PIEZOELECTRIC

MATR 4347

Piezoelectric effect

Discovered in 1880 by Jacques and Pierre Curie during studies into the effect of pressure on the generation of electrical charge by crystals (such as quartz).

Piezoelectricity is defined as a change in electric polarization with a change in applied stress (direct piezoelectric effect).

The converse piezoelectric effect is the change of strain or stress in a material due to an applied electric field.

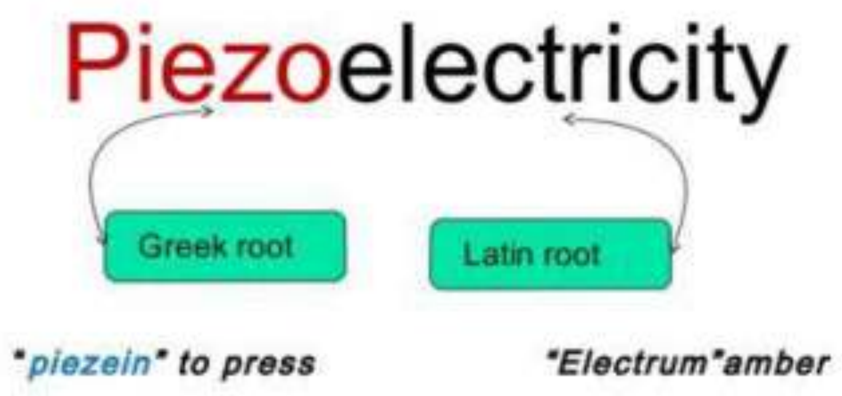
Piezoelectric effect

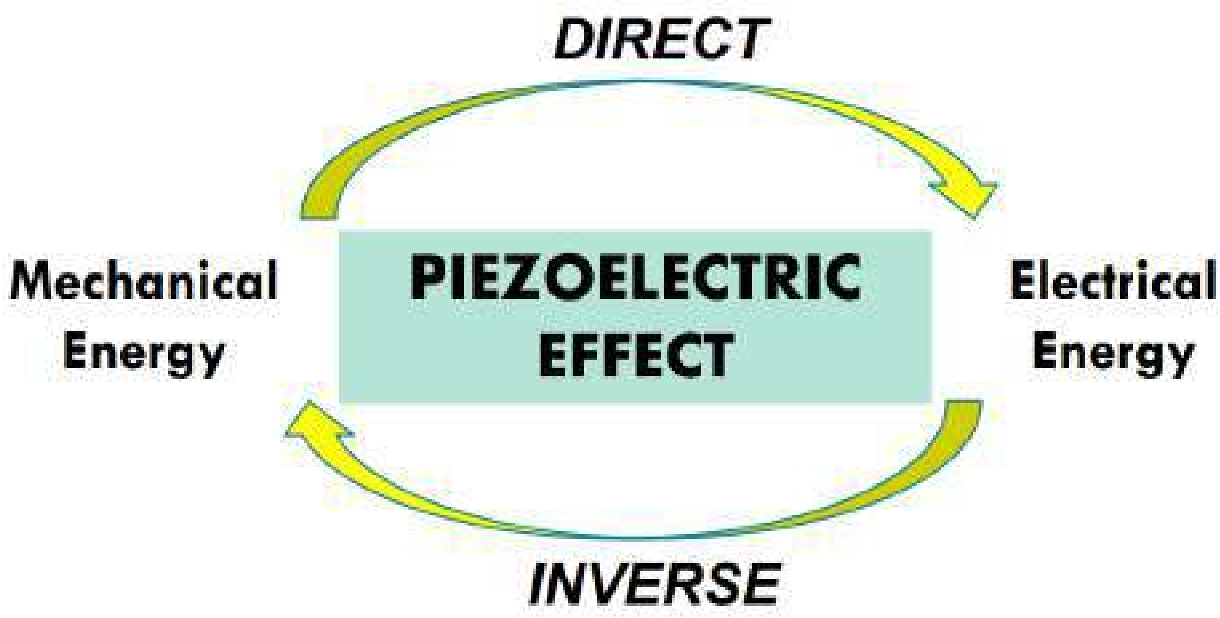
The piezoelectric effect is a property that exists in many materials.

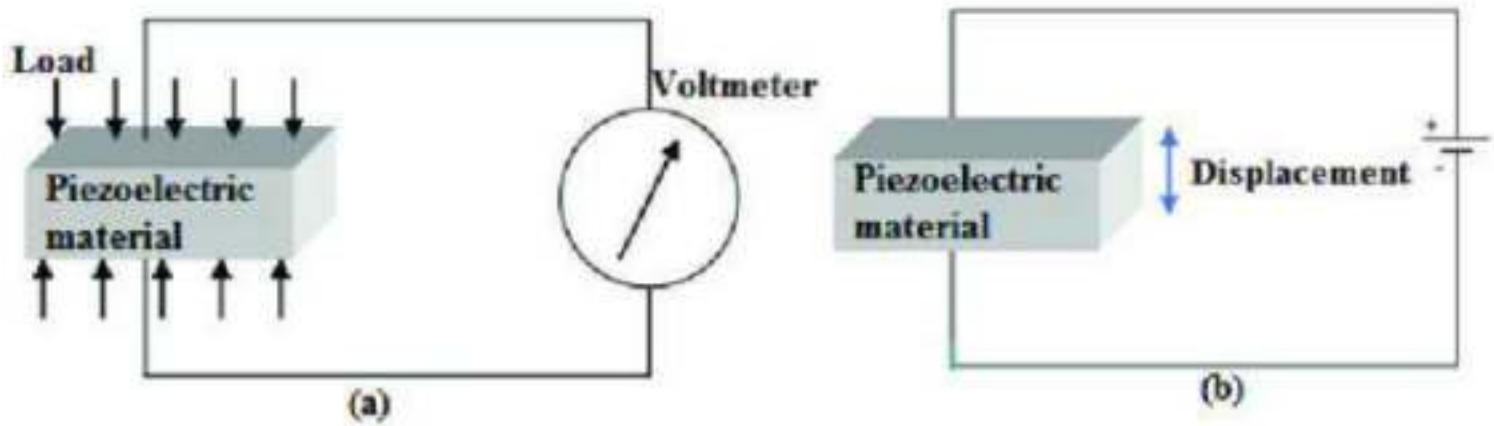
- "**piezo**" which is derived from the Greek word for pressure

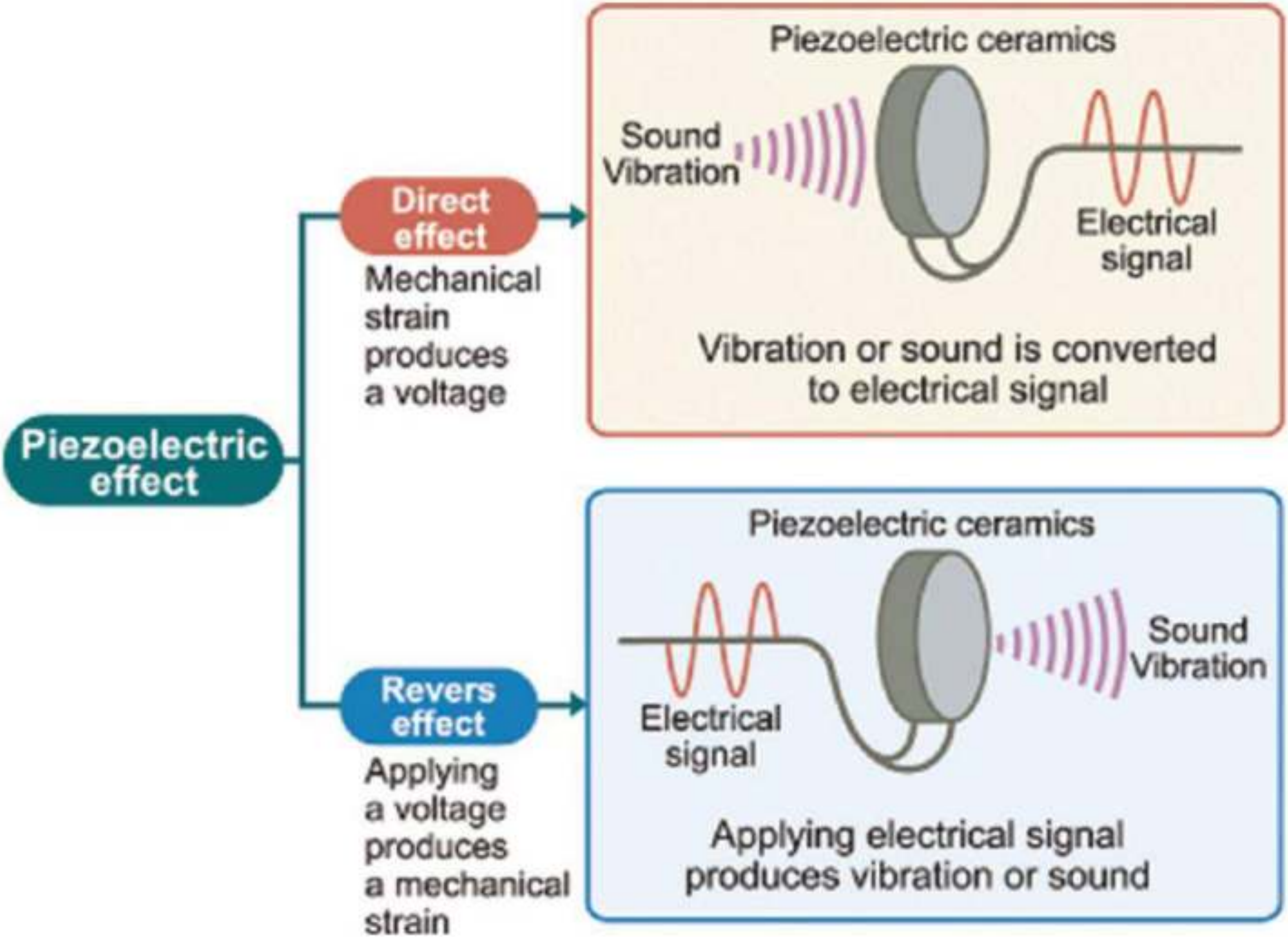
- "**electric**" from the Greek word for static electricity generated.

Piezoelectric effect: Conversion of mechanical energy to electronic signals (i.e., voltage) and vice versa




DIRECT
Mechanical Energy
PIEZOELECTRIC EFFECT
Electrical Energy
INVERSE


Load
Piezoelectric material
Voltmeter
(a)
Piezoelectric material
Displacement
+
-
(b)


Piezoelectric effect
Direct effect
Mechanical strain produces a voltage
Piezoelectric ceramics
Sound Vibration
Electrical signal
Vibration or sound is converted to electrical signal
Revers effect
Applying a voltage produces a mechanical strain
Piezoelectric ceramics
Electrical signal
Sound Vibration
Applying electrical signal produces vibration or sound

DIRECT EFFECT:

- In a piezoelectric material, the application of a force or stress results in the development of a charge in the material.

INVERSE EFFECT:

- Conversely, the application of a charge to the same material will result in a change in mechanical dimensions or strain.

Piezoelectric materials are characterized by a linear shape change in response to an electric field.

The electricity makes the material expand or contract almost instantly and exhibit a reversal in direction of geometrical change when direction of electric field is reversed.

- The direct effect:
  - Strain sensor, microphones, gas lighters, ultrasonic detectors etc.
- The inverse effect:
  - Crystal oscillators, crystal speakers, record player pic ups, actuators etc.

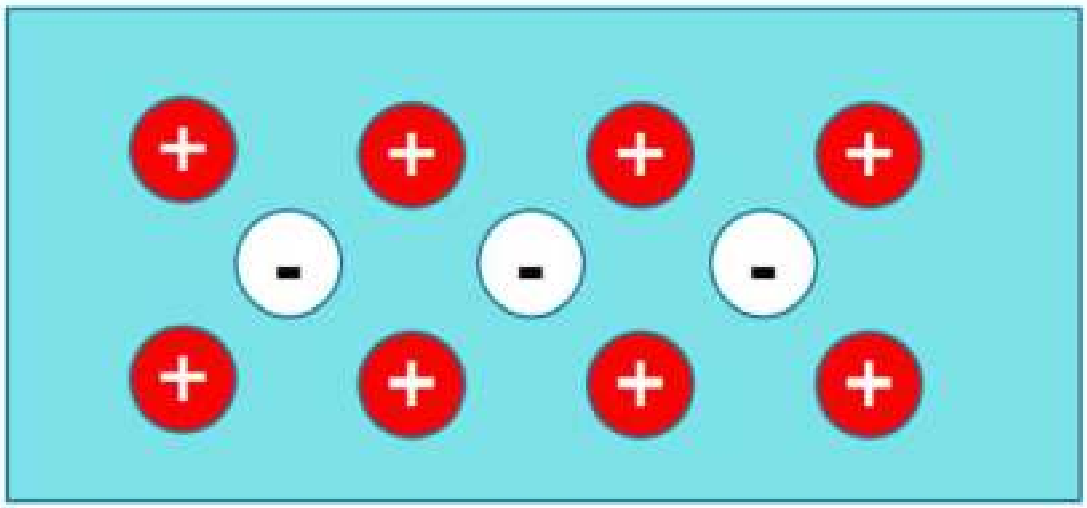
The microscopic origin of the piezoelectric effect is the displacement of **ionic charges** within a crystal structure.

In the absence of external strain, the charge distribution is symmetric, and the net electric dipole moment is zero.

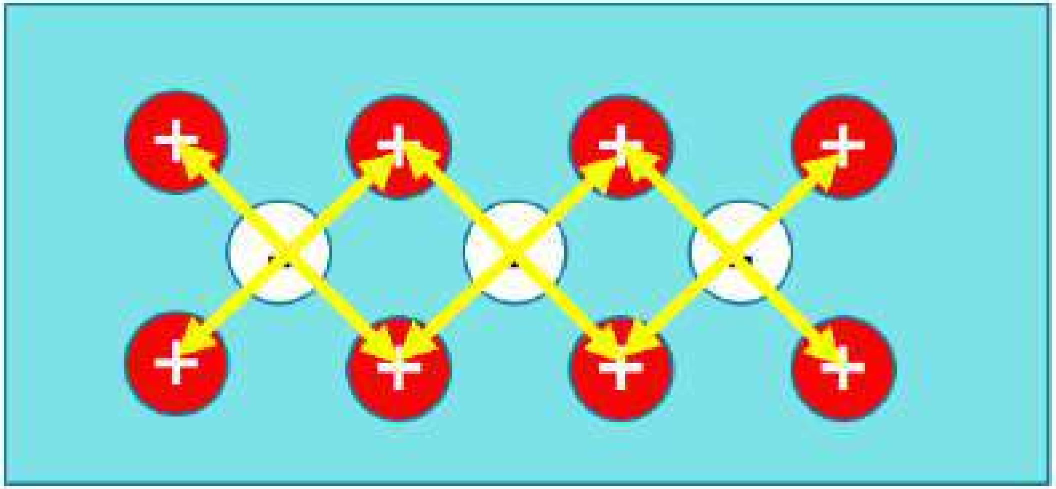
However, when an external stress is applied, the charges are displaced, and the charge distribution is no longer symmetric, and a net polarization is created.

How piezoelectric work

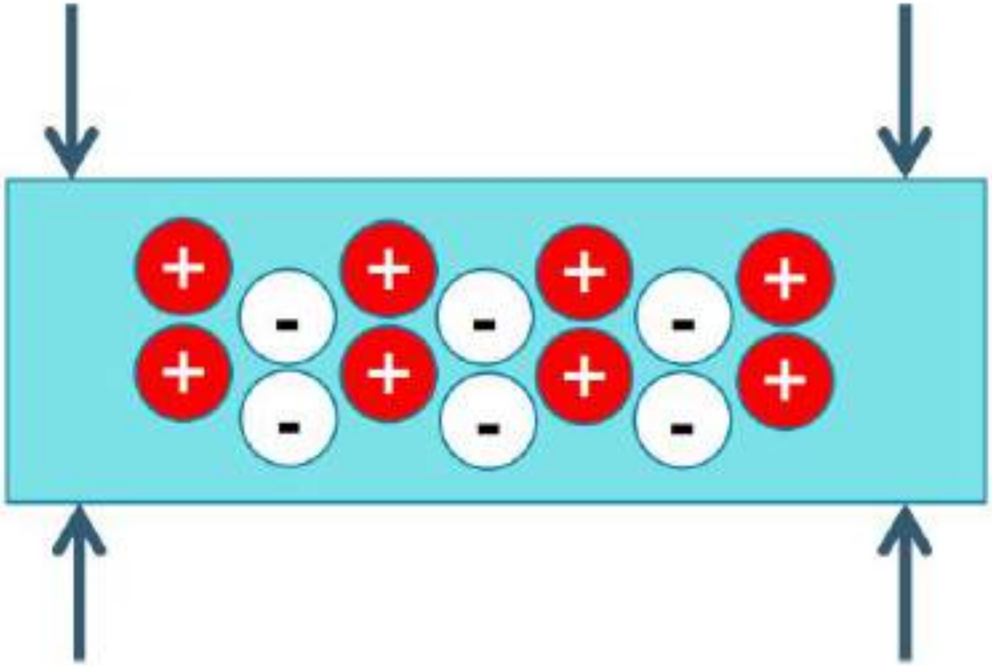
1. Normally, the charges in a piezoelectric crystal are exactly balanced (neutral) or distribution of charges are symmetric, even if the atoms (unit cell) are not symmetrically arranged.



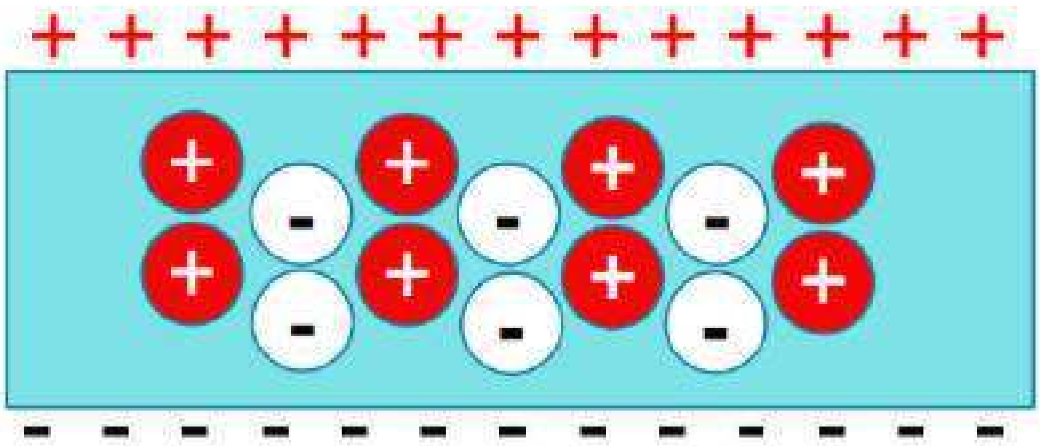
2. The effects of the charges exactly cancel out, leaving no net charge on the crystal faces. In other words, the electric dipole moments (vector lines separating opposite charges) cancel one another out



3. If we squeeze the crystal, we force the charges out of balance.



4. Now, the effects of the charges (their dipole moment) no longer cancel one another out, and net positive and negative charges appear on opposite crystal faces. By squeezing the crystal, we produced a voltage across its opposite faces.



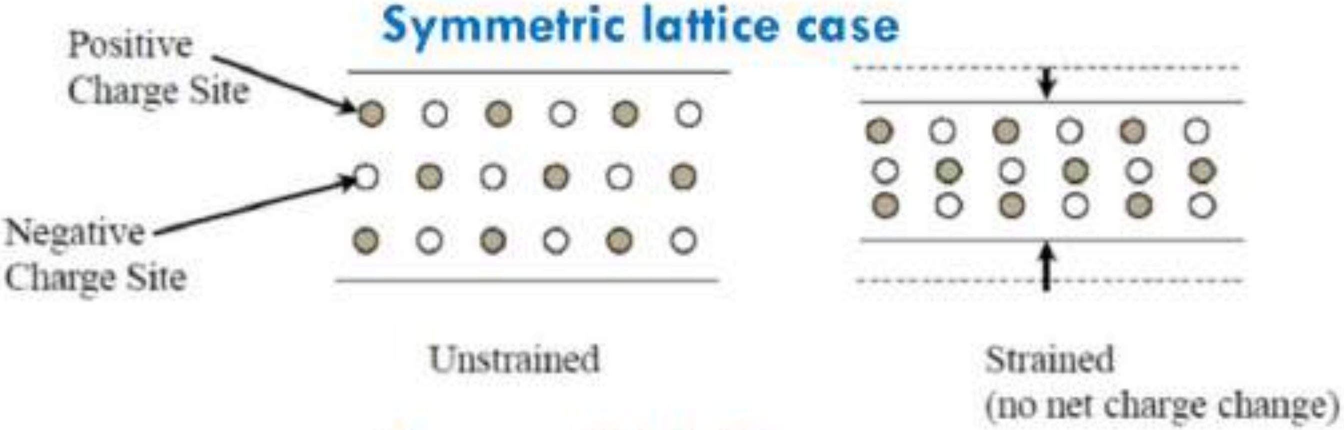
PIEZOELECTRIC MATERIALS: CRYSTAL STRUCTURE

- The microscopic origin of piezoelectricity is the displacement of ion charges within a crystal.

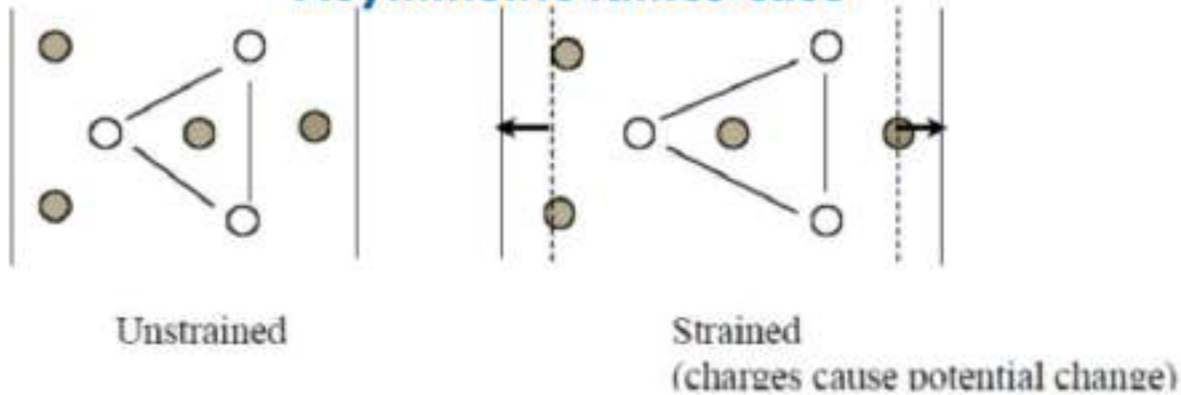
- Symmetric lattice structure (isotropic) does not produce piezoelectricity when deformed.
- Asymmetric lattice structures (anisotropic) will create an electrical potential when deformed.

- This is because, for the piezoelectric phenomenon to occur in a material, the crystal lattice should have no center of symmetric.
- There must be at least one axis in the lattice along which the atomic structure is different along other axes.

Symmetric lattice case

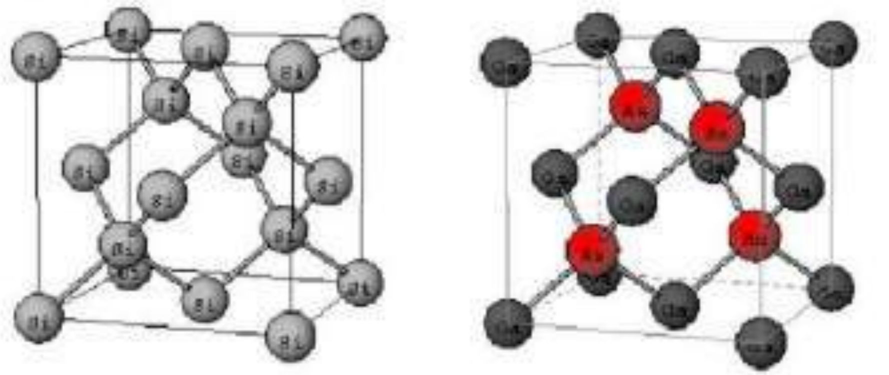


Asymmetric lattice case



PIEZOELECTRIC MATERIALS: CRYSTAL STRUCTURE

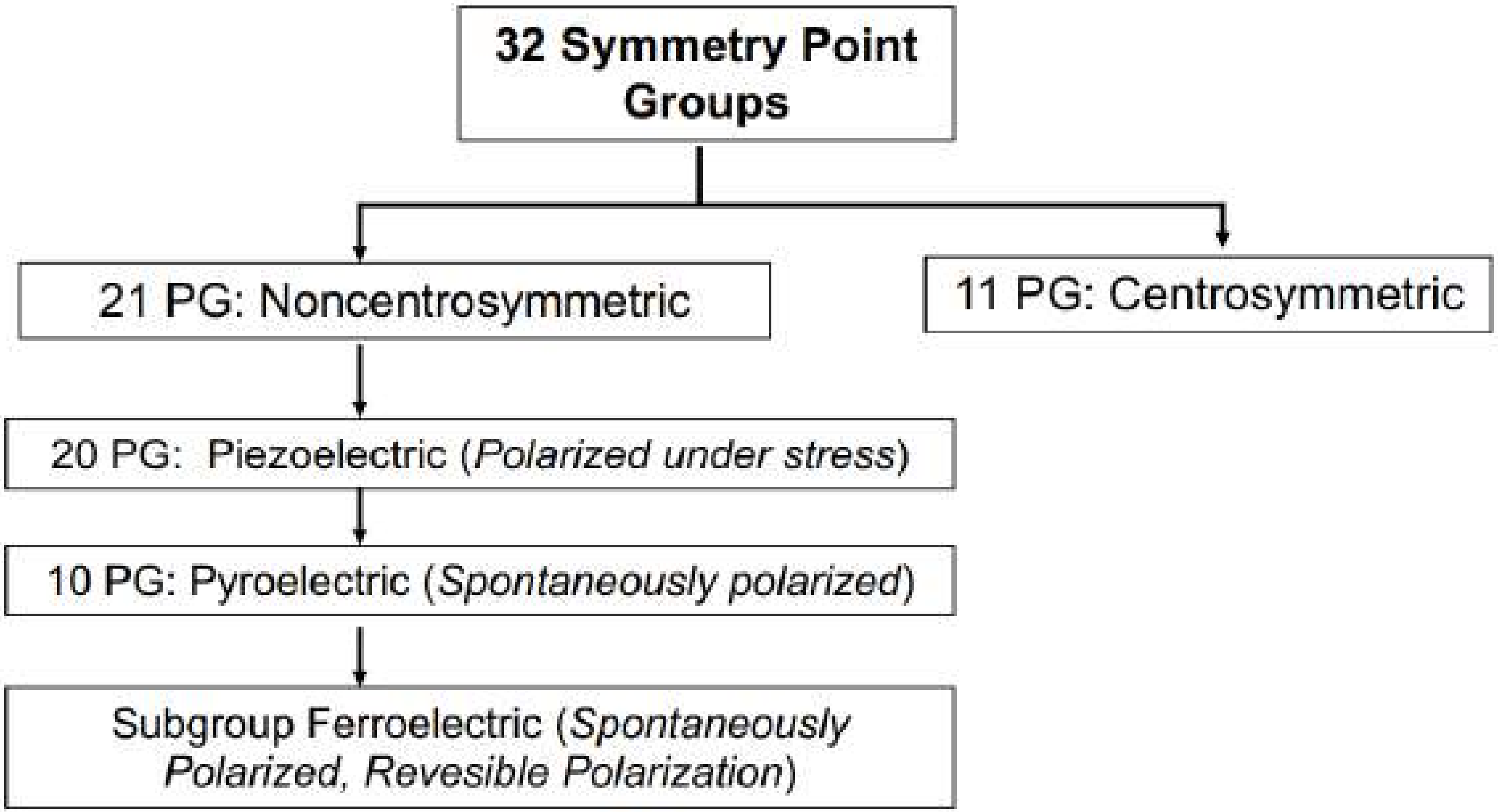
- Silicon, Si
  - Si is symmetric and does not exhibit piezoelectricity
- Gallium Arsenide, GaAs
  - GaAs lattice is not symmetric and exhibits piezoelectricity
  - However, it has poor piezoelectric material properties



Silicon	**GaAs**
Diamond Cubic Structure	ZnS (Zinc Blende) Structure
4 atoms at (0,0,0)+ FCC translations	4 Ga atoms at (0,0,0)+ FCC translations
4 atoms at (¼,¼,¼)+FCC translations	4 As atoms at (¼,¼,¼)+FCC translations
Bonding: covalent	Bonding: covalent, partially ionic

- *Of the 32 crystal classes, only 20 exhibit piezoelectricity with non-centrosymmetric*

PIEZOELECTRIC MATERIALS: CRYSTAL STRUCTURE



PIEZOELECTRIC MATERIALS: CRYSTAL STRUCTURE

- Quartz, SiO_2 (natural materials)
  - Bulk single crystal, simple asymmetric crystal
  - d_{33} = 2.33 pC/N
- Zinc Oxide, ZnO (engineered materials)
  - Single crystal, or Sputtered thin film (polycrystalline-ceramic)
  - d_{33} = 246 pC/N
- Barium Titanate, $BaTiO_3$ (engineered materials)
  - Ceramic material
  - d_{33} = 160 pC/N
- Lead Zirconate Titanate, PZT (engineered materials)
  - Ceramic bulk, or sputtering thin film
  - d_{33} = 110 pC/N
- Polyvinylidene Fluoride (PVDF) (engineered materials)
  - Polymer , d_{33} = 1.59 pC/N

** d_{33} is the piezoelectric constant for each materials*

Material	Relative permittivity (Dielectric constant)	Young's modulus (GPa)	Density (kg/m^3)	Coupling factor (k)	Curie temperature (°C)
ZnO	8.5	210	5600	0.075	**
PZT-5A (PbZrTiO3)	1730	48-135	7750	0.66	365
Quartz (SiO2)	4.52	107	2650	0.09	**
Lithium tantalite (LiTaO3)	41	233	7640	0.51	350
PVDF	13	3	1880	0.2	80

PIEZOELECTRIC MATERIALS

Curie temperature
- Temperature above which the piezoelectric property will be lost

Material purity
- The piezoelectric constant is sensitive to the composition of the material and can be damaged by defects

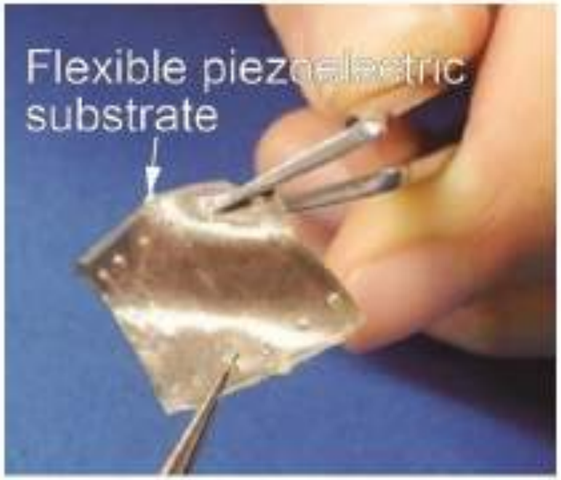
Frequency response
- Most materials have sufficient leakage and cannot hold a DC force. The DC response is therefore not superior but can be improved by materials deposition/ preparation conditions

Bulk vs thin film
- Bulk materials are easy to form but can not integrate with MEMS or IC easily. Thin film materials are not as thick and overall displacement is limited

ENGINEERED PIEZOELECTRIC MATERIALS

Advantages of engineered (man-made) piezoelectric materials;

- Physically strong
- Chemically inert
- Inexpensive
- Can be molded to fit many shapes
- Survive at high temperature

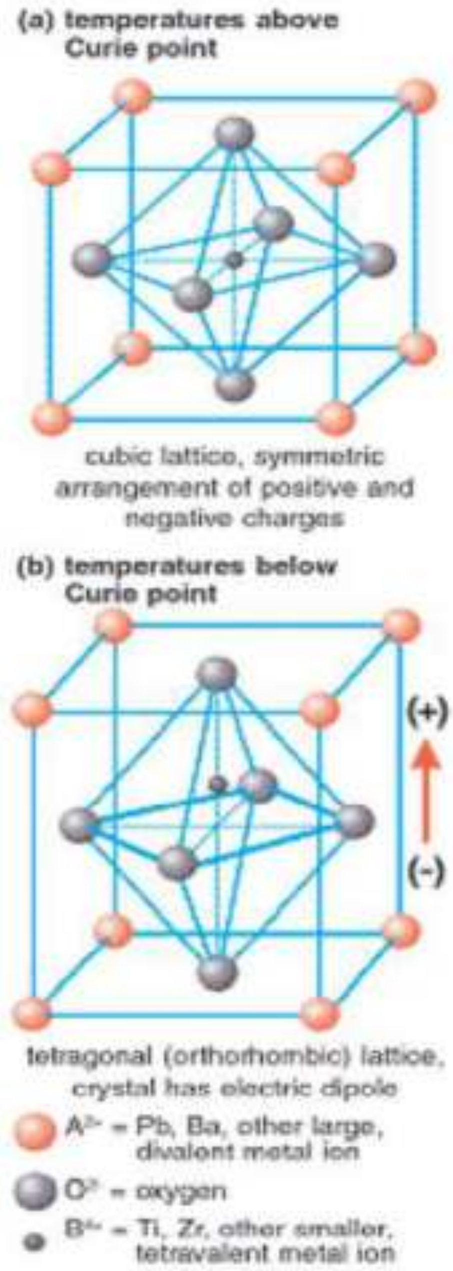


HOW ARE PIEZOELECTRIC CERAMICS MADE?

A traditional piezoelectric ceramic is perovskite crystal with non-centrosymmetric.

Each consisting of a small tetravalent metal ion (usually titanium or zirconium), in a lattice of larger divalent metal ions (usually lead or barium, and O_2- ions).

Under conditions that confer tetragonal or rhombohedral symmetry on the crystals, each crystal has a dipole moment.



POLARIZATION OF PIEZOELECTRIC

1. **Above the Curie point:**

Each perovskite crystal exhibits a simple cubic symmetry with no dipole moment.

2. **Below the Curie point;**

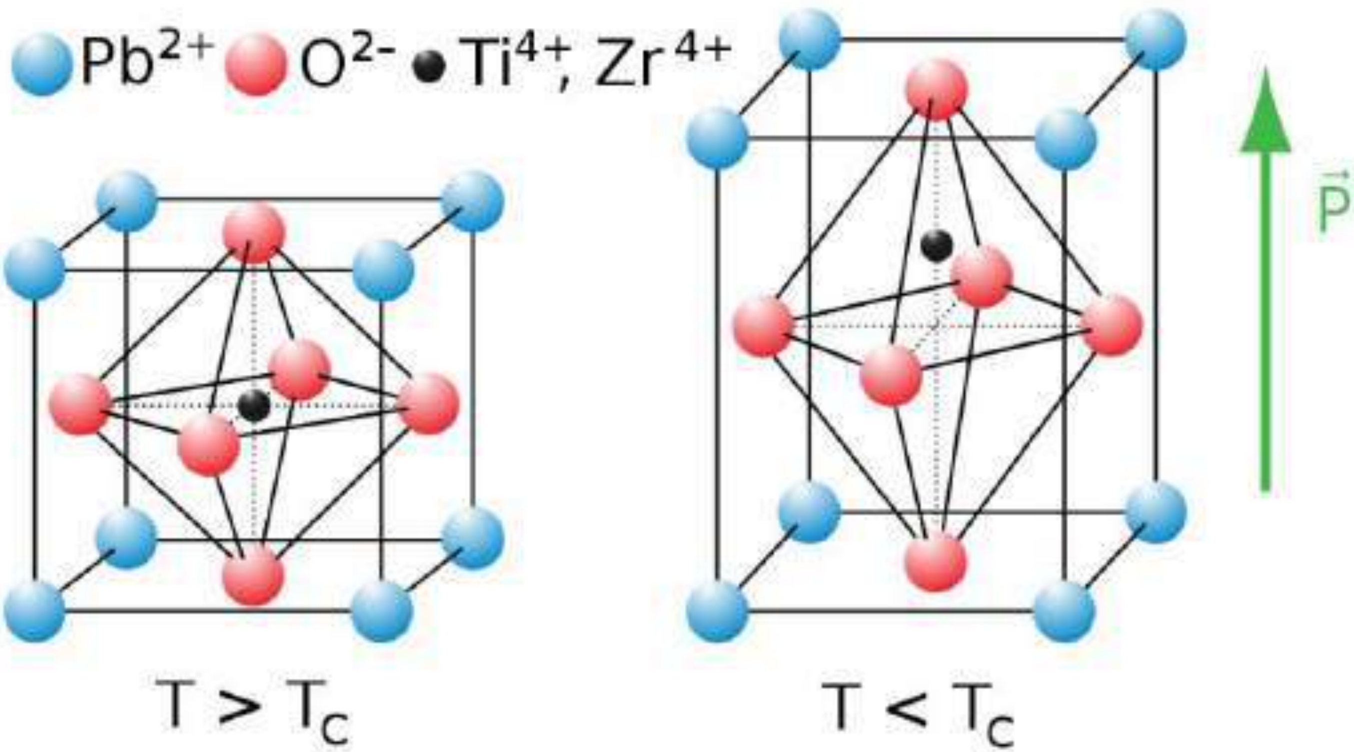
Each crystal has tetragonal or rhombohedral symmetry and can form a dipole moment.

Adjoining dipoles form regions of local alignment called *domains*.

The alignment gives a net dipole moment to the domain, and thus a net polarization.

However, the direction of polarization among neighboring domains is random, so the ceramic element has no overall polarization.

EXAMPLE : PZT



- Cubic lattice, symmetric arrangement of +ve and –ve charges
- Tetragonal lattice, asymmetric arrangement and crystal has electric dipole

EXAMPLE : PZT

Lead Zirconate Titanate (PZT)

(1) Above the Curie Temperature,

the crystal structure is cubic and has no electric dipole movement.

(2) Below this temperature,

the positively charged Ti or Zr ion shifts from its central location along one of several allowed directions.

This slightly distorts the crystal lattice into a a tetragonal (rhombohedra) shape and can produces an electric dipole.

After sintering, groups of molecular dipoles align within small areas (Weiss domains) to form large dipole moments. PZT is made up of many such domains; however, as they are randomly oriented, their net electric dipole is zero.

POLARIZATION OF PIEZOELECTRIC

The domains in a ceramic element are aligned by exposing the element to a strong, direct current electric field, usually at a temperature slightly below the Curie point.

This is called as polarization or poling treatment.

Through this polarizing *(poling)* treatment,

- 1. Domains most nearly aligned with the electric field expand below the Curie temperature
- 2. The element lengthens in the direction of the field (increases in dimension between the poling electrodes and decreases in dimensions parallel to the electrodes.).

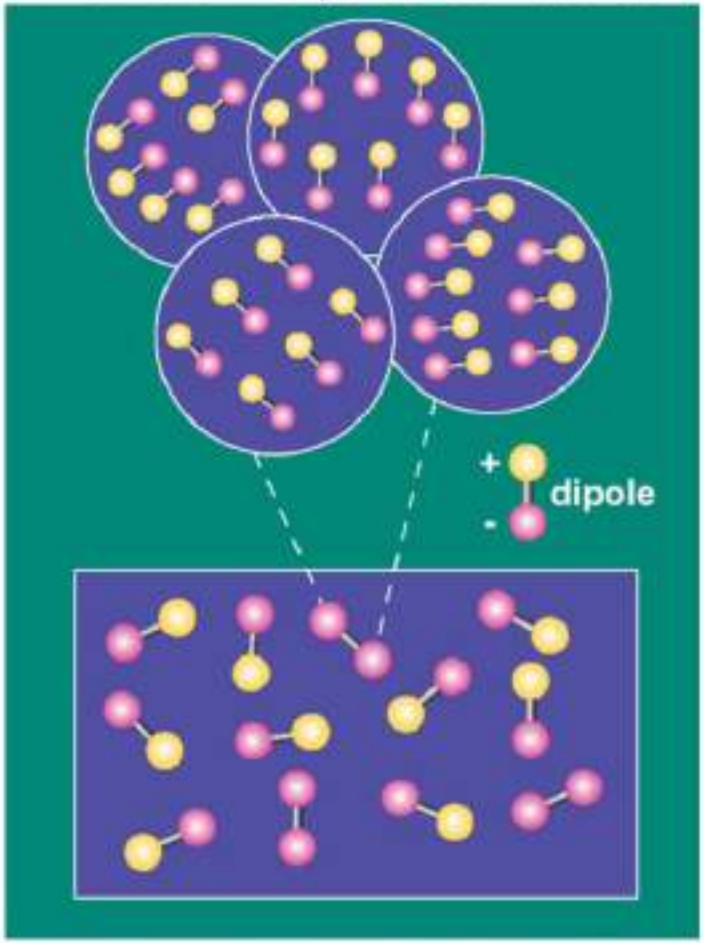
When the electric field is removed most of the domains are locked into a configuration of near alignment. It should be noted that not all the domains become exactly aligned.

The number of domains that align depends upon the poling voltage, temperature, and the time the voltage is held on the material.

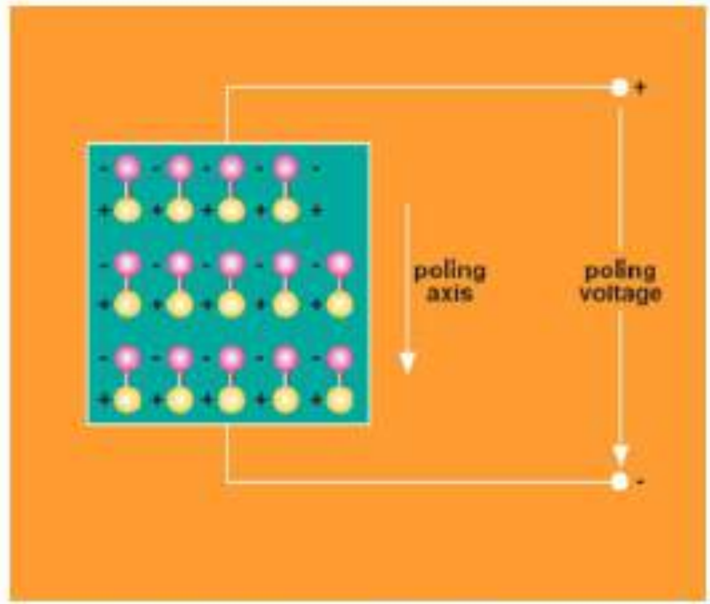
The element now has a permanent polarization (the remanent polarization) and is permanently elongated.

POLING TREATMENT

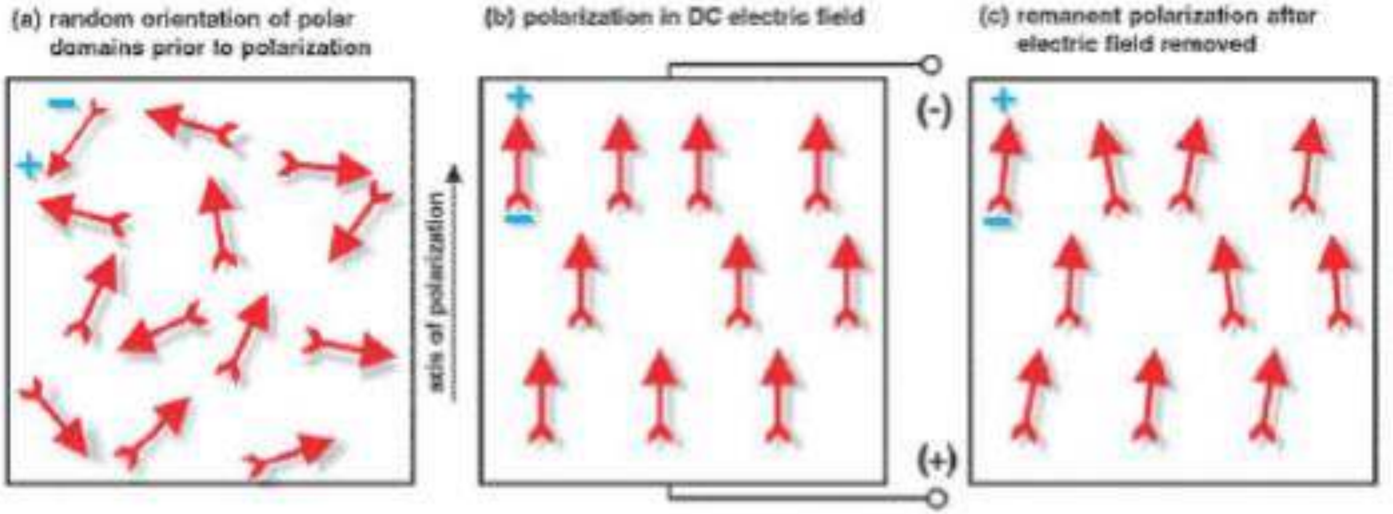
Domains → dipoles near each other tend to be align in regions



Before Poling – Random direction of dipoles



During Poling - Rearrangement of dipoles

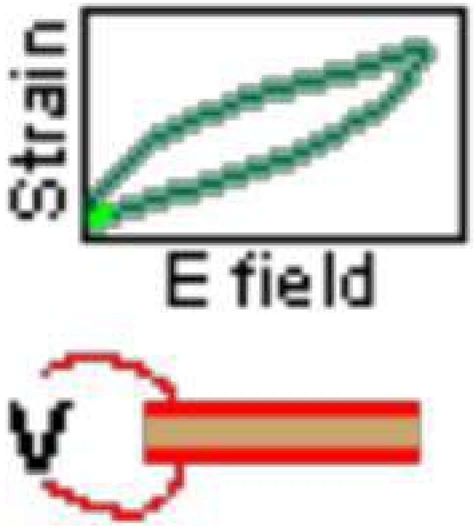


(a) The random domains of un-poled material below Curie temperature (Before Poling)

(b) The domains alignment after DC voltage application. The high electric field orients all the dipoles in the direction of the field. (During Poling)

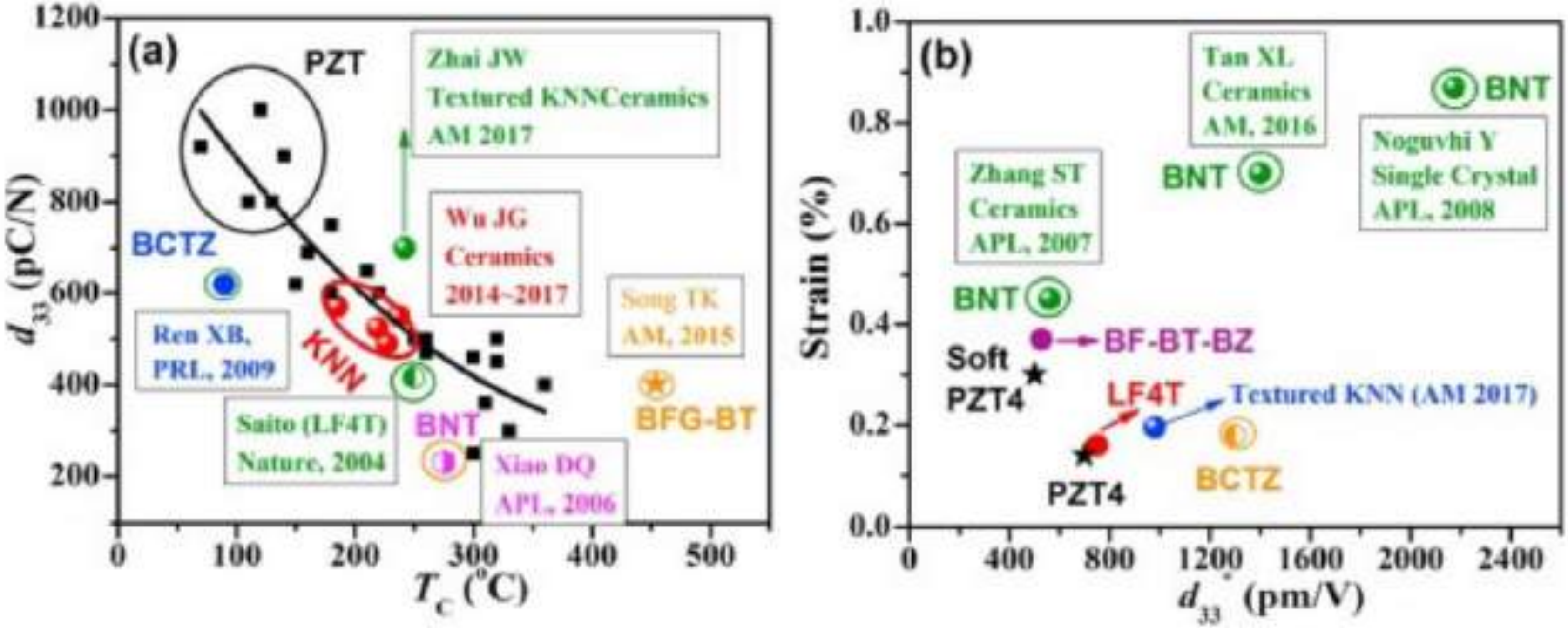
(c) The remnant domainss after the electric field is removed, roughly align and resulting in a permanent polarization (After poling)

AFTER POLING: PIEZOELECTRIC CERAMIC

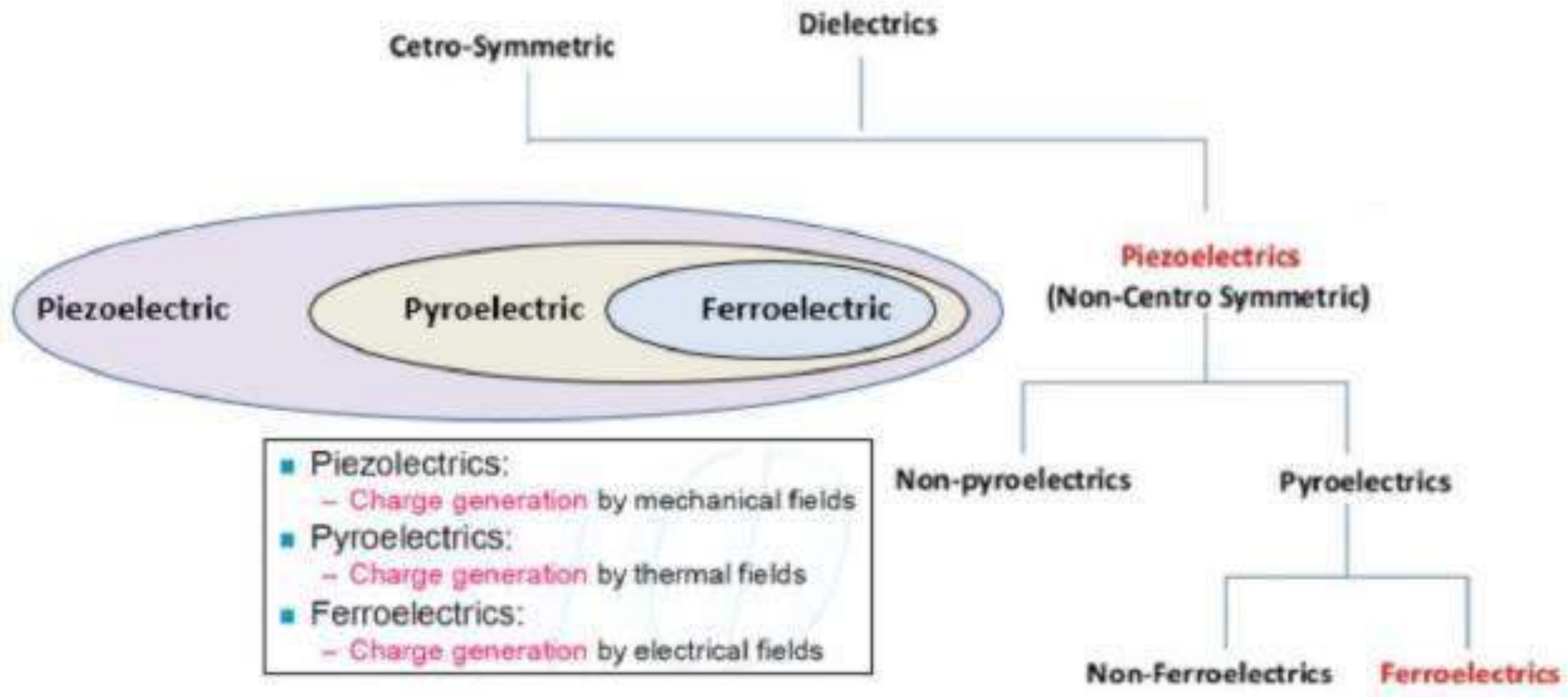


- The material can be de-poled by;
  - reversing the poling voltage with high electric field
  - increasing the temperature beyond the Currie point
  - inducing a large mechanical stress.

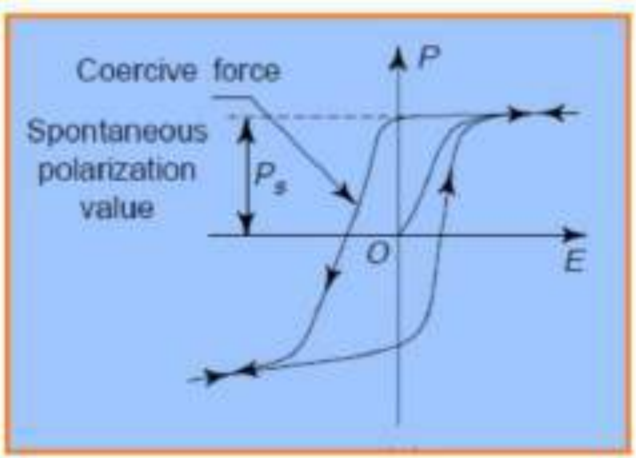
LEAD FREE PIEZO CERAMICS



PIEZOELECTRIC, FERROELECTRIC & PYROELECTRIC

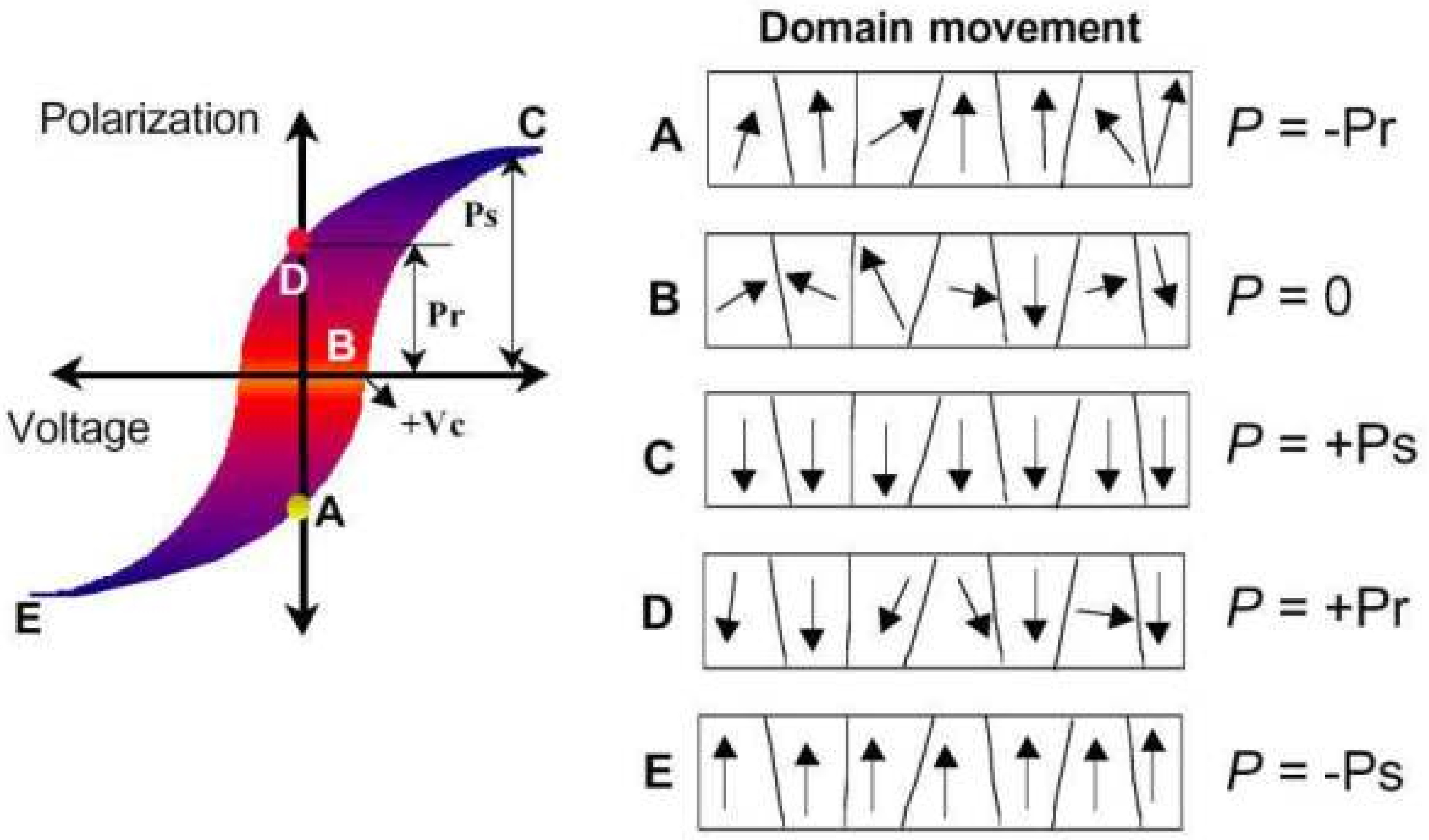


FERROELECTRIC MATERIALS

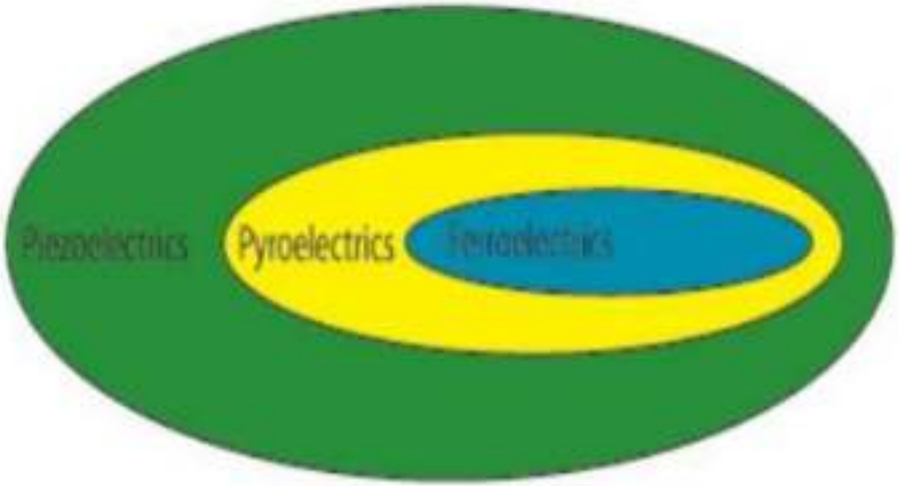


- All the ferroelectric materials exhibit piezoelectric effect due to lack of symmetry.
- Special class of piezoelectric materials exhibit certain other characteristics also.
- It exhibits spontaneous polarization i.e. polarization in absence of electric field.
- Ferroelectrics are electric analog of ferromagnets. This may display permanent magnetic behaviour. The first ferromagnetic material named Rochelle Salt has been discovered by Valasek.
- In ferroelectic, the polarization can be changed and reversed by external electric field. This is shown in the figure-3.

DOMAIN WALL MOVEMENT IN FERROELECTRIC MATERIALS



All Ferroelectric materials are Piezoelectric, But all Piezoelectric materials are not Ferroelectric!

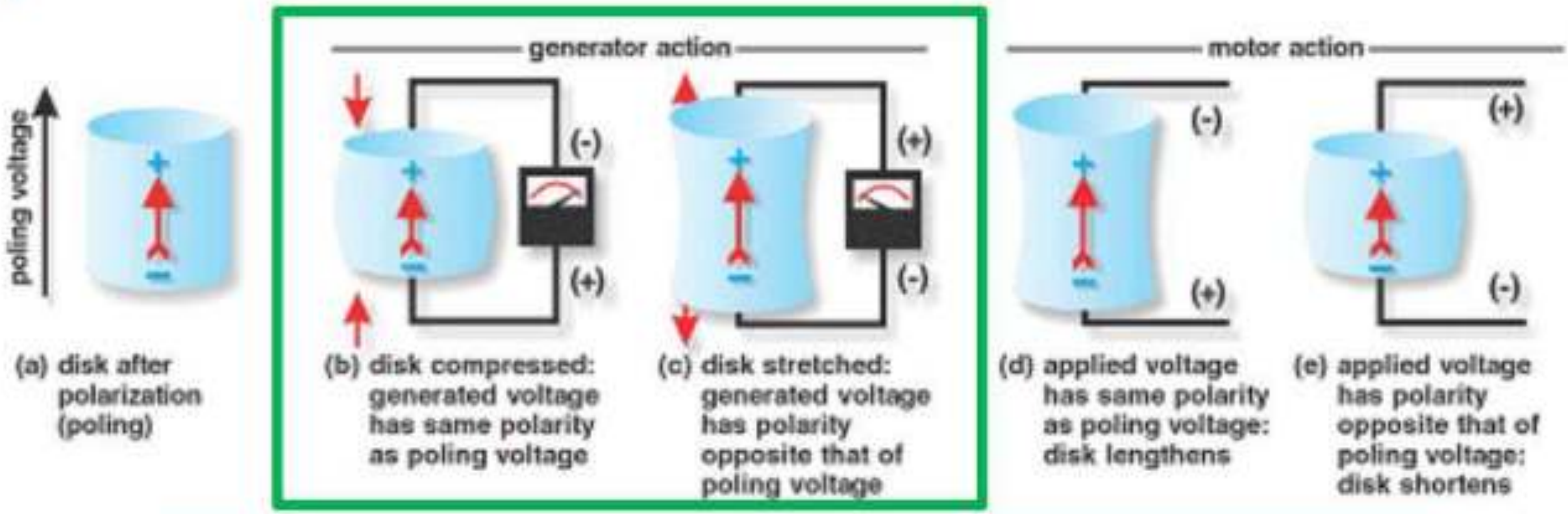


Ferroelectrics are spontaneously polarised, but are also piezoelectric, in that their polarisation changes under the influence of a stress. This is because while all ferroelectrics are piezoelectric, not all piezoelectrics are ferroelectric.

PIEZOELECTRIC VS FERROELECTRIC

Features	Piezoelectric	Ferroelectric
Characteristics	Generates electric potential when subjected to mechanical energy (viz. compression or tension) is applied.	Polarization can be changed and reversed with the applied external electric field.
Material classes	Organic, Ceramic, single crystal	Organic, Ceramic
Examples of materials	PVF2, PZT, PLZT, Quartz, LiNbO3	PVF2, Liquid Crystals, PZT (Lead [Pb], Zirconate, Titanate) thin film
Applications	actuator, transducer, optical, frequency control, SAW devices, ultrasonic receiver	non-volatile memory, displays

WHAT CAN PIEZOELECTRIC CERAMICS DO?

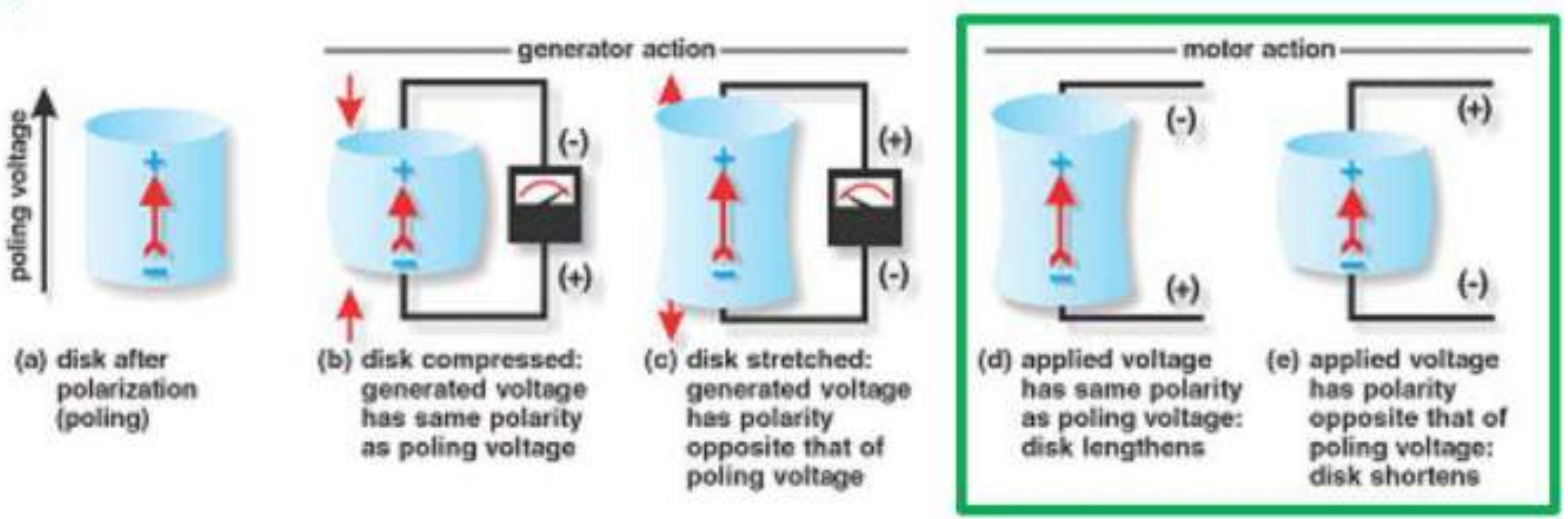


If mechanical compression or tension is applied on a poled piezoelectric ceramic element, changes the dipole moment, creating a voltage.

This is **generator action,** where by the ceramic element converts the mechanical energy into electrical energy.

Generator and motor actions of a piezoelectric element

WHAT CAN PIEZOELECTRIC CERAMICS DO?



If an alternating voltage is applied, the element will lengthen and shorten cyclically, at the frequency of the applied voltage.
This is **motor action**, where by electrical energy is converted into mechanical energy.

Generator and motor actions of a piezoelectric element

PIEZOELECTRIC CERAMICS- APPLICATION

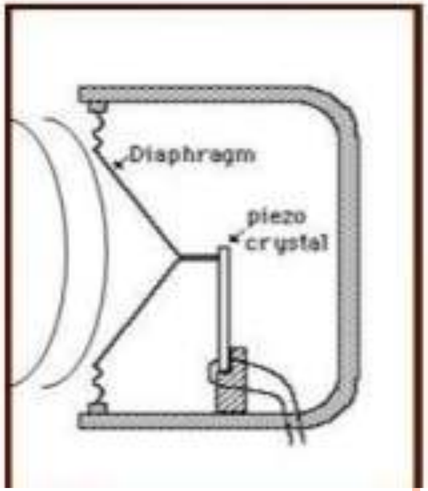
The principle is adapted to piezoelectric motors, sound or ultrasound generating devices, and many other products.

Generator action is used in fuel-igniting devices, solid state batteries, and other products;

Motor action is adapted to piezoelectric motors, sound or ultrasound generating devices, and many other products.

PIEZOELECTRIC CERAMICS- APPLICATION

- Microphones (Crystal microphone or Piezo microphone)
  - Use the phenomenon of piezoelectricity to convert vibrations (sound energy) into an electrical signal
  - Use a thin strip of piezoelectric material attached to a diaphragm. Sound waves cause the diaphragm to move which in turn communicates the resulting vibration to the piezo crystal. Charges and voltages are proportional to the amount of deformation and disappear when stress on the crystal disappears.
  - A diaphragm is used to amplify the sound vibrations.
  - Later microphones use ceramic materials such as
    - Barium Titanate ($BaTiO_3$) and PZT.



Sciencedirect

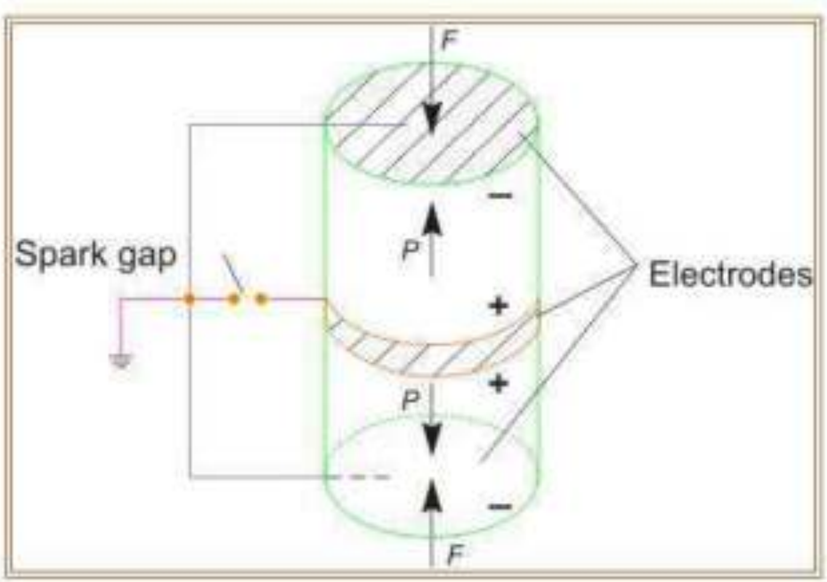
Applications of Piezoelectric Ceramics

- Piezoelectric ceramics are used in a variety of applications utilizing either direct or converse piezoelectric effect.

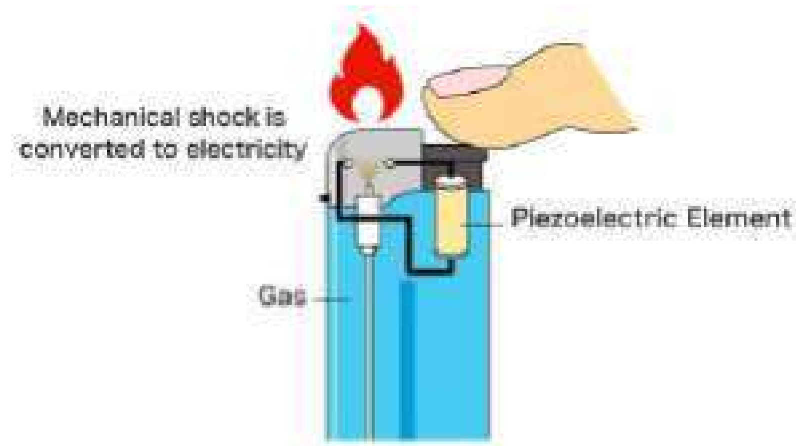
Power Generation

Gas Lighter

- Piezoelectric material can ignite the gases by generating a spark via an electric current.
- This requires two piezoelectrics with opposite polarization states which are brought close to each other so those polarization vectors are in the opposite directions i.e. faces containing similar charges are together.
- The piezoelectric are placed in a circuit with a spark gap.
- application of a mechanical stress or force will induce change in the polarization.
- The force brings together these two pieces which then gives rise to creation of charges.
- The charges flow from the end faces and the middle (pressed) faces through the circuit giving rise to a spark in the spark gap which can be used to ignite a gas.
- One must apply the force quickly otherwise the voltage generated disappears because the charges leaks away through the piezoceramic, across its surfaces and via the apparatus.



Schematic of operation of a gas lighter made using piezoelectric material

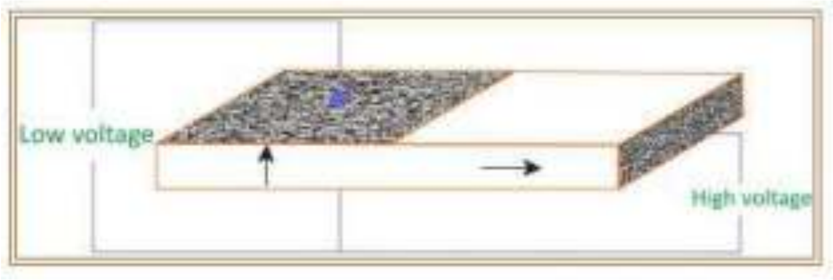


An example of how a lighter using a piezoelectric material works.

Faculty Science, 2010. Piezoelectricity [online]. Available from: http://faculty-science.blogspot.co.uk/2010/11/piezoelectricity.html [21/10/2013]

Power Transformer

- A piezoelectric transformer works like an AC voltage multiplier.
- While conventional transformers utilize magnetic coupling between input and output, the piezoelectric transformer exploits the acoustic coupling utilizing inverse piezoelectric effect.
- Piezo transformers can be quite compact high voltage sources.
- An input smaller voltage across the thickness of a piezoceramic creates an alternating stress in the bar by the inverse piezoelectric effect.
- This causes the bar to vibrate with vibration frequency chosen to be the resonant frequency of the block, typically in the 100 kHz to 1 MHz range.
- This generates a higher output voltage in the other section of the bar by the direct piezoelectric effect.
- One can achieve the step-up ratios of more than 1000:1 using this technique.

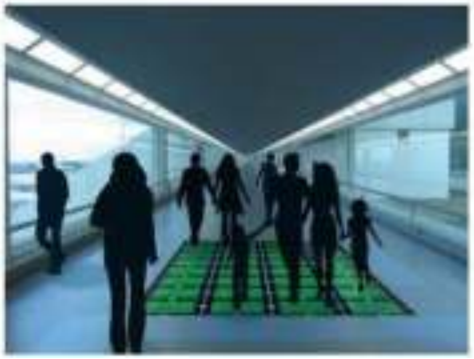


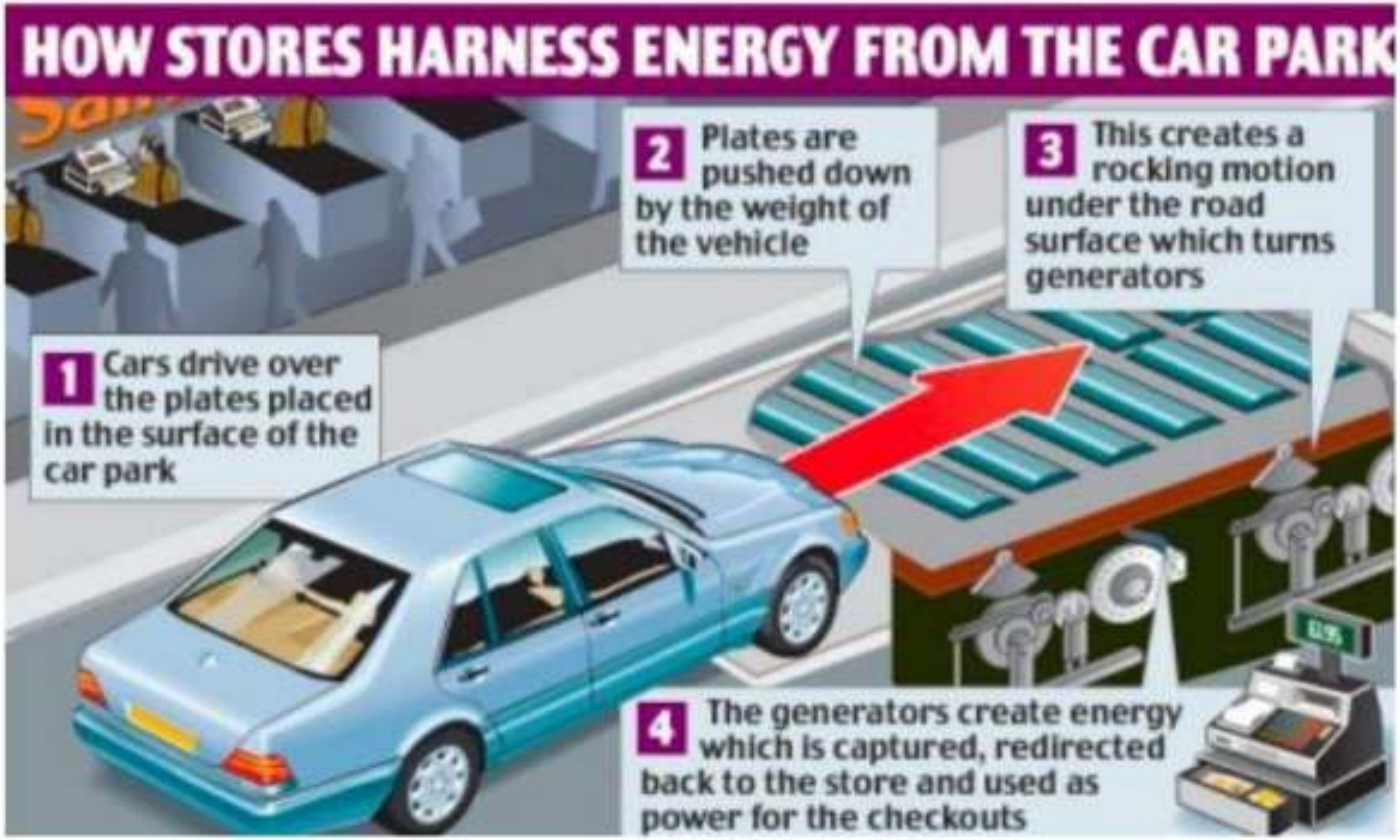
Schematic of a piezoelectric transformer

- Piezoelectric actuators in inkjet printer by EPSON
  - Micro Piezo print heads feature microscopic piezoelectric actuators that are built behind the print nozzles.
  - When an electrical charge is applied to them, the piezoelectric elements bend backward, drawing precise amounts of ink from the ink chamber into the firing chamber.
  - When the electrical pulse is reversed, the piezoelectric elements bend the opposite way very rapidly, propelling the ink out of the nozzles at high speed.

[Wikipedia]

- Piezoelectric generators
  - Piezoelectric generators produce electricity whenever certain types of material are strained or pressed. East Japan Railroad Company installed stone piezoelectric tiles in one of their train stations in Tokyo that are expected to produce 58 kilowatts per hour.
  - Similarly, a Sainsbury's supermarket in the United Kingdom installed piezoelectric generators in their parking lots and produce up to 30 kw per hour. Although piezoelectric technology cannot produce enough electricity to power a whole city, it reduces the need for more power due to growing population.


HOW STORES HARNESS ENERGY FROM THE CAR PARK
1 Cars drive over the plates placed in the surface of the car park
2 Plates are pushed down by the weight of the vehicle
3 This creates a rocking motion under the road surface which turns generators
4 The generators create energy which is captured, redirected back to the store and used as power for the checkouts

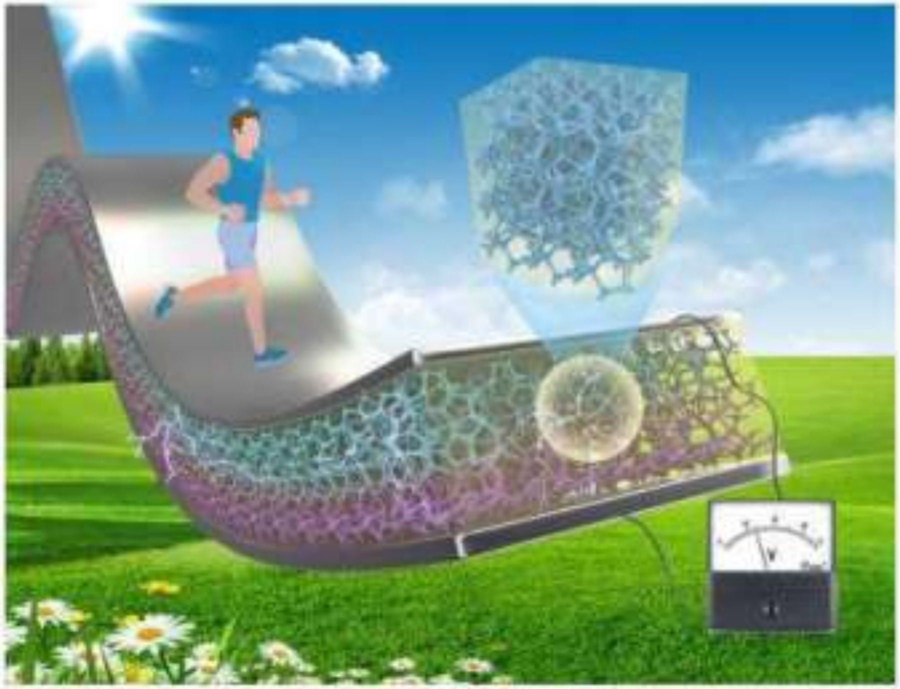
- Ultrasound systems for non-invasive biomedical imaging.
- Piezo tube actuators and piezo elements in SPM (Scanning Probe Microscopy)
- Ultrasonic applications in cosmetics and medical tooth cleaning
- High-energy shock waves use in orthopedics for the therapy of bone and joint damage

FIGURE 1.1 Echoscopy image of an unborn baby in a womb

Flexible piezoelectric materials are attractive for power harvesting applications because of their ability to withstand large amounts of strain.

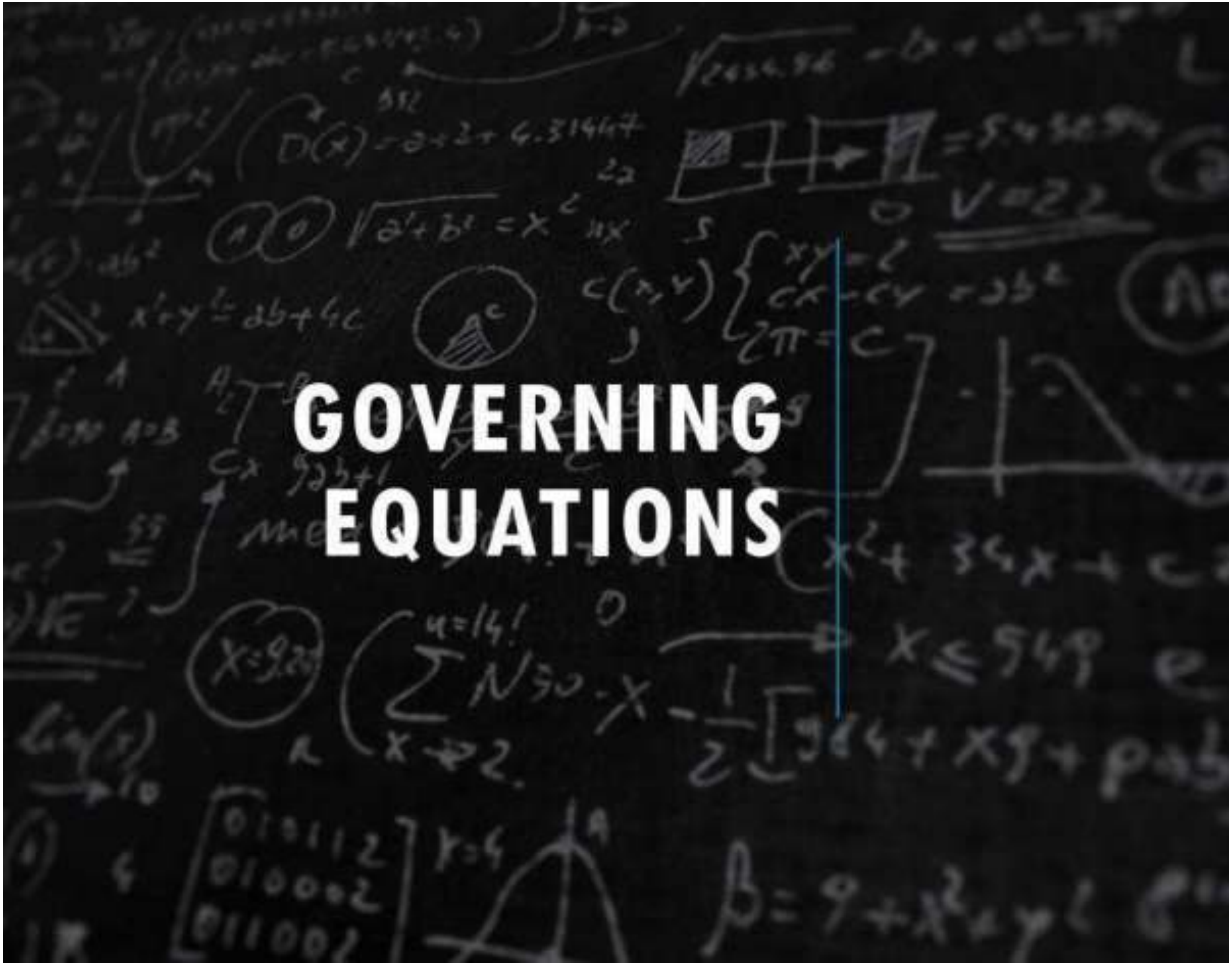
Larger strains provide more mechanical energy available for conversion into electrical energy.

A second method of increasing the amount of energy harvested from a piezoelectric is to utilize a more efficient coupling mode.



Piezoelectric ceramic foam : Reference

GOVERNING EQUATIONS



PIEZOELECTRIC EQUATION ~ Basic

- The basic equations of piezoelectricity are:

$$P = D \times \text{stress}\ (T)$$

and

$$E = \text{strain}\ (S)\ / d_{ij}$$

where,

- P = Polarization
- E = Electric field generated
- D or d_{ij} = Piezoelectric coefficient/constant in meters per volt.

PIEZOELECTRIC EQUATION ~ Basic

- Furthermore, piezoelectricity also is the combined effect of the electrical behavior of the material and Hooke's Law :

$$D = \varepsilon \cdot E$$

$$S = s \cdot T$$

- D = Electric displacement
- ε = permittivity
- E = Electric field strength
- S = Strain, s = compliance
- T = Stress

PIEZOELECTRIC EQUATION ~ Basic

- These maybe combined into so-called coupled equations, of which the strain-charge form is:

$$D = d_{ij}t \cdot T + \varepsilon T \cdot E$$

$$S = sE \cdot T + d_{ij} \cdot E$$

- These equations describe potential developed due to pressure of the piezoelectric and stress developed when the piezoelectric is subjected to an electric field, respectively.

PIEZOELECTRIC EQUATION ~ Basic

- The constant d_{ij} is known as the piezoelectric charge constant.
- It is generally obtained by measuring the density of charge which appears on the surfaces of the film when a mechanical stress is applied.
- The d_{31} indicates that a stress in the 1 direction will produce charge in the 3 direction.
- Fortunately, many of the constants are equal to zero for PZT piezoelectric ceramics. The non-zero constants are:

$$d_{31} = d_{32},\ d_{33},\ d_{15} = d_{24}$$

- Greater constants thus correlate to a higher strain

PIEZOELECTRIC CONSTANTS

- Axis Nomenclature
  - The piezoelectric effect relates mechanical effects to electrical effects. These effects depend highly upon their orientation to the poled axis. Therefore, the physical constants also relate to both directions.
  - Each constant generally has two subscripts that indicate the directions of the two related quantities, such as stress (force on the ceramic element / surface area of the element) and strain (change in length of element / original length of element) for elasticity.
  - The direction of positive polarization usually is made to coincide with the Z-axis (refer figure in the next slide).
  - Definition of the most frequently used constants are as below;

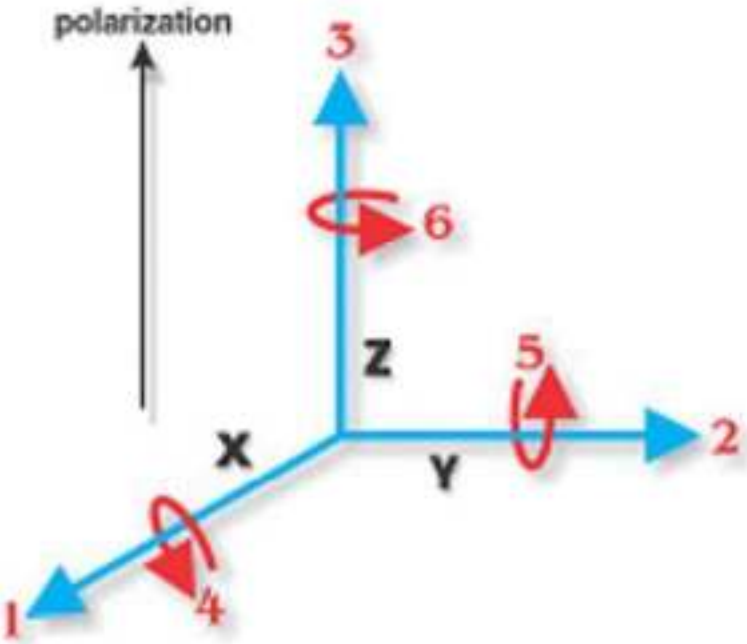
    d = piezoelectric charge constant

    g = piezoelectric voltage constant

    ε = permittivity

PIEZOELECTRIC CONSTANTS

Figure 1.6 Directions of forces affecting a piezoelectric element



#	Axis
1	X
2	Y
3	Z (poled)
4	Shear Around X
5	Shear Around Y
6	Shear Around Z

for example, piezoelectric charge constants:

d_{ij}, i = electrical direction

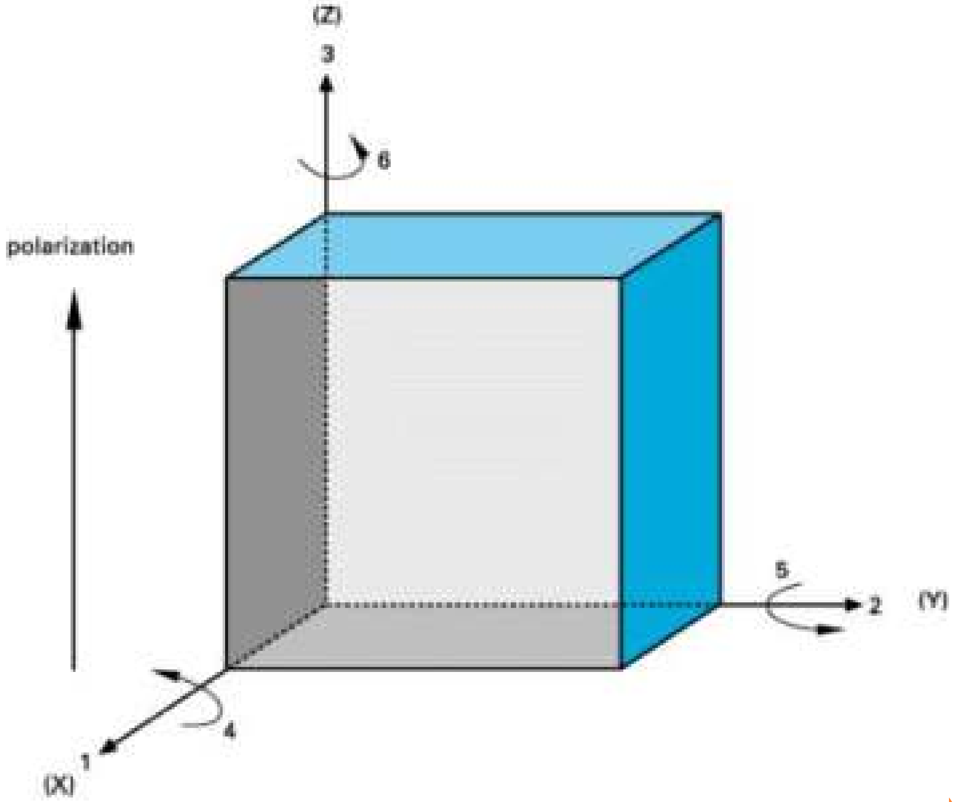
j = mechanical direction

DEFINITION OF PIEZOELECTRIC COEFFICIENTS AND DIRECTIONS

Orthogonal system describing the properties of a poled piezoelectric ceramic.

Axis 3 is the poling direction.

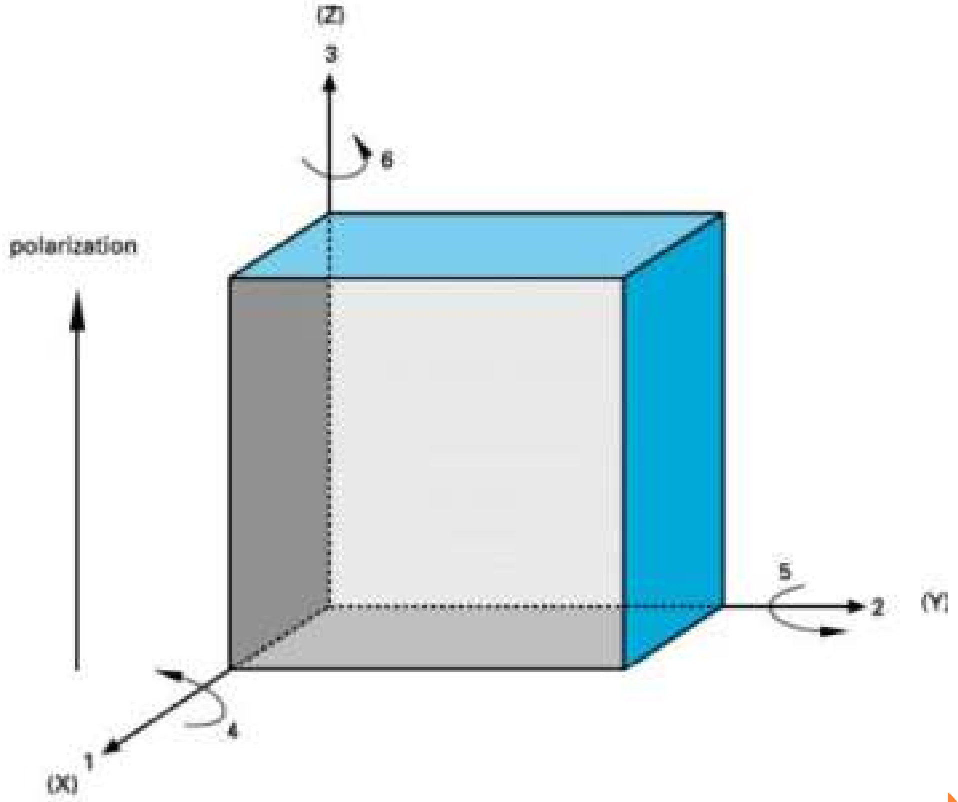
Because of the anisotropic nature of Piezo ceramics, effects are dependent on direction.



DEFINITION OF PIEZOELECTRIC COEFFICIENTS AND DIRECTIONS

To identify directions the axes, termed 1, 2, and 3, are introduced (analogous to X, Y, Z of the classical right hand orthogonal axial set).

The axes 4, 5 and 6 identify rotations (shear).



DEFINITION OF PIEZOELECTRIC COEFFICIENTS AND DIRECTIONS

The direction of polarization (3 axis) is established during the poling process by a strong electrical field applied between two electrodes.

For actuator applications the piezo properties along the poling axis are most essential (largest deflection).

The piezoelectric coefficients described here are not independent constants.

They vary with ***temperature, pressure, electric field, form factor, mechanical and electrical boundary conditions etc.***

The coefficients only describe material properties under small signal conditions.

PIEZOELECTRIC CONSTANTS

Piezoelectric materials are characterized by several coefficients:

Examples are:

d_{ij}: Strain coefficients [m/V]: strain developed (m/m) per electric field applied (V/m) **or** (due to the sensor / actuator properties of Piezo material).

Charge output coefficients [C/N]: charge density developed (C/m^2) per given stress (N/m^2).

g_{ij}: Voltage coefficients or field output coefficients [Vm/N]: open circuit electric field developed (V/m) per applied mechanical stress (N/m^2) **or** (due to the sensor / actuator properties of Piezo material) strain developed (m/m) per applied charge density (C/m^2).

k_{ij}: Coupling coefficients [no Dimensions].

The coefficients are energy ratios describing the conversion from mechanical to electrical energy or vice versa. k^2 is the ratio of energy stored (mechanical or electrical) to energy (mechanical or electrical) applied.

PIEZOELECTRIC CONSTANTS

Other important parameters are the Young's modulus (*describing the elastic properties of the material*) and the dielectric constant (*describing the capacitance of the material*).

To link electrical and mechanical quantities double subscripts (i.e. d_{ij}) are introduced.

The first subscript gives the ***direction of the excitation***,

the second describes the ***direction of the system response***.

COUPLING MODES

There are two practical coupling modes exist; the −31 mode and the −33 mode.

In the −31 mode, a force is applied in the direction perpendicular to the poling direction, an example of which is a bending beam that is poled on its top and bottom surfaces.

d_{31} applies if the electric field is along the polarization axis (direction 3), but the strain is in the 1 axis (orthogonal to the polarization axis).

COUPLING MODES

In the −33 mode, a force is applied in the same direction as the poling direction, such as the compression of a piezoelectric block that is poled on its top and bottom surfaces.

d_{33} applies when the electric field is along the polarization axis (direction 3) and the strain (deflection) is along the same axis.

Conventionally, the −31 mode has been the most commonly used coupling mode: however, the −31 mode yields a lower coupling coefficient, *k*, than the −33 mode.

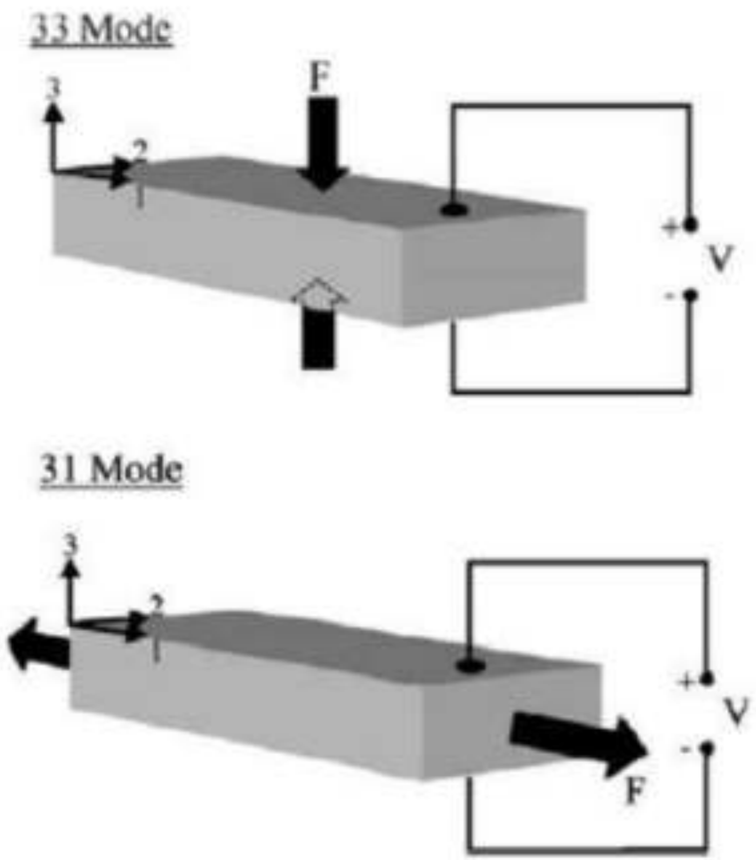


Illustration of −33 mode and −31 mode operation for piezoelectric materials. (Figure from Roundy *et al* 2003, © 2003, Elsevier.)

EXAMPLES QUESTION

- Describe how are the ferroelectric materials differ from piezoelectric materials?
- Why is silicon not piezoelectric? What structure of a material is required for it to be piezoelectric?
- With the aid of illustrations, explain the mechanism of the poling process in piezoelectric ceramic materials.
- What kinds of common devices or applications utilize piezoelectricity?