Piezoelectric effect

What is piezoelectricity?

Piezoelectricity is an effect exhibited by some crystalline materials (for example quartz) in which **mechanical stress** induces **electrical polarization**. Discovered in the late 19th century, it now has numerous applications - in high voltage sources (e.g. as the ignition source in gas lighters) or pressure sensors; the inverse piezoelectric effect (electric polarization causing deformation) is used in precise actuators and in frequency standards.

The mechanism by which the polarization arises is shown in a simplified way in Figure 1.

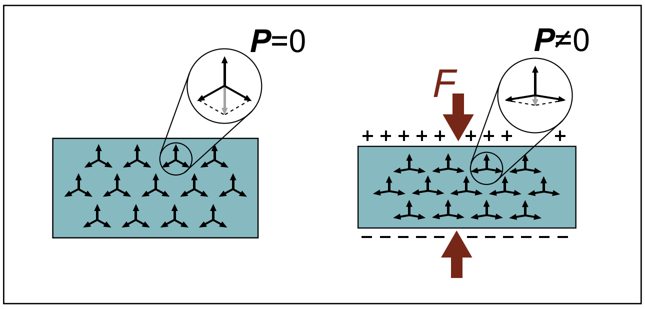

Figure 1 (adapted from [1])

The stress-induced deformation of the crystal results in a displacement of the atoms inside the unit cell. Consequently, their corresponding dipole moments change in direction and magnitude and add up to a generally non-zero total dipole moment. This argument also implies that crystals with **inversion symmetry** (which is preserved even if the crystal is under strain) do not exhibit piezoelectric behaviour. However, the converse is not true and the absence of inversion symmetry is not a sufficient criterion for piezoelectricity.

Materials which exhibit spontaneous polarization even in the absence of strain - so-called **ferroelectrics** (for example **barium titanate**) - are always piezoelectric. The magnitude of their polarization changes with applied force.

Theory

The polarization vector $\boldsymbol{P}$ of a piezoelectric material is related to the symmetric stress tensor $\boldsymbol{T}$ (with six independent components T_j, j = 1,...,6) by the linear relation

$$P_i = \sum_{j=1}^{6} d_{ij}\, T_j\,, \qquad (1)$$

where d_{ij} are so-called piezo modules of the material. The form of the matrix formed by the piezo modules depends on the symmetry group of the crystal. For example, for the symmetry group D3d of quartz, there are only two independent piezo modules:

$$(d_{ij}) = \begin{pmatrix} d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & -2d_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Equation (1) also implies a relation between the directly measurable normal force F_j applied to a face of the crystal perpendicular to the axis j and the total charge Q_i accumulated on the face perpendicular to the axis i:

$$Q_i = d_{ij}\, F_j$$

Measurement

The presence of the induced charge can be detected by a voltmeter, as indicated in Figure 2a. Alternatively, in the case of an oscillating deformation, the charging current flowing between the two electrodes can be rectified and measured by a sensitive ammeter (Figure 2b).

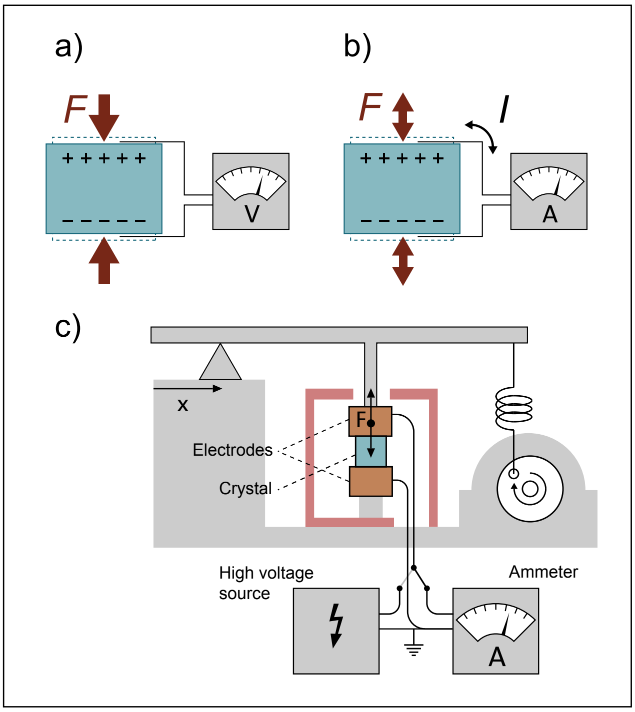

Figure 2

In the VP experiment, students investigate the piezoelectric effect in quartz and barium titanate using a setup shown in Figure 2c. An oscillatory force generated by a rotating eccentric is applied to the crystal through a lever with an adjustable fulcrum which can be used to change the amplitude of the force. The AC current induced by the periodic charging of the crystal faces is then amplified and measured. The crystal is placed in an oven, allowing measurements at different temperatures and can be connected to a high voltage source to polarize the ferroelectric barium titanate sample. Students should verify the linear relation between the polarization and the applied force, study the temperature dependence of the piezo module and observe the difference between the piezoelectric properties of a polarized and an unpolarized barium titanate crystal.

[1] C. Kittel, Introduction to Solid State Physics, John Wiley & Sons, Inc. 1996

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