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DIELECTRIC AND ELECTROSTRICTIVE PROPERTIES OF FERROELECTRIC RELAXORS

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On the basis of ferroelectric relaxors electrostrictive ceramics has been obtained. Searching for electrostrictive ceramic transducers with optimal electromechanical parameters include the following: 1) investigation of different types of complex oxides with the perovskite structure (OPS): ferroelectric, antiferroelectric, non-polar; 2) investigation of OPS with different degree of the cation order; 3) measurements of the electrostrictive coefficient (Q), Curie–Weiss constant (C), coefficient of linear thermal expansion (λ), polarization (P) and permittivity (ε); 4) X-ray structure analysis. The following rules have been stated out during the experimental investigations: 1) values of the electrostrictive coefficients (Q_{ijkl}) depend not only on the chemical constitution of OPS but, first of all, on the degree of cation order (i.e. the coefficients increase with an increase in the degree of cation order: non-ordered state — simple state — ordered state; 2) products of the hydrostatic electrostrictive coefficient (Q_h) and the Curie–Weiss (C) constant of all ferroelectric and antiferroelectric OPS are nearly equal; 3) value of the hydrostatic electrostrictive coefficient (Q_h) is nearly proportional to the linear thermal expansion coefficient square (λ^2). Taking into account the above mentioned rules the detailed and systematic investigations of OPS with non-ordered cations and high value of the Curie-Weiss constant (C) and permittivity (ε) were carried out. In such OPS high value of induced polarization leads to considerable electrostrictive deformation described by the M_{ijkl} tensor ($M_{ijkl} \approx Q_{ijkl}\varepsilon_r^2$). One can mention $PbNb_{2/3}Mg_{1/3}O_3$ and solid solution prepared on the basis of $PbNb_{2/3}Mg_{1/3}O_3$ as an example. Devices fabricated on the basis of electrostrictive ceramics provide a relative displacement of about 10^{-3} what is few times more than the one provided by devices on the basis of piezoelectric ceramics.

1. Introduction

Among ferroelectrics, *relaxors* are mainly characterized by:

1) a very broad permittivity (ε) vs. temperature peak;

2) hysteresis loops above the temperature T_m (the temperature at which the permittivity is a maximum, i.e., ε_m);

3) a frequency dependence of permittivity maximum ($\varepsilon_m(\omega)$) and of $T_m(\omega)$;

4) a depolarization temperature T_d (as defined in reference [1]) lower than the temperature T_m (for $\nu = 10^1 - 10^6$ Hz);

5) no evidence for any symmetry transformation;

6) when the temperature is higher than T_m, $\varepsilon(T)$ does not obey the Curie–Weiss law:

$$\varepsilon = \varepsilon_0 + \frac{C}{T - T_0} \approx \frac{C}{T - T_0}, \tag{1}$$

where C — the Curie–Weiss constant; T_0 — the Curie–Weiss temperature ($T > T_0$, T_0 is different from the Curie point T_c; in the case of the first-order phase transition, $T_0 < T_c$, while for the second-order phase transition $T_0 = T_c$); ε_0 — the temperature-independent term ε_0 can be neglected, because it is much smaller than the term $C/(T - T_0)$ when T is near T_0.

In fact, $\varepsilon(T)$ of the relaxors changes with T in the following manner:

$$\frac{1}{\varepsilon} - \frac{1}{\varepsilon_m} = C'(T - T_m)^n, \tag{2}$$

where C' — a constant, n — a constant ($1 < n < 2$).

It has been shown that the largest relative strains (η) of the electrostrictive nature take place in the case of the *ferroelectric relaxors* and of the *ferroelectrics with a diffuse phase transition.* The value of such strains ($\sim 10^{-3}$) may exceed relative strains of magnetostrictive or piezoelectric nature ($10^{-4} - 10^{-5}$).

When the electric field is applied to a dielectric material, it produces a strain proportional to the square of the field ($\eta \sim E^2$). This effect is called the *electrostrictive effect.* Electrostrictive effect is a quadratic effect and the electrostrictive strain is not related to the sign of the applied field. In fact, *electrostriction is a result of the polarization P induced by the applied field* and the electrostrictive strain is directly proportional to the square of the polarization ($\eta \sim P^2$). Unlike the piezoelectric effect, electrostriction may occur in all crystals whether or not the crystals have polarity.

In the case of ferroelectric crystal (e.g. $BaTiO_3$ in $T < T_c$) the electromechanical effect has a complex nature ($\eta(E)$ effect must be a function of the domain structure, the spontaneous (P_s) and induced (P_{ind}) polarizations, etc.).

In the case of a *centrosymmetric crystal* (e.g., barium titanate in its paraelectric state), the electrostrictive effect has rather simple form. In this case, the equations of state for stress (σ_{ij}) and for strain (η_{ij}) components can be written as:

$$\sigma_{ij} = c^P_{ijkl}\eta_{ij} + q_{ijkl}P_kP_l\,, \tag{3}$$

$$\sigma_{ij} = c^E_{ijkl}\eta_{ij} + m_{ijkl}E_kE_l\,, \tag{4}$$

$$\eta_{ij} = s^P_{ijkl}\sigma_{kl} + Q_{ijkl}P_kP_l\,, \tag{5}$$

$$\eta_{ij} = s^E_{ijkl}\sigma_{kl} + M_{ijkl}E_kE_l\,, \tag{6}$$

where $c^{P(E)}_{ijkl}$ — the elastic stiffness constants at constant electric field (the superscript E) or polarization (the superscript P), $s^{P(E)}_{ijkl}$ — the elastic compliance constants at constant E or P.

Equations (3) – (6) are called *elestrostriction equations.* In each of these equations, the first term on the right-hand side corresponds to Hooke's law and the second term to the electrostrictive effect. These equations define the electrostrictive coefficients Q, q, M and m. Each of the four electrostrictive coefficients is a fourth-rank tensor. Among these four coefficients, Q and M are most useful and its unit are $\mathrm{m}^4/\mathrm{C}^2$ and $\mathrm{C}^2/\mathrm{N}^2$ respectively. The relationship between Q_{ijkl} and M_{ijkl} is:

$$M_{ijkl} = \varepsilon_0^2 \left(\varepsilon_r^\sigma - 1\right)^2 Q_{ijkl}, \tag{7}$$

where ε_0 — the permittivity of free space ($\varepsilon_0 = 8.854 \cdot 10^{-12}\,\mathrm{F/m}$), ε_r^σ — the relative permittivity at stress $\sigma = \text{const.}$, or $\sigma = 0$ (the superscript σ).

The aim of the present work was to obtain different types of complex oxides with the *perovskite* type structure (OSP) and with the *tetragonal tungsten bronze* type structure, to investigate of these ceramic materials (ferroelectric, antiferroelectric, non-polar) with different degree of the cation order and to search for electrostrictive ceramic transducers with optimal electromechanical parameters.

2. Methods for measuring the electrostrictive coefficients

Using the Voigt notation (with two subscripts to replace the four subscripts), Eq. (5) can be written as:

$$\eta_i = s_{ij}^P \sigma_j + Q_{ijkl} P_k P_l \qquad (i, j = 1, 2, ..., 6; \quad k, l = 1, 2, 3). \tag{8}$$

Furthermore, upon stipulating that

$$Q_{i\mu} = Q_{ikl} \qquad (\text{for} \quad k = l), \tag{9}$$

and

$$Q_{i\mu} = 2Q_{ikl} \qquad (\text{for} \quad k \neq l), \tag{10}$$

Q_{ikl} becomes $Q_{i\mu}$ (with two subscripts). Thus, 81 components of the fourthrank tensor are reduced to 36 components. Due to the crystal's macroscopic symmetry, the number of independent components $Q_{i\mu}$ can furher be reduced. For centrosymmetric crystals (such as $\overline{4}3m$, 432, $m3m$, etc) as well as unpoled ceramics, the $Q_{i\mu}$ tensor is

$$\begin{array}{c|cccccc}
 & P_1^2 & P_2^2 & P_3^2 & P_2P_3 & P_1P_3 & P_1P_2 \\
\hline
\eta_1 & Q_{11} & Q_{12} & Q_{12} & 0 & 0 & 0 \\
\eta_2 & Q_{12} & Q_{11} & Q_{12} & 0 & 0 & 0 \\
\eta_3 & Q_{12} & Q_{11} & Q_{11} & 0 & 0 & 0 \\
\eta_4 & 0 & 0 & 0 & Q_{44} & 0 & 0 \\
\eta_5 & 0 & 0 & 0 & 0 & Q_{44} & 0 \\
\eta_6 & 0 & 0 & 0 & 0 & 0 & Q_{44}
\end{array} \tag{11}$$

In the present experiment with a sample in the zero-stress state ($\sigma_j = 0$), we obtain from Eqs. (8) and (11) relationships between components of strain (η_i) and components of polarization (P) as follows:

$$\begin{aligned}
\eta_1 &= Q_{11}P_1^2 + Q_{12}P_2^2 + Q_{12}P_3^2, \\
\eta_2 &= Q_{12}P_1^2 + Q_{11}P_2^2 + Q_{12}P_3^2, \\
\eta_3 &= Q_{12}P_1^2 + Q_{12}P_2^2 + Q_{11}P_3^2, \\
\eta_4 &= Q_{44}P_2P_3, \\
\eta_5 &= Q_{44}P_3P_1, \\
\eta_6 &= Q_{44}P_1P_2.
\end{aligned} \tag{12}$$

These formulae are essential in the measurement of electrostrictive coefficients. Most of the practical electrostrictive materials are used in their paraelectric state, because in this state the remanent strain is avoidable. For studying the electrostrictive effect, direct and indirect methods have been designed.

In general, electrostrictive coefficients ($Q_{\lambda\mu}$) are obtained by measuring the electrostrictive strain directly. For example, if an electric field is applied in the direction 2 on a dielectric material with cubic symmetry (paraelectric phase), a transverse electrostrictive effect occurs, i.e., a strain develops along the direction 1. In this case the electrostriction equations (12) can be simplified to the form (transverse electrostrictive effect; $\eta_1 \perp P_2$):

$$\eta_1 = Q_{12}P_2^2, \tag{13}$$

where $\eta_1 = (\Delta l_1/l_1)$ — the strain in direction 1.

By applying an electric field on a sample, we can measure the strain η_1 and the polarization P_2 as a function of the applied field E. A plot of η_1 as a function of P_2^2 is a straight line with slope Q_{12}. The extension Δl_1 as a function of the applied field is measured by a micro-displace meter with an X-Y recorder, while the polarization P_2 as a function of the applied field is measured by a Sawyer–Tower circuit. If the strain is measured in the direction of the field, one obtains the longitudinal electrostrictive coefficient Q_{11} ($\eta_2 \parallel P_2$):

$$\eta_2 = Q_{11}P_2^2. \tag{14}$$

A plot of η_2 as a function of P_2^2 is a straight line with slope Q_{11}. The schematic diagram of a typical experimental set-up for direct measurement of the electrostrictive coefficients $Q_{\lambda\mu}$ has been shown in the book [2].

Block diagram of a set-up for indirect measurement of the electrostrictive coefficients has been shown in the paper [3].

According to thermodynamics, in the case of an isotropic material

$$(\partial\beta/\partial p_h)_T = 2Q_{11} + 4Q_{12} = 2Q_h, \tag{15}$$

where β — the impermeability, p_h — the hydrostatic pressure, Q_h — is defined as the electrostrictive coefficient under hydrostatic pressure.

As sample is inserted into a high-pressure container where it is subjected to a hydrostatic pressure p_h ($0 - 10^3$ MPa). The variation of β is measured as a function of p_h

under isothermal conditions. β is usually calculated from the dielectric permittivity ε using the following equations:

$$\beta_{mn} = (-1)^{m+n}\Delta^{\varepsilon}_{mn}/\Delta^{\varepsilon}, \tag{16}$$

$$\varepsilon_{mn} = (-1)^{m+n}\Delta^{\beta}_{mn}/\Delta^{\beta}, \tag{17}$$

where Δ^{ε} (or Δ^{β}) — an algebraic determinat of ε_{mn} or β_{mn} tensor, $\Delta^{\varepsilon}_{mn}$ (or Δ^{β}_{mn}) — represents a remanent subdeterminant in which the term ε_{mn} (or β_{mn}) is removed.

Q_h is then obtained from the slope of the β versus p_h curve. In practice, the hydrostatic pressure is raised to a maximum value in the beginning of the experiment and then allowed to drop gradually in steps. At each pressure step p_h, after the sample temperature becomes stable the sample capacity is measured by an *a.c.* bridge.

The method of indirect measurement has also been applied to a system under a uniaxial pressure. Thus, each independent component of the electrostrictive coefficient may be obtained separately. For example, if a stress σ_1 is applied in the direction 1, we obtain

$$2Q_{11} = -(\partial\beta_1/\partial\sigma_1). \tag{18}$$

For studying high-frequency piezoelectric and electrostrictive strains, a double-beam laser interferometr has been designed. This system is capable of resolving a displacement of 10^{-1}nm with the lock-in detection device and measuring strains up to the piezoelectric resonance frequencies using a digital oscilloscope. The interference of the sample bending in signal detection is effectively avoided. The schematic diagram of the double-beam laser interferometer along with the electronic accessories is shown in the paper [4].

3. Results of investigations and their interpretation

The following parameters are used for estimation of electric field induced electrostrictive deformations of dielectric and for practical estimation of usefulness of electrostrictive transducer:

1. Coefficients of electrostriction (M_{ij}, Q_{ij}):

$$M_{ij} = Q_{ij}\varepsilon_0^2\left(\varepsilon_r^{\sigma} - 1\right)^2, \tag{19}$$

where

$$M_{ij} = \left(\frac{\partial^2\eta_i}{\partial E_k \partial E_l}\right)_{\sigma,T}, \tag{20}$$

$$Q_{ij} = \left(\frac{\partial^2\eta_i}{\partial P_k \partial P_l}\right)_{\sigma,T}, \tag{21}$$

$$\varepsilon_r^{\sigma} = \frac{\varepsilon^{\sigma}}{\varepsilon_0}. \tag{22}$$

2. Hydrostatic coefficient of electrostriction:

$$Q_h = Q_{11} + 2Q_{12}. \tag{23}$$

3. Temperature coefficient of electrostriction

$$k_e = \frac{\Delta Q_{ij}}{\Delta T Q_{ij}} 100 \quad [\%\mathrm{K}^{-1}], \tag{24}$$

where

$$\Delta T = T_2 - T_1\,, \qquad \Delta Q_{ij} = |Q_{ij}(T_2) - Q_{ij}(T_1)|, \qquad Q_{ij} = Q_{ij}(T_{1/2}). \tag{25}$$

4. Linear expansion coefficient:

$$\lambda = \frac{\Delta x}{x_0 \Delta T} \quad [\mathrm{K}^{-1}]. \tag{26}$$

5. Curie–Weiss constant (C):

$$\varepsilon = \frac{C}{T - T_0}\,. \tag{27}$$

The values of M_{ij}, Q_{ij}, Q_h, ε_r^σ of electrostrictive materials used for production of electromechanical transducers (micromotors, micromanipulators etc.) should be as high as possible while values of λ and k_e should be as small as possible.

Ceramic compounds and ferroelectric solid solutions ($BaTiO_3$ (BT), $PbTiO_3$ (PT), $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN), $Pb(Zn_{1/3}Nb_{2/3})O_3$ (PZN), $Pb(Sc_{1/2}Nb_{1/2})O_3$ (PSN), (x)PT-(1-x)PMN, $(Pb_{1-x}La_x)(Zr_yTi_{1-y})O_3$ (PLZT), $Sr_{5-x}Ba_xNb_{10}O_{30}$ (SBN)), antiferroelectric ($PbZrO_3$ (PZ), $Pb(Co_{1/2}W_{1/2})O_3$, (PCW), $Pb(Fe_{2/3}U_{1/3})O_3$ (PFU)) and non polar ($BaZrO_3$ (BZ), $(K_{3/4}Bi_{1/4})(Zn_{1/6}Nb_{5/6})O_3$ (KBiZnN)), of perovskite type structure (BT, PT, PMN, PZN, PSN, PLZT, PZ, PLW, PFU, BZ, KBiZnN) and of tetragonal bronze type structure (SBN), ordered, partially ordered and disordered of (A'A")(B'B")O_3, A(B'B")O_3 and another were the material of investigations.

Samples for investigations have been obtained by classic ceramic technology and by hot pressing method in conditions presented in our previous papers [e.g. 2]. Technological conditions substantially influence on the density of ceramics: from $\rho = (0.90 \div 0.93)\rho_{\mathrm{rtg}}$ (for classic technology) to $\rho > 0.96\rho_{\mathrm{rtg}}$ (for hot pressed ceramics). The increase of density influence on the value of dielectric permittivity at room temperature ($T_r = 293\,\mathrm{K}$) well as at T_m temperature. The degree of the diffusion of the phase transition (δ) in ferroelectric and antiferroelectric solid solutions decreases with increasing density (up to $\rho = 0.92\rho_{\mathrm{rtg}}$). For samples with $\rho > 0.92\rho_{\mathrm{rtg}}$ the degree of diffusion does not depends neither on conditions of deposition or on the method of sintering. In temperature range $T > T_m$ dielectric permittivity changes according to equation

$$1 - \varepsilon = \frac{1}{\varepsilon_m} + \frac{(T - T_m)^2}{2\varepsilon_m \delta}\,. \tag{28}$$

With increasing dielectric permittivity caused by increasing density of samples increase also the values of electrostriction coefficients M_{ij}.

Furthermore during the experimental investigations there were stated the following relations:

1) The values of electrostriction coefficients (Q_{ijkl}, Q_h) depend not only on the chemical composition of perovskite type oxides but first of all on the degree of ordering of

cations in solid solutions A(B'B")O_3 (i.e. increase after transition from disordered state through simple (ABO_3) to ordered state):

- simple compound (for example $BaTiO_3$) :$Q_h \approx 0.02\,\mathrm{m}^4/\mathrm{C}^2$;
- ordered solid solution (for example $Pb(Co_{1/2}W_{1/2})O_3$) :$Q_h \approx 0.027\,\mathrm{m}^4/\mathrm{C}^2$;
- partially ordered solid solution (for example $Pb(Sc_{1/2}Nb_{1/2})O_3$) :$Q_h \approx 0.008\,\mathrm{m}^4/\mathrm{C}^2$;
- disordered solid solution (for example $Pb(Mg_{1/3}Nb_{2/3})O_3$) :$Q_h \approx 0.006\,\mathrm{m}^4/\mathrm{C}^2$.

2) With increasing degree of ordering of cations in perovskite type oxides increases Q_h, while in ferroelectrics and antiferroelectrics decreases Curie–Weiss constant (C). The product of Curie–Weiss constant (C) and hydrostatic coefficient of electrostriction (Q_h) is approximately constant for all ferroelectric and antiferroelectrics perovskite type oxides:

$$Q_h \cdot C = (3.1 \pm 0.6) \cdot 10^3\,\mathrm{m}^4\mathrm{C}^{-2}\mathrm{K}. \tag{29}$$

This relation allows to estimate the value of Q_h for ferroelectrics and antiferroelectrics if the value of Curie–Weiss constant (C) is known (for example from the dependency $\varepsilon^{-1}(T)$ in temperatures higher than T_c (or T_m):

- simple compound (for example $BaTiO_3$) :$C = 1.5 \cdot 10^5\,\mathrm{K}$,
- ordered solid solution (for example $Pb(Co_{1/2}W_{1/2})O_3$) :$C = 1.2 \cdot 10^5\,\mathrm{K}$,
- partially ordered solid solution (for example $Pb(Sc_{1/2}Nb_{1/2})O_3$:$C = 3.5 \cdot 10^5\,\mathrm{K}$,
- disordered solid solution (for example $Pb(Mg_{1/3}Nb_{2/3})O_3$) :$C = 4.7 \cdot 10^5\,\mathrm{K}$.

3) The value of hydrostatic electrostriction coefficient is approximately proportional to square of linear expansion coefficient:

$$\begin{aligned} Q_h &\sim \lambda^2, \\ \lambda &= (3.8 \pm 0.4) \cdot 10^{-5} Q_h^{0.5} \quad [\mathrm{K}^{-1}]. \end{aligned} \tag{30}$$

In perovskite solid solution the value of λ decreases with increasing degree of disorder of cations:

- simple compound :$\lambda \approx 5.88 \cdot 10^{-6}\,\mathrm{K}^{-1}$,
- ordered solid solution :$\lambda \approx 6.72 \cdot 10^{-6}\,\mathrm{K}^{-1}$
- partially ordered solid solution :$\lambda \approx 3.78 \cdot 10^{-6}\,\mathrm{K}^{-1}$
- disordered solid solution :$\lambda \approx 3.36 \cdot 10^{-6}\,\mathrm{K}^{-1}$

Very small value of λ in wide temperature range is typical for ferroelectric perovskite structure relaxors with low degree of ordering of cations. For such materials low value of hydrostatic electrostriction coefficient (Q_h) is also characteristic, independent on temperature. It means that it is not possible to obtain materials with high Q_h and low λ.

4) The highest stability of hydrostatic electrostriction coefficient (Q_h) is characteristic for ferroelectrics with diffused phase transition and ferroelectric relaxors. Estimated from Eq. (24) values k_e oscillated in the range from 0.4% K^{-1} for three component solid solution PMN-PT-BZN ($M_{13} \approx 12 \cdot 10^{-16}\,\mathrm{m}^2/\mathrm{V}^2$), to 3.5% K^{-1} for two component solid solution PMN-PT ($M_{13} \approx 0.2 \cdot 10^{-16}\,\mathrm{m}^2/\mathrm{V}^2$). In order to decrease the temperature coefficient of electrostriction (k_e) we should take into account that the increase of degree of diffusion of the phase transition leads to decrease of ε_r^σ and as a consequence to

decrease of the electrostriction coefficient M_{ij}. It means that it is not possible to obtain electrostrictive ceramics with high M_{ij} and simultaneously with low temperature coefficient k_e.

5) The value of the product $Q_{ij}\varepsilon_0^2(\varepsilon_r^\sigma - 1)^2 = M_{ij}$ used for estimation of the electrostrictive deformation is very high for ferroelectric relaxors i.e. solid solution with disordered structure. Such materials are obviously used as electrostrictive materials because in spite of their low Q_{ij} value their dielectric permittivity ε_r^σ in the surrounding of T_m temperature is very high (where T_m temperature in which dielectric permittivity reaches their maximal value). For example in pure PMN $\varepsilon_m = 16470$; $Q_{11} = 0.006\,\mathrm{m^4/C^2}$, $\varepsilon_0 = 8.854 \cdot 10^{-12}\,\mathrm{F/m}$, and as a result $M_{11} = 1.31 \cdot 10^{-16}\,\mathrm{m^2/V^2}$, however for solid solution 0.975 PMN – 0.025 PT: $\varepsilon_m = 19390$, $Q_{11} = 0.011\,\mathrm{m^4/C^2}$, and $M_{11} = 3.5 \cdot 10^{-16}\,\mathrm{m^2/V^2}$.

High values of M_{ij} electrostriction coefficients allows to obtain relative deformation of order $\eta \approx 10^{-3}$ in low electric fields.

The regularities in ε_r^σ, Q_{ij}, M_{ij}, k_e, λ and C related with different degree of cations ordering may be explained on the base of *ordered and disordered crystal structures model* for complex $A(B'_{1/2}B''_{1/2})O_3$ oxides. According to this model in ordered structure small B ions surrounded by bigger A and O ions have relatively small free space than in disordered structure. It leads to higher polarization related to the unit of electric field tension, and as a consequence to higher values of dielectric permittivity and Curie–Weiss constant. As a result the deformation related to the unit of polarization is smaller what gives smaller value of electrostriction coefficient Q_{ij}.

Regularities typical for ferroelectric relaxors presented in this work are in good agreement with results of investigations presented by another authors for example [5].

4. Conclusions

- In relaxor ferroelectrics and ferroelectrics with diffused phase transition (at $T > T_m$) the effect of electrostriction (deformation of the mechanically free sample ($\sigma_{\text{ext}} = 0$) in external electric field ($\eta \sim E^2$) or appearance stresses proportional to the square of electric field ($\sigma \sim E^2$) in mechanically short circuited sample ($\eta = 0$)) are very high. The main cause of observed electromechanical effects is arising in investigated samples strong field induced polarization and as a result we can write that $\eta \sim P_{\text{ind}}^2$ (for $\sigma_{\text{ext}} = 0$) and $\sigma \sim P_{\text{ind}}^2$ (for ($\eta = 0$)).
- Strong electrostrictive effect in ferroelectric relaxors and in ferroelectrics with diffused phase transition has wide practical applications.
- The electromechanical transducers based on electrostrictive ceramics can be applied in microengines, microactuators, micromanipulators, etc. One can mention the following unique advantage of electrostrictive ceramics namely:

1) high value of dielectric constant ($\varepsilon \approx 10^4$);

2) small coefficient of linear thermal expansion (λ);

3) independence of the deformation sign on direction of the external electric field intensity (simplified control of the deformation by electric field);

4) ability of reaching high tensile stresses ($< 4 \cdot 10^3\,\mathrm{N/cm^2}$);

5) high value of the relative strain ($\eta \approx 10^{-3}$);
6) low inertia (short turn on- and off-time: $\sim 10\,\mu s$);
7) small driving power;
8) absence of the remanent strain;
9) absence of the electromechanical hysteresis.

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