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Piezoelectric microspeakers with high compressive ZnO film and floating electrode

SeungHwan Yi · ManSoon Yoon · SoonChul Ur

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Abstract This paper describes micromachined piezoelectric microspeakers that can produce an audible signal supplied from an MP3 player through the use of $5V_{\text{peak-to-peak}}$ signal amplification circuit modules. The Sound Pressure Level (SPL) of the fabricated microspeakers is higher than that of previous results even though the input voltage is reduced. The success of this technology is based upon two distinct features; one is the use of a high quality compressive ZnO thin film, the other is the implementation of a floating electrode beneath the piezoelectric ZnO film in order to induce more strain in the diaphragm of the microspeaker when two top electrodes are biased with different polarities. A high quality piezoelectric ZnO film is achieved using an Ar/O_2 gas ratio of 4:1, an R.F. power of 1,500W, a substrate temperature of 150°C, and a chamber pressure of 23mTorr. In this condition, the deposited ZnO film shows a compressive residual stress of −1.3GPa. The fabricated piezoelectric microspeakers were tested over a frequency range of 400Hz to 12kHz with a $5V_{\text{peak-to-peak}}$ input signal, the maximum SPL of the fabricated microspeakers was shown to be more than 97.2dB at 7.1kHz with a distance of 3mm between the fabricated microspeakers and the reference microphone (B&K type 2,669 and 4,192L).

Keywords Micromachined piezoelectric microspeaker · Sound pressure level (SPL) · Piezoelectric ZnO film · Composite residual stress · Floating electrode

1 Introduction

Currently, Personal Communication Systems (PCSs) highlight the demand of a lightweight and compact cellular phone, so the components of PCSs are becoming smaller than ever before. In the area of acoustic components for mobile phone applications, the two main parts comprise of microphones and microspeakers. In the case of microphones, nowadays the conventionally used electrets-microphone, which has some difficulties for mass production, is being substituted with a capacitive-type micromachined silicon microphone. The microspeakers used in PCSs are all of an electrodynamic-type, the diameter of such microspeakers has decreased from around 21 to 15mm and their shape has changed to an oval structure in order to meet geometrical issues faced in PCSs. However, the conventional manufacturing technology of electrodynamic microspeakers faces too many difficulties in the production of speakers with a diameter of less than 10mm and a thickness of less than 2mm without hindering their performance.

MEMS (Micro Electro Mechanical Systems) technology has been used to fabricate miniaturized microphones and microspeakers [1–3], as well as a FBAR for mobile phone [4] and piezoelectric sensor and actuator applications [5] through the use of a ZnO thin film on a silicon wafer. This technique has the following advantages over the traditional

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S. Yi (✉)
Department of Mechanical Eng./Research Center for Sustainable Eco-Devices and Materials (ReSEM),
Chungju National University,
123, GeomDanRi, IryuMyeon,
Chungju, Chungbuk 380-702, South Korea
e-mail: isaac_yi@cjnu.ac.kr

M. Yoon · S. Ur
Department of Material Sci. and Eng./Research Center for Sustainable Eco-Devices and Materials (ReSEM),
Chungju National University,
123, GeomDanRi, IryuMyeon,
Chungju, Chungbuk 380-702, South Korea

methods; potentially low cost due to batch fabrication, the ability to integrate transducers and signal conditioners on a single chip of less than 2mm in total thickness, and size miniaturization including the thickness of a transduction film on the micron scale. Compared to more popular capacitive-type MEMS acoustic devices, piezoelectric MEMS transducers are simpler to fabricate, free from polarization-voltage requirements, and are responsive over a wider dynamic range [6–8].

Even though piezoelectric MEMS transducers possess the advantages listed above, they suffer from a relatively low sensitivity for use in microphones and a low sound output pressure in microspeakers, this is mainly due to the tensile residual stress in the transducer diaphragm. Compressive residual stress of the diaphragm can solve these problems [9] but tends to wrinkle the diaphragm. This can however, produce large diaphragm deflection according to the inputs: air pressure in a microphone and large sinusoidal voltage in case of a microspeaker. The problem being is that it is very difficult to form a compressive silicon nitride film on a 6in. silicon substrate.

So, in this paper, we try to use composite diaphragm materials in order to control the total residual stress of the diaphragm structure so as to give more deflection of the diaphragm and present a piezoelectric microspeaker with an R.F. magnetron sputter-deposited ZnO film, through the use of simple, robust fabrication process steps in conjunction with a floating electrode. Finally, we compare the sound output pressure to previously reported results.

2 Experiments

Device concept Three types of materials are used for the diaphragm in order to support the structure in the microspeaker fabrication; the first is a tensile-stressed silicon nitride diaphragm which is used to make a diaphragm type microspeaker [10], the second is a Parylene diaphragm in order to give more flexibility in terms of diaphragm deflection [11], the third is a compressive silicon-nitride diaphragm structure [9] to provide large diaphragm deflection. The tensile-diaphragm structure exhibits a high sound pressure level (SPL) around its resonant frequency region, however, the SPL is low throughout the majority of the tested frequency range even with a high input voltage. This might be due to a high Young's modulus of the diaphragm material. The Parylene diaphragm seemed to be a promising material because it has a low Young's modulus, which is about 100 times lower than that of silicon nitride. But, it also did not exhibit a high SPL even with a 15–17$V_{\text{peak-to-peak}}$ sinusoidal input. However, the microspeaker with a compressive silicon nitride diaphragm showed a large SPL with a low applied input voltage of around 6$V_{\text{peak-to-peak}}$. The microspeaker with a compressive diaphragm produces a large sound pressure with low input voltage as previously reported [9].

Characterization of deposited films In this research, we used a 6in. silicon substrate for the characterization of films as well as the fabrication of piezoelectric microspeakers. After cleaning a silicon substrate, the thermal oxide layer was grown to a thickness of about 0.2μm (this is known to be a compressively stressed material) which was then followed by the deposition of the silicon nitride layer (Si_3N_4, which forms a highly tensile-stressed film) with a thickness of 0.1μm. Then, the low temperature oxide (LTO, which is a mildly compressive film depending on the following heat treatment) film was deposited onto the silicon-nitride film with a thickness of about 0.7μm. Then, a 0.5μm thick Al film was deposited onto the front side of the silicon substrate in order to be used as a seed layer for the piezoelectric ZnO film and the floating electrode. The curvature of the wafer and the thickness of each film were measured after the deposition of each film in order to figure out the exact residual stress of the films by using Stoney's equation [12] as shown by Eq. 1:

$$\sigma = \frac{E_s \cdot t_s^2}{6(1-\nu_s)t_f}\left(\frac{1}{R_s} - \frac{1}{R_f}\right) \tag{1}$$

Where, $E_s = 1.301 \times 10^5$ (MPa), $\nu = 0.279$, t_s is the thickness of the substrate (μm), t_f is the thickness of the film (μm), R_s is the curvature of the substrate (m), and R_f is the curvature of the substrate after depositing the film (m).

Since the quality of the ZnO film is highly related to the performance of the resulting piezoelectric microspeaker, the piezoelectric ZnO films were deposited using R.F. magnetron sputtering and have been characterized as a function of the Ar/O_2 gas ratio. The cross-sectional SEM photos were taken in order to confirm the crystalline structure of the deposited film and the XRD spectrum has been obtained to determine the orientation of the film according to the gas ratio. This is because the intensity of the XRD spectrum and the measured product (Bd_{31}) of the biaxial modulus (B) and the piezoelectric coefficient (d_{31}) are strongly related to each other as previously reported [13].

Device fabrication Four masks were used in the fabrication processes for the piezoelectric microspeaker shown in Fig. 1. First, a thermal oxide film was grown on bare silicon wafers in an oxidation furnace and then the stoichiometric silicon nitride film was deposited by LPCVD which was followed by low temperature oxide (LTO) deposition (a). The composite diaphragm (oxide/silicon nitride/low temperature oxide, ONO structure) is used to support the piezoelectric material and electrode,

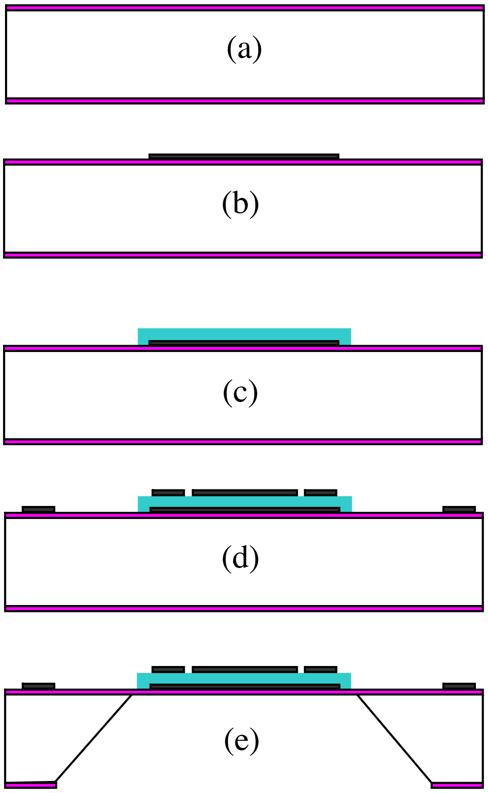

Fig. 1 Fabrication steps for the piezoelectric microspeaker with floating electrode

the total thickness of diaphragm is about 1.0μm. Next, a 0.5μm thick Al film was deposited on the front side of the wafers for the floating electrode in the microspeaker configuration. After patterning the Al film (b), a 0.5μm thick piezoelectric ZnO film was deposited by R.F. magnetron sputtering at a substrate temperature of 150° C, a chamber pressure of 23mTorr, an R.F. power of 1,500W and with an optimum Ar/O_2 gas ratio that was determined from previous test experiments. After pattering the ZnO with the second mask (c), a 0.5μm thick Al film was deposited to form the top electrodes and contact pads, which was then wet-etched by a wet Al etchant (a combination of $K_3Fe(CN)_6$, KOH and water) that does not attack the ZnO film (d). Then the backside ONO films were patterned by CF_4 RIE, followed by KOH etching of the silicon bulk (e) from the backside to release the diaphragm [14].

Figure 2 shows the photo of a fabricated 6in. silicon wafer that contains the microspeakers built on the ONO diaphragm sandwiched between Al electrodes. We designed and fabricated various kinds of piezoelectric microspeakers (on a 4.5 × 4.5mm2 diaphragm) with circular electrode shapes (2 to 3mm in diameter), as well as grand cross (1.67mm wide and with its four edges freed from silicon), and square shapes as can be seen in Fig. 2. Among the various microspeakers shown in Fig. 2, two distinct fabricated microspeakers were tested. They have two topside electrodes; one is located at the center of the diaphragm and another surrounds the peripheral of the inner electrode.

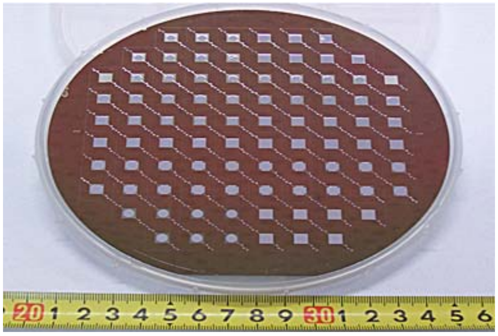

Fig. 2 Photo of fabricated microspeakers on a 6 in. wafer

Testing of fabricated microspeakers After fabricating the microspeakers, the characteristics of the microspeakers were measured in order to compare the performance of the microspeakers.

Figure 3 shows the experimental setup for measuring the acoustic output pressure level. The sinusoidal output signal, which is coming from an NI sound and vibration board, is fed to the PCB that has an amplification circuit and two opposite signal output ports. Two amplified output signals, which have different polarities with $5V_{\text{peak-to-peak}}$ voltages, are applied to the fabricated microspeakers. The output pressure generated by the fabricated microspeakers was measured by the reference microphone (B&K 4192L with a preamplifier, the sensitivity of the microphone was 1V/Pa), then the converted output voltages coming from the reference microphone were stored in the main computer

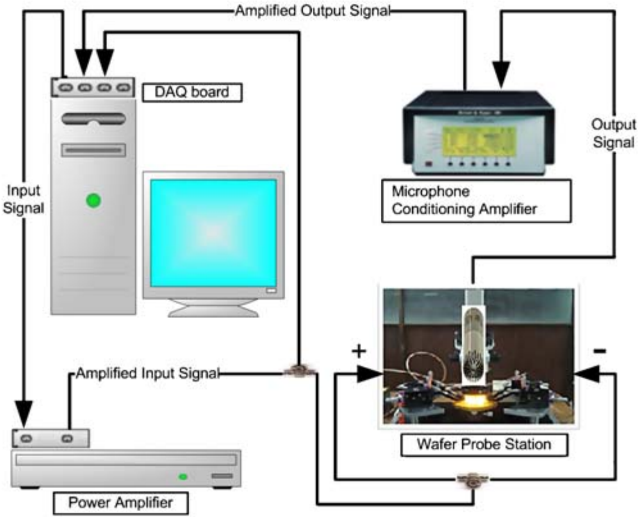

Fig. 3 Experimental setup for the testing of fabricated microspeakers

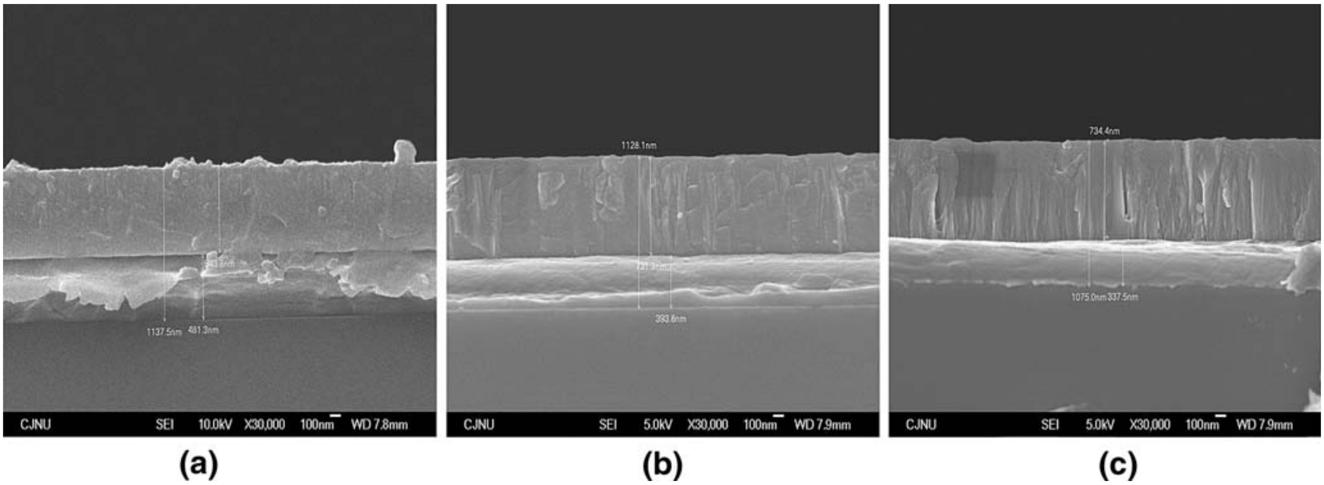

Fig. 4 Cross-sectional SEM photos of ZnO films deposited using different Ar/O_2 gas ratios; (**a**) Ar/O_2=30/75, (**b**) Ar/O_2=75/30, (**c**) Ar/O_2=120/30

via a DAQ (Data Acquisition) board. The distance from the fabricated microspeakers to the reference microphone was 3mm. The input signal frequency range was from 400Hz to 12kHz. After finishing the measurement, the SPL of the fabricated microspeakers was calculated. In order to obtain a reliable SPL of the fabricated microspeakers, we tested the microspeakers more than ten times and averaged the measured data.

3 Experimental results and discussion

In order to enhance the quality of ZnO films for improving the microspeaker performance, we have investigated the ZnO film quality as a function of the Ar/O_2 gas ratio, and have reported the results below.

Figure 4 shows the cross-sectional SEM photos of deposited ZnO films as a function of the Ar/O_2 gas ratio. In this experiment, the other deposition conditions are as follows; the substrate temperature was maintained at 150°C, the R.F. power was 1,500W and the chamber pressure was 23mTorr. As can be seen in Fig. 4(a), when the gas ratio is 30/75, the deposited film shows an amorphous state. However, as the Ar/O_2 gas ratio is increased from 75/30 to 120/30, a ZnO (002) orientation that is perpendicular to the substrate becomes dominant.

Figure 5 shows an XRD spectrum of the ZnO films deposited at various Ar/O_2 gas ratios. As previously described in Fig. 4, when the Ar/O_2 gas ratio is 120/30, the XRD spectrum shows the highest intensity as can be seen in Fig. 5. Since the XRD peak intensity is strongly related to the piezoelectric properties [13], the deposition conditions for the microspeaker were set as follows; the substrate temperature was 150°C, the R.F. power was 1,500W, the chamber pressure was 23mTorr and the Ar/O_2 gas ratio was 120:30.

Since the residual stresses of the deposited films are very critical for the fabrication and the performance of microspeakers, they were quantified after the growing and the deposition of the films. The thermally grown oxide film was near to −350MPa (compressive stress), the silicon nitride was about +1.1GPa (highly tensile) and the residual stress of the LTO was −50MPa (mild compressive stress). The residual stress of the deposited ZnO films decreased from −1.71 to −1.37GPa, as the Ar/O2 gas ratio was increased from 30:75 to 120:30.

Figure 6 shows the tested microspeakers that were fabricated onto a 6in. silicon wafer as shown in Fig. 2. Underneath the top electrodes and piezoelectric ZnO film, there is a floating electrode as described in Fig. 1 in order to cause a high strain in the diaphragm due to piezoelectric actuation.

The frequency responses of the microspeakers were measured between 400Hz and 12kHz, and the results are shown in Fig. 7 along with previous experimental results [13].

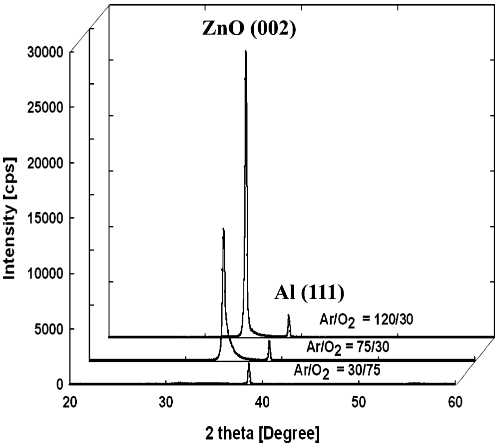

Fig. 5 XRD spectrum of ZnO films deposited using different Ar/O_2 gas ratios

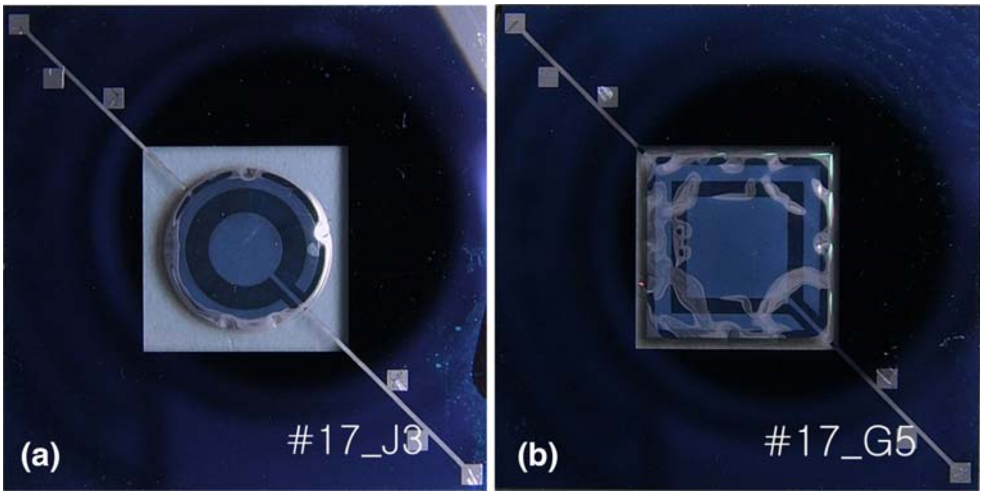

Fig. 6 Fabricated microspeakers tested in this research; (**a**) circular type, (**b**) square type

The reasons for the differences between the previous results and the current results are as follows first is the use of a high quality ZnO film and a floating electrode, second is a difference in input voltages. In the frequency range between 400 and 2,700 Hz, the fabricated microspeaker (#17_G5, which was tested with a 5 $V_{\text{peak-to-peak}}$ input signal) resulting from this research produces comparable sound output pressure as the previously reported one, which was tested with a 6 $V_{\text{peak-to-peak}}$ input signal. From 2,800 Hz to nearly 3100 Hz, the previous microspeaker shows a high sound pressure output. However, the newly fabricated microspeaker (#17_G5) has a large sound pressure output level throughout the testing frequency range even with a 5 $V_{\text{peak-to-peak}}$ input signal. The circular-type microspeaker (#17_J3) produces a relatively smaller output pressure level than that of the square-type (#17_G5). So, we can say that the larger the actuation area, the higher the SPL that can be achieved. As can be clearly seen in Fig. 6, the diaphragm of the microspeaker looks flat at the outside of the active piezoelectric film, even though the inside of the outer top-electrode is severely wrinkled. This may be due to the etching of the thermally grown oxide during the silicon substrate releasing process using KOH etchant at 80°C. In this case, the total residual stress except for the thermal oxide is calculated to be+94 MPa by the use of Eq. (2) [15]:

$$\sigma_{\text{total}} = \frac{\sigma_{\text{Si}_3\text{N}_4} \cdot t_{\text{Si}_3\text{N}_4} + \sigma_{\text{LTO}} \cdot t_{\text{LTO}}}{t_{\text{total}}} \tag{2}$$

where, $\sigma_{\text{Si}_3\text{N}_4}$: is the residual stress of the silicon nitride, $t_{\text{Si}_3\text{N}_4}$: is the thickness of the silicon nitride, σ_{LTO}: is the residual stress of the LTO, and t_{LTO}: is the thickness of the LTO.

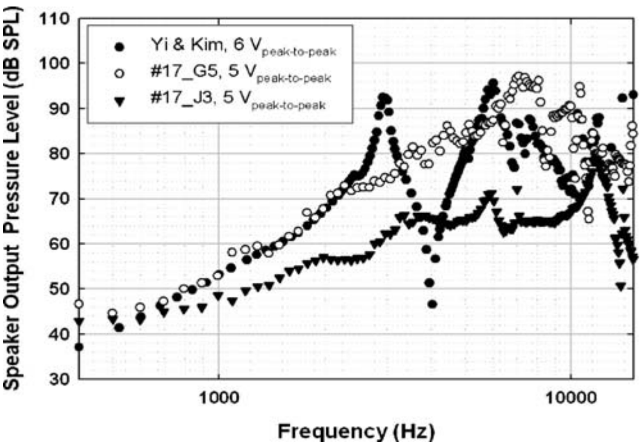

Fig. 7 Frequency responses of MEMS piezoelectric microspeakers between 0.4 and 15 kHz (without acoustic coupler)

However, since the residual stress of the deposited ZnO film is around −1.37 GPa, the actuation region of the fabricated microspeakers is wrinkled in both cases shown in Fig. 6.

As shown in Fig. 7, the circular-type microspeaker exhibits a smaller sound output pressure than that of the square-type. Even though the two devices are on the same wafer, the square-type exhibits a more winkled diaphragm structure than that of the circular-type. So, we could say that the more compressive the diaphragm is, the easier it is to achieve a large deflection. Also, the fabricated microspeakers having a floating electrode beneath the piezoelectric film seem to produce a higher diaphragm deflection. Since input voltages of opposite polarities are applied at the top electrodes, the diaphragm expands and contracts around the areas of electrodes, thus providing more upward movement. This achieves a higher sound output pressure with a lower driving voltage (5 $V_{\text{peak-to-peak}}$) than the previous result actuated at 6 $V_{\text{peak-to-peak}}$.

4 Conclusion

The piezoelectric microspeakers are fabricated with a high quality ZnO film and a floating electrode with a mildly tensile stressed ONO diaphragm. The ZnO film deposited with a high Ar/O_2 gas ratio has a slightly smaller compressive stress than that using a low Ar/O_2 gas ratio, furthermore, it shows excellent *c*-axis orientation and fine grains as the Ar/O_2 gas ratio is increased. The piezoelectric microspeakers built with a large compressive residual stress in a composite diaphragm are shown to produce a large sound output pressure. Since the top electrodes are biased with opposite polarities, there is a greater strain in the diaphragm with the floating electrode. Even though the fabricated microspeakers don't have a final housing structure, the sound output is comparable to the previous results even with a reduced input voltage. It is therefore apparent that the fabricated microspeaker presented in this research is a promising candidate for the next generation acoustic components.

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