (Figure 3). Then, the wafer was removed from the Oxygen Plasma Asher. Since the photoresist thickness from previous measurement was 1764.3 ± 2.7 nm and it was placed in the Oxygen Plasma Asher for 4.5 hours, we can calculate that the etching rate is 6.53nm per minute. This calculation is shown in Equation 3.

The wafer was then placed under the micromanipulator connected to CCD camera in order to see the devices on the monitor. We used the probes and made contact with the pads of the heat actuator as seen in Figure 4. We checked the conductivity to make sure the probes are on the pads, and then we applied voltage to see deflection of the heat actuator. We did this twice with two different actuators as seen in Figure 5 (a) and 5 (b). We applied voltage until the heat actuators were broken as seen in Figure 6(a) and 6(b).

The maximum deflection occurred at 8.44 ± 0.005V with a deflection of 6.25 ± 0.3 um and it broke when 9V was applied to the heat actuator in both cases. The deflection is measured from the pictures like 5(a) and 5(b). The collected information can be seen in Table 1. Graph 1 shows the result from the experiment of Deflection (um) vs Power (mW), which is a linear relationship since the deflection is proportional to the heat or temperature and temperature is proportional to the power applied to the system. The sensitivity is 0.0056, which is the slope of the graph. The lowest power between two points in order to be resolved is approximately 157mW, and the lowest deflection between two points in order to be resolved is approximately 1.2um.

In conclusion, we learned how the oxygen plasma ash etches the photoresist without affecting the aluminum. We characterized our own heat actuator by inputting a voltage and getting a deflection.

MEMORANDUM
MEMS LAB #6

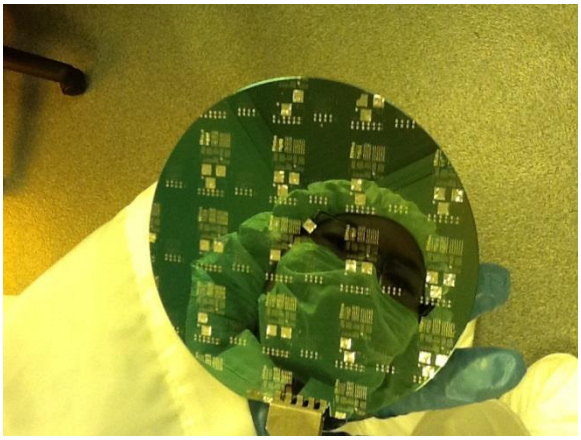


Figure 1. Wafer with devices on it.

Figure 2. Plasma inside the Oxygen Plasma Asher.

Figure 3. Data seen from the monitor of the Oxygen Plasma Asher such as, Oxygen and Argon flow and the pressure.

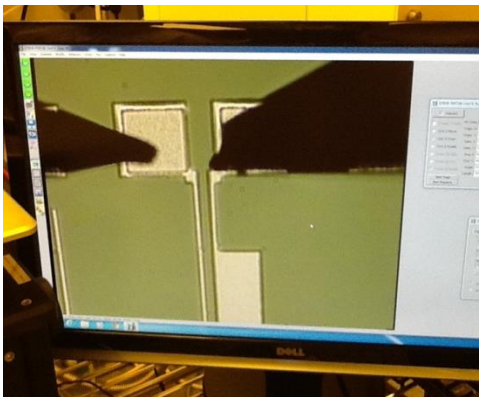


Figure 4. Probes on the heat actuator.

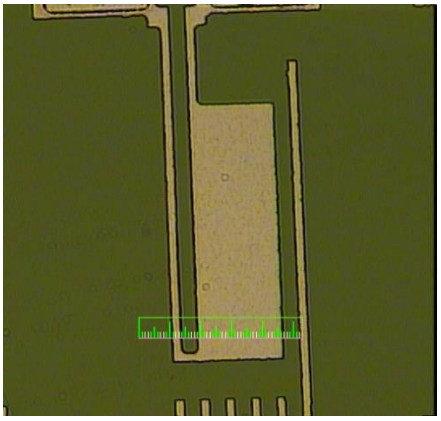


Figure 5(a). First heat actuator when 4V was applied it deflected. Objective: 10X, Zoom 1X, tick mark : 2.5um

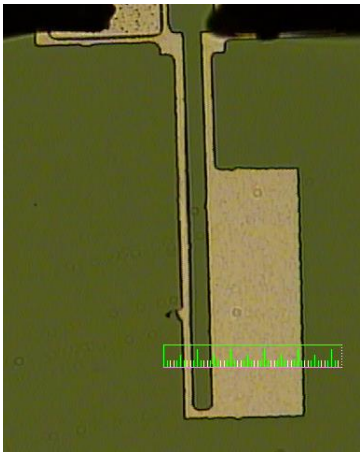


Figure 5(b). Second heat actuator when 4V was applied it deflected. Objective: 10X, Zoom 1X, tick mark : 2.5um

MEMORANDUM
MEMS LAB #6

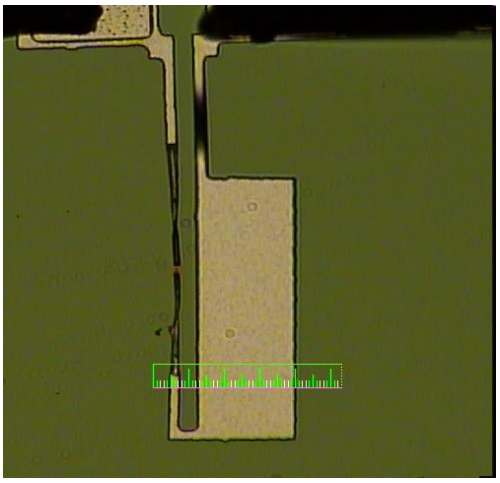


Figure 6(a). Second heat actuator broke when 9V was applied to it. Objective: 10X, Zoom 1X, tick mark : 2.5um

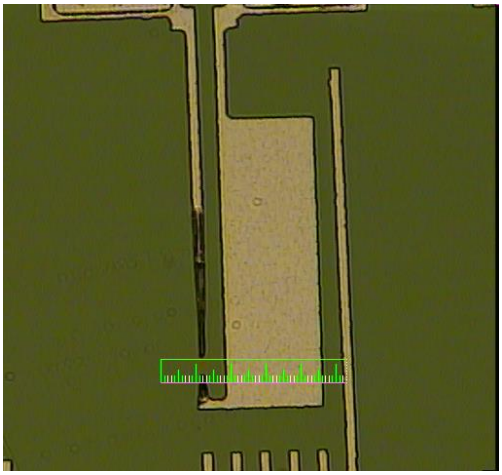
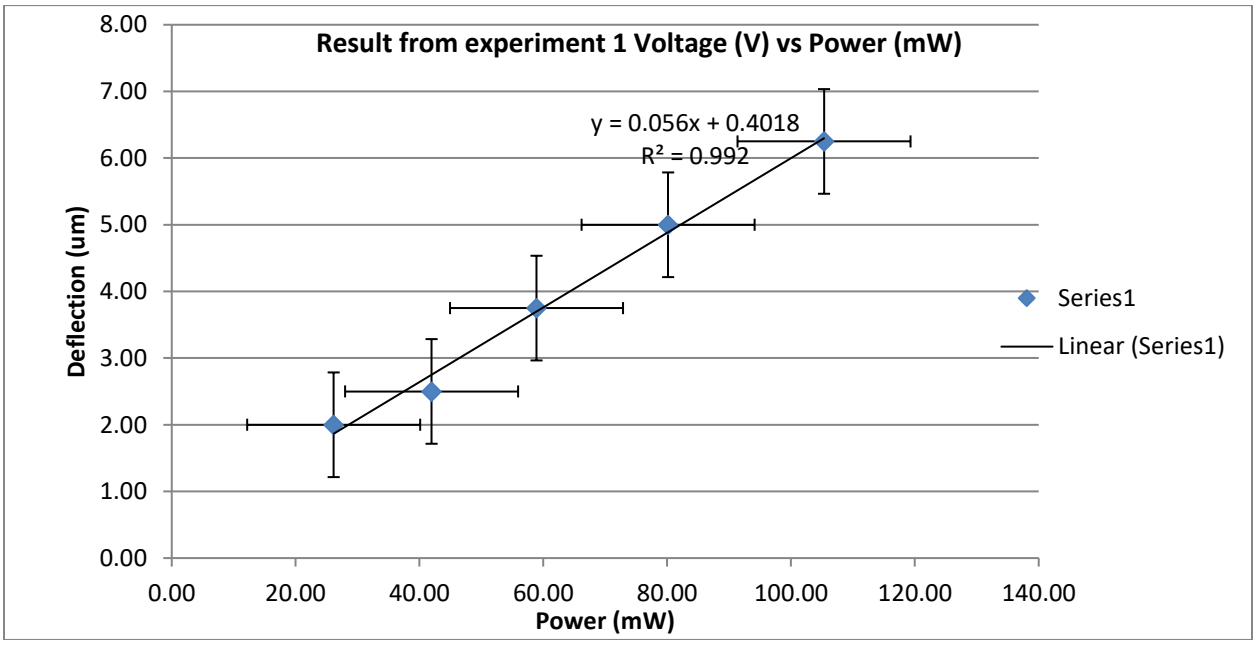


Figure 6(b). First heat actuator broke when 9V was applied to it. Objective: 10X, Zoom 1X, tick mark : 2.5um



Graph 1. Result from experiment 1 Deflection vs Power. Data from Table 1.

Table 1. These are the information from characterizing one of the heat actuator.

Actual Voltage (V)	Uncertainty (V)	Current (mA)	Uncertainty (mA)	Power (mW)	Uncertainty (mW)	Deflection (um)	Uncertainty (um)
0.42	0.005	62.40	0.05	26.15	0.31	2.00	0.30
0.54	0.005	77.70	0.05	41.96	0.39	2.50	0.30
0.63	0.005	93.50	0.05	58.91	0.47	3.75	0.30
0.73	0.005	109.20	0.05	80.15	0.55	5	0.30
0.84	0.005	124.80	0.05	105.33	0.63	6.25	0.30

9.04	0.005	Broken		broken			

Calculation

Power: P= V*I **(Equation 1)**
where P is power (mW), V is voltage (V), and I is current (mA).
Example:
.42V*62.4mA = 26.15mW

Error Propagation of Power: $\delta P = \sqrt{(I \cdot \delta V)^2 + (V \cdot \delta I)^2}$ **(Equation 2)**
Where δP is the uncertainty of power, I is the current, V is the voltage, δV is the uncertainty of voltage and δI is the uncertainty of current.
Example: $\delta P = \sqrt{(62.4 \cdot 0.005)^2 + (0.42 \cdot 0.05)^2}$ = 0.31mW

Etching rate of Photoresist:
4.5hr = 270min. 1764nm/270min = 6.53nm/min **(Equation 3)**