PYL 102

Monday, Oct. 14, 2024

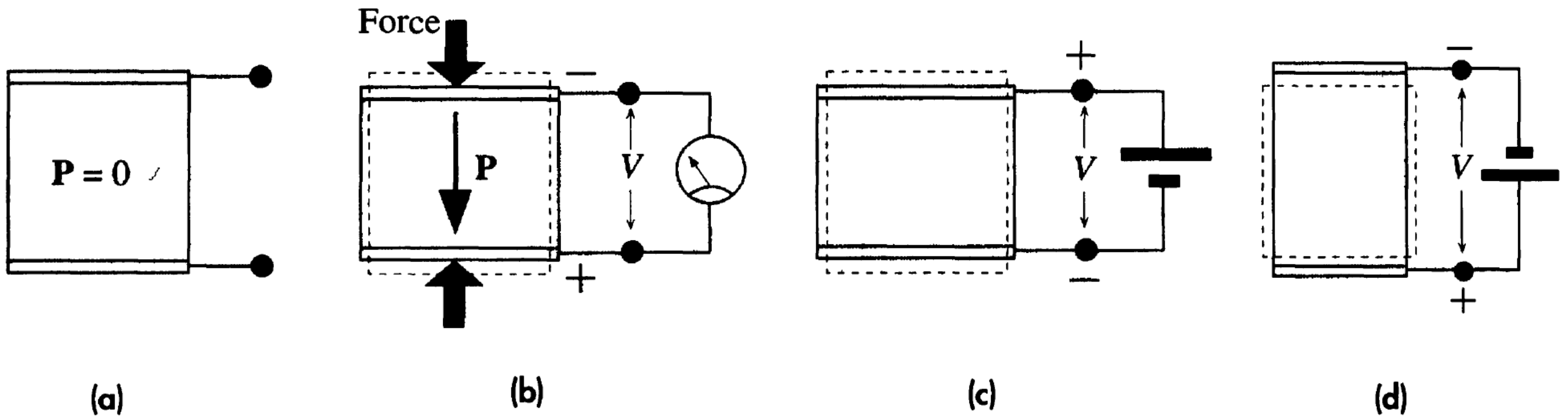
Piezoelectricity, Ferroelectricity and Pyroelectricity

The piezoelectric effect

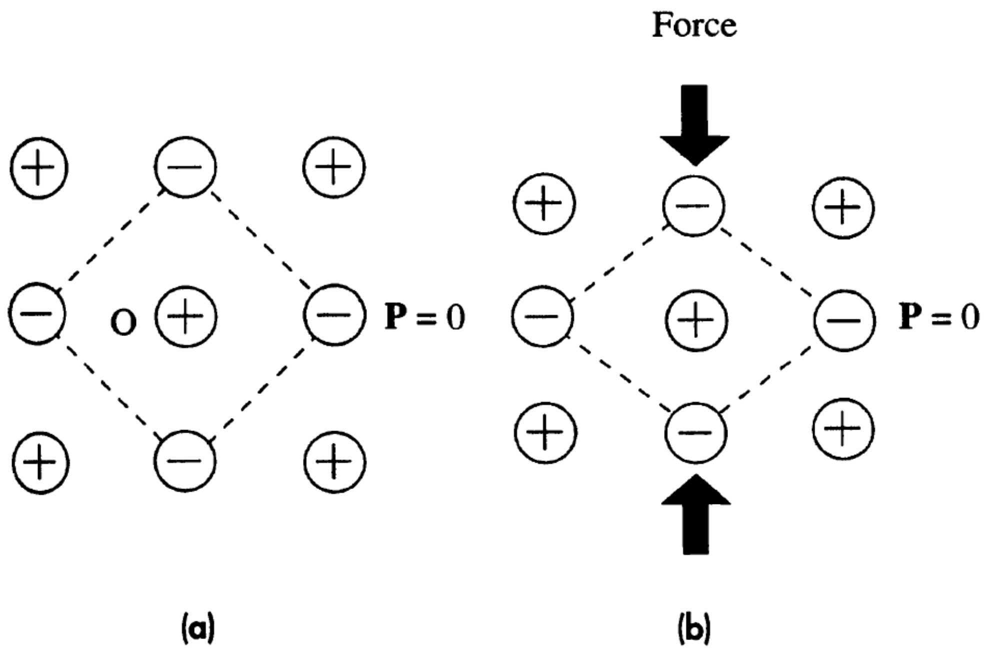
Certain crystals, for example, quartz and BaTiOs, become polarized when they are mechanically stressed. Charges appear on the surfaces of the crystal. The appearance of surface charges leads to a voltage difference between the two surfaces of the crystal. The same crystals also exhibit mechanical strain or distortion when they experience an electric field.

The direction of mechanical deformation (e.g., extension or compression) depends on the direction of the applied field, or the polarity of the applied voltage.

Only certain crystals can exhibit piezoelectricity because the phenomenon requires a special crystal structure-that which has no center of symmetry.



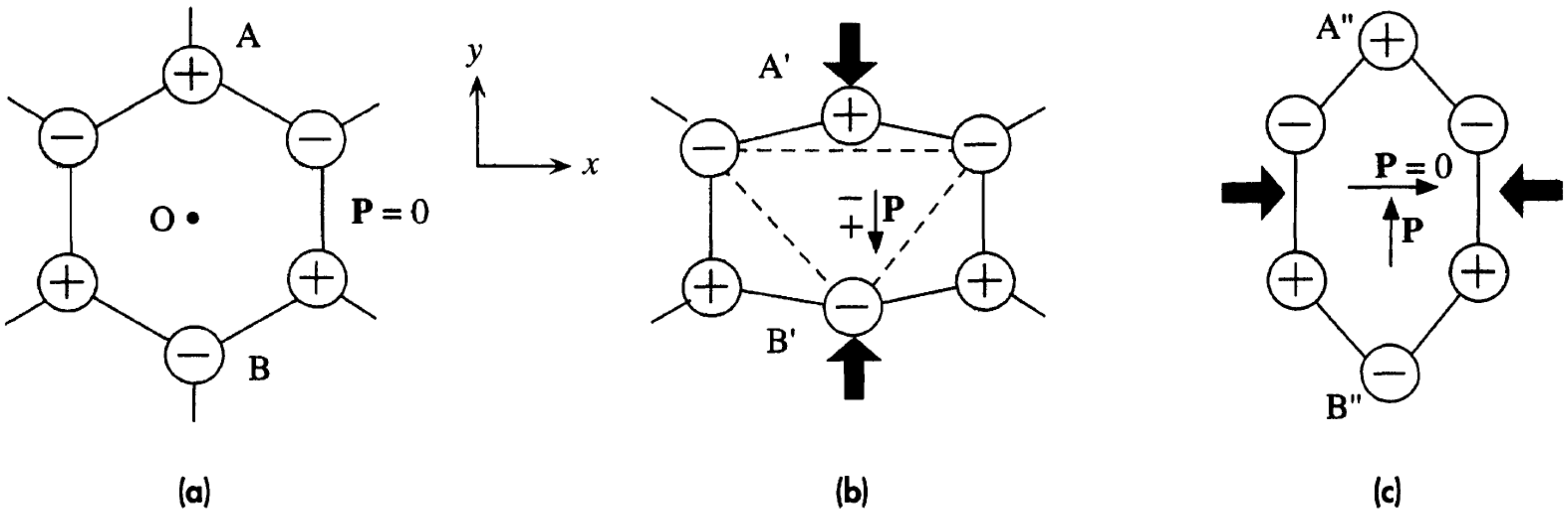
(a) A piezoelectric crystal with no applied stress or field.
(b) The crystal is strained by an applied force that induces polarization in the crystal and generates surface charges.
(c) An applied field causes the crystal to become strained. In this case the field compresses the crystal.
(d) The strain changes direction with the applied field and now the crystal is extended.



NaCl-type cubic unit cell has a center of symmetry.
(a) In the absence of an applied force, the centers of mass for positive and negative ions coincide.
(b) This situation does not change when the crystal is strained by an applied force.

The centers of mass of negative and positive charges in the unit cell remain coincident when the crystal is strained.

Piezoelectric crystals have no center of symmetry.



A hexagonal unit cell has no center of symmetry.

(a) In the absence of an applied force, the centers of mass for positive and negative ions coincide.

(b) Under an applied force in the / direction, the centers of mass for positive and negative ions are shifted, which results in a net dipole moment, P, along y.

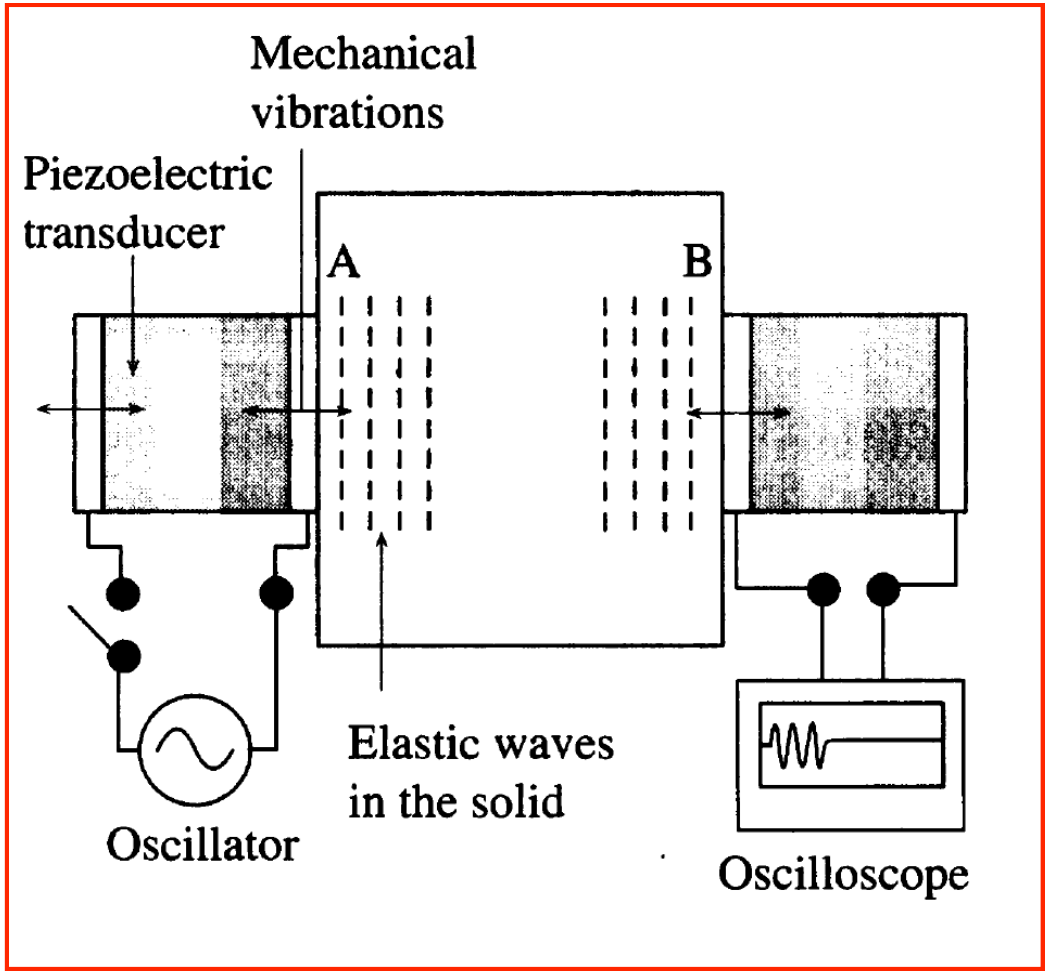
(c) When the force is along a different direction, along x, there may not be a resulting net dipole moment in that direction though there may be a net P along a different direction (y).

The direction of the induced polarization depends on the direction of the applied stress. Generally, an applied stress in one direction can give rise to induced polarization in other crystal directions. Suppose that Tj is the applied mechanical stress along some j direction and Pi is the induced polarization along some i direction; then the two are linearly related by

$$P_i = d_{ij} T_j$$

where dij are called the piezoelectric coefficients. Reversing the stress reverses the polarization. Although we did not specifically consider shear stresses, they, as well as tensile stresses, can also induce a net polarization, which means that T in above equation can also represent shear stresses.

piezoelectric crystals are essentially electromechanical transducers because they convert an electrical signal, an electric field, to a mechanical signal, strain, and vice versa. Piezoelectric transducers are widely used to generate ultrasonic waves in solids and also to detect such mechanical waves. The transducer is simply a piezoelectric crystal, for example, quartz, that is appropriately cut and electroded to generate the desired types of mechanical vibrations (e.g., longitudinal or transverse vibrations). The transducer on the left is attached to the surface A of the solid under examination. It is excited from an ac source, which means that it mechanically vibrates. These vibrations are coupled to the solid by a proper coupling medium (typically grease) and generate mechanical waves or elastic waves that propagate away from A. They are called ultrasonic waves as their frequencies are typically above the audible range. When the waves reach the other end, B, they mechanically vibrate the transducer attached to B, which converts the vibrations to an electrical signal that can readily be displayed on an oscilloscope.



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 as schematically shown in Figure below. Consider a piezoelectric sample in the form of a cylinder as in Figure 7.42a. Suppose that the piezoelectric coefficient d = 250 x 10^{12} m V^{-1} and εr = 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? Is this a realistic force?

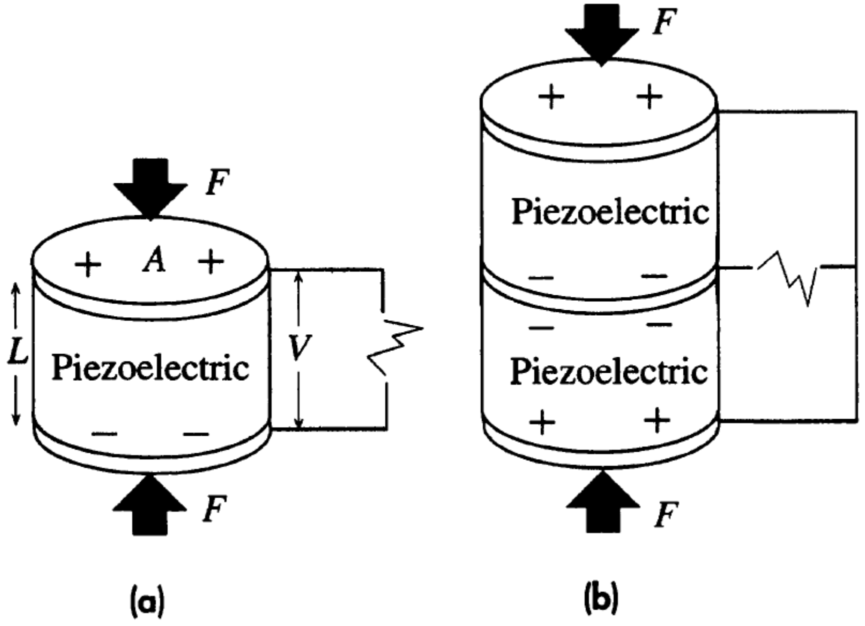


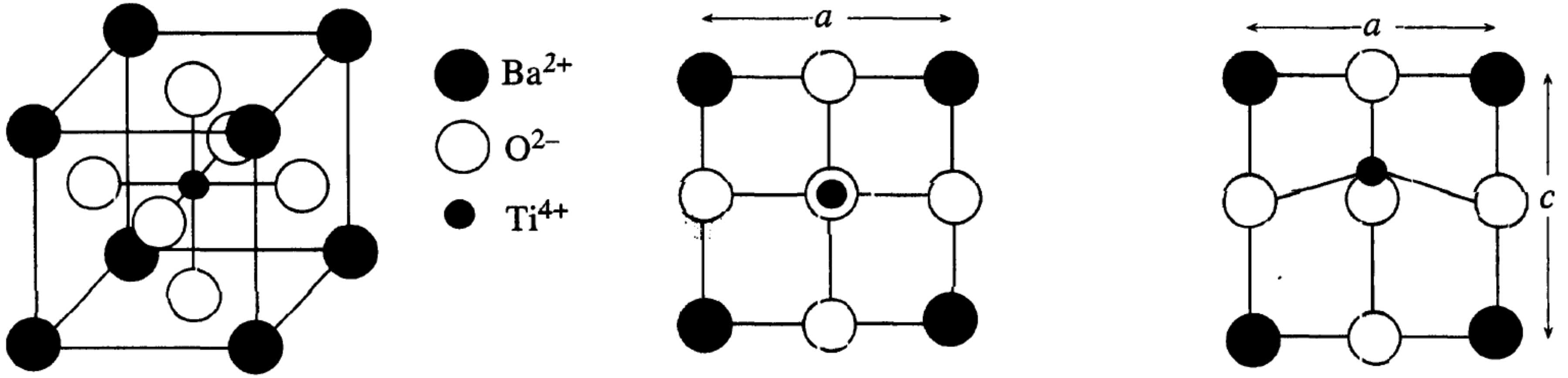
Figure 7.42 The piezoelectric spark generator.

Ferroelectric Crystals

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.

The centers of mass of the negative charges (O^{2-}) and the positive charges, Ba^{2+} and Ti^{4+}, coincide at the Ti^{4+} ion above 130 ^{o}C. Therefore, no net polarization and P = 0.

However, below 130 ^{0}C, the structure of barium titanate is tetragonal, in which the Ti^{4+} atom is not located at the center of mass of the negative charges. The crystal is therefore polarized by the separation of the centers of mass of the negative and positive charges. The crystal possesses a finite polarization vector P and is ferroelectric.



(a) $BaTiO_3$ cubic crystal structure above 130 °C

(b) $BaTiO_3$ cubic structure above 130 °C

(c) $BaTiO_3$ tetragonal structure below 130 °C

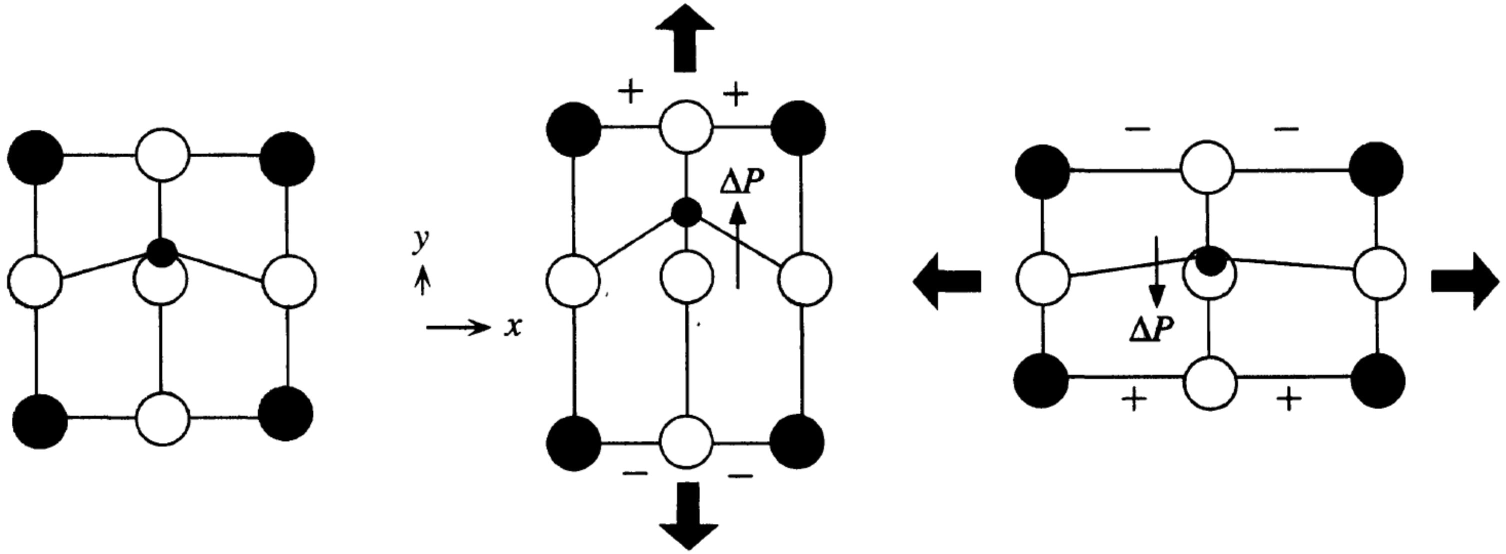
Figure 7.44 $BaTiO_3$ has different crystal structures above and below 130 °C that lead to different dielectric properties.

The critical temperature above which ferroelectric property is lost, in this case 130 ^{0}C, is called the Curie temperature. Below the Curie temperature, the whole crystal becomes spontaneously polarized. The onset of spontaneous polarization is accompanied by the distortion of the crystal structure.

The distortion of the crystal that takes place when spontaneous polarization occurs just below Tc is very small relative to the dimensions of the unit cell.

Above 130 ^{0}C there is no permanent polarization in the crystal. If we apply a temporary electric field E and let the crystal cool to below 130 ^{0}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. This process is called poling. The c axis is the polar axis along which P develops (ferroelectric axis).

An applied field along the a axis can displace the Ti^{4+} ion more easily than that along the c axis, and experiments show that $\varepsilon_r = 4100$ along a is much greater than $\varepsilon_r = 160$ along c. Because of their large dielectric constants, ferroelectric ceramics are used as high-K dielectrics in capacitors.



(a) $BaTiO_3$ tetragonal structure below 130 °C

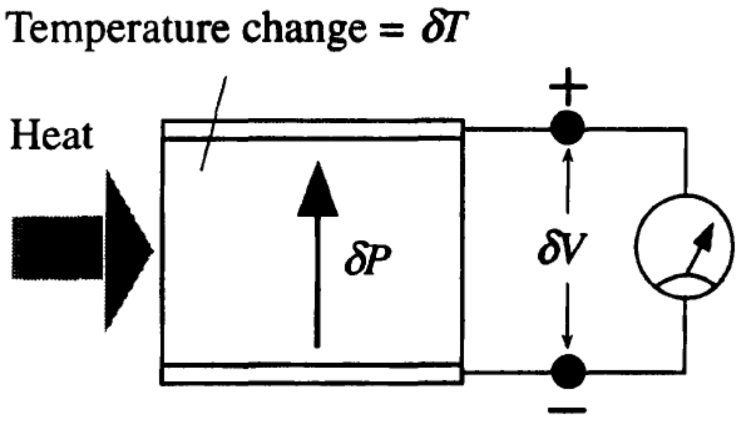
(b) $BaTiO_3$ crystal under stress along *y*

(c) $BaTiO_3$ crystal under stress along *x*

Figure 7.45 Piezoelectric properties of $BaTiO_3$ below its Curie temperature.

All ferroelectric crystals are also piezoelectric, but the reverse is not true: not all piezoelectric crystals are ferroelectric. When a stress along y is applied to the BaTiO3 crystal, the crystal is stretched along y, as a result of which the Ti^{4+} atom becomes displaced. There is, however, no shift in the center of mass of the negative charges, which means that there is a change in the polarization vector along y. Thus, the applied stress induces a change in the polarization, which is a piezoelectric effect. If the stress is along x, then the change in the polarization is along y. In both cases, ΔP is proportional to the stress, which is a characteristic of the piezoelectric effect.

Figure 7.46 The heat absorbed by the crystal increases the temperature by δT, which induces a change δP in the polarization.
This is the pyroelectric effect. The change δP gives rise to a change δV in the voltage that can be measured.



The barium titanate crystal is also pyroelectric because when the temperature increases, the crystal expands and the relative distances of ions change. The Ti^{4+} ion becomes shifted, which results in a change in the polarization. Thus, a temperature change δT induces a change δP in the polarization of the crystal. The magnitude of this effect is quantized by the pyroelectric coefficient p, which is defined by $p = dP/dT$

Very small temperature changes, even in thousandths of degrees, in the material can develop voltages that can be readily measured. For example, for a PZT-type pyroelectric ceramic (thickness 0.1 mm)

For $\delta T = 10^{-3}\,K$, $p = 380 \times 10^{-6}$ $\quad \delta P = 3.8 \times 10^{-7}\ Cm^{-2}$

$\varepsilon_r \sim 290$ $\quad \boxed{\delta P = \varepsilon_0(\varepsilon_r - 1)\delta E} \Rightarrow \delta E = 148\ V/m \Rightarrow \delta V = 15\,mV$

Pyroelectric crystals are widely used as infrared detectors. Any infrared radiation that can raise the temperature of the crystal even by a thousandth of a degree can be detected. For example, many intruder alarms use pyroelectric detectors because as the human or animal intruder passes by the view of detector, the infrared radiation from the warm body raises the temperature of the pyroelectric detector, which generates a voltage that actuates an alarm.

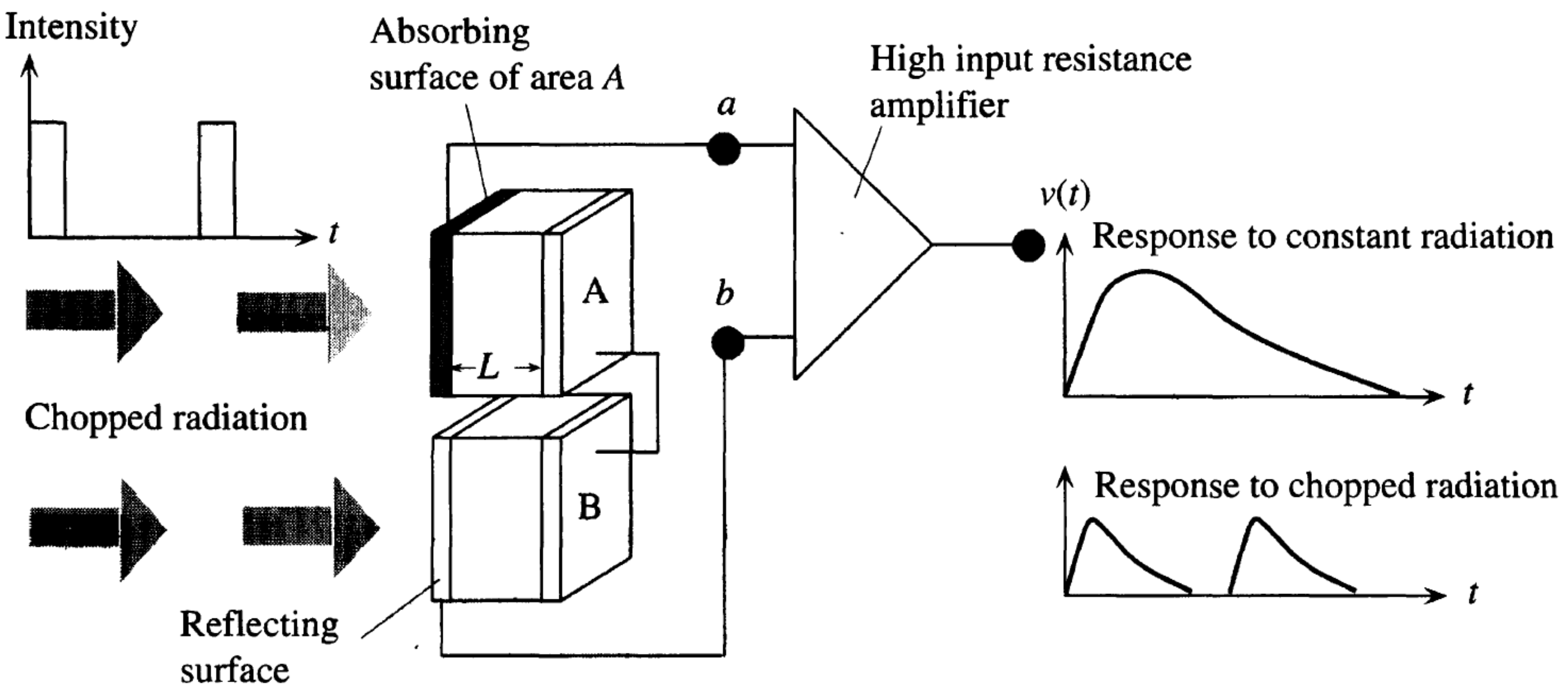


Figure 7.47 The pyroelectric detector.