PIEZOELECTRIC ALN CANTILEVER ARRAY ON A SU-8 SUBSTRATE FOR FLEXIBLE ARTIFICIAL BASILAR MEMBRANE

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ABSTRACT
Artificial basilar membrane (ABM) has been developed to mimic the cochlea's transduction and mechanical frequency selectivity. In our previous study, ABM was designed as a cantilever array on silicon substrate using aluminum nitride. However, its frequency range was relatively high (2.92 – 12.6 kHz) compared to the communication range of human (300 – 3,400 Hz). To lower the frequency response range of the ABM, we fabricated piezoelectric aluminum nitride (AlN) cantilever array on a flexible SU-8 substrate. The deposited AlN thin film exhibited c-axis orientation on the cured SU-8 film, which was identified by SEM and XRD. The fabricated AlN cantilever array demonstrated piezoelectric characteristics with mechanical frequency selectivity, which is a vital function for artificial basilar membrane.

INTRODUCTION
The cochlea is a transducer and frequency analyzer for hearing [1]. Basilar membrane (BM) is a flexible membrane in cochlea to separate sound frequency [2]. The vibration of the BM initiates the ion channel opening, which causes the action potential for stimulating auditory neurons [3]. In addition, the BM mechanically separates the frequencies of sound because the BM have variable width, thickness, and stiffness by its location [4].

Both the transduction and the mechanical frequency selectivity of the cochlea have been motivated to several researcher who attempted to develop artificial basilar membranes (ABMs) [5-14]. The ABMs are acoustic transducers having mechanical frequency filters. The transduction mechanism was mainly realized by piezoelectric effect [5-10], optical readout [11], and recently triboelectric effect [12]. The frequency separation also was achieved by several design parameters such as variable length of beam [8-10, 13], wide of membrane [5-7], and beam thickness [14].

Previously, our group have developed ABMs by arrays of beams or cantilevers using piezoelectric aluminum nitride (AlN) [8-10]. However, the AlN ABM had relatively high frequency response ranges (2.92 kHz – 12.6 kHz) comparing with communication range of human (300 Hz – 3,400 Hz) [10]. To lower the frequency response range of the AlN ABM, we propose another AlN ABM based on a flexible SU-8 substrate.

Among the flexible piezoelectric materials, the Polyvinylidene fluoride (PVDF) was the most commonly used for flexible devices. Although, the PVDF has a high flexibility, there are several disadvantages for traditional microelectromechanical system (MEMS) fabrication [15]. The curie temperature of PVDF is relatively low (120℃) and melting point is 150℃. In addition, PVDF requires poling process to keep piezoelectric properties [16]. To overcome the disadvantages of PVDF, researchers attempted to deposit AlN on polyimide film using DC magnetron sputter. AlN on polyimide film successfully showed highly c-axis orientation with piezoelectric characteristics [15-17]. However, there are limited studies for device fabrication using AlN on polyimide because basically the polyimide is not a photosensitive material.

In this research, we proposed AlN cantilever array on a SU-8 substrate for flexible ABM. SU-8 is well-known negative-tone thick photoresist for microfabrication technology. In addition, the Young's modulus of SU-8 (4.4 GPa) was lower than silicon substrate (170 – 190 GPa) [18], which will effectively lower the frequency response range of the ABM. Here, we characterized the piezoelectric characteristics and mechanical frequency selectivity of the SU-8 based flexible ABM for mimicking the functionality of cochlea.

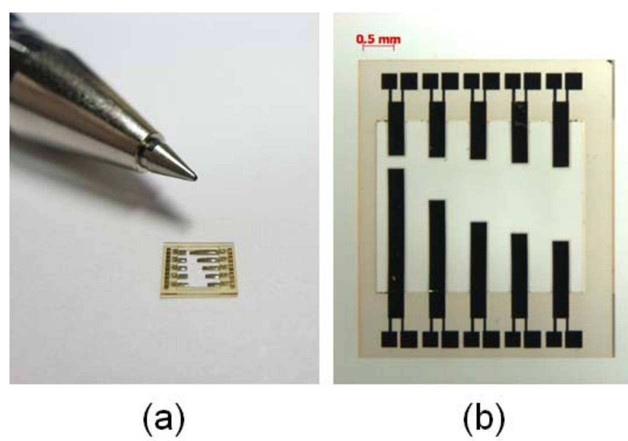


Figure 1 : (a) Optical images of the fabricated artificial basilar membrane (ABM). (b) Optical micrograph of the ABM.

DESIGN AND FABRICATION
The SU-8 based ABM consists of ten cantilevers in the array. The length of cantilever is a design parameter for

mechanical frequency selectivity. Figure 1 shows the optical images (Figure 1a, 1b) of the fabricated ABM. The length of beam varies from 580 μm to 2,000 μm (Table 1) and the width of beam is 300 μm. The footprint of the device is $4\times4.5mm^2$.

Table 1: Lengths of the cantilevers and the resonance frequencies measured by mechanical displacement.

Channel	Length of beam [μm]	Resonance frequencies [Hz]
1	580	5,181
2	610	4,847
3	645	4,509
4	700	3,819
5	765	3,381
6	850	3,041
7	970	2,288
8	1,150	1,931
9	1,500	1,409
10	2,000	968

The fabrication process is schematically shown in Figure 2. First, a Cr/Au/Cr (5 nm/50 nm/20 nm) was deposited on the silicon wafer as a sacrificial layer (Figure 2a). A 1.5 μm-thick- SU-8 2002 was spun on the wafer and patterned (Figure 2b). A Ti/Au/Mo (20nm/100nm/100nm) bottom electrode was deposited by sputtering and patterned by lift off process (Figure 2c). Molybdenum (Mo) was used for growing (002) oriented AlN film with good crystal uniformity [19]. Then, AlN was deposited by DC reactive sputtering system (SRN-120, SORONA, South Korea) as shown Figure 2d. The sputtering conditions were following: 1200 W for 390 sec, 2.5mTorr at room temperature. Target to substrate distance: 60 mm, and Ar/N_2 flow rate: 20 sccm/10 sccm. Top electrode (Ti/Au) was coated by sputtering and patterned by lift off (Figure 2e). As shown in Figure 2f and 2g, a 10 μm-thick SU-8 2010 and a 300 μm-thick SU-8 2100 were patterned to form the cantilever beams and the frames of the device, respectively. Finally, the cantilever array were released from the silicon wafer by using Cr etchant to remove the sacrificial layer (Figure 2h).

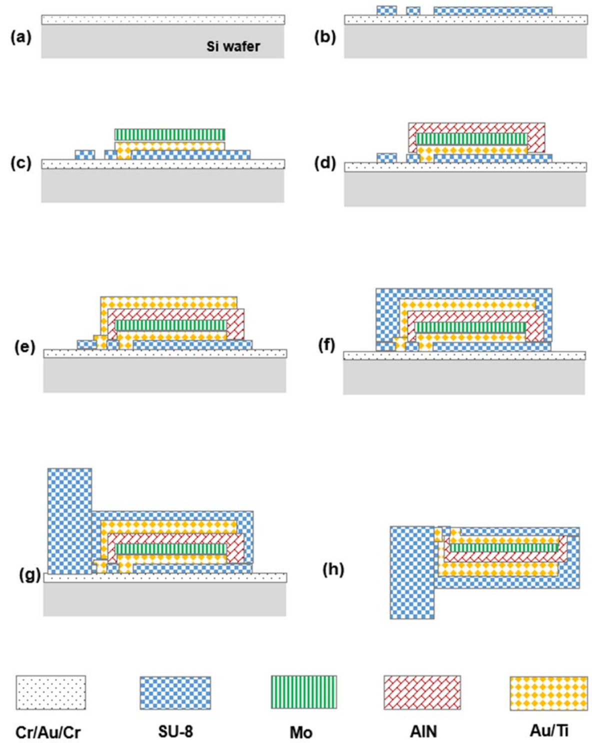


Figure 2: Schematic view of the fabrication process for the SU-8 based artificial basilar membrane.

RESULTS AND DISCUSSION

AlN Film Characterization

The crystal orientation of AlN film on SU-8 was characterized using scanning electron microscopy (SEM, (S-4800, Hitachi, Japan)) and X-ray diffractometer (XRD, (Empyrean, PANalytical, Netherland)) θ-2θ. Figure 3 shows a cross sectional micrograph SEM image of the AlN film on Mo/Ti/SU-8 (20nm/100nm/1.5um) layers. The AlN film shows the columnar c-axis (002) orientation of the AlN grain on the SU-8 substrate. As shown in Figure 4, θ-2θ XRD scan exhibits peaks at 36°, 38º, 41º, and 44º. The peak at 36° corresponds to the (002) AlN, which means that the AlN film have c-axis orientation. The other peaks are corresponds to the bottom electrode layer (Mo/Au/Ti).

Device Performance

To characterize the piezoelectric properties and mechanical frequency selectivity, the mechanical vibration of cantilever was measured using scanning laser Doppler Vibrometer (MSA-500, Polytech GmbH, Germany). An AC 1 V amplitude electrical stimulus (a periodic chirp signal, 100 - 10,000 Hz) was applied by a MSA-500 junction box (Polytech GmbH, Germany) to the fabricated SU-8 based ABM.

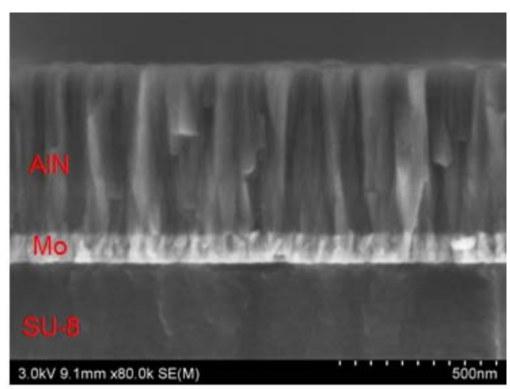


Figure 3: The cross-sectional SEM image of the aluminum nitride (AlN) thin film on the SU-8 substrate. The titanium (Ti) /molybdenum (Mo) was used as the bottom electrode layer. The SEM image shows the columnar c-axis (002) orientation of the AlN grain on the SU-8 substrate.

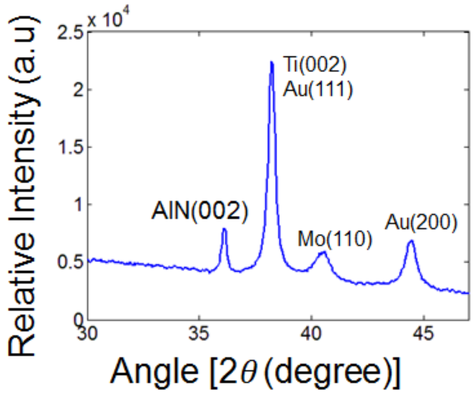
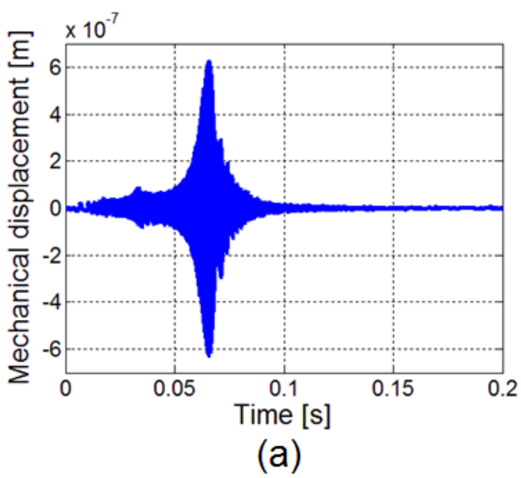


Figure 4: XRD pattern of the AlN film on the SU-8 substrate. The peak at 36 ° corresponds to (002) AlN, which means that the AlN film have c-axis orientation. The peaks at 38°, 41°, and 44 ° are corresponds to bottom electrode layer (Mo/Au/Ti).

Figure 5a shows the mechanical displacement of the eighth channel of the SU-8 based ABM. The peaks was shown at around 0.07 s. Figure 5b shows the frequency response of the eight channel. The largest peak at 1,900 Hz means the resonance frequency of the eighth channel of the ABM. Figure 6 presents the mechanical displacements of all the channels in frequency domain to demonstrate the resonance frequencies of the cantilever array. The resonance frequencies of each channel are increased from 968 to 5,181 Hz as channel number is decreased (i.e., with increasing cantilever length). It means that the fabricated flexible AlN cantilever array have not only piezoelectric characteristics but also mechanical frequency selectivity. The more detail variations of resonance frequencies are presented in the Table 1.

Additional works are underway to estimate the piezoelectric output by applying acoustic stimulus to use acoustic sensor for next generation auditory prostheses. Although the frequency response range is not yet cover the human voice range (300 – 3,400 Hz), we successfully lowered the frequency response range of the ABM by using flexible SU-8 substrate.



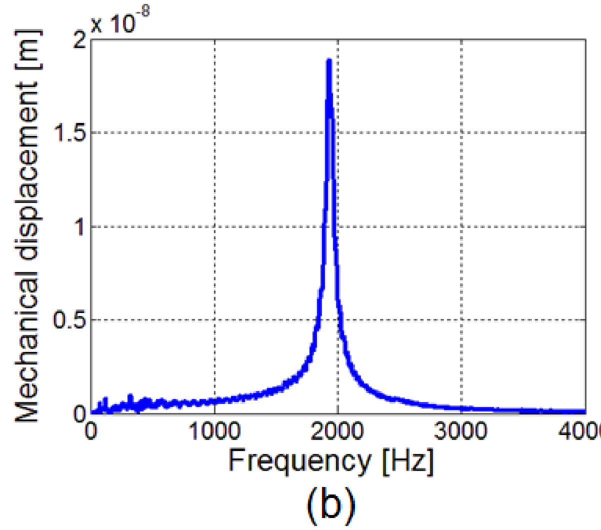


Figure 5: (a) Mechanical displacement during the application of electrical stimulation to the eighth channel of artificial basilar membrane (b). Frequency response of the mechanical displacement measured in (a).

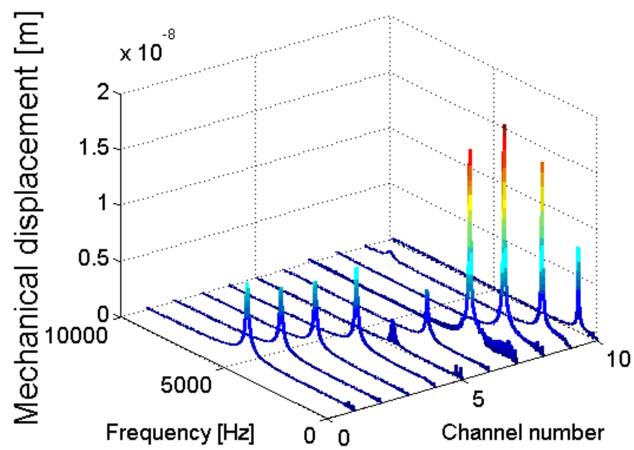


Figure 6: Frequency responses of mechanical displacements for all cantilevers of the fabricated artificial basilar membrane. It shows that the fabricated device has not only piezoelectric characteristics but also mechanical frequency selectivity.

COCLUSION

The piezoelectric cantilever array was fabricated by using flexible AlN based on SU-8 substrate for artificial basilar membrane. XRD and SEM was used to characterize the AlN film on SU-8. The deposited AlN film shows a c-axis orientation on SU-8 substrate. Also, mechanical displacements of all channels of the ABM were measured by SLDV when we apply electrical stimulus. All channels of ABM show different peaks at its resonance frequency, which means that the fabricated ABM have piezoelectric properties and mechanical frequency selectivity.

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REFERENCES

[1] R. D. White and K. Grosh, "Microengineered hydromechanical cochlear model," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 102, pp. 1296-1301, 2005.

[2] P. Sellick, R. Patuzzi, and B. Johnstone, "Measurement of basilar membrane motion in the guinea pig using the Mössbauer technique," *The journal of the acoustical society of America,* vol. 72, pp. 131-141, 1982.

[3] L. Robles and M. A. Ruggero, "Mechanics of the mammalian cochlea," *Physiological reviews,* vol. 81, pp. 1305-1352, 2001.

[4] G. von Békésy, "Travelling waves as frequency analysers in the cochlea," *Nature,* vol. 225, pp. 1207-1209, 1970.

[5] H. Shintaku, T. Nakagawa, D. Kitagawa, H. Tanujaya, S. Kawano, and J. Ito, "Development of piezoelectric acoustic sensor with frequency selectivity for artificial cochlea," *Sensors and Actuators A: Physical,* vol. 158, pp. 183-192, 2010.

[6] T. Inaoka, H. Shintaku, T. Nakagawa, S. Kawano, H. Ogita, T. Sakamoto, *et al.*, "Piezoelectric materials mimic the function of the cochlear sensory epithelium," *Proceedings of the National Academy of Sciences,* vol. 108, pp. 18390-18395, 2011.

[7] H. S. Lee, J. Chung, G. T. Hwang, C. K. Jeong, Y. Jung, J. H. Kwak, *et al.*, "Flexible Inorganic Piezoelectric Acoustic Nanosensors for Biomimetic Artificial Hair Cells," *Advanced Functional Materials,* vol. 24, pp. 6914-6921, 2014.

[8] S. Kim, W. J. Song, J. Jang, J. H. Jang, and H. Choi, "Mechanical frequency selectivity of an artificial basilar membrane using a beam array with narrow supports," *Journal of Micromechanics and Microengineering,* vol. 23, p. 095018, 2013.

[9] J. Jang, S. Kim, D. J. Sly, S. J. O'leary, and H. Choi, "MEMS piezoelectric artificial basilar membrane with passive frequency selectivity for short pulse width signal modulation," *Sensors and Actuators A: Physical,* vol. 203, pp. 6-10, 2013.

[10] J. Jang, J. Lee, S. Woo, D. J. Sly, L. J. Campbell, J.-H. Cho, *et al.*, "A microelectromechanical system artificial basilar membrane based on a piezoelectric cantilever array and its characterization using an animal model," *Scientific reports,* vol. 5, 2015.

[11] T. Xu, M. Bachman, F.-G. Zeng, and G.-P. Li, "Polymeric micro-cantilever array for auditory front-end processing," *Sensors and Actuators A: Physical,* vol. 114, pp. 176-182, 2004.

[12] J. Jang, J. Lee, J. H. Jang, and H. Choi, "A Triboelectric□Based Artificial Basilar Membrane to Mimic Cochlear Tonotopy," *Advanced Healthcare Materials,* 2016.

[13] W. J. Song, J. Jang, S. Kim, and H. Choi, "Piezoelectric performance of continuous beam and narrow supported beam arrays for artificial basilar membranes," *Electronic Materials Letters,* vol. 10, pp. 1011-1018, 2014.

[14] H. Shintaku, T. Kobayashi, K. Zusho, H. Kotera, and S. Kawano, "Wide-range frequency selectivity in an acoustic sensor fabricated using a microbeam array with non-uniform thickness," *Journal of Micromechanics and Microengineering,* vol. 23, p. 115014, 2013.

[15] S. Petroni, F. Guido, B. Torre, A. Falqui, M. T. Todaro, R. Cingolani, *et al.*, "Tactile multisensing on flexible aluminum nitride," *Analyst,* vol. 137, pp. 5260-5264, 2012.

[16] N. Jackson, L. Keeney, and A. Mathewson, "Flexible-CMOS and biocompatible piezoelectric AlN material for MEMS applications," *Smart Materials and Structures,* vol. 22, p. 115033, 2013.

[17] M. Akiyama, Y. Morofuji, T. Kamohara, K. Nishikubo, Y. Ooishi, M. Tsubai, *et al.*, "Preparation of oriented aluminum nitride thin films on polyimide films and piezoelectric response with high thermal stability and flexibility," *Advanced functional materials,* vol. 17, pp. 458-462, 2007.

[18] M. Im, I.-J. Cho, K.-S. Yun, and E. Yoon, "Electromagnetic actuation and microchannel engineering of a polymer micropen array integrated with microchannels and sample reservoirs for biological assay patterning," *Applied Physics Letters,* vol. 91, p. 124101, 2007.

[19] J. Olivares, E. Iborra, M. Clement, L. Vergara, J. Sangrador, and A. Sanz-Hervás, "Piezoelectric actuation of microbridges using AlN," *Sensors and Actuators A: Physical,* vol. 123, pp. 590-595, 2005.

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