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04/29/2015

ECE 557
MEMS Report

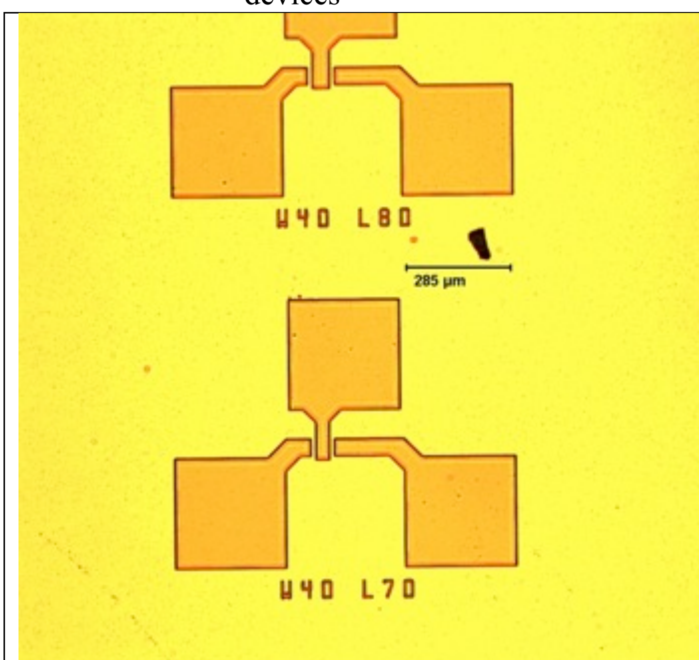
Objective:

The purpose of this project was to understand and manufacture a micro-electrical mechanical system or MEMS device on a silicon wafer. The MEMS for this project is undergoing the switch fabrication procedure. The devices are single and double anchor cantilever devices made of Gold and Titanium in the micrometer size. The procedure in this project is similar to Module 1, 2 and 3 where photolithography, etching and electrical characterization were done to analyze the final structure and properties of the MEMS devices.

Process & Observations:

Here is the process that was conducted for the project.

- At the start of the lab, an 8”x8” square, silicon wafer was handed out. The wafer was sputtered with 800nm of gold on the surface and underneath the gold, was 100nm of Titanium. (Note, some of the wafers were slightly larger than other samples by 1” due to the uneven cutting of the larger circular wafer sample.)
- The mask aligner before exposure is the MEMS mask#1 where it will create the contact pads for the devices.
- The development process for this process is different from the run sheet. The ratio of AZ340 and DI water is 100mL: 100mL. The time for development was 12 seconds. This time was selected from observation of development process from Module 1. Here are the images and description of the contact pads for the MEMS devices

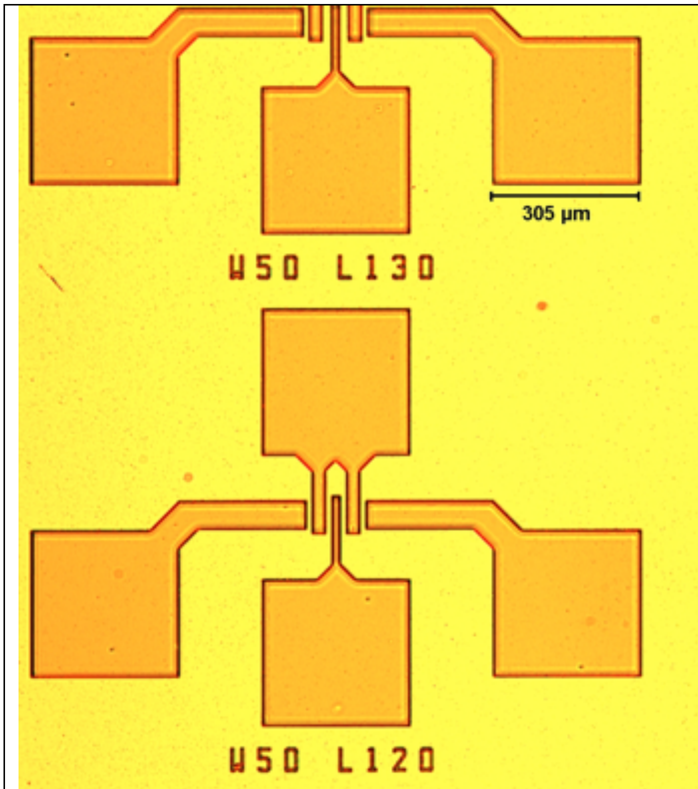
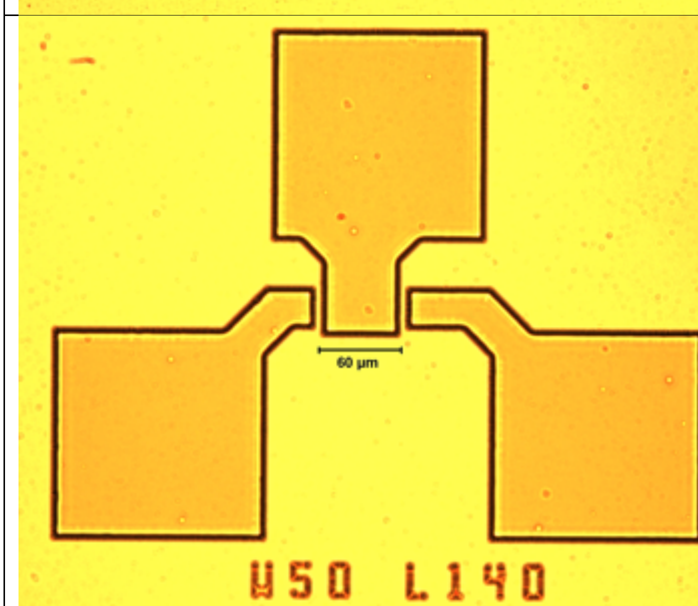


Cantilever Device: Contact Pad Patterns of size 40-80 and 40-70

Magnification: 5x

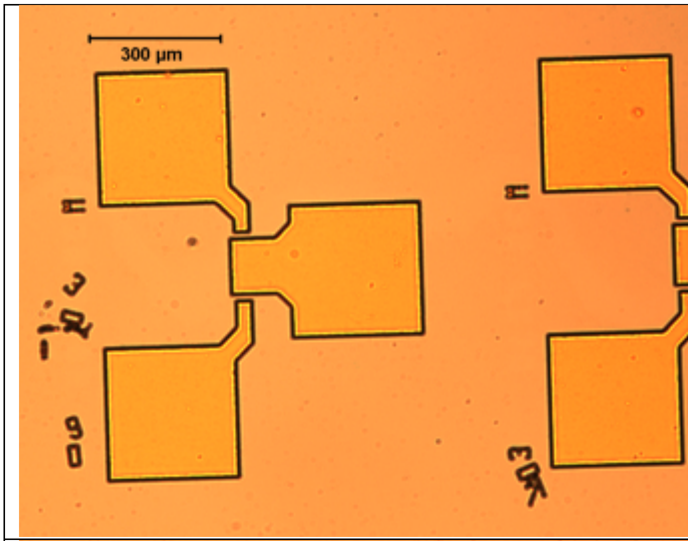
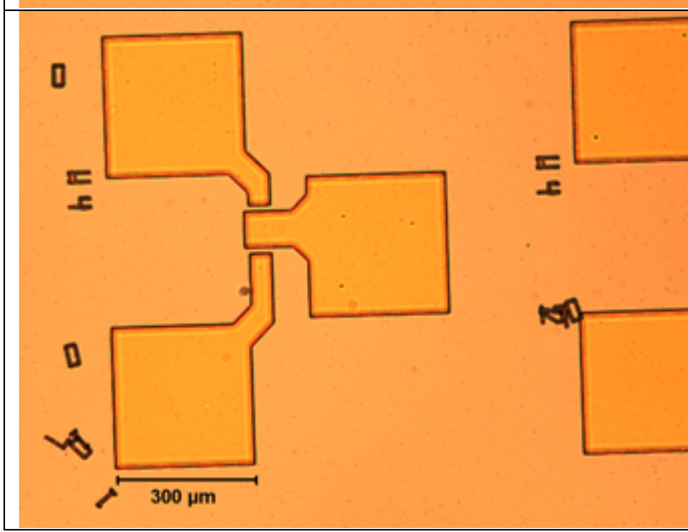
Observations:

- Slight scratches on the surface.
- Dark spots on the image are few, mostly likely remains of photoresist left.
- Clear, halo edges on patterns indicate exposure on positive photoresist is achieved. No signs of overdevelopment or overexposure.

	Bridge Device: Contact Pad Patterns of size 50-130 and 50-120 Magnification: 5x Observations: • There are slight, light dots on the surface, likely to be photoresist that was not removed during development process. • Pattern is fully exposed and developed as no signs of incomplete shapes.
	Cantilever Device: Contact Pad Patterns of size 50-140 Magnification: 20x • On the contact pads, there are signs of small bubbles. Likely from the spin coating process where the photoresist was not spread out uniformly and baking it cause some small air pockets. • Pattern is fully exposed and developed as no signs of incomplete shapes.

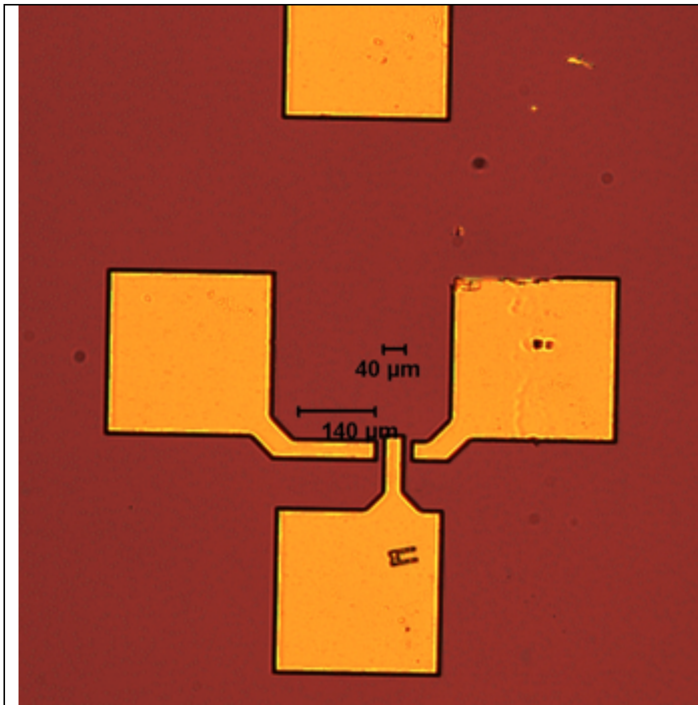
- After clearing post-development of the contact pads, the Gold and Titanium etching process started. This is to shape the contact pad out of Au and Ti.
  i) First, the time for etching the gold was calculated to be 4 minutes and 12 seconds. This comes from the amount of gold sputtered in the beginning and the etch rate of the Gold Etchant used. (Calculation found in appendix)

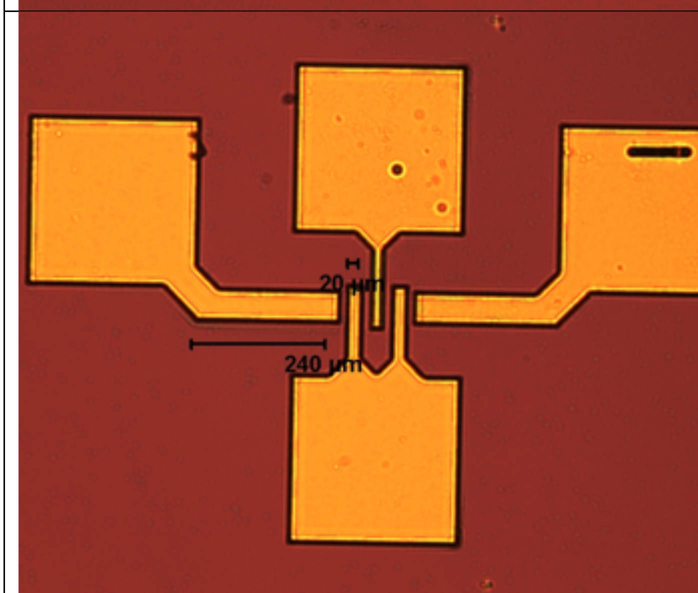
ii) Here are the images after Au etching

	Cantilever Device: Contact Pad Pattern of size 90-130 Magnification: 5x • Lettering and Numbers were moved away from etchant. • Dark background is the Ti layer of the wafer. • No damage to photoresist and leftover photoresist likely flaked off with the Au • No “colored” halos, indicating no overetching of this part of wafer.
	Cantilever Device: Contact Pad Pattern of size 40-170 Magnification: 5x • Lettering and Numbers were moved away from etchant. • Dark background is the Ti layer of the wafer. • No signs of scratches and particles on photoresist • “Colored” halos indicate over etching of pattern on this part of the wafer.

iii) The next step was to etch the Ti layer. This took 7 seconds and the calculations are in the appendix.

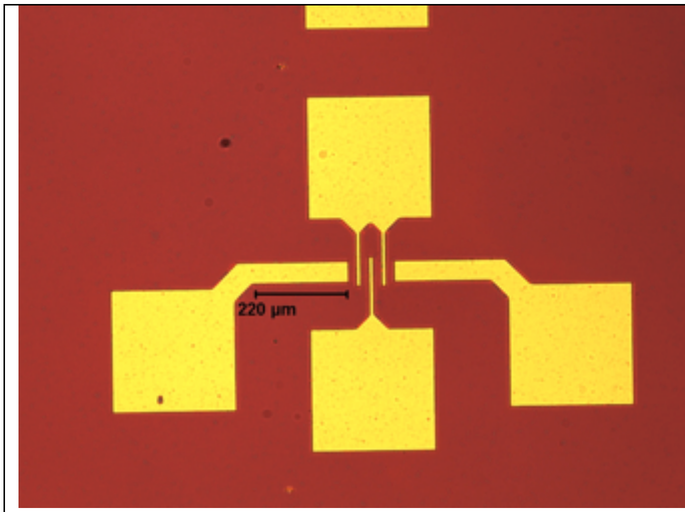
iv) Here are the images of the wafer after Ti etching:

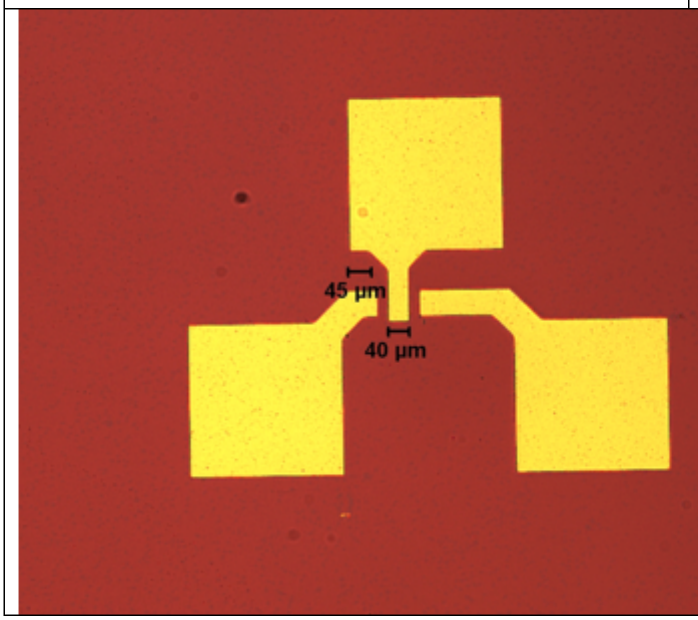
<table>
<tr>
<td>
</td>
<td>Cantilever Device: Contact Pad
Magnification: 5x

This cantilever had it top right contact pad damaged. The edge was crumbled and most likely from the Ti etch
There are small flecks of Au on the Silicon Wafer, probably from the Au etching and some flakes may have stuck on the Ti layer during the Ti etching
The top right photoresist contact pad has wave-like pattern across vertically which indicates the photoresist may have slightly changed in uniformity.
The lettering and numbers from the first exposure and development step are mostly gone; this is fine as there is a sheet how to characterize which device is which.
</td>
</tr>
<tr>
<td>
</td>
<td>Bridge Device: Contact Pad
Magnification: 5x

Very small signs of colored halo around the photoresist edges could be signs of overetching with the Ti or Au etchant.
The straight, dark line on the right side of the bridge device is just the letter or number from the earlier step. It is just photoresist.
Photoresist on this part of the wafer has small, light circles. This indicates the spinning of the photoresist may have not been done uniformly and through baking caused etch crystallization.
Oxide thickness of the Silicon appears to be 460 nm as the color is red-violent from color sheet.
Black dots on the Silicon Dioxide layer may be flecks of Ti or Au.
</td>
</tr>
</table>

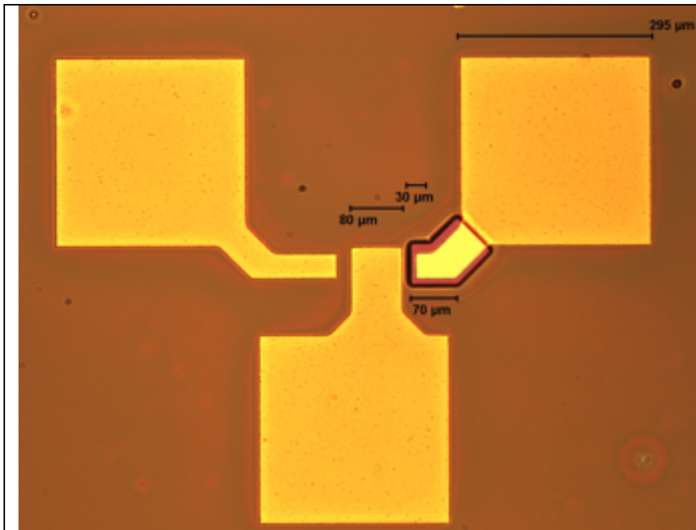
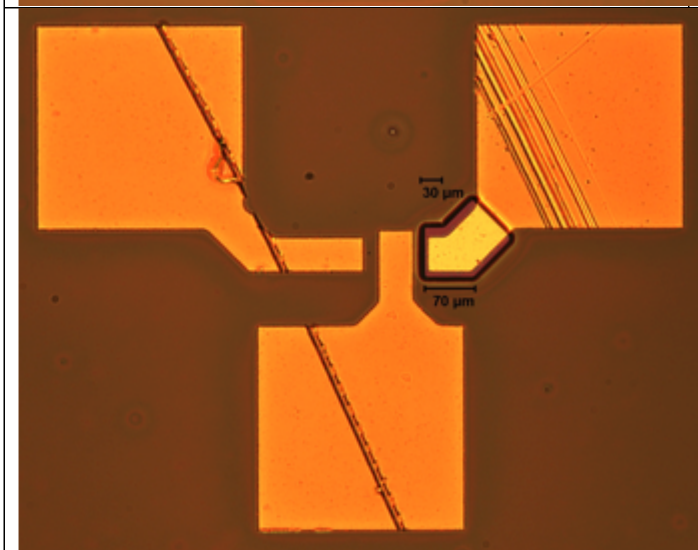
- Here are the photos of the state of the cantilever and bridge contact pads after removing the photo resist:

<table>
<tr>
<td>
</td>
<td>Bridge Device: Contact Pad
Magnification: 5x

The photoresist lettering and numbers were removed.
The contact pads now made of Au on top, followed by Ti and placed on Silicon Dioxide surface.
Small, dark flecks on the Silicon Dioxide wafer are likely remains of the Ti and Au etched away from the contact pads.
Patterns of the contact pad in this part of the wafer are clear, no signs of scratches or any other particles.
</td>
</tr>
<tr>
<td>
</td>
<td>Cantilever Device: Contact Pad
Magnification: 5x

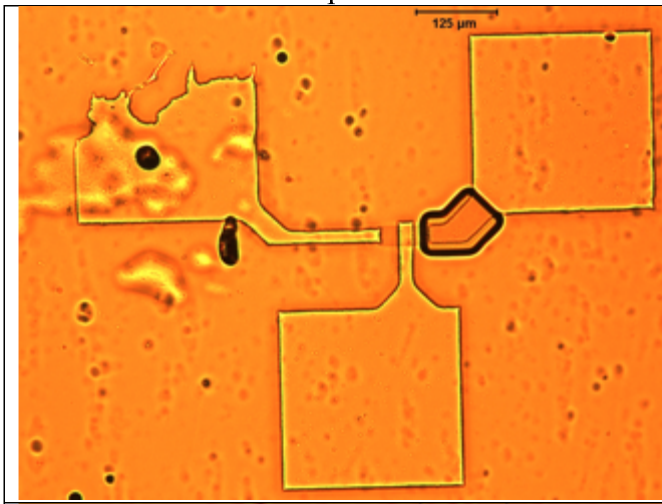
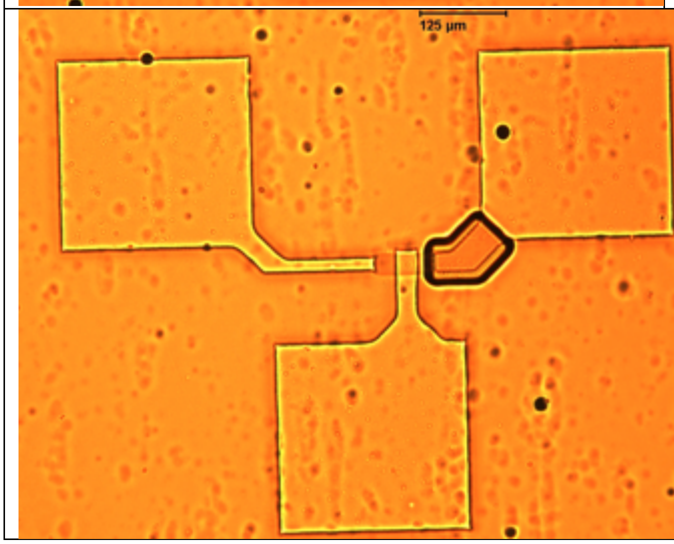
Same observations from Bridge Device contact pads
Note that there are small, red dots on the contact pad are probably photoresist.
The reason why these red flecks are on the contact pad is likely when drying the wafer with the N_2 after development, the photoresist was not baked and possibly was shifting inside of the contact pad pattern until it was baked and stuck to the pattern.
</td>
</tr>
</table>

- After finishing constructing the contact pad that will be used for electrical characterization later, the next step was to construct the anchor point where the beam will be established.
- Exposure was done using the MEMS Mask #2, which creates the anchor point pattern on the center of the devices. There are two different anchor points, one is a single anchor point and the other is a double anchor point.
- Development and rinse of the photoresist was 12 seconds. The mixture for this was 1:4 of AZ-340 and DI water instead of 1:1. 50 mL of AZ-340 and 200 mL of DI were used.
- Here are the images of the devices after removal of photoresist and post baking for 5 minutes:

<table>
<tr>
<td>
</td>
<td>Cantilever Device: Contact Pad with Single Anchor Point
Magnification: 10x
• The Anchor point is the shape standing on bottom left part of the top-right contact pad.
• The edges look sharp and non-cracked, so the development was fine.
• Dark flecks in the background likely remains of Au and/or Ti from the contact pad construction or photoresist from the anchor point construction. This means that the development did not remove all of the photoresist.</td>
</tr>
<tr>
<td>
</td>
<td>Cantilever Device: Contact Pad with Single Anchor Point
Magnification: 10x
• This part of the wafer has a darker background color compared to the previous photo. Likely this is the photoresist being more thicker here than at other parts of the wafer.
• Scratches are on the Gold and Au contact pads. The ones of the left are likely from the tweezers, as the prongs may have scratched over contact pad during development as sometimes one can lose grip of the wafer when stirring the wafer. Other scratches were there when the TA ripped off the samples from the large wafer.
• Slight halo color around the contact pad, probably signs of uneven photoresist being harden from baking</td>
</tr>
</table>

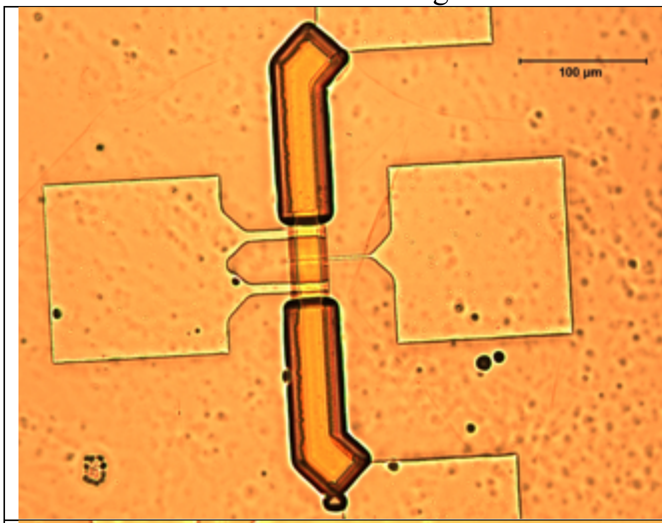
- After post-baking to harden the photoresist on the contact pad and anchor point, the wafers were turned in to sputter Ti and Au. 30nm of Ti was added and then on top, 1.5um of Au was added. Both were sputtering at a rate of 1 Angstrom per second.
- Once the sputtering was finished, we start on creating the cantilever that connects from the anchor point to the contact pads. This part is crucial for electrical measurements as the beam must be align correctly so when released, there will be a conducting path from one contact pad to another.
- Applying photoresist like the previous steps and use the MEMS mask #3 which creates the cantilever for the devices.
- Alignment took some time as if the exposure and development from the earlier stages were not done correctly, the patterns for checking the alignment may be too blurred to see.
- Development time of the cantilever pattern was 12 seconds and standard procedure for cleaning and baking.

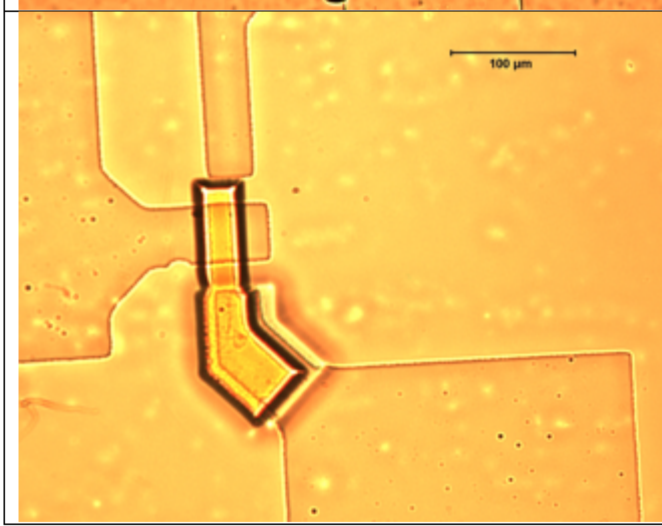
- Here are the images of the devices with a cantilever on the single and double anchor points:

	Cantilever Device: Contact Pad with Single Anchor Point Magnification: 10x • This single anchor device has one of the contact pads destroyed. Most likely from the sputtering of Ti and Au. • The black blobs are likely photoresist residue that has not been rinsed off completely. • Surfaces looks blurred, this can be attributed to underexposure, as the UV light may not have cleared the pattern properly. • Photoresist underneath the surface may have been cleaned from the failure of the first attempt.
	Cantilever Device: Contact Pad with Single Anchor Point Magnification: 10x • This device has a deformed contact pad at the bottom, caused probably from the development and exposure of the pattern. The UV light probably did not exposure through the photoresist clear enough that the pattern is slightly uneven. • Black dots are signs of residue photoresist as likely during rinsing in the mixture; it remained stuck on the wafer.

- The etching and development were done twice due to no changes to wafer in etchant solution.
  i) After development, the wafer had many problems. The alignment and exposure went fine. However, under the microscope, showed the surface covered in black blobs. Thinking there were photoresist, the wafer was subjected to countless development and rinsing for 5 times. Some of the particles went away but there were still some left. Plus the cantilever pattern started to break up after repeated development and rinse.
  ii) After trying to etch the wafer in Au etchant for some time, the wafer under the microscope show no changed in the patterns and the color did not change either as it was suppose to be darker. This meant the excess Au was not removed.
  iii) Under advice from the TA, the wafer underwent solvent clean and tried to do the development and etching again.
- The etch time for the Au etching was 9 minutes. (Calculations are in appendix)

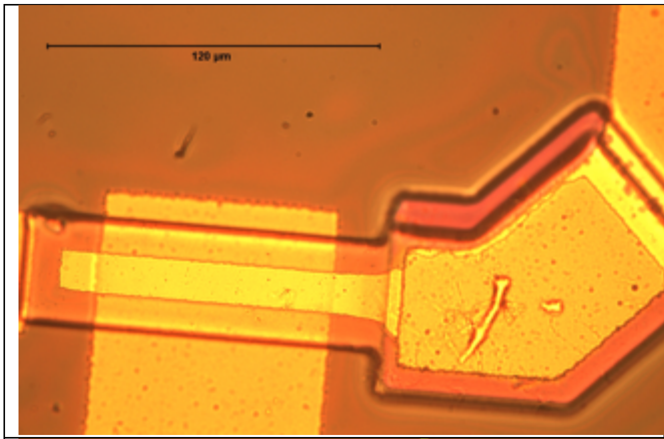
- The etch time for Ti was 10 seconds. However, there was a second time to etch the Ti for 25 seconds because of the remains of the Au may have shielded some of the Ti away. (Calculations are in appendix)
- Here are the photographs of the wafer after Ti and Au etching the second time:
  After Au etching for 9 minutes:

<table>
<tr>
<td>
</td>
<td>Bridge Device: Contact Pad with Double Anchor Point
Magnification: 10x

The black dots are leftover photoresist that did not come off from rinsing and development.
The contact pads are still intact.
The device looks slightly mottled and there are signs of small holes, likely from over etching and overdevelopment of the device.
There are signs of overetching due to the cantilever pattern not very clear and looks a bit cracked.
</td>
</tr>
<tr>
<td>
</td>
<td>Cantilever Device: Contact Pad with Single Anchor Point
Magnification: 20x

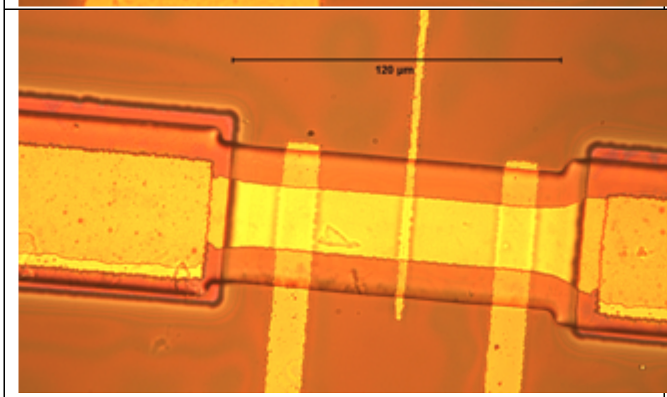
The cantilever pattern is not placed properly, as the end that is facing the other contact pad is not aligning with that contact pad.
Contact pad is slightly broken, likely to etching rate being different or due to etching the wafer twice.
Mottled surface on the Ti layer, very small dots on the contact pad, which could be very small amounts of Au or photoresist.
</td>
</tr>
</table>

After Ti Etching for 10 seconds:



Cantilever Device: Contact Pad with Single Anchor Point
Magnification: 50x

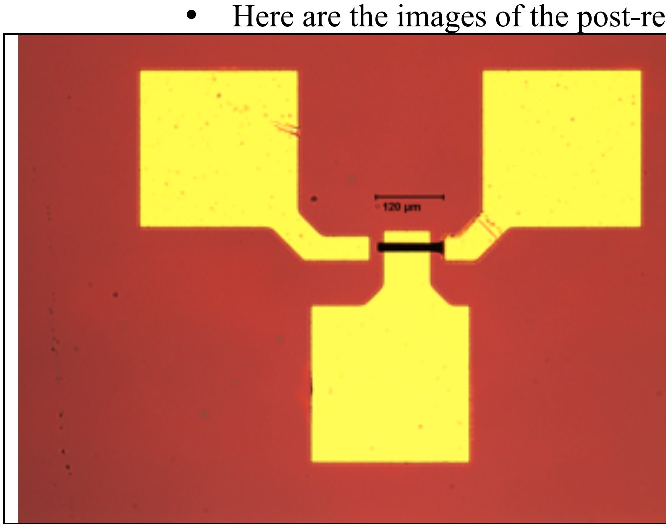
- The placement of the cantilever is a single point.
- Small flecks of Au or Ti are on the Silicon surface.
- The contact pads have small traces of photoresist, which indicates not 100% removal.
- Connection looks fine.
- The cantilever pattern is clear.
- The little scar pattern is just the crystallization of etch which does nothing to the device.



Bridge Device: Contact Pad with Double Anchor Point
Magnification: 50x

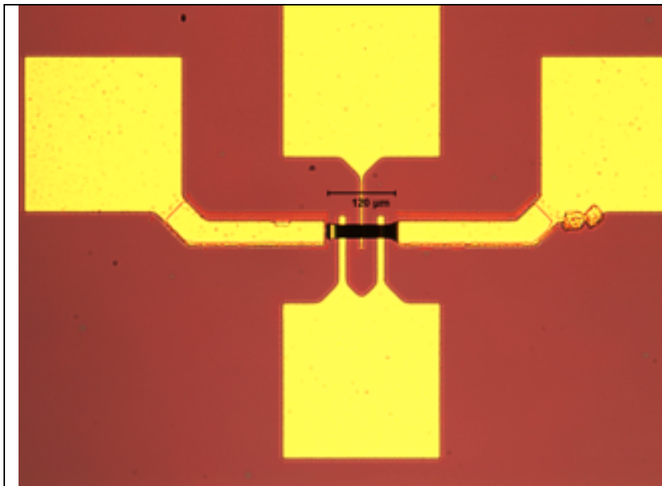
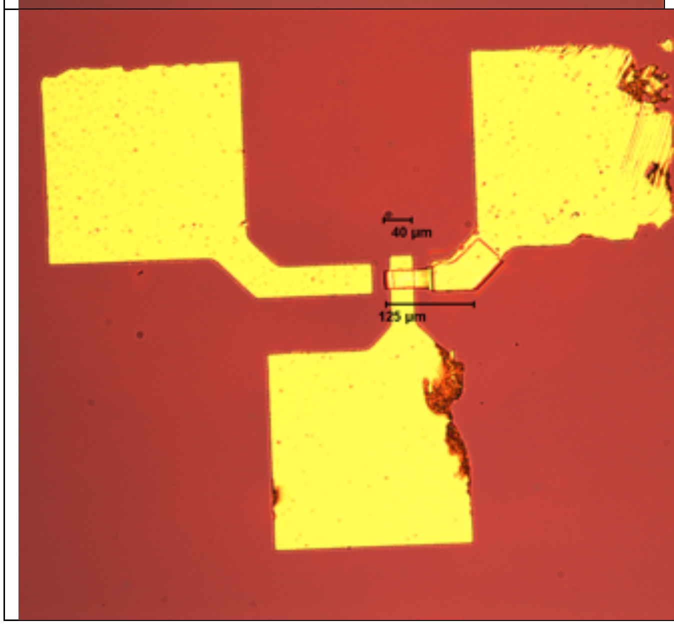
- The small red flecks on the surface of the device, are likely
- There is a faint halo color surrounding the anchor point and the cantilever, this is likely from overetching which may causes the Silicon Dioxide to decrease.
- The jagged edges may be from when it was still a photoresist structure, the Nitrogen from the N_2 gun caused the photoresist to flake and went unnoticed until the later stages of etching and sputtering.

- Once the etching is complete, the wafer was turned in to release the cantilever beam and then performed electrical characterization.
- The color of the oxide thickness of the wafer was dark red-violet, make it around 460nm thick.
- Here are the images of the post-release of the devices:



Cantilever Device: Contact Pad with Single Anchor Point
Magnification: 10x

- Contact pad undamaged from the 2nd round of Au and Ti etching at this part of the wafer.
- The black line at the center is the cantilever after being released.
- Small scratch on the surface of the Silicon Dioxide surface.
- Hard to determine if the anchor point and the cantilever are in contact with the contact pad.

	Bridge Device: Contact Pad with Double Anchor Point Magnification: 10x • There is a blob of Au and Ti on the right-most contact pad. This likely came from the etching where the excess material did not fly off the wafer but stuck to the device. This is not a concern as it is not blocking the contact pad to the cantilever device itself. • Small outline of color surrounding the pads indicates slight over etching. This is due to going over the 2nd etching process twice that cause the initial patterns to eaten into the Silicon wafer.
	Cantilever Device: Contact Pad with Single Anchor Point Magnification: 10x • This single anchor device is one of several devices found to have its contact pads damaged. Normally, this is ok as long as there is a connection to the anchor point and cantilever. • The cause for this was likely from the tweezers that went too deep on the wafer and scrapped off the Ti and Au covering. This could occur at some point after the construction of the contact pad. • No halo color around the device which means the etching did not eaten through the wafer.

- Once the wafer is inspected after release of the cantilevers, it was taken to the probe station to check for comparing the measured voltage values to the expected values calculated in the Appendix. Also, it is a good check to see if the device structure may have been damaged from the any part of the process so that graph would show a different shape.
- First, the spring constant is calculated and then plugged in the equation for the pull-down voltage. This also assumes that the cantilever beam for the single anchor devices has a distributed load, and then the double anchor device is a clamped-clamped beam with a distributed load.
- We get the gap between the beam and contact pad from the amount of photoresist removed from the anchor point insertion and the contact pad insertion
- Here are the expected pull-down voltages of the each of the devices:
  (These values were calculated in MATLAB so the code is shown in the appendix)

Width(um)	Length(um)	Vp(V)
30	50	1.24E-10
30	60	8.62E-11
30	70	6.34E-11
30	80	4.85E-11
30	90	3.83E-11
30	100	3.10E-11
30	110	2.57E-11
30	120	2.16E-11
30	130	1.84E-11
30	140	1.58E-11
30	150	1.38E-11
30	160	1.21E-11
30	170	1.07E-11
30	180	9.58E-12
30	190	8.60E-12
40	80	4.85E-11
40	90	3.83E-11
40	100	3.10E-11
40	110	2.57E-11
40	120	2.16E-11
40	130	1.84E-11
40	140	1.58E-11
40	150	1.38E-11
40	160	1.21E-11
40	170	1.07E-11
40	180	9.58E-12
40	190	8.60E-12
50	60	8.62E-11
50	70	6.34E-11
50	80	4.85E-11
50	90	3.83E-11
50	100	3.10E-11
50	110	2.57E-11
50	120	2.16E-11
50	130	1.84E-11
50	140	1.58E-11
50	150	1.38E-11
50	160	1.21E-11
50	170	1.07E-11
50	180	9.58E-12
50	190	8.60E-12
50	200	7.76E-12

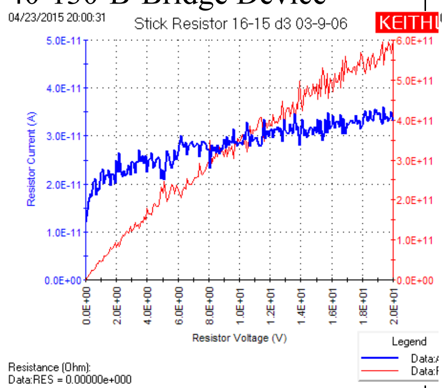
Single Anchor Devic

Width(um)	Length(um)	Vp(V)
40	100	2.15E-10
40	110	1.78E-10
40	120	1.49E-10
40	130	1.27E-10
40	140	1.10E-10
40	150	9.56E-11
40	160	8.40E-11
40	170	7.44E-11
50	100	2.15E-10
50	110	1.78E-10
50	120	1.49E-10
50	130	1.27E-10
50	140	1.10E-10
50	150	9.56E-11
50	160	8.40E-11
50	170	7.44E-11
60	100	2.15E-10
60	110	1.78E-10
60	120	1.49E-10
60	130	1.27E-10
60	140	1.10E-10
60	150	9.56E-11
60	160	8.40E-11
60	170	7.44E-11

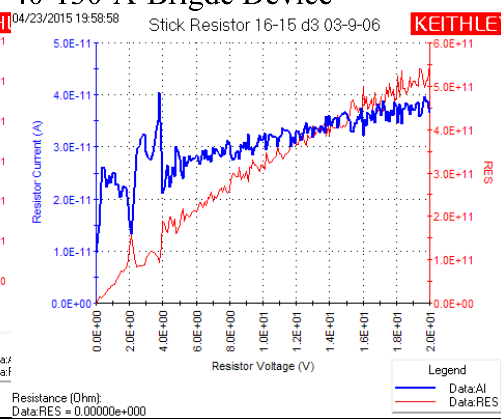
Double Anchor Device

- After checking the voltages on many of the devices for several hours, it was found that every device had failed. The plots have given very noisy figures and the values were jumping all over the place, giving no consistent pattern. Here are some of the measured data of the some of the devices: ('Width'-'Length'- Point-Device)

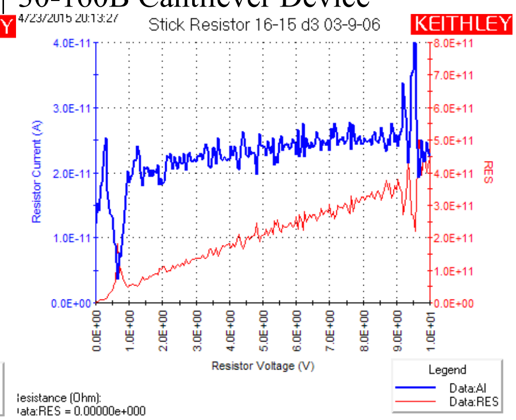
40-130-B-Bridge Device



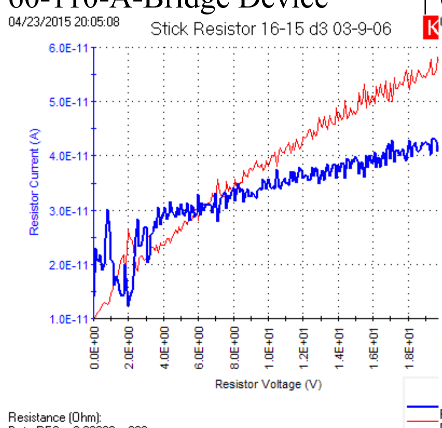
40-130-A-Brigde Device



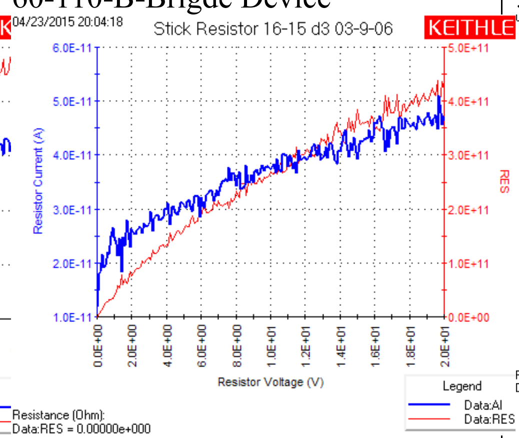
30-160B Cantilever Device



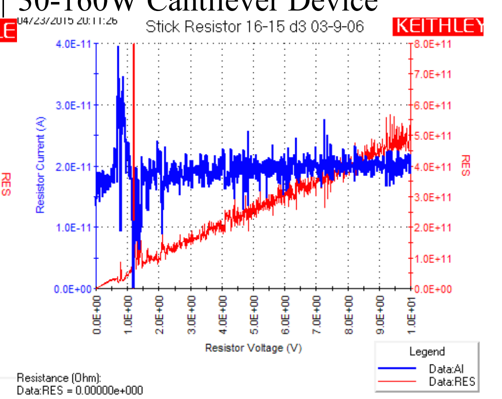
60-110-A-Bridge Device



60-110-B-Brigde Device

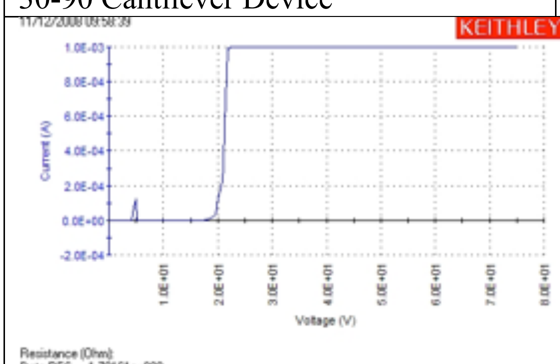


30-160W Cantilever Device

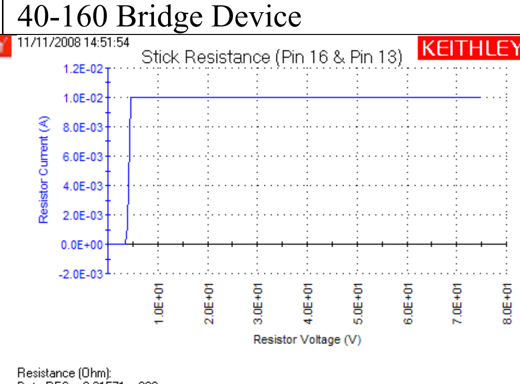


Here are the sample data of the measured voltages that was supposed to occur:

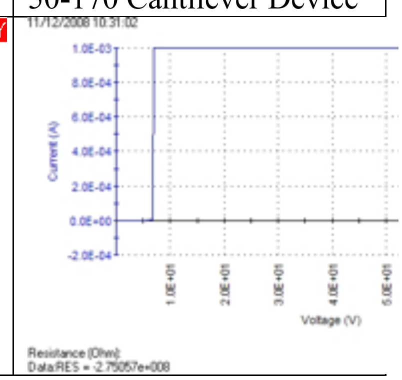
30-90 Cantilever Device



40-160 Bridge Device



50-170 Cantilever Device



- The difference between the sample and the measured data was that the resistance for the sample was a constant after several seconds. This indicated that the contact was established when applying the voltage sweep. These plots display a standard V = I*R curve. The beam makes contact with the contact pads, which establishes a connection between the probes. This shows the pull-down voltage is varied depending on the beam length and width. In the measured plots, there is no value give for the resistance that showed that the contact was not made and even suggests that the devices were not conducting properly. It is showing similarly to measuring the probes themselves, so this suggests that all devices have failed.

Conclusion:

The main cause for the error and/or malfunction of the MEMS devices was because of conducting issues. Possibly during the alignment of the cantilever pattern in the second time, the wafer was not fully in position and caused the beam to be placed incorrectly on the anchor point. Another explanation is that during the second attempt of putting the cantilever on the anchor point, the etchant from the first attempt may have removed some of the photoresist underneath the Ti and Au, which may have unbalanced the load location for the cantilever.

Looking at the images, the patterns showed the cantilever aligned or missing cantilevers. Because of this, when releasing the cantilever, the beams were likely blown away or forced out of their place. This causes the devices to have no electrical conduction because there is no physical connection of the anchor points and cantilever beam hence the mess of plots and measured voltage values. This makes any guess of what the voltage impossible as it is like measuring the voltage with an empty section of the path.

Appendix:

First Etching Process

Au Etchant Rate: 28 Angstroms per second or 2.8nm/s
Length of Au: 800nm
Round rate to ~ 3nm/s
Time: 800nm / (3nm/s) = 266.6seconds x (1 min / 60seconds) = 4 minutes and 12 seconds.

Ti Etchant Rate: 1100 Angstroms per second or 110 nm/s
Length of Ti: 100nm
Time: 100nm / (110nm / s) = 0.909090 seconds ~ 1 second but to remove the Ti completely, 7 seconds was selected.

Second Etching Process

Au Etchant Rate: 28 Angstroms per second or 2.8nm/s
Length of Au: 1.5um
Round rate to ~ 3nm/s
Time: 1.5um / (3nm/s) = 571.4seconds x (1 min / 60seconds) = 9 minutes

Ti Etchant Rate: 1100 Angstroms per second or 110 nm/s
Length of Ti: 30nm
Time: 30nm / (110nm / s) = 0.272727 seconds ~ to remove the Ti completely, 10 seconds was selected.

Here is the layout of the wafer with the cantilever and bridge devices for comparison of the expected and measured values of the pull-up voltage:

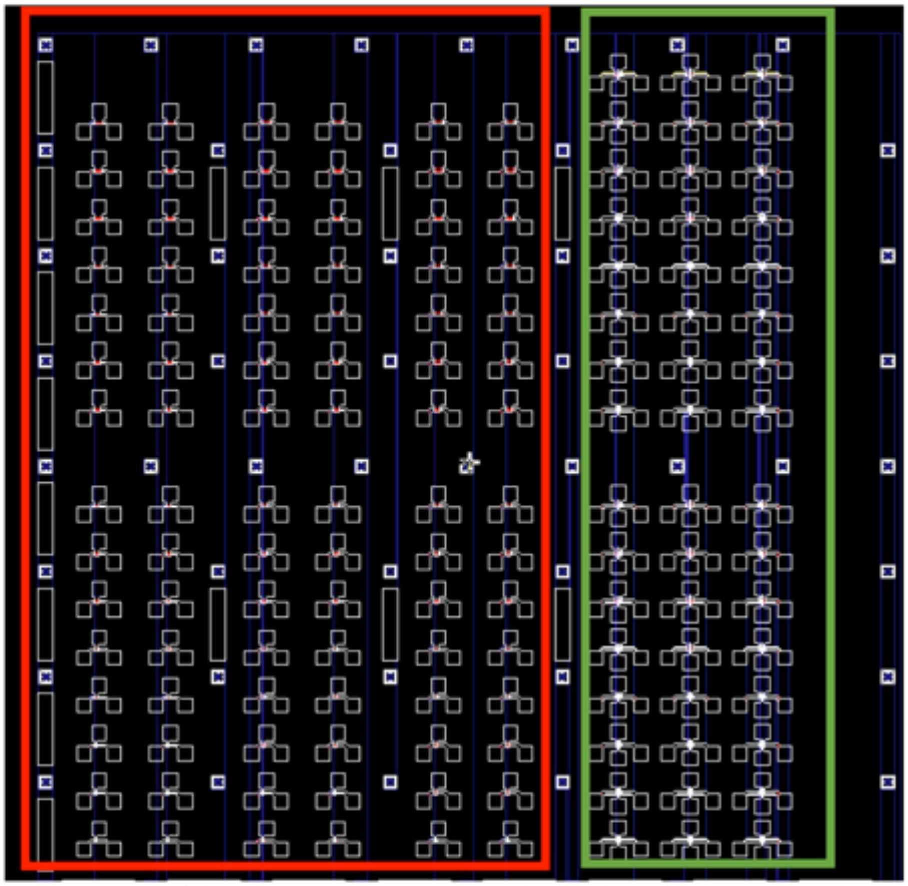
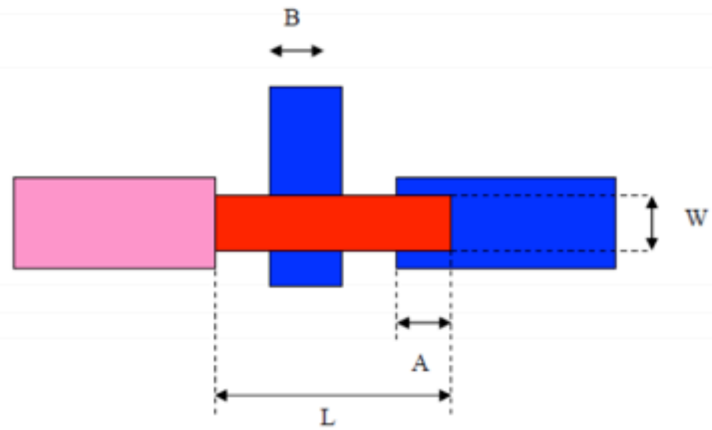


Figure 6: Layout of the MEMs wafer. Devices marked in the red box are a) ***Single Anchor Point (Cantilever).*** *Devices marked in the green box are b)* ***Double Anchor Point (Bridge)***

(Taken from Electrical Characterization MEMS procedure)

Dimensions from Mask

a) Single Anchor Point (Cantilever)

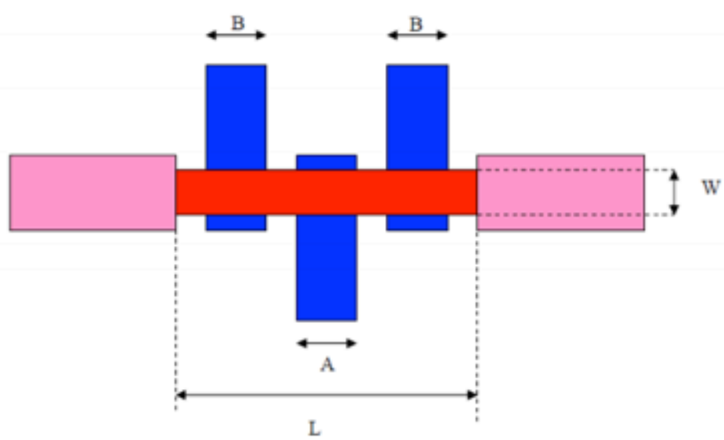


Width of beam, W = 30 µm & 40 µm; Length of beam, L = 50 µm to 190 µm, 10 µm increment

Width of beam, W = 50 µm; Length of beam, L = 60 µm to 200 µm, 10 µm increment

Beam contact width, A = 10 µm Actuation width, B = L – A – 20 µm

b) Double Anchor Point (Bridge)



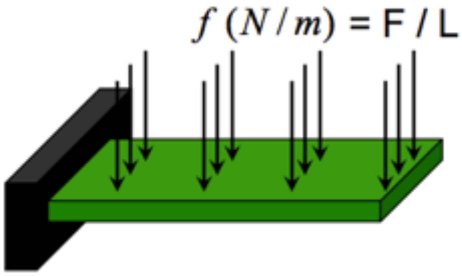
This is the 2-D figures of what the devices should be. The pink contact means to place one probe on it while having the second probe is in contact with each blue contact pad separately to take the values.

The voltage sweep is from 0 to 10V in steps of 0.05V or 0.1V for the single anchor devices. For double anchor devices, it is from 0 to 16V in steps of 0.5V.

These were the settings used for finding the pull-down voltages.

Electrical Characterization Calculations
It is assumed that the cantilever beam will have distributed load for the single anchor devices, so the spring constant is shown below to get it:

Cantilever beam with distributed load



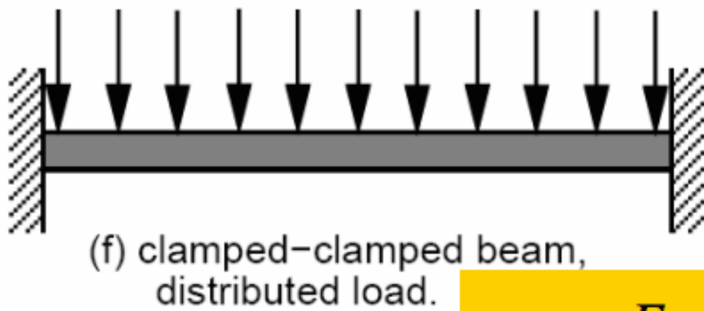
Deflection

$$\delta = \frac{3}{2}\frac{f}{Ew}\frac{L^4}{h^3}$$

Spring constant

$$k @ \frac{F}{\delta} = \frac{2}{3}\frac{Ewh^3}{L^3}$$

For the double anchor device, it also assumed to have a distributed load when voltage is applied:



$$k = 32\frac{Ewh^3}{L^3}$$

To get the pull-down voltage, we find it by first using the force equation. The force is applied to the beam when the voltage is applied, so at static equilibrium, the electrostatic force and mechanical force are equal. The pull-down voltage is the voltage in the electrostatic force equation, so here is the formula:

$$V_p = \sqrt{\frac{8k\left(g_0 + t_d/\varepsilon_r\right)^3}{27\varepsilon_0 A}}$$

Here is the MATLAB code
```
%From lecture slides
clc;
clear all;

%All of the beam widths
```

```
W1 = 30;
W2 = 40;
W3 = 50;
W4 = 60;

%All of the beam lengths
L1 = [50:10:190];
L2 = [60:10:200];
L3 = [100:10:170];

E = 79e9; %Young's Modulus for Gold
h = 1.5e-6; %thickness of the beam, taken from runsheet from the sputtering
        %of Au in the late part of the process
e0 = 8.854e-12; %F/m  %The vaccum permaittivity
er = 6.9; %the dielectric constant of Au with respect to air
td = 900e-9;  %this is the contact pad so it is the amount of Au and Ti
         %from the first sputtering
g0 = 2.4e-6; %the gap is found from taking the amount of photoresist lost
         %between the anchor point and cantilevel

%Spring constant for distrubated load for cantilever beam
% k_can = (2/3)*(E*W*(h^3)/(L^3));

% %Spring constant for distrbuted load for clamped-clampled beam
% k_clam = 32*(E*W*(h^3)/(L^3));





%Single Anchor Point for Width = 30
% A1 = W1.*L1;
% k_can_1 = (2/3)*(E.*W1*(h^3)./(L1.^3));
% num = 8.*k_can_1*(g0 + (td/er))^3;
% den = 27*e0.*A1;
% Vp_30 = sqrt(num./den);
% W1_cell = repmat(30',numel(Vp_30),1);
%
% Table = [W1_cell,L1',Vp_30'];



% %Single Anchor Point for Width = 40
% A2 = W2.*L1;
% k_can_2 = (2/3)*(E.*W2*(h^3)./(L1.^3));
```

```
% num = 8*k_can_2*(g0 + (td/er))^3;
% den = 27*e0.*A2;
% Vp_40 = sqrt(num./den);
% W2_cell = repmat(40',numel(Vp_40),1);
%
% Table = [W2_cell,L1',Vp_40'];


%Single Anchor Point for Width = 50
% A3 = W3.*L2;
% k_can_3 = (2/3)*(E.*W3*(h^3)./(L2.^3));
% num = 8*k_can_3*(g0 + (td/er))^3;
% den = 27*e0.*A3;
% Vp_50 = sqrt(num./den);
% W1_cell = repmat(50',numel(Vp_50),1);
%
% Table = [W1_cell,L2',Vp_50'];

%Double Anchor Point with Width = 40
% A1 = W2.*L3;
% k_clam_1 = 32*(E.*W2*(h^3)./(L3.^3));
% num = 8*k_clam_1*(g0 + (td/er))^3;
% den = 27*e0.*A1;
% Vp_40 = sqrt(num./den);
% W2_cell = repmat(40',numel(Vp_40),1);
% Table = [W2_cell,L3',Vp_40'];

%Double Anchor Point with Width = 50
% A2 = W3.*L3;
% k_clam_2 = 32*(E.*W3*(h^3)./(L3.^3));
% num = 8*k_clam_2*(g0 + (td/er))^3;
% den = 27*e0.*A2;
% Vp_50 = sqrt(num./den);
% W3_cell = repmat(50',numel(Vp_50),1);
% Table = [W3_cell,L3',Vp_50'];

A3 = W4.*L3;
k_clam_3 = 32*(E.*W4*(h^3)./(L3.^3));
num = 8*k_clam_3*(g0 + (td/er))^3;
den = 27*e0.*A3;
Vp_60 = sqrt(num./den);
W3_cell = repmat(60',numel(Vp_60),1);
Table = [W3_cell,L3',Vp_60'];
```