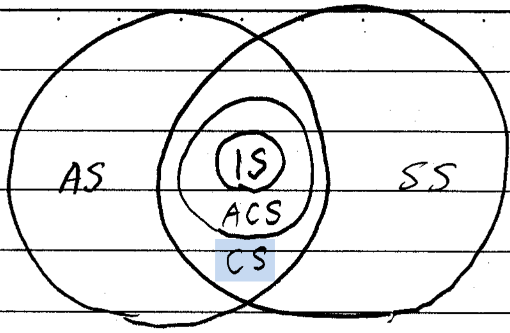
# Smart Materials and Structures

- What?
  - Possess the capability to sense and actuate in a controlled manner in response to variable ambient stimuli
  - Involve combinations of actuators, sensors, and controllers (muscles, nerves, and brains)
  - Also referred to as <u>adaptive</u> or <u>intelligent</u> materials and structures

- Several types of smart materials
  - Piezoelectric materials
  - Electrostrictive materials
  - Magnetostrictive materials
  - Electro-rheological (ER) fluids
  - Magneto-rheological (MR) fluids
  - Shape memory alloys (SMAs)
  - Optical fibers

- Applications
  - Automation: actuators/sensors/motors; robots
  - Transportation: cars, trains, airplanes
  - Infrastructures: bridges and buildings
  - Biomedicine: surgical tools; microsensors
  - Daily life applications: temperature control valves; toys
  - Precision machinery: computer hard disk drives

- How?
  - This is why we offer this course ...




AS = Actuated Structures
SS = Sensory Structures
CS = Controlled Structures
ACS = Active Structures
IS = Intelligent Structures

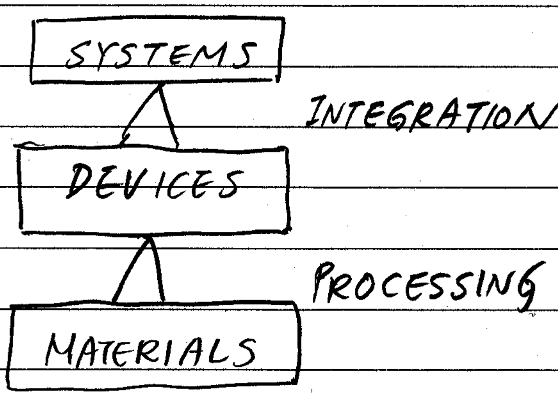
AS : Actuated Structures — structures have distributed actuators (may not have sensors)

SS : Sensory Structures — structures configured with distributed sensors, to monitor characteristics of the system

CS : Controlled Structures — integration of sensory and actuated structures with a closed-loop control system

ACS : Active Structures
— structures with embedded components serving some function in the load carrying capability of the system

IS : Intelligent Structures (Smart Structures)
— those which incorporate actuators and sensors that are highly integrated into the structure and have structural functionality, as well as highly integrated control logic, signal conditioning and power amplification electronics



# Piezoelectric Materials

- most commonly used in smart structures
- produce voltage when subject to mechanical strain
  (direct piezoelectric effect) → sensing capabilities
- induced strain when electric field applied
  (converse piezoelectric effect) → actuation
- used as both actuators / sensors

• Constitutive relations

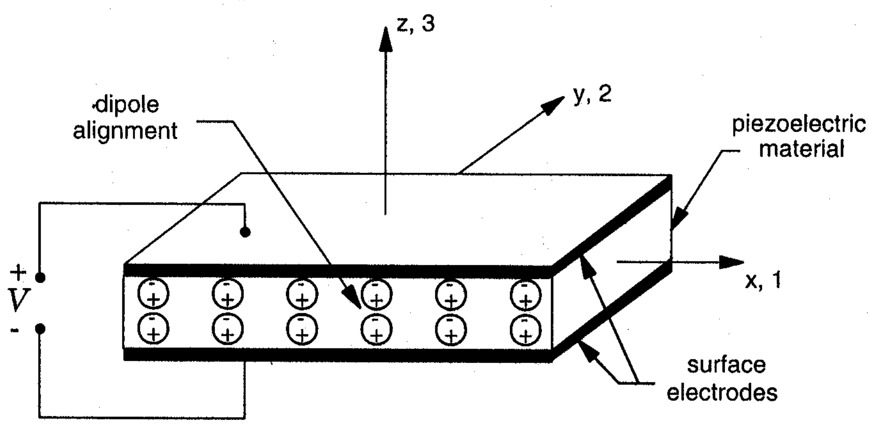



**Figure 5.2:** Schematic diagram of dipole effect induced in piezoelectric material.

Elastic materials : $T = c\,S$ (1)

where $T$ mechanical stresses
$S$ mechanical strains
$c$ material stiffness matrix

In piezoelectric materials,

$$D = \varepsilon^{S} E + e\,S \qquad (2)$$

$$T = -e^{t} E + c^{E} S \qquad (3)$$

where $D$ electrical displacements (charge/area)
$E$ electrical fields (vol/meter)

$\varepsilon^S$ dielectric constants obtained at constant strain (permitivity matrix)
$e$ piezolectric constants relating voltage to stress
$c^E$ stiffness matrix measured at constant electric field

More often, an alternate form of constitutive equations:

$$D = dT + \varepsilon^T E \qquad (4)$$
$$S = s^E T + d^t E \qquad (5)$$

where $d$ piezoelectric constants indicating the strength of the piezoelectric effect
$\varepsilon^T$ dielectric constants for constant $T$
$s^E$ elasticity matrix for constant $E$

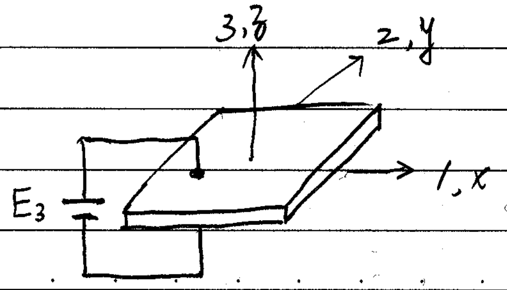
The coefficients appearing in the constitutive equations can be obtained, e.g.,

$$e = d c^E \qquad (6)$$

(see IEEE Std. 176-1987)

With the coordinate system in Fig. 5.2

$d_{ij}$
voltage applied in the $i$ direction
strain developed in the $j$ direction




Induced strain in the $x$ direction,

$$S_1 = d_{31} E_3 \qquad (7)$$

**TABLE 5.1 Piezoelectric Material Properties**

| Property | Symbols | Values PVDF | PZT | Units |
|---|---|---|---|---|
| Strain constant | $d_{31}$ | $23 \times 10^{-12}$ | $166 \times 10^{-12}$ | (m/V) |
| | $d_{32}$ | $3 \times 10^{-12}$ | $166 \times 10^{-12}$ | (m/V) |
| | $d_{33}$ | $-30 \times 10^{-12}$ | $360 \times 10^{-12}$ | (m/V) |
| Relative dielectric constant | $K_3$ | 12 | 1700 | |
| Young's modulus | $E_{11}$ | $2 \times 10^9$ | $6.3 \times 10^{10}$ | (N/m$^2$) |
| Density | $\rho$ | 1780 | 7600 | (kg/m$^3$) |

- PZT (Lead Zirconate Titanate)
  - ceramic based
  - brittle and stiff
  - most commonly used as actuators

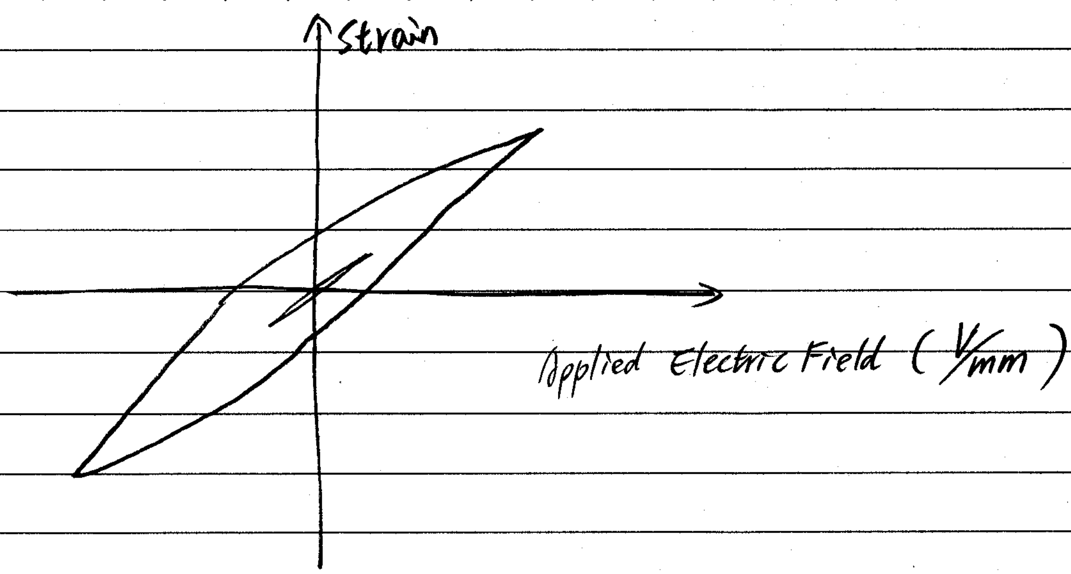
- PVDF (Polyvinylidene Fluoride)
  - polymer based
  - soft (compliant)
  - readily cut and shaped
  - suitable for sensing applications

Comparisons:

$\rho$: PZT $\simeq$ 4 times as dense compared to PVDF

$E_{11}$: PZT $\simeq$ 30 times stiffer "

$d_{31}$: PZT $\simeq$ 7 times "




* For smaller electric fields, strain-field relation is nearly linear

* For higher fields, show significant hysteresis and strain-based nonlinearities

- Advantages:

  - Relative temperature insensitivity
  - Linear response at low excitation levels
  - Broadband frequency response

- Disadvantages:

  - Significant hysteresis at large electric field levels
  - Brittleness and small tensile strength of PZTs
  - Weak electromechanical coupling coefficients for PVDFs