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Biomimetic acoustic sensor based on piezoelectric cantilever array

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Abstract: In this research, a biomimetic acoustic sensor that can mimic the functional properties of basilar membrane in mammalian cochlea was fabricated with PMN-PT piezoelectric cantilever array. The piezoelectric cantilever array with ten different lengths was designed to obtain different resonant frequencies. It was fabricated by semiconductor processes and was poled to generate an electrical signal from an audible sound source. The fabricated acoustic sensor was tested by experimental setup. As an experimental result, the resonant frequencies of each cantilever and corresponding electrical signals were measured from 490 Hz to 13,600 Hz and the displacement sensitivity was measured with the audible frequency range.

Keywords: biomimetic, piezoelectric, cantilever array, acoustic sensor
Classification: Micro- or nano-electromechanical systems

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1 Introduction

Current technologies of artificial cochlea implants have limited its widespread use among the majority of the hearing-impaired due to its high expense, inconvenience, and the need for frequent recharging caused by heavy power consumption [1]. In respect to this point, piezoelectric materials have the unique property of being able to generate an electrical current when an external sound pressure transforms it. Due to their self-powering property, these materials are ideally suited as a replacement for the cochlear function of patients suffering from profound sensorineural hearing loss. The development of a working piezoelectric cochlear implant poses serious challenges for piezoelectric materials. Current piezoelectric materials have not sufficient properties so that the generated charge can't stimulate the nerves, without any need for amplification [2]. Several researchers carried out various studies on the artificial basilar membrane mimicking structure and function of human cochlea. Tanaka et al. [3] and Xu et al. [4] developed acoustic sensors with the function of frequency selectivity by the use of resonance of cantilever arrays. Ito et al. [5] developed a PVDF piezoelectric artificial cochlea which worked as a sensor with the acoustic/electric conversion and with the frequency selectivity based on MEMS technology. In this paper, we studied the feasibility of single crystal PMN-PT piezoelectric cantilever array as an alternative for basilar membrane and mechanosensitive ion channel of cochlea. The single crystal PMN-PT ($(1\text{-x})[Pb(Mg_{1/3}Nb_{2/3})O_3]\text{-x}[PbTiO_3]$) is a new generation of piezoelectric materials and have higher piezoelectric constants and lower dielectric losses compared to PZT materials [6]. The PMN-PT cantilever array was fabricated and tested to find resonant frequencies, generated voltages and sensitivity within the audible frequency range. The experimental results show that the biomimetic acoustic sensor based on PMN-PT cantilever array exhibits proper resonant frequency and displacement sensitivity for a sound signal of audible frequency bandwidth. Also, the biomimetic acoustic sensor generates a voltage signal corresponding to each resonant frequency of each piezoelectric cantilever. This implies that the fabricated biomimetic acoustic sensor can be applied as a potential candidate for the next artificial cochlear implant.

2 Design and fabrication process

The natural frequency for the first mode of the cantilever can be calculated by using formula (1). We want to obtain the resonant frequency components between 400 Hz and 14,000 Hz by using ten piezoelectric cantilevers so that we can mimic the frequency separation characteristics of basilar membranes.

$$\omega_{\mathrm{n}} = (1.875)^2 \sqrt{\frac{\mathrm{EI}}{\mathrm{mL}^4}} \quad (1)$$

E: Young's modulus of elasticity, I: bending moment of inertia,
m: mass of cantilever, L: length of the cantilever beam,
$\alpha_{\mathrm{n}}A$: coefficients of first mode shape ($\alpha = 1.875$, $n = 1$)

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Ten piezoelectric cantilevers with lengths of 550, 800, 950, 1150, 1350, 1600, 1900, 2300, 2700 and 3000 μm, width of 300 μm and thickness of 15 μm were designed with formula (1). The density and elastic modulus of PMN-PT materials is 8200 kg/m^3 and 20 GPa. A pair of interdigitated electrodes with 5 μm comb width and 10 μm comb gap was designed to obtain the maximum strain at the supporting position of the cantilever.

The fabrication process of PMN-PT piezoelectric cantilever array is explained here. The <001> oriented 500 μm-thick single crystal PMN-PT film was glued on a Si wafer substrate. The PMN-PT layer was mechanically polished down to a 20–25 μm-thick film. Inductively coupled plasma (ICP) etching was performed to make the PMN-PT layer thinner, and the etching resulted in about 15 μm-thick PMN-PT layer. To pattern the upper electrode, Au e-beam sputtering was used, following the photo-resistive coating for the 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 performed on the backside of the wafer. PMN-PT piezoelectric cantilever array with interdigitated electrodes was fabricated as shown in Fig. 1. For convenience, the electrodes are named as Ch. 1–Ch. 10 as shown in Fig. 1. A gold mark was made to measure a vibration movement of each microcantilever by using LDV (Laser Doppler Vibrometer) scanning system.

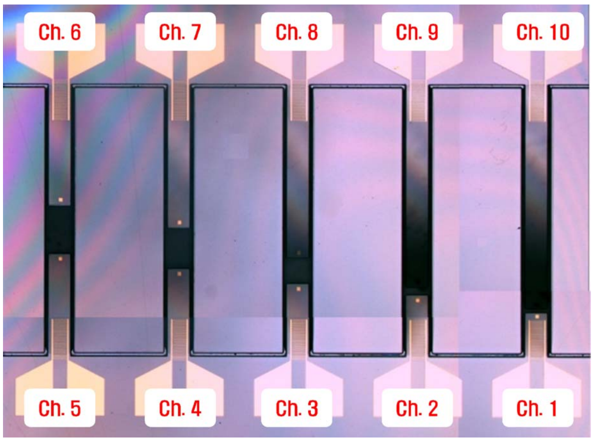

Fig. 1. Fabricated sample of single crystal PMN-PT piezoelectric cantilever array.

3 Measurements results

Each of the PMN-PT piezoelectric cantilevers were poled with polarization conditions of DC 30 V for 20 min. The experimental setup for measuring the resonant frequencies of PMN-PT piezoelectric cantilever array consisted of an impedance analyzer (Agilent 4294A) and probe station. Two probe tips of the probe station were contacted with the positive and negative electrodes of the PMN-PT piezoelectric cantilever. The voltage signal of DC 20.0 V and AC 1.0 Vp-p, current 10 mA with a sine wave between 50 Hz and 15,000 Hz was swept to measure the resonant frequency.

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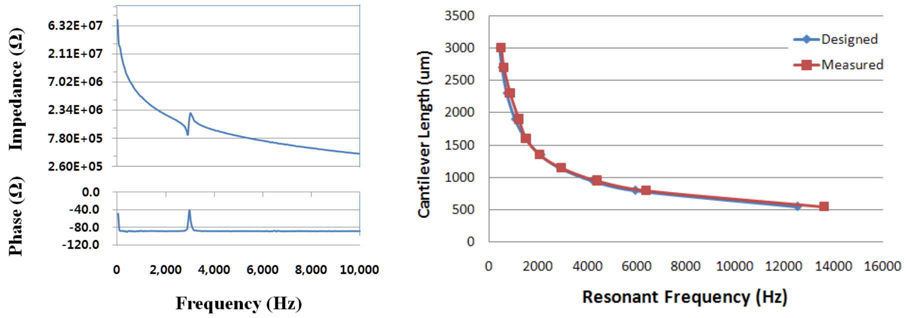
Fig. 2 (a) shows the impedance and phase behavior of the PMN-PT cantilever (Ch. 4) measured by an experimental setup. The resonant frequencies of PMN-PT piezoelectric cantilevers were measured with a rapid change of impedance and phase. The resonant frequencies of ten piezoelectric cantilevers were measured between 490 Hz and 13,600 Hz and were similar with the designed resonant frequency as shown in Fig. 2 (b).



(a) (b)

Fig. 2. Electromechanical measurement of PMN-PT piezoelectric cantilever array, (a) impedance and phase measurements (b) comparison of designed and measured resonant frequency for cantilever lengths.

The experimental setup for measuring acoustic sensitivity of PMN-PT piezoelectric cantilever array was composed with LDV scanning head, vibrometer controller (Polytec OFV-5000), Junction box (Polytec PSV-400), mouth simulator (Type 4227 B&K), Condenser microphone (Type 4176 B&K) and personal computer. Mouth simulator (sound generator) was connected with a junction box that can generate sine signals from 20 Hz to 20,000 Hz and the condenser microphone was connected with input reference of the junction box. To measure the vibration behavior of piezoelectric cantilevers, each gold mark on a cantilever tips was sequentially scanned by a laser spot of an LDV scanning system.

Fig. 3 (a) shows displacement behaviors that exhibit a peak of the first mode shape of each PMN-PT piezoelectric cantilever. It shows that the displacement values of cantilever Ch. 10, 9, 8 and 7 are larger than ten times of the remaining cantilever. The displacement of cantilever Ch. 10, 9, 8, 7 and 6 are 6.28 nm, 12.6 nm, 13.0 nm, 6.77 nm and 0.83. Also, the displacement of cantilever Ch. 5, 4, 3, 2 and 1 are 0.42 nm, 0.35 nm, 0.04 nm, 0.01 and 0.01 nm. It shows that the longer the cantilever is, the larger the displacement value is generated. Also, the resonant frequencies measured by LDV scanning techniques were similar with those measured using an impedance analyzer.

Fig. 3 (b) shows the acoustic sensitivity of each PMN-PT piezoelectric cantilever. The acoustic sensitivity was calculated by measuring the generated voltage of the piezoelectric cantilever corresponding to the constant sound pressure of 1 Pa. The maximum voltage generated from the piezo-

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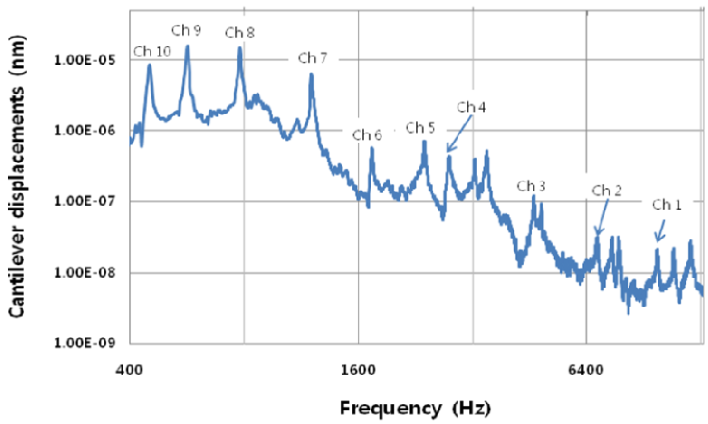
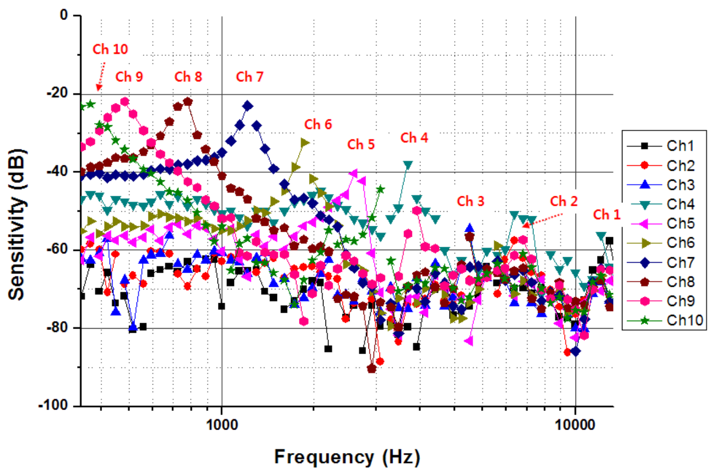
electric cantilever is 80.4 mV on cantilever Ch. 9 and the minimum voltage is 1.27 mV on cantilever Ch. 1. The frequency response curve of each cantilever shows a maximum voltage value at the resonant peak and exhibits similar frequency envelops with basilar membrane of mammalian cochlea. It shows that the longer the cantilever is, the higher the sensitivity is obtained. However, the sensitivity of small cantilevers needs to be improved by an electrical signal conditioner to use as a core device for next generation artificial cochlear implants.



(a)



(b)

Fig. 3. The measurement results of cantilever displacement and sensitivity of PMN-PT piezoelectric cantilever array, (a) cantilevr displacement vs. frequency by LDV and (b) sensitivity vs. frequency by acoustic analyzer.

4 Conclusion

In this study, we have studied the feasibility of single crystal PMN-PT piezoelectric cantilever array as an alternative for basilar membrane and

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mechanosensitive ion channel of mammalian cochlea. PMN-PT piezoelectric cantilevers array was designed to imitate signal processing functions of basilar membranes. It was fabricated and tested to find a resonant frequency and sensitivity within an audible frequency range. Each cantilever showed different resonant frequencies from 490 Hz to 13,600 Hz. The resonant frequencies of PMN-PT piezoelectric cantilevers array measured by using an impedance analyzer were similar with the designed frequency. Also, the displacement and sensitivity of PMN-PT piezoelectric cantilever was measured by using an LDV scanning system. The experimental results show that the PMN-PT cantilever arrays exhibit proper sensitivity with an applied sound signal. This implies that the single crystal PMN-PT piezoelectric cantilever array is a candidate as a potential alternative for the current artificial cochlear implant.

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