Piezoelectric Materials

Corso Materiali intelligenti e Biomimetici
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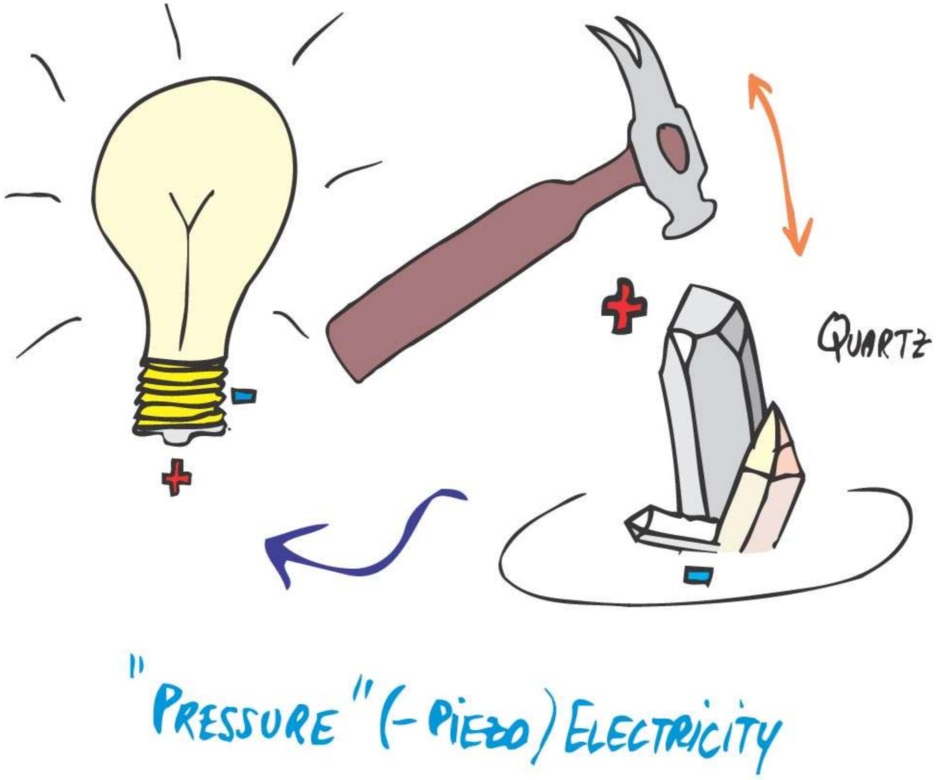
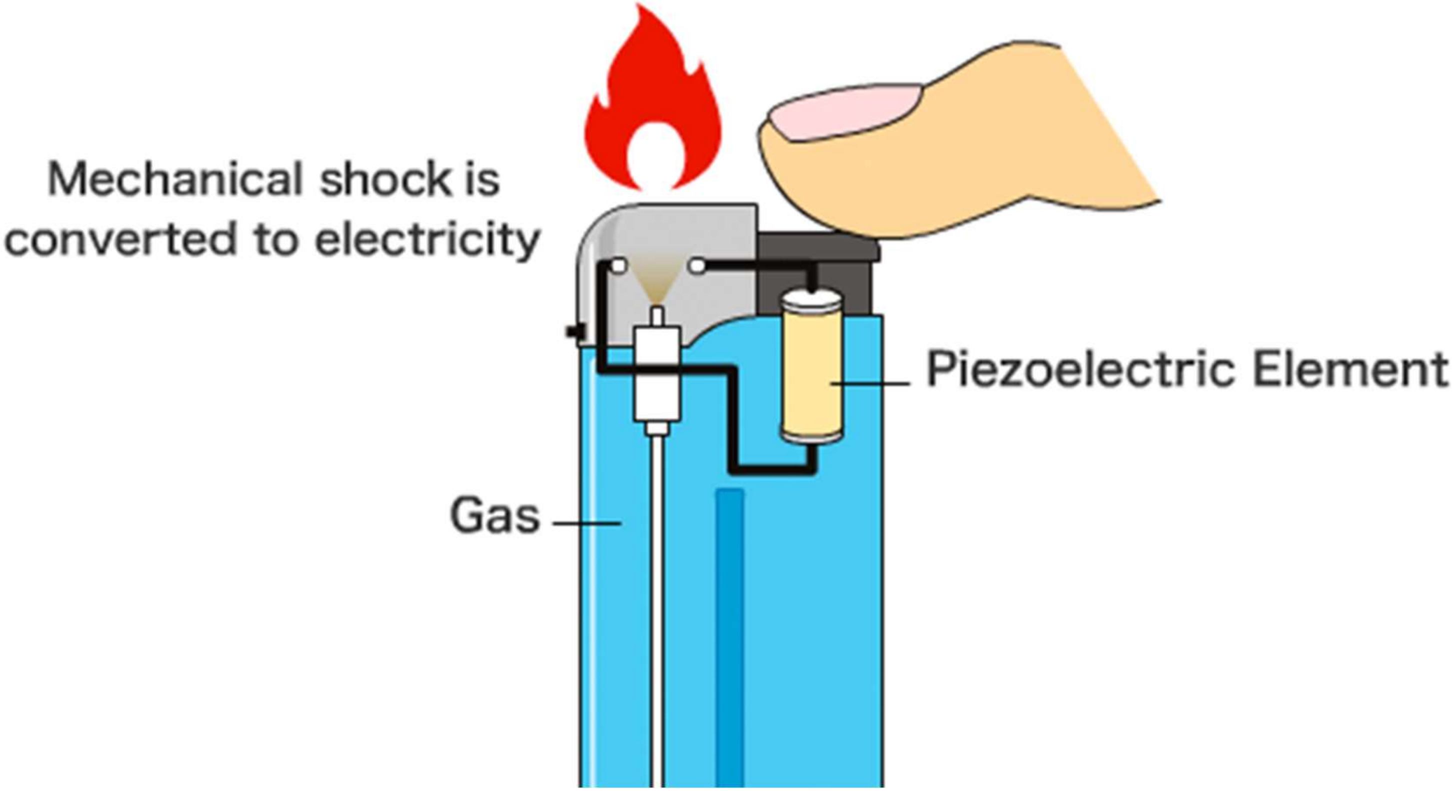
ludovica.cacopardo@ing.unipi.it

Piezoelectricity – *electromechanical coupling*



The word piezoelectricity is derived from the ancient Greek words *piezo*, "to squeeze or press," and *electric*. So, piezoelectricity literally means electricity from pressure.

Example

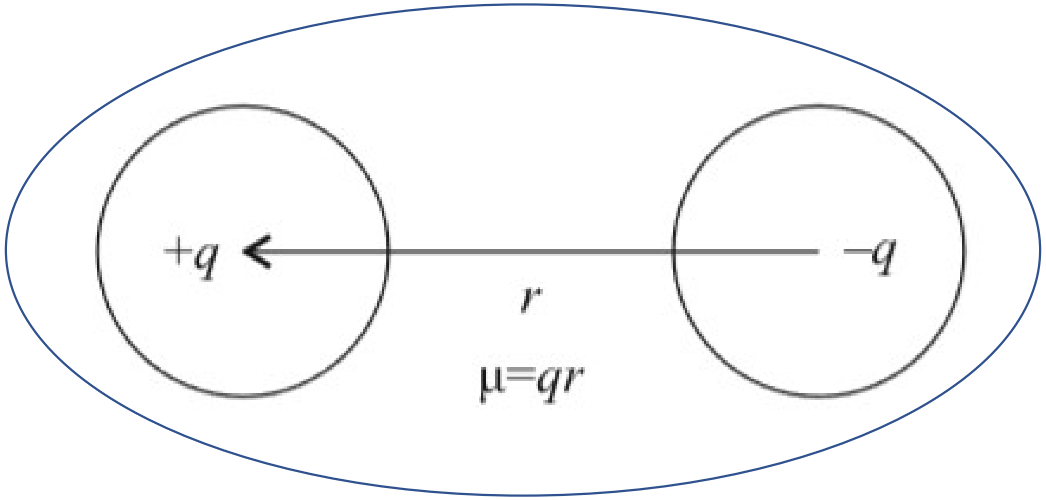

Mechanical shock is converted to electricity
Piezoelectric Element
Gas

Material electric properties

Conductors — **Electric charges flows** within the material under an external electric field

Dielectrics — Electric charges **do not flow** (no free electrical charge), they are only slightly ***displaced from their equilibrium positions***

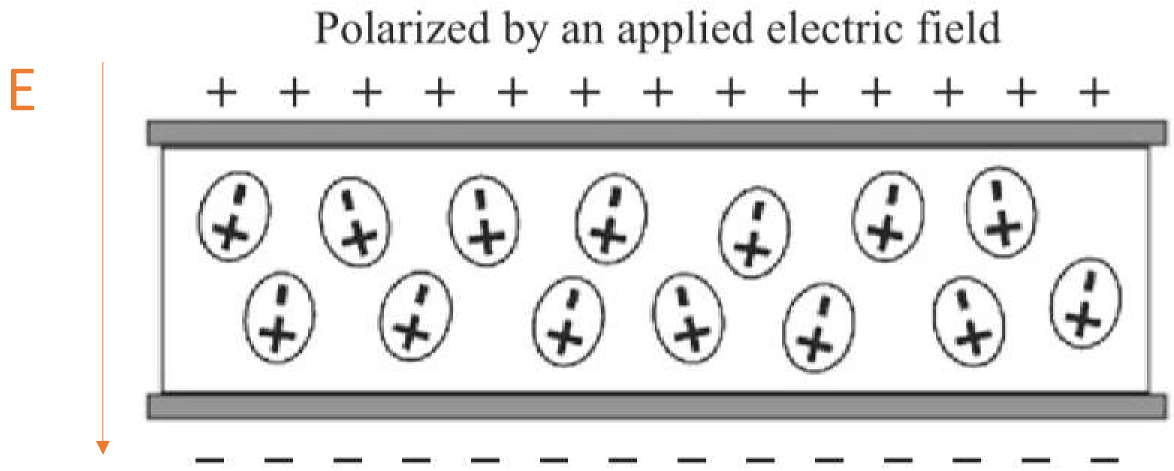
Dipole: volume unit with a neutral global charge, but where q+ and q- are dislocated



μ = dipole moment,
r=distance between the charges,
q=charge

Material electric properties

When a **dielectric is placed in an electric field, it becomes polarized** – positive and negative charges are separated, producing a dipole with dipole moment given by the product of the charges and their separation distance**.**


Polarized by an applied electric field

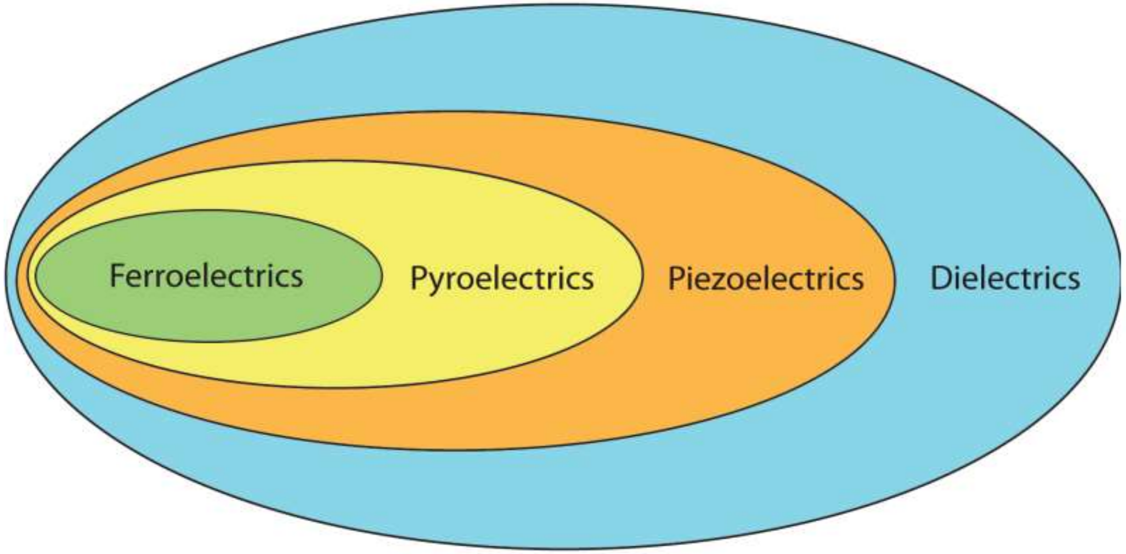
Material polarization

$$P = \frac{1}{V}\sum_i \mu_i$$

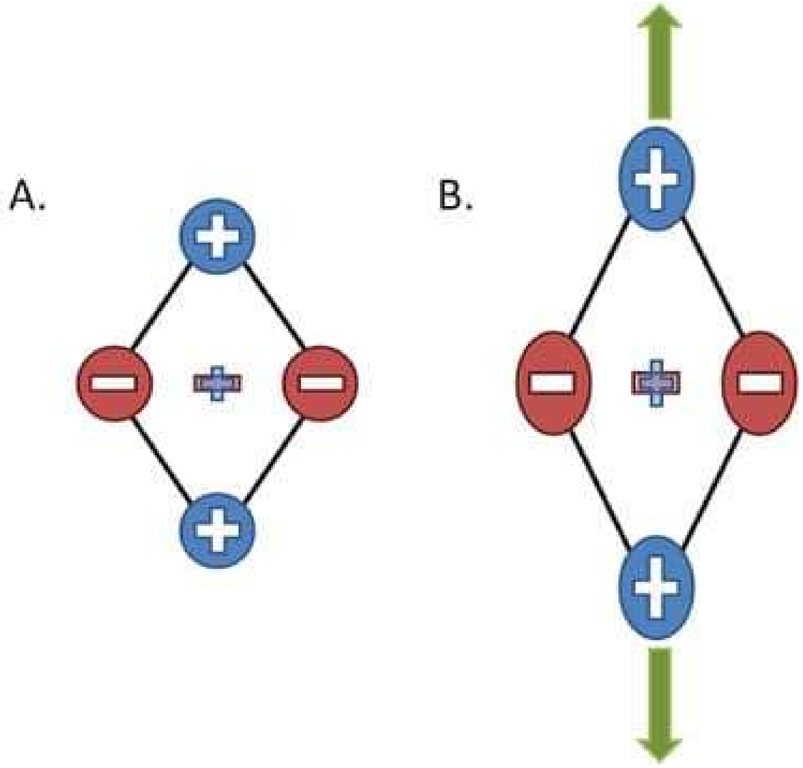
Piezoelectric Materials

Simultaneously to polarization, the dielectric experiences an electrostrictive strain. However, the electrostriction is usually negligibly small and bears no practical significance.

However, **if the dielectric has an asymmetric atomic structure, a relatively large piezoelectric strain** proportional to the electric field is also possible**.** Vice versa, when a piezoelectric material is loaded then the electrical dipoles appear.



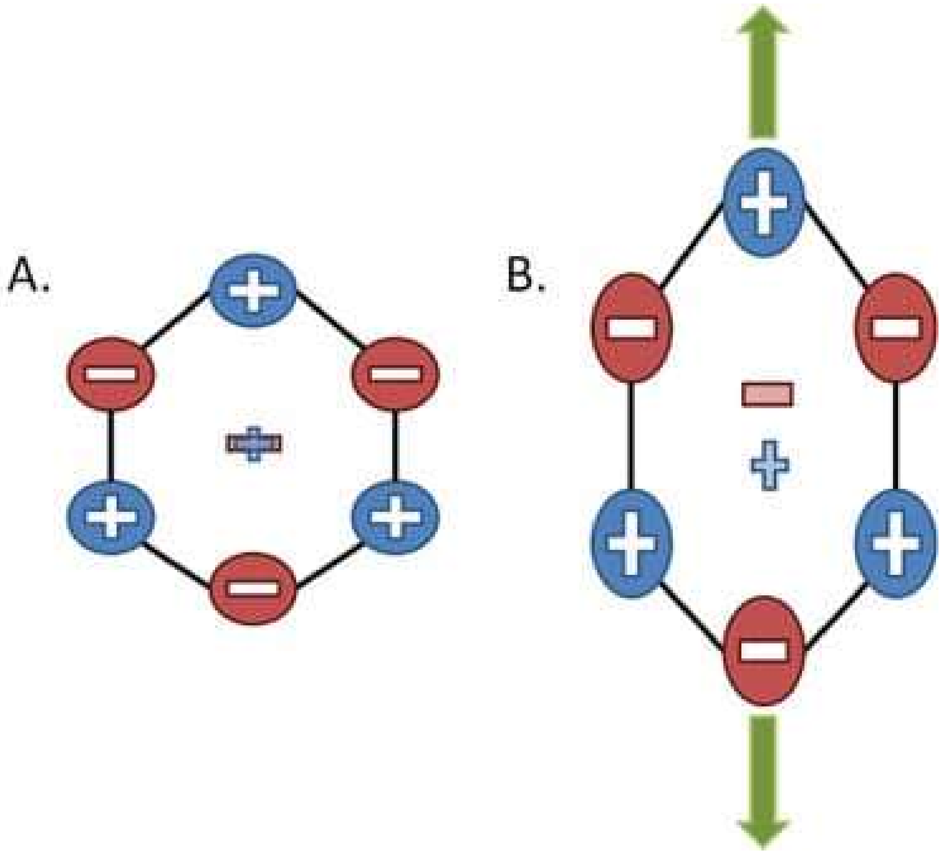
Atomic structure in not piezoelectric materials



Example: c*rystal containing four total atoms, two positively charged and two negatively charged*, arranged in a diamond pattern. When we look at the average location of the negative charges and the average location of the positive charges, we notice that they are the same. Thus, **no electric potential exists**.

Similarly, **when the crystal is mechanically deformed no change results in the average locations of the charges**. This material shows **no electrical response** to a mechanical force and thus is not piezoelectric. The symmetry can be demonstrated by drawing an arrow to any of the four atoms with a starting point in the center of the crystal, and then drawing the same arrow in the opposite direction. If they point to the same type of atom, it is symmetrical.

Atomic structure in piezoelectric materials

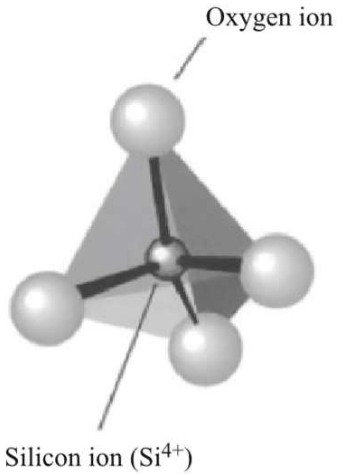


The atomic structure of piezoelectric materials is not completely symmetric.

If we calculate the average location of the positive and negative charges, we find that they are the same.

However, **when the material is deformed the average positions of the charges are different**. Performing the same arrow-drawing exercise as before, we find that while this material may look symmetric, drawing the opposite arrow does not point to the same type of atom. Thus, **this material has an electrical response to a mechanical force** (and vice versa) and is piezoelectric.

Piezoelectric materials



Natural

Rochell salt, Quartz, bones, etc

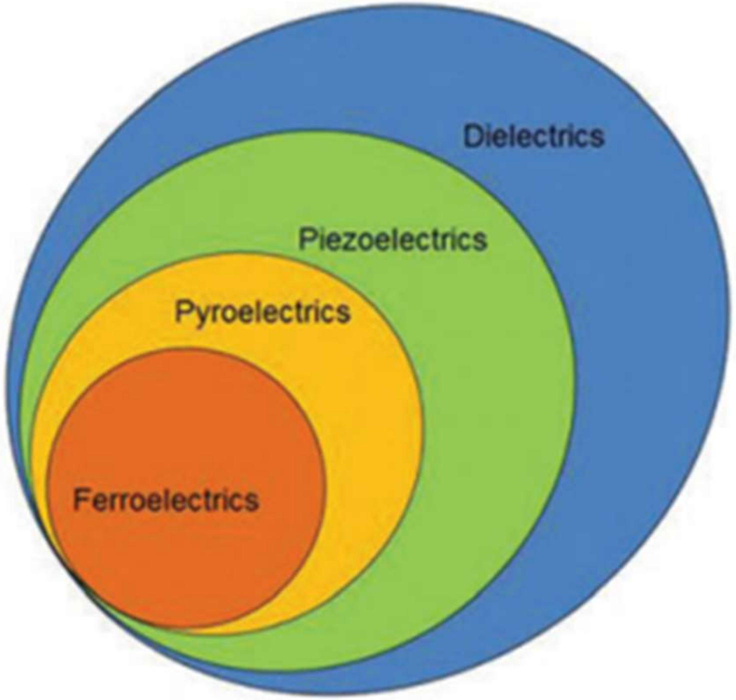
Synthetics

- **Ceramics**:
  Lead zirconate titanate (PZT); Barium titanate (BaTiO3); Lead titanate (PbTiO3);

- **Polymers**:
  polyvinylidene fluoride (PVDF)

- **Composites**:
  - **piezo-polymer** in which the piezoelectric material is immersed in an electrically passive matrix (e.g. PZT in epoxy matrix)
  - **two different ceramics** (for example BaTiO3 fibers reinforcing a PZT matrix).

In summary



- **Dielectric materials** -> polarized under an **external electric field**
- **Piezoelectric** materials are ‘special’ dielectric materials -> **polarization *occurs* after the application of a mechanical stress** due to the asymmetric atomic structure
- Some of them (**pyroelectric and ferroelectric**) presents a **spontaneous polarization (T<Tcurie)** -> the polarization *increases or decreases* after the application of a mechanical stress

2 way coupling

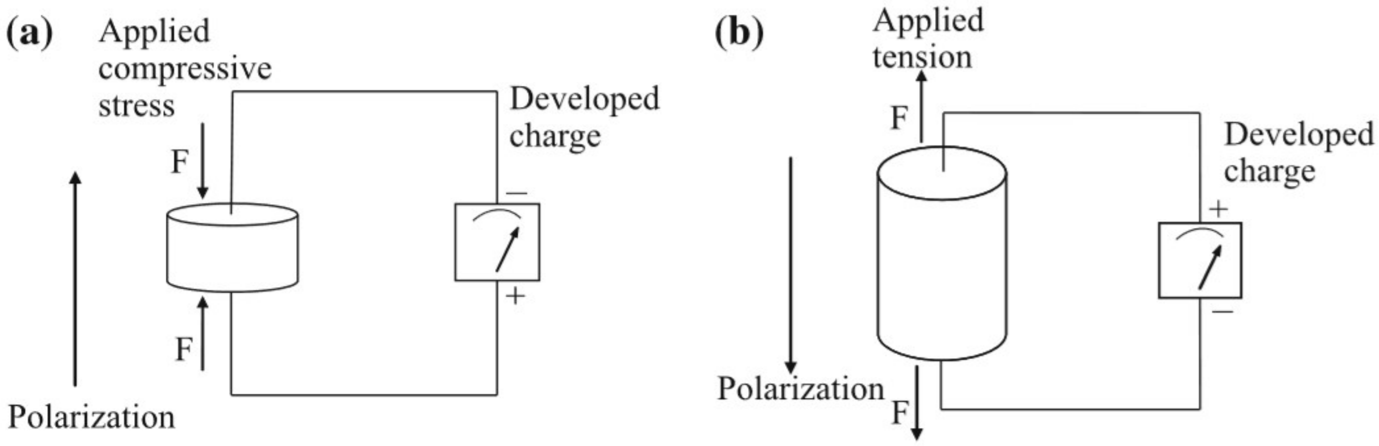


Fig. 2.1 Direct piezo-effect: **a** at applied compressive stress, **b** at applied tension

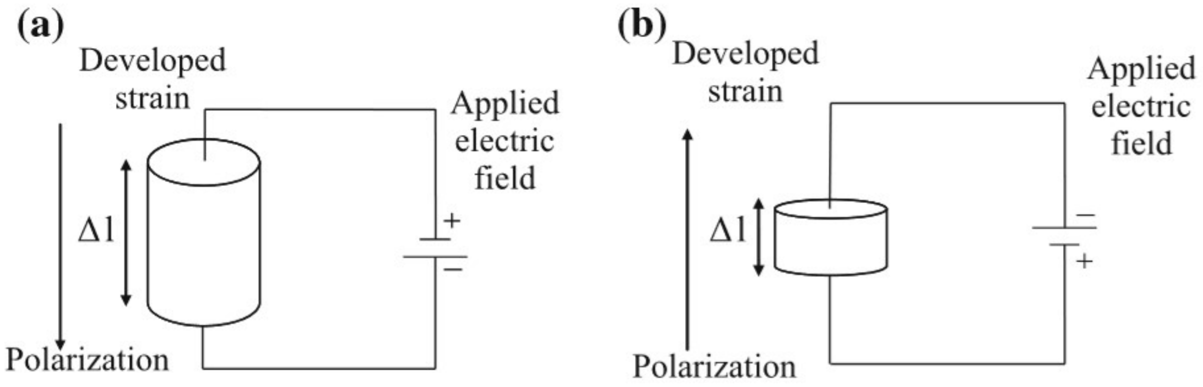


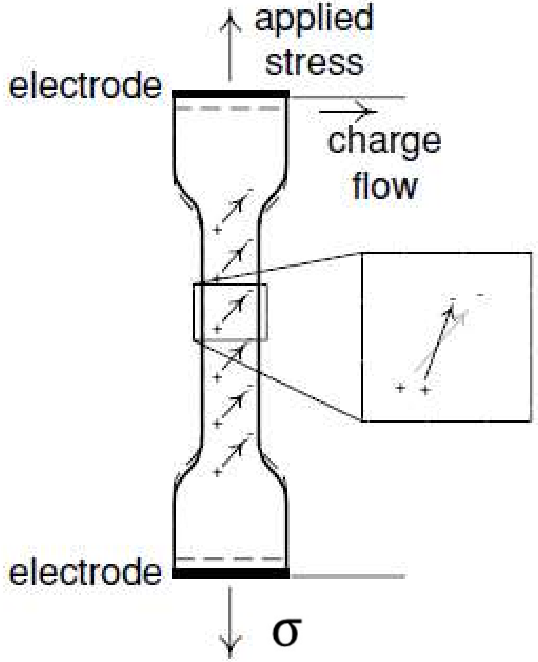
Fig. 2.2 Inverse piezo-effect at applied electric field

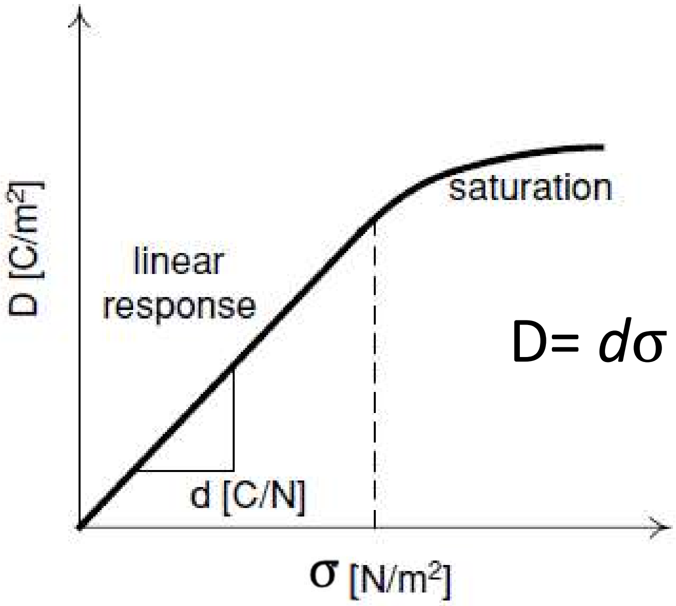
The conversion of mechanical forces into electrical potential is called the **direct piezoelectric effect.**

On the other hand, if a piezoelectric material is subjected to an external electric field, the response is mechanical deformation of the material—called the **inverse piezoelectric effect**.

Direct piezoelectric effect

Applying an *increasing stress level will produce an increase in the rotation of the electric dipoles* and an increase in the electric displacement (D).
Over a certain range of applied mechanical stress, there is a **linear relationship between applied stress and measured electric displacement**. At sufficient levels of applied stress, the relationship between stress and electric displacement will become **nonlinear due to *saturation of electric dipole motion***.



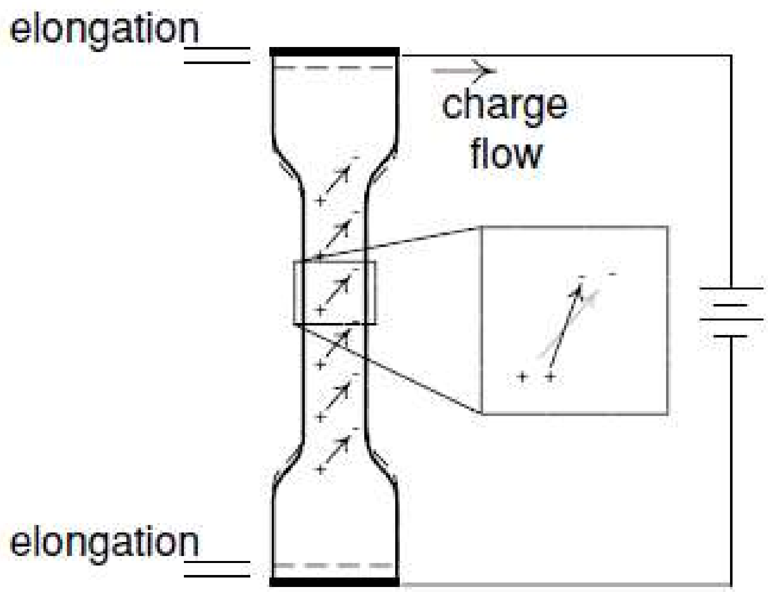


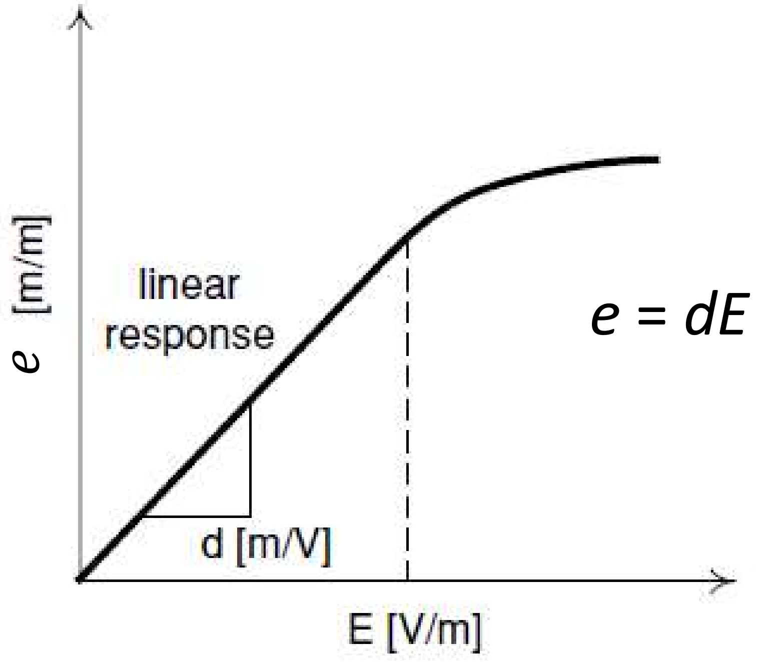
$$D = d\sigma$$

The slope of the curve,
called the direct
piezoelectric coefficient,
is denoted *d* (C/N).

Inverse piezoelectric effect

Upon application of an electric field, *dipole rotation will occur and produce a strain in the material*. Applying sufficiently low values of electric field we would see a **linear relationship between the applied field and mechanical strain**.





e = dE

the slope of the field-to-strain relationship would be equal to the ***inverse piezoelectric coefficient***.

Constitutive equations & piezoelectric coupling coefficient

$$\begin{Bmatrix} e \\ \mathrm{D} \end{Bmatrix} = \begin{bmatrix} C & d \\ d & \varepsilon \end{bmatrix} \begin{Bmatrix} \sigma \\ \mathrm{E} \end{Bmatrix}$$

$e = d\,\mathcal{E} \longrightarrow \left[\frac{C}{N}\right]$

$$\begin{tikzcd}
D \arrow[d] & = & d \arrow[d] & \sigma \arrow[d] \\
\left[\frac{C}{m^2}\right] & & \left[\frac{C}{N}\right] & \left[\frac{N}{m^2}\right]
\end{tikzcd}$$

$\mathcal{E} \longrightarrow \left[\frac{V}{m}\right] = \left[\frac{N}{C}\right]$

$e = C\,\sigma$

$D = \varepsilon\,\mathcal{E}$

$\mathcal{E} \to$ campo

$\varepsilon \to$ cost. dielettrica

$D \to$ induzione elettrica

$\left[\frac{C^2}{N m^2}\right]$

$$\begin{bmatrix} e \\ D \end{bmatrix} = \begin{bmatrix} C & d \\ d & \varepsilon \end{bmatrix} \begin{bmatrix} \sigma \\ \mathcal{E} \end{bmatrix} \Rightarrow \begin{cases} e = C\sigma + d\,\mathcal{E} \\ D = d\,\sigma + \varepsilon\,\mathcal{E} \end{cases}$$

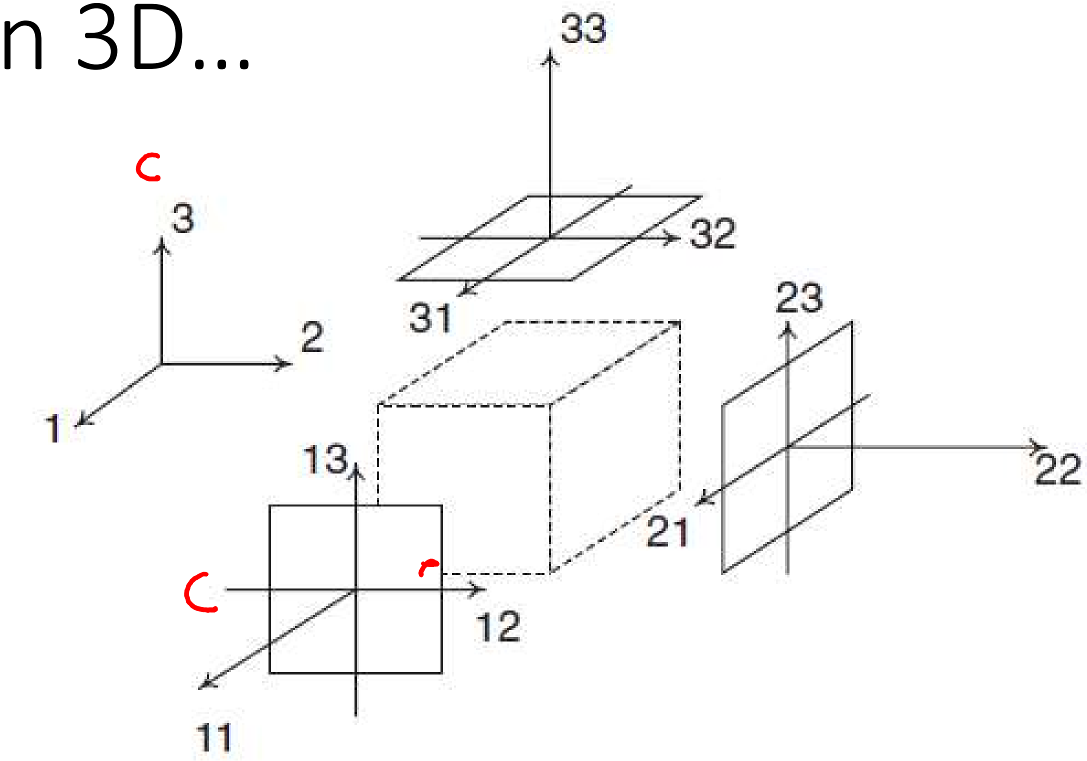
$$\begin{bmatrix} \sigma \\ \mathcal{E} \end{bmatrix} = \frac{1}{C\varepsilon - d^2} \begin{bmatrix} \varepsilon & -d \\ -d & C \end{bmatrix} \begin{bmatrix} e \\ D \end{bmatrix}$$

$$\frac{1}{C\varepsilon - d^2} \Longrightarrow 1 - \frac{d^2}{C\varepsilon} = K$$

coeff. accoppiam piezo

$0 < K < 1$

In 3D…



$$\underline{E} = \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \qquad \underline{D} = \begin{Bmatrix} D_1 \\ D_2 \\ D_3 \end{Bmatrix}$$

Three directions associated with the electric field and three associated with the electric displacement.
In the case of a **general state of stress and strain** for the cube of material, we see that **nine terms** are required for complete specification (six shear components τ12, τ13, τ23, τ21, τ32, τ31 and three normal components σ11, σ22, σ33)

Constitutive equations

Electric induction

Direct Piezoelectric effect

$$D_i = \varepsilon_{ij} E_j + d_{ijk} \sigma_{jk}$$

Permittivity

Electrical field

Direct piezoelectric effect matrix

Mechanical stress

Mechanical strain

Inverse Piezoelectric effect

$$e_{ij} = d_{kij} E_k + C_{ijkl} \sigma_{kl}$$

Inverse piezoelectric effect matrix

Electrical field

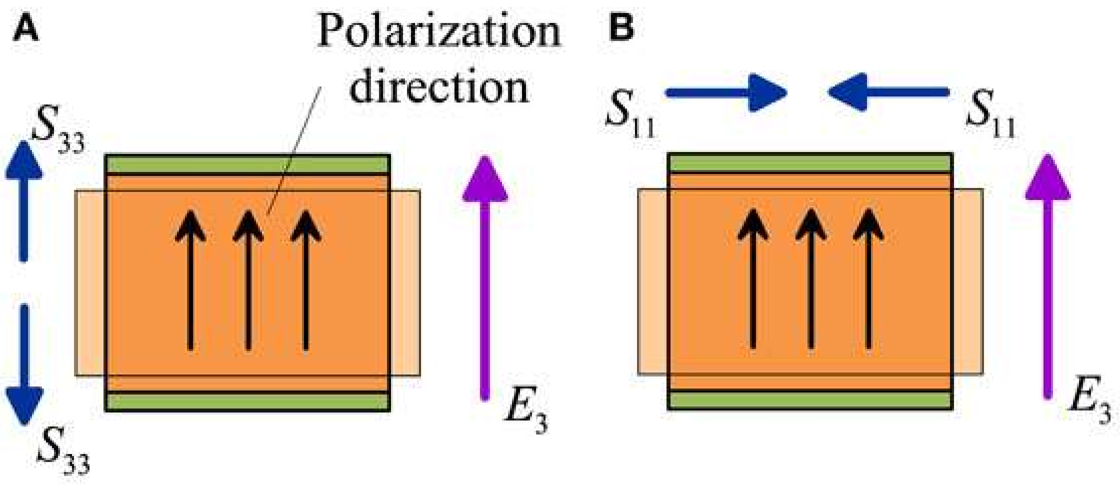
Mechanical compliance

Mechanical stress

Operation modes

The peculiarity of piezoelectricity is the third order coupling tensor $\boldsymbol{d_{kij}}$ that couples mechanical and electrical quantities. Assuming **polarization on direction k=3 (E_3)**:

$S_{ij} = e_{ij}$
(strain)

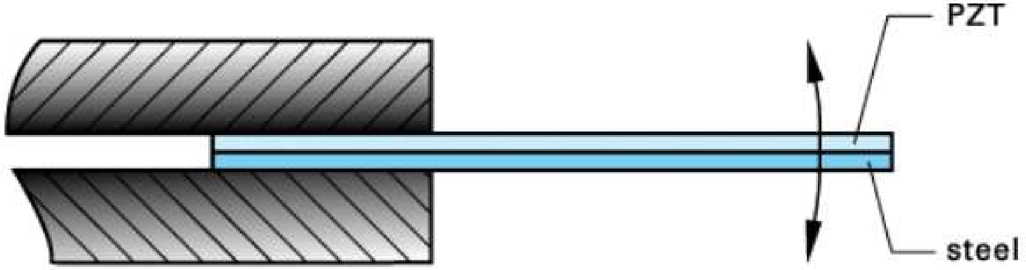


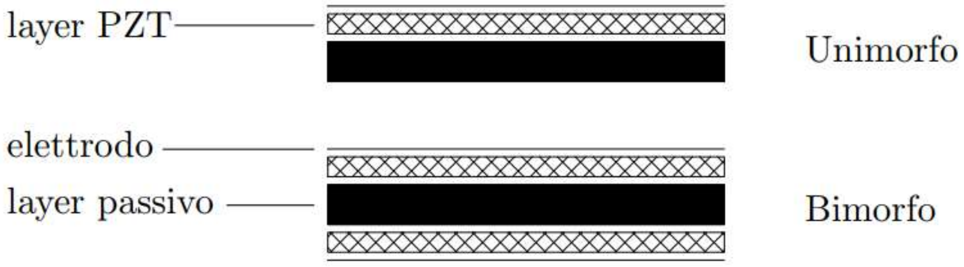
(a) **33-mode**: the piezoelectric element **stretches in the same direction** of E3 (and vice versa);
(b) **31-mode**: **the piezoelectric element shrinks in the orthogonal plane** with respect to E3 (and vice versa);

Bending Actuator (*31-mode*)

L’attuatore **unimorfo** è costituito da una **lamina piezoelettric**a e da uno **strato passivo** di materiale genericamente metallico che funge anche da elettrodo.
L’attuatore **bimorfo** invece presenta uno **strato centrale di materiale passivo** sulle cui superfici superiore e inferiore vengono incollati due strati di materiale piezoelettrico. Gli elettrodi sono applicati sulle superfici superiore e inferiore di ciascuno strato piezoelettrico.

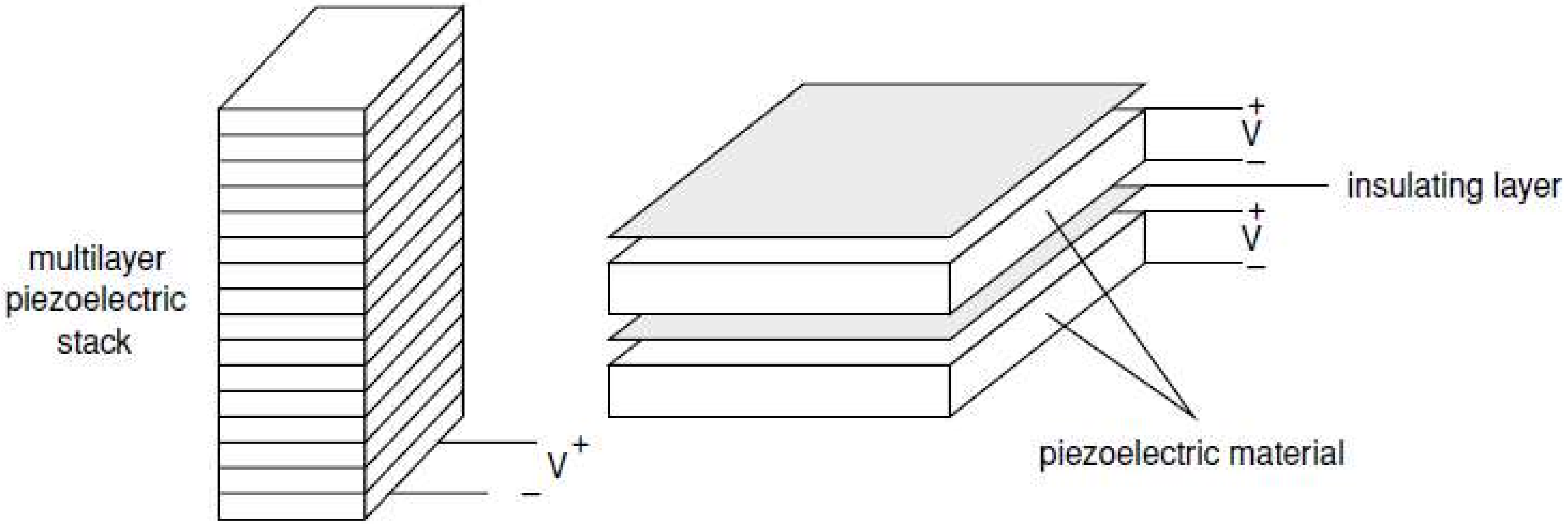
Attuatori in grado di generare una ***flessione dovuta alla deformazione dello uno strato attivo***.





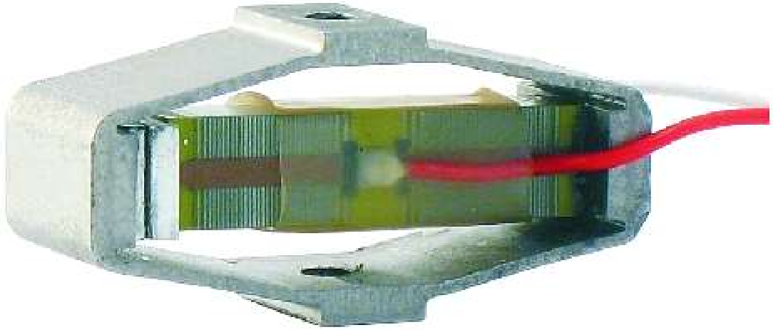
Stack actuators *(33-mode)*

The stack geometry produces an **amplification of the displacement** since each layer (ideally) will displace the same amount.

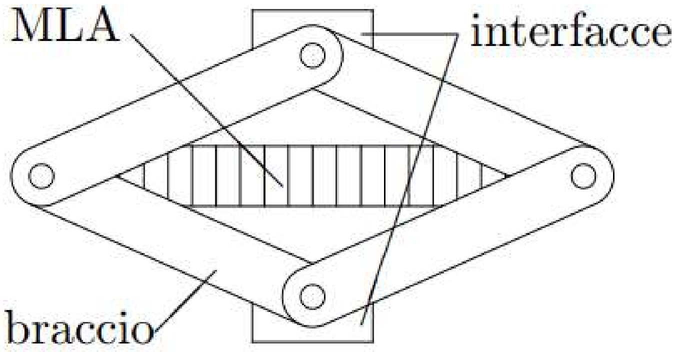


Displacement amplification with external mechanisms

Linear displacement

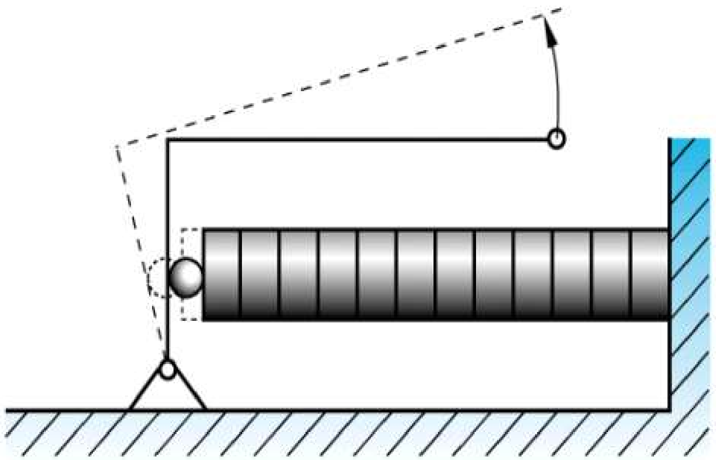


(7.a)



(7.b)

Angular displacement



Piezoelectric ‘inch-worm’ motors

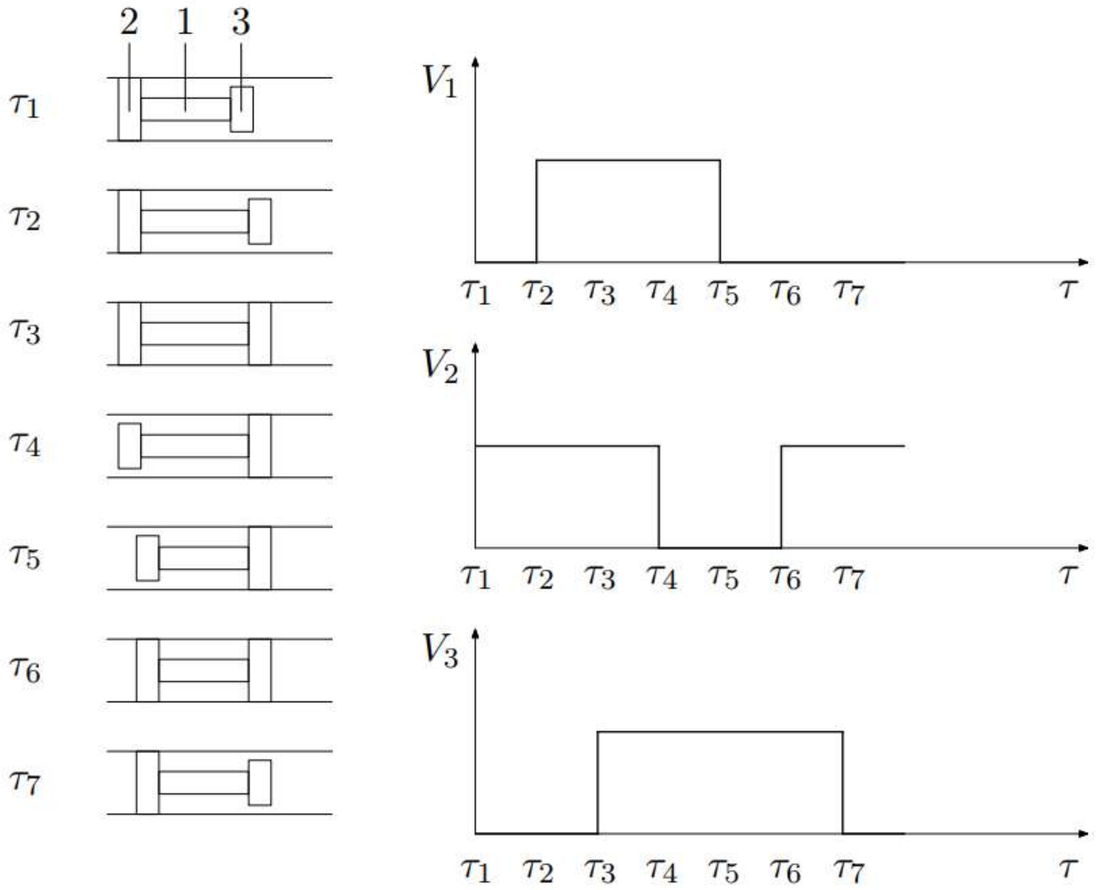


Figura 11: Motore inchworm e segnali di pilotaggio

Il motore \`e costituito da una **parte fissa esterna** e da una parte mobile formata da **tre attuatori** piezoelettrici (parti 1, 2 e 3).

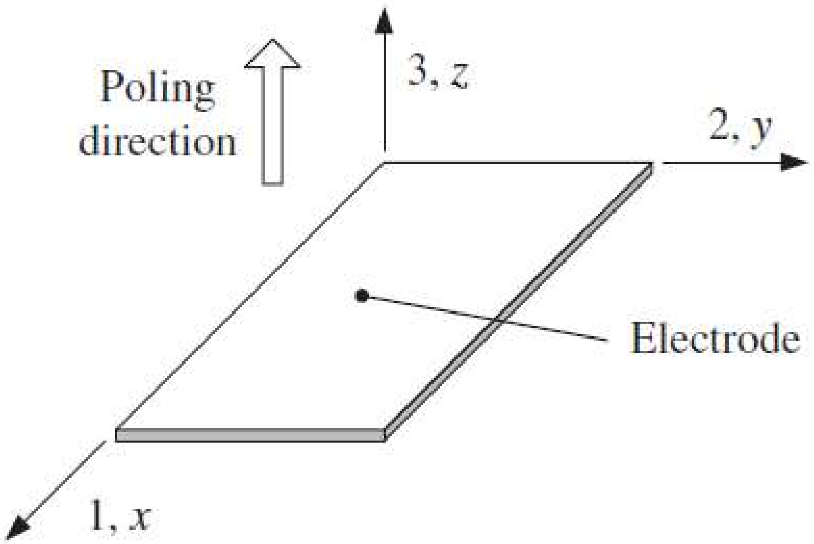
L’attuatore **1** \`e responsabile della **traslazione** mentre gli attuatori **2 e 3 vincolano la parte mobile a quella fissa**.

Un’opportuna sequenza di segnali di pilotaggio consente una traslazione lungo la parte fissa.

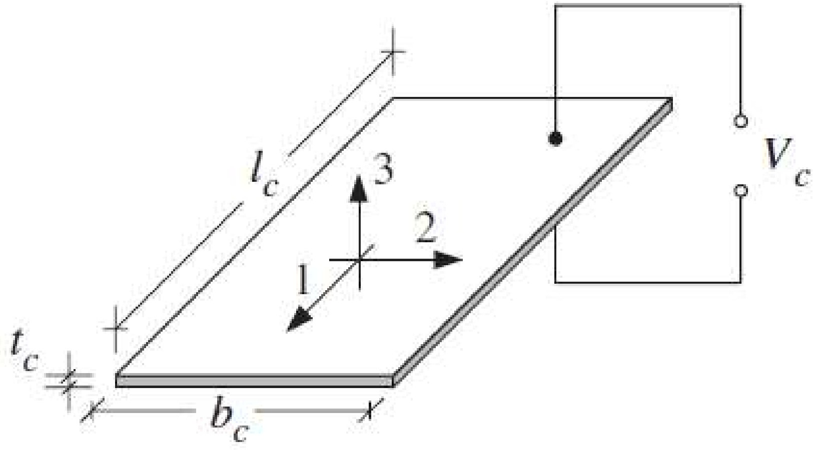
Table 4.3 Energy density of different types of piezoelectric materials in extensional and bending mode at an electric field of 1 MV/m

Company		d_{33} (pm/V)	d_{13} (pm/V)	Y_3^E (GPa)	Y_1^E (GPa)	E_v: Extensional (kJ/m^3)	E_v: Bending (kJ/m^3)
Piezo Systems	PSI-5A4E	390	190	52	66	4.0	0.7
	PSI-5H4E	650	320	50	62	10.6	1.8
American Piezo	APC 840	290	125	68	80	2.9	0.4
	APC 850	400	175	54	63	4.3	0.5
	APC 856	620	260	45	58	8.6	1.1
Kinetic Ceramics	PZWT100	370	170	48	62	3.3	0.5
TRS Ceramics	PMN-PT	2250	1050	12	17	30.4	5.3
	TRSHK1 HD	750	360	57	65	16.0	2.4

Piezolectric sensors



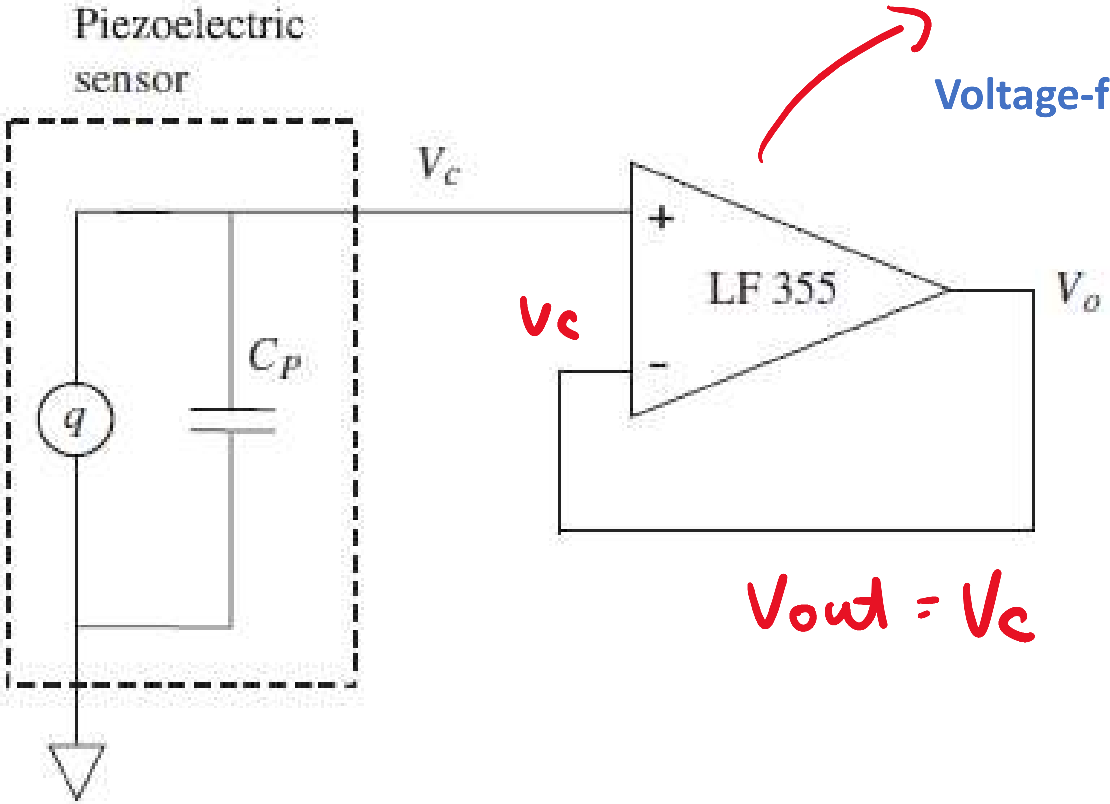
(a) Piezoelectric sheet



(b) Measuring output voltage

Piezolectric sensors

INAMP



Voltage-follower

Vc

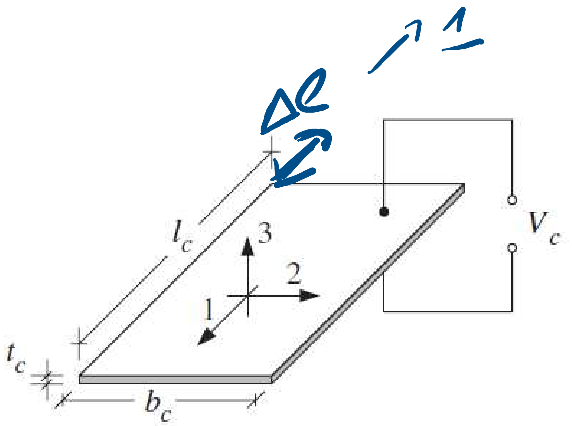
Vout = Vc

$$\boxed{\epsilon_1 = \frac{V_c C_p}{S_q}}$$

$$C_p = \varepsilon_{33} \frac{\ell b}{t}$$

$$q = \iint \underset{\downarrow \; d\sigma}{D_3} \, \underbrace{dA}_{dxdy} = \int_{\ell} d_{31} \, \underset{\downarrow \; E e_1}{\sigma} \, b \, dx$$

$$[C] \quad \left[\frac{C}{m^2}\right] [m^2] \, . \qquad = d_{31} E b \int_{\ell} e_1 \, d\cancel{x}$$



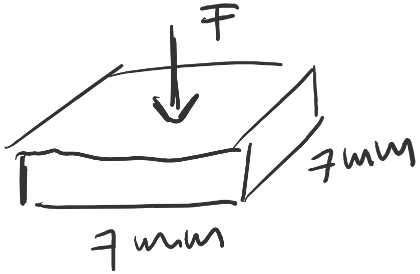
(b) Measuring output voltage

Sensitivity $\left[\frac{C}{\cancel{N}} \frac{\cancel{N}}{\cancel{m^2}} \cancel{m^2}\right]$

$$S = \frac{\Delta out}{\Delta in} = \frac{\Delta q}{\Delta \ell} \quad [C]$$

$$V_c = \frac{q}{C_p} = \frac{d_{31} E b \ell \; e_1}{C_p}$$

$$\boxed{e_1 = V_{out} \frac{C_p}{S}}$$



$\rightarrow d = 550 \times 10^{-12}$ m/V (C/N)

$C = 20 \times 10^{-12}\ \text{Pa}^{-1} = \frac{1}{E}$

$F = 100$ N

a) STRAIN e @ $\epsilon = 0$ $\Rightarrow$ $\sigma = \frac{F}{A} = \frac{100\ \text{N}}{(7\times10^{-3}\,\text{m})^2\ \text{m}^2} = 2.04\ \text{MPa}$

$e = \frac{\sigma}{E} = 2.04\ \text{MPa} \times \underset{[\text{Pa}^{-1}]}{\boxed{C}} = \underbrace{40.8 \times 10^{-6}}_{\mu\text{STRAIN}}$

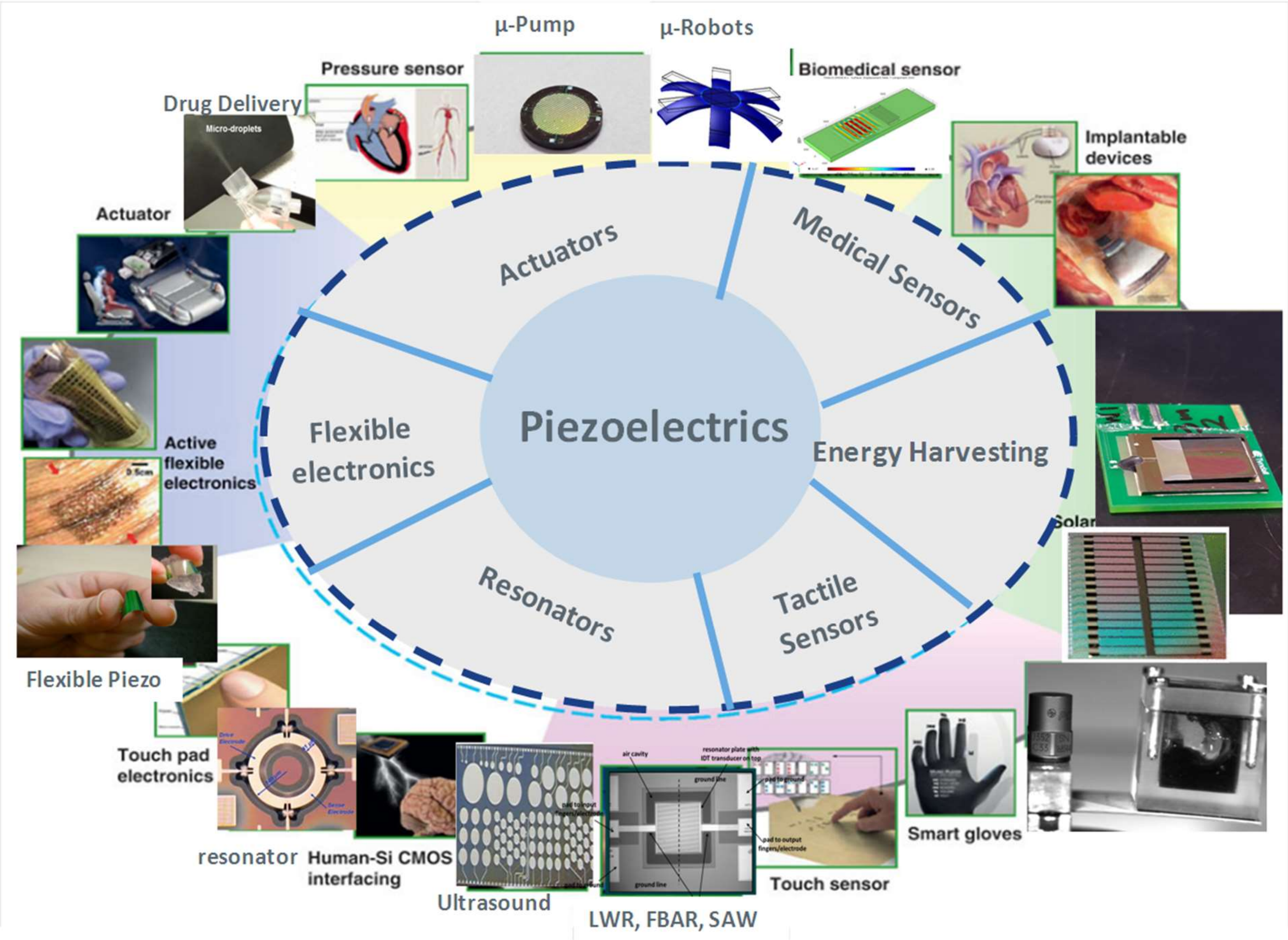
b) ϵ_{nec}

$e = d\,\epsilon \Rightarrow \epsilon = \frac{e}{d} = \frac{40.8 \times 10^{-6}}{550 \times 10^{-12}\ \text{m/V}} = 74.2\ \text{K}\ \frac{\text{V}}{\text{m}}$

$\left(" \frac{\text{N}}{\text{C}} \right)$

$$K = \sqrt{\frac{d^2}{c\varepsilon}} = 0.6 \qquad \varepsilon\,?$$

$$\varepsilon = \frac{d^2}{cK^2} = \frac{(550 \times 10^{-12}\ m/V)^2}{\left(20 \times 10^{-12}\ \frac{m^2}{N}\right)(0.6)^2} = 42 \times 10^{-9}\ \frac{C^2}{Nm^2}$$


μ-Pump
μ-Robots
Pressure sensor
Biomedical sensor
Drug Delivery
Micro-droplets
Implantable devices
Actuator
Actuators
Medical Sensors
Piezoelectrics
Flexible electronics
Energy Harvesting
Active flexible electronics
Solar
Resonators
Tactile Sensors
Flexible Piezo
Touch pad electronics
Smart gloves
resonator
Human-Si CMOS interfacing
Ultrasound
LWR, FBAR, SAW
Touch sensor