ABSTRACT
Piezoelectric micro-machined ultrasonic transducers (pMUTs) for air-coupled ultrasound applications were fabricated using aluminum nitride (AlN) as the active piezoelectric material. Earlier pMUTs based on a fully clamped membrane design suffered from high sensitivity to residual stress, causing large variations in the operating frequency, and have a reduced dynamic range due to nonlinearity at large drive voltages. Here we evaluate a new design based on a membrane that is supported by three flexures and a thin oxide layer, aiming to release residual stress, extend the mechanical dynamic range, and improve the acoustic coupling. The acoustic performance of this flexurally suspended design is compared with a fully clamped one, showing a piston-like mode shape, which translates to improved output sound pressure.

KEYWORDS
Aluminum nitride, ultrasound transducers, piezoelectric MEMS.

INTRODUCTION
Piezoelectric MEMS devices have been generating growing interest for future innovations in inertial sensors for navigation, micro-actuators for RF applications, gyroscopes and Lamb wave resonators. In particular, aluminum nitride (AlN) based bulk acoustic resonators (FBAR) have already been successfully commercialized. AlN is a promising piezoelectric material [1-4]; although the piezoelectric coefficients are smaller than that of ZnO [5] or PZT [6,7], its other material properties (e.g. high elastic modulus, low density and low dielectric constant) and post-CMOS compatible fabrication make it ideal for many applications.

Piezoelectric micromachined ultrasonic transducers (pMUTs) arise as an interesting device for acoustic-based applications such as in medical imaging, nondestructive evaluation and proximity detection. In comparison to capacitive micromachined ultrasonic transducers (CMUTs) [8], pMUTs have the advantages that they do not require a DC polarization voltage, which can exceed 100V in CMUTs, and their fabrication is simple, since they do not require a small capacitive air gap beneath the transducer.

Here we present pMUTs fabricated using AlN. The pMUT design relies on a partially released membrane [5,6] supported by three flexures and a thin oxide layer. Previously reported pMUT devices [9] based on a fully-clamped membrane showed an undesired reduced dynamic range due to nonlinearity at high drive voltages. The new flexurally-suspended design is evaluated in comparison to the earlier fully-clamped design, showing a piston-like displacement that results in a higher sound pressure output and improved mechanical linear displacement limit.

MICRO-FABRICATION
Figure 1 shows a schematic with the four main steps of the fabrication process. Fabrication started with the deposition of 1 µm thick PECVD SiO₂ layer on a Si substrate, followed by the bottom electrode metallization (15 nm TiW/40 nm Pt) and a 1 µm sputtered 002-oriented AlN layer. The 0.2 µm Al top electrode was patterned by a lift-off process (Figure 1-A), after which contacts to the Pt bottom electrode were defined by wet etching the AlN layer (Figure 1-B). The membrane structure was defined by wet etching the AlN, and reactive ion etch (RIE — CF₄ plasma) of the TiW/Pt and SiO₂ layers. The SiO₂ was not fully etched; instead, 0.02 µm of SiO₂ was left to ensure the two sides of the membrane are not air coupled, which could lead to reduced output pressure (Figure 1-C). Finally, the wafer backside was patterned and the Si trenches defined by deep reactive ion etch (DRIE), stopping on the thin SiO₂ layer and releasing the membrane (Figure 1-D).

Figure 1. pMUT fabrication steps: A = 0.2 µm Al top electrode definition by lift-off; B = Open via to bottom electrode by wet etching the AlN; C = Membrane definition by etching the AlN, Pt and SiO₂ layers; D = Final membrane release, Si DRIE backside etch.
The devices were wire-bonded to a PCB for testing. Peak-to-peak displacement was studied using a Laser Doppler Vibrometer (LDV, Polytec OFV 501/OFV 3001), and sound pressure output was characterized using a highly sensitive microphone [10].

RESULTS

Figure 2 shows a micrograph of one of the fabricated pMUT’s, taken before the final DRIE backside release step. Figure 3(a) plots the LDV displacement results for a pMUT with a 400 µm diameter membrane and a 275-µm top electrode, for several drive voltages. The resonance frequency (for low voltages) was 121.3 kHz, which matches the FEM model of this device. Nonlinear behavior was not observed for drive voltages up to 10 Vrms (displacement \(d > 1 \mu m\)), an important improvement when compared to a fully-clamped pMUT design previously studied in [9].

Figure 2. Optical picture of the fabricated pMUT, prior to the backside Si release etch. The membrane and the top electrode have diameters of 400 and 200 \(\mu m\), respectively. The three supporting flexures are 40×30 \(\mu m^2\).

Figure 3(b) compares the peak-to-peak displacement (at the reference resonance frequency) as a function of the drive voltage for both the flexurally-suspended and the fully-clamped design. Although the clamped design attains higher displacement for lower voltages, it rapidly exhibits nonlinear stiffening (onset of nonlinearity \(\sim 2 V_{\text{rms}}\), 0.45 \(\mu m\) displacement amplitude). On the other hand, the flexurally-suspended design exhibits an extremely linear voltage-displacement characteristic. This flexurally-suspended pMUT exceeds the clamped one, in terms of displacement, for drive voltages higher than 8 Vrms, as seen in Figure 3(b). The nonlinear displacement characteristic of the clamped design arises from displacement-induced tensile stress occurring at large deflection of the membrane, and is a common phenomenon observed in clamped-clamped MEMS structures. The flexurally suspended design more closely approximates the vibration behavior of a free disk and the displacement-induced tensile stress in the membrane is greatly reduced. In the clamped design, the apparent natural frequency (i.e. the frequency at which maximum displacement is achieved) increases with the drive voltage level, an effect that is nearly absent in response of the flexurally-suspended design, shown in Figure 3(a).

![Figure 3](image)

Figure 3. (a) Flexurally-suspended pMUT peak-to-peak displacement vs. drive voltage. \(f_n = 121.3\) kHz. (b) Maximum displacement vs. drive voltage for flexurally-suspended and fully-clamped designs.

In order to further understand the mechanical and acoustic behavior of the two designs, a study on the deflection modes of the membranes was performed. Using the LDV, the displacement profile was scanned and the mode-shape of the two structures was acquired. The result, displayed in Figure 4, shows that the flexurally-suspended pMUT has a piston-like mode-shape where the displacement is nearly uniform across the membrane surface. In contrast, the fully-clamped device has a Gaussian-like shape and achieves maximum displacement solely in the center of the membrane.

The pressure created on the axis by a moving circular piston, at a distance \(r\), is given by:

\[
P_{\text{rms}} = \frac{P_0 R_0}{\sqrt{2r}}
\]

\(P_0\) is the theoretical surface pressure given by \(P_0 = u_0 \rho_0 c_0\), where \(u_0\) is the velocity of the membrane, \(\rho_0\) the density of air and \(c_0\) the velocity of sound. \(R_0\) is
known as the Rayleigh distance and is a function of the wave number $k$ and the membrane radius $a$. Expression (1) becomes:

$$p_{rms} = \frac{u_0 p_c c_o ka^2}{2\sqrt{2}r}$$  \hspace{1cm} (2)

Expression (2) can easily be re-written in terms of displacement $d$ and frequency $f$:

$$p_{rms} = \frac{d p_c (2\pi f)^2 a^2}{2\sqrt{2}r}$$  \hspace{1cm} (3)

Figure 5 compares the measured sound pressure level (SPL) of the flexurally-suspended device and the clamped one, for the same peak displacement ($d = 0.3 \mu m$, measured in the center of the membrane), acquired at a distance of $r = 9.5 \text{ mm}$ to the microphone. The sound pressure is approximately two times higher for the flexurally-suspended device, as seen in Figure 5(a), corresponding to a sound pressure level (SPL) difference of 6 dB. The piston-like movement in the flexurally-suspended device is responsible for the improved acoustic performance of the pMUT.

Since the pMUTs from the two different designs have different resonance frequencies (flexurally suspended: $f_{n1} = 121.3 \text{ kHz}$ and the fully clamped: $f_{n2} = 169 \text{ kHz}$) and, as described in expression (3), the pressure $p_{rms}$ is proportional to $f_{n}^{2}$, the output pressure of the flexurally suspended device should be corrected by a factor of $(f_{n2}/f_{n1})^{2}$, for proper comparison. Based on this relationship, we can say that if the two different devices had identical resonant frequencies and were driven to the same displacement amplitude, the flexurally suspended device would see a total improvement of 9 dB SPL when compared with the clamped one.

In order to study the device directionality the pMUT was placed in a computer-controlled rotation stage next to the microphone. When measurements were performed with continuous-wave acoustic output, acoustic reflections create spurious intensity minima and maxima. To avoid these errors, the pMUT was driven with a short pulse (20 cycles, $f = 121.3 \text{ kHz}$, $r = 3.4 \text{ cm}$, 20 V $p_p$) and the main pressure wave was recorded using an oscilloscope. Figure 6 shows the burst acoustic signal acquired by the microphone, as seen in the oscilloscope. Figure 7 displays the directivity result, showing full 360-degree omni-directionality. An important observation is that the sound pressure generated by the backside of the device is slightly higher when compared with the frontside. We attribute this result to a concentration horn effect created by the silicon trench present in the backside of the pMUT device as seen in Figure 1-D.
CONCLUSIONS

AlN piezoelectric micromachined ultrasonic transducers based on a partially-suspended membrane were fabricated and characterized. The pMUT device, a circular membrane supported by three flexures and a thin oxide layer, shows an improved linear displacement limit for high drive voltages when compared with a previously fabricated clamped membrane. Acoustic characterization, performed with a highly sensitive microphone, shows that when driven to the same displacement amplitude, this device outputs a factor of two more acoustic pressure (6 dB) when compared with a clamped one. If the two different designs had similar frequencies, this improvement is expected to be of 9 dB (3 times higher pressure). The pMUT showed a maximum acoustic output of 87 dB SPL, as seen in figure 7 (backside), for a drive voltage of 20 Vpp, r = 3.4 cm from the surface of the device. The directivity of the pMUT as a transmitter was studied, showing a constant output pressure in the full 360 degree range.

REFERENCES:


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