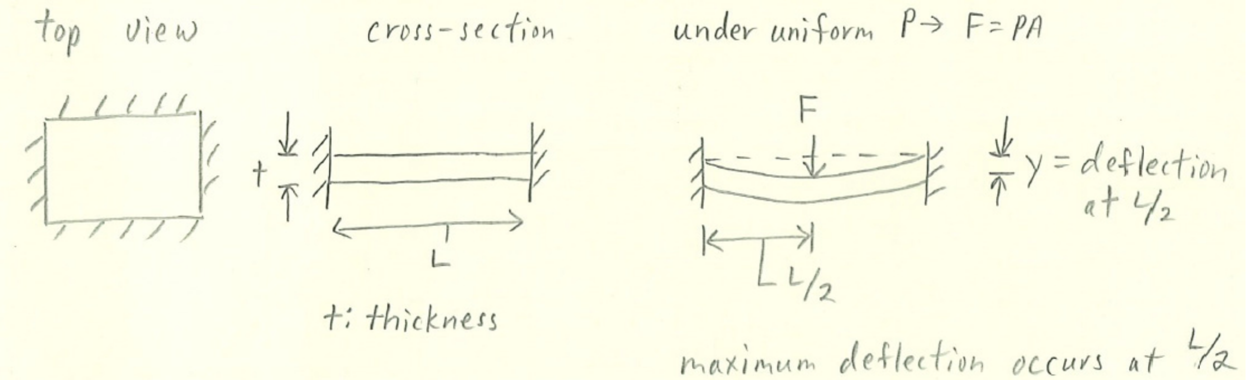
Lecture 10/22/24

Pressure Sensing Structures

1) Diaphragm

A diaphragm is a rigid, planar member clamped on all sides:



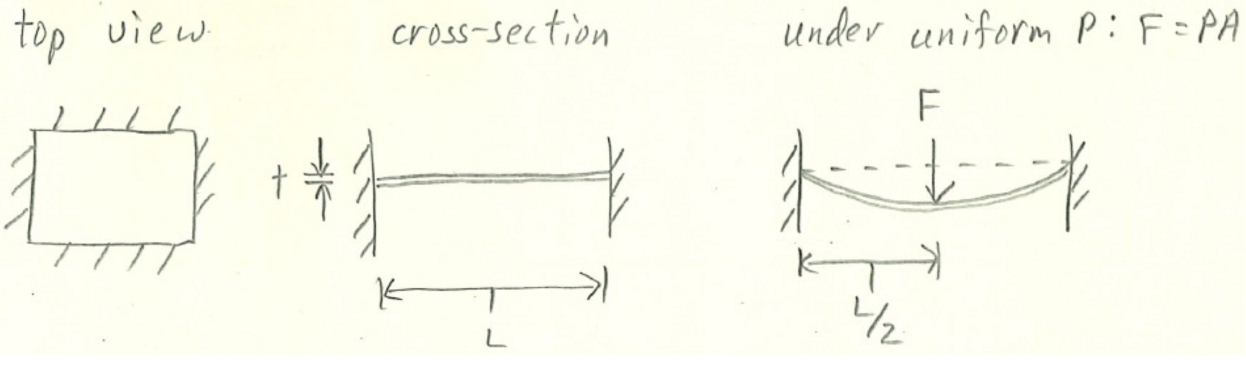
A diaphragm experiences bending stress *and* tensile stress.

For small deflections (y ≤ ~30% t) → $y \propto P$.

In this range of deflections, the deformations are elastic.

2) Membrane

A membrane is a very thin, planar, flexible member clamped on all sides:

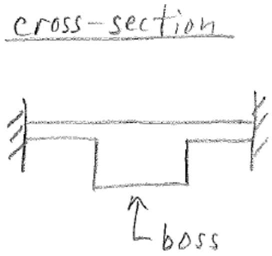


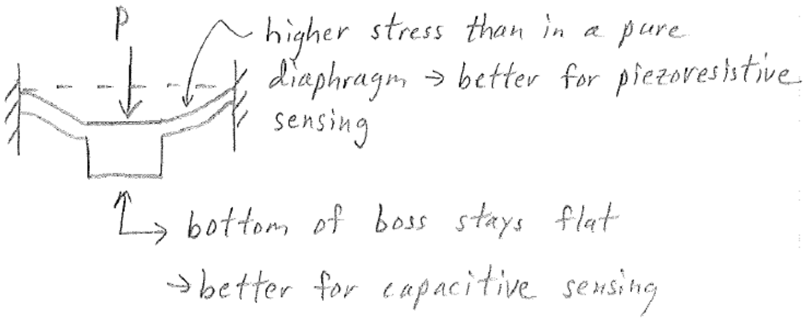
A membrane experiences *only* tensile stress, *not* bending stress.

Membranes can experience large deflections: y often > t.

3) Bossed Diaphragm

A “boss” is a thicker area in the center of a bossed diaphragm, far more rigid than the rest of the diaphragm:

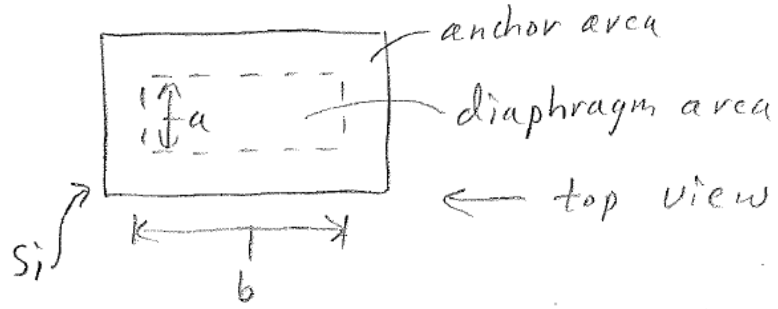


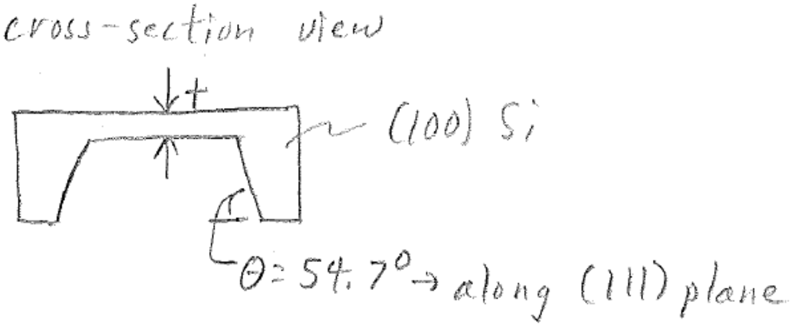


The boss is at least six times thicker than the diaphragm.

4) Bulk Micromachining of a Diaphragm Pressure Sensor

The diaphragm based pressure sensor is fabricated by etching bulk material out of the substrate:

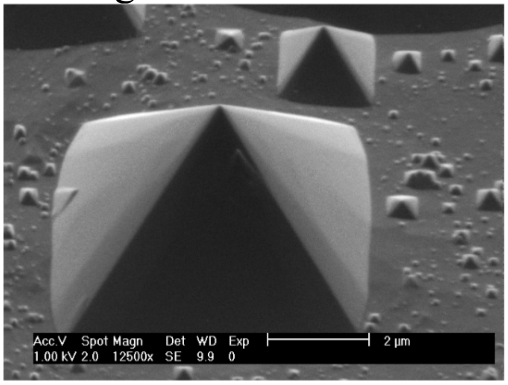




In the example above, the backside etched volume was fabricated using an anisotropic (crystal plane dependent) wet etch of Si, example: KOH or TMAH etching solutions.

This timed etch "results" in a rectangular, uniform thickness diaphragm, where the time of etch determines the diaphragm thickness.

Etching defects sometimes occur, called hillocks:

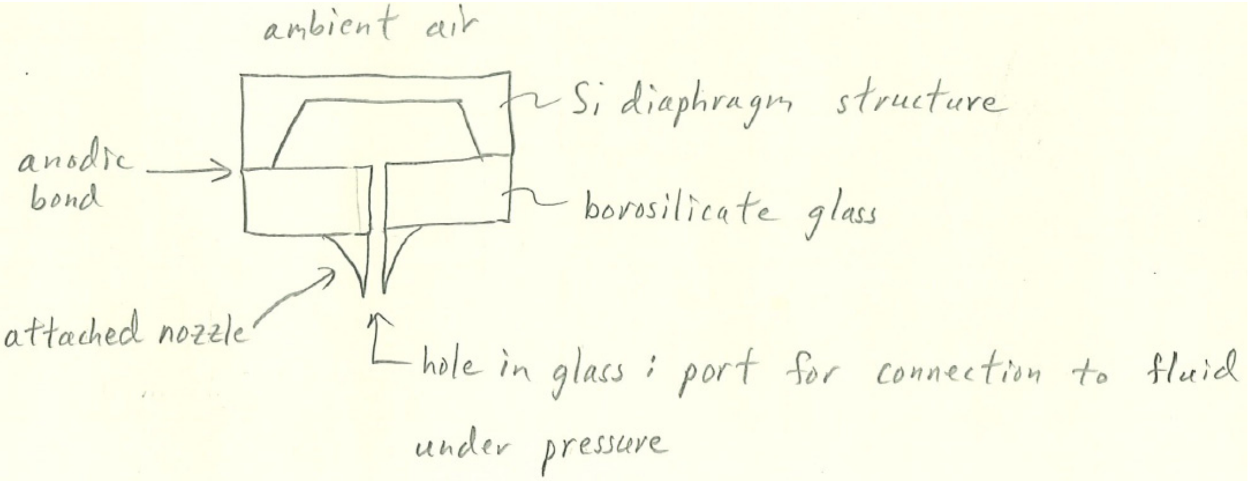


J. Thong et al., "Evolution of hillocks during silicon etching in TMAH," J.M.M. (11), 2001.

Kind of like fire ant mounds in your lawn…

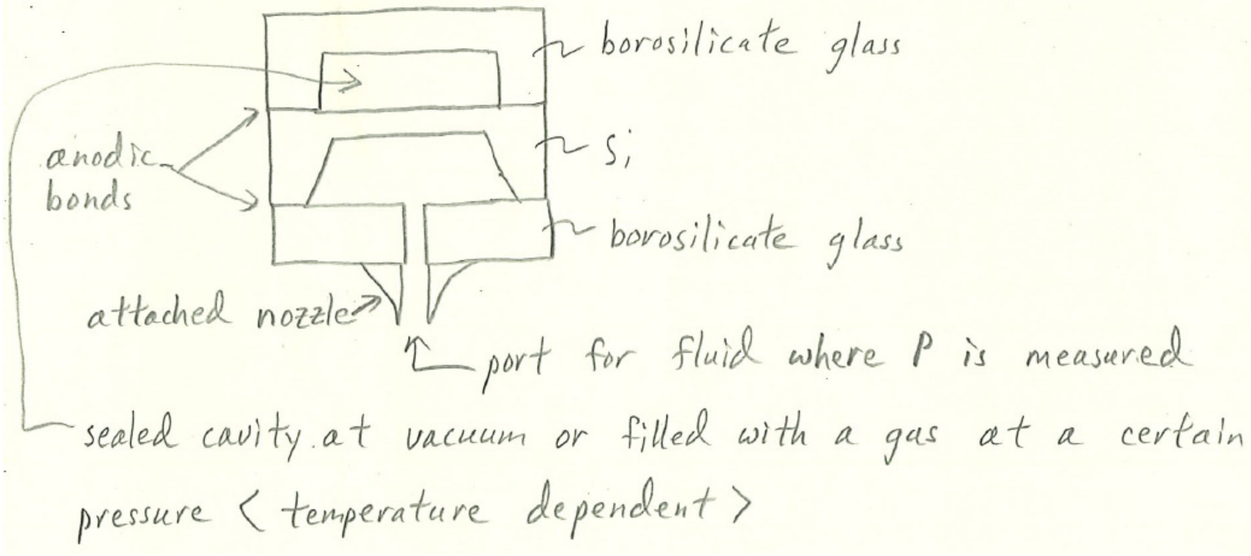
Typically, a micromachined diaphragm is designed to have a resonant frequency above the audio frequency range, to avoid microphone behavior if damping is low. 80 kHz or higher is typical for the resonant frequency.

a. Pressure sensor structure 1



This design would be for measuring pressure w.r.t. ambient air pressure.

b. Pressure sensor structure 2

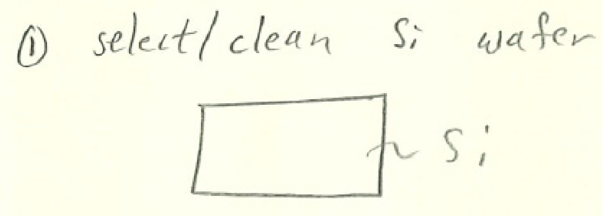


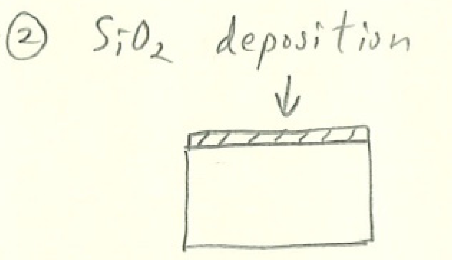
This structure could be an absolute P sensor (measure P w.r.t. a full vacuum).

5) Surface Micromachining of Pressure Sensors

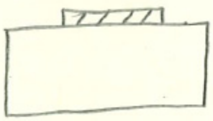
The diaphragm or membrane structure is fabricated on top of the Si substrate using additive or subtractive processes.

Example fabrication sequence:

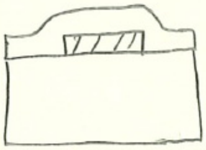




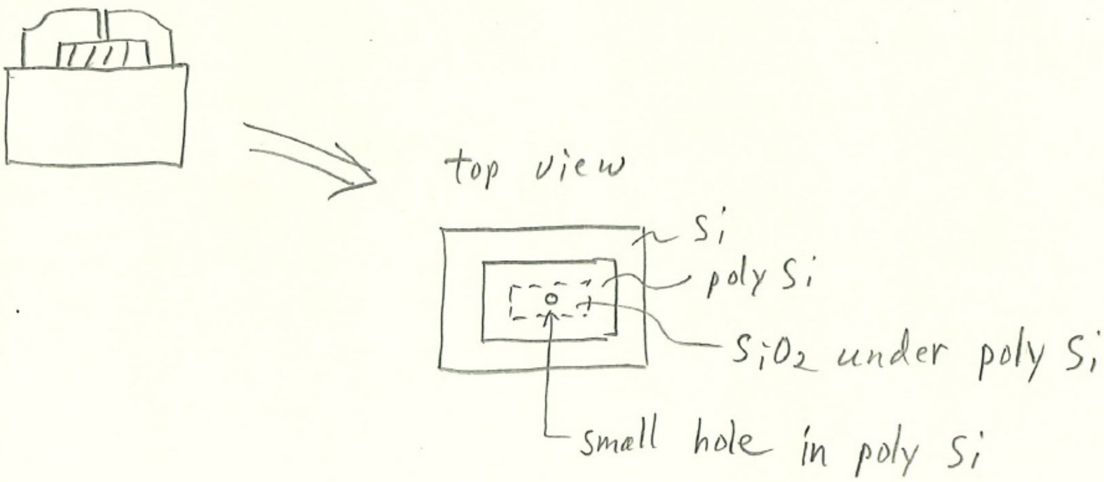
③ SiO_2 patterning ⟨to be used as a sacrificial layer⟩



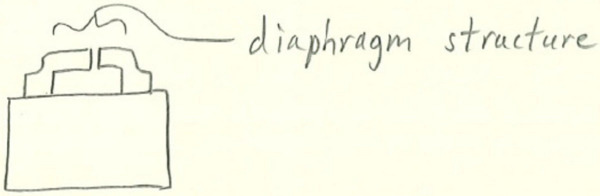
④ Poly Si deposited (using LPCVD) → conformal coating



⑤ Poly Si patterning with small hole in diaphragm center



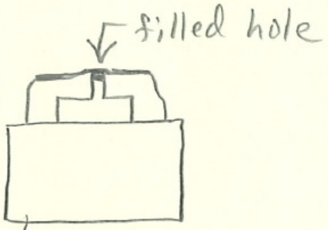
⑥ SiO_2 sacrificial layer is chemically removed (release etch), leaving the anchored poly Si diaphragm



⑦ Fill the hole in the poly Si : ex : using silicon nitride (SiN)

low P process that leaves the void at a near vacuum

↳ ∴ an absolute P sensor

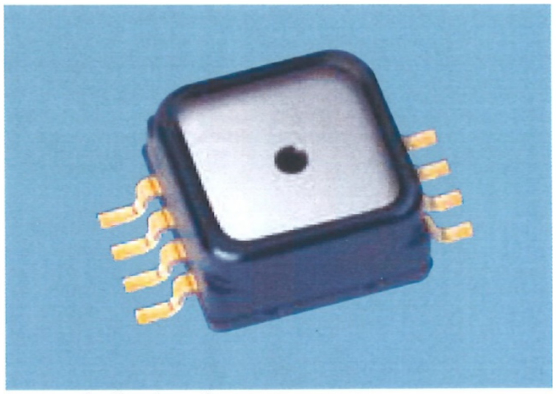


↳ various techniques can be used to measure diaphram or membrane deflection, y, where $y \propto P$

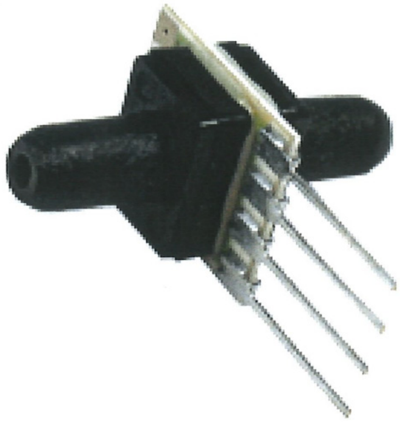
*Membranes can be made with this process (instead of a diaphragm) where other materials are used in place of polysilicon, such as silicon nitride.

Pressure Sensors (Continued)

1) Some examples of commercially available MEMS pressure sensors

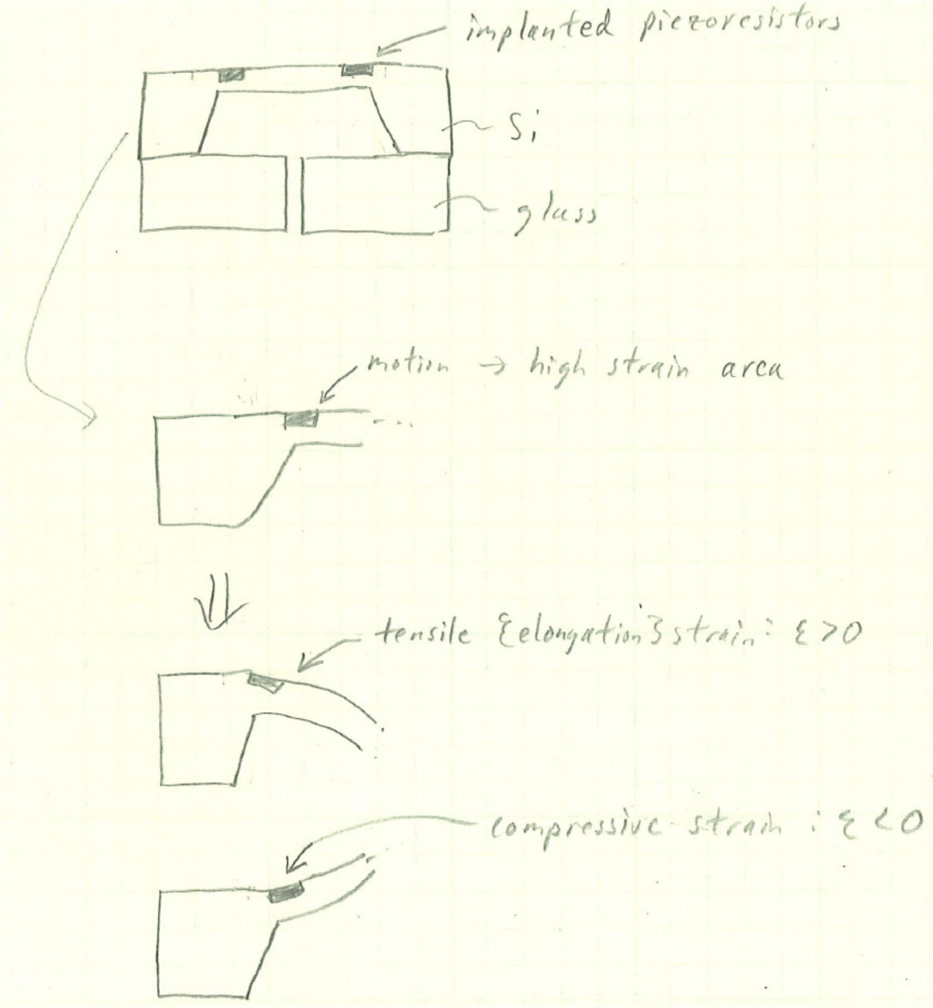


Freescale Semiconductor



AllSensors.com

2) Identical piezoresistors in bulk micromachined pressure sensors



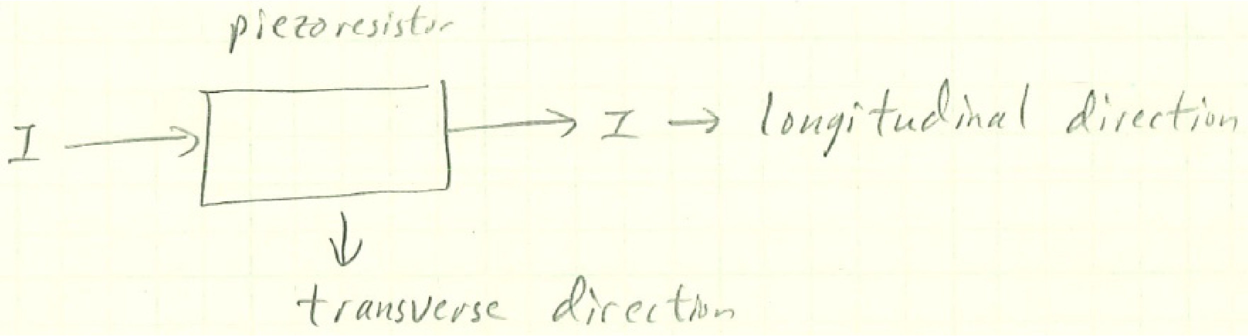
Since $GF = \frac{dR/R}{\varepsilon_1}$ and $\Delta R = R\varepsilon_1 GF$,

If GF = +200 (single crystal Si, p-doped)

For tensile strain: R_{new} increases because $\Delta R > 0 \rightarrow \varepsilon > 0$

For compressive strain: R_{new} decreases because $\Delta R < 0 \rightarrow \varepsilon < 0$

From a review of piezoresistors (PRs):



$$\frac{d\rho}{\rho} = \pi_l \sigma_l + \pi_t \sigma_t$$

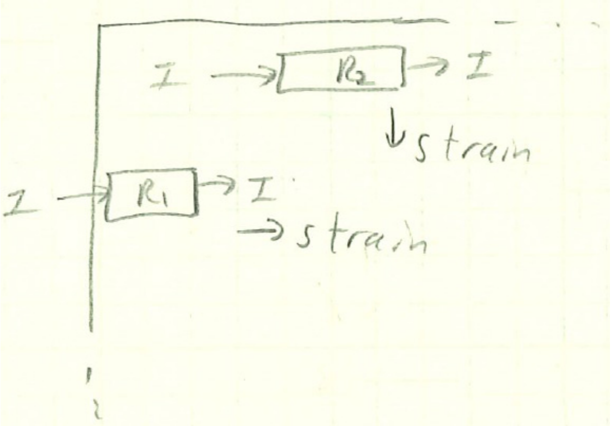
Where: $\pi_l = longitudinal\ piezoresistive\ coefficient$
$\pi_t = transverse\ piezoresistive\ coefficient$
$\sigma_l = longitudinal\ stress$
$\sigma_t = transverse\ stress$

For a p-type (100) Si wafer, reasonable values for π_l and π_t:

π_l: +69 m^2/N and π_t: -69 m^2/N are reasonable values.

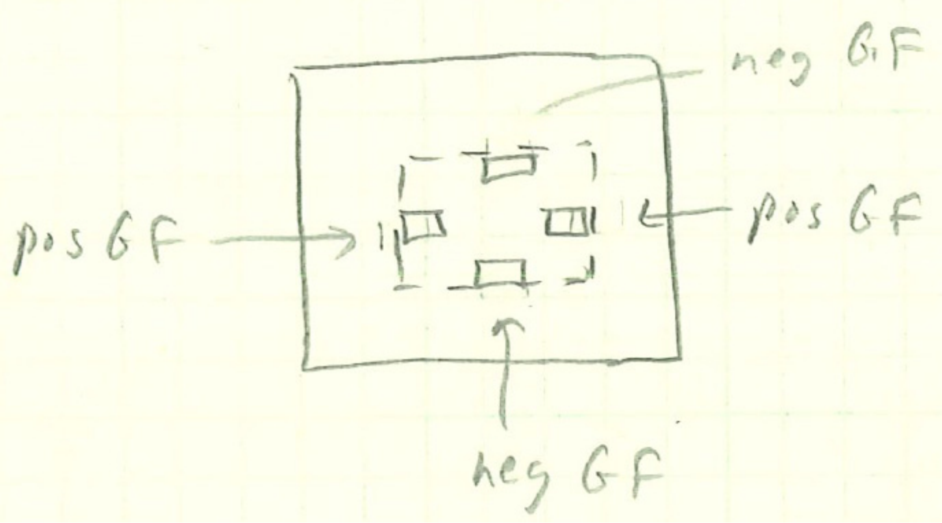
However, π_l and π_t are a function of crystal orientation, doping, and temperature. So obtaining exact values is challenging.

Observe that π_l and π_t have the same magnitude but opposite sign. This can be used to realize a Wheatstone bridge on the pressure sensor. Consider this PR configuration:



Here, there are two PRs of the same size and shape (sorry for the poor artwork!), and same doping: the bulk single crystal Si is doped to realize the PRs. However, the stress is different for the PRs: one PR will experience longitudinal stress, while the other PR experiences transverse stress.

So with this technique, it is possible to make 2 identically doped PRs where one has +GF and the other one has –GF, where they are closely matched in magnitude. Expanding this to 4 PRs in a bulk micromachined diaphragm:



All 4 PRs have the same doping, so that this configuration can realize a Wheatstone bridge.

3) Temperature dependence

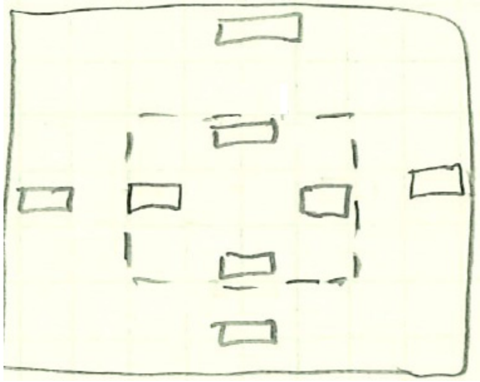
Piezoresistors → R = f(temperature)

The Wheatstone bridge reduces temperature sensitivity (all PRs should change the same way due to temperature changes), but temperature sensitivity is not completely eliminated, due to fabrication tolerances.

So, a couple of things can be done to improve temperature insensitivity:

a. Add a temperature sensor to the MEMS pressure sensor and calibrate the pressure sensor over P and T. This results in a table of correction values for each P and T combination that can be used to remove temperature induced biases (as well as nonlinearities in P measurement). However, this is a time consuming and therefore expensive process, and the resulting correction table must be stored in computer memory.

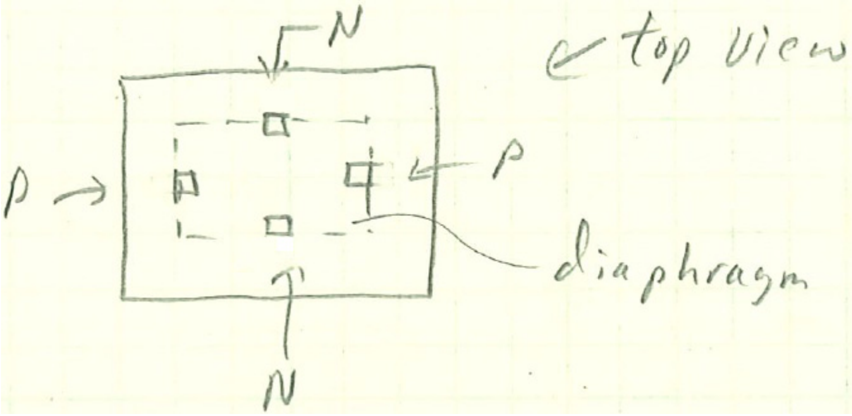
b. Add a dummy set of PRs to the pressure sensor chip that are not affected by the diaphragm strain:



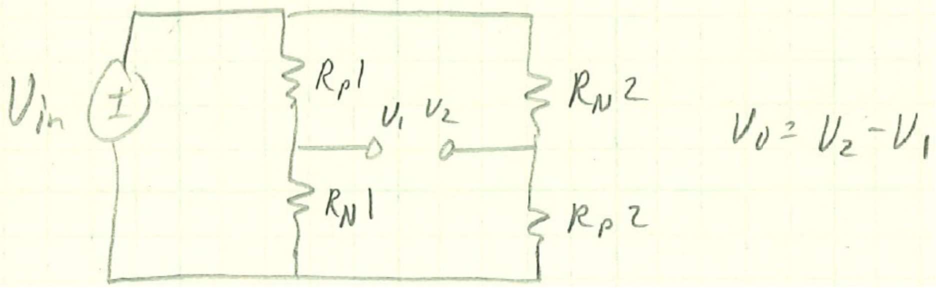
Use a 2^{nd} Wheatstone bridge with the dummy PRs and subtract its output voltage from the pressure sensor output voltage.

4) p- and n-type PRs in bulk micromachined pressure sensors

Consider this bulk micromachined pressure sensor configuration:



Two of the PRs are p-type (GF ~ +200), while the other two are n-type (GF ~ -125). They could be connected in a Wheatstone bridge configuration:



However, for a given strain, ε, that all PRs experience, the p-type PRs will increase more in resistance than the n-type PRs decrease → undesirable.

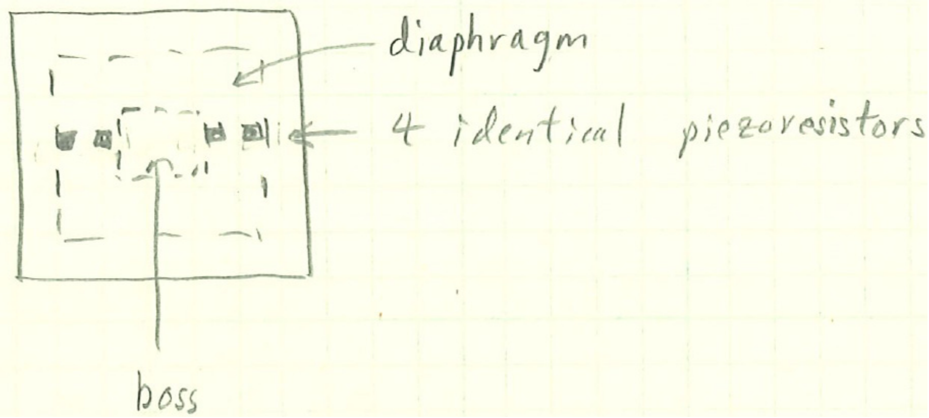
So, instead of doping regions of the Si diaphragm to realize PRs, consider depositing and patterning a thin layer of polysilicon on top of the diaphragm, and doping regions of it to realize polysilicon PRs:

Advantage: p-type GF ~ +30, n-type GF ~ -30: nearly matched

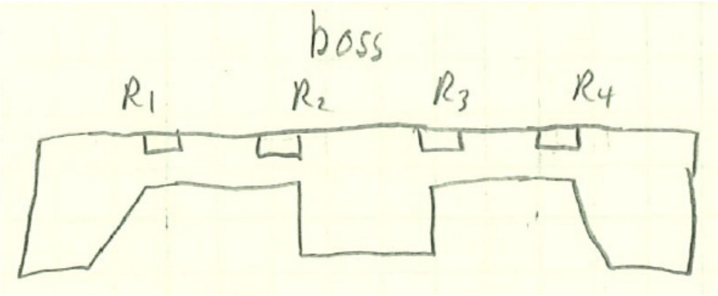
Disadvantage: more processing steps: lower yield, more expensive

5) Bossed diaphragm with PRs

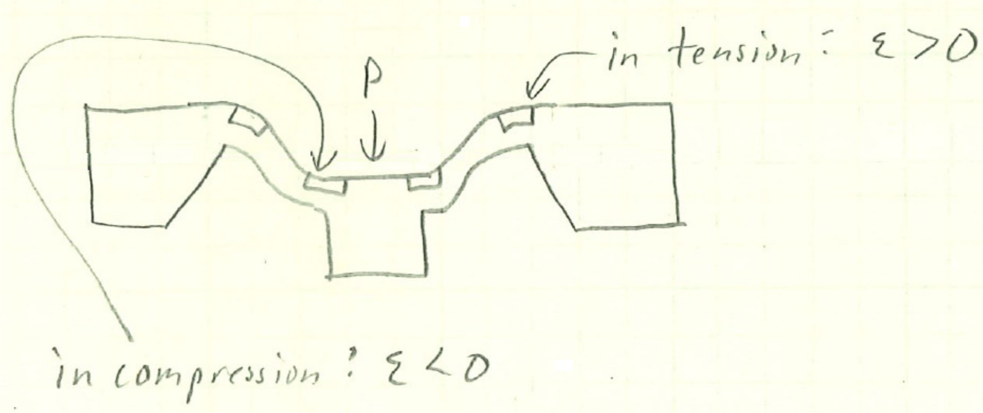
Top view:



Cross sectional view:



When pressure above > pressure below (exaggerated):



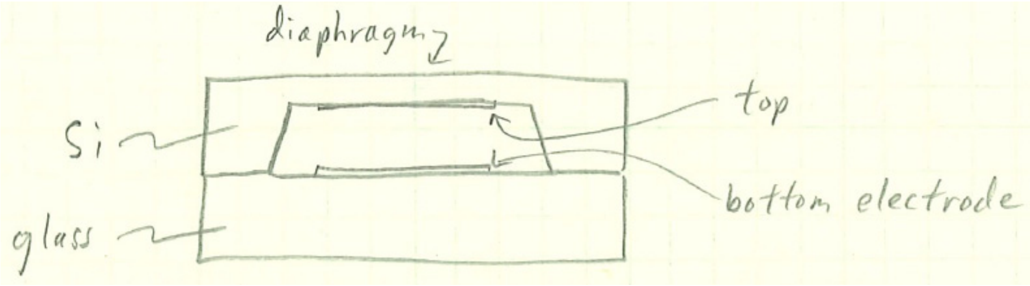
As a result:

$R_1 \rightarrow R\uparrow$
$R_2 \rightarrow R\downarrow$
$R_3 \rightarrow R\downarrow$
$R_4 \rightarrow R\uparrow$

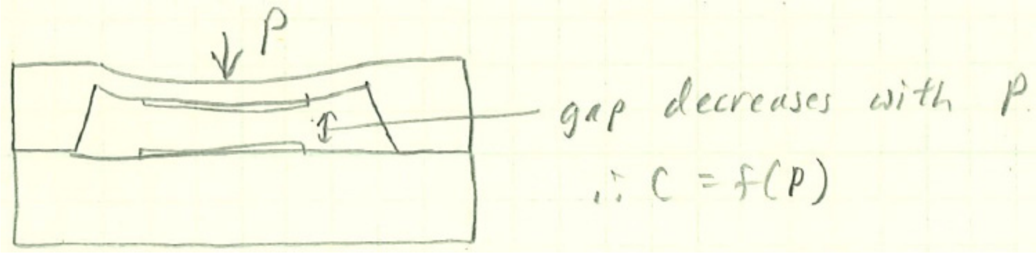
Then connect the four PRs on-chip with metal traces (another photolithography mask), and we have a Wheatstone bridge.

6) Capacitive pressure sensors

Often, a parallel plate capacitor is used where pressure changes the distance between the electrodes:



Then when the pressure outside > pressure inside:



Usually, capacitance is a nonlinear function of P: 1/x relationship.

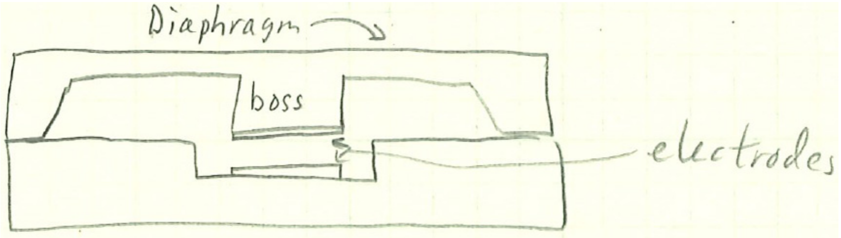
Fabrication is simpler (less expensive, higher yield) than with PRs; however, the interface electronics is more complicated than with PRs.

Capacitive detection is usually less sensitive to temperature than with PRs.

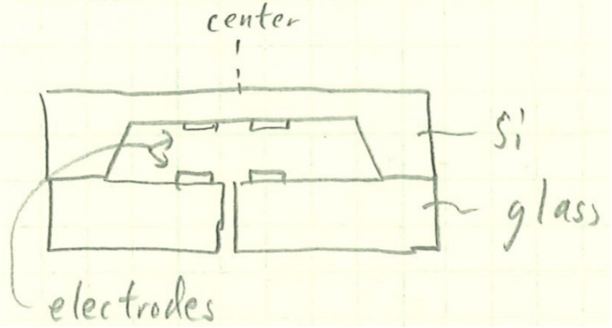
Also, the diaphragm deflects the greatest amount at the center, which has an additional nonlinearity.

a. Capacitive detection with the bossed diaphragm

The boss has a flat, nearly rigid bottom, which can be used as the movable electrode:



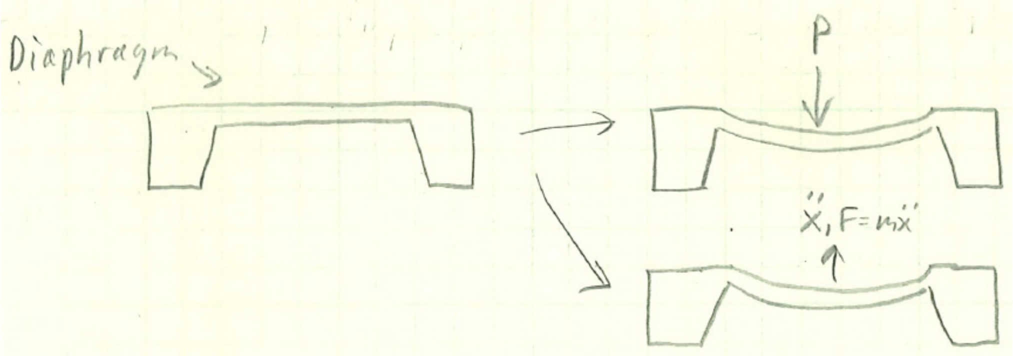
Use a donut shaped electrode around the center of the diaphragm



Advantages: smaller nonlinearity
Disadvantages: lower sensitivity and more complicated to fabricate

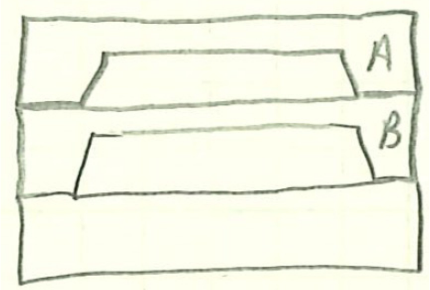
7) Acceleration effects

Consider a diaphragm structure:



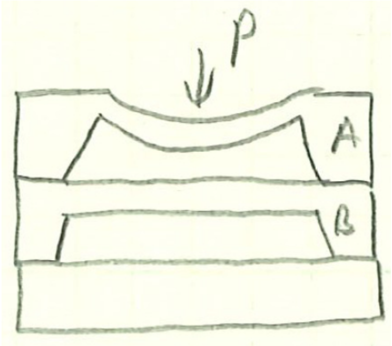
Is the diaphragm deflection due to pressure or to acceleration (or both)?

Consider this structure with two identical Si diaphragms bonded together:



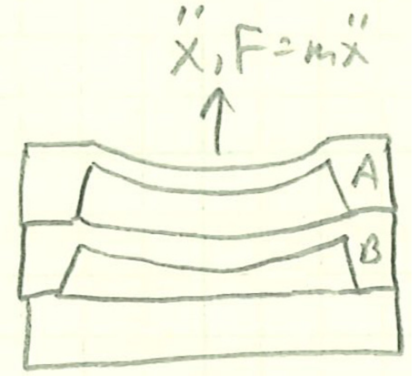
Diaphragms A and B with identical volumes in their sealed cavities.

Once external pressure is applied:



Observe that diaphragm A deflects but B does not (assuming high vacuum in both sealed chambers). Measure capacitance between A and B to determine pressure.

With acceleration:



A and B deflect together: capacitance is mostly not a function of acceleration.

Note: instead of capacitive detection, PRs could be used for detection here.