Piezoelectric Property Enhancement in Polycrystalline Lead Zirconate Titanate by Changing Cutting Angle

多結晶ジルコン酸チタン酸鉛における切断角度変更による圧電特性の向上

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The effective piezoelectric strain constant d_{33} and electromechanical coupling factor k_{33} of polycrystalline lead zirconate titanate (PZT) at different cutting angles have been measured by using the IEEE standard resonance method. It was found that for tetragonal PZT 48/52, the effective d_{33} and k_{33} monotonously decreases as the cutting angle canted from the poling direction increases. However, for rhombohedral PZT 54/46, the effective d_{33} has the maximum value along a direction which is canted about 45° away from the poling direction, while the effective electromechanical coupling factor is not sensitive to the cutting direction and remains almost constant in the cutting angle range from 0° to 45°.

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Lead zirconate titanate (PZT) ceramics have been widely used in transducers and actuators due to the large piezoelectric coefficients and high electromechanical coupling factors. In these applications, the ceramic is electrically driven along a direction either parallel to the poling direction (0° cutting angle) to utilize the longitudinal extension deformation or perpendicular to the poling direction (90° cutting angle) to utilize the shear deformation. To the author's knowledge, no systematic investigations have been done to enhance the piezoelectric properties by choosing an electrical driven direction which is canted between 0° and 90° away from the poling direction. This paper presents the experimental results about such enhancement.

In the previous papers,^{1,2)} we reported the phenomenological calculations of the piezoelectric and dielectric constants of hypothetical single crystals of PZT in different crystal orientations. For a tetragonal PZT, the effective piezoelectric constant d_{33} monotonously decreases as the crystal cutting angle from the spontaneous polarization direction [001] increases. However, for a rhombohedral PZT, the effective piezoelectric constant $d_{33[001]}$ along the perovskite [001] direction was found to be much larger than those along the spontaneous polarization direction [111]. A similar tendency can be expected for polycrystalline samples, though the enhancement might be less significant than single crystals.

Tetragonal PZT 48/52 and rhombohedral PZT 54/46 ceramic plates with sizes about 10 mm × 10 mm × 1 mm were poled along one of the large sides, as shown in Fig. 1. Then, the plates were cut into small bars along the directions canted 0°, 15°, 30°, 45°, 60° and 75° away from the poling direction, respectively. The sizes of the samples are listed in Table 1. For each cutting direction, a plate normal to the direction was also cut for permittivity measurement. We used gold as the electrode material. The IEEE Standard resonance method³⁾ was used to measure the

longitudinal extensional piezoelectric constant d_{33} and electromechanical coupling factor k_{33} for each bar. Figure 2 shows the values of d_{33} with respect to the cutting angles away from the poling direction. The values of d_{33} have been normalized by $d_{33//Ps}$, the d_{33} along the poling direction. Figure 3 shows the results for k_{33} . For tetragonal PZT 48/52, both d_{33} and k_{33} monotonously decrease as the cutting angle increases. However, for rhombohedral PZT 54/46, d_{33} increases as the cutting angle increases from 0° to 45°, leading 1.25 time enhancement at 45°; k_{33} is not sensitive to the cutting direction and remains almost constant in this cutting angle range. Beyond this cutting angle range, both d_{33} and k_{33} decrease as the cutting angle increases. The angle with maximum d_{33} is little smaller than the calculated angle 56°–59° for the hypothetical PZT crystals. Figure 4 shows the dielectric constants in different directions; for both rhombohedral and tetragonal PZT, the dielectric constants monotonously increase as the cutting angle increases.

In conclusion, for tetragonal PZT 48/52, the effective

Fig. 1. Illustration of sample cutting.

Table 1. Sizes of Samples (mm)

Angles	0°	15°	30°	45°	60°	75°
PZT 54/46	10.54×0.98 ×1.04	7.05×0.67 ×1.04	8.13×0.93 ×1.04	11.40×1.12 ×1.05	7.10×0.72 ×1.05	6.80×0.64 ×1.04
PZT 48/52	10.03×0.87 ×0.98	6.87×0.65 ×1.01	7.32×0.69 ×1.01	10.03×0.97 ×1.01	6.30×0.62 ×1.00	6.52×0.58 ×1.01

Fig. 2. The effective d_{33} normalized by d_{33}/P_s , the d_{33} along the poling direction, with respect to cutting angles from the poling direction. For tetragonal PZT 48/52, $d_{33}/P_s = 98 \text{ pC/N}$. For rhombohedral PZT 54/46, $d_{33}/P_s = 148 \text{ pC/N}$.

Fig. 3. The effective k_{33} with respect to cutting angles from the poling direction.

Fig. 4. The dielectric constants with respect to cutting angles from the poling direction.

piezoelectric constant d_{33} and electromechanical coupling factor k_{33} have the maximum values along the poling direction and decrease monotonously as the cutting angle from the poling direction increases. However, for rhombohedral PZT, d_{33} has the maximum value at a cutting angle about 45° away from the poling direction. This shows us that the enhancement of piezoelectric properties by changing the cutting direction away from the polarization direction exists not only in single crystals, but also in polycrystalline solids. By choosing an appropriate cutting direction, the piezoelectric properties can be improved.

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