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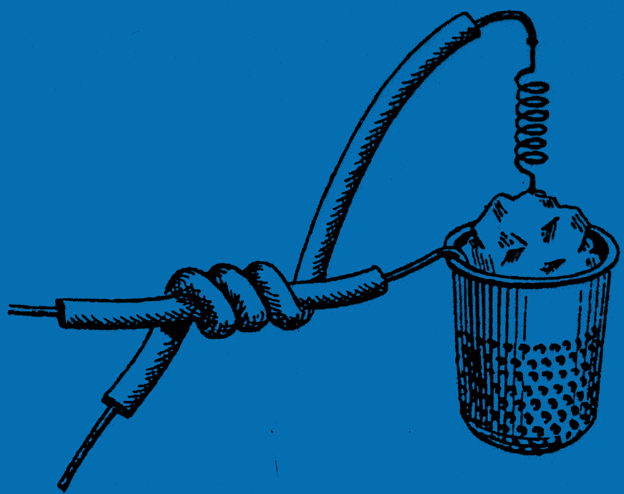
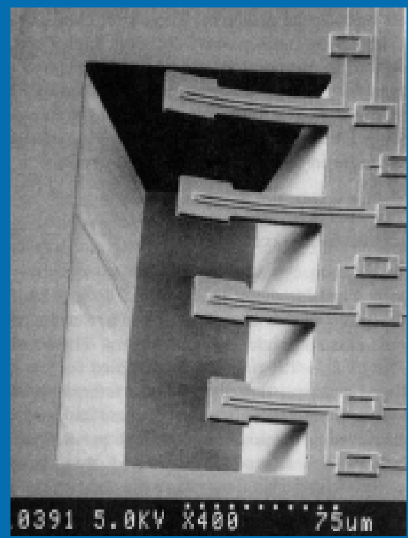
ELECTRONICS
Design Division

SENSOR DEVICES
MECHANICAL SENSORS





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OUTLINE

- 4 Mechanical Sensors
  - •Introduction
  - •General mechanical properties
  - •Piezoresistivity
  - •Piezoresistive sensors
  - •Capacitive sensors
  - •Applications

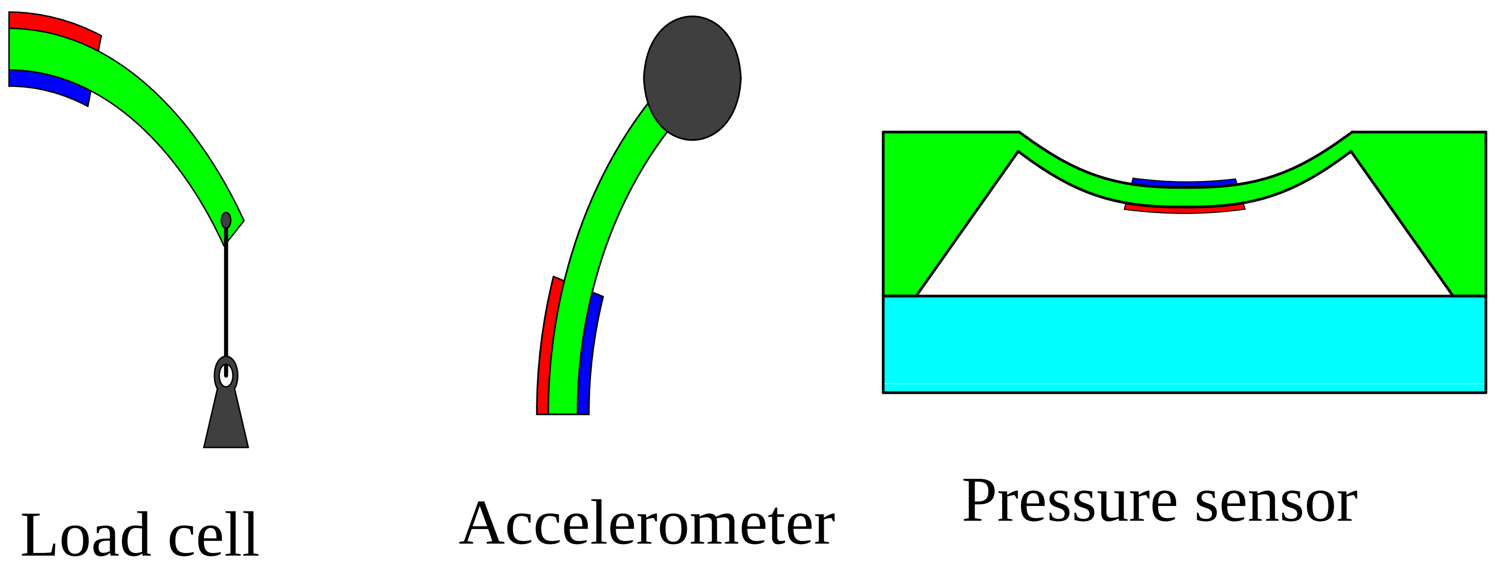
INTRODUCTION

- MECHANICAL SEMICONDUCTOR SENSORS
  - Combine electronic properties of semiconductorswith its excellent mechanical properties
- TWO MAJOR CLASSES OF MECHANICAL SENSORS
  - **Piezo**restistive sensors (material property in silicon)
  - Capacitive sensors (relative motion of electrodes)
- APPLICATIONS
  - Pressure sensors
  - Accelerometer
  - Flow sensors

”Piezo” = ”squeeze” or ”press”

INTRODUCTION

Piezoresistive sensing applications



General mechanical properties

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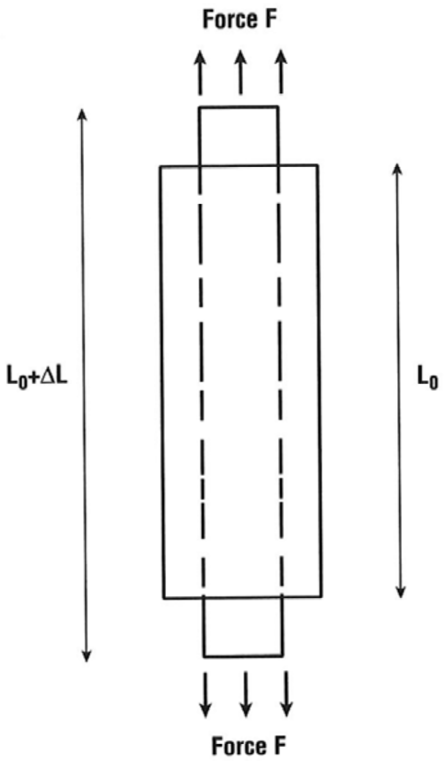

Figure 19.1 Rod elongation due to a tensile force *F*.

Hooke's law: $\sigma = E\varepsilon$

Stress: $\sigma = F/Area$, [N/m^2]

Strain: $\varepsilon = \Delta L/L$

➡ Young's module: E, [N/m^2=Pa],

Volumetric change:

$$\frac{\Delta V}{V} \approx \frac{\Delta L}{L} - \frac{2\Delta L_l}{L} = (1-2\nu)\frac{\Delta L}{L}$$

➡ Poisson's ratio: $\nu = \frac{\Delta L_l}{\Delta L} = -\frac{\varepsilon_l}{\varepsilon}$, l =lateral

Silicon: E_{Si} 190 GPa, $\nu_{Si} \approx 0.28$

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General mechanical properties

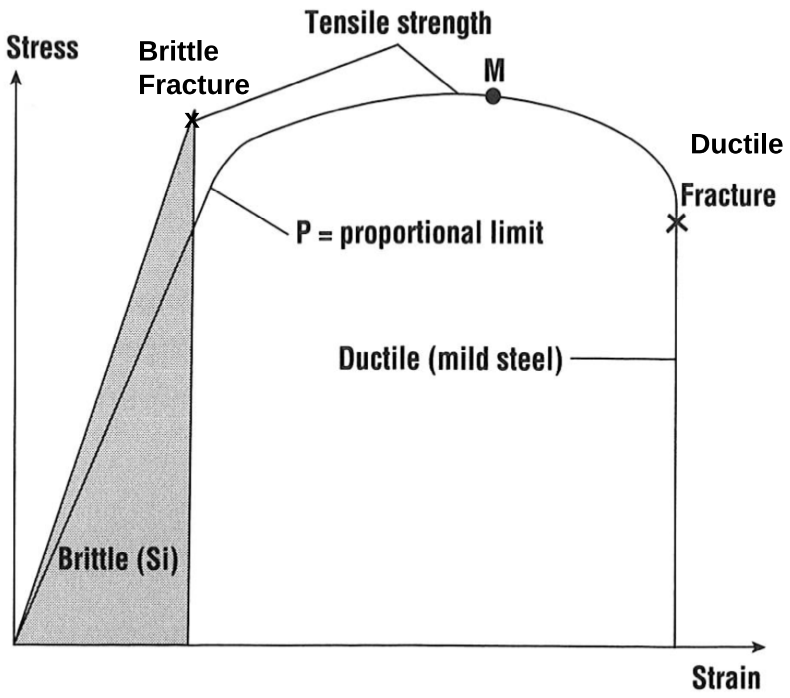

Figure 19.2 Stress–strain curve for a typical metal as well as for a brittle material like silicon (high Young's modulus and no plastic deformation region) *(reprinted with premission from Madou [7]. Copyright CRC Press)*.

- **Silicon**
  - Linear elasticity until fracture
  - No plastic deformation
  - Excellent for sensor applications
- **Metals**
  - Linear elastic behaviour for small strain only
- **Strength**
  - Yield strength = tensile stress where plastic deformation starts (non-reversible)
  - Tensile strength = maximum tensile stress before facture

General mechanical properties

Table 19.1 Properties of materials

	Yield Strength (10^9 Pa)	Young's Modulus (10^9 Pa)	Density (g/cm^3)	Thermal Conductivity (W/cm °C)	Thermal Expansion (10^{-6}/°C)
Diamond (single crystal)	53.0	1035.0	3.5	20.0	1.0
SiC (single crystal)	21.0	700.0	3.2	3.5	3.3
Si (single crystal)	7.0	190.0	2.3	1.6	2.3
Al_2O_3	15.4	530.0	4.0	0.5	5.4
Si_3N_4 (single crystal)	14.0	385.0	3.1	0.2	0.8
Gold	—	80.0	19.4	3.2	14.3
Nickel	—	210.0	9.0	0.9	12.8
Steel	4.2	210.0	7.9	1.0	12.0
Aluminum	0.2	70.0	2.7	2.4	25.0

General mechanical properties

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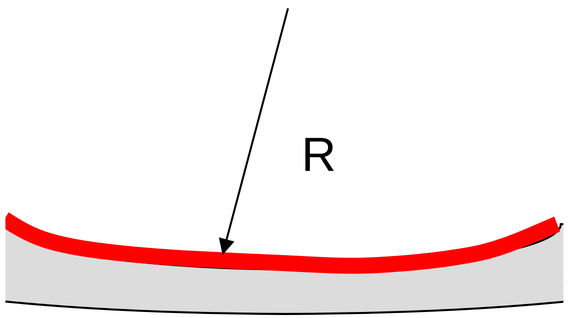
Stress in thin film

unstressed



stressed

Stress in thin film cause a curvature of the sample, which can be measured using a laser system

$$\frac{1}{R} = 6(1-\nu)\frac{\Delta s}{ET^2}$$

$$\Delta s = \sigma t$$

$$= \text{surface stress [N/m]}$$

R= radius
E= Young's module in substrate
T= substrate thickness
t = thin film thickness
v = Poisson's ratio in substrate

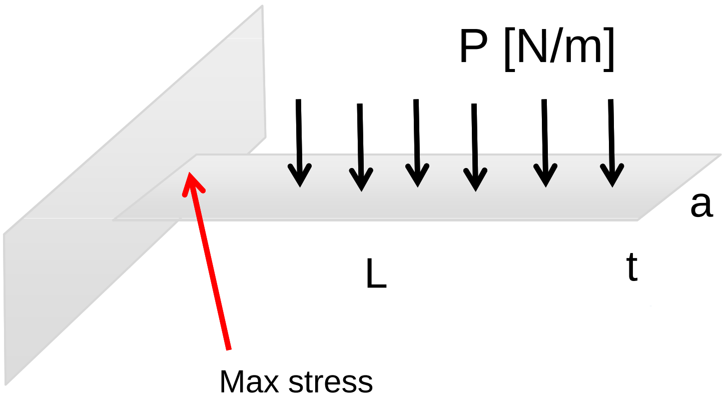
General mechanical properties

- Cantilever beams
  - Max deflection
  - Max longitudinal stress
  - Resonant frequency

- Square membranes
  - Max deflection
  - Max longitudinal and transverse stress
  - Resonant frequency

General mechanical properties

Cantilever beam with uniform distributed load (P=F/Δx)



Beam equation: $EI \frac{d^4 w(x)}{dx^4} = P$

Beam stifness: $EI = Eat^3/12$

$I = at^3/12$ (2nd moment of inertia)

Deflection: $w(x) = \frac{P}{24EI} x^2 \left(6L^2 - 4Lx + x^2\right)$

$w(L) = \frac{PL^4}{8EI}$

Surface stress: $\sigma(x) = -\frac{tE}{2} \frac{d^2 w(x)}{dx^2}$

Max stress: $\sigma(0) = \frac{PL^2 t}{4I} = \frac{3PL^2}{at^2}$

SENSOR:

$P = at\rho \cdot \text{acceleration}$

$\Delta P = at\rho_{measurand} \cdot g$

General mechanical properties

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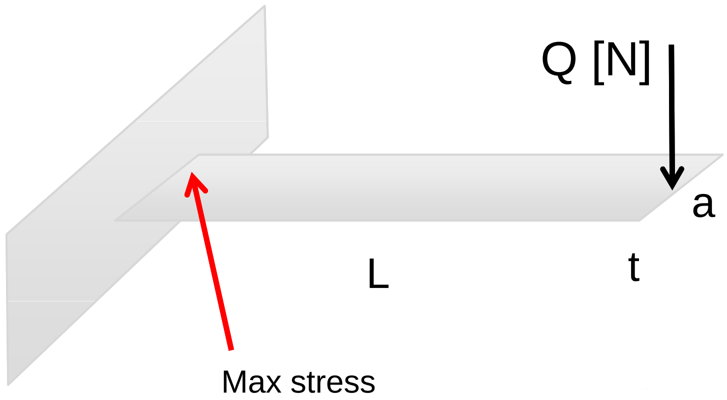
Cantilever beam point load at the end



Defelction: $w(x) = \frac{Qx^2}{6EI}(3L - x)$

$$w(L) = \frac{QL^3}{2EI}$$

Max stress: $\sigma(0) = \frac{QLt}{2I} = \frac{6QL}{at^2}$

Resonant frequency:

$$F_0 = 0.161\frac{t}{L^2}\sqrt{\frac{E}{\rho}} = 0.161\frac{t}{L}\sqrt{\frac{Eta}{ML}}$$

Quasi-static sensing

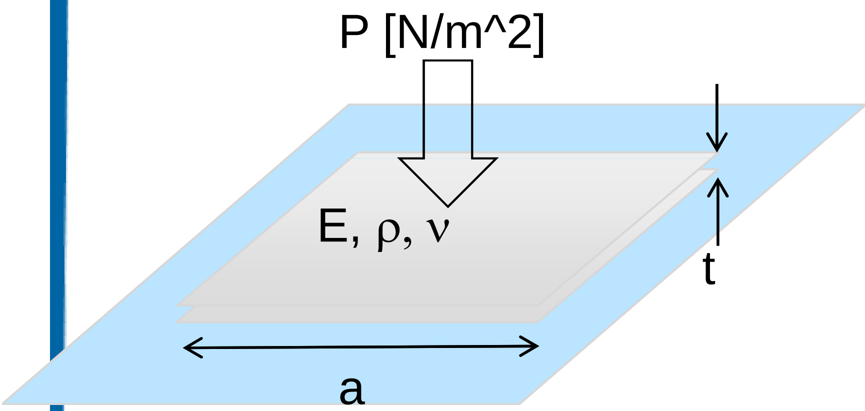
$$\mathrm{f}_{measure} < F_0$$

SENSOR:

$Q = \text{mass} \cdot \text{acceleration}$

General mechanical properties

SQUARE MEMBRANES (UNIFORM LOAD)



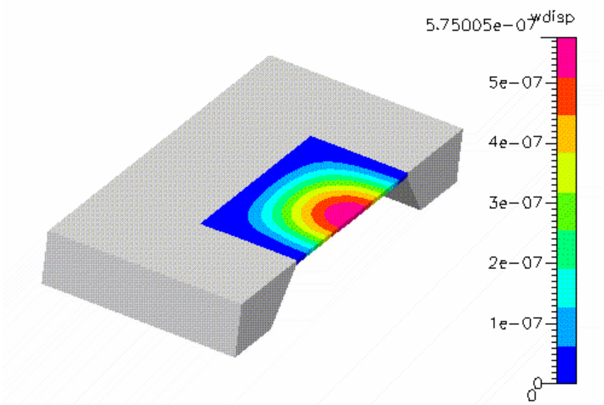


Plate equation: $D\nabla^4 w(x,y) = P$

Membrane stiffness: $D = \dfrac{Et^3}{12\left(1-\nu^2\right)}$

Max deflection: $w_{\max} = 0.001265\dfrac{Pa^4}{D}$

Max longitud. stress: $\sigma_l = 0.3081\dfrac{Pa^2}{t^2}$

Max transverse stress: $\sigma_t \approx \nu\sigma_l$

Resonant frequency: $F_0 = 1.654\sqrt{\dfrac{12D}{\rho t a^4}}$

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Piezoresistivity

$$R = \rho \frac{L}{a^2}$$

Resistivity change in semiconductor:

- Resistivity change due to mechanical stress
  - **piezoresistive effect**
- Large resistivity change
- Dependence on
  - Doping (n- or p-type, doping concentration)
  - Temperature
  - Direction of force and direction of current flow (anisotropic effect)

$$\rho = \rho(\sigma)$$

$$R(\sigma) = R + \rho' \sigma \frac{L}{a^2}$$

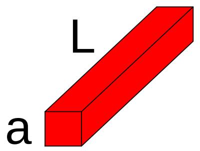
$$\Delta R / R = (\rho' / \rho)\, \sigma$$

$$\equiv \pi \sigma$$

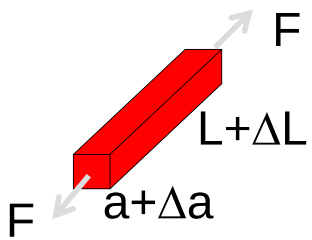
$$= \pi E \varepsilon$$

$$\Delta R / R \approx 100 \varepsilon$$

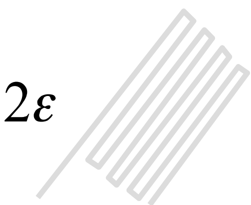
Resistivity change in **metal strain gauge** – mainly due to geometric effect



$$R = \rho \frac{L}{a^2}$$

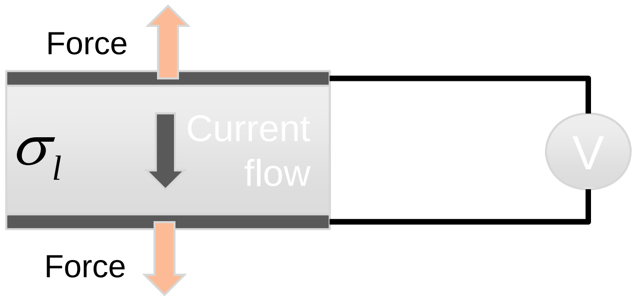


$$\frac{\Delta R}{R} = (1 + 2\nu) \frac{\Delta L}{L} \sim 2\varepsilon$$

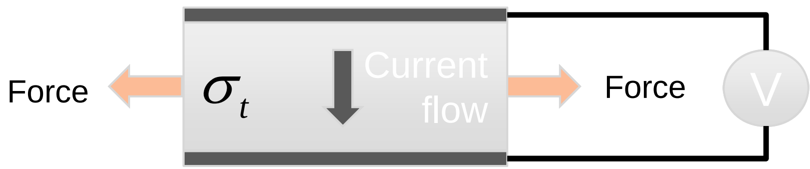


Piezoresistivity

Longitudinal and transverse piezoresistance coefficients



- Longitudinal stress: $\Delta R/R = \pi_l \sigma_l$
  π_l = longitudinal piezoresistance coefficient



- Transverse stress: $\Delta R/R = \pi_t \sigma_t$
  π_t = transverse piezoresistance coefficient

Stress: σ=Force/Area

$$E_i = \sum_j \rho_{ij} j_j$$

$$\rho_{ij} = \sum_k \sum_l \pi_{ijkl} \sigma_{kl}$$

- In general we have both longitudinal and transverse stresses:

$$\Delta R/R = \pi_t \sigma_t + \pi_l \sigma_l$$

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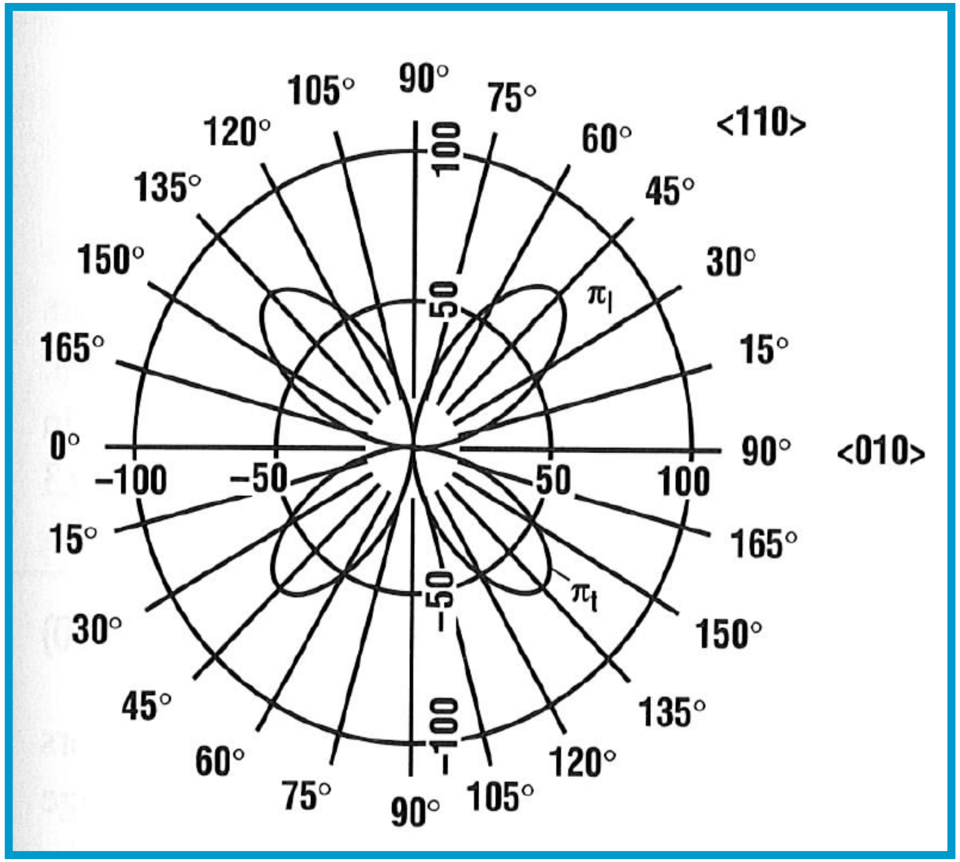
PIEZORESISTIVITY

Piezoresistance coefficients in p-type silicon [10^{-11} /Pa]



- 100 plane
- Upper half
  - Longitudinal coefficient π_l
- Lower half
  - Transverse coefficient π_t

In sensor application the π should be as large as possible, i.e. resistors along <110> direction

$$\pi_l = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$

$$\pi_t = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44})$$

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PIEZORESISTIVITY

Resistors along <110> direction in (100) wafers (common for bulk micromachining)

$$\pi_l = \tfrac{1}{2}\left(\pi_{11} + \pi_{12} + \pi_{44}\right)$$

$$\pi_t = \tfrac{1}{2}\left(\pi_{11} + \pi_{12} - \pi_{44}\right)$$

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t$$

$$\approx \frac{\pi_{44}}{2}\left(\sigma_l - \sigma_t\right)$$

Table 18.1. Typical room-temperature piezoresistance coefficients for n- and p-type silicon [98].

Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ω-cm	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1

$$\frac{\Delta R}{R} \approx \frac{\pi_{44}}{2}\sigma \approx \frac{\pi_{44}}{2}E\varepsilon \approx 100\varepsilon$$

Piezoresistive Sensors

Piezoresitive pressure sensor

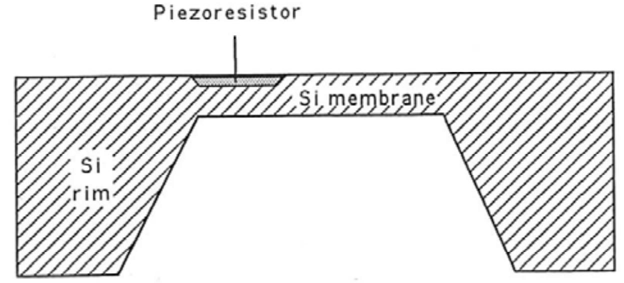
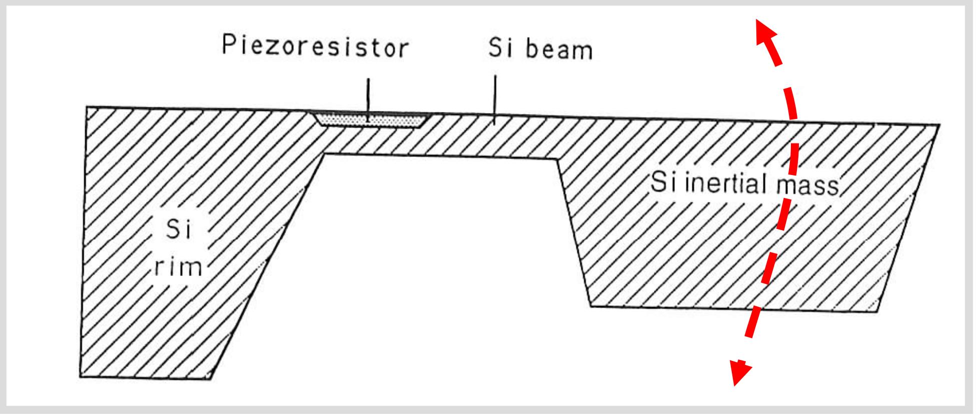


Fig. 13 Schematic cross-section of a piezoresistive pressure sensor.

- Membrane fabrication
  - Anisotropic etch
- Piezoresistor fabrication
  - doped area
  - or deposited polysilicon resistor on an insulator (SiO_2 or Si_3N_4)
- Piezoresistor position
  - at the edges of the membrane where the stress is maximal

Piezoresistive Sensors

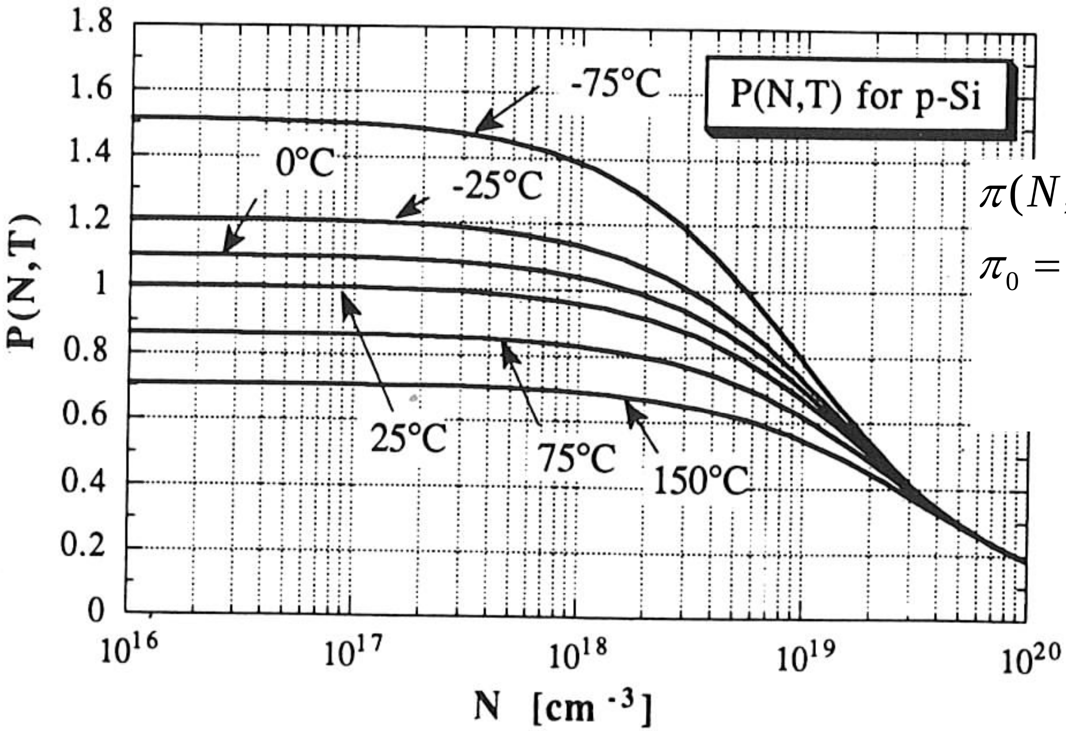
Piezoresistive accelerometer



- The piezoresistor must be places where the stress is maximal
- To increase the sensitivity an inertial mass is included

Piezoresistivity

$$R = \rho \frac{L}{w \cdot t}$$



$$\pi(N,T) = \pi_0 P(N,T)$$

π_0 = low-doped room-temerature value

Fig. 10 Piezoresistance factor $P(N, T)$ as a function of impurity concentration and temperature for *p*-type silicon. (After Ref. 49)

Piezoresistiv Sensor

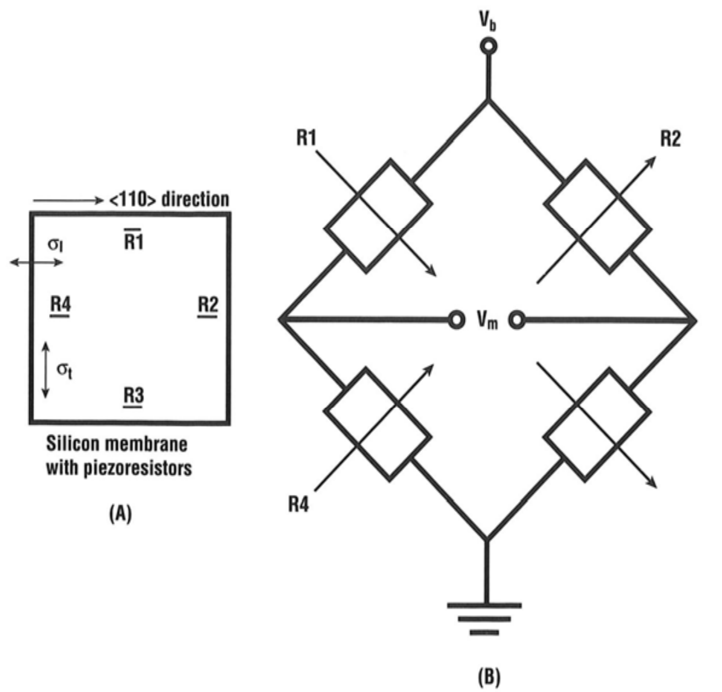


Figure 19.7 (A) Schematic drawing of the position and orientation of four piezoresistance elements on a silicon membrane with sides defined by anisotropic silicon etching of a (100) silicon wafer; (B) Wheatstone bridge configuration of the four piezoresistive elements, with arrow directions indicating resistance increases or decreases for membrane deflection downward *(after Sze [15], © 1994, reprinted with permission of John Wiley & Sons, Inc.).*

Wheatstone Bridge Configuration

- R1 and R3 under lateral stress and decrease $\frac{\Delta R}{R} \approx -\frac{\pi_{44}}{2}\sigma$
- R2 and R4 under longitudinal stress and increase $\frac{\Delta R}{R} \approx \frac{\pi_{44}}{2}\sigma$

$$R_1 = R_3 = R - \Delta R$$

$$R_2 = R_4 = R + \Delta R$$

$$\frac{\Delta R}{R} = \frac{\pi_{44}}{2}(\sigma_l - \sigma_t)$$

$$V_m = V_b\left(\frac{\Delta R}{R}\right) = V_b\frac{\pi_{44}}{2}(\sigma_l - \sigma_t)$$

Piezoresistive Sensors

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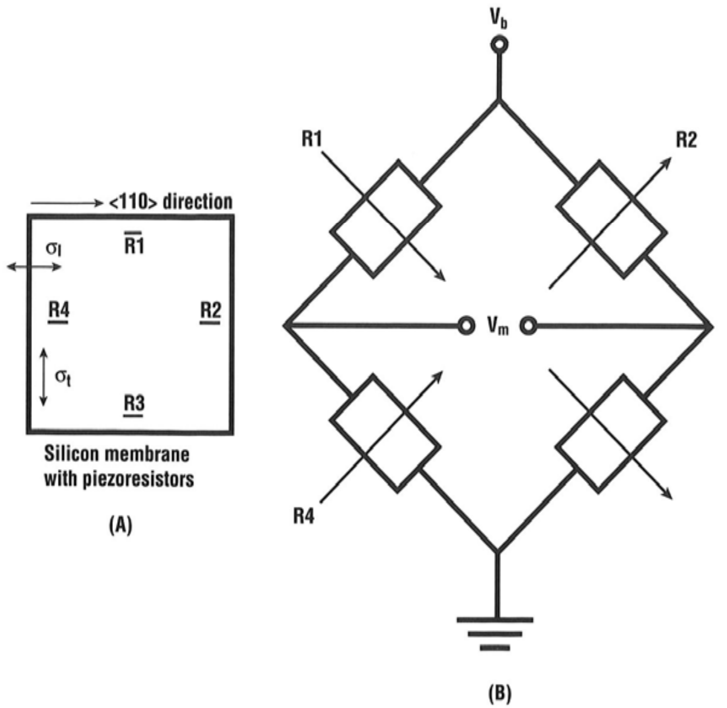

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Pressure sensitivity for constant V_b:

$$S_v = \frac{\Delta V / V_b}{\Delta P} \quad \text{[mV/V-bar]}$$

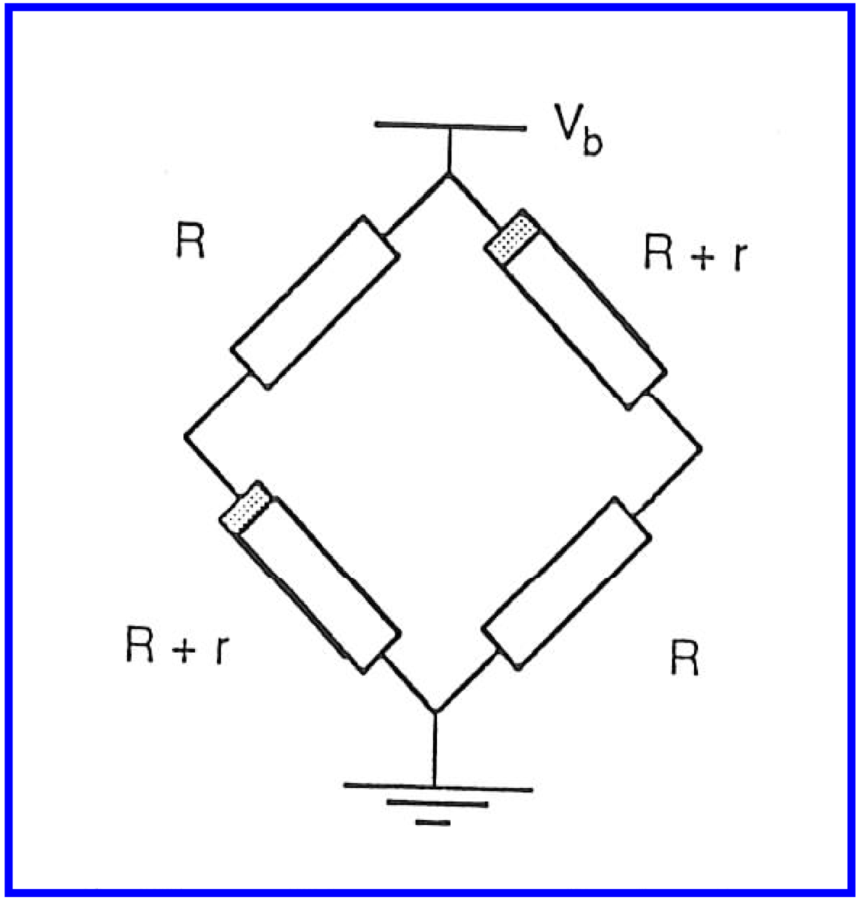
$$= \frac{\Delta R / R}{\Delta P} = \frac{1}{2\Delta P}\pi_{44}\left(\sigma_l - \sigma_t\right)$$

Pressure sensitivity for constant I_b:

$$S_i = \frac{\Delta V / I_b}{\Delta P} \quad \text{[mV/mA-bar]}$$

$$= \frac{\Delta R}{\Delta P} = \frac{1}{2\Delta P} R\pi_{44}\left(\sigma_l - \sigma_t\right)$$

Piezoresistive Sensors
Offset voltage



Symmetrical mismatch of the resistors, caused by difference in layout (parallel and perpendicular to the edges of the membrane)

$$R_1 = R_3 = R$$

$$R_2 = R_4 = R + r$$

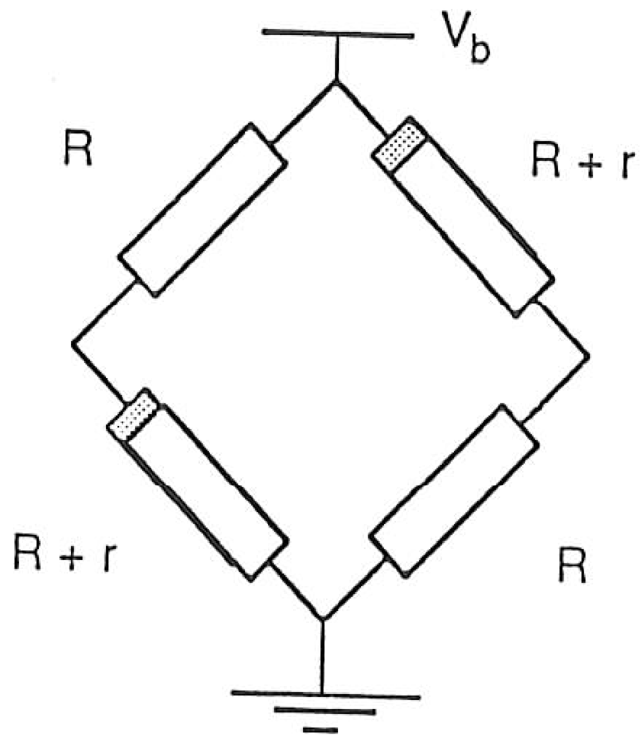
$$V_o = V_b \left(\frac{r}{2R + r} \right)$$

$$O = \frac{V_o}{V_b} = \frac{r}{2R + r} = \frac{1}{1 + 2R/r}$$

Offset also caused by residual stress on resistors

- pre-stress due to passivation layers and packaging

Piezoresistive Sensors
Temperature coefficient of offset



$$\frac{\partial O}{\partial T} = \frac{2Rr}{(2R\pi + r)^2}\left(\frac{\dot{r}}{r} - \frac{\dot{R}}{R}\right)$$

If resistors have equal temperature coefficients

$$\frac{\dot{r}}{r} = \frac{\dot{R}}{R}, \quad \frac{\partial O}{\partial T} = 0$$

However, temperature dependence of pre-stress might be significant.

Piezoresistive Sensors
Temperature coefficient of sensitivity

Constant bridge voltage

$$S \propto \pi_{44}(\sigma_l - \sigma_t)$$

$$\mathrm{TCS}_v = \frac{1}{S}\frac{\partial S}{\partial T} = \frac{1}{\pi_{44}}\frac{\partial \pi_{44}}{\partial T} + \frac{1}{\sigma_l - \sigma_t}\frac{\partial(\sigma_l - \sigma_t)}{\partial T}.$$

Temperature coefficient for π_{44} can be high for p–type silicon

Constant bridge current

$$S \propto \pi_{44} R(\sigma_l - \sigma_t)$$

$$\mathrm{TCS}_i = \frac{1}{S}\frac{\partial S}{\partial T} = \frac{1}{\pi_{44}}\frac{\partial \pi_{44}}{\partial T} + \frac{1}{R}\frac{\partial R}{\partial T} + \frac{1}{\sigma_l - \sigma_t}\frac{\partial(\sigma_l - \sigma_t)}{\partial T}.$$

\- +

Piezoresistance Sensors

Place your resistors this way:

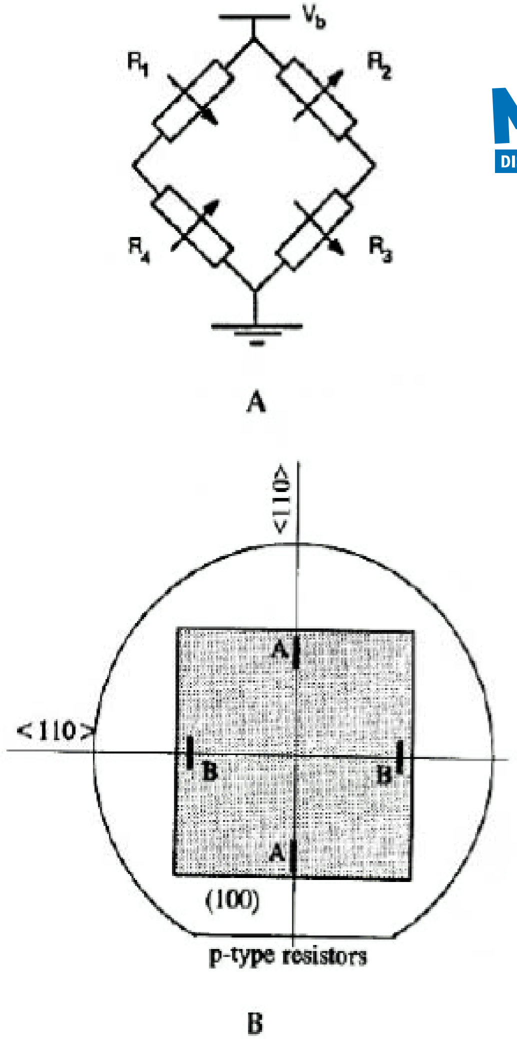


FIGURE 4.18 Measuring on a membrane with piezoresistors. (A) Wheatstone-bridge configuration of four in-diffused piezoresistors. The arrows indicate resistance changes when the membrane is bent downward. (B) Maximizing the piezoresistive effect with p-type resistors. The A resistors are stressed longitudinally and the B resistors are stressed transversally. (From Peeters, E., Ph.D. Thesis, KUL, Belgium, 1994. With permission.)

σ_l =10 MPa, σ_t=50 MPa:
$\Delta R/R$ = 3%

Up to about 10 mV/kPa sensitivity of a final pressure sensor

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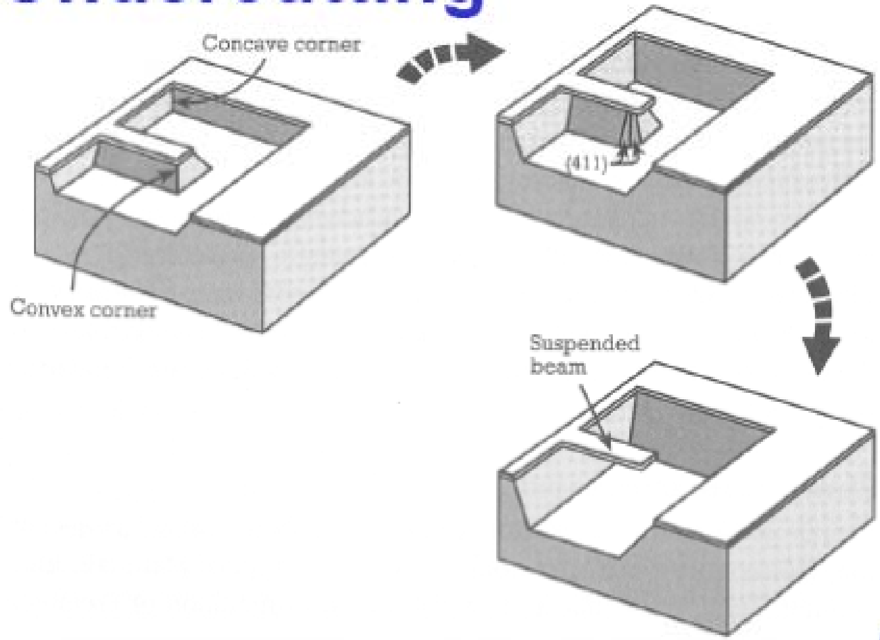
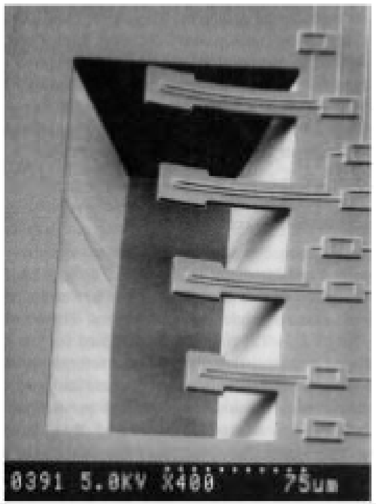
Piezoresistive Sensors

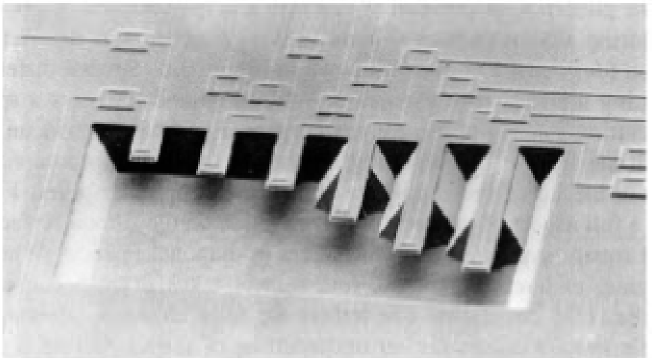
Undercutting

- Convex corners bounded by {111} planes are attacked



Maluf





Ristic

Capacitive Sensors

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Capacitor two electrodes separated by a dielectric

$$C_0 = \varepsilon \frac{S}{d}.$$

Electronic should be close to the sensor, minimising the stray capacitance

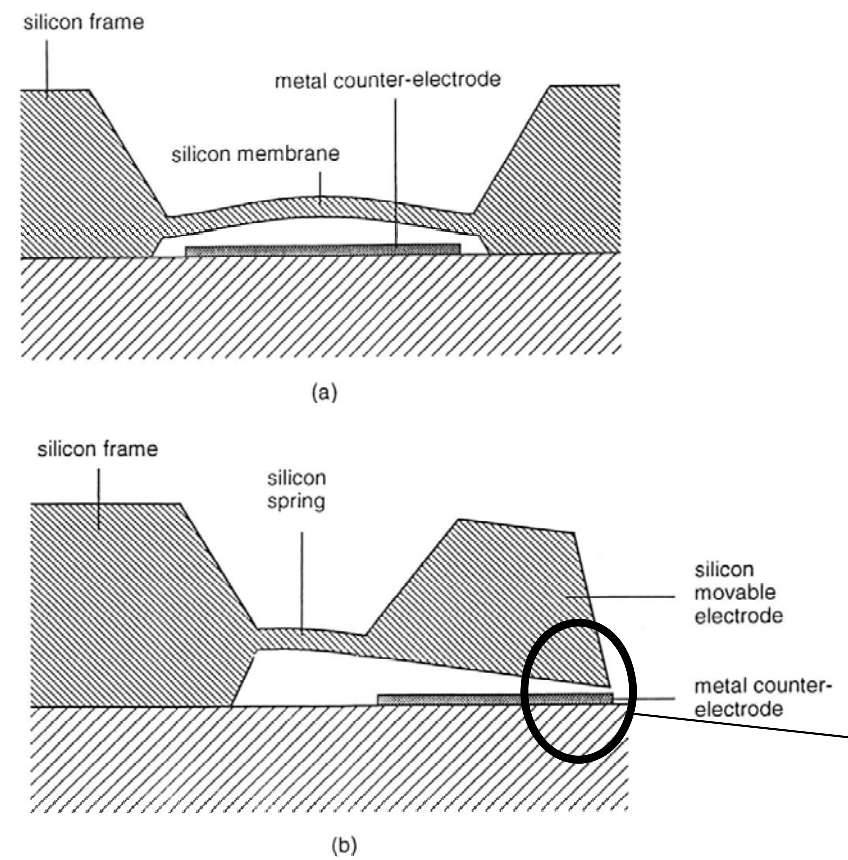
$$\frac{\Delta C}{\Delta d} = -\varepsilon \frac{S}{d^2}.$$

Δd<< d result in

High sensitivity means Large area *S* and a small distance *d*

Advantage with capacitive sensors no direct sensitivity to temperature

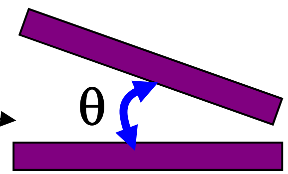
Capacitive Sensors



a) Pressure sensor
b) Accelerometer

$$C(\theta) = \frac{\varepsilon S}{l\theta} \ln\left(\frac{2d + l\theta}{2d + l\theta}\right)$$

?



Comparison of different technologies

TABLE 3 Comparison of Some Characteristics of Three Common Sensing Technologies for Accelerometers (Adapted from Ref. 67)

	Capacitive	Piezoelectric	Piezoresistive
Impedance	High	High	Low
Size	Medium	Small	Medium
Temperature range	Very wide	Wide	Medium
Linearity error (sensor only)	High	Medium	Low
DC response	Yes	No	Yes
AC response	Wide	Wide	Medium
Damping available	Yes	No	Yes
Sensitivity	High	Medium	Medium
Zero shifts due to shock	No	Yes	No
Electronics required	Yes	Yes	No
Cost	Medium	High	Low

Applications

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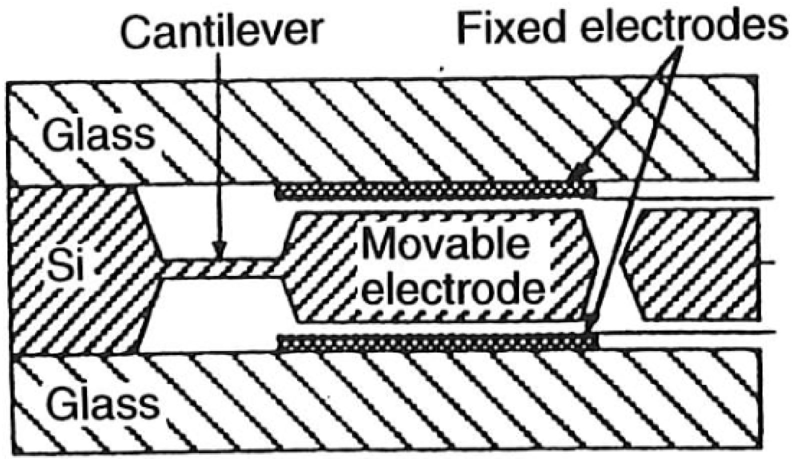

Symmetric capacitive accelerometer with low thermal sensitivity

In some cases the movabel electrode must be damped to avoid serious oscillations. A small cavity with a viscous liquid or gas can fulfil the requirements

Flow sensors (gas)

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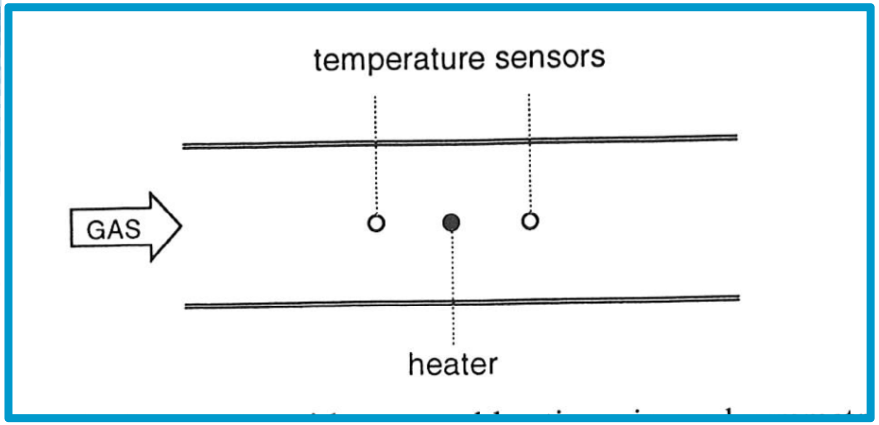

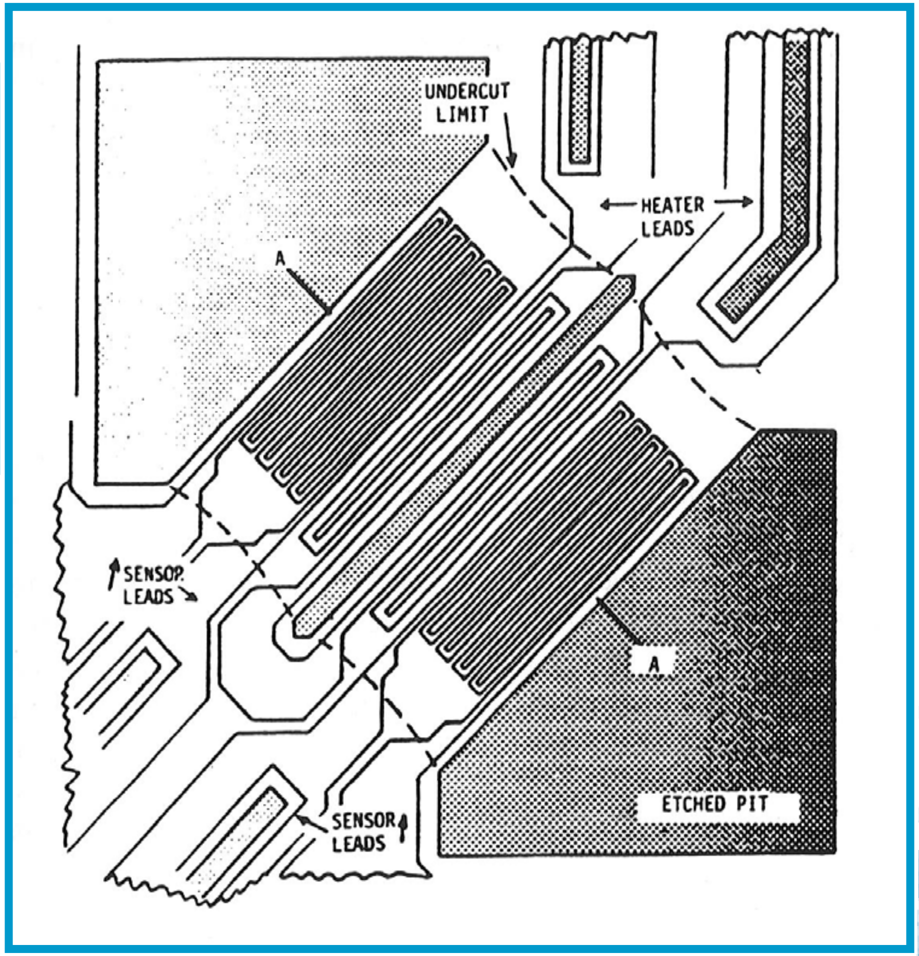

With no flow the two sensors display the same temperature

With gas flow the first sensor is cooled , while the second is heated up by the gas

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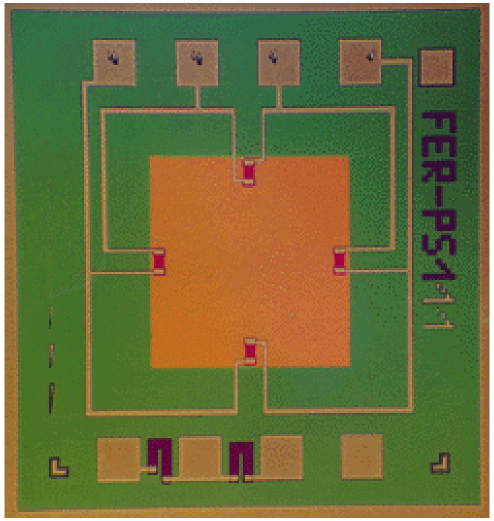
Some examples, Bulk micro-machined piezoresistive sensor



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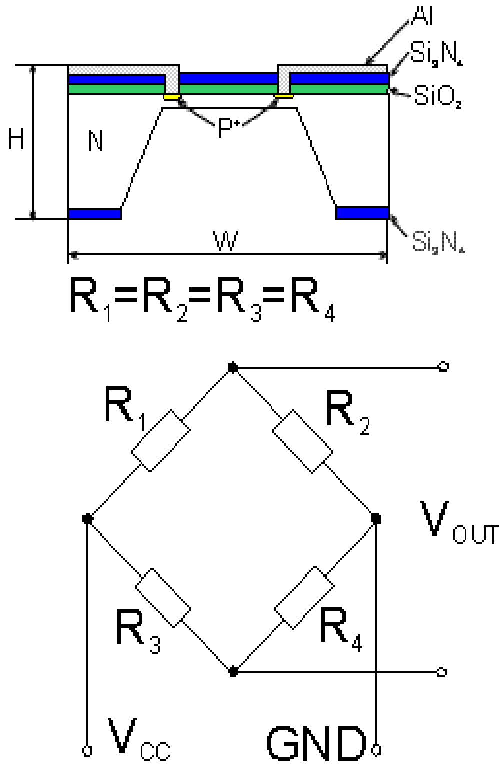
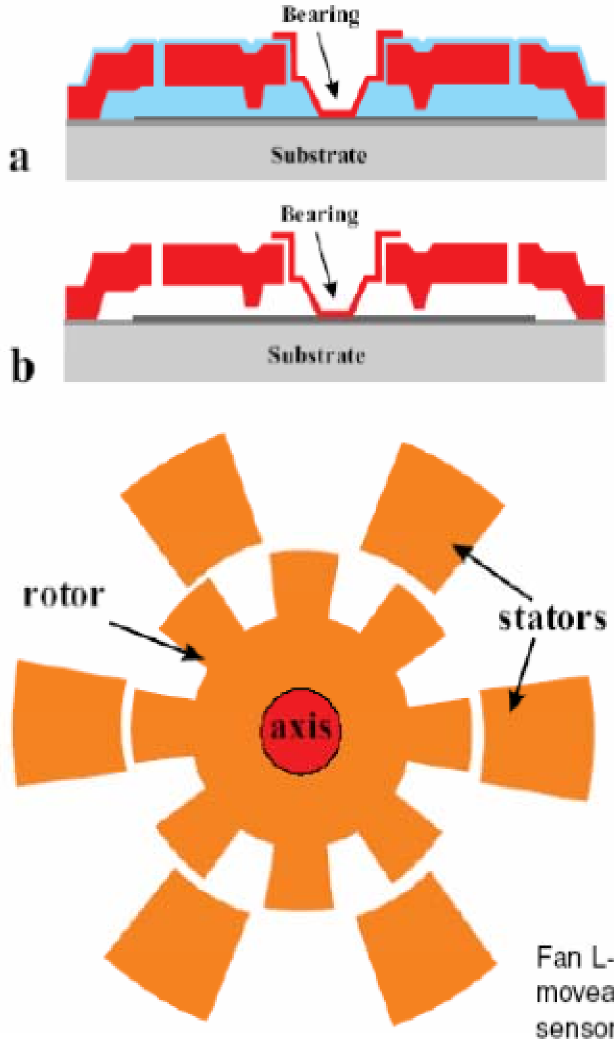


Surface Micromachined Motor



Fan L-S, Tai Y-C and Muller R S 1988 Integrated moveable micromechanical structures for sensors and actuators *IEEE Trans. Electron Devices* **ED-35** 724–30

Rotary Electrostatic Micromotor

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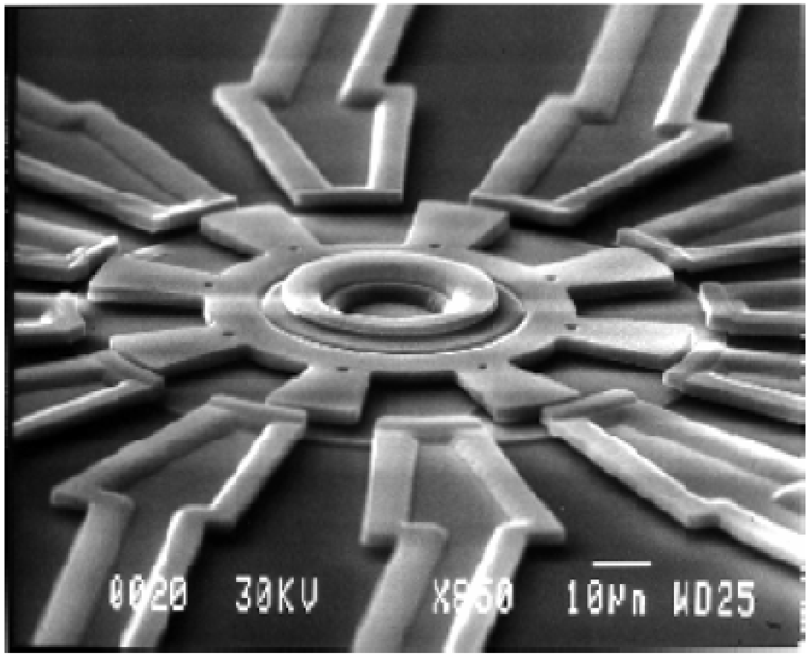

Fan Long-Shen, Tai Yu-Chong and Muller R S 1989 IC-processed electrostatic micromotors *Sensors Actuators* **20** 41–7

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World's Smallest Guitar

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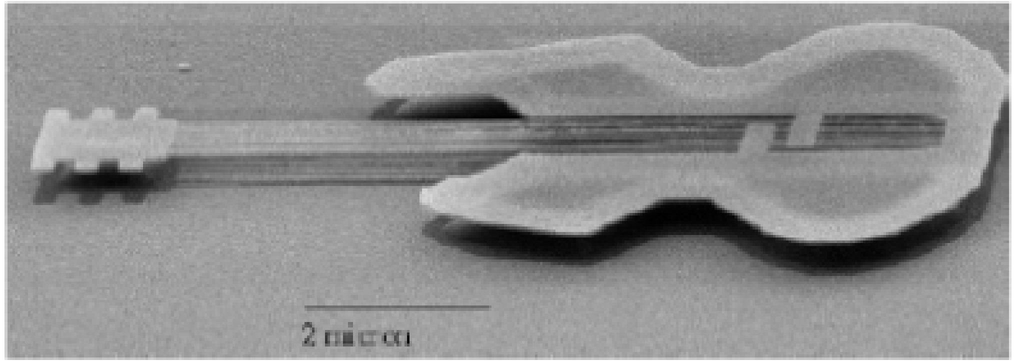

A 10 µm long Si guitar (same size as a single cell) with six strings, each ~50 nm (100 atoms) wide. (Cornell University)

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Automotive Airbag Accelerometer

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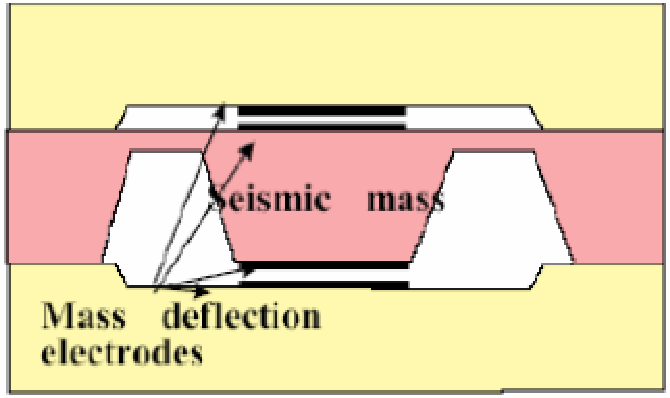
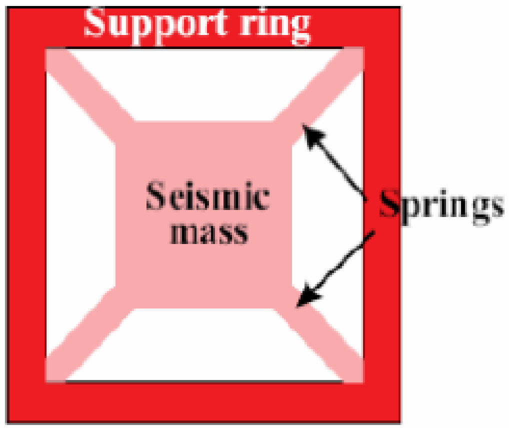
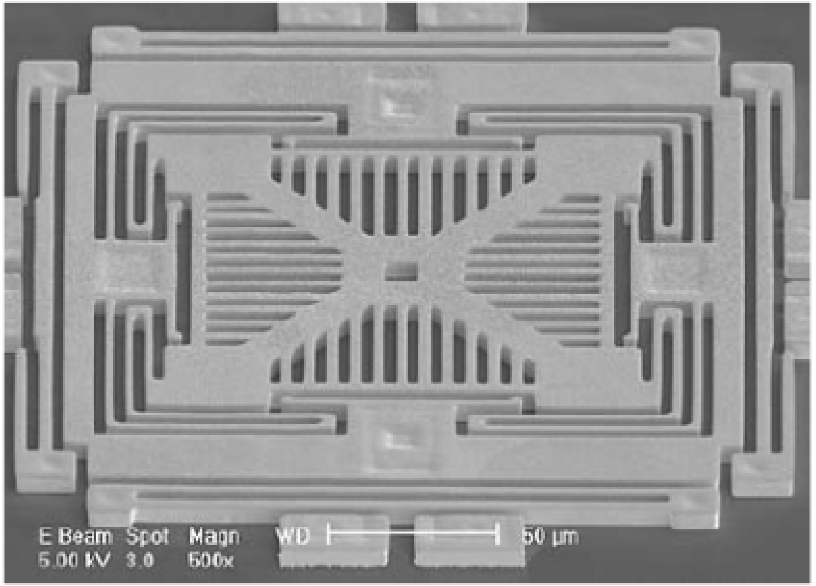
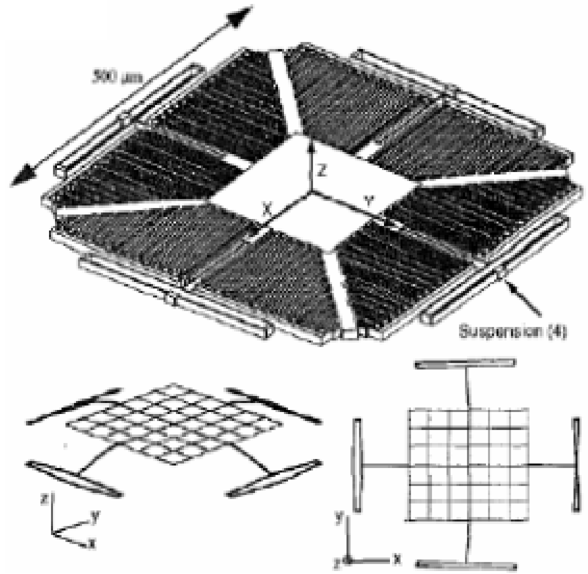




Bulk micromachined proof mass suspended between mass deflection electrodes attached by wafer bonding

Automotive Airbag Accelerometer

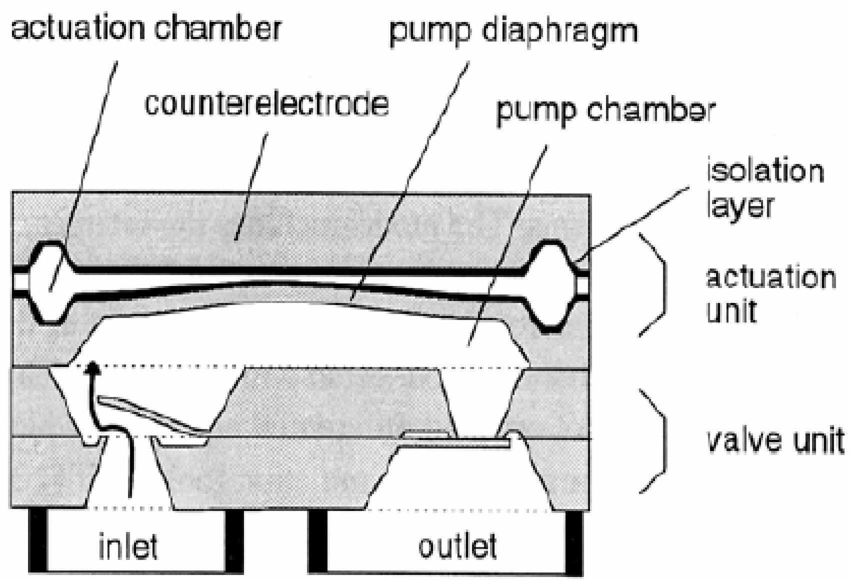




A 3-Axis Force Balanced Accelerometer Using a Single Proof-Mass

Mark A. Lemkin, Bernhard E. Boser, David Auslander*, Jim H. Smith**

Fluidic MEMS



Electrostatic micropump with two one-way check valves

Zengerle R, Ulrich J, Kluge S, Richter M and Richter A 1995, A bi-directional silicon micropump *Sensors Actuators* A50 81–6

EXERCISES

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1) Calculate the maximum deflection and maximum stresses for a square silicon membrane of thickness 10 μm and side length 2 mm for an applied pressure of 1000 Pa.

For silicon, $E = 190$ GPa and $\nu = 0.28$.

2) A silicon cantilever beam with a piezoresistor located at the point of maximum stress is subjected to a point load Q at the end of the beam. Q is 10 μN, the length of the beam is 1000 μm, and the beam thickness is 3 μm. Calculate the beam width that results in a 3% resistance change for the piezoresistor due to the load Q. Assume the beam lies perpendicular to the silicon <110> lattice direction.

3) What is the resonant frequency F_o for a silicon cantilever beam 1000 μm long, 100 μm wide, and 3 μm thick? The density of silicon is 2.3 g/cm^3.

EXERCISES

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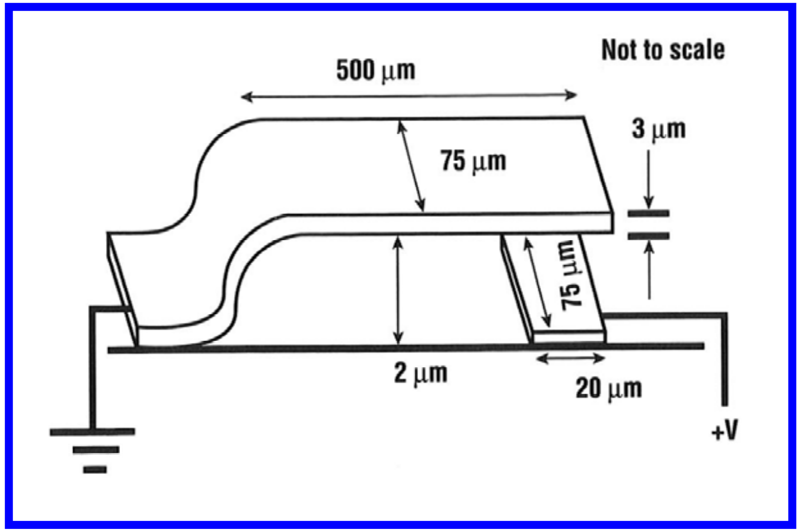
4) A polysilicon cantilever fabricated using surface micromachining is 500 μm long, 75 μm wide, and 3 μm thick. The sacrificial layer thickness for the process was 2.0 μm. The electrically grounded beam is electrostatically actuated using a positive voltage *V* applied to a conducting bottom electrode (length 20 μm, width 75 μm) under the end of the beam. Neglecting fringing effects, estimate the voltage *V* required to deflect the beam by 0.2 μm.



Force Q between two parallel plates of area A, separation d and applied voltage V

$$Q = 0.5\, \varepsilon_0 \varepsilon_r \frac{AV^2}{d^2}$$

EXERCISES

ANSWER:

1) Wmax=1.17µm,
   σl=12.3 MPa,
   σt=3.45 MPa
2) σmax= 4.3*10^{7} Pa,
   a=150 µm
3) fo= 4.39 kHz
4) V=9.6V