Piezoelectric actuators, next driver for MEMS market?

S. Fanget, F.Casset, S. Nicolas, C. Dieppedale, M. Allain, B. Desloges and G. Le Rhun

Univ. Grenoble Alpes
CEA - LETI

ABSTRACT

Over the past three decades, huge progresses have been made in MEMS technologies. Hundreds of millions of MEMS, principally: accelerometers, gyroscopes and microphones, are commercialized yearly. This should continue to increase rapidly with upcoming new applications related to IOT or autonomous cars. These new opportunities could be the trigger for a rapid growth of the MEMS actuators market. To perform micro-actuators, LETI has been developing for more than 25 years a large know-how on piezoelectric thin films: Lead Zirconate Titanate (PZT) and Aluminum Nitride (AlN). Using PZT or AlN thin films deposited by sol-gel method and sputtering respectively on a released silicon membrane, two powerful technological platforms have been developed for a large number of applications. These platforms and some of these applications are presented below.

Keywords: Piezoelectric thin films, MEMS, Micro-actuators

1 PIEZOLECTRIC MEMS PLATEFORM

Piezoelectric micro-actuators are manufactured out of 200 mm standard silicon wafers. At first, a structural layer is deposited, it is generally composed of a 2 µm silicon-oxide and 4 µm poly-silicon. Then a thermal SiO2 (is grown at 1100◦C in oxygen on poly-silicon. A TiO2 layer is then obtained by depositing 10 nm of Ti followed by annealing at 700◦C in oxygen for 30 min. TiO2 is both an adhesion layer for the Pt electrode on SiO2 and a lead diffusion barrier. The 100 nm bottom Pt electrode is sputter deposited at 450◦C. The final bottom electrode/substrate heterostructure is hence Pt(111) 100 nm, TiO2 20 nm, SiO2 500 nm, Poly-Si 4µm, SiO2 2µm and Si 750 µm. PZT layers are grown using the sol-gel technique. A 2 µm thick PZT film is grown, composed of 36 layers. Each layer of PZT is spun, dried at 130◦C and calcinated at 360◦C. A rapid thermal annealing (RTA) step is performed repeatedly at 700◦C for 1 min under oxygen atmosphere after each calcination of 3 layers. This step enables crystallization of the PZT film in the perovskite structurea. Then a passivation silicon oxide layer followed by gold lines and pads are deposited and patterned. Depending on application, membranes are released if needed by back side etching the substrate. A tipical micro-actuator is depicted in Figure 1.

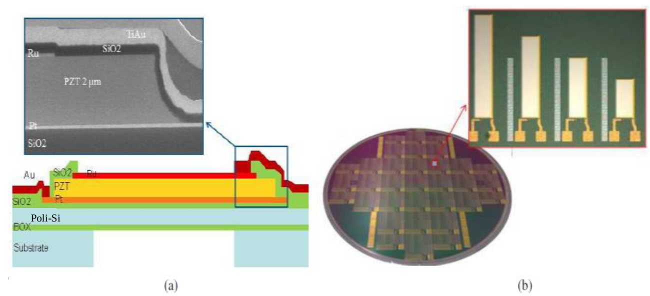


Figure 1: (a) 2 µm thick (100) sol-gel PZT actuated membrane schematic and SEM cross section view, (b) Optical view a various sizes PZT- actuated membranes on a 8 inches substrates.

Using this technology differents designs: circular anchored actuators, cantilevers or more advanced shapes can be achieved. Presented applications belowed are based on these technologies.

2 A PIEZOELECTRIC VARIFOCAL LENS

Today, there is a continuous trend in camera modules integrated in mobile phones or tablets to increase performances while still gaining on size and cost. Generally, the tuning of the focal length to perform auto-focus or zoom functions is obtained by mechanically adjusting the position of the lenses system using stepper motors. Another way to modify focus is to change the lens curvature by bending a deformable membrane that encapsulates a liquid. This can be obtained by applying a hydraulic pressure in a hermetic chamber which displaces the liquid towards the center of the lens and thus changing the curvature of the membrane (Figure 2). We have proposed an anular piezoelectric actuator to provide the desired pressure. We presented in Ref [1] the integration of a thin film piezoelectric actuator that improves the varifocal lens performances.

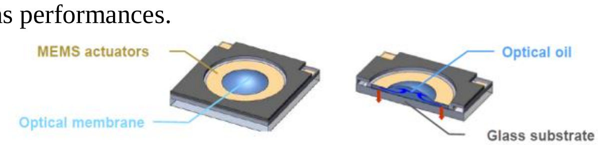


Figure 2: Actuation principle of the varifocal liquid lens

The varifocal lens consists of an optical flexible membrane released onto an optical oil-filled cavity, with integrated PZT actuators embedded at the membrane periphery (Figure 3).

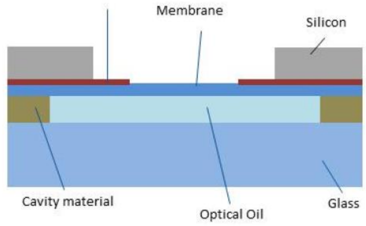


Figure 3: Cut-view of the varifocal liquid lens with embedded MEMS actuators

More details concerning the fabrication of the lens can be found in Ref [1], actuator is based on PZT technology previously described.

Optical characterizations of varifocal lenses are performed using a Shack-Hartmann wavefront sensor. On Figure 4, a typical optical power variation response of the varifocal liquid lens with an applied voltage ranging from 0 to 15 V is reported. It is demonstrated that an optical power variation of 10 diopters can be obtained with a voltage as low as 10V.

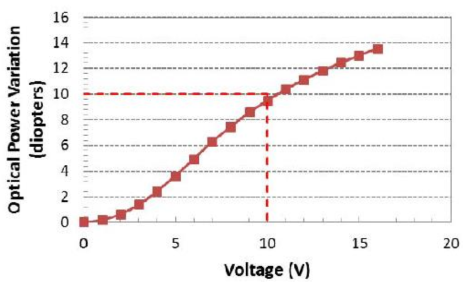


Figure 4: Typical optical power variation in diopters versus applied voltage obtained with our varifocal lens

It has to be noted that due to the resulting small current (few nA), the power consumption needed to actuate the varifocal lens is very low (< 0.1 µW). Note that the typical power consumption of VCM is 100 mW. Moreover very fast response time can be achieved depending on the initial optical aperture of the varifocal lens. For small apertures, a response time of 1 ms can be obtained whereas, for larger apertures (3 mm), typical response time is 3 ms. This is one order of magnitude faster that the response time of a VCM.

3 A PIEZOELECTRIC RESONANT MICRO-MIRROR

Optical scanners are widely used in applications such as displays, confocal microscopes, barcode readers and laser printers. MEMS scanners have the potential to meet the critical specifications, in terms of speed, size and cost. It has been demonstrated that deposited piezoelectric thin-films suit very well for resonant micro actuators in MEMS applications Ref [2]. In a previous paper Ref [3], we presented the fabrication and the characterization of a silicon micro-mirror excited by thin-film piezoelectric bimorph actuators for high speed and high resolution scanning. The whole mechanical structure of the device is formed in the 20 µm thick silicon layer of a SOI substrate and the bulk is opened so that it is suspended. As shown in figure 5, it consists of a 500 µm circular mirror asymmetrically mounted on two lateral torsional hinges linked to actuators.

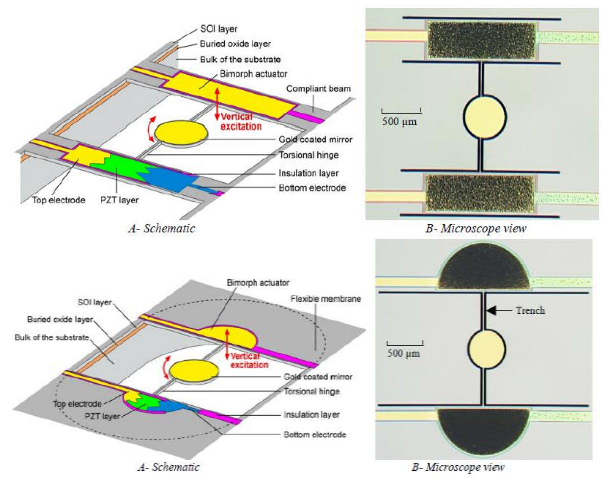


Figure 5: Silicon micro-mirror with beam-shaped and half-circular piezoelectric bimorph actuators.

The center of mass of the mirror is 50 µm off the axis of the torsional arms, so that the vertical translational excitation is efficiently converted into a rotational oscillatory movement of the mirror. A large angular rotation is obtained when the micro-mirror is operated at resonance. The actuator is formed using our piezoelectric MEMS platform. As a voltage is applied across the PZT layer, the reverse piezoelectric effect bends the beams or the circular membranes with a maximum in their middle, so that the vertical translational excitation is applied to the end of the torsional hinges. Different designs have been realized for the two kinds of actuators. Devices with resonant frequencies ranging from 1.8 to 25.4 kHz have been tested at the atmospheric pressure. Results obtained are summarized in table 1. A comparison between beam and half circular actuators which have nearly the same resonant frequencies, shows that the beam design is more efficient.

Chip	Signal amplitude	Scanning angle	Frequency (resonance)	Quality factor
A	37.2 V_{pp}	99.1°	10.6 kHz	300
C	41.4 V_{pp}	40.8°	25.4 kHz	38
D	41.6 V_{pp}	58.1°	10.8 kHz	285
E	40.6 V_{pp}	19.8°	1.8 kHz	205

Table 2. Optical scanning at atmospheric pressure

The response curve for chip A is shown in figure 6. It is almost linear, but a change is observed at high voltage. Moreover, the resonant frequency is dependent upon the oscillation amplitude. Both phenomenon can be accounted for by the non-linearity of the torsion beams stiffness at large angular amplitudes.

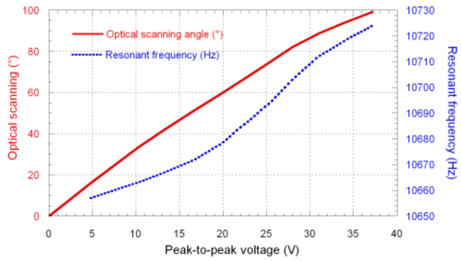


Figure 6: Optical scanning amplitude for chip A at 10.6 kHz

Figure 7 shows a 60°- wide optical scan obtained with chip A. The central spot is due to a non-optimized optical set-up and could be suppressed. More info concerning optical performances of these micro-mirrors can be found in Ref [3].

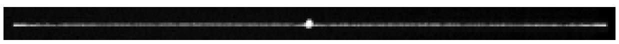


Figure 7: Photograph of the scanned optical beam

Thus we have demonstrated the efficiency of a piezoelectric actuator for a resonant torsional micro-mirror. Fast optical scannings over large angles have been achieved with low actuation voltages.

4 PIEZOELECTRIC HAPTICS INTERFACE

Recent demand in new tactile interfaces in many customers application such as smart-phones or tablet PCs, has focused research efforts towards developing high performances transparency haptic interfaces. Among the different haptic solutions, squeeze-film effect is one of the most promising ones. It provides high granularity level of haptic sensation, playing with the variable friction between a finger and a resonant haptic plate, when the Plate Displacement Amplitude (PDA) reaches about 1µm in a flexural anti-symmetric Lamb mode Ref [4]. To address transparency, low temperature process was used, to deposit AlN actuators directly on transparent glass substrate.

The design of a thin-film AlN actuated haptic plates is reported in Ref [4]. Using predictive models, we proposed an actuator design able to promote the required PDA to a 4-inch transparent plate (diagonal of the plate). The designed was made using Finite Element Method (FEM) approach and CoventorWare® tool. The model consists in the study of unclamped 700 µm thick plates made of glass (EAGLE XG®) with 2 µm thick AlN actuators. Top and bottom electrodes on both sides of the AlN layer have been neglected due to their low impact on the plate displacement amplitude (PDA). First, modal simulation performed on a 110×65 mm² plate gives the frequency of the desired mode, namely 24.68 kHz. We accurately positioned an actuator column by taking the deformed shape of the selected mode into account, and matching the actuators' position with the maximum PDA as shown in Figure 8. The actuator column consists in 5 individual actuators (each actuator width, W = 12208 µm in the y direction).

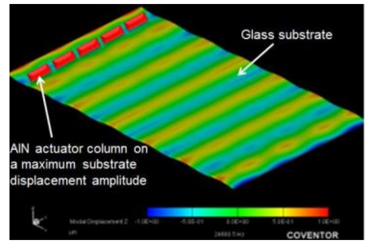
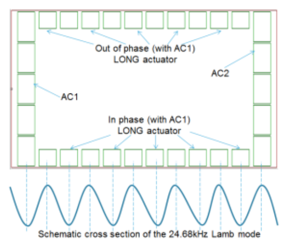


Figure 8: Modal simulation on a 110×65mm² glass plate for actuator column positioning.

Then, harmonic simulations were performed in order to define the optimum actuator column length, and localization. Using this approach different designs have been proposed (Figure 9).



Dimension		Value
Plate size		110×65 mm²
AC1, AC2	Actuator width, W	12208 µm
	Actuator length, L	7175 µm
	Actuator column position, B	6110 µm
	Actuator column number	2
LONG	Actuator width, W	5000 µm
	Actuator length, L	7125 µm
	Actuator spacing	1714 µm
	Actuator number	2 × 10

Figure 9: Optimum design for the 24.68 kHz Lamb mode obtained on the 110×65 mm² glass plate and main dimensions of the 4-inch haptic plate.

Using a piezoelectric AlN stack consisting in a 2 µm thick AlN in between 200 nm thick Molybdenum bottom and top electrodes covered by a passivation silicon oxide layer associated to gold lines and pads (Figure 10), demonstrators have been fabricated.

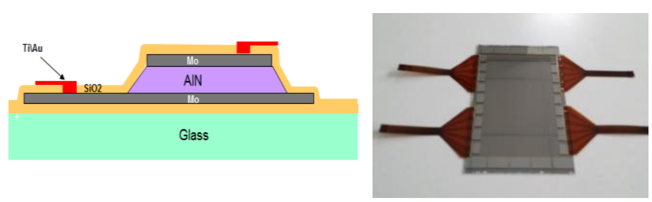


Figure 10: AlN-on-glass technological stack and AlN haptics plate demonstrator with electrical connexions

Electrical characterizations through capacitance measurements versus frequency and relative dielectric confirmed the good quality of AlN. Preliminary measurements have shown that only 53 mW (under 57 V peak to peak) were necessary to meet the required micrometric PDA on a 30×40 mm² glass plate with AlN actuators with a Lamb mode at 34 kHz Ref [5]. Electromechanical characterizations are in progress on the

4-inch AlN on glass plates, they should soon validate the designs and the functionality of demonstrators.

5 PIEZOELECTRIC MEMS DIGITAL LOUDSPEAKER

A Digital Loudspeaker Array (DLA) is an electromechanical transductor which receives a numerical signal as input data and allows the analogical conversion directly in the air. Previous work about MEMS DLA used an electrostatic actuation Ref [6], which presents pull-in limitation. We designed high performances PZT actuated membranes in order to obtain the higher acoustic pressure as possible. In a published paper Ref [7], the actuation principle is presented. Due to the ferroelectric properties of PZT, we implemented a double-actuators design able to generate positive or negative acoustic pulses (Figure 11).

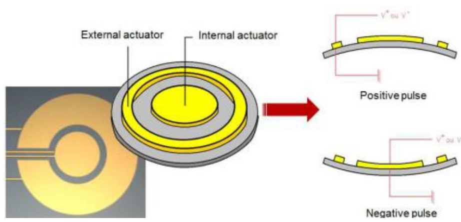


Figure 11: Thin-film PZT actuated membrane schematic view with a double actuators.

The PZT MEMS platform presented above has been used to fabricate the demonstrators. In parallel, an electronic board was design and manufactured using discrete components. It consists in a microcontroller, two FPGA and 512 drivers (one driver per actuator). Moreover a socket with 576 micro-pins was used to electrically connect the 576 pads of the DLA. Figure 12 gives a view of the system.

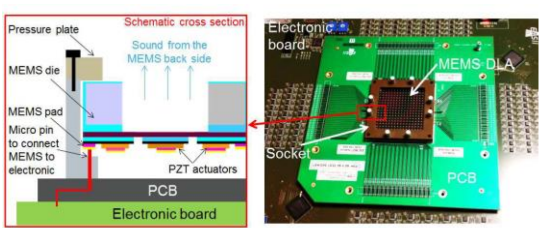


Figure 12: Picture of the MEMS DLA (256 membranes) based on PZT actuators connected with its electronic board and Schematic cross section and photography.

Electromechanical characterizations have been performed using WYKO optical profilometer to measure the maximum deflection experienced by the membrane, more details can be found in Ref [7]. Acoustic characterizations were performed on 256 membranes MEMS-DLA. We measured the response spectrum of the DLA playing in the digital reconstruction mode a 5.5 kHz sinus with a sampling rate of 44.1 kHz. It shows a satisfactory limited number of harmonic parasitic peaks and a high SPL value of about 100 dB at 13 cm (Figure 13)

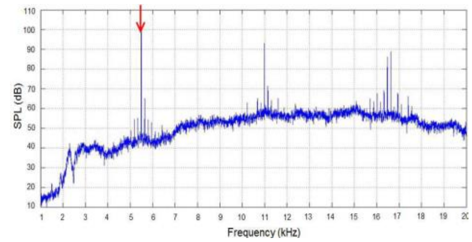


Figure 13: Response spectrum of the 256-MEMS DLA playing in digital mode a 5.5 kHz sinus

These measurements confirm that audible sounds as far as several meters can be generated with sound pressure levels higher than previous works and using low actuation voltage (8V). These results are very promising for the development of ultra-thin silicon loudspeakers.

6 CONCLUSION

As a conclusion, we can affirm that the two piezolectric MEMS platforms developped at LETI integrating respectively PZT and AlN thin films are very promising candidates for the fabrication of future comercialized devices. A lot of various applications from optics to acoustics can be adressed using these technologies. This potential for MEMS industry is confirmed by recent press releases anouncing joint developments between ST-Microlectronics and poLigh for MEMS autofocus and with Usound for loudspeakers inside mobiles.

REFERENCES

[1] S. Nicolas and al., in Proceedings of IEEE International Conference on Micro Electro Mechanical Systems (MEMS) pages 65-68, 2015

[2] C. Zinck and al. in Proceedings of Eurosensors 2003, Guimarães, Portugal, pp 474-477, 2003

[3] Filhol and al., Sensors and Actuators A 123–124, pp 483-489, 2005

[4] F. Casset et al., in Proceedings of The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), pp. 2733-2736, 2013

[5] F. Bernard and al., in Proceedings of European Conference on Solid-State Transducers (Eurosensors), pp. 1877-7058, 2014

[6] BM. Diamond et al., in Proceedings of IEEE International Conference on Micro Electro Mechanical Systems (MEMS), pp. 292-295, 2002

[6] F. Casset and al., in Procedia Engineering, Volume 120, Pages 49-52, 2015