ACOUSTIC TRANSDUCERS BUILT ON EDGE-RELEASED MEMS STRUCTURES

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ABSTRACT

This paper presents acoustic transducers built on edge-released MEMS structures, i.e., cantilever diaphragm and spiral-beam-supported diaphragm that are designed to release residual stress and also to avoid in-plane tension when bent. Sputter-deposited ZnO on the diaphragms is used as the piezoelectric thin film to sense and generate acoustic pressure. Typical diameter and thickness of the edge-released diaphragm are 1 mm and 1.6 μm , respectively. The maximum strain on the spiral-beam-supported diaphragm is about an order of magnitude larger than that of a cantilever diaphragm transducer for a given pressure level and diaphragm size. The spiral offers a higher sensitivity at the cost of a lower usable bandwidth and less tolerance on the fabrication process variation.

INTRODUCTION

Piezoelectric MEMS acoustic transducers offer advantages of simple fabrication process, no need for a polarization voltage, bi-directional actuation and wide dynamic range. A piezoelectric MEMS transducer is built on a thin micromachined diaphragm with a piezoelectric thin film. The bending of the diaphragm due to an applied sound pressure causes a stress change in the piezoelectric film, which generates an electric polarization in the film. To detect acoustic sound pressure level (e.g., for a microphone application), the diaphragm must be compliant. In this paper, we present a piezoelectric bimorph acoustic transducer built on a cantilever and a spiral-beam-supported diaphragm, both single-transducer and arrayed transducer.

TRANSDUCER DESIGN

In case of the spiral-beam-supported transducer (Fig. 1), we used bimorph (with two ZnO layers) on a spiral beam to minimize the beam curling. A straight bimorph beam (500 μm long, 50 μm wide) acts as a strain detector, while one-turn spiral is used to relieve the boundary constraint on the free end of the strain-detecting beam and to support a large center circular diaphragm (500 μm in diameter). The spiral-beam-supported diaphragm is mechanically compliant, and generates large electrical polarization on the piezoelectric bimorph when an acoustic pressure is applied to the diaphragm. A number of such transducers can be connected into an appropriate array to increase the sensitivity as a microphone and/or the sound output as a speaker.

Figure 1: Schematic diagram of the spiral-beam-supported diaphragm (Left) and mechanical model (Right).

The voltage induced on a piezoelectric transducer (built on a diaphragm) when an acoustic pressure impinge up the diaphragm can be obtained by

$$V = \frac{P(\text{Pa}) \times M \times A_{\text{active}}(\text{m}^2) \times d_{31}(\text{pC/N})}{C_{\text{load}}(\text{pF}) + C_{\text{active}}(\text{pF})} \quad (1)$$

where P is the applied acoustic pressure; M is the average stress-magnification factor over A_{active} , the active area (i.e., the piezoelectric area covered by top and bottom electrodes); d_{31} is the piezoelectric coefficient; C_{load} is the load capacitance of the pre-amplifier; and C_{active} is the capacitance of the piezoelectric film over A_{active} ($=\epsilon A_{\text{active}}/t$ with ϵ and t being the dielectric constant and thickness of the piezoelectric film, respectively). Piezoelectric ZnO is a sensible choice for sensing applications with its proven and reliable sputter deposition. Though PZT has a higher piezoelectric coefficient (Table 1), its dielectric constant is also higher, consequently canceling the beneficial effect of the larger d_{31} , as you can see in Eq. 1, when C_{active} dominates over C_{load} .

Table 1: Piezoelectric thin film properties [11]

Material	Density (kg/m ³)	Relative Dielectric Constant	Piezoelectric Coefficient d_{31} (pC/N)
ZnO	5,680	8.8	-3.4
AlN	3,300	8.5	-2
Sol-Gel PZT	7,500	1,300	-70

Mechanical Simulation

Finite element modeling (FEM) with COMSOL software was used to explore the stress distribution and dynamic response of the cantilever and spiral-beam-supported diaphragms. All diaphragms were chosen to have the same area (1 mm by 1 mm) and thickness (0.7 μm) in the simulations (Table 2).

The FEM static analyses gave us the distributions of stress developed in the edge-released transducers under a uniform acoustic pressure of 1 μPa . The induced stress is integrated over the piezoelectric areas covered by top and bottom electrodes to obtain the average stress-magnification factor M in Eq. 1. The largest stress is distributed along the anchor of the diaphragm edges for all the diaphragm cases investigated. Thus, the electrodes are located near the diaphragm edges. If the induced stress level were the only parameter that affects the sensitivity, it would be desirable to make the electrode area as small as possible and place it as close to the edge as possible. But in that case, the capacitive loading effect that is described in the next section would have killed the sensitivity.

Among the cantilever square diaphragm, cantilever-supported circular diaphragm and spiral-beam-supported diaphragm (Table 2), the spiral-beam-supported diaphragm is most compliant, and produces the largest strain (and stress on the piezoelectric bimorph beam) in response to an applied pressure. Thus, the transducer built on a spiral-beam-supported diaphragm is expected to give a better sensitivity than that built on a cantilever diaphragm.

Table 2: FEM simulations of cantilever square diaphragm, cantilever-supported circular diaphragm, and spiral-beam-supported diaphragm (1 mm² large and 0.7μm thick)

Cantilever square diaphragm	Cantilever-supported circular diaphragm	Spiral-beam-supported circular diaphragm
pressure:1μPa maximum value E=-0.254 V/m strain=-3.46e-11	pressure:1μPa maximum value E=-0.255V/m strain=-4.18e-11	pressure:1μPa maximum value E=-1.054 V/m strain=-2.07e-10

Modeling and Analysis of Equivalent Circuit with Voltage Amplifier

A piezoelectric microphone (based on a unimorph structure) and a voltage amplifier are equivalently modeled with a circuit in Fig. 2. A diode D (shown in Fig. 2a) is present only to provide a very high resistance ($>10^{10}\Omega$) so that a tiny leakage path will be present to drain off stray charges that might otherwise accumulate on the exposed electrode. Without the diode, the input node will have a resistance in the range of 10^{12} ohm for an op-amp that uses a pair of field effect transistors at its input, and the amplifier will be out of a proper bias. The capacitor C_e is comprised of parasitic capacitances due to the amplifier, the diode, and the conductor line connecting the microphone to the amplifier.

Figure 2: (a) Equivalent circuit for the piezoelectric microphone with a voltage amplifier. (b) Simplified circuit for analysis.

The capacitances on the equivalent circuit for the microphone are due to the ZnO layer (C_p), and to the two insulating layers on the top and bottom of the ZnO layer (C_1 and C_2). The current source represents the piezoelectric activity of the ZnO that becomes strained when pressure deflects the silicon-nitride diaphragm. Strain in the piezoelectric material produces a polarization and surface charges that are mirrored on the top and bottom aluminum electrodes. For a sinusoidal pressure variation at a radial frequency ω , there is a piezoelectrically induced sinusoidal charge of $Q_o e^{j\omega t}$ where Q_o is proportional to the applied pressure. The current delivered by the current source is $dQ/dt (=j\omega Q_o e^{j\omega t})$.

The simplified circuit shown in Fig. 2b simplifies further to a parallel-connected RC with an equivalent current source and capacitance as follows:

$$\frac{dQ_a}{dt} = \frac{dQ/dt}{1 + C_p \left(\frac{1}{C_1} + \frac{1}{C_2} \right)} \quad C_T = C_e + \frac{C_p}{1 + C_p \left(\frac{1}{C_1} + \frac{1}{C_2} \right)}$$

Solving for v_m , the unamplified output of the microphone, we find

$$v_m = \frac{j\omega R}{1 + j\omega R C_T} \cdot \frac{Q_o e^{j\omega t}}{1 + C_p (1/C_1 + 1/C_2)}$$

For $\omega R C_T \gg 1$, the condition for a good low frequency response,

$$\text{we have } v_m \approx \frac{1}{C_T} \cdot \frac{Q_o e^{j\omega t}}{1 + C_p (1/C_1 + 1/C_2)} = \frac{Q_a}{C_T}$$

Parallel combination of many piezoelectric transducers usually increases the sound output when those are used as a transmitter, but does not necessarily improve the receiving sensitivity when those are used as a receiver. Thus, we simulated the equivalent circuit model (Fig. 3) with Agilent's ADS to determine an optimal number for serial connection of certain parallel-connected transducers. For example, for a total of 256 cantilever-like-diaphragm transducers, we calculated the sensitivity as a function of number of parallel connection, and found that 64 transducers in parallel followed by serial connection of 4 such sets (64x4) would give the highest sensitivity (Fig. 4).

Figure 3: Equivalent circuit model of the arrayed ultrasound transducer and the loading capacitance and resistance.

Figure 4: (Left) Normalized sensitivity and noise floor for an array of 256 transducers as a function of number of parallel connection for a given loading capacitance. Since the total number of transducers is 256, the number of parallel connection automatically determines the number of serial connection (Right) Normalized sensitivity vs. number of parallel connections as a function of total number of devices.

FABRICATION

Cantilever diaphragms were bulk-micromachined with KOH on a (110) silicon wafer, while the spiral diaphragms are bulk-micromachined with KOH on a (100) wafer, with LPCVD low-stress silicon nitride as a supporting layer for ZnO film and electrodes.

To balance out the residual stresses in the films and also to increase the sensitivity, a bimorph structure with two 0.3-μm-thick ZnO films is used. Each of the ZnO films is encapsulated with two

0.1- μm -thick plasma-enhanced chemical-vapor-deposited (PECVD) Si_3N_4 insulating layer to improve the transducer's low-frequency response. A 0.2- μm -thick aluminum is used for the top, middle, and bottom electrodes. The top and bottom aluminum electrodes are electrically grounded (Fig. 5).

Figure 5: Brief fabrication process flow for a piezoelectric bimorph transducer built on a spiral-beam-supported diaphragm

For forming an array of cantilever-diaphragm transducers, a (110) silicon wafer is used to exploit the vertical sidewalls in densely packing the diaphragms over a relatively small area. Consequently, we were able to put a 64 element array of $250 \times 250 \mu\text{m}^2$ transducers over a mere $2 \times 2.5 \text{ mm}^2$. The individual diaphragm having $250 \times 250 \mu\text{m}^2$ area was chosen for a fundamental resonant frequency of 20 kHz (Fig. 6).

Figure 6: (Top) 64 transducers connected in parallel on a (110) Si wafer. (Bottom) SEM and CCD photos of the transducers

In case of the spiral-beam-supported-diaphragm transducers, we fabricated an array of 16 transducers as show in figure 7. There is some warping on the center circular diaphragm, which stiffens the diaphragm, and affects the sensitivity and frequency response of the transducer. The warping is due to residual stress gradient in the multiple-layer diaphragm, and can be reduced by increase the thicknesses and/or stiffness of the diaphragm.

Figure 7: Photo of 16 spiral transducers connected in parallel.

MEASUREMENT RESULTS

The fabricated microphones were tested in an anechoic box with a set-up shown in Fig. 8, with sound wave generated by a commercial speaker. The sound signal detected by the fabricated microphone was then amplified before being input to the oscilloscope, collected and analyzed with Labview software. A similar setup was used to measure sound output from the fabricated transducers.

Figure 8: Testing setup

Cantilever Diaphragm Transducer

In case of the fabricated microspeaker, the sound pressure output was measured about 3 mm away from the microspeaker in an open field with a calibrated microphone. A single microspeaker built on a cantilever diaphragm was measured to produce 0.8 Pa at 22 kHz when it was driven with $75V_{\text{peak-to-peak}}$. The same device was measured in a setup shown in Fig. 8 to have a receiving sensitivity of $100 \mu\text{V}/\text{Pa}$ at the resonant frequency of 22 kHz. When 16 such transducers were connected in parallel, both the sound output and the sensitivity were improved to 4 Pa and $1.05 \text{ mV}/\text{Pa}$, respectively. When 64 such transducers were connected in parallel, followed by 4 such sets in series, the sound output and the sensitivity were improved to 10Pa and $2.9 \text{ mV}/\text{Pa}$, respectively (Fig. 9).

Array of Transducers

Figure 9: Acoustic sensitivity for array of cantilever-like transducers connected in parallel and/or series.

Spiral-beam-supported Diaphragm Transducer

The bending displacement of a single spiral-diaphragm transducer was measured to be 300 and 50 nm/V at its fundamental frequency of 1.5 kHz and at 0.1 – 1 kHz range, respectively. It was also measured to have a receiving sensitivity of 1 mV/Pa at the resonant frequency and 150 μ V/Pa in 0.1 – 1 kHz range (Fig. 10). When 16 such transducers were connected in parallel, the sensitivity was improved to 5.5 mV/Pa at the first resonant frequency and 420 μ V/Pa in 0.1 – 1 kHz range.

Figure 10: (Left) Measured sound sensitivities of a single spiral transducer. (Right) 16 spiral transducers connected in parallel.

CONCLUSION

Acoustic transducers built on edge-released MEMS structures have been designed and fabricated on silicon wafers. The transducers were tested both as a sound receiver and a sound transmitter, and were appropriately connected in a form of array for higher sensitivity and broader bandwidth. When 64 cantilever diaphragm transducers were connected in parallel, followed by 4 such sets in series, the sound output and sensitivity at the fundamental resonant frequency of 22 kHz were 10Pa and 2.9mV/Pa, respectively. By parallel connections of 16 spiral-beam-supported diaphragm transducers, the receiving sensitivity at the fundamental resonant frequency was improved to 5.5mV/Pa, more than 5 times that of a single device.

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