MICROMACHINED MULTIFUNCTIONAL PIEZOELECTRIC T-BEAM TRANSDUCERS

Z. Zhang¹, K. Mateti², C.D. Rahn¹ and S. Tadigadapa^{2*}

¹The Pennsylvania State University, Department of Mechanical Engineering, Pennsylvania, USA

²The Pennsylvania State University, Department of Electrical Engineering, Pennsylvania, USA

ABSTRACT

This paper presents a novel MEMS piezoelectric cantilever beam with a T-shaped cross-section that can be used as both an actuator and a sensor. The micro T-beams are directly micromachined from bulk lead zirconate titanate (PZT) via deep reactive ion etching. The micromachined PZT T-beams are capable of in-plane and out-of-plane motion sensing and actuation via selective activation and measurements at different electrodes. The T-beam structures are tested as flexural actuators and also configured as accelerometers for sensing applications. Nine micromachined T-beams are fabricated and achieve up to 129 μm of out-of-plane displacement, 11.6 μm of in-plane displacement, 694 μN of out-of-plane blocking force, and an average acceleration sensitivity of 30.5 mV/g in 1 - 4.6 g's range at a frequency of 1.3 kHz.

INTRODUCTION

Piezoelectric MEMS sensors and actuators have many applications, including micropositioning systems, RF switches, micropumps, and accelerometers [1, 2]. Lead zirconate titanate (PZT) is attractive for MEMS sensors and actuators because it provides large piezoelectric coefficient and electromechanical coupling coefficients [3, 4]. Additionally, bulk PZT has superior properties than thin films and new fabrication processes allow bulk micromachining of PZT [1]. An inherent challenge of PZT actuators is amplifying the low strain (0.1%) to produce large displacement. Multilayer actuators increase displacement by summing the displacement of multiple electroded PZT layers using the d_{33} coefficient [5]. Unimorph, bimorph, and multilayer beam bending actuators amplify displacement using the d_{31} piezoelectric coefficient, and are capable of much larger deflections [6, 7]. Both of these types of actuators require bonding of one or more layers of passive material. De-lamination, adhesive wear and resistance associated with these layers reduce performance and lifetime. Recently, piezoelectric T-beam actuators have been micromachined from bulk PZT using a deep reactive ion etching process [8]. The T-beam transducer structure has top of flange, top of web and bottom electrodes deposited. Selective application of electric field to the web region or flange regions of the beam can produce in-plane and out-of-plane displacement. Also, by using the direct piezoelectric effect, T-beams can sense accelerations by measuring the charge generated in the web and flange regions. This work presents the piezoelectric T-beam as a multifunctional transducer structure capable of both in-plane and out-of-plane actuation and sensing.

FABRICATION PROCESS

Figure 1 shows the fabrication process of the T-beam transducers. Previous modeling [9] determines the optimal cross section design for maximum mechanical energy output with T-beams parameters, L , length, b , web width, s , total width, t , flange thickness, and h , total thickness as shown in Figure 2. 12.5 mm $\times$ 12.5 mm $\times$ 100 μm , finely polished, bulk PZT-4 with 100 nm of Cr and 350 nm of Au electrodes from Boston Piezo-Optics are used as the substrates to micromachine the T-beam structures as in Figure 1(a).

Figure 1: Fabrication process for piezoelectric T-beams: (a) bulk 100 μm PZT, (b) 12-14 μm Ni electroplated, (c) 65 μm DRIE etch, (d) flange electrode deposition and (e) released by 100 μm dicing saw.

Figure 2: (a) Top view and (b) cross section of T-beam structure.

To reach an etch depth of 65 μm at an etch rate of 15 $\mu\text{m/hr}$, the PZT must be deep reactive ion etched for over four hours. This requires a hard mask with high etch selectivity over PZT that protects the web regions to define a T-shaped cross section. Nickel is chosen as the hard mask because of its high resistivity against ion

bombardment and ease of electroplating. In preparation, the substrates are cleaned and mounted onto a carrier glass slide using a drop of SU-8-10 photoresist. 13 μm thick SPR-220 7.0 photoresist features are then patterned on the PZT wafer to define the web-regions of the T-beams. The substrate is then put into the oxide etcher for surface cleaning and functioning under 75 W for 3 minutes. Using a Techni Nickel S electroplating solution, 12~14 μm Ni is deposited over 80 minutes at room temperature, using constant agitation and a current density of approximately 16 mA/cm^2 (Figure 1(b)).

Figure 3: SEM image of the micromachined T-beam transducer.

The PZT is etched (see Figure 1 (c)) using an Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE) system that can achieve an etch rate of 15 $\mu\text{m}/\text{hr}$ using 2000 W of ICP power, 475 W of substrate power, 5 sccm of sulphur-hexafluoride (SF_6), and 50 sccm of argon (Ar) [10]. During the etch process, surface temperatures can reach very high levels causing damage and burning. The bulk PZT is mounted onto a 4" silicon wafer using an indium-tin alloy to allow thermal conductivity to the sample holder, which is maintained at 20° C by helium gas. Figure 3 shows an SEM photograph of a T-beam etched 65 μm in 5 hours. The selectivity of nickel over PZT-4 is calculated to be around 1:5.

Figure 4: Top view of the micromachined T-beam transducer and package.

Flange electrodes are deposited using an evaporation and liftoff process shown in Figure 1(d). Shipley 1805 photoresist is spray coated and patterned to prevent metal vapor deposition on the side walls of the web and flanges. 100 nm of Cr and 200 nm are deposited forming a conformal coating over the T-beams using an electron-beam (E-beam) evaporator with planetary sample holder. An ultrasonic bath with Remover PG® completes the liftoff process. Individual T-beams are released using a K&S 980 Series high precision dicing saw with a 100 μm wide diamond coated blade spinning at 30 krpm as in Figure 1(e). The dimensions of the micromachined T-beams are given in Table 1. T-beams are mounted onto a flat alumina package using silver epoxy, and wire bonded using a K&S Model 4524 wire bonder, as shown in Figure 4.

Table 1: Dimensions of and tests performed on fabricated T-beam transducers.

Device	L (mm)	b (μm)	s (μm)	t (μm)	h (μm)	Test*
1	7.7	61	139	39	100	w, a
2	3.8	52	208	36	100	w
3	10.4	49	149	35	100	w
4	5.8	62	144	42	100	w
5	7.8	195	601	35	100	f
6	11.7	203	599	36	100	f
7	3.6	53	143	35	100	bf
8	4.4	49	153	35	100	bf
9	5.8	30	72	38	100	bf

* w for web actuated out-of-plane displacement, f for single flange in-plane displacement, bf for out-of-plane blocking force, and a for accelerometer testing.

EXPERIMENTAL RESULTS

T-beam Actuator

A photograph of the experimental setup for the T-beam actuator is shown in Figure 5. A Trek Model 609E-6 high voltage amplifier amplifies the output voltage signal from a LabView system. A Polytec laser vibrometer with a 10 $\times$ objective focuses a 20 μm laser onto the T-beams with 20 nm resolution. An Aurora Scientific, Inc. force transducer measures blocking force with 10 μN resolution. Newport and Misumi linear stages allow precise positioning of the T-beams, vibrometer and force transducer.

Figure 5: Experimental setup for T-beam actuator measurements.

Applying a positive field in the direction of poling from the web electrode to the bottom electrode produces out-of-plane displacement. The out-of-plane results in Figure 6 show a linear and predictable response with displacement proportional to applied voltage. Different devices yield different slopes of displacement versus field, showing that displacement depends on the square of the actuator length. Device 2 produces the largest response while Device 3 produces the smallest. These two devices also have the longest and shortest beam length, respectively. The experimental results are compared with a model developed previously in [9]. The model and theory match quite well and show that displacement is proportional to the length squared (see inset in Figure 6).

Figure 6: Experimental data and theoretical prediction of out-of-plane displacement (μm) versus electric field ($\text{V}/\mu\text{m}$): Device 1: predicted (solid), measured (star); Device 2: predicted (dash-dot), measured (diamond); Device 3: predicted (dashed), measured (x); Device 4: predicted (dotted), measured (square).

Applying a positive field in the direction of poling from a single flange electrode to the bottom electrode produces in-plane displacement. It should be noted that lower voltages produce equivalent fields compared to web actuation. Figure 7 shows left and right in-plane displacement of fabricated Devices 5 and 6.

These devices show a linear response at lower fields, but an increase in displacement over the model at higher fields. The right (square) and left (circle) flange actuated results for Device 5 should be identical but opposite in sign. The in-plane magnitude plotted in Figure 7 for Device 5 showed slightly different response, indicating asymmetries in the fabricated device. Device 6, however showed symmetric left (diamond) and right (x) in-plane response. The model in [9] matched well with the measured response.

Figure 7: Experimental data and theoretical prediction of in-plane displacement (μm) versus electric field ($\text{V}/\mu\text{m}$): Device 5: predicted (solid), measured left(circle), measured right (square); Device 6: predicted (dash-dot), measured left (diamond), measured right (x).

To measure the blocking force, the device is packaged such that it extends out of the package. The web electrode is actuated and the glass tube of the force transducer is positioned just in contact with the end (tip) of the beam. Figure 8 shows the blocking force measurement result of Devices 7 to 9. Experimental data shows much greater blocking force than the model predicts. The cause of the observed over performance and the saturation behavior is currently being investigated.

Figure 8: Experimental data and theoretical prediction of blocking force (μN) versus electric field ($\text{V}/\mu\text{m}$): Device 7: predicted (dash-dot), measured (circle); Device 8: predicted (solid), measured(diamond); Device 9: predicted (dotted) , measured (x).

T-beam Accelerometer

Figure 9 shows a schematic of the experimental setup in which the T-beam transducer is tested as an accelerometer. Device 1 is rigidly mounted onto a Wilcoxon Research Model F3 electromagnetic shaker system powered by a AE Techron LVC5050 linear amplifier. The laser vibrometer measures velocity data from the rigid base which is differentiated to obtain input acceleration. A charge amplifier with 10× gain amplifies the T-beam signal.

Figure 9: Schematic of experimental setup of T-beam accelerometer measurement.

Test results in the 1-4 g's ($g = 9.81 \text{ m/s}^2$) range at 1.3 kHz are shown in Figure 10 and demonstrate the sensitivity and linearity of the T-beam as an accelerometer. The output voltage amplitude scales linearly with applied acceleration. The sensitivity is constant over the range of accelerations tested. Since the T-beam structure or the proof mass design is not particularly optimized for acceleration measurements, these results show the initial unoptimized performance of the transducer structure as an accelerometer.

Figure 10: T-beam voltage (solid circle) and sensitivity (dashed square) versus acceleration at 1.3 kHz.

CONCLUSIONS AND FUTURE WORK

Piezoelectric T-beam transducers can be reliably micromachined from bulk PZT using an ICP-RIE process. The fabricated T-beams are capable of producing in-plane and out-of-plane displacement, and out-of-plane blocking force. They can also be used to sense out-of-plane acceleration. Nine prototype micromachined T-beams are fabricated and tested, showing up to 129 μm of out-of-plane displacement, 11.6 μm of in-plane displacement, 694 μN of out-of-plane blocking force, and an average acceleration sensitivity of 30.5 mV/g in the 1- 4.6g's range at 1.3kHz. Future work includes dynamic modeling of out-of-plane and in-plane displacement and force. Flange sensing of in-plane acceleration would allow two-axis sensing with one transducer.

ACKNOWLEDGEMENTS

The authors would like to thank the Air Force Office of Scientific Research for their support of this work under grant #FA9550-07-1-0367.

REFERENCES

- [1] S. J. Gross, S. Tadigadapa, T. N. Jackson, S. Trolier-McKinstry, and Q. Q. Zhang, "Lead-zirconate-titanate-based piezoelectric micromachined switch," *Applied Physics Letters*, vol. 83, pp. 174-176, 2003.
- [2] H. G. Yu, L. Zou, K. Deng, R. Wolf, S. Tadigadapa, and S. Trolier-McKinstry, "Lead zirconate titanate MEMS accelerometer using interdigitated electrodes," *Sensors and Actuators A: Physical*, vol. 107, pp. 26-35, 2003.
- [3] P. Muralt, "Ferroelectric thin films for micro-sensors and actuators: a review," UK, 2000, pp. 136-46.
- [4] S. Trolier-McKinstry and P. Muralt, "Thin film piezoelectrics for MEMS," *Journal of Electroceramics*, vol. 12, pp. 7-17, 2004.
- [5] V. Giurgiutiu, C. A. Rogers, and Z. Chaudhry, "Energy-based comparison of solid-state induced-strain actuators," *Journal of Intelligent Material Systems and Structures*, vol. 7, pp. 4-14, 1996.
- [6] V. Giurgiutiu, C. A. Rogers, and Z. Chaudhry, "Design of displacement-amplified induced-strain actuators for maximum energy output," *Journal of Mechanical Design, Transactions of the ASME*, vol. 119, pp. 511-517, 1997.
- [7] G. Percin and B. T. Khuri-Yakub, "Micromachined piezoelectrically actuated flexensional transducers for high resolution printing and imaging," in *Ultrasonics Symposium, 2001 IEEE*, 2001, pp. 921-924 vol.2.
- [8] H. K. R. Kommepalli, C. D. Rahn, A. D. Hirsh, and S. A. Tadigadapa, "Piezoelectric T-beam microactuators," New York City, NY, United states, 2009, pp. 909-914.
- [9] H. K. R. Kommepalli, "Design, modeling and optimization of piezoelectric actuators," in *Mechanical Engineering*. vol. Doctoral University Park: the Pennsylvania State University, 2010.
- [10] S. S. Subasinghe, A. Goyal, and S. Tadigadapa, "High aspect ratio plasma etching of bulk lead zirconate titanate," USA, 2006, pp. 61090-1.

CONTACT

*S. Tadigadapa, tel: +1-814-865-2730; SAT10@PSU.EDU