Case study on Energy Storage: Piezoelectric

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Lecturer notes on topic “Case study on Energy Storage: Piezoelectric” prepared from the following sources:

- J Li, Microstructure and Piezoelectric Properties, Materials, 15, 2-17, 2022
- T Lusiola, A Soppelsa et al., The impact of microstructure in (K,Na)NbO3-based lead-Free piezoelectric fibers: From processing to device production for structural health monitoring, Journal of the European ceramic society, 36, 2745-2754, 2016.
- W. G. Cady, Piezoelectricity, Dover Publications, New York, (1964) and McGraw-HillBook Co., (1946)
- M F ashby, “Materials Slection in Mechanical Design”, 4th Edition, Butterworth-Heinemann 2011
- NPTEL lecture notes
- Internet open source

Case study on Energy Storage: Piezoelectric

History: Piezoelectricity

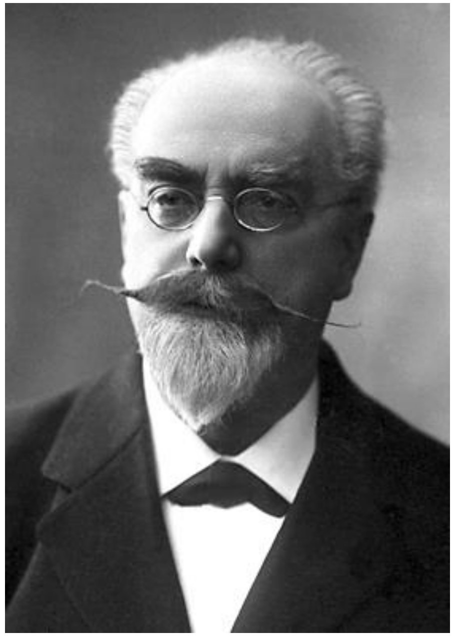
- Piezoelectricity: Electricity form mechanical pressure discovered in the year 1880 by two great named Pierre and P J Curie

- Contemporary: Contact electricity-static electricity generated from friction

- Pyro electricity: Electricity generated from crustal while heating. For example: Sugar crystal and Salt are naturally occurring piezo electric material

Pierre Curie (1859-9016)
Noble prize (1903)

Paul Jacques Curie (1856-1941)



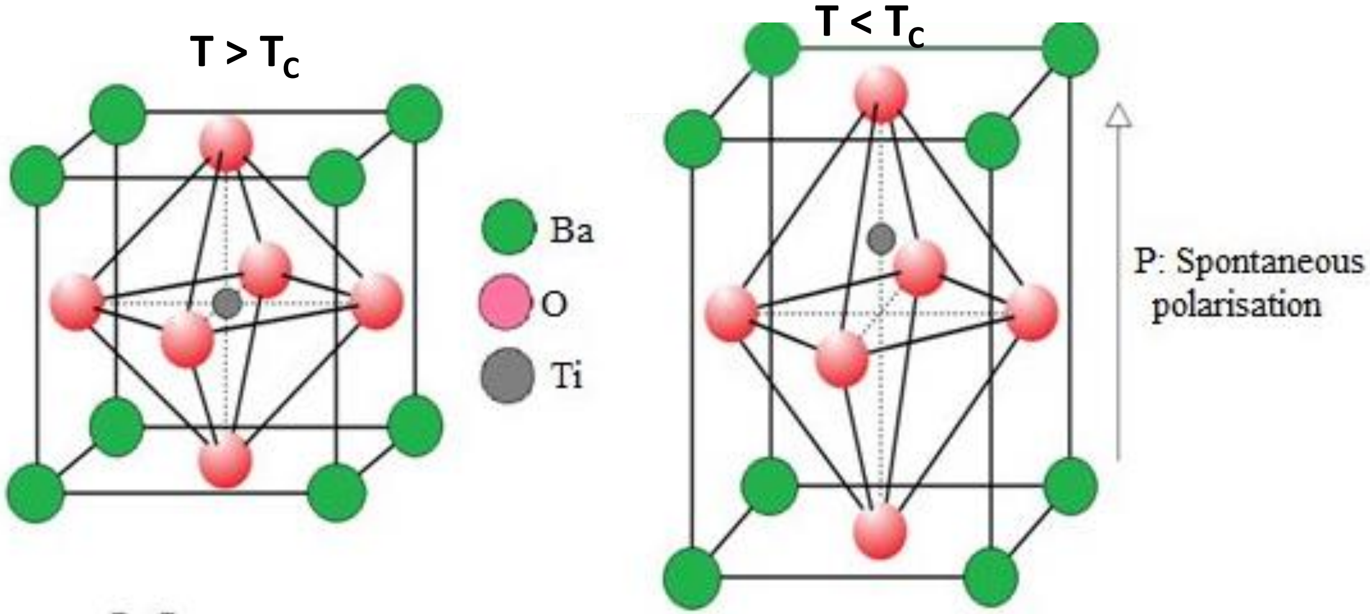
Gabriel Lippmann (1845-1921)
Noble prize (1908)

Piezoelectricity in Perovskites

Perovskite: A ternary (3 component structure)

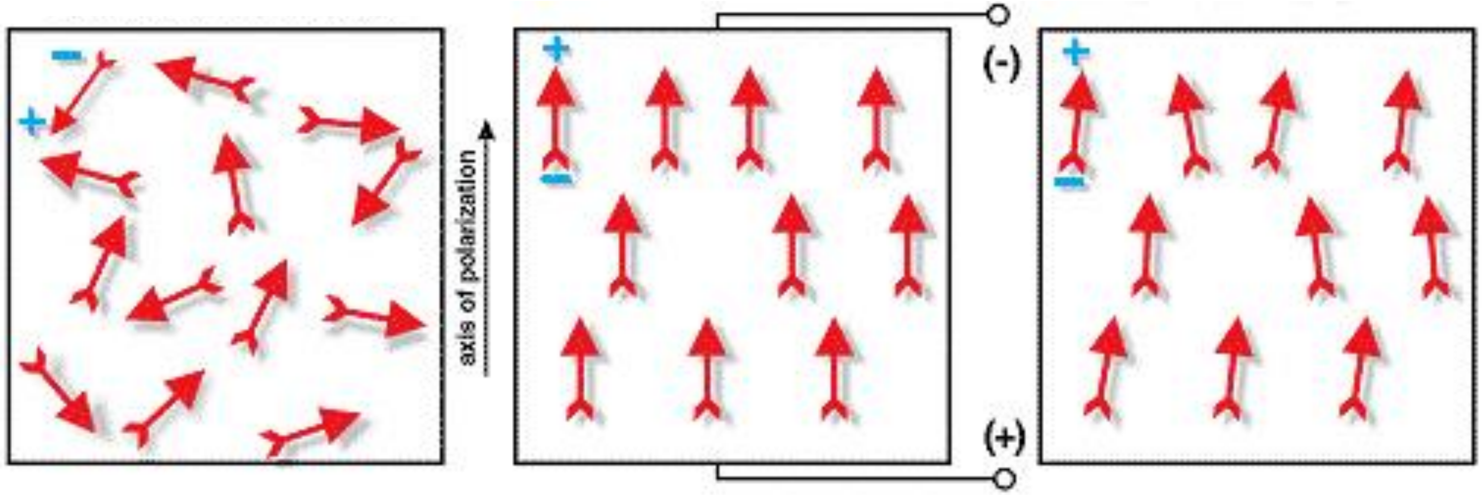
For Example: $BaTiO_3$ a common piezoelectricity material

Other materials: PZT family, LiNb family, PbNb family, YMn family, NH4-Cd family



Tetragonal symmetry with dipole moment below curie temperature

Polarization of Piezoelectric material



Random orientation of polar domains prior to polarization

Polarization in DC electric field

Polarization after electric field removed

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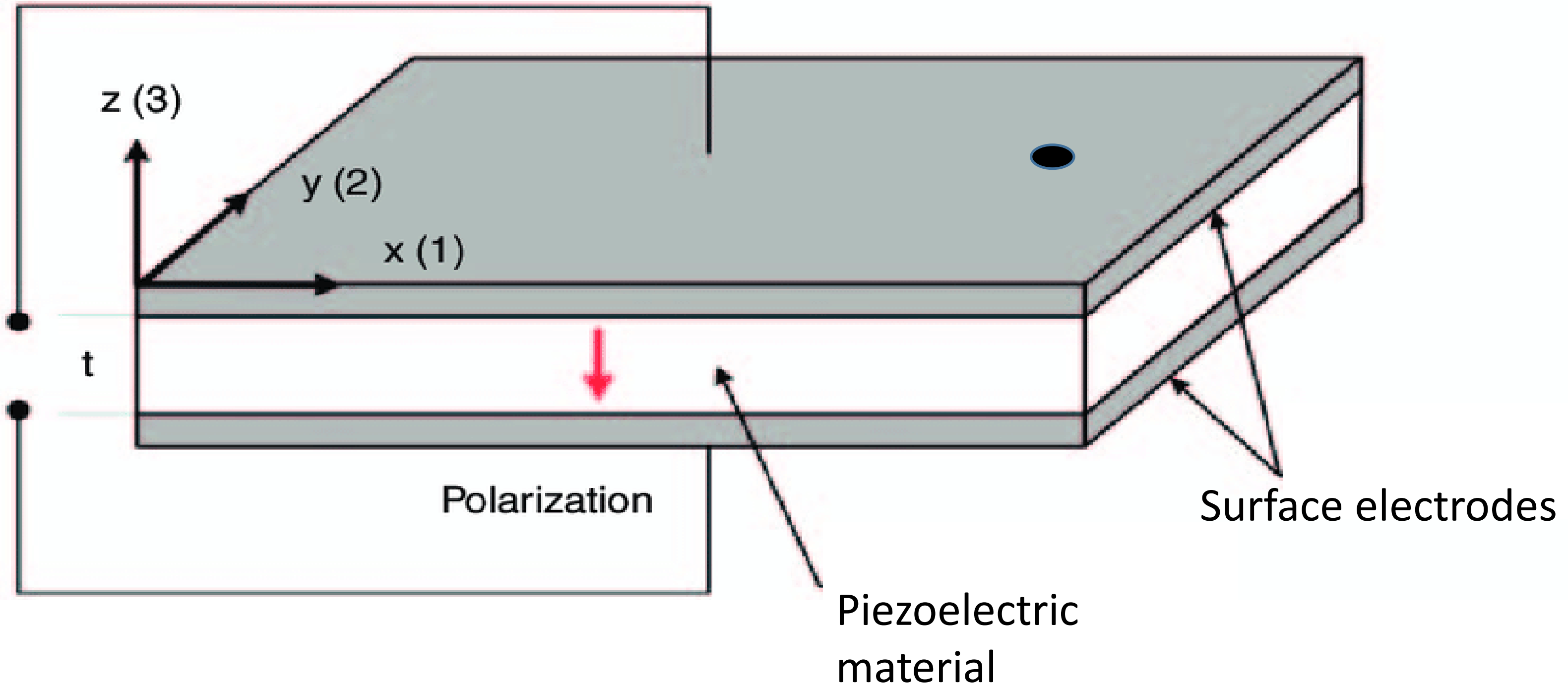
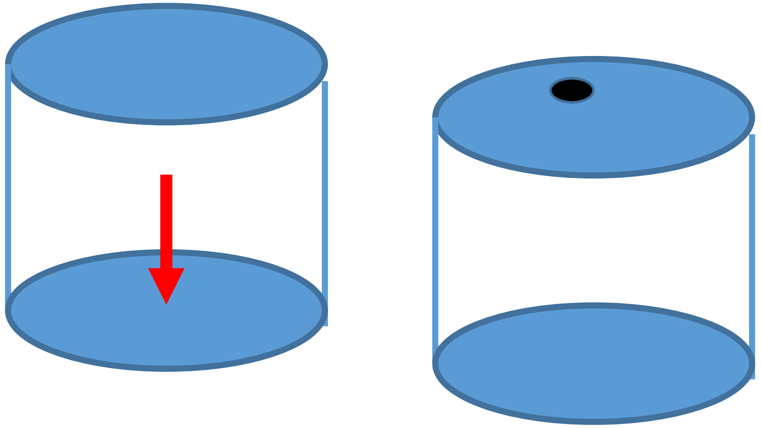
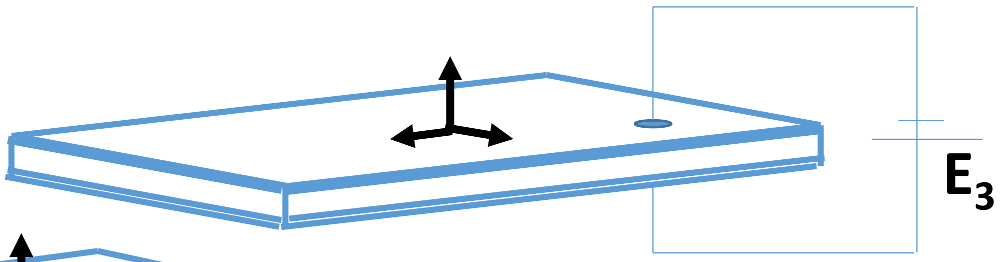
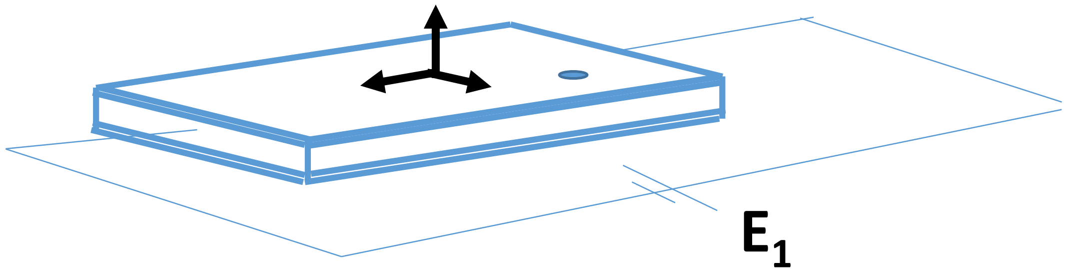


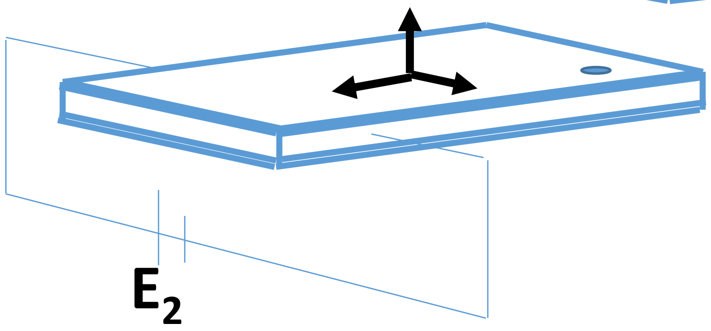


Polarization direction

Coordinate axis and direction for a piezo-ceramic sheet







Electric field directions for a piezoelectric sheet

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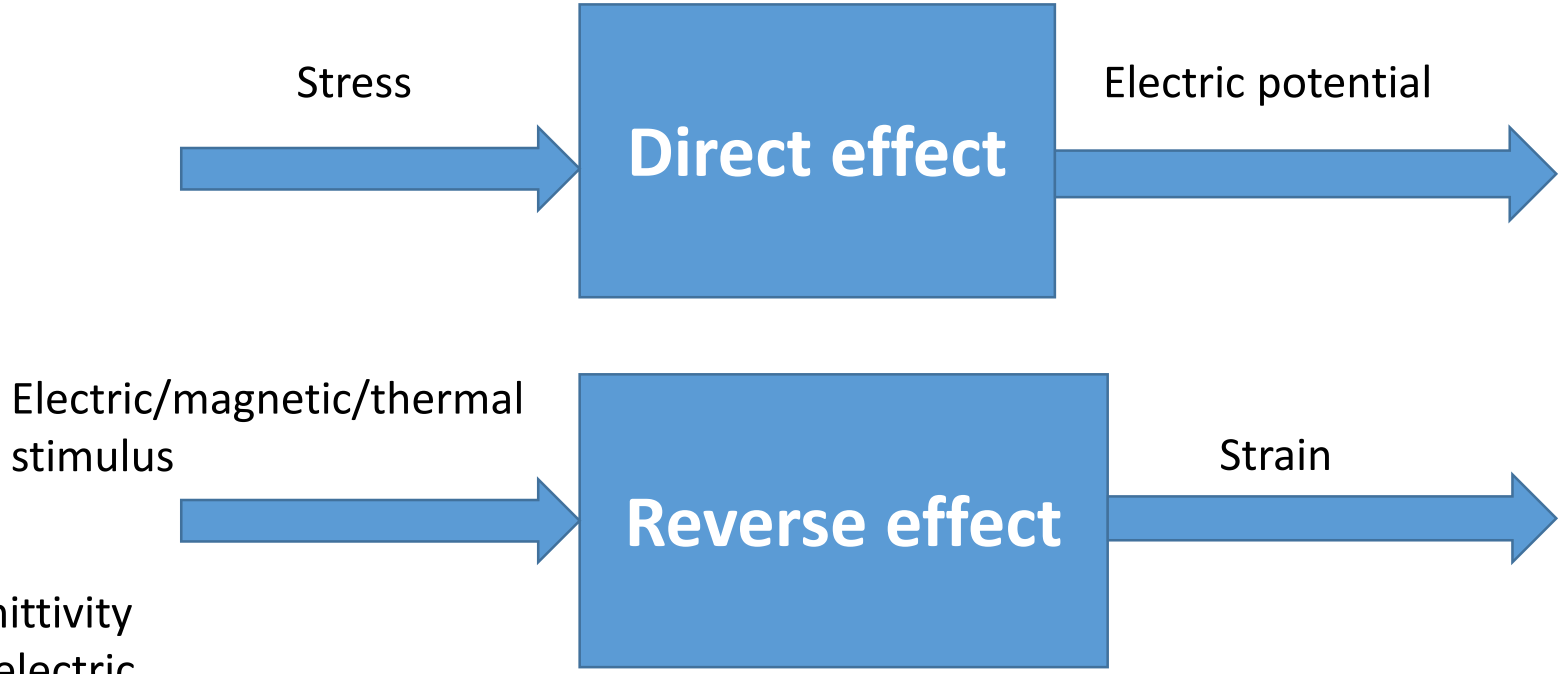
Constitutive equations of piezoelectricity

$$D = dX + \varepsilon^{X} E$$

$$x = S^{E} X + dE$$



Superscripts denote the measurement of permittivity at constant stress and compliance at constant electric field intensity

Where,
X is stress (N/m^2)
X is strain
D is eclectic displacement/flux density (C/m2)
S is compliance (m2/N)
E is electric field intensity (V/m or N/C)
ε is permittivity (F/m)
D is piezoelectric constant (C/N or m/V)

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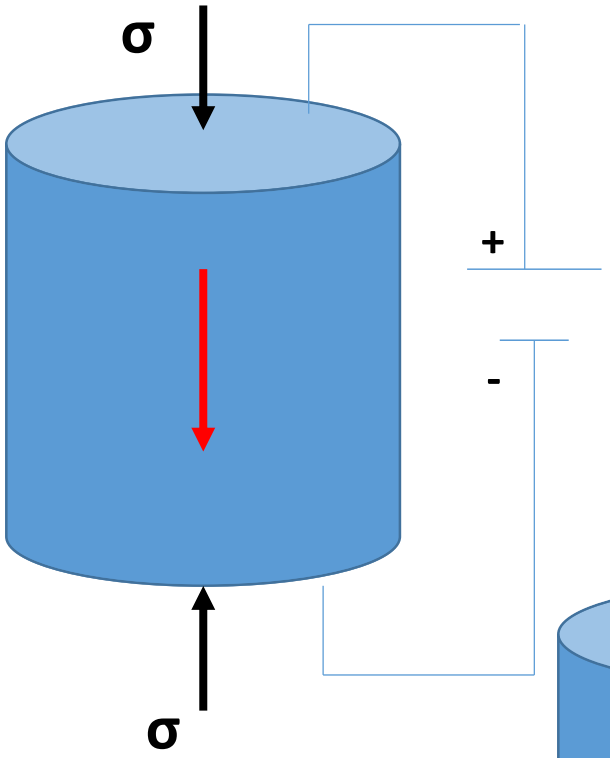
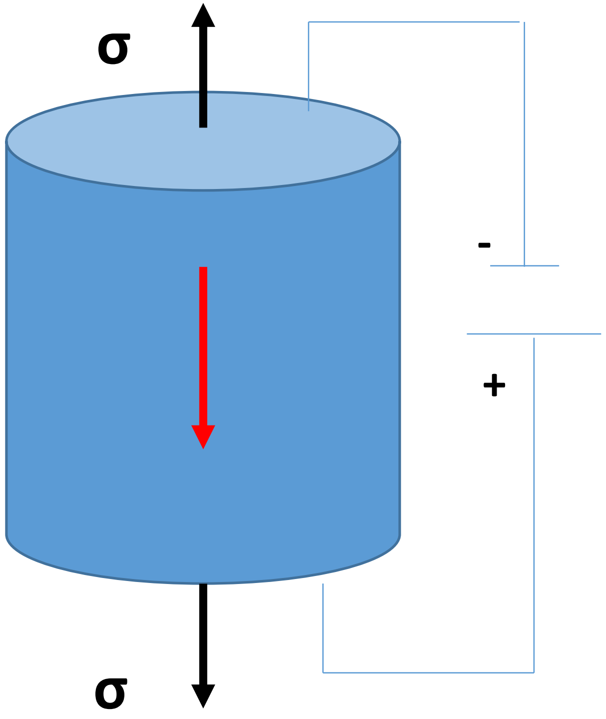
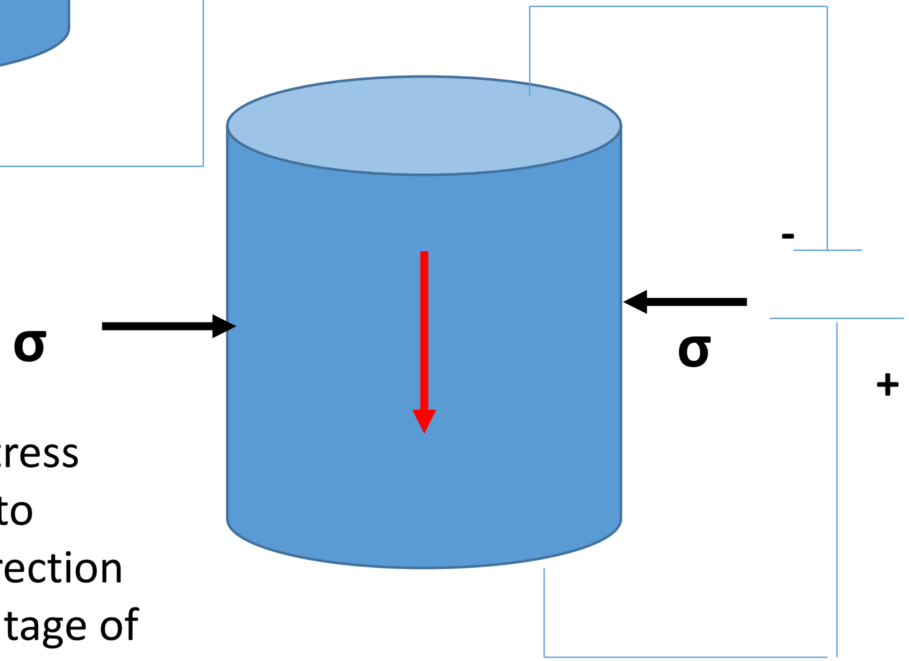
Direct piezoelectric effect



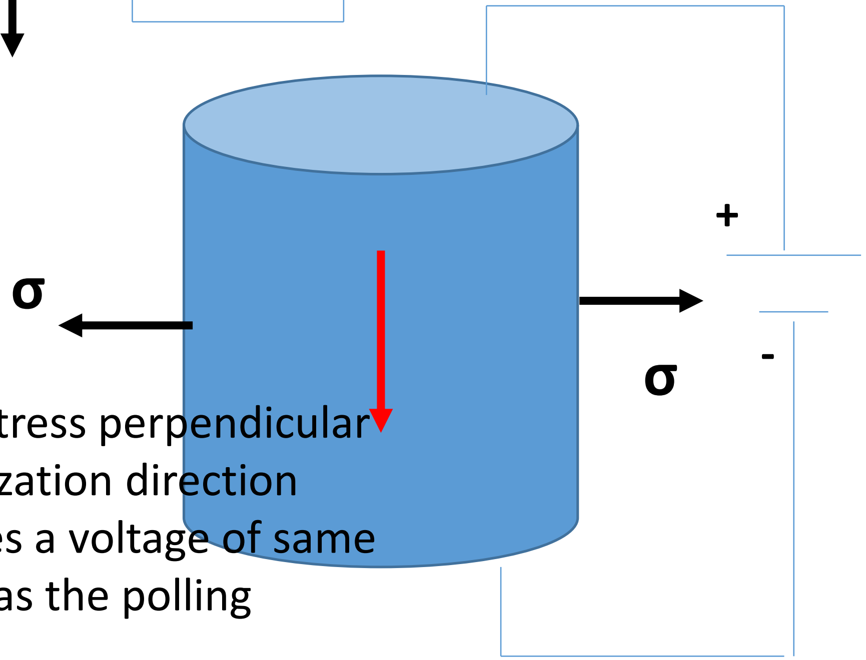
- Compressive stress along the polarization direction generates a voltage of the same polarity as the polling voltage



- Tensile stress along the polarization direction generates a voltage of the opposite polarity to the polling voltage



- Compressive stress perpendicular to polarization direction generates a voltage of opposite polarity to the polling voltage



- Tensile stress perpendicular to polarization direction generates a voltage of same polarity as the polling voltage

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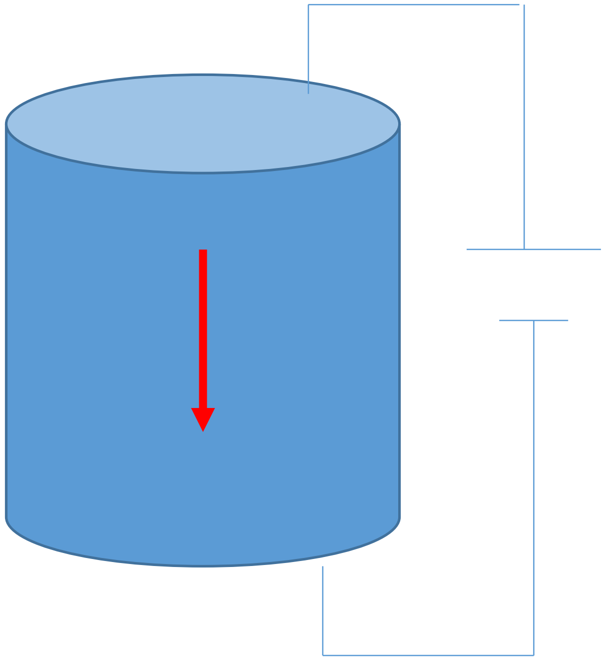
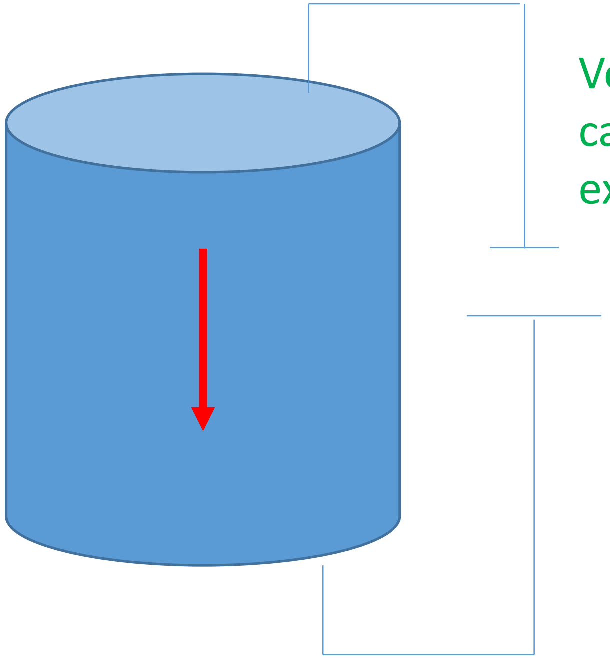
Reverse/converse piezoelectric effect



Voltage of the same polarity as the polling voltage cause an extension along the poling direction and contraction perpendicular to the polling direction



Voltage of the opposite polarity as the polling voltage cause an contraction along the poling direction and extension perpendicular to the polling direction

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Piezoelectric constant

Stress → **Direct effect** → Electric potential

$$d_{ki}^{d} = \frac{\text{charge generated in k-direction}}{\text{mechanical stress applied in i-direction}} \quad \text{C/N}$$

Electric/magnetic/thermal stimulus → **Reverse effect** → Strain

$$d_{ik}^{c} = \frac{\text{charge generated in i-direction}}{\text{mechanical stress applied in k-direction}} \quad \text{m/V}$$

For most practice purpose d^d and $d^c = d^T$, T is transpose of the matrix, thus m/V is equivalent to C/N

Electro mechanical coupling coefficient

$$k_{ij} = \sqrt{\frac{\text{Mechanical energy stored in direction j}}{\text{Electrical energy applied in direction i}}}$$

$$k_{ij} = \sqrt{\frac{\text{Electrical energy stored in direction i}}{\text{Mechanical energy applied in direction j}}}$$

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How to prepare a piezoceramic actuator

- Start with fine powders of metal oxides (PZT/Barium Titanate) , for example: PZT → PbO, ZrO_2 and TiO_2 powders
- Mix them in a fixed proportions
- Use an organic binder
- Form into specific shape
- Heat for a specific time and specified temperature 650^O C to 800^OC
- Cool-apply electrode (sputtering)
- Polarize the sensor or actuator using a DC electric field

Powder processing steps

Powder preparation → Solid-state reaction co-precipitation sol-gel spray pyrolysis emulsion synthesis hydrothermal synthesis

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Shape forming → Pressing casting plastic forming colloidal processing

↓

High temperature sintering → Pressure less hot press hot iso-static press

↓

Finishing → Mechanical laser water jet ultrasonic

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Commercial piezoelectric material property set

Prop.	Unit	$BaTiO_3$	PZT-A	PZT-B	$PbNb_2O_6$	$LiNbO_3$	$PbTiO_3$
ρ	Mg/m^3	5.7	7.9	7.7	5.9	4.6	7.1
k_{31}		0.21	0.33	0.39	0.04	0.02	0.05
k_{33}		0.49	0.68	0.72	0.38	0.17	0.35
d_{31}	pCN^{-1}	79	119	234	11	.85	7.4
S	$\mu m^2/N$	8.6	12.2	14.5	29	5.8	11

Observation

- PZT family has highest piezoelectric coupling

- Curie point: PZT family 220 ^{O}C to 315 ^{O}C and Li family 600 ^{O}C to 1200 ^{O}C

- Instead of polycrystalline piezo ceramics, a single cut PMN could give k_{33} = 0.92 and d_{33} = 2070 pC/N

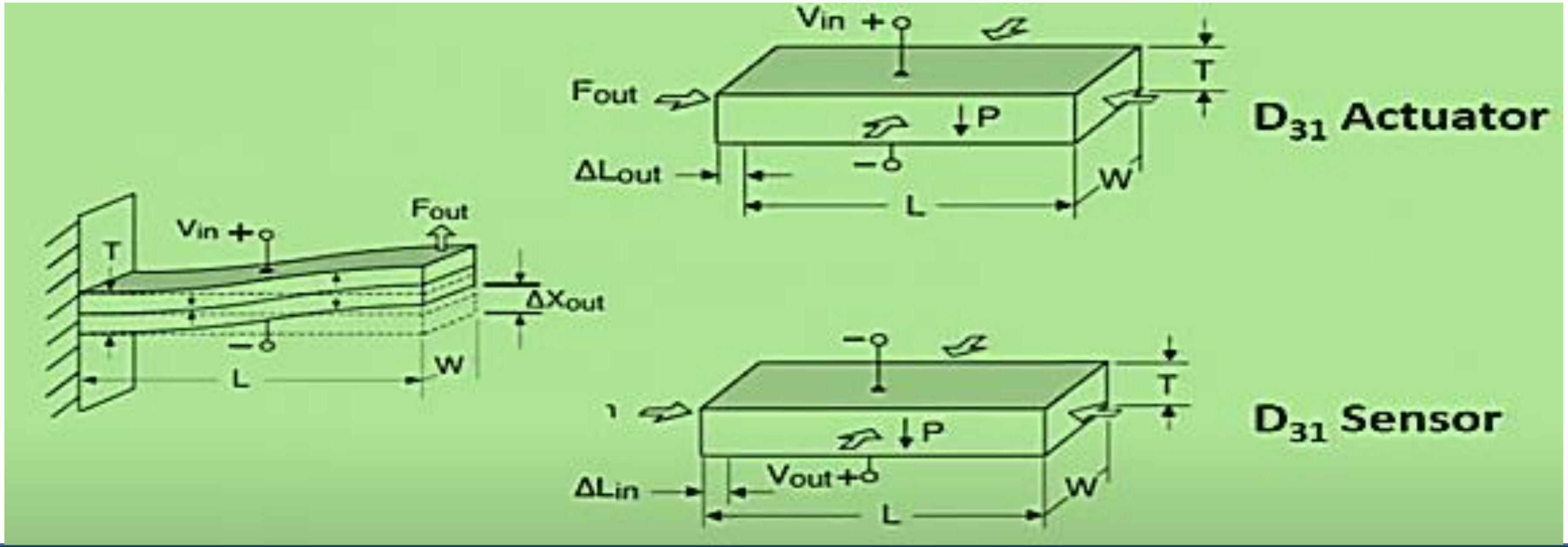
Piezoelectric polymer

- PVDF (Poly Vinyledene Fluoride) a semi-crystallanie polymer consist of long-chain molecules with the repeat unit of CF_2CH_2
- PVDF (all transition) shows all chain oriented parallel to the axis of the unit cell and the dipoles pointing in the same direction
- d_{31}: 4.2 - 19 pC/N (for PZT 234)
- K_{31}: 3 – 14.7 %
- E: 1.6 – 3.8 GPa

Piezoelectric composite

- Composite made of a polymer and PZT
- Polymer phase – lower density, permittivity and increased elastic compliance
- Smaller PZT particle (5 – 10 micron) in polyurethane (PU) matrix
- Larger 120 micron particle in a silicon rubber matrix.
- Smaller particles generate series connectivity, while larger generate parallel connectivity

Applications: Bimorph



Piezostack