Ferroelectrics in student labs

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Ferroelectrics have many practical applications for their unique physical properties. Therefore this is a main reason why students of technical high schools should learn ferroelectric physics and know about investigation methods. Based on simple measurement arrangements we offer a wide research program of ferroelectrics investigation along with a plain phenomenological model involved.

Introduction

Ferroelectrics, i.e. materials which can change the polarization direction by an external electric field, show many fascinating properties applied in the modern technology. The pyroelectric effect, for instance, is employed in thermovision cameras and irradiation sensors. The reverse piezoelectric effect is used in mechanoelectric transducers, piezoelectric motors, sensors and micromanipulators in scanning microscopes, as well as in ultra- and hyper-sound generators. Moreover, unique optical properties such as the piezooptical and electrooptical effects, the second-harmonic generation, optical frequency-mixing and parametric amplifying processes find more and more implementations.

Currently, the greatest interest comes from the fact that the dielectric hysteresis, typical for ferroelectrics, is employed to write and read information bits in non-volatile memories and logic systems. As the physics education program should follow novel technological achievements, basic problems and ferroelectrics investigation must be included in the teaching syllabi at major technical high schools. At the Wrocław University of Technology the ferroelectric physics is recognized as an important discipline, and selected elementary problems are introduced to the General Physics Laboratory at the basic level, whereas more sophisticated issues are taught at the expert level in the Faculty of Fundamental Problems of Technology.

All the quoted results come from our students' reports. The reports have the form of a research article and are scored adequately to give a final grading. Students' experiments were carried out for three crystals, namely TGS, MAPCB and MAPBB with phase transitions at 49^{o}C, 35^{o}C and 39^{o}C, respectively.

Phenomenological description of ferroelectrics

The easiest way to describe physical properties of ferroelectrics is to employ the Ginsburg model adapted from the Landau theory.

According to the theory, the free energy of the ferroelectric with the second-order phase transition, not undergoing any mechanical strain, can be developed in a power series with respect to the ordering parameter, i.e. the spontaneous polarization:

$$\Phi = \Phi_0 + \frac{1}{2}\alpha(T - T_c)P^2 + \frac{1}{4}\beta P^4 - EP \tag{1}$$

Where: Φ_0 is the free energy in the paraelectric phase,
ά, β are the development factors,
E is the electric field intensity,
P is the polarization.

When looking for the minimum free energy at E = 0 we can have the temperature dependence of the spontaneous polarization:

$$P_s^2 = -\frac{\alpha}{\beta}(T - T_c) \quad \text{for} \quad T<T_c \tag{2}$$

Relation between the polarization and the electric field intensity is the following:

$$E = \alpha(T - T_c)P + \beta P^3 \qquad (3)$$

Temperature dependence of the coercive field can be derived from $\frac{\partial E}{\partial P} = 0$.

The hysteresis loop can be measured with the Sowyer-Tower circuit, as illustrated in Fig.1.

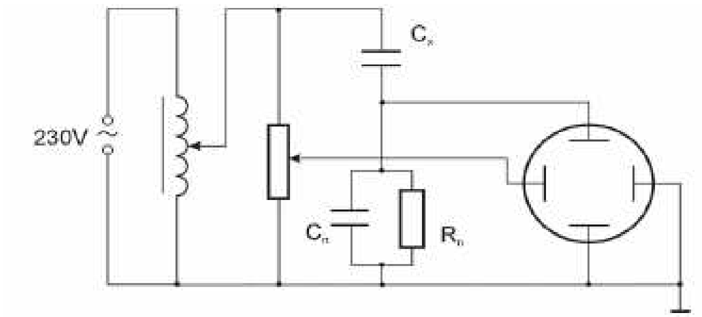

Fig.1. The circuit diagram for measurements of the spontaneous polarization.

In order to determine the temperature dependence of $P_s(T)$ and $P_s^2(T)$ (Fig.2) we can record the dielectric hysteresis with the digital oscilloscope within the phase transition temperature range.

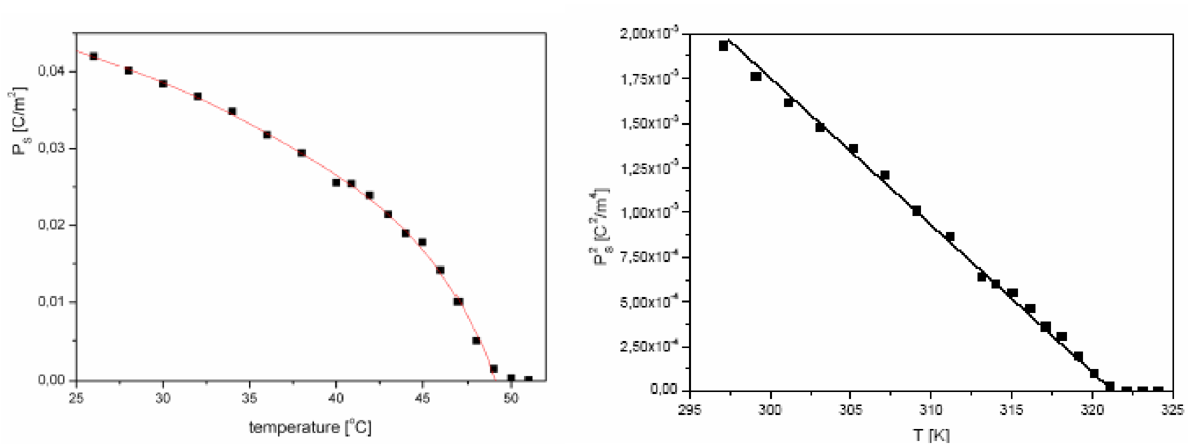

Fig.2. Temperature dependence of $P_s(T)$ and $P_s^2(T)$.

The temperature dependence of the pyroelectric coefficient can be calculated from the first derivative of the spontaneous polarization over temperature. This can be obtained from either the temperature dependence of the spontaneous polarization or from a measurement of the pyroelectric current intensity flowing through the crystal under a constant temperature change (see Fig.3).

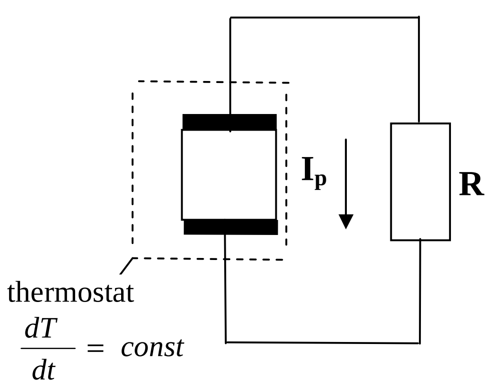

Fig.3. Measurement setup for an investigation of the pyroelectric properties with aid of the quasi-static method.

The temperature dependence of the electric susceptibility can be obtained from the first derivative of the polarization over the electric field intensity.

$$\frac{\partial E}{\partial P} = \frac{1}{\chi} = \alpha(T - T_c) \text{ for } T>T_c \tag{4a}$$

$$\frac{\partial E}{\partial P} = \frac{1}{\chi} = 2\alpha(T - T_c) \text{ for } T<T_c \tag{4b}$$

The temperature dependence of the dielectric constant (ε) can be measured with aid of either the capacitance bridge or the capacitance meter. It can be assumed that the approximate equation: $\chi \approx \varepsilon$ holds true for ferroelectrics.

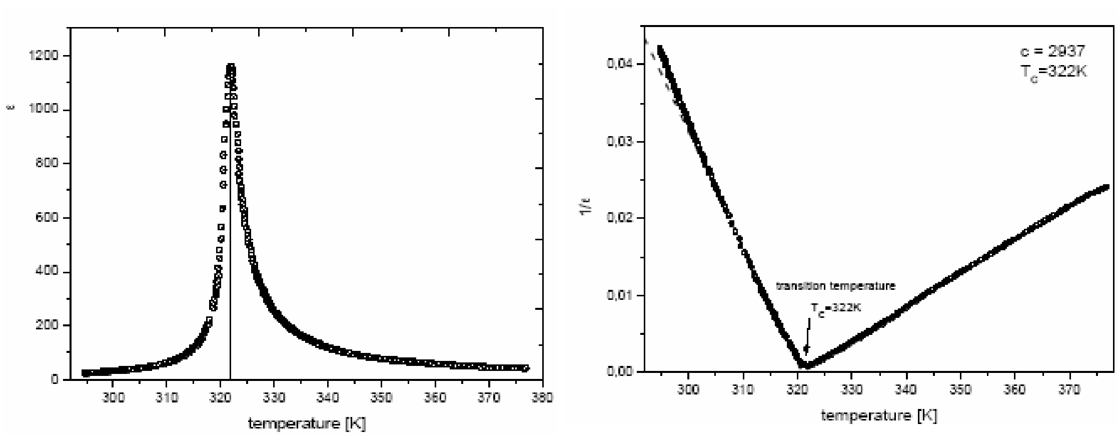

Fig.4. Temperature dependence of ε and $1/\varepsilon$ for TGS crystal.

By plotting the obtained results as $1/\varepsilon$ versus temperature (as in Fig.4) we can determine α coefficient in Eqn.4a for $T>T_c$, as well as α coefficient in Eqn.1. Moreover, we can compare both wings of the $1/\varepsilon(T)$ graph for $T>T_c$ and $T<T_c$ in order to check whether a law of the doubled slope is fulfilled (Eqns. 4a and 4b). Then, having known the α coefficient, we can determine the β coefficient from $P_s^2(T)$ graph.

Optical properties of ferroelectrics (the spontaneous birefringence)

The spontaneous birefringence of the centrosymmetric ferroelectrics in the paraelectric phase shows a nature of the spontaneous Kern effect, therefore:

$$\delta(\Delta n) = \kappa P_s^2 = -\kappa\frac{\alpha}{\beta}(T - T_c) \tag{5}$$

where κ is the proportionality factor.

Fig.5 presents a diagram of the polarization-interference setup for measurements of the temperature dependence of the spontaneous birefringence. More details can be found in Ref.[1].

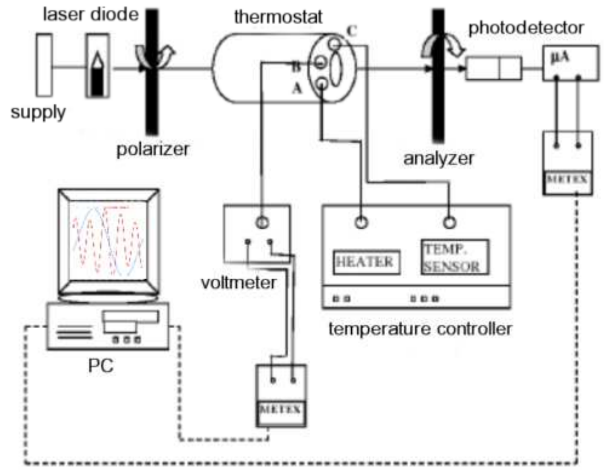

Fig.5. Diagram of the setup for the spontaneous birefringence measurements.

The temperature dependence of the system transmission is shown in Fig.6. The phase shift between the ordinary and extraordinary beams as a function of temperature is presented in Fig. 7a. Thermal changes in the spontaneous birefringence of TGS crystal are illustrated in Fig.7b.

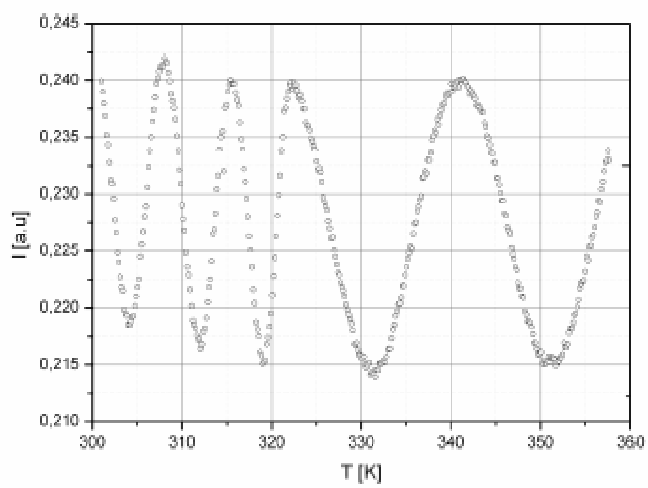

Fig.6. Temperature dependence of the system transmission for TGS crystal.

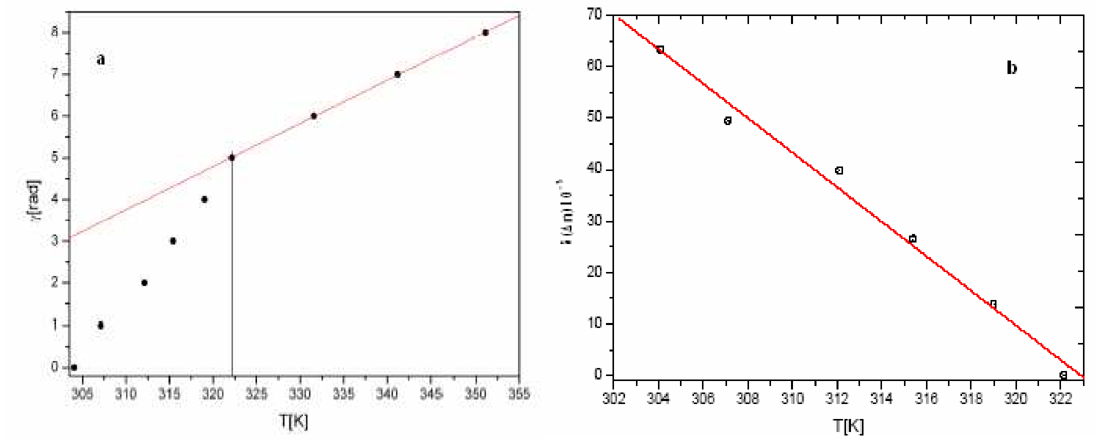

Fig. 7a. Phase shift between the ordinary and extraordinary beams as a function of temperature for TGS.

Fig.7b. Thermal changes in the spontaneous birefringence of TGS crystal.

Piezoelectric properties of ferroelectrics

The spontaneous deformation η in a form of the spontaneous electrostriction appears during the phase transition in centrosymmetric ferroelectrics in the paraelectric phase.

$$\eta = gP_s^2 = -g\frac{\alpha(T-T_c)}{\beta} \tag{6}$$

where g is the electrostriction module.

The electric field dependence of the deformation for the ferroelectric can be described:

$$\eta = q(P_s + P_{ind})^2 = q(P_s + \chi\varepsilon_0 E)^2 = qP_s^2 + 2q\chi\varepsilon_0 E + 2q\chi^2\varepsilon_0^2 E^2 \tag{7}$$

where P_{ind} denotes the polarization induced by the electric field.

The first component of Eqn.7 describes the spontaneous deformation of the crystal, the second compound expresses the linear relation, and the third shows a deviation from the linearity.

The temperature dependence of the spontaneous deformation can be determined with aid of the capacitance dilatometer [2] and its linearity (Eqn.6) can be easily checked.

The electric field dependence of the deformation can be measured by the Caspari-Mertz method. It should be noticed that expression $2q\chi\varepsilon_0$ is the piezoelectric coefficient with the linear dependence on temperature. Moreover, a sign of the coefficient can be changed by the external electric field. A graph of the electric field dependence of the deformation has a shape of a butterfly.

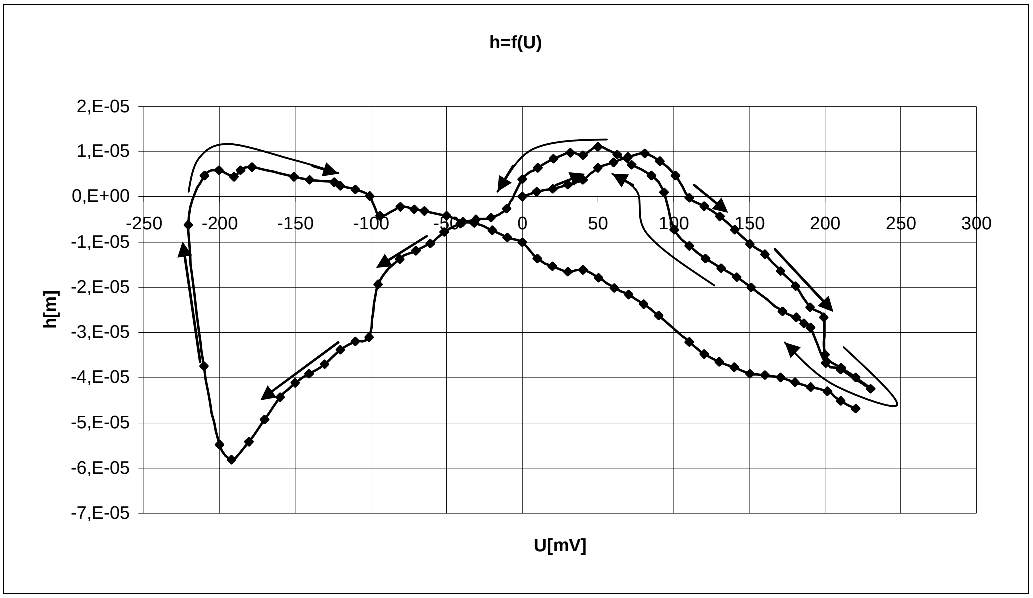

Fig.8. The electric field dependence of the piezoelectric deformation for a piezoelectric ceramic.

It should be pointed out that an equation for the electric field dependence of the birefringence is analogous to that of the deformation, so electrooptical coefficients depend significantly on temperature, and their sign can be changed by an external electric field.

Summary

It comes from the above that ferroelectrics show remarkably interesting physical properties especially for practical applications. An introduction of these phenomena into the teaching process does not require either any complex theory or expensive and complicated measuring devices. A knowledge acquired in this field can be useful in the future regardless a student's specialization.

Literature:

[1]. A.Ciżman, R.Poprawski, „Set-up for spontaneous and induced birefringence measurements", Optica Applicata, Vol.XXXV, No.1, 2005.
[2]. J.Dziedzic, R.Poprawski, W. Bronowska Acta Phys. Pol. A **63**, (1983) 45.