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Aspect ratio dependence of d_{15} measurements in Motorola 3203 material

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Abstract

The measurement of piezoelectric coefficients is a subject that has received considerable attention, with the exception of shear mode excitation. The aspect ratios necessary to provide accurate, reproducible measurements of d_{15} in Motorola 3203 are explored using impedance spectroscopy. It is shown that a minimum aspect ratio of 20:1 is necessary in the dimensions of the ceramic between the field and the polarisation directions (l/t) to provide reproducible measurements, contrary to previous work. A width contribution to the measurement results is highlighted leading to a minimum aspect ratio of 6:1 between the width and the thickness (w/t). It is suggested that the width contribution is a result of a distribution of dipole vectors around the poled direction. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Aspect ratio; Impedance spectroscopy; Piezoelectric properties; PZT

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1. Introduction

Piezoelectric materials based on the lead zirconate titanate (PZT) system may be found in a large array of everyday devices from the simple (i.e. spark igniters and phonograph pick-ups) to the very complex (i.e. medical ultrasound and active damping).[1,2]

The majority of this literature is concerned with piezoelectric activity in the poled direction (33 mode) or in the transverse direction (31 mode); very little exists on the use and measurement of shear mode (15).

Shear mode excitations occur when an electric field is applied in a direction perpendicular to the net polarisation (Fig. 1). Such modes are employed in a variety of technologies such as ink-jet printing.[3] It is important for such applications to have an accurate method for the determination of piezoelectric coefficients. Such parameters may be measured mechanically[4–6] (using laser interferometry, for example[7,8]). Parameter determination using mechanical methods is, in some cases, very onerous and only comparative with other materials,[5] i.e. a previously characterised material is used in the measurement of further materials; in such a case the characterisation of further materials relies on all piezoelectrics having the same d_{15}/d_{31} ratio, which is untrue in the majority of cases.

Shear mode parameters such as d_{15} (the shear mode piezoelectric coefficient) are commonly obtained using impedance analysis. This technique provides the electromechanical resonance, f_r, from the local impedance minimum, antiresonance, f_a, from the local impedance maximum (Fig. 2), and the low frequency, unclamped capacitance. The piezoelectric activity can be calculated from these parameters.

To obtain accurate piezoelectric measurements, it is important to excite only one specific mode, i.e. all extraneous modes must be clamped. The simplest way to achieve this is to make the resonant direction significantly different in size from all other directions, to reduce the effect of coupling. A variety of values are suggested for the minimum aspect ratio, ranging from 5:1[9] to 10:1.[8]

2. Experimental

Motorola 3203 material (supplied in wafers 72.5 × 72.5 × 0.9 mm, thickness poled) was cut into test

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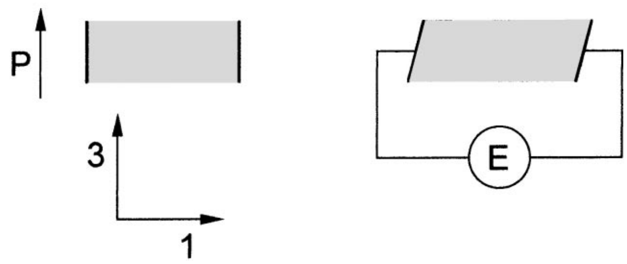

Fig. 1. Shear mode piezoelectric effect.

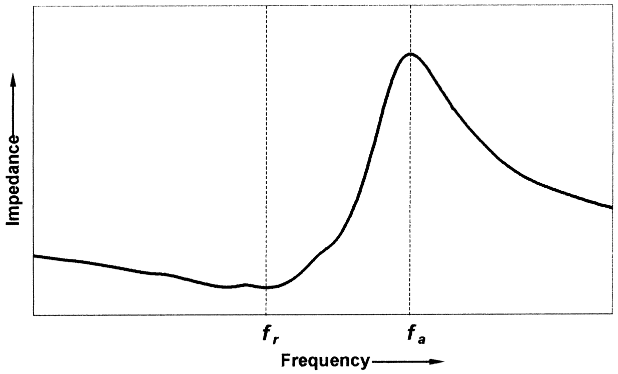

Fig. 2. Impedance vs. frequency for a piezoelectric material showing electromechanical resonance (f_r) and antiresonance (f_a).

samples using a diamond saw, to a tolerance of ±25 μm. The lengths of the samples were varied, whilst holding the width constant, and vice versa. Electrodes were applied to the sawn surfaces using silver paint, and the wires attached using silver epoxy, which was subsequently cured at 90°C for 15 min (such temperatures did not effect the piezoelectric activity of the material, which had a Curie point around 250°C). The other ends of the wires were attached to the terminals of a Hewlett-Packard HP 4194A impedance analyser, using a HP 16047A test fixture. Such a test mechanism, avoiding test rig compensation, did not alter the positions of the resonant and antiresonant frequencies, although the magnitude of the impedance was altered slightly (<2%).

Impedance/frequency data, and the capacitance were acquired by a PC. This data was used to determine f_r and f_a, which, in turn provide d_{15}, employing Eqs. (1)–(3)[8].

$$s_{55}^{E} = \frac{1}{\rho(2lf_r)^2} \tag{1}$$

$$k_{15} = \left(1 - \frac{f_r^2}{f_a^2}\right) \tag{2}$$

$$d_{15} = k_{15}\sqrt{\varepsilon_1^T s_{55}^E} \tag{3}$$

Here, s_{55}^E is the short circuit compliance, ρ the density, l the resonant length, k_{15} the shear mode coupling coefficient, and ε_1^T the relative permittivity under constant (zero) stress, which is measured at 1 kHz, well below any resonances.

A variety of different methods exist to extract k_{15} from impedance/admittance data.[7,9] All these methods, however, still rely on unimodal impedance data, and are therefore ignored here.

3. Results

The variation of impedance with frequency and sample length, for samples 2 and 20 mm wide, are shown in Figs. 3 and 4, respectively. The interference between the primary resonant/antiresonant mode and secondary modes for low sample length is clear, as shown by the highly undulating surface of the plots. The frequency of resonance and antiresonance for the primary mode is very difficult to determine, until the sample is approximately 20 mm long due to this interference.

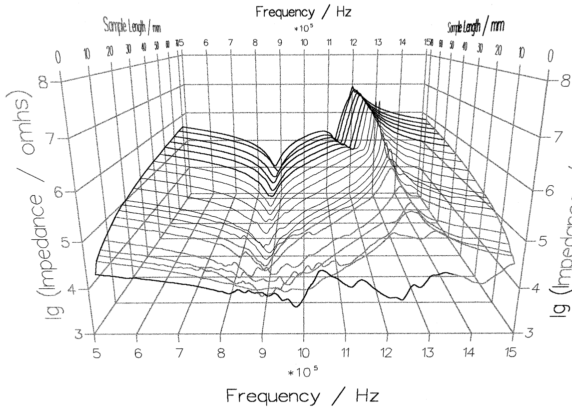

Fig. 3. Impedance vs. frequency and sample length for sample 2 mm wide.

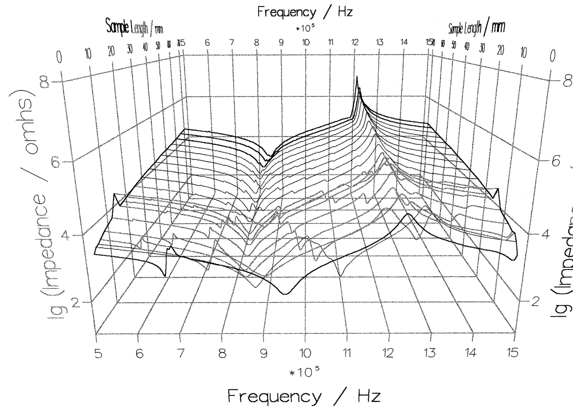

Fig. 4. Impedance vs. frequency and sample length for sample 20 mm wide.

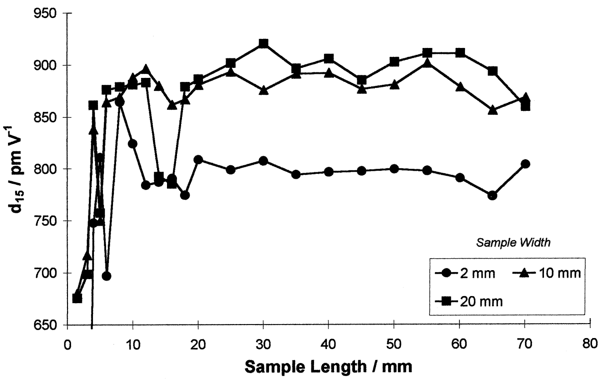

Fig. 5. d_{15} vs. sample length.

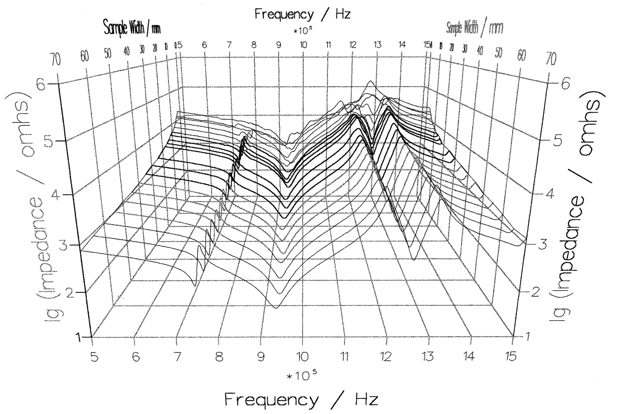

Fig. 6. Impedance vs. frequency and sample width for sample 5 mm long.

Fig. 5 shows the value of d_{15} for a variety of fixed sample widths. The figure shows that until an aspect ratio of 20:1 is reached, that no level of measurement reliability can be expected. For sample lengths between 5 and 20 mm, for example, the measured values are up to 220 pm V^{-1} lower than the more stable results obtained for samples longer than 20 mm. The narrowest (2 mm wide) samples that were between 20 and 70 mm long show consistent, but lower d_{15} parameters.

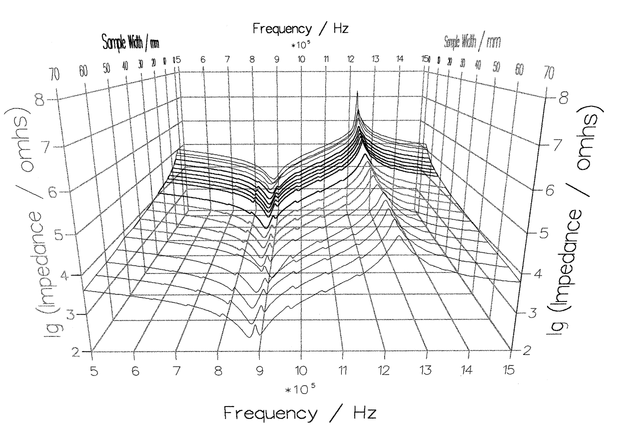

Fig. 7. Impedance vs. frequency and sample width for sample 30 mm long.

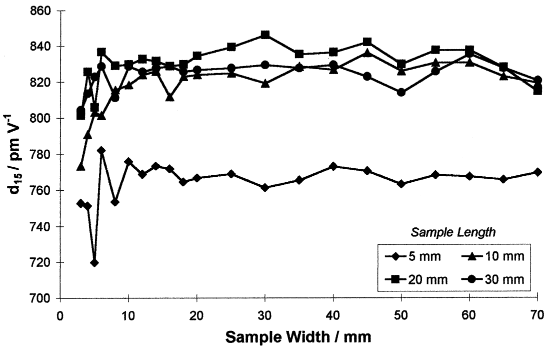

Fig. 8. d_{15} vs. sample width.

It is observed that the sample width can also strongly affect the measurement reliability (Figs. 6 and 7). Fig. 8 shows that reliability is not achieved until the sample is 6 mm wide, in the case where the length/thickness aspect ratio is above 20:1.

The results presented here show that increasing the aspect ratio above 20:1 does not exclude extraneous modes (i.e. the slight deviations below resonance shown in Fig. 2), such as longitudinal excitations, but reduces their influence on the primary, thickness, shear mode excitation, to a level where reproducible measurement can be achieved. As the length of the sample is increased, the difference between the maximum and minimum of impedance resulting from the secondary acoustic system becomes more and more slight when compared to the primary thickness shear mode, therefore having a reduced effect on the primary impedance/frequency profile.

It is interesting that the width appears to influence the thickness shear mode, other than providing a lower

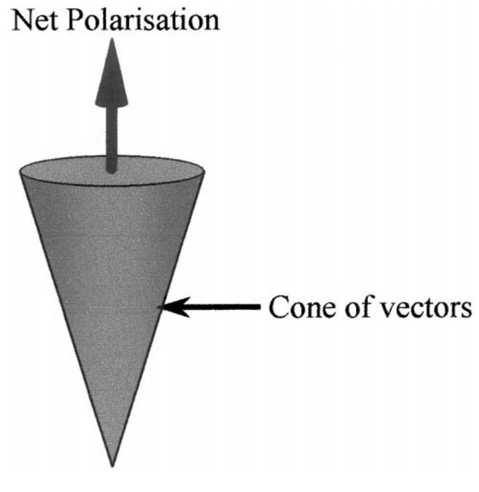

Fig. 9. Diagram of cone of vectors which combine to provide the net polarisation.

impedance as the width is increased. This result is unexpected if one considers a simple two-dimensional model involving shear and longitudinal excitations in the length and thickness directions alone. This effect of width must be a consequence of some component of the bulk polarisation aligned in a direction perpendicular to both the *net* spontaneous polarisation (resulting from electrical poling), and the applied field direction, i.e. the existence of a cone of vectors (Fig. 9). This cone of vectors would allow the transferral of motion in the plane of the poling direction and the electric field into a direction orthogonal to the plane.

4. Conclusions

It is shown that extreme care must be taken when deriving shear piezoelectric coefficients from impedance data, and that a length/thickness aspect ratio of 20:1 may be necessary. Aspect ratios between 5 and 10 to 1 can lead to errors greater than 25%. The width/thickness aspect ratio also affects measurement.

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