CHAPTER - 5

PIEZOELECTRIC PROPERTIES OF MODIFIED

(NaK) NbO₃ CERAMICS
5.1 INTRODUCTION

5.1.1 Piezoelectricity

A number of materials with acentric structure develop an electric polarization in response to mechanical stress. The magnitude of the charge is linearly proportional to the applied stress through the piezoelectric coefficient $d$ and the sign of the charge can be changed by reversing the direction of the stress.

The Figure of merit of the piezoelectric materials is the Coupling factor $K_p$, the square of which gives the efficiency of the Conversion of electrical energy to mechanical energy and vice versa. Extremely high coupling factors represent the great advantage of ferroelectric ceramics, which are applied wherever high piezoelectric activity is needed. Polycrystalline materials are generally isotropic after densification but can be made piezoelectric, if the material is ferroelectric.

A polar axis is introduced by electroding the ceramic and applying a high electric field at temperatures just below the Curie temperature. Polycrystalline ceramic piezoelectrics are easily fabricated in desired shape and are less expensive than single crystals.
The polarization \( P_i \) developed in a piezoelectric under applied stress \( T_j \) is

\[
P_i = d_{ij} T_j
\]

The converse piezoelectric effect is given by \( S_i = d_{ji} E_j \) where \( S_i \) is the strain component, \( E_j \) is the applied electric field and \( d_{ij} \) is the piezoelectric coefficient expressed in coulombs per Newton. \( i \) and \( j \) refer to orthogonal directions within the specimen. In ceramics poling direction is taken as \( X_3 \).

For hydrophones a useful figure of merit is the piezoelectric voltage coefficient

\[
S'_{ij} = d_{ij} / \varepsilon_i
\]

where \( \varepsilon_i \) is the dielectric permittivity of the material.

A ceramic is an agglomeration of small crystals, fitted together in a random way. As a ceramic is cooled from the high-temperature paraelectric state to the ferroelectric state, the unit cell deforms usually with a lengthening in the direction of the polar axis. Intergranular stresses are minimized by the formation of domains, regions within each grain that have common orientation of the spontaneous dipole. The polarization directions of domains are basically high temperature symmetry axes (such as \( \langle 001 \rangle \), \( \langle 110 \rangle \), or \( \langle 111 \rangle \)). Angles between the dipoles of adjacent domains are those between such symmetry axes e.g. \( 90^\circ \), \( 180^\circ \), \( 71^\circ \) etc., modified slightly by the ferroelectric deformation. Crystallographically, domain structure is a type of twinning.
It is evident that since the original crystallographic directions of the grains in the ceramic were oriented at random, the line-up of polar axes can be as perfect as in a single crystal of the material. A good indication of this dipole alignment in the measured value of polarization. Baerwald, assuming a random initial orientation of the grains and domains, and as complete a dipole alignment as is allowed by the grain orientations, has calculated the fraction of the single crystal polarization that can be realized in pseudocubic ceramics of various symmetries. With a larger number of allowable polar directions, the maximum deviation of the polar axis of a grain from the average polar direction will be smaller, and the lowering of the polarization will be minimized, assuming optimum alignment. The proportion of the single crystal distortion which is realized as strain in a fully oriented ceramic is also given in Table 5.1.

**TABLE - 5.1**

<table>
<thead>
<tr>
<th>Crystal symmetry and polar axis</th>
<th>No. of equivalent directions</th>
<th>Fraction of single crystal polarization that can be realized ideally</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetragonal [001]</td>
<td>6</td>
<td>0.831</td>
</tr>
<tr>
<td>Orthorhombic [110]</td>
<td>12</td>
<td>0.912</td>
</tr>
<tr>
<td>Rhombohedral [111]</td>
<td>8</td>
<td>0.866</td>
</tr>
</tbody>
</table>
In fact, the practical dipole orientation in a ceramic does not reach the fully oriented value for several reasons. Intergranular stresses tend to keep the polarity of the domains in their initial orientation, thus preventing switching to the most favourable direction. Imperfections cause strains within the grains, with the same result. Ideally, the ceramic which should most closely remain free of stresses caused by switching would be one in which the domains switched only by 180°, involving no external shape change. As an example of what is realized in practice, well poled BaTiO₃ ceramic has a polarization of $8 \times 10^{-6}$ C/cm$^2$ versus a single crystal value of $26 \times 10^{-6}$ C/cm$^2$. This is equivalent to switching of all domains where 180° switching gives the closest possible alignment to the field direction, but with no more than 12 per cent of the remaining domains switching by 90° to a direction closer to the field direction.

The effect of symmetry on the piezoelectric matrices relating strain and electric field were worked out by Voigt before the turn of the century and are fully discussed by Cady. Three crystal classes contain most of the ferroelectric compounds which have proved important in the field of piezoelectric ceramics: 4 mm (tetragonal), 3 m (rhombohedral) and mm2 (orthorhombic). A piezoelectric ceramic, however, has only one type of piezoelectric matrix regardless of the symmetry of the constituent...
crystals. The ceramic is initially isotropic. This isotropy is destroyed in the direction of the poling field, but is maintained in the plane at right angles to it. By analogy with the clause 4 mm and 6 mm, we can express the symmetry of any initially random ceramic which has been poled to give a piezoelectric body as \( \infty \) mm (cylindrical polar symmetry). For the dielectric, piezoelectric and elastic constants, a 6-fold symmetry axis is equivalent to the infinite-fold axis. The tensors of piezoelectric, elastic and dielectric constants for these crystal classes are given in Appendix.

The equations of state of the piezoelectric effect relate the elastic variables, stress and strain, to the electric variables, field and displacement. Dielectric displacement \( (D) \) is the electric flux density per unit area, having the properties of a vector. Strain \( (S) \) and stress \( (T) \) are tensor magnitudes.

The complete equations relating to the electric and elastic variables are:

\[
\begin{align*}
D_1 &= \varepsilon_1 E_1 + d_{15} T_5 \\
D_2 &= \varepsilon_1 E_2 + d_{15} T_4 \\
D_3 &= \varepsilon_3 E_3 + d_{31} (T_1 + T_2) + d_{33} T_3 \\
S_1 &= S_{11}^E T_1 + S_{12}^E T_2 + S_{13}^E T_3 + d_{31} E_3 \\
S_2 &= S_{11}^E T_2 + S_{12}^E T_1 + S_{13}^E T_3 + d_{31} E_3 \\
S_3 &= S_{13}^E (T_1 + T_2) + S_{33}^E T_3 + d_{33} E_3
\end{align*}
\]
Here, the subscript 3 refers to the poling axis and 1 and 2 refer to arbitrarily chosen orthogonal axes in the plane normal to 3. Subscripts 4, 5 and 6 refer to shear stress and strain in planes normal to the 1, 2 and 3 axes respectively. A shear strain, such as $S_4$, is a measure of the change of angle between the two initially orthogonal axes in the plane perpendicular to axis 1. Conventionally, the first subscript of the $d$ constant gives the electrical direction (field or dielectric displacement) while the second gives the component of mechanical deformation or stress. Since all the effective stress and field components appear on the right-hand side of equations, the constants have the nature of partial derivatives. The permittivities $\varepsilon_1$ and $\varepsilon_3$ give the electric displacement while the stresses remain constant, usually zero, they are the free permittivities sometimes indicated by the superscript T. Similarly, the elastic compliances $S_{11}$ denote the interaction of a strain and a stress, with the condition of constant field, they are the short-circuit compliances marked, if necessary, by the superscript E, which indicates constant (usually zero) field. Moreover, each elastic coefficient $S_{11}$ relates to

\[
S_4 = S_{44}^E T_4 + d_{15} E_2 \\
S_5 = S_{44}^E T_5 + d_{15} E_1 \\
(S_6 = S_{66}^E T_6)
\]
application of a single stress component while the others are kept fixed (condition of no lateral restraint). Within this limitation, stress and strain are interchangeable, \( S_{31} = S_{13} \). Rigorously the permittivity \( \varepsilon \) is also a tensor and should have two subscripts. However, for ceramics without oblique forces or fields one subscript is sufficient to describe the system completely. Note also that a shear strain in a plane perpendicular to the polar axis is not excited piezoelectrically, the last equation is included only for completeness. The coefficient of the equations of state are Conventionally arranged in a 9 x 9 matrix wherein each column refers to one elastic or electric field component as independent variable and each row to one geometric strain or electric displacement component as dependent variable. For cylindrical symmetry only ten are independent nonzero terms and the corresponding matrix of Table 5.2 (in which the relative dielectric constant \( K = \varepsilon / \varepsilon_0 \) is used rather than permittivity \( \varepsilon \)).

Matrices analogous to that shown in Table 5.2 for \( d_{ij} \) also apply to the other piezoelectric constants \( e_{ij}, e_{ij}', h_{ij} \) and appropriate electromechanical coupling factors.

The planar isotropy of poled ceramics is expressed in their piezoelectric constrains by the equalities \( d_{32} = d_{31} \) and \( d_{24} = d_{15} \). The former means that an electric field parallel to the poling axis (3) interacts in the same way with axial stress along either the Y-axis (2) or the X axis (1). The
second relation states that an electric field parallel to the Y axis interacts in the same way with a shear in the YZ plane as a field along the X axis with a shear in the XZ plane. Similar relations hold for the elastic constants, with \( s_{13} = s_{23} \), because of the isotropy in the plane perpendicular to the polar axis.

**TABLE - 5.2**

Elastic, dielectric *, and piezoelectric matrices for crystal class 6 mm and cylindrical symmetry

\[
\begin{array}{cccccc}
S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\
S_{12} & S_{11} & S_{13} & 0 & 0 & 0 \\
S_{13} & S_{13} & S_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & S_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & 2(S_{11} - S_{12}) \\
\end{array}
\]

\[
\begin{array}{cccccc}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{15} & 0 & 0 \\
d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \\
\end{array}
\]

* Since only diagonal terms occur in these crystal classes, a single subscript is used.
5.1.2 Measurements

The principal evaluation of the piezoelectric activity was a measure of the radial coupling coefficient of the disks. This was determined by measuring the resonant and antiresonant frequencies of the radial fundamental mode using a scheme similar to that of Mason $5, 6$.

Poled ferroelectric ceramics in their normal operating range show substantially linear relations between stress and strain components on the one hand and electric field and displacement component on the other called piezoelectric ceramics. In addition, mechanical and dielectric loss factors are functions of mechanical strain and electric field respectively. One of the fundamental measurements for piezoelectric ceramics is that of determining the planar coupling factor $k_p$. The term planar is used because the stress is two-dimensional (plane) isotropic. The planar coupling factor is obtained from the fundamental mode $f_p$ and $f_s$ of a thin disc with faces perpendicular to the $z$ axis as follows $7$

\[
\frac{k_p^2}{1 - k_p^2} = \frac{(1 - \sigma_E) J_1 \left[ \eta_1 (1 + \Delta f/f_s) \right] - \eta_1 (1 + \Delta f/f_s) J_0 \left[ \eta_1 (1 + \Delta f/f_s) \right]}{(1 + \sigma_E) J_1 \left[ \eta_1 (1 + \Delta f/f_s) \right]}.
\]
where

\[ J_0 = \text{Bessel function of first kind and zero order} \]

\[ J_1 = \text{Bessel function of first kind and first order} \]

\[ \eta_1 = \text{lowest positive root of } (1 + a^E) J_1 (\eta) = \eta J_0 (\eta) \]

for \( a^E = 0.31, \eta_1 = 2.05 \)

The resonance method is covered in the IRE standards on piezoelectric crystals, 1958\(^8\). The simplified circuit is shown in Figure 5.1. The signal generator should have an output impedance lower than the minimum impedance of the test specimen. The terminating resistance (\( R_T \)) should be lower than the minimum impedance of the test specimen. The frequency at maximum impedance can be determined accurately only if the harmonic content of the signal generator is relatively low. The effective shunt or fringing capacitance across the test specimen should be very low compared to the capacitance of the test specimen. The shunt capacitance affects the determination of the frequency at maximum impedance \( f_n \) but not the frequency at minimum impedance \( f_m \) and its effect is such that the apparent maximum impedance frequency is lowered. The shielding should be adjusted for the highest maximum - impedance frequency.

The planar coupling factor \( (K_p) \), frequency constant \( (N_p) \) the mechanical quality factor \( (Q_m) \) which represents the
FIG. 5.1: Transmission network for determination of $f_m$ and $f_n$ of piezoelectric continue vibrator.

FIG. 5.2: PLOT OF $K_P$ AND $K_{31}$ Vs. IONIC RADIUS.
reciprocal proportion of energy consumed by the material during the electrical and mechanical energy interconversion were computed by the following equations

\[
\frac{K_p^2}{1 - K_p^2} = \frac{2.51 (f_a - f_r)}{f_r}
\]

\[
N_p = f_r d
\]

\[
Q_M = \frac{f_a^2}{[2 \pi f_c f_r (f_a^2 - f_r^2)]}
\]

where

- \(f_r\) and \(f_a\) are resonance and anti-resonance frequencies
- \(d\) = diameter of the disk in metres
- \(c_0\) = capacitance measured at 1 KHz
- \(R_0\) = resistance at resonance

The transverse coupling factor \((K_{31})\), the two transverse piezoelectric coefficients, the charge coefficient \((d_{31})\) and voltage coefficient \((g_{31})\) were determined from the following expressions given by Mason\(^5\). The first subscript 3 refers to the direction of the stress and the second subscript 1 refers to the direction of the strain.
\[ d_{31} = \frac{k_p \left( (1 - \sigma) \varepsilon_o \varepsilon_T \right)^{1/2}}{2 \gamma_o^E} \]

\[ g_{31} = \frac{d_{31}}{\varepsilon_o \varepsilon_T} \]

\[ k_{31}^2 = \frac{(1 - \sigma \varepsilon)}{2} k_p^2 \]

where

\( \varepsilon_o, \varepsilon_T \) are the permittivity in vacuum and relative dielectric constant at room temperature determined at 1 kHz respectively. \( \sigma \) is the Poisson's ratio taken as 0.27.

\[ \gamma_o^E = \frac{\left[ 2 \pi a \tau \right]^2}{2.03 [\rho (1 - \sigma^2)]} \]

\( \gamma_o^E \) is the elastic modulus.

\( a \) is the disk radius in metres.

\( \rho \) is the density in Kg/m³.

The piezoelectric strain constant \( d_{33} \) values are measured with Berlincourt \( d_{33} \) meter.
The piezoelectric voltage constant ($g_{33}$) may be calculated \(^\text{as}^{15}\)

\[
g_{31} = \frac{d_{31}}{\varepsilon_{33} T}
\]

\[
g_{33} = \frac{d_{33}}{\varepsilon_{33} T}
\]

Although piezoelectricity in NaK NbO\(_3\) is reported by several workers, the effect of rare earth doping has not been investigated. In this chapter the effect of rare earth doping on the piezoelectric properties is studied.

Sodium potassium niobate ceramics are widely used for transducer applications. The low dielectric constants and high coupling coefficients of this system make these materials promising for use in ultrasonic delay lines especially where thin sectioned plates are required, as in high-frequency thickness extensional or thickness shear mode transducers. At the frequencies employed thin transducer sections must be used. With high dielectric constant materials in thin sections any appreciable electroded area results in high capacitance. The associated problems in circuitry are simplified if the capacitance of the transducer can be kept low. At the same time, high
Electromechanical coupling coefficients are desirable in order to obtain large band widths. Dielectric measurements in this system were first made on single crystals of each end member. Several investigators have studied this system both in single crystals and ceramics. Piezoelectric data in this system were first reported by Egerton and Dillon. Piezoelectric ceramics based on the Perovskite alkali niobates have been shown to support higher sound velocities than conventional piezoelectrics based on lead titanate zirconate.

5.2 SPECIMEN PREPARATION

The specimens were prepared by high temperature solid state reaction as described in Chapter 4. Sintered specimens are machined into discs of 10 - 12 mm diameter and 1 - 2 mm thickness, polished and furnished with fired silver paste electrodes.

5.3 POLARIZATION

The specimens were poled by the method of Belding and McLaren in silicon oil bath between 80 and 120°C for 1/2 hour under the field strength of 30 kV/cm. High viscous silicon oil of viscosity 200 centistokes with electric resistance of 13.78 kV/mm was used as oil bath. The bath temperature was slightly decreased during a 30 minute period to maintain
constant specimen resistivity. The specimens were taken out from the hot oil immediately after the removal of the poling electric field.

Piezoelectric and dielectric measurements were carried out on specimens 24 hours after poling, in accordance with the IRE standards\textsuperscript{17}.

5.4 EXPERIMENTAL

Piezoelectric coupling coefficients are measured by resonance-antiresonance technique\textsuperscript{6} using an Hewlett Packard L.F. Impedance Analyzer model 4192 A. The probe fixture model No.16095 A was used as accessories for connecting the sample holder to the Impedance Analyzer with the aid of BNC adaptor.

5.5 RESULTS AND DISCUSSION

The electric and electromechanical measurements were made by the resonance - antiresonance method in radial mode vibrations. The piezoelectric coupling coefficients are shown in Table 5.3 and 5.4. The radial coupling coefficient ($K_p$) is found to be 17 per cent for unmodified sample. It is decreased to 13 per cent with $\text{Pr}^{3+}$ addition and $\text{Sm}^{3+}$ addition and 14 per cent with $\text{Ce}^{3+}$ addition. However, the mechanical quality factor $Q_M$ and frequency constant are more pronounced with rare earth doping. Both the $Q_M$ and $N_P$ values are increasing with the
<table>
<thead>
<tr>
<th>Sample</th>
<th>Ionic radius of rare earth (Å)</th>
<th>$K_P$</th>
<th>$K_{31}^{\prime}$</th>
<th>$Y_{31}^{\prime}$ ($10^{11}$) N/m²</th>
<th>$Q_M$</th>
<th>$N_P$ Hz-m</th>
<th>$d_{31}$ ($10^{-12}$) C/N</th>
<th>$\varepsilon_{31}$ ($10^{-3}$)</th>
<th>$d_{33}$ ($10^{-12}$) C/N</th>
<th>$\varepsilon_{33}$ ($10^{-3}$) v-m/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Na$<em>{0.5}$K$</em>{0.5}$NbO$_3$</td>
<td>--</td>
<td>0.17</td>
<td>0.102</td>
<td>2.85</td>
<td>83</td>
<td>2749</td>
<td>25</td>
<td>6.3</td>
<td>29</td>
</tr>
<tr>
<td>II</td>
<td>Sm$<em>{0.05}$Na$</em>{0.35}$K$_{0.5}$NbO$_3$</td>
<td>0.964</td>
<td>0.13</td>
<td>0.078</td>
<td>3.19</td>
<td>49</td>
<td>2983</td>
<td>14</td>
<td>1.5</td>
<td>27</td>
</tr>
<tr>
<td>III</td>
<td>Pr$<em>{0.05}$Na$</em>{0.5}$K$_{0.35}$NbO$_3$</td>
<td>1.013</td>
<td>0.13</td>
<td>0.078</td>
<td>35.8</td>
<td>420</td>
<td>4930</td>
<td>1.79</td>
<td>0.97</td>
<td>--</td>
</tr>
<tr>
<td>IV</td>
<td>Ce$<em>{0.05}$Na$</em>{0.5}$K$_{0.35}$NbO$_3$</td>
<td>1.034</td>
<td>0.14</td>
<td>0.084</td>
<td>5.28</td>
<td>98</td>
<td>3591</td>
<td>1.7</td>
<td>45</td>
<td>9.5</td>
</tr>
<tr>
<td>Composition</td>
<td>$\epsilon_{RT}$</td>
<td>$\epsilon_{TG}$</td>
<td>$T^\circ C$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>I $\text{Na}<em>{0.5}\text{K}</em>{0.5}\text{NbO}_3$</td>
<td>274</td>
<td>1649</td>
<td>401</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II $\text{Sm}<em>{0.05}\text{Na}</em>{0.35}\text{K}_{0.5}\text{NbO}_3$</td>
<td>654</td>
<td>1915</td>
<td>441</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III $\text{Pr}<em>{0.05}\text{Na}</em>{0.5}\text{K}_{0.35}\text{NbO}_3$</td>
<td>172</td>
<td>1196</td>
<td>395</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Pr}<em>{0.10}\text{Na}</em>{0.5}\text{K}_{0.20}\text{NbO}_3$</td>
<td>674</td>
<td>1418</td>
<td>360</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV $\text{Ce}<em>{0.05}\text{Na}</em>{0.5}\text{K}_{0.35}\text{NbO}_3$</td>
<td>67</td>
<td>516</td>
<td>333</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
increase of ionic radius of the rare earth and high values are obtained for \( \text{Pr}^{3+} \) composition. The mechanical quality factor \( Q_M \) is one of the most important factors for an ultrasonic transducer. Low \( Q_M \) piezoelectric ceramic is suitable for wide band ultrasonic transducers. The transverse coupling factor \( K_{31} \) is quite low for these ceramics. For unmodified samples it is about 0.102. It decreases to 0.078 for \( \text{Sm}^{3+} \) and \( \text{Pr}^{3+} \) doped samples and increases to 0.084 for \( \text{Ce}^{3+} \) composition. The elastic modulus \( Y_E \) attains the highest value in Praseodymium modification as can be seen from Table 5.3. For this composition \( Q_M \) is highest. The charge coefficient and voltage coefficient decreases with rare earth addition. The piezoelectric constant values for the unmodified compositions are in good agreement with the literature values \(^{13,18}\).

The variation of piezoelectric coefficients with ionic radius is shown in Figures 5.2 and 5.3. Both the planar coupling factor and transverse coupling factor increase steadily with the increase of ionic radius of the rare earth ion. There is a steep increase in the \( Q_M \) and \( N_P \) values initially and then decreases with the increase of ionic radius of the rare earth ion. Both the \( d_{33} \) and \( g_{33} \) values are gradually increasing with the increase of ionic radius of the rare earth. Maximum value of elastic modulus \( Y_E \) was observed in \( \text{Pr}^{3+} \) composition. However, all the values are in order of \( 10^{11} \, \text{N/m}^2 \).
FIG. 5.3: VARIATION OF PIEZOELECTRIC COEFFICIENTS WITH IONIC RADIUS.
Ferroelectric ceramics consist of many randomly oriented crystallites. For any crystallite there are certain allowable directions for the polar axis and a region in which the polar axis is oriented in one direction only is a domain. In a tetragonal crystal such as barium titanate and lead titanate zirconate both 180° and 90° domain reorientations occur under the influence of a high d.c. field and the ceramic becomes polar and exhibits piezoelectric properties.

With perovskite ferroelectrics and dimension of the unit cell along its polar axis is greater than that along the other allowable directions for the polar axis. For this reason, any domain reorientation by other than 180° is marked by a change in the external dimensions of a test specimen. With tetragonal symmetry electrical stresses can cause both 180° and 90° domain reorientations. But mechanical stress can cause only 90° switching. In the case of orthorhombic symmetry 1/12th of the domains are oriented 180° to the polar axis 1/6th 90°, 1/3rd 60° and 1/3rd 120° with respect to polar axis.

Normally introduction of rare earth ions in the perovskite lattice lead to sharp decrease in $T_c$. But in Sm and Pr doped compositions $T_c$ is quite high. Also these modifications exhibit high value of $\varepsilon_{RT}$ and $\varepsilon_{Tc}$. Introduction of rare earth ion of higher valency the Na or K which it substitutes leads to A position vacancies. It is well known that A position vacancies
facilitates domain motion. All effects due to rare earth doping can be largely attributed to an increased mobility of domain walls. In this way additional contributions to the dielectric displacement develop leading to a rise of dielectric constant. As more number of 90° domains reorient along the poling direction the planar coupling factor decreases. The relative increase in room temperature dielectric constant is probably due to more number of domains contributing to polarization in the C direction. High value of $T_c$ confirm the above hypothesis. Frequency constant $N_p$ is enhanced in rare earth doped samples. It can be concluded that in $(\text{NaK})\text{NbO}_3$ rare earth doping leads to stabilization of ferroelectric structure and decreases $K_p$. Frequency constant is enhanced. The results with Ce doping need further investigations.
REFERENCES


