PERFORMANCE OF PIEZOELECTRIC CERAMIC MULTILAYER COMPONENTS BASED ON HARD AND SOFT PZT

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Abstract

The use of piezoelectric materials for actuator applications has been steadily increasing in recent years and for the design of devices there is a need for the knowledge of relevant properties at working conditions. Piezoelectric actuators are usually operated at high electrical field and in the present work, various high-field properties have been measured for a range of commercial materials, soft- or hard-doped PZT and electrostrictive PMN-PT. For the soft and electrostrictive materials, both the real and the imaginary parts of the permittivity show a linear dependence on the electric field, as predicted by the Rayleigh law. The hard PZT materials do not obey the Rayleigh law, however. For the soft materials, also the piezoelectric d_{33} coefficient increases linearly with the field, but not for the hard ones.

Introduction

In recent years, the range of applications for piezoelectric multilayer components has rapidly expanded. Traditionally, such components have been used as actuators mainly for micro- and nanopositioning applications. However, due to the fact that multilayer components are now commercially available in various sizes, shapes and materials, multilayer components are now utilised in a much broader range of applications, as actuators, benders, generators and transformers.

The typical material used in ceramic multilayer actuators (CMA) is a soft-doped PZT well suited for micropositioning applications due to a high d_{33} constant. However, many new applications often require not only a high stroke, but sometimes that the CMA should work at high temperature, e.g. in fuel injection up to 200 °C, or should work at high frequency without significant heat generation, e.g. in ultrasonic motors operating at 20 – 30 kHz. Moreover, in some applications the high permittivity of soft-doped PZT materials results in very high capacitances of the CMAs, thus requiring complicated driving electronics. Here, a hard-doped, low-permittivity PZT material offers significant advantages.

To date, very limited information about high-field properties of piezoelectric materials has been available in the documentation from suppliers of piezoelectric materials. In order to better understand the advantages of the different piezoelectric materials operated at high field, a study comparing the performance of piezoelectric CMAs based on hard and soft doped PZT materials has been carried out.

Experimental

A number of CMAs with dimensions 7 mm x 7 mm x 2 mm have been prepared of six of Ferroperm's commercial compositions, Table 1.

Material	$\varepsilon_{33,r}^T$	tan δ (%)	d_{33} (pm/V)	Curie T_C (°C)
Pz21	3800	1,8	640	215
Pz24	400	0,2	190	330
Pz26	1300	0,3	290	330
Pz27	1800	1,7	425	350
Pz29	2900	1,9	575	235
Es91	18000	≈ 8	-	-

Table 1. Selected properties of tested actuator materials (standard catalogue material data).

Pz21 and Pz29 are very soft PZTs, Pz27 a medium soft PZT, Pz24 and Pz26 hard PZTs and Es91 is a PMN-PT material. All components except those used for dielectric/piezoelectric measurements had 18 active layers with a thickness of 100 µm ± 5 µm.

The study of the CMAs included:

- Dielectric properties at high field strength
- Microstructure
- Electrical field for reversion of polarisation
- Insulation resistance at high field
- Breakdown DC field strength

The multilayer components have been examined by means of scanning electron microscopy in order to examine the microstructure and especially the porosity of the materials.

Measurements of dielectric and piezoelectric properties under high electric field have also been carried out. The CMAs used here had only four active layers ranging from 435 µm to 545 µm in thickness, however in the case of Es91 the CMAs had 2 x 917 µm layers. Unlike the 18 x 100 µm CMAs, these components had a sufficiently low capacitance for precise high-field measurements. The field has been applied as an amplified sinus AC signal at 1 kHz. In order to avoid overheating, the measurements were made with burst signals of 3 oscillations, at a frequency of 3 Hz. Three types of measurements have been carried out: dielectric permittivity, loss tangent and velocity of a face. A modified capacitance comparison bridge has been used for the dielectric measurements. The dependence of piezoelectric coefficient on the electric field, $d_{33}(E)$, has also been measured using a laser vibrometer (Polytec OFV3001), allowing the measurement of the velocity produced by burst signals. All the values presented are r.m.s.

The insulation resistance of the CMAs has been measured at room temperature in 1 min at a voltage of 250 V (i.e., a field of 2,5 MV/m), using a Sefelec MMG500 megohmmeter.

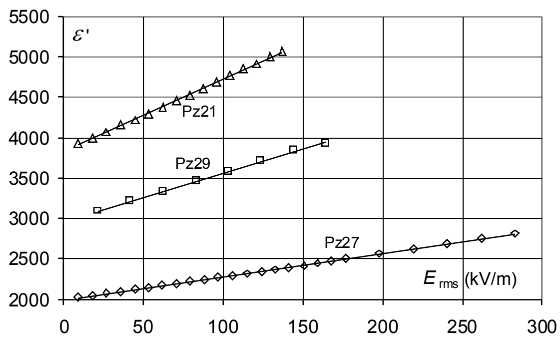


Fig. 1. Real relative permittivity for soft PZT multilayers versus the electric field. Linear fits.

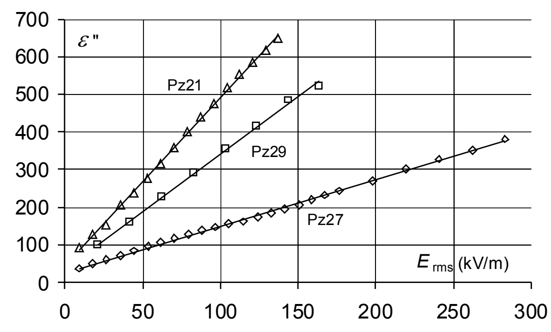


Fig. 2. Imaginary relative permittivity for soft PZT multilayers versus the electric field. Linear fits.

Results and Discussion

As expected, the electrical field strength strongly influences the performance of materials. A comparison of the field dependence shows marked differences, and it is evident that low-field properties do not accurately describe the performance of ceramic multilayer components operated at high electrical fields.

For the *soft* materials CMA (Pz21, Pz27 and Pz29), the real part of the relative permittivity versus the electric field $\varepsilon'(E)$ (Fig. 1) shows a linear dependence on E, as well as the imaginary relative permittivity $\varepsilon''(E)$ (Fig. 2). These linear dependencies are in agreement with the prediction of the Rayleigh law [1], which can be written for the dielectric behaviour as:

$$D/\varepsilon_0 = (\varepsilon'_0 + \alpha E_0)E \pm \frac{\alpha}{2}(E_0^2 - E^2) \qquad (1)$$

where D is the charge density, ε'_0 the linear real relative permittivity at low signal, E_0 the field amplitude and α the slope of the linear dependence $\varepsilon'(E_0)$. The measured values are: α = 6.3 mm/V for Pz21, α = 4.2 mm/V for Pz29, α = 2.0 mm/V for Pz27.

The second term of this equation takes into account the dielectric losses. From the Rayleigh law, the ratio of the increments of the imaginary and the real permittivity $\Delta\varepsilon''/\Delta\varepsilon'$ is expected to be equal to $4/(3\pi) \approx 0.42$. The measured dependence $\varepsilon''(\varepsilon')$ (Fig. 3) is linear and the slope is between 0.43 and 0.51, only slightly higher than predicted by the Rayleigh law. It is observed that the dependence of $\varepsilon''(E)$ is more linear than the dependence of the dielectric losses $\tan \delta_e(E)$, where $\varepsilon'' = \varepsilon' \tan \delta_e$.

For *hard* materials (Pz24 and Pz26), these linear dependencies are not verified and quadratic (Pz26) or cubic (Pz24) dependencies are observed (Figs. 4, 5). These relationships are in agreement with the observations of Hall [2]. This behaviour is observed in the real $\varepsilon'(E)$ as well as in the imaginary permittivity dependencies $\varepsilon''(E)$. The dependence $\varepsilon''(\varepsilon')$ is also linear, as in the soft materials, but the slope is lower than 0.5: it is 0.16 for Pz26 and 0.24 for Pz24. The lower slope is in agreement with the lower losses of hard materials at low signal.

The *electrostrictive* CMA material (Es91) shows behaviour similar to the soft CMA, with a quite linear dielectric dependence with the applied electric field E, in spite of the high real and imaginary permittivity (Fig. 6). Also the plot of the imaginary versus real permittivity $\varepsilon''(\varepsilon')$ is linear with a slope near 0.5.

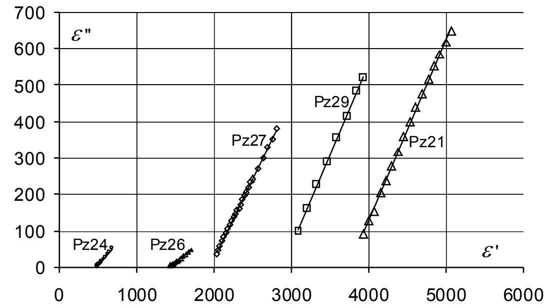


Fig. 3. Imaginary versus real relative permittivity for PZT multilayers. Linear fits.

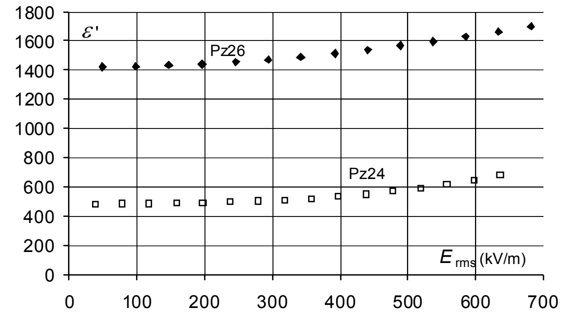


Fig. 4. Real relative permittivity for hard PZT multilayers versus the electric field.

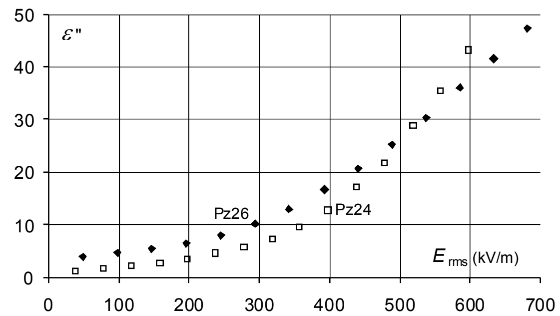


Fig. 5. Imaginary relative permittivity for hard PZT multilayers versus the electric field.

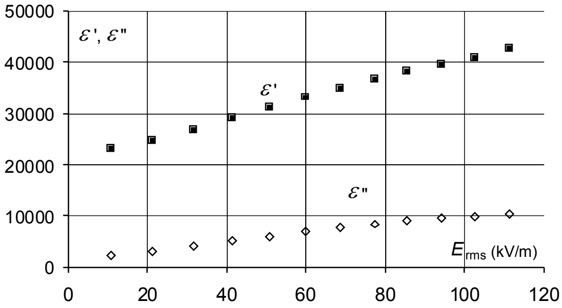


Fig. 6. Real and imaginary relative permittivity for the electrostrictive Es91 versus electric field.

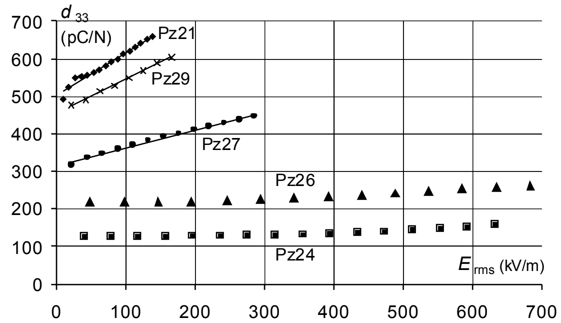


Fig. 7. Piezoelectric coefficient d_{33} for piezoelectric multilayers versus the electric field. Linear fits for soft PZT (Pz21, Pz27 and Pz29).

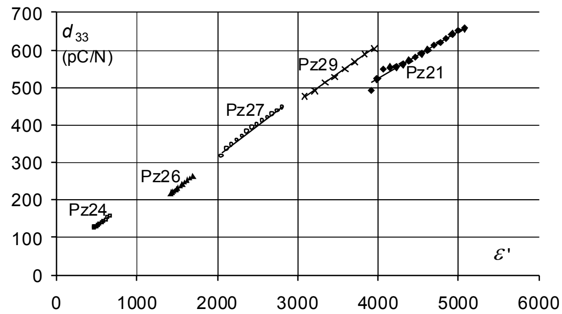
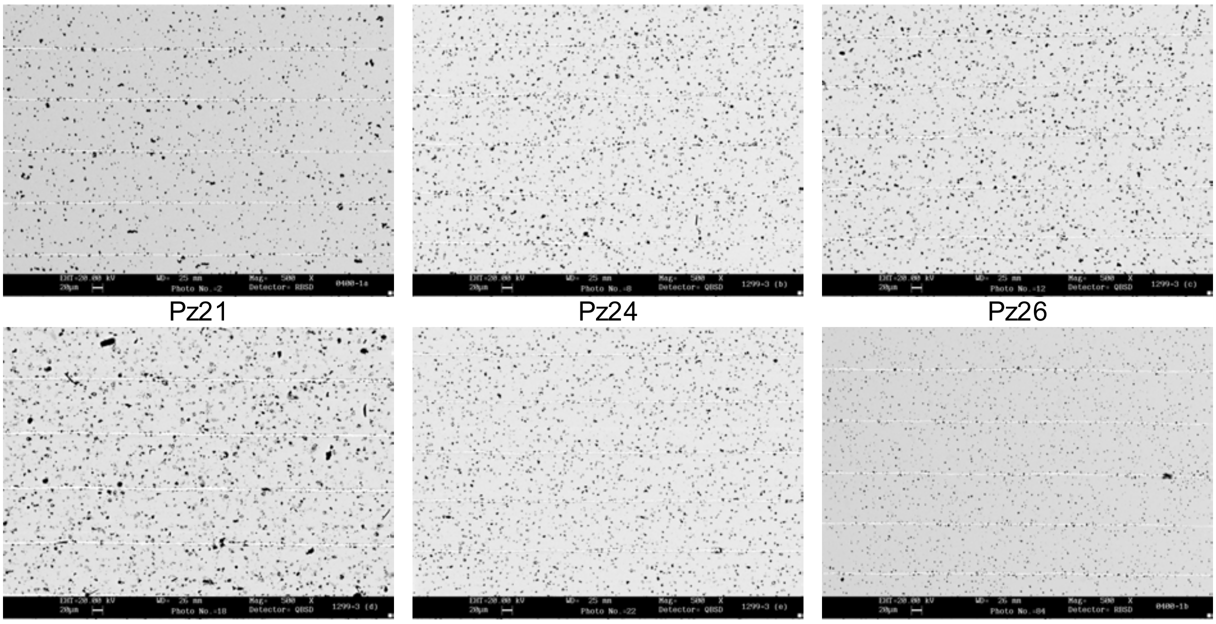


Fig. 8. Piezoelectric coefficient d_{33} for piezoelectric multilayers versus the real relative permittivity ε'. Linear fits.

As for the piezoelectric measurements, a linear dependence in *soft* CMA materials is observed in the plot $d_{33}(E)$ (Fig. 7). This dependence is quadratic or cubic for *hard* CMA materials as in the $\varepsilon'(E)$ dependence.

The dependence between the piezoelectric coefficient and the real relative permittivity $d_{33}(\varepsilon')$ is shown in Fig. 8. The relationship between these coefficients is linear to a good approximation, not only for the *soft* materials but also for the *hard* ones. The slope of this linear relation is the same for all samples, and d_{33} is proportional to the permittivity ε'. The latter relation would imply that the coefficient g_{33} is field-independent. This interesting point will be investigated in a future paper. Generally, the low-field d_{33} values measured in this paper using the laser vibrometer are lower than the catalogue values given in Table 1, which are measured with a Berlincourt-type instrument. The relative tendencies are quite clear, however.

The microstructure of the actuator materials is shown in Fig. 9. Some five ceramic layers are seen and all materials are clearly very homogeneous with evenly distributed porosity. It is also apparent that the Pz21 and Es91 materials are somewhat denser than the other materials.



Pz21 Pz24 Pz26

Pz27 Pz29 Es91

Fig. 9. SEM micrographs of the six types of CMA components. The layer thickness is ≈ 100 µm.

Table 3. E_{rev}, E_b and ρ for CMA components, average values.

Material	E_{rev} (MV/m)	E_b (MV/m)	ρ (TΩ m)
Pz21	-0,49	10,1	0,085
Pz24	-1,54	11,9	0,16
Pz26	-2,09	11,4	0,11
Pz27	-0,97	14,0	0,30
Pz29	-0,57	12,7	0,39
Es91	-	14,1	0,30

For many applications, it can be feasible to utilise the contraction of the material obtained by applying a negative electrical field (with respect to poling direction). The negative electrical field E_{rev} leading to reversion of polarisation was measured for all materials at room temperature, Table 2. This parameter is closely related to the coercive field measured at AC field. Noticeable is the high E_{rev} for the hard-doped materials, Pz24 and Pz26.

The DC insulation resistivity, ρ, and the breakdown electrical field, E_b, are important measures of the quality of the ceramic materials and hence important parameters for selecting actuator materials. Insulation resistivity and breakdown electrical field measured at room temperature are shown in Table 2.

As expected, the highest ρ values were measured for the typical soft PZT materials Pz27 and Pz29 and the electrostrictive Es91. The lower resistivity of Pz21 is due to the special composition of this high-permittivity material. For all materials, the average breakdown electrical field was above 10 MV/m and all measured values were in the range of 8 – 16 MV/m. These data are indicative for the large safety margin obtained with CMA components with embedded electrodes, i.e. the internal electrodes do not extend to the surface of the CMA components.

Conclusion

The measurements at high electric field have shown quite interesting tendencies. Firstly, the permittivity depends on the electric field, but not in the same way for soft- and hard-doped PZT. The soft materials and the electrostrictive one follow the Rayleigh law to a good approximation, whereas the hard ones show nonlinear field dependence. Secondly, also the piezoelectric coefficient d_{33} increases linearly with the electric field for the soft materials.

The results of the measurements of E_{rev} and ρ show the expected differences between the materials. As for the breakdown fields, it is interesting to note that all average values are above 10 MV/m.

References

(1) Damjanovic, D., Demartin, M. (1996): The Rayleigh Law in Piezoelectric Ceramics. *J. Phys. D*, **29** [7] 2057-2060.

(2) Hall, D.A. & Stevenson, P.J. (1999): High Field Dielectric Behaviour of Ferroelectric Ceramics. *Ferroelectrics*, **223** 319-328.