Smart Materials – II

(*Piezoelectric materials*)

Smart Materials Structures and Systems
Laboratory
IIT Kanpur

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- History of Piezoelectricity
- Piezoelectric Materials
- How to prepare a Piezoceramic Actuator?
- Constitutive Relationship
- Piezoceramic Polymers & Composites
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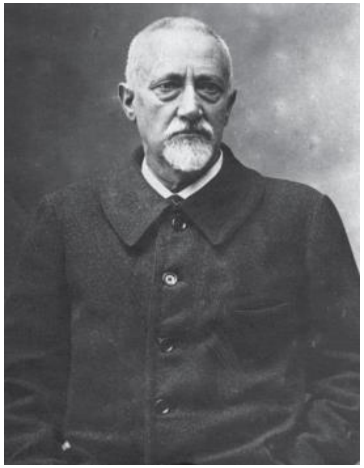
History of Piezoelectricity

- **Piezoelectricity** : Electricity from Pressure was discovered by Pierre and Jacque Curie in 1880.
- Contemporary: **Contact Electricity** – Static Electricity generated from Friction.
- **Pyroelectricity**: Electricity generated from crystals while heating.

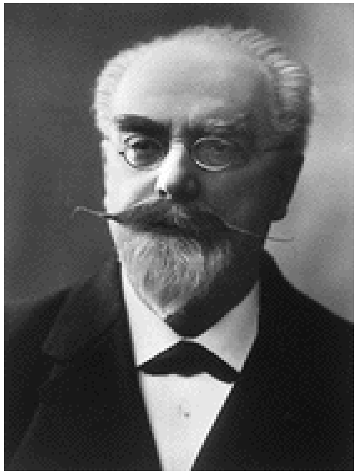
Who's who in Piezoelectricity?

Pierre Curie (1859-1906), Nobel Prize in Physics, 1903



Paul-Jacques Curie (1856-1941)

Direct Piezoelectric Effect (1880)



Gabriel Lippmann (1845-1921), Nobel Prize in Physics, 1908

Source: Wikipedia

Reverse Piezoelectric Effect (1881)

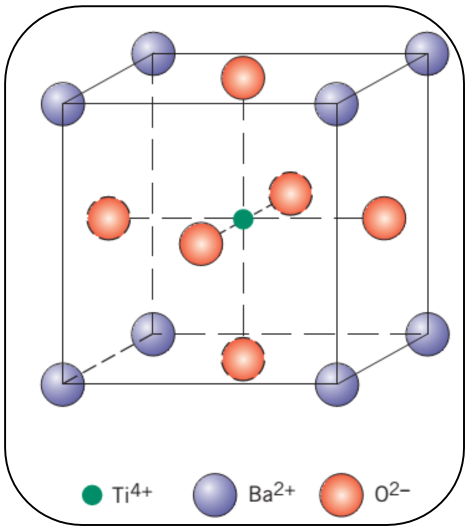
Piezoelectricity – Time Line

- The effect observed by **Pierre and Jacque Curie** is called as Direct Piezoelectric Effect (Hankel 1881).
- The direct effect was found in Zinc Blende, Boracite, Tourmaline, Quartz, Cane Sugar and Rochelle Salt.
- The reverse effect was theoretically predicted by Lippman (1881) and experimentally confirmed by Voight in 1894.
- First application – Langvein (1917) in Sonar Transducer (composite made of steel plate & quartz) – later Ceramic Phonograph, Ceramic Electret Microphone.

Piezoelectricity in Perovskites (1949-60)

Perovskite: A Ternary (3 Component structure)

Example: $BaTiO_3$ a common piezoelectric material



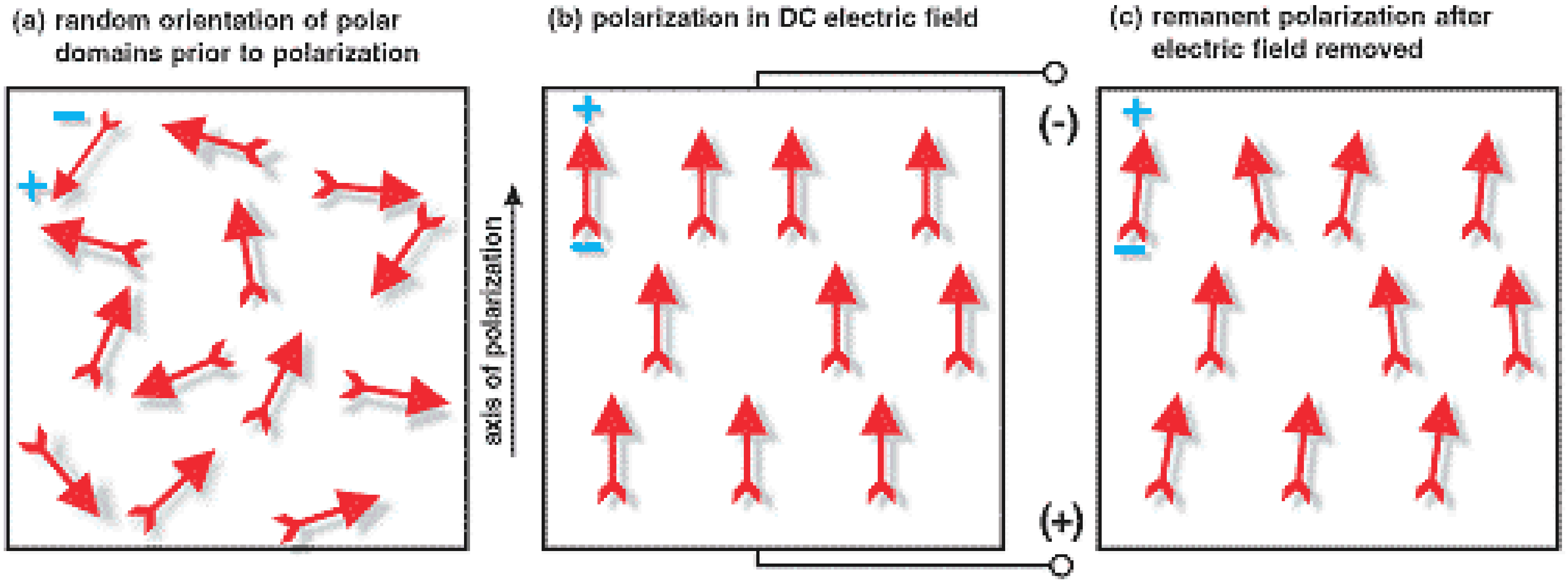
Piezoceramic

Tetragonal Symmetry with Dipole moment below Curie Temperature

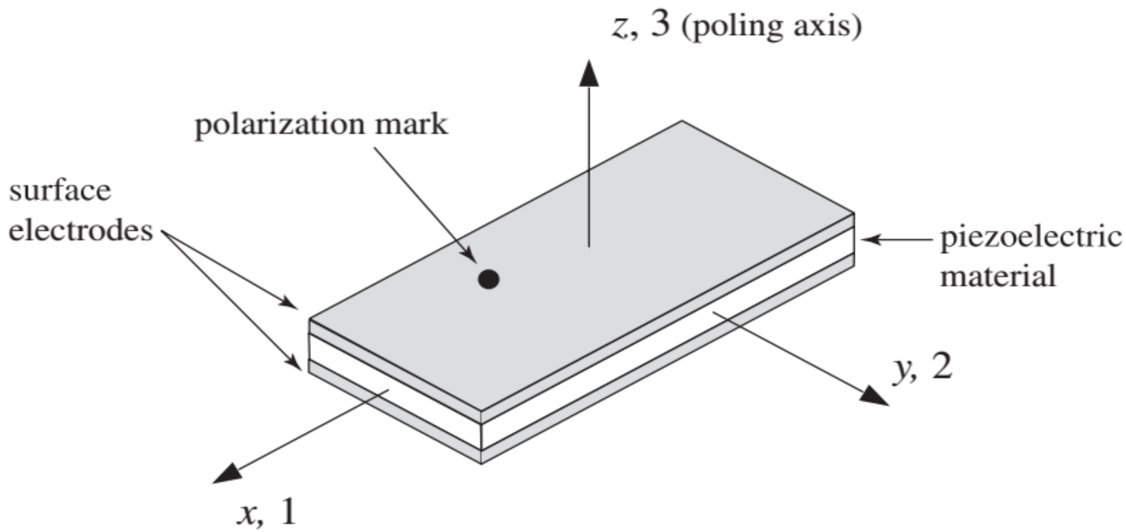
Similar material: PZT family, LiNb family, PbNb family, YMn family, $(NH_4)Cd$ family (1970--)

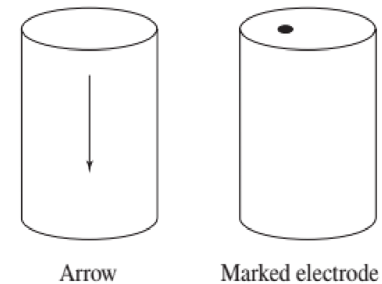
Reference: W.D Callister, 7 Ed.

Polarization of Piezoelectric Material



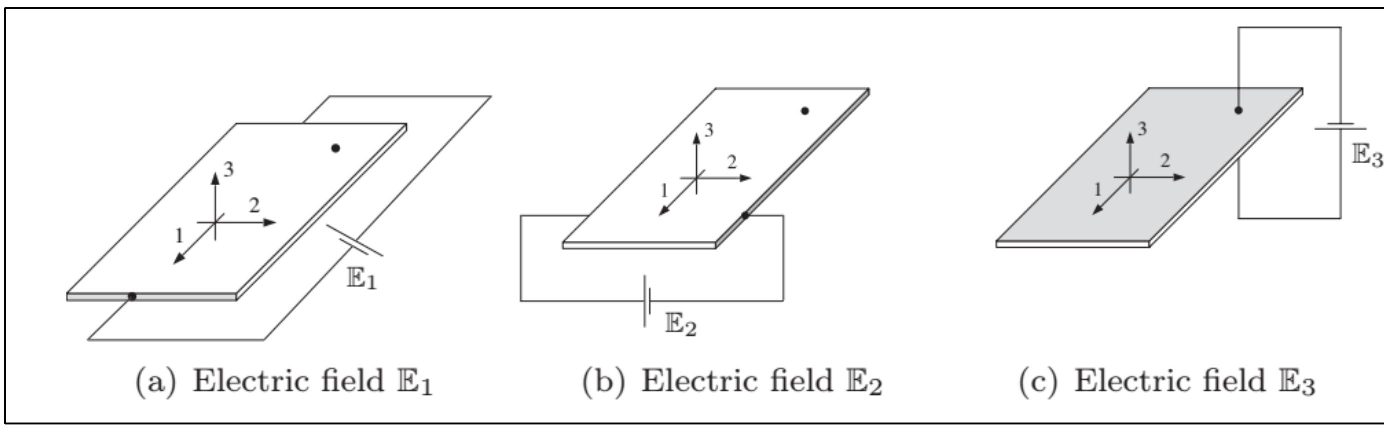
Reference: https://www.pc-control.co.uk/piezoelectric_effect.htm





Polarization direction

Definition of co-ordinate axes and poling direction for a piezoceramic sheet



Possible electric field directions for a piezoceramic sheet

Source: Smart Structures Theory by I. Chopra and J.Sirohi (2013)

Constitutive Equation of Piezoelectricity

$$D = dX + \varepsilon^{X} E$$ ← **Direct Effect**

Stress → **DIRECT Effect** → Electric potential

$$x = S^{E} X + dE$$ ← **Converse Effect**

Electric stimulus → **CONVERSE Effect** → Strain

X – Stress (N/m²)

***x*- Strain**

D - Electric displacement / flux density (C/m²)

S – Compliance (m²/N),

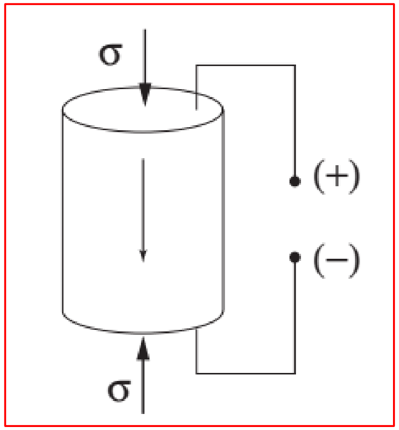
E - Electric field intensity (V/m or N/C)

ε - Permittivity (F/m)

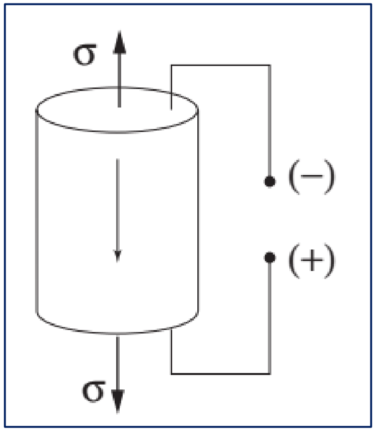
d - Piezoelectric constant (C/N or m/V)

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

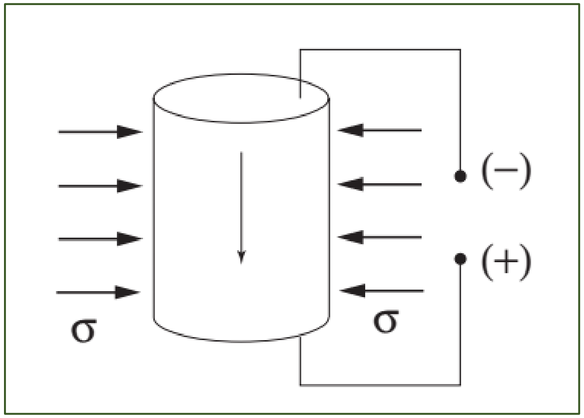
Direct piezoelectric effect



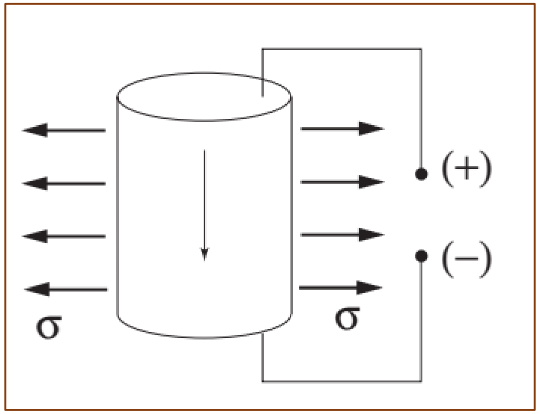
Compressive stress** along **the polarization direction generates a voltage of the same polarity as the poling voltage



Tensile stress along the polarization direction generates a voltage of polarity opposite to that of the poling voltage



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

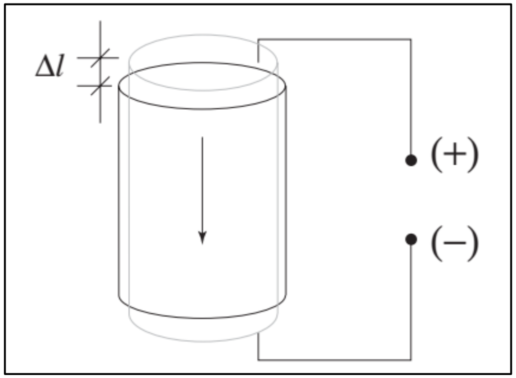


Tensile stress perpendicular to the polarization direction generates a voltage of the same polarity as the poling voltage

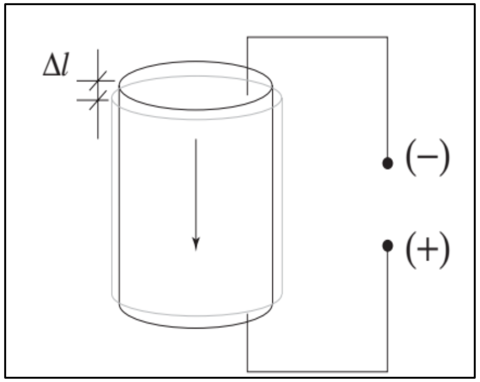
Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

Converse piezoelectric effect

Effect of applied voltage on change in dimensions



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



Voltage of the opposite polarity as the poling voltage causes a contraction along the poling direction and extension perpendicular to the poling direction

Source: Smart Structures Theory by I. Chopra and J.Sirohi (2013)

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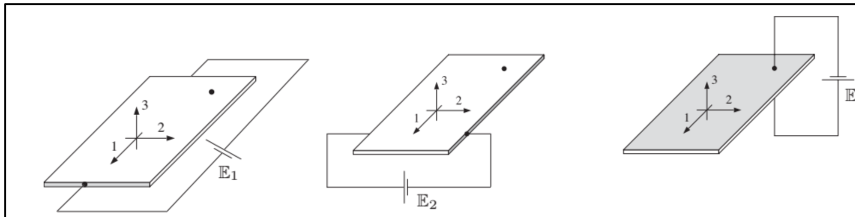
Piezoelectric constant

Stress → **DIRECT Effect** → Electric potential



(a) Electric field $\mathbb{E}_1$ (b) Electric field $\mathbb{E}_2$ (c) Electric field $\mathbb{E}_3$

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

Unit : Coulomb/Newton

Electric stimulus → **CONVERSE Effect** → Strain

$$d^c_{ik} = \frac{\text{strain induced in } i\text{-direction}}{\text{electric field applied in } k\text{-direction}}$$

Unit : metre/Volt

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

Electro-mechanical coupling coefficient

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

Source: Smart Structures Theory by I. Chopra and J.Sirohi (2013)

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**

A few observations

- PZT family has highest piezoelectric coupling.
- Curie Point: PZT family 220-315°C,

  Li family 600-1200°C
- Instead of polycrystalline Piezoceramics, a single cut PMN could give $k_{33} = 0.92$ and $d_{33} = 2070$ pC/N

Piezoelectric Polymer

- PVF_2 (Poly Vinylidene Fluoride) a semi-crystalline polymer consist of long-chain molecules with the repeat unit of CF_2CH_2
- Form I PVDF (all trans) 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

How to prepare a Piezoceramic Actuator?

- Start with fine powders of component metal oxides (PZT or Barium Titanate family) e.g.. for PZT you need PbO, ZrO_2 and TiO_2 powders.
- Mix them in fixed proportions.
- Use an organic binder.
- Form into specific shapes.
- Heat for a specific time and specified temperature 650-800^{o}C
- Cool – apply electrode (sputtering).
- Polarize the sensor/actuator using a DC electric field.

4 steps for Powder Processing

Powder preparation
- solid-state reaction
- coprecipitation
- sol-gel
- spray pyrolysis
- emulsion synthesis
- hydrothermal synthesis

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Shape forming
- pressing
- casting
- plastic forming
- colloidal processing

↓

High temperature sintering
- pressureless
- hot press
- hot isostatic press

↓

Finishing
- mechanical
- laser
- water jet
- ultrasonic

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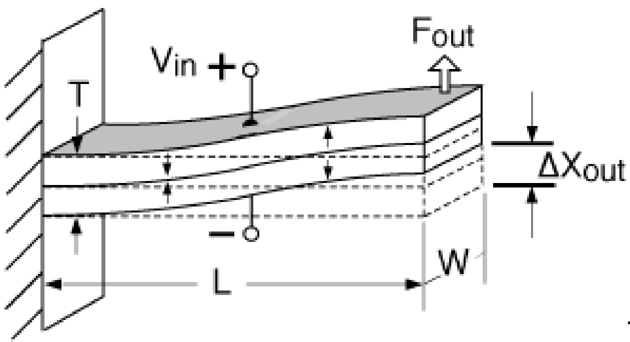
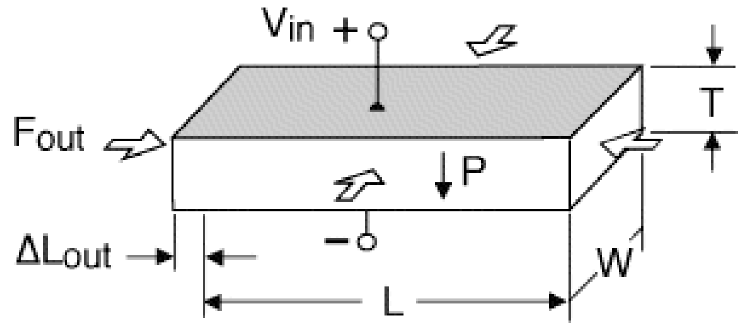
Piezoelectric Composite

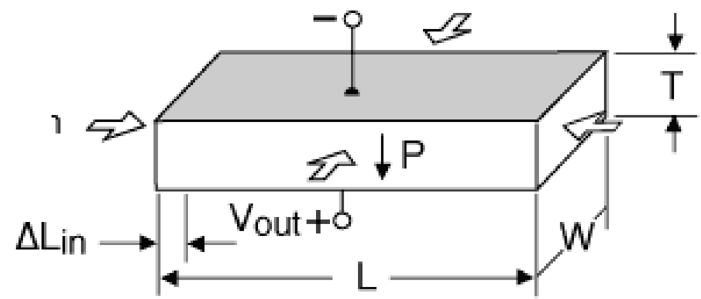
- Composite made of a polymer and PZT
- Polymer phase – lower density, permittivity and increased elastic compliance.
- Smaller PZT particles (5-10 μm) in Polyurethane (PU) matrix.
- Larger 120μm particles in a silicone rubber matrix.
- Skinner et.al: Smaller particles generate series connectivity, while larger generate parallel connectivity.

Applications: Bimorph



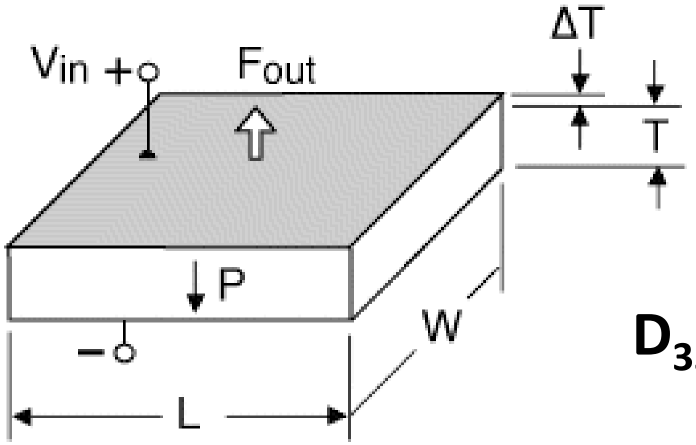


D_{31} Actuator

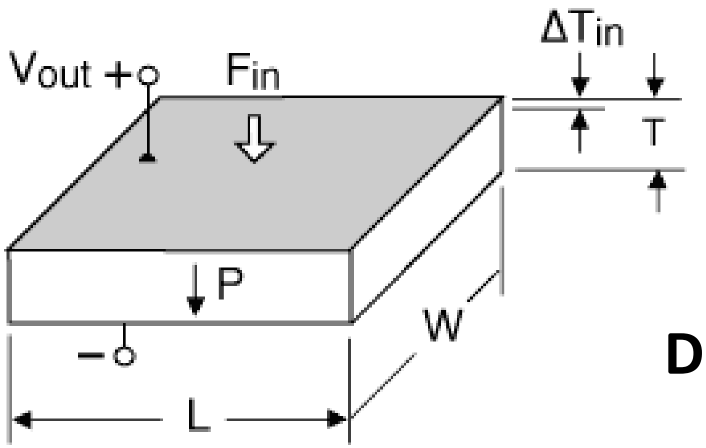


D_{31} Sensor

PIEZOSTACK

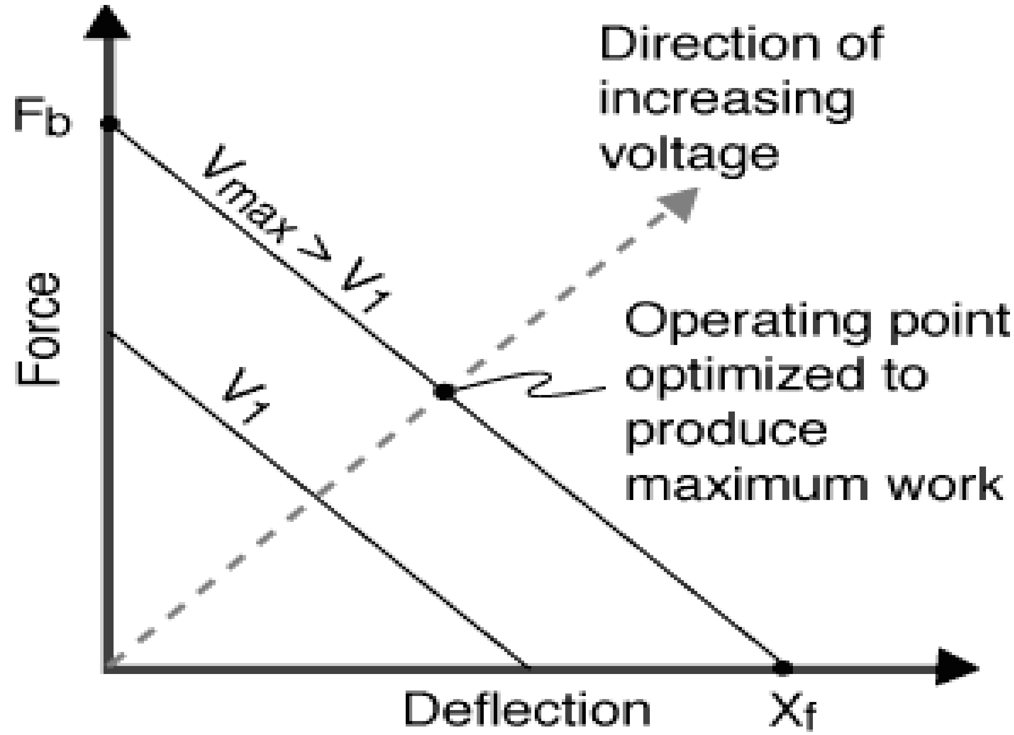


D_{33} Actuator



D_{33} Sensor

Operating Point



Actuator load line

Source: Smart Structures Theory by I. Chopra and J. Sirohi

In the **next lecture**, we will learn about

- ✓ Magnetostrictive materials
- ✓ Constitutive Equations
- ✓ Different effects of Magnetostriction

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