Piezoelectric Materials

Corso Materiali intelligenti e Biomimetici
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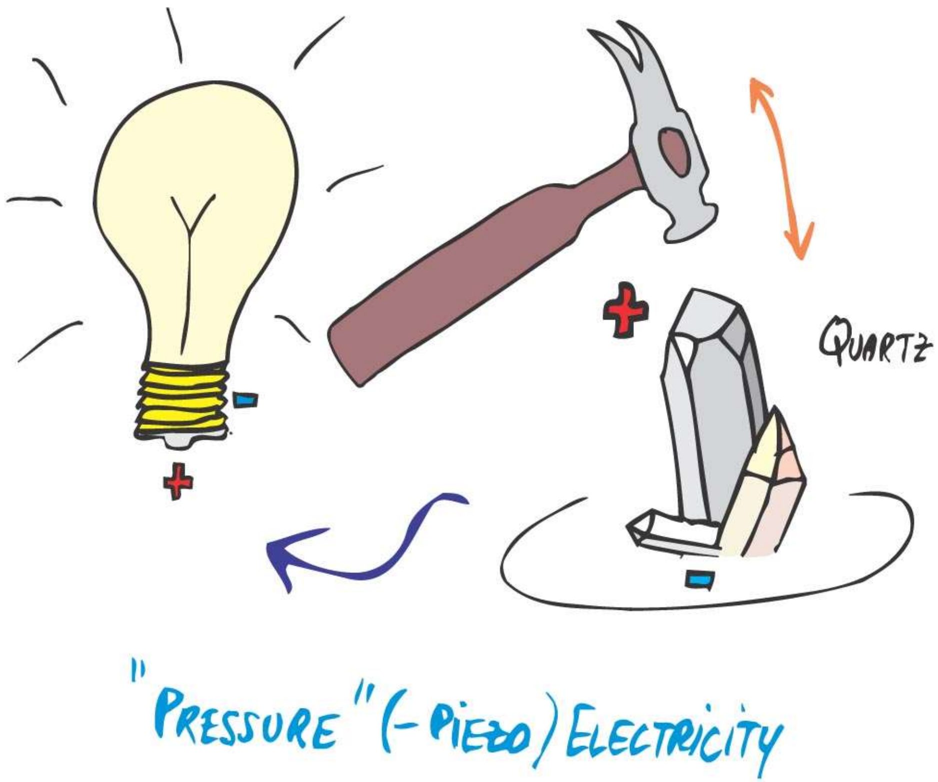
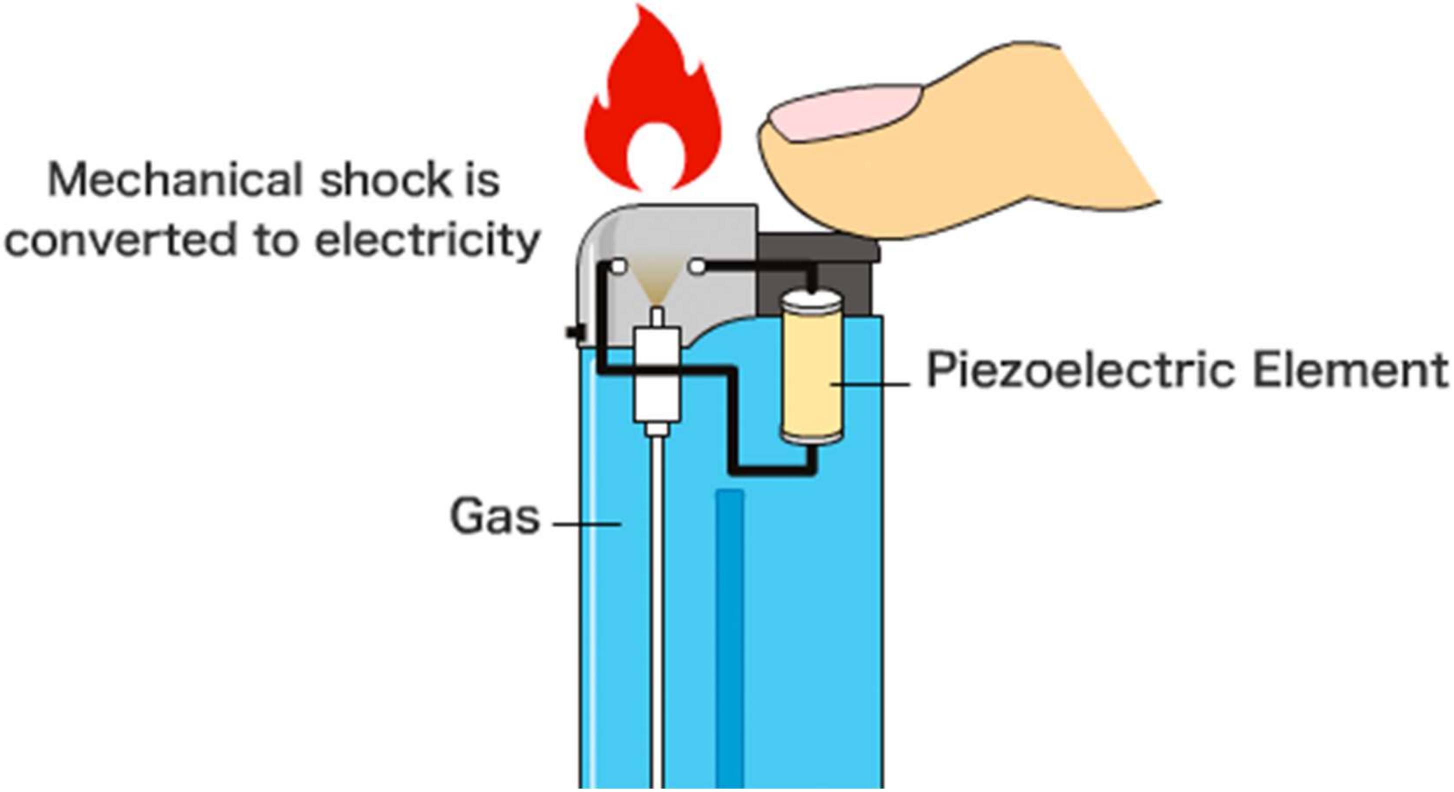
Piezoelectricity



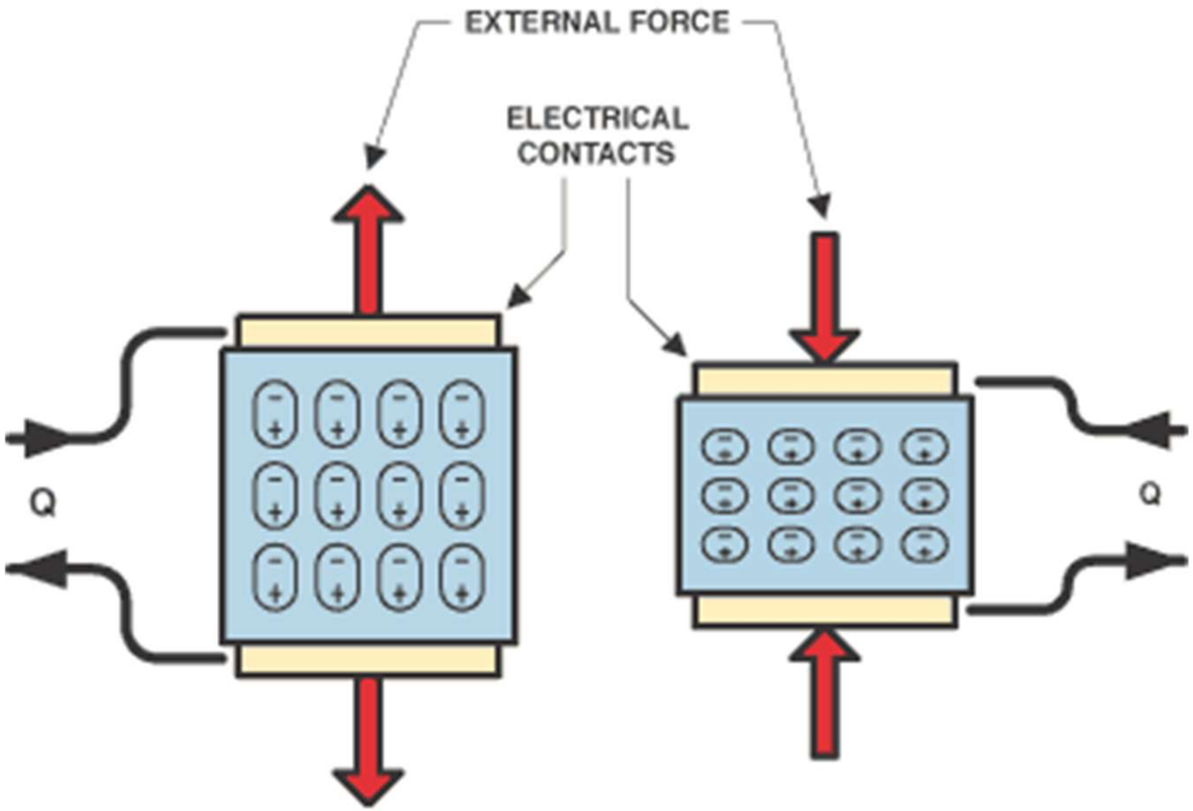
The word piezoelectricity is derived from the ancient Greek words *piezo*, "to squeeze or press," and *electric*.
So, piezoelectricity literally means electricity from pressure.

Example



Mechanical shock is converted to electricity
Piezoelectric Element
Gas

The piezoelectric effect



In piezoelectric materials, **when a mechanical stress (pressure) or strain (deformation) is applied to the material, the response is the generation of an internal charge**. This charge can be described as electrical potential energy (voltage) that can be used like any other energy source.

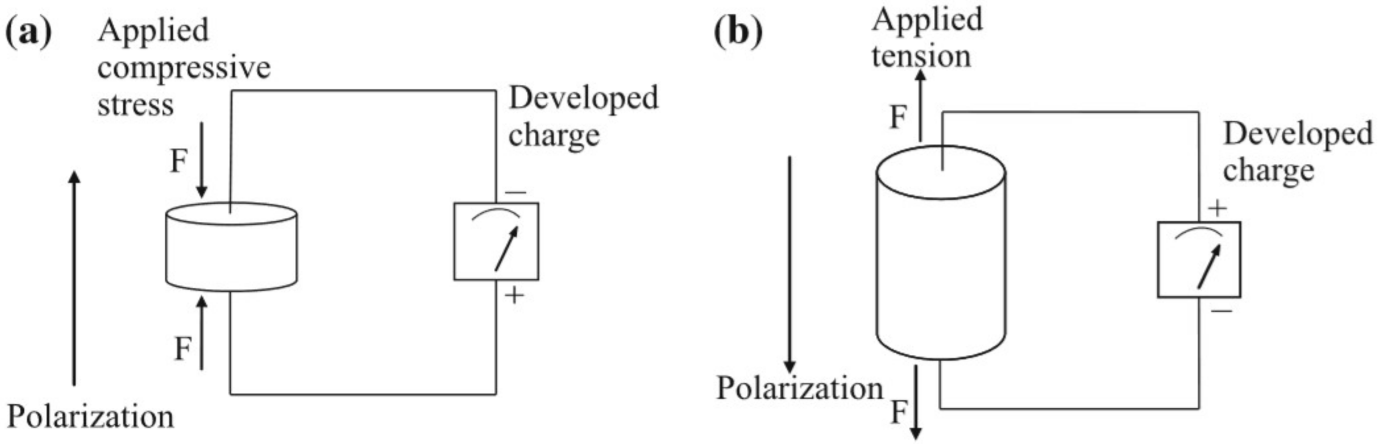


Fig. 2.1 Direct piezo-effect: **a** at applied compressive stress, **b** at applied tension

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

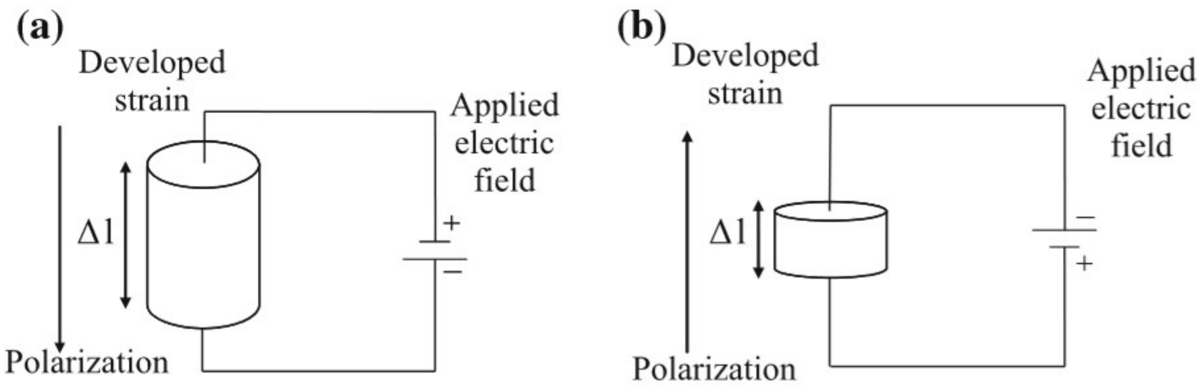


Fig. 2.2 Inverse piezo-effect at applied electric field

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**.

Constitutive equations

Electric displacement

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

Permittivity

Electrical field

Direct piezoelectric effect matrix

Mechanical stress

Mechanical strain

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

Inverse piezoelectric effect matrix

Electrical field

Mechanical compliance

Mechanical stress

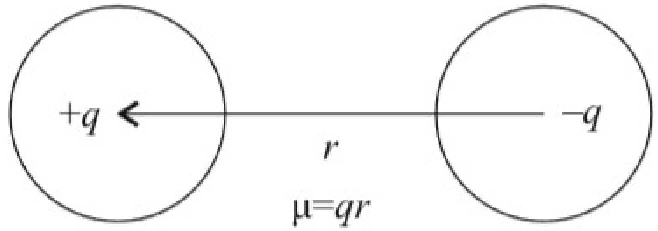
Dielectric materials

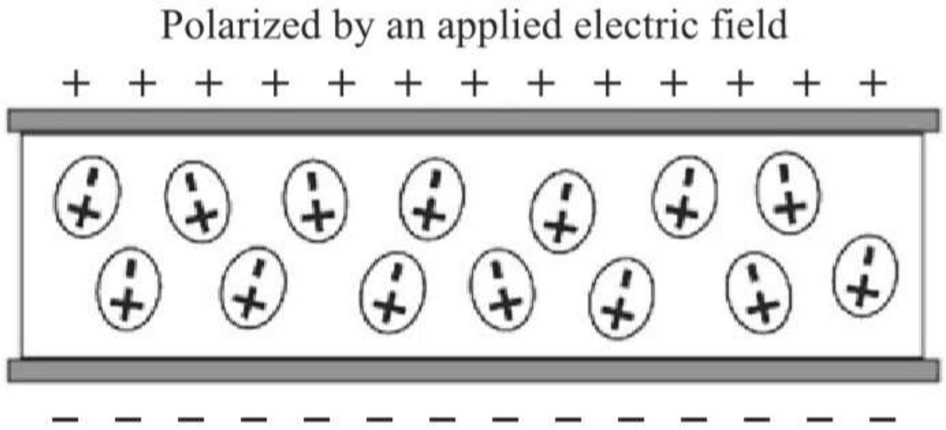
Piezoelectric materials are **anisotropic dielectrics** of special type. When a piezoelectric material is loaded electrically then the **electrical dipoles** appear.

The *electric dipole*, is an electro–neutral unit volume in which the centers of the positive +q and negative −q electric charges (poles) do not coincide and are at distance r, so that the dipole moment μ =qr arises.

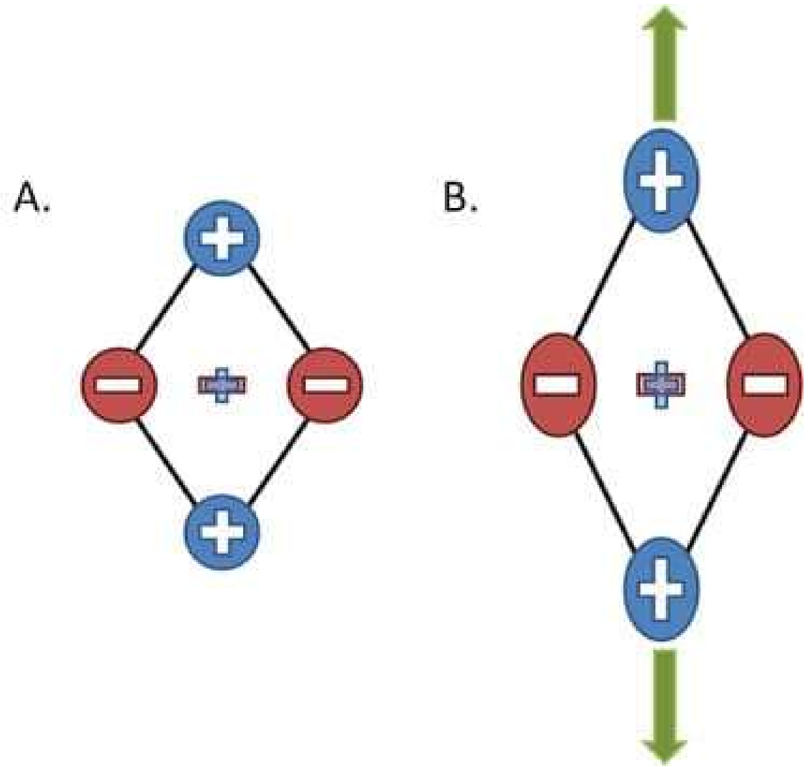
A dielectric material have **no free electrical charges**, but when an external electrical field is applied the **electric dipoles align** with it. The **polarization of a materia**l is simply the total dipole moment for a unit volume:

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





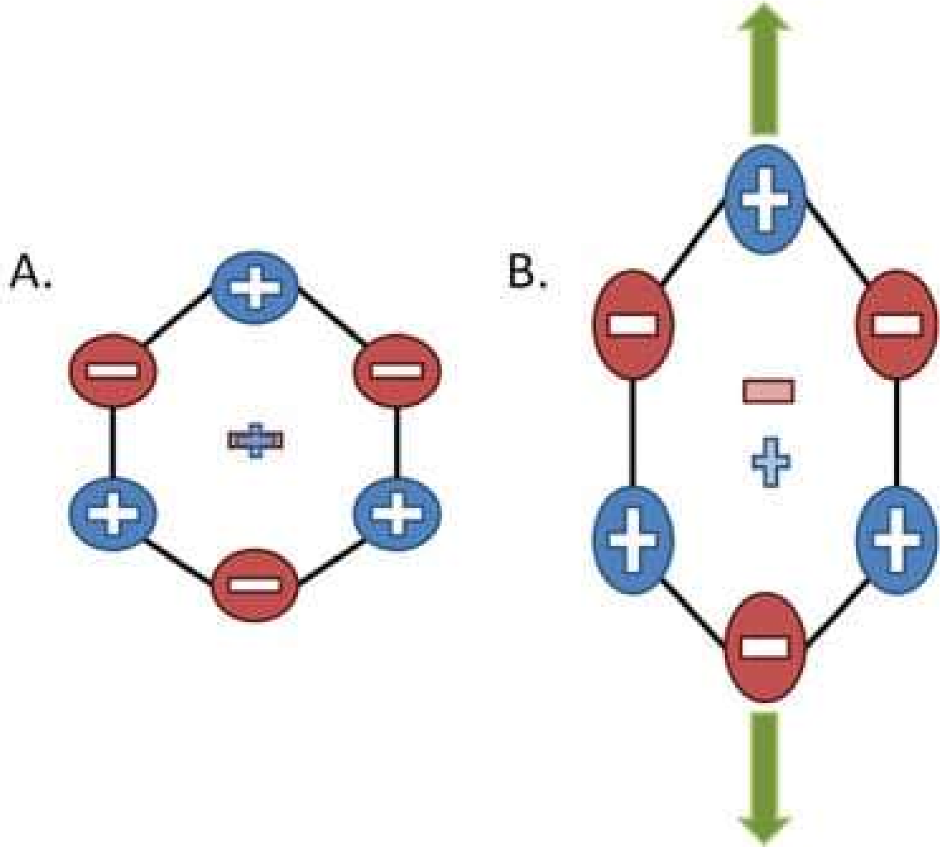
Atomic structure in not piezoelectric materials



Example: *crystal 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

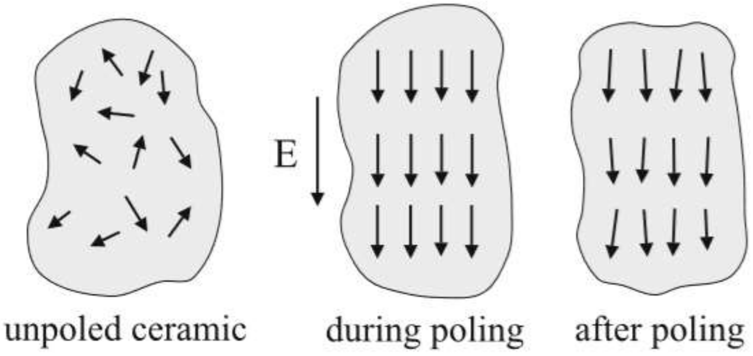


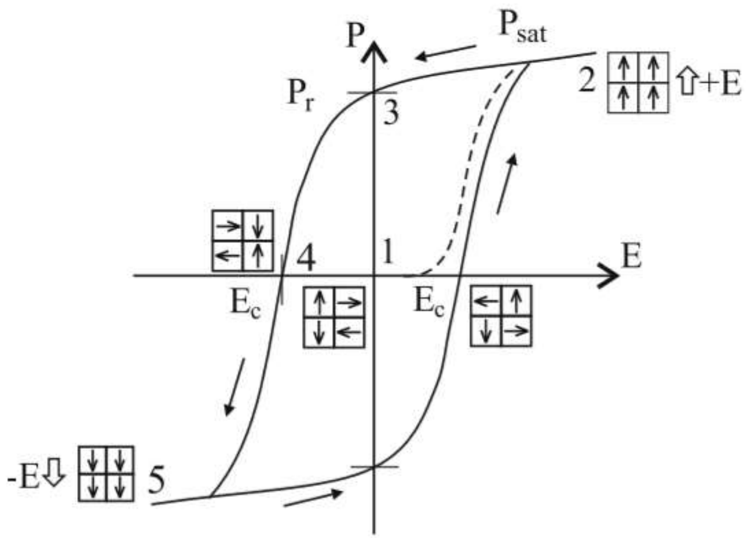
The atomic structure of piezoelectric materials is not completely symmetric.

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.

Ferroelectric materials





The other types of piezoelectric materials are with ferroelectric properties, i.e. **spontaneous polarization and electric dipoles** exist in their structure even in the absence of electrical field.

If a *mechanical stress is applied to the ferroelectric*, then there are *domains which will experience an increase in dipole moment and some which will experience a decrease in dipole moment*. Overall, there is **no net increase in polarization**. This makes the material useless as a piezoelectric unless it is put through some additional processing.

Poling: an electric field is applied to the ferroelectric below its *Curie temperature*, so that its spontaneous polarization develops and it is aligned in a single direction. When the electric field is removed most of the dipoles are locked in a configuration of near alignment.

In summary

- ‘special’ dielectric material-> dipoles form after the application of a mechanical stress -> the formation of dipoles depends from the asymmetric atomic structure
- Ferroelectric material -> spontaneous dipoles (T<Tcurie) -> the polarization increases or decreases after the application of a mechanical stress

Natural Piezoelectric Materials

Quartz crystal cluster from Tibet

Topaz

Sugar Cane

Tendon

DNA

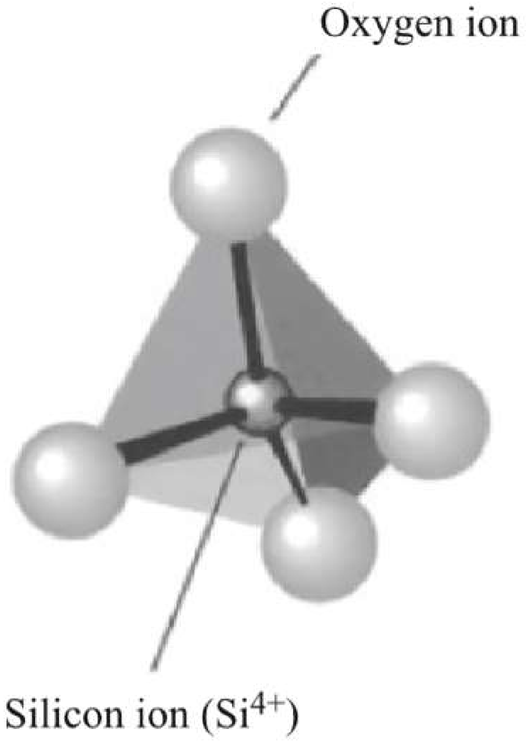
Bone

Rochelle Salt

Schorl Tourmaline

Dentine/ Enamel

Example: atomic structure of Quartz



The lattice structure is a *tetrahedron* built of *four oxygen atoms around a silicon atom*.
Each oxygen atom has the same distance to the silicon atom, and the distances between the oxygen atoms are all the same.

The **change in the position of the atoms due to applied stress** leads to the formation of net dipole moments that causes polarization and an electric field, respectively.

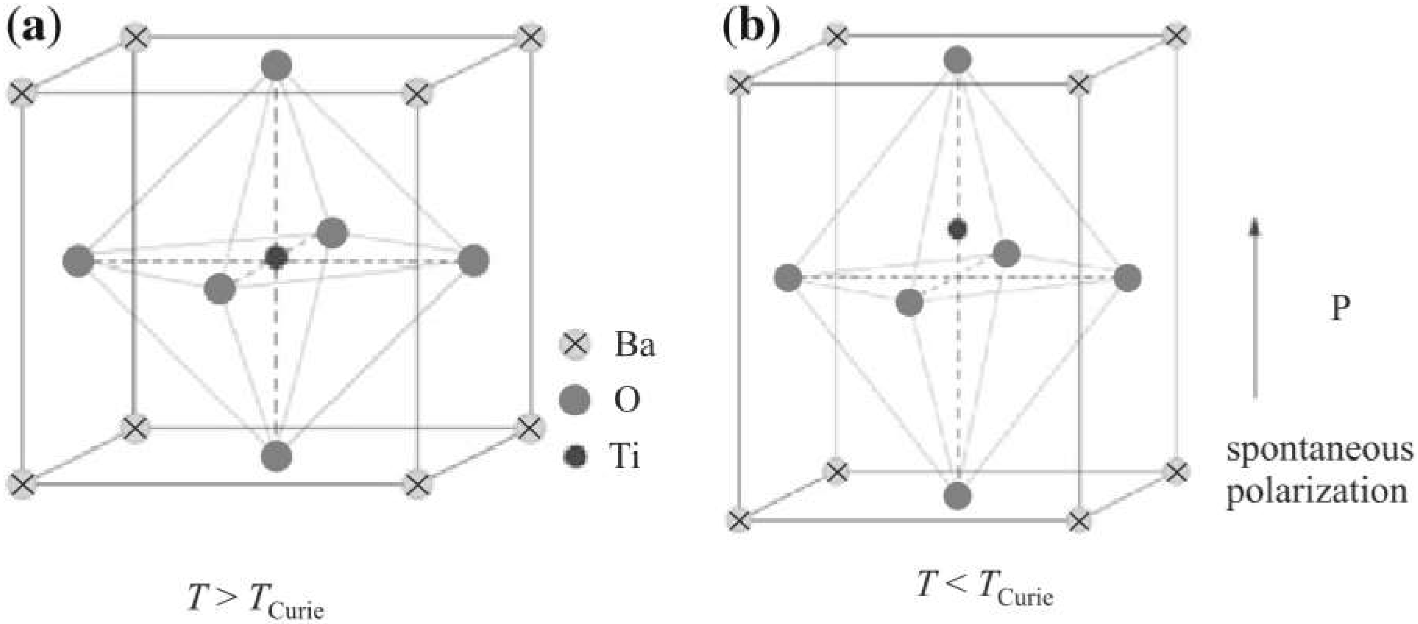
Synthetic piezoelectric materials

- **Ceramics**:
  The general chemical formulae of perovskite crystal *s*tructure is *ABO3*
  where A is a larger metal ions (e.g. Pb or Ba), B is a smaller metal ion (e.g. Ti or Zr) .
  Examples: *Barium titanate* ($BaTiO_3$); *Lead titanate* ($PbTiO_3$); *Lead zirconate titanate* (PZT)

- **Polymers**:
  polyvinylidene fluoride – polivilidene fluoruro - (PVDF) is a ferroelectric polymer.

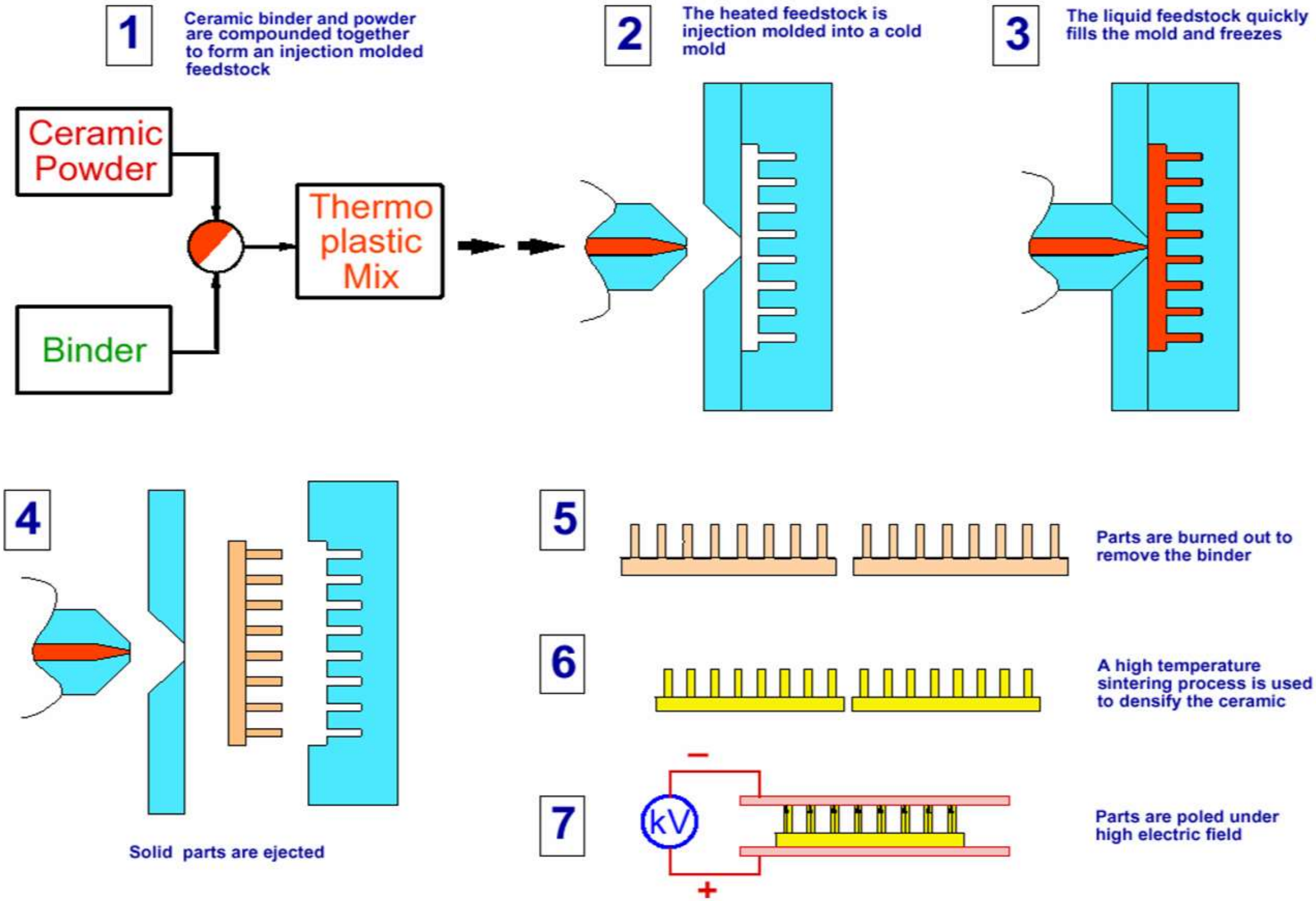
- **Composites**:
  - *piezo-polymer* in which the piezoelectric material is immersed in an electrically passive matrix (e.g. PZT in epoxy matrix)
  - two different ceramics (for example $BaTiO_3$ fibers reinforcing a PZT matrix).

Example: Atomic structure of BaTiO3

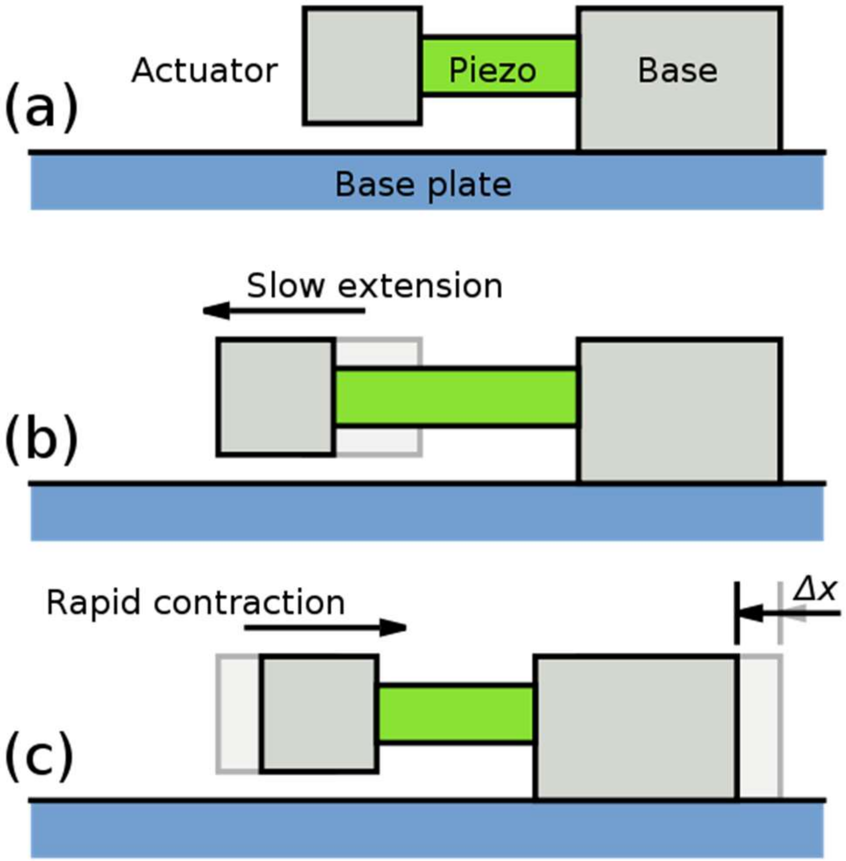


Above the Curie T, each perovskite crystal exhibits a *simple cubic symmetry with no dipole momen*t.

At temperatures **below the Curie point,** each crystal exhibits a *tetragonal symmetry* leading to a *dipole moment*; this phase of the material is called ferroelectric phase.


1
Ceramic binder and powder are compounded together to form an injection molded feedstock
Ceramic Powder
Binder
Thermo plastic Mix
2
The heated feedstock is injection molded into a cold mold
3
The liquid feedstock quickly fills the mold and freezes
4
Solid parts are ejected
5
Parts are burned out to remove the binder
6
A high temperature sintering process is used to densify the ceramic
7
–
kV
+
Parts are poled under high electric field

Piezoelectric actuator and motors



Gli attuatori e i motori piezoelettrici sfruttano l’**effetto piezoelettrico inverso** *convertendo energia elettrica (tensione e corrente) in energia meccanica (forze e spostamenti*).

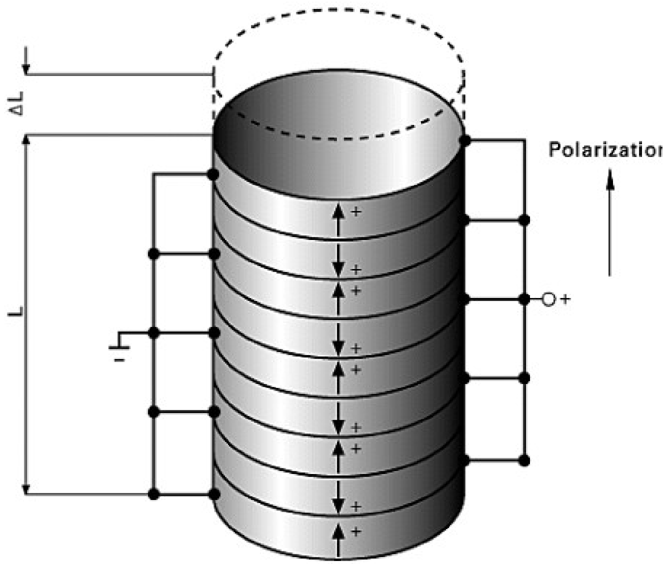
Gli **attuatori** propriamente detti sono dei dispositivi che si presentano *monolitici* (Solid-State Actuators) mentre i **motori** sono costituiti da *più parti*.

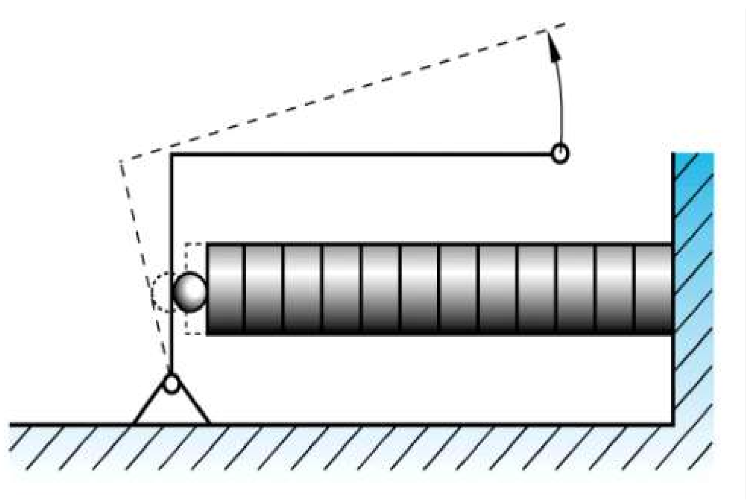
Multilayer actuators

Un attuatore piezoelettrico multilayer è costituito da una serie di **lamine piezoelettriche impilate** una sopra l’altra e racchiuse tra due elettrodi.

Per un’ottimizzazione delle dimensioni e del numero di componenti, tra due lamine adiacenti vi è un solo elettrodo: i **campi elettrici** generati dalla differenza di potenziale applicata agli elettrodi, perpendicolari alle lamine, **cambiano quindi verso ad ogni strato**.

Perchè le deformazioni indotte si sommino in maniera costruttiva le lamine piezoelettriche adiacenti devono avere **polarizzazione di verso alterno**.

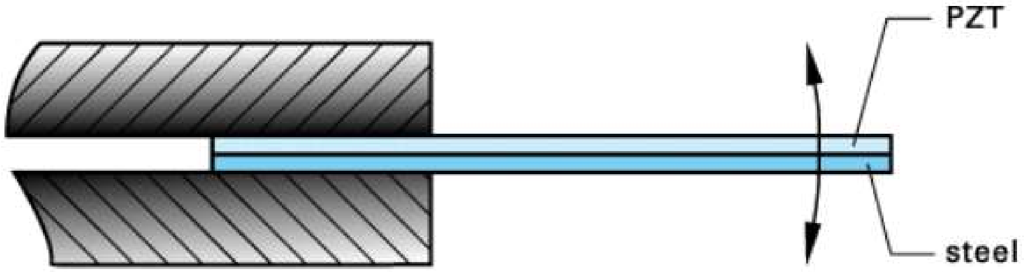




Bending Actuator

Attuatori in grado di generare una flessione dovuta alla contrazione di uno strato e all'espansione dell'altro adiacente.

L'attuatore **unimorfo** è costituito da una lamina piezoelettrica e da uno strato passivo di materiale (genericamente metallico).
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. Lo strato passivo genericamente funge anche da elettrodo.



Piezoelectric ‘inch-worm’ motors

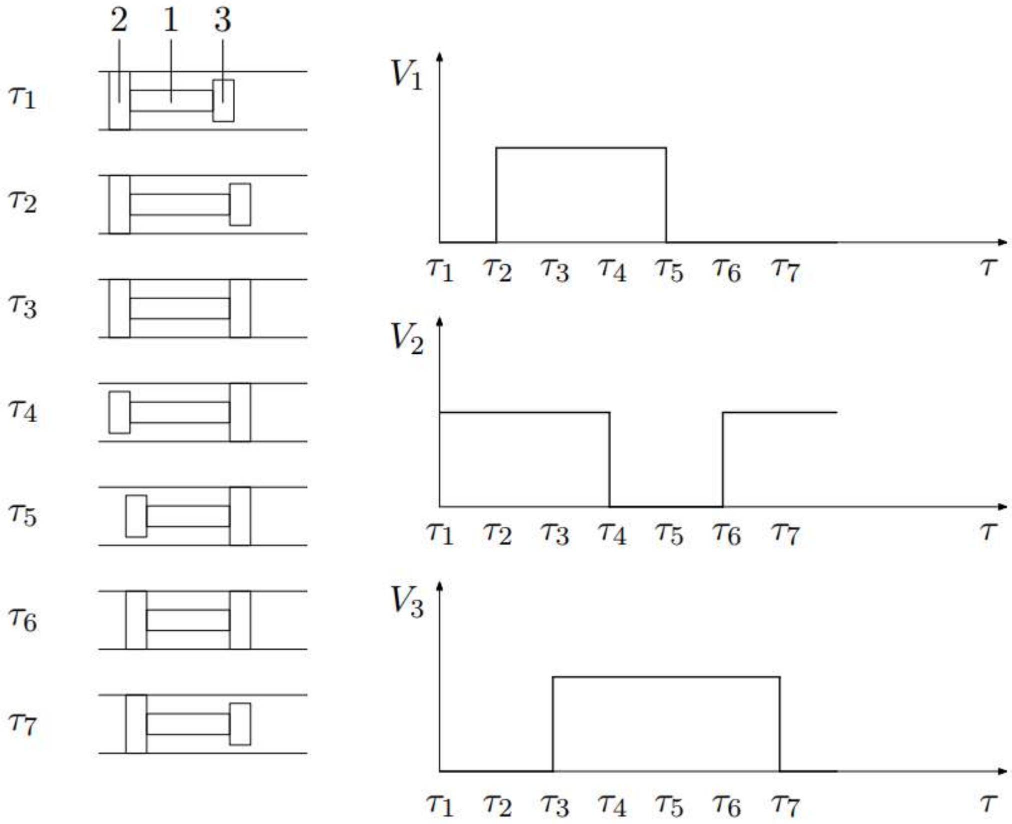
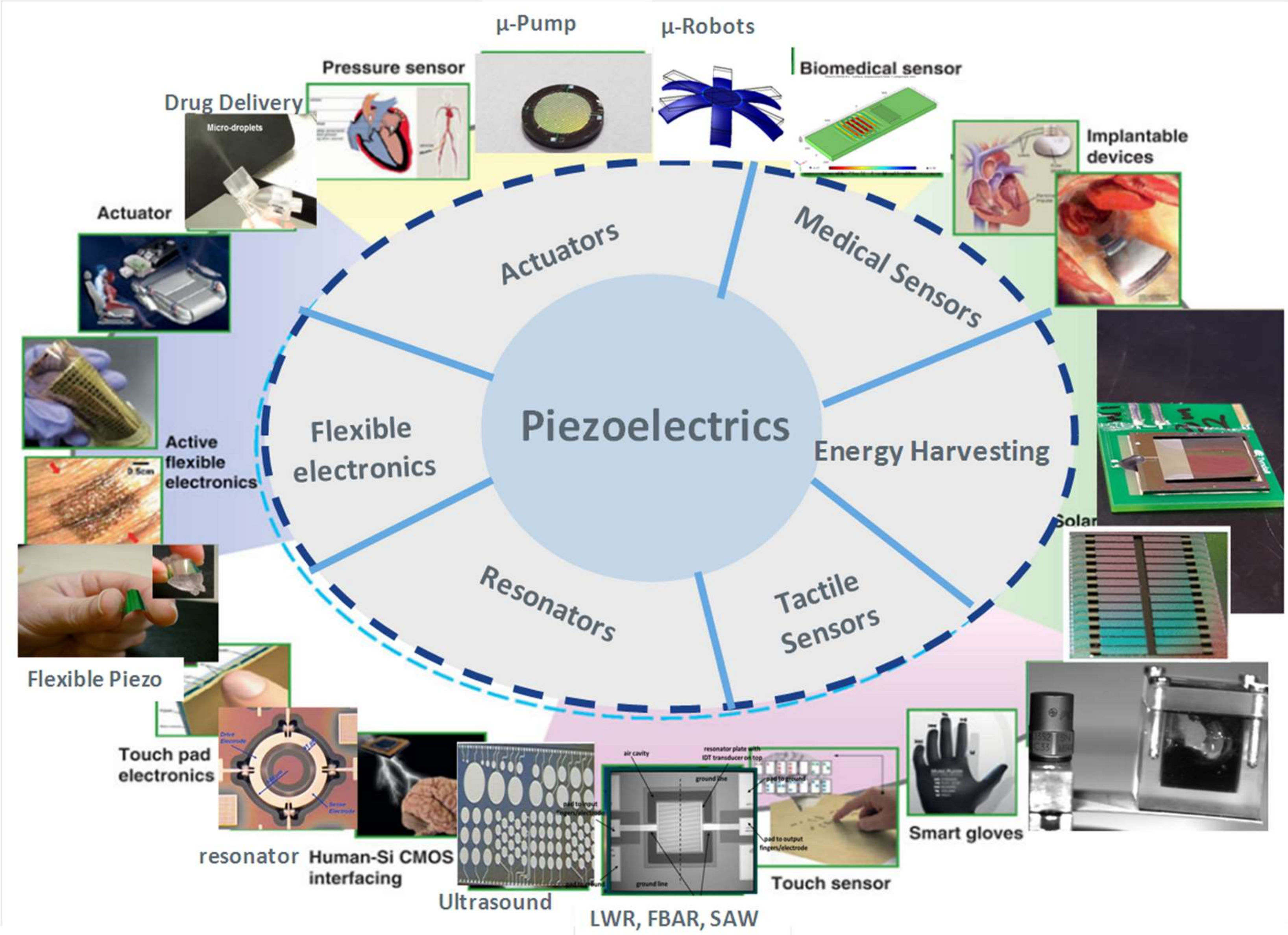


Figura 11: Motore inchworm e segnali di pilotaggio

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.



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

Attività di gruppo

- Trovare un articolo con un’applicazione interessante di un materiale piezoelettrico (non necessariamente biomedica) e realizzare una slides riassuntiva che evidenzi come le proprietà del materiale sono state sfruttate ai fini dell’applicazione