Lecture 6, part II (week 6: 24-25 March 2025)

Piezoelectric properties of crystalline materials

- part II: applications

Piezoelectric materials:

<u>Inorganic monoscrystals</u>

Insulators, such as quartz, SiO_2
Semiconductors, e.g. CdS, GaAs
Polar materials such as ZnO
Ferroelectrics, $LiNbO_3$

<u>Ferroelectric ceramics</u>
$BaTiO_3$
$Pb(Zr,Ti)O_3$

<u>Polymers</u>
Polyvinylidien flouride ($(-CH_2-CF_2-)_n$, ou PVDF)
Its copolymers,
Polyvinyle chloride and others

<u>Biological materials</u>
Cellulose
Amulose
Keratine (hair, wool)
Polyaminoacides
Polypeptides

Applications:

Direct piezoelectric effect

Sensors

$$\varepsilon_n = d_{in} E_i$$

$$Di = d_{in} \sigma_n$$

Converse piezoelectric effect

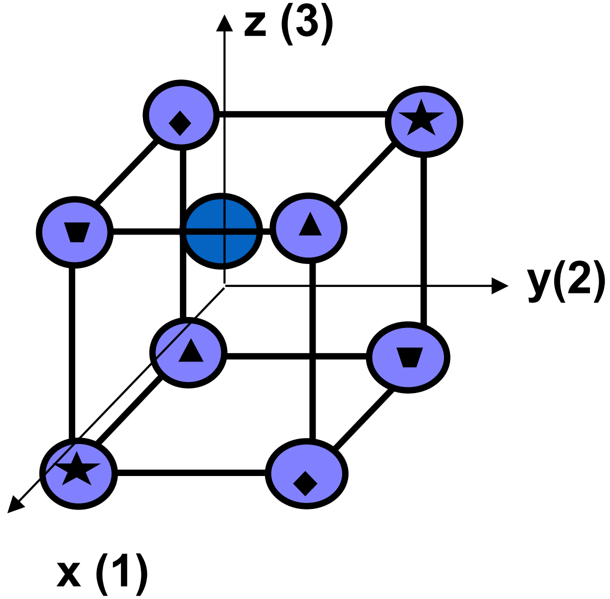
Actuators

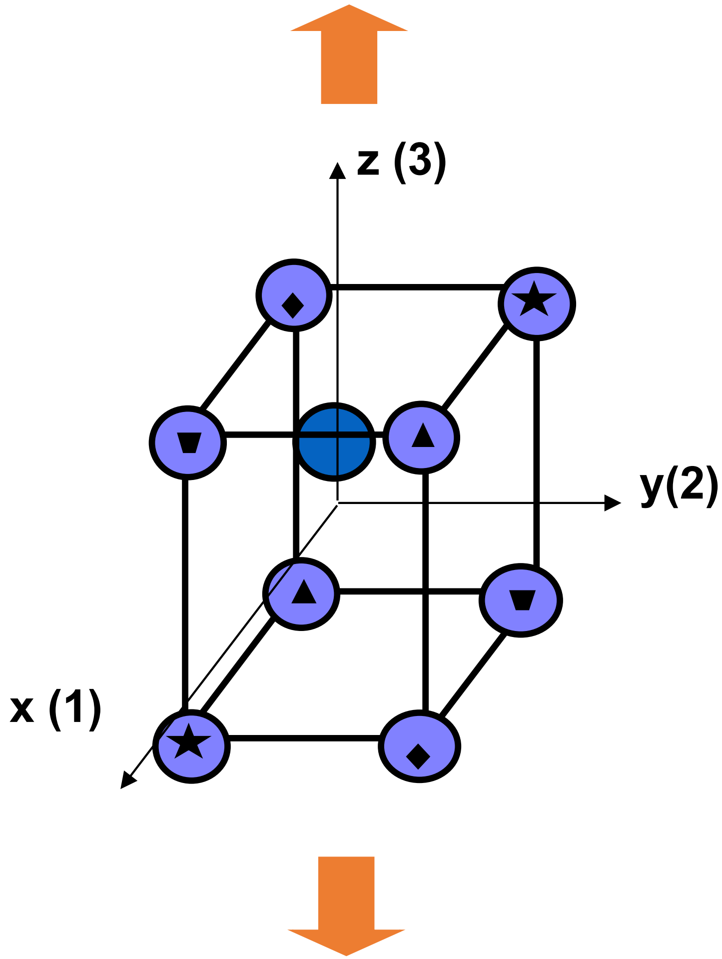
$$\varepsilon_n = d_{in} E_i$$

$$D_i = d_{in} \sigma_n$$

Polar structures

- Polar crystals possess dipoles even if they are not subject to pressure. Under pressure, the dipole changes. Those crystals are thus ***piezoelectric***.





Electromechanical coupling coefficient

- The piezoelectric effect converts electric energy to mechanical energy (converse effect), and mechanical energy into electrical (direct effect).

- The electromechanical coupling factor *K* is defined as:

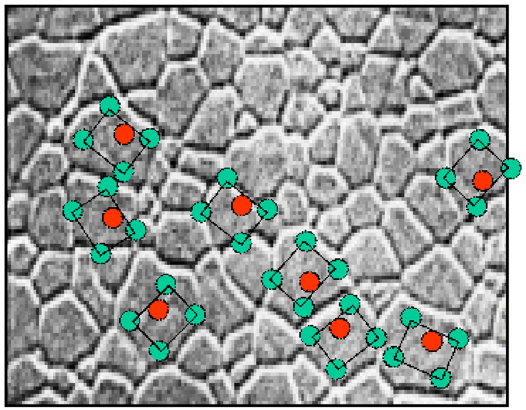
$$K^2 = \frac{W_{\text{converted}}}{W_{\text{supplied}}}$$

- The value *K* varies between 0.1 (quartz), over 0.6 in PZT ceramics, and more than 0.9 in certain crystals.

- The electromechanical coupling factor is an important parameter in applications where efficiency of the energy conversion is important.

Piezoelectric ceramics

- Ceramics are macroscopically isotropic (unless textured) and their global symmetry is centro-symmetric.
- This global symmetry does not allow piezoelectricity, even if the individual grains are piezoelectric or polar.



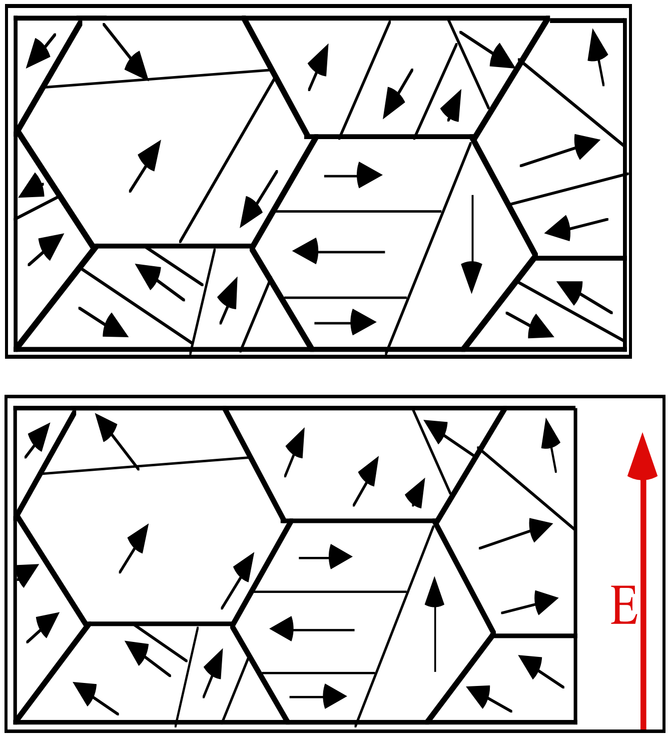
Silica (SiO_2 ceramics), cannot exhibit piezoelectricity, even though monocrystals of quartz SiO_2 are piezoelectric.

Ferroelectric ceramics

- The situation is different with ferroelectric ceramics*:*

  The spontaneous polarization of a ferroelectric can be ***reversed*** by an electric field, in such a way to obtain a ***nonzero polarization*** in the direction of the applied electric field. A nonzero polarization remains after the field is removed

Global polarization is zero



poled

Poling of a ferroelectric ceramics with an electric field makes them piezoelectric

The poling process

- The process of polarizing a ferroelectric ceramics by an external electric field is called "*poling*".
- In contrast to non-poled ceramics, which exhibit a centrosymmetric symmetry (symmetry of a sphere), the *poled ceramics are poled* an possess piezoelectric (and ferroelectric) properties.

Typical conditions for poling of ceramics

temperature: ***100°C to 200°C close to Curie temperature)***

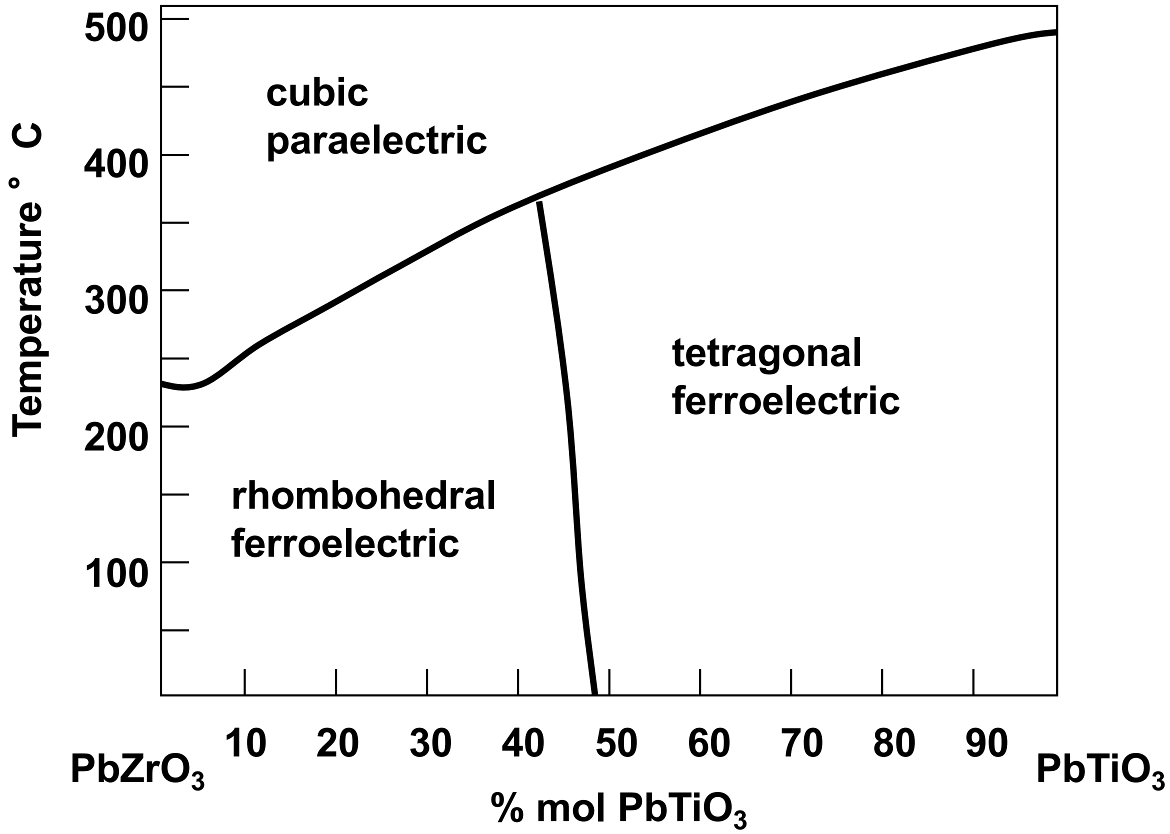
electric field: ***20 kV/cm to 100 kV/cm***

duration of poling: ***minutes to half an hour***

Lead zirconate titanate $Pb(Zr,Ti)O_3$ or PZT

The ceramic with the best piezoelectric properties is a solid solution of two perovskites: $PbTiO_3$ and $PbZrO_3$ - $Pb(Ti,Zr)O_3$

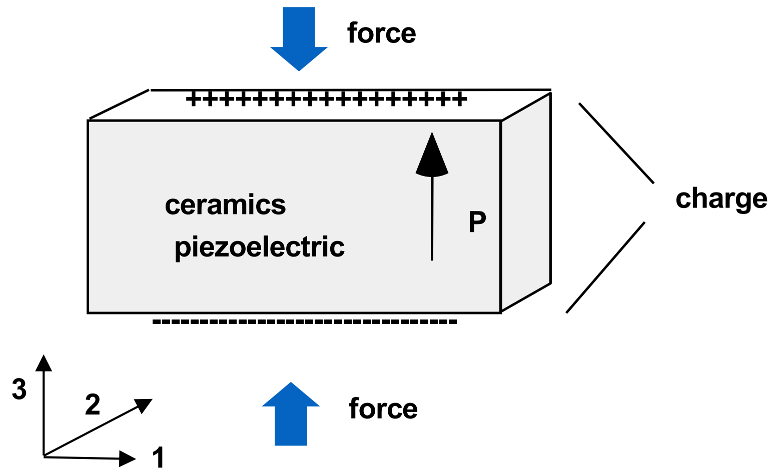
This solid solution (an alloy) is known as PZT.



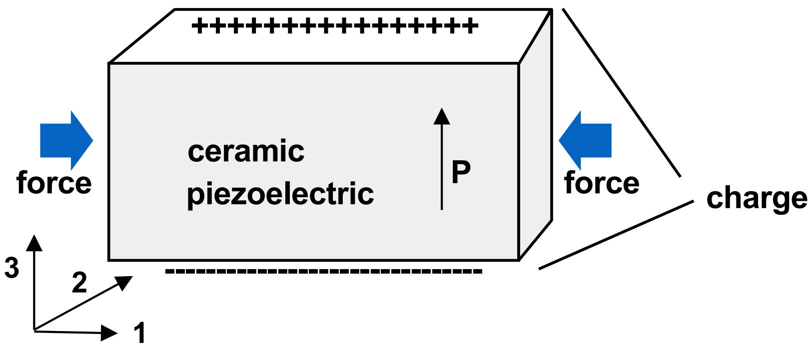
PZT

The piezoelectric coefficients

d_{33} is the coefficient which relates charge generated at the surface perpendicular to the pressure applied at that same surface



d_{31} is the coefficient which relates charge generated at the surface perpendicular at the axis 3 to the pressure applied on the surface perpendicular to the axe 1.



The typical values for PZT are:
d_{33} = 400 pC/N, d_{31} = -170 pC/N.

Gas lighter

$$V = \left(\frac{F^2 k^2 L^2}{E A^2 \varepsilon_o \varepsilon_r} \right)^{1/2}$$

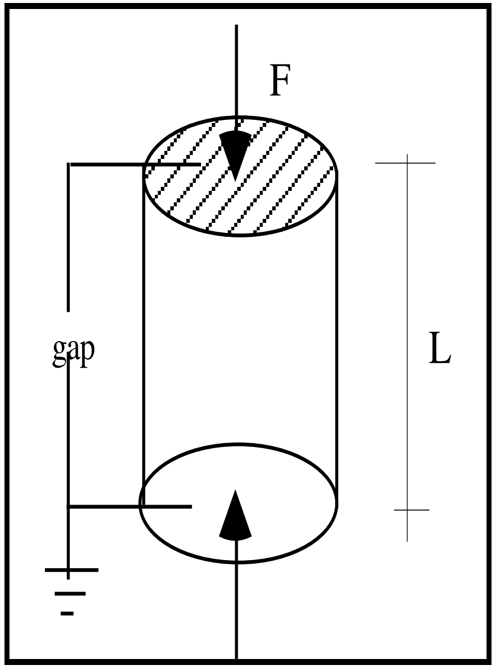
For:

$k = 0.7$, $\varepsilon_r = 1000$, $F = 100$ N

$A = 10$ mm^2 (10^{-5} m^2),

$L = 10$ mm (10^{-2} m)

$E = 10^{+11}$ N/m^2

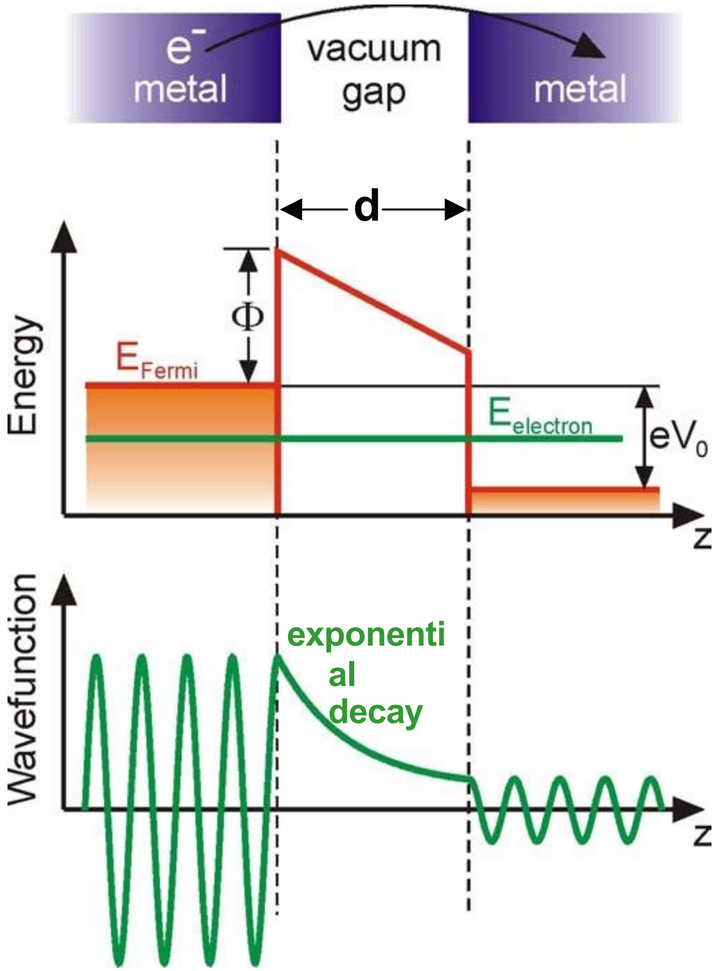


V = 2000 Volts

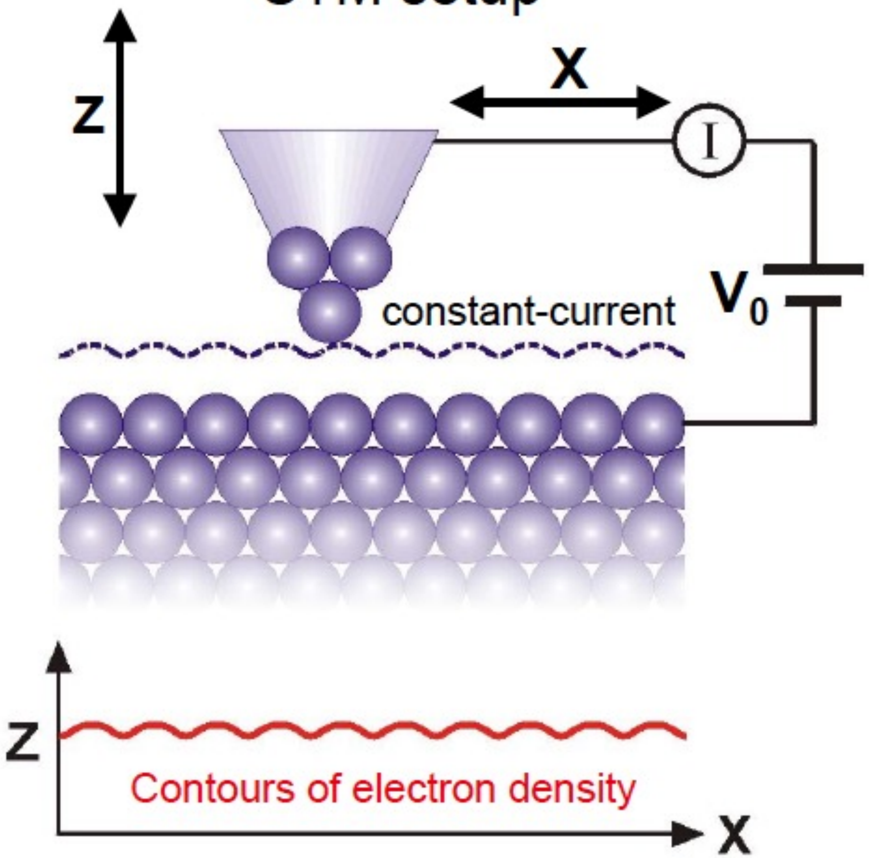
(For a gap of 1 mm, this gives a charge of 20 KV/cm, sufficient for discharge)

Scanning tunneling microscopy (STM): piezoelectric scanners for sub-angstrom resolution

1D tunnel contact



STM setup



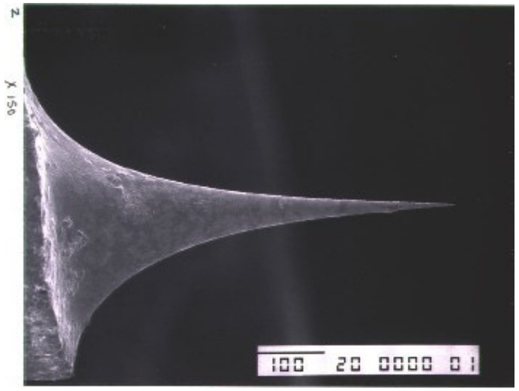
- **Topography information**
  (constant-current mode)

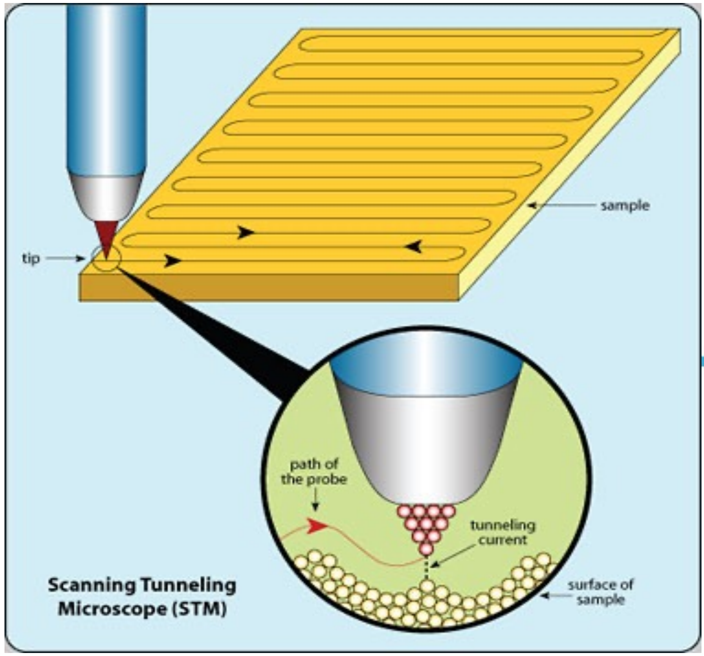
$$I(z) \sim e^{-2kz}$$

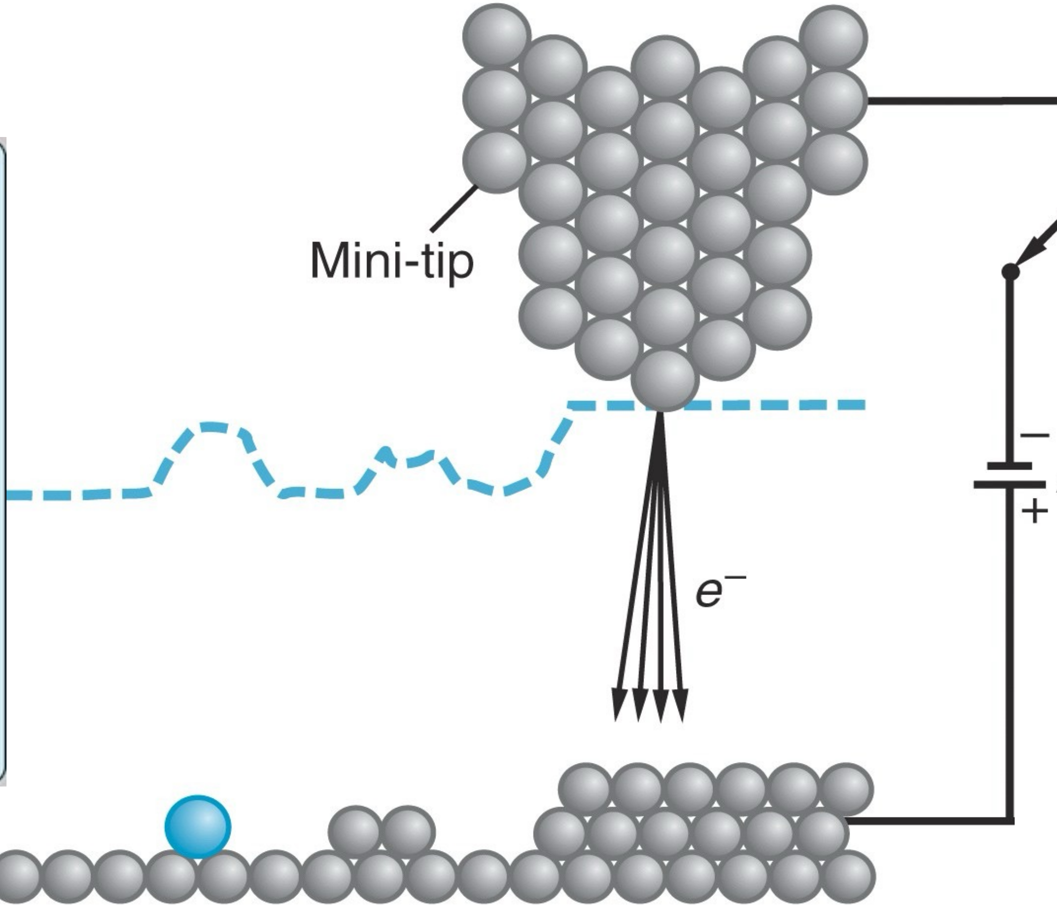
Scanner: an ultra-precise actuator

STM: imaging with atomically sharp tip

End of tip is atomically sharp.
Various techniques are used for tip conditioning (e.g. voltage pulses)







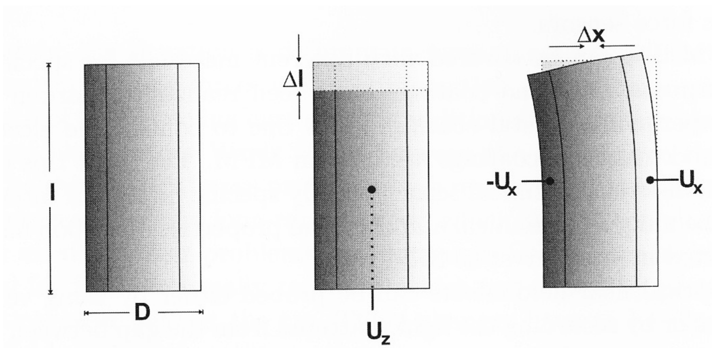
For true atomic resolution the tip has to be positioned vertically and laterally with accuracy of 1-2 pm (0.01 Å). Hence a good scanner is an essential part of the system

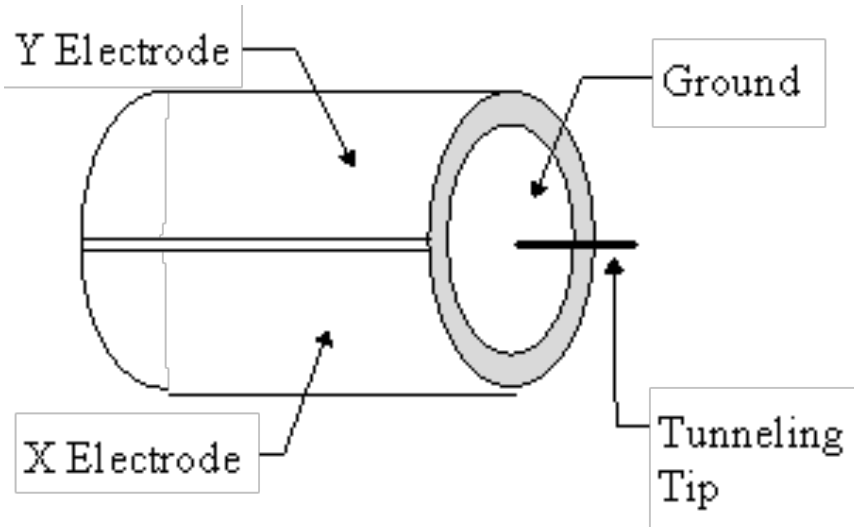
Piezoelectric scanners for scanning probe microscopy

Scanners for STM are piezoelectric actuators fabricated from PZT ceramics in the shape of cylindrical tubes. In this configuration the most important characteristic parameter is the transverse piezoelectric coefficient d_{31}: $\Delta l/l = d_{31}E$, where E is electric field applied between the inner and outer electrodes

A typical value for PZT scanners: $d_{31}=250pm/V = 0.25nm/V$ i.e. to elongate a bar of 1cm by 1 μm on needs to apply 400V (for wall thickness of 1mm).

For tube geometry: $\Delta l = d_{31} l \, V/h$, where *h* is the wall thickness of the tube.





- **Vertical movement: tube elongation**
- **Horizontal movement: tube bending**

For horizontal movement the outer surface of the tube is contacted by four symmetric electrodes separated along the tube. By applying +/- voltages to opposing electrodes the the opposite sides of the tube will experience expansion/contraction, hence the tube will bend.

The inner wall is contacted by a single electrode in order to ensure vertical movement.

In reality design of piezoactuators involves a lot of complicated solutions to account for:

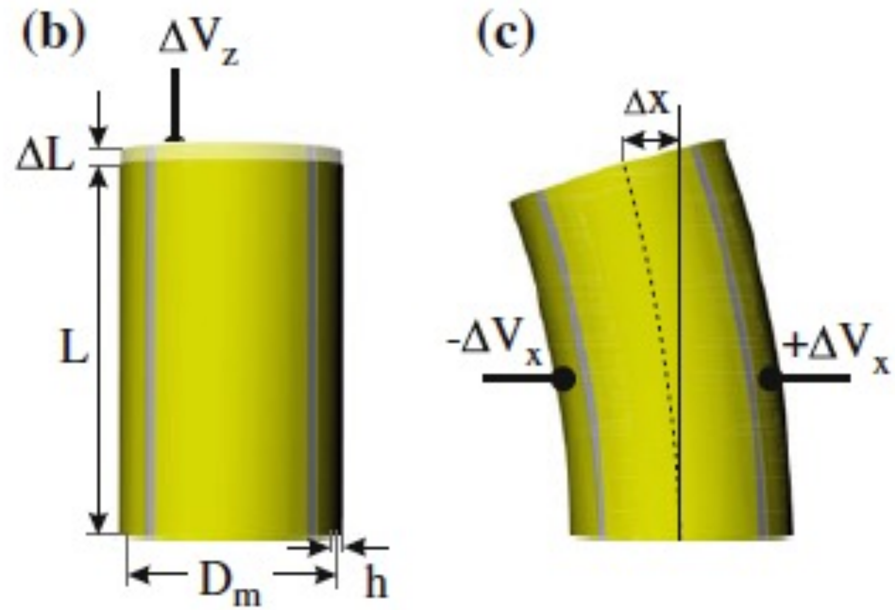
-non-linearity of the mechanical response

-hysteresis of scanner movement

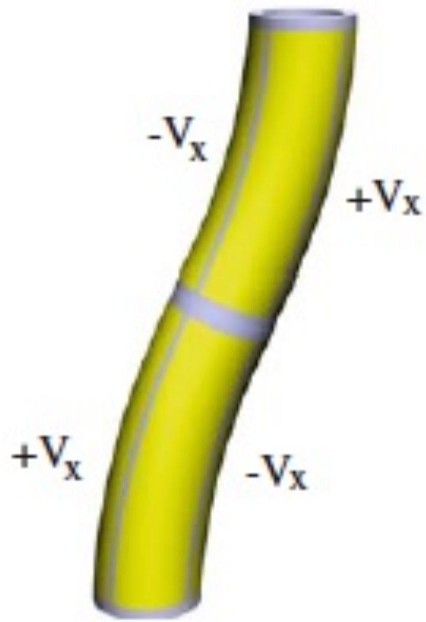
-creep of the material

-thermal drift

Different types of cylindrical piezoelectric tubes

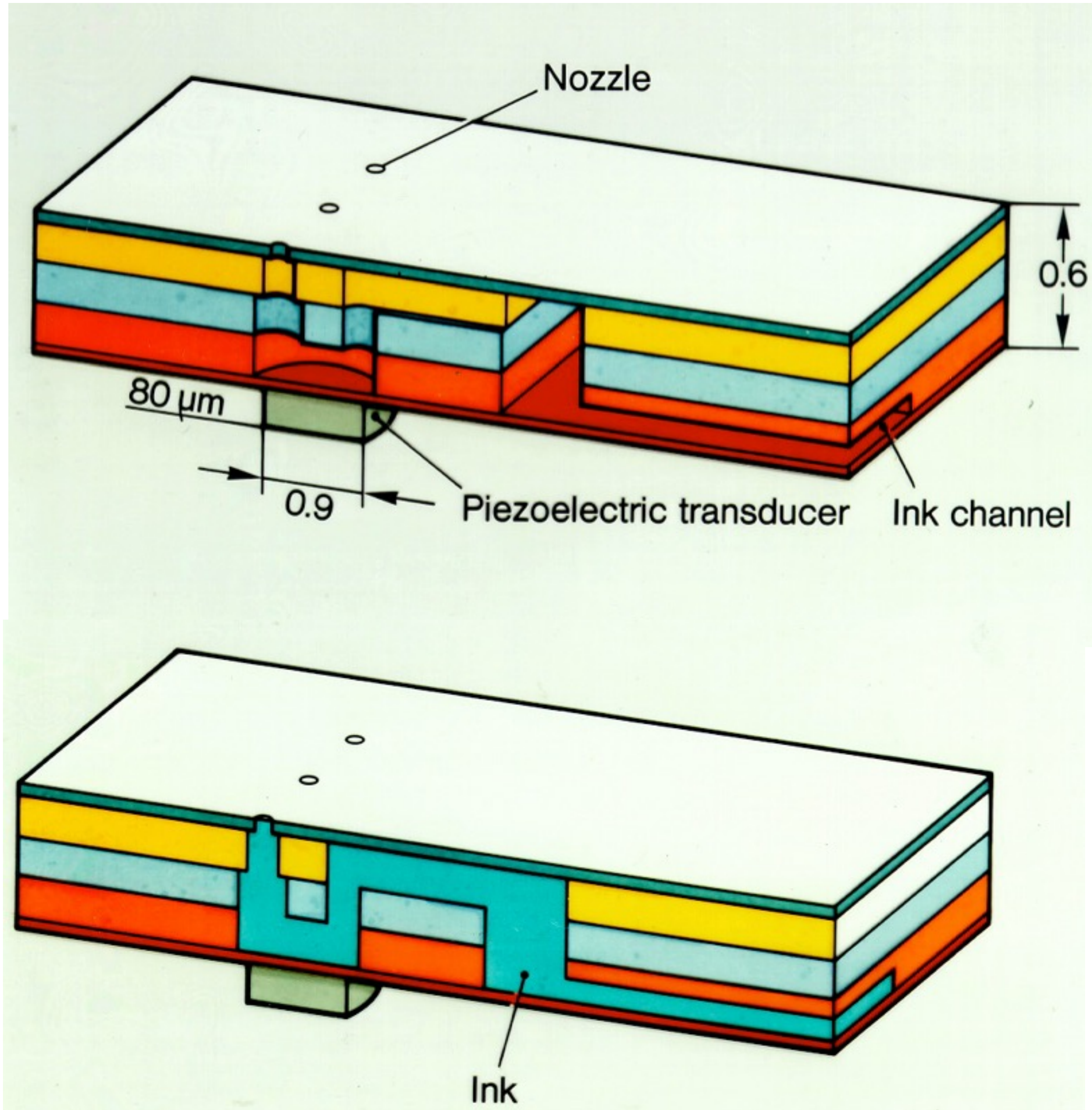


Schematic side view of a
tube scanner, and its lateral
movement in the x-direction under voltage

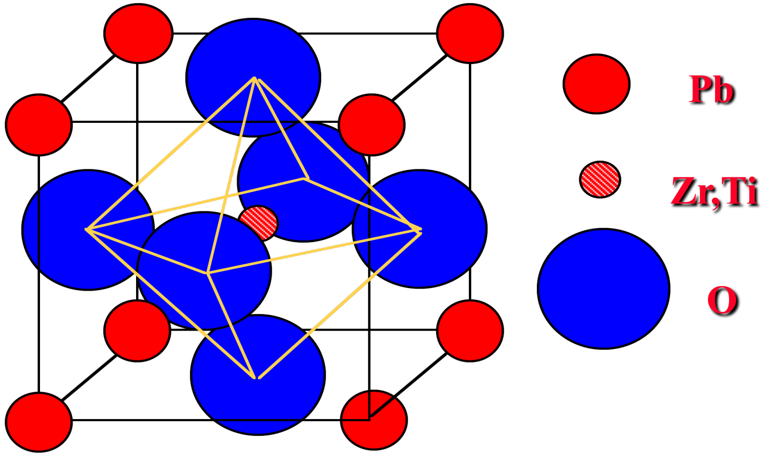


Instead of an outside electrode divided into four segments the outer electrode has eight segments.
The upper part of the piezo is bent in the opposite direction to prevent a displacement in the z-direction

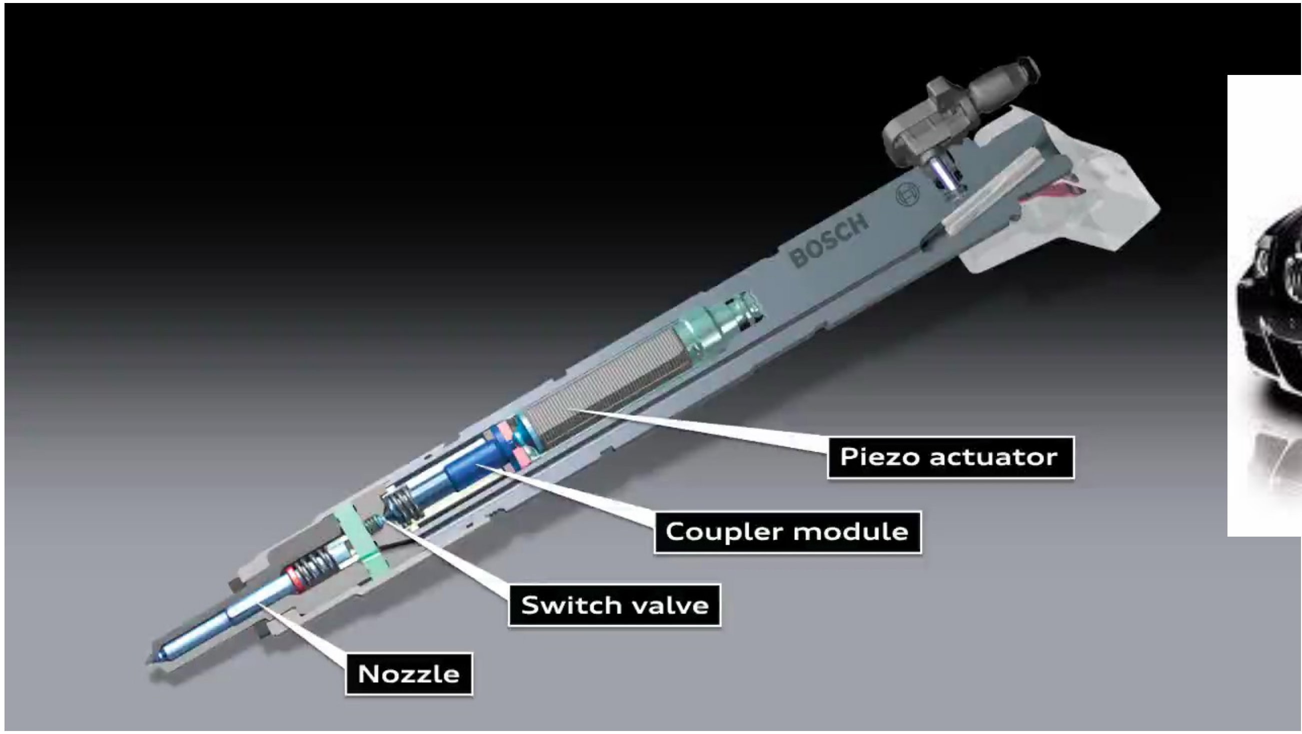
Ink-jet printer: PZT actuators are used to control the droplets with pL accuracy



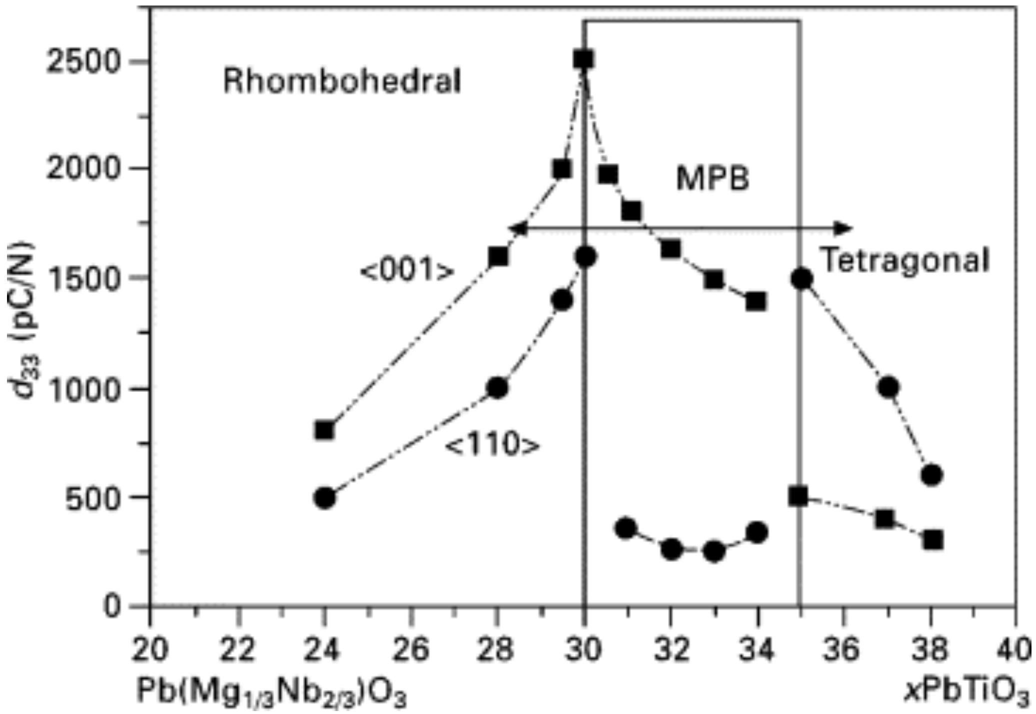
$Pb(Zr,Ti)O_3$



Fuel injection actuator



Giant piezoelectric response PMN-PT



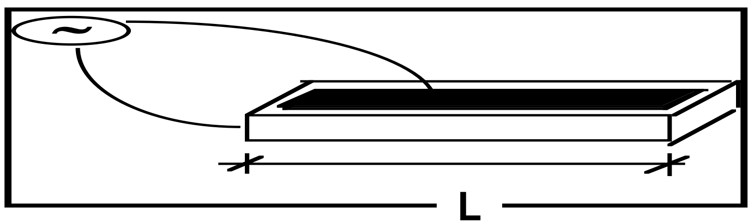
PMN: $Pb(Mg_{1/3}Nb_{2/3})O_3$; PT: $PbTiO_3$

The piezoelectric resonance

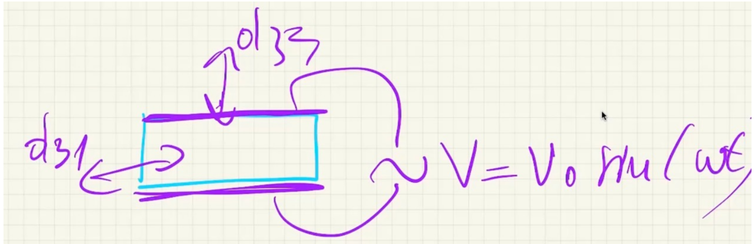
- If a piezoelectric samples is covered with electrodes and connected to an alternating voltage, the sample will vibrate

- If the frequency of oscillation of the field is equal to the frequency of the mechanical resonance of the sample, the elastic vibrations become very large.

- Thus, a mechanical resonance is induced in a piezoelectric sample by the converse piezoelectric effect.



Piezoelectric resonance

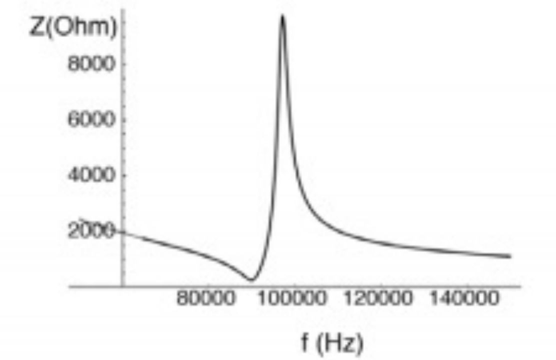


- The frequency of the longitudinal mode of vibration

$$f = \frac{1}{2L\sqrt{\rho/E}}$$

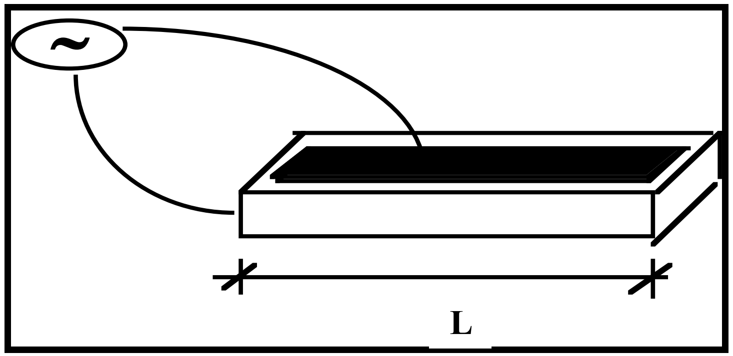
where E is Young modulus and ρ is the density of the material, L- dimension

- **d31 – f $\propto$ 1/L (lenth)**
- **d33 – f $\propto$ 1/t (thickness)**



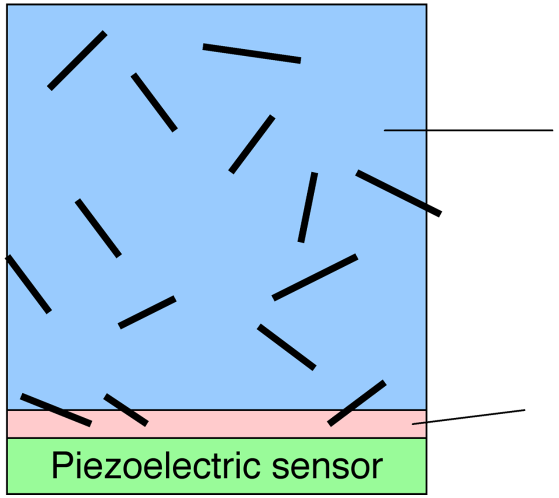
PZT coefficients:
ρ= 7.6 g/cm^3
S_{11}=1/E=1.5E-11 ms^2/kg

Due to excellent thermal stability of its mechanical properties, quartz single crystals are used for frequency control and related applications (filters, time measurements…)

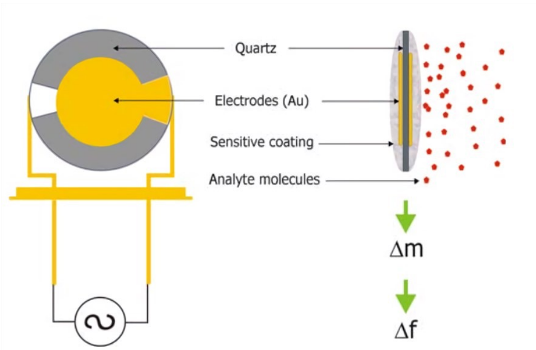


Application of resonance phenomenon- Microbalances

Mass increase on the sensor surface – a decrease of the resonance frequency, can be calibrated for sensing single atomic layers

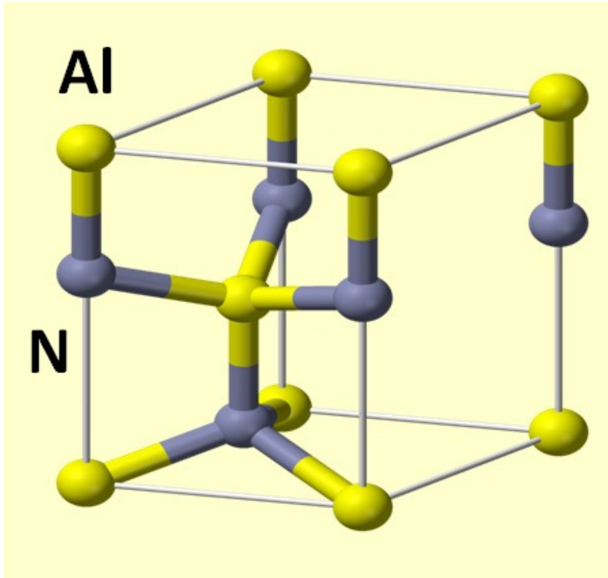


$$f = \frac{1}{2L\sqrt{\rho/E}} \qquad \Delta f \sim \Delta \rho$$



In biological sensors the piezoelectric material is covered by biologically selective layer, and then immersed into environment in which this layer reacts with certain biological species. The resonant frequency will change due to the weight of reacted species. Thus, one can determine not only the presence of certain biological specie but also its abundance in the examined medium.

Applications: AlN BAW resonators



6mm

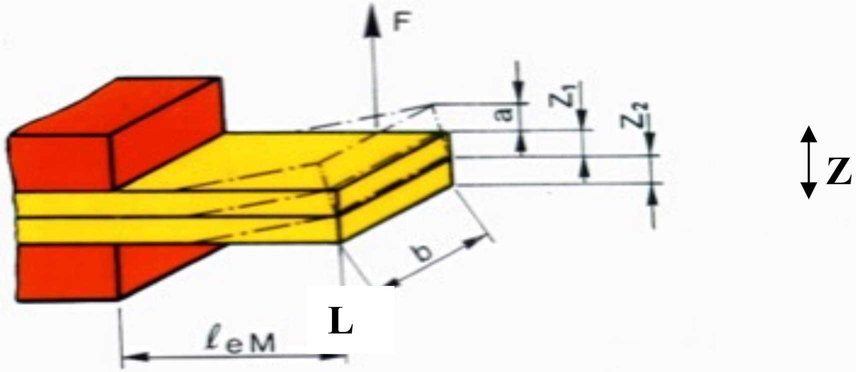
$$d_{11} = 5.1\,\mathrm{pC/N}$$

Film Bulk Acoustic wave Resonator (FBAR)

In 2018, Qorvo supplied the Xr version of the iPhone with a module that is pin-to-pin compatible with the Broadcom AFEM-8092, the QM76018. Like the AFEM-8092, the QM78016 is a Mid/High-Band Long Term Evolution (LTE) FEM. As usual, it features several dies: Power Amplifier, Silicon-on-Insulator (SOI) Switch, Filters and Power Management Integrated Circuit (PMIC). The Filters still use Qorvo's Copper Flip technology with a polymer cavity enabling thermal dissipation. For the first time, the Bulk Acoustic Wave (BAW) filters are using Scandium Doped Aluminum Nitride (AlScN) as a piezoelectric material and integrate passive capacitor devices on the die.

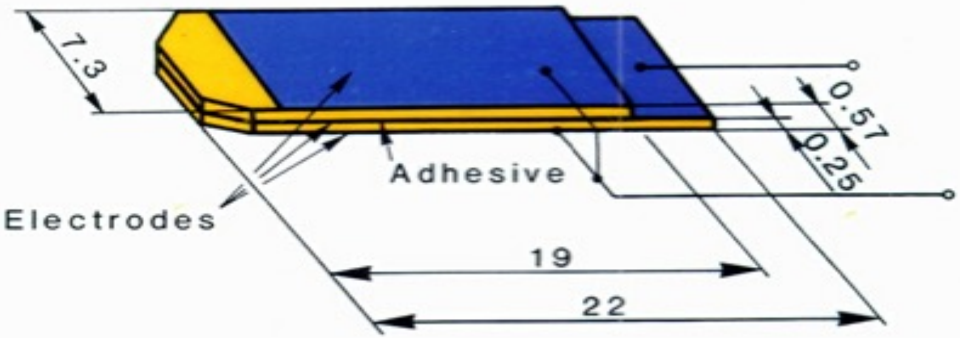
https://www.systemplus.fr/reverse-costing-reports/qorvo-qm76018-rffem-in-the-apple-iphone-xr/

Flexional actuators



$$a \propto \left(\frac{L}{Z}\right)^2$$

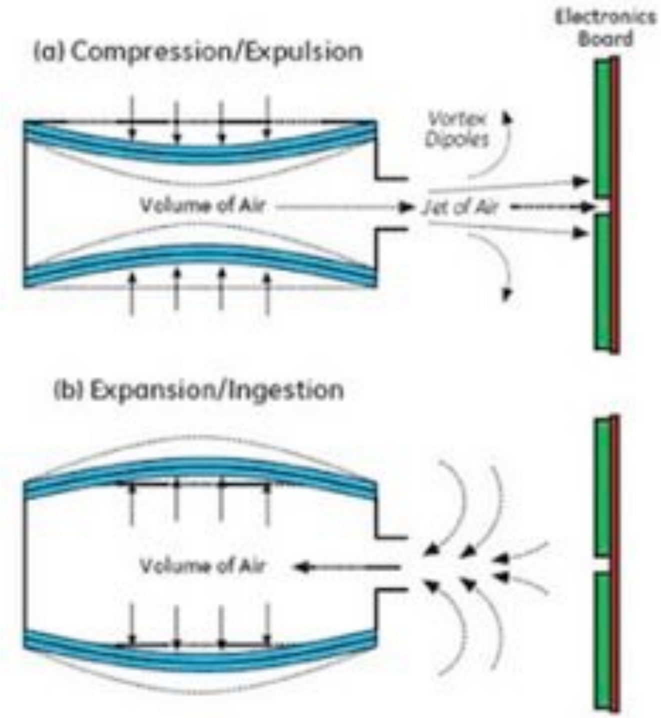
Example of a typical strip bending element

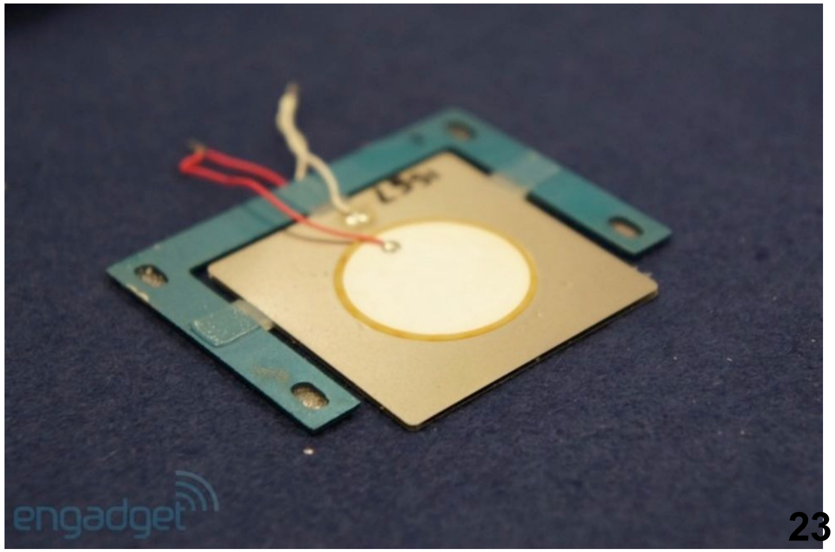


maximum stroke a=0.16mm
operating voltage U =150V

Cooler for electronic boards

https://www.youtube.com/watch?v=Hm5fXj-hUpk

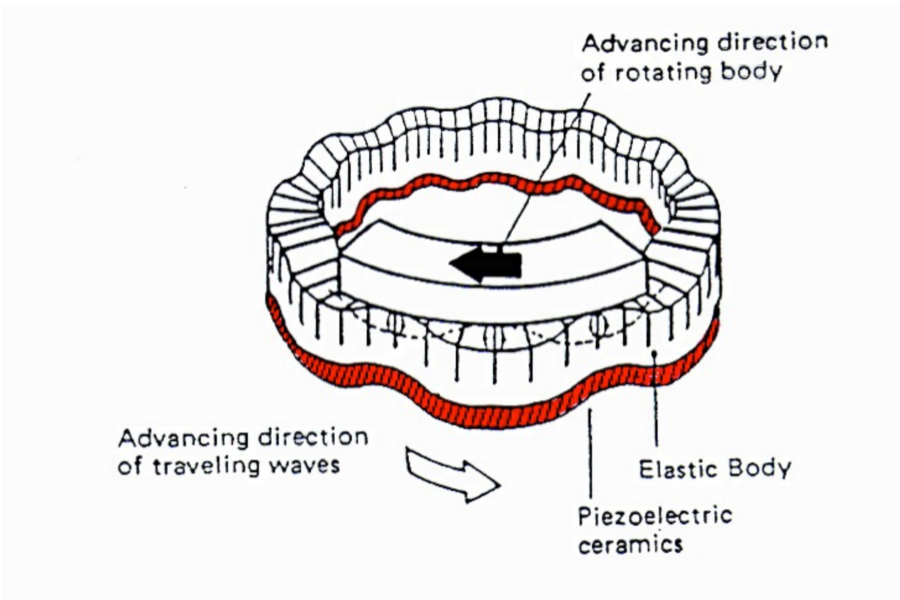




Piezoelectric motors

An alternating field is applied on the actuator creating alternating deformation

The most widely used are the motors which use acoustical surface ways to create a rotating movement in a body which is in contact with the surface of the transducer



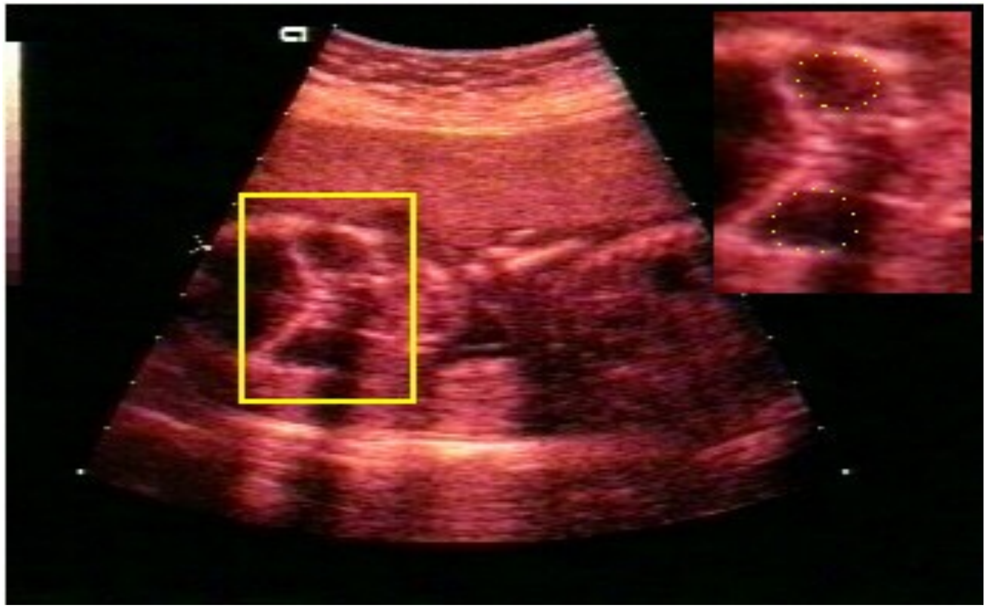
Autofocus of a Canon camera

Piezoelectric sensors

- The piezoelectrics are used to sense : pressure , force, vibration, acceleration

- Typical applications:
  - Pressure sensors in motors with internal combustion.
  - Measurements of vibrations in different aerospace applications
  - Control of fabrication (e.g., control of pressure in injection machines)
  - Biomedical applications (ultrasonic imaging)
  - Underwater detection (sonars)

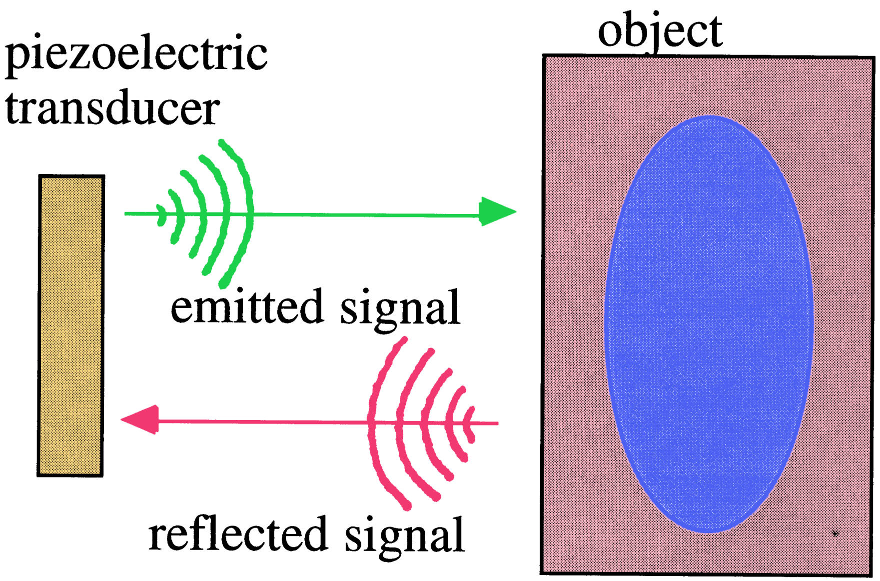
Ultrasonic medical imaging

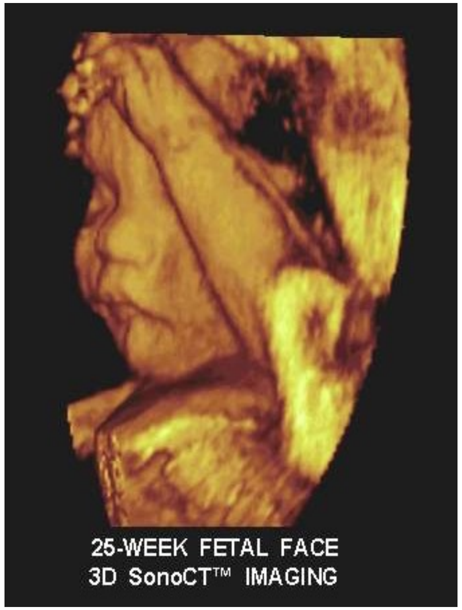


The piezoelectric materials are emitters (converse effect) and receptors (direct effect) of acoustic waves in ultrasonic imaging.

Ultrasonic medical imaging

Piezoelectric sensor&actuator is called piezoelectric transducer



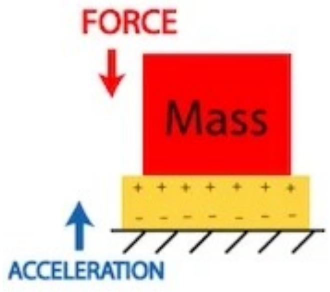


in medical imaging, a piezoelectric resonator (usually called transducer) is driven by a voltage pulse into a short but powerful vibration at its natural frequency (from few tens of kHz to several tens of MHz). The acoustic wave produced by the piezoelectric effect will travel to the object that needs to be examined, will reflect from it and come back to the same piezoelectric resonator. By the time reflected signal arrives to the transducer, the transducer is no longer oscillating from the original pulse. Reflected acoustic pulse produces in the resonator charge through the direct piezoelectric effect. This charge can be analysed to give information on the object.

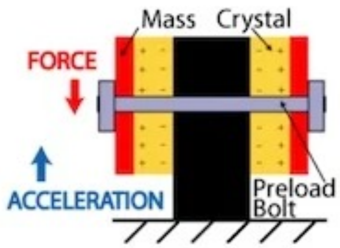
Accelerometers

Piezoelectric accelerometers detect force/acceleration is a wide range of environments

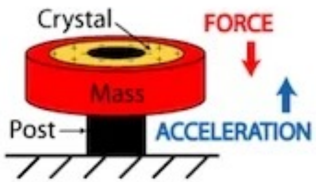
- Used in cars (airbags),
- phones,
- industrial equipment to detect vibration or movement
- wearables



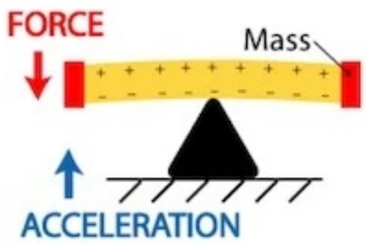
(a) Compression Mode



(b) Planar Shear Mode



(c) Annular Shear Mode



(d) Flexural Mode

Summary: piezoelectric materials

- PZT ferroelectric ceramics are widely used and piezoelectric components in electromechnaical sensors, actuators, and transducers
- Piezoelectrics with low piezoelectric coefficients like SiO_2, AlN are used for frequency generation/control, filters in microwave applications etc.
- PMN-PT piezoelectrics (**lead magnesium niobate–lead titanate**, or **$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$**) with d_{33}>2000 pC/N — way higher than PZT, but they are **expensive, and less thermally stable than PZT**
- High performance Pb-free piezoelectrics is a challenge for industry and research community

Summary: applications

1. Sensors & Detectors:
-Accelerometers, pressure sensors, aviation, and robotics.
-Ultrasound transducers: For medical imaging, industrial non-destructive testing, and sonar systems.
-Biosensors: Detect biomolecules by sensing mechanical or mass changes
- Underwater microphones in sonar systems and marine biology

2. Actuators
-Micro-positioning systems: Used in precision devices like microscopes and semiconductor manufacturing tools.
- Inkjet printers: Piezoelectric actuators control the ink droplets with high precision.
-Ultrasonic motors: Used in camera lens focusing systems, robotics
- MEMS (Microelectromechanical Systems): Piezoelectric materials act as tiny actuators or switches in micro devices.

3. Vibration energy harvesters: Convert vibrations (from machines, roads, or shoes!) into usable electrical power

Summary: applications 2

4. Medical Devices
Ultrasound imaging (sonography): Piezoelectric crystals generate and receive ultrasound waves.
- Lithotripsy devices: Break up kidney stones using focused ultrasonic waves.
- Dental scalers: Ultrasonic vibration to remove tartar from teeth.

5. Scientific & Industrial Equipment
- Atomic force microscopes (AFM): Piezo actuators control precise positioning.
- micromanipulators
- **Piezo valves and pumps: Used in chemical analysis and microfluidics.**

6. Fuel injectors: In modern diesel engines, piezo actuators control fuel spray very precisely.

7. Aerospace and Defense
Structural health monitoring: Embedded piezo sensors detect cracks or damage in aircraft and spacecraft.