Piezoelectric transducers

• Piezoelectric transducers are based on the property of accumulating charges if stressed (direct effect) and to strain in case of an electric signal is applied across their electrodes (inverse effect).
Piezoelectric transducers

Basics

• Considering the individual molecules that make up a crystal. Each molecule has a polarization, one end is more negatively charged and the other end is positively charged, and is called a dipole.

• The polar axis is an imaginary line that runs through the center of both charges on the molecule.

• In a monocrystal the polar axes of all of the dipoles lie in one direction. The crystal is said to be symmetrical.

In most crystals (such as metals), the unit cell (the basic repeating unit) is symmetrical.
Piezoelectric transducers

• The piezoelectric effect is formed in materials that have no center of symmetry and have a polar axis.
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• In a polycrystal, there are different regions within the material that have a different polar axis.

• It is asymmetrical because there is no point at which the crystal could be cut that would leave the two remaining pieces with the same resultant polar axis.

• Originally piezoelectric ceramics shows a random orientation of dipoles leading to a null polarization.
Piezoelectric transducers

• In order to obtain a preferential axis (**polar axis**) a polling process is required.

  • 1) heating the material close to the Curie temperature
  • 2) applying an electric field (10kV/cm) parallel to the polar axis
  • 3) cooling the material exposed to the electric field

---

![Diagram showing unpoled and poled states of a piezoelectric material](image)
Piezoelectric transducers

• Normally, **piezoelectric crystals are electrically neutral.** A positive charge in one place cancels out a negative charge nearby.

• However, **if the piezoelectric crystal in squeezed,** pushing some of the atoms closer together or further apart (upsetting the balance of positive and negative), this will bring to a **net electrical charges.**

• This effect carries through the whole structure so net positive and negative charges appear on opposite, outer faces of the crystal.
Piezoelectric transducers

• Piezoelectricity is due to asymmetries in the crystallographic structure.

• **If the piezoelectric crystal is squeezed, this will bring to a net electrical charges.**

![Diagram of piezoelectric transducers with labels for null polarization, polarization in the same direction as the stress, and perpendicular polarization.](image-url)
Piezoelectric transducers

Piezoelectric Cristals

• Piezoelectric behavior in lithium niobate (LiNbO3) and lithium tantalate (LiTaO3) was first studied in the mid-1960s [2]. Both have ε values of approximately 40. If cut correctly, they have coupling coefficient (k) values of 0.65 and 0.4, respectively. In addition, the Curie points for both are extremely high (T0 ~ 1210°C for LiNbO3, and 620°C for LiTaO3).

• PbTiO3 shows to posses excellent piezoelectric properties when oriented along the [001] direction. The piezoelectric charge coefficient d33 of 25 × 10⁻¹⁰ C N⁻¹, coupling coefficient k of more than 0.9, and ultrahigh strain of 1.7% were achieved in Pb(Zn1/3Nb2/3)O3-PbTiO3 solid solution.

• These single-crystal relaxor materials are now being intensively investigated and show great promise for future generations of piezoelectric transducers and sensors.
Piezoelectric transducers

Piezoelectric Ceramics

Perovskites
Perovskite is the name given to a group of materials with general formula ABO3 having the same structure as the mineral calcium titanate (CaTiO3), barium titanate (BaTiO3), lead titanate (PbTiO3), lead zirconate titanate (PbZrxTi1-xO3, or PZT), lead lanthanum zirconate titanate [Pb1-xLax(ZryT1-y)1-x/4O3, or PLZT], and lead magnesium niobate [PbMg1/3Nb2/3O3, or PMN].

**Es.** The $d_{15}$ and $d_{33}$ coefficients of BaTiO3 are 270 and 191 $10^{-12}$ C N$^{-1}$, respectively. The $k$ for BaTiO3 is approximately 0.5. Calcium-doped PbTiO3 has a relative dielectric constant $e_{33}$ of 200, a $d_{33}$ of 65 $10^{-12}$ C/N, and a $k$ of approximately 0.5. The addition of calcium results in a lowering of the Curie point to 225°C.
Piezoelectric transducers

An example.....

• Barium Titanate (BaTiO$_3$)
**Piezoelectric transducers**

**Ceramics**

**Ex. Barium Titanate:**

The Curie point is about 130°C. Above 130°C, a nonpiezoelectric cubic phase is stable, where the center of positive charge (Ba\(^{2+}\) and Ti\(^{4+}\)) coincides with the center of the negative charge (O\(^{2–}\)) (Figure a).

When cooled below the Curie point, a tetragonal structure (shown in Figure b) develops where the center of positive charge is displaced relative to the O\(^{2–}\)-ions, leading to the formation of electric dipoles.

(a) *Cubic lattice (above Curie temperature).* (b) *Tetragonal lattice (below Curie temperature).*
Piezoelectric transducers

• Rosettes of piezoelectrics exist to detect deformation in two or three direction

Piezoelectric transducers

Advantages

• High stiffness, to measure force.
• High resonant frequency (up to 500 kHz)
• Stability, reproducibility and linearity
• Large operating temperature range
• Low sensitivity to external magnetic field.

Drawbacks

• Curie Temperature, $T_c$
• Resonant behavior
• High output impedance
• Cannot be used to detect static quantities
Piezoelectric transducers

Benchmark between sensors

<table>
<thead>
<tr>
<th>Transduction Principle</th>
<th>Strain Sensitivity V/με</th>
<th>Threshold (1 to 100 Hz) με</th>
<th>Span-to-threshold Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric</td>
<td>5</td>
<td>0.00001</td>
<td>100 000 000</td>
</tr>
<tr>
<td>Capacitive</td>
<td>0.005</td>
<td>0.0001</td>
<td>750 000</td>
</tr>
<tr>
<td>Inductive</td>
<td>0.001</td>
<td>0.00005</td>
<td>2 000 000</td>
</tr>
<tr>
<td>Piezoresistive</td>
<td>0.0001</td>
<td>0.0001</td>
<td>2 500 000</td>
</tr>
<tr>
<td>(semiconductor)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strain gage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistive</td>
<td>0.000005</td>
<td>0.01</td>
<td>50 000</td>
</tr>
<tr>
<td>(wire/metal film)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strain gage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Low threshold!!

High responsitivity!!

High operating range!!

Table 1.1 Piezoelectric Sensors Versus Passive Sensors. The comparison is based on the stress sensitivity of the different systems. The figures give only a general indication to illustrate the key characteristics and orders of magnitude.
Piezoelectric transducers

Modelling.....

The relationship between mechanical Stress and Strain

\[
T = \frac{F}{A} = Y \frac{\Delta l}{l} = YS
\]

\[
S = sT; \quad s = \frac{1}{Y} \quad Y = \text{Young module}
\]

In case an electric field is applied to a dielectric material

\[
D = \varepsilon E = \varepsilon_0 E + P
\]

Where

D is the electric displacement vector and
P is the polarization
Piezoelectric transducers

Modelling.....

In case of a piezoelectric the mutual effects come to play:

\[ D = dT + \varepsilon^T E \]
\[ S = s^E T + dE \]

\( \varepsilon^T \)  dielectric constant for a constant stress
\( s^E \)  softness for a constant E field
\( d \)  Piezoelectric constant

![Diagram](image)

**FIGURE 6.38**  Schematic representations of the direct and converse piezoelectric effect: (a) an electric field applied to the material changes its shape; (b) a stress on the material yields a surface charge.
Piezoelectric transducers

In real devices **6 possible axis** must be considered:

3 for stress due to compression/expansion

3 for torsional stress
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The matrix form of equations are:

\[
[S_i] = [s_{ij}] \begin{bmatrix} T_j \end{bmatrix} \quad \begin{cases} i = 1, 2, 3 \\ j = 1, \ldots, 6 \end{cases}
\]

\[
[D_i] = [\varepsilon_{ij}] \begin{bmatrix} E_j \end{bmatrix} \quad i, j = 1, 2, 3
\]

\[
[S_i] = [s_{ij}] \begin{bmatrix} T_j \end{bmatrix} + [d_{ik}] \begin{bmatrix} E_k \end{bmatrix} \\
[D_i] = [\varepsilon_{im}] \begin{bmatrix} E_m \end{bmatrix} + [d_{in}] \begin{bmatrix} T_n \end{bmatrix} \\
\begin{cases} j, n = 1, \ldots, 6 \\ i, k, m = 1, 2, 3 \end{cases} \quad d_{ij} = d_{ji} \\
\varepsilon_{im} = 0 \quad \text{for} \quad i \neq m
\]

In parameters: the first index defines the polarization axis while the second index states for the stress direction!
Piezoelectric transducers

Example 6.5  PXE 5 material (Philips) has the following specifications:

<table>
<thead>
<tr>
<th>Piezoelectric Charge Constants</th>
<th>Piezoelectric Voltage Constants</th>
<th>Coupling Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{33} = 384 \text{ pC/N}$</td>
<td>$g_{33} = 24.2 \times 10^{-3} \text{ V.m/N}$</td>
<td>$k_{33} = 0.70$</td>
</tr>
<tr>
<td>$d_{31} = -169 \text{ pC/N}$</td>
<td>$g_{31} = -10.7 \times 10^{-3} \text{ V.m/N}$</td>
<td>$k_{31} = 0.34$</td>
</tr>
<tr>
<td>$d_{15} = 515 \text{ pC/N}$</td>
<td>$g_{15} = 32.5 \times 10^{-3} \text{ V.m/N}$</td>
<td>$k_{15} = 0.66$</td>
</tr>
</tbody>
</table>

Ex. In case of a torsional stress of $1 \text{ N/m}^2$ applied to axis 2 (direction 5) will produce a charge density of $515 \text{ pC/m}^2$ along direction 1.
Piezoelectric transducers

Modelling…..

\[ D = dT + \varepsilon^T E \]
\[ S = s^E T + dE \]

1) Actuator working mode:

\[ D = \varepsilon^T E \]
\[ S = dE \]

2) Sensor working mode in short circuit (E=0)

\[ D = dT \]
\[ S = s^E T \]

3) Sensor working mode in open circuit (D=0):

\[ 0 = dT + \varepsilon^T E \]
\[ S = s^E T + dE \]

\[ E = \frac{d}{\varepsilon^T} T = gT \]

\( g \) is the voltage piezoelectric constant
### Table 6.5: Some Properties for Common Piezoelectric Materials

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Density (kg·m(^{-3}))</th>
<th>(T_C) (°C)</th>
<th>(\epsilon_T^{11}/\epsilon_0)</th>
<th>(\epsilon_T^{33}/\epsilon_0)</th>
<th>(d) (pC/N)</th>
<th>(d_{11})</th>
<th>(d_{14})</th>
<th>(d_{33})</th>
<th>(d_{31})</th>
<th>Resistivity (Ω·cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2649</td>
<td>550</td>
<td>4.52</td>
<td>4.68</td>
<td>2.31</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td>(\approx 10^{14})</td>
</tr>
<tr>
<td>PZT</td>
<td>7500–7900</td>
<td>193–490</td>
<td>—</td>
<td>425–1900</td>
<td>80–593</td>
<td></td>
<td></td>
<td>(d_{33})</td>
<td>(d_{31})</td>
<td>(\approx 10^{13})</td>
</tr>
<tr>
<td>PVDF (Kynar)</td>
<td>1780</td>
<td>—</td>
<td>—</td>
<td>12</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\approx 10^{15})</td>
</tr>
</tbody>
</table>
Piezoelectric transducers

Examples

FIGURE 6.45  Schematic designs of the displacement sensor based on piezoelectric ceramic (a) and of the pressure sensor based on piezoelectric polymer film (b). Arrows indicate the directions of ferroelectric polarization in the piezoelectric material.
Piezoelectric transducers

Example 1:

Lead titanate:

d\(=\)\(-44\) pC/N;

\(\varepsilon_T = 600\varepsilon_0;\)

g\(=\)\(-8\) (mV/m)/(N/m\(^2\));

We are looking for the Voltage (open circuit) due to a force of 1000 N applied to a cube with a 1 cm side.

**SOLUTION:**

Open circuit operation:

\[ D = 0 \]

\[ E = -\frac{d}{\varepsilon_T} T = -\left(\frac{-44 \cdot 10^{-12}}{600 \cdot 8.85 \cdot 10^{-12}}\right) = -82.9 \text{ kV/m} \]

\[ V = E \cdot h = 82.9 \cdot 10^3 \cdot 1 \cdot 10^{-2} = 829 \text{ V} \]
Piezoelectric transducers

EXAMPLE 2:

Requirements:
The strain due to an applied voltage $V=1\text{kV}$ (no mechanical load).

SOLUTION

\[
T = 0
\]

\[
S = dE = \frac{(-44 \cdot 10^{-12}) \cdot 1000}{0.01} = -4.4 \cdot 10^{-6} = -4.4 \mu\varepsilon
\]

\[
\Delta h = (-4.4 \cdot 10^{-6}) \cdot 0.01 = -4.4 \cdot 10^{-8} = -44\text{nm}
\]
Piezoelectric transducers

A method for the estimation of the $d$ parameter

\[ D = d_{33}T \]
\[ Q = d_{33}F \]
\[ I = \frac{dQ}{dt} = d_{33} \frac{dF}{dt} \]

\[ I_C = I \frac{R}{R + \frac{1}{sC}} = I \frac{sCR}{1 + sCR} \]

\[ V = \frac{1}{sC} I_C = \frac{1}{sC} I \frac{sCR}{1 + sCR} = I \frac{R}{1 + sCR} = \]
\[ = d_{33}sf \frac{R}{1 + sCR} = \frac{d_{33}F}{C} \frac{sRC}{1 + sCR} = \frac{d_{33}F}{C} \frac{\tau s}{1 + \tau s} \]

• In the high frequency domain the relationship between $V$ and $F$ is frequency independent

• Forcing the device with a known force and measuring $V$ it is possible to estimate $d_{33}$

• In case of a unknown $C$ a high value capacitor can be added in parallel.
Piezoelectric transducers

A method for the estimation of the \( d \) parameter

\[
D = d_{33} T \\
Q = d_{33} F \\
I = \frac{dQ}{dt} = d_{33} \frac{dF}{dt}
\]

\[
V = d_{33} \frac{\pi s}{C(1 + \pi s)} \text{ con } \tau = RC
\]

- The circuit is a high pass filter.

Ex: In case of \( C = 0.1 \text{pF}, R = 1 \text{T}\Omega \):
\[
f_{t,\text{Amp}} = \frac{1}{(2\pi RC)} = 3 \text{Hz}
\]

- Moreover, the high output impedance of the piezoelectric can cause coupling problem with the amplifier.
Piezoelectric transducers

The Charge Amplifier

\[ V' = -\frac{V}{A} \]

\[ A \approx 10^5 \]

\[ I + I_{eq} + I_2 = 0 \]

\[ sd_{33}F - V' \frac{l + sRC}{R} + (V - V')sC_f = 0 \]

\[ V \left( \frac{1}{A} \frac{1 + sCR}{R} + sC_f + \frac{sC_f}{A} \right) = -sd_{33}F \]

\[ \frac{V}{F} = -\frac{Ad_{33}}{C_f l + sR(C + C_f(l + A))} \frac{sRC_f}{sC_f} \]

\[ \frac{V}{F} \approx -\frac{Ad_{33}}{C_f} \frac{sRC_f}{l + sRC_f A} \]

\[ f_{t,ChA} = \frac{1}{2\pi RC_f A} \ll f_{t,Amp} \]
Piezoelectric transducers

A method for the estimation of the $d$ parameter

**The Drift problem!!**

\[
V' = -\frac{V}{A}
\]

\[
Q = d_{33} F
\]

\[
R \frac{1}{1 + sCR}
\]

\[
f_{t,ChA} = \frac{1}{2\pi R_f C_f}
\]

suitable feedback parameters can allow to obtain:

\[
f_{t,ChA} < f_{t,Amp}
\]

Ex: if $C_F = 10\,\text{pF}$, $C = 0.1\,\text{pF}$, $R = 1\,\text{T}\Omega$, $R_f = 1\,\text{T}\,\Omega$ si ha:

\[
f_{t,\text{Amp}} = \frac{1}{(2\pi RC)} = 3\,\text{Hz}
\]

\[
f_{t,\text{ChA}} = \frac{1}{(2\pi R_f C_f)} = 0.03\,\text{Hz}
\]
Pyroelectric materials

• Among Piezoelectric, some materials exist which show a spontaneous polarization: these materials are called Piroelectrics and shows a relationship between the polarization and the temperature.

\[ DP = A \Delta T \]
Ferroelectric materials

- Ferroelectric materials are a special class of non linear **Piroelectric materials** where the spontaneous polarization can be reversed by an external electric field.

- Domain wall
- Dipoles inertia!
Ferroelectric materials

$V(P)$

$DV$

$P_-$ $P_+$

VIDEO
Sumarizing...

Piezoelectrics

Ferroelectrics

Piroelectrics

Perovskite:
(BaTiO₃);
PbTiO₃);
(CaTiO₃);
PZT;
PLZT;
ceramics