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Modelling and Characterization of PZT-based High Performance PMUTs for In-Air Applications

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Summary:

Micro-Electromechanical systems (MEMS) structures using piezoelectric thin films have often delicate mechanical structures (e.g. membranes) combined with a thin-film stack consisting of electrodes, the piezoelectric material and other materials such as stress compensation layers. Analytical models have been developed for the design of a membrane structure that is used as piezoelectric micromachined ultrasound transducers (PMUT). The validity of this models has been checked with measurements of the devices. An example of a sensing application is presented.

Keywords: piezoMEMS, PZT, modeling, PMUT, ultrasound

Background

piezoMEMS – MEMS including piezoelectric thin-films for actuation and/or sensing - is a technology which is already wide-spread used in e.g. RF-filters or ink jet print heads. The potential for applications is, however, much bigger and piezoelectric miniaturized ultrasound transducers (PMUT) are an emerging technology e.g. for applications in air [1]. Such devices can be used as arrays and enable e.g. activity detection. These industrial devices are based on thin-film AlN, but higher performance for actuation can be achieved with thin-film PZT due to its ca. 6 times higher piezoelectric coefficient $e_{31,f}$ [2]. To unlock the full design potential good models are necessary. We present here an analytical modelling framework and the validation of it with measurements on manufactured devices.

Analytical modelling framework

Fig. 1 shows a schematic cross-section of multilayered membrane structure consisting of silicon, silicon dioxide, a Pt bottom electrode (which is very thin, therefore, not visible in the figure), the PZT layer and the gold top electrode. This is circular structure and therefore the polar coordinate system and the radius of the inner electrode r_1 and membrane radius r_2. To describe flexural rigidity D_m of this multilayered structure with materials of different mechanical properties one must calculate the z-coordinate of the neutral plane z_n (Eq. (1)) including the thicknesses t_i, the Young's modulus E_i and the Poisson ratio v_i of the *i*th layer.

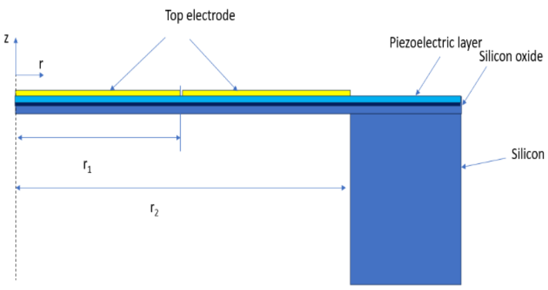

Fig. 1. Cross-section of a circular multilayered

$$z_n = \frac{\frac{E_1}{1-\nu_1^2}\frac{t_1^2}{2} + \sum_{i=2}^{n}\frac{E_i}{1-\nu_i^2}\left[\left(\sum_{j=1}^{i-1} t_j\right)+\frac{t_i}{2}\right]}{\sum_{i=1}^{n}\frac{E_i}{1-\nu_i^2}t_i} \qquad (1)$$

We calculate the flexural rigidity D_m (2) of the multimorph structure taking also into account the flexural rigidity for one single layer $D_i= E_i t_i^3/12(1-v_i^2)$ using Steiner's theorem

$$D_m = \frac{E_1}{1-\nu_1^2}\left[\frac{t_1^3}{12} + t_1\left(\frac{t_1}{2} - z_n\right)^2\right] + \sum_{i=2}^{n}\frac{E_i}{1-\nu_i^2}\left\{\frac{t_i^3}{12} + t_i\left[\left(\sum_{j=1}^{i-1} t_j\right) + \frac{t_i}{2}\right] - z_n^2\right\} \qquad (2)$$

The areal mass density μ_{weigh} can be calculated using the mass density $\rho_{i:}$

$$\mu_{weight} = \sum_{i=1}^{n} \rho_i t_i \qquad (3)$$

The frequency of the first eigenmode can be calculated with the following [3]:

$$f_{eigen} = \frac{3.19^2}{2\pi r_2^2}\sqrt{\frac{D_m}{\mu_{weight}}} \qquad (4$$

Results

PMUT devices were designed and manufactured according to specifications to have a resonance at 50kHz. Due to uncertainties in the manufacturing process (residual stress, underetch) different device layer thicknesses of the used silicon on insulator (SOI) wafers and membrane radii were applied (version AA: r_2 =650 µm, BB: r_2 = 680 µm, CC: 620 µm). A photograph of a manufactured PMUT including a 2µm PZT layer and gold electrodes on top is shown in Fig 2.

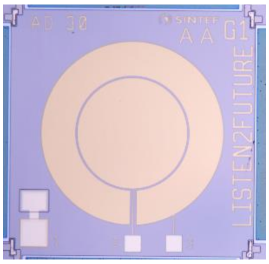

Fig. 2. PMUT design AA fabricated

The fabricated samples were characterized by their frequency of the first mechanical eigenmode.

Tab. 1:Measured resonant frequency and its std deviation of the different PMUT design,

Chip design	Device layer thickness [µm]	Resonance frequency [kHz] (first eigenmode)	
		Analytical model	Measured
BB	6	52	48 +/- 1.1
CC	6	53	57.5 +/- 1.5
AA	5	49	45,2 +/- 1,3
BB	5	45	41.3 +/- 1.9
CC	5	53	49.0 +/- 1.4

Tab1. shows that the multilayered analytical model delivers results quite close to the actual values. The actual values are deviating mostly due to manufacturing effects such as residual stress in the different thin-film layers as well as non-ideal etching profiles.

The functionality for the intended application for activity detection was tested with a set-up to detect a moving hand using the PMUTs as transmitters.

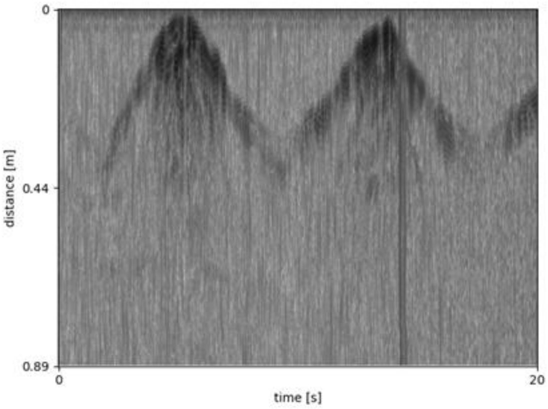

Fig. 3. Echoes from a hand moving at a varying distance.

Conclusions

We have shown a powerful analytical model for multilayered mechanical structures, which was applied to design PMUT devices. The PMUT devices were successfully manufactured using a thin-film PZT based piezoMEMS process using silicon on insulator wafers and release of the membrane by bulk-micromachining. The validity of the analytical model was verified by measurements on the finalized devices.

The functionality of the devices for the intended use in the field of activity detection was tested successfully by using them as transmitters in a set-up for echo detection.

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