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All Lab Experiments

B.Sc. => Solid-State Physics

Chapter - 5

Ferroelectric Properties of Materials

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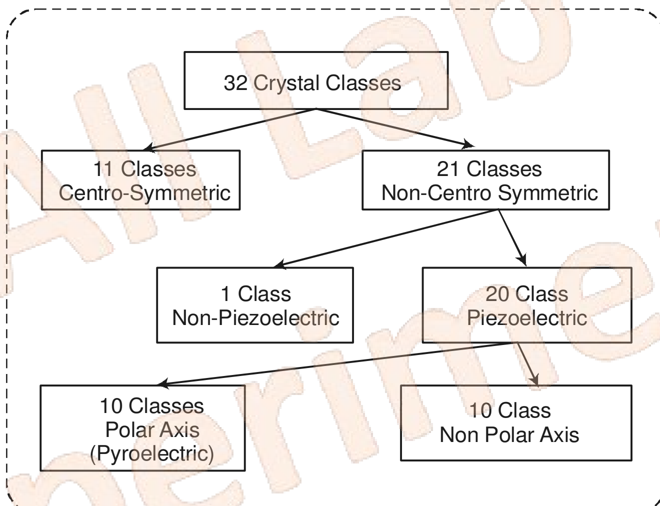
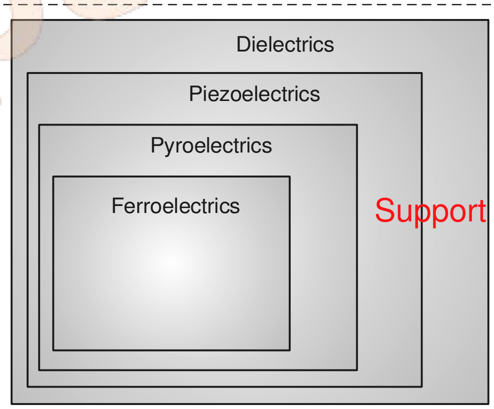
Ferroelectric Properties of Materials

Syllabus: Structure phase transition, Classification of crystal, Piezoelectric effect, Pyroelectric effect, Ferroelectric effect, Electrostrictive effect, Curie-Weiss Law, Ferroelectric domains, PE hysteresis loop.

Q.1. Draw a diagram of classification of crystals?

Ans.





Crystal can be divided into groups. Of the possible crystal classes (i.e. point groups), 11 are Centro symmetric and thus cannot exhibit polar properties. The remaining 21 lacks a center of symmetry and thus can posses one or more polar axes,. Among these, 20 classes are piezoelectric, the on exception being cubic class (Figure). Piezoelectric crystals have the property that the application of mechanical stress induces polarization, and conversely, the application of an electric field produces machanical deformation. Of the 20 piezoelectric classes, 10 have a unique polar axis and thus are spontaneously polarized, i.e. polarized in the absence of an electric field. Crystals belonging to these 10 classes are called pyroelectric. The intrinsic polarization of pyroelectric crystals in often difficult to detect experimentally because of the neutralization of the charges on the crystal surfaces by free charges from the atmosphere and by conduction within the crystal. However, because the polarization is a function of temperature, it is often possible to observe the spontaneous moment in these crystal by changing the temperature, hence the name pyroelectric. Ferroelectric crystal belong to the pyroelectric family, but they also exhibit the additional property that the direction of the spontaneous polarization can be reversed by the application of an electric field.

Thus, we have the following simple definition for a ferroelectric crystal: "A ferroelectric crystals is a that possesses reversible spontaneous polarization as exhibited by a dielectric hysteresis loop". A more detailed discussion on ferroelectric is given the subsequent sections.

Q.2. What is Piezoelectric, pyroelectric and ferroelectric effect?

Ans. Piezoelectricity: is the phenomenon in which the electric charge accumulates in certain solid materials (such as crystals or certain ceramics) in response to applied mechanical stress.

$$D_{ij} = d_{ijk} T_{jk} + \in_{ij} E_j$$

An electrical charge proportional to an applied mechanical stress. This is also called the direct piezoelectric effect. Piezoelectric materials also show a converse effect, where a geometric strain (deformation) is produced up on the application of a voltage. The direct and converse piezoelectric effects can be expressed in tensor notation as,

$$\vec{P} = d_{ijk}\sigma_{jk} \text{ (direct piezoelectric effect)} \quad ...(1.2)$$

$$x_{ij} = d_{kij}E_k \text{ (converse piezoelectric effect)} \quad ...(1.3)$$

application of electric field $\vec{E}_k$ along the k-axis.

Pyroelectricity: (from the Greek pyr, fire, and electricity) is the property of certain crystals which are naturally electrically polarized and as a result contain large electric fields. The most important example is the gallium nitride semiconductor. Alternatively, pyroelectricity is interpreted as the ability of certain materials to generate a temporary voltage when they are heated or cooled. The change in temperature modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the material changes. This polarization change gives rise to a voltage across the crystal.

The pyroelectric coefficient may be described as the change in the spontaneous polarization vector with temperature.

$$p_i = \frac{\partial P_{s,i}}{\partial T}$$

where p_i ($Cm^{-2}K^{-1}$) is the vector for the pyroelectric coefficient.

Ferroelectricity: is a characteristic of certain materials that have a spontaneous electric polarization that can be reversed by the application of an external electric field. All ferroelectrics are pyroelectric, with the additional property that their natural electrical polarization is reversible. The term is used in analogy to ferromagnetism, in which a material exhibits a permanent magnetic moment.

Electrostriction: (cf. Magnetostriction) is a property of all electrical non-conductors, or dielectrics, that causes them to change their shape under the application of an electric field. Electrostriction is a property of all dielectric materials, and is caused by a slight displacement of ions in the crystal lattice upon being exposed to an external electric field. Positive ions will be displaced in the direction of the field, while negative ions will be displaced in the opposite direction. This displacement will accumulate throughout the bulk material and result in an overall strain (elongation) in the direction of the field.

The resulting strain (ratio of deformation to the original dimension) is proportional to the square of the polarization. Reversal of the electric field does not reverse the direction of the deformation.

Q.3. Write a note on Curie-Weiss Law?

Ans. Ferromagnetic substances lose their spontaneous magnetization at temperature above the Curie temperature, Tc, and become paramagnetic. This involves a phase transition in the crystal structure. Similarly, ferroelectrics lose their intrinsic polarization at temperatures above a transition temperature and become paraelectric, χ, of the substance follows the law.

$$\chi = \frac{A}{T - T_c} \quad ...(1)$$

where A is a constant [2]. This is the same form of expression as the Curie-Weiss law of magnetic susceptibility. For ferroelectrics, expression (1) is no more than a mean-field approximation applied to the fluctuating local electric fields in the crystal structure.

A simple method of determining electrical susceptibility is to measure the capacitance of a parallel plate capacitor containing the ferroelectric substance as a dielectric. Capacitance, C, is related to susceptibility through the expression.

$$C = C_0(1 + \chi) \quad ...(2)$$

where C_0 is the capacitance without a dielectric and is determined from

$$C_0 = \frac{\epsilon_0 A}{d} \qquad ...(3)$$

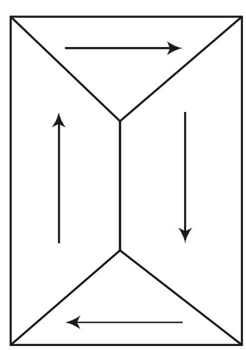
where A is the capacitance without plate, d is the distance between the plates and $\epsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$.

Q.4. What are ferroelectric domains? Explain its structures by the help of a diagram.

Ans. Ferroelectric domains: A ferroelectric material in general is defined by the existence of a permanent spontaneous polarization P_s at temperatures below the Curie temperature whereby the direction of P_s can be reversed by the application of an electric field exceeding the coercive field E_c. The value of E_c is defined using the hysteresis loop which can be recorded during a poling cycle ramping up and down the applied electric field. Theoretical calculations of the value of E_c failed up to now.

In general, uniform alignment of electric dipoles occurs in a certain region of a ferroelectric crystal. These regions are called the ferroelectric domains and the boundary between two domains is called the domain walls. Domain wall are characterized by the angle between the directions of polarization on their side of the wall. Generally domains are formed to reduce the energy of the wall, which changes with direction.

Wave applying the weak electric field on the ferroelectric crystal, rotation of electric dipoles will change in the direction, leading to the rotation of the ferroelectric domains. When a strong electric field, is applied the rotation of electric dipoles is occurred in the first step, and the domain which are aligned in the direction of electric field has the maximum area domain which has the direction opposite to the electric field gets minimized. [30].



Ideal domain configuration in a single crystal of cubic ferroelectric material.

Q.5. Explain a PE hysteresis loop?

Ans. A PE-loop for a device is a plot of the charge or polarisation* (P) developed, against the field applied to that device (E) at a given frequency.

The significance of this measurement can be more easily understood by examining the *P-E* loops for some simple linear devices. The *P-E* loop for an ideal linear capacitor is a straight line whose gradient is proportional to the

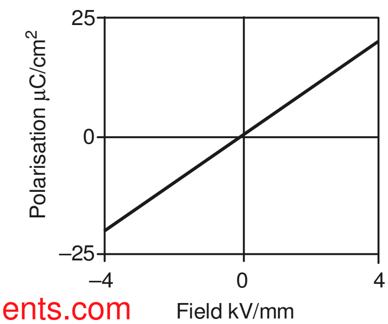


Fig. (a) Ideal linear capacitor response

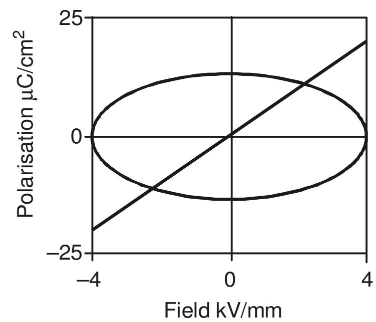


Fig. (b) Ideal resistor response

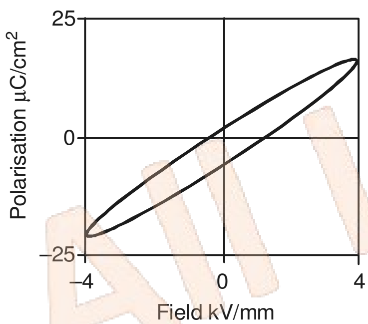


Fig. (c) Lossy capacitor response.

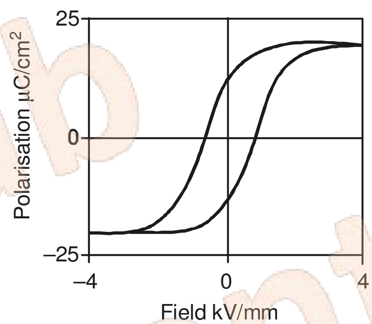
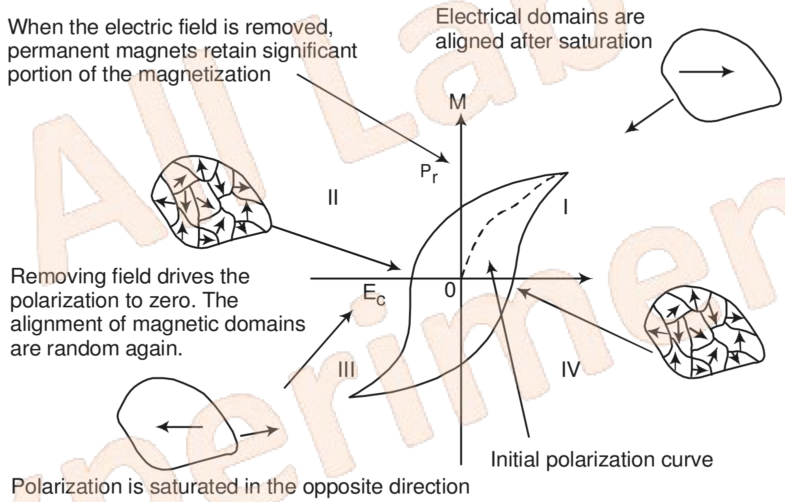


Fig. (d) Non-linear ferroelectric response.

Capacitance (figure 1a). This is because for an ideal capacitor the current leads the voltage by 90 degrees, and therefore the charge (the integral of the current with time) is in phase with the voltage. For an ideal resistor the current and voltage are in phase and so the *P-E* loop is a circle with the centre at the origin (figure 1b). If these two components are combined in parallel we get the *P-E* loop in figure 1*c* which is in effect a lossy capacitor, where the area within the loop is proportional to the loss tangent of the device, and the slope proportional to the capacitance. If we now consider less ideal devices such as non linear ferroelectric materials we would get a *P-E* loop such as figure (d).



Note-Ferroelectric & Ferromagnetic branches of solid state physics are equivalent to each other. The branch ferroelectric has nothing to do with iron (Ferro) but it was named like this just because the similarity of concepts. Ferroelectric (PE loop) loop is similar to ferromagnetic loop (MH loop) both graphically & conceptually.

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