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Experimental comparison of receive sensitivity of circular and ring piezo-electrodes geometries for PMUT resonator membranes designed in PiezoMUMPS process

Niko Plantak[1], Mihael Katalenić[1], Dinko Oletić[1]
[1] University of Zagreb Faculty of Electrical Engineering and Computing,
Unska 3, HR-10000 Zagreb, Croatia,
dinko.oletic@unizg.fer.hr

Summary:
Piezoelectric micromachined ultrasonic transducers (PMUT) elements in SOI technologies based on circular resonator membranes, often employ fully covered circular, or ring-shaped piezo-electrodes. However, depending on the exact piezo material stack, their placement and geometry may introduce mechanical clamping or residual stress, causing a loss of sensitivity, or unwanted resonant frequency shifts. Here we show early FEM and experimental results of geometric optimization of circular, and ring piezo-electrodes for 1 MHz PMUT resonator membranes designed in PiezoMUMPS process.

Keywords: ultrasonic, piezoelectric, PMUT, resonator, membranes.

Introduction

Piezoelectric micromachined ultrasonic transducers (PMUT) elements, designed in SOI technologies in form of circular-shaped device-layer silicon resonator membranes, most often use circular or ring-shaped piezo-electrodes [1], [2]. However, an exact set of material layers constituting the piezo-electrode stack, their mechanical properties, thicknesses, limitations of patterning individual layers etc. may introduce mechanical clamping or residual stress, causing a loss of sensitivity, or unwanted resonant frequency shifts [3, 4]. Therefore, it is necessary to specifically tailor the geometry, sizes, and alignment of individual thin-film piezo-electrode stack layers for a specific technological process. In this paper we do this by parametrizing circular, and ring piezo-electrodes geometries for PMUT membranes designed around 1 MHz in PiezoMUMPS process [5].

Methodology

In PiezoMUMPs (Fig. 1, left), a 10 µm P-doped silicon acting simultaneously as a structural device-layer defining PMUT membrane thickness, and as a relatively resistive bottom electrode. The piezo-electrode stack consists of AlN as a piezoelectric material, and a relatively thick 1 µm top metal electrode.

Modal response, and harmonic receive sensitivity (resonant frequency, displacement, piezo-voltage) of a PMUT were simulated by a harmonic coupled-physics FEM model (COMSOL), exploring the design-space of parametrized geometry elements (Fig. 1, right): membrane radius r_m, horizontal ring electrode thickness r_t, and position of the electrode's outer edge with respect to membrane. For each r_m, the design goal was to identify r_t, r_e, maximizing piezo-voltage, while minimizing relative frequency-shift Δf [%] and change in displacement Δd [%], compared to a referent PMUT design with a completely covered circular electrode aligned to the membrane edge ($r_t = r_m$, $r_e = 0$, Fig. 1, left). PMUT samples were microfabricated, and preliminary characterized by electrical impedance (Agilent), laser-doppler vibrometry (SmarAct), compensated for differences in membrane radius r_m due to back-side DRIE blowout.

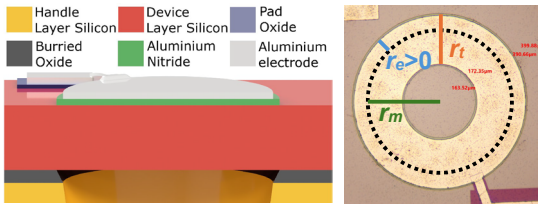

Fig 1. PiezoMUMPs technological cross-section (left), designed PMUT devices (right).

Experimental results

Compared to a fully covered membrane, frequency-shift can be minimized (Fig. 2, white iso-surface Δf = 0%) by designing thin ring-electrodes surpassing the membrane edge (r_e > 0, r_t << r_m,), with an optimal r_t changing more linearly starting from at least r_e > 15 µm. With smaller r_t resulting in lower Δd, Δd < -2% can

be expected in the region of intersection with the Δf = 0% iso-surface (Fig. 3, orange arrow). Voltage obtained at this intersection is maximized for r_e = 15 µm (Fig. 4, orange arrows). Optimal ring thickness r_t scales linearly with membrane radius r_m. If maintaining Δf = 0 is not relevant, Fig. 5 (orange arrows) confirms the presence of an additional piezo-voltage maximum, obtained for a thick ring-electrode, placed inside the membrane (r_e < 0) around the second point of maximal stress gradient, closer to its center. These findings were preliminarily confirmed by vibrometry (Fig. 6).

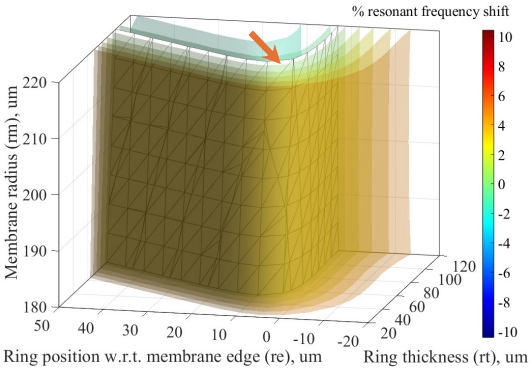

Fig. 2, Minimal change in resonant frequency Δf.

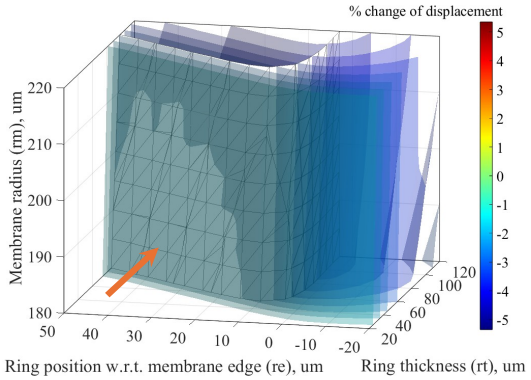

Fig. 3, Minimal change of displacement Δd, FEM.

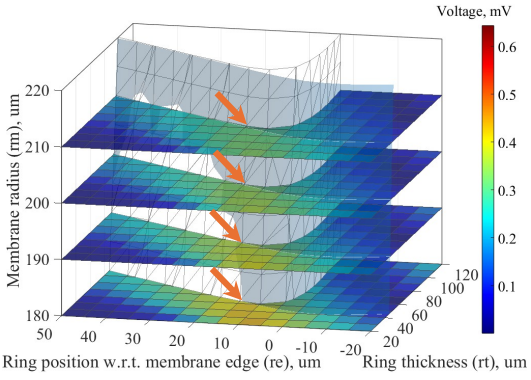

Fig. 4. Piezo-voltage for minimal Δf and Δd, FEM.

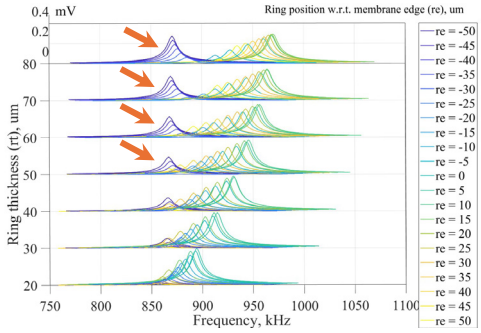

Fig. 5. Piezo-voltage, for fixed r_m = 200 µm, FEM.

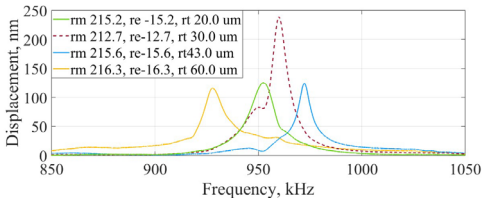

Fig. 6. Measured displacement, vibrometry.

Conclusion

An optimal placement and ring-thickness was derived for thin ring piezo-electrodes at the PMUT membrane edge, while minimizing the changes between the designed and obtained resonant frequency. More experimental work is planned to validate the FEM findings.

Acknowledgment

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