Abstract—In this paper, we report an air-coupled piezoelectric ultrasonic micromachined transducer (PMUT) using a lead-zirconate-titanate (PZT) piezoelectric layer. A dc bias voltage applied to the PZT film controls its polarization and intrinsic stress, tuning the frequencies of two closely-spaced resonance modes of the rectangular shaped PMUT. At an optimal bias voltage of approximately 5 V, the modes nearly overlap at 230 kHz, increasing the bandwidth by a factor of 8 relative to the zero dc biased state. Measurements of the electromechanical coupling coefficient of the PZT film show that it is maximized at 5-6 V, agreeing with device performance experiments. Acoustic transmission and reception were demonstrated using two identical PMUTs by adding the optimum dc bias of 6 V to the 1.4 V peak-to-peak ac voltage which is maximum within the linear displacement regime. The signal detectable range of the transmit and receive measurement with optimum dc bias tuning was 4 cm to 19 cm in air.

Index Terms—Microelectromechanical devices, piezoelectric transducers, ultrasonic, PMUT, PZT, dc bias.

I. INTRODUCTION

ULTRASONIC transducers are widely used in various applications including medical imaging, nondestructive evaluation, object recognition, and range-finding [1], [2]. Based on MEMS technology, micromachined ultrasonic transducers (MUTs) have many advantages over conventional ultrasonic transducers such as miniature size, low cost, low power consumption, wafer-scale fabrication, ability to create 1-D and 2-D array structures, and easy integration with supporting electronics.

The capacitive-MUT (CMUT) is one of the best-known MUTs. In a CMUT, the electromechanical coupling from input voltage to output pressure depends on the bias voltage and the inverse square of the capacitor gap. Therefore, CMUTs achieve high electromechanical coupling when the capacitor gap is small, on the order of 100 nm to 200 nm. However, air-coupled operation requires much larger gaps, on the order of 1 to 3 microns, in order to achieve sufficient sound pressure output. Maintaining high electromechanical coupling in an air-coupled CMUT therefore typically requires high bias voltages of 150 V or more [3]. For example, recent work on air-coupled CMUTs with perforated membranes achieved improved performance and bandwidth by biasing at 250 V [4].

In contrast, piezoelectric-MUTs (PMUTs) [5] can be utilized without high bias voltages, resulting in simpler electronic interfaces. A typical PMUT device vibrates in a flexural mode to emit ultrasound into the surrounding environment, air or fluid. Taking advantage of improved availability of high-quality piezoelectric films, PMUTs have recently been demonstrated for many applications, for instance, range-finding [6], low-power 3-D ultrasonic imaging [7], and ultrasonic fingerprint sensors [8]. Among many piezoelectric MEMS devices, lead-zirconate-titanate (PZT) and aluminum nitride (AlN) are the two most commonly-used piezoelectric materials [9], [10]. While the low dielectric constant of AlN makes it the best material for receiving ultrasound, PZT’s much higher piezoelectric coefficient makes it the best material for transmitting ultrasound. Here, we study PMUTs fabricated from thin-film PZT with the intent to reduce the required transmit voltage from ~30 V [7] to below 10 V, reducing the cost and complexity of the supporting electronics.

A second goal of this work is to increase the PMUT’s bandwidth. In pulse-echo range-finding, the transducer’s bandwidth contributes to several important performance parameters: (1) the minimum duration of the transmitted pulse which in turn determines the minimum measurement range (since the transducer cannot receive while it is transmitting); (2) the axial resolution, which is the minimum separation between two resolved objects; and (3) the RMS range noise [7]. In addition, transducers with wide bandwidth enable more sophisticated signal processing schemes such as pulse encoding (e.g. chirped transmissions).

Fluid-coupled PMUTs used at high resonance frequencies (>5 MHz) often have high bandwidth (>30%) because fluid damping is high compared to air damping. Additionally, the higher speed of sound in fluid means that the size of a
TABLE I

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
<th>Approximate Thickness [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IrO₂</td>
<td>290 [16]</td>
<td>100</td>
</tr>
<tr>
<td>PZT 52/48</td>
<td>60.5 [17]</td>
<td>475</td>
</tr>
<tr>
<td>Pt</td>
<td>182 [17]</td>
<td>100</td>
</tr>
<tr>
<td>TiO₂</td>
<td>250 [18]</td>
<td>30</td>
</tr>
<tr>
<td>SiO₂</td>
<td>72.3 [17]</td>
<td>500</td>
</tr>
</tbody>
</table>

Fluid-coupled PMUTs are usually large relative to the transmitted wavelength. These factors allow efficient coupling in immersed PMUTs [11], [12]. On the contrary, PMUTs operating in air require lower frequencies (<1 MHz) and are usually smaller than the wavelength (λ = 1.9 mm at 175 kHz), resulting in poor coupling and low bandwidth (1%–5%) [13]. An air-coupled PMUT with 10% bandwidth was reported [14], but required a Helmholtz resonant tube etched into the backside of MUT to achieve this result. Another method to extend the bandwidth is to use multiple transducers with closely-spaced natural frequencies so that the composite bandwidth is the sum of the individual transducer bandwidths; this approach has been demonstrated with an array that contains five different membranes of slightly different dimensions [15]. Here, we use a rectangular membrane design and, through appropriate selection of the length-to-width ratio, demonstrate that two vibration modes with closely-spaced resonance frequencies can be achieved in a single membrane [2]. Because these modes have different sensitivities to piezoelectric stress, we are able to tune the frequency spacing of the two modes by adjusting a dc bias voltage applied across the PZT layer. At the optimum bias point, a 12% bandwidth is achieved without the need for a Helmholtz resonator.

II. PMUT DESIGN

An optical top view image, a schematic top view and a schematic cross-section of a 1200 μm × 230 μm rectangular shaped PMUT is shown in Fig. 1(a)-(c). Table 1 lists the elastic modulus and layer thicknesses of the materials in the device [16]–[18]. Note that only the inner top electrodes were used in this work.

A. Fabrication

A simplified fabrication process flow is shown in Fig. 2. The fabrication process starts by growing a 500 nm layer of SiO₂ on a silicon wafer via thermal oxidation. Titanium is sputtered with a thickness of 30 nm and oxidized in a furnace to create titanium dioxide which creates a good template for the subsequently sputtered, (111)-textured platinum electrode with a thickness of 100 nm [19]. The oriented platinum forms a templating layer for a 475 nm thick, chemically-deposited, (001)-textured PZT film with a Zr/Ti ratio of 52/48 [20]. The PZT is then capping with a 100 nm thick iridium oxide electrode that is sputter deposited and furnace annealed in oxygen at 650 °C for 30 minutes. Next, the actuator stack is patterned using three argon ion milling steps. In the first etch, the iridium oxide is patterned to define the top electrode of the device. The second etch removes the PZT and bottom platinum from the field, stopping on the silicon dioxide layer. The bottom electrode is accessed by a third ion-mill step followed by a PZT wet-etch using a combination of HCl:HF:H₂O (120:1:240) to remove any residual PZT. The wafers are annealed at 500°C in an oxygen environment to mitigate any physical etch and hydrogen damage from the ion milling steps.

With the actuator stack patterned, a tri-layer Au/Pt/Cr (730nm/20nm/20nm) is deposited using electron beam evaporation and patterned via liftoff, Fig. 2(b). This gold layer is used for contact pads for electrical probe testing. The silicon dioxide layer is then patterned by reactive ion etching to define
the etch holes for release. Next, a sacrificial photoresist layer is defined, and a thick gold layer is deposited via electron beam evaporation and liftoff. This gold layer bridges from the top electrode to the metal interconnect on the silicon dioxide in the field without shorting the top and bottom electrodes. The sacrificial photoresist layer is removed with an oxygen plasma to form the Au air bridge. Finally, the wafer is exposed to XeF$_2$, which isotropically etches the underlying silicon, releasing the device.

Fig. 3 shows SEM images of the top view and cross-section of the PMUT following XeF$_2$ release. As shown in the figure, the top electrode is divided into two sections, separated by etch-holes that perforate through the PZT/SiO$_2$ layer. The total 3 μm thick gold layer at the left and right edge of the PMUT stiffens these edges such that variations in the Si undercut in the XeF$_2$ etch have minimal effect on the PMUT’s resonance frequency [10]. Small etch holes were designed along the center of the membrane to enable the membrane to be released through a front side etch, since this process allows closer spacing of PMUTs than processes that require a through-wafer etch [21], [22]. As demonstrated in recent work on air-coupled CMUTs, small perforations in the MUT membrane have a negligible effect on the output pressure [23].

B. PZT Film Characterization

The dielectric constant, $\varepsilon_{33}$, and corresponding loss tangent, tan $\delta$, of the PZT film were measured as a function of bias voltage over a range from 0V to 10 V, Fig. 4(a). The transverse thin-film piezoelectric coefficient $e_{31,f}$ and dielectric constant $\varepsilon_{33}$ are compared in Fig. 4(b). The laser Doppler vibrometer (LDV) was used to measure the deflection of a cantilever beam under varying bias voltage. The change in PZT stress that would be necessary to create the deflection-bias profile was extracted, and then $e_{31,f}$ was determined by differentiating with respect to the electric field. Note that the film reaches maximum piezoelectric coefficient at 3 V, corresponding to an electric field of 63 kV/cm. At voltages above 5V the piezoelectric coefficient is seen to decrease. The dielectric constant is maximum at 1 V, after which it decreases steadily with voltage. The voltage-dependence of the dielectric constant, dielectric loss, and piezoelectric coefficient is inherent to all ferroelectric materials and is related to the polarization reversal mechanisms within the ferroelectric material. In particular, $e_{31,f}$ diminishes as the voltage is increased above 3V. While this reduction is due to many factors, one important factor is that the piezoelectric coefficient is proportional to the dielectric constant. Once the film is fully polarized, reductions in the dielectric constant tend to reduce the piezoelectric coefficients. [24], [25]. As the nonlinear relationship with voltage is unique to ferroelectric materials such as PZT, non-ferroelectric piezoelectric materials such as AlN will not exhibit these characteristics. Moreover, the ability to tune the bandwidth by modulating the stress in the piezoelectric films through bias voltage will be limited.

A figure of merit (FOM) for transducer performance is the transverse electromechanical coupling coefficient $k_{t,w}^2$, which is proportional to $(e_{31,f})^2/\varepsilon_{33} [\text{GPa}]$ [26]. The FOM, plotted in Fig. 4(c), reaches a maximum of 8 GPa at 6 V, and is roughly constant over the range from 5 V to 8 V. The peak FOM does not occur at the voltage that maximizes the piezoelectric coefficient. Instead, it peaks at a much higher voltage where the dielectric constant is lower. Note that the values in Fig. 4 were collected from a particular wafer which
Current-voltage (I-V) measurements were conducted to identify the breakdown voltage of the PZT film. The breakdown voltage was measured to be 35 V, corresponding to a breakdown field of 760 kV/cm as Fig. 5 shows. The inset of Fig. 5 shows that, when the applied voltage reaches the breakdown, the Au bridge interconnecting top electrode and the probing pad collapsed.

The static shape of the PMUT membrane was measured using a Wyko optical profilometer system. The cross-section height profile across the width of the rectangular PMUT membrane is shown in Fig. 6, where the height at SiO₂ surface is set to zero. At 0 V bias, the center of the membrane is deflected 3.6 μm above the membrane anchors due to the large residual stress gradient through the composite stack [27], [28]. The membrane’s curvature is reduced as the applied bias voltage is increased and at +10 V the center of the membrane moves downwards by approximately 1.6 μm relative to the unbiased state.

The frequency response of the PMUT in air was measured via LDV showing the presence of two vibration modes with closely spaced natural frequencies near 180 kHz. The LDV measurements were done at a single point of the membrane indicated on Fig. 1(b). The measurement location was chosen on the top electrode surface to avoid the etching holes and the transparent SiO₂ surface. A dc bias voltage applied to pole the PZT layer creates in-plane piezoelectric stress that enables the frequencies of the two modes to be tuned. As the dc bias voltage was varied between ±10 V, a significant change in the resonant frequencies, displacement sensitivities, and 3-dB bandwidth was clearly observed for the two resonance modes. In Fig. 7, the frequency response of the two resonance modes with dc bias voltages of 0 V, +6 V, and +10 V respectively are shown. The FEM-simulated mode shapes of the two modes ((1,1) mode and (1,3) mode) are shown in the inset. The two modes independently have 2.4 kHz bandwidth with displacement sensitivity of approximately 2000 nm/V with small ac voltage (−10 dBm) and without any dc bias voltage. As a result of increasing the dc bias to +6 V, the highest 3-dB bandwidth of 20.3 kHz with displacement sensitivity of approximately 2000 nm/V was observed. The bias voltage of 6 V coincides with the value when the $k^2$ is maximized, Fig. 4(b).

For a rectangular membrane clamped at all four boundaries, the stress-free resonance frequency of the $(n, m)$ mode $f_{nm}$ can be calculated from [29] and [30]:

$$f_{nm} = \frac{\pi t}{4} \sqrt{\frac{E}{6 (1 - \nu^2) \rho}} \left[ \left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 \right]$$

where $t$ is the total membrane thickness, $E$, $\nu$, and $\rho$ are the average Young’s modulus, Poisson’s ratio and mass density, and $a$, $b$ are the length and width of the membrane ($a \gg b$). Here, we used $a = 1200 \mu m$, $b = 230 \mu m$ resulting in $f_{11} = 121$ kHz and $f_{13} = 136$ kHz. FEM simulation was used to increase the accuracy by modeling the precise structure, resulting in stress-free frequencies $f_{11} = 134$ kHz and $f_{13} = 155$ kHz, corresponding to the mode.
shapes shown in the inset of Fig. 7. Because residual stress has a strong effect on the resonant frequencies of a thin membrane (~1 μm thick), simulations were also performed using estimates of the residual stresses in the membrane layers: −300 MPa (compressive) in the thermal SiO$_2$ layer, 700 MPa and 200 MPa (tensile) in the Pt and PZT layers [27], [28]. Under the above stressed condition, the FEM-simulated natural frequencies increased to $f_{11} = 175$ kHz and $f_{13} = 194$ kHz, close to the experimentally-observed frequencies. Note that, because the PZT and SiO$_2$ layers have nearly equal thickness, the contributions of their stresses nearly cancel, and the dominant effect is residual stress in the 0.1 μm Pt electrode. We also simulated the stress in the PZT layer required to achieve the 60 kHz frequency shift observed in dc bias tuning experiments— a 60 kHz increase in the resonant frequency was observed when the PZT stress was increased by 40 MPa in simulation, comparable to the 45 MPa value predicted using the maximum value of the piezoelectric coefficient ($e_{31, f_{\text{max}}} = 7.5$ C/m$^2$) multiplied by the electric field at 3V bias (60 kV/cm).

Fig. 8(a), (b) shows the dependence of the PMUT resonant frequency and displacement sensitivity when tuning the dc bias voltage between −10 V and +10 V. Color-filled triangles correspond to the first resonance mode and open triangles correspond to the second mode observed. In addition, upward pointing triangles present the points when sweeping up from −10 V to +10 V, while downward pointing triangles present the points when sweeping down from +10 V to −10 V.

The frequencies of the two modes are nearly overlapping with certain dc bias voltages applied, especially −5 V / +6 V while increasing and −5 V / +5 V while decreasing. From the same measurement results, the dependence of the 3-dB bandwidth on dc bias was analyzed and is shown in Fig. 8(c). Wide 3-dB bandwidth above 20 kHz was achieved with dc bias near ±5 V when the two closely-spaced modes have overlapping bandwidths. For other dc bias voltages, the 3-dB bandwidth was only few kHz to 10 kHz since the two resonance peaks were separated and only the first resonance mode’s bandwidth was taken into account. Compared to the non-biased condition, displacement sensitivity increased by a factor of 2.5 and the 3-dB bandwidth increased by a factor of 8 through dc bias tuning.

B. Time Response

Increasing the bandwidth by overlapping multiple modes allows the transmission time to be shorter and hence reduces the minimum measurable range and improves the axial resolution in time-of-flight (ToF) measurements [2], [15]. At the bias conditions where the bandwidth is maximum, the PMUT is capable of transmitting shorter pulses for ToF measurements, where the speed of the wave, ultrasound in this case, determines the distance to the target. The time response in air was demonstrated from pulsed ring-down measurement via LDV. The PMUT was excited using a function generator with a 20-cycle square wave at the resonant frequency for the two different dc bias conditions. The drive voltage amplitude was 200 mVpp for 0 Vdc and 50 mVpp for +5 Vdc to produce similar displacement. In both cases, unipolar drive voltages were used to prevent repoling of the PZT thin film. Fig. 9(a) shows the driving voltage and the PMUT time-response measured at zero dc bias using the resonant frequency of 185 kHz. Fig. 9(b) shows the optimum tuning result with +5 V dc bias using the resonant frequency of 240 kHz. The frequency of the driving pulse train was increased from 185 kHz to 240 kHz because the resonance frequency of the PMUT shifted due to the dc bias applied, as shown in Fig. 8(a). Comparing the two time-response plots, the decay time constant $\tau$ significantly decreases from 0.28 ms to 0.05 ms.

The pulse transmissions were simulated with a model of two second-order systems in series, corresponding to the two resonance modes. This model was chosen based on an empirical fit of the measured frequency response at the various
Fig. 9. Experimentally measured pulsed-response via LDV. The PMUT device was excited at the resonant frequencies corresponding to (a) 0 V dc bias and (b) +5 V dc bias, demonstrating five-fold reduction of the decay time constant.

Fig. 10. Simulated pulse transmission by a model with a cascaded 2nd-order system representing each of the two resonance modes measured via LDV at (a) 0 Vdc bias and (b) +5 Vdc bias matching the experimental results in Fig. 9.

bias voltages, in order to validate that the observed pulse-input time-response was consistent with the observed changes in the frequency response. The normalized transfer function of the cascaded second-order systems can be expressed as

$$ TF(s) = \frac{\omega_2^4}{s^2 + \frac{\omega_1}{Q_1} s + \omega_1^2} \times \frac{\omega_2^4}{s^2 + \frac{\omega_2}{Q_2} s + \omega_2^2} \tag{2} $$

where \(\omega_1, \omega_2\) are the two resonant frequencies (in rad/s) and \(Q_1, Q_2\) are the corresponding quality factors. Using the quality factors and resonant frequencies measured in the frequency-domain LDV measurements (Fig. 7), the PMUT time-response was simulated using Eq. (2), with the results shown in Fig. 10. The input pulse waveforms were replicated from the measurements except both amplitudes were normalized to 1. The decay time-constant of the simulated pulse transmission was 0.3 ms for 0 V dc bias and 0.05 ms for +5 V dc bias, which coincide with the experimental results.

The approximately five-fold reduction in decay time is equal to the increase in the bandwidth, from roughly 4 kHz at 0 V bias, to 20 kHz at +5 V bias. The minimum pulse transmission time is approximately \(4r = 0.2\) ms. In pulse-echo measurements, the first echoes that can be received must arrive later than the end of pulse transmission. Therefore, this time defines the minimum range for pulse-echo measurements, \(r_{min} = 4rc/2 = 3.4\) cm at +5 V bias, compared to a minimum range of 19 cm at 0 V bias.

C. Maximum Linear Operating Range

Ideally, using a short and high-power pulse for the transmit signal would give the highest ultrasound output. However, as reported previously, a fully-clamped membrane shows an undesired limitation in dynamic range due to nonlinearity at high drive voltages [6], [7]. At the limit of the linear operating range, increasing the voltage no longer produces a proportionate increase in ultrasound output. Fig. 11 shows the measured displacement amplitude with various excitation voltages for the 6 Vdc biased PMUT, with the inset showing some of the pulsed time-responses. The displacement scales linearly with voltage up to a maximum displacement amplitude of 1.2 \(\mu\)m at 1.4 V peak-to-peak (Vpp) ac voltage. Considering this result, experiments from the next section are using 1.4 Vpp for driving ac voltage.

D. Distance Sensor

To demonstrate the range-finding concept [31], [32], pulsed transmit and receive measurements were performed using two identical PMUT devices, each wire-bonded to a printed circuit board (PCB). The basic experimental setup and the result are shown in Fig. 12. The receive PMUT was placed 4 cm apart from the transmit PMUT within an acrylic tube to reduce the noise from the surrounding environment, Fig. 12(a). The tube was lined with an acoustically-absorbing foam in order to
prevent reflections from the sidewall. A burst signal was sent from a function generator to the transmit PMUT, producing an ultrasound wave which propagated acoustically to the receive PMUT which converted the ultrasound pressure to a charge output. The charge was detected using a low-noise charge amplifier (gain 10 V/pC, noise $90 \times 10^{-21}$ C/$\sqrt{\text{Hz}}$) connected to the receive PMUT and the out-of-band noise was filtered out by post processing.

Applying 6 V dc bias in addition to 1.4 Vpp drive voltage at resonance frequency of 230 kHz for 5 pulse transmission was successfully detected at the receive PMUT, Fig. 12(b). The first ultrasound burst was received at $t_{rx} = 0.116$ ms which matches the travel distance of 343 m/s × $t_{rx} = 3.98$ cm. The detected time of the second echo was three times of $t_{rx}$ agreeing with the expected travel distance. The estimated bandwidth calculated from the rise time $t_{rise} = 0.014$ [ms] was $\text{BW} = 0.35t_{rise} = 25$ [kHz] similar to measured value via LDV shown in Fig. 7. The ringdown time $t_{ringdown} = 0.05$ [ms] was equivalent to the transmission decay time in Fig. 9(b).

E. Path Loss and Free-Space Measurements

The ultrasonic wave spreads and attenuates while traveling through the air. Because it is small relative to the acoustic wavelength, the PMUT is a nearly-omnidirectional radiator, causing a linear spreading of pressure with distance [6]. In addition, at 230 kHz, ultrasound is significantly absorbed by air [33]. From the two factors of spreading and absorption loss, the ratio of the received pressure $p_{rx}$ to the transmitted pressure $p_{tx}$ is

$$G = \frac{p_{rx}}{p_{tx}} = G_{ac} \frac{a}{4D} \cdot 10^{-\alpha D}$$

where $G_{ac}$ is the acoustic gain (=1), $a$ is the effective membrane length, $D$ is the distance, $\alpha = 3.61 \times 10^{-5} f - 0.985$ [dB/m] is the attenuation coefficient, and $f$ is the frequency of the ultrasound wave. The attenuation coefficient $\alpha$ increases with frequency and humidity [34]. Under the condition of 60% relative humidity and room temperature, $\alpha$ is 7.3 dB/m at 230 kHz. At 20 cm distance, for example, the spreading term is $-77$ dB and absorption loss term is $-6$ dB, generating total attenuation $G$ of $-83$ dB.

Fig. 13 shows the measured SNR for free-space transmit-receive measurements conducted between two PMUTs separated by 4 cm to 19 cm. The PMUTs were tuned optimally to 6 V dc bias at the 230 kHz operating frequency. The theoretical limit of the detection of 12 dB SNR was nearly 45 cm, however, the maximum range measured was 19 cm due to the limitation in the experimental setup. The measurements in this section were conducted in free-space without any foams to absorb the surrounding noise, resulting in increasing the path-loss and noise detected at the receive PMUT. On the other hand, the minimum detectable range was 4 cm in this experiment thanks to the wide bandwidth and fast time response achieved through dc bias tuning. For comparison, the zero biased PMUT could not detect signal at any range because of the overlap of the transmission signal feedthrough and the received signal at short range (less than 10 cm), while at further ranges, the signal was too small to detect.

IV. CONCLUSION

We have presented a method to increase bandwidth and reduce transmission time of air-coupled PZT PMUTs. Through dc bias tuning at ±5 V, where the FOM of electromechanical coupling coefficient, $(e_{31,f})^2/\varepsilon_0\varepsilon_{33}$, is maximum, two adjacent resonance modes almost overlapped, resulting in
significantly improved displacement sensitivity and 3-dB bandwidth compared to zero dc bias condition. Consequently, the time-response measurement results showed that the decay time constant was reduced nearly five-fold by adding +5 V dc bias to the driving voltage. An optimum tuning of the dc bias also increased the transmit and receive sensitivity, allowing in-air transmit and receive measurement to be performed. The proposed dc bias tuning of the PMUT achieving wideband and short pulse demonstrated a good potential to improve the minimum range and axial resolution for in-air range-finding applications.

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