proceedings

MDPI

Squared PMUT with Enhanced Pressure Sensitivities [†]

**Eyglis Ledesma [1], Iván Zamora [1], Francesc Torres [1], Arantxa Uranga [1], Vassil Tzanov [1],
Nuria Barniol [1,*], Eloi Marigó [2] and Mohan Soundara-Pandian [2]**

[1] Electronics Eng. Dept, Universitat Autónoma de Barcelona, 08193-Bellaterra, Spain;
eyglis.ledesma@uab.cat (E.L.); ivan.zamora@uab.cat (I.Z.); francesc.torres@uab.cat (F.T.);
Arantxa.uranga@uab.cat (A.U.); vassil.tzanov@uab.cat (V.T.)

[2] Silterra Malaysia Sdn. Bhd, Kulim 09090, Malaysia; eloi_marigo@silterra.com (E.M.);
mohanraj_soundara@silterra.com (M.S.-P.)

* Correspondence: nuria.barniol@uab.cat; Tel.: +34-93-581-1361

† Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Abstract: This study presents a squared AlN piezoelectric micromachined ultrasonic transducer (PMUT). Using this PMUT greater level of output pressure and higher reception sensitivity has been achieved, compared with the state-of-the-art. Another outstanding characteristic for this PMUT is that it can be monolithically integrated on CMOS substrate, being remarkably advantageous in relation to the bonding method implemented until now.

Keywords: piezoelectric micromachined ultrasonic transducer (PMUT); differential excitation; transmitting sensitivity; receiving sensitivity

1. Introduction

PMUTs are widely used in smart sensing applications as fingerprint recognition. This new technology has important advantages over conventional ultrasonic transducers such as low cost, small size, low power consumption, and compatibility with integrated circuit manufacturing methods [1]. One of the most important Figures of Merit to characterize and evaluate its behavior as an actuator and sensor is the sensitivity, being the main parameter that will focus our attention. For this reason, it is necessary to look for the best structures, materials and electrode configuration in order to increase sensitivity.

2. Materials and Methods

PMUT Device

In this paper, we have used a squared AlN PMUT with an 80 μm side (Figure 1a). The piezoelectric layer has a 1.3 μm thickness with 0.35 μm top and 0.40 μm bottom Al electrodes and a 1.5 μm Si_3N_4 passive layer. It was fabricated using the MEMS-on-CMOS process from Silterra already used for SAW devices [2].

Squared PMUTs have a better performance than circular PMUT [3], the main reason is because the fill factor is considerably higher and for this the output pressure is also bigger.
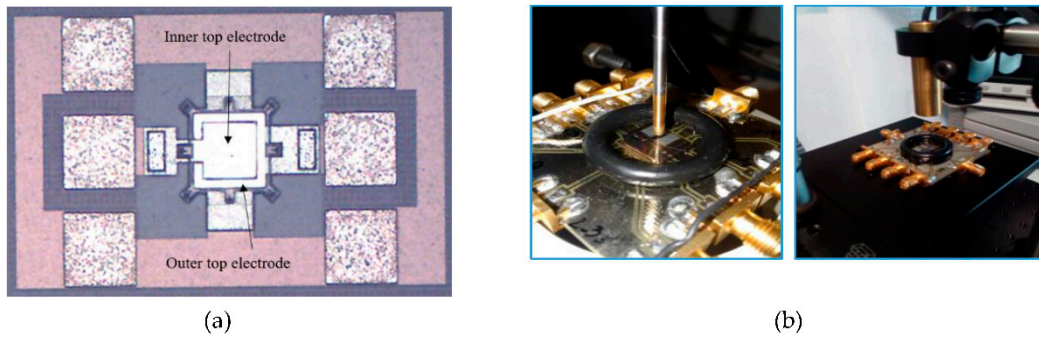
Figure 1. (**a**) Optical image of the squared 80 μm PMUT device. (**b**) Setup for the acoustic characterization in a liquid environment as an actuator with hydrophone (left) and as a sensor with a commercial ultrasound transducer (right).

Our proposal use two top electrodes for differential transduction and a common bottom electrode. This configuration has the property that it can improve considerably the sensitivity and coupling efficiency [4]. To achieve this is necessary that the relation between inner electrode and cavity radius will be $\sqrt{2}/2$ and the gap among inner and outer electrode must be minimized, in our case we have used 1.5 μm.

3. Results

3.1. Simulation and Electrical Measurements

Comsol Multiphysics was used to simulate this PMUT in H_2O and FC-70. Figure 2a shows the membrane deflection in these media using 1V in differential excitation. The resonance frequency obtained in H_2O was 3.7 MHz and 2.8 MHz in FC-70.

In addition, the PMUT was electrically characterized in air by a probe table using a network analyzer. A 5.9 MHz resonance frequency for the first flexural mode as drum resonator with a quality factor of $Q = 153$ and a piezoelectrical coupling coefficient $k_t^2 = 1.6\%$ is obtained, Figure 2b.
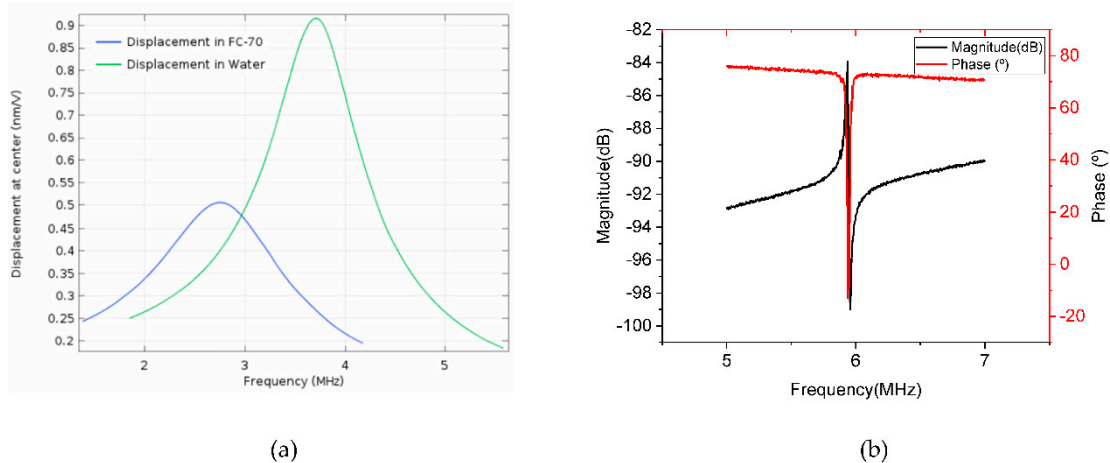

Figure 2. Frequency responses for the PMUT: (**a**) COMSOL simulation of PMUT displacement in different media; (**b**) Electrical PMUT characterization in air, using inner top electrode as input and outer top electrode as output.

3.2. Acoustic Characterization of the PMUT as Actuator and Sensor

In order to characterize the output acoustic pressure of the PMUT as an actuator, a commercial hydrophone (HNC-1500) from ONDA has been used in H_2O and FC-70 (c = 1468 m/s; ρ= 1000 kg/m³ and c = 700 m/s; ϱρ = 1940 kg/m³ respectively) (see Figure 1b). The characterization of the PMUT as

sensor has been made with a commercial transducer from OPTEL, which has been previously calibrated (see Figure 1b).

Figure 3 shows the response in the media when the electrodes were excited differentially with a 6 cycles, 20 Vpp input signal at a distance of 3.8 mm between the PMUT and hydrophone in water (Figure 3a), and 3 mm in FC-70 (Figure 3b). The maximum peak-to-peak pressure obtained is 388 Pa in H_2O and 360 Pa in FC-70. Computing the FFT from the ring down time response of the PMUT, the resonance frequencies are 3.1 MHz (in H_2O) and 2.4 MHz (in FC-70), close to the simulated ones. The quality factor in H_2O and FC-70 was computed obtaining 7.1 and 2.7 respectively.
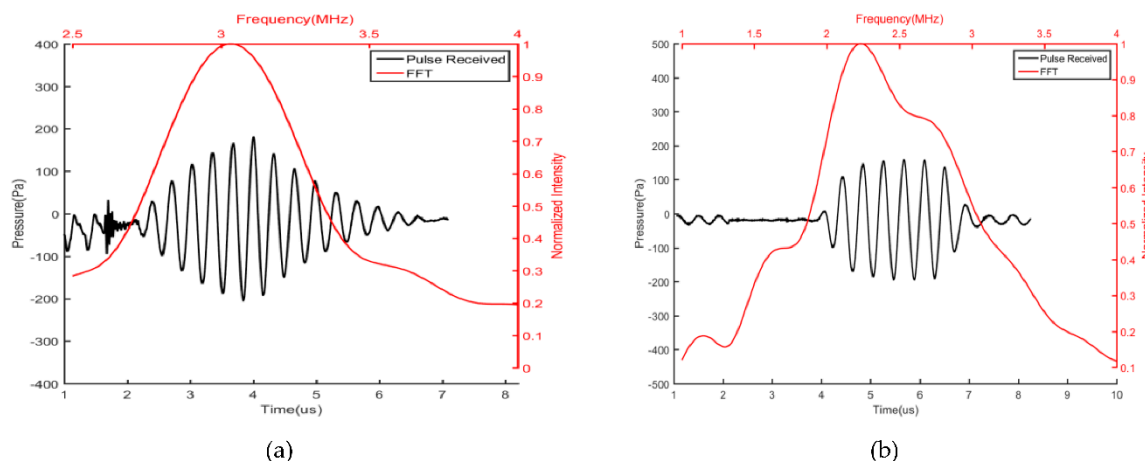

(a)	(b)

Figure 3. Acoustic pressure measurement with the hydrophone: (**a**) H_2O at 3.8 mm; (**b**) FC-70 at 3 mm. In each figure, left axis and bottom axis (black) corresponds to the acoustic pressure and time respectively, while right axis and top axis (red) corresponds to the frequency domain.

For comparison with other PMUTs, the surface pressure defined as $P_0 = z/R_0 \cdot p(z)$ (being R_0, the Rayleigh distance), has been calculated in both media (R_0 = 10.6 μm in H_2O and R_0 = 17.2 μm in FC-70). In H_2O the pressure at 3.8 mm was 388 Pa, obtaining a surface pressure of 138 kPa and consequently a transmitting sensitivity (ST) of 6.9 kPa/V. In FC-70, at 3 mm, the measured pressure was 360 Pa, the surface pressure was 63.5 kPa and the corresponding transmitting sensitivity, 3.2 kPa/V. From the simulated dynamic displacement (*d*) (Figure 2), the surface pressure of the PMUT ($ST_{EOC} = P_o(1\ V) = 2\pi\rho fdc$, and considering a 1/3 factor for not being and ideal piston) in both media was computed, given ST_{EOC} = 8.86 kPa/V in water, and 3.98 kPa/V in FC-70, obtaining a good correlation between COMSOL simulations and experimental results. Table 1 contains the results as actuator in FC-70, compared with other devices using AlN as piezoelectric material. The results show that this squared PMUT has bigger transmission sensitivities than the reported ones.

Table 1. Comparison Performance of the PMUT in FC-70 as actuator.

	Freq (MHz)	ST (kPa/V)	Comments
This work	2.4	3.2	Squared PMUT (80 μm side, 1.3 μm AlN)
[5]	2.5	1.1	Circular PMUT (80 μm diameter, 1.3 μm AlN)
[6]	14	1.38	Extrapolated value for a single 1 μm AlN PMUT (array of 110 × 56)

The sensitivity as sensor (SR) was computed using the measured signal acquired directly from the PMUT (sensor) by the oscilloscope. Due to the small capacitance of our single PMUTs (~150 fF), the parasitic capacitances due to all the electrical set-up (pads, cables and oscilloscope) have been considered to compute the PMUT intrinsic sensitivity, or SR_{EOC} (End Open Circuit sensitivity).

$$SR = \frac{C_{PMUT}}{C_{PMUT} + C_{Cable} + C_{Osc} + C_{Set-up}} * SR_{EOC}, \qquad (1)$$

where SR is the receiving sensitivity, C_{PMUT} is PMUT capacitance and the values associated to the inner and outer electrode are 196 fF and 146 fF approximately, C_{Cable} is cable capacitance (96 pF/m), C_{OSC} is the oscilloscope capacitance (8 pF) and C_{Set-up} (9 pF) accounts for all the parasitic capacitances associated with bondings, pads, connectors, etc.

To characterize the PMUT as acoustic sensor, the commercial transducer (@ OPTEL) was excited with 20 Vpp at 3.1 MHz in H_2O and at 2.4 MHz in FC-70. Figure 4 shows the received signal at an axial distance from the PMUT of 4.17 mm in H_2O and 5.30 mm in FC-70. The voltage signal from the PMUT is around 800 µV in H_2O, while it is around 500 µV in FC-70 (Figure 4). Note that these signals correspond to the differentiation of the inner and outer signals acquired. Knowing the pressure already calibrated from the OPTEL at the same distance, frequency and media, the computed SR is 45.6 mV/MPa and 36.4 mV/MPa in H_2O and FC-70 respectively. Considering all the capacitances and applying Equation (1) to correct both inner and outer signals, the final SR_{EOC} in H_2O and FC-70 would be in the range of 30 V/MPa, which is under our knowledge higher than other reported PMUTs in an array configuration [3,7]. We expect an improved measurement performance, decreasing the influence of the parasitic capacitances through the monolithical integration with the CMOS circuitry, and provide further evidences on this very high sensitivity single PMUT as sensor.
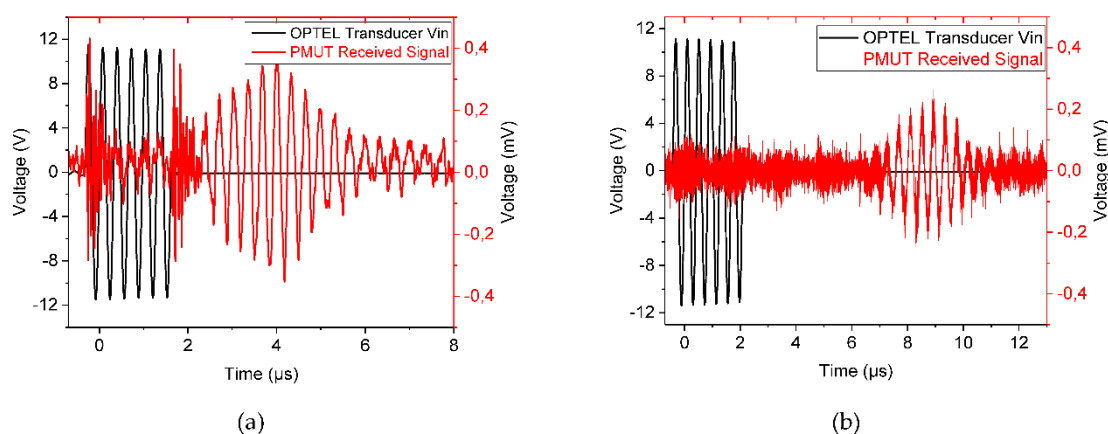

(a)　　　　　　　　　　　　　　　　　　(b)

Figure 4. Measurement of PMUT response as sensor when an acoustic pressure is applied: (**a**) in H_2O at 4.17 mm; (**b**) in FC-70 at 5.30 mm.

Conflicts of Interest: The authors declare no conflict of interest.

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