Micromachined piezoelectric microphones with in-plane directivity

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Micromachined piezoelectric microphones with in-plane directivity are introduced. A beam rotates about center torsional pivots and is attached to piezoelectrically active end-springs. Rotation of the beam in response to sound pressure gradients produces spring deflections, which, in turn, produce an open-circuit voltage at the piezoelectric films. Prototypes are presented that contain a 20- μm -thick silicon beam and end-springs with 900-nm-thick chemical solution deposited lead zirconate titanate atop the surface of the end-springs. Acoustic directivity measurements are presented that confirm device functionality. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4776687>]

Microphones are one of the hottest growth areas of MEMS with 1-billion units shipped globally in 2011 and 2.9 billion anticipated in 2015.¹ The majority of MEMS microphones are omnidirectional. Directional microphones have been shown to benefit source localization and improve speech clarity in noisy environments^{2–5} and are commonly implemented by utilizing a pair of spaced omnidirectional microphones to compute the pressure gradient between two points in space. The cost of directionality is increased self-noise of the configuration due to the measurement of small pressure differences. For a spaced pair, the ratio of pressure difference, $|\Delta P|$, to acoustic pressure is $k\Delta x$ where k is the wavenumber and Δx is the spacing between the pair. For a pair of microphones separated by 4 mm measuring sound at 1 kHz, the driving pressure difference is 23 dB below the acoustic pressure, and the input-referred self-noise of the configuration increases proportionally. Considering MEMS microphones have noise floors typically in the 32 dBA range, total noise in excess of 55 dBA is anticipated.

Miles *et al.* introduced and developed a biologically inspired “rocking” structure that is hinged by a torsional pivot and mechanically selective to the direction of incoming sound.^{6,7} In addition to offering a very compact pressure gradient microphone with experimentally verified “figure-of-8” directivity, laboratory prototypes simultaneously demonstrated a 10-dB lower noise floor and ten times reduction in size compared to state-of-the-art low-noise miniature microphones used in hearing aids. Demonstrations to date have relied on an optical readout approach.^{8–10} Although advances in low-profile packaging of optical microphones have been recently demonstrated,¹¹ consideration of other approaches may prove advantageous.

Piezoelectric MEMS microphones have been explored and advanced by many research teams.¹² Piezoelectric materials commonly used for micromachined microphones are zinc oxide (ZnO),^{13–15} aluminum nitride (AlN),^{16,17} and lead zirconate titanate (PZT).^{18–20} PZT is a commonly favored material for piezoelectric acoustic sensors because it has sig-

nificantly higher piezoelectric coefficients and coupling factors than AlN and ZnO, although AlN has recently garnered attention due to low dielectric loss and the potential for overall signal-to-noise ratio (SNR) improvements.¹⁶ In this Letter, we present a device innovation that synthesizes the pioneering directional microphone work by Miles *et al.* with advances in piezoelectric MEMS fabrication to produce a rocking style microphone with an integrated PZT readout mechanism. The microfabrication process is presented along with directivity measurements, which confirm the anticipated functionality of the device.

Fig. 1 presents a scanning electron micrograph (SEM) of a completed device, which consists of a 20- μm -thick beam anchored by two torsional pivots to a bulk silicon substrate. As in the case of Ref. 9, the pivots are designed to provide

FIG. 1. Labeled SEM of device. Inset micrograph shows details of pivot structure.

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FIG. 2. Cross-sectional schematic of device.

high rotational compliance to facilitate rotation of the beam about the y -axis and high bending stiffness to resist translational deflection of the beam in the z -direction. Four springs are attached to the ends of the rotating beam so that the springs deflect upon rotation of the beam. The springs contain a thin piezoelectric film (900 nm) operating in the 3–1 mode to convert elastic strain at the spring surface to an electric potential that can be read across platinum (Pt) electrodes, with signals routed to the edge of the die to bond pads as shown in Fig. 1. The device is designed to rotate in response to sound arriving from the x -direction due to pressure differences applied across the beam resulting from the finite speed of sound. Sound waves arriving from the y and z -directions apply a balanced pressure to both sides of the beam. A dipole or figure-8 response to sound pressure is therefore anticipated, with the x -axis as the sensitive axis of the dipole.

Fig. 2 presents additional details via a device cross section. The device is fabricated on a silicon-on-insulator (SOI) wafer with 2- μm buried oxide thickness and 20- μm epitaxial silicon device layer. Low pressure chemical vapor deposition (LPCVD) silicon dioxide is deposited on the front and back of the wafer. The backside oxide is used as an etch mask for a deep reactive ion etch (DRIE) later in the process. Titanium (Ti) is deposited by e-beam evaporation and is thermally oxidized to form titanium oxide (TiO_x), which serves as a lead diffusion barrier. The bottom and top electrodes are deposited by DC and RF magnetron sputtering of Ti and Pt, respectively. PZT is deposited using a chemical solution process. The beam, springs, and pivot structures are patterned together in a top side etch, and the backside cavity is formed using a DRIE process. The inset of Fig. 1 shows that the device layer silicon is etched around the perimeter of the pivot, which might give the false impression of a free-floating hinge. As the cross section in Fig. 2 makes clear, the pivot is anchored through the embedded oxide layer.

The ferroelectric properties of the PZT films were verified by measuring polarization vs. electric field using a standard Sawyer-Tower circuit.²¹ The anticipated hysteresis behavior is observed in Fig. 3, where saturation and remnant polarizations of 22 and 10 $\mu\text{C}/\text{cm}^2$, respectively, are observed. These values are similar to those presented by other researchers in the field and indicative of films with strong ferroelectric properties.^{22–24} The directivity of the structure was verified by applying a broadband chirp signal

through an Adam A5 studio monitor and measuring the device output spectrum with a Prism dScope Series III audio signal analyzer. A standard non-inverting amplifier with 10-M Ω input bias resistor and 10 $\times$ gain was used to amplify the signal from the device. The frequency response in proximity of the first rotational mode of the device is presented in Fig. 4(a) for multiple angles of incidence. As anticipated, the amplitude of the output is highly sensitive to angle of incidence. Full 360 $^\circ$ measurements were performed at the first mode frequency to generate the measured directivity plot in Fig. 4(b), demonstrating the anticipated device function.

Rigorous experimental evaluation of sensitivity, noise, and minimum detectable signal remains the subject of future investigation. With some assumptions permitted, a simple analysis can be used to explore performance possibilities. A description of variables in the analysis is presented in Table I. The mechanical response of a rotational system may be expressed as

$$\theta(\omega) = \frac{M_0/I}{\omega_0^2 + j2\omega_0\omega\zeta - \omega^2}, \quad (1)$$

FIG. 3. Polarization hysteresis loop.

FIG. 4. (a) Response to acoustic excitation at the 1st mode natural frequency and (b) measured directivity of the microphone at 11.9 kHz.

where M_0 is the applied moment. The device is small relative to the wavelength of incoming sound, so pressure arriving along the sensitive axis can be approximated using a two-term Taylor series about the pivot location, $x = 0$, as

$$p(x, t) \approx p(0, t) + x \frac{\partial p}{\partial x} \Big|_{x=0} = P_0(1 - jkx)e^{j\omega t}, \quad (2)$$

where the second form assumes time-harmonic plane waves, and P_0 is the amplitude of the incident sound pressure. Only the smaller kx term contributes to the moment, which can be computed as $M_0 = -jkP_0I_A$. Substituting known formulae for I and I_A and defining rotational sensitivity, S_{rot} , as the beam rotation per sound pressure leads to

$$S_{rot} = \frac{-jk}{\rho t \omega_0^2} \left(\frac{1}{1 - r^2 + 2j\zeta r} \right), \quad r \equiv \frac{\omega}{\omega_0}. \quad (3)$$

For a design with a 4- μm -thick Si device layer, 1 mm $\times$ 2 mm beam size, $f_n = 1$ kHz, and $\zeta = 0.5$, the beam tip deflection at each end can be computed as 50 nm/Pa at a frequency of 1 kHz. Modeling the end-springs as cantilevers fabricated in the device layer yields a simple approach to computing the open-circuit voltage from thin PZT films atop the spring surface. Reference 25 provides an analytical expression for this situation and summarizes experimentally derived properties of microfabricated PZT films. For a 1-mm-long, 200- μm -wide

spring with a 2- μm -thick film covering 2/3 of a spring's length, an open circuit voltage of 0.61 mV/Pa is computed. The dominant noise source in small-scale piezoelectric sensors is most commonly the result of dielectric loss in the film—typically expressed as the ratio of real to imaginary film impedance, or $\tan \delta$. The loss resistance in series with the device capacitance is $R_L = \tan \delta / \omega C_{cb}$ and its generated noise appears directly at the sensor output. $\tan \delta$ values of 0.03 are common for PZT.²⁶ Again using film properties from Ref. 25, a noise density of 13 nV/ $\sqrt{\text{Hz}}$ is computed at 1 kHz which, when referred to the input sensitivity of 0.61 mV/Pa, yields an equivalent pressure noise of 22 $\mu\text{Pa}/\sqrt{\text{Hz}}$ at 1 kHz. The combined effect of the frequency-dependent loss resistance and sensitivity governed by Eq. (3) results in an input referred pressure noise that has a minimum value at the resonant frequency, f_n , has a slope of -30dB/dec below f_n , and a $+10\text{dB/dec}$ slope above f_n . A-weighted integration of this noise results in a 48 dBA noise floor for a single spring. Summing the output from four springs should yield a 6 dB improvement and a device noise of 42 dBA. As shown by Miles *et al.*,⁹ the equivalent noise of two Knowles EM microphones separated by 10 mm is approximately 48 dBA. The simple analysis of the device technology under study suggests that better noise floors are achievable (6-dB improvement) from a single sensor more than $5\times$ smaller in size. The intent of this discussion is not to present an optimized design, but rather to demonstrate feasibility of the device innovation. Use of different device dimensions, thicker films, bimorph films as opposed to single layer films, and/or different materials with lower $\tan \delta$, such as AlN, may enable the possibility to yield lower noise.

TABLE I. Summary of device parameters.

Parameter	Description
θ	Angular rotational displacement of beam
C_{eb}	Blocked capacitance of PZT film
ω_0	Natural resonant frequency
C_m	Rotational compliance
ζ	Damping ratio
t	Beam thickness
b	Beam width
L	Beam length
m	Beam mass
$I_A = \frac{bL^3}{12}$	Second moment of area
$I = \frac{mbL^2}{12}$	Mass moment of inertia

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