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Low voltage MEMS digital loudspeaker array based on thin-film PZT actuators

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Abstract

This paper reports on the development of a Digital Loudspeaker Array (DLA) solution based on $Pb(Zr_{0.52},Ti_{0.48})O_3$ (PZT) thin-film actuated membranes. These membranes called speaklets are arranged in a matrix and operate in a binary manner by emitting short pulses of sound pressure. Using the principle of additivity of pressures in the air, it is possible to reconstruct audible sounds. For the first time, electromechanical and acoustic characterizations are reported on a 256-MEMS-membranes DLA. Sounds audible as far as several meters from the loudspeaker have been generated using low voltage (8V).

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Keywords: MEMS; Digital Loudspeaker; PZT; Actuators; Piezoelectric; Silicon membranes

1. Introduction

A Digital Loudspeaker Array (DLA) is an electromechanical transducer which receives a numerical signal as input data and allows the analogical conversion directly in the air. Previous works on MEMS-DLA used an electrostatic actuation (Diamond et al. (2002) and Cohen et al. (2009)), which presents pull-in limitation. Presented work uses membranes (speaklets) actuated by the combination of the indirect piezoelectric effect and the bimorph effect. Piezoelectric actuation was chosen to decrease the actuation voltage and to avoid pull-in effect. Moreover it is expected to obtain very low power consumption using piezoelectric actuation. The piezoelectric actuation has the further advantage of not being sensitive to dust and is in this sense more reliable and less fragile than the electrostatic actuation.

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Due to the ferroelectric properties of PZT, a double-actuator design able to generate positive or negative acoustic pulses has been implemented in the DLA (Fig.1). The design of this system is compatible with a multiple-level command of membranes as described by Monkronthong et al (2014) and therefore opens the perspective of 16-bits-DLA using a limited number of membranes.

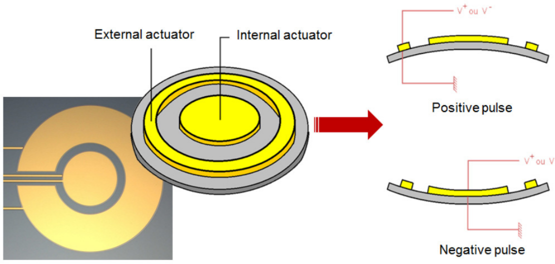


Fig.1. Schematic view and photography of the double-PZT actuator design able to generate positive and negative elementary acoustic pulses

2. DLA and speaklets designs

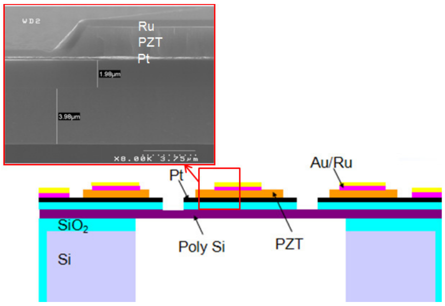
Speaklets have been modeled using FEM software to fix their first resonant frequency nearby 25 KHz. Stresses inside the different layers of the speaklets have been included in the calculations. The impact of mechanical nonlinear effects due to large deformations of membranes compared to their thickness has also been taken into account. From these calculations, a first resonant frequency at 25 KHz was obtained for a radius fixed at 1300 µm. This frequency is higher than the audible limit, therefore direct emitted signal from speaklets will not be detected by humans.

The number of speaklets implemented on a DLA has been fixed at 256 in order to increase the sound pressure level and to enhance the quality of the reconstructed sound. The final dimension of the DLA chip is 6 X 6 cm^2.

3. DLA Fabrication

Demonstrators were fabricated using a generic piezoelectric technology developed at CEA-LETI compatible with the fabrication of other piezoelectric MEMS like RF switches (M. Cueff et al. (2010)) or haptic components (F. Casset et al. (2013)). Devices were manufactured out of 200mm standard silicon wafers. First, silicon dioxide (1.9µm) and poly-silicon (4µm) layers were deposited. The piezoelectric actuator stack is then deposited and etched (Fig. 2.). The stack is composed of a 2µm thick sol-gel PZT layer in between a 100nm thick Pt bottom electrode and a Gold/Ru top electrode. Membranes were released by back side etching the silicon substrate. Finally, the substrate is sawed to obtain an ultra-thin DLA (thickness < 735 µm).

(a)



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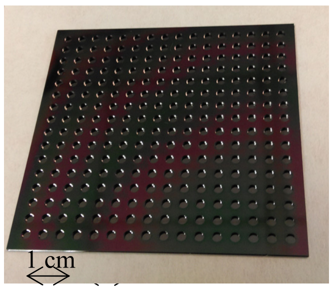

Fig. 2. (a) Schematic cross section of the technological stack and SEM cross section of the PZT actuator; (b) Photography of the final DLA chip

4. Characterizations and results

A dedicated electronic board was designed and manufactured using discrete components to individually actuate each of the 256 membranes per DLA (2 actuators per membrane). The board is composed of a microcontroller, two FPGA and 512 drivers. The electronics is interfaced with a computer using an USB port. A custom-made socket with several micro-pins has been developed to electrically connect the 576 pads allowing the DLA actuation. An overview of the whole system: MEMS-DLA connected with the electronic board using the socket is depicted on FiG. 3.

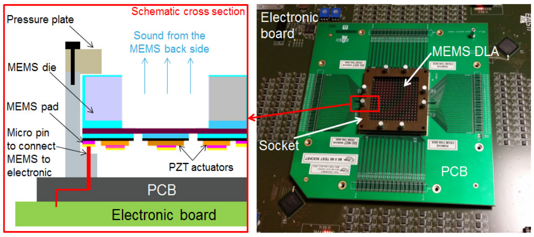

Fig. 3. Picture of the MEMS DLA system (256 membranes, membrane radius = 1300µm) based on PZT actuators connected with its electronic board using a custom-made socket

Electromechanical characterizations were performed on MEMS membranes to validate their functionality. In particular, a WYKO optical profilometer has been used to characterize the membrane differential displacement amplitude (MDDA), which is the membrane maximum displacement at a given actuation voltage minus the membrane position at 0V. Fig. 4 shows the MDDA for internal and external actuators of 3 different membranes (radius=1300µm). It can be noticed that the MDDA reaches 4µm under only 10V. Internal and external actuators allow obtaining symmetric responses insuring symmetric negative and positive acoustic pulses as expected. Nevertheless, a discrepancy until 20% was observed between different membranes, which can potentially introduce sound distortions.

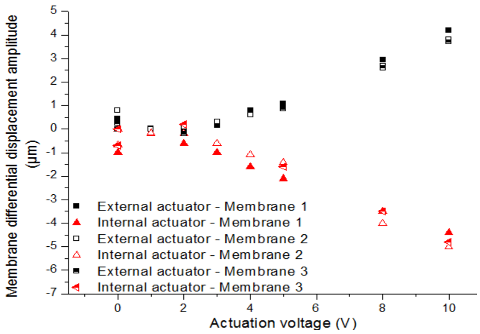

Fig. 4. Membrane differential displacement measurements (membrane radius = 1300µm) for external and internal actuators measured on 3 different membranes versus applied voltage.

Acoustic characterizations consist in the measurement of the response spectrum of the DLA playing in the digital reconstruction mode a 5.5 kHz sinus. For this measurement, the sampling rate for the digital reconstruction was fixed at 44.1 kHz. Results presented in Fig. 5 show a very well experimental digitally reconstructed peak at 5.5 KHz as expected, with a high SPL value (measured at 13 cm) of about 100 dB under an actuation voltage of only 8V. It is worth to notice that a satisfactory limited number of harmonic parasitic peaks appears in this experimental response.

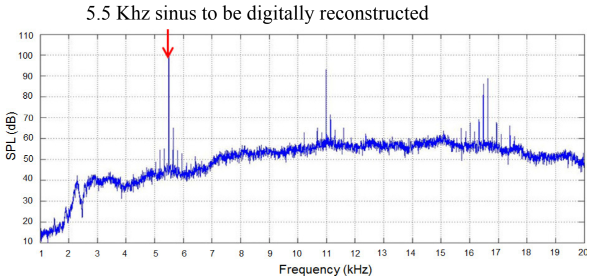

Fig. 5. Response spectrum of the MEMS-DLA playing in digital mode a 5.5kHz sinus, 8V. DLA composed of 256 membranes with membrane radius = 1300µm

The response spectrum of the MEMS-DLA in analogic mode has also been investigated using as actuation signal a varying sinus with frequency ranging from 300 Hz up to 20 KHz , the amplitude of the actuation signal was fixed at 8V. The acoustic pressure measured using a microphone placed 13 cm face to the MEMS-DLA is reported in Fig. 6 and compared with the same measurements performed on a 64-membranes MEMS-DLA with speaklets radius of 800 µm from previous works (Dejaeger et al. (2012)). Results show an acoustic pressure increased of about 40 dB that can be explained by the increase of the emitting surface: higher number of speaklets (+ 8 dB) and a higher speaklets size (+12 dB). Remaining 20 dB are explained by a large decrease of the electric access resistance in this work compared to previous work that allows a better actuator excitation for the same input voltage applied to electrical pads.

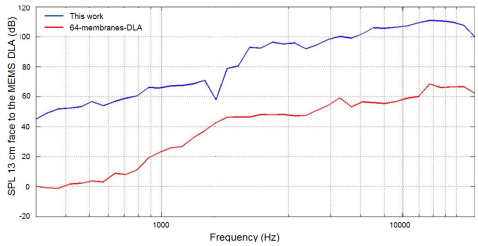

Fig. 6. Comparison of the measured acoustic pressure between a 256- MEMS DLA and a 64- MEMS DLA (Actuation amplitude 8V)

5. Conclusion

This paper reports the design, the fabrication and the characterization of a 256-MEMS-DLA based on a piezoelectric technology developed on 200mm standard silicon wafers using PZT. Digital acoustic reconstructions using the 256-MEMS-DLA have been demonstrated using low actuation voltage (8V). Sounds audible as far as several meters have been generated with sound pressure levels higher than previous works. These results are very promising for the development of ultra-thin DLA. Further investigations will be performed to quantify the sound quality through Total Harmonic Distortion evaluations.

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