

IRE Standards on Piezoelectric Crystals: Measurements of Piezoelectric Ceramics, 1961*

61 IRE 14.S1

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* Approved by the IRE Standards Committee, May 12, 1960. Reprints of this Standard 61 IRE 14.S1 may be purchased while available from the Institute of Radio Engineers, 1 East 79th Street, New York, N. Y., at \$0.70 per copy. A 20 per cent discount will be allowed for 100 or more copies mailed to one address.



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1. CLASSIFICATION OF PHENOMENA

Certain polycrystalline ferroelectric substances, of which ceramic barium titanate (BaTiO_3) is the prototype, can be given lasting polar properties, including pyroelectric and piezoelectric effects, by treatment with high electric fields for a short time. The term "to pole" is recommended for this treatment.

Poled ferroelectric ceramics have become an important component in electromechanical devices along with piezoelectric crystals and magnetostrictive materials. The purpose of this standard is to adapt the definitions, relations and measurement methods developed for piezoelectric crystals in general [1]–[3] to ferroelectric ceramics. The higher symmetry of these ceramics leads to simpler relations than for most piezoelectric crystals. The high coupling constants, low mechanical quality factor Q , and noticeable dielectric loss factor of the ferroelectrics, on the other hand, limit the applicability of some approximation formulas of the 1957 and 1958 Standards. Piezoelectric ceramics are sometimes also referred to as "electrostrictive." The choice of designation depends on the degree of penetration into the basic mechanisms involved, but the formalism of piezoelectricity is applicable within the limits stated in the following sections.

1.1 Symmetry Relations

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 components on the other, just as do piezoelectric crystals, and are called piezoelectric ceramics for this reason. However, with ferroelectric crystals and poled ceramics these relationships are linear only over limited ranges of the input signal. In addition, mechanical and dielectric loss factors are functions of mechanical strain and electric field, respectively.

The symmetry elements of poled ferroelectric ceramics are an axis of rotation of infinite order in the direction of polarization and the infinite set of all planes parallel to that axis as reflection planes. This axis, chosen as the Z axis, is polar. Any direction perpendicular to the Z axis may be chosen as X axis. The set of independent elastic, piezoelectric, and dielectric constants¹ different from zero for this symmetry are

$$s_{11}, s_{33}, s_{55}, s_{12}, s_{13}; d_{31}, d_{33}, d_{15}; \epsilon_{11}, \epsilon_{33}.$$

Additional coefficients are given by the symmetry relations

$$s_{22} = s_{11}; s_{23} = s_{13}; s_{44} = s_{55}; s_{66} = 2(s_{11} - s_{12}); \\ d_{32} = d_{31}, d_{24} = d_{15}; \epsilon_{22} = \epsilon_{11}.$$

¹ See Table II at end of Standards for identification of symbols.

This is the same set as for the dihexagonal polar crystal class ($6 \text{ mm} = C_{6v}$).

1.2 Electrostrictive Effects

Before poling, the ferroelectric ceramic material is isotropic and shows no piezoelectric effect. For small applied signals ordinary electrostrictive effects are present; there is a strain proportional to the square of the applied electric field and a change in permittivity proportional to an applied mechanical stress. For high electric fields hysteresis effects are pronounced, and it is not possible to derive electromechanical behavior from electrostrictive coefficients relating strain to field strength. Total strain is, however, found approximately proportional to the square of the total electric displacement. Linear terms are thus obtained in a relation between an applied small signal electric displacement and the change in strain caused by this signal. If vectorial superposition of remanent and signal displacement is assumed, and dependence of dielectric and electrostrictive coefficients on magnitude of displacement is disregarded, the following relations between piezoelectric and electrostrictive coefficients result:²

$$\begin{aligned} d_{31}/\epsilon_{33}^T &= g_{31} = 2q_{31}D_0, \\ d_{33}/\epsilon_{33}^T &= g_{33} = 2q_{33}D_0, \\ d_{15}/\epsilon_{11}^T &= g_{15} = 2(q_{33} - q_{31})D_0, \\ d_p/\epsilon_{33}^T &= g_p = 4q_{31}D_0, \\ d_h/\epsilon_{33}^T &= g_h = 2D_0(q_{33} + 2q_{31}). \end{aligned} \quad (1)$$

Measurements indicate the assumptions upon which these relations depend are valid in rough approximation. Refined relations have been derived [4], [5].

1.3 Ferroelectric Crystals and Ceramics

Ferroelectric single crystals in general have lower symmetry than the poled ceramic form of the same substance. For this reason measurement methods described in this Standard do not in all cases apply to ferroelectric single crystals. The 1958 Standards on Piezoelectric Crystals describe measurement methods for the most general symmetry conditions, and are, therefore, applicable to ferroelectric single crystals or poled ceramics. In both ferroelectric crystals and ceramics, however, the relations between stress and strain components on the one hand and electric field and displacement on the other are linear only over limited ranges of the input signal; higher signals cause domain reversals resulting in gross deviation from linearity.

² All equations in the present Standard are written in rationalized form.

The most widely used piezoelectric ceramic is barium titanate (BaTiO_3). Frequently, barium is replaced in part by lead or calcium. Other ceramic systems showing strong piezoelectric effects are lead metaniobate (PbNb_2O_6), solid solutions of lead titanate (PbTiO_3) with lead zirconate (PbZrO_3), and sodium niobate (NaNbO_3) with partial replacement of sodium by potassium, lead, or cadmium.

2. MEASUREMENT METHODS

Methods developed for measurement of dielectric, elastic and piezoelectric constants of crystals are generally applicable to poled ferroelectric ceramics, but the particular properties of the latter make some special methods advantageous. High values of permittivity usually allow one to disregard stray capacitances, and the relatively high internal mechanical damping (low Q) of the material permits the use of relatively crude specimen holders. High values of piezoelectric coupling generally require the use of complete rather than approximate formulas relating ($f_p - f_s$) with coupling factors.

The properties of ceramics are functions of the preparation process, and are subject to systematic and statistical fluctuations within a given batch. These fluctuations may be caused by inhomogeneous chemical composition, mechanical differences in the forming process, varying shrinkage and chemical modification

during firing, and by varying response to the poling treatment. Nevertheless, measured coefficients of ceramics of definite composition and high density (95 per cent or more of crystal density) converge to values which vary no more than 5 per cent for elastic, 10 per cent for piezoelectric, and 20 per cent for dielectric constants. Proper statistical sampling is necessary to obtain representative constants for a given material. To obtain a complete set of constants for a composition, one must either measure each constant on a large number of samples, or make experiments giving ratios of constants, since such ratios are much less variable than the individual constants. Compliances s_{11}^E and s_{12}^E , for instance, may be determined from the resonance frequencies of two contour-extensional modes of a square plate. Compliance s_{11}^E may also be determined from the resonance frequency of a slim transversely poled bar, and s_{55}^D can be calculated from f_p of overtones of the thickness shear mode of the same bar with electrodes applied to another pair of faces. This establishes ratios s_{12}^E/s_{11}^E and s_{55}^D/s_{11}^E , and thus s_{12}^E/s_{55}^D . An outline of a measurement scheme for determining all the piezoelectric, dielectric, and elastic constants in this manner is shown in Table I. Resonance methods of measurement are preferred, and one procedure is described in detail in the next section. Static and quasi-static methods are then described, and finally measurements and terms in the nonlinear or high-signal range are discussed.

TABLE I
MEASUREMENT SCHEME FOR PIEZOELECTRIC CERAMICS

Constants	Specimen and Orientation	Measurement Scheme, or Calculation Method
s_{11}^E, k_{31}, d_{31} s_{11}^D ϵ_{33}^T s_{55}^D	Bar plated on faces perpendicular to Z . Bar plated on faces perpendicular to Z . Bar plated on faces perpendicular to Z . Bar poled along Z , but with plating on faces perpendicular to X .	Resonance measurements of the length extensional mode. From above, using $s_{11}^D = (1 - k_{31}^2)s_{11}^E$. Measurement of low-frequency capacitance. Overtones of thickness shear mode of the same bar as above, but with signal field along X .
ϵ_{11}^T ϵ_{11}^S k_{15} s_{55}^E s_{11}^E, s_{12}^E	Bar poled along Z , but with plating on faces perpendicular to X . Bar poled along Z , but with plating on faces perpendicular to X . Bar poled along Z , but with plating on faces perpendicular to X . Bar poled along Z , but with plating on faces perpendicular to X . Square plate with faces perpendicular to Z .	Measurement of low-frequency capacitance. Measurement of high-frequency (clamped) capacitance. $k_{15}^2 = 1 - \epsilon_{11}^S/\epsilon_{11}^T$. $s_{55}^E = s_{55}^D/(1 - k_{15}^2)$. Fundamental resonance frequencies of the two contour-extensional modes of a square plate.
s_{12}^D s_{33}^D, d_{33}, k_{33} s_{33}^E s_{11}^E, k_p, d_{31} k_t d_h d_{33} c_{33}^D s_{13}^D s_{13}^E	Square plate with faces perpendicular to Z . Bar plated on faces perpendicular to Z , and with length along Z . Bar plated on faces perpendicular to Z , and with length along Z . Disk with faces perpendicular to Z . Disk with faces perpendicular to Z . Disk with faces perpendicular to Z . Disk with faces perpendicular to Z . Disk with faces perpendicular to Z . Calculation. Calculation.	$s_{12}^D = s_{12}^E - k_{31}^2 s_{11}^E$. Resonance measurements of length extensional mode. $s_{33}^E = s_{33}^D/(1 - k_{33}^2)$. Resonance measurements of planar extensional mode. Resonance measurements of thickness extensional mode. Measurement of response to hydrostatic pressure. $d_{33} = d_h - 2d_{31}$. Overtones f_p of thickness extensional mode. Calculated from $c_{33}^D, s_{12}^D, s_{11}^D$, and s_{33}^D . $s_{13}^E = s_{13}^D + d_{31}d_{33}/\epsilon_{33}^T$.
ϵ_{33}^S	Calculation.	$\epsilon_{33}^S = \epsilon_{33}^T \left[1 - \frac{k_p^2 + k_{33}^2 + 2Ak_p k_{33}}{1 - A^2} \right]$, where
or		$A = \frac{\sqrt{2} s_{13}^E}{\sqrt{s_{33}^E(s_{11}^E + s_{12}^E)}}$
	Plate with faces perpendicular to Z .	Measurement of high-frequency (clamped) capacitance.

Note: s_{12} , s_{13} , and d_{31} are generally negative. k_p is taken to be positive when d_{31} is negative.