Pressure sensor

Kelsey Ganzon[1]

[1]Department of Mechanical Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

April 8, 2024

1 Introduction

1.1 :

In this project, pressure sensors were fabricated of four size windows to determine the dependence of window size and pressure. The figure 1 below shows the device layout on the wafer with A, B, C, and D representing window sizes of 8, 6, 4, 2mm side lengths respectively. The current was measured at various pressures to determine the performance of the device. The pressure sensors that were fabricated in this project are known as strain gauges. A strain gauge utilizes the dependence of resistance of an electrical component on its geometry. As shown in Figure 2, strain gauges are composed of a flexible membrane diaphragm and a thin resistive foil wrapped in a serpentine pattern that is attached to the top of the membrane. A Wheatstone bridge circuit was used to determine the deflection that can be measured as a change in current in the system. This is related to the applied pressure of membranes material properties.

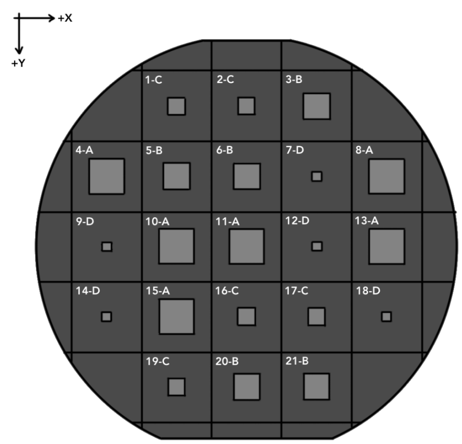


Figure 1: device layout of wafer (not shown to scale)

1.2 :

The following Figure 2 shows the device schematic and what kind of material composition of each part of the device.

1.3 :

The table below shows values of the width of the wire (w), the gap between each serpentine(g), the lateral l height of the pattern (b), and the number of runs in the grid(n). These values are theoretical

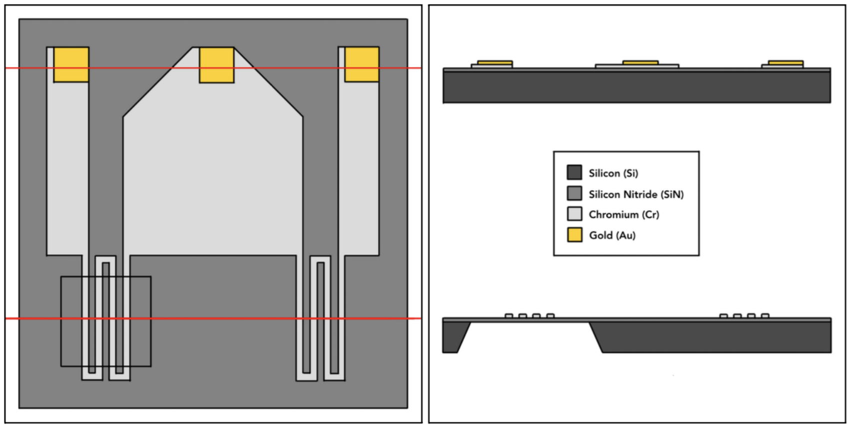


Figure 2: Top (left) and side (right) view schematics of pressure sensor devices

values intended for the geometries for each window size. In order to calculate the theoretical effective resistor length L_e for each of the four strain gauge sizes, we use the following equation below:

$$L_e \approx nb + (n-1)g \tag{1}$$

Using Table 1 1, we can manually plug in the theoretical values to the Equation (1). After doing so, we get L_e values for 8 , 6, 4, 2 mm windows of 30240, 22180, 21300, 12350 respectively. These calculations were done using the follow code 7.1 in python

In order to calculate the standard deviation for L_e, we can use the equation 2 :

$$\sigma_{L_e}^2 = (n\sigma_b)^2 + ((n-1)\sigma_g)^2 \tag{2}$$

The code 7.2was used to calculate σ_{L_e}

Devices	**4,8,10,11,13,15**	**3,5,6,20,21**	**1,2,16,17,19**	**7,9,12,14,18**
Window	8 mm	6 mm	4 mm	2 mm
w(μm)	60	40	40	30
g(μm)	80	60	60	50
b(μm)	7500	5500	3500	1500
n	4	4	6	8

Table 1: Intended geometries for each window size

1.4 :

Geometries of the resistors in each device were measured and categorized by the size of the window as shown in 1. Using an optical profilometer, the width, thickness of the wires, and the gap between the wires were measured as is denoted by w, t, and g respectively. The averages were taken from each window size and is shown in 2. The standard deviations were also calculated ($\sigma_w, \sigma_t, \sigma_g$) and are given in 2. The lateral height measurement was not able to be measured due to the constrain of the size, so the average height (b) was measured to be taken as the theoretical height. Since the width is also lateral, the standard deviation for the height (σ_b) can be assumed to be the same as the width.

$$\sigma_X^2 = \left(\frac{\partial f}{\partial A}\sigma_A\right)^2 + \left(\frac{\partial f}{\partial B}\sigma_B\right)^2 + \left(\frac{\partial f}{\partial C}\sigma_C\right)^2 + ... \tag{3}$$

Equation 4 can be used to determine the percent error between our theoretical and our actual length of the resistor. The percent error was calcuated for all windows sizes with the code 7.8

$$\epsilon L_e = 100 * \frac{L_{e(exp)} - L_{e(th)}}{L_{e(th)}} \tag{4}$$

Devices	**4,8,10,11,13,15**	**3,5,6,20,21**	**1,2,16,17,19**	**7,9,12,14,18**
Window	8 mm	6 mm	4 mm	2 mm
n	4	4	6	8
w(μm)	52.10	54.44	53.62	57.60
σw(μm)	12.33	6.28	15.61	14.40
g(μm)	42.32	45.78	50.44	553.24
σg(μm)	9.55	2.42	10.17	13.84
b(μm)	7500	5500	3500	1500
σb(μm)	7.18	6.80	8.73	4.64
t(nm)	53.10	48.44	36	57.60
σt(nm)	12.33	10.29	8.94	14.40
$L_{e(th)}$	30240	22180	21300	12350
$L_{e(exp)}$	21211.6	22137.34	30151.32	12372.68
$\sigma L_{e(exp)}$	41.93	28.16	70.92	103.75
ϵ_{Le}(%)	-0.294	-1.193	-0.417	0.183

Table 2

1.5 :

The resistance of the device depends on the geometry of the component as given in equation 5. Chromium was deposited to create the resisitors which has a bulk density of $\rho = 0.129\Omega$-μm. By substituting equation 5 into equation 2, the standard deviation of the effective resistor length $\sigma_{L_{e(exp)}}$ can be calculated as shown in 6. The code 7.5 and 7.6 was used to calculate the average Resistance (R) and standard deviations using values from 2 and are shown in 3.

$$R = \frac{\rho L}{A} = \frac{\rho L}{\omega t} \tag{5}$$

$$\sigma_R^2 = \left(\frac{\rho}{\omega t}\sigma_L\right)^2 + \left(-\frac{\rho L}{\omega^2 t}\sigma_\omega\right)^2 + \left(-\frac{\rho L}{\omega t^2}\sigma_t\right)^2 \tag{6}$$

The reference resistances were measured across the wire with no window, and the average resistance

Devices	**4,8,10,11,13,15**	**3,5,6,20,21**	**1,2,16,17,19**	**7,9,12,14,18**
Window	8 mm	6 mm	4 mm	2 mm
R	1.008	1.083	2.015	0.481
σR	0.337	0.261	0.771	0.170
R_{ref}	32.53	32.18	30.63	22.36
σR_{ref}	2.24	2.065	1.72	1.55

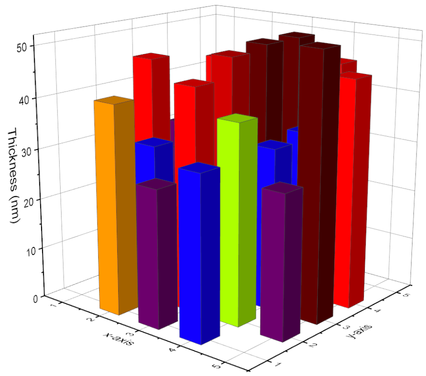
Table 3

(R_{ref}) and the standard deviation ($\sigma_{R_{ref}}$) were given in Table 3. The predicted resistances were observed to be an order of magnitude less than the measured resistances. The measured resistances were accounting for errors in length, widths, and thicknesses of the resistors. Evidently, the assumption about the resistivity of chromium being the same as the bulk must be incorrect.

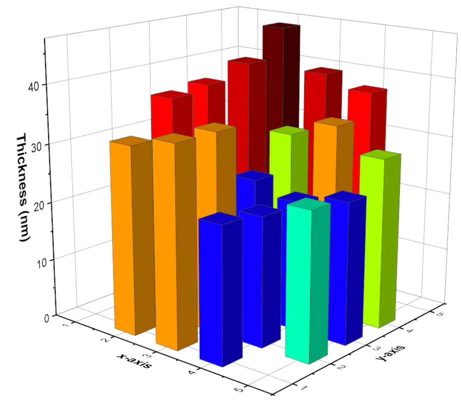
2 Three-Dimensional Plots of Metal Deposition Thickness

2.1 :

The wafers from Thursday PM sections groups A and B were further analyzed to determine deposition thickness. The thickness distributions for both wafers are shown in figure 3. Each (X,Y) coordinate represents a specific device. For example, device one corresponds to the coordinate (2,1) and device 21 corresponds to (4,5).



(a) Group A



(b) Group B

Figure 3: Deposition Thickness 3D bar graph for Thursday PM sections

2.2 :

The minimum and maximum thickness (t_{min}, t_{max}). average thickness (t_{ave}), and the standard deviations (σ_t) were calculated and shown in table 4. The combined data statistics were also calculated. The combined standard deviation was greater than both of the wafers individually which indicated that the thickness variate between wafers rather than within the wafer itself. The standard deviations for each data set is greater than 10% of the average thickness which may indicate that the deposition was not uniform across the wafer.

Wafer	**TH-A**	**TH-B**	**Combined**
t_{min}(nm)	27	18	18
t_{max}(nm)	52	48	52
t_{ave}(nm)	38.47	30.61	34.55
σ_t(nm)	8.30	7.37	8.72

Table 4

2.3 :

Chromum was sputtered onto the wafer at a power of 400W for 4 minutes. The average deposition rate can be determined by the dividing average chromium thickness by the sputtering time. These values are given in table 5 The expected deposition rate for the sputterer was 80$\AA$/min. For group

Wafer	**TH-A**	**TH-B**
Average Deposition Rate (nm)	9.617	7.652

Table 5: Average Deposition Rate for each wafer in nm/minute

A, the deposition rate was larger than the expected deposition rate for group B, the rate was smaller. This implies that there was a systematic error int he deposition rates. Some of these sources of errors could have been due to not timing the deposition accurately which will result in unequal deposition rates. In Figure 3, it is observed that the thickness on the outer edge of the wafer is smaller than the thickness towards the center of the wafer. The devices concentrated in the center must have had a larger deposition. This also can result in discrepancies in deposition measurements.

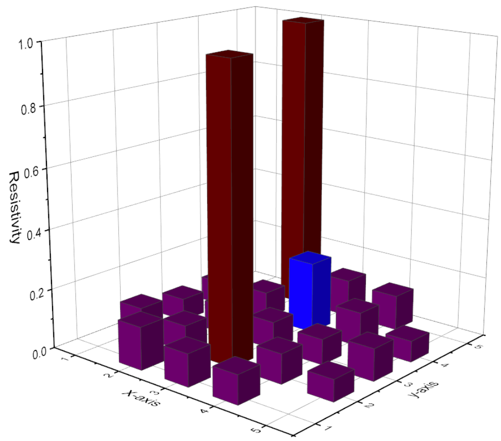


Figure 4: Resistivity distribution for Group A

3 Three-Dimensional Plots of Resistivity

3.1 :

The resistivity (ρ_e) of the resistor is calculated using equation 5 as shown in equation 7. The standard deviation ($\sigma_{\rho e}$) for the resistivity can be determined using equation 8. The calculations were done using the code 7.3 and 7.4 and are shown in Table 6

$$\rho_e = \frac{R\omega t}{L_e} \tag{7}$$

$$\sigma_\rho^2 = (\frac{wt}{L_e}\sigma_{Re})^2 + (\frac{Rt}{L_e}\sigma_w)^2 + (\frac{Rw}{L_e}\sigma_t)^2 + (-\frac{Rwt}{L_e^2}\sigma_{Le})^2 \tag{8}$$

Devices	**4,8,10,11,13,15**	**3,5,6,20,21**	**1,2,16,17,19**	**7,9,12,14,18**
Window	8 mm	6 mm	4 mm	2 mm
n	4	4	6	8
w(μm)	52.10	54.44	53.62	57.60
σw(μm)	12.33	6.28	15.61	14.40
g(μm)	42.32	45.78	50.44	553.24
σg(μm)	9.55	2.42	10.17	13.84
b(μm)	7500	5500	3500	1500
σb(μm)	7.18	6.80	8.73	4.64
t(nm)	53.10	48.44	36	57.60
σt(nm)	12.33	10.29	8.94	14.40
$L_{e(th)}$	30240	22180	21300	12350
$L_{e(exp)}$	21211.6	22137.34	30151.32	12372.68
$\sigma L_{e(exp)}$	41.93	28.16	70.92	103.75
$\epsilon_{Le}(\%)$	-0.294	-1.193	-0.417	0.183
R_{ref}	35.53	32.18	30.36	22.36
σR_{ref}	2.24	2.07	1.72	1.55
$\rho_e(\Omega\mu m)$	0.128	0.128	0.129	0.128
$\sigma_{\rho e}(\Omega\mu m$	0.288	0.249	0.121	0.420

Table 6

3.2 :

The average resistivity for Group A wafer was 0.189 $\Omega\mu m$. The standard resistivity for bulk chromium is 0.129 $\Omega\mu m$. The experimental resistivity is has a percent error of about 41%. This could be due to the facts that the bulk resistivity may not apply at the nano-scale. The micro structures of the material may cause the bulk resistivity to not apply to the nano-scale. Since the chromium was sputtered onto the wafer, smaller grains make up the structure compared to bulk chromium. The grain boundaries act as scattering sites for electrons which causes resistivity in thin films to be much larger than in bulk materials.

3.3 :

Ideally, the resistivity distribution across the wafer should be completely flat, however Figure 4, there are a few outliers in the data. This could be due to differences in the electrical resistance since some of the windows could have been scratched causing a higher resistance for that window. Another factor could come from contamination, defects, micro structures, and surface damage from lift off. The most crucial processing variable to control is deposition uniformity since film thickness is the most important contributor to resistivity. The other variables are very difficult to adjust.

4 Theoretical Analysis of Pressure Sensor

4.1 :

Silicon nitride membranes were fabricated by anistropic etching of 500μm thick silicon wafers in KOH. Equation 9 can be used to calculate the width (W_0) of these membranes, where W_m is the mask opening and z is the thickness of the wafer. The z term accounts for the sidewall slope of the etch. The membrane widths of each window were calculated by the code7.7 and are shown in Table 7

$$W_0 = W_m - z\sqrt{2} \tag{9}$$

Window size(mm)	**8**	**6**	**4**	**2**
Membrane Width (mm)	0.655	0.652	0.653	0.649

Table 7: Widths of the Membranes

4.2 :

Assuming that the membrane deflection (W_c) is much larger than the membrane thickness (h) and the circular diaphragm. the following relationship can be derived in Equation 10

$$\omega_c = \frac{d}{2}\sqrt[3]{\frac{pd}{2Eh}} \tag{10}$$

where p is the applied pressure, d is the diameter of the diaphragm, and E is the elastic modulus of the membrane.

Given that the elastic modulus is E= $2.959x10^7$psi and the thickness of the membrane is h = 0.95μm, the deflection (in μm) can be simplified as seen in Equation 11

$$\omega_c = 8.6403d\sqrt[3]{pd} \tag{11}$$

Figure 5 shows the relationship between Deflection and Pressure under the assumption that the Deflection is much greater than the membrane thickness is valid for pressures above 1 psi. This is shown in Equation 10

4.3 :

Assuming uniaxial strain, the dimensionless length changes (Λ) can be estimated with integrating the deflection over the length of the membrane. The following taylor series expansion in Equation 12 can

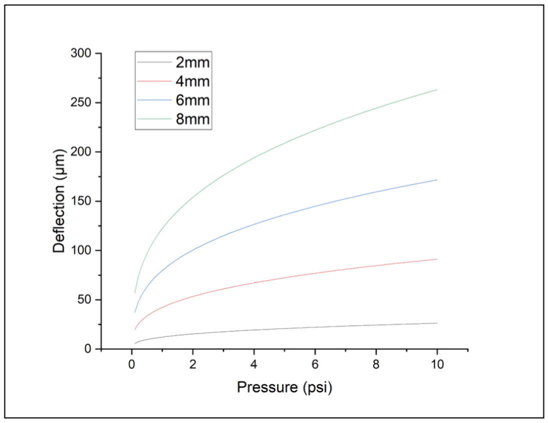


Figure 5: Theoretical Deflection vs Pressure of each window size

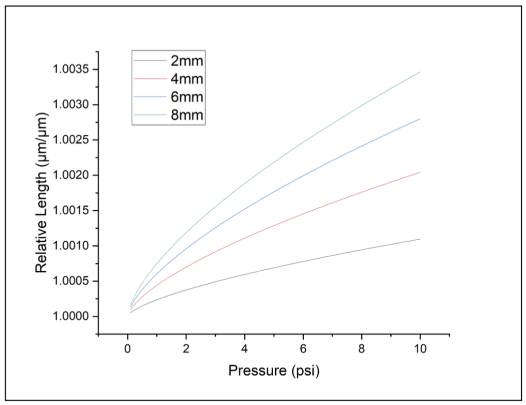


Figure 6: Relative length vs pressure

approximate the dimensionless length changes (Λ).

$$\Delta = \frac{1}{2}\left(1 + \sqrt{1 + \left(\frac{4w_c}{d}\right)^2}\right) - \frac{4}{3}\left(\frac{w_c}{d}\right)^2 + \frac{48}{5}\left(\frac{w_c}{d}\right)^4 \tag{12}$$

Figure 6 shows thew dimensionless length change of the membrane, or the relative length of the resistor plotted against applied pressure.

4.4 :

The next step is to convert the resistor length change into a dimensionless change in resistance (Ω) of the device. Equation 13 can be used to estimate the change in resistance, where v is the Poisson's ratio for the membrane which can be assumed to be 0.25. The relative change in resistance in the device vs pressure is plotted below as shown in Figure 7.

$$\Omega = \frac{\Lambda}{(1 - v(\Lambda - 1)^2)} \tag{13}$$

4.5 :

The theoretical Wheatstone bridge current is approximated using the relative resistance as shown in Equation 14. The DC voltage (V) applied to the circuit was 5 V and the resistance R is 11kΩ. We

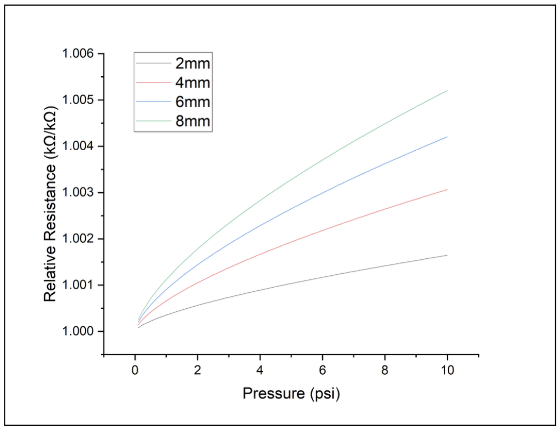


Figure 7: Relative Resistance vs Pressure

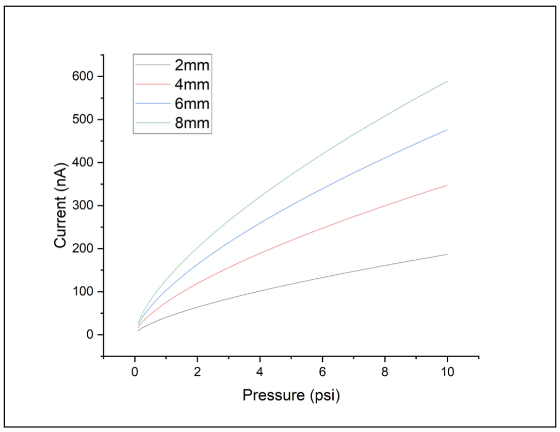


Figure 8: Theoretical Wheatstone current vs pressure

can assume that the Wheatstone bridge resistors have the resistance of $R_1 = R_2 = R = R_{ref}$ and $R_{sen}/R = \Omega$. This relation can be simplified shown by Equation 15. Figure 8 shows the theoretical current plotted against pressure.

$$I_m = \frac{V(R_{sen} - R_{ref})}{R(R_{sen} - R_{ref}) + 2(R_{sen}R_{ref}} \tag{14}$$

$$I_m = \frac{5 * 10^9}{11 * 10^3} \frac{(\Omega - 1)}{(3\Omega + 1)} \tag{15}$$

5 Theoretical vs. Experimental Data

5.1 :

Two devices of each window size from Group A and Group B were tested for pressure sensing. Wheatstone bridge currents ($I_m in nA$) were plotted as a function of pressure (p in psi) and are shown in Figure 9. The theoretical Wheatstone current was also plotted alongside the experimental curve to compare results.

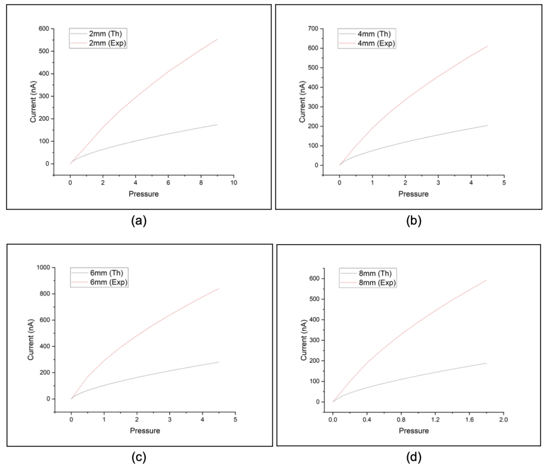


Figure 9: Theoretical vs Experimental Wheatstone bridge current vs pressure for window sizes (a)2 mm, (b) 4mm, (c) 6mm, (d) 8mm

5.2 :

According to Figure 9, it is clear to see that the experimental current-pressure curves are above the theoretical curves. Furthermore, the experimental curves are scaled almost by a factor of 3, but share similar shape. This means that the general trend of the theoretical curve matches the experimental values with a difference of a scaling factor.

In a theoretical point of view, there are multiple assumptions that play a part in the disparity between curves. All the given devices have square windows so immediately, it can be assumed that the model given by Equation 10 is inaccurate due to its circular diaphragm. Along those lines, another inaccurate factor is that the membrane is isotropic and uniaxially strained because the pressure was applied to the surface of the diaphragm rather than on the axis. Besides, the strain of the membrane and the resistor do not lie on the same plane consequently making the assumption that the two are the same also inaccurate. There is also a high possibility that material thickness is not uniform which means that the assumption that the resistivity of the resistor is uniform throughout the device is unreliable. Ultimately, assuming the Wheatstone bridge resistances R_1 and R_2 are equal to R_{ref} causes errors in the measurement because R_2 is unadjustable.

In this lab window shape and load state played the main role in assuming the disparity. However, throughout the experiment, the assumption that the Wheatstone bridge resistances might not be equal to R_{ref} is already adjusted. Hypothetically speaking, if these assumptions were accounted for in the model, that means a square diaphragm deforms less than that of a circle which causes a smaller increase in resistance. This directs to a higher theoretical Wheatstone bridge current. Also taking into account that the warping causes less deformation than uniaxial stress which is conventional to tell in advance that the current should increase. The telling of the increase in current will reduce the error between the model and experimental values despite that the extent of these two corrections are not known.

Fabrication errors may also affect the current measurements because thickness plays a hefty role in resistivity of the material because some parts of the resistor may be strained more than others. While conducting the experiment, some parts of the resistor were either more or less strained than other parts because the deformation of the membrane is also not uniform.

6 Testing

6.1 :

After devices were fabricated, each device was inspected under a microscope before testing. It was clear that some of the devices had contamination that caused there to be some scratches. Since these devices are very surface sensitive, even the smallest amount of contamination that drags across the wafer can cause scratched to the device. This resulted in a higher resistivity. My group was Friday

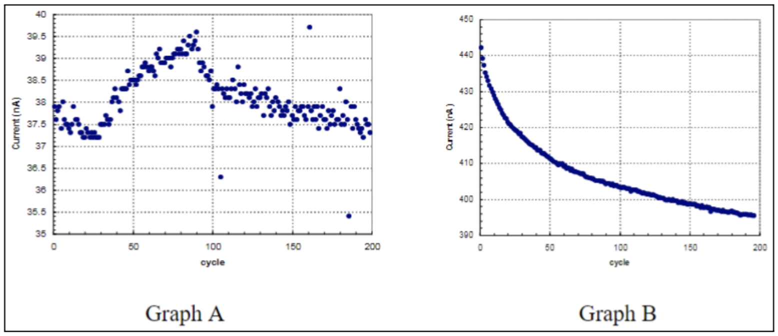


Figure 10

PM section Group A and our wafer did not have a chromium layer deposited which was supposed to serve as the adhesion layer for the gold. Since this step was skipped, the gold that was deposited came off and most of the devices were not able to be tested. Instead, the TA wafer was tested. The devices that had bigger windows were a lot more fragile and did not withstand a lot of pressure and ended up breaking during testing.

Another reason for device failure could have been device handling. When probing the device, small probes were placed on top of the pads. With improper care of lowering the stage and placing the probes on the pads may have caused more scratches to the devices. This will create the resistivity measurement to go up or even result to device failure.

Another important factor could have been the deposition thickness. Since the devices on the outer edges had a smaller deposition thickness than the devices concentrated in the center, this may cause the performance of the outer devices to weaken. According to the class data, one of the devices from Friday AM Group A sections broke. This device was number 8 of window size 8mm. This device is located at the edge which has a deposition thickness of 30 nm which is less than the average. The durability of the device may be dependent on the deposition thickness.

6.2 :

Of the 4 devices tested, I anticipated window size 8 to be less reliable and most sensitive to pressure. Window size 8 reaches 500 nA of current at a low pressure of 1.4 psi. This window size is also the more fragile, breaking at roughly 5 psi. Conversely window size 2 mm is the most robust, surviving roughly 14 psi, making it the least sensitive to pressure. The 2mm window was measuring the same 500 nA at around 8 psi. A trade off between sensitivity and durability is observed, one consideration is finding a more durable material than silicon nitride and that responds better to deflection.

6.3 :

Figure **??** shows two graphs of current with respect to time for pressure sensor tests that corresponds to input voltages of 1.5 V and 20 V. By Ohm's law, voltage is directly proportional to current. Graph A measures lower current than Graph B, which means Graph A must correspond to the input voltage of 1.5 V and Graph B corresponds to input voltage of 20 V. Also, for lower currents, noise poses a significant effect on measured current. This increases the resistance and reduces the measured current over time, making Graph B corresponding to error via heat effects.

6.4 :

After the etching process, the devices were diced and put into a plastic sample holder. The top part of the plastic sample holder contains adjustable pins to make electrical contact between the devices and the probes. Both parts contain inlet and outlet ports to control the pressure being applied to the diaphragm. An O-ring was put in between the two halves to form an airtight seal. The most important part of the setup was to make sure the pins had good contact to the pads. Failing to make good contact will result in inaccurate measurements and artificially high resistance.

6.5 :

Overall, the lab was very straight forward and gave me a better understanding the steps of how manufacturing a device looks like. The repetitiveness allowed me to understand the steps and remember the concepts a lot more. I think the lab aligns perfect with the lecture content. One suggestion I would say is maybe have a concept review at the end of the lab to make sure we fully understand what happened for that day as well as test us on concepts in preparation for the exams.

7 Appendix

Here are the following python codes used to calculate data:

7.1

```
def ResistorLength():
    w = [60,40,40,30]
    g = [80,60,60,50]
    b = [7500,5500,3500,1500]
    n = [4,4,6,8]

    L = []

    for i in range(4):
        L.append(n[i] * b[i] +(n[i]-1) * g[i]   )

    print(L)
```

7.2

```
    #calcuate standard deviation for Length
def SigmaResistorLength():
    n = [4,4,6,8]
    Sig_g =[10.179, 2.423, 9.559, 13.840]
    Sig_b=[7.184 ,6.801 ,8.733 , 4.642] #8,6,4,2
    Sig_L=[]

    for i in range(4):
        Sig_L.append((n[i]*Sig_b[i])**2+((n[i]-1)*Sig_g[i])**2)

    print(np.sqrt(Sig_L))
```

7.3

```
    #calculate resistivity
def resistivity():
    R=[ 1.00806 ,1.0829 , 2.015, 0.481 ] #8 6 4 2
    w=[52.10, 54.44 , 53.62 ,57.60]
    t=[52.10 , 48.44 , 36 , 57.60 ]
    Le=[21211.6, 22137.34, 30151.31, 12372.68]
    p=[]
    for i in range(4):
        p.append((R[i]*w[i]*t[i])/Le[i])
    print(p)
```

7.4

```
    #calculate standard deviation for resistivity
def sigmaResistivity():
    R=[ 1.00806 ,1.0829 , 2.015, 0.481 ] #8 6 4 2
    w=[52.10, 54.44 , 53.62 ,57.60]
    t=[52.10 , 48.44 , 36 , 57.60 ]
    Le=[21211.6, 22137.34, 30151.31, 12372.68]
    sigRref=[2.241855965        ,2.065911131      ,1.724261291,    1.558858974]
    sigL = [  31.554 ,32.038, 58.335 , 48.044 ]
    sigw = [    6.277977381, 12.3298013, 15.60871551     ,14.40381894]
    sigt = [10.29626146 ,12.3298013      ,8.94427191      ,14.40381894]

    sigR = []
    for i in range(4):
        sigR.append(((w[i]*t[i])/(Le[i])*sigRref[i])**2 +
                    ((R[i]*t[i])/(Le[i])*sigw[i])**2 +
                    ((R[i]*w[i])/(Le[i])*sigt[i])**2 +
                    ((-R[i]*w[i]*t[i])/(Le[i]**2)*sigL[i])**2)
    print(np.sqrt(sigR))
```

7.5

```
    # Table 3 values and calculations
def Resistance():
    p= 0.129
    w = [53.62  ,54.44, 52.10,  57.60] #4 6 8 2
    L = [30151.32, 22137.34, 21211.6, 12372.68]
    t = [36,48.44,52.10,57.60]
    R = []
    for i in range(4):
        R.append((p*L[i])/(w[i]*t[i]))
    print(R)
```

7.6

```
    #calculating sigma for resistance
def SigResistance():
    p= 0.129
    w = [53.62  ,54.44, 52.10,  57.60] #4 6 8 2
    L = [30151.32, 22137.34, 21211.6, 12372.68]
    t = [ 36, 48.44 , 52.10 , 57.60 ]
    sigL = [ 32.038 , 31.554 , 58.335 , 48.044 ]
    sigw = [15.60871551 ,6.277977381,   12.3298013       ,14.40381894]
    sigt = [8.94427191  ,10.29626146     ,12.3298013      ,14.40381894]

    SigL = []

    for i in range(4):
        SigL.append(((p*sigL[i])/(w[i]*t[i]))**2 + ((p*L[i]*sigw[i])/(w[i]**2*t[i]))**2 +

    print(np.sqrt(SigL))
```

7.7

```
    #width of the membrane
def width():
    wm=[52.10/1000, 54.44/1000 , 53.62/1000 ,57.60/1000] #8 6 4 2
    z= [0.5,0.5,0.5,0.5]
    w0=[]
    for i in range(4):
        w0.append(wm[i]-z[i]*np.sqrt(2))
    print(w0)
```

7.8

```
    def eL():
    Le= [30151.32, 22137.34, 21211.6, 12372.68]
    Lth=[30240, 22180, 21300, 12350]
    eL=[]
    for i in range(4):
        eL.append(((Le[i]-Lth[i])/Le[i])*100)
    print(eL)
```