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## Design and Fabrication of Fully Implantable MEMS Cochlea

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### Abstract

The micro-electro-mechanical array for application as fully implantable cochlea is presented in this paper. The complete system including a short overview of energy harvesting and the system configuration is proposed. This study mainly covers mechanical properties of cochlea microfabricated silicon structure. Electro-mechanical simulations are proceeded to optimize the material used for resonators, the size of array membranes and to estimate the resistive change due to the input sound signal. The sound is detected by thin Si<sub>3</sub>N<sub>4</sub> diaphragm due to resonant frequency and the displacement of the membrane caused by acoustic pressure. The displacement is detected employing piezoresistive electrodes (NiCr). Design and fabrication process based on MEMS technology are described and discussed. The response measurement of the cochlea structure is performed. The sizes of the membranes vary from (0.5 × 0.5) mm to (2.0 × 2.0) mm and the average current change is 6.55 · 10<sup>-3</sup> % corresponding to the acoustic pressure of 0.01 Pa.

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*Keywords:* Cochlear implant; MEMS; proceeding electronics; fabrication; simulation; diaphragm

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### 1. Introduction

Hearing loss affecting all age groups may be arisen from anywhere in the auditory pathway including the cochlea or the cochlear nerve [1]. Cochlea is a part of inner ear where the acoustic signal is transferred into the electrical

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signal, and it is consequently proceeded by brain [2]. In some cases, a cochlear implant represents the possibility how to return hearing at least particularly [3]. The recent conventional implants are electronics systems composed of two fundamental parts namely inner and outer one. The inner part contains a receiver processing the signal from the outer part and stimulates the electrodes connected to hearing nerve. The outer part contains a microphone, the speech processor, a transmitter and a power supply for the entire system [4]. These implants are not fully implantable and the common power consumption is around 10 mW which results in necessity of recharging the batteries in 12–24 hours period [5]. Creating the fully implantable cochlea becomes an important task and a significant trend in artificial implants production [6].

The microelectromechanical system (MEMS) represents a promising solution which will help to create a fully implantable cochlea. One of the used MEMS approach is stiff silicon probes which are considered for possible application as a detection element [7]. The miniaturized size of MEMS device caused no biocompatibility problem and also allows reaching minimum power consumption which can be compensated using suitable energy harvesting system. Several types of energy harvesting systems are currently developed as a source of energy for CI applications, e.g. [8]. Based on the initial analyses and experience with energy harvesting systems only three types of energy converters in the head area appear as sufficient power sources [9]. Namely, thermal gradient, mechanical movement (shocks) and bending movement of neck muscles or an artery in the head area can be considered [10].

A similar concept to ours was presented in paper [11] but the pattern of sensing electrode and the applied pressures for CI characterization is more likely not suitable for implant application.

Our research presents a unique concept considering complex view of the cochlear implants including the detection element, processing electronics, and the proposal of suitable energy harvester. Considering the proposed MEMS based cochlea is fully implantable, it should have very low power consumption. The whole concept is the fabrication of energy autonomous device which uses ambient energy in head for self-powering without any outside charging.

## 2. Proposed Solution

The sensing element consists of several individual active piezoresistive thin diaphragms which are tuned up in the range of hearing frequency. The number of piezoresistive diaphragms provides electromechanical filtering and sensing system for observing dominant acoustic frequencies. The MEMS sensors are actuated by acoustic waves propagated through a fluid medium by vibrating middle ear prosthesis similarly like in the real cochlea. A schematic configuration of the proposed fully implantable MEMS cochlea is shown in the Fig. 1. The cochlear implant is where the middle ear cavity is placed. The energy harvesting system is placed behind the ear inside of the skull.

This configuration of MEMS sensor enables a full encapsulation of the sensors and eliminates problems with biocompatibility. A schematic configuration of the proposed fully implantable MEMS cochlea is shown in the Fig. 1. The cochlear implant is placed inside of the middle ear cavity. The energy harvesting system is placed behind the ear inside of the skull. This place is occupied by a receiver in currently used implants.

## 3. Experimental

### 3.1. Fabrication process

The fully implantable cochlea device consists of a MEMS sensor produced by standard micromachining techniques. The process flow of the MEMS cochlea is schematically shown in the Fig. 2. The fabrication process starts with the deposition of  $\text{Si}_x\text{N}_y$  isolation layer on the silicon substrate (step 1). Next step is the deposition of the NiCr piezoresistive layer (step 2). The NiCr film with a thickness of 100 nm is deposited by reactive sputtering from a NiCr target. Next step is the deposition of gold film with a thickness of 250 nm as a contact layer (step 3). Two lithographic and etching processes follow for patterning the gold contact layer (step 4) and for patterning the piezoresistive elements (step 5). On the backside of the wafer, the  $\text{Si}_x\text{N}_y$  is patterned as protective mask for KOH wet etching. The diaphragm is released with KOH etching and the complete release (step 6) is done using top  $\text{Si}_x\text{N}_y$  etch stop (diaphragm layer) due to good etch selectivity towards Si and  $\text{Si}_x\text{N}_y$ . The thickness of the diaphragm is defined by the thickness of  $\text{Si}_x\text{N}_y$  layer.

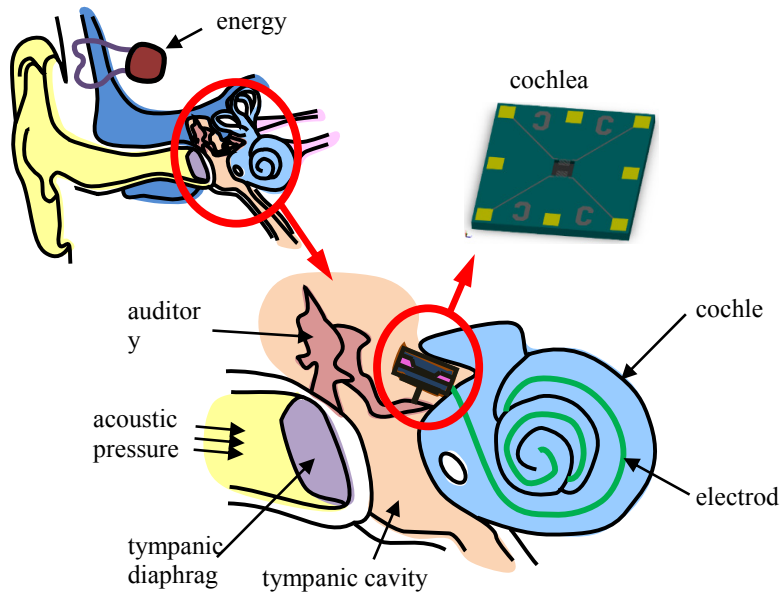


Fig. 1. The basic scheme of proposed design of cochlear implant.

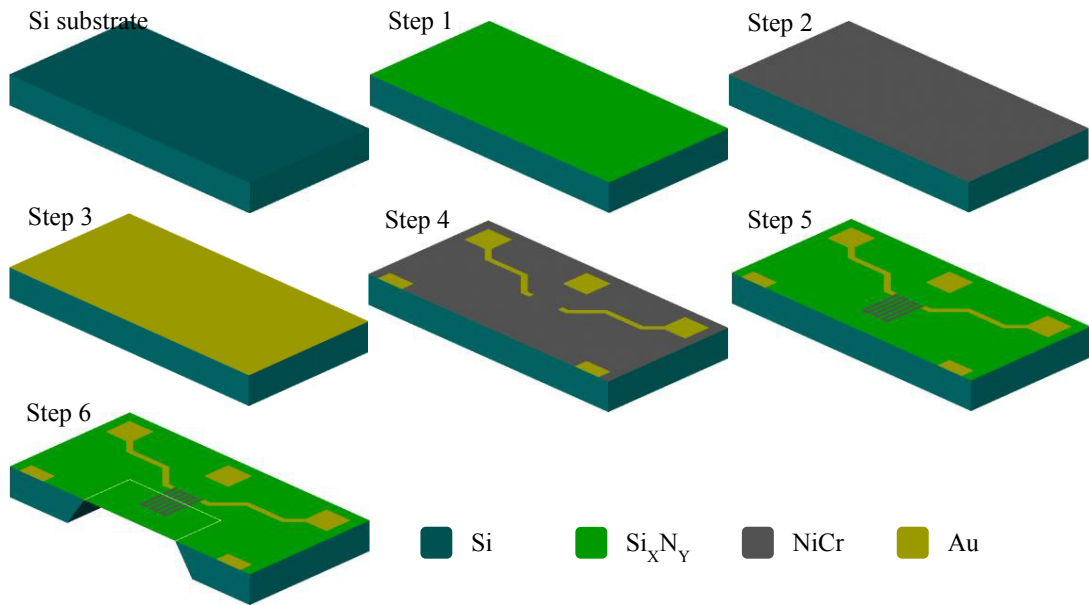


Fig. 2. Process flow of the MEMS cochlea.

Piezoresistors are located in the center of the edges of the flexible diaphragm. The location of these piezoresistors corresponds to regions of maximum tensile stress when the diaphragm is bent by a uniformly applied acoustic pressure.

### 3.2. Processing electronics

Low power signal processing electronics was designed for the implantable cochlea device. It consisted of the Wheatstone bridge connected to operational transconductance amplifier (OTA) and output pulse generation circuits (see Fig. 3). Two piezoresistive sensing elements of the acoustic sensor were connected into the Wheatstone bridge. A dummy sensor element without diaphragm was used for bridge balancing. Dummy sensors were the exactly same patterned design as acoustic sensors and they were fabricated on the same wafer for appropriate matching of their resistances. A single frequency alternating voltage was generated by high selective MEMS sensor connected to the Wheatstone bridge. The signal from the sensor was amplified by OTA and collected in the integration capacitor  $C_{INT}$ . The output bipolar current pulse was generated to the cochlear electrodes by MOSFET output buffer when integrated signal reaches the threshold reference value.

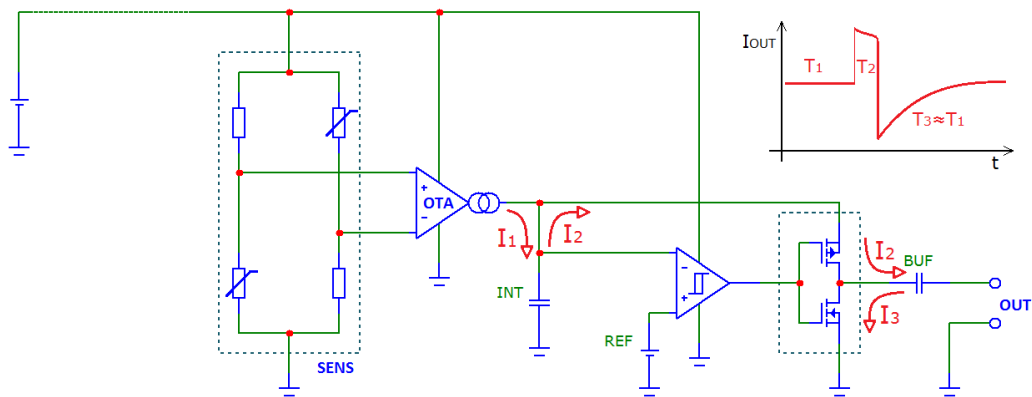


Fig. 3. Schematic of the cochlea signal processing electronics.

The proposed MEMS sensors were tested in laboratory conditions. A simple electronic circuit was designed for this purpose. It consists of the Wheatstone bridge shown in the Fig 3 which was connected to a two-stage instrumentation amplifier. Total amplification of the instrumentation amplifier was set to 60 dB. This value was selected after simulations to assure maximal signal value due to sensing element noise level. An output value of the circuit was represented by alternating voltage. The voltage value corresponded to the acoustic pressure level transformed to the MEMS diaphragm displacement.

Two measurement methods were used for characterization of the (2 mm × 2 mm) acoustic sensor. The real eigenfrequencies of the mechanical diaphragm oscillations were determined by the first method. The diaphragm deformations were driven by vibration table in this measurement. The second characterization method used defined acoustic signal for diaphragm stimulation. This type of stimulation has significantly lower power transfer efficiency and cannot be measured in a simple way. For this purpose, a special measurement workplace for automated measurement was created. It consists of anechoic chamber, sound generator, reference microphone, lock-in amplifier and personal computer with specialized software installed (see Fig. 4).

The anechoic chamber was constructed as double-walled cushioned box with multiple special sonic wave absorbent materials. The chamber minimized multiple sound reflections during diaphragm stimulation and prevented the measurement from external noise. The MEMS sensor with its electronics, reference microphone and loud speaker was located inside the box during every measurement to ensure defined measurement conditions. The amplitude of the generated signal was automatically set to a constant value by electronic feedback. The feedback was realized through the reference microphone with compensated frequency dependence. The amplified signal from the MEMS sensor was measured by lock-in amplifier for significant noise level reduction. The reference signal of the lock-in amplifier was phase locked directly to the generated frequency.

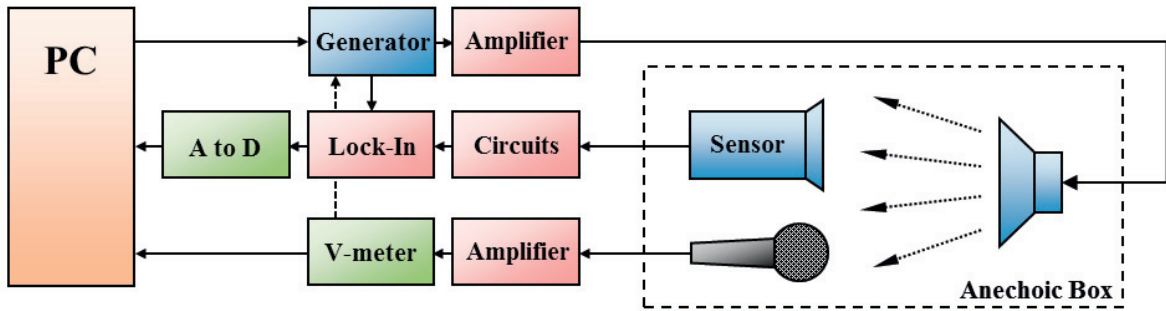


Fig. 4. The workplace setup for MEMS sensor measurement during acoustic stimulation.

The entire measurement was controlled by PC with an application in the computer which was programmed especially for this purpose. The complete the measurement setup can be seen in the Fig. 5.



Fig. 5. a) MEMS sensor and reference microphone, b) the anechoic box and c) the measurement setup detail.

The first eigenfrequencies of resonant diaphragms with different dimensions were calculated in finite element systems Ansys and CoventorWare. Both were used because CoventorWare includes the connection into the fabrication process, but on the other hand it does not embrace the analysis of acoustic fluid-structure interaction with silicone oil that we suppose to use for the final configuration of the implant. The calculations involved the edges of diaphragms that are fixed (without the influence of any fluid structure interaction as mentioned). In this case, it was



suggested placing to place diaphragms into the silicone oil that will cause a decrease in the eigenfrequencies to lower values due to added mass of the fluid medium. The influence of the fluid structure interaction will be discussed in future papers.

The results of eigenfrequencies calculated in Ansys and CoventorWare for resonant diaphragms with different dimensions are listed in Table 1 representing that the results calculated in both software products show very good coincidence. The lowest eigenfrequency is about 1 kHz for the largest diaphragm and about 7 kHz for the smallest one. Human ear is the most sensitive in the frequency range from 1 kHz to cca. 4 kHz and conventional cochlear implants work in this frequency range. It means that the dimensions of resonant diaphragms without the interaction of the fluid structure could be in the range between 2 mm × 2 mm to 1 mm × 1 mm.

Table 1. Eigenfrequencies calculated in Ansys and CoventorWare for resonant diaphragms with different dimensions.

Dimensions [mm]	Ansys [Hz]	CoventorWare [Hz]
2 × 2	991	983
1.5 × 1.5	1752	1742
1 × 1	3915	3899
0.75 × 0.75	6934	6928

The example of fabricated cochlea diaphragm is shown in the Fig. 6. The detail of NiCr electrode is shown and the diaphragm prepared for response measurement.

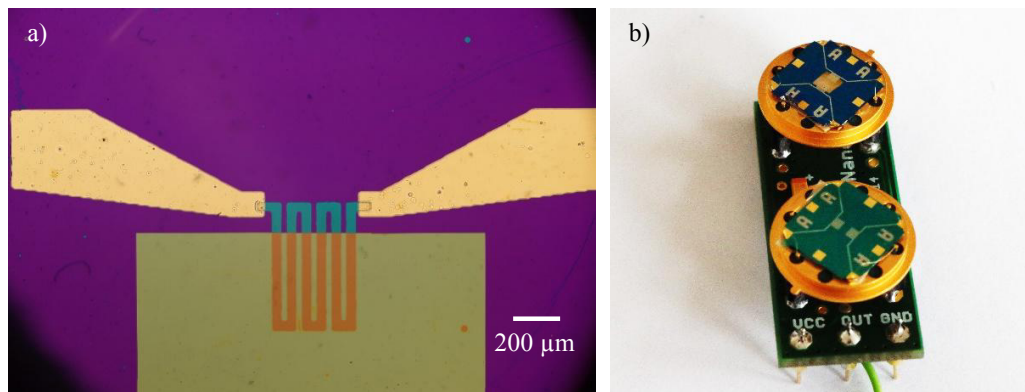


Fig. 6. Fabricated cochlea diaphragm: a) detail of NiCr electrode and b) diaphragm with electronics assembly for measurement.

During the first measurement on vibration table, the sensor was shaken by vibrations in perpendicular direction relating to the diaphragm surface orientation. No response was observed during stimulation due to the wide spectrum white noise where the total vibration power is lower. The single frequency stimulation with frequency sweep was performed for reaching the better detection limit. The amplitude of single frequency vibrations was about  $0.2 \text{ m}\cdot\text{s}^{-2}$  in the frequency range from 100 Hz to 20 kHz. Small resonant peaks were observed about 3840 Hz and 7400 Hz during sweep single frequency stimulation. The second resonant peak had significantly lower amplitude (approx. 80 dB) as it was predicted by simulations. The frequencies around the first and the second detected eigenfrequencies were measured again with finer frequency step (see Fig. 7). The resonant frequencies were approximately 3 times greater compared to the simulated values. We expect that this difference is given by inner mechanical stress in the  $\text{Si}_x\text{N}_y$  diaphragm created during fabrication process. Using the  $\text{Si}_x\text{N}_y$  deposited by PECVD (plasma enhanced chemical vapor deposition) can solve this problem. The measured signal amplitude was very low. It was caused by ultra-low diaphragm mass for effective vibration energy transfer from the packaging to the diaphragm. The measured AC voltage could not be compared with real mechanical movement of the membrane

movement because optical sensor with sufficient sensitivity could not measure transparent material. Transparency can be suppressed by thin metallic layer deposition to the membrane but it negatively affects measured response.

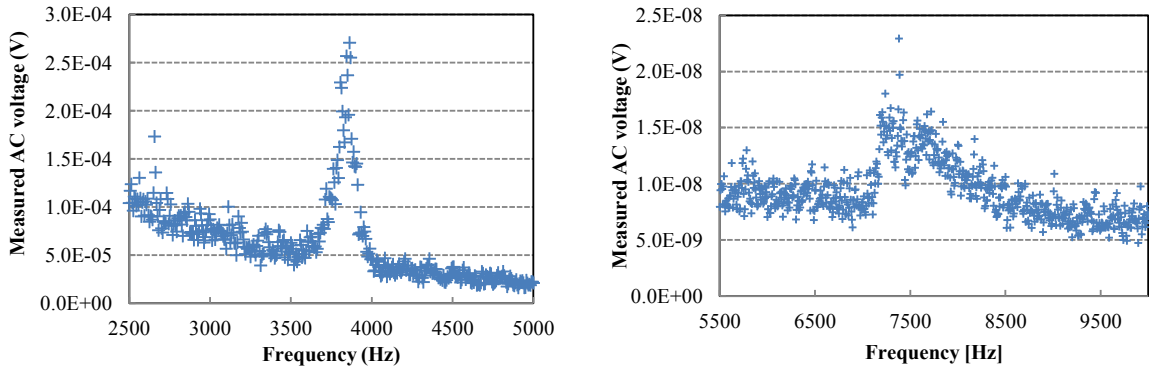


Fig. 7. The first (left) and the second (right) resonant peak measured during the first measurement on vibration table.

During the acoustic driven measurement, drab increase of the signal (see Fig. 8) was observed near eigenfrequency determined by the first vibration driven measurement method. As we expected, the signal was very low due to lower diaphragm displacement by acoustic signal against mechanical vibrations. The second eigenfrequency was totally hidden inside the noise. The more efficient transfer of acoustic pressure to diaphragm has to be reached for measured signal response increasing. The noise value can be also lowered if fully integrated electronic design will be used.

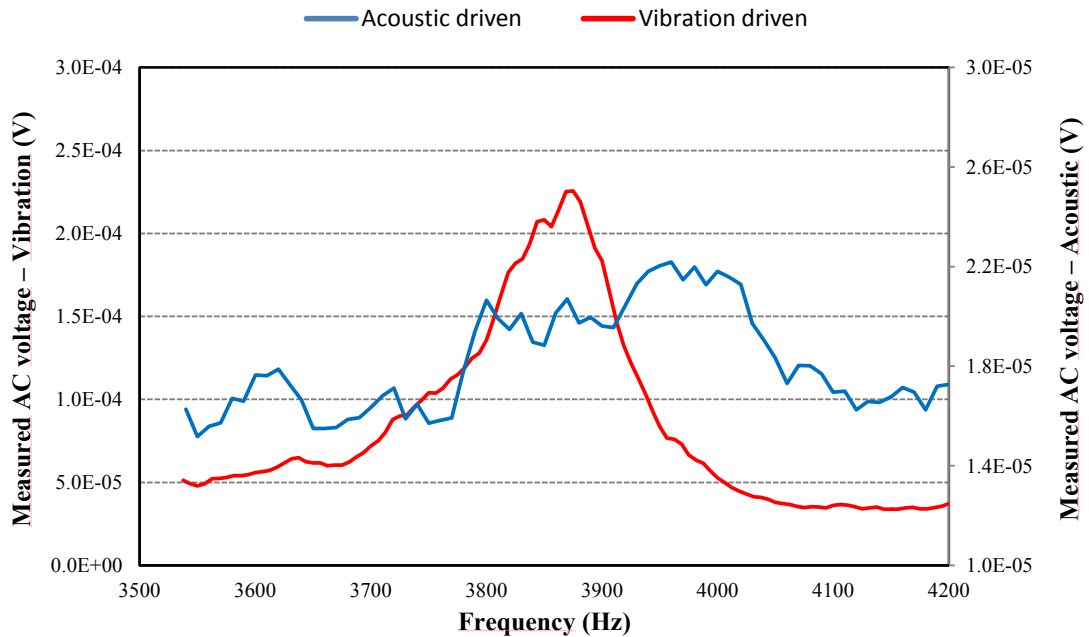


Fig. 8. Comparison of data measured by vibration and acoustic driven method.

## Conclusion

The proposal for MEMS based cochlear implant is introduced and briefly discussed including the possible energy harvesting for cochlear device. The design and fabrication process of fully implantable cochlea is presented. The simulation was proceeded to optimize design and to choose suitable materials for intended application. The simulation results shown that this acoustic signal detection method is suitable but with limited accuracy due to ultra-low sensor response.

The developed MEMS acoustic sensor for cochlear implants was measured. It was realized by vibration driven and acoustic driven measurement method. The results corresponded with theoretical values but significant frequency shift was observed. It was influenced by selected diaphragm fabrication method probably as it was discussed in the article. Due to low signal response detected during the acoustic stimulation, the integrated electronic amplifier with major noise reduction has to be used. Although, it is important to consider the acoustic signal will be amplified by the system of inner ear. The second approach to increase the sensor signal is to use active piezoelectric sensing layer against passive piezoresistive layer. The experiments dealing with the piezoelectric layers is planned to be done and published in the future papers.

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