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Origin of Piezoelectricity in Piezoelectric Ceramics from the Viewpoints of Elastic Constants Measured by Acoustic Wave Velocities

Toshio Ogawa

Abstract

This chapter consists of two parts; the first part describes “how can high piezoelectricity be realized from measuring acoustic wave velocities?” That is, the measurement of sound velocities resulted in an effective tool for researching and developing piezoelectric materials, and, furthermore, it was possible to design the material compositions of lead-free piezoelectric ceramics as well as lead-containing ceramics. The second part describes the “effects of firing and DC poling treatments on elastic constants measured from acoustic wave velocities in barium titanate piezoelectric ceramics”. Namely, it could be applied to manufacturing processes such as firing and DC poling treatments in piezoelectric ceramics, which is accompanied with densification of ceramics and ferroelectric domain alignment, respectively. It is clarified through the two parts that the evaluation of elastic constants leads to the origin of piezoelectricity in piezoelectric ceramics.

Keywords: origin of piezoelectricity, piezoelectric ceramics, acoustic wave velocities, elastic constants, domain alignment
1. Introduction

1.1. How can high piezoelectricity be realized from measuring acoustic wave velocities?

Lead-free piezoelectric ceramics have been studied by many researchers [1-4], because of replacing Pb(Zr, Ti)O$_3$ (PZT) ceramics. There are three major chemical compositions: alkali niobate [5], alkali bismuth titanate [6], and barium titanate [7]. While relatively high piezoelectricity is realized in alkali niobate (the piezoelectric strain $d_{33}$ constant is 307 pC/N in 0.95(Na, K, Li, Ba)(Nb$_{0.9}$Ta$_{0.1}$)O$_3$-0.05SrZrO$_3$ with a small amount of MnO [5, 8]) and barium titanate, low piezoelectricity with low dielectric constant and high mechanical quality factor is obtained in alkali bismuth titanate.

Improving the piezoelectricity in lead-free ceramics, a study on Young’s modulus (Y) vs. piezoelectricity is important how to realize higher piezoelectricity in piezoelectric materials. We have already reported Y in PZT [9-13], PbTiO$_3$ (PT) [14], BaTiO$_3$ (BT) [7], alkali niobate ceramics composed of (Na, K, Li, Ba)(Nb$_{0.9}$Ta$_{0.1}$)O$_3$-SrZrO$_3$ (SZ) [5, 8] and in a relaxor single crystal of Pb[(Zn$_{1/3}$Nb$_{2/3}$)$_{0.91}$Ti$_{0.09}$]O$_3$ (PZNT) [15-17] by measuring the impedance responses in various kinds of piezoelectric resonators. Figure 1 shows the relationships between Y and electromechanical coupling factors of transverse mode ($k_{31}$) and longitudinal mode ($k_{33}$) in piezoelectric materials. From these figures, it is clarified that the decrease in Y increased the piezoelectricity such as $k_{31}$ and $k_{33}$, because materials with lower Y were easy to deform by DC poling field. Therefore, it is said that the measurement of Y was important to obtain high piezoelectricity.

![Figure 1](image.png)

Figure 1. Relationships between Young’s modulus (Y) and coupling factors of transverse mode ($k_{31}$) and longitudinal mode ($k_{33}$) in piezoelectric ceramics and relaxor single crystals; giant $k_{31}$ was realized in Pb[(Zn$_{1/3}$Nb$_{2/3}$)$_{0.91}$Ti$_{0.09}$]O$_3$ (PZNT) single-crystal plate and there is blank space for coupling factors in the range of $Y = 1 - 5 \times 10^{10}$ N/m$^2$; PZT, PT, BT, and SZ mean Pb(Zr, Ti)O$_3$, PbTiO$_3$, BaTiO$_3$, and alkali niobate, respectively.
Recently, we developed a novel method to easily measure acoustic wave velocities suitable for conventional disk samples with ordinary dimensions (10-20 mm diameter and 0.5-2.0 mm thickness) by an ultrasonic thickness gauge with high-frequency pulse oscillation [18-20]. Therefore, this method was applied to hard and soft PZT [9-13, 21] and lead-free ceramics composed of alkali niobate [5, 8] and alkali bismuth titanate [6]. In this pursuit, we report the acoustic wave velocities in piezoelectric ceramics measured by our developed method and the calculation results of Young’s modulus, Poisson’s ratio, modulus of rigidity and bulk modulus, especially to obtain high piezoelectricity in lead-free ceramics. Furthermore, we propose the design for R&D on piezoelectric materials from a viewpoint of measuring acoustic wave velocities.

1.2. Experimental procedure

The piezoelectric ceramic compositions measured were as follows: 0.05Pb(Sn$_{0.5}$Sb$_{0.5}$)O$_3$-(0.95-x)PbTiO$_3$-xPbZrO$_3$ (x = 0.33, 0.45, 0.48, 0.66, 0.75) with (hard PZT) and without 0.4 wt% MnO$_2$ (soft PZT) [9-13, 21]; 0.90PbTiO$_3$-0.10La$_{2/3}$TiO$_3$ (PLT) and 0.975PbTiO$_3$-0.025La$_{2/3}$TiO$_3$ (PT) [14]; (1-x)(Na, K, Li, Ba)(Nb$_{0.9}$Ta$_{0.1}$)O$_3$-xSrZrO$_3$ (SZ) (x = 0.00, 0.02, 0.04, 0.05, 0.06, 0.07) [5, 8]; (1-x)(Na$_{0.5}$Bi$_{0.5}$)TiO$_3$ (NBT)-x(K$_{0.5}$Bi$_{0.5}$)TiO$_3$ (KBT) (x = 0.08, 0.18) and 0.79NBT-0.20KBT-0.01Bi(Fe$_{0.5}$Ti$_{0.5}$)O$_3$ (BFT) (x = 0.20) [6]; and (1-x)NBT-xBaTiO$_3$ (BT) (x = 0.03, 0.07, 0.11) [6].

DC poling was conducted for 30 minutes at the most suitable poling temperature ($T_p$) depending on the Curie points of the ceramic materials. The DC poling field (E) depended on the coercive fields and the insulation resistance of the piezoelectric ceramics. The DC poling conditions are as follows: $E = 3,000 \text{ V/mm and } T_p = 150 \text{ °C for } \text{SZ}$; $E = 2,500-3,000 \text{ V/mm and } T_p = 70 \text{ °C for } \text{KBT and BT}$; $E = 3,000 \text{ V/mm and } T_p = 80 \text{ °C for hard and soft PZT}$; $E = 4,000 \text{ V/mm and } T_p = 80 \text{ °C for PLT}$; $E = 4,000 \text{ V/mm and } T_p = 200 \text{ °C for PT}$, respectively. Before and after DC poling, the dielectric and piezoelectric properties were measured at room temperature using an LCR meter (HP4263A), a precision impedance analyzer (Agilent 4294A), and a piezometer (Academia Sinica ZJ-3D). Furthermore, the acoustic wave velocities were measured using an ultrasonic precision thickness gauge (Olympus 35DL), which has PZT transducers with 30 MHz for longitudinal wave ($V_L$) generation and 20 MHz for transverse wave ($V_S$) generation [22]. The acoustic wave velocities were evaluated on the basis of the propagation time between the second-pulse echoes in the thickness of ceramic disks parallel to the poling field with dimensions of 14 mm diameter and 0.5-1.5 mm thickness [18-20]. The sample thickness was measured using a precision micrometer (Mitutoyo MDE-25PJ). The number ($n$) of disk samples measured was $n = 5-8$, and the data in the figures indicate the average of individual measured values. In addition, Young’s modulus (Y), Poisson’s ratio ($\nu$), modulus of rigidity (G), and bulk modulus (K) in the thickness direction of ceramic disks were calculated on the basis of the $V_L$ and $V_S$ as shown in the following equations [23, 24]:

\[
Y = 3\rho V_s^2 \left( \frac{V_L^2}{V_L^2 - V_S^2} \right)
\]

(1)
where \( \rho \) is the bulk density of the ceramic disks. Figure 2 shows the relationships between the ratio of sound velocities \( \left( \frac{V_S}{V_L} \right) \), the elastic constants, and dielectric and piezoelectric constants.

\[
\sigma = \frac{1}{2} \left[ 1 - \frac{1}{\left( \frac{V_L}{V_S} \right)^2} \right] 
\]

(2)

\[
G = \rho V_S^2 \]

(3)

\[
K = \rho \left( V_L^2 - \frac{4}{3} V_S^2 \right) \]

(4)

![Figure 2. Relationships between the ratio of sound velocities \( \left( \frac{V_S}{V_L} \right) \), elastic constant and dielectric and piezoelectric constants.](image)
1.3. Results and discussion

1.3.1. Dependence of planar coupling factor on elastic constant

Figure 3 shows the relationships between longitudinal (V\textsubscript{L}) and transverse (V\textsubscript{S}) wave velocities, Young’s modulus (Y), Poisson’s ratio (\sigma), modulus of rigidity (G), and bulk modulus (K) vs. planar coupling factors (k\textsubscript{p}) of disk in (1- x)(Na, K, Li, Ba)(Nb\textsubscript{0.9}Ta\textsubscript{0.1})O\textsubscript{3}-xSZ (abbreviated to “SZ”), (1-x)NBT-xKBT (“KBT”), 0.79NBT-0.20KBT-0.01BFT (“KBT”), and (1-x)NBT-xBT (“BT”) lead-free ceramics compared with 0.05Pb(Sn\textsubscript{0.5}Sb\textsubscript{0.5})O\textsubscript{3}-(0.95-x)PbTiO\textsubscript{3}-xPbZrO\textsubscript{3} ceramics with ("hard PZT") and without 0.4 wt% MnO\textsubscript{2} ("soft PZT"), and with 0.90PbTiO\textsubscript{3}-0.10La\textsubscript{2/3}TiO\textsubscript{3} ("PLT") and 0.975PbTiO\textsubscript{3}-0.025La\textsubscript{2/3}TiO\textsubscript{3} ("PT") ceramics before and after fully DC poling. In the case of after poling (marks and solid lines in Figure 3), although the V\textsubscript{L} values of the PZT ceramics were almost constant at approximately 4, 600-4, 800 m/s independently of the composition x, their V\textsubscript{S} values linearly decreased from 2, 500 to 1, 600 m/s with increasing k\textsubscript{p} from 20% to 65% (solid line). In addition, the V\textsubscript{L} and V\textsubscript{S} values of the PZT ceramics were smaller than those of the lead-free ceramics (V\textsubscript{L} = 5,000-5,800 m/s and V\textsubscript{S} = 2, 600-3, 000 m/s; solid lines). Although the V\textsubscript{L} values of the PT ceramics were almost the same (4, 800 m/s) as those of the PZT ceramics, the V\textsubscript{S} values of the PT ceramics were approximately 2, 700 m/s. On the other hand, the V\textsubscript{L} values of the SZ ceramics were relatively high (5,500-5,800 m/s); furthermore, the V\textsubscript{S} values of the SZ ceramics also increased (2, 600-2, 700 m/s) and linearly decreased with increasing k\textsubscript{p} from 25% to 50% (solid line), the behavior of which was almost the same as that of the V\textsubscript{S} values of the PZT ceramics. The V\textsubscript{L} values of the KBT, BT, and PLT ceramics (5,000-5,400 m/s) were between those of the PZT, PT, and SZ ceramics. However, the V\textsubscript{S} values of the KBT, BT, and PLT ceramics (2, 800-3, 000 m/s) were the highest. Therefore, it was clarified that higher k\textsubscript{p} values can be realized at lower Y and G, and higher \sigma and K.

In comparison with the values of before poling (the k\textsubscript{p} was made use of the values after poling; marks and dash lines in Figure 3), V\textsubscript{L}, \sigma, and K increase and V\textsubscript{S}, Y, and G decrease after poling because of ferroelectric domain alignment. In addition, while the correlation coefficients in the k\textsubscript{p} vs. Y, \sigma, and G were almost independent of poling treatment, the coefficients in the k\textsubscript{p} vs. K after poling increases from 0.49 to 0.74. It is thought that the increase in K is significant to realize piezoelectricity as mentioned below.

Figure 4 shows the relationships between k\textsubscript{p} vs. changes (\Delta) in longitudinal (V\textsubscript{L}) and transverse wave velocities (V\textsubscript{S}) \[\Delta V\textsubscript{L}/\Delta V\textsubscript{S}\] and changes in Young’s modulus (Y), Poisson’s ratio (\sigma), bulk modulus (K), and rigidity (G) \[\Delta Y/\Delta \sigma/\Delta K/\Delta AG\] before and after DC poling in soft and hard PZT, PbTiO\textsubscript{3} (PT/PLT), alkali niobate (SZ), and alkali bismuth titanate (KBT/ BT). Higher k\textsubscript{p} was realized in the regions of large +\DeltaV\textsubscript{L} and +AK, and larger -\DeltaV\textsubscript{S}, -\DeltaY, and -\DeltaG. There were thresholds regarding k\textsubscript{p} vs. \DeltaV\textsubscript{S}, \DeltaY, and \DeltaG around -5%, -7%, and -10%, respectively. On the other hand, there were no thresholds in the cases of k\textsubscript{p} vs. \DeltaV\textsubscript{L} and \DeltaK, especially \Delta\sigma. As there were k\textsubscript{p} peaks regarding \Delta\sigma in hard and soft PZT ceramics and k\textsubscript{p} maximum in alkali niobate (SZ) ceramics, the compositions in k\textsubscript{p} peaks and k\textsubscript{p} maximum correspond to a morphotropic phase boundary (MPB) in PZT [25] and to take lowest value of V\textsubscript{S}/V\textsubscript{L} in SZ (see the following...
Figure 10. We believe that the origin of piezoelectricity in piezoelectric ceramics was due to large change in $V_S (-\Delta V_S)$ while applying DC poling field parallel to the thickness of disks. Therefore, the larger changes in $V_S (-\Delta V_S)$ correspond to larger changes in Y ($-\Delta Y$) and G ($-\Delta G$). These phenomena mean that the origin of high piezoelectricity was due to the mechanical softness of the materials under compress stress (large $+\Delta V_L$ and $+\Delta K$). In addition, the realization of high piezoelectricity is easy deformation by DC poling field in diameter (large $-\Delta G$) as well in thickness (large $-\Delta Y$).

Figure 5 shows schematic charts between domain alignment and the changes in Y, $\sigma$, G, and K after DC poling. Comparing domain alignment before poling to the alignment after poling, same charges (+ or -) are generated and gathered in the regions of each ends by opposite charge due to DC poling field, namely orientation polarization which occurs by domain alignment. The orientation polarization acts by reducing of Y and G by repulsion to each other because there are same charges in domain alignment. The enhancing $\sigma$ and K can be explained by the same phenomena. Therefore, it can be said that higher domain alignment leads to large changes in Y, G, and K. However, large change in $\sigma (+\Delta \sigma$ in Figure 4) does not lead to higher domain alignment since $\sigma$ value is decided by the combinations of Y (G) and K after poling.
Figure 4. Changes (Δ) in $V_L$, $V_S$, Y, $\sigma$, G, and K vs. $k_p$ before and after poling in lead-containing and lead-free ceramics.

Figure 5. Effect of ferroelectric domain alignment by DC poling on Y, $\sigma$, G, and K; generated charges (-→ +) accompanied with domain alignments, displacement (→) and changes in Y, $\sigma$, G, and K (↓: decrease, ↑: increase) after poling are also shown in this figure.
1.3.2. Design for research and development on lead-free piezoelectric ceramics

Figure 6 shows the relationship between $V_S/V_L$ vs. $k_p$. The $k_p$ linearly increased with decreasing $V_S/V_L$ in lead-free ceramics as well as lead-containing ceramics such as PZT, PLT, and PT. Furthermore, it was confirmed that $V_S/V_L$ was an effective figure to evaluate both the elastic constants and the piezoelectric constants.

![Figure 6. Relationship between ratio of sound velocities ($V_S/V_L$) and planar coupling factor ($k_p$) in lead-free and lead-containing ceramics.](image)

When we research and develop new piezoelectric ceramics with high piezoelectricity in lead-free ceramics, we must need a new concept different from the conventional research looking for chemical compositions such as MPB [25]. From the equations (1)-(4) and the change in $V_L$ and $V_S$ before and after poling as mentioned previously (Figure 4), we focused on the ceramic bulk density ($\rho$). Figure 7 shows the relationship $V_S/V_L$ vs. $\rho$: $\rho$ of lead-containing ceramics (PZT, PLT, and PT) was independent of $V_S/V_L$. However, in lead-free ceramics (SZ, KBT, and BT) $\rho$ decreased with decreasing $V_S/V_L$. In the case of $\rho$ vs. $k_p$ in Figure 8, although $k_p$ in lead-containing ceramics (PZT, PLT, and PT) is independent of $V_S/V_L$, $k_p$ in lead-free ceramics (SZ, KBT, and BT) increased with decreasing $\rho$. From the above results, we came to an important concept to obtain lead-free ceramics with high piezoelectricity, namely the R&D on lead-free ceramics with lower bulk density. As a result, it confirmed the importance of measuring $V_L$ and $V_S$ to evaluate the piezoelectricity.

It was said that the direction of the R&D on lead-free piezoelectric ceramics with high piezoelectricity was looking for ceramics with lower bulk density. For example, in perovskite structure, small cations at A and B sites in perovskite structure of $\text{ABO}_3$ were selected. In
addition, for practical use, the Curie point (Tc) or depolarization temperature must be over 250 °C. From the two items we will expect the candidates for new lead-free ceramics such as SrTeO$_3$ ($\rho = 4.82 \text{ g/cm}^3$, Tc = 485 °C) and YMnO$_3$ (Tc = 640 °C), in addition to KNbO$_3$ ($\rho = 4.62 \text{ g/cm}^3$, Tc = 418 °C) and LiNbO$_3$ ($\rho = 4.46 \text{ g/cm}^3$, Tc = 1,210 °C), respectively [26, 27]. In fact, the bulk density ($\rho$) of SZ, which possessed the highest $k_p$ [5, 8] in lead-free ceramics we investigated, was around 4.6 g/cm$^3$.

Figure 7. Relationship between ratio of sound velocities ($V_S/V_L$) and ceramic bulk density ($\rho$) in lead-free and lead-containing ceramics.

Figure 8. Relationship between ceramic bulk density ($\rho$) and planar coupling factor ($k_p$) in lead-free and lead-containing ceramics.
In addition to the relationships between $V_S/V_L$ vs. $k_p$ in Table 1, we evaluated the chemical composition dependence of $V_S/V_L$ in piezoelectric ceramics. Figure 9 shows the composition $x$ dependence of $k_p$ and $d_{33}$ in $(1-x)(\text{Na, K, Li, Ba})(\text{Nb}_{0.9}\text{Ta}_{0.1})\text{O}_3$-$x\text{SrZrO}_3$ (SZ) ($x = 0.00, 0.02, 0.04, 0.05, 0.06, 0.07$). While the $k_p$ in SZ compositions of $x = 0.00$ - $0.07$ was independent of $\rho$ in Figure 8, the maximum $k_p$ and $d_{33}$ were obtained at $x = 0.04$ and 0.05, respectively (Figure 9). Figure 10 shows the $x$ dependence of $V_S/V_L$ in SZ before and after poling. The minimum $V_S/V_L$ after poling were obtained at $x = 0.04$ - 0.05. From both figures, it was concluded that the highest $k_p$ appeared in the case of the minimum $V_S/V_L$. However, there is a composition without MPB at $x = 0.04$ - 0.05 in SZ [5, 8]. Therefore, we could introduce the novel method to evaluate the piezoelectricity by measuring acoustic wave velocities of $V_L$ and $V_S$ in spite of the existence of MPB.

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<td>Longitudinal wave velocity ($V_L$)</td>
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<td>$V_L^{\prime}$; independent of $k_p$</td>
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<td>Transverse wave velocity ($V_S$)</td>
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<td>Ceramic bulk density ($\rho$)</td>
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<td>$\rho^{\prime}$; independent of $V_S/V_L$ and $k_p$</td>
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Table 1. Relationships between longitudinal wave velocity ($V_L$), transverse wave velocity ($V_S$), ratio of sand velocities ($V_S/V_L$), ceramic bulk density ($\rho$), and planar coupling factor ($k_p$) in lead-free and lead-containing ceramics.

![Figure 9. Composition dependence of $k_p$ and $d_{33}$ in $(1-x)(\text{Na, K, Li, Ba})(\text{Nb}_{0.9}\text{Ta}_{0.1})\text{O}_3$-$x\text{SrZrO}_3$ (SZ) ($x = 0.00, 0.02, 0.04, 0.05, 0.06, 0.07$).](image-url)
We applied this novel method to $0.05\text{Pb}(\text{Sn}_{0.5}\text{Sb}_{0.5})\text{O}_3-(0.95-x)\text{PbTiO}_3-x\text{PbZrO}_3$ ($x = 0.33$, 0.45, 0.48, 0.66, 0.75) with (hard PZT) and without 0.4 wt% MnO$_2$ (soft PZT) to confirm the effectiveness of our developed $V_s/V_L$ evaluation. While $k_p$ in PZT compositions of $x = 0.33 - 0.75$ was independent of $\rho$ in Figure 8, the maximum $k_p$ was obtained at MPB around $x = 0.45 - 0.48$ [11, 21]. Figure 11 shows the $x$ dependence of $V_s/V_L$ in PZT before and after poling. The minimum $V_s/V_L$ before and after poling appeared around $x = 0.45 - 0.48$. From the relationships between $x$ vs. $k_p$ and $V_s/V_L$, it was concluded that the highest $k_p$ was realized in the case of minimum $V_s/V_L$. These compositions around $x = 0.45 - 0.48$ correspond to MPB in hard and soft PZT. Therefore, it was said that we could introduce the novel method to evaluate the piezoelectricity by measuring acoustic wave velocities of $V_L$ and $V_s$ in the compositions with MPB.

1.3.4. Relationship between the ratio of transverse wave velocity to longitudinal wave velocity and Poisson’s ratio

Figure 12 shows the relationship between $V_s/V_L$ vs. $\sigma$ in solids including piezoelectric ceramics. The equation between $\sigma$, $V_L$, and $V_s$ is shown in this figure. All of the $\sigma$ in solids was plotted on a line of the equation. The $V_s/V_L$ regions of Poisson’s ratio in soft PZT, hard PZT, lead-free and PbTiO$_3$ (PLT and PT) were also shown in this figure. The regions of $\sigma$ regarding $V_s/V_L$ increased from PbTiO$_3$ lead-free, hard PZT to soft PZT with increasing piezoelectricity. In addition to higher Poisson’s ratio, it was clarified that higher $k_p$ can be realized in lager $K$ as shown in Figure 3. We believe the physical meaning of this behavior toward $\sigma$ is as follows: increasing mechanical softness (lower $Y$) in piezoelectric materials, it becomes easy to deform by DC poling field. The $\sigma$ becomes larger while the materials become softer, and furthermore, the $K$ must become larger in order to transmit effectively from longitudinal deformation (the directions of poling and applying electric field are thickness direction of disk) to transverse deformation (the radial direction of disk). In this study, it was described a road map in
piezoelectric ceramics regarding the relationships between longitudinal and transverse wave velocities, Young’s modulus, Poisson’s ratio, modulus of rigidity and bulk modulus to research and develop new piezoelectric ceramic materials, especially lead-free ceramics with high piezoelectricity.

Figure 11. Composition $x$ dependence of ratio of sound velocities ($V_S/V_L$) in $0.05\text{Pb}(\text{Sn}_{0.5}\text{Sb}_{0.5})\text{O}_3-(0.95-x)\text{PbTiO}_3-x\text{PbZrO}_3$ ($x = 0.33, 0.45, 0.48, 0.66, 0.75$) with (hard PZT) and without 0.4 wt% MnO$_2$ (soft PZT) ceramics before and after poling.

Figure 12. Relationship between ratio of sound velocities ($V_S/V_L$) and Poisson’s ratio ($\sigma$) in solids including piezoelectric ceramics.
1.4. Conclusions in this part

Longitudinal and transverse wave velocities in PZT, lead titanate, and lead-free ceramics were measured by an ultrasonic precision thickness gauge with high-frequency pulse generation to calculate elastic constants such as Young’s modulus, Poisson’s ratio, and so forth. Since the ceramic bulk density was focused on to improve piezoelectricity in lead-free ceramics, the candidates of lead-free ceramic compositions with high piezoelectricity were proposed. It was confirmed that our evaluation method was an effective tool for R&D on piezoelectric material. Furthermore, the origin of piezoelectricity in piezoelectric ceramics could be explained by the elastic constants before and after DC poling.

2. Effects of firing and DC poling treatments on elastic constants measured from acoustic wave velocities in barium titanate piezoelectric ceramics

2.1. Introduction

Recently, we have developed a method to evaluate elastic constants, such as Young’s modulus and Poisson’s ratio, by measuring longitudinal and transverse wave velocities using an ultrasonic thickness gauge with high-frequency generation in comparison with a conventional method [28]. This method has been confirmed to be useful for measuring ceramic disks with diameters of 10-20 mm and thicknesses of 0.5-2.0 mm. In addition, it has been clarified that this method is suitable for evaluating cases involving (1) firing process analysis, such as the analysis of the effect of lead oxide (PbO) atmosphere during firing on the dielectric and piezoelectric properties of lead zirconate titanate (PZT) ceramics, and the oxygen atmosphere firing of PZT ceramics to realize pore-free ceramics, (2) DC poling process analysis, such as the analysis of the DC poling field dependence in as-fired (before poling) ceramics and relaxor single crystals, and (3) piezoelectric materials research and development (R&D) for lead-free ceramics with high piezoelectricity from the viewpoints of elastic constants [18-20].

In this part, to clarify the effects of firing temperature and DC poling on barium titanate (BT) piezoelectric ceramics, we studied the firing temperature and DC poling dependences on acoustic wave velocities and dielectric and piezoelectric properties of BT ceramics. Here, we report the relationships between firing temperature and DC poling effect vs. acoustic wave velocities, Young’s modulus, Poisson’s ratio, modulus of rigidity, and bulk modulus.

2.2. Experimental procedure

The BT raw materials in this study were utilized for two types of powder particle with high purities above 99.95% and average particle sizes of 0.2 μm (abbreviated to BT02) and 0.5 μm (BT05) (Sakai Chemical Industry). After firing at 1, 300-1, 350 °C for BT02 and at 1, 300-1, 360 °C for BT05 for 2 h, the bulk density (ρ) and microstructure of the obtained ceramic disks were evaluated. DC poling was conducted at a temperature of 60 °C and a field of 2.0 kV/mm for 30 min. After DC poling, dielectric and piezoelectric properties were measured at room temperature using an LCR meter (HP4263A), a precision impedance analyzer (Agilent 4294A), and a
piezo-d$_{33}$ meter (Academia Sinica ZJ-3D). Furthermore, the acoustic wave velocities of the BT ceramics before and after poling were measured using an ultrasonic precision thickness gauge (Olympus 35DL), which has PZT transducers with a frequency of 30 MHz for longitudinal wave generation and a frequency of 20 MHz for transverse wave generation. The acoustic wave velocities were evaluated on the basis of the propagation time between the second-pulse and the third-pulse echoes in the thickness direction parallel to the DC poling field for the ceramic disks with 14 mm diameter and 0.9-1.2 mm thickness [18-20]. The sample thickness was measured using a precision micrometer (Mitutoyo MDE-25PJ). The number (n) of disk samples measured was $n = 5-8$, and the data in the figures indicate the average of individual measured values. Furthermore, Young’s modulus (Y), Poisson’s ratio ($\sigma$), modulus of rigidity (G), and bulk modulus (K) in the thickness direction of ceramic disks were calculated on the basis of the longitudinal ($V_L$) and transverse ($V_S$) wave velocities using the equations (1)-(4) in Section 1.2. We investigated the relationships between firing temperature and DC poling effect vs. $V_L$, $V_S$, Y, $\sigma$, G, and K; furthermore, we clarified the relationships between $\rho$, the microstructure, and the elastic constants.

2.3. Results and discussion

2.3.1. Firing temperature dependence of dielectric and piezoelectric properties

Figures 13(a)-(d) show the relationships between firing temperature ($F_T$) and (a) relative dielectric constant ($\varepsilon_r$), (b) planar coupling factor ($k_p$) for the radial mode on the disks, (c) frequency constant ($f_{cp}$), and (d) piezoelectric strain $d_{33}$ constant in the cases of BT02 and BT05 ceramics before and after DC poling. Although $\varepsilon_r$ decreases with increasing $F_T$, $k_p$, $f_{cp}$, and $d_{33}$ with increasing $F_T$; furthermore, there is an optimum $F_T$ of 1,340 °C in BT02 for obtaining the highest $k_p$ and $d_{33}$. The differences in the dielectric and piezoelectric properties vs. $F_T$ between BT02 and BT05 were due to the ceramic bulk density, as mentioned later (see the following Figure 17), and the powder particle activity during firing because the specific surface areas of BT02 and BT05 powder particles measured by the Brunauer, Emmett, and Teller (BET) method were 9.4 and 2.3 m$^2$/g, respectively.

2.3.2. Effects of firing temperature and DC poling on acoustic wave velocities and elastic constants

Figures 14(a)-(d) show the relationships between $F_T$ and (a) longitudinal wave velocity ($V_L$), (b) transverse wave velocity ($V_S$), (c) Young’s modulus (Y), and (d) Poisson’s ratio ($\sigma$) in the cases of BT02 and BT05 ceramics. Although $V_L$, $V_S$, and Y before and after DC poling increase with increasing $F_T$, $\sigma$ after poling is almost independent of $F_T$; furthermore, there is an optimum $F_T$ of 1, 340 °C in BT02 from the plots of $F_T$ vs. $V_L$ and Y. The increase in Y with increasing $F_T$ indicates the increase in the mechanical hardness of the ceramic disks. By comparing $F_T$ vs. $V_L$ in Figure 14(a) with $F_T$ vs. $2f_{ct}$ ($f_{ct}$ is shown in Figure 13(c), the dependences of $V_L$ and $2f_{ct}$ on $F_T$ were almost the same, because both of them correspond to longitudinal wave velocities, as shown in Figure 15. In addition, we confirmed that $V_L$ precisely corresponded to $2f_{ct}$, which is twice the frequency constant ($f_{ct}$) of the coupling factor ($k_t$) for the thickness mode on the disks measured using the typical impedance vs. frequency response (Figure 15) [29].
Therefore, it is considered that our measurement method using the ultrasonic precision thickness gauge is suitable for evaluating acoustic wave velocities, especially in piezoelectric ceramics.

Figures 16(a)-(b) show the changes in $\Delta Y$ and $\sigma$ ($\Delta\sigma$) during poling, respectively. $\Delta Y$ decreases with increasing $F_T$, regardless of the types of BT powder particle. This phenomenon indicates that the ceramics become mechanically softer after DC poling. It is considered that such a change is due to the ferroelectric domain ($\uparrow\downarrow$) alignment induced by the poling field, such as a change in the configuration from a random orientation ($\uparrow\downarrow$) before poling to a directional orientation ($\uparrow\uparrow$) after poling [5-7, 9-15]. $\Delta\sigma$ abruptly increases from $F_T$ of 1,320 °C and shows almost the same tendency as in the case of $F_T$ vs. $k_p$ in Figure 13(b). By comparing $F_T$ vs. $k_p$ (Figure 13(b)) with $F_T$ vs. $\Delta\sigma$ (Fig. 16(b)), a higher $k_p$ was obtained in the case of a larger $\Delta\sigma$. The physical meaning of the phenomenon regarding $\sigma$ was deduced, that is, a larger $\Delta\sigma$ was needed to realize a higher $k_p$ because of the easy deformation of the bulk perpendicular to the poling field (radial direction in the disks) as well as parallel to the poling field (thickness direction in the disks).

Figure 13. Firing temperature ($F_T$) vs. (a) relative dielectric constant ($\varepsilon_r$), (b) planar coupling factor ($k_p$) for radial mode on disks, (c) frequency constant ($f_{cp}$), and (d) piezoelectric strain $d_{33}$ constant in BT02 and BT05 ceramics before and after DC poling.
Figure 14. Firing temperature ($F_T$) vs. (a) longitudinal wave velocity ($V_L$), (b) transverse wave velocity ($V_S$), (c) Young’s modulus ($Y$), and (d) Poisson’s ratio ($\sigma$) in BT02 and BT05 ceramics before and after DC poling.

Figure 15. Comparison between longitudinal wave velocity ($V_L$), $2f_c t$, and $2f_c p$, which are twice the frequency constants of $f_c$ for the thickness mode and $f_c$ for the radial mode on disks in BT02 and BT05 ceramics after DC poling; $2f_c t$ and $2f_c p$ correspond to acoustic wave velocities.
2.3.3. Relationship between ceramic microstructure and elastic constants

Figure 17 shows the $F_T$ dependence of the bulk density ($\rho$) of the ceramic disks. The relative bulk density ($\rho/\rho_0$) became over 94% for both BT02 and BT05 during firing at 1,340-1,360 °C, where $\rho_0$ (6.02 g/cm$^3$) is the theoretical density of BT ceramics [25]. From our previous study on the relationships between $k_p$ vs. $Y$ and $\sigma$ in piezoelectric ceramics, a higher $k_p$ was realized at a lower $Y$ and a higher $\sigma$ [18-20]. However, there is no correspondence between the lower $Y$ (Fig. 14(c)), the higher $\sigma$ (Fig. 14(d)), the lower $k_p$ (Fig. 13(b)), and the lower $d_{33}$ (Fig. 13(d)) during firing at 1,300-1,320 °C because of the low relative bulk density of $\rho/\rho_0$ (< 0.94). On the other hand, while $Y$ became almost constant during firing at 1,340-1,360 °C (Fig. 14(c)), $\sigma$ before poling decreased with increasing $F_T$ (Fig. 14(d)). It was considered that the decrease in $\sigma$ with increasing $F_T$ was due to the increase in the density of coarse grains with average diameters of 50 μm as mentioned later. As $F_T$ vs. $\sigma$ before poling (Fig. 14(d)) shows the same tendency as $F_T$ vs. $\epsilon_r$ (Fig. 13(a)), the $\epsilon_r$, of which is directly related to ferroelectric domain structures, the $\sigma$ dependence of $F_T$ was considered to be due to the domain structures and anisotropy of coarse
grains being different from those of fine grains with average diameters of 1.2 μm. Since the ferroelectric domain size increases with increasing grain size of BT ceramics, the domain density decreases in the case of coarse grains [30-33]. Therefore, the ceramics with coarse grains exhibit a lower \( \varepsilon_r \) and a larger crystal anisotropy than the ceramics with fine grains [34-38]. Furthermore, \( \sigma \) decreases with increasing \( F_T \) because it approaches a behavior similar to that of a BT single crystal, \( \sigma \) of which is 0.29 while \( \sigma \) of the ceramics is 0.31 [25]. In order to evaluate the physical characteristics of ceramic grains, the modulus of rigidity \( (G) \) and bulk modulus \( (K) \) were calculated by the equations (3) and (4) in Section 1.2. [23, 24]: \( G \) and \( K \) before poling increase with increasing \( F_T \) during firing at 1,300-1,360 °C, as shown in Figures 18(a)-(b), respectively, because the ceramic bulk density is improved in BT ceramics as shown in Figure 17; as a result, \( G \) and \( K \) are obtained from the equations (3) and (4), as well as \( Y \) in Figure 14(c) from equation (1). On the other hand, \( \sigma \) is independent of the ceramic bulk density, as shown in equation (2). Figures 19(a)-(d) show the relationships between \( \rho/\rho_0 \) vs. \( Y, \sigma, G, \) and \( K, \) respectively. \( Y, G, \) and \( K \) depend on \( \rho/\rho_0 \) because they are affected by increasing the mechanical strength, especially the hardness of the ceramics, with \( F_T \). As mentioned previously regarding Figure 14(d), \( \sigma \) is independent of \( \rho/\rho_0 \) except when \( \rho/\rho_0 \) is above 0.94, as shown in Figure 19(b), which corresponds to ceramics with a larger domain size and a lower domain density with coarse grains. \( G \) decreased and \( K \) increased after poling owing to the domain alignment as shown in Figure 18. In addition, the change in \( G (\Delta G) \) in BT ceramics during poling linearly decreased with increasing \( F_T \) and peaks of the changes in \( K (\Delta K) \), which correspond to the peaks of \( \Delta \sigma \) (Figure 16(b)), were obtained at \( F_T \) of 1340 °C in the BT02 ceramics and at \( F_T \) of 1, 350-1, 360 °C in the BT05 ceramics, as shown in Figures 20(a)-(b). Therefore, a higher \( k_p \) could be realized at \( F_T \) at the peaks of \( \Delta K \) and \( \Delta \sigma \). Since ceramic grains with a higher \( K \) due to domain alignment during DC poling, indicating a high ceramic bulk density for obtaining a higher \( k_p \), are difficult to change in terms of their volume while applying external stress, the deformation of grains is practically transferred from the parallel direction to the perpendicular direction toward the direction of the applied stress; as a result, a higher \( \sigma \) is achieved. We believe that the increase in \( \sigma \) (\( \Delta \sigma \)) as a result of the increase in \( K (\Delta K) \) indicates fundamental issues regarding the poling of ceramic grains to obtain a higher \( k_p \); therefore, the R&D of piezoelectric ceramics with high piezoelectricity must be focused on to realize a lower \( G \) and a higher \( K \) during DC poling from the viewpoints of elastic constants. From the above-mentioned results, it was considered that the values of \( F_T \) vs. \( G \) and \( K \) in BT02 and BT05 ceramics after poling (Figures 18(a)-(b)) correspond to the values of \( k_p \) vs. \( F_T \) (Figure 13(b)).

Figure 21(a) shows the \( F_T \) dependence of microstructures in the BT02 ceramics. With the increase in \( k_p \), with \( F_T \), ceramic grains grew from 1.2 μm (fine grains shown as white parts in the figures) to 50 μm (coarse grains shown as black parts in the figures) in diameter; moreover, the ratio of black parts to whole parts (black parts plus white parts) increased. The border between fine and coarse grains is shown in Figures 21(b)-(c). Furthermore, it was found that the black parts consist of several coarse grains, as shown in Figure 21(b). This phenomenon was almost the same as in the case of the microstructure in the BT05 ceramics. Figure 22 shows the relationship between \( k_p \) and the area ratio of coarse grains (black parts) measured by image-analyzing software (WinROOF [39]). In this figure, when the area ratio increases, \( k_p \) increases because of the increase in the density of coarse grains. Therefore, the coarse grains in the dense
ceramic bulk contribute to a higher \( k_p \) and \( V_L, V_T, Y, \) and \( \sigma \) in the coarse grains correspond to those at \( F_T \) of 1, 360 °C in Figures 14(a)-(d), which almost agree with the values previously reported [25].

![Figure 17](https://example.com/figure17.jpg)

**Figure 17.** Firing temperature \( (F_T) \) dependence of bulk density \( (\rho) \) in BT02 and BT05 ceramic disks.

![Figure 18](https://example.com/figure18.jpg)

**Figure 18.** Firing temperature \( (F_T) \) vs. (a) modulus of rigidity \( (G) \) and (b) bulk modulus \( (K) \) in BT02 and BT05 ceramics before and after DC poling.
Figure 19. Relative bulk density ($\rho/\rho_0$) dependences of (a) Young’s modulus (Y), (b) Poisson’s ratio ($\sigma$), (c) modulus of rigidity, and (d) bulk modulus (K) in BT02 and BT05 as-fired (before poling) ceramics sintered during firing at 1, 300-, 360 ℃, where $\rho$ and $\rho_0$ (6.02 g/cm$^3$) are the measured bulk density and theoretical density [25] of BT ceramics, respectively.

2.3.4. Firing temperature dependence of elastic constants in barium titanate ceramics

Figure 23 shows that the relationships between $k_p$ vs. Y, $\sigma$, G, and K in BT02 and BT05 ceramics fired at different temperatures were inserted into the relationships between $k_p$ vs. Y, $\sigma$, G, and K in lead-containing and lead-free piezoelectric ceramics (Figure 3), which were fired at the optimal temperatures for each composition to realize the maximum $k_p$. Higher $k_p$ is obtained in the cases of lower Y and G, and furthermore, higher $\sigma$ and K, which are indicated by yellow arrows in Figure 23. This figure also indicates the firing temperature dependence of the bulk density vs. Y, $\sigma$, G, and K in Figure 19. $k_p$ increases with the increase of Y, G, and K because of the increase in bulk density with increasing firing temperature. On the other hand, $\sigma$ was independent of $k_p$ because $\sigma$ is an intrinsic material constant. These phenomena are indicated by green arrows in Figure 23. It is predicted the same phenomena regarding the firing temperature and bulk density dependences on $k_p$ vs. Y, $\sigma$, G, and K in cases of lead-containing and lead-free ceramics.
Figure 20. Changes in modulus of rigidity (ΔG) and bulk modulus (ΔK) in BT02 and BT05 ceramics during DC poling.

Figure 21. (a) Firing temperature (F\textsubscript{T}) dependence of microstructures in BT02 ceramics, (b) border between fine grain [see (c), average grain size of 1.2 μm] and coarse grain [see (b), average grain size of 50 μm], and relationship between black parts and coarse grains.
Figure 22. Planar coupling factor ($k_p$) vs. area ratio of coarse grains of black parts measured by an image-analyzing software program (WinRoof [39]).

Figure 23. Planar coupling factor ($k_p$) vs. $Y$, $\sigma$, $G$, and $K$ in BT02 and BT05 ceramics fired at different temperatures. These data were inserted into the relationships between $k_p$ vs. $Y$, $\sigma$, $G$, and $K$ in lead-containing and lead-free piezoelectric ceramics (Figure 3), which were fired at the optimal temperatures for each composition to realize maximum $k_p$.

2.4. Conclusions in this part

The effects of firing temperature and DC poling on the longitudinal and transverse wave velocities in barium titanate ceramics were investigated using an ultrasonic precision thickness...
gauge with high-frequency pulse generation. The results could explain the relationships between acoustic wave velocities, Young’s modulus, Poisson’s ratio, the modulus of rigidity, and the bulk modulus vs. firing temperature, and the changes in elastic constants during DC poling.

3. Summary of this chapter

Sound velocities were evaluated in ceramic disks composed of lead-containing and lead-free ceramics using an ultrasonic precision thickness gauge with high-frequency pulse generation, and furthermore, dielectric and piezoelectric constants were simultaneously measured utilizing the same disk samples. Calculating elastic constants by using the sound velocities, higher piezoelectricity in ceramics were obtained in lower Young’s modulus and rigidity, and furthermore, higher Poisson’s ratio and bulk modulus. Piezoelectric ceramics with lower Young’s modulus and rigidity caused by ferroelectric domain alignment while DC poling were easy to deform by electric field and external force. In addition to these phenomena, higher bulk modulus needs to realize higher Poisson’s ratio. Lower Young’s modulus means mechanical soft in ceramics; however, higher bulk modulus, which means mechanical hard in ceramics, need to obtain higher piezoelectricity. It was thought that these characteristics run counter to the mechanical characteristics of piezoelectric ceramics; however, it was the origin of piezoelectricity in ceramics.

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Author details

Toshio Ogawa

Address all correspondence to: ogawa@ee.sist.ac.jp

Department of Electrical and Electronic Engineering, Shizuoka Institute of Science and Technology, Toyosawa, Fukuroi, Shizuoka, Japan
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