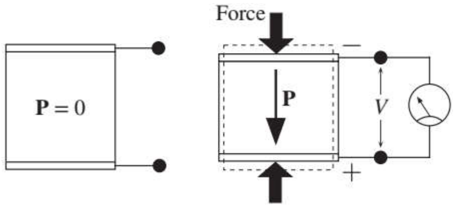
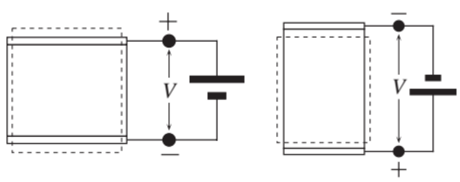
PIEZOELECTRICITY

Piezoelectricity

- Mechanical stress creates polarization and hence potential across the surfaces.
- **Examples:** Quartz (crystalline SiO_2), BaTiO3



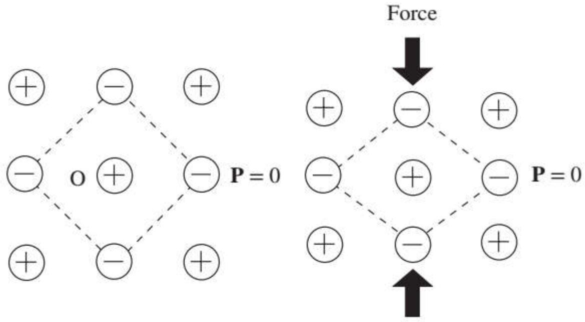
- Electric field creates mechanical strain/deformation: A complementary effect.
- The direction of deformation depends on the direction of applied field.



2

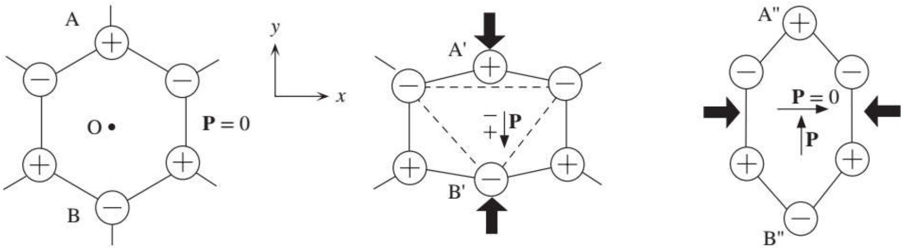
Why Piezoelectricity

- Consider a NaCl-type cubic unit cell that has center of symmetry.
- When unstressed, the center of mass of the negative charges at the corners of the unit cell coincides with the positive charge at the center: **P** = 0.
- Under stress, the unit cell becomes strained, but the center of mass of the negative charges still coincides with the positive charge: **P** = 0.



Why Piezoelectricity

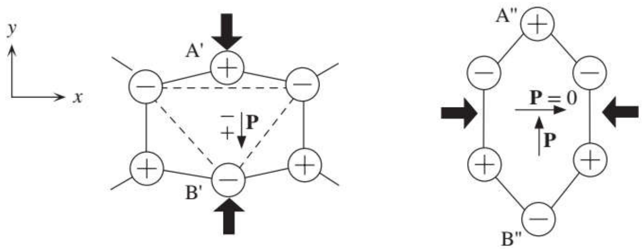
- Piezoelectric crystals have no center of symmetry.
- When unstressed, the center of mass of the negative charges coincides with the center of mass of the positive charges, both at O: **P** = 0.
- When stressed, the positive charge at A and the negative charge at B both become displaced inwards to A′ and B′, respectively: **P** ≠ 0.



Stress vs. Induced Polarization

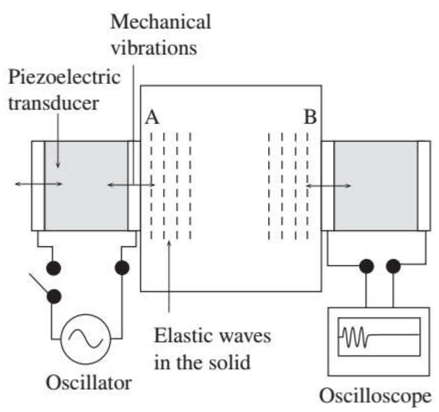
- Generally, an applied stress in one direction can give rise to induced polarization in other crystal directions.
- Suppose that T_j is the applied mechanical stress along j direction and P_i is the induced polarization along some i direction; then the two are linearly related by

  $P_i = d_{ij}T_j$; d_{ij}: **piezoelectric coefficients.**
- The converse piezoelectric effect is that between an induced strain S_j along j and an applied electric field E_i along i, $S_j = d_{ij}E_i$



5

Piezoelectric Transducers



6

Electromechanical Coupling Factor

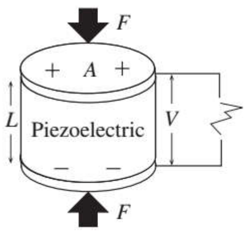
$$k^2 = \frac{\text{Electrical energy converted to mechanical energy}}{\text{Input of electrical energy}}$$

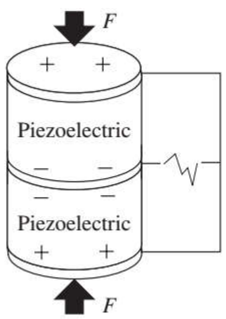
$$k^2 = \frac{\text{Mechanical energy converted to electrical energy}}{\text{Input of mechanical energy}}$$

Crystal	d (m V^{-1})	k
Quartz (crystal SiO_2)	2.3×10^{-12}	0.1
Rochelle salt ($NaKC_4H_4O_6 \cdot 4H_2O$)	350×10^{-12}	0.78
Barium titanate ($BaTiO_3$)	190×10^{-12}	0.49
PZT, lead zirconate titanate	480×10^{-12}	0.72

Piezoelectric Spark Generator

- The piezoelectric spark generator, as used in various applications such as lighters and car ignitions, operates by stressing a piezoelectric crystal to generate a high voltage which is discharged through a spark gap in air.
- The energy can increase by using two piezoelectric crystals back to back.



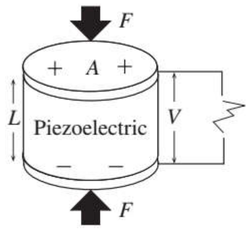


Force Needed for Spark

- Suppose that the piezoelectric coefficient $d = 250 \times 10^{-12}$ m V^{-1} and $\varepsilon_r = 1000$. The piezoelectric cylinder has a length of 10 mm and a diameter of 3 mm. The spark gap is in air and has a breakdown voltage of about 3.5 kV. What is the force required to spark the gap?

$$P = dT = d\frac{F}{A}$$

$$V = \frac{Q}{C} = \frac{AP}{\left(\frac{\varepsilon_0 \varepsilon_r A}{L}\right)} = \frac{LP}{\varepsilon_0 \varepsilon_r} = \frac{L\left(d\frac{F}{A}\right)}{\varepsilon_0 \varepsilon_r} = \frac{dLF}{\varepsilon_0 \varepsilon_r A}$$

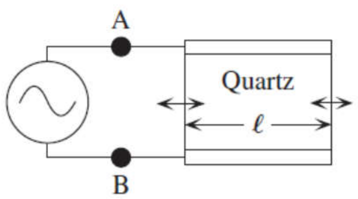


$$F = \frac{\varepsilon_0 \varepsilon_r AV}{dL} = 87.6 \text{ N}$$

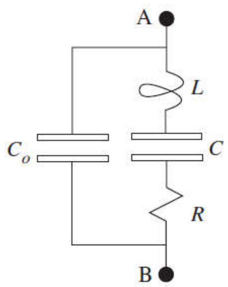
- This force can be applied by squeezing by hand an appropriate lever arrangement; it is the weight of 9 kg.

9

Quartz Oscillators

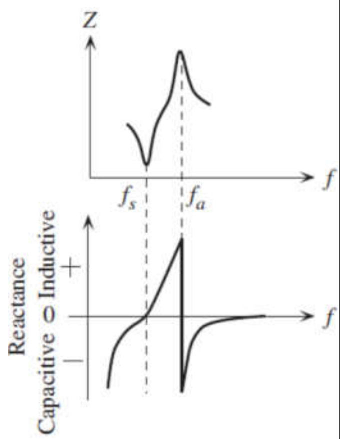


$$n\left(\frac{1}{2}\lambda\right) = \ell$$



$$f_s = \frac{1}{2\pi\sqrt{LC}}$$

$$f_a = \frac{1}{2\pi\sqrt{LC'}}$$



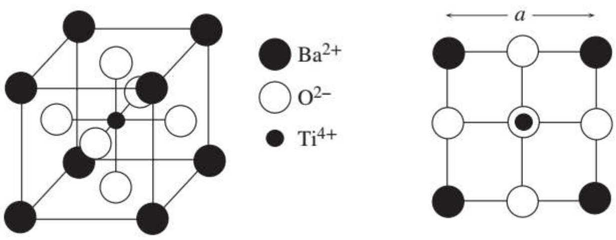
10

FERROELECTRICITY

Ferroelectricity

- Certain crystals are permanently polarized even in the absence of an applied field. The crystal already possesses a finite polarization vector due to the separation of positive and negative charges in the crystal. These crystals are called **ferroelectric.**

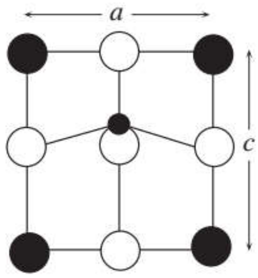
- BaTiO3 cubic crystal above 130 °C.



- **P** = 0 above 130 °C → Not ferroelectric.

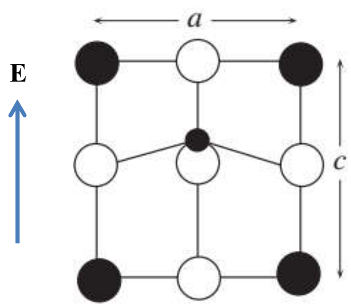
Ferroelectricity

- Below 130 °C, the structure of barium titanate is tetragonal.
- **P** ≠ 0 → Ferroelectric.
- **Curie temperature (T_c):** Above which ferroelectricity is lost.
- The development of the permanent dipole moment below T_c involves long-range interactions between the ions outside the simple unit cell. The energy of the crystal is lower when the Ti^{4+} ion in each unit cell is slightly displaced along the *c* direction, which generates a dipole moment in each unit cell.



Poling

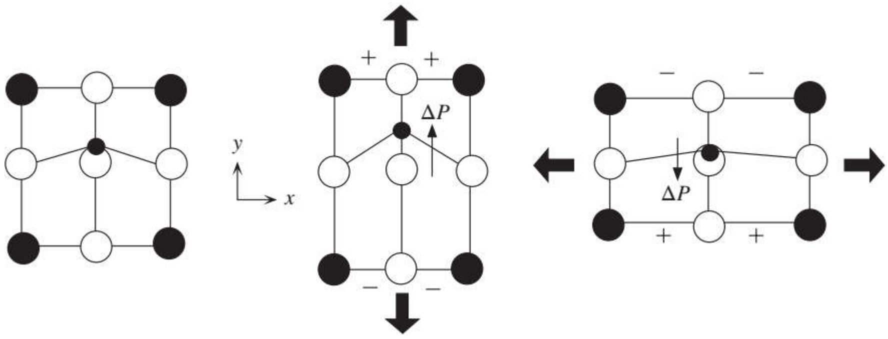
- If we apply a temporary field E and let the crystal cool to below 130 °C, we can induce the spontaneous polarization **P** to develop along the field direction.
- In other words, we would define the *c* axis by imposing a temporary external field.



- At < T_c: $P = \varepsilon_0(\varepsilon_r - 1)E$ cannot be used → Already has permanent polarization
- Rather, $\Delta P = \varepsilon_0(\varepsilon_r - 1)\Delta E$ should be used.

Ferroelectricity → Piezoelectricity

- All ferroelectric crystals are also piezoelectric, but the reverse is not true: not all piezoelectric crystals are ferroelectric.



15