Uniform deformation and birefringence of crystals in a nonuniform electric field

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A nonuniform electric field is shown to induce uniform components of deformation and birefringence in crystals, which are linear with respect to field gradient. Magnitudes of these effects in NaCl are measured interferrometrically.

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A uniform deformation of a crystal belonging to any symmetry group should give rise to an electric field that corresponds to its macroscopic quadrupole moment. This piezoelectric effect may readily be observed under experimental conditions in axisymmetric crystals in which more intense electrical effects that are associated with variation of the dipole moment, are forbidden.[1]

In this work, using NaCl crystals, we report for the first time on the identification and measurement of two inverse effects: the occurrence in a nonuniform field of a uniform deformation u_{ij} and permittivity ϵ_{ij} terms that are linear with respect to the field gradient.

The equations that relate u_{ij} and ϵ_{ij} of an axisymmetric medium with a field E_l are as follows

$$u_{ij} = Q_{ijkl} E_k E_l + D_{ijkl} \nabla_k E_l, \quad \epsilon_{ij} = R_{ijkl} E_k E_l + C_{ij.kl} \nabla_k E_l . \qquad (1)$$

All the coefficients in Eq. (1) are components of fourth-rank tensors, which are nontrivial in a medium with an arbitrary symmetry. Q_{ijkl} represents electrostriction, R_{ijkl}, the electro-optic Kerr effect, and D_{ijkl} and C_{ijkl}, effects investigated in this work.

We shall calculate the value of these coefficients. If $E \sim e/a^2$, $\nabla E \sim e/a^3$, and

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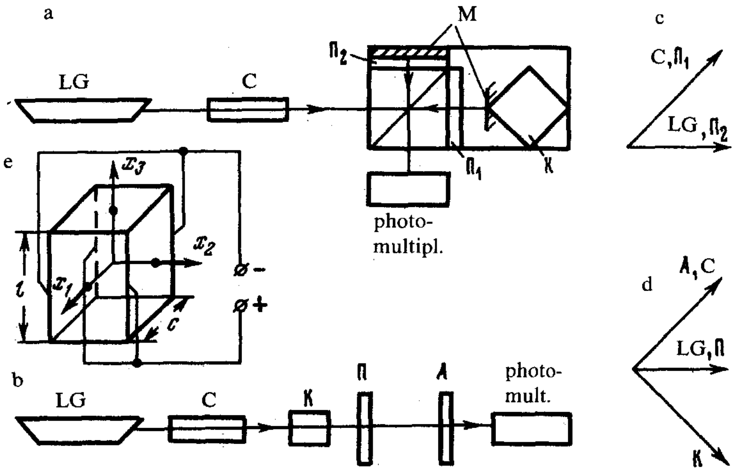

FIG. 1. Measurement scheme for: a—deformation and b—birefringence; c and d—directions of optical axes of elements in schemes a and b; e—shape of specimen and geometry of electrode distribution; LG—laser; C—electrooptic cell; Π, Π_1, Π_2—quarter-wave plates; A—analyzer; M—mirrors; K—crystal.

$u \sim \epsilon \sim 1$, then $D \sim C \sim a^3/e \sim 10^{-11}$–$10^{-13}$, and $Q \sim R \sim a^4/e^2 \sim 10^{-10}$–$10^{-11}$ CGSE units (a is the value of an elementary cell parameter and e is the electron charge).

Let us consider an axisymmetric cubic crystal in the shape of a rectangular bar with dimensions $c \times c \times l$ to which a voltage V is applied across that l side, as in Fig. 1. The field in a specimen with $l \gg c$ is described by, with accuracy to second-order in the coordinates, the potential $\phi \approx (4V/c^2)x_1x_2$. According to Eq. (1), the matrix elements are as follows

$$u_1 = u_2 = Q_{11}E_1^2 + Q_{12}E_2^2, \quad u_6 = 2Q_{66}E_1E_2 + D_{66}(\nabla_1 E_2 + \nabla_2 E_1).$$

Equations for ϵ_i are similarly expressed. Thus, a change in the length of the diagonal of the [110] crystal face perpendicular to the edge l is

$$\Delta L = \int_0^{c/2} (2u_1 + u_6)dx_1 = -\frac{4}{c} D_{66}V + \frac{4}{3c}(Q_{11} + Q_{12} + Q_{66})V^2, \tag{2}$$

and the field-induced birefringence when an optical beam passes near the specimen center in the direction of edge l is

$$\Delta n = \Delta n_1 - \Delta n_2 \approx \frac{\Delta\epsilon_6}{2n} \approx \frac{2}{c^2 n} C_{66}V, \tag{3}$$

where Δn_1 and Δn_2 are changes in the refractive index n along the diagonals [$\bar{1}$10] and [110], respectively.

We verified Eqs. (2) and (3) experimentally. The dimensions of our NaCl speci-

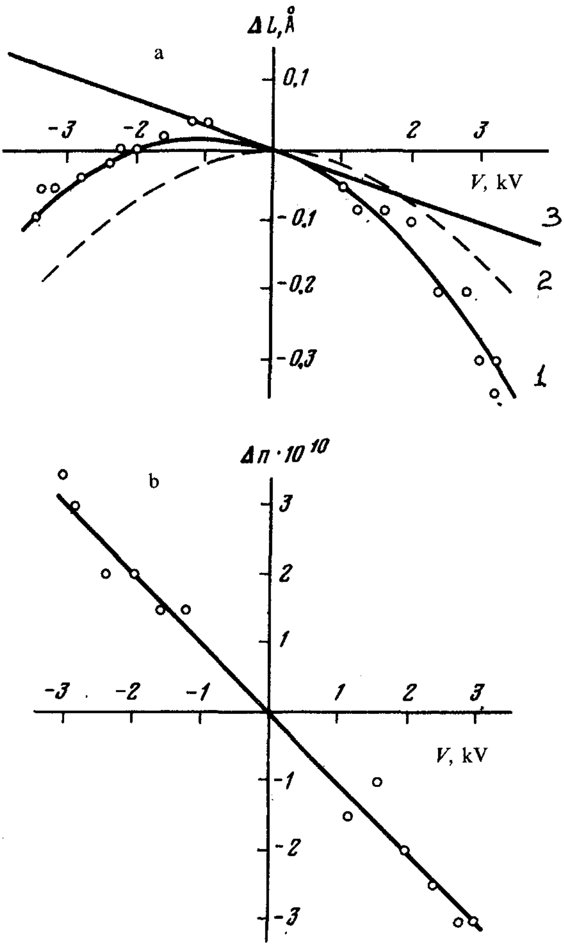

FIG. 2. Dependence of (a)—variation of legnth of diagonal ΔL and (b)—birefringence Δn of NaCl crystal on the electric voltage V; 1—measured data; 2—component of ΔL corresponding to electrostriction; 3—ΔL, corresponding to uniform deformation, linear with respect to electric field.

men were $5\times5\times7$ mm^3. The value of ΔL was measured by means of a polarization interferometer of the Michelson interferometer type, and Δn, by means of an ellipsometric scheme (Fig. 1). Because the output signal was proportional to the product of the measured and modulating values, and the effect of the instability of the working point of the electro-optic cell on the measurements was excluded, the threshold sensitivity (for a highly stabilized beam path) attained $3\times10^{-6}\lambda$ for the interferometer and $5\times10^{-7}\lambda$ for the ellipsometer ($\lambda = 6328$ Å).[2] Determination of the sensitivity and direction of the phase shift in both schemes was carried out by way of a comparison with the linear electro-optic effect in quartz.

Figure 2 shows the measurement results. The dependence of ΔL and Δn on V are well described by Eqs. (2) and (3), respectively, with coefficients $D_{66}\approx1.3\times10^{-11}$, $C_{66}\approx-6\times10^{-12}$, $Q_{11}+Q_{12}+Q_{66}=-5.7\times10^{-12}$ CGSE units. The order of magnitude of the coefficients agrees with calculations made above. The accuracy of measurements was $\pm30\%$.

Measurement of the foregoing effects in the region of structural phase transitions with a parameter which is a component of a second-rank tensor is of interest. It is naturally to be expected that in this case the effects shall be anomalously high and their temperature dependence may be used to judge the behavior of the transition parameter.

We should note that the observed effects may be considered as analogs of the inverse piezoelectric and linear electro-optic effects in non-axisymmetric crystals. A distinction between them is that the former are associated with changes in the macroscopic quadrupole moment, and the latter, with changes in the dipole moment due to external effects.

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