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Non-uniform electric field in poling of structurally graded monolithic piezoactuator

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Abstract In this paper the effect of a non-uniform electric poling field and its optimisation for structurally graded piezoelectric actuators are investigated. The two compared actuator structures were both based on commercial PZT 5H bulk discs with thicknesses of 375 μm (Ø 25 mm), where one was machined into a graded structure with a step-like decrease of the thickness towards the centre and one intact. The hysteresis loops of the pre-stressed concave shaped actuators were measured under 0.5–5.0 kV/mm electric fields at 25–100°C temperatures, and the remanent polarization and coercive electric field were determined. The graded structured actuator obtained ~10% higher coercive field compared to the non-graded actuator, when measured at 25°C and 5.0 kV/mm. On the other hand the remanent polarisation values of the graded actuator were slightly lower than non graded bulk values. However the maximum decrease was only 9.6% under 5.0 kV/mm. The results show that strain and stress gradients in the structure are generated when exposed to an electric field. Furthermore, as a consequence of the restricted dimension changes, an inherent bending of the monolithic ceramic structure was obtained which can be utilised, for example, in miniaturised micro-machined actuators or in larger pre-stressed benders.

Keywords Piezoelectric · Gradient · Actuator · Monolithic

1 Introduction

Piezoactuators are widely used as a consequence of their fast response times, high resolution, compactness, durability, and operating frequency. Utilizing the electric field gradient, bending actuators can be fabricated from bulk samples without any additional layer [1, 2]. Displacement capabilities of recently developed structurally graded piezoelectric bending actuators can be improved further by optimisation of the poling process [3–5]. Since the poling determines the final piezoelectric properties of the actuator and only slightly weakens afterwards due to ageing [6–8], the poling conditions have been widely studied [3]. Wang et al. for example have shown that optimised poling of bulk actuators can be developed through predetermination of saturation polarisation and the coercive field [9]. In this paper optimisation of the poling conditions for structurally graded piezoelectric actuators is studied by measuring the remanent polarisation and coercive electric field at different temperatures and electric fields. The results are compared with bulk and pre-stressed actuators, especially with RAINBOW actuators [1, 3, 10].

2 Experiments

Commercial PZT 5H bulk discs (Morgan Electro Ceramics ∅ 25 mm, thicknesses of 375 μm) with factory mounted electrodes (thickness of ~15 μm) were micro-machined with a Nd:YVO$_4$ laser system (Siemens Microbeam 3200, Siemens AG, Germany) to fabricate structures having cross-sections similar to that shown in Fig. 1. The laser machined steps were designed to produce cross-sections with a linearly decreasing thickness of ~30 μm at 2 mm intervals towards the centre of the actuators, resulting in the

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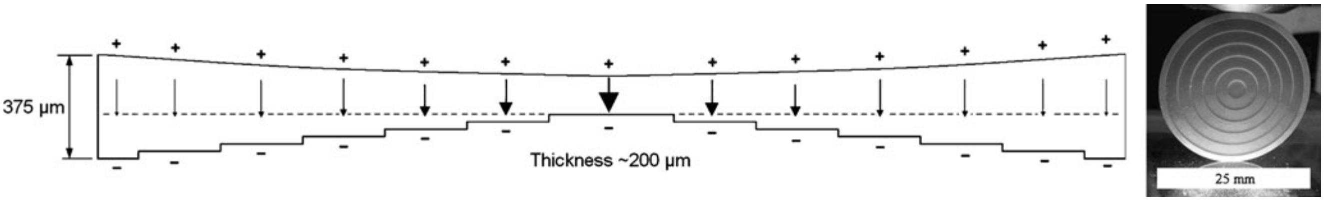

Fig. 1 Schematic profile and picture of the actuator with linearly decreased thickness. Black arrows describe how the electric field decreases towards the edges

thinnest circle with a diameter of 3 mm and thickness close to 200 µm.

In total, three samples were micro-machined with identical gradient profile after which the residues from micro-machining were burned at 600°C oven. Heat treatment cleaned the sample surfaces and removed internal stresses, making the electrical measurements more reliable. Next the profile and the curvature of the actuators were measured with a DEKTAK 8 Stylus Profiler (Veeco, USA). The electrodes were sprayed on the micro-machined bottom surfaces using conductive silver paint (Electrolube, UK) with moderately low adhesion to avoid the constraining effect associated with fired electrodes [11]. Hysteresis measurements were then performed in silicone oil at 25–100°C temperatures with 0.5–5.0 kV/mm electric fields for both the graded samples and a bulk disc (PZT 5H, ∅ 25 mm) with thickness of 375 µm. The applied voltage for each electric field was calculated according to the thinnest region of the actuator. The measurements were made with a Radiant RTV6000HVS system (Radiant technologies,

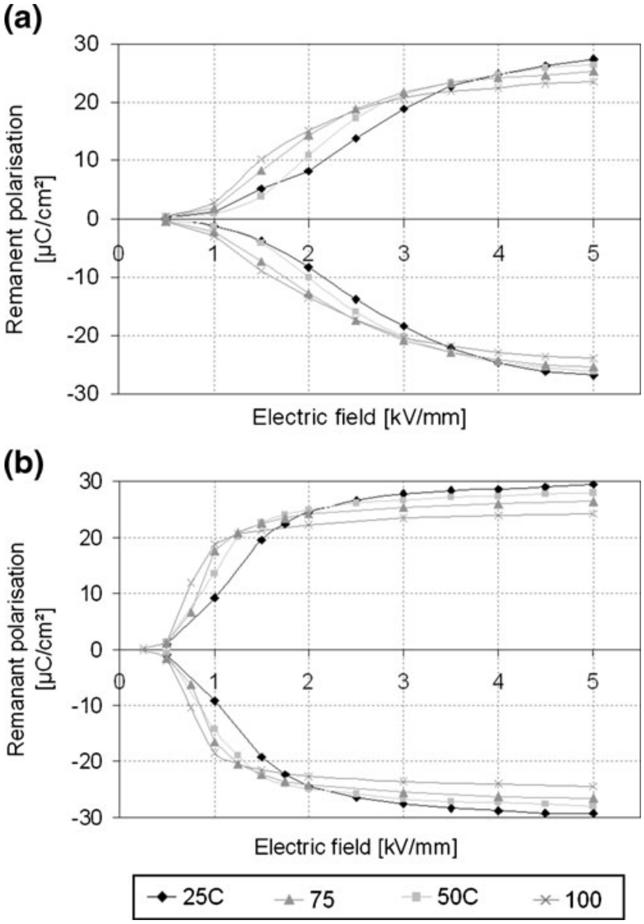

Fig. 2 Remanent polarisation of the (**a**) graded and (**b**) bulk actuators measured at 25–100°C temperatures with 0.5–5.0 kV/mm electric fields

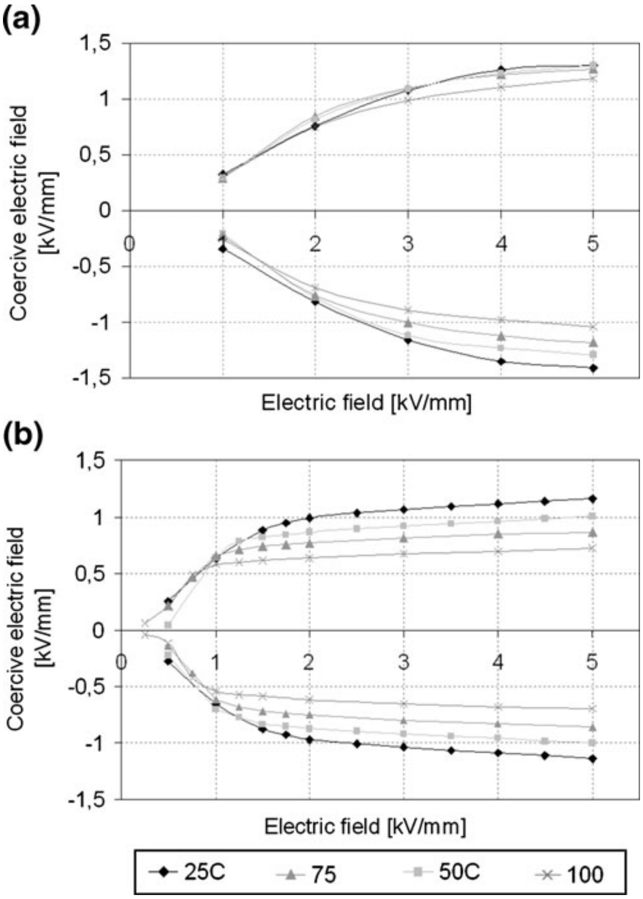

Fig. 3 Coercive electric field of the (**a**) graded and (**b**) bulk actuators measured at 25–100°C temperatures with 0.5–5.0 kV/mm electric fields

USA), determining the remanent polarisation and coercive electric field [1, 3, 12]. Profiles of the actuators were measured again after measurements.

3 Results and discussion

The samples exhibited a concave shape (Fig. 1) as a consequence of slight pre-stressing caused by the factory mounted top electrode. The three fabricated samples showed curvatures of ~200 µm, ~230 µm and ~170 µm when measured from the top side. During the hysteresis measurements at high electric fields and temperatures, some residual self-strain opposite to the initial stress was generated, thus decreasing the curvatures to ~125 µm, ~65 µm and ~95 µm respectively. The remanent polarisation and coercive field measurements for the graded actuators and the bulk disc are presented in Figs. 2 and 3. The maximum deviation between the three graded samples at 25°C under 5 kV/mm was only 3.0% for the remanent polarisation and 4.2% for the coercive field.

As a consequence of the graded actuator profile, the driving electric field and the area subjected to the field varied along the cross-section of the actuator. Thus determination of the coercive field and remanent polarisation values was not straightforward. The electric field in the outermost region is ~55% compared to the electric field in the thinnest region in the middle, but outermost region has also approximately a ten times larger surface area. Thus each step has its own electrical conditions and the value obtained from measurements represents the net value of parallel connected nonlinear capacitors. On the other hand, electroding and measuring of each gradual step individually would give values of mechanically constricted piezoelectric material thus giving slightly different response [3]. Due to this complexity of the electrical conditions, accurate values were difficult to measure directly. In order to make comparison easier, calculations were made based on measurements from the bulk sample to represent the expected behaviour of the bulk actuator with the same geometry. The driving electric field of the graded and bulk actuators in Figs. 2, 3 and 4 is according to the thinnest layer of the actuator. However, in the estimation 7 different thicknesses were taken into account as individual contributors to the final remanent polarisation and coercive field values. Estimated remanent polarisation (P_{re}) was calculated with Eq. 1

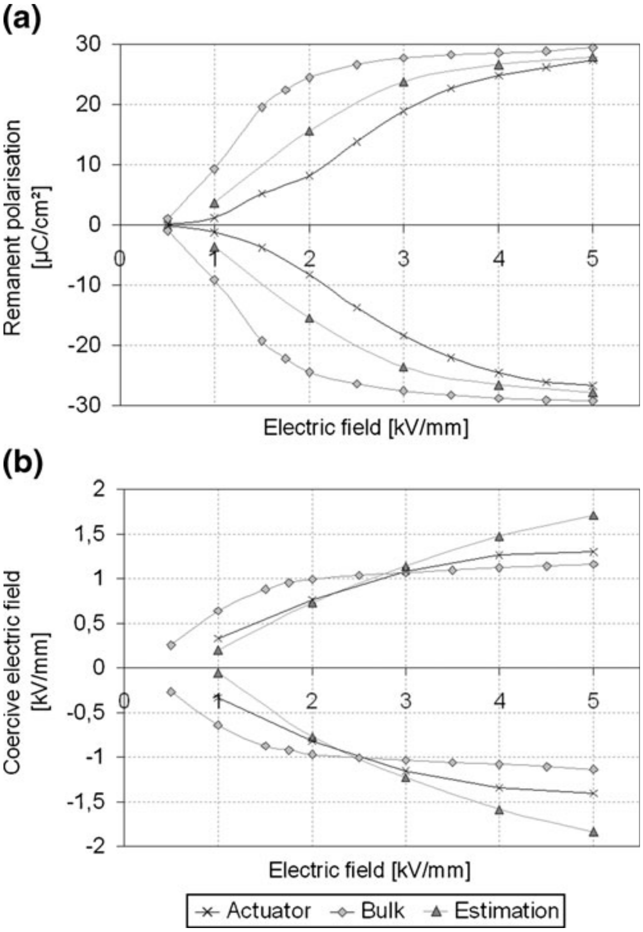

Fig. 4 (**a**) remanent polarisation and (**b**) Coercive electric field of the graded and bulk actuators measured at 25°C and the estimated behaviour of the graded actuator based on bulk values

$$P_{re} = (P_{r1}A_1 + P_{r2}A_2 + P_{r3}A_3 + P_{r4}A_4 + P_{r5}A_5 + P_{r6}A_6 + P_{r7}A_7)/A_{tot}$$

where P_{r1}–P_{r7} are remanent polarisation values of the bulk actuator for the particular electric field under investigation and A_1–A_7 are the surface areas of the gradual steps, A_{tot} representing the total surface area. An estimated curve for the coercive field was calculated from the measured bulk actuator coercive fields using the same principle. The highest measured remanent polarisations and coercive fields were obtained in all cases at 25°C under 5 kV/mm, as shown in Fig. 4.

The highest remanent polarisation values of 29.4 µC/cm² and 27.3 µC/cm² were obtained for bulk and graded actuators, respectively. When comparing the estimated and measured remanent values at 25°C under 5.0 kV/mm, the difference was ~3.9% in favour of the estimated value and additionally the highest bulk actuator value was 5.45% higher than estimated value.(Fig. 4(a)). This behaviour can be caused by a slight pre-stressing due to the factory mounted top electrode and constraining from the graded structure, which is released under higher electric fields. The remanent polarisation values at lower electric fields were much lower for the graded actuator than for the bulk actuator, as can be expected.

Dausch reported a higher remanent polarisation of 18.0 μC/cm² for the RAINBOW (PZT 5H, 250 μm, ∅ 25.4 mm) actuator under 1.5 kV/mm electric field at room temperature [6]. Under the same conditions P_r=4.70 μC/cm² was obtained for a pre-stressed PRESTO actuator (PZT 5H, 375 μm, ∅ 25 mm), which is much closer to P_r=4.53 μC/cm² obtained from the graded actuator. The bulk actuator's remanent polarisation value of 19.55 μC/cm² was somewhat different from that measured by Dausch for a bulk actuator (14,1 μC/cm²). One explanation could be the higher pre-stress of the PRESTO actuator which increases stress induced domain reorientation. While in the case of the presented structural gradient actuators the lower P_r with the graded actuator might be caused by constraining due to the graded structure and decreased electric field towards the edges [3, 6].

Figure 4(b)) shows that, compared to the values of bulk and estimated behaviour of graded bulk actuators, the coercive fields of the graded actuator was clearly higher under electric fields over 3.0 kV/mm, especially at higher temperatures. The maximum difference between the measured and the estimated curve was 10.1% in favour of the former, under a field of 5.0 kV/mm at 25°C. The highest coercive field values of 1.16 kV/mm and 1.33 kV/mm were also measured at 25°C under the same electric field for the bulk and graded actuators, respectively.

The highest coercive field values were quite close to each other for all structures but this was not true in the case of remanent polarisation. The coercive field for a RAINBOW actuator by Dausch was measured to be 0.42 kV/mm under 1.50 kV/mm, 0.63 kV/mm for PRESTO and 0.55 kV/mm (estimation 0.71 kV/mm) for the graded actuator under the same conditions.

4 Conclusions

The results showed that poling conditions of the structurally graded actuator have to be more carefully selected compared to the case of the bulk actuator. Remanent polarisation and coercive electric field values of the graded actuator depend more on the poling field than in the case of the bulk actuator. The highest remanent polarisation of 27.34 μC/cm² and coercive field of 1.33 kV/mm were measured at 25°C under 5 kV/mm electric field for the graded actuator. Remanent polarisation was a maximum of 3.9% lower than the estimated curve. The maximum difference in coercive field between the estimated curve from the bulk actuator and measured from the graded actuator was ~10.1% at 25°C under 5 kV/mm electric field in favour of the graded actuator. The higher remanent polarisation values for RAINBOW can be assumed to derive from the higher pre-stress state of the PRESTO and constraining and the electrical gradient in the case of the graded actuator.

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References

1. J. Palosaari, E. Heinonen, J. Juuti, V.-P. Moilanen, H. Jantunen: Electromechanical performance of structurally graded monolithic piezoelectric actuator. Journal of Electroceramics. Published online (March 2008)
2. Heinonen E, Juuti J, Moilanen P, Palosaari J, Jantunen H; Structurally graded monolithic piezoelectric actuators, modelling and optimization with FEM, Journal of Intelligent Material Systems and Structures (November 2008)
3. J. Juuti, H. Jantunen, V.-P. Moilanen, S. Leppävuori, Poling conditions of pre-stressed piezoelectric actuators and their displacement. Journal of Electroceramics **15**(1), 57–64 (2005)
4. K. Bhattacharya, G. Ravichandran, Acta Mater **51**, 5941 (2003)
5. D.H. Pearce and T.W. Button, in Proceedings of the Eleventh IEEE International Symposium on Applications of Ferroelectrics, p. 547, (IEEE, Piscataway, 1998)
6. D.E. Dausch, J Am Ceram Soc **80**(9), 2355 (1997)
7. Q. Jiang,W. Cao, and L.E. Cross, in Proceedings of the Eighth International Symposium on Applications of Ferroelectrics, p. 107, (IEEE, New York, 1992)
8. W.Y. Shih, W.-H. Shih, I.A. Aksay, J Am Ceram Soc **80**(5), 1073 (1997)
9. H.Wang, R.E. Newnham, L.E. Cross, andW.Y. Pan, in IEEE Seventh International Symposium on Applications of Ferroelectrics p. 422, (IEEE, New York, 1990)
10. H.-W.Wang, S.-Y. Cheng, and C.-M.Wang, in Proceedings 1989 Japan International Electronic Manufacturing Technology Symposium, p. 263, (IEEE, New York, 1989),
11. J. Juuti, H. Jantunen, V.-P. Moilanen, S. Leppävuori, IEEE Trans Ultrason Ferroelectr Freq Control **53**(5), 838 (2006)
12. G.H. Haertling, in Proceedings of the Tenth IEEE International Symposium on Applications of Ferroelectrics, p. 65, (IEEE, Piscataway, 1996)