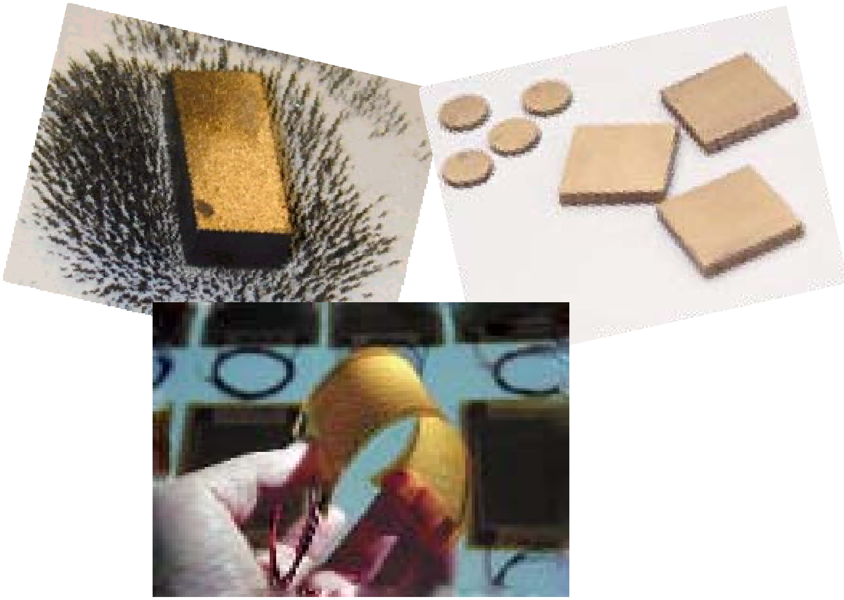
Module 1: Overview of Smart Materials



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Lecture #2: Introduction to Piezoelectric Materials

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

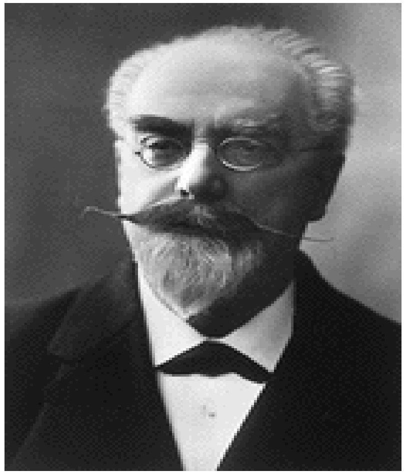
History of Piezoelectricity

- Piezoelectricity i.e. 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

<u>Direct Piezoelectric Effect</u>



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

<u>Reverse Piezoelectric Effect</u>

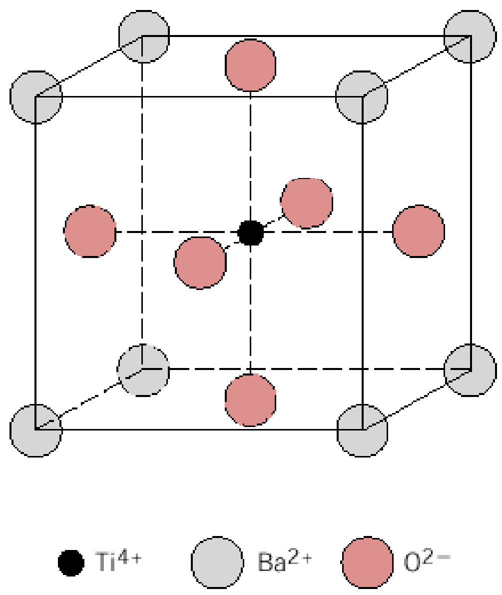
Piezoelectricity – Time Line

- 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)

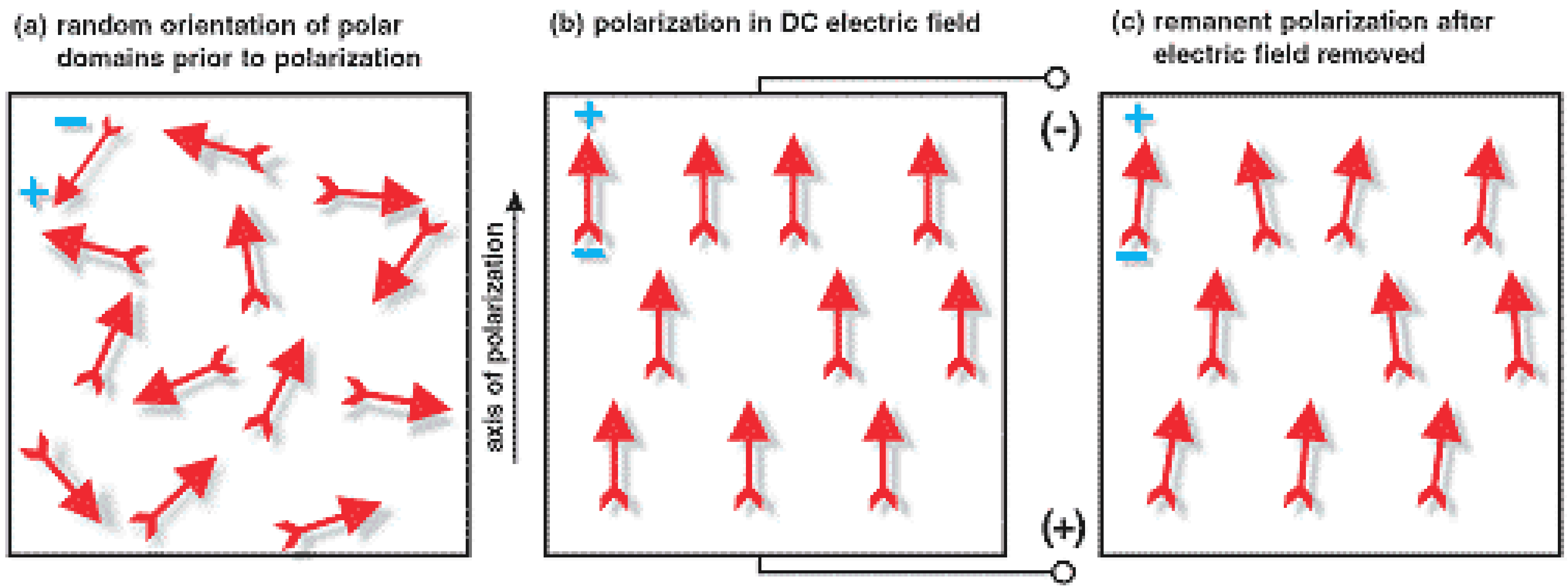
Example: $BaTiO_3$ a common piezoelectric material



Tetragonal Symmetry with Dipole moment below Curie Temperature

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

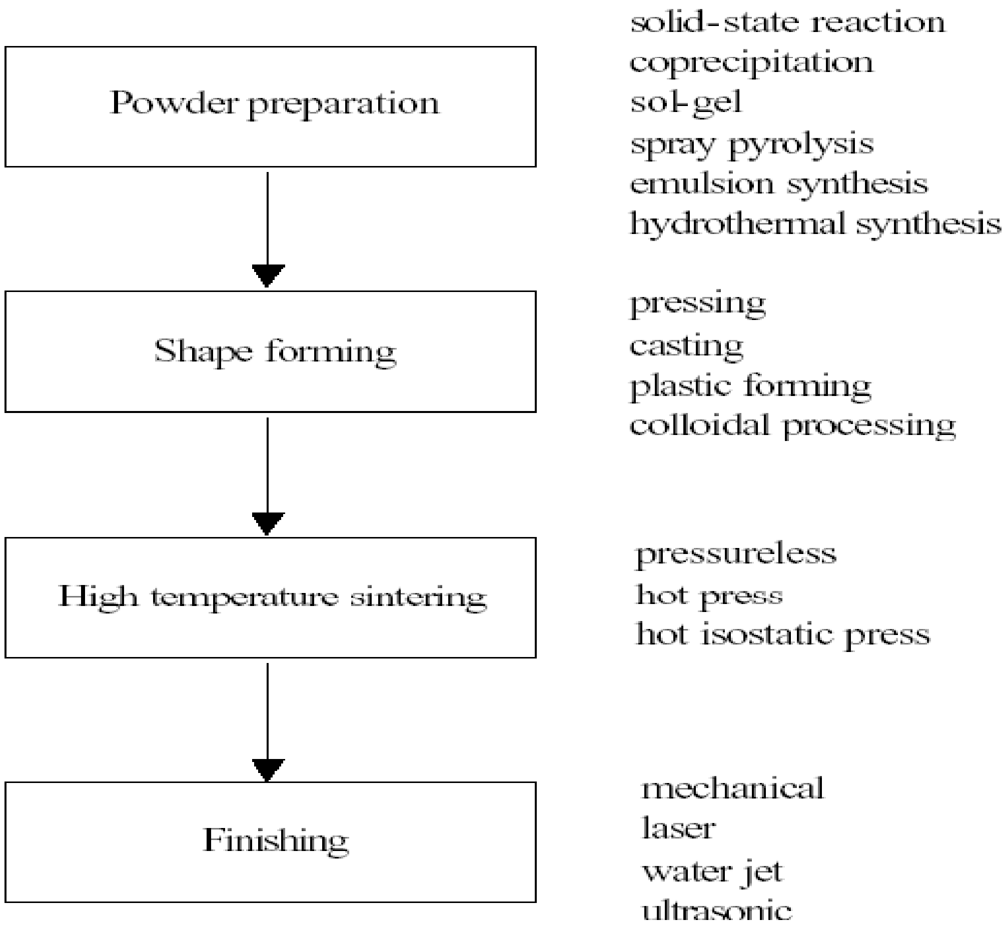
Polarization of Piezoelectric Material



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^oC
- Cool – apply electrode (sputtering)
- Polarize the sensor/actuator using a DC electric field

4 steps for Powder Processing



Constitutive Equation of Piezoelectricity

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

Direct Effect

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

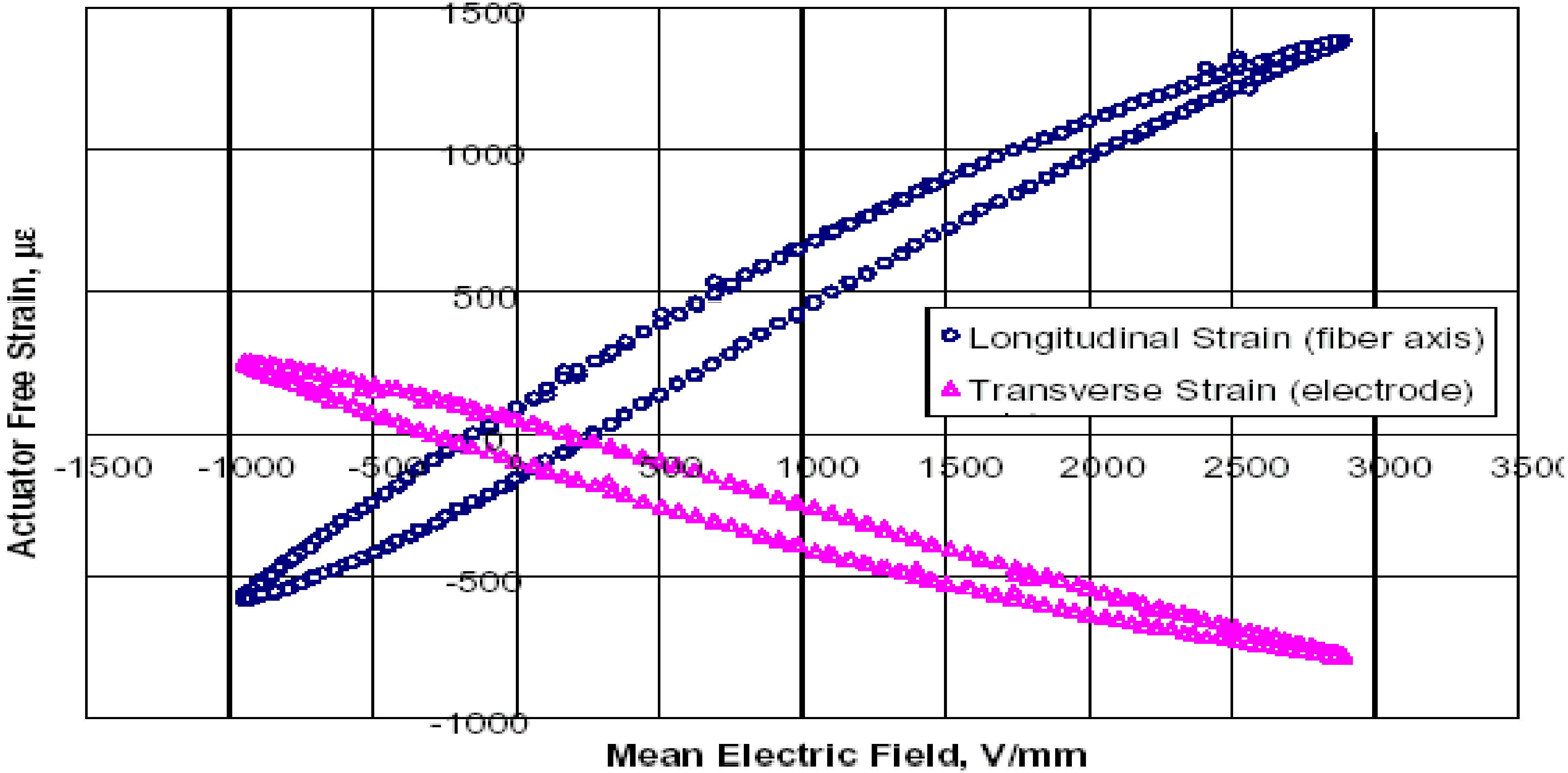
Converse Effect

X-stress, *x*-strain, D-electric displacement/flux density, S-compliance, E-Electric field intensity

ε-permittivity, d-piezoelectric constant

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

Response of a Piezo-fibre



Electromechanical Coupling Coefficient

- Due to nonlinearity the equations represented in Variational form:

$$\delta D = d\,\delta X + \varepsilon^{x}\,\delta E$$

$$\delta x = S^{E}\,\delta X + d\,\delta E$$

- Electromechanical coupling Coefficient:

$$k^2 = W^2{}_{12} / W_1 W_2$$

W_{12} – Piezoelectric Energy Density, W_1 Mechanical and W_2 Electrical energy density

Commercial Piezoelectric Material Property Set

Prp	unit	$BaTiO_3$	PZT-A	PZT-B	$Pb\ Nb_2O_6$	$LiNbO_3$	$Pb\ Ti\ O_3$
ρ	Mg/m^3	5.7	7.9	7.7	5.9	4.6	7.1
k_{31}		.21	.33	.39	.04	.02	.05
k_{33}		.49	.68	.72	.38	.17	.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^{o}C, same for Li family 600-1200^{o}C**
- **Instead of polycrystalline Piezoceramics a single cut PMN could give k_{33} = 0.92 and d_{33} = 2070 pC/N**

Piezoelectric Polymer

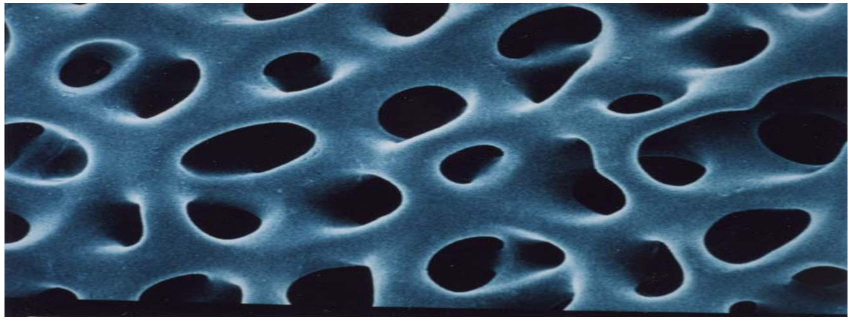
- PVF_2 (Poly Vinylidene Fluoride) a semi-crystalline polymer consist of long-chain molecules with the repeat unit of CF_2CH_2
- Form I PVDF (all trans) shows all chain oriented parallel to the axis of the unit cell and the dipoles pointing in the same direction
- d_{31} 4.2-19 pC/N (for PZT ~ 234)
- k_{31} 3-14.7%
- E – 1.6 – 3.8 GPa

Piezoelectric Composite

- Composite made of a polymer and PZT
- Polymer phase – lower density, permittivity and increase 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 parallel

Piezoelectric Composites

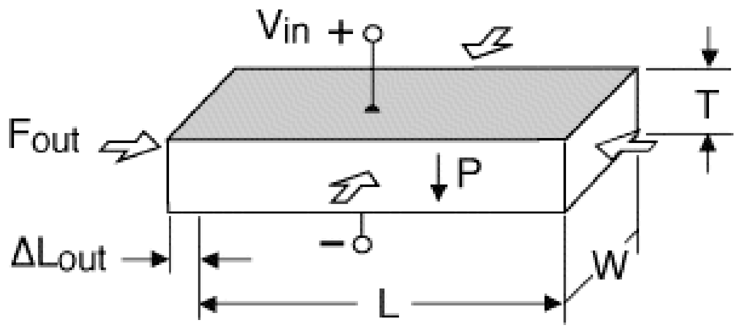
- For series connection, even very low volume fraction of polymer (1%) drastically reduces ‘d’ however ‘g’ remains unaffected
- For parallel connection ‘d’ remains unchanged, ‘g’ increases
- Replamineform process to enhance interconnectivity



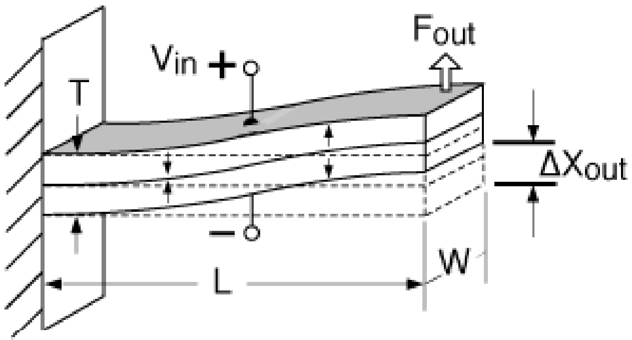
Inspiration from Coral structure:

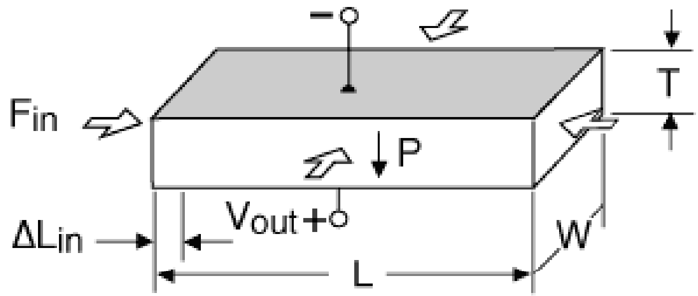
Narrow pore-size distribution, complete pore interconnectivity

Applications: Bimorph



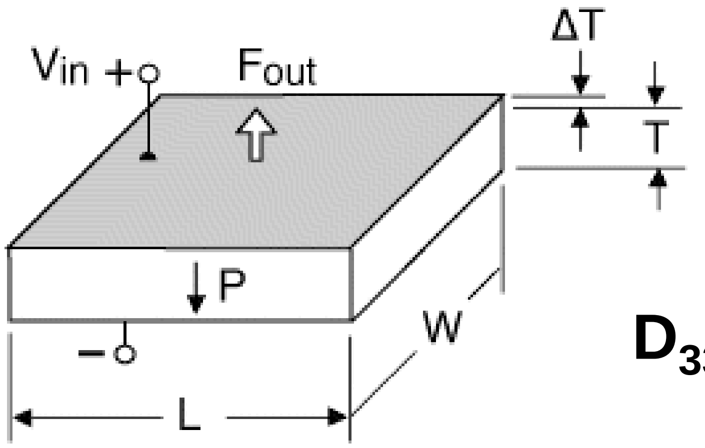
D_{31} Actuator



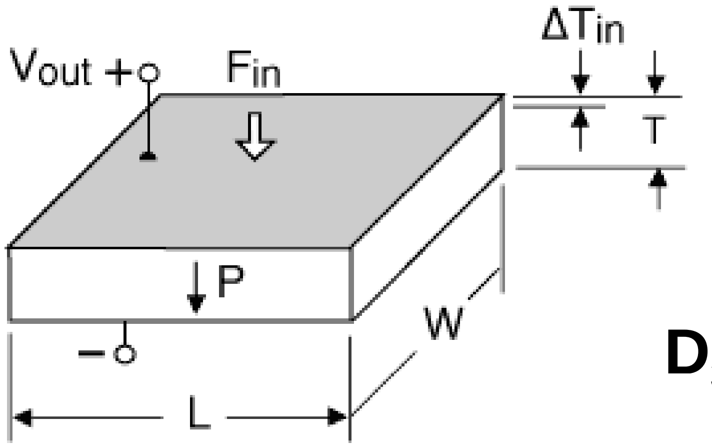


D_{31} Sensor

Piezostack

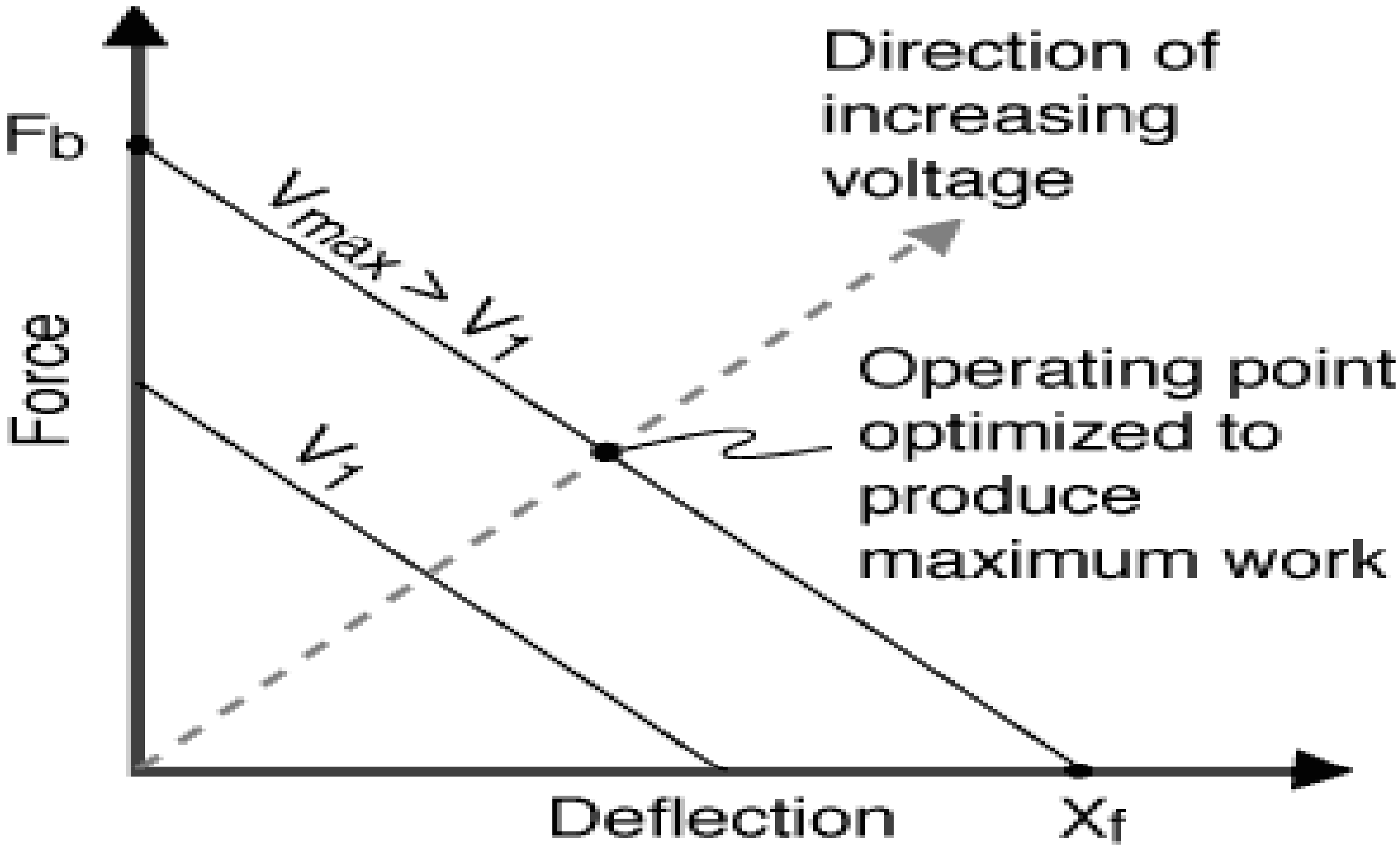


D_{33} Actuator



D_{33} Sensor

Operating Point



END OF LECTURE 2