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Thin Film PZT Acoustic Sensor for Fully Implantable Cochlear Implants †

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Abstract: This paper presents design and fabrication of a MEMS-based thin film piezoelectric transducer to be placed on an eardrum for fully-implantable cochlear implant (FICI) applications. Resonating at a specific frequency within the hearing band, the transducer senses eardrum vibration and generates the required voltage output for the stimulating circuitry. Moreover, high sensitivity of the sensor, 391.9 mV/Pa @900 Hz, decreases the required power for neural stimulation. The transducer provides highest voltage output in the literature (200 mVpp @100 dB SPL) to our knowledge. A multi-frequency piezoelectric sensor, covering the daily acoustic band, is designed based on the test results and validated through FEA. The implemented system provides mechanical filtering, and mimics the natural operation of the cochlea. Herewith, the proposed sensor overcomes the challenges in FICI operations and demonstrates proof-of-concept for next generation FICIs.

Keywords: cochlear implant; acoustic sensor; MEMS vibration-based transducers; thin film PZT

1. Introduction

The cochlea, the eardrum, and the ossicles together form one of the most elaborated structures in mammalians. They provide frequency selectivity and sound perception, which makes ear the best acoustic sensor in the nature. According to the World Health Organization (WHO), approximately 15% of the world's adult population has some degree of hearing loss. In total, there are 360 million people living with disabling hearing loss greater than 40 dB SPL as of 2015, 32 million of which are children [1]. Amount of hearing loss can be classified as mild, moderate, severe or profound. For mild-to-moderate damage a hearing aid can be used to restore the hearing loss by sound amplification. Whereas, Cochlear Implants (CIs) can be utilized for treatment of severe-to-profound hearing loss. CIs recover hearing to a certain extend by directly stimulating the auditory nerves via electrodes. However, current state of the commercial CIs has some drawbacks such as high cost and the need for frequent battery charging/replacement preventing patients' continuous access to sound. Another disadvantage of CIs is that wearing external components causes patients to feel stigmatized. Also, there is a risk of damage especially when exposed to water (shower, pool). In this study, we present a novel method utilizing a multi-frequency thin film piezoelectric transducer that eliminates main bottlenecks of CIs. The transducer consists of several cantilever beams each of which resonates at a specific frequency within the hearing band that covers the daily acoustic band. The design of the transducer is accomplished considering volume and mass limitations. Finally, achieved results, generated signals on the piezoelectric transducers, will be shaped by interface electronics to stimulate the auditory neurons at cochlea.

2. Design and Modelling

In conventional CIs', the entire natural hearing mechanism is bypassed, although most parts of the hearing system are operational such as the eardrum and ossicles. In the proposed system, an array of piezoelectric cantilever transducers is going to be placed on the eardrum or ossicles to provide the necessary signal for neural stimulation. However, it is quite challenging to implement piezoelectric cantilevers, which can stimulate nerves while covering the acoustic band with enough number of channels, in such a small volume as of the middle ear. PZT thin films are superior over bulk structures for CI applications since bulk PZTs cannot satisfy the volume requirement to be mounted on the eardrum. Furthermore, extra mass inhibits the vibration characteristics of the eardrum [2]. Pulsed Laser Deposited (PLD) PZT has been preferred among other thin film piezoelectric alternatives for acoustic sensing of vibration due to its superior ferroelectric and piezoelectric properties [3]. Figure 1 shows the proposed system for sensing the incoming sound, which consists of several cantilever beams resonating at specific frequencies within the hearing band. Schematic view of the proposed thin film PZT on cantilever structure is presented in Figure 2. When an acoustic sound pressure impinges on the eardrum, the cantilever beam matched with excited frequency starts to vibrate along with it.

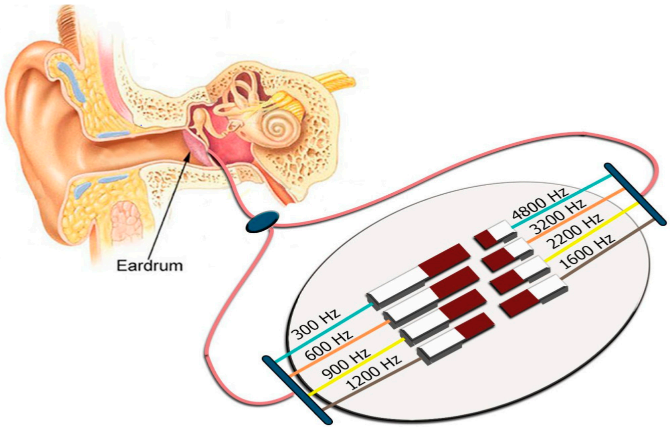

Figure 1. The proposed system for sensing the sound.

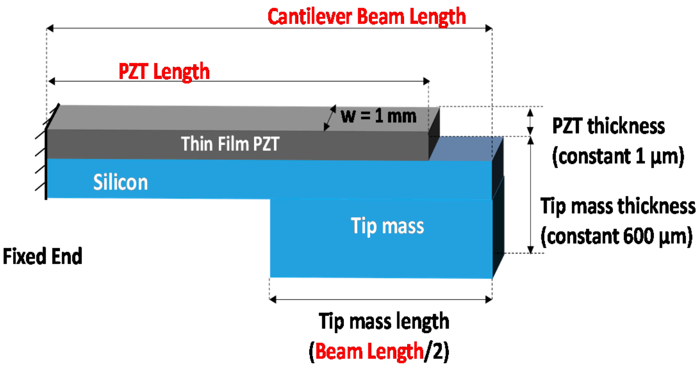

Figure 2. Schematic view of the transducer.

Figure 3 shows the proposed 8-channel multi-frequency structure, where each cantilever corresponds to a selected frequency band in cochlea. FEM is established for designing the 8-channel transducer within limited weight (<25 mg) and volume (<1 cm^3). Table 1 lists obtained piezoelectric output voltage, sensitivity to sound and quality factor for each frequency. Results show that the proposed design has a clear frequency selectivity with a minimum quality factor of 1285 and mimics the natural operation of cochlea. Both the sensitivity and the quality factor of the proposed system are higher than the state-of-the-art piezoelectric transducers [4].

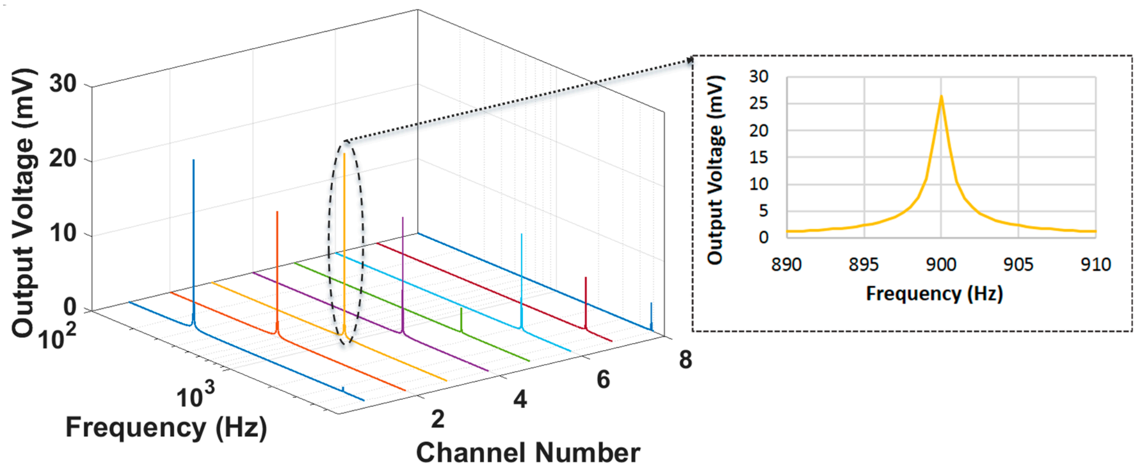

Figure 3. Frequency response of the transducers for all channels with a close-up view of channel 3.

Table 1. Specifications of 8-channel structure.

Frequency (Hz)	Beam Length (mm)	Output Voltage (mV)	Sensitivity (mV/Pa)	Quality Factor
300	3.4	22.98	363.34	984
600	2.4	16.87	265.4	1012
900	1.9	24.79	391.9	1285
1200	1.7	15.88	251.2	1196
1600	1.4	22.71	358.94	976
2200	1.2	13.12	204.6	1043
3200	1	7.21	114.1	996
4800	0.8	3.75	59.3	1121

3. Fabrication

Figure 4 shows the detailed fabrication process flow. Initially, the deposited PLD-PZT (1 µm) layer at Solmates (SMP-700 PLD) was patterned and then Ti/Pt (10/100 nm) was used as bottom electrode. Parylene layer of 5 µm was deposited and patterned for insulation. Cr/Au (30–400 nm) was used as top electrode and the remaining parylene layer was striped. Finally, cantilever beam structure was formed through front and back-side DRIE process, and individual devices were released. In this case, PLD-PZT fabrication procedure eliminates the thinning and bonding stages of the bulk structures.

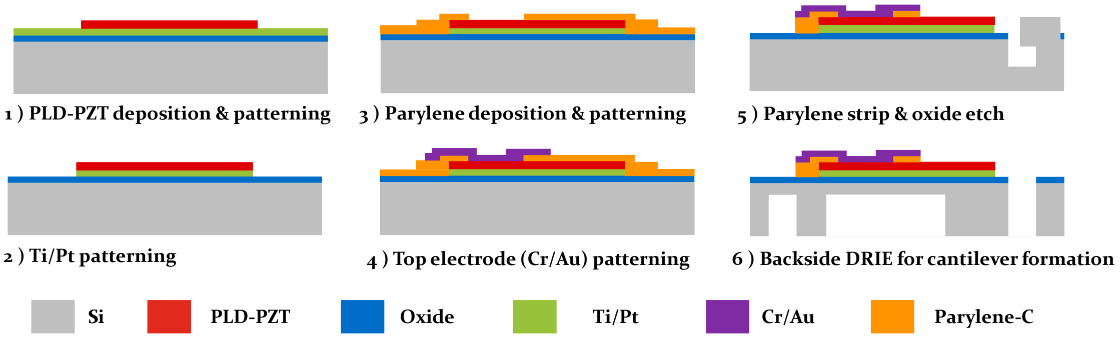

Figure 4. Fabrication flow of the thin film sensor.

4. Results and Discussion

Figure 5 illustrates the test setup and the fabricated MEMS device. In order to analyze the transducer's performance, device is assembled to a PCB and attached on a shaker table. Figure 6 shows the frequency response of the device under various acceleration levels corresponding to the vibration of the umbo at specific sound levels [5]. The output of the piezoelectric acoustic sensor is going to be processed by an interface circuit and converted into current pulses which are sent to corresponding electrodes to stimulate the auditory neurons. Experimental results show that the device generates 200 mV_{pp} at 100 dB Sound Pressure Level (SPL) which is the required sensing voltage of state-of-the-art neural stimulation circuitry [4]. High output voltages make implementation of the FICI systems more feasible. Figure 7 shows that simulations and experimental results are within 92% agreement. Transducer filters the sound mechanically by exciting only the beam with the matching resonance frequency. This system provide a perfect excitation signal as an acoustic sensor that mimicking the natural operation of the cochlea. Hence, the proposed 8-channel thin film multi-frequency cantilever array model verifies the proof-of-concept for next generation FICI, which can stimulate nerves while covering the acoustic band with enough number of channels, in such a small volume as of the middle ear.

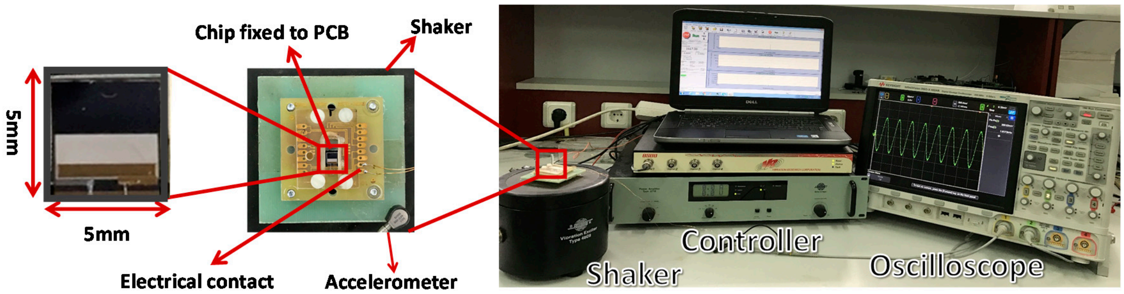

Figure 5. The test setup and the fabricated MEMS device with a close-up view of the transducer.

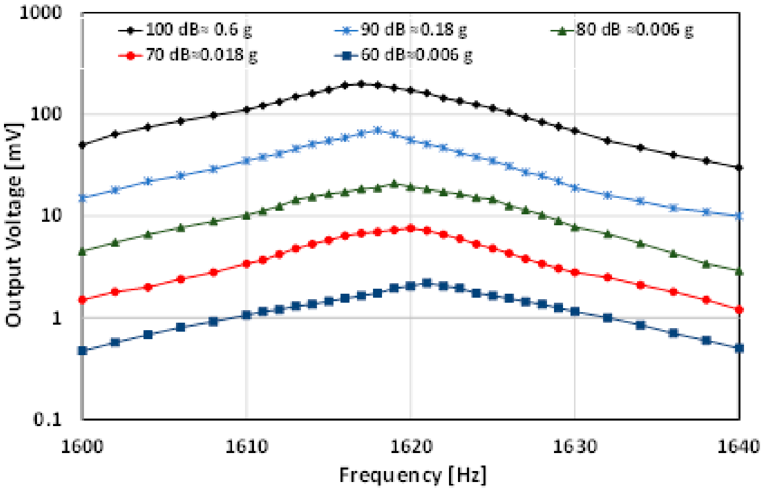

Figure 6. Frequency response of device at different umbo vibration levels.

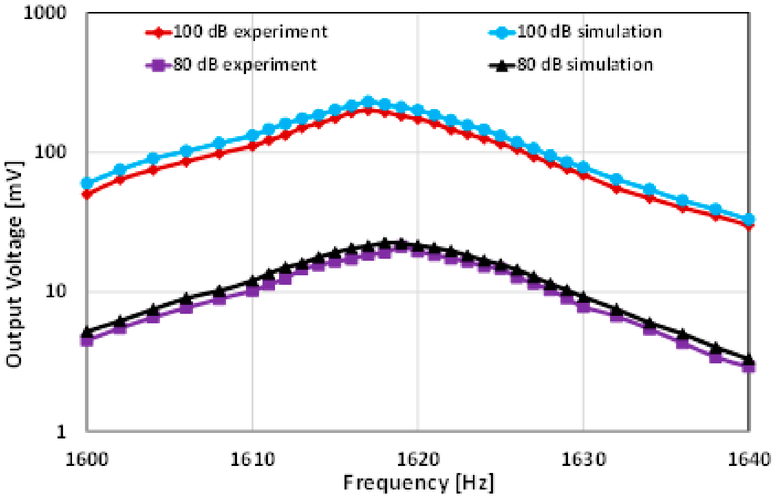

Figure 7. Simulation and test results of the device at different vibrations.

5. Conclusions

This study presents the modelling and the design of a MEMS based thin film PLD-PZT acoustic sensor for fully implantable CI applications. The proposed model utilizes natural hearing mechanism and mimics the hair cells via a set of frequency-selective piezoelectric cantilevers to stimulate the auditory nerve. Moreover, the design takes volume and mass limitations into consideration covering the daily acoustic band. In this sense, a single channel thin film PLD-PZT chip was designed and fabricated. Test results show that the device is able to generate the required sensing voltage for neural stimulation circuitry and the feasibility of the proposed method. As a result, the proposed method and the fabricated device demonstrates the proof-of-concept for next generation CIs for overcoming the challenges in conventional CIs.

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Conflicts of Interest: The authors declare no conflict of interest.

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