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Fabrication and characterization of PMN-PT single crystal cantilever array for cochlear-like acoustic sensor †

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Abstract

We have successfully fabricated piezoelectric PMN-PT single crystal cantilever array. Each PMN-PT cantilever has a different length to achieve different resonance frequencies. The width and thickness of PMN-PT cantilever array are 200 μm and 10 μm, respectively. Resonance frequencies of PMN-PT cantilevers were measured with laser interferometer, and charge sensitivity was measured with charge-measuring device. PMN-PT cantilever array was installed in a noise-shield case. The array was then exposed to sound pressure frequency corresponding to resonance frequency to measure its sensitivity. The experimental results show that the PMN-PT cantilever array has high sensitivity to the sound pressure. This implies that the single crystal PMN-PT cantilever array is a potential candidate for a cochlear-like acoustic sensor.

Keywords: PMN-PT; Piezoelectric; Cantilever array; Resonance; Acoustic sensor

1. Introduction

Studies of artificial sensory systems mimicking human and animal senses are increasing worldwide, with scientists looking to nature to find the solution. Currently, artificial cochlea have been developed in an effort to correct the sensorineural hearing loss of patients. An artificial cochlea consists of a microphone for converting sound to electrical signal, a signal processor for handling the sound signal, inductive coil for transmitting sound signal from outside to inside of the body, and electrode array for stimulating nerve cells. Current technologies of the artificial cochlea have limited its widespread use among the majority of the hearing-impaired people due to the high expense, inconvenience, and the frequent recharging requirement caused by large power consumption [1, 2]. Piezoelectric materials have the unique property of being able to generate electrical charge when an external mechanical force is applied. Conceptually speaking, due to their nonexistent transduction mechanism, these materials are ideally suited as replacement of "organs" for patients suffering from profound sensorineural hearing loss [3].

In this paper, we have studied the feasibility of using PMN-PT ((1-x)Pb $(Mg_{1/3}Nb_{2/3})O_3$-x$PbTiO_3$) single-crystal piezoelectric cantilever array as an alternative to conventional artificial cochlea. For this purpose, we fabricated piezoelectric PMN-PT cantilever arrays with a width of 200 μm and a thickness of 10 μm. The length of the cantilever was varied to achieve target resonance frequency. Resonance frequency of the PMN-PT cantilevers was measured with laser interferometer, and charge sensitivity was measured with a charge-measuring device. The PMN-PT cantilever arrays were exposed to sound pressure frequency corresponding to resonance frequency to measure the sensitivity of the array. The experimental results show that the PMN-PT cantilever arrays exhibit high sensitivity to the applied sound pressure. This implies that the single crystal PMN-PT cantilever array is a potential substitute for the current cochlear-like acoustic sensor.

2. Experimental procedure

2.1 Fabrication of PMN-PT cantilever

Fig. 1 shows the dimensions of the PMN-PT single crystal cantilever and the interdigitated electrode. A pair of interdigitated electrodes was designed with 5 μm comb width and 10 μm comb gap. The interdigitated electrodes were located at the supporting position of the cantilever because the strain is maximized near the supporting position.

A flow diagram of the fabrication process is shown in Fig. 2. A poled <001> oriented 500 μm-thick PMN-PT single crystal was glued on a Si substrate. The PMN-PT layer was mechanic-

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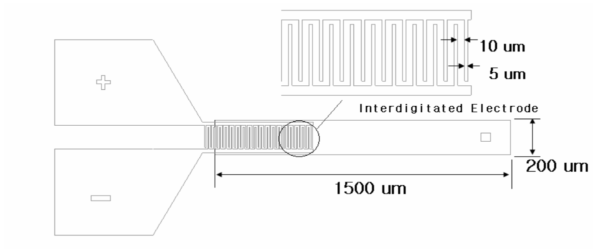


Fig. 1. Dimensions of PMN-PT cantilever and interdigitated electrode.

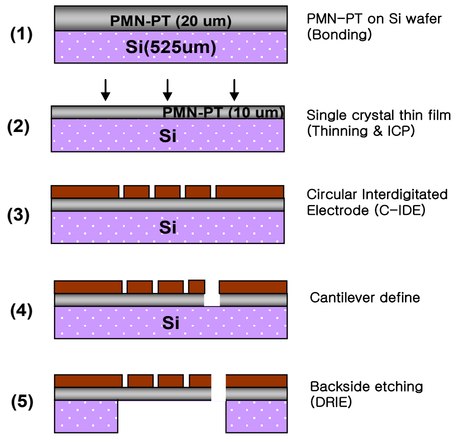


Fig. 2. Fabrication process for PMN-PT single crystal cantilever.

cally polished down to a 20-25 μm-thick film. Inductively coupled plasma (ICP) etching was done to make the PMN-PT layer thinner, and the etching resulted in a 13 μm PMN-PT layer. To pattern the upper electrode, Au e-beam sputtering was used, following the photo-resistive coating for lift off process. The ICP etching process was applied again to define the cantilever shape. As a final step, deep reactive ion etching (DRIE) was done on the backside of the wafer.

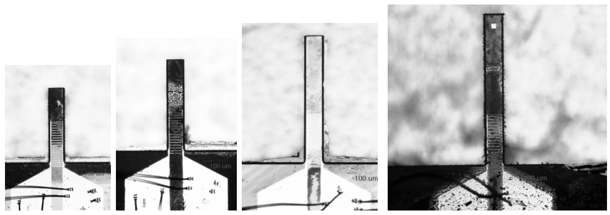
The lengths of the fabricated PMN-PT single crystal cantilevers were varied at 900, 1000, 1300, and 1500 μm, as shown in Fig. 3. Wire bonding was done for each pair of two cantilevers with the same length.

2.2 Characterization of PMN-PT cantilever

To measure the resonance frequency of a fabricated PMN-PT single crystal cantilever, a probe was connected to the positive and negative electrodes of the PMN-PT single crystal cantilever. The voltage signal of DC 2.5 V and AC 1.0 $V_{p\text{-}p}$ with a sine wave form 200 Hz to 4000 Hz was swept. The electric field was applied between the interdigitated electrodes, and the cantilever was deflected following the sine wave signal. The experimental setup for measuring the deflection of PMN-PT cantilever consisted of vibrometer controller (Polytec OFV-5000), fiber interferometer (Polytec OFV-512), and dynamic signal analyzer (Agilent 35670A). The measured deflection of PMN-PT cantilever was about 13 μm, peak to peak. We also measured impedance magnitude and impedance phase angle using HP 4194A impedance analyzer. A typical impedance measurement result is shown in Fig. 4. Two cantilevers with the same size (Set 4 in Table 1) were connected to the impedance analyzer. The impedance measurement was done for both of the cantilevers at the same time, and the resonance frequencies were measured at 4.25 kHz and 4.96 kHz. This discrepancy might be caused by the microelectromechanical systems (MEMS) fabrication methods, especially DRIE, with acceptable tolerance of a few microns.

Table 1. Resonance frequencies for PMN-PT cantilevers.

Cantilever length (μm)	Resonance frequency (measured)	Resonance frequency (designed)	Remarks
1500	1.74/1.93 kHz	1.46 kHz	Cant. Set 1
1300	2.41/2.62 kHz	1.94 kHz	Cant. Set 2
1000	3.26/3.97 kHz	3.28 kHz	Cant. Set 3
900	4.25/4.96 kHz	4.05 kHz	Cant. Set 4



(a) Length= 900μm (b) Length= 1000μm (c) Length= 1300μm (d) Length= 1500μm

Fig. 3. The fabricated PMN-PT cantilevers.

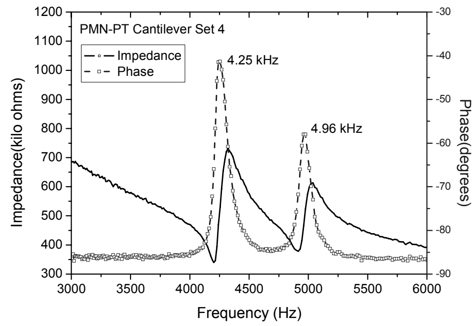


Fig. 4. Impedance measurement for the PMN-PT cantilever Set 4.

Table 1 shows the designed and measured resonance frequencies of the fabricated PMN-PT single crystal cantilevers using HP 4194A impedance analyzer. It was shown that two cantilevers of the same length have relatively different resonance frequencies. However, the measured resonance frequency is similar to the designed frequency. The density and elastic modulus used to calculate the designed resonance frequencies are 8200 kg/m^3 and 20 GPa.

The mechanism of generating charge in a PMN-PT cantilever is as follows: as PMN-PT cantilever deflects along the interdigitated electrode, causing stress on the cantilever, the variation of stress in the cantilever produces a self-generated charge on the electrode. Fig. 5 shows an experimental setup of the charge-measuring system, which can measure piezoelectric charges. The system consisted of differential charge amplifier, laser displacement measuring device, and precision

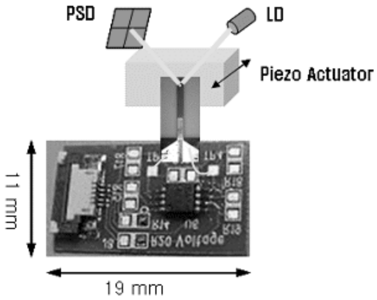


Fig. 5. Experimental setup for charge measurement.

displacement actuator. The differential charge amplifier used feedback capacitance and feedback resistance of 5 pF and 22M Ω, respectively. The generated charge signal was amplified 10 times with an instrumental amplifier.

To reduce measuring noise, the PMN-PT single crystal cantilever was directly installed on the circuit board of the charge amplifier. A precise piezoelectric actuator was used to test the PMN-PT single crystal cantilever with displacement range of 40 nm to 330 nm, using a square wave of 10 Hz. Piezoelectric charge was measured with charge-measuring system as the piezo-actuator moved the tip of cantilever up and down. The deflection was measured with laser diode and photo sensitive detector.

3. Results and discussions

Shown in Fig. 6 are the results for charge sensitivity as a function of PMN-PT cantilever deflection. We measured two samples of PMN-PT single crystal cantilevers. The charge sensitivity of two samples was measured at 2.1 fC/nm and 2.2 fC/nm.

Fig. 7 shows the experimental setup for acoustic sensitivity measurement. The PMN-PT cantilever was installed 4 cm away from the speaker. This experimental setup was placed in an anechoic chamber (Type 4232 B&K) to reduce surrounding noise. Speaker improved the equalized sound pressure of 1 Pa from 1 kHz to 6 kHz with sound signal sweep. The charge signal generated in the PMN-PT cantilever was processed with sound processing software.

Fig. 8 shows the acoustic sensitivity and the signal- to-noise ratio of PMN-PT cantilever Set 3. This PMN-PT cantilever can detect 1000 times of the signal to noise ratio and can selectively detect the specific frequency with 18 times higher than signal level. Fig. 9 shows the acoustic sensitivity for each set of PMN-PT cantilever. The resonance frequencies from 1741 Hz to 4960 Hz were obtained from the four sets of PMN-PT cantilevers.

The responses of PMN-PT cantilevers in dB as functions of sound pressure are given in Fig. 10 for cantilevers 1500 μm and 500 μm in length. The linearity is valid for both 1.2 kHz and 11.5 kHz. Fig. 11 shows the directivity of sound pressure level of PMN-PT cantilever with 1500 μm length at 1.2 kHz. The measurement was done in an anechoic chamber (Type 4232 B&K) at a distance of the 4 cm. As can be seen from Fig.

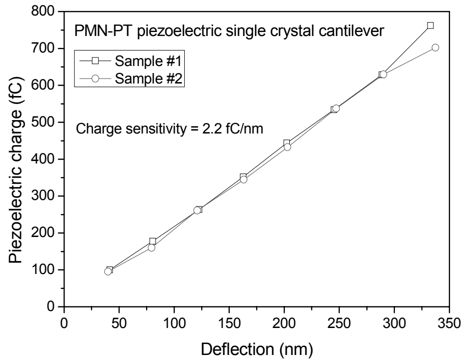


Fig. 6. Piezoelectric charge output as a function of PMN-PT cantilever deflection.

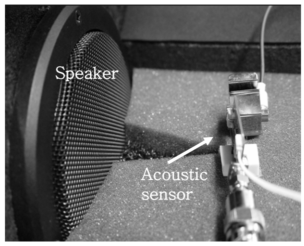


Fig. 7. The experimental setup for acoustic sensitivity measurement of PMN-PT cantilever.

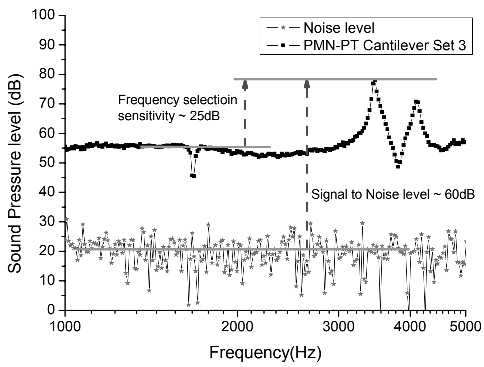


Fig. 8. The acoustic sensitivity of PMN-PT cantilever Set 3.

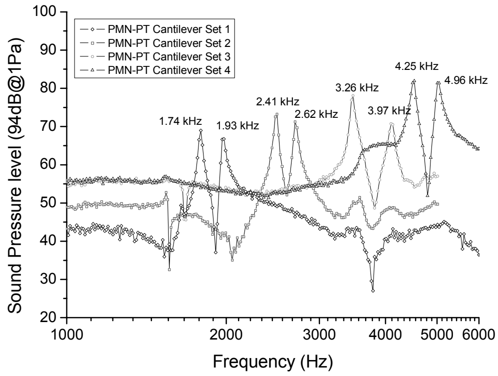


Fig. 9. The experimental results of acoustic sensitivity for each PMN-PT cantilever.

11, the directivity of the PMN-PT cantilever is almost symmetrical for 1.2 kHz.

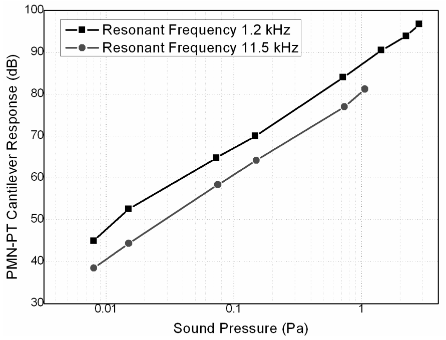


Fig. 10. Acoustic sensitivity vs. sound pressure (lengths are 1500 µm and 500 µm for 1.2 kHz and 11.5 kHz, respectively).

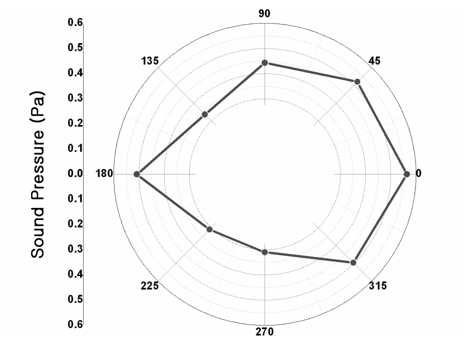


Fig. 11. Directivity of PMN-PT cantilever with 1500 µm length.

4. Conclusions

In this study, PMN-PT cantilevers with six different lengths were designed, fabricated, and characterized using impedance measurement, charge-measuring device, laser interferometer, and microphone. The acoustic characterization was done in an anechoic chamber to minimize external noise. The fabricated PMN-PT cantilevers were subsequently exposed to sound pressure frequency corresponding to resonance frequency to measure their sensitivity. The experimental results show that the PMN-PT cantilever array has high sensitivity to sound pressure. The linearity of the PMN-PT cantilever as a function of deflection and sound pressure was also demonstrated. The directivity of the PMN-PT cantilever was almost symmetrical at 1.2 kHz. Thus, the single crystal PMN-PT cantilever array is a potential candidate for cochlear-like acoustic sensor. The PMN-PT cantilever presented in this study represents the first generation of our design. Further research is underway to improve the performance and to more precisely characterize the PMN-PT cantilever.

Acknowledgement

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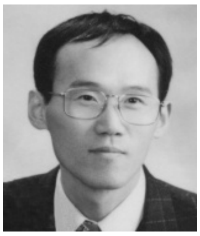

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