CMOS-Compatible AlN Piezoelectric Micromachined Ultrasonic Transducers

Stefon Shelton, Mei-Lin Chan, Hyunkyu Park, David Horsley
Berkeley Sensor & Actuator Center
University of California, Davis
Davis, CA, USA

Bernhard Boser, Igor Izyumin, Richard Przybyla
Berkeley Sensor & Actuator Center
University of California
Berkeley, CA, USA

Tim Frey, Michael Judy, Kieran Nunan, Firas Sammoura, Ken Yang
Analog Devices, Inc.
Cambridge, MA, USA

Abstract—Piezoelectric micromachined ultrasonic transducers for air-coupled ultrasound applications were fabricated using aluminum nitride (AlN) as the active piezoelectric layer. The AlN is deposited via a low-temperature sputtering process that is compatible with deposition on metalized CMOS wafers. An analytical model describing the electromechanical response is presented and compared with experimental measurements. The membrane deflection was measured to be 210 nm when excited at the 220 kHz resonant frequency using a 1Vpp input voltage.

Keywords—microelectromechanical devices; piezoelectric transducers; acoustic devices.

I. INTRODUCTION

Ultrasonic transducers have a wide variety of applications in medical imaging, nondestructive evaluation, ranging and proximity detection. Conventional ultrasonic transducer technology is largely based on bulk piezoelectric ceramic materials which suffer from poor acoustic coupling to air and are expensive to machine into two-dimensional (2D) transducer arrays. In comparison, micromachined ultrasonic transducers (MUTs) are compliant membrane structures which can be designed for good coupling to air and liquids and have the advantage that they are fabricated using integrated circuit (IC) manufacturing technology, allowing compact 2D arrays to be realized and offering the potential for integration with signal processing electronics.

Here we describe piezoelectric micromachined ultrasonic transducers (pMUTs) fabricated using aluminum nitride (AlN). Relative to capacitive micromachined ultrasonic transducers (cMUTs), pMUTs have lower electromechanical coupling but do not need the high polarization voltages (approaching 1000V) and small capacitive gaps required by cMUTs [1]. There is a long history of research on piezoelectric microelectromechanical systems (MEMS) including pMUTs composed of zinc oxide (ZnO) [2] and lead zirconate titanate (PZT) [3-6]. However, with the exception of ink-jet print-heads, piezoelectric materials have seen little use in commercial MEMS devices until the recent success of AlN thin-film bulk acoustic wave RF filters.

AlN is attractive because it is compatible with standard CMOS technology, allowing monolithic integration of MEMS transducers and circuitry. Although the integration of ZnO MEMS devices with circuitry has been successfully demonstrated [7], ZnO films are higher in conductivity than AlN (resulting in power loss) and the fact that Zn is a fast-diffusing ion may result pose contamination issues for CMOS manufacturing [8]. In comparison with PZT, the lower piezoelectric coefficients of AlN are mitigated by a significantly reduced dielectric constant (e.g. $\varepsilon_{31,f} = -1.0 \text{ C/m}^2$ and $\varepsilon_{33,f} = 10.7$ for AlN versus $\varepsilon_{31,f} = -9.6 \text{ C/m}^2$ and $\varepsilon_{33,f} = 650-1300$ for PZT [9]). The reduced capacitance of AlN PMUTs in comparison with earlier PZT pMUTs can result in improved signal-to-noise ratio (SNR) but implies a significantly higher sensitivity to parasitic capacitance.

II. DEVICE DESIGN AND MODELING

The pMUT structure, illustrated in Fig. 1, is a unimorph design with an AlN piezoelectric layer and a SiO$_2$ passive layer. Prototype devices were fabricated with a 1 µm thick AlN layer deposited using a low-temperature sputtering process that allows deposition on fully metalized CMOS wafers. Based on an analytical model for membrane deflection, a 1 µm SiO$_2$ layer was selected to help maximize the displacement of the membrane and by extension the output sound pressure level of our transducers. For our application, short-range air-coupled ultrasound, we have targeted an operating frequency in the 200 kHz range as this allows the possibility for highly directional emission from small ($< 1 \text{ cm}^2$) pMUT arrays. Devices with membrane radius $a = 175$, 200, and 225 µm were fabricated. The top electrode, having radius $\gamma a$, is located at the center of each membrane.

Figure 1. pMUT cross section showing device geometry.

Figure 2. Optical image of a 5x5 pMUT array.
A brief description of the fabrication process is as follows. Beginning with 150 mm diameter Si substrates, a 1 µm SiO$_2$ layer is deposited using a plasma-enhanced chemical vapor deposition (PECVD) process. The bottom electrode metallization, 15 nm TiW beneath 40 nm of Pt, is then deposited, after which AlN is sputtered to a thickness of 1 µm. The PECVD SiO$_2$ has an average compressive residual stress deposited, after which AlN is sputtered to a thickness of 1 µm. Metallization, 15 nm TiW beneath 40 nm of Pt, is then deposition (PECVD) process. The bottom electrode neutral plane developed using an energy method [4, 11]. The location of the A. An analytical model for membrane deflection was developed using an energy method [4, 11]. The location of the neutral plane $z_d$ and the flexural rigidity $D$ were computed using standard formulas for a laminated plate [4]. The axisymmetric membrane deflection is written $w(x) = w_0 f(x)$, where $w_0$ is the deflection at the membrane center, $x = r/a$ is the normalized radial distance, and $f(x)$ is a function representing the normalized displacement. The total potential energy functional is:

$$
\Pi(w) = U_e + W_m
$$

(1)

where $U_e$ is the elastic strain energy and $W_m$ is the work done by the piezoelectric bending moment. Assuming a clamped plate model, these are defined as:

$$
U_e = D \pi \frac{w_0^2}{a^2} I_e
$$

(2)

$$
W_m = 2\pi M w_0 I_m
$$

(3)

where

$$
I_e = \int_0^1 \left[ \left( \frac{d^2 f}{dx^2} \right)^2 + 2 \frac{v}{x} \frac{df}{dx} \left( \frac{d^2 f}{dx^2} \right) + \frac{1}{x^2} \frac{df}{dx} \right] dx
$$

(4)

$$
I_m = \frac{1}{1-v} \int_0^1 f \left( \frac{d^2 f}{dx^2} + \frac{1}{x^2} \frac{df}{dx} \right) dx
$$

(5)

and $v$ denotes the effective Poisson’s ratio for the composite plate. In (3), $M$ indicates the piezoelectric bending moment, given by:

$$
M = e_{31,f} z_p V
$$

(6)

where $e_{31,f}$ is the transverse piezoelectric coefficient, $V$ is the applied voltage, and $z_p$ is the distance from the AlN midplane to the neutral plane.

To obtain the static deflection due to the bending moment $M$, we minimize the energy functional $\Pi$:

$$
\frac{d\Pi}{dw_0} = 2\pi \frac{D}{a^2} w_0 I_e + 2\pi M I_m = 0.
$$

(7)

Solving (7) yields the static deflection as a function of applied voltage:

$$
w_0 = - \left( \frac{a^2 I_e}{D} \right) M = - \left( \frac{a^2 I_m}{D} \right) e_{31,f} z_p V.
$$

(8)

B. Frequency response

The frequency response of the pMUT is modeled using an equivalent circuit, shown in Fig. 3, whose parameters were computed using the analytical model described above. Using this model, the static membrane deflection is given by:

$$
w_0 = \varphi C_m V
$$

(9)

and it is evident that maximizing the membrane deflection per unit voltage requires maximizing $\varphi C_m$. Comparing (9) with (8), the mechanical compliance is:

$$
C_m = a^2 / 2\pi D I_e
$$

(10)

and the transformer ratio is:

$$
\varphi = \pi I_M e_{31,f} z_p.
$$

(11)

A common figure of merit for piezoelectric devices is the electromechanical coupling coefficient, defined as [12]:

$$
k_{eff}^2 = \varphi^2 C_m / (\varphi^2 C_m + C_0).
$$

(12)

The coupling coefficient can be calculated from the series and parallel resonant frequencies extracted from electrical impedance measurements:

$$
k_{eff}^2 = \left( \omega_p^2 - \omega_y^2 \right) / \omega_p^2
$$

(13)
where \( \omega_p \) is the parallel resonance and \( \omega_s \) is the series resonance. The series resonance occurs at the frequency of the 01 mode mechanical resonance of the membrane. Assuming a clamped plate model this frequency is [11]:

\[
\omega_s^2 = \frac{\lambda_{01}}{a^4} \left( \frac{D}{\mu} \right)
\]

where \( \lambda_{01} = 3.19 \) is the eigenvalue for the 01 mode and \( \mu \) is the mass per unit area of the composite plate.

Due to the fact that the pMUT is composed of a relatively thin (~2\( \mu \)m) membrane, residual stress in the SiO\(_2\) and AlN layers has an impact on the natural frequency. An approximate model for the natural frequency of a stressed membrane [13] allows the relative importance of the residual stress to be quantified using a non-dimensional tension parameter defined as:

\[
K = a \sqrt{S/D}
\]

where \( S \) is the tension per unit length on the membrane perimeter. Representing the residual stress and thickness of the SiO\(_2\) by \( \sigma_{ox} \) and \( t_{ox} \) and those of the AlN by \( \sigma_{AIN} \) and \( t_{AIN} \) the tension is given by:

\[
S = \sigma_{ox} t_{ox} + \sigma_{AIN} t_{AIN}
\]

The resulting natural frequency is then computed as:

\[
\tilde{\omega}_s^2 = \omega_s^2 \left[ 1 + \frac{K}{\lambda_{01}} \right]^2
\]

where \( \omega_s \) is the unstressed natural frequency and \( \tilde{\omega}_s \) is the natural frequency including stress. When the tension \( S \) is small relative to the flexural rigidity \( D \), the pMUT follows the plate model whereas at large values of \( K \) (indicating \( S >> D \)) the tension dominates and the natural frequency is predicted by a membrane model.

**III. EXPERIMENTAL RESULTS AND DISCUSSION**

**A. Displacement measurements**

The displacement of the center of the membrane is measured in air using a laser doppler vibrometer (LDV). National Instruments signal generator and A/D cards are used to drive the pMUT and capture the results to a computer.

The frequency response of an individual transducer with a 350 \( \mu \)m diameter membrane and 225 \( \mu \)m diameter top electrode, driven at 1 volt peak-to-peak, is shown in Fig. 4. The measured natural frequency is 219.2 kHz with a \( Q \) of 50 and maximum displacement of 0.21 \( \mu \)m.

The maximum displacement predicted using the analytical model described in (8) is 0.45 \( \mu \)m, approximately twice the measured value. We attribute the difference between model and experiment to two factors. The first factor is the quality of our AlN film. The model uses the full values for the piezoelectric coefficient, \( e_{31f} = -1.0 \) C/m\(^2\). Based on the measured rocking curve FWHM and \( d_{31f} \) for our wafer we believe that the actual value of \( e_{31f} \) is significantly reduced.

The second factor is misalignment of the top electrode relative to the membrane center. This misalignment, which is approximately 17 \( \mu \)m, reduces the electromechanical coupling.

We also explored the effects of driving the pMUTs with voltages in the range of 0.5 to 7 V\(_{pp}\) in half volt increments. The results are shown in Fig. 5. The maximum achieved displacement is 1.27 \( \mu \)m when driven at 7 V\(_{pp}\). However, we see significant nonlinear response when the displacement amplitude reaches approximately half of the membrane thickness (~1 \( \mu \)m) which occurs at a drive voltage of 5 V\(_{pp}\). The nonlinear response is due to membrane stiffening from tension occurring at large deformations.

**B. Impedance measurements**

The measured impedance of a single pMUT is shown in Fig. 6. The series and parallel resonant frequencies were extracted using a 2nd order model. Using (13), we calculate \( k_{eff}^2 = 0.056\% \). In comparison, the coupling coefficient calculated using the equivalent circuit model (12) is 0.137%.
The difference between experiment and model is similar to that observed in the displacement measurement and is attributable to reduction in $e_{31f}$ and electrode misalignment.

The coupling coefficient (both theoretical and measured) is significantly reduced by the parasitic capacitance of our current design. The total measured capacitance is $C_0 = 11.51 \text{ pF}$, whereas the calculated capacitance for our 225 $\mu$m top electrode is $3.66 \text{ pF}$. The difference, $7.37 \text{ pF}$, is parasitic capacitance contributed by bond pads and interconnect. Consulting (12), the coupling coefficient is approximately given by $k_{eff}^2 \approx \frac{\phi^2 c_m}{C_0}$. If the parasitic capacitance were entirely eliminated, the coupling coefficient would be improved by roughly a factor of four, and we anticipate that coupling coefficients on the order of 0.5% should be achievable in our technology.

C. Fabrication variations

For good acoustic performance, the natural frequencies of the elements of a pMUT array must be matched to within $1/Q \approx 2\%$. The main source of variation in our devices is stress on the pMUT die due to packaging, residual stress in the AlN layer, or both. Across-wafer stress maps were collected on 21 wafers following deposition of the AlN layer and the average residual stress in the AlN layer of each wafer ranged from -100 MPa compressive to 150 MPa tensile. In addition, for each wafer measured, the residual stress was observed to vary by 50 MPa across the 150 mm diameter, a gradient of approximately 0.37 MPa/mm. As a result, the residual stress level across a 6.7 mm die is expected to vary by 2.5 MPa. Using the model from (17), this stress variation would produce approximately 3%-4% variation in the natural frequency across a single die. The actual variation observed on a typical die was closer to 10%, a difference which would require $\sim 8 \text{ MPa}$ stress difference across the die.

IV. CONCLUSION

In this paper we have explored the design, modeling, fabrication, and characterization of AlN unimorph pMUTs. These devices are fabricated using a process which is suitable for integration with standard CMOS electronics. The performance of prototype devices compared well with the predictions of a simple equivalent circuit model, although the measured displacement and coupling coefficient were both somewhat lower than predicted from the analytical model. We attribute the majority of the difference between experiment and model to a reduced piezoelectric coefficient due to the relatively poor alignment of the AlN film used. In addition, the measured coupling coefficient was significantly degraded by parasitic capacitance present on the pMUT die. These parasitics can be greatly reduced by improved layout and will be further reduced by the use of integrated on-chip electronics. Finally, the thin (2 $\mu$m) membrane used to construct our devices results in a relatively high sensitivity to residual stress, a sensitivity that could be reduced by partially freeing the membrane edge to allow stress relief.

REFERENCES


