Frequency-Interleaved MEMS Ultrasound Transducer

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ABSTRACT

This paper presents a sensitive, broad-bandwidth MEMS ultrasound transducer based on frequency interleaving of resonant transducers. Cantilever-like diaphragm transducers with piezoelectric ZnO films have been connected in parallel, so that the sensitivity as a receiver and the sound output as a transmitter are measured to be about 30 times larger than those of a single transducer. The interleaving of the transducers not only increases the sensitivity but also broadens the useable bandwidth greatly.

Keywords: MEMS ultrasound transducer, piezoelectric, frequency-interleaved, array of cantilevers

1 INTRODUCTION

Ultrasonic transducers [1-8] based on Microelectromechanical Systems (MEMS) technology offer many advantages for applications to healthcare, distance alarming systems, and consumer electronics. Among various transduction methods, capacitive and piezoelectric actuation/sensing are the dominant methods used for ultrasound transducers fabricated by MEMS technology.

In this paper, we present a piezoelectric ultrasound transducer built on arrayed cantilever diaphragms with high compliance. Through connecting the transducers in parallel, both the sensitivity as a receiver and acoustic output as a transmitter are improved greatly.

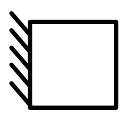
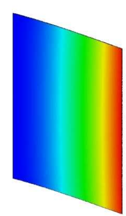
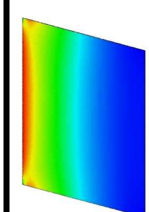
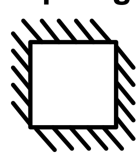
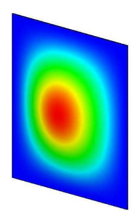
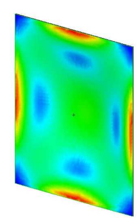
2 DESIGN AND FABRICATION

A piezoelectric transducer converts mechanical strain into electrical polarization and vice versa, and its sensitivity and sound output depend on the mechanical compliance of the transducer structure. Thus, the residual stresses of the films used in a MEMS diaphragm-based transducer would affect the transducer performance as well as the frequency response of the transducer. Especially, with MEMS diaphragm-based transducers, the initial warping due to the stress gradient in the thickness direction of a cantilever diaphragm plays a very important role in the diaphragm's mechanical stiffness, if more than two edges of the diaphragm are released. Also, when some edges of a diaphragm are released, there is potential issue of acoustic shunting through the openings of the diaphragm, and consequently, keeping the diaphragm flat is important for a good low frequency response of the acoustic transducer

2.1 Simulation

Two different types of square diaphragm have been analyzed with Finite Element Modeling (FEM): a cantilever diaphragm with its three-edges free and a four-edge-clamped diaphragm (Table 1). A cantilever diaphragm is the most compliant among the two, and can be made very small in top-view area without its resonant frequency being too high or its displacement too small. Thus, we chose a cantilever diaphragm as the building block for an arrayed transducer for 10 – 20 kHz applications such as velocity and range sensing.

Table 1: FEM simulations of cantilever diaphragm and four-edge-clamped diaphragm (250 x 250 μm^2, 1.5μm thick silicon nitride).

	Mode I	Max Strain
Cantilever Diaphragm 	 20kHz	 7.9E-7/Pa
Square Diaphragm 	 215kHz	 0.7E-7/Pa

2.2 Process Flow

Cantilever diaphragms are bulk-micromachined with KOH on a (110) silicon wafer, with 0.8μm thick LPCVD low-stress silicon nitride as a supporting layer for ZnO film

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and electrodes. Piezoelectric cantilever diaphragms are composed of low-stress LPCVD silicon nitride, aluminum, PECVD silicon nitride, piezoelectric ZnO, PECVD silicon nitride and aluminum (from bottom to top), and are fabricated according to the steps shown in Figure 1. The cantilever structure is formed through reactive ion etching (RIE) of the low-stress silicon nitride in CF_4 after all the films are deposited and patterned over the silicon nitride diaphragm (that has been formed by KOH etching on a (110) silicon wafer).

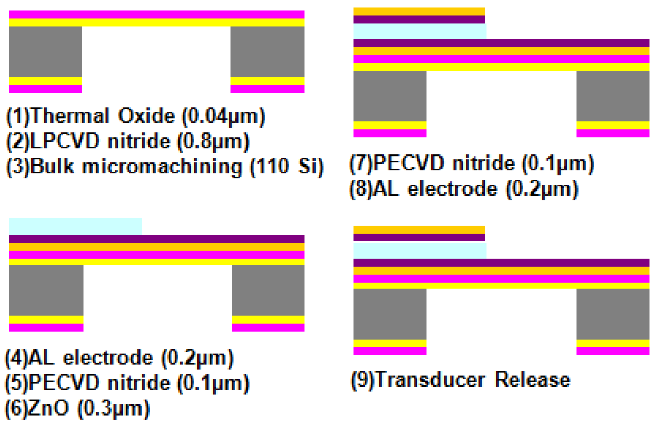

Figure 1: Brief fabrication process flow of the cantilever diaphragm transducer.

2.3 Fabricated Single Transducer

In an effort to make a flat cantilever diaphragm, we optimized the thicknesses for the films on the diaphragm to reduce the stress gradient of the cantilever diaphragm. Then we fabricated several cantilever diaphragms having various widths to determine the maximum width which we can use to form the transducer. All the fabricated transducers with large width such as 300, 500, 800, 1000 µm width showed some noticeable initial warping due to a large compressive stress in the ZnO film (Fig. 2). We observe that for cantilever diaphragms with less than 300 µm width, the initial warping is very small.

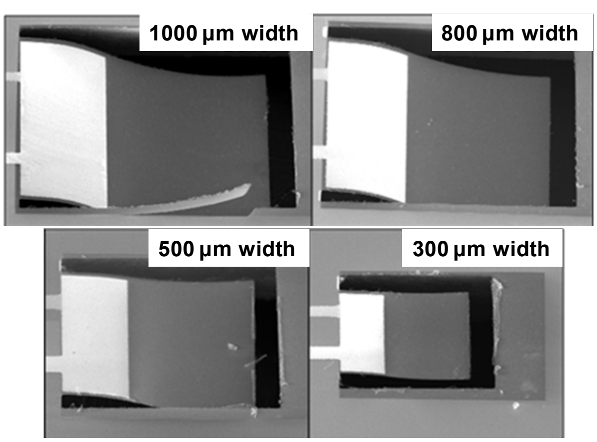

Figure 2: SEM pictures for the cantilever diaphragms with 300, 500, 800, 1000µm width.

We measured the sound output pressure levels of the cantilever diaphragm transducers at 22 kHz, and observed a decrease of more than 50% as the open gap width of the cantilever diaphragm increases from 5 to 25µm (Fig. 3) for a cantilever having a width of 250 µm.

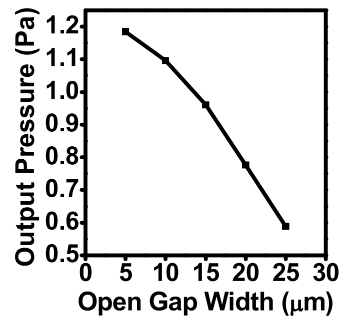

Figure 3: Measured sound pressure level generated by a cantilever-diaphragm transducer operating at 22 kHz, as the open gap width increases.

The (110) silicon wafer is used for vertical sidewalls to densely pack the diaphragms over a relatively small area, and consequently, the total area of the 64 element array is mere 2 x 2.5 mm^2, while the size of a single diaphragm is 250 x 250 μm^2 which is chosen for a fundamental resonant frequency of 20 kHz (Fig. 4).

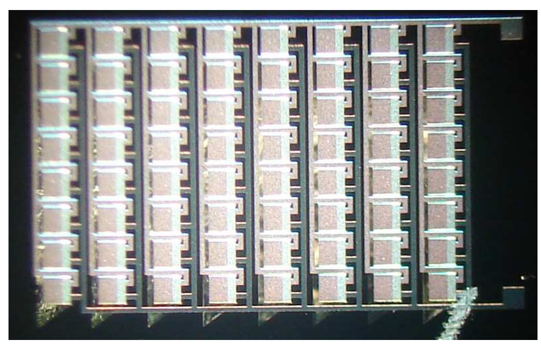

Figure 4: Photo of 64 transducers connected in parallel on a (110) Si wafer.

3 ELECTRICAL MODEL

When we operate the transducer as a transmitter, it is reasonable to assume the ultrasound output would increase in proportion to the number of parallel connections. However, when the transducer is operated as a receiver, a parallel connection of multiple transducers does not necessarily increase the sensitivity, as explained below.

We model the transducer and pre-amp as in Figure 5, where we use R to represent the input resistance of the diode and pre-amp in parallel, while the capacitance C_e accounts for the loading capacitance from the connecting wire and pre-amp. The following equation gives the voltage V_m:

$$v_m = j\omega Q_0 e^{j\omega t} \frac{R}{1 + C_p(1/C_1 + 1/C_2) + j\omega R[C_p + C_p C_e(1/C_1 + 1/C_2) + C_e]}$$

If the frequency is much higher than

$$f_{3dB} = \frac{1 + C_P(1/C_1 + 1/C_2)}{2\pi R[C_p + C_p C_e(1/C_1 + 1/C_2) + C_e]} \quad (1)$$

then the voltage V_m is approximately equal to

$$v_m = \frac{Q_0 e^{j\omega t}}{[C_p + C_p C_e(1/C_1 + 1/C_2) + C_e]} \equiv \frac{Q_0 e^{j\omega t}}{A(i) C_p(i)} \quad (2)$$

We can then define a normalized sensitivity for an arrayed transducer by dividing the sensitivity of an arrayed transducer with that of a single transducer.

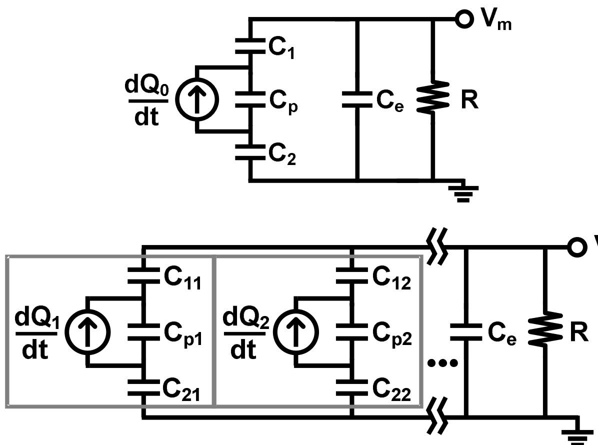

Figure 5: Equivalent circuit model of a single cantilever diaphragm transducer (*Top*) and an arrayed transducer (*Bottom*).

The capacitances of a single transducer were measured with an LCR meter (Fig. 6), and were used in calculating the normalized sensitivity of an arrayed transducer, as the number of parallel connections increases. Since the transducer's capacitance increases as the number of the transducers in parallel is increased, the effect of the loading capacitance (stemming from the connecting wire and pre-amp) on the sensitivity decreases, and the sensitivity increases as the number of parallel connections increases. As can be seen in Figure 6, the improvement of the sensitivity diminishes as the number of the parallel combination is increased beyond 16, for the case of a single transducer having a top-view area of 62,500 μm^2. The sensitivity finally approaches to its peak sensitivity, as the capacitance of the transducer becomes much larger than the loading capacitance.

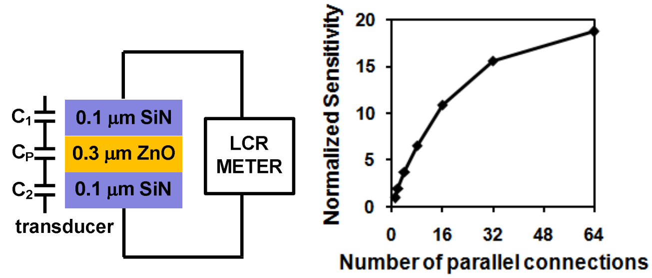

Figure 6: Normalized sensitivity of an arrayed transducer that has been calculated based on the measured capacitances of a single transducer having the thicknesses as shown above and the top-view area of 62,500 μm^2. The transducers are connected in parallel, and the sensitivity was calculated as the number of parallel connections increases.

4 MEASUREMENT

To characterize the mechanical response of the fabricated cantilever diaphragm, we use the Optodyne™ laser vibrometer (LDDM) to measure the bending displacement of a single fabricated cantilever-diaphragm transducer at its tip. The first and second harmonic responses were measured to be at 22 and 41 kHz (Fig. 7).

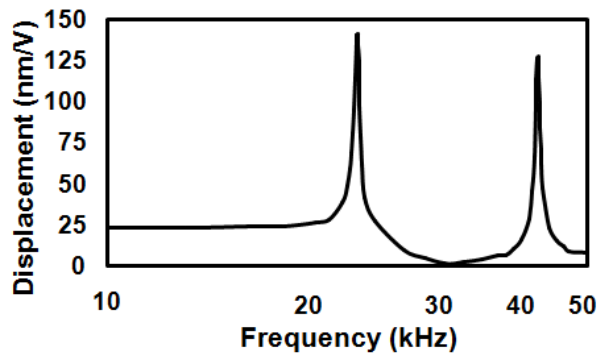

Figure 7: Mechanical displacement at tip of the single 250 μm wide ultrasound transducer measured with Laser Doppler Displacement Meter.

Each individual transducer's sound pressure output was measured about 3 mm away from the front side of the transducer in an open field with a LinearX™ M31 calibrated microphone that can measure up to 40 kHz. The single transducer was measured to produce 0.8 Pa at the fundamental resonant frequency of 22 kHz when it was driven with 75 Vpeak-to-peak. The single transducer was measured to have a receiving sensitivity of 100 μV/Pa at the resonant frequency (Fig. 8).

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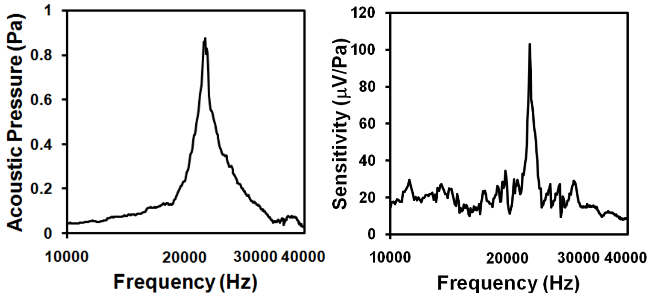

Figure 8: Ultrasound sensitivity and output sound pressure of a single transducer.

According to simulations, we fabricated a variety of arrayed transducers, and measured their sensitivities. When 16 single transducers were connected in parallel, both the sound output and the sensitivity were improved to 4Pa and 1.05 mV/Pa, respectively. For 64 transducers were connected in parallel, both the sound output and the peak sensitivity were improved to 9.4Pa and 2.8 mV/Pa, respectively (Fig. 9). The useable bandwidth also was greatly improved.

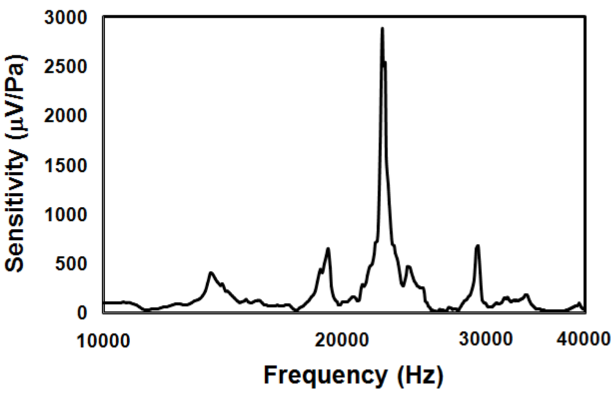

Figure 9: Measured sensitivity of an array of 64 transducers connected in parallel.

5 CONCLUSION

A cantilever-diaphragm-based ultrasound transducer has been fabricated on a silicon wafer with a MEMS fabrication process. By controlling the size of the cantilever diaphragm and optimizing the thickness of each layer of the transducer, we obtained a receiving sensitivity of 100 µV/Pa at 22 kHz and transmitting sound output of 0.8 Pa at 22 kHz with the transmitter driven with 75 $V_{peak\text{-}to\text{-}peak}$ sinusoidal signal. By connecting 64 cantilever diaphragms in parallel, we increased both the sound output and the sensitivity to 9.4 Pa and 2.8 mV/Pa, respectively.

6 ACKNOWLEDGMENT

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7 REFERENCES

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