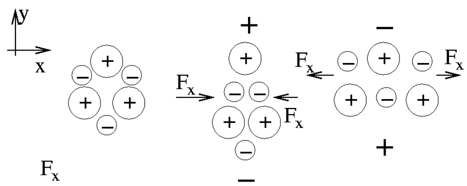
Piezoelectric sensors

Mechanical stress on some crystal lattices results in a potential difference across the solid.

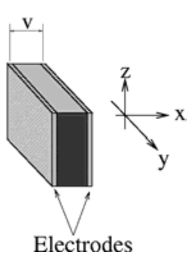


This is an extremely useful effect. Reversible too!

- For quartz, stress in x-direction results in a potential difference in the y-direction.
- This can be used as a traffic weighing and counting sensor!
- A piezoelectric sensor can be thought of as a capacitor, with the piezoelectric material acting as the dielectric. The dielectric acts a generator of electric charge resulting in a potential V across the capacitor.
- The process is reversible. An electric field induces a strain in the material. Thus a very small voltage can be applied, resulting in a tiny change in the size of the crystal.

Characterisation of Piezoelectrics

We quantify the piezoelectric effect using a vector of Polarisation.



$$\vec{P} = \vec{P}_{xx} + \vec{P}_{yy} + \vec{P}_{zz}$$

$$P_{xx} = d_{11}\sigma_{xx} + d_{12}\sigma_{yy} + d_{13}\sigma_{zz}$$

$$P_{yy} = d_{21}\sigma_{xx} + d_{22}\sigma_{yy} + d_{23}\sigma_{zz}$$

$$P_{zz} = d_{31}\sigma_{xx} + d_{32}\sigma_{yy} + d_{33}\sigma_{zz}$$

Where d_{mn} are coefficients, i.e. numbers that translate applied force to generated charge and are a characteristic of the piezoelectric material.

Units are Coulomb/Newton.

Characterisation of Piezoelectrics

Piezo crystals are transducers;

They convert mechanical to electrical energy.

The conversion efficiency is given by the coupling coeffient:

$$K_{mn} = \frac{d_{mn}^2 Y}{\varepsilon_0 \varepsilon_{mn}}$$

Where Y is Young's Modulus = Stress/strain

$$Y = \frac{\sigma}{\frac{dl}{l}}, \quad \sigma = stress = \frac{F}{A} = \frac{Force}{Area}$$

The charge generated is proportional to the applied force

The charge generated in the X-direction from an applied stress in y

$$Q_x = d_{12} F_y$$

Using our Q = CV, we get a generated voltage

$$V = \frac{Q_x}{C} = \frac{d_{12} F_y}{C}$$

The capacitance is:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{l}$$

Area of electrodes (A)

Thickness of crystal (l)

So the Voltage is

$$V = \frac{d_{12} l F_y}{\varepsilon \varepsilon_{0r} A}$$

Some Piezoelectrics

Table 3-5 Properties of piezoelectric materials at 20°C

	PVDF	$BaTiO_3$	PZT	Quartz	TGS
Density ($\times 10^3$ kg/m^3)	1.78	5.7	7.5	2.65	1.69
Dielectric constant, ε_r	12	1700	1200	4.5	45
Elastic modulus (10^{10} N/m)	0.3	11	8.3	7.7	3
Piezoelectric constant (pC/N)	d_{31}=20 d_{32}=2 d_{33}=-30	78	110	2.3	25
Pyroelectric constant (10^{-4} C/m^{2}K)	4	20	27	-	30
Electromechanical coupling constant (%)	11	21	30	10	-
Acoustic impedance (10^6 kg/m^{2}s)	2.3	25	25	14.3	-

Numerical Example.

What is the sensitivity of 1 mm thick, $BaTiO_3$ sensor with an electrode area of 1 square cm?

$$V = \frac{d_{12} l F}{\varepsilon_r \varepsilon_0 A} = \frac{78 \times 1 \times 10^{-3} F}{1700 \times 8.8 \times 10^{-12} 1 \times 10^{-4}} = \frac{7.8 \times 10^{-2} F}{1.5 \times 10^{-12}}$$

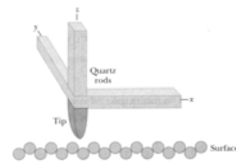
So $\frac{V}{F} = 5.2 \times 10^{10}$ Volts/Newton

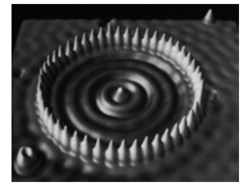
This is a big number because the effective capacitance is so small. In the real world the voltage is smaller.

C = $\frac{1.5 \times 10^{-12}}{1 \times 10^{-3}} = 1.5nF$ *Very Small!*

Atomic Scale Microscopy

Use Piezoelectric crystals as transducers to do atomic scale microscopy



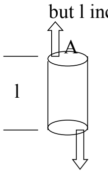


Piezoresistive Sensors

The stress on a material is $\sigma = \frac{F}{A} = \frac{Ydl}{l}$

Strain = dl/l

A cylinder stretched by a Force F keeps constant volume but l increases and A decreases.



Resitance $R = \frac{\rho l}{A} = \frac{\rho l^2}{vol}$

Sensitivity of the sensor is $\frac{dR}{dl} = \frac{2\rho l}{vol}$

Longer wires give more sensitivity

Characterizing Piezoresistors

Normalised resistance is a linear function of strain: $\frac{dR}{R} = S_e e$

Where e is the strain, and

S_e is the **gauge factor** or sensitivity of the strain.

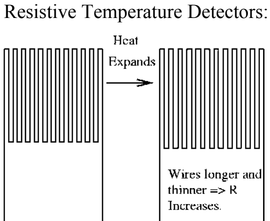
Metals	$2 < S_e < 6$
Semiconductors	$40 < S_e < 200$

Semiconductor strain gauges are 10 to 100 times more sensitive, but are also more temperature dependent.

Usually have to compensate with other types of sensors.

Piezoresistive Heat Sensors.

Resistive Temperature Detectors: on demand "RTD"s



RTD's used at Belle

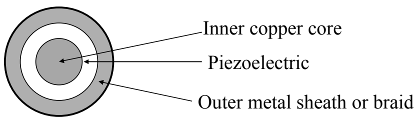
Thin platinum wire deposited on a substrate.

Other piezoresistive issues

- Artificial piezoelectric sensors are made by poling; apply a voltage across material as it is heated above the Curie point (at which internal domians realign).
- The effect is to align natural dipoles in the crystal. This makes the crystal a Piezoelectric.
- PVDF is of moderate sensitivity but very resistant to depolarization when subject to high AC fields.
- PVDF is 100 times more resistant to electric field than the ceramic PZT [Pd(Ze,Ti)O_3] and useful for strains 10 times larger.

Example: acceleration Sensor.

- Piezoelectric cable with an inner copper core.
- The piezoelectric acts as an insulator, clad by an outer metal sheath and flexible plastic and rubber coating.
- Other configurations exist: see www.pcb.com/techsupport/tech_accel.aspx



Plan view of cable

Remember that $F=ma$, so if the sensor mass is known, then the force measured can be converted into an acceleration.

Applications for piezoelectric accelerometers

- Vibration monitor in compressor blades in turboshaft aircraft.
- Detection of insects in silos
- Automobile traffic analysis (buried in highway): traffic counting and weighing.
- Force and pressure sensors (say, monitoring jolts to packages).
- Tactile films: thin silicone rubber film (40 μm) sandwiched between two thin PVDF films.

If tactile sandwich is compressed, the mechanical coupling in the PVDF/rubber/PVDF sandwich changes, the measured AC signal changes, and the demodulation voltage changes