

Elastic, Dielectric and Piezoelectric Coefficients of Domain Engineered $0.70\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-}0.30\text{PbTiO}_3$ Single Crystal

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Abstract. A complete set of elastic, dielectric and piezoelectric coefficients for the domain engineered $0.70\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-}0.30\text{PbTiO}_3$ [PMN-30%PT] single crystal was measured by a hybrid method combining ultrasonic and resonance techniques. At room temperature, the PMN-30%PT single crystal has rhombohedral symmetry. After being poled along [001] of the cubic axes, four degenerate domain states are present, which means that the system is macroscopically pseudo-tetragonal. The complete data set of material constants was determined for this domain engineered system based on the effective tetragonal 4mm symmetry. The sources of experimental errors and the error propagation for derived constants were analyzed in detail. Based on the analysis, an improved characterization scheme was formulated to minimize the relative errors of derived constants. In this optimized scheme, the elastic stiffness coefficients under constant electric field c_{ij}^E , piezoelectric stress coefficients d_{ij} and dielectric permittivities under constant stress ϵ_{ij}^T were first determined, from which all other constants were derived to ensure self-consistency of the data set. It was found that the electromechanical coupling coefficient k_{33} for the domain engineered sample is about 92% and the piezoelectric constant d_{33} is 1980 pC/N. Because PMN-30%PT composition is slightly away from the Morphotropic Phase Boundary (MPB), its properties exhibit much better stability. An overall comparison among all measured data sets for the domain engineered PMN-PT and PZN-PT single crystals is provided.

INTRODUCTION

The relaxor based $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ [PZN-PT] and $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ [PMN-PT] ferroelectric single crystal systems exhibit superior electromechanical property at room temperature after being poled along [001] direction of the cubic coordinates [1]-[5]. The electromechanical coupling factor k_{33} is about 0.94 for PMN-33%PT single crystal. The measured piezoelectric coefficient d_{33} of PMN-33%PT and PZN-8%PT samples could reach 2820 pC/N and 2900 pC/N, respectively. Compared to modified $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ (PZT) ceramics, which have been dominating piezoelectric applications for more than 40 years, these single crystal systems possess extremely attractive application potential in making large displacement actuators, high sensitivity medical ultrasonic imaging transducers with superior broadband characteristics, and many other electromechanical devices.

It is very useful for theoretical studies and device designs to obtain complete electromechanical coefficient data sets of these crystals. The resonance methods described in IRE and IEEE standards can be used to measure these piezoelectric single crystals. However, if the symmetry of the crystal is lower, the measurement process becomes complicated. More samples must be prepared because there are more independent physical constants need to be measured. Moreover, the resonance method requires the measured sample to have large aspect ratio in order to avoid mode interference. For example, it has been proved that the aspect ratio should be larger than 20 for a shear piezoelectric vibrator to obtain a nearly pure shear mode, and the influence of other low frequency mode could not be totally eliminated even at such a large aspect ratio [6]. Since only small size uniform crystals are available for some new crystals, it is difficult to meet the large aspect ratio requirement.

The other method for characterizing piezoelectric single crystal is the ultrasonic method. By sending longitudinal and shear waves into specified orientations of a crystal all material constants can be measured. The ultrasonic method is performed under non-resonance condition. Hence, it is more accurate than resonance method since there are no mode interference effects. The advantage of ultrasonic method is that the measured samples require only one set of precisely aligned faces and no aspect ratio limitation. However, the solution of the Christoffel equation for materials with low symmetry is usually coupled, and large errors may be resulted while extracting derived constants from some mixed modes.

Combing the advantages of ultrasonic and resonance techniques, a hybrid method was developed to characterize those single crystals, and the complete electromechanical coefficients have been successfully measured for PZN-4.5%PT, PZN-8%PT and PMN-33%PT single crystals [7-10]. In characterization of these single crystals, we noticed that although there are four equivalent kinds of constitutive equations for a piezoelectric system, some relationships become unstable because of the large k_{33} , d_{33} and d_{31} . It is very important to choose proper equations and characterization scheme to minimize the errors.

In this paper, the causes of measurement errors and the error propagation condition using different constitute equations to derive other constants were analyzed in detail. Based on the analysis, an improved characterization scheme was proposed to minimize the relative errors of derived constants. Using this characterization scheme, a complete set of elastic, dielectric and piezoelectric coefficients for the domain engineered $0.70\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3 - 0.30\text{PbTiO}_3$ [PMN-30%PT] single crystal was measured.

MEASUREMENT PROCEDURE

For the tetragonal symmetry, there are total eleven independent material coefficients: 6 elastic, 3 piezoelectric and 2 dielectric constants [11]. In the ultrasonic measurements, a 15MHz longitudinal wave transducer (Ultran Laboratories, Inc.) and a 20MHz shear wave transducer (Panametrics Com.) were used for the pulse-echo measurements. The electric pulses used to excite the transducer were generated by a Panametrics 200MHz pulser/receiver, and the time of flight between echoes were measured using a Tektronix 460A digital oscilloscope. The phase velocities of

longitudinal and shear waves are measured in the three pure mode directions [100], [001] and [110]. Since shear waves could have their displacements parallel or perpendicular to the poling direction, we can measure 8 velocities total in those three pure mode directions. The relationships between these velocities and elastic stiffness constants, together with the measured phase velocity of PMN-30%PT single crystal are given in Table 1. It is seen that there are more than one method to determine c_{44}^D and c_{12}^E , which provides us with some consistency checks.

TABLE 1. The Relationships between Phase Velocity and Elastic Constants, and Measured Phase Velocity of Ultrasonic Waves in PMN-30%PT Crystal Poled in [001] Direction

v	$v_x^{[001]}$	$v_y^{[001]}$	$v_z^{[100]}$	$v_{s\perp}^{[100]}$	$v_{s\parallel}^{[100]}$	$v_z^{[110]}$	$v_{s\perp}^{[110]}$	$v_{s\parallel}^{[110]}$
$\rho v^2 =$	c_{33}^D	c_{44}^E	c_{11}^E	c_{66}^E	c_{44}^D	$\frac{1}{2}(c_{11}^E + c_{12}^E + 2c_{66}^E)$	$\frac{1}{2}(c_{11}^E - c_{12}^E)$	c_{44}^D
Velocity (m/s)	4620	2978	3800	2864	3100	4680	930	3100

Two length-extensional and one thickness resonance measurements were performed on an HP 4194A impedance/gain-phase analyzer to obtain the corresponding electromechanical coupling coefficients k_{33} , k_{31} and k_1 , as well as elastic compliance s_{11}^E , s_{33}^D and elastic stiffness c_{33}^D . The dielectric measurements were carried out at 1kHz using a Stanford Research System SR715 LCR Meter. From capacitance measurements, the free dielectric permittivity ϵ_{11}^T and ϵ_{33}^T were measured. Also, the piezoelectric strain constant d_{33} was checked by quasi-static method on a ZJ-2 Piezo Meter.

Combining all the above-mentioned measurements, the following material constants can be directly obtained: $c_{11}^E, c_{12}^E, c_{44}^E, c_{66}^E, c_{33}^D$ and c_{44}^D ; s_{11}^E and s_{33}^D ; ϵ_{11}^T and ϵ_{33}^T ; d_{33} as well as the coupling coefficients k_{33} , k_{31} and k_1 . Altogether 14 constants have been determined. Based on our detailed error analysis, an improved characterization scheme was developed to obtain a self-consistent complete data set of PMN-30%PT single crystal based on these direct measurements.

DERIVED CONSTANTS AND ERROR PROPAGATION

It is well known that if a quantity $q = f(x_1, x_2, \dots)$ is related to some quantities x_1, x_2, \dots , with uncertainties $\delta x_1, \delta x_2, \dots$, the uncertainty of q can be expressed as $\Delta q = \sum_i |\partial f / \partial x_i| \Delta x_i$ or $\Delta q = [\sum_i (\partial f / \partial x_i \Delta x_i)^2]^{1/2}$. Here we use the former expression, which provides the upper limit for the total error. In order to isolate all six independent elastic stiffness constants $c_{\alpha\beta}^E$ first, c_{33}^E and c_{13}^E need to be derived. The quantity c_{33}^E can be easily obtained from the measured c_{33}^D and k_1 by using the relation

$$c_{33}^E = c_{33}^D(1 - k_t^2) \quad (1)$$

The errors in the measurements of c_{33}^D and k_t , will propagate to c_{33}^E ,

$$\frac{\Delta c_{33}^E}{c_{33}^E} = \frac{\Delta c_{33}^D}{c_{33}^D} + 2\left(\frac{\Delta k_t}{k_t}\right)\left(\frac{k_t^2}{1 - k_t^2}\right) \quad (2)$$

If $k_t > 1/\sqrt{3}$, the error term $(\Delta k_t/k_t)$ is magnified. For PMN-30%PT, k_t is 0.62, so that $2k_t^2/(1 - k_t^2) = 1.24$, which will slightly enlarge the relative error $\Delta k_t/k_t$. Thus, error for c_{33}^E comes from two parts, the relative error of k_t and c_{33}^D . We found that in our experiments, the relative error of k_t is 1.1%, and the relative error of c_{33}^D from the ultrasonic measurement is 0.9% for a sample with a thickness of 5mm, so the relative error of c_{33}^E from Equation (1) could reach about 2.0% in the extreme circumstance.

In order to determine c_{13}^E we can use the formula:

$$c_{13}^E = -s_{13}^E(c_{11}^E + c_{12}^E)/s_{33}^E \quad (3)$$

which requires s_{13}^E and s_{33}^E to be determined first. The IEEE standard suggests s_{33}^E to be calculated from the measured s_{33}^D and k_{33} by the relation

$$s_{33}^E = s_{33}^D/(1 - k_{33}^2) \quad (4)$$

In this case, the relative error of s_{33}^E is given by

$$\frac{\Delta s_{33}^E}{s_{33}^E} = \frac{\Delta s_{33}^D}{s_{33}^D} + 2\left(\frac{\Delta k_{33}}{k_{33}}\right)\left(\frac{k_{33}^2}{1 - k_{33}^2}\right) \quad (5)$$

For PMN-30%PT the measured $k_{33} = 0.92$, then $2k_{33}^2/(1 - k_{33}^2) = 11.0$, which is to say that if there is a 0.5% error in k_{33} , the calculated s_{33}^E has more than 5.5% error. Considering the relative error of s_{33}^D could reach 0.9%, the relative error of s_{33}^E could be larger than 6.4%. This method is obviously less stable.

The other way to get s_{33}^E is from quasi-statically measured d_{33} using the formula

$$s_{33}^E = \frac{d_{33}^2}{\epsilon_{33}^T k_{33}^2} \quad (6)$$

In this case, relative error of calculated s_{33}^E is given by

$$\frac{\Delta s_{33}^E}{s_{33}^E} = 2\frac{\Delta d_{33}}{d_{33}} + \frac{\Delta \epsilon_{33}^T}{\epsilon_{33}^T} + 2\left(\frac{\Delta k_{33}}{k_{33}}\right) \quad (7)$$

which is dependent only on the relative error of k_{33} but not on its value. Considering the worst situation, the relative error of calculated s_{33}^E from Equ. (6) is about 2.7%. Obviously, for piezoelectric materials with large k_{33} it is better to use Equ. (6) instead of Equ. (4) to determine s_{33}^E . After obtaining c_{33}^E and s_{33}^E , s_{13}^E may be calculated by

$$s_{13}^E = -\left(\frac{s_{33}^E (s_{33}^E c_{33}^E - 1)}{2(c_{11}^E + c_{12}^E)}\right)^{\frac{1}{2}} \quad (8)$$

The relative error is given by

$$\frac{\Delta s_{13}^E}{s_{13}^E} = \frac{1}{2} \left[\left(\frac{\Delta s_{33}^E}{s_{33}^E} \right) \left(\frac{2c_{33}^E s_{33}^E - 1}{c_{33}^E s_{33}^E - 1} \right) + \left(\frac{\Delta c_{11}^E}{c_{11}^E} \right) \frac{1}{(1 + c_{12}^E/c_{11}^E)} + \left(\frac{\Delta c_{12}^E}{c_{12}^E} \right) \frac{1}{(1 + c_{11}^E/c_{12}^E)} + \left(\frac{\Delta c_{33}^E}{c_{33}^E} \right) \frac{s_{33}^E c_{33}^E}{s_{33}^E c_{33}^E - 1} \right] \quad (9)$$

For PMN-30%PT, $c_{33}^E s_{33}^E \gg 1$, thus Equ. (9) can be approximately expressed as

$$\frac{\Delta s_{13}^E}{s_{13}^E} = \frac{1}{2} \left[\frac{\Delta c_{33}^E}{c_{33}^E} + 2 \frac{\Delta s_{33}^E}{s_{33}^E} + \frac{\Delta c_{11}^E}{c_{11}^E} \left(\frac{c_{11}^E}{c_{11}^E + c_{12}^E} \right) + \frac{\Delta c_{12}^E}{c_{12}^E} \left(\frac{c_{12}^E}{c_{11}^E + c_{12}^E} \right) \right] \quad (10)$$

Finally, the constant c_{13}^E is calculated from Equ. (3), and the relative error is given by

$$\frac{\Delta c_{13}^E}{c_{13}^E} = \frac{\Delta s_{13}^E}{s_{13}^E} + \frac{\Delta s_{33}^E}{s_{33}^E} + \left(\frac{\Delta c_{11}^E}{c_{11}^E} \right) \frac{c_{11}^E}{c_{11}^E + c_{12}^E} + \left(\frac{\Delta c_{12}^E}{c_{12}^E} \right) \frac{c_{12}^E}{c_{11}^E + c_{12}^E} \quad (11)$$

Up to this point, all six independent elastic stiffness constants under constant electric field have been determined. Since the elastic compliance matrix is the inversion of elastic stiffness matrix, all six independent elastic compliance constants s_{ij}^E can be easily determined. The measured s_{11}^E from the resonance bar can be used as a consistency check.

The piezoelectric stress constants d_{31} is readily obtained from the measured quantities

$$d_{31} = -\sqrt{\varepsilon_{33}^T s_{11}^E k_{31}^2} \quad (12)$$

The measured errors of ε_{33} , s_{11} and k_{31} will transfer to the calculated d_{31} with the relative error given by

$$\frac{\Delta d_{31}}{d_{31}} = \frac{1}{2} \left[\frac{\Delta \varepsilon_{33}^T}{\varepsilon_{33}^T} + \frac{\Delta s_{11}^E}{s_{11}^E} + 2 \frac{\Delta k_{31}}{k_{31}} \right] \quad (13)$$

From the measured c_{44}^E and c_{44}^D , the electromechanical coupling coefficient k_{15} is determined by

$$k_{15}^2 = \left(1 - \frac{c_{44}^E}{c_{44}^D} \right) \quad (14)$$

The possible error of k_{15} determined by the method depends on the ratio of c_{44}^E/c_{44}^D ,

$$\frac{\Delta k_{15}}{k_{15}} = \frac{1}{2} \left(\frac{\Delta c_{44}^D}{c_{44}^D} + \frac{\Delta c_{44}^E}{c_{44}^E} \right) \left(\frac{c_{44}^E}{c_{44}^E - c_{44}^D} \right) \quad (15)$$

If the ratio $\frac{c_{44}^E}{c_{44}^D} > 2/3$, the error term $\left(\frac{\Delta c_{44}^D}{c_{44}^D} + \frac{\Delta c_{44}^E}{c_{44}^E} \right)$ will be magnified. For PMN-

30%PT single crystal $\frac{c_{44}^E}{c_{44}^D - c_{44}^E} = 10.1$, therefore, the term $\left(\frac{\Delta c_{44}^D}{c_{44}^D} + \frac{\Delta c_{44}^E}{c_{44}^E} \right)$ will be magnified by a factor of 5.0.

Since

$$k_{15}^2 = \frac{d_{15}^2}{\varepsilon_{11}^T \varepsilon_{44}^E} = \frac{d_{15}^2 c_{44}^E}{\varepsilon_{11}^T} \quad (16)$$

d_{15} is given by

$$d_{15}^2 = \varepsilon_{11}^T k_{15}^2 / c_{44}^E = \varepsilon_{11}^T \left(\frac{1}{c_{44}^E} - \frac{1}{c_{44}^D} \right) \quad (17)$$

Thus, d_{15} calculated by this procedure will have large uncertainty because of the uncertainty in k_{15} . The error of derived d_{15} can be estimated by

$$\frac{\Delta d_{15}}{d_{15}} = \frac{1}{2} \left[\left(\frac{\Delta \varepsilon_{33}^T}{\varepsilon_{33}^T} \right) + \left(\frac{\Delta c_{44}^D}{c_{44}^D} \right) \frac{c_{44}^E}{c_{44}^D - c_{44}^E} + \left(\frac{\Delta c_{44}^E}{c_{44}^E} \right) \frac{c_{44}^D}{c_{44}^D - c_{44}^E} \right] \quad (18)$$

Now the three independent piezoelectric strain constants d_{33} , d_{31} and d_{15} have been calculated. The piezoelectric stress constant e_y can be derived by the corresponding formulae:

$$e_{31} = d_{31}(c_{11}^E + c_{12}^E) + d_{33}c_{13}^E \quad (19)$$

$$e_{33} = 2d_{31}c_{13}^E + d_{33}c_{33}^E \quad (20)$$

$$e_{15} = d_{15}c_{44}^E \quad (21)$$

For PMN-30%PT single crystal, the estimated errors of e_{31} caused only by c_{12}^E and c_{13}^E is given by

$$\frac{\Delta e_{31}}{e_{31}} = 39.2 \left(\frac{\Delta c_{12}^E}{c_{12}^E} \right) + 82.6 \left(\frac{\Delta c_{13}^E}{c_{13}^E} \right) \quad (22)$$

So that a very small change in c_{12}^E and c_{13}^E will lead to great uncertainties in the derived value of e_{31} . Also, the error of e_{33} caused only by c_{33}^E and c_{13}^E can be estimated by

$$\frac{\Delta e_{33}}{e_{33}} = 7.6 \left(\frac{\Delta c_{33}^E}{c_{33}^E} \right) + 14.3 \left(\frac{\Delta c_{13}^E}{c_{13}^E} \right) \quad (23)$$

This shows that the calculated values of e_{31} and e_{33} are very sensitive to the values of c_{12}^E and c_{13}^E , especially c_{13}^E , when d_{33} and d_{31} are very large. In order for e_{31} to have a reasonable value, c_{12}^E and c_{13}^E must be very accurately determined. Interestingly, the reverse is not true, the change value of e_{31} has little influence to the value of c_{12}^E or c_{13}^E . From the derived piezoelectric constants, the coupling coefficients k_{33} , k_{31} and k_t can be calculated. Comparing the calculated coupling coefficients with the measured ones, if these values are in good agreement, the data set is confirmed.

RESULTS AND DISCUSSIONS

Employing the optimized characterization scheme, the complete constant set of PMN-30%PT domain engineered crystal has been measured. The results are shown in Table 2, where δ denotes the absolute error of a constant. The relative errors of each constant $\Delta\delta$ are also shown in Table 2.

From Table 2, the electromechanical coupling coefficient k_{33} for the domain engineered PMN-30%PT single crystal is about 92%. The piezoelectric constant d_{33} and d_{31} are 1980 pC/N and -920 pC/N, respectively. It can also be seen that the relative errors of measured coefficients are generally lower than those of derived coefficients.

Some overall comparison among all measured data sets for the domain engineered PMN-PT and PZN-PT crystals could be performed since we already measured four complete data sets of relaxor based single crystal systems: PMN-33%PT, PMN-30%PT, PZN-4.5%PT and PZN-8%PT. The piezoelectric properties of relaxor based single crystal systems near the MPB are obviously much larger than those away from the MPB. For example, compared to the piezoelectric constant $d_{33} = 2820$ pC/N of PMN-33%PT, the d_{33} of PMN-30%PT single crystal is only 1980 pC/N, about 30 percent drop. The d_{33} of PZN-PT crystal dropped about 31 percent when PT content decreased from 8% to 4.5%. However, those relaxor based single crystal systems with composition a little away from the MPB exhibiting much better property stability, which makes them more practical in new device applications.

We noticed that the elastic stiffness constants did not change very much as the composition of single crystal moves away from the MPB, while the elastic compliance constants changed significantly. Moreover, it seems that the superior piezoelectric property of these systems related with the large s_{33} value, which is much larger than conventional PZT ceramics.

These relaxor based single crystal systems also exhibit special anisotropy property compared to conventional single crystal. In order to investigate the anisotropy of the multi-domain PMN-PT and PZN-PT single crystal systems, some constant ratios are calculated in Table 3. Since there are no data available for the single domain single crystal PMN-PT and PZN-PT system at the moment, the corresponding ratios for single crystal BaTiO₃ are also listed in Table 3 for comparison.

From Table 3, it can be seen that the measured anisotropy of PMN-PT single crystal is comparable to that of the PZN-PT single crystal and it is generally less than that of single domain BaTiO₃. Particularly, the dielectric anisotropy of measured PMN-PT and PZN-PT is much smaller than that of BaTiO₃. This may be caused by the averaging effect of the multi-domain structure of PMN-PT and PZN-PT crystals. The composition variation did not bring great change to the anisotropy of these crystal systems except the anisotropy of dielectric constants and s_{13}^E/s_{12}^E . On the other hand, the anisotropy for shear waves that propagate in the X-Y plane with displacement also in the same plane is larger for PMN-PT and PZN-PT than that for conventional single crystal BaTiO₃. The “soft shear wave mode” along [110] is related to domain wall motion, since the dynamics of domain wall motions will contribute to the effective elastic compliance.

TABLE 2. Complete electromechanical constants of PMN-30% PT single crystal poled along [001]

$$\text{Density: } \rho = 8038.4 \text{ kg/m}^3$$

Elastic Stiffness Constants: c_{ij}^E, c_{ij}^D (10^{10} N/m^2)												
	c_{11}^{E*}	c_{12}^{E*}	c_{13}^E	c_{33}^E	c_{44}^{E*}	c_{66}^{E*}	c_{11}^D	c_{12}^D	c_{13}^D	c_{33}^{D*}	c_{44}^{D*}	c_{66}^D
value	11.7	10.3	10.1	10.8	7.1	6.6	11.8	10.4	9.5	17.4	7.8	6.6
$\Delta\delta$	0.9	2.1	5.5	2.0	0.9	2.5	2.9	5.0	7.5	0.9	1.0	2.5
δ	± 0.1	± 0.2	± 0.5	± 0.2	± 0.1	± 0.2	± 0.3	± 0.5	± 0.7	± 0.2	± 0.1	± 0.2
Elastic Compliance Constants: s_{ij}^E, s_{ij}^D ($10^{-12} \text{ m}^2/\text{N}$)												
	s_{11}^{E*}	s_{12}^E	s_{13}^E	s_{33}^E	s_{44}^E	s_{66}^E	s_{11}^D	s_{12}^D	s_{13}^D	s_{33}^{D*}	s_{44}^D	s_{66}^D
value	52.0	-18.9	-31.1	67.7	14.0	15.2	39.7	-31.2	-4.7	10.8	12.9	15.2
$\Delta\delta$	0.9	12.0	4.8	2.7	0.9	2.5	4.9	16.9	9.1	0.9	1.0	2.5
δ	± 0.5	± 2.3	± 1.5	± 1.8	± 0.1	± 0.4	± 2.0	± 5.3	± 0.4	± 0.1	± 0.1	± 0.4
Piezoelectric Constants: $e_{i\alpha}$ (C/m^2) $d_{i\alpha}$ (10^{-12} C/N) $g_{i\alpha}$ (10^{-3}Vm/N) $h_{i\alpha}$ (10^8V/m)												
	e_{15}	e_{31}	e_{33}	d_{15}	d_{31}	d_{33}^*	g_{15}	g_{31}	g_{33}	h_{15}	h_{31}	h_{33}
value	13.6	-2.4	27.1	190	-921	1981	6.0	-13.3	28.7	4.6	-2.2	24.6
$\Delta\delta$	11.6	6.3	6.3	10.7	1.7	1.0	12.2	3.2	2.5	13.2	15.7	15.7
δ	± 1.6	± 0.2	± 1.7	± 20	± 17	± 20	± 0.7	± 0.4	± 0.7	± 0.6	± 0.3	± 3.8
Dielectric Constants: ϵ (ϵ_0) β ($10^{-4}/\epsilon_0$),						Electromechanical Coupling Constants						
	ϵ_{11}^S	ϵ_{33}^S	ϵ_{11}^{T*}	ϵ_{33}^{T*}	β_{11}^S	β_{33}^S	β_{11}^T	β_{33}^T	k_{15}	k_{31}^*	k_{33}^*	k_r^*
value	3307	1242	3600	7800	3.0	8.0	2.8	1.3	0.29	0.49	0.92	0.62
$\Delta\delta$	2.7	9.4	1.5	1.5	2.7	9.4	1.5	1.5	9.5	0.5	0.5	1.1
δ	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm
	90	120	60	120	0.1	0.8	0.04	0.02	0.03	0.01	0.01	0.01

* Measure properties

TABLE 3. Anisotropy of material properties of PMN-PT and PZN-PT single crystal poled in [001]

	$\epsilon_{11}^T / \epsilon_{33}^T$	$\epsilon_{11}^S / \epsilon_{33}^S$	s_{33}^E / s_{11}^E	s_{33}^D / s_{11}^D	s_{44}^E / s_{66}^E	s_{44}^D / s_{66}^D	s_{13}^H / s_{12}^H	s_{13}^D / s_{12}^D
PMN-33%PT	0.195	2.10	1.73	0.25	0.95	0.86	5.02	0.12
PMN-30%PT	0.462	2.66	1.30	0.27	0.93	0.85	1.65	0.15
PZN-8%PT	0.377	2.84	1.61	0.25	1.03	0.96	4.60	0.22
PZN-4.5%PT	0.596	3.00	1.32	0.33	0.98	0.94	1.79	0.18
BaTiO ₃ *	17.4	18.1	1.95	1.49	2.08	1.40	2.32	1.03

* D. A Bertincoart, D. R. Curran and H. Jaffe, In Physical Acoustics, Edited by W. P. Mason, Vol. 1A, P 218.

SUMMARY AND CONCLUSIONS

Combining a hybrid measurement technique and an improved characterization scheme, a complete self-consistent data set of elastic, dielectric and piezoelectric coefficients for the domain-engineered 0.70Pb(Mg_{1/3}Nb_{2/3})O₃-0.30PbTiO₃ [PMN-30%PT] single crystal was measured. The characterization scheme proposed here can minimize the relative errors of derived constants. It was found that the electromechanical coupling coefficient k_{33} for the domain engineered sample is about 92% and the piezoelectric constant d_{33} is 1980 pC/N. Although the PMN-33%PT single crystal processes much higher electromechanical properties, the PMN-30%PT single crystal exhibits much better property uniformity from sample to sample compared to that of PMN-33%PT single crystal.

ACKNOWLEDGEMENTS

Crystals for this study was provided by Dr. Ahmed Amin of the NUWC. Financial support for this work was provided by the ONR under grant number N00014-01-1-0960.

REFERENCES

1. Nomura S., Yonezawa M., Doi K., Nanamatsu S., Tsubouchi N., and Takahashi M., "Crystal structure and piezoelectric properties of Pb(Zn_{1/3}Nb_{2/3})O₃-PbTiO₃ solid solution," NEC Res. & Dev., 29, 15-21 (1973)
2. Kuwata K., Uchino K., and Nomura S., "Dielectric and piezoelectric properties of 0.90PZN-0.10PT single crystals," Jpn. J. Appl. Phys., 21, 1298-1302 (1982)

3. Park S. E., and Shrout T. R., "Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals," *J. Appl. Phys.* 82, 1804-1811 (1997)
4. Park S. E., and Shrout T. R., "Characteristics of relaxor-based piezoelectric single crystals for ultrasonic transducers," *IEEE Trans. UFFC*, 44, 1140-1147 (1997)
5. Liu S. F., Park S. E., Shrout T. R., and Cross L. E., "Electric field dependence of piezoelectric properties for rhombohedral $0.955\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.045PbTiO_3 single crystal," *J. Appl. Phys.*, 85, 2810-2814 (1999)
6. Cao W., Zhu S. and Jiang B., "Analysis of shear modes in a piezoelectric vibrator," *J. Appl. Phys.*, 83, 4415-4420 (1998)
7. Yin J. H., and Cao W., "Domain Configurations in Domain Engineered $0.955\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.045PbTiO_3 Single Crystals", *J. Appl. Phys.*, 87, 7438-7441 (2000)
8. Yin J. H., Jiang B. and Cao W., "Elastic, Piezoelectric, and Dielectric Properties of $0.955\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.045PbTiO_3 Single Crystal with Designed Multidomains", *IEEE Transactions on UFFC.*, 47, 285-291 (2000)
9. Zhu S., Jiang B. and Cao W., "Characterization of piezoelectric materials using ultrasonic and resonant techniques," *Proceedings of SPIE, Medical Imaging*, 3341, 154-162 (1998)
10. Zhang R., Jiang B. and Cao W., "Elastic, piezoelectric, and dielectric properties of multi-domain $0.67\text{Pb}(\text{Mn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.33PbTiO_3 Single Crystals", *J. Appl. Phys.*, 90, 3471-3475 (2001)
11. Nye J. F., "*Physical properties of crystals*", (Oxford University Press, 1957)