Delta Pressure Sensors

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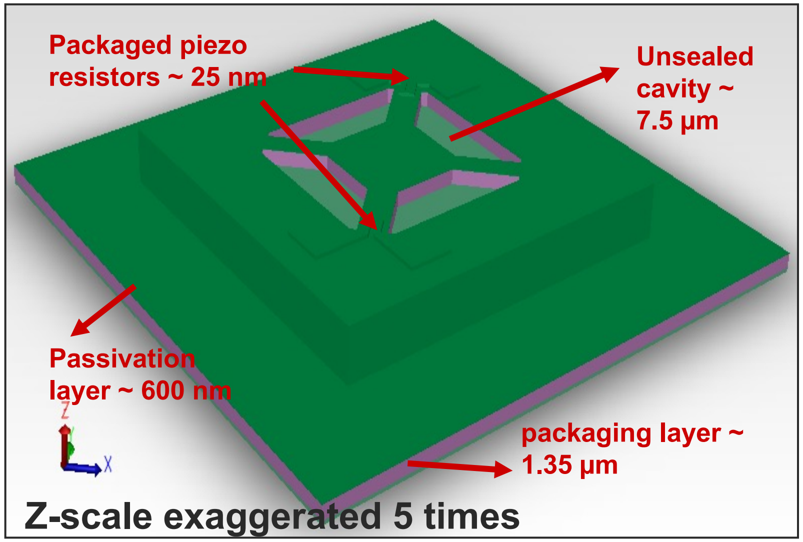
Delta Pressure Sensor Model

Delta Pressure Sensor Final Model



- Delta pressure (differential pressure) sensor is a type of pressure sensor which is used to detect pressure changes
- Delta pressure measures the pressure between two different points
- Here the pressure sensor is not sealed

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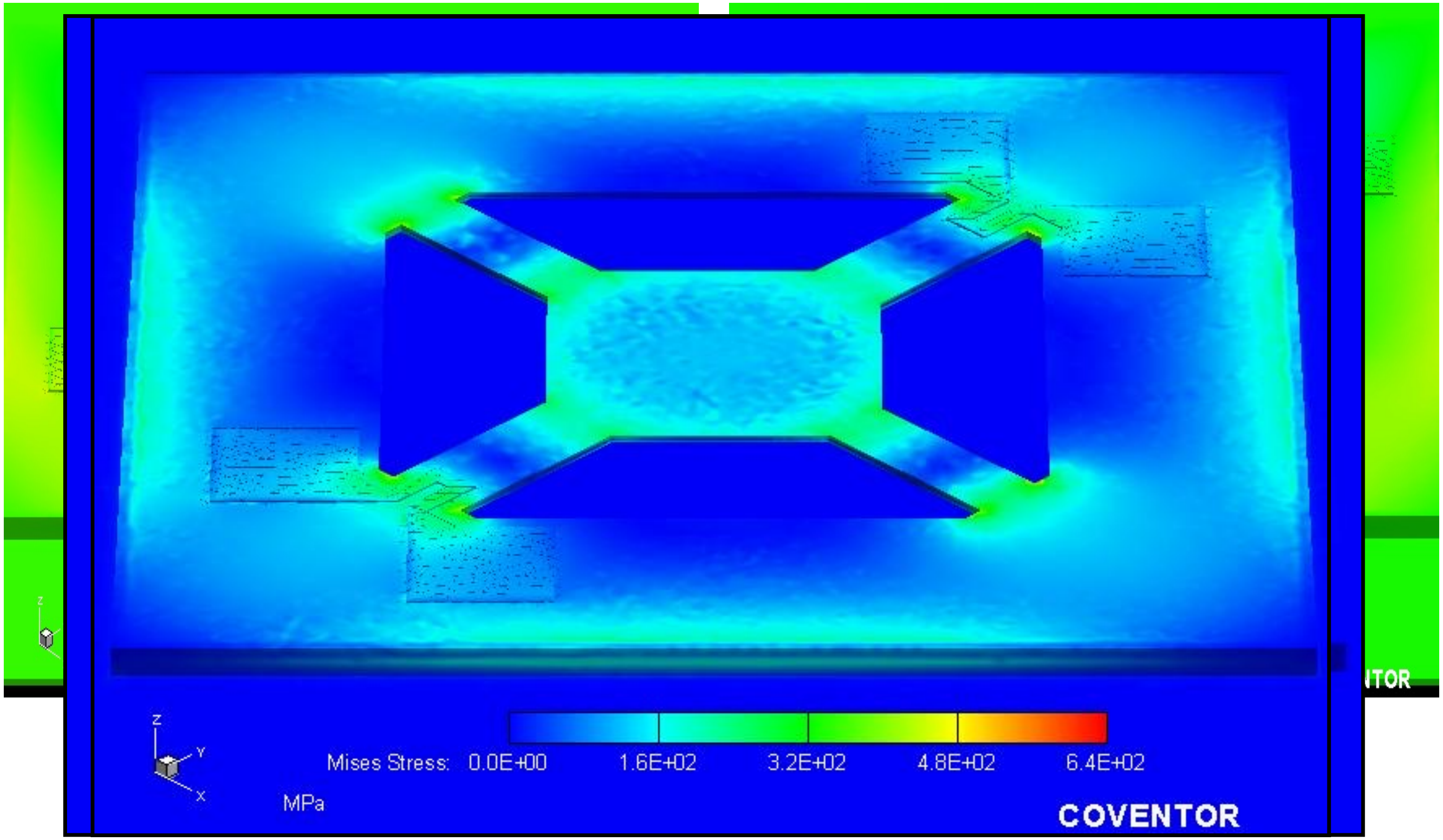
Delta Pressure Sensor Results

STRAIN YY PLOT

DISPLACEMENT PLOT
MISES STRESS PLOT

STRAIN XX PLOT



Delta Pressure Sensor Fabrication

STEP 1

- On a clean wafer spin-coat ~ 40 μm flexible polyimide as the substrate layer followed by 600 nm passivation layer

STEP 2

- Spin polyimide and cure

STEP 3

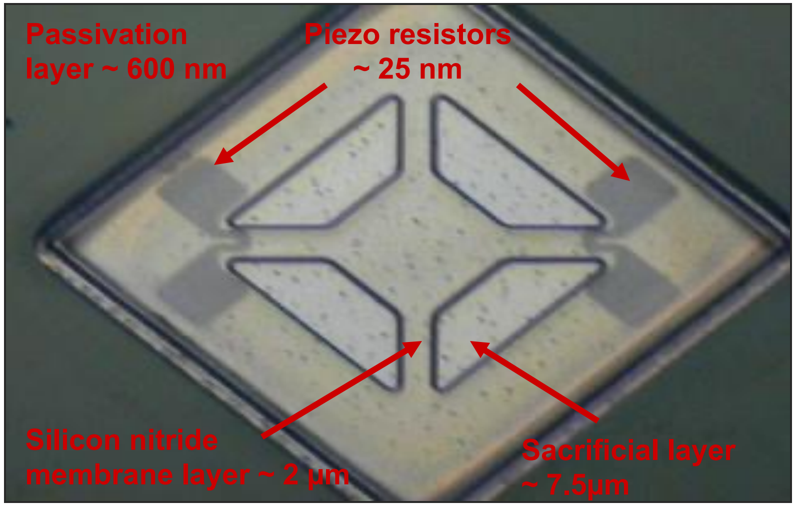
- Deposit ~ 2 μm membrane layer

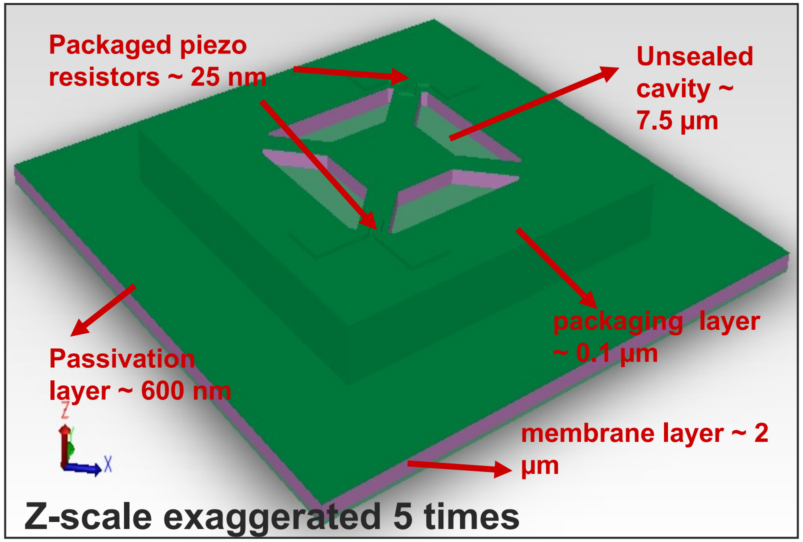
STEP 4

- Deposit ~ 25 nm thick Piezoresistors

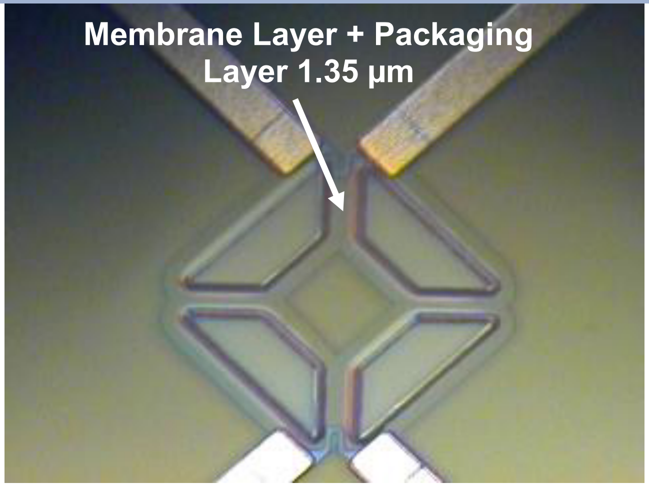
NEXT STEPS

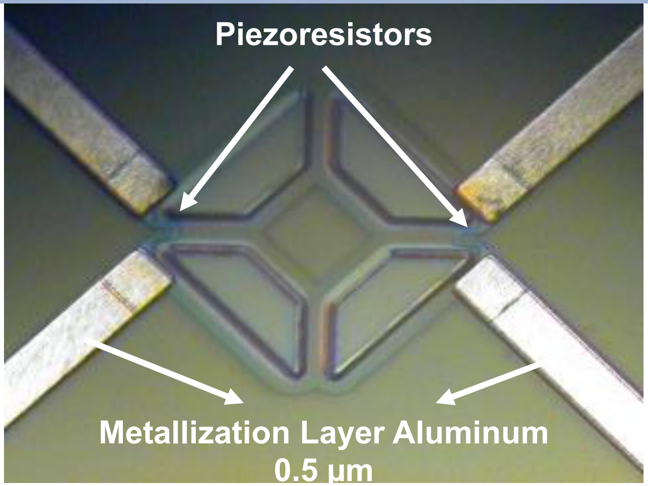
- Deposit ~ 500 nm thick aluminum as the metallization layer
- Deposit ~ 100 nm thick packaging layer to package the pressure sensors
- Ash the sacrificial layer using oxygen plasma to suspend the membrane
- Etch the silicon wafer from the back side to get access to the bond pads and characterize the delta pressure sensors

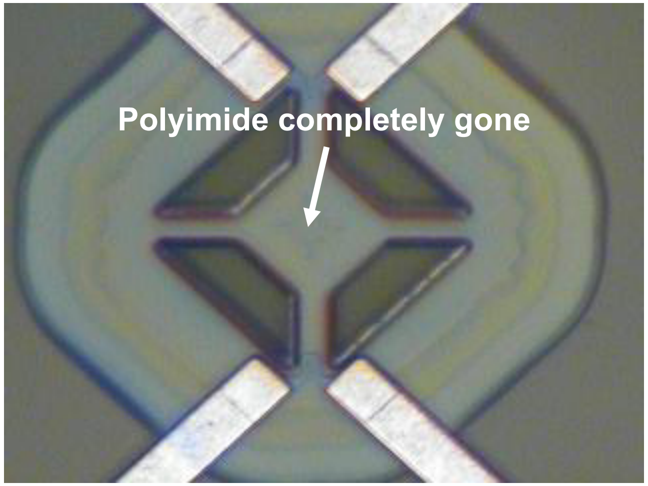


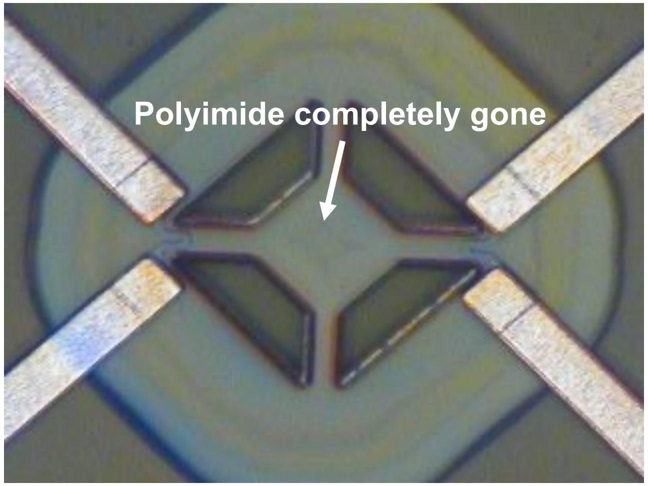


Delta Pressure Sensor Fabrication Steps

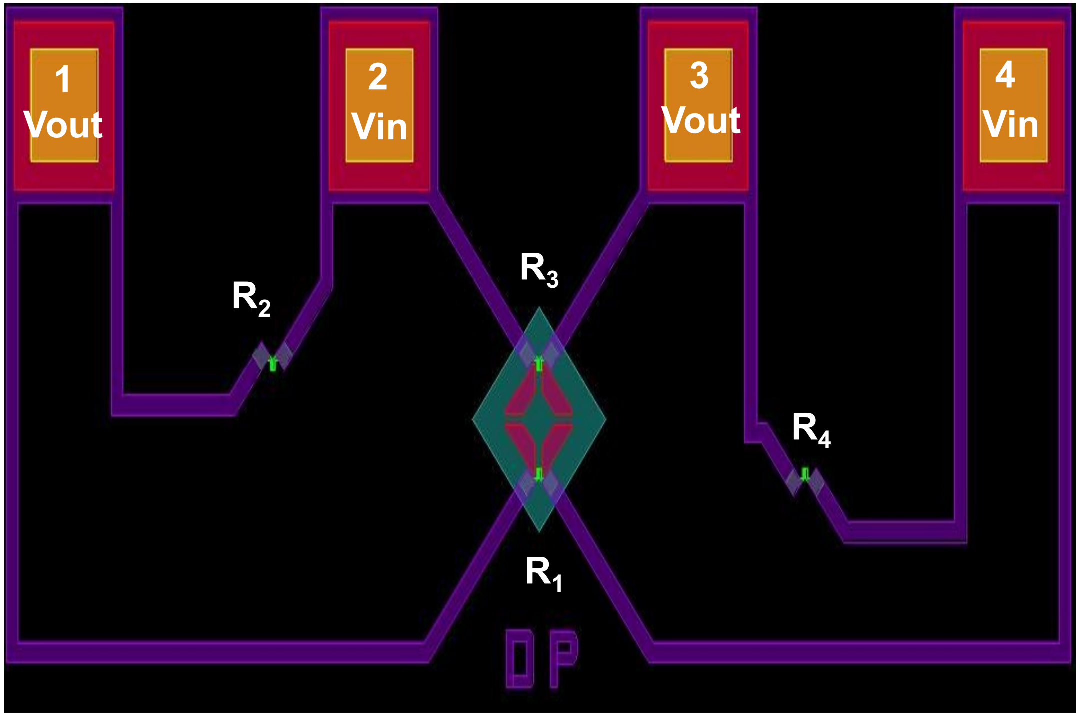


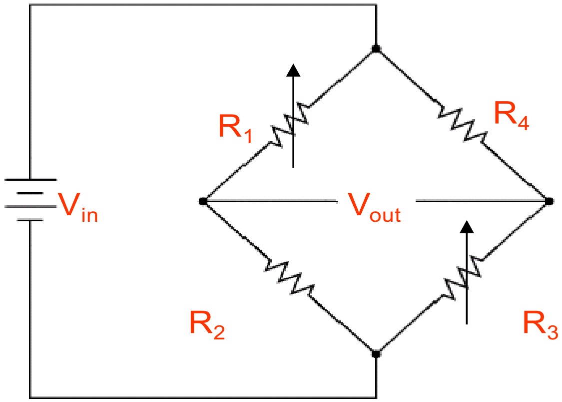






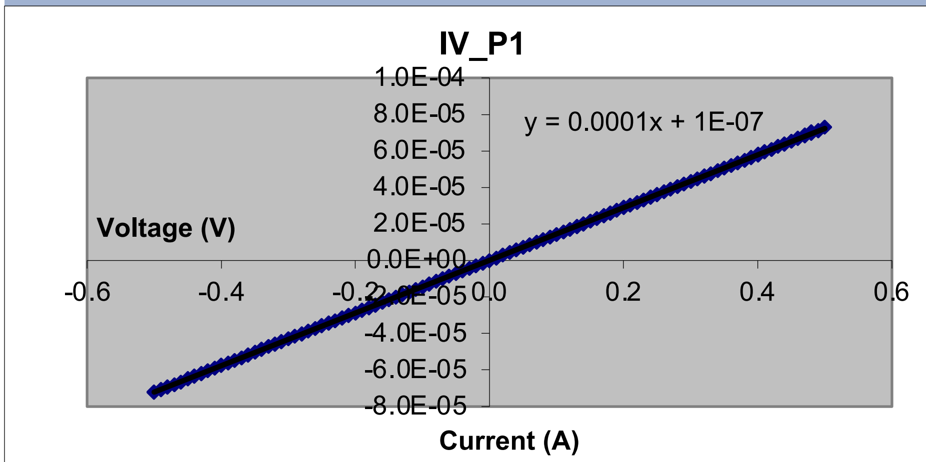
Delta Pressure Sensor Characterization

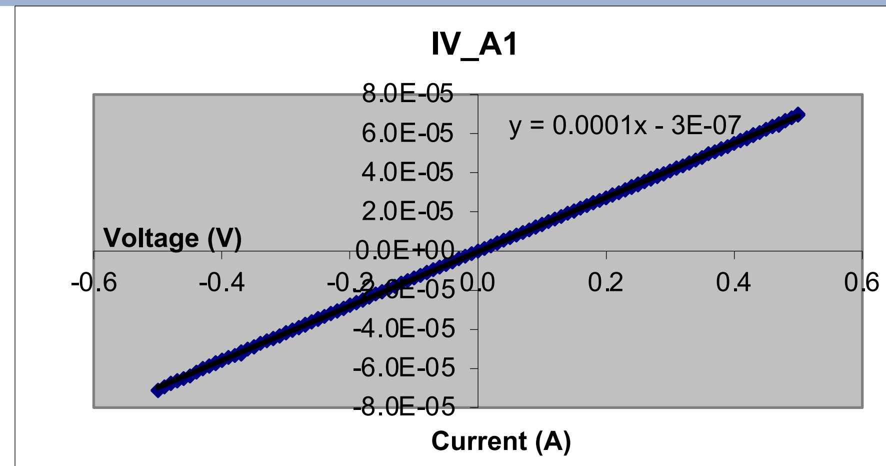


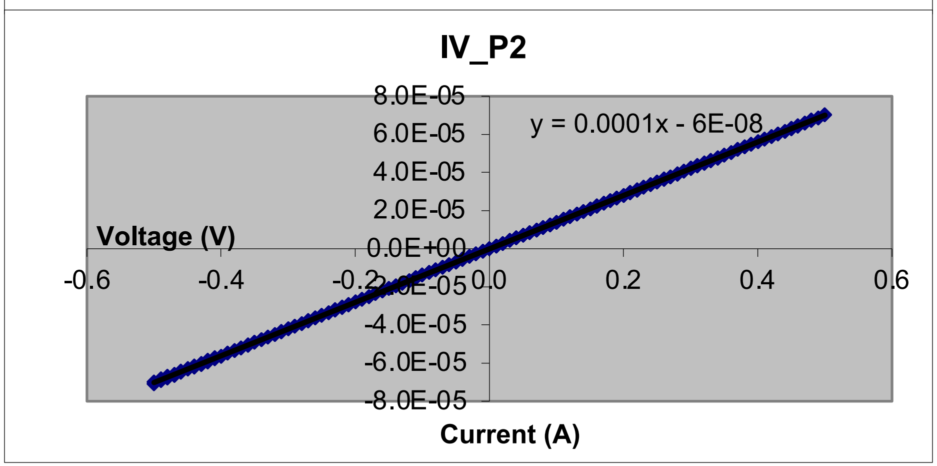


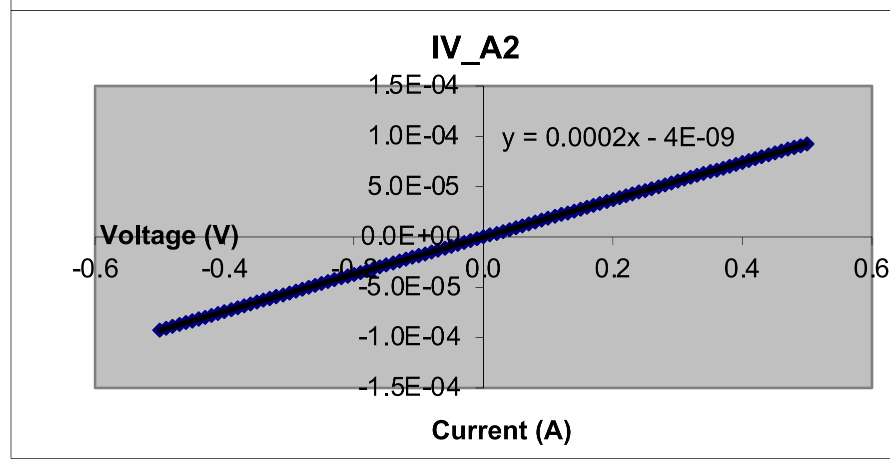
- The electrical circuit is complete with two active piezoresistors (R_1 and R_3) and two passive piezoresistors (R_2 and R_4) in a Wheatstone bridge configuration
- The current-voltage characteristics is plotted and the true resistances are found

Delta Pressure Sensor Characterization









- **P1 and P2 are passive piezoresistors whereas A1 and A2 are active piezoresistors**
- **R_{P1}=9.386 KΩ R_{A1}=9.987 KΩ R_{P2}=9.824 KΩ R_{A2}=6.625 KΩ**

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Structural Health Monitoring via Delta Pressure Sensors

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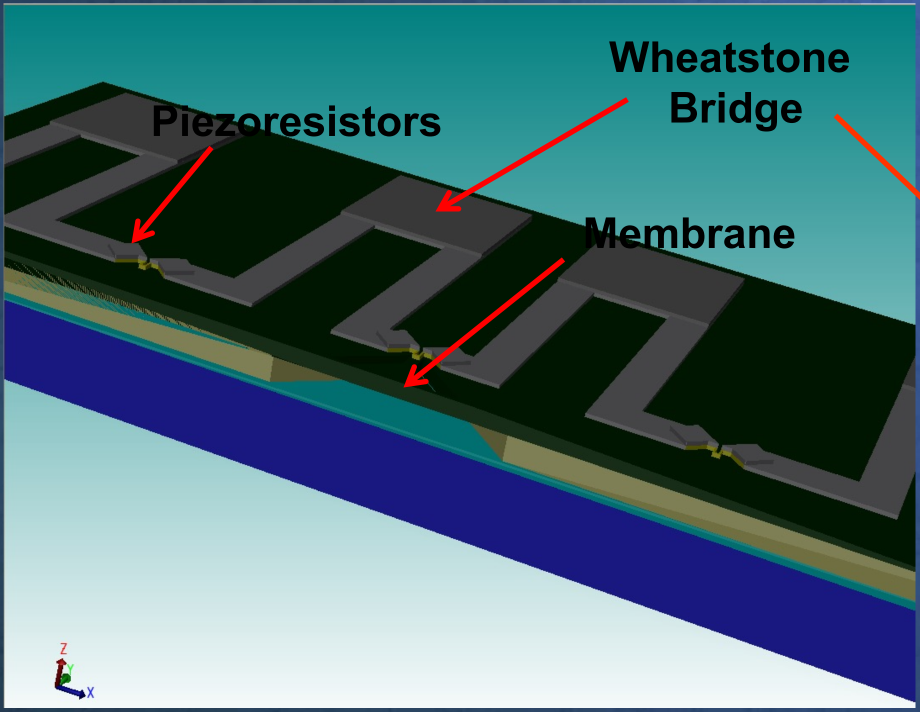
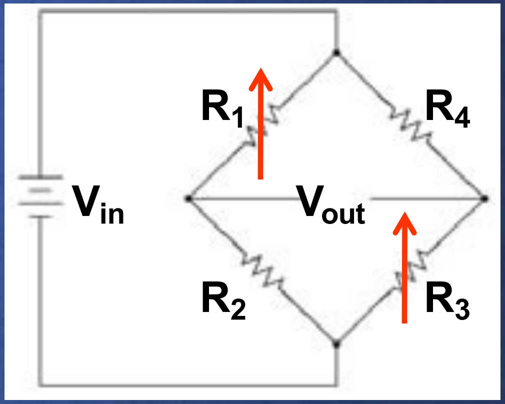
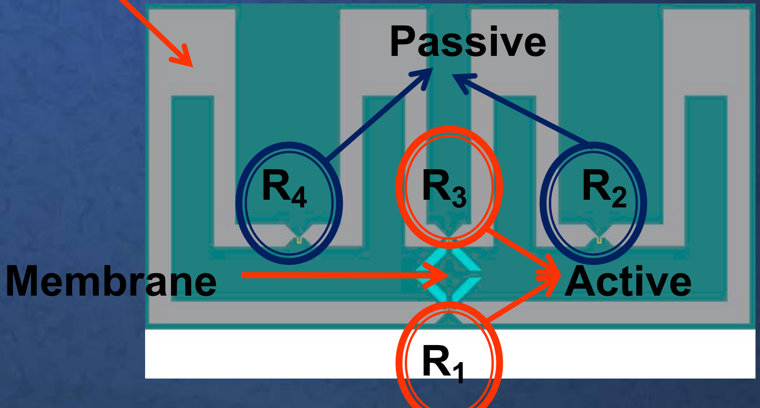
Theory of Pressure Sensor

- Membrane serves to amplify the pressure, convert into mechanical strain and then transfer it to the piezoresistor.
- Piezoresistors convert strain into resistance change which is transferred into electrical signal by the Wheatstone bridge.







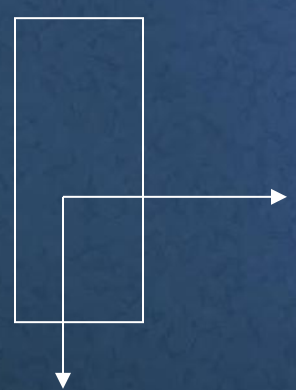
Piezoresistivity

- Linear coupling between mechanical stress and change in resistivity given by:

$$\frac{\Delta R}{R} = \Pi_l \sigma_l + \Pi_t \sigma_t$$

where $\Delta R/R$ is the change in resistance, Π_l and Π_t and σ_l and σ_t are longitudinal and transverse piezoresistive coefficients and applied stresses respectively.

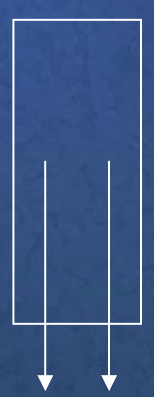
Transverse stress σ_t



Direction of Current Flow

Direction of Stress

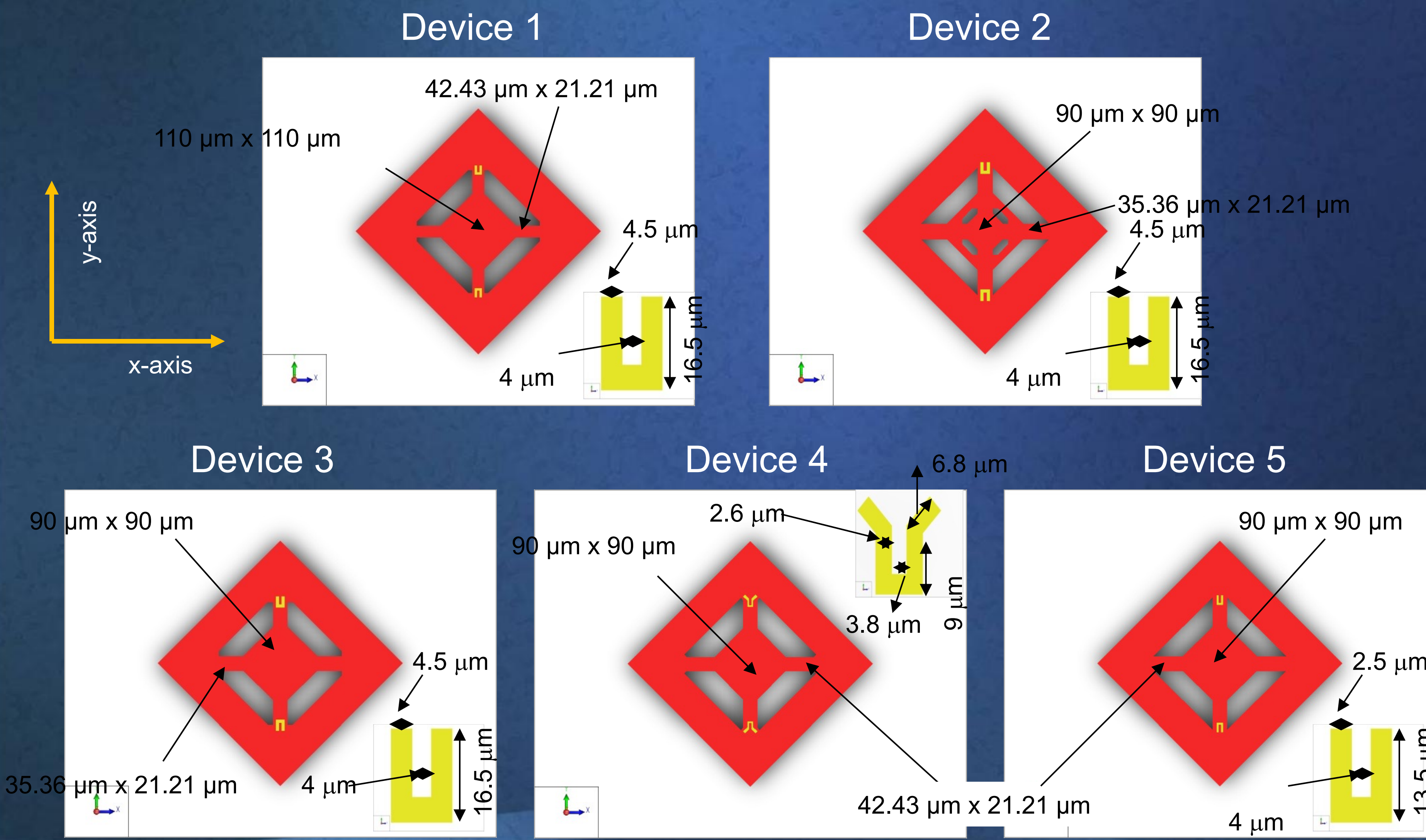
Longitudinal stress σ_l



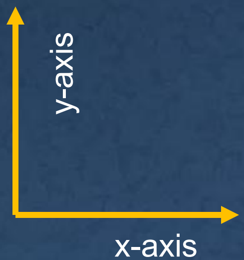
Direction of stress and current flow are the same

- **S. Sze, "Semiconductor Sensors", *John Wiley & Sons, Inc., New York*, 1994**

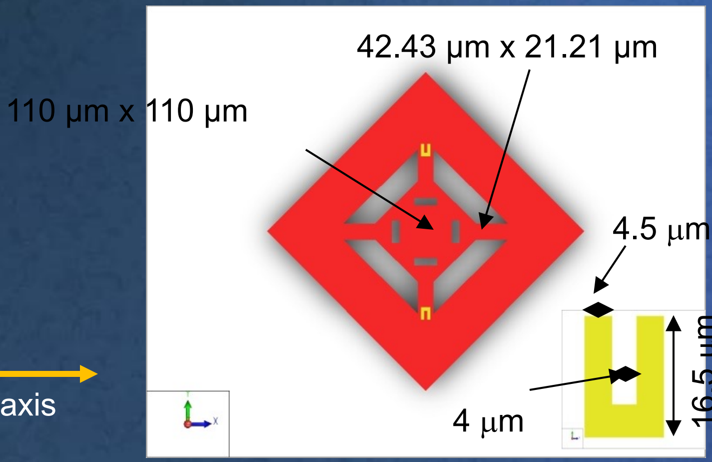
Pressure Sensor Design



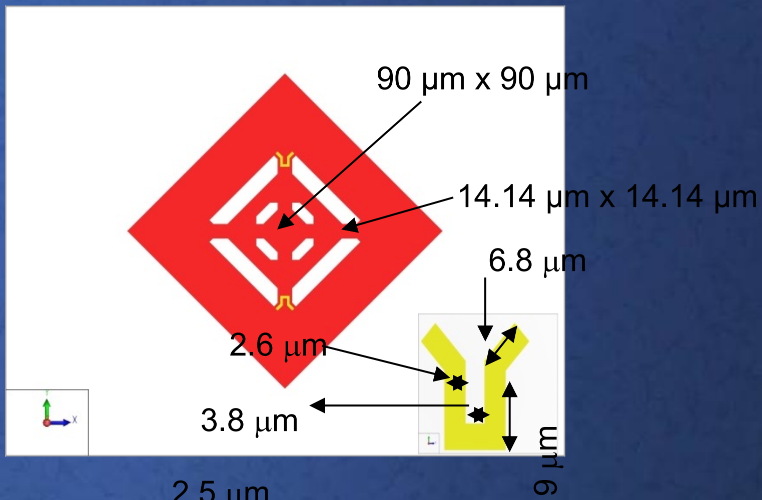
Pressure Sensor Design



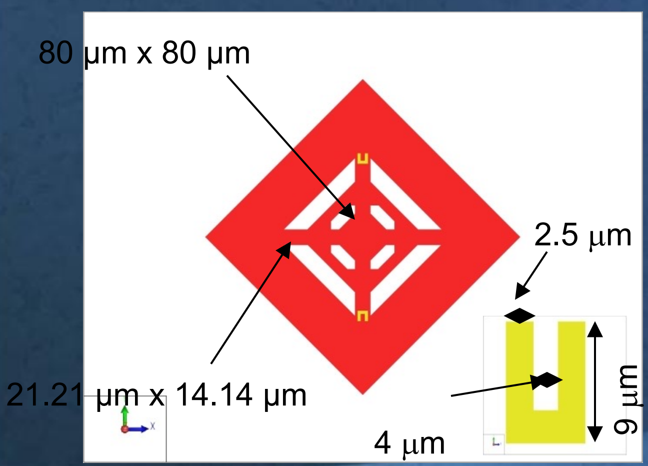
Device 6



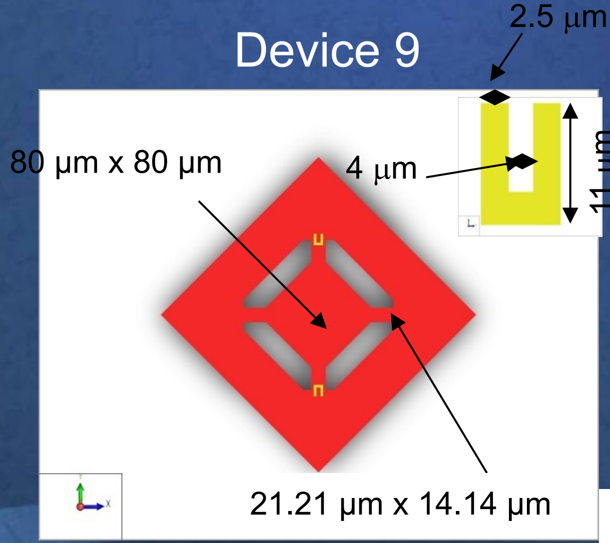
Device 7



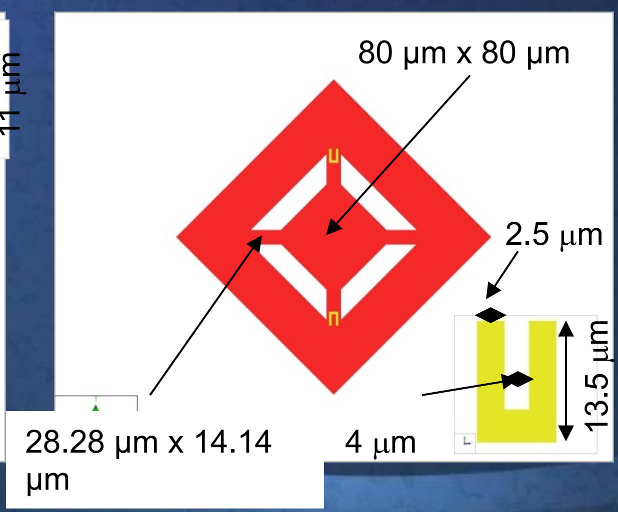
Device 8



Device 9

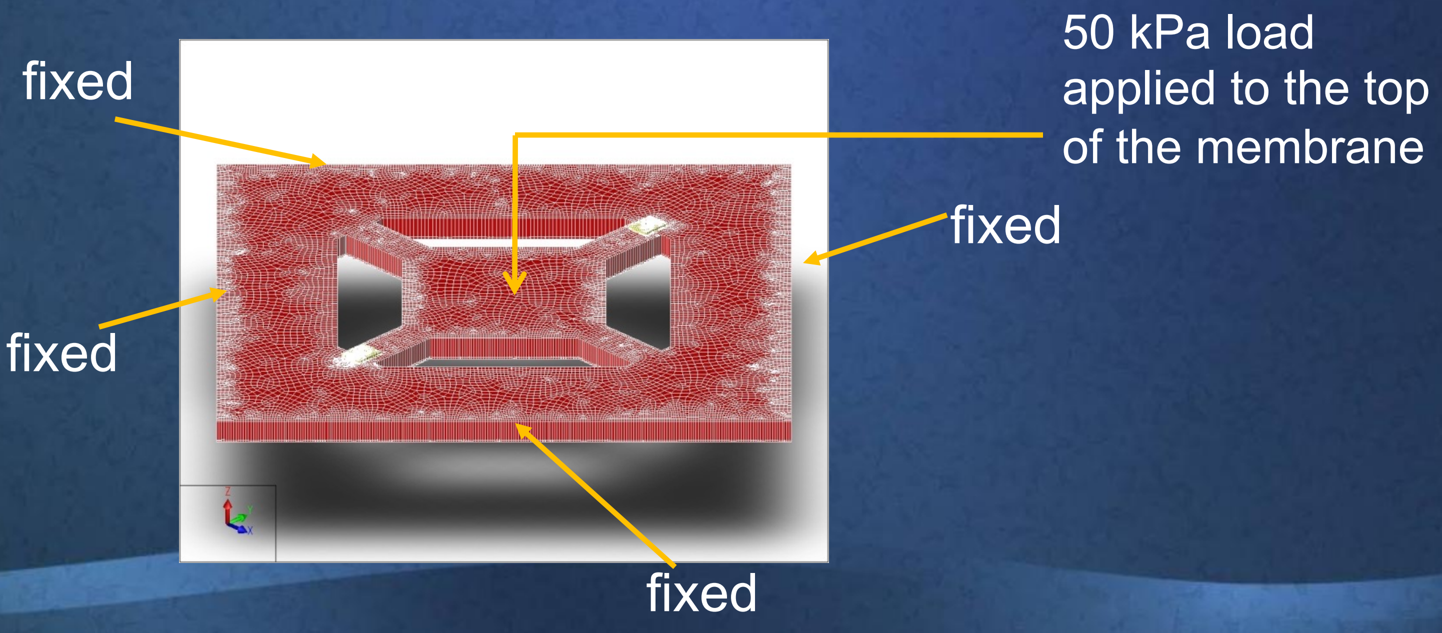


Device 10



Pressure Sensor Simulations

- Simulations were performed using Coventorware™
- Twenty one pressure sensors with different membrane and piezoresistor dimensions and shapes were simulated among which ten showing best properties were selected.
- The normalized change in resistance is found to be 0.84-3.5% assuming a gauge factor of 50.
- Differential output voltages between 4.18-17.20 mV were obtained for 1 V input with a sensitivity range of 0.08 mV/kPa-0.34 mV/kPa.

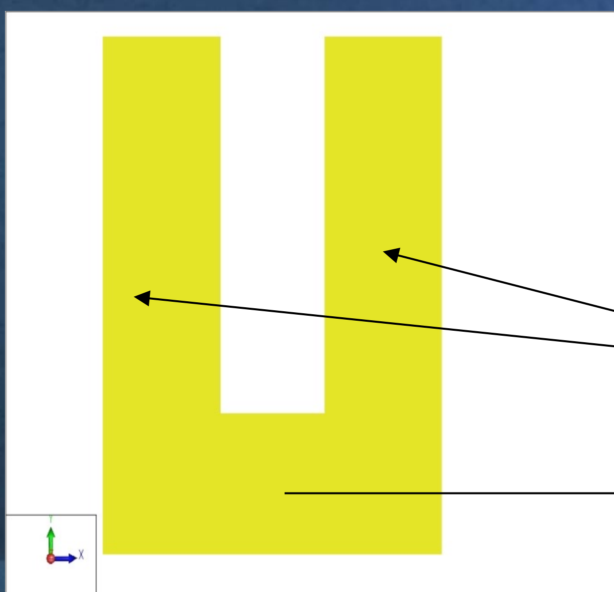


Calculations

a- Calculation of the Average Strain

$$Strain_{AVG} = \frac{Strain_{TOTAL}}{Area_{TOTAL}} = \frac{\iint [\varepsilon_{XX} + \varepsilon_{YY}]dxdy}{\iint dxdy}$$

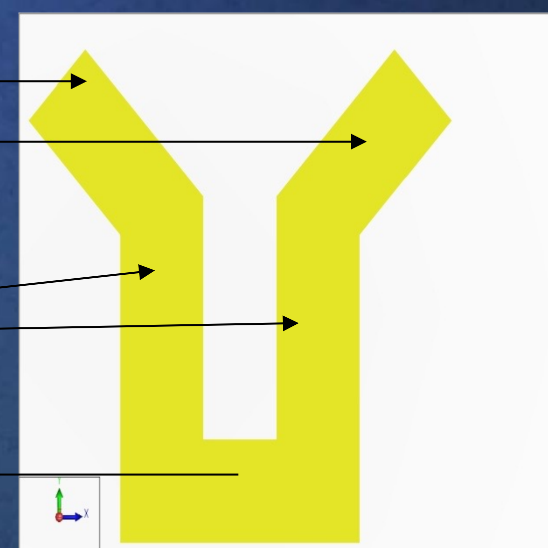
$$\varepsilon_x = \varepsilon_{xx}\cos^2\theta + \varepsilon_{yy}\sin^2\theta + \gamma_{xy}\sin\theta\cos\theta$$ ← Axis transformation



Axis transformation has been applied

ε_{yy} used for these parts

ε_{xx} used for these parts



Calculations

b- Calculation of the Output Voltage and Percent Change in Resistance

$$\frac{\Delta R}{R} = Strain_{AVG} * 50$$

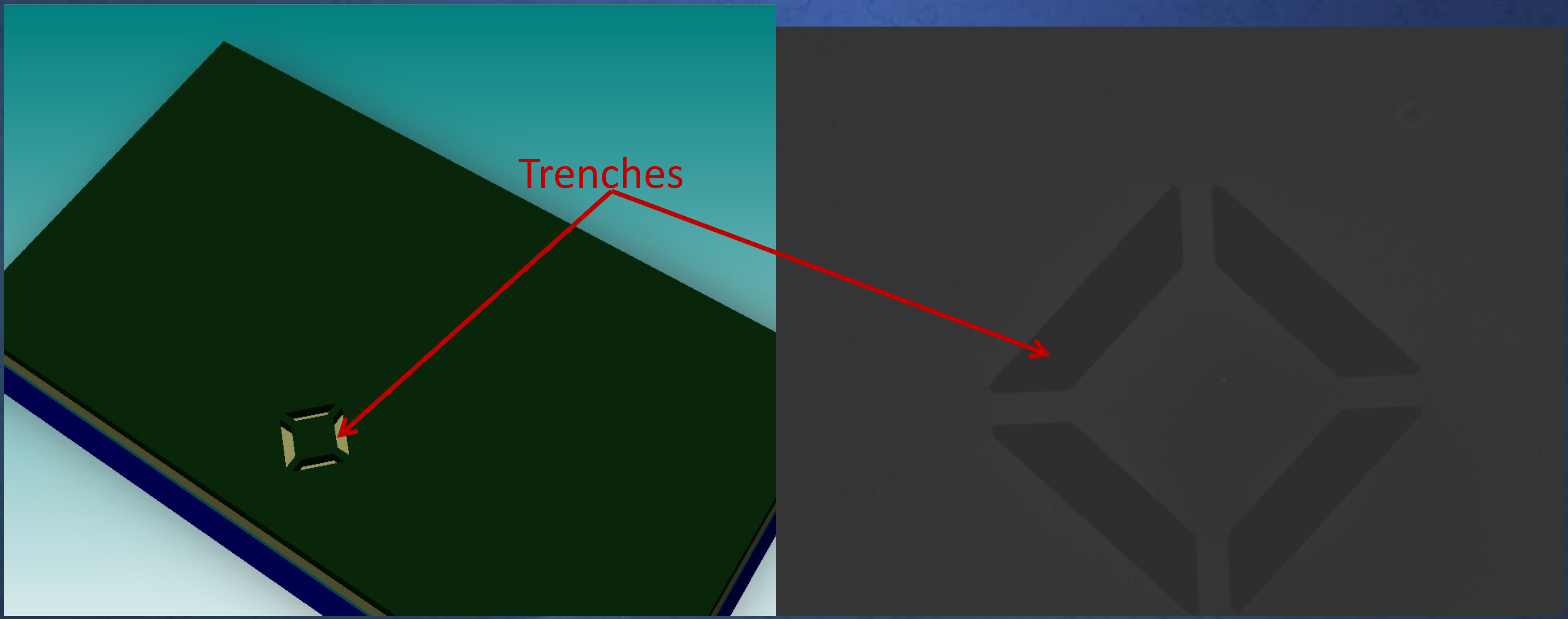
where 50 is the gauge factor for polysilicon

$$V_{out} = \frac{\frac{\Delta R}{R}}{2+\frac{\Delta R}{R}} V_{in}$$

for half bridge wheatstone structure

Pressure Sensor Fabrication

- Si/ Si_3N_4 passivation layer/ flexible substrate (50 μm)/ Si_3N_4/ sacrificial layer/ Si_3N_4 membrane layer (~1.9 μm).
- Deep reactive ion etch to etch Si_3N_4 membrane and open trenches.
- Trenches on flexible substrate were fabricated by lift-off

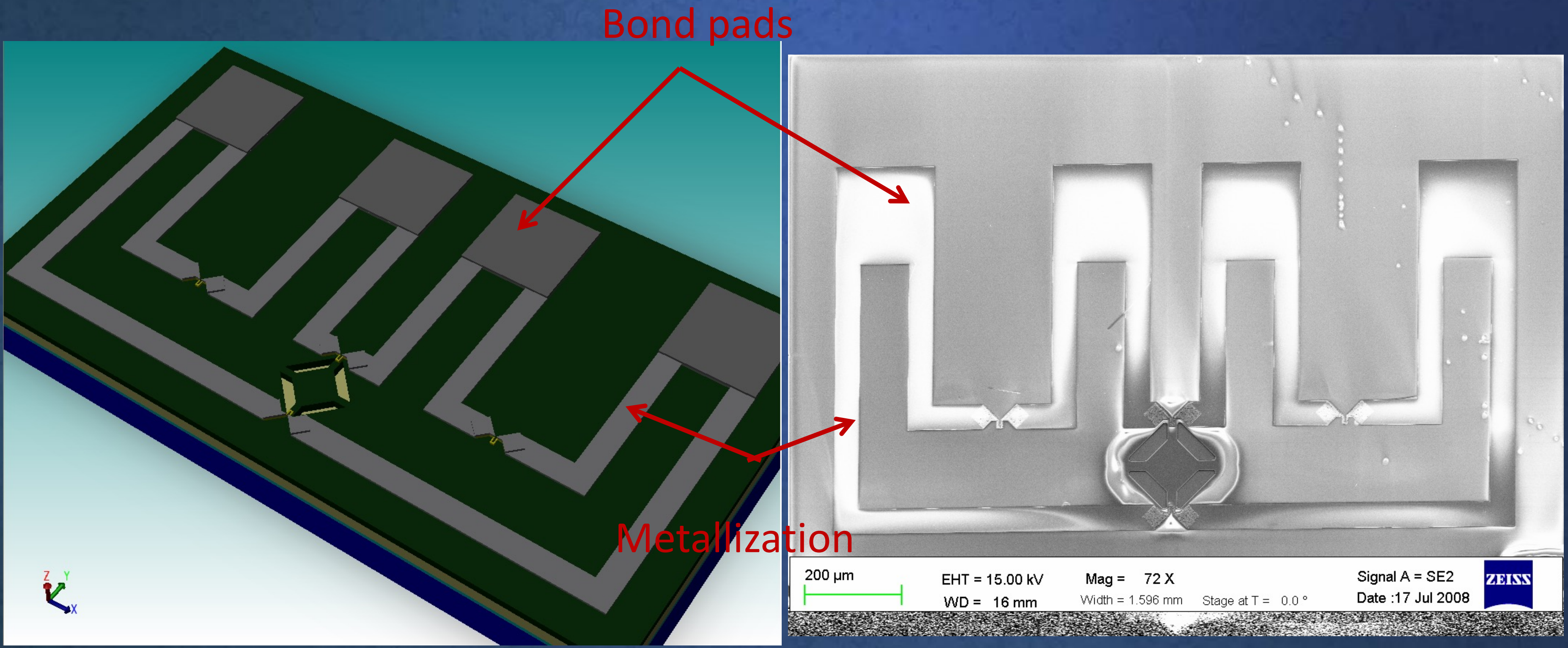


Pressure Sensor Fabrication

- Al layer (~0.5 μm)/ a-Si layer (~0.5 μm).
- Piezoresistor fabrication.

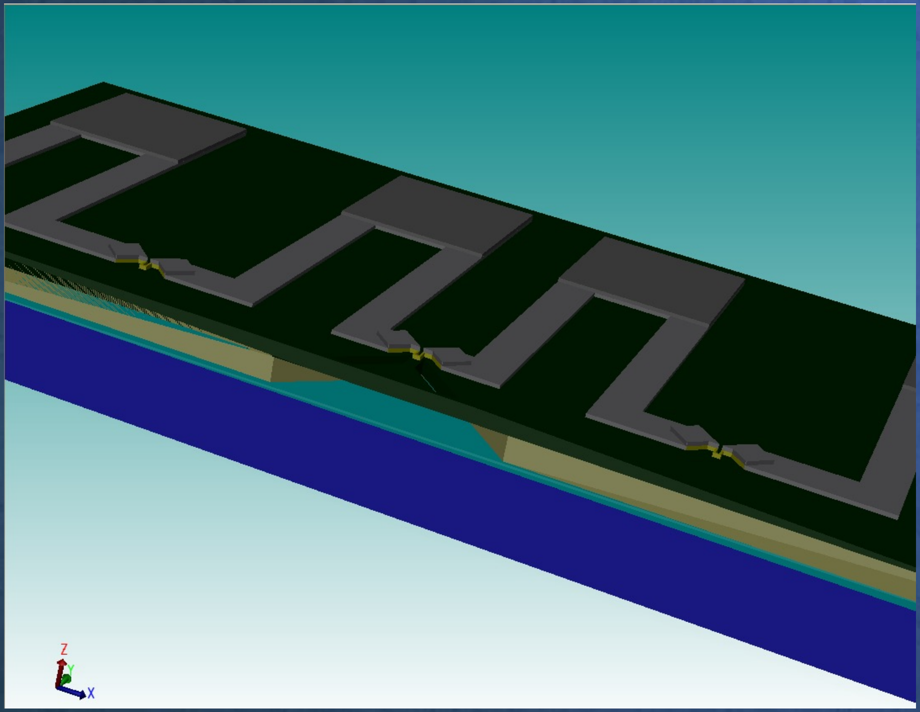
Pressure Sensor Fabrication

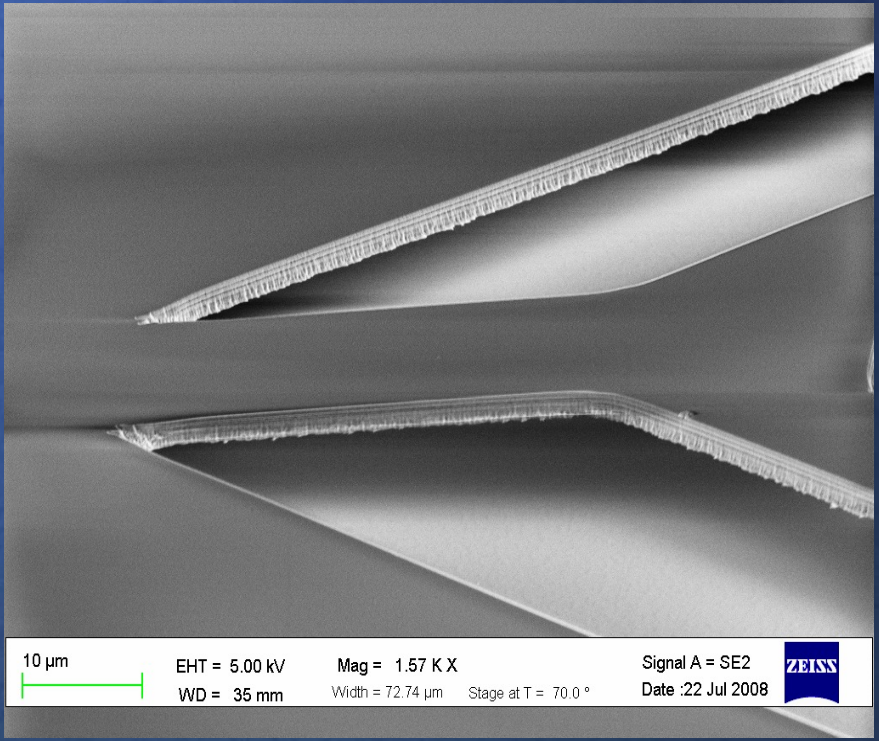
- Al metallization layer (~0.5 µm).
- Patterning metallization layer.
- Al bond pads (~0.5 µm).



Pressure Sensor Fabrication

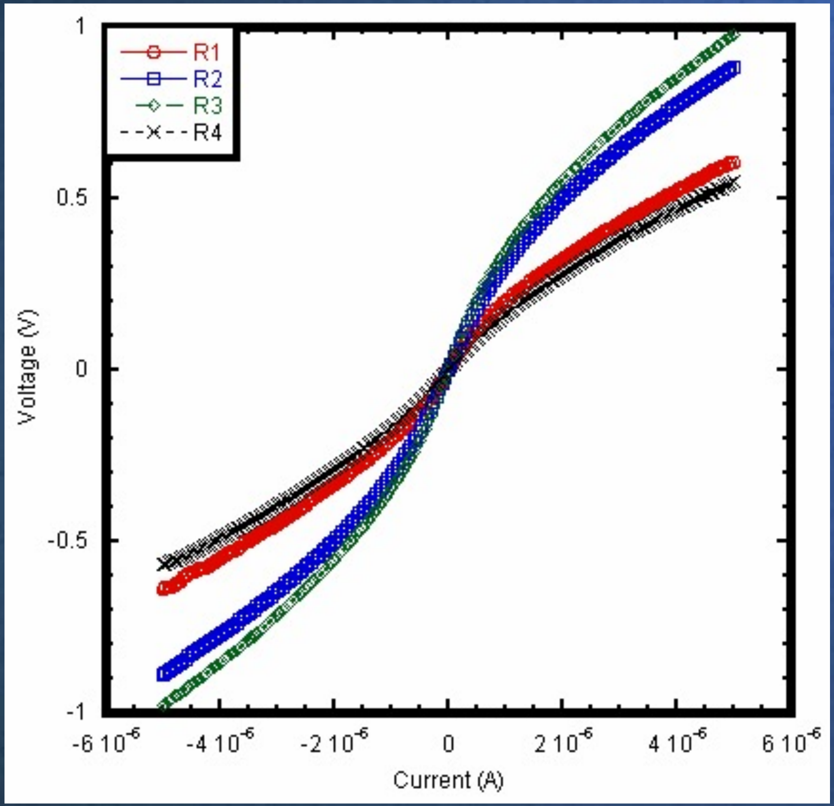
- Oxygen plasma ashing to release the structure.

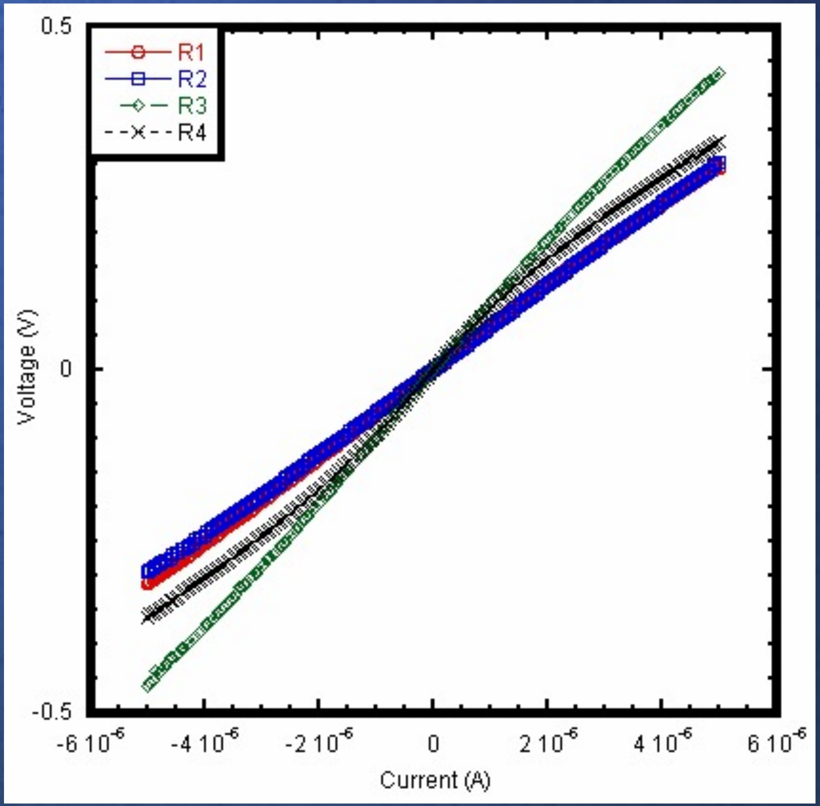




Pressure Sensor I-V Characterization

- Non-linear I-V characteristics with resistances tens to hundreds of kΩ were obtained

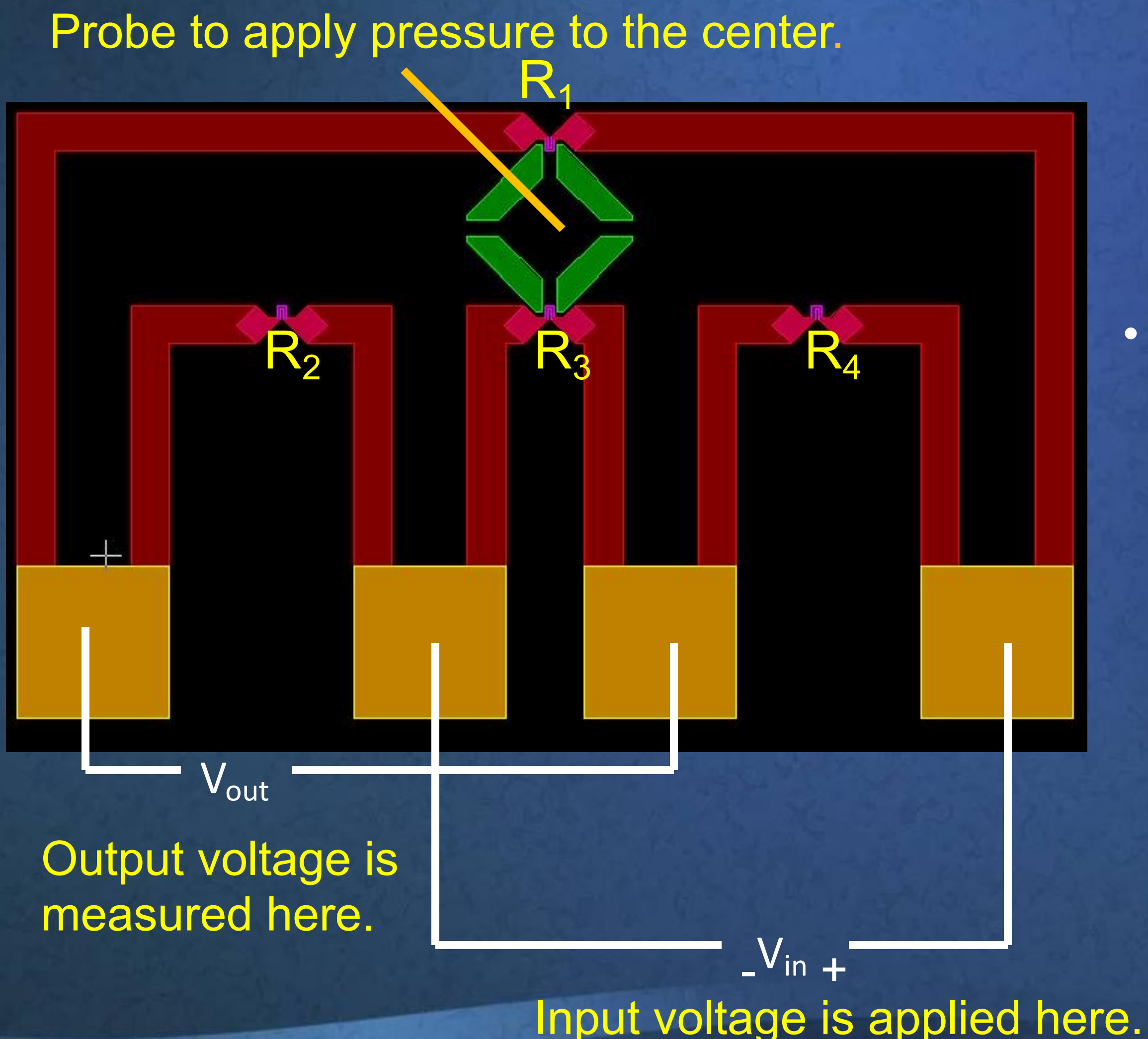




Before wire bonding

After wire bonding

Characterization

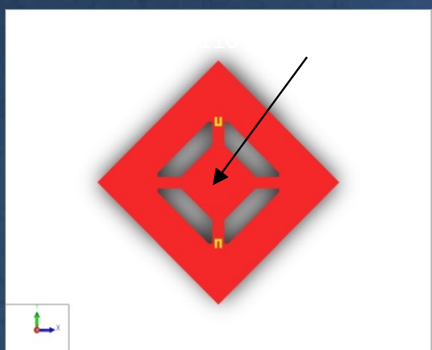


- A maximum differential output voltage of 13.7 mV has been obtained for 1V bias at full membrane deflection.

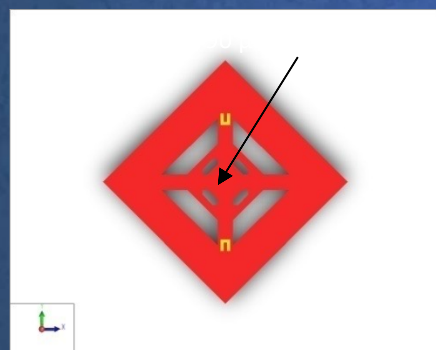
Determination of the Actual Gauge Factor

- Four devices (Device 1, Device 2, Device 3 and Device 6) giving the highest voltage output in response to pressure were selected for determination of the actual piezoresistive gauge factor.

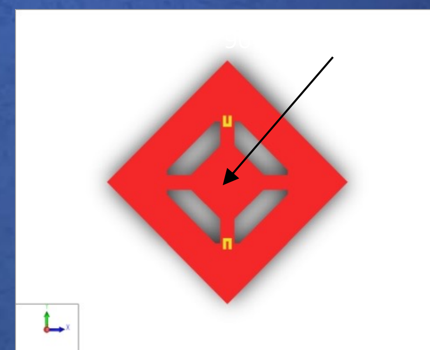
Device 1



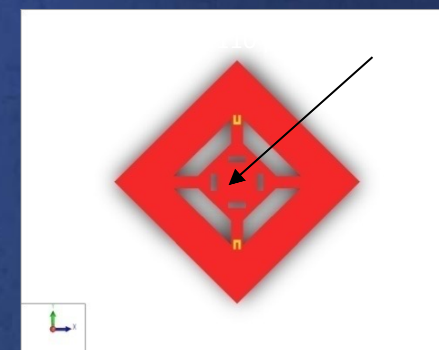
Device 2

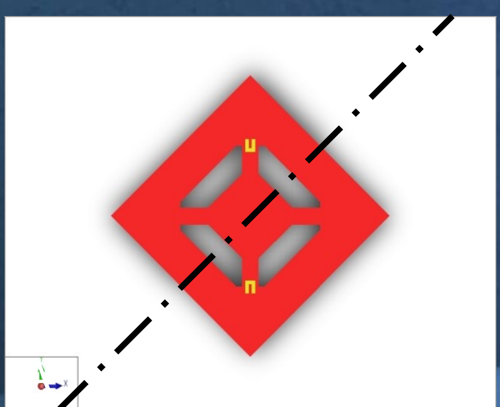


Device 3

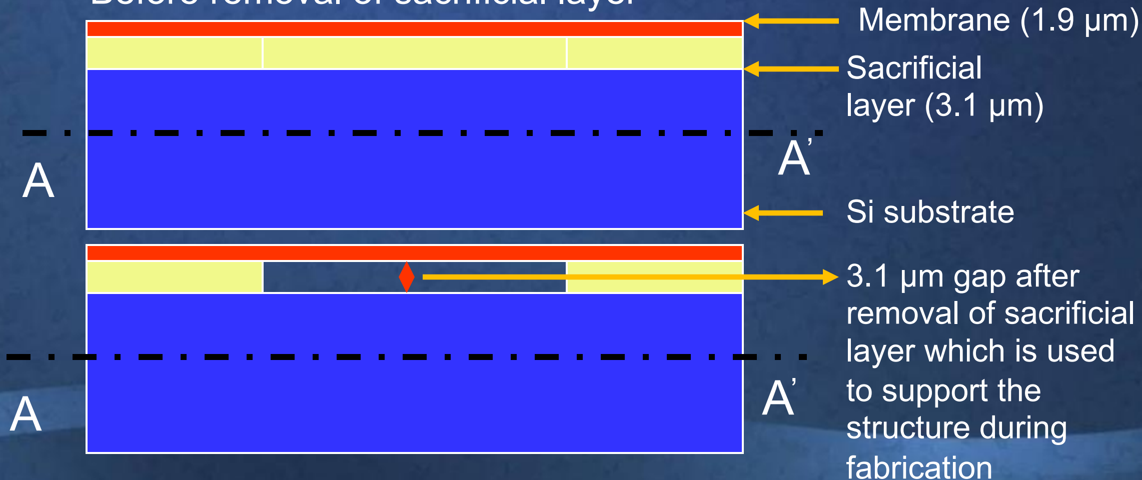


Device 6



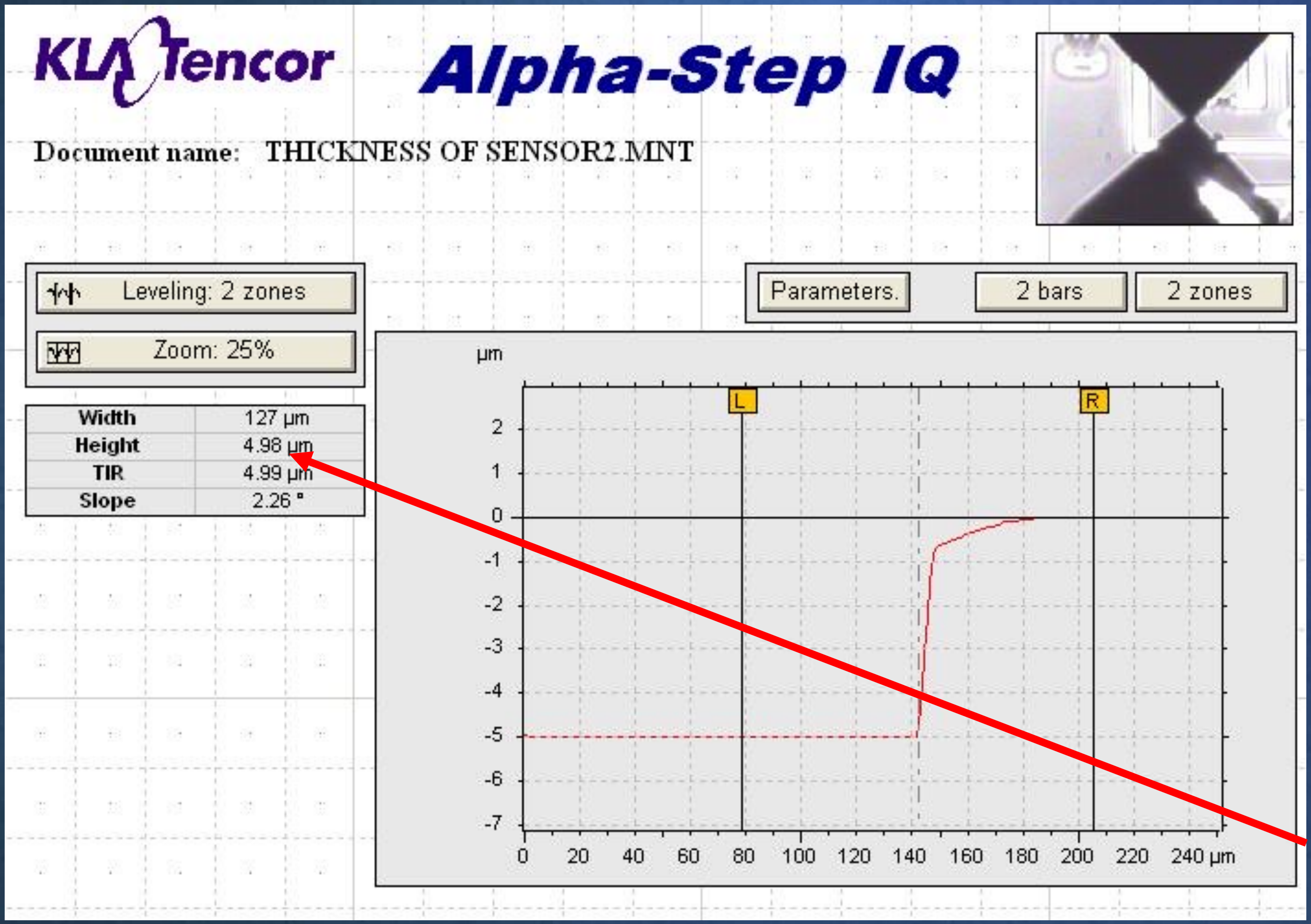


Before removal of sacrificial layer



After removal of sacrificial layer

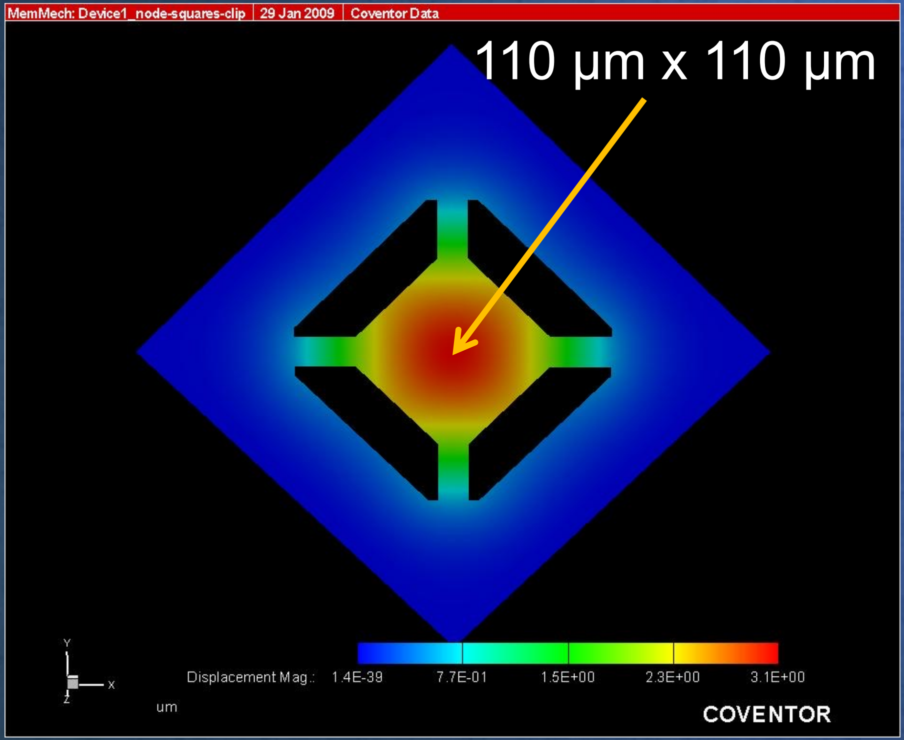
Sacrificial Layer Thickness



The height given as around 5 µm includes the membrane which is around 1.9 µm thick. The remainder is the distance taken at full membrane deflection.

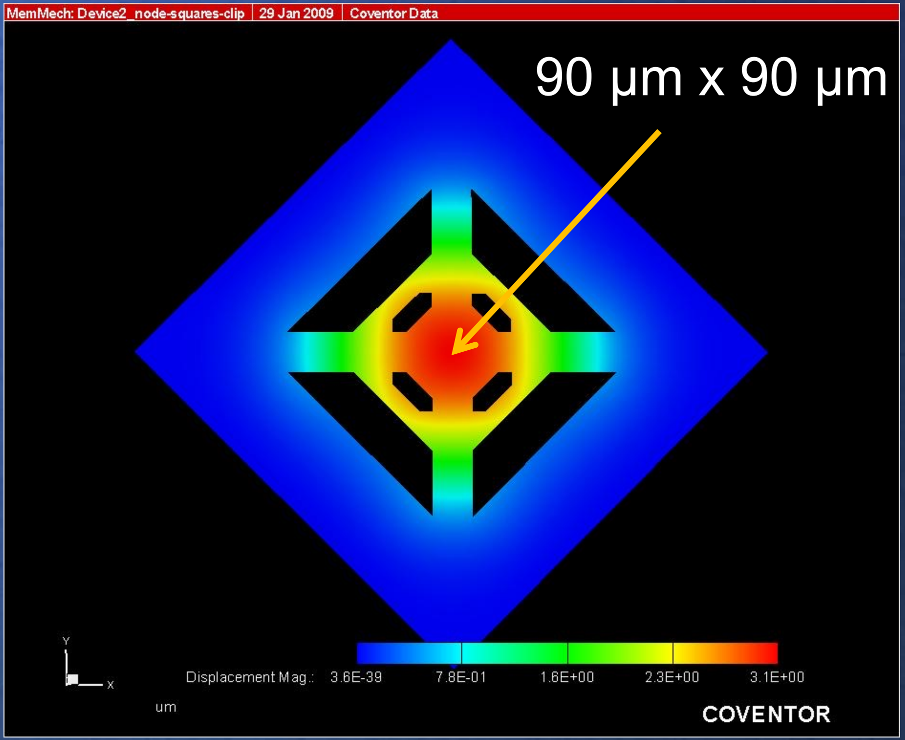
Maximum Displacement

Device 1



Applied Pressure: 78 MPa

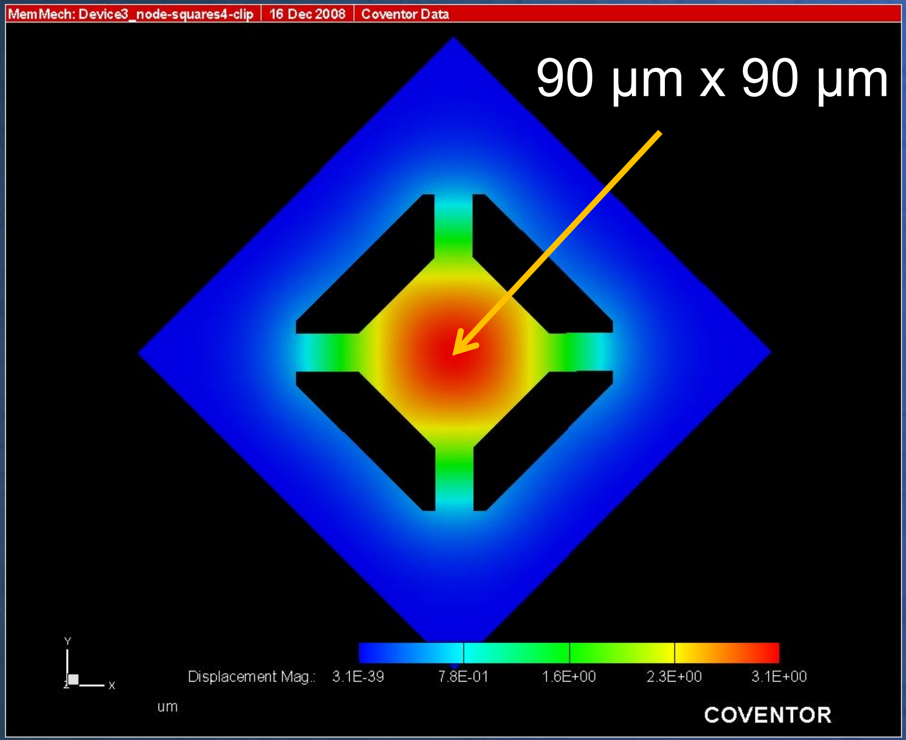
Device 2



Applied Pressure: 120 MPa

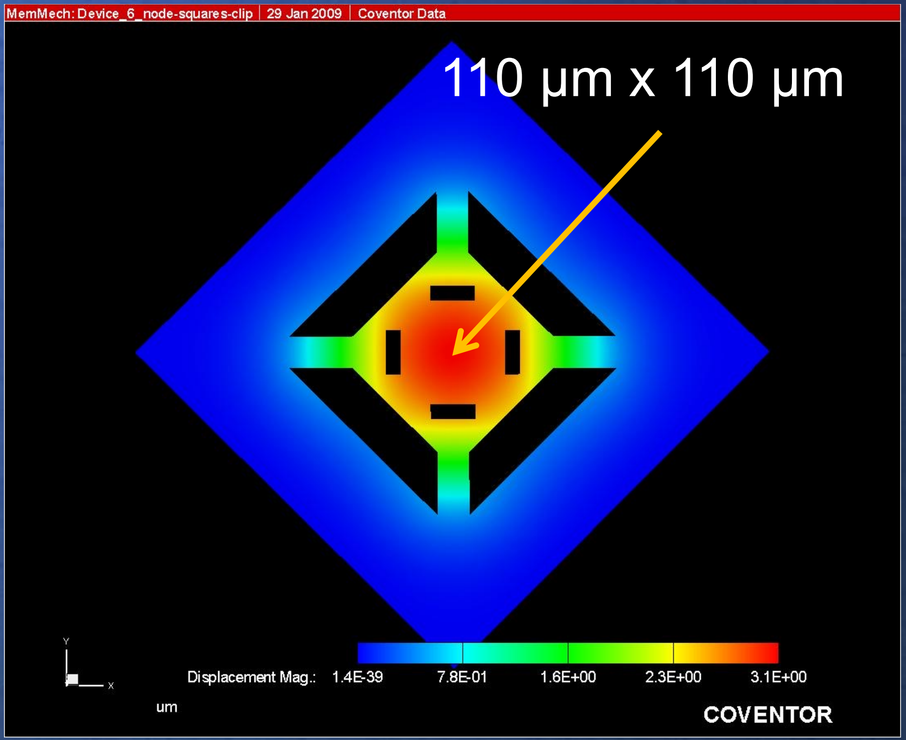
Maximum Displacement

Device 3



Applied Pressure: 128 MPa

Device 6



Applied Pressure: 73 MPa

$\Delta R/R$ and V_{out} Results from Simulations Assuming a Gauge Factor of 50

Device 1
Results in Response to 78 MPa :
Average Strain: $7.05\ 10^{-4}$
Change in Resistance (%) : 3.52
Output Voltage: 17.30 mV for 1 V input

Device 2
Results in Response to 120 MPa :
Average Strain: $9.9\ 10^{-4}$
Change in Resistance (%) : 4.95
Output Voltage: 24.15 mV for 1 V input

Device 3
Results in Response to 128 MPa :
Average Strain: $9.46\ 10^{-4}$
Change in Resistance (%) : 4.73
Output Voltage: 23.10 mV for 1 V input

Device 6
Results in Response to 73 MPa :
Average Strain: $7.53\ 10^{-4}$
Change in Resistance (%) : 3.76
Output Voltage: 18.45 mV for 1 V input

Simulated Gauge Factors of Pressure Sensors

Sample	Actual Gauge Factor	Type of Device
1	6.36	Device 3
2	19.998	Device 1
3	18.533	Device 3
4	24.121	Device 6
5	22.878	Device 1
6	25.764	Device 1
7	13.615	Device 6
8	17.766	Device 3
9	6.079	Device 2
10	29.366	Device 3
11	14.903	Device 3
12	7.992	Device 6