Piezoelectric Micromachined Ultrasonic Transducers with Increased Coupling Coefficient via Series Transduction

Yipeng Lu, Qi Wang, and David A. Horsley
University of California
Davis, CA, USA

Abstract—This work demonstrates a new electrode configuration for piezoelectric micromachined ultrasonic transducers (PMUTs) with increased electromechanical coupling coefficient \( k_t^2 \). The electrodes, a center electrode surrounded by a ring electrode, are identical to those used in differential PMUTs. Unlike a differential PMUT, where the two top electrodes (TEs) are referenced to a common ground electrode, here only the two TEs are used, effectively putting the two piezoelectric transducers in series. The benefit of series readout is that the transducer’s electrical capacitance is halved, doubling the receive sensitivity and electromechanical coupling coefficient \( k_t^2 \).

Keywords—PMUT; Piezoelectric; Ultrasonic Transducers; Ultrasound; Electromechanical Coupling; Series Transduction

I. INTRODUCTION

Micromachined ultrasonic transducers (MUTs) have recently gained much interest and been developed for applications such as medical imaging [1-2], gesture recognition [3], ultrasonic fingerprint sensors [4] and others. Unlike conventional ultrasonic transducers whose acoustic impedance is defined by the transducer’s material properties, MUTs have a compliant thin membrane structure operating in a flexural vibration mode with acoustic impedance that can be well-matched to a surrounding environment. Compared with well-developed capacitive MUTs (CMUTs) [5], PMUTs do not require a high polarization voltage and small gap to achieve high sensitivity, and thereby reduce circuit and fabrication complexity. However, PMUTs require a piezoelectric layer that is not part of standard semiconductor processes. Lead zirconate titanate (PZT), Aluminum Nitride (AlN) and Polyvinylidene fluoride (PVDF) are among the piezoelectric materials used for ultrasonic transducers. Optimization of piezoelectric material properties (such as the piezoelectric coefficients \( e_{31}, e_{33} \) and dielectric constant etc.) has been studied to maximize transducer sensitivity. Moreover, optimizing the piezoelectric/elastic layer stack thicknesses and electrode coverage have also been demonstrated to further improve PMUT transmit or receive sensitivities [6-7].

The coupling coefficient (power conversion efficiency) is a key figure-of-merit for PMUT performance. There are three energy domains involved with PMUTs: electrical, mechanical and acoustic domains. Increasing the mechanical-acoustic coupling coefficient (power conversion efficiency between mechanical and acoustic domains) allows the PMUT’s bandwidth to be increased, resulting in shorter minimum pulse length and higher axial resolution. PMUT’s with a thin membrane and dual resonance modes are among the approaches that have been demonstrated to increase bandwidth [8]. Another power conversion is the electromechanical coupling between electrical and mechanical domains. PMUTs with differential transmitting or receiving electrodes improve the electromechanical coupling coefficient \( k_t^2 \). However, differential excitation makes the pulser circuit more complicated, and requires twice as many contacts to the PMUT, complicating signal routing in dense PMUT arrays. Here we propose PMUTs with series transduction, doubling the electromechanical coupling coefficient \( k_t^2 \) and receive sensitivity while requiring only two contacts to the PMUT.

II. DESIGN AND MODELING

A. Electrode Design

A PMUT can work as both a transmitter and receiver. As a transmitter, the electric field between the top electrode (TE) and the bottom electrode (BE) creates transverse stress in the piezoelectric layer due to the converse piezoelectric effect. The generated stress causes a bending moment which forces the membrane to deflect out of plane and launch an acoustic pressure wave into the environment, as shown in Figure 1. In the receive mode, an incident pressure wave deflecting the plate creates transverse stress which results in charge between the electrodes due to the direct piezoelectric effect. Unlike a cantilever, the curvature of a clamped beam or membrane has an inflection point and the electrodes should be appropriately shaped based on this information. For a circular clamped membrane with radius \( a \), the static deflection \( w(x) \) under uniform pressure can be expressed as:

\[
w(x) = w_0 \varphi(x)
\]  

where \( x = r/a \) is the normalized radial coordinate, \( w_0 \) is the peak deflection, and \( \varphi(x) \) is the normalized mode-shape as below:

![Figure 1: Cross-section of a traditional PMUT with exaggerated deformation.](image-url)
\[ \varphi(x) = (1 - x^2)^2 \]  

(2)

A PMUT can be modeled using an equivalent circuit model with two transformers [6]: electromechanical and mechanical-acoustic coupling transformers. The former transformer can be expressed:

\[ F_{in} = \eta V_{in} \]  

(3)

where \( V_{in} \) is the input voltage, \( F_{in} \) is the effective piezoelectric force and \( \eta \) is the transformer ratio:

\[ \eta = \frac{1}{2} \varepsilon_{31, f} \bar{Z}_p \rho_{piezo} \]  

(4)

where \( \varepsilon_{31, f} \) is the effective thin-film piezoelectric coefficient, \( \bar{Z}_p \) is the distance from the center of the piezoelectric layer to the neutral axis of the membrane, and \( \rho_{piezo} \) is an integral that captures the effect of the electrode layout and the particular mode-shape:

\[ I_{piezo} = 2\pi \int_{r_1}^{r_2} \left( \frac{d^2\varphi(x)}{dx^2} + \frac{1}{x} \frac{d\varphi(x)}{dx} \right) dx \]  

(5)

where \( r_1 = r_1/a \) and \( r_2 = r_2/a \) are normalized radial coordinates of the inner radius \( r_1 \) and outer radius \( r_2 \) of an annular top electrode. For a traditional PMUT with only a center top electrode, \( r_1 = 0 \) and \( r_2 = r \), we obtain the electromechanical transformer ratio as below:

\[ \eta = 4 \pi r^2 (r^2 - 1) \varepsilon_{31, f} \bar{Z}_p \]  

(6)

The electrode radius which maximizes \( \eta \) is \( r = \sqrt{2}/2 \) and the corresponding transformer ratio \( \eta_t \) is:

\[ \eta_t = -\pi \varepsilon_{31, f} \bar{Z}_p \]  

(7)

Note that since the top electrode is thin compared with the whole membrane stack, we neglect the effect of the electrode pattern on the stiffness of the membrane.

B. Differential electrode structure

PMUTs with multiple electrodes for differential driving or sensing [9-10] have been studied to improve PMUT sensitivity and coupling efficiency. Cross-section and top views of a differential PMUT with two top electrodes and one common bottom electrode are shown in Figure 2. If we assume the boundary between the inner and outer electrodes is optimal at a normalized radius of \( r = \sqrt{2}/2 \) and there is no gap between them, the transformer ratio of the inner and outer electrodes, \( \eta_{dt} \) and \( \eta_{do} \), will have the same magnitude with opposite sign:

\[ \eta_{dt} = -\eta_{do} = \eta_t \]  

(8)

Therefore, the total transformer ratio is \( 2\eta_t \) for differential driving or receiving. In addition to doubling the sensitivity, a differential PMUT has greater electromechanical coupling coefficient because the area used for electromechanical coupling is doubled. For example, in transmit mode, half the input voltage magnitude, \( V/2 \), is needed to achieve the same output pressure. To show that this is accomplished using half the electrical energy, we start with \( E_1 = CV^2/2 \), the electrical energy stored on a single-electrode PMUT driven with a voltage \( V \). For a dual-electrode PMUT driven with \( V/2 \), the inner and outer electrodes have the same capacitance and the total stored electrical energy is half the value of the single-electrode PMUT:

\[ E_2 = C(V/2)^2/2 + C(V/2)^2/2 = E_1/2 \]  

(9)

C. Series Transduction

One drawback to the differential PMUT design is that it requires at least 3 electrical contacts, complicating the layout of interconnect and bond-pads for large PMUT arrays. To increase the coupling coefficient but avoid increasing the number of PMUT contacts, we propose a PMUT with series transduction as shown in Figure 3. The electrodes, a center electrode surrounded by a ring electrode, are identical to those used in the differential PMUT. Unlike a differential PMUT, where the two top electrodes are referenced to a common ground electrode, the only the two top electrodes are used. The piezoelectric transduction is based on two series piezoelectric capacitors formed between the two top electrodes (TE-1 and TE-2) and a floating bottom electrode, effectively putting the piezoelectric transducers in series.

In transmit mode, voltage applied across TE-1 and TE-2 results in opposite electric fields, creating opposite curvature beneath these electrodes and exciting the PMUT’s fundamental vibration mode. If voltage \( V \) is applied on electrode TE-1 and TE-2 is grounded, the floating bottom electrode will have potential \( V/2 \). While only half the potential is applied between
each electrode (TE-1 or TE-2) and the bottom electrode, the total transformer ratio is equal to that of a traditional single-electrode PMUT. As a result, the displacement per volt is unchanged but a number of other advantages arise, the most obvious of which is that the maximum displacement is doubled in PMUTs which are limited by the breakdown electric field of the piezoelectric layer. In addition, the transducer’s electrical capacitance is halved and therefore half the current is needed to achieve a given vibration amplitude, which decreases the difficulty of pulser circuit design to provide high frequency and high voltage pulses. Furthermore, the input power is halved, reflecting the design’s doubled electromechanical coupling coefficient $k_t^2$. In receive mode, because the same amount of charge is generated as for the traditional PMUT, but the capacitance is halved, both the coupling coefficient and receiving sensitivity are doubled. Reduced capacitance is also helpful to reduce the noise gain of the receiving amplifier, leading to increased signal-to-noise ratio (SNR). Finally, fabrication can be simplified because the bottom electrode layer need not be patterned and connected to bond pads. Note that if there are multiple PMUTs on the same die, the bottom electrode layer of each PMUT must be separated to reduce cross-talk.

III. DEVICE CHARACTERIZATION

A. Characterization in Mechanical Domain

PMUTs with 50 µm diameter were fabricated via a simple cavity-SOI process [11]. The PMUT consists of a sputtered 1.1 µm thick PZT layer deposited on a 2.5 µm thick single-crystal Si passive elastic layer. The bottom and top electrodes are composed of 100 nm thick Pt and 150 nm Al respectively. The PZT layer was patterned by wet etching in order to access the bottom electrode. The displacement frequency responses of several PMUTs were measured in air via a laser Doppler vibrometer (LDV, OFV 512 and OFV 2700, Polytec) in conjunction with a network analyzer (E5061B, Agilent Technologies). Both types of devices were measured after poling with 20V DC between the top and bottom electrodes for 1 minute at room temperature and a small-signal driving source (~10dBm) was applied to avoid depoling the PZT film. Figure 4 shows the measured frequency response of both a traditional PMUT driven using the top and bottom electrodes (TE-BE) and the proposed series-transduction PMUT driven through two top electrodes (TE-TE). Both have ~12 MHz resonant frequency in air. The peak displacement per volt of the series-transduction PMUT is 130 nm/V, slightly lower than that of the traditional PMUT with a single top electrode, 160 nm/V. The small difference is caused by imperfect layout of the inner and outer electrodes due to manufacturing limitations which require a 3 µm wide gap between electrodes.

B. Characterization in Electrical Domain

The electrical impedance spectrum of each PMUT was measured using a Network Analyzer and transimpedance amplifier (TIA), as shown in Figure 5. Measured electrical impedance results are shown in Figure 6. The PMUT response is capacitive, with the impedance magnitude decreasing approximately linearly with frequency except near the PMUT’s mechanical motional resonance. At 11.6 MHz, the impedance magnitude of the traditional and series-transduction PMUTs are 86.6 Ω and 176 Ω, respectively. This result indicates that the capacitance of the proposed PMUT is ~78 pF, about half that of the traditional PMUT, 158pF, in agreement with the analysis presented above.

The electromechanical coupling coefficient can be extracted from the impedance measurement using:

$$k_t^2 = \frac{\pi^2 f_r}{4 f_a} \frac{f_a - f_r}{f_a}$$

Figure 3: Cross-section of the proposed PMUT with series transduction.

Figure 4: Measured displacement frequency response for a traditional PMUT and the proposed series-transduction PMUT with the same 50 µm diameter.
where $f_a$ and $f_r$ are the anti-resonant frequency and resonant frequency, respectively. However, this equation yields a poor estimate for $k_t^2$ when the parasitic capacitance of the measurement setup is large relative to the PMUT capacitance. As shown in Figure 6, the traditional PMUT has $f_a = 12.18$ MHz, and $f_r = 12.15$ MHz; the series-transduction PMUT has $f_a = 12.21$ MHz and resonant frequency $12.15$ MHz. Using equation (10), $k_t^2$ is calculated to be 0.6% and 1.2% for the traditional and series-transduction PMUTs, respectively. However, the motional capacitance of the PMUT, $C_m$, is relatively small in comparison to the PMUT’s total electrical capacitance, $C_0$ which is the sum of the capacitance between PMUT’s top and bottom electrodes, $C_e$, and the stray capacitance in the test setup, $C_p$. Using these values and neglecting $C_p$ we solve for $k_t^2$ via:

$$k_t^2 = \frac{\pi^2 c_m}{8 c_0} \left(1 - \frac{c_m}{c_0}\right)$$  \hspace{1cm} (11)

Equation (11) yields $k_t^2 \sim 15.2\%$ and $\sim 25.2\%$ for the traditional and series transduction PMUTs, respectively, in agreement with the basic device models.

IV. CONCLUSION

This paper presented a new electrode configuration for piezoelectric micromachined ultrasonic transducers (PMUTs) with increased electromechanical coupling coefficient ($k_t^2$). While the peak displacement per volt is slightly lower than that of the single-electrode design due to imperfect electrode layout, electrical impedance measurements confirm that the capacitance is halved (from 158 pF to 78 pF), resulting in $k_t^2$ increasing from 15.2% to 25.2% after calibration to remove parasitic capacitance caused by bond pads. Furthermore, the reduced PMUT capacitance can reduce the difficulty of transmit pulser circuit design and reduce noise, therefore increasing the overall SNR.

ACKNOWLEDGMENT

The authors thank the UC Berkeley Marvell Nanofabrication Laboratory for device fabrication, and Berkeley Sensor and Actuator Center (BSAC) Industrial Members for financial support.

REFERENCES