High Fidelity Loud Microspeaker Based on PZT Bimorph Diaphragm

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ABSTRACT

This paper describes a microspeaker (composed of a 8 x 8 mm^2 square mechanically-polished PZT bimorph diaphragm and bulk-micromachined silicon top cover) that shows flat diaphragm displacement from DC to 11 kHz. The microspeaker with an encapsulating cylindrical package of about 0.7 cc inside volume produces sound pressure level (SPL) of 118 ~ 125 dB between 1 and 10 kHz when measured 5 mm away from the diaphragm with $190V_{peak\text{-}to\text{-}peak}$ sinusoidal input. The maximum displacement at the center of the diaphragm was measured to be 7.25 μm at the fundamental resonance frequency of 14.3 kHz, and the corresponding sound pressure level (SPL) was measured to be 133 dB.

Keywords: high fidelity, loud microspeaker, PZT, diaphragm, bimorph

1 INTRODUCTION

Electromagnetic microspeakers are used for most of mobile devices such as cell phone, portable media players (PMP), and laptop computers. The electromagnetic microspeakers are prone to failure under high temperature due to material characteristic of polymer diaphragm and permanent magnet, and have to be hand-assembled during the manufacturing process of mobile devices. In addition, the voice coil structure of the electromagnetic microspeaker is inherently tall, and limits the form factor of a mobile device in the thickness dimension.

Lead zircornate titanate (PZT) has high piezoelectric constant, electromechanical coupling coefficient, and high curie temperature. The curie temperature of PZT is 350°C which is higher than normal soldering temperature with reasonable margin. In spite of the above advantages, PZT substrate has rarely been used to fabricate microspeakers, likely due to the fabrication difficulty. Also, PZT substrate has high mechanical stiffness and consequent low bending displacement for sound generation. To enhance the bending displacement, we employed a bimorph structure for our microspeaker.

This paper describes a microspeaker built on a 8 x 8 mm^2 square, 254 μm thick PZT bimorph diaphragm with top and bottom patterned electrodes. By placing the fundamental resonant frequency at 14.3 kHz, we could obtain loud acoustic pressure with high fidelity in most of audible frequency range.

2 DESIGN

The normal stresses in x and directions (σ_x and σ_y) of a four-edge-clamped, isotropic diaphragm under a uniform loading (Φ_Z) can be calculated using approximate equations (Eqs. 1 and 2) with less than 10% error [1], where a is diaphragm side and h is diaphragm thickness.

$$\begin{aligned}\sigma_x \approx \frac{24a^2\Phi_Z}{\pi^3h^3}\Bigg[&\cos\frac{\pi x}{a}\left(2-1.4375\cosh\frac{\pi y}{a}+0.3828\frac{\pi y}{a}\sinh\frac{\pi y}{a}\right)\Bigg]\\ &-\cos\frac{3\pi x}{a}\left(\frac{2}{27}-0.0008638\cosh\frac{3\pi y}{a}-0.0000363\frac{\pi y}{a}\sinh\frac{3\pi y}{a}\right)\\ &-\cos\frac{\pi y}{a}\left(0.147\cosh\frac{\pi x}{a}+0.1038\frac{\pi x}{a}\sinh\frac{\pi x}{a}\right)\end{aligned} \tag{1}$$

$$\begin{aligned}\sigma_y \approx \frac{24a^2\Phi_Z}{\pi^3h^3}\Bigg[&\cos\frac{\pi x}{a}\left(0.6+0.01573\cosh\frac{\pi y}{a}-0.3828\frac{\pi y}{a}\sinh\frac{\pi y}{a}\right)\Bigg]\\ &-\cos\frac{\pi y}{a}\left(0.2385\cosh\frac{\pi x}{a}+0.1038\frac{\pi x}{a}\sinh\frac{\pi x}{a}\right)\end{aligned} \tag{2}$$

The normalized contour plots of Eqs. 1 and 2 are shown in Figure 1 [1]. If we overlay the σ_x and σ_y plots, we can see that opposite type of stress (i.e., tensile and compressive stresses) exist at the same time at certain locations. These opposite-type stresses at the same area cancel the effects of each other, and consequently decrease the bending displacement when the diaphragm is piezoelectrically actuated.

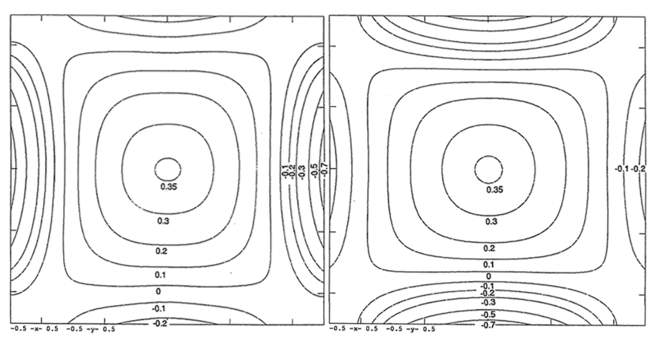

Figure 1. Normalized contour plots of the normal stresses σ_x (*Left*) and σ_y (*Right*)

Thus, the electrodes of the front side and backside of the PZT bimorph are placed so that the areas covered by the electrodes have a same type of stress in both x and y directions (Figure 2).

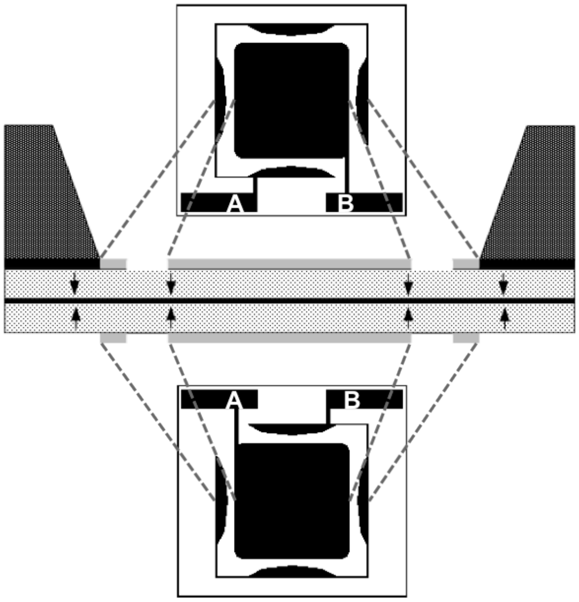

Figure 2. Top and bottom electrodes of the piezoelectric bimorph microspeaker. The pad A of the top electrode is electrically connected to the pad A of the bottom electrode.

3 FABRICATION

The microspeaker was formed by gluing two 127µm thick PZT sheets and attaching them onto a micromachined silicon substrate, in steps briefly illustrated in Figure 3. A pre-deposited nickel layer was completely etched out on the same side of two PZT sheets, and the etched surface was mechanically polished with diamond lapping film (Figure 3a). A low viscosity resin epoxy with viscosity less than 150 cps was spin-coated onto one PZT sheet at 6 kRPM speed, and then two PZT sheets were glued back-to-back (Figure 3b). The low viscosity resin epoxy was cured at around 70°C to reduce curing time and decrease the viscosity further. After the low viscosity epoxy is completely cured, the top and bottom electrodes were patterned with two sides of square diaphragm as alignment mark (Figure 3c). The patterned diaphragm was aligned and temporarily fixed to micromachined Si in a mask aligner, and completely glued with low viscosity glue through a wicking process driven by capillary force (Figure 3d) [2]. The bulk micromachined silicon top-cover provides the clamped boundary condition for the PZT bimorph diaphragm.

It is important to reduce the thickness of the glue layer between two PZT sheets, in order to maximize the electrical field inside the PZT sheets, since the glue layer takes some of the applied voltage away. To calculate the electric field loss in the low viscosity resin epoxy layer, we measured total capacitance (C_{Total}) of bimorph diaphragm which is equivalent to the total capacitance of three capacitors ($C_{PZT-Top}$, C_{glue}, $C_{PZT-Bottom}$) connected in series. Since total capacitance is calculated using Eq. 3, we can calculate relative dielectric constant of the low viscosity resin epoxy using Eq. 4. The calculated relative dielectric constant of the low viscosity epoxy was about 63, about 20 times less than dielectric constant of PZT. In other words, the electrical field loss per unit thickness in a low viscosity epoxy is 20 times that in PZT. With mechanical polishing of the PZT surface and spin-coating of low viscosity resin epoxy at 6 kRPM rotational speed, we were able to reduce the glue layer thickness to about 1 µm with variation less than 0.5 µm (Figure 4) from a typical 50 µm thickness.

$$\frac{1}{C_{Total}} = \frac{1}{C_{PZT-Top}} + \frac{1}{C_{glue}} + \frac{1}{C_{PZT-Bottom}} = \frac{2}{C_{PZT-Top}} + \frac{1}{C_{glue}} \tag{3}$$

$$where, C_{PZT-Top} = \frac{Area \cdot \varepsilon_0 \cdot \varepsilon_{PZT}}{PZT\ thickness},\ C_{glue} = \frac{Area \cdot \varepsilon_0 \cdot \varepsilon_{glue}}{glue\ thickness}$$

$$\varepsilon_{glue} = \frac{C_{Total} \cdot \varepsilon_{PZT} \cdot glue\ thickness}{\varepsilon_0 \cdot \varepsilon_{PZT-Top} \cdot Area - 2C_{Total} \cdot PZT\ thickness} \tag{4}$$

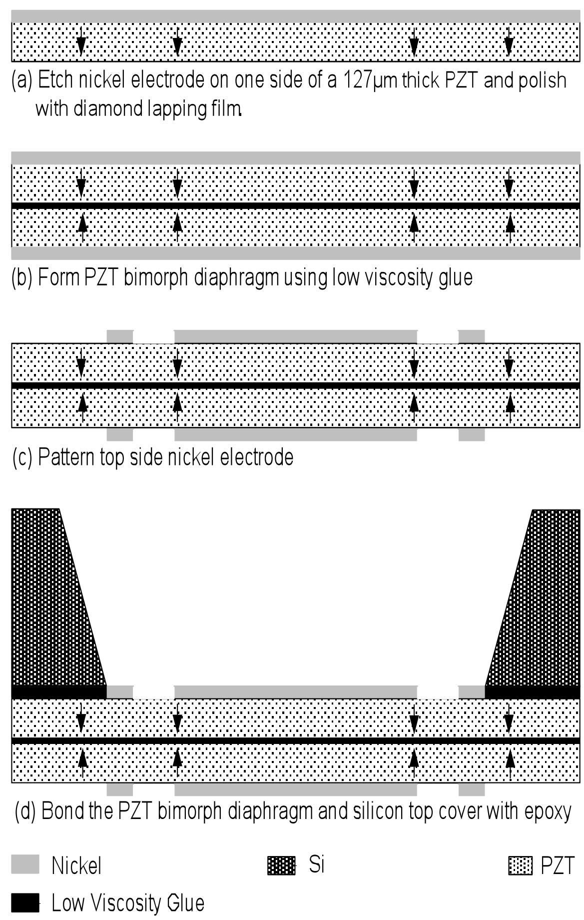

Figure 3. Brief fabrication steps for a PZT-based bimorph microspeaker.

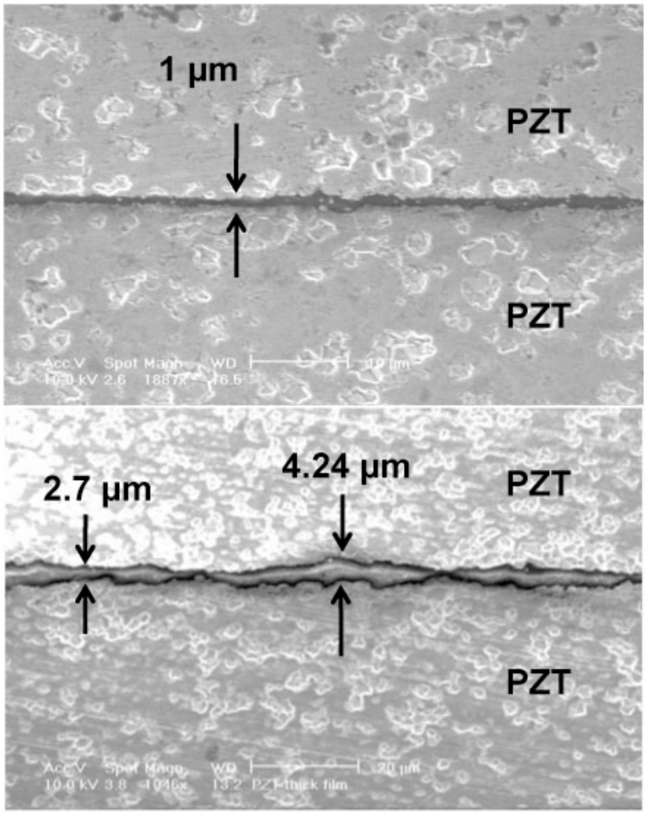

Figure 4. SEM photos of the cross-section of PZT bimorph with (*Top*) and without (*Bottom*) the mechanical polishing.

4 EXPERIMENTAL SETUP

The microspeaker was packaged on dual-in-line package (DIP) and the electrodes were connected using silver paste as shown in Figure 5. The displacement was measured at the center of the 8 x 8 mm^2 diaphragm with Laser Doppler Displacement Meter (LDDM) which has 6.3 nm resolutions. Due to the rough PZT surface, nickel electrode does not reflect the focused laser beam efficiently, and we attached 1.5 x 1.5 mm^2 aluminum foils with double sided tape to enhance the laser beam reflection for the LDDM measurement. The displacement was measured with the microspeaker driven by 190V$_{peak\text{-}to\text{-}peak}$ sinusoidal signal from 50 Hz to 20 kHz, in a setup shown in Figure 6.

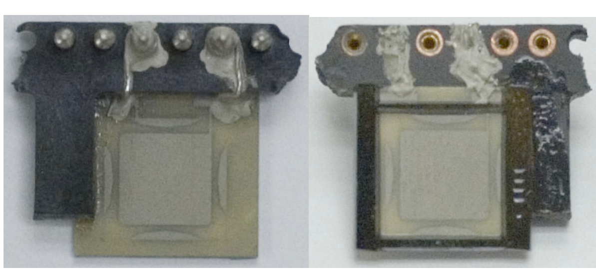

Figure 5. (*Left*) Picture of the fabricated microspeaker taken from the backside. (*Right*) Picture of the fabricated microspeaker taken from the front side.

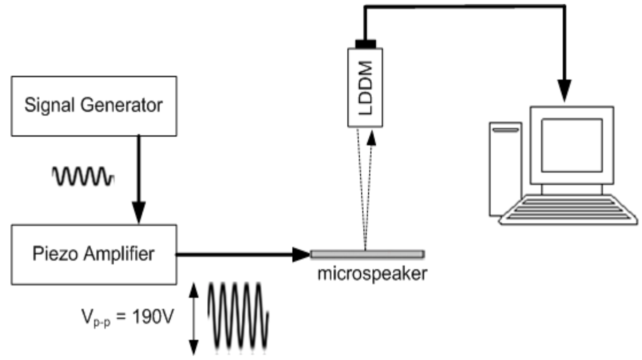

Figure 6. Measurement setup for the diaphragm displacement of the microspeaker.

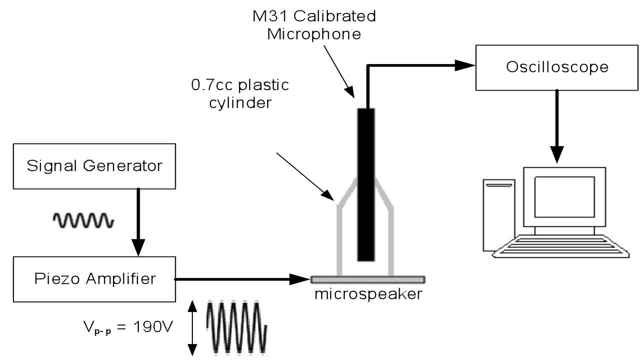

Figure 7. Testing setup for measuring the sound pressure level by the microspeaker.

The sound pressure level (SPL) was measured from 5 mm away from the diaphragm with M31 calibrated microphone with the microspeaker driven by 190V$_{peak\text{-}to\text{-}peak}$ sinusoidal signal from 50 Hz to 20 kHz. The microspeaker was encapsulated with a cylindrical plastic package having about 0.7 cc volume, and the SPL of the microspeaker was measured in a setup shown in Figure 7. The captured voltage level from the M31 was transferred to a computer and translated into SPL. The frequency was swept from 50 Hz to 20 kHz with 800 equidistant data points in log scale.

5 MEASUREMENT RESULT

With 190V$_{peak\text{-}to\text{-}peak}$ sinusoidal signal, the bending displacement was measured to be 0.9 ~ 1.3 µm from 100 Hz to 9 kHz as shown in Figure 10. The maximum displacement was measured to be 7.25 µm at its fundamental resonance frequency of 14.3 kHz.

The microspeaker with an encapsulating cylindrical package of 0.7 cc inside volume produced sound pressure level (SPL) of 118 ~ 125 dB between 1 and 10 kHz as shown in Figure 11. The maximum sound pressure level was measured to be 133 dB at its fundamental resonant frequency. Due to the large displacement of 1 µm between 100 Hz and 9 kHz, the microspeaker produces uniform and large level of sound pressure between 1 and 10 kHz. In spite of the uniform level of the displacement, the measured SPL decreased as the frequency was reduced below 1 kHz, due to the increasing wavelength and consequent acoustic energy density decrease.

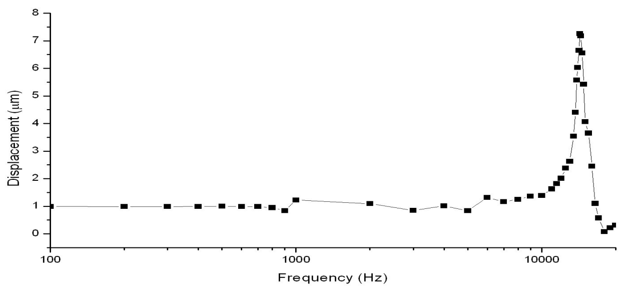

Figure 8. Measured displacement at the center of the PZT bimorph diaphragm (8 x 8 mm^2 square).

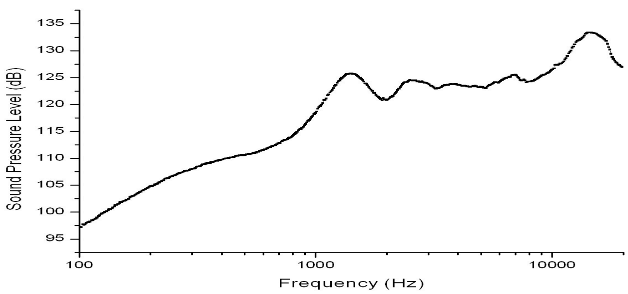

Figure 9. Sound pressure level measured at 5 mm away from the microspeaker diaphragm with 0.7 cc cylindrical encapsulating package.

6 CONCLUSION

A high fidelity loud microspeaker based on PZT bimorph diaphragm has been fabricated on a wafer with a process similar to semiconductor fabrication process. By reducing the glue layer thickness and patterning the top and bottom electrodes according to the stress pattern over a four-edge-clamped diaphragm, we were able to obtain loud and uniform acoustic pressure of 122 dB SPL (± 3dB SPL) from 1 kHz to 10 kHz and the maximum pressure of 133 dB SPL at 14.3 kHz, into 0.7 cc volume, when the microspeaker was driven with $190V_{peak\text{-}to\text{-}peak}$ sinusoidal signal.

7 ACKNOWLEDGMENT

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