POLITECNICO MILANO 1863

Strain and Force sensors

SENSOR SYSTEMS

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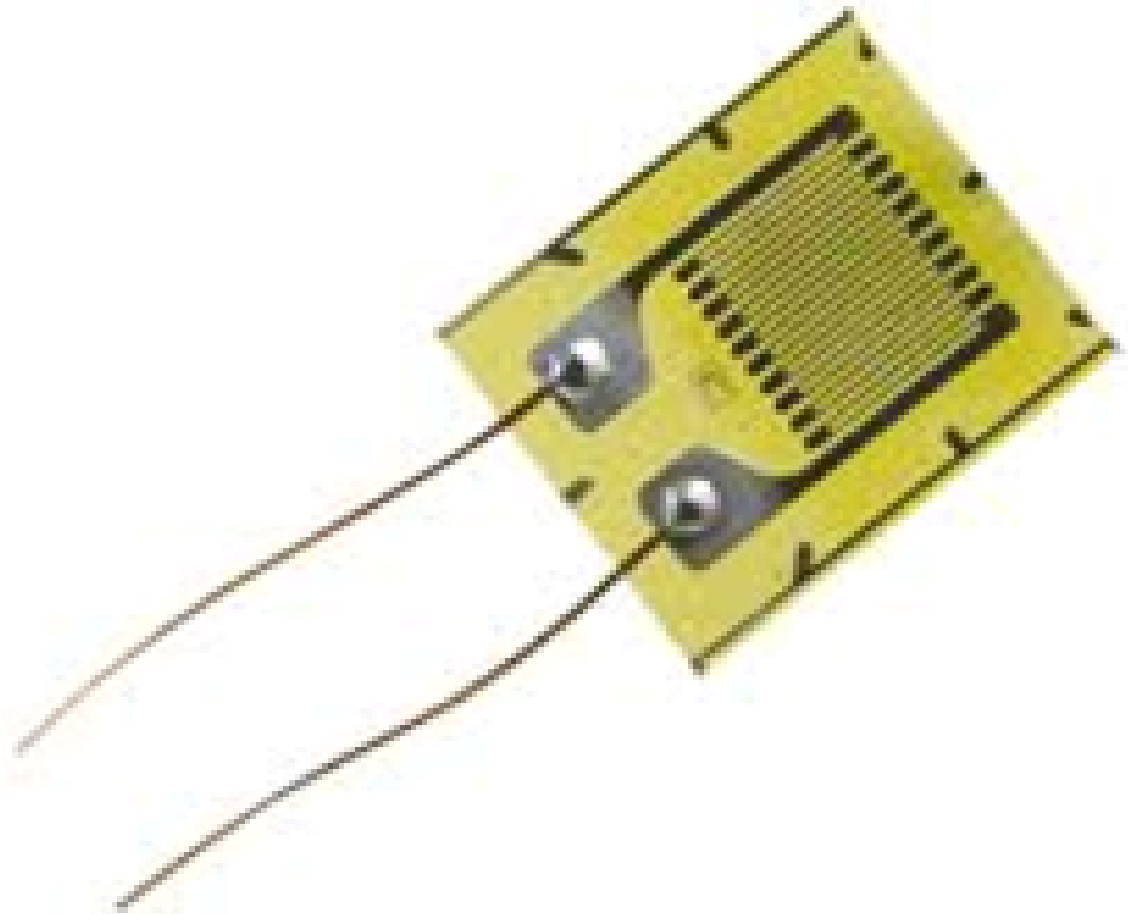
- Strain Gauges
- Piezoelectric force sensors

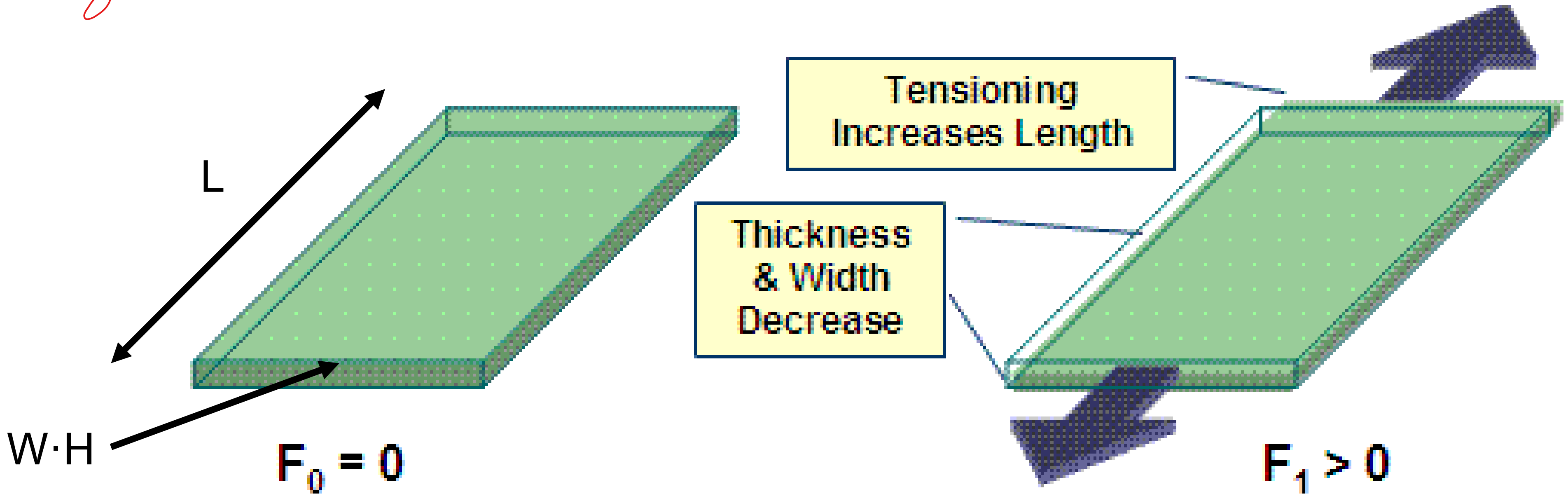


BeeP: 12 – Strain Gages

Basics of mechanics

Total volume equal

Force ⇒ elongation ⇒ cross section becomes thiner



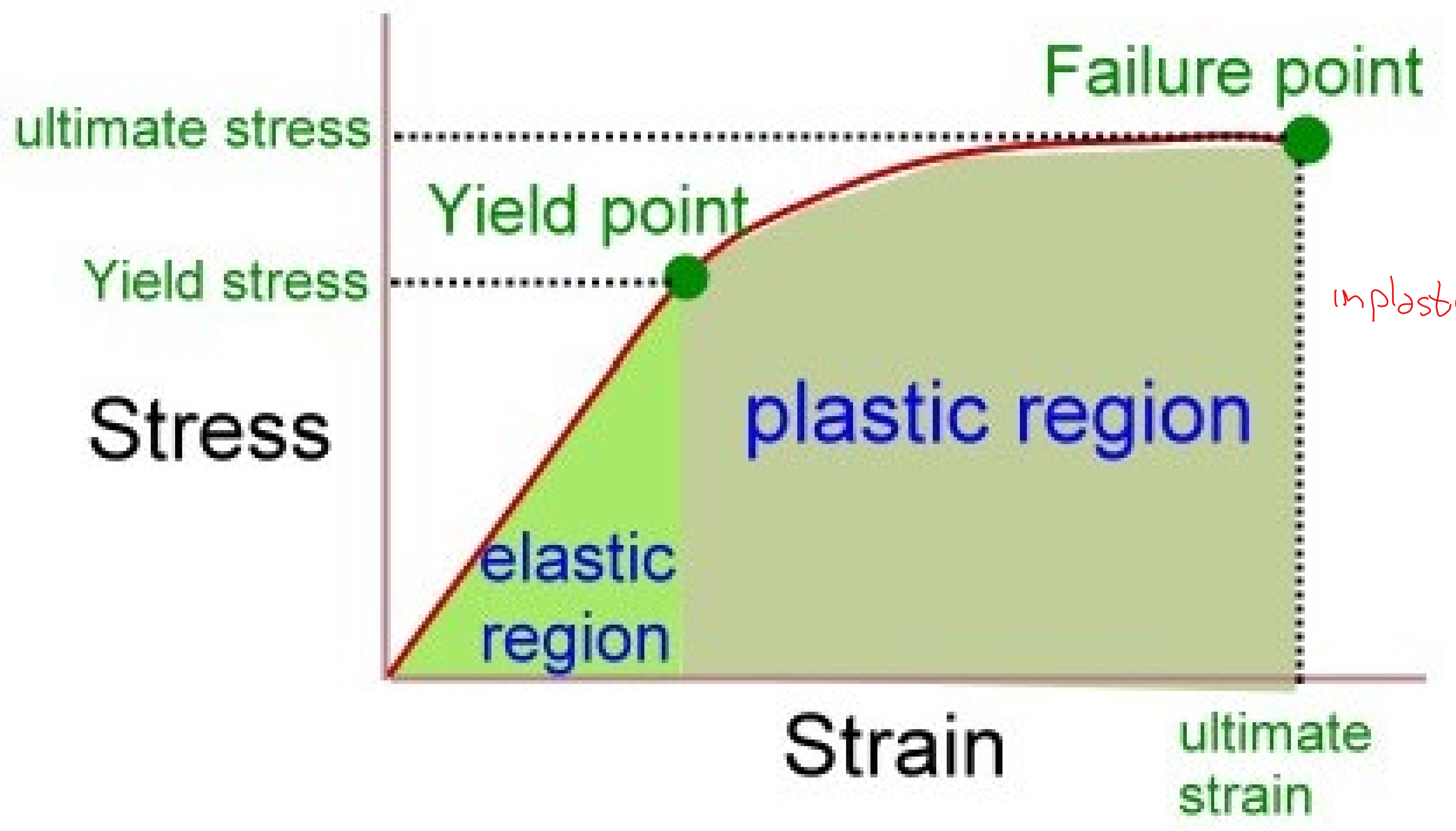
Stress: $\sigma = \frac{F}{WH} \left(Pa = \frac{N}{m^2}\right)$ → cross section area

Young modulus: $E = \frac{\sigma}{\varepsilon} \left(Pa = \frac{N}{m^2}\right)$

Strain: $\boxed{\varepsilon = \frac{\Delta L}{L}}$ $(a.u. \;\; typically\ \mu\varepsilon)$

adimentional 10^{-6}

Poisson ratio: $\nu = -\frac{dW/_W}{dL/_L} = -\frac{dH/_H}{dL/_L}\ (a.u.)$



In the elastic region:

$\sigma = E \cdot \varepsilon$ → E slope of the curve

in plastic region this fails

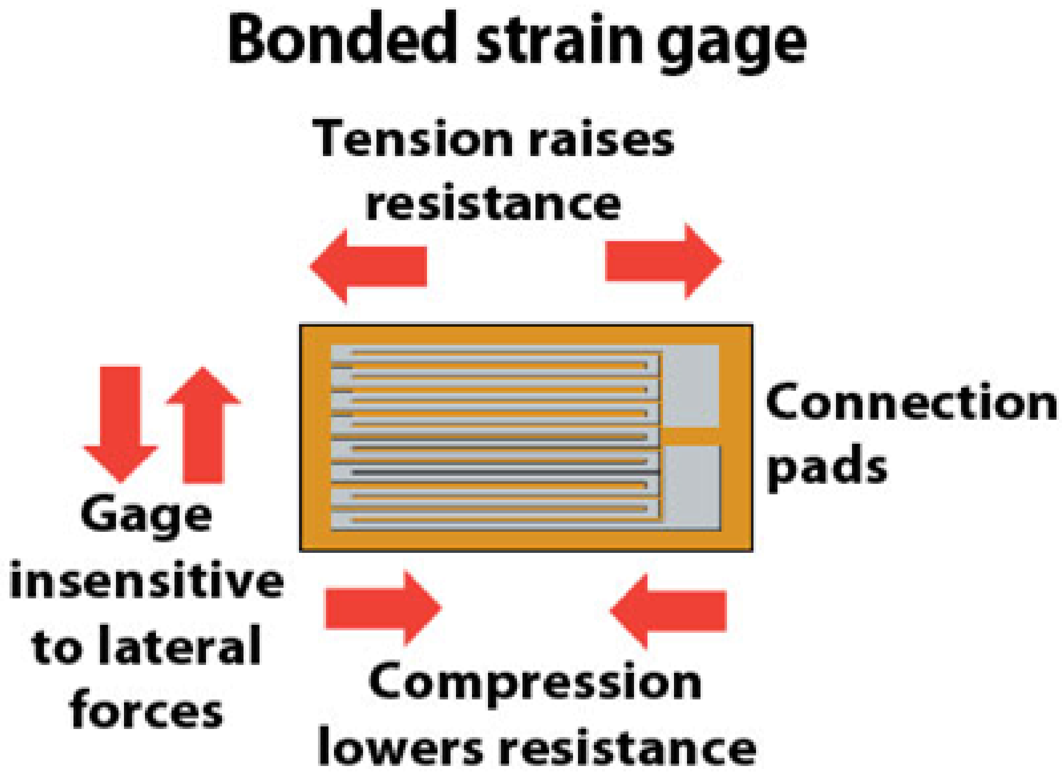
$$R = \rho \cdot \frac{L}{A} = \rho \cdot \frac{L}{WH}$$

- Tension:

  L increases
  A decreases (necking)
  → R increases

- Compression:

  L decreases
  A increases
  → R decreases



Materials with piezo-resistive effect: $\frac{d\rho}{\rho} = \beta \cdot \sigma = \beta \cdot E \cdot \varepsilon = \beta \cdot E \cdot \frac{dL}{L}$

Sensibility of the strain gauge: $G = \frac{dR/R}{\varepsilon} = \frac{dR/R}{dL/L}$

$$R = \rho \cdot \frac{L}{WH}$$

$$\rightarrow \quad \frac{dR}{R} = \frac{dL}{L} - \frac{dW}{W} - \frac{dH}{H} + \frac{d\rho}{\rho}$$

In piezo-resistive materials: $\frac{dR}{R} = \frac{dL}{L} + \nu\frac{dL}{L} + \nu\frac{dL}{L} + \beta E\frac{dL}{L}$

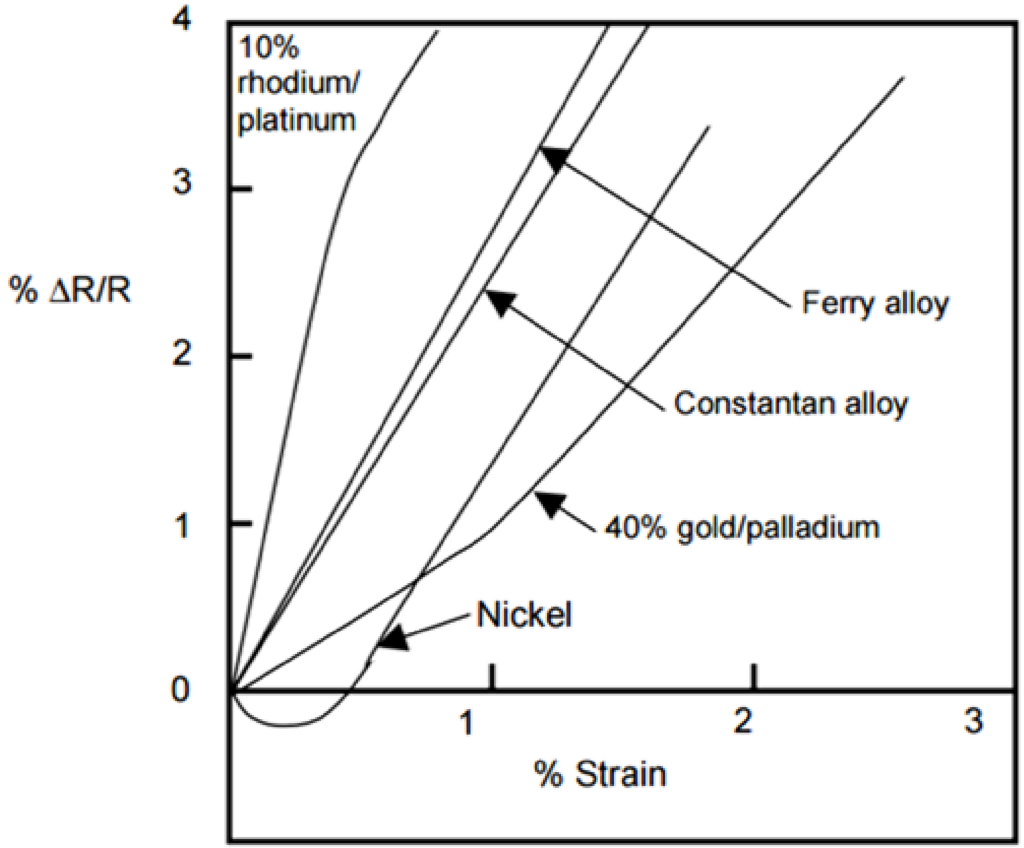
$$\frac{dR}{R} = (1 + 2\nu + \beta E)\frac{dL}{L}$$

$$\rightarrow G = 1 + 2\nu + \beta E$$

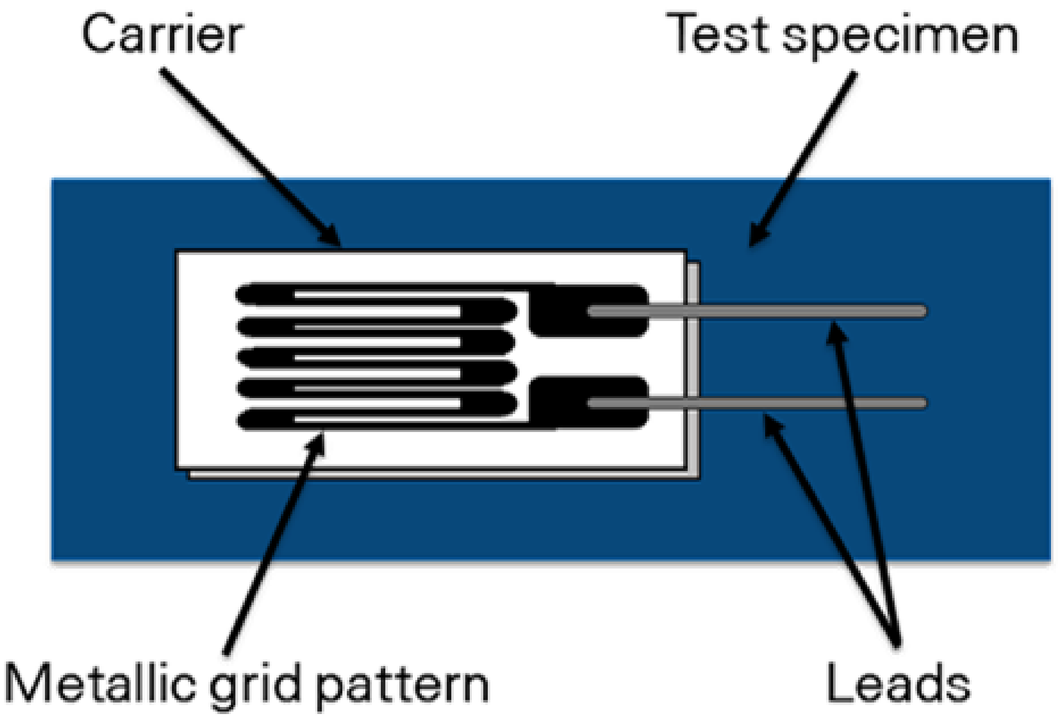
Material	Gage Factor (GF)	
	Low Strain	High Strain
Copper	2.6	2.2
Constantan*	2.1	1.9
Nickel	-12	2.7
Platinum	6.1	2.4
Silver	2.9	2.4
40% gold/palladium	0.9	1.9
Semiconductor**	~100	~600

* similar to "Ferry" and "Advance" and "Copel" alloys.

** semiconductor gage factors depend highly on the level and kind of doping used.



Strain gauge structure and fabrication



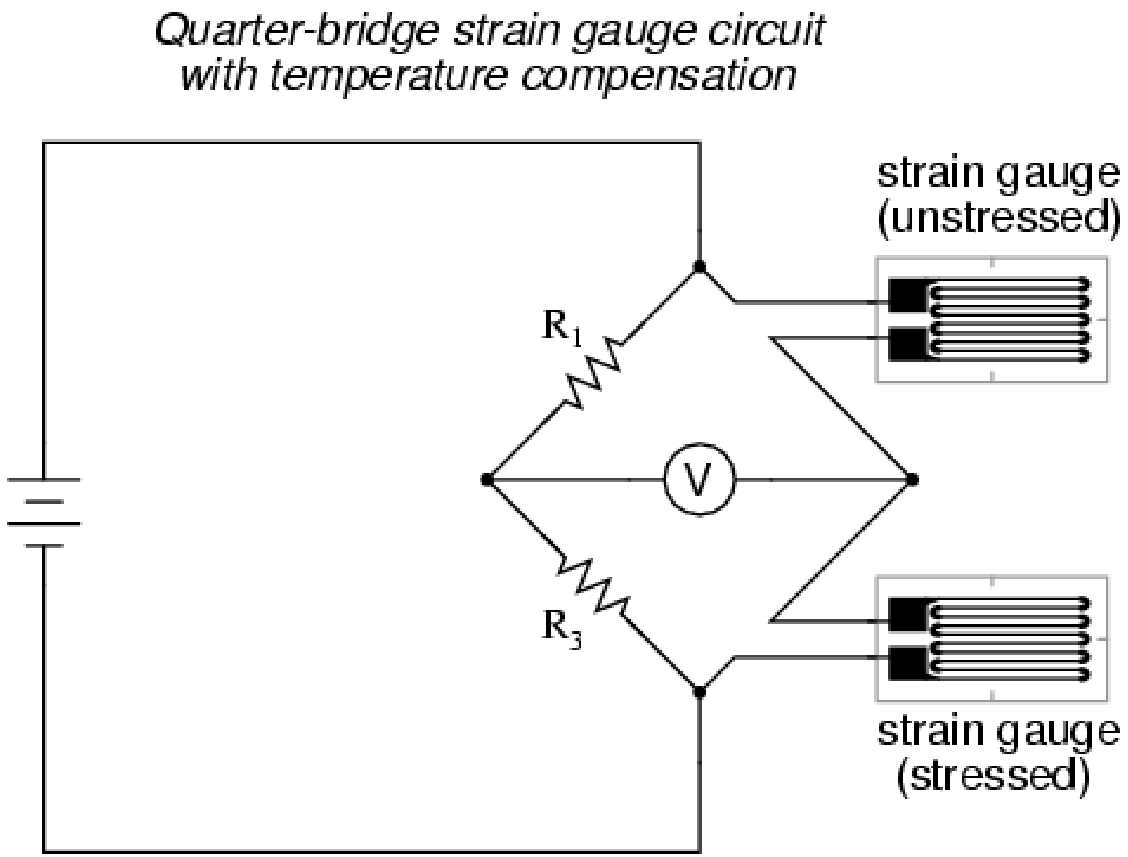
Carrier:

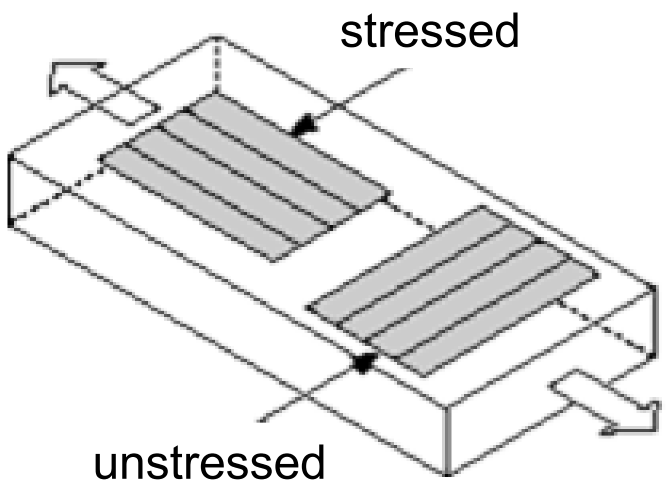
- flexible
- electrical insulation

Fabrication → photolithography

- photoresist deposition (positive or negative)
- exposure to light
- etching
- photoresist removal

Temperature compensation

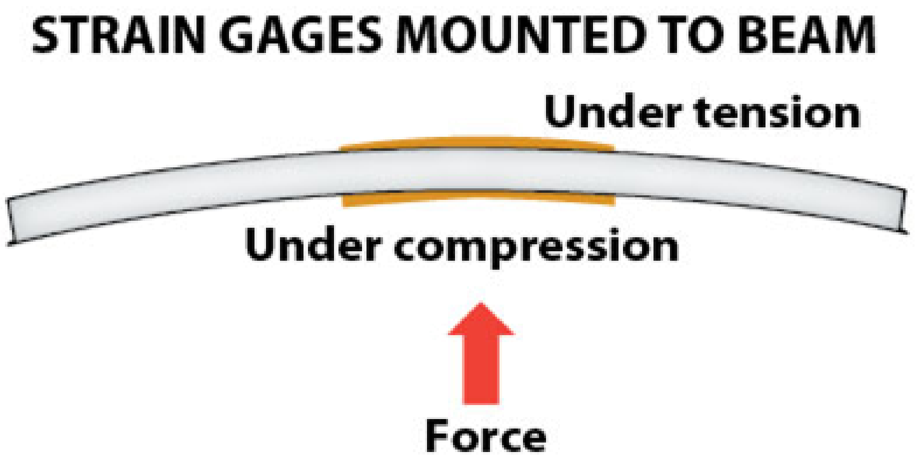


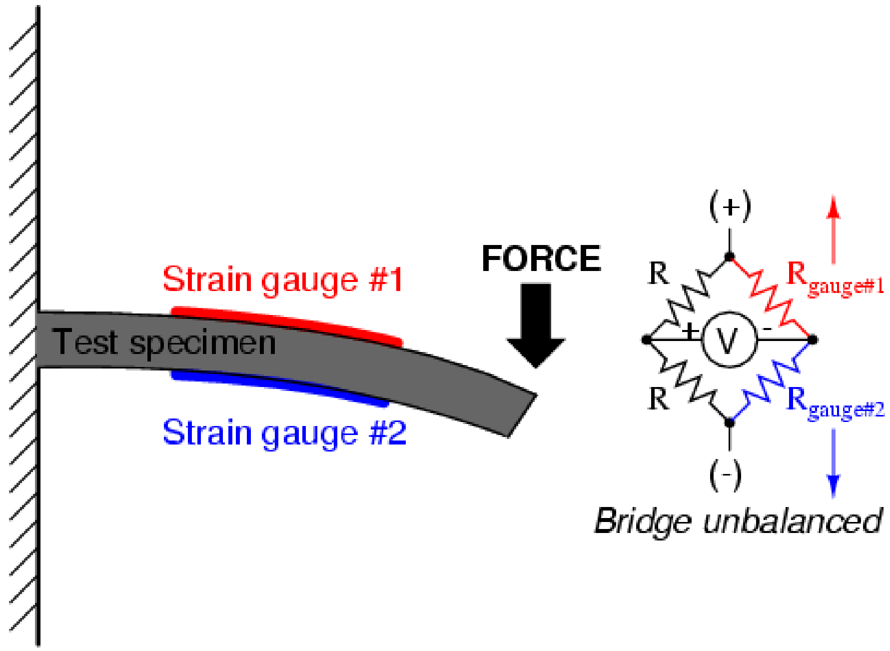


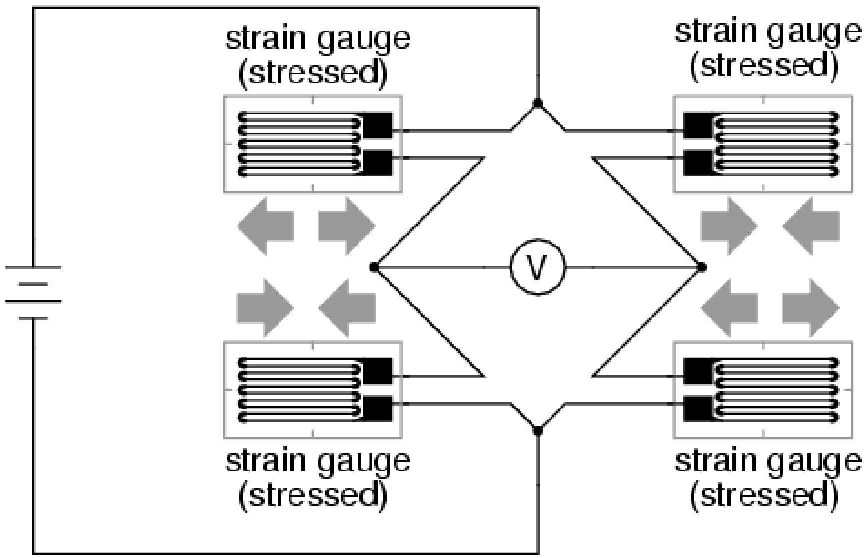
Two orthogonal strain gauges

are used to compensate

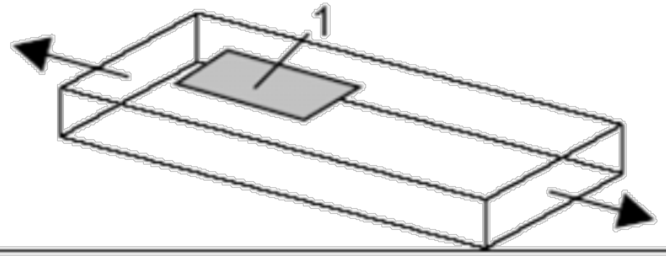
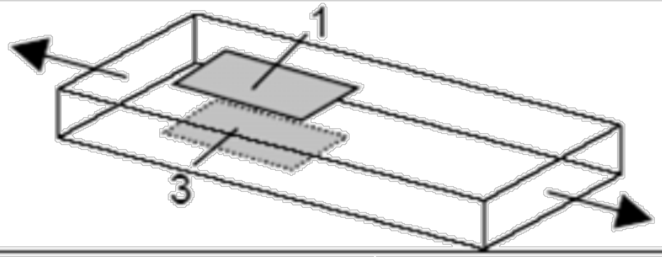
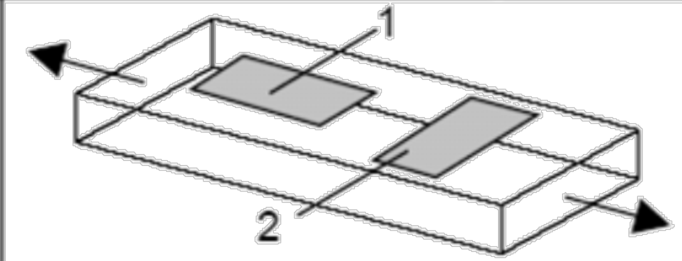
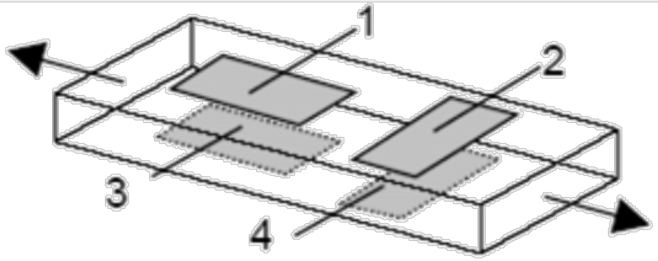
the temperature variations

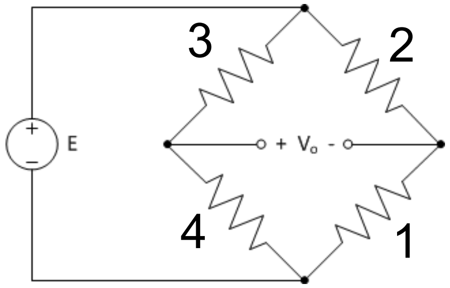

STRAIN GAGES MOUNTED TO BEAM
Under tension
Under compression
Force


Strain gauge #1
Test specimen
Strain gauge #2
FORCE
(+)
R
$R_{gauge\#1}$
V
R
$R_{gauge\#2}$
(-)
Bridge unbalanced


strain gauge (stressed)
strain gauge (stressed)
V
strain gauge (stressed)
strain gauge (stressed)

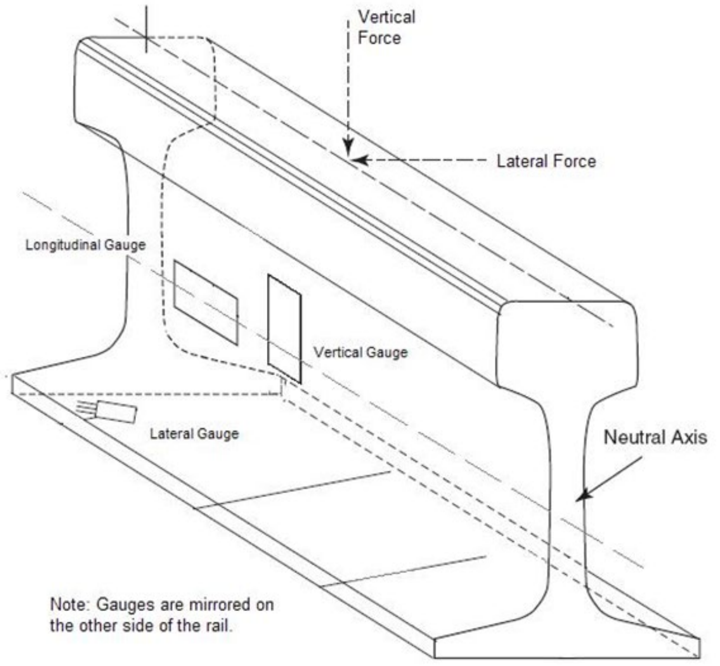
Strain gauge configurations

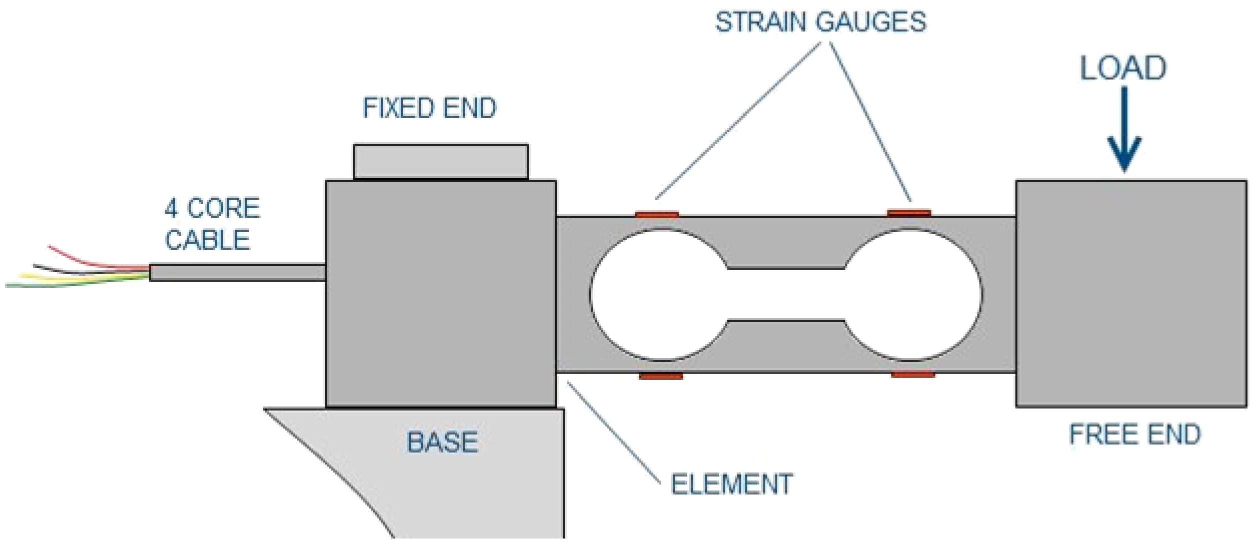
Configuration	Notes
	Must use dummy gage in an adjacent arm (2 or 4) to achieve temperature compensation
	Rejects bending strain but not temperature compensated; must add dummy gages in arms 2 & 4 to compensate for temperature.
	Temperature compensated but sensitive to bending strains
	**Best**: compensates for temperature and rejects bending strain.

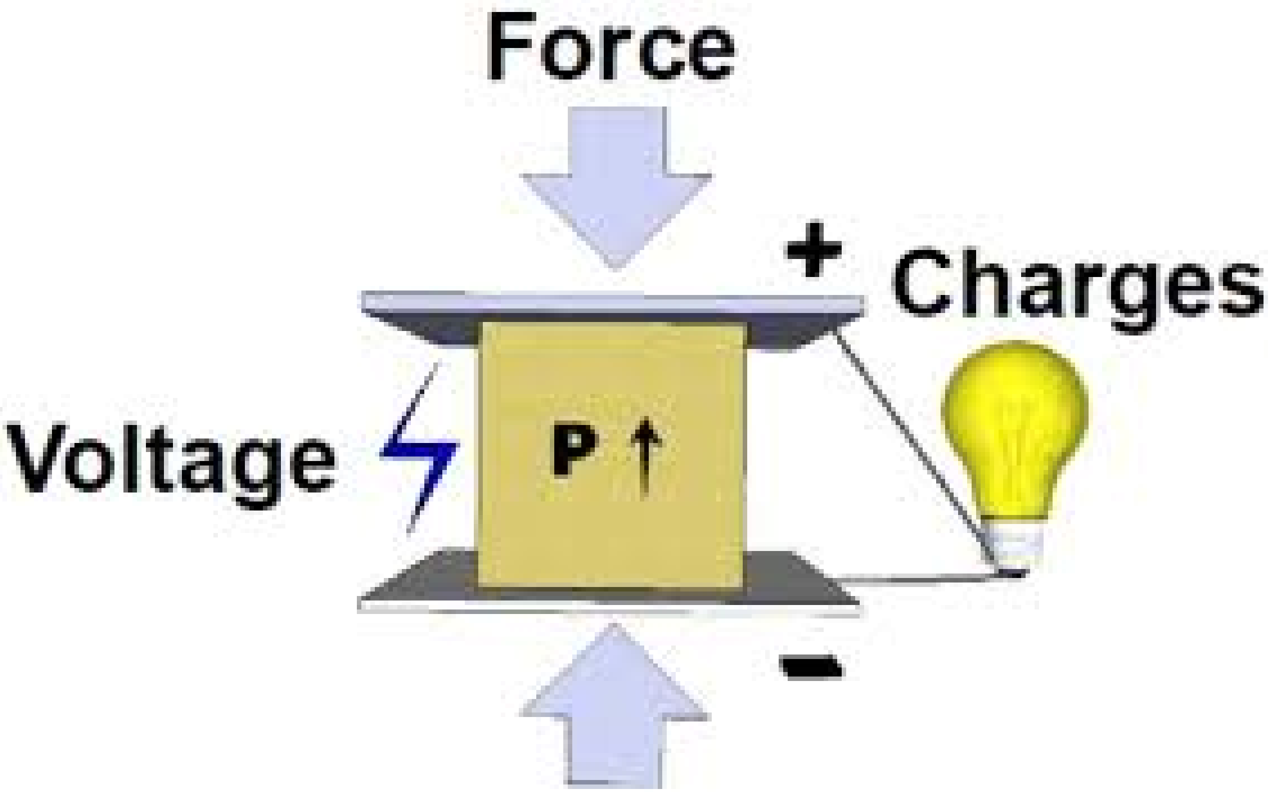


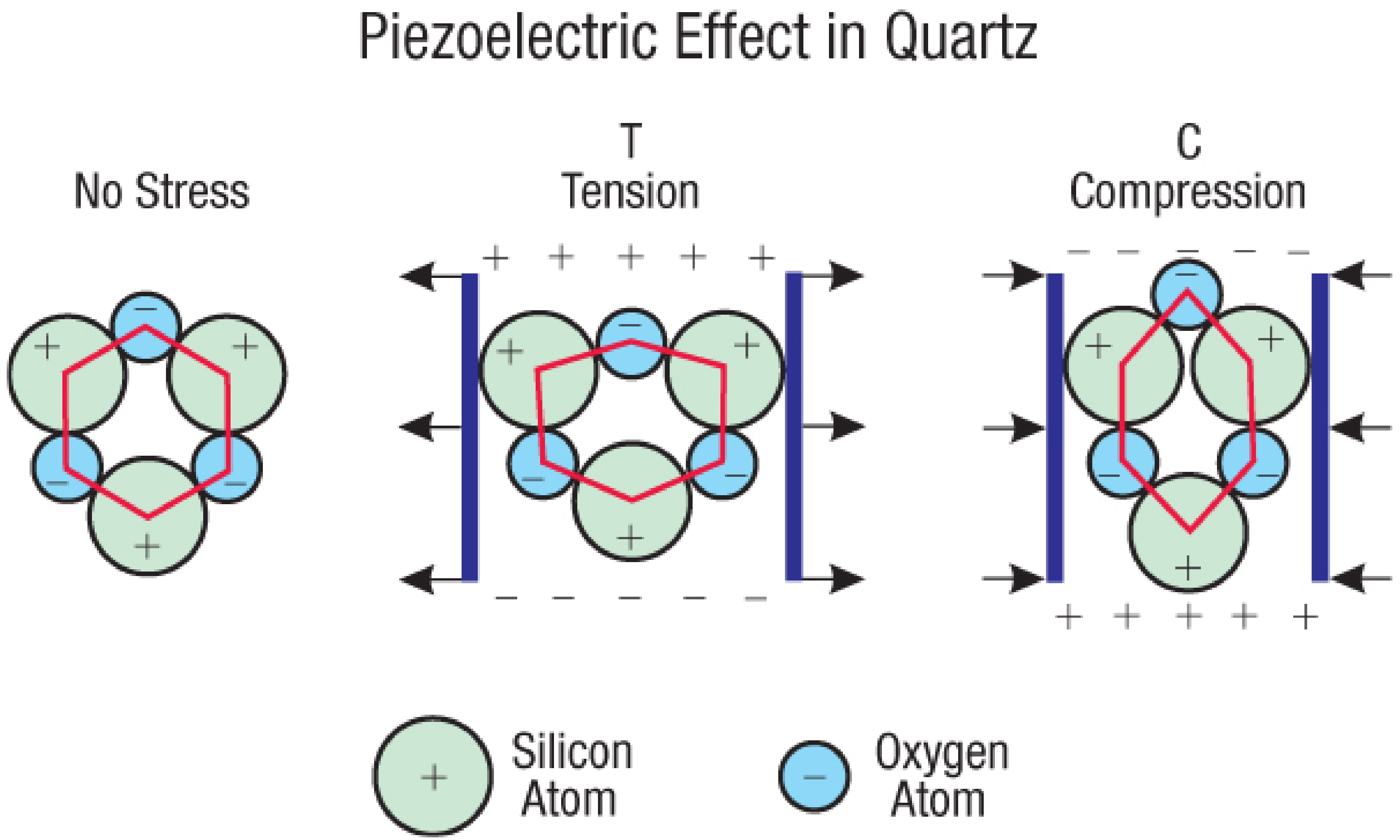
Applications

- Railroad maintenance
- Smart bridges
- Wind tunnels
- High precision robotic for medical applications
- Bathroom scales
- …





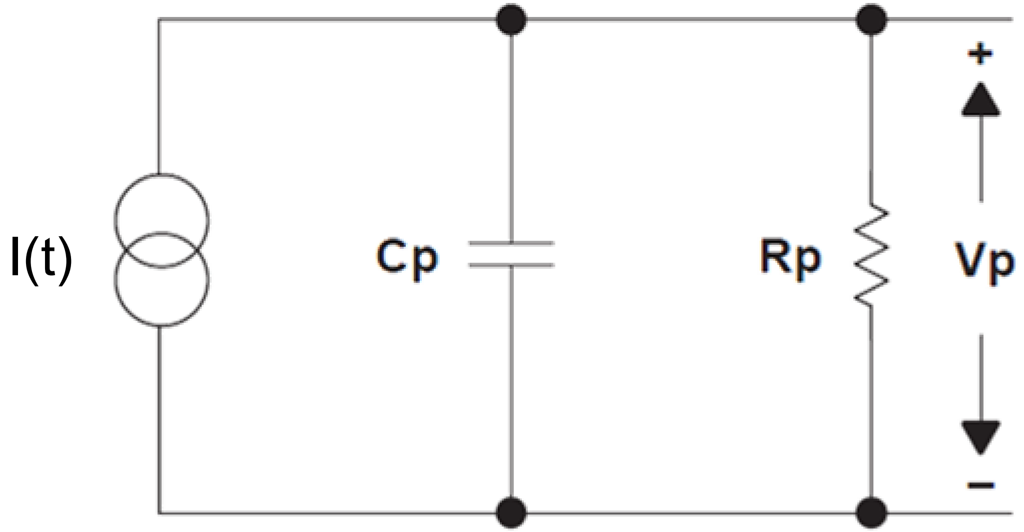

Force
+
Charges
Voltage
P
-



= electric charge that accumulates in certain solid materials (e.g. crystals, ceramics, and biological matter) in response to applied mechanical stress.

Or opposite phenomena: voltage → displacement

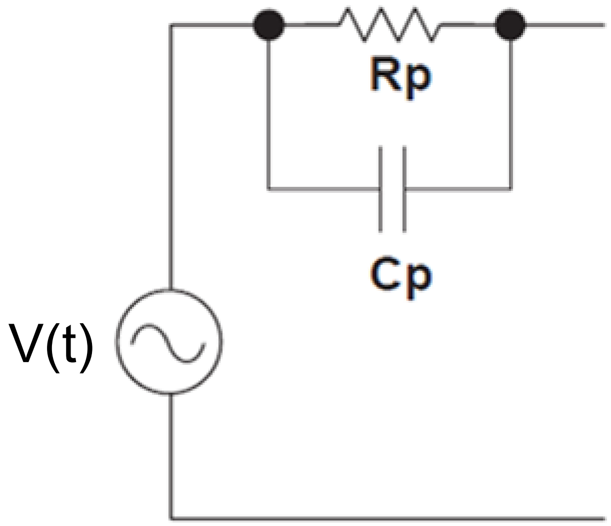
Charge Model



$$I(t) = \frac{dQ(t)}{dt}$$

$$I(s) = s \cdot Q(s)$$

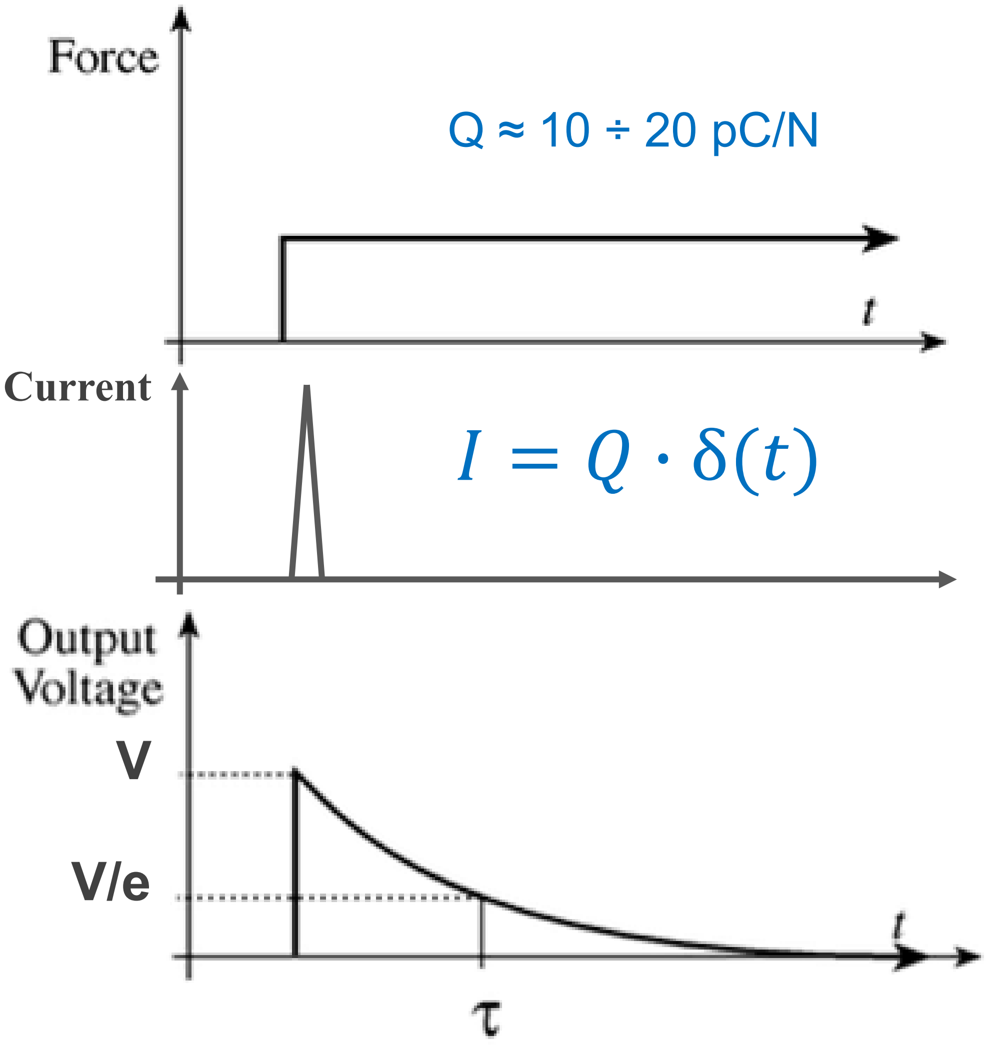
Voltage Model



$$V(t) = \frac{dQ(t)}{dt} \cdot R_p \cdot \left(1 - e^{-t/(R_p C_p)}\right)$$

$$V(s) = s \cdot Q(s) \cdot \frac{Rp}{1 + sC_p R_p}$$

Sensor response



$Q \approx 10 \div 20$ pC/N

$$I = Q \cdot \delta(t)$$

Piezoelectric sensors are **not suited for DC applications** because the electrical charge produced decays due to the internal impedance of the sensor and the input impedance of the conditioning circuits.

$$V = \frac{Q}{C_p}$$

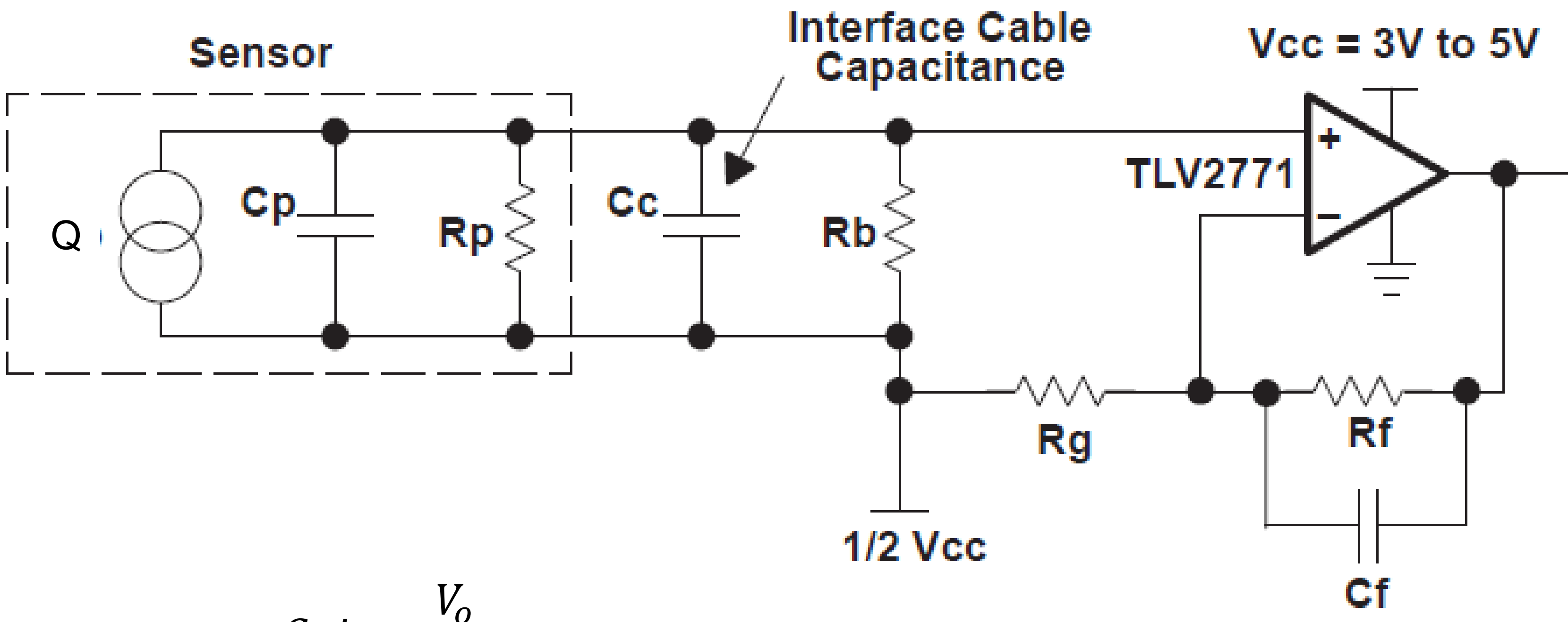
$$\tau = C_p \cdot R_p$$

Considering also stray capacitances:

$$V = \frac{Q}{Cp + C_{stray}}$$

→ Stray capacitance are not under control!

Voltage mode amplifier



$$V_o = \frac{Q}{(Cp+Cc)} \times \left[1 + \frac{Rf}{Rg}\right] + \frac{Vcc}{2}$$

$$G_{Opa} = 1 + \frac{Rf}{Rg}$$

Cc = cable capacitance

Rb = DC bias path

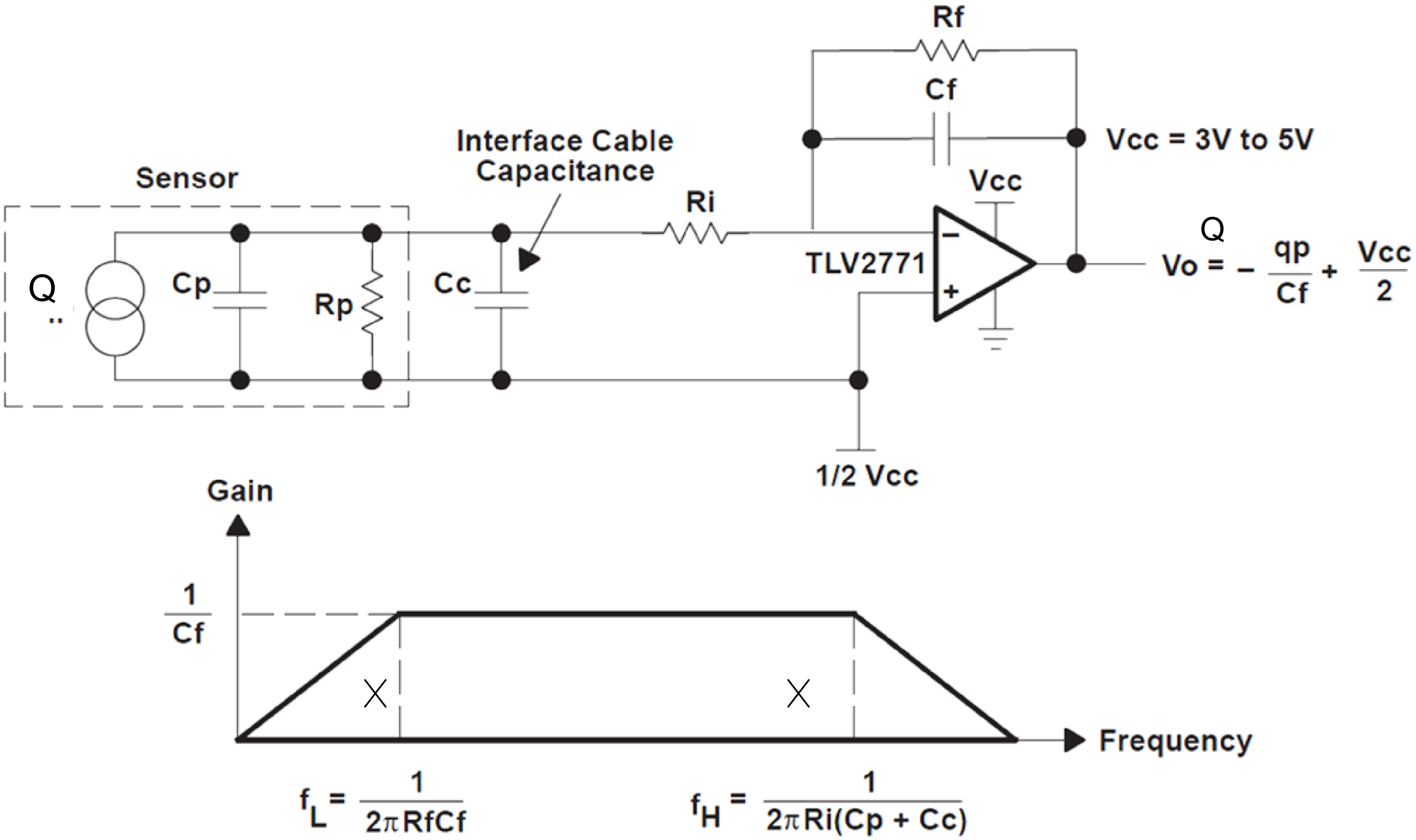
$$Gain = \frac{V_o}{Q}$$

$$f_L = \frac{1}{2\pi (Rp \parallel Rb)(Cp \parallel Cc)}$$

$$f_H = \frac{1}{2\pi RfCf}$$

$$f_z = \frac{1}{2\pi Cf \cdot Rf//Rg}$$

Charge mode amplifier



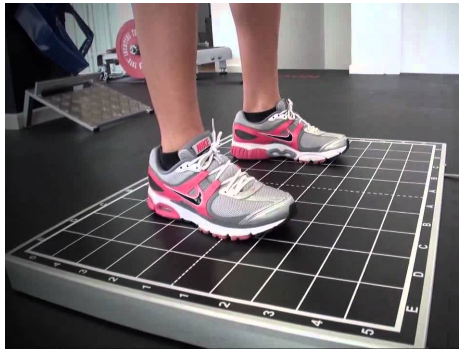
$$G = \frac{Cp + C_C}{C_f}$$

Rp >> Ri

V_{out} depends only on the small and well controlled C_f

Working frequencies: $f_L < f < f_R$ (f_R = resonance frequency)

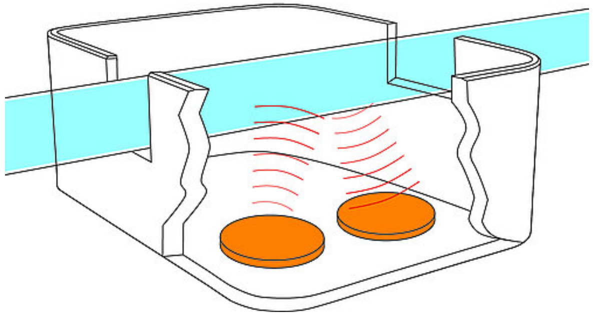
Applications



- Force measurements
  (e.g., force platform for rehabilitation or sport)

- Energy harvesting

  (converting the available energy from the environment from sources such as ambient temperature, vibration or air flow)



- Ultrasonic technology
  (both actuator and sensor,
  e.g. proximity, detection of gas bubbles)

- Actuators
  (pumping and dosing, production of homogeneous aerosol)