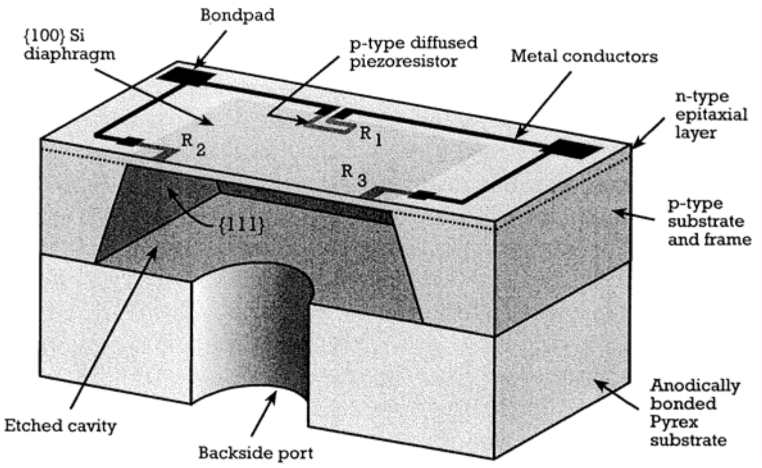
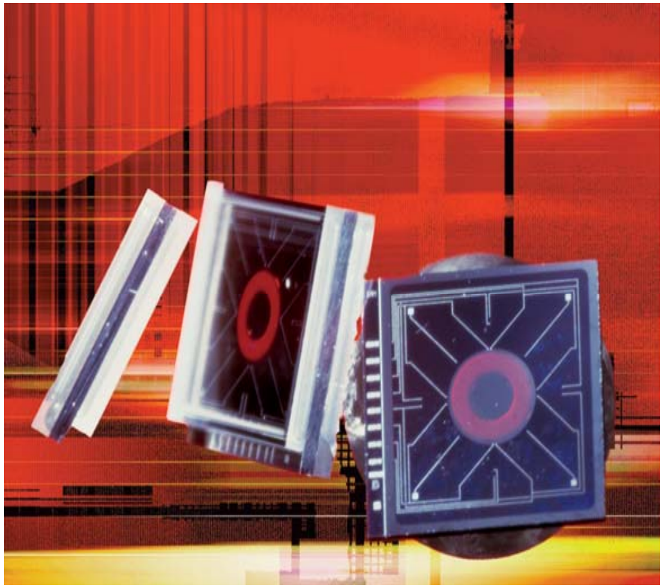
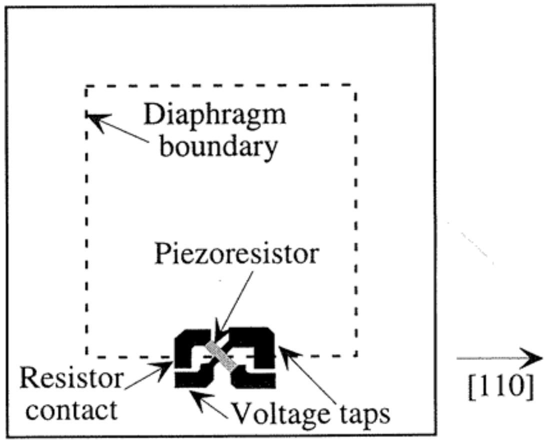
Piezoresistive pressure sensors



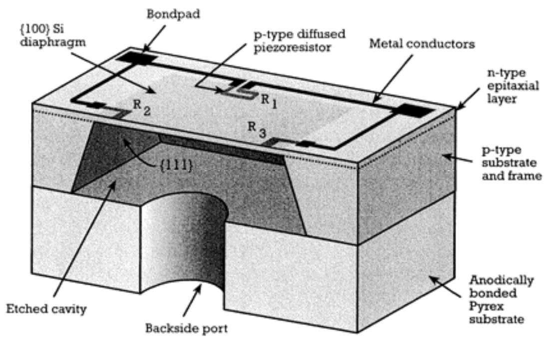


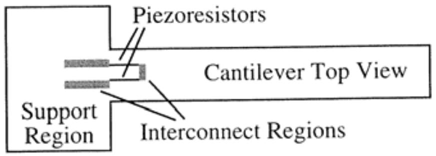


Two sensing principles

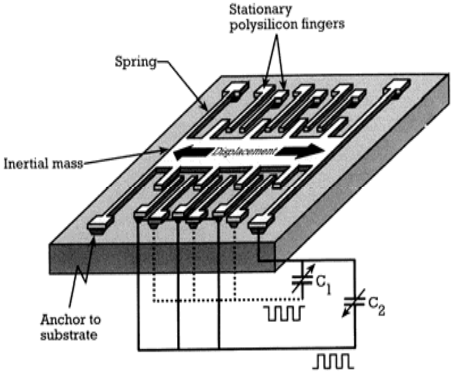
- <u>Piezoresistive</u>
- measure mechanical stress in doped resistor-area
- <u>diaphragm</u> pressure sensor
- bending <u>beam</u> due to
  - volume forces (e.g. acceleration)
  - end force (e.g. protein attached)

- <u>capacitive</u>
- measure deflection (distance to other capacitor plate)
- <u>diaphragm</u> pressure sensor
- bending <u>beam</u> due to
  - volume forces (e.g. acceleration)
  - end force (e.g. protein attached)

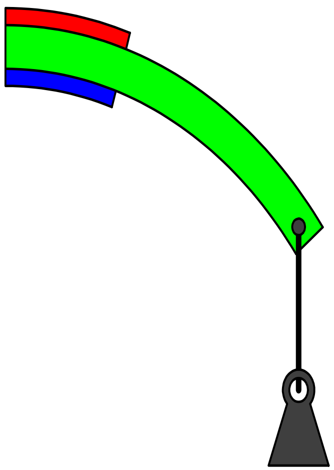




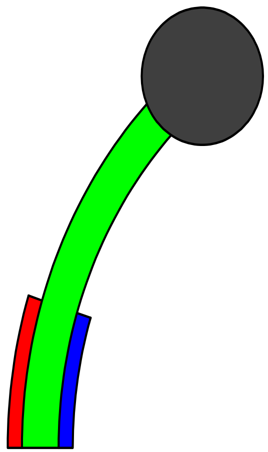
8.4. An example using piezoresistance to measure the deflection of a cantilever.



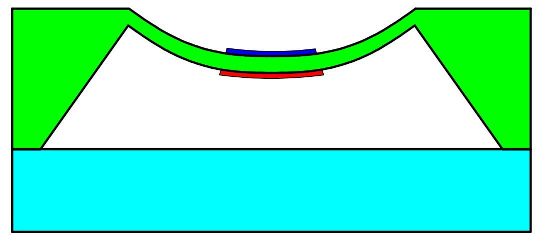
Piezoresistive sensing applications



Load cell

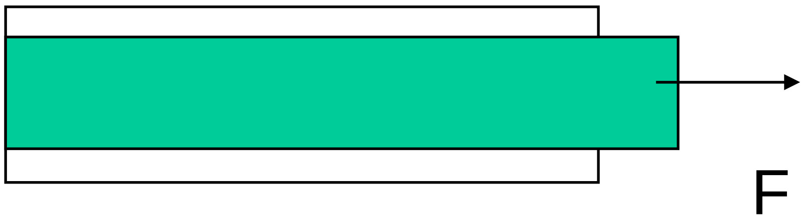


Accelerometer



Pressure sensor

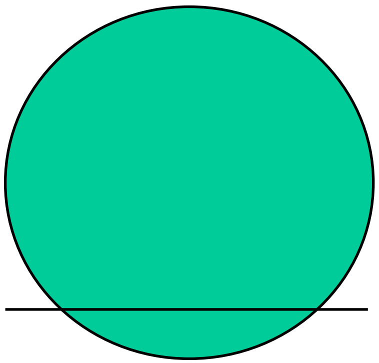
Relation between stress and strain in a coordinate system with axes equivalent to the axes of the unit cell

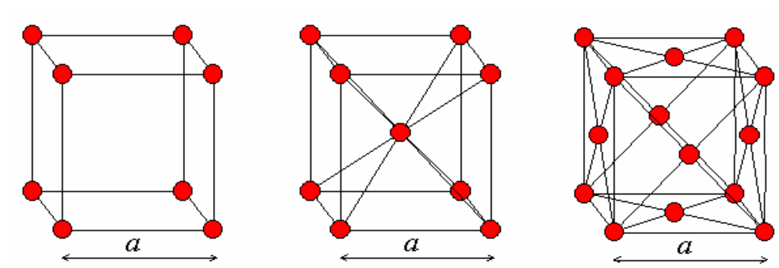


$\sigma_x = E\,\varepsilon_x$

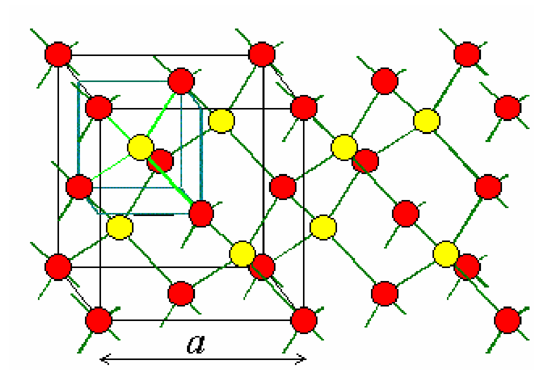
1D Hooke's law

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yx} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix}$$





(a) (b) (c)



Small deflections
Beam equation, plate equation

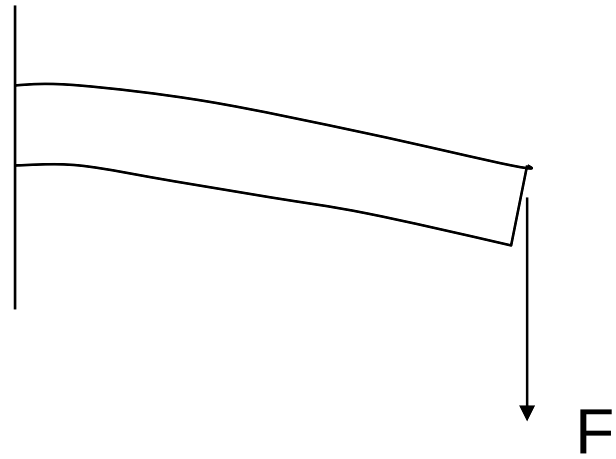
- Beam equation:

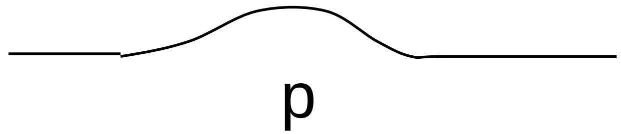
$$EI\frac{d^4 w}{dx^4} = q$$

- Plate equation:

$$D\left(\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial^2 x \partial^2 y} + \frac{\partial^4 w}{\partial y^4}\right) = q(x,y)$$

- Find displacement and stress





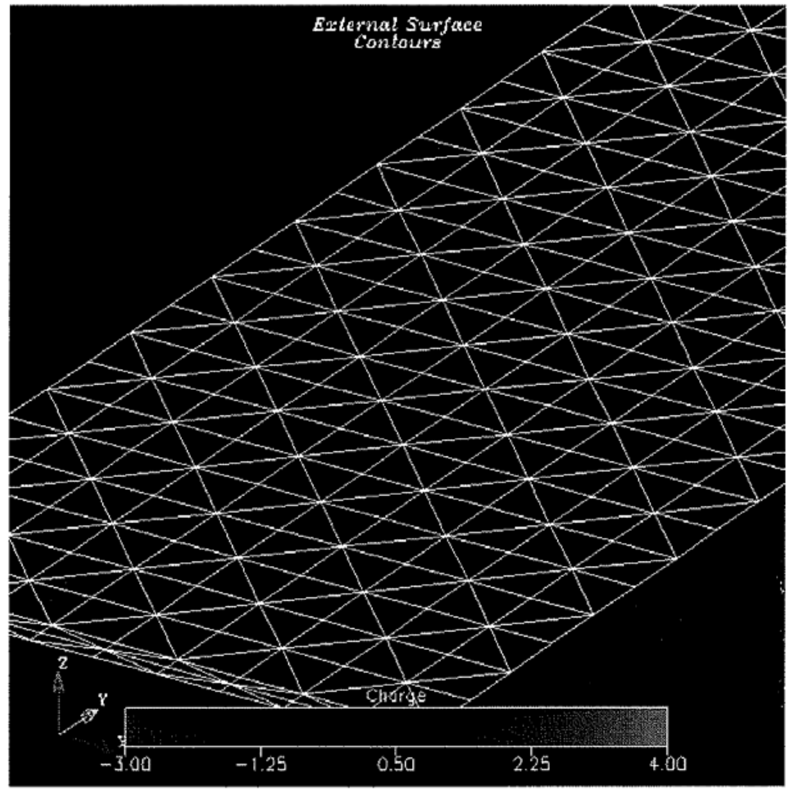
General: Finite Element Analysis

- Solve Navier's equation (partial differential equation)

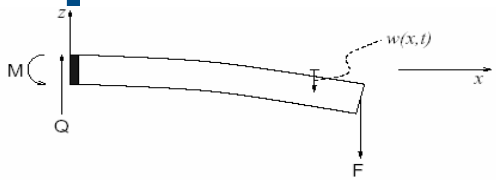
$$(\lambda + \mu)\nabla(\nabla \cdot \vec{u}) + \mu\nabla^2\vec{u} = 0$$

- Divide domain into elements
- Approximation of function (solution to partial differential equation) over domain
- Simple function over each element (linear, parabolic)
- Connect elements at nodes

Figure T1-20 Viewing the mechanical mesh



Example: beam with end load



- Assumption: constant rectangular cross section, width a and height b
- By integration or from tables: $I = ab^3/12$
- Loads: $q = 0$, end load D prescribed
- Governing equation:

$$EI\frac{d^4w}{dx^4} = 0$$

- Clamped left end $x = 0$: $w(0) = w'(0) = 0$
- Right end with load: $EIw'''(L) = F$, $s'' = 0$
- Integrate differential equation four times:

$$w(x) = C_1x^3 + C_2x^2 + C_3x + C_4$$

- Determine $C_1, \ldots, C_4$ from end conditions:

$$w(x) = \frac{FL^3}{6EI}\left(\frac{x}{L}\right)^2(3 - x/L)$$

$$w(x) = \frac{FL^3}{6EI}\left(\frac{x}{L}\right)^2(3 - x/L)$$

- Moment:

$$M(x) = F(L - x)$$

- Shear force (constant here):

$$Q(x) = F$$

- Normal stress in a cross section:

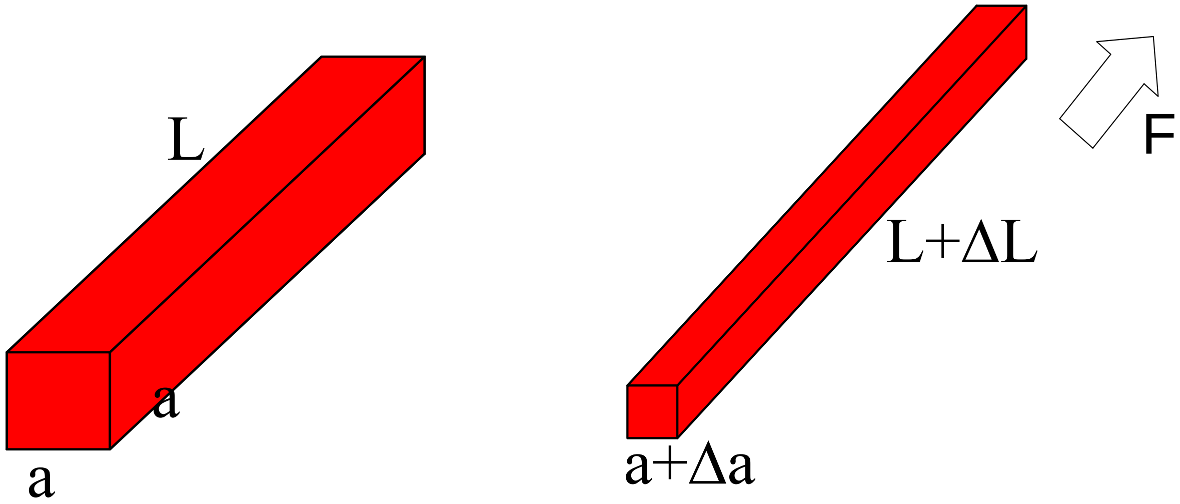
$$\sigma_{xx} = z\frac{F}{I}(L - x)$$

- Largest stress at $x = 0$ and for $z = \pm b/2$

35

Resistor change in metal strain gauges

Mainly due to change of resistor FORM (geometric effect)



$R_0 = \rho\, L/a^2$

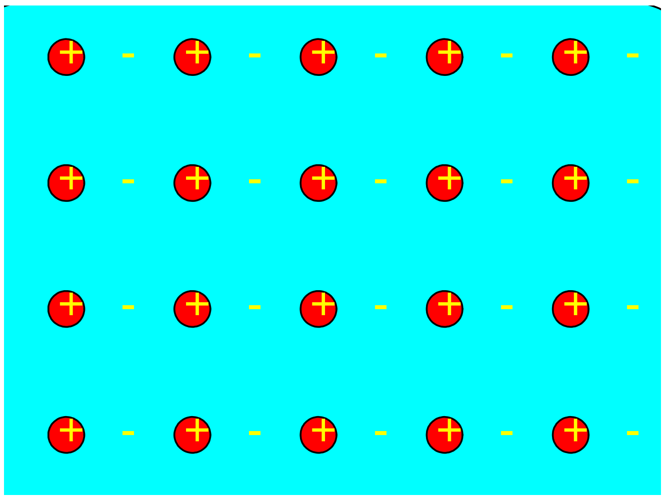
$\Delta a/a = -\nu\, \Delta L/L$

$\nu = 0.3$

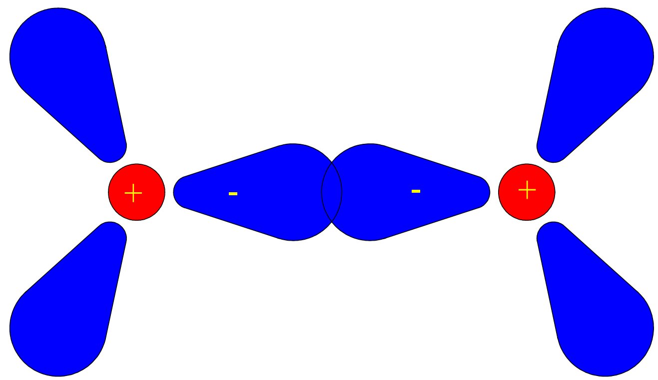
For silicon: large RESISTIVITY change with stress

(not mainly a geometric resistor-change factor)

Metal:



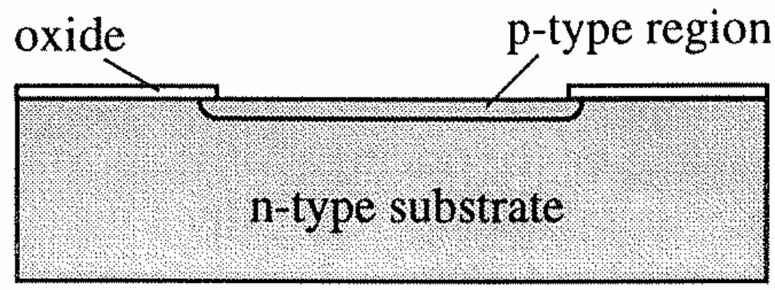
Silicon:



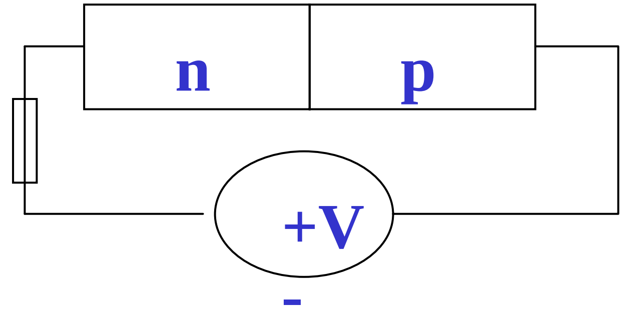
$\Delta R/R \approx 2\ \varepsilon$

$\Delta R/R \approx 90\ \varepsilon$

Electronics (Chapter 14.1 - 14.4)
Doped resistors



Define a p-type circuit
in a n-type wafer



n-type wafer must be at positive potential relative to the p-type circuit

Reverse biased diode → no current between circuit and wafer/substrate

Alternative methods:
- SOI
- Surface micromachining

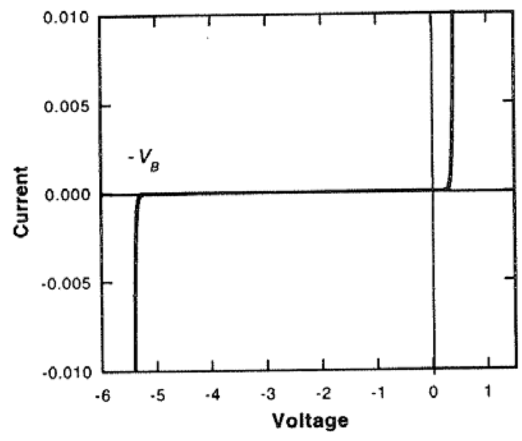


Figure 14.3. A typical diode current-voltage characteristic.

The resistivity changes with the mechanical stress

- E - electric field, three components
- j - current density, three components
- ρ_0 – homogeneous resistivity, unstressed silicon

- When mechanical stress is applied, the resistivity changes depending on the stress in different directions and the piezo coefficients

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \rho_0 \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix} + \rho_0 \begin{bmatrix} d_1 & d_6 & d_5 \\ d_6 & d_2 & d_4 \\ d_5 & d_4 & d_3 \end{bmatrix} \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix}$$

Silicon: Three independent piezoresistive coefficients

- Example of piezoresistive coefficients:

- doping: p-type
- sheet resistivity: 7.8 Ωcm

- value of Π_{11}= 6.6 10^{-11} Pa^{-1}
- value of Π_{12}=-1.1 10^{-11} Pa^{-1}
- value of Π_{44}= 138 10^{-11} Pa^{-1}

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \rho_0 \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix} + \rho_0 \begin{bmatrix} d_1 & d_6 & d_5 \\ d_6 & d_2 & d_4 \\ d_5 & d_4 & d_3 \end{bmatrix} \begin{bmatrix} j_1 \\ j_2 \\ j_3 \end{bmatrix}$$

$$\begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \end{bmatrix} = \begin{bmatrix} \Pi_{11} & \Pi_{12} & \Pi_{12} & 0 & 0 & 0 \\ \Pi_{12} & \Pi_{11} & \Pi_{12} & 0 & 0 & 0 \\ \Pi_{12} & \Pi_{12} & \Pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \Pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \Pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \Pi_{44} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yx} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix}$$

  - Equations 18.3, 18.4, 18.5 in Senturia

Dependence of piezoresistivity on doping

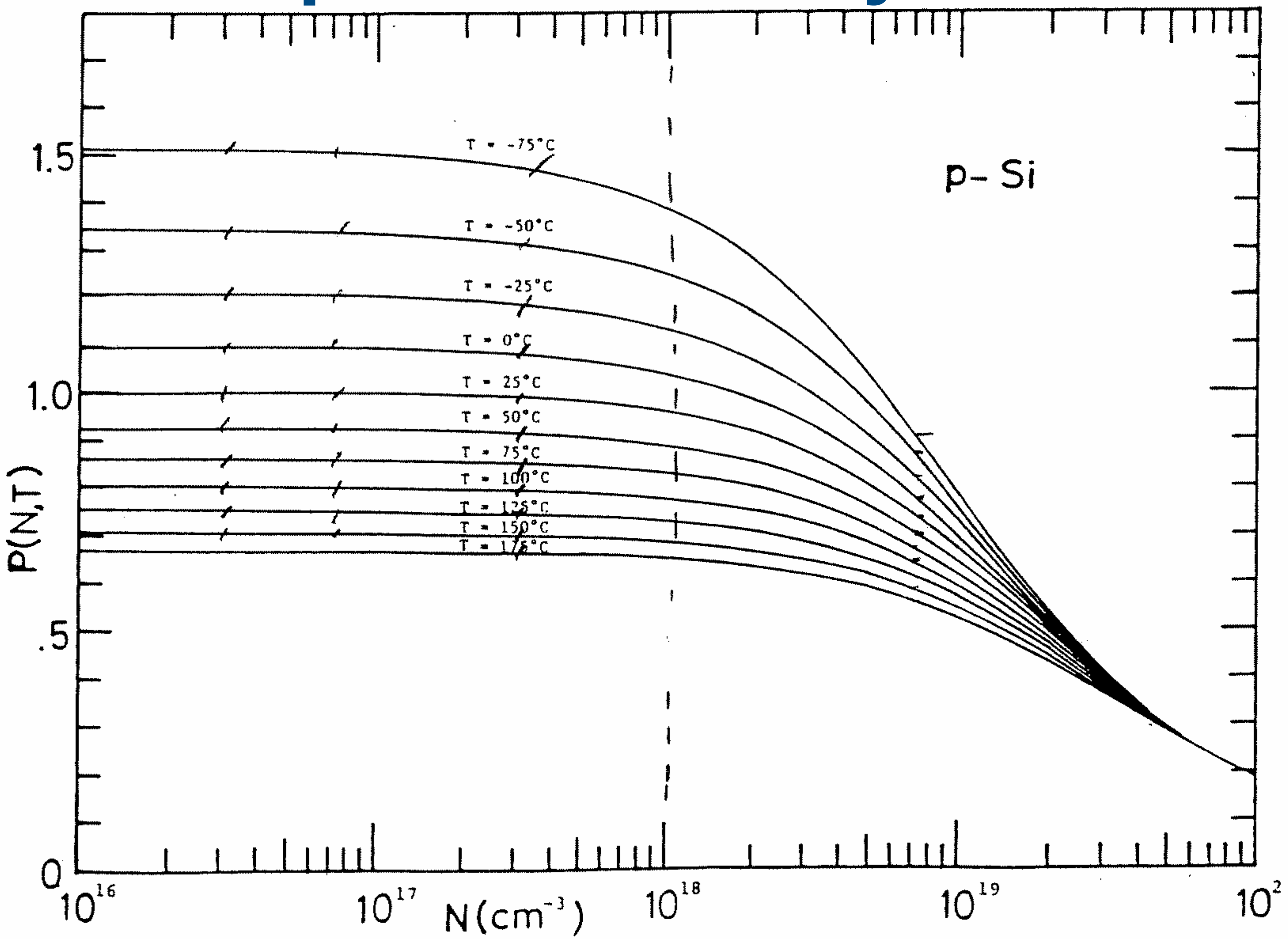
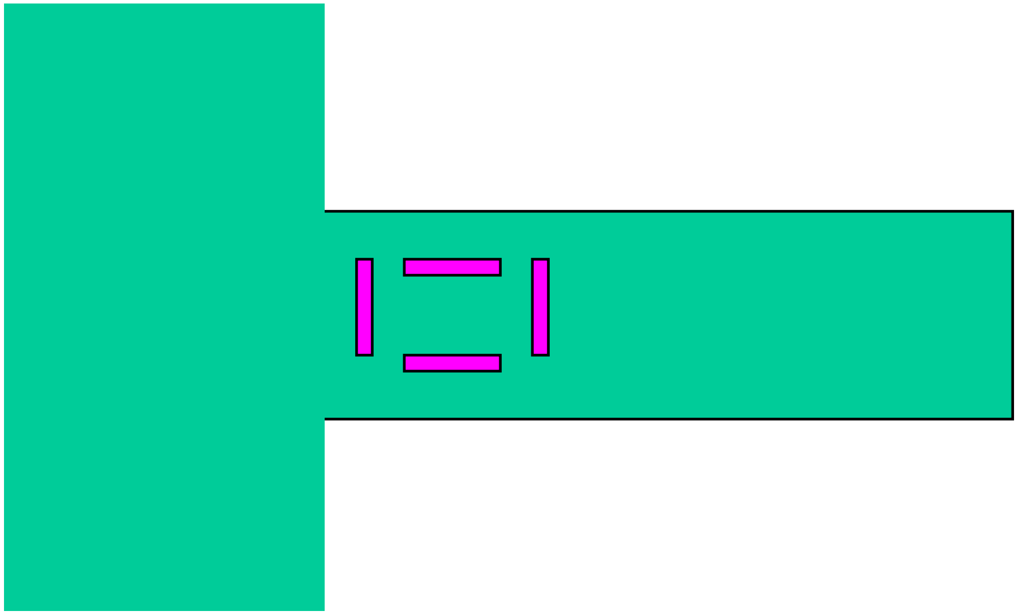


Fig. 9. Piezoresistance factor $P(N, T)$ as a function of impurity concentration and temperature for p-Si.

Long, narrow resistors

- Pre-calculated “piezocoefficients” that enables the designer to calculate the resistivity change for a long, narrow resistor
- Often given for a resistor that is placed in the <110> direction
- Transverse and longitudinal coefficients



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

The resistor axis is defined according to the direction of the current through the resistor

Resistors along <110> direction in (100) wafers

- Much used direction for piezoresistors, bulk micromachining
- Pre-calculated longitudinal and transverse piezo-coefficients

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

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

- σ positive: tensile stress
- σ negative: compressible stress
- π positive: increased resistivity with tensile stress
- π negative: decreased resistivity with tensile stress

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

- p-type silicon: π_{44} dominates

Beam accelerometer

- Long resistors in <110> direction

$$\pi_{l,110} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$

$$\pi_{t,110} = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44})$$

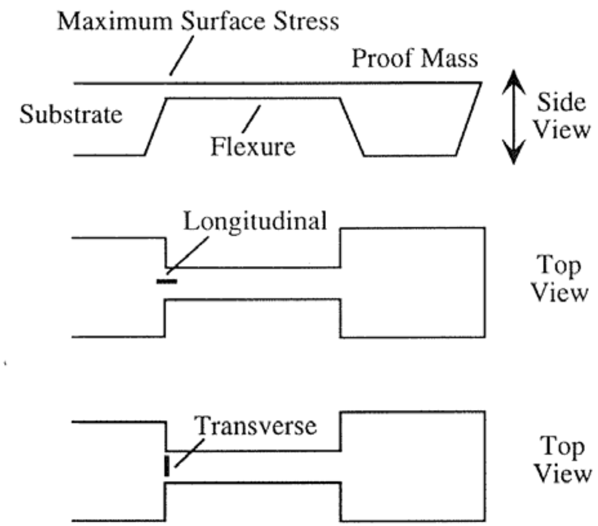


Figure 18.1. Illustrating lateral and transverse piezoresistor placements using an accelerometer flexure as an example.

- Piezoresistive coefficients

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

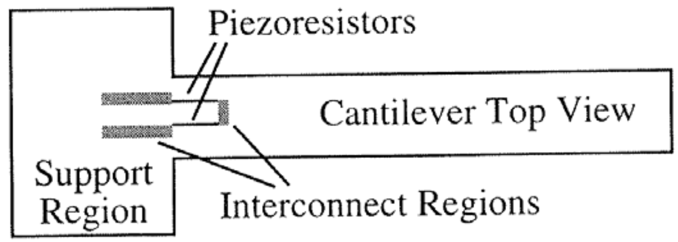
Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ω-cm	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1

n-type: π_l = -31.2 π_t = -17.6

p-type: π_l = 71.8 π_t = -66.3

Cantilever with piezoresistors

- length 200 μm
- width 20 μm
- thickness 5 μm



8.4. An example using piezoresistance to measure the deflection of a cantilever.

- point load at free end
- 1 μm deflection

$$w = \frac{3}{2} w_{max} \left(\frac{x}{L_c}\right)^2 \left(1 - \frac{x}{3L_c}\right)$$

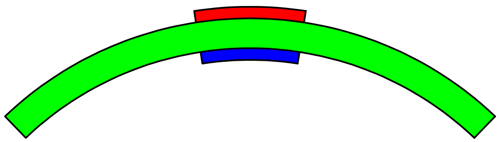
- p-type piezoresistor
- length 20 μm
- width 2 μm
- depth 0.2 μm

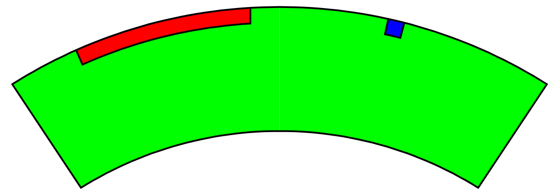
$$\frac{1}{\rho} = \left|\frac{d^2 w}{dx^2}\right| = \frac{3 w_{max}(L_c - x)}{L_c^3}$$

$$\sigma_l = \frac{EH}{2\rho} = \frac{3 E w_{max}(L_c - x)}{2 L_c^3}$$

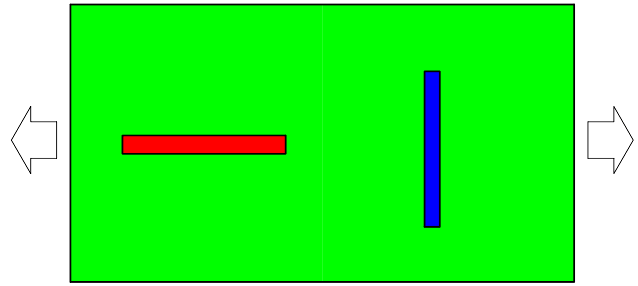
- $\Delta R/R = \pi_l \sigma_l = 0.02$

Placement of piezoresistors on diaphragm





Over/under konfigurasjon
er ikke praktisk i silisium.



Men vi kan snu retningen
på motstandene

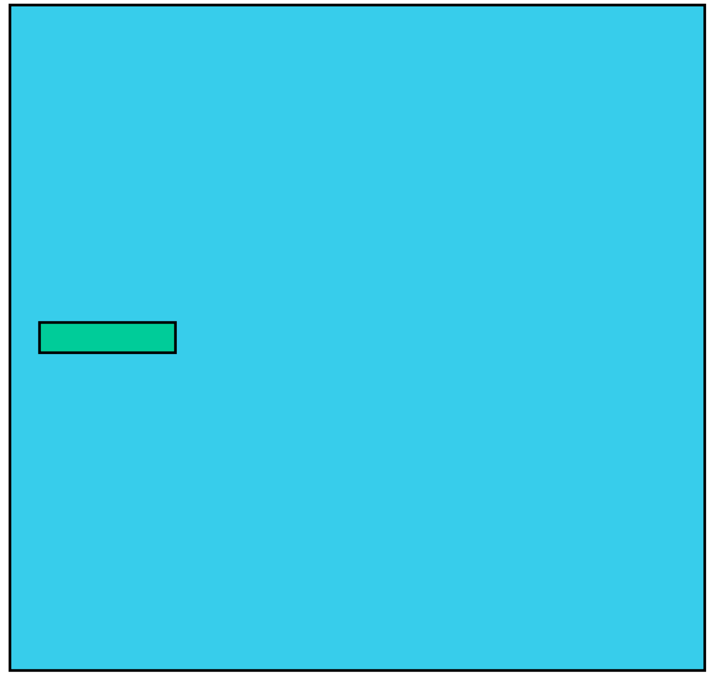
Piezoresistor placed normal to diaphragm edge

- Apply pressure from above
- Diaphragm bends down
- Piezoresistor is stretched longitudinally
- σ_l is positive, tensile stress
- Rough argument for mechanical stress in transversal direction: stress must avoid contraction: $\sigma_t = \sigma_l \nu$
- Transverse stress is tensile/positive
- Change in resistance:

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

$$\Delta R_1 / R_1 = (\pi_l + \nu \pi_t) \sigma_l$$

- (π_t is negative)
- Resistance increases



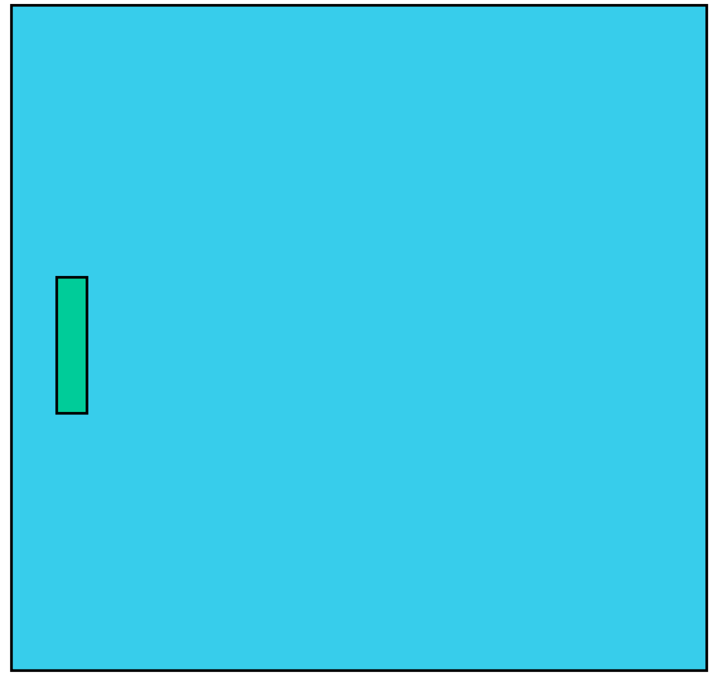
p-type piezoresistor along <100> direction in (100) wafer

Piezoresistor placed parallel to diaphragm edge

- Apply pressure from above
- Diaphragm bends down
- Piezoresistor is stretched transversally
- σ_t is positive
- Rough argument for mechanical stress in longitudinal direction: stress must avoid contraction: $\sigma_l = \sigma_t \nu$
- Tensile, positive stress in longitudinal dir.
- Change in resistance:

$$\Delta R_2 / R_2 = (\pi_t + \nu \pi_l)\sigma_t$$

- (π_t is negative)
- Resistance decreases

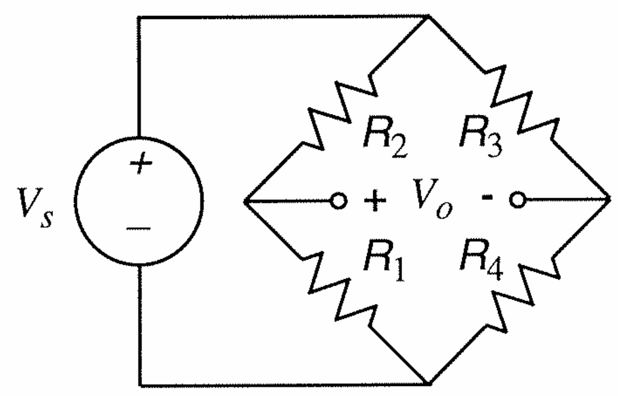


p-type piezoresistor along <100> direction in (100) wafer

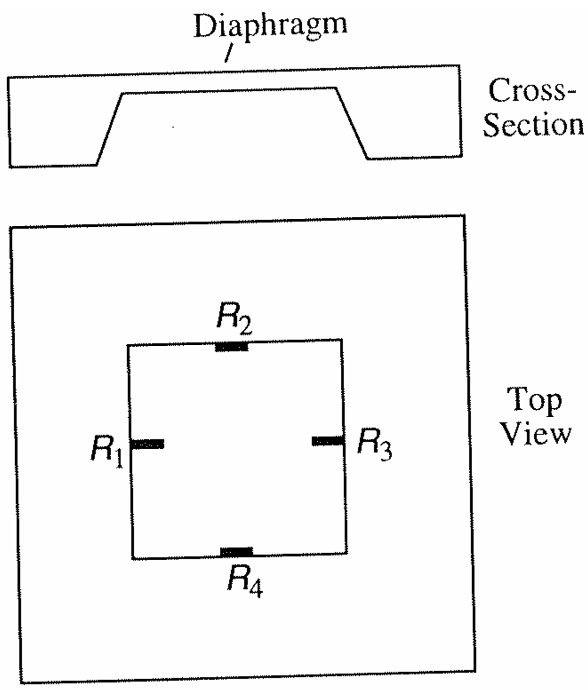
Membrane pressure sensor

$$\frac{\Delta R_1}{R_1} = \left(67.6 \times 10^{-11}\right) \sigma_l$$

$$\frac{\Delta R_2}{R_2} = -\left(61.7 \times 10^{-11}\right) \sigma_l$$



Wheatstone-bridge circuit constructed from the resistors in Fig. 18.2.



Wheatstone bridge circuit

- <100> direction

$\pi_l = 71.8$ $\quad \sigma$ positive, tensile stress

$\pi_t = -66.3$ $\quad \sigma$ negative, compressible stress

$$V_0 = V_s\left(\frac{R_2}{R_2+R_1} - \frac{R_3}{R_3+R_4}\right)$$

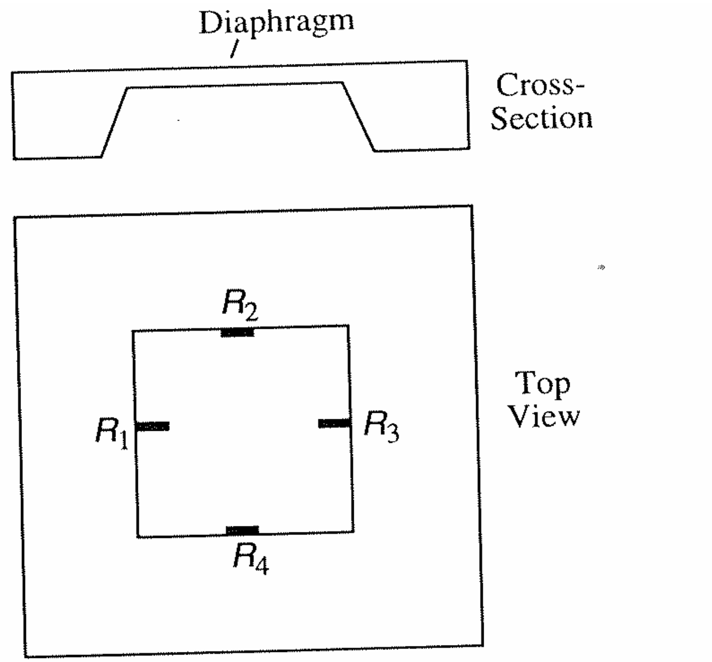
$$R_1 = R_1 - \Delta R$$

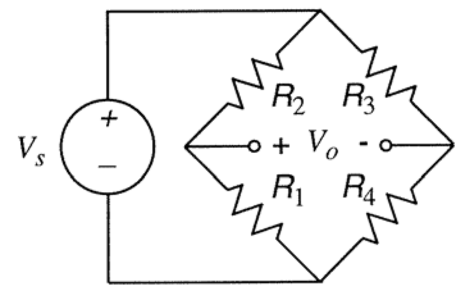
$$R_2 = R_2 + \Delta R$$

$$R_3 = R_3 - \Delta R$$

$$R_4 = R_4 + \Delta R$$

$$V_0 = V_s\left(\frac{\Delta R}{R}\right)$$

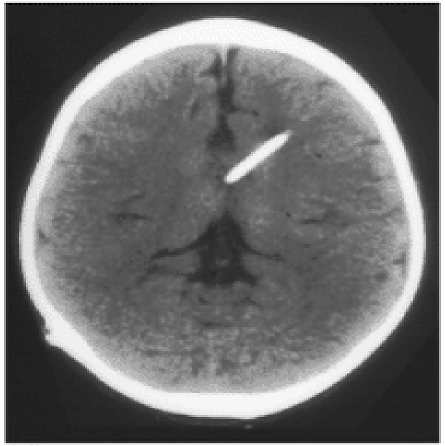




Wheatstone-bridge circuit constructed from the resistors in Fig. 18.2.

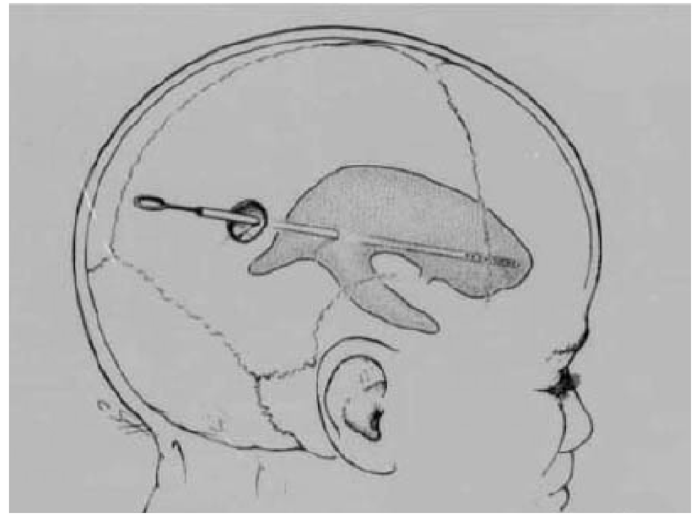
Pressure Measurement in Medicine Example: Hydrocephalus

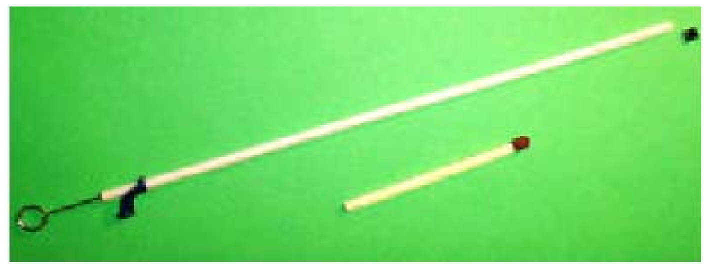
- abnormal accumulation of brain fluid
- increased brain pressure
- occurs in approximately one out of 500 births
- treated by implantation of a shunt system

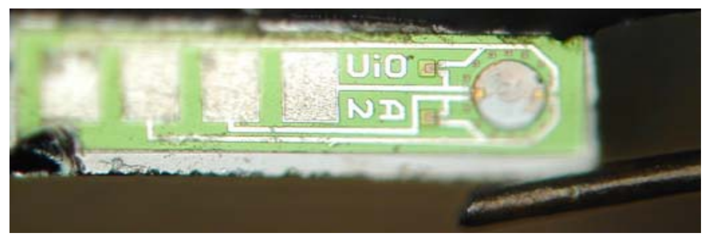


Complex requirements for the measurement system

- Small dimensions
- Effective pressure transmission
- No wires through the skin
- No batteries
- Material acceptable for MRI scans

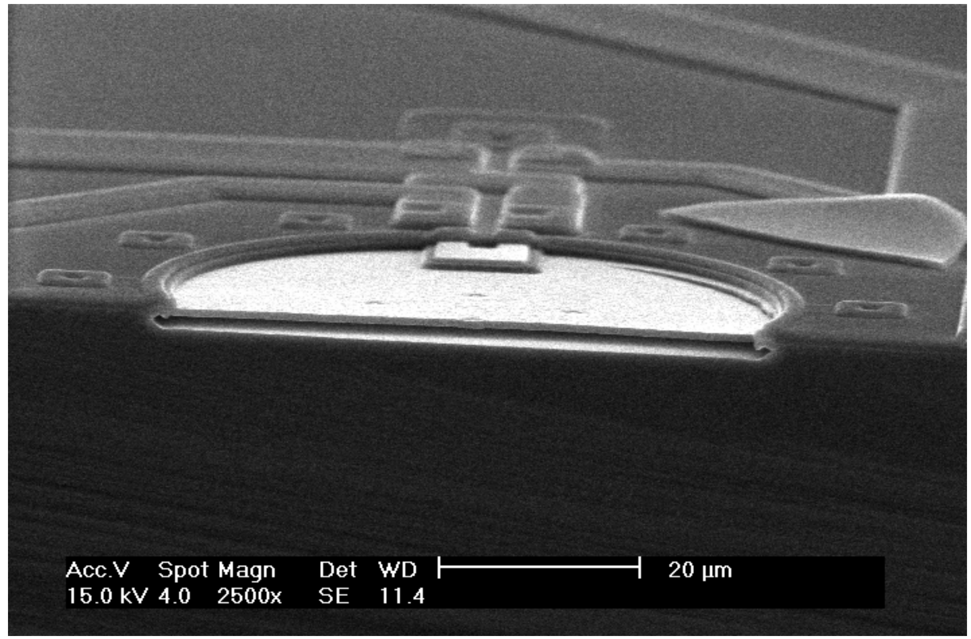




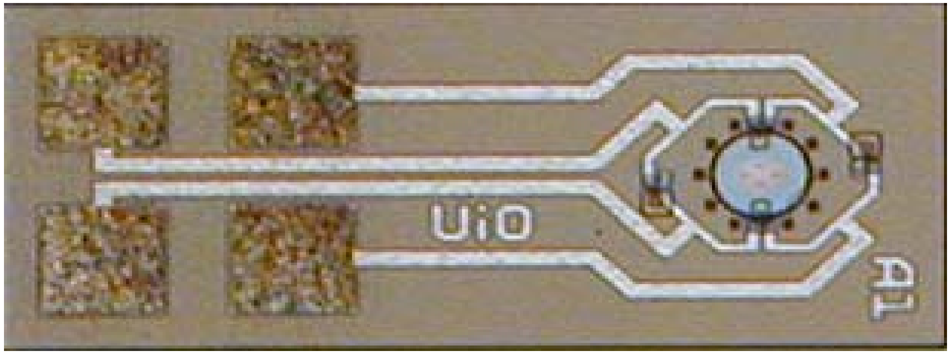


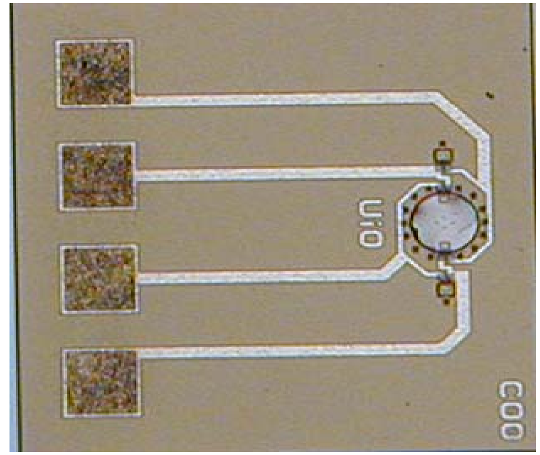
The sensor

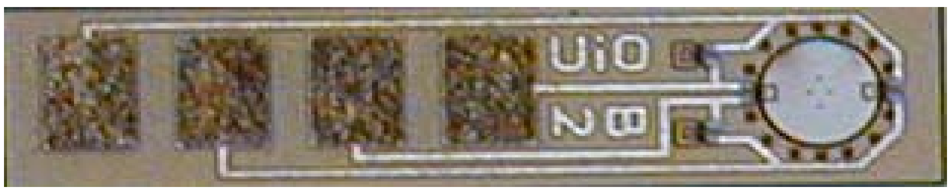
- Piezoresistive
- Surface micro machined
- Wheatstone bridge
  - two piezoresistors on diaphragm
  - two on substrate for temperature reasons
- Absolute pressure sensor

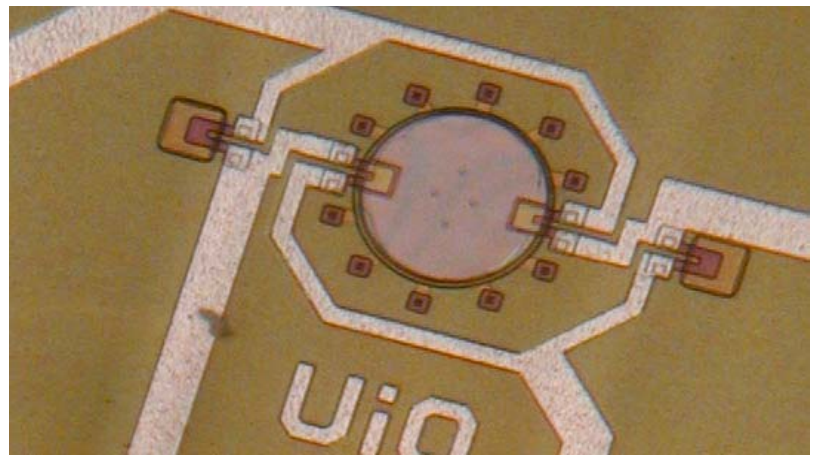


Sensor design

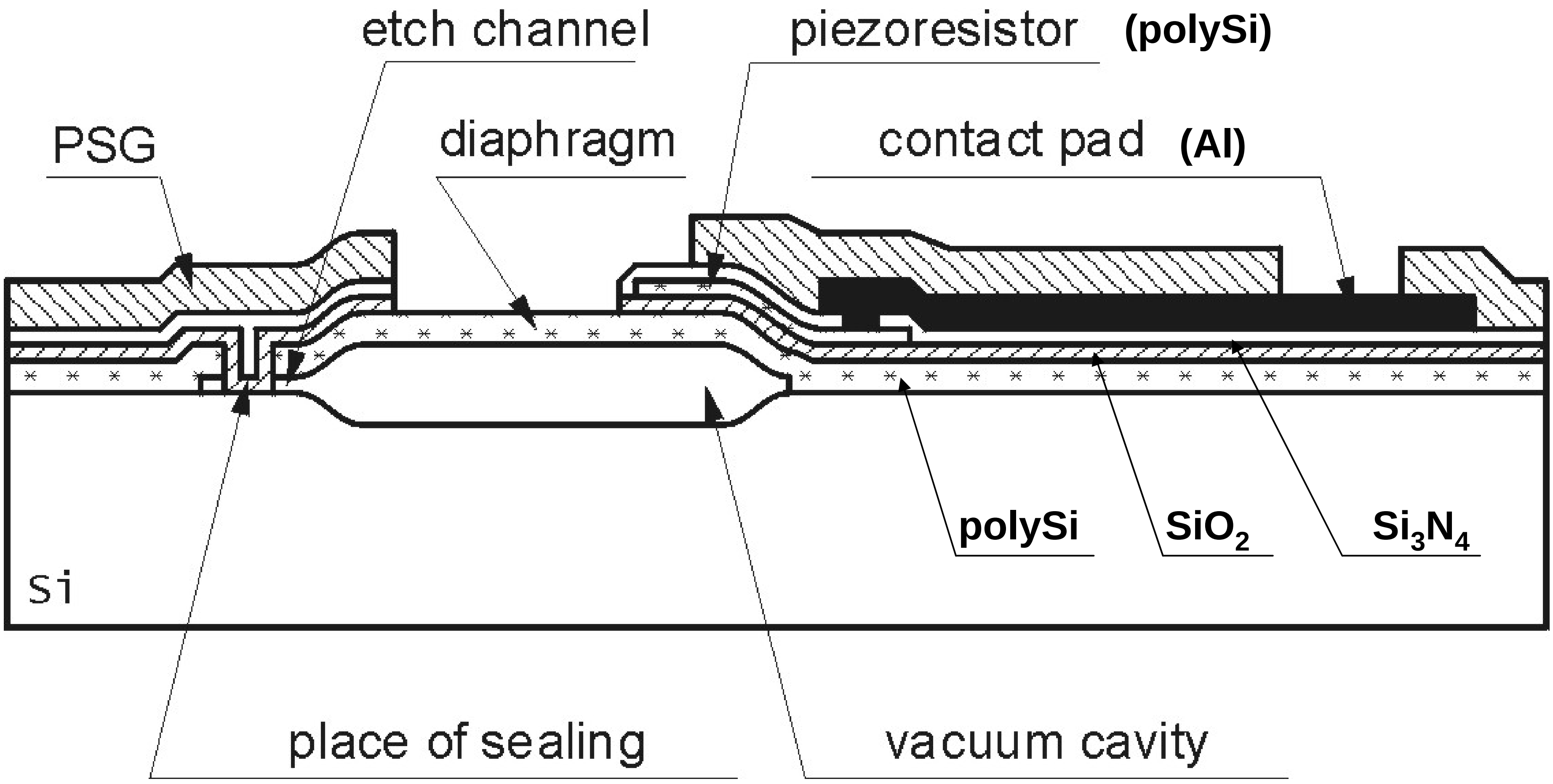








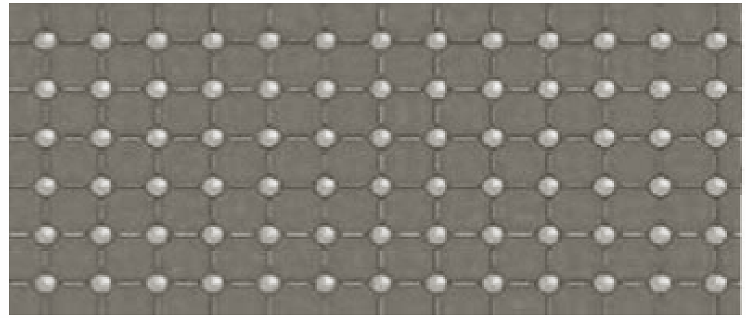
Sensor design

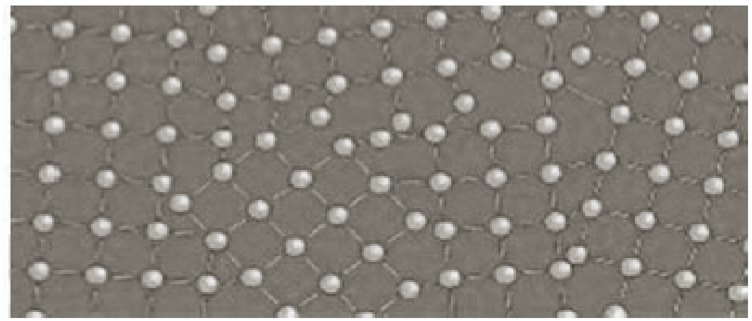


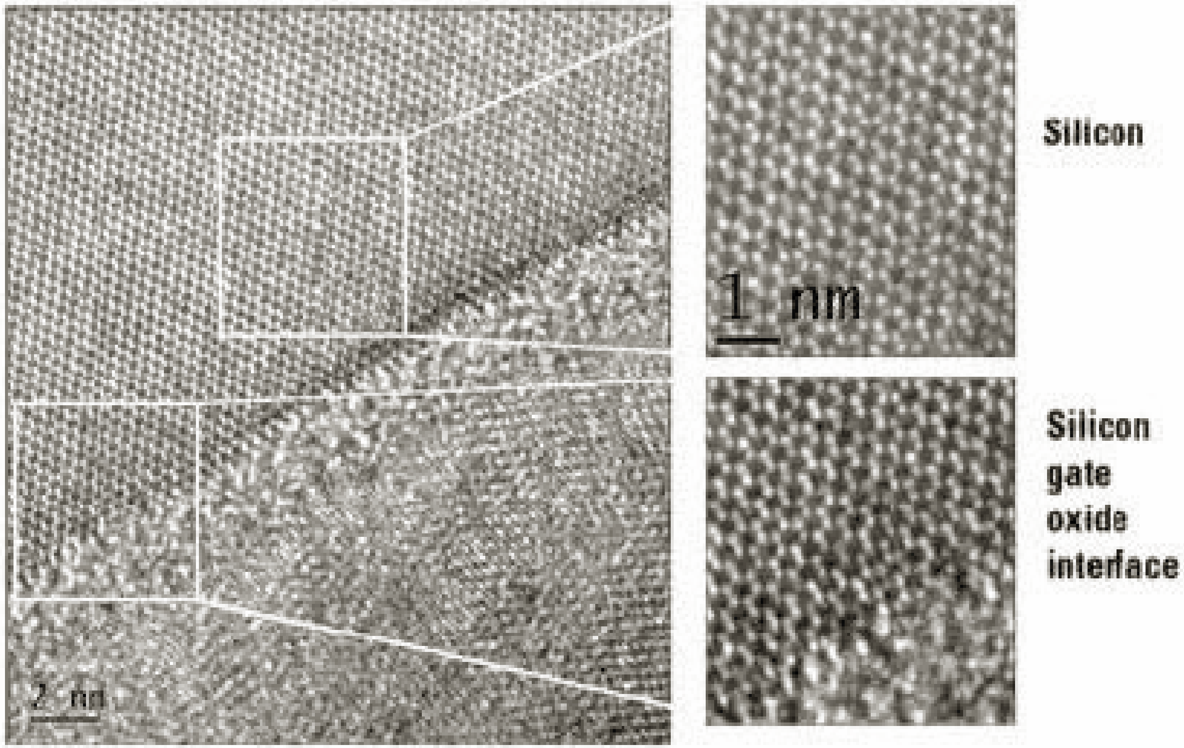
(not to scale)

Polysilicon

- Silicon exists in any of three forms:
  - monocrystalline silicon
  - poly crystalline silicon, also called polysilicon or poly-Si
  - amorphous
- The extent of regular structure varies from amorphous silicon, where the atoms do not even have their nearest neighbors in definite positions, to monocrystalline silicon with atoms organized in a perfect periodic structure.



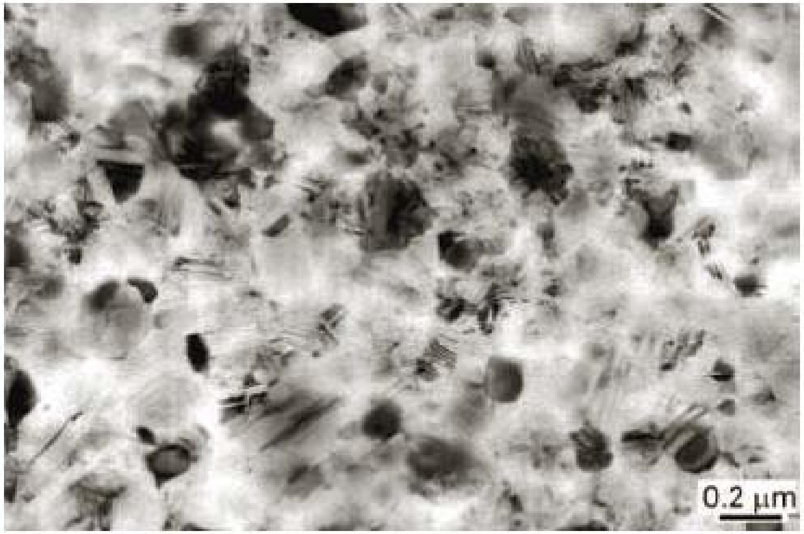




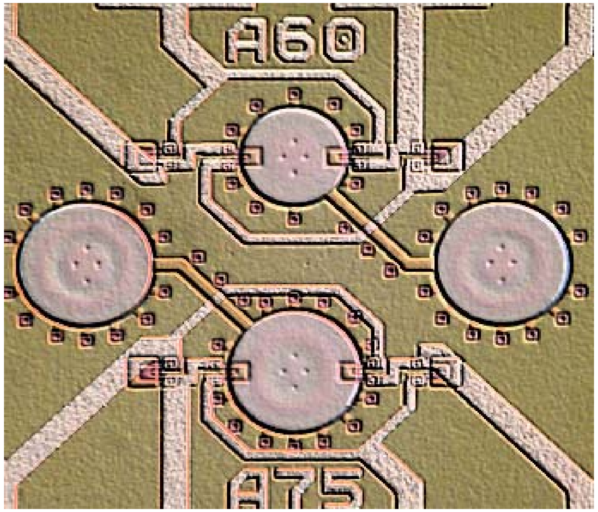
Transmission electron microscope (TEM) picture of a Metal-Oxide Semiconductor Field-Effect Transistor (MOSET) gate consisting of a 2 nm thick amorphous silicon oxide layer between crystalline silicon (top) and polycrystalline silicon (bottom). Image by Reed electronics group/FEI Company.

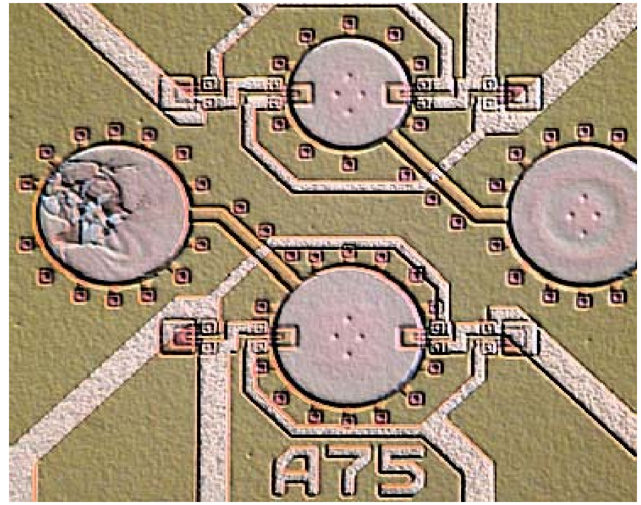
Piezoresistivity in polysilicon

- The piezoresistive coefficients loose sensitivity to crystalline direction
- Average over all orientations
- Gauge factor of 20 – 40, about one fifth of the gauge factor of monocrystalline silicon
- Gauge factor up to 70% of monosilicon has been reported
- The structure; i.e. the grain size and the texture (preferred orientation of the crystallites) is decisive for the piezoresistivity
- The longitudinal gauge factor is always larger than the transverse one



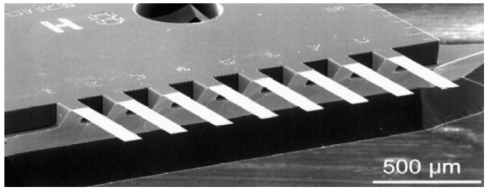
Functionality & sensitivity

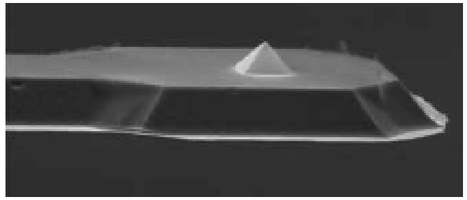


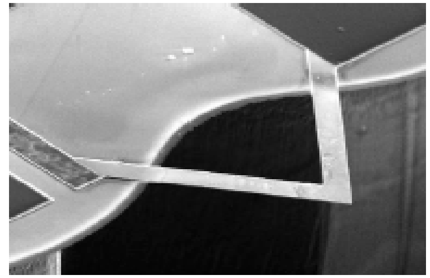


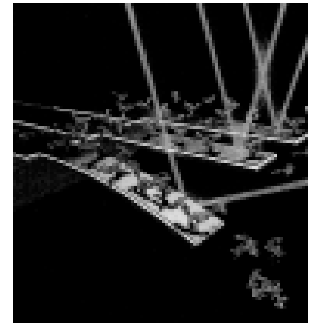
Bridge resistance before and after breaking dummy diaphragm.

Diaphragm diameter of sensor, um	75		60	
	before breaking	after breaking	before breaking	after breaking
Bridge resistance, Ohm	4244	4220	4236	4224
	4250	4227	4230	4217
	4271	4250	4215	4203
	4281	4259	4253	4240
	4257	4235	4213	4200
Resulting sensitivity (approximate), mV/V/atm	5.5		3.0	

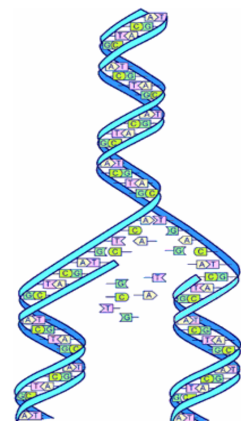






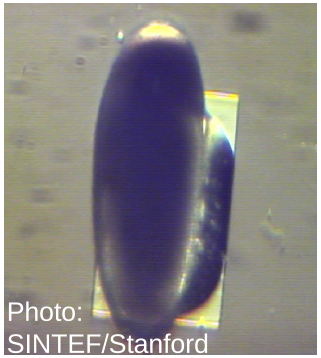


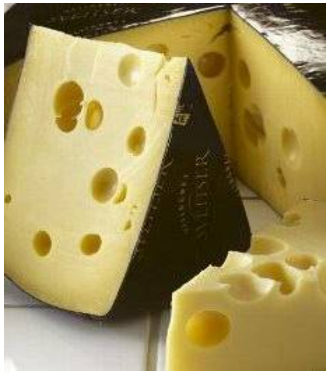
Microcantilevers with piezoresistiv sensing; applications in biochemical and chemical sensors



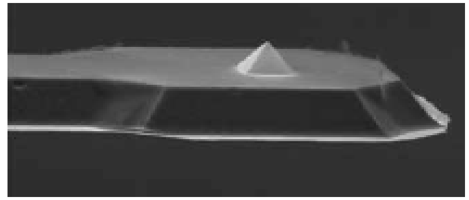
Application Areas

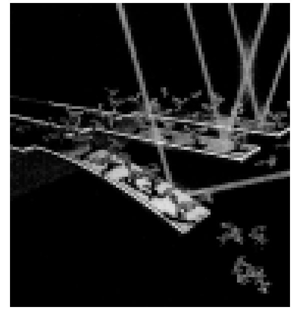
- Life sciences research
- Medical diagnostics and analysis
- Drug discovery
- Drug delivery
- Environmental monitoring
- Process control e.g. oil industry and food industry
- Food analysis
- Security devices e.g. detection of explosives
- Energy technology including fuel cells





Beam Bending





- Beam bending
- The difference in surface tension (upper side/lower side) and the radius of curvature are related through

$$\frac{1}{R} = 6\left(\frac{1-\nu}{Eh^2}\right)(\Delta\sigma)$$

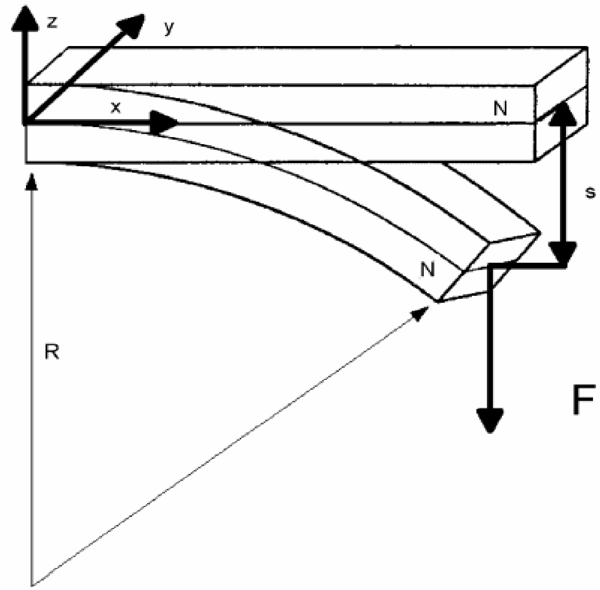
- For a cantilever
- ^

$$\frac{1}{R} = \frac{M}{EI} \qquad I = \frac{1}{12}bh^3$$

- Stoney's formula

$$s = \frac{3L^2(1-\nu)}{Eh^2}\Delta\sigma$$

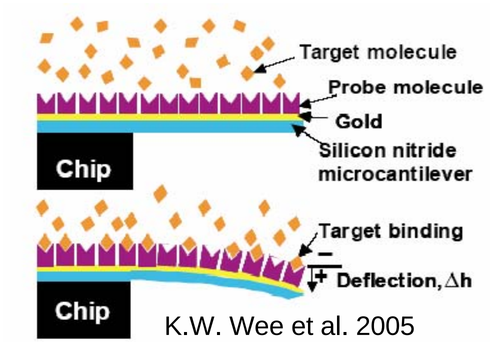
- Typical beam dimensions: 150 x 50 x 0,5 µm
- Beams often made of Si, SiN_x or a polymer width a thin functional layer on top of one of the beam surfaces, typical 30 nm



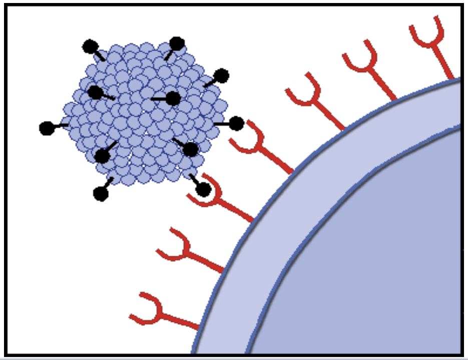
Ref: C. Ziegler, anal. Bioanal Chem 379 (2004)

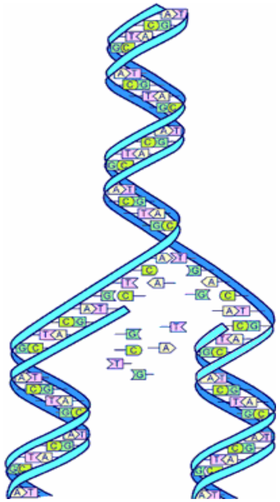
Add-on processes – bioactive layers

- Functional surfaces for attachment of:
  - proteins (antibodies)
  - single stranded oligo-nucleotides
  - glucose molecules
  - …
- Au or NiCr/Au films on silicon
- Commercial or customers' own biochemistry
- To be combined with lab-on-chip systems



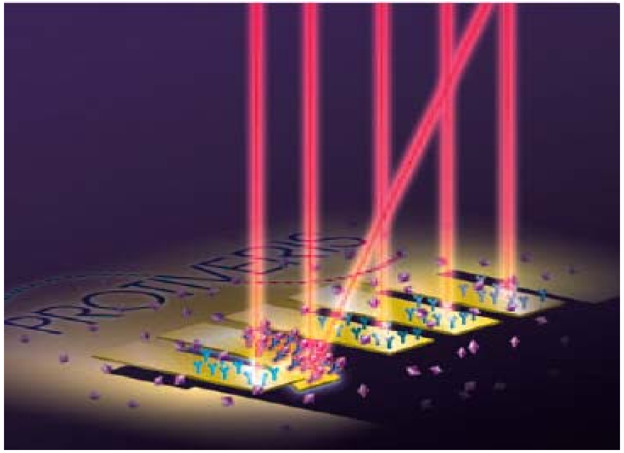
K.W. Wee et al. 2005

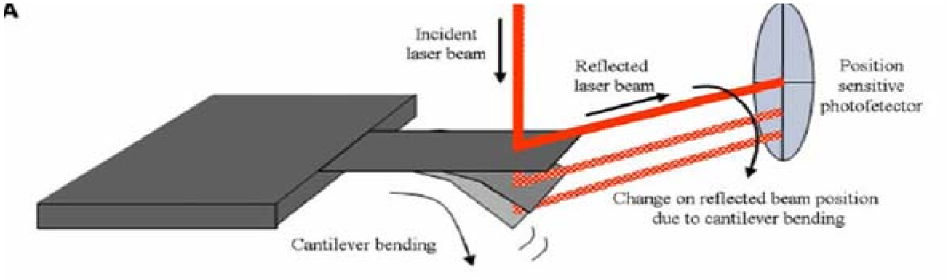




Påvisning av biokjemisk eller kjemisk effekt

- Optisk vektstangsprinsipp
- Interferometri
- Optiske filtre
- Kapasitiv
- Piezoresistiv





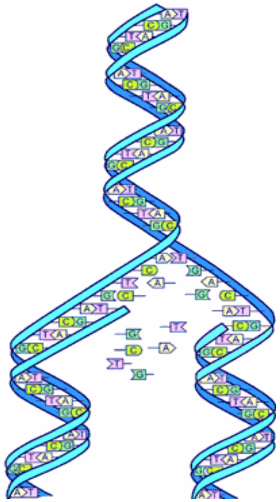
Bilde fra Protiveris, figur fra L. G Carrascosa et a. Trends in Analytical Chemistry, 25 (2006)

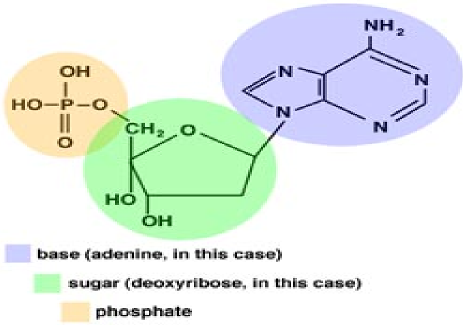
Piezoresistiv utlesning

+ Store og kostbare optiske komponenter samt tidkrevende laseroppstilling er unødvendig
+ Fungerer i både gass (luft) og væsker, også i ugjennomsiktige væsker
+ Utlesningselektronikk og temperaturkontroll kan integreres på samme chip som bjelken(e)
+ Temperaturen på bjelkene kan endres ved å endre strømmen gjennom motstandene, gjenbruk ved å bryte molekylbindinger?
- Innebygget støy som påvirker oppløsing og følsomhet
- Krever elektrisk tilkopling

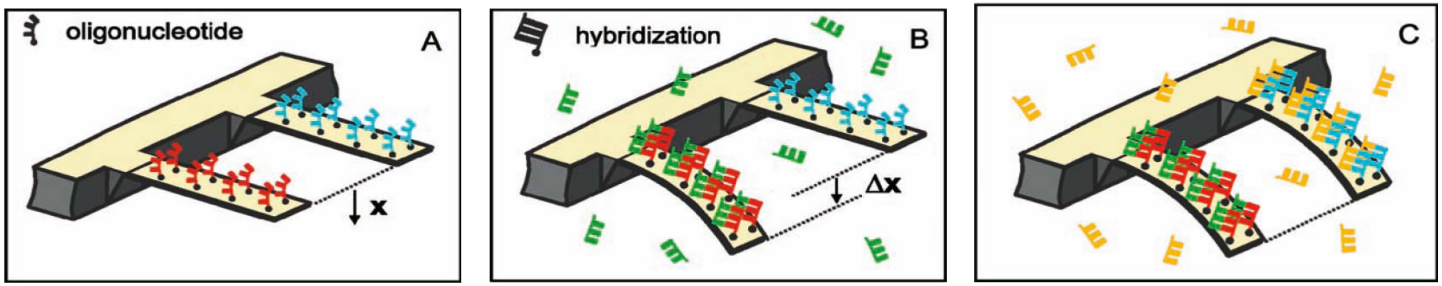
DNA-analyse

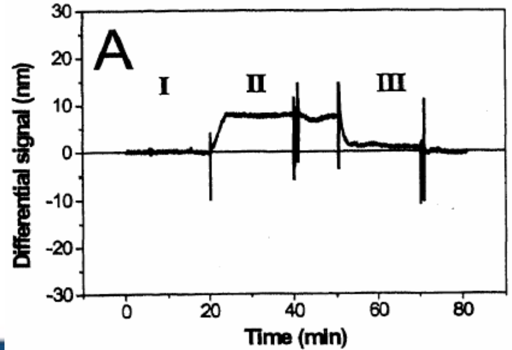
- Bjelkens overflate belagt med Au
- Differensiell måling
- To nukleotidkjeder bestående av 12 baser, hvor to av basene er ulike:
  - CTATGTCAGCAC
  - CTATGTAAGCAC
- Nedbøyning 1: 10 nm ,
- Nedbøyning 2:   0 nm
- Forskjeller i ett basepar kan detekteres!





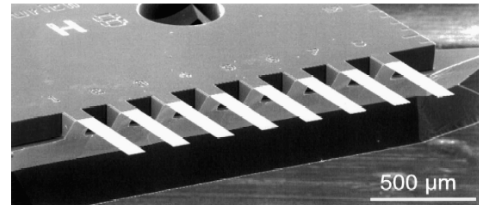
nukleotid

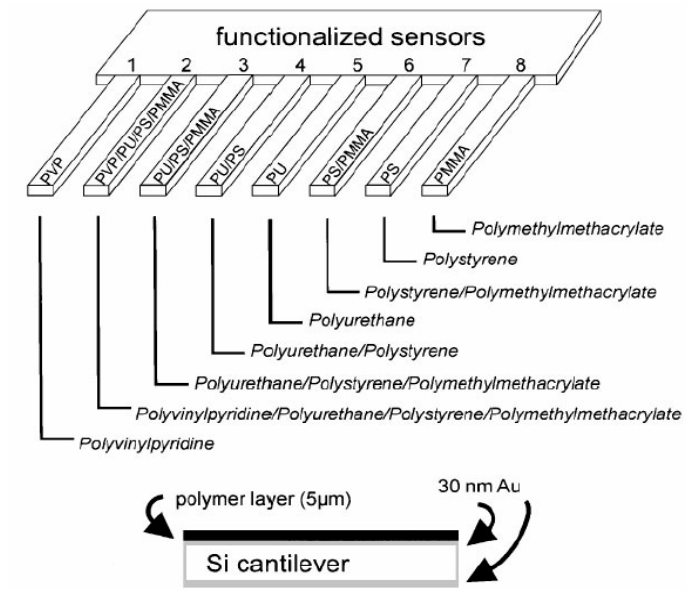


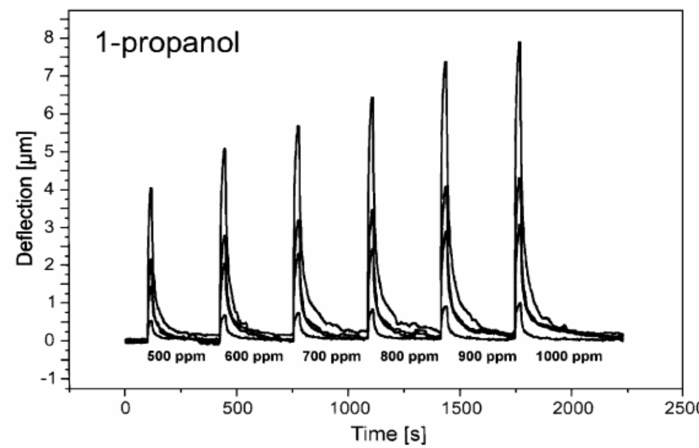


Ref.: J. Fritz et al. Science 288 (2000)

Elektronisk nese







- Hver bjelke er belagt med ulike polymerer (~ 5µm) på gull (30 nm)
- Polymerlagene sveller under kontakt med gasskomponenter
- Svelle- eller fordampnings-prosessens forløp er avhengig av damptrykk og løselighet i den enkelte polymer og gir et ”fingeravtrykk”
- Informasjonen analyseres av et mønstergjenkjenningssystem
- Følsomhet for 1-propanol: ca.30 ppm/µm nedbøyning

Ref.: M. K Baller et al. Ultramicroscopy 82 (2000)