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The Influence of Hydrostatic Pressure on the Field-Induced Dielectric Constant Maxima of SrTiO₃

By

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The field induced maxima in the temperature dependence of the dielectric constants of SrTiO₃ are shifted down to the temperature range around $T = 20$ K by hydrostatic pressure. The connection between the temperature T_m of the maximum, the inducing field strength E , and the pressure p is nonlinear and corresponds to a relation deduced previously.

Die feldinduzierten Maxima in der Temperaturabhängigkeit der Dielektrizitätskonstanten von SrTiO₃ werden durch hydrostatischen Druck zu niedrigen Temperaturen im Bereich um $T = 20$ K verschoben. Die Verknüpfung zwischen der Temperatur T_m des Maximums, der induzierenden Feldstärke E und dem Druck p ist nichtlinear und entspricht einer früher abgeleiteten Beziehung.

1. Introduction

The dielectric constant of SrTiO₃ increases with decreasing temperature. Below the structural phase transition from cubic to tetragonal symmetry at $T_a \approx 105$ K the dielectric constant is always smaller than given by the Curie-Weiss law, which is valid above T_a [1], and at very low temperatures it reaches constant values of the order 10^4 [1 to 4], as recently investigated down to $T = 0,025$ K [5].

Below the structural phase transition at $T_a \approx 105$ K the dielectric properties are anisotropic. Usually regions with different orientations of the tetragonal axes with respect to the applied field are formed within the crystal lattice, the so-called paraelectric domains.

In dielectric measurements the contributions of the individual regions are averaged, thus blurring almost completely the structural phase transition at T_a and the resulting anisotropy in a polydomain crystal. In general the domain distribution and the corresponding dielectric constant values are hardly reproducible, as stated also by other authors [4, 6].

On the basis of lattice dynamical investigations [7], Pietrass and Hegenbarth [8] demonstrated by means of earlier measurements of several authors [4, 9] that the dielectric behaviour of SrTiO₃ within the temperature range 20 to 70 K may be favourably described using a quadratic temperature dependence in the thermodynamic potential. This is confirmed also by recent measurements [10] which are reported in this paper.

Without a dc field the $\epsilon(T)$ dependence of SrTiO₃ shows no maximum. Applying an electric field, however, the dielectric constant at low temperatures decreases and with sufficiently strong fields maxima in the $\epsilon(T)$ dependence

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occur [2, 4, 10 to 12]. Previous preliminary investigations [9] yielded that the maxima are influenced by pressure. In the present paper the $\epsilon(T)$ dependence is investigated under the simultaneous influences of an electric field E and hydrostatic pressure p .

2. Experimental

For the pressure generation and as pressure transmitting medium helium gas was used. Thus strict hydrostatic conditions existed in all our measurements. The gas was thermally compressed to 1.5 kbar. Construction and manipulation of the device as well as the used measuring instruments have been already described in an earlier paper [9].

The temperature was determined inside the pressure vessel by means of a platinum-resistance thermometer. The influence of pressure on the resistance was corrected [10].

The investigations were carried out on a SrTiO_3 single crystal with the dimensions of $44.7 \text{ mm}^2 \times 0.39 \text{ mm}$.

3. Results

The temperature dependence of the dielectric constant without pressure is represented in Fig. 1 for different field strengths. Already at field strengths $E \geq 1.6 \text{ kV/cm}$ maxima can be induced at temperatures $T > 15 \text{ K}$, having smaller absolute values with increasing field strength and lying at higher temperatures, as shown already by several authors [2, 5, 10 to 12].

The curve with $E = 0$ shows no dielectric constant maximum. By applying pressure the dielectric constant values decrease. The curves are flatter and do not show a maximum, as already seen in other papers [9, 13].

The influence of pressure on the field-induced maxima of Fig. 1 is represented for some curves in Fig. 2. Contrary to the field influence the maxima are shifted

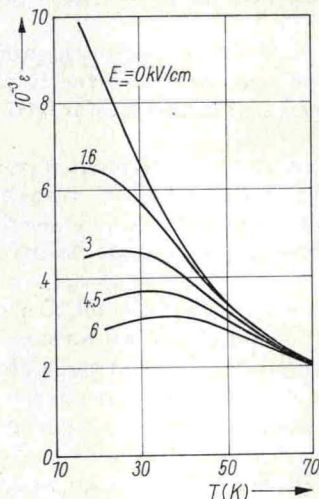


Fig. 1. The influence of an electric field on the $\epsilon(T)$ dependence of a SrTiO_3 single crystal ($p = 0$)

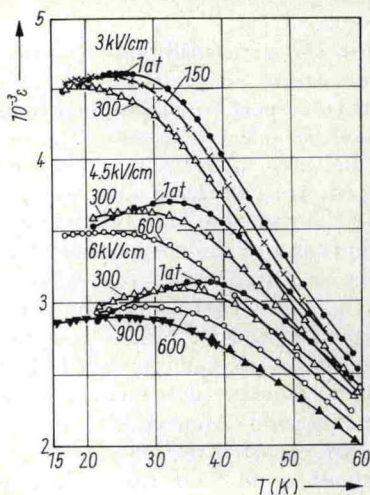


Fig. 2. The influence of the hydrostatic pressure on the $\epsilon(T)$ dependence of SrTiO_3 with a simultaneously applied electric field (1 at = 0.981 bar)

Fig. 3. The temperature T_m of the $\epsilon(T)$ maximum in dependence on the pressure (1 at = 0.981 bar). The curves correspond to the equations (1) and (4) with the constants according to (2). They are equivalent to the straight lines in the right diagram of Fig. 4. The dash-dotted straight lines correspond to the initial value of the pressure shifting according to equation (5)

by pressure to lower temperatures and their absolute values decrease. The maximum values of the dielectric constant decrease irregularly with pressure, although we carefully operated in changing the pressure and the field. Thus a quantitative relation for the pressure dependence of the maximum values of the dielectric constant cannot be given. The reason for this behaviour may be due to changes of the domain distribution. For shifting the temperature T_m of the dielectric constant maximum by means of an electric field a non-linear dependence has been indicated already in an earlier paper [2]. As can be seen in Fig. 3 non-linearities may be observed also in the pressure shift of the field-induced maxima.

4. Discussion

A suitable representation of the behaviour can be found in the analysis of Pietrass and Hegenbarth [8], starting from a simple thermodynamic potential with quadratic temperature dependence of the coefficient A .

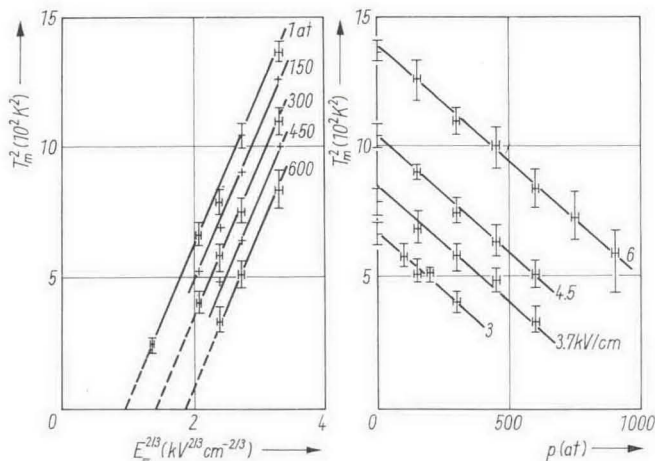
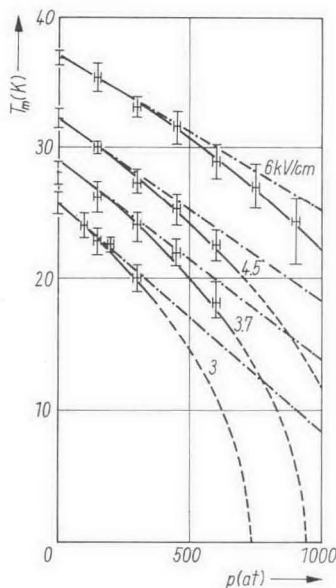


Fig. 4. The temperature T_m of the $\epsilon(T)$ maxima of SrTiO₃ in dependence on the electric field $T_m^2 = f(E^{2/3})$ and in dependence on the pressure $T_m^2 = f(p)$ (1 at = 0.981 bar). The straight lines correspond to equation (1) with the constants according to (2)

For the temperature T_m of the dielectric constant maximum as a function of hydrostatic pressure p and dc field E the relation

$$T_m^2 = \alpha^{-1}(\beta E^{2/3} - A_0 - Kp) \quad (1)$$

was found [8], with $\beta = (3/2)(B/2)^{1/3}$. The constants A_0 , B , K , and α are the same as in paper [8].

Plotting the T_m values determined from the measurements in the manner as in Fig. 4, equation (1) is confirmed:

In the left diagram of Fig. 4 the isobars $T_m^2 = f(E^{2/3})$ yield parallel straight lines. The shift of the isobars by pressure is linear. The measuring points in the right diagram are generally well represented also by a set of parallel straight lines for $T_m^2 = f(p)$ at $E = \text{const}$.

From Fig. 4 and from other experimental results [10] we obtained

$$\begin{aligned} A_0 &= 4.6_6 \times 10^6 \text{ Vm/As}, & K &= 0.075_2 \text{ m}^4/\text{A}^2\text{s}^2, \\ \alpha &= 8.2_4 \times 10^3 \text{ Vm/K}^2 \text{ As} & B &= 0.65_8 \times 10^{10} \text{ Vm/A}^3\text{s}^3. \end{aligned} \quad (2)$$

These values deviate somewhat from those in [8], but they are likely to be more reliable. They describe the behaviour of T_m at the influence of dc field and pressure quantitatively.

Now we consider the equation (1) and Fig. 4 for the case $T_m \rightarrow 0$. A maximum in the $\varepsilon(T)$ dependence only occurs, if an electric field strength

$$E_0 = [(A_0 + Kp)/\beta]^{3/2} \approx \left(0.97 + 1.55 \frac{p}{\text{kbar}}\right)^{3/2} \frac{\text{kV}}{\text{cm}} \quad (3)$$

is exceeded. The existence of a critical field strength has been already demonstrated earlier [2]. From (3) we get $E_0 \approx 0.94 \text{ kV/cm}$ for $p = 0$. In [5] no maximum was found at $E_0 \approx 0.95 \text{ kV/cm}$ down to temperatures $T = 0.045 \text{ K}$. It has to be noted that (3) can only be derived with the assumption of the validity of a quadratic temperature dependence in the coefficient A of the thermodynamic potential [8]. Since, however, for $T \rightarrow 0$ a term with T^4 dominates [7] in the coefficient A , equation (3) can only represent an approximation. This behaviour could be studied more exactly at weak fields $E = 1$ to 2 kV/cm which induce dielectric constant maxima in the temperature range of liquid helium.

For the pressure dependence of T_m the relations

$$T_m^2 = T_0^2(1 - p/p_0) = T_0^2 - Kp/\alpha = \alpha^{-1}(\beta E^{2/3} - A_0)(1 - p/p_0) \quad (4)$$

can be given, with $T_0 = (T_m)_{p=0}$ and $T_m \rightarrow 0$ for $p \rightarrow p_0$ [8]. In the investigated range the quadratic temperature dependence is confirmed well (Fig. 4).

For small pressure we get for the initial value of the pressure shift of T_m

$$\left(\frac{dT_m}{dp}\right)_{p=0} = -\frac{K}{2\alpha T_0}. \quad (5)$$

This shift still depends on the field strength through T_0 . The initial pressure shift is plotted in Fig. 3 as dash-dotted line. Experimental investigations by Martin [14] show that the dielectric constant maxima do not fulfill the relation (4) at higher pressures and they do not vanish at p_0 . This behaviour is caused by influences [14] not being important in the investigated temperature range.

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