A 3.2

Integrated Actuators Based on PZT Thick Films for Microsystems Applications

S. Gebhardt[1], A. Schönecker[1], C. Bruchmann[2]
[1]Fraunhofer Institute for Ceramic Technologies and Systems, Dresden, Germany
[2]Friedrich Schiller University of Jena, Institute of Applied Physics, Jena, Germany

Abstract:
Piezoceramic thick films based on lead zirconate titanate (PZT) offer the possibility of integrated actuator structures for microsystems applications. By use of the screen printing technology, thick film actuators can be directly prepared on the substrate with high accuracy and reproducibility. Compared to conventional assembling techniques PZT thick films show strong bonding to the substrate and high interface reliability under operation.
We developed a screen printable PZT thick film paste which shows excellent dielectric and electromechanical properties like dielectric constant value of $\varepsilon_{33}{}^T/\varepsilon_0 = 1900$ and piezoelectric coefficient of $d_{33} = 210$ pC/N after sintering. It has been used for actuator, sensor and ultrasonic transducer applications so far. The paper will report in detail on PZT thick film actuators for adaptive optics.

Keywords: PZT, thick film, piezoceramic, MEMS, adaptive optics

Introduction

Piezoceramic thick films have attained rising interest during the last 20 years due to increasing functional integration and miniaturisation of micromechanical devices. As dimensions of these devices become smaller assembling or mounting techniques to apply sensors and/or actuators become laborious and thus insufficient. Piezoceramic thick films offer the possibility of integrated solutions for microsystems applications.

Up to now formulations based on $Pb(Zr_{1-x}Ti_x)O_3$ (lead zirconate titanate - PZT) are mainly used for thick film preparation because of the excellent ferroelectric and electromechanical properties attainable in that material system. Different technologies to apply PZT thick films on microelectronic substrates have been introduced so far. PZT thick films with thicknesses up to 30 µm have been built e.g. using electrophoretic, hydrothermal or modified sol gel deposition [1-3]. Thereby the substrate is fully covered by the PZT thick film. To obtain discrete sensors and/or actuator elements the film has to be structured by photolithography, etching or mechanical treatment, subsequently. Patterned PZT thick films of similar thickness can be directly deposited by aerosol deposition [4].

To prepare structured PZT thick films with thicknesses between 20 µm and 150 µm screen printing technology is well suited. The process is industrially established and allows for excellent accuracy and reproducibility. Miniaturisation as well as batch production is possible.

As a prerequisite, thick film pastes based on a low sintering PZT material mixed with an organic vehicle have to be developed. Sintering of such films turned out to be difficult due to constrained sintering conditions, decomposition by PbO loss and reaction with the substrate material which results in increased residual porosity and minor functional properties compared to bulk ceramics. Therefore adjusted PZT formulations and specific sequences of technology have to be found. Table 1 gives an overview on selected PZT thick film properties on Al_2O_3 substrates which have been found in literature for different research groups within Europe and which are known to the author. These films have been mainly introduced for applications as sensors, resonators or ultrasonic transducers.

***Table 1:** Comparison of selected PZT thick film properties on Al_2O_3 substrates achieved by European research groups*

Nr.	Sintering	Poling Conditions	$\varepsilon_{33}{}^T/\varepsilon_0$	d_{33} [pC/N]	Ref.
1	850°C/1 h	10 kV/mm, 150 °C, 10 min, mineral oil	386	185	[5, 6]
2	850 °C/20 min	5 kV/mm, 160 °C, 15 min, oil bath	521	120	[7]
3	890 °C/belt furnace	4 kV/mm, 200 °C, 5 min, oil bath	n.n.	78	[8]
4	1000 °C/8 min	8 kV/mm, 120 °C, 2 min, oil bath	841	129	[9]
5	900 °C/1 h	8 kV/mm, 110 °C, 10 min, hot plate	970*	135*	[10]

* Data obtained on thermally oxidised Si

We started the development of PZT thick films on Al_2O_3 and ZrO_2 substrates in 1990 for use as a charge and information storage device for ferroelectric printing. Meanwhile we have obtained great expertise on PZT thick films also on low temperature cofired ceramics (LTCC) and silicon for use as pressure sensors, high frequency ultrasound transducers and active optical devices as described before [11,12].

The present paper will give a summary on dielectric and electromechanical properties of PZT thick films on different substrate materials suitable for optical devices. A detailed description of the dependence of actuator performance on actuator size and substrate material will be presented in [13].

Preparation of PZT Thick Films

We developed a PZT thick film paste based on a PZT-PMN formulation with the addition of a borosilicate glass and a eutectic mixture of Bi_2O_3-ZnO as sintering aids called IKTS-PZ5100.

It has been applied on Al_2O_3 (99.6% - Rubalit 710, CeramTec), LTCC (DP 951 – DuPont) and thermally oxidised silicon (Si-Mat).

PZT thick films with fired thicknesses of 80-150 µm were built up by repeated screen printing and sintering. Sintering was performed at 900 °C/2 h. Gold electrodes and insulation layers were sintered at 850 °C/0.5 h in a steel belt furnace.

For preparation of an adaptive laser beam shaping mirror a DuPont DP 951 LTCC multilayer substrate was manufactured as shown in Fig. 1. It consisted of a LTCC frame with a thickness t_{frame} = 660 µm and a membrane with a diameter of $d_{membrane}$ = 34.7 mm and a thickness of $t_{membrane}$ = 220 µm. PZT thick film actuator pattern with a diameter d_{PZT} = 34.2 mm and a thickness t_{PZT} = 100 µm as well as bottom and top electrodes were screen printed on top of the membrane. For the mirror face a copper metallization was electroplated at the opposite side of the membrane and finished by single point diamond tuning to reach a high reflective surface. A detailed description of the mirror can be found in [14].

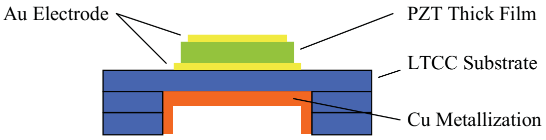

Fig. 1: *Design of adaptive laser beam shaping mirror*

In cooperation with the Active Structures Laboratory of Brussels University, Belgium, we built a deformable mirror for large lightweight telescopes based on a thermally oxidised silicon wafer with a diameter $d_{silicon}$ = 150 mm and a thickness $t_{silicon}$ = 700 µm as shown in Fig. 2. Honeycomb like PZT thick film actuator pattern with a thickness of t_{PZT} = 80 µm were screen printed at the back side of the wafer. The pattern was thoroughly calculated and arranged to allow combination of segments to built large-area mirrors. The front side of the wafer was used as mirror face. More information on this development will be given in [15].

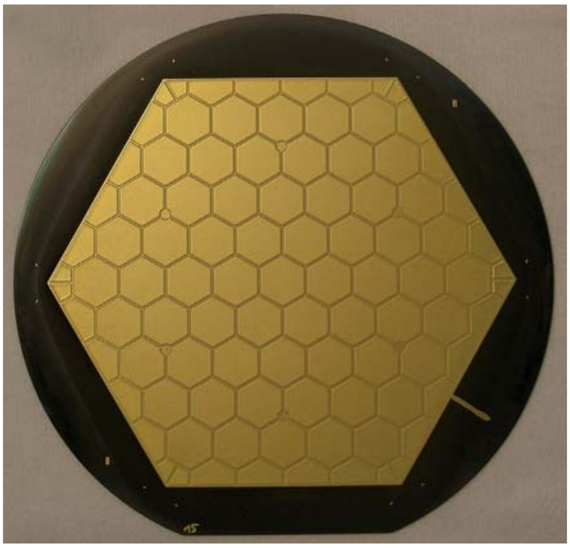

Fig. 2: *Deformable mirror based on a 6' silicon wafer with screen printed PZT thick film actuators at the back side. The typical dark halo around the bottom electrode corresponds to a reaction zone of lead silicates. It occurs only at the back side of the wafer.*

Properties of PZT Thick Films

Typical thick film properties were measured on samples prepared by the IKTS standard technology. This technology has been proofed to confect sensors and actuators for various applications. Polarisation is typically performed at room temperature with E = 2 kV/mm, 5 min.

Dielectric constants were measured at f = 1 kHz, U_{ac} = 1 V using a Hewlett Packard 4194A Impedance Analyzer at least 24 h after poling. Resonance behaviour and deflection of the thick film devices were characterized by a Polytec laser scanning vibrometer PSV 400.

The measurement of the piezoelectric coefficient d_{33} was performed at the Department of Physics of the Martin-Luther-University Halle at 130 Hz, using equipment based on a capacitive detector.

Ferroelectric hysteresis loops were determined by a Sawyer-Tower circuit.

Properties of PZT thick films strongly depend on the substrate material. Best results have been obtained on Al_2O_3 substrates with almost no silica content. As the silicon content in the substrate material increases attainable polarisation is reduced as can be seen in Fig. 3. Deposition of PZT thick films on LTCC and silicion substrates is only possible by the use of a diffusion barrier. We solved this problem by the development of a gold intermediate layer, serving as electrode and diffusion barrier, likewise.

The silicon content in the substrate also influences the dielectric and piezoelectric properties as summarized in Table 2. Compared to PZT thick film properties listed in Table 1 values measured exceed state-of-the-art even by use of much lower poling fields and temperatures. They justify good actuator performance.

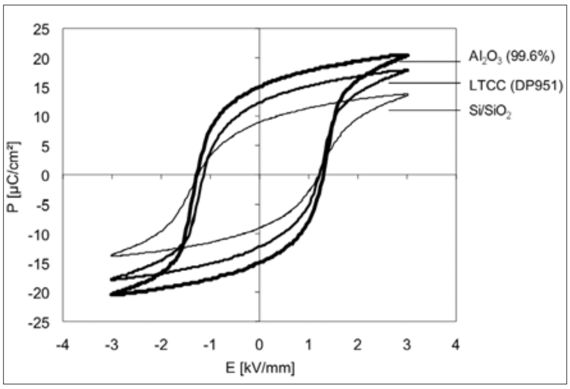

Fig. 3: *Ferroelectric hysteresis loops of IKTS-PZ5100 PZT thick films on different substrates*

Table 2*: Properties of IKTS-PZ5100 PZT thick film (active area a = 400 mm^2) on various substrate materials*

Property	PZT on Al_2O_3 (99.6 %)	PZT on LTCC (DP 951)	PZT on Si/SiO_2
Dielectric constant $\varepsilon_{33}{}^T/\varepsilon_0$	1900	1500	1600
Dielectric loss tan δ	0.038	0.033	0.055
Piezoelectric coefficient d_{33} [pC/N]	210	180	140

Application of PZT Thick Films for Active Optics

Piezoelectric actuators are well suited for adjusting purposes in active optics because of their high positioning accuracy in the nm-range and their quick response time of only few µs.

Piezoceramic thick films offer the possibility of integrated solutions with a strong and thus reliable coupling between active component and optical substrate.

For the development of a laser beam shaping mirror we screen printed four different thick film actuator pattern on a LTCC substrate as shown in Fig. 4. Therefore the LTCC multilayer was structured as described in Fig. 1.

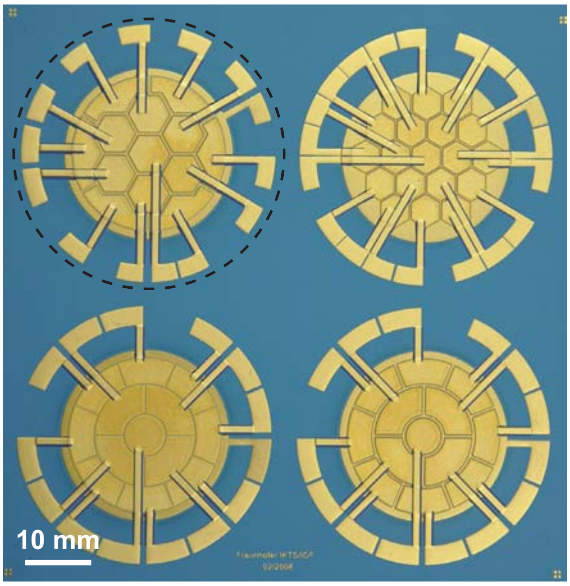

Fig. 4: *Different layouts of PZT thick film actuators on LTCC substrate for use as laser beam shaping mirrors*

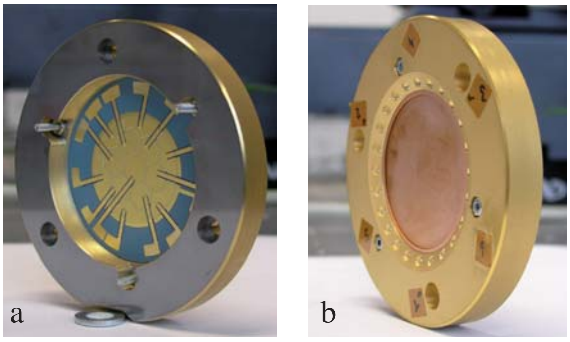

Fig. 5: *Mirror 1 (dashed detail of Fig. 4) in a mounting: a) actuator side, b) mirror side*

The mirrors were cut single and fixed in a mounting as shown in Fig. 5. The clamping of the mirror is a crucial factor since it affects strongly deformation and resonance frequency of the system. Solder jet bumping was used to achieve a reliable and rigid clamping of the mirror.

Static deflection of the mirror was measured at the centre of the membrane by laser triangulation method. By driving all 13 actuators of mirror 1 with E = 2 kV/mm a maximum deflection of Δl = 45 µm could be obtained meeting the requirements for laser beam shaping. Resonance frequency was determined at f = 1450 Hz.

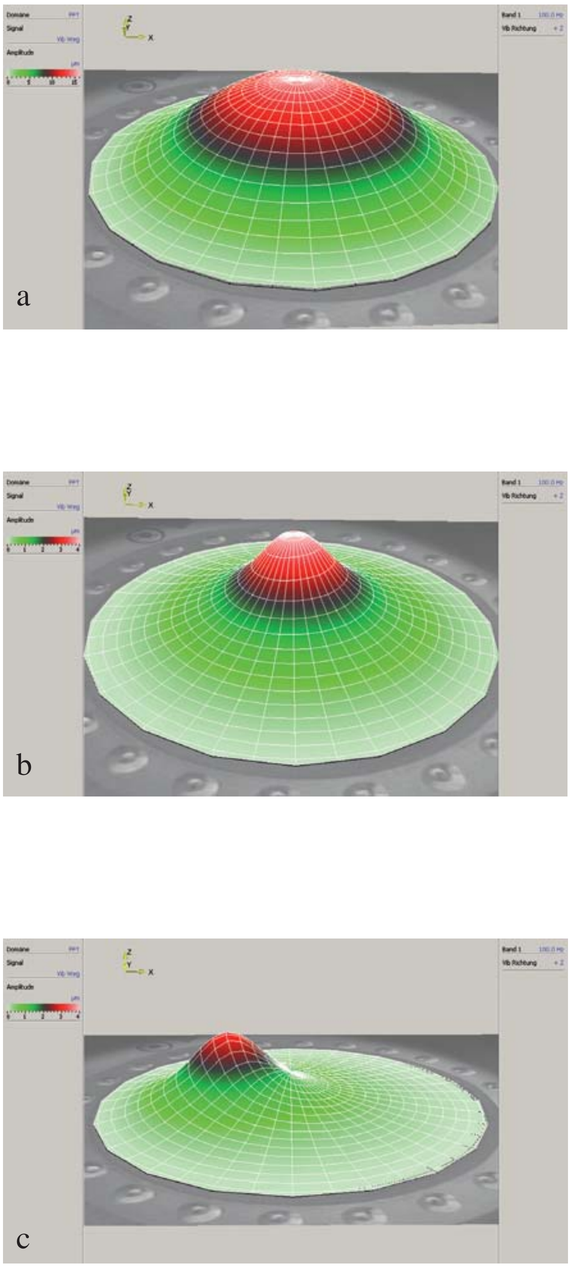

Fig. 6: Deflection of mirror 1 by driving with E = 0.75 kV/mm at f = 100 Hz a) all 13 actuators, b) only middle actuator, c) one actuator of second raw

Dynamic deformation of the mirror has been also evaluated by laser scanning vibrometer. Therewith, shaping of the mirror by driving one or more actuators can be made visible. Fig. 6 shows deformation of the mirror face when driving single or all actuator pads with E = 0.75 kV/mm.

More complex mirror shapes can be achieved by controlled driving of the thick film actuators. This confirms the idea of a mirror which is able to shape laser wave fronts with large working frequencies up to f = 1400 Hz.

Acknowledgment

The authors would like to thank support in development and preparation of PZT thick film actuators by S. Hallmann, L. Seffner and S. Uhlig.

References

[1] S. Schimpf, B. Schmidt, Proc. IMAPS/ACerS CICMT 2009, 000043-000046

[2] M. Ishikawa, M. Kurosawa, T. Hasegawa, A. Endoh, S. Takeuchi, IEEE Ultrasonics Symposium 2005, 2231-2234

[3] R. Dorey, R. Whatmore, J. Europ. Ceram. Soc. 24 (2004), 1091-1094

[4] J. Akedo, M. Lebedev, Appl. Phys. Lett. 77 (2000), 1710-1712

[5] T. Zawada , K. Hansen, R. Lou-Moller, D. Jurkow, E. Ringgard, L. Golonka, IMAPS/ACerS CICMT 2009, 000052-000058

[6] R. Lou-Moller, C. Hindrichsen, L. Thampdrup, T. Bove, E. Ringgard, A. Pedersen, E. Thomsen, J. Electroceram (2007) 19, 333-338

[7] M. Hrovat, D. Belavic, H. Ursic, J. Kita, J. Holc, S. Drnovsek, J. Cilensek, M. Zarnik, M. Kosec, Proc. IMAPS/ACerS CICMT 2009, 000149-000156

[8] R. Torah, S. Beeby, N. White, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 52 (2005) 1, 10-16

[9] S. Le Dren, L. Simon, P. Gonnard, M. Troccaz, A. Nicolas, Materials Research Bulletin (2000), 2037-2045

[10]E. Thiele, D. Damjanovic, N. Setter, J. Am. Ceram. Soc. 84 (2001) 12, 2863-2868

[11]S. Gebhardt, T. Rödig, U. Partsch, A. Schönecker, Proc. EMPC 2007, 177-181

[12]S. Gebhardt, A. Schönecker, C. Bruchmann, E. Beckert, G. Rodrigues, R. Bastaits, A. Preumont, Proc. CICMT 2008, 000087-000093

[13]B. Bramlage, S. Gebhardt, Proc. Actuator 2010

[14]C. Bruchmann, T. Burkhardt, A. Kamm, S. Gebhardt, E. Beckert, R. Eberhardt, A. Tünnermann, Proc. SPIE, Vol. 7595, 75950J (2010); doi:10.1117/12.843810

[15]G. Rodrigues, A. Preumont, S. Gebhardt, Proc. Actuator 2010