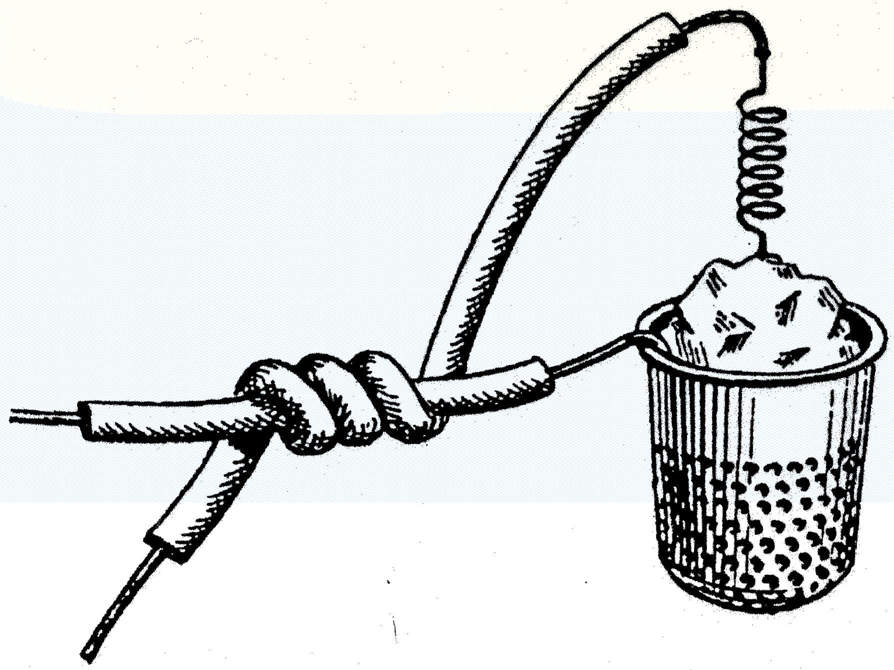
Sensor devices



Outline

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

Introduction

- Two Major classes of mechanical sensors
  - **Piezorestistive (material property in silicon)**
  - **Capacitive sensors**
- In applications as
  - **Pressure sensors**
  - **Accelerometer**
  - **Flow sensors**

General Mechanical properties

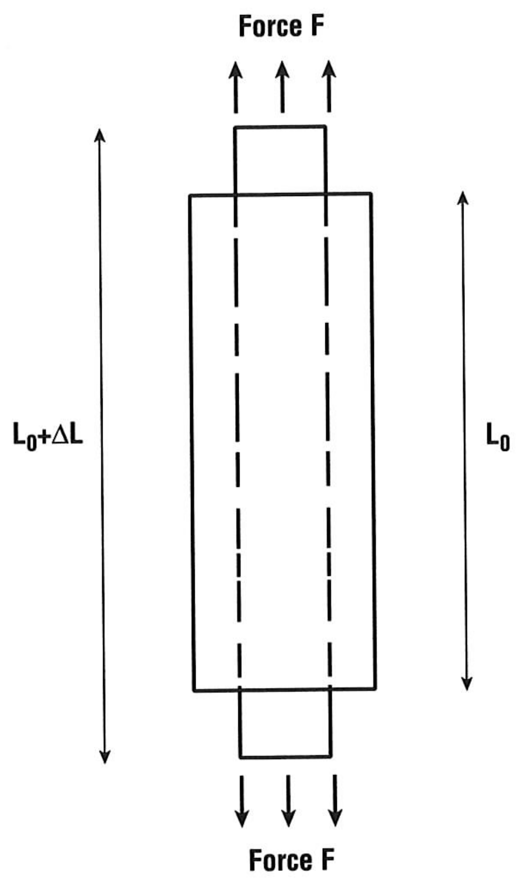


Figure 19.1 Rod elongation due to a tensile force *F*.

Strain $\varepsilon_a=\Delta L/L_0$ (no unit) (a "axial")

Stress $$\sigma = \frac{F}{\text{Area}} = \frac{F}{\pi(D/2)^2}$$ (N/m)

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

E= Young's module (Elasticity module)

Poisson's ratio $$\nu = -\frac{\varepsilon_l}{\varepsilon_a}$$

l="lateral"

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General Mechanical properties

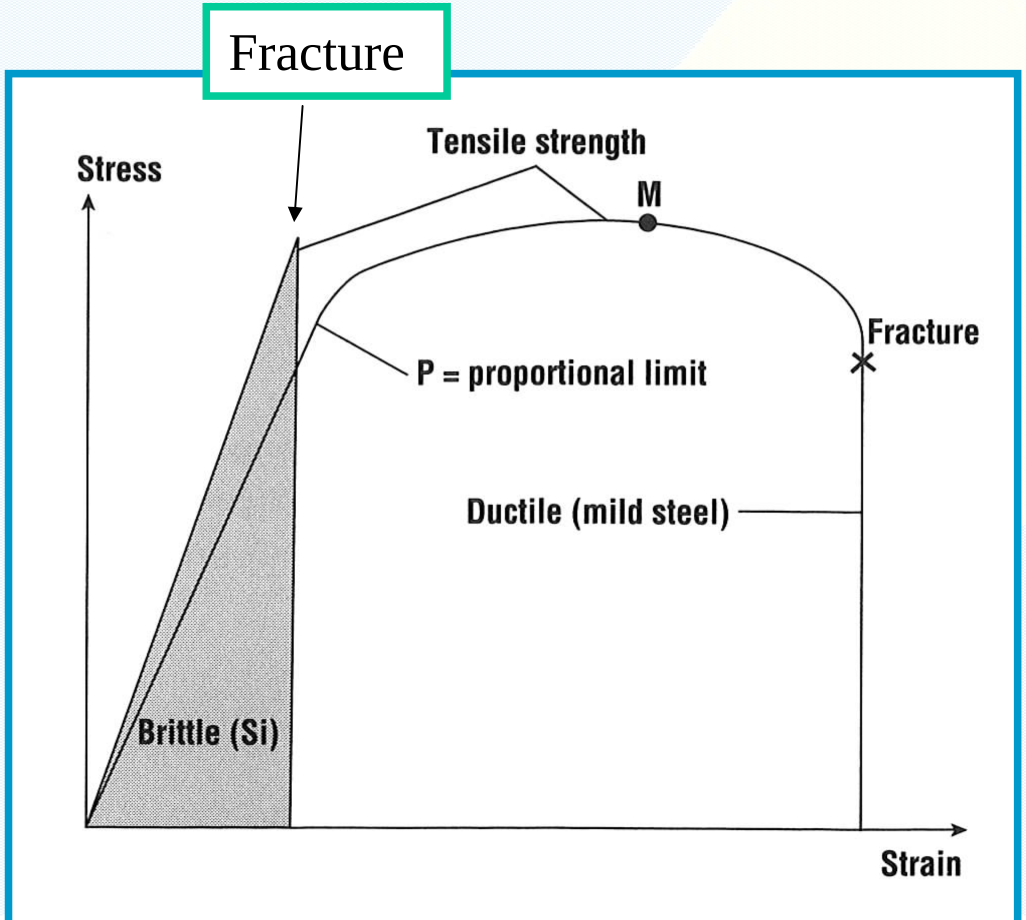


Figure 19.2 Stress–strain curve for a typical metal as well as for a brittle material like silicon (high Young's modulus and no plastic deformation region) *(reprinted with premission from Madou [7]. Copyright CRC Press).*

Silicon is a brittle material with no plastic deformation region (Gray area), which is an advantage in sensor application

For example Steel have a proportional limit where its dimension remain after unloading. At higher stresses the material "float" and become longer even after unloading

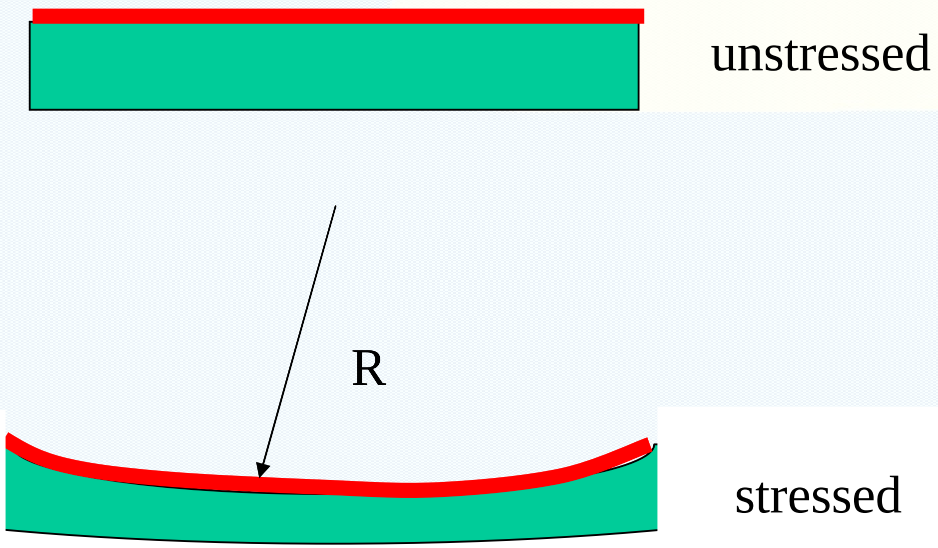
General Mechanical properties

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

Stress in thin film



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

$$\sigma = \frac{1}{R}\frac{E}{6(1-\nu)}\frac{T^2}{t}$$

R= radius

E= Young's module in substrate

T= substrate thickness

T= thin film thickness

V= poisson's ratio in substrate

General Mechanical properties

- Calculation
  - **Square membranes**
  - **Cantilever beams**
    - Max deflection
    - Max longitudinal stress
    - Max transverse stress
    - Resonant Frequency

General Mechanical properties

Square membranes

For a square membrane of side a, thickness t, Young's Modulus E, density ρ, and Poisson's ratio ν, subjected to a uniform pressure P, the maximum membrane deflection $W_{\max}$, maximum longitudinal and transverse stress σ_l and σ_t, and fundamental mode resonant frequency of vibration F_o are defined as

Max deflection $W_{\max} = 0.001265 Pa^4/D$

Max longitudinal stress $\sigma_l = 0.3081 P(a/t)^2$

Max transverse stress $\sigma_t = \nu\sigma_l$

Resonant frequency $F_o = \dfrac{1.654t}{a^2}\left[\dfrac{E}{\rho(1-\nu^2)}\right]^{1/2}$

D, measure the stiffness of the membrane

$$D = \frac{Et^3}{12(1-\nu^2)}$$

General Mechanical properties

Cantilever beam uniform distributed load

Uniform distributed load P (F is uniformed distributed over L)

$$P = F/a$$

Max stress

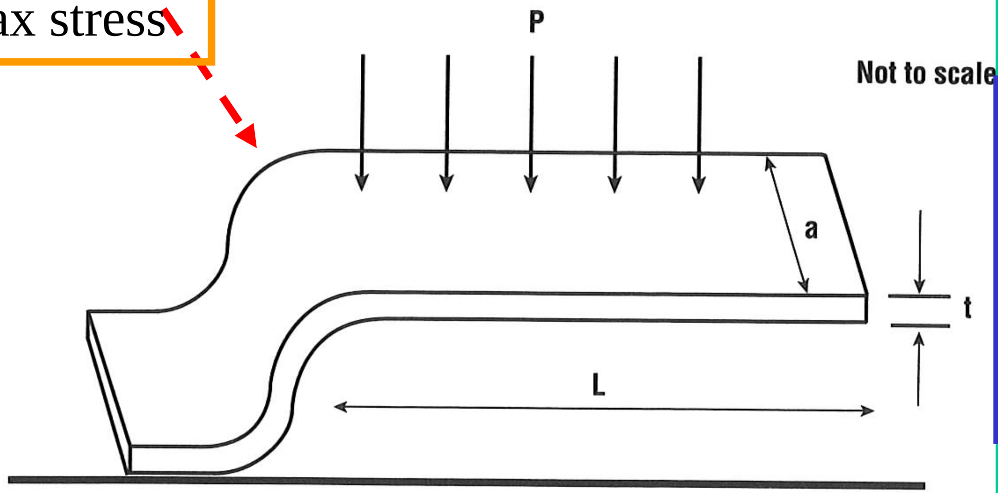


Figure 19.8 Cantilever beam fixed at one end, subjected to downward force per unit length P.

$$\text{Deflection } W(P, x) = \frac{Px^2}{24EI}(6L^2 - 4Lx + x^2)$$

$$\text{Max Stress } \sigma = \frac{PL^2 t}{4I}$$

I, bending of inertia "bending resistance"

$$I = \frac{at^3}{12}$$

General Mechanical properties

Cantilever beam point load at the end

Max stress

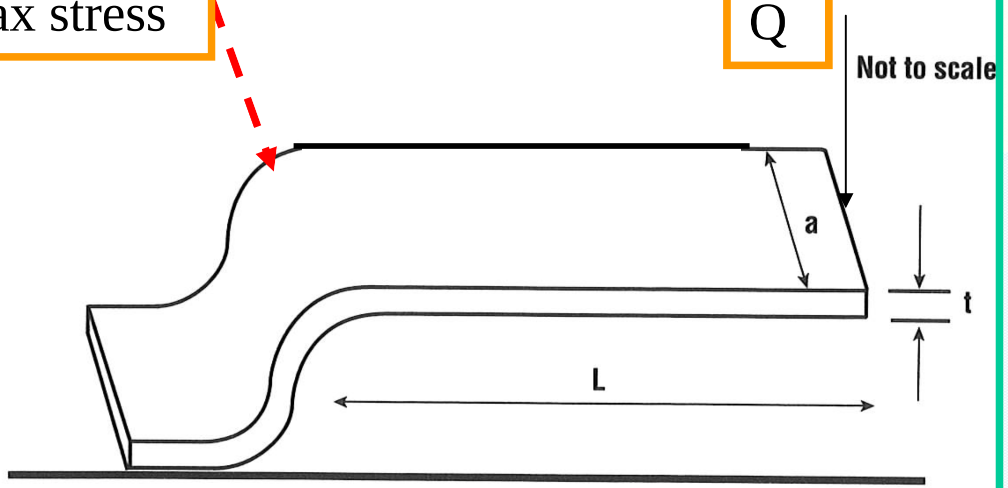


Figure 19.8 Cantilever beam fixed at one end, subjected to downward force per unit length P.

$$\text{Deflection } W(P,x) = \frac{Qx^2}{6EI}(3L\text{-}x)$$

$$\text{Max stress } \sigma = QLt/2I$$

Fundamental mode resonant frequency

$$F_o = 0.161\,\frac{t}{L^2}\left(\frac{E}{\rho}\right)^{1/2}$$

Cantilever beam mass M

$$F_o = 0.161\,\frac{t}{L}\left(\frac{Eta}{ML}\right)^{1/2}$$

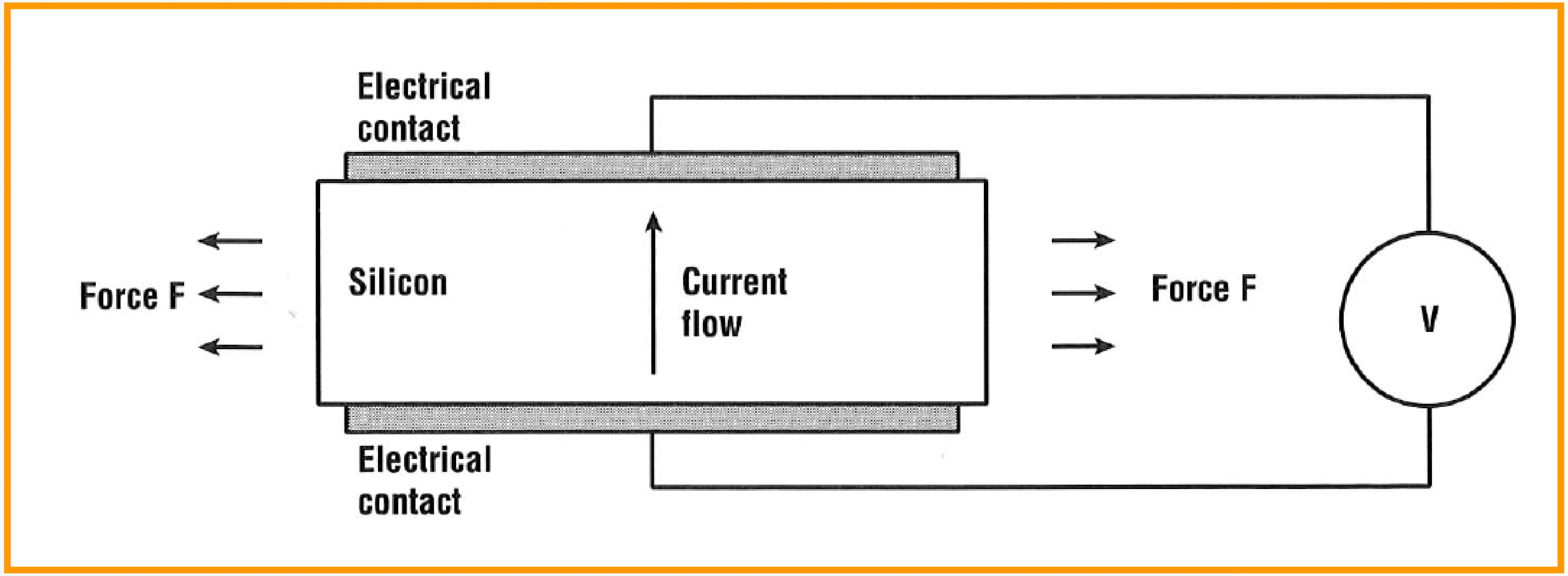
Piezoresistivity

1. The silicon doping type (n- or p-type) and concentration
2. Temperature
3. The direction of the current flow relative to the orientation of the crystal lattice
4. The direction and type of force (tensile or compressive) relative to the orientation of the crystal lattice.

Resistivity changes when introducing of mechanical stress

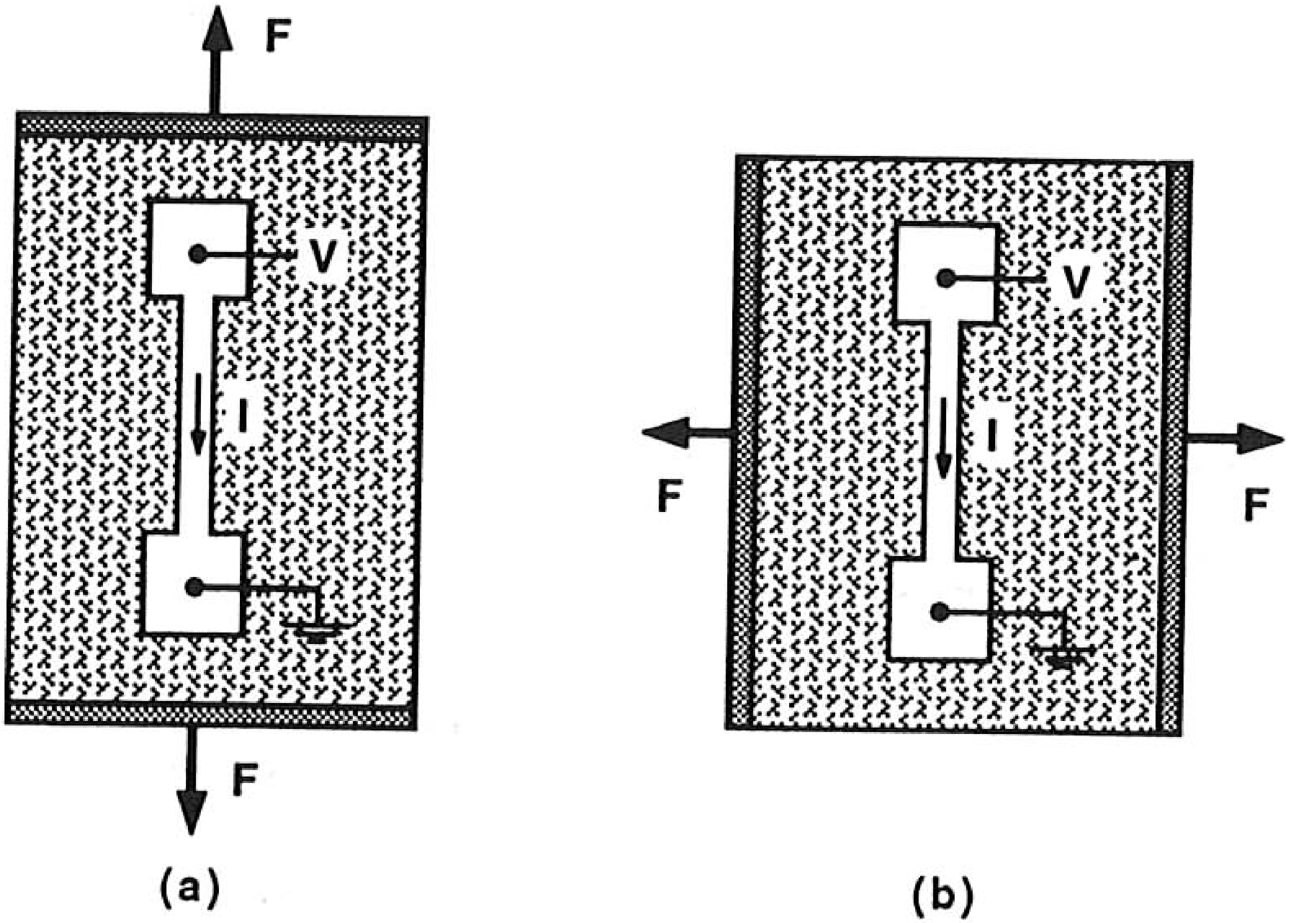
The pizoresistivity have a large influence for the resistance change in semiconductor, the effect is small for metal where the change is caused by “pure” geometrical distortions.

Piezoresistivity



A semiconductor under measurement. A tensile force is applied, perpendicular to the current flow.

Piezoresistivity



a) Stress is defined as

$\sigma = F/A$

F=Force, A=Area

$\Delta R/R = \pi_l \sigma_l$

π_l is the longitudinal piezoresistance coefficient

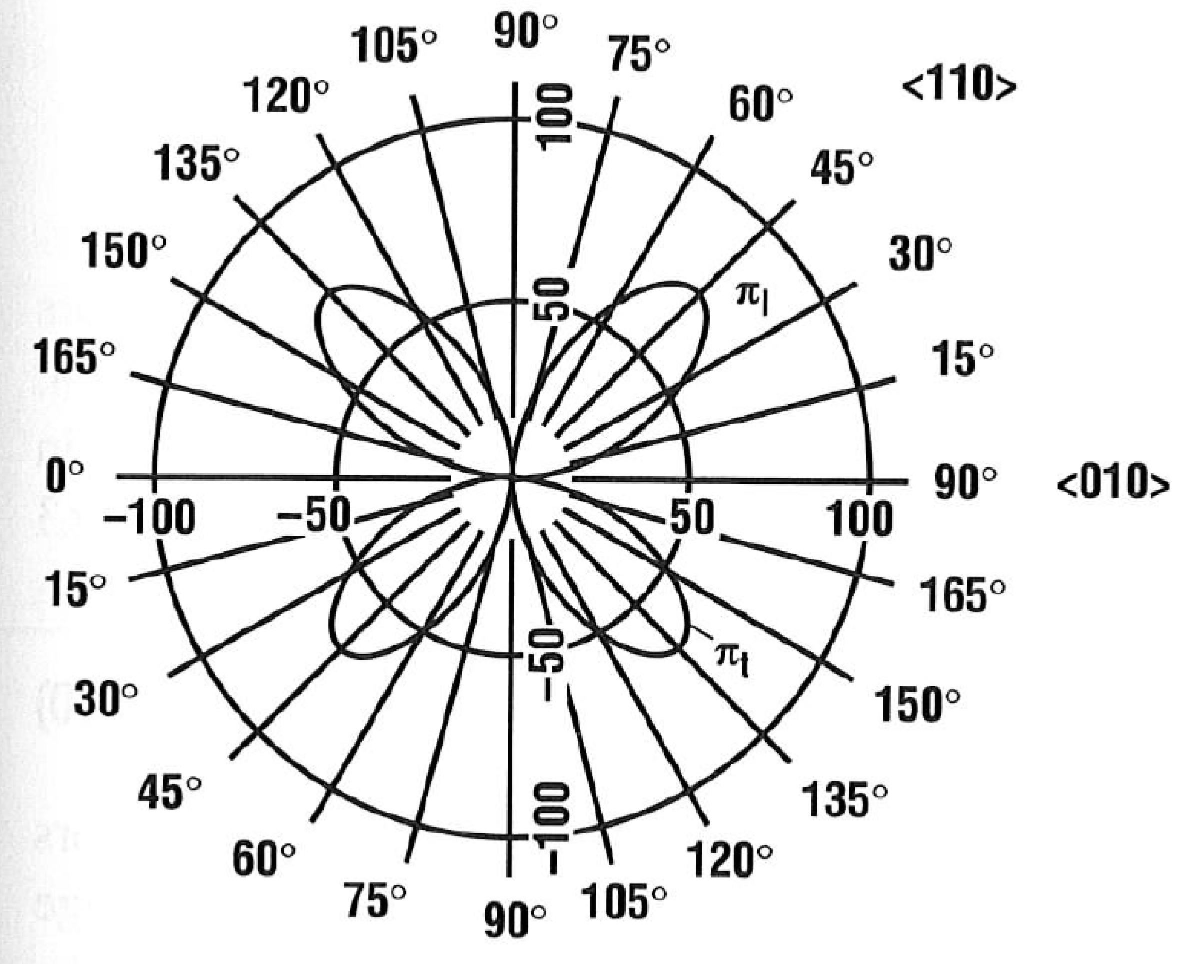
b) $\Delta R/R = \pi_t \sigma_t$

π_t is the transverse piezoresistance coefficient

! In general when both longitudinal and transverse stresses are present we have

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

Piezoresistivity



The picture show the π_l and π_t for the 100 plane, p-type silicon. Π_l is in the upper half and π_t in the lower half

Units are 10^{-11} Pa^{-1}

In sensor application the π should be as large as possible

Piezoresistance Sensors

Place your resistors this way:

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

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

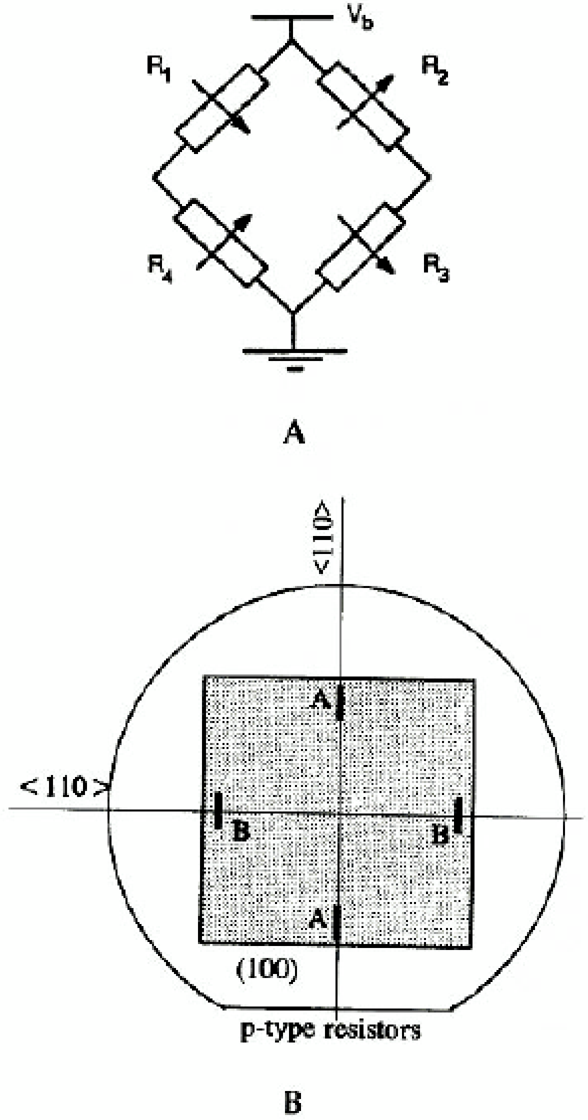


FIGURE 4.18 Measuring on a membrane with piezoresistors. (A) Wheatstone-bridge configuration of four in-diffused piezoresistors. The arrows indicate resistance changes when the membrane is bent downward. (B) Maximizing the piezoresistive effect with p-type resistors. The A resistors are stressed longitudinally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

Piezoresistivity

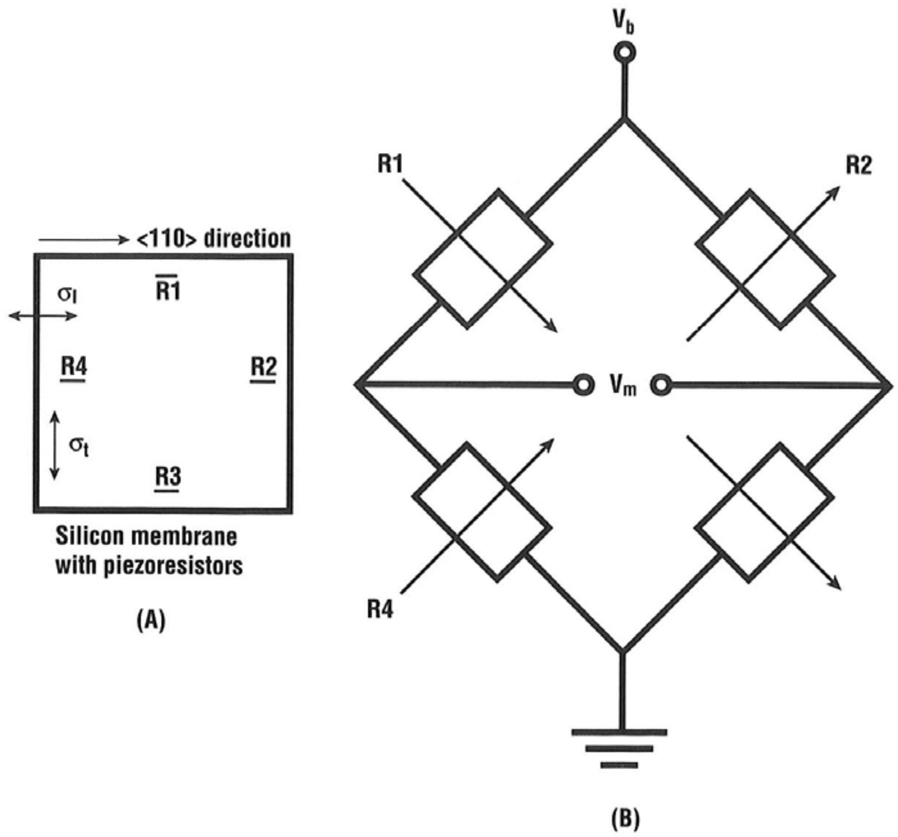


Figure 19.7 (A) Schematic drawing of the position and orientation of four piezoresistance elements on a silicon membrane with sides defined by anisotropic silicon etching of a (100) silicon wafer; (B) Wheatstone bridge configuration of the four piezoresistive elements, with arrow directions indicating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

Better identification of resistor in the bridge

Piezoresistivity

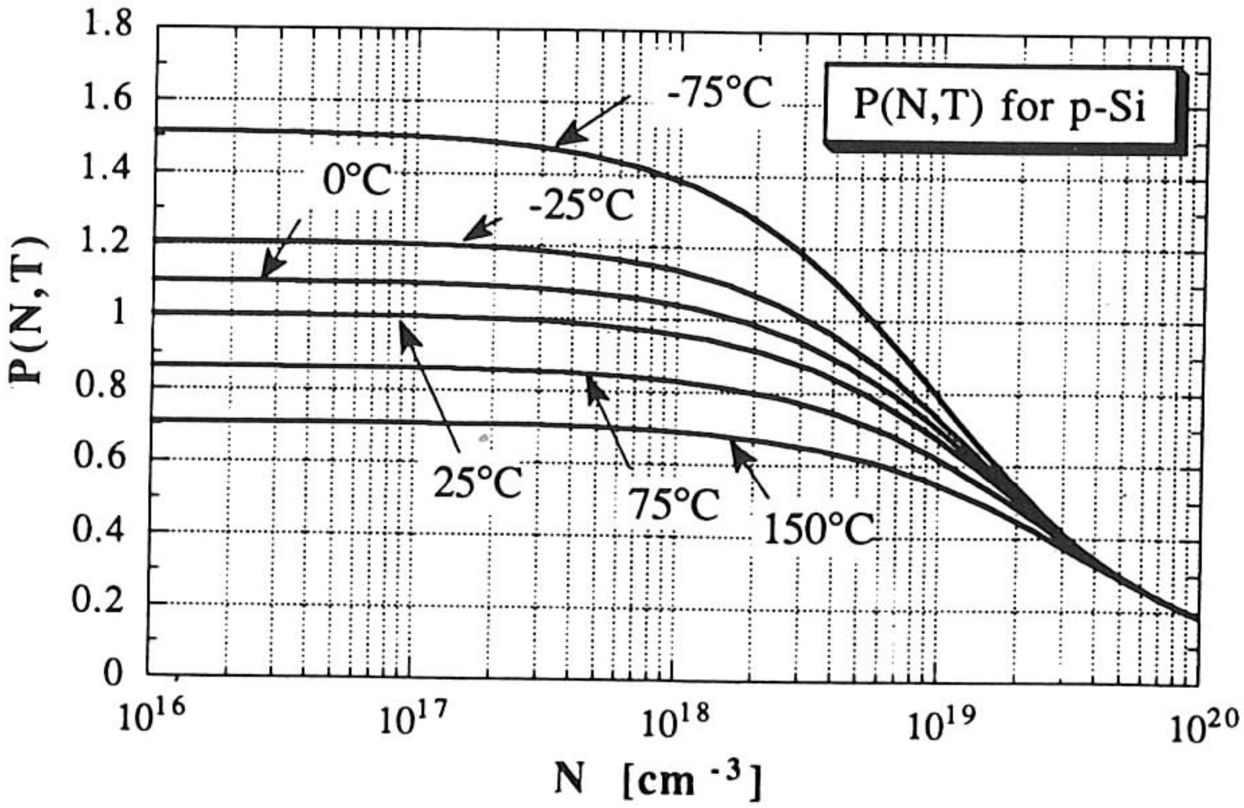


Fig. 10 Piezoresistance factor $P(N, T)$ as a function of impurity concentration and temperature for *p*-type silicon. (After Ref. 49)

Piezoresistive Sensors

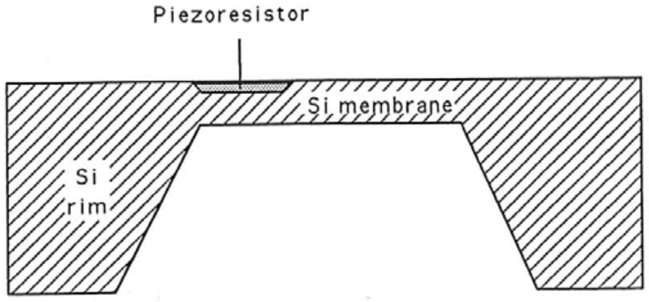


Fig. 13 Schematic cross-section of a piezoresistive pressure sensor.

- Piezorestive pressure sensor
  - Fabrication
    - Anisotropic etch
    - Piezoresistor could be by doped area
    - or deposited polysilicon resistor on an insulator (SiO_2 or Si_3N_4)
  - The stress is maximal at the edges of the membrane, where the resistor should be placed

Piezoresistive Sensors

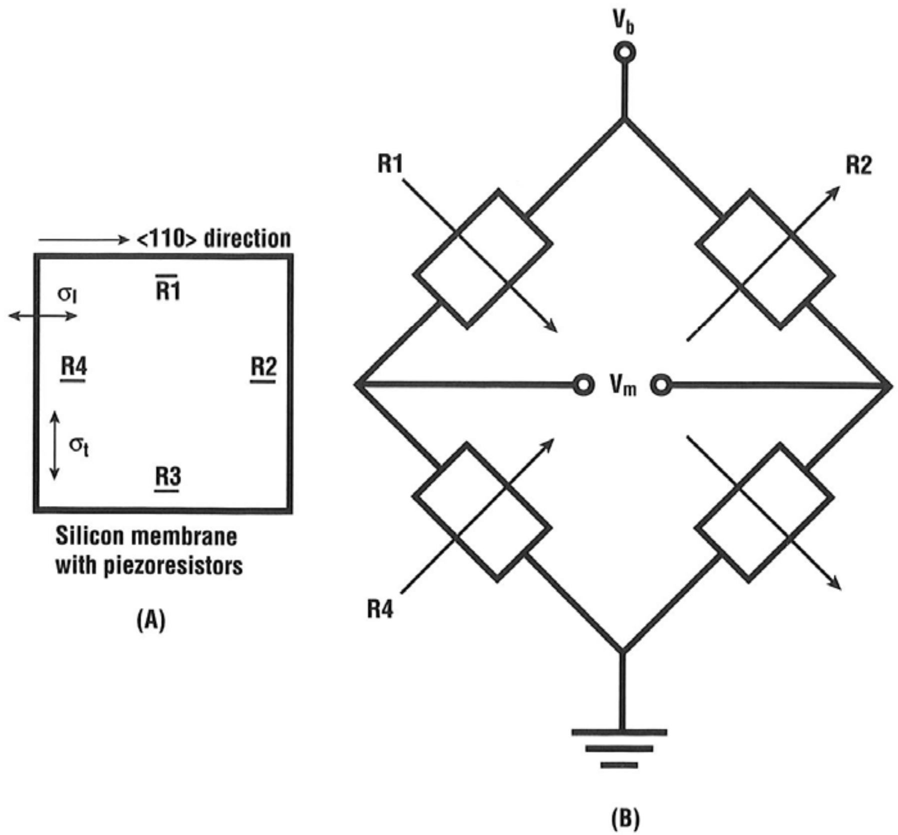


Figure 19.7 (A) Schematic drawing of the position and orientation of four piezoresistance elements on a silicon membrane with sides defined by anisotropic silicon etching of a (100) silicon wafer; (B) Wheatstone bridge configuration of the four piezoresistive elements, with arrow directions indicating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

Advantage

Convert directly change in resistance to voltage

$$\Delta V = \frac{\Delta R}{R} V_b$$

Constant bridge voltage

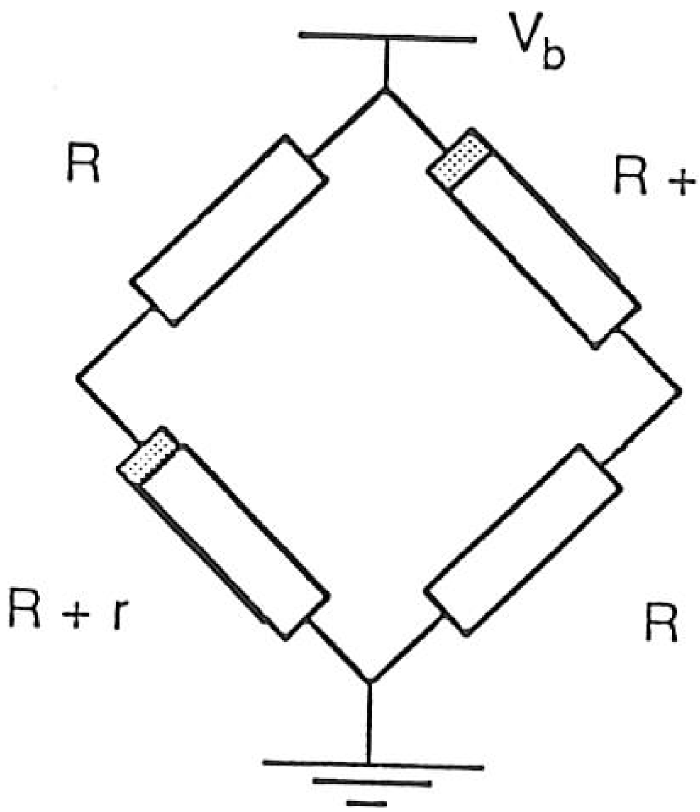
$$S = \frac{\Delta V}{\Delta P}\frac{1}{V_b} = \frac{\Delta R}{\Delta P}\frac{1}{R}.$$

Constant bridge current

$$S = \frac{\Delta V}{I_b}\frac{1}{\Delta P} = \frac{\Delta R}{\Delta P}.$$

A built in temperature sensor is often used to improve the temperature stability

Piezoresistive Sensors
Temperature coefficient of offset



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

$$O = \frac{V_0}{V_b} = \frac{r}{2R + r}.$$

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

Equal temperature coeff. result in zero dependence

$$\frac{\dot{r}}{r} = \frac{\dot{R}}{R}$$

Piezoresistive Sensors
Temperature coefficient of sensitivity

Constant bridge voltage

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

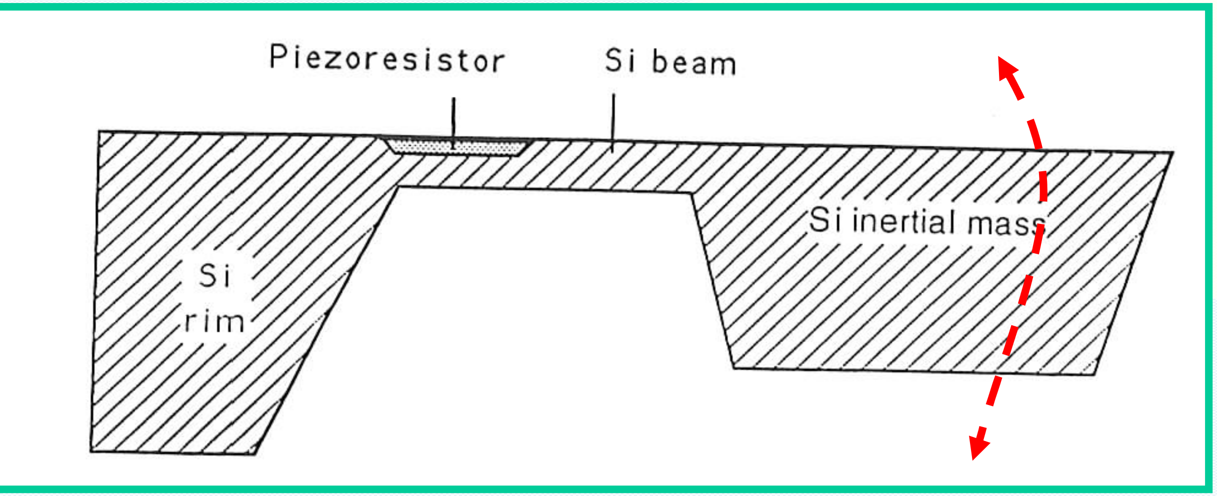
Temperature coefficient for π_{44} can be high for p –type silicon

Constant bridge current

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

- +

Piezoresistive Sensors

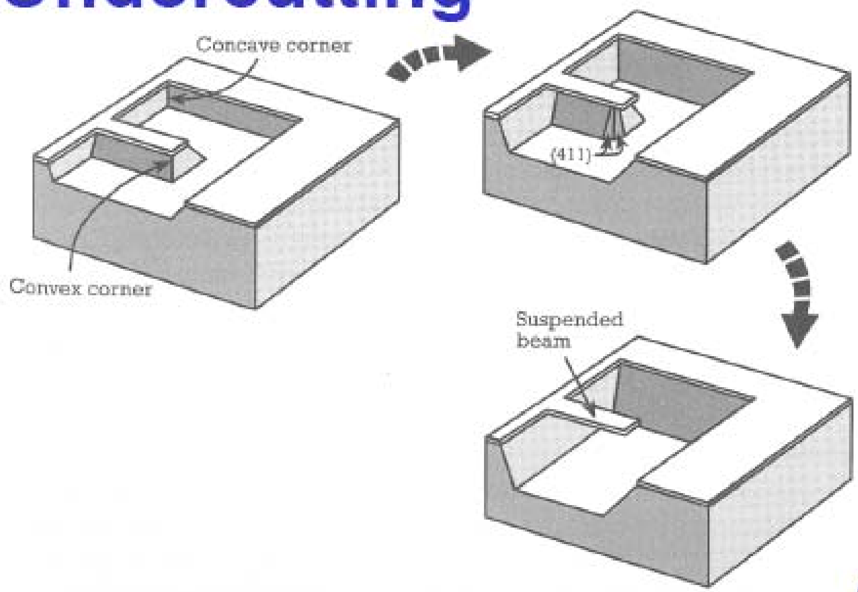


- Piezoresistive accelerator sensor
- The piezoresistor must be places where the stress is maximal
- To increase the sensitivity an inertial mass is included

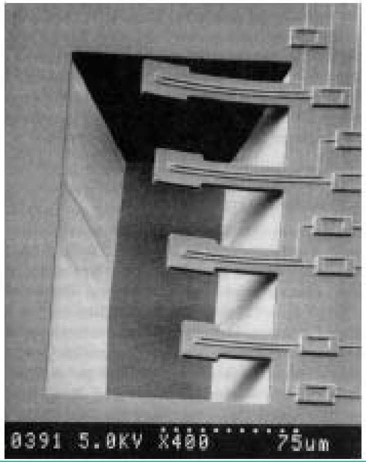
Piezoresistive Sensors

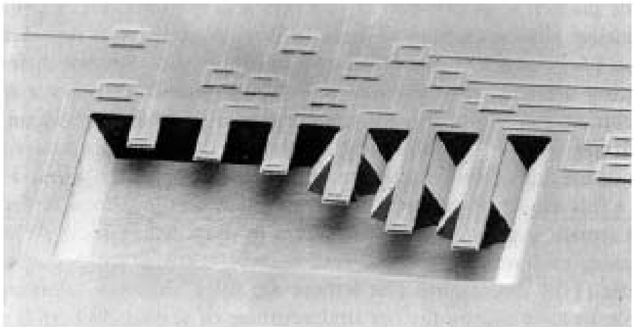
Undercutting

- Convex corners bounded by {111} planes are attacked



Maluf

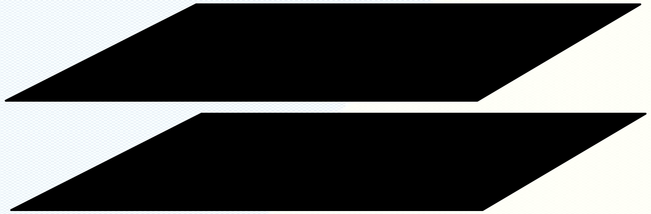




Ristic

Capacitive Sensors

Capacitor two electrodes separated by a dielectric



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

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

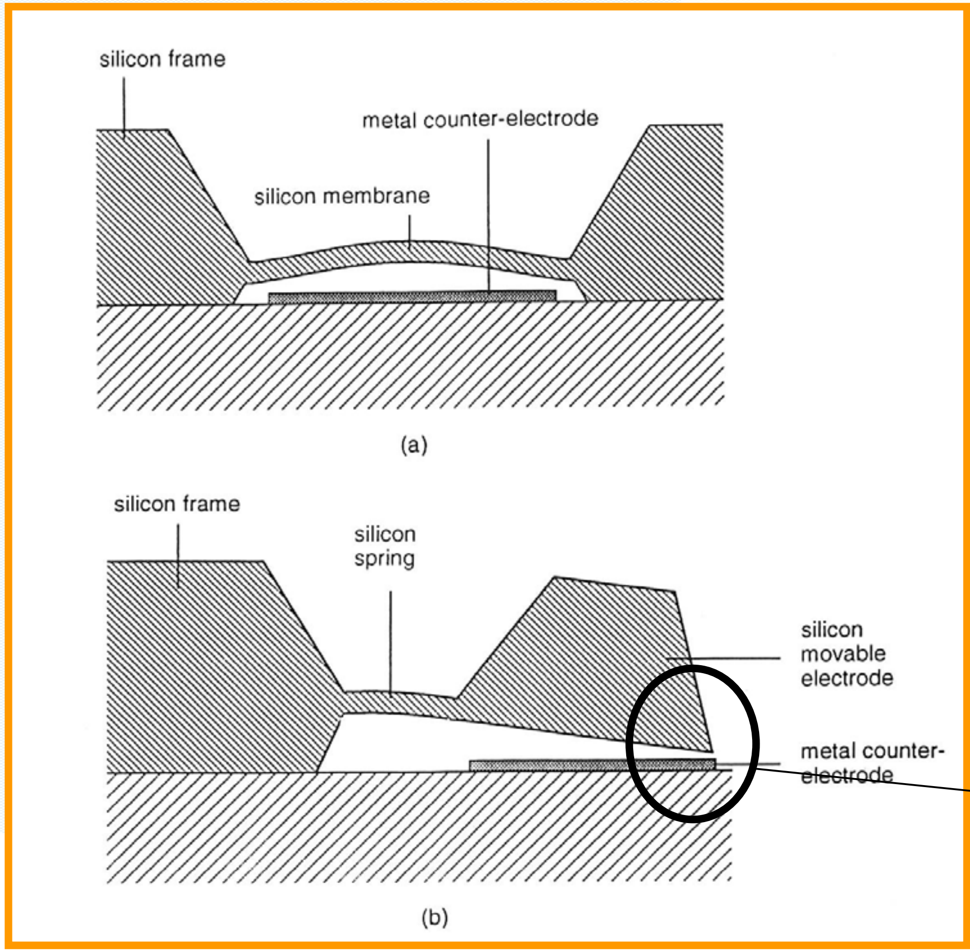
$\Delta d \ll d$ result in

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

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

Advantage with capacitive sensors no direct sensitivity to temperature

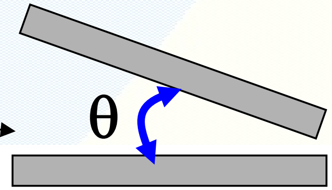
Capacitive Sensors



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

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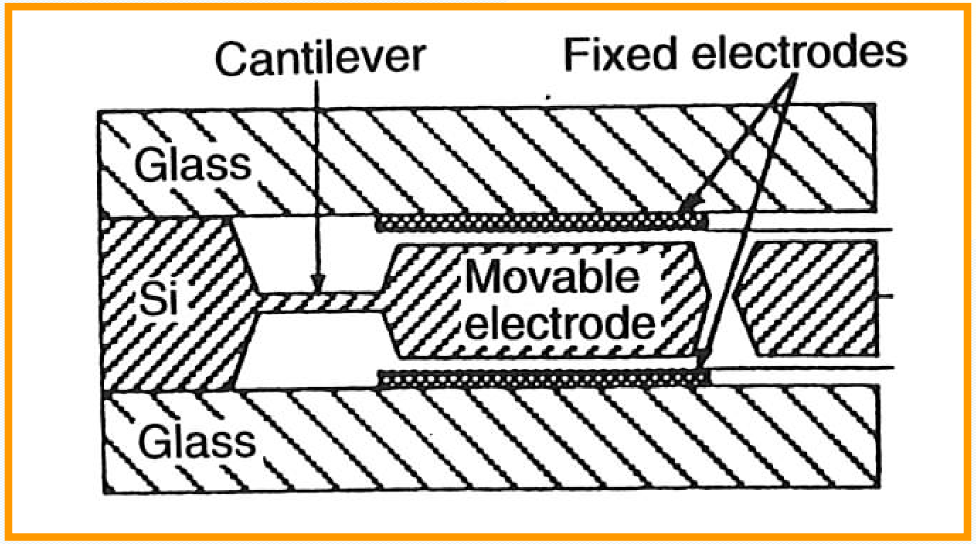
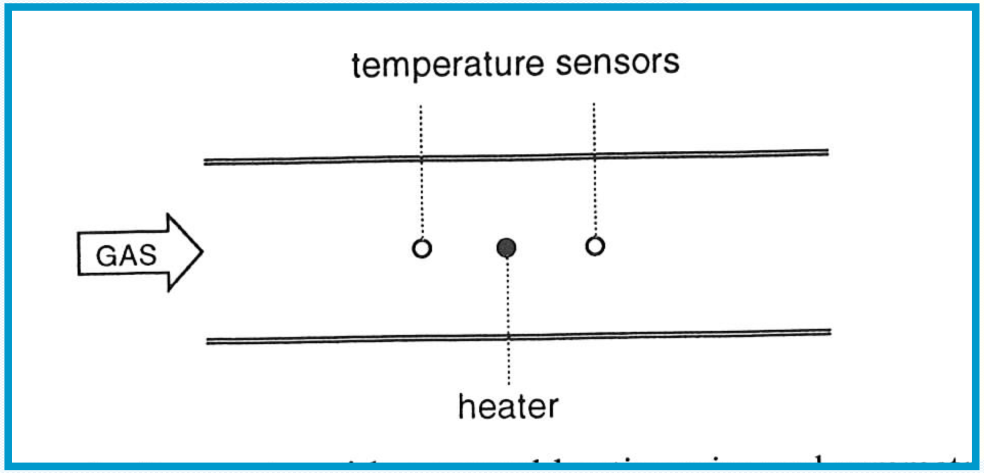
Applications

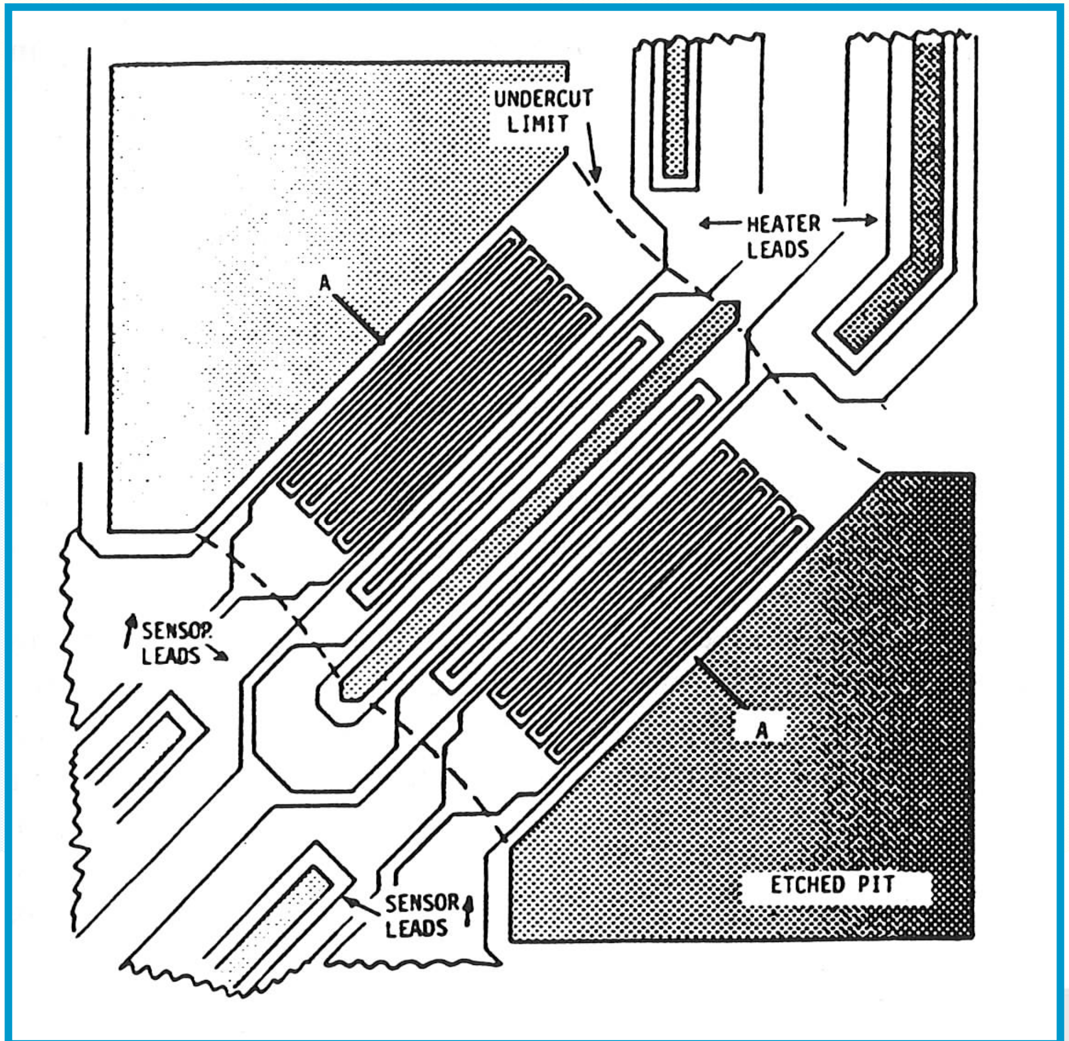


Symmetric capacitive accelerometer with low thermal sensitivity

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)

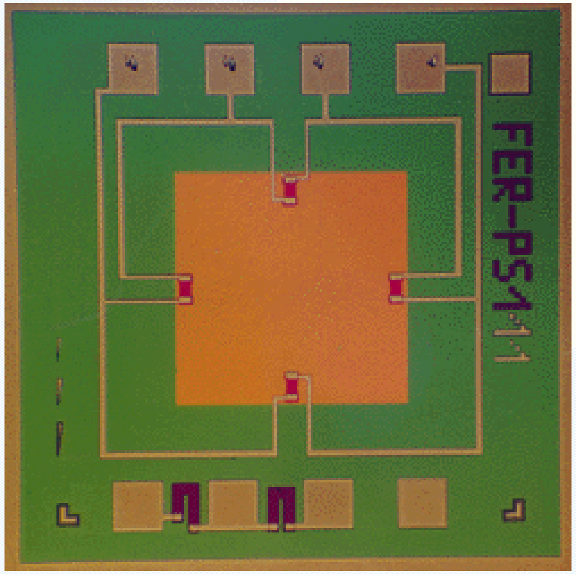




With no flow the two sensors display the same temperature

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

Some examples, Bulk micro-machined piezoresistive sensor



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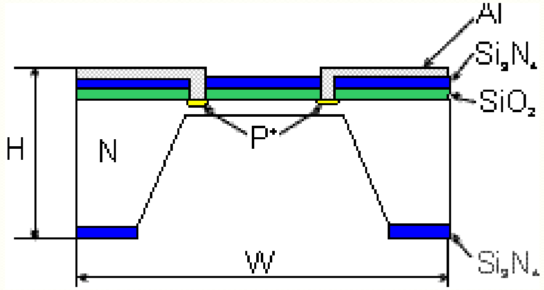
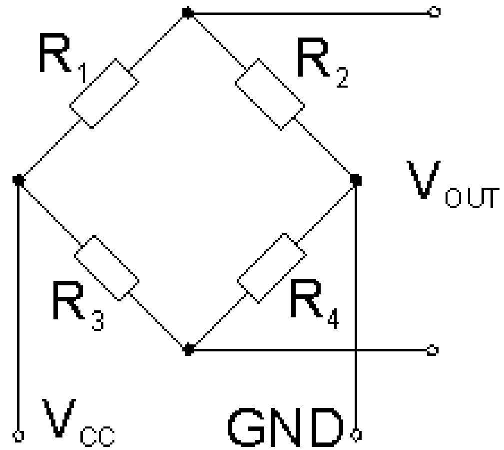


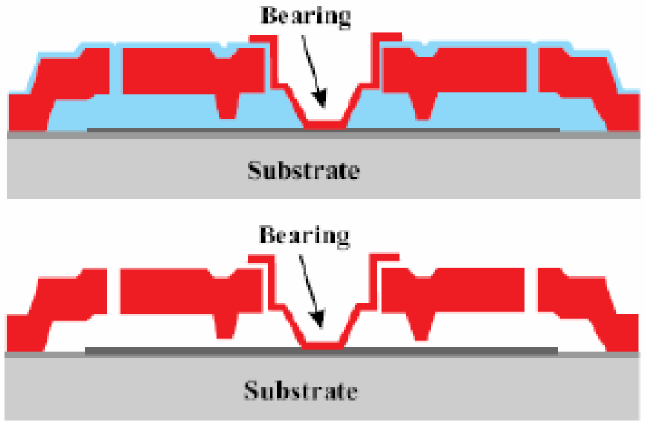
$R_1 = R_2 = R_3 = R_4$

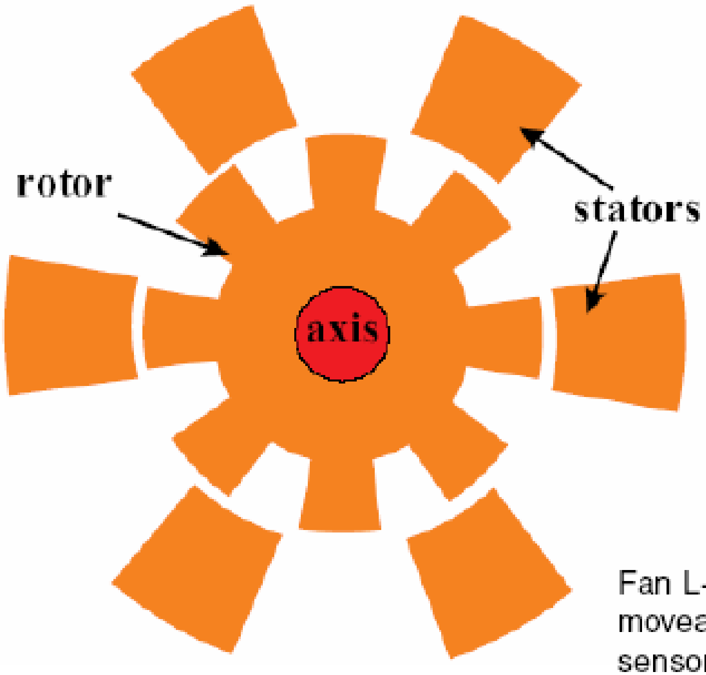


Surface Micromachined Motor

a

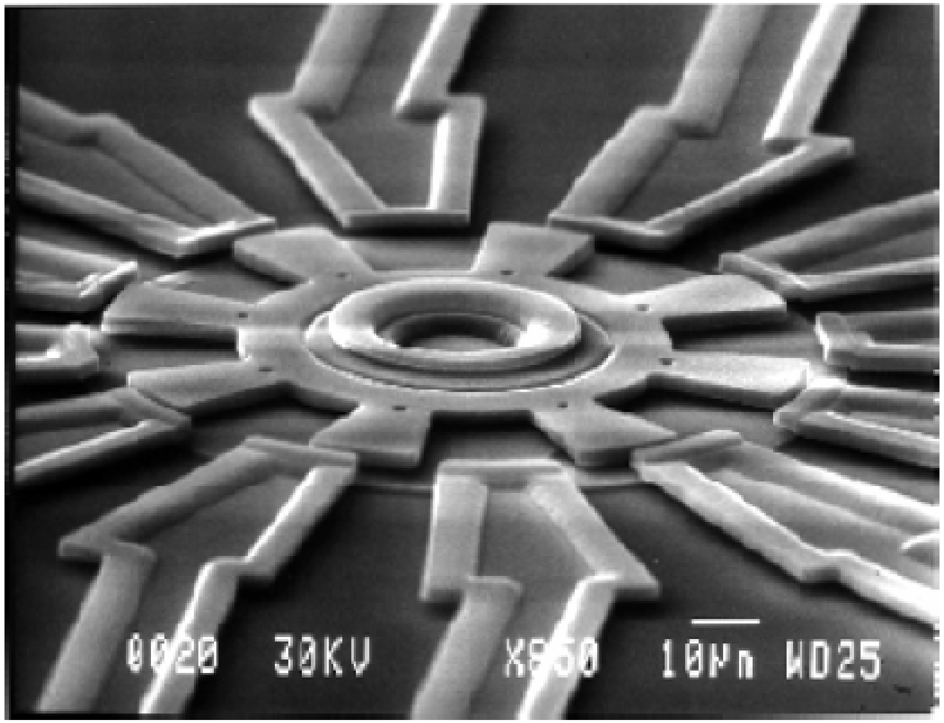
b





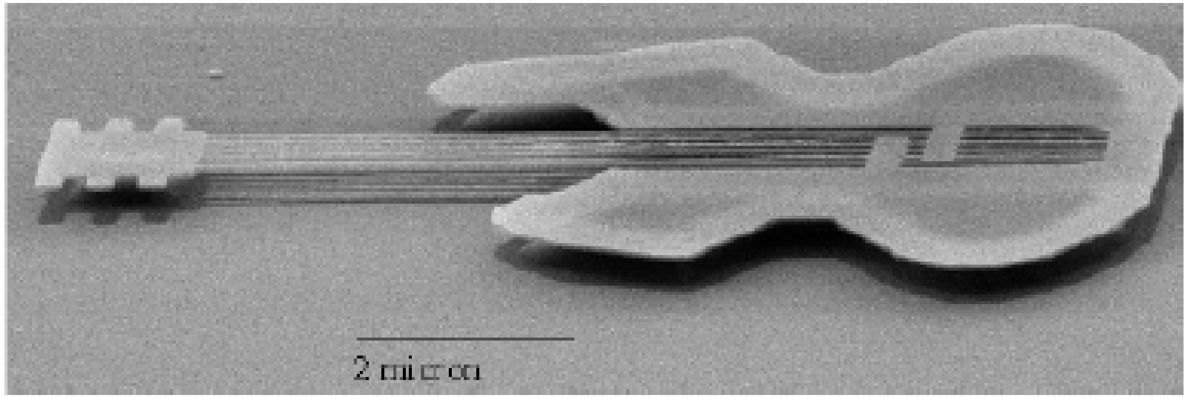
Fan L-S, Tai Y-C and Muller R S 1988 Integrated moveable micromechanical structures for sensors and actuators *IEEE Trans. Electron Devices* **ED-35** 724–30

Rotary Electrostatic Micromotor



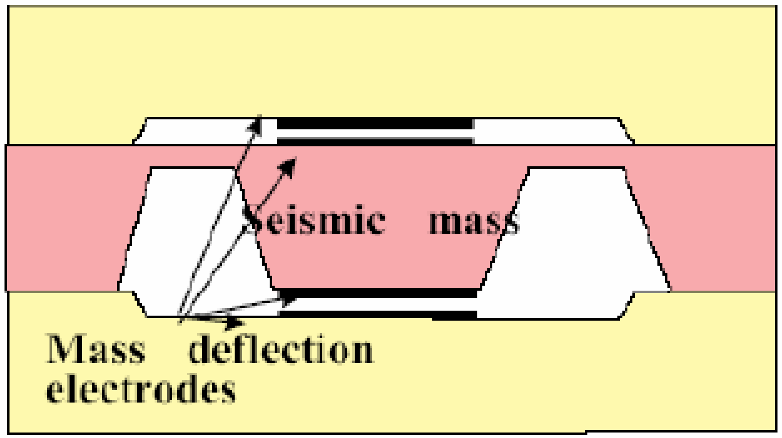
Fan Long-Shen, Tai Yu-Chong and Muller R S 1989 IC-processed electrostatic micromotors *Sensors Actuators* **20** 41–7

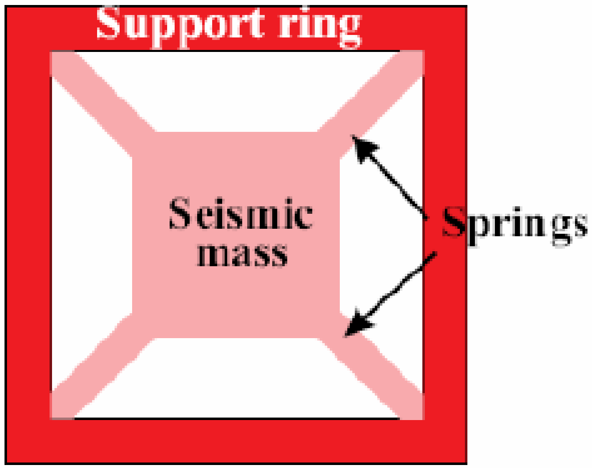
World's Smallest Guitar



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

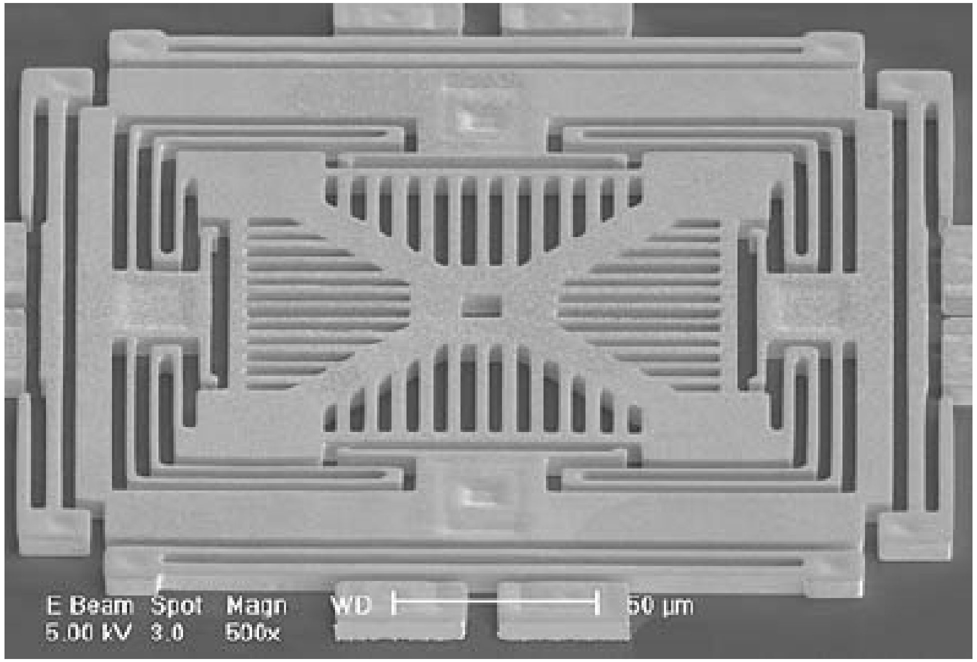
Automotive Airbag Accelerometer

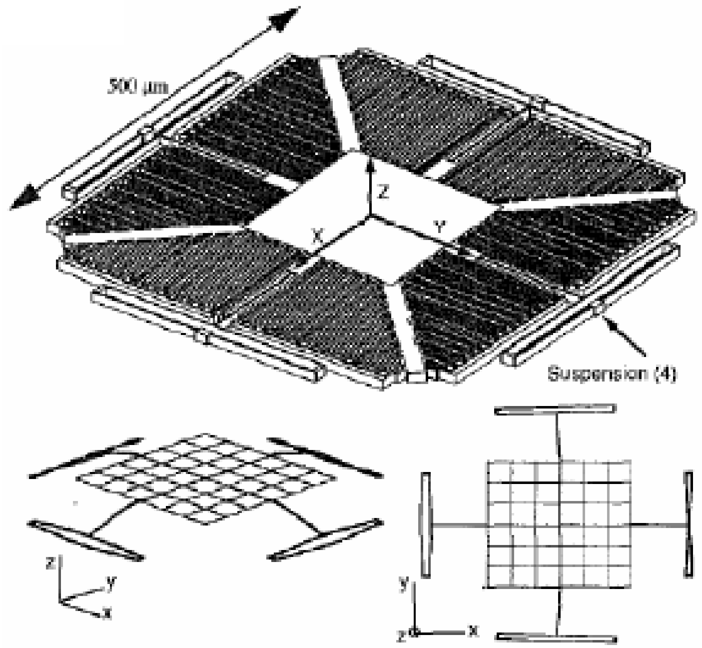




Bulk micromachined proof mass suspended between mass deflection electrodes attached by wafer bonding

Automotive Airbag Accelerometer

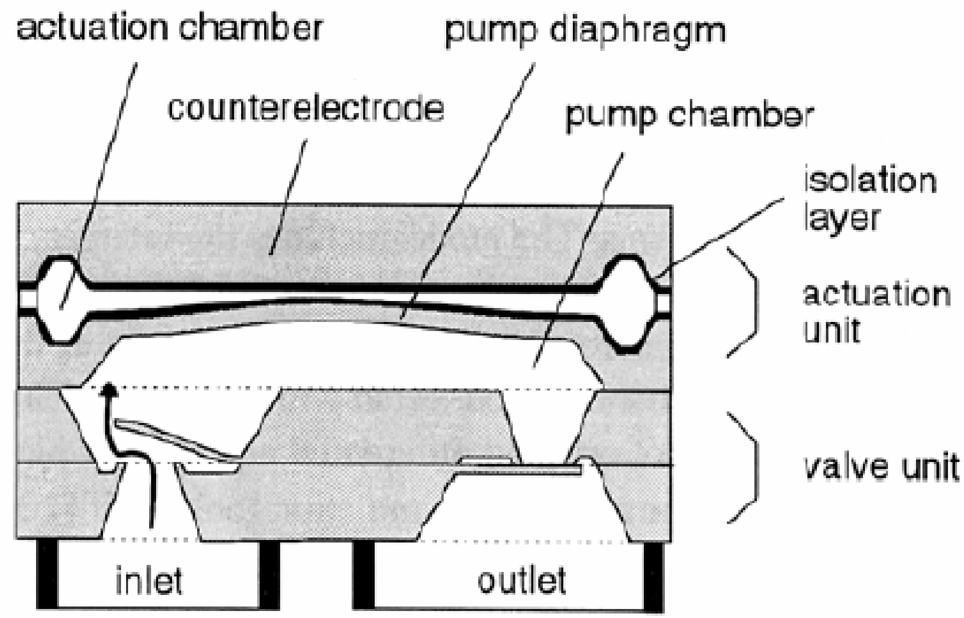




A 3-Axis Force Balanced Accelerometer Using a Single Proof-Mass

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* A**50** 81–6

Exercises

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.

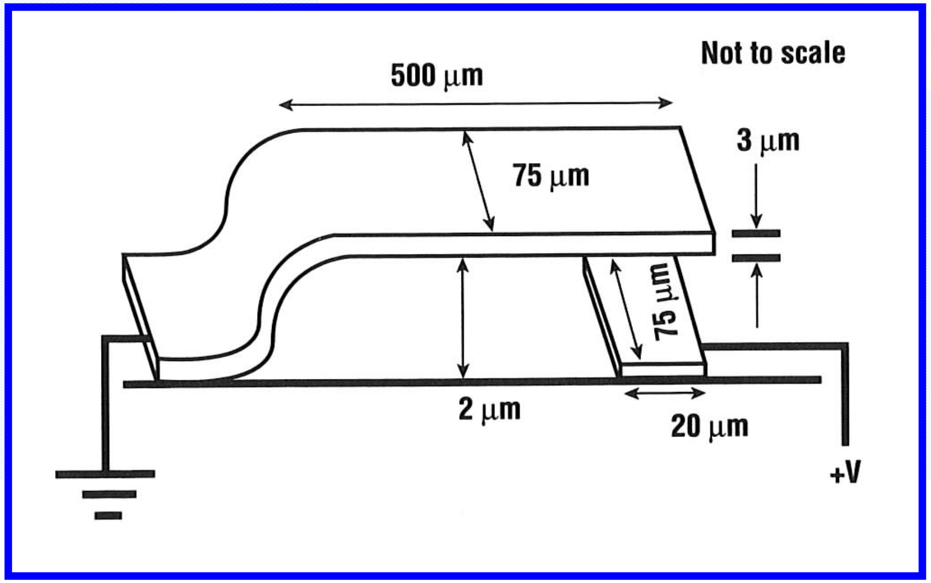
For silicon, $E = 190$ GPa and $\nu = 0.28$.

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

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=1.17um, σl=12.3 MPa, σt=3.45 MPa

2) σmax= $4.3*10^7$ Pa, a=150 um

3) fo= 4.39 kHz

4) V=9.6V


That's All Folks!