Nanotechnology and Nanosensors-Final Project

Flexible Inorganic Piezoelectric Acoustic Nanosensors for Biomimetic Artificial Hair Cells

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1. Introduction:

1.1 Anatomical and psychophysical basics

The Human Ear is a complex series of organs that allow for the processing of sonic inputs in a manner that specific frequencies can be distinguished and processed, and that the location of the source of these sounds can be identified. The outer structure of the ear essentially funnels sound waves onto a membrane (tympanic membrane) that captures the sound waves as vibrational energy. The vibrations from this larger membrane are mechanically transferred by a series of bones that move in response to these vibrations and impact a much smaller membrane on the external surface of the cochlea. This transfer of the vibrations from the larger surface to the smaller surface amplifies this vibrational signal. Inside the cochlea organ, there are complicated mechanisms that transform the vibrational signals into electrical signals that can be interpreted by the central nervous system.

The cochlea contains a pair of membranes (Reissner’s membrane and the basilar membrane) that surrounds an internal duct called the cochlear duct. The narrowest part of the duct is located at the widest portion of the cochlea, and the widest apex of the duct is located in the narrowest portion of the cochlea. This allows for the membrane to vibrate in response to a specific wavelength of sound running across it, with highest frequency signals (10 to 20 kHz) at the beginning of the membrane, and lowest frequencies (100 Hz) at the end of the membranes. The vibration of the membrane moves a type of nerve cell called an inner hair cell, so the hair cells associated with the particular portion of the membrane that moves at a particular frequency bend. This bending of the hair cells physically opens a potassium channel, generating an electrical signal that is interpreted as a signal of that specific frequency. A second set of hair cells, called the outer hair cells, move in response to the resonance of the membrane, and generates its own electrical signal due to the manual opening of a potassium channel. This second signal acts as an amplifier, confirming the specific frequency of the initial signal.
1.2 Cochlear implant as a neural prosthesis

Cochlear implants (CI) are neural prostheses, surgically implanted electronic devices that provide a sense of sound to a person who is profoundly deaf or severely hard of hearing.

The main task of CI is to transduce physical signals (sound) into neural signals, which in the next step have to be correctly interpreted by the human auditory cortex. In this way, CI is related to neuroscience, biomedical engineering, and nowadays, nanoscience. In contrast to a brain–computer interface, which connects the brain to a computer, the main idea of neural prostheses is to replace missing biological functionality. Cochlear implants may help provide hearing in patients who are deaf because of damage to sensory hair cells (body’s own transducers) in their cochlea. CI is mostly based on direct stimulation of the VIII cranial nerve. In those patients, the implants often can enable sufficient hearing for better understanding of speech.

After the first known cochlear implant (CI) was created in 1957, there have been several scientific and technological breakthroughs. In addition to CI and other techniques must be mentioned, which are built to improve hearing, like auditory brain stem implants (ABIs), and auditory midbrain implants (AMIs). Furthermore there are hybrid approaches, like the concept of combining simultaneous electric-acoustic stimulation (EAS), which bases on modulation of hearing frequencies and focuses mostly on the low frequency range.

Especially for CI, there are several techniques, based on nanoscience, which are focused on the improvement of the electrode-neuro-interface and on minimize the anatomical gap between the electrode array and the peripheral processes of the auditory nerve in the cochlea. Here, the nano-technique is used to forward the already recorded and (pre-) processed environmental signal to nerve fibres, unlike the majority of nano-sensorial implants, where nanosensors are used as an interface between the physical signal and an electrical/ mechanical etc. output. Within CI, the nanotechnology has the potential to greatly improve such interfaces.
2. Project Goal

As great as this system is for allowing humans to hear in the fashion that we do, this system can be damaged, primarily by the loss of hair cells. Hair cells are lost as a function of aging, in response to damage when exposed to very loud sounds, and hair cells are also damaged by exposure to high levels of certain drugs, such as aminoglycoside antibiotics. Therefore, there is a strong need for a nanotechnology based solution to the loss of use of the cochlea that many people experience.

3. Overall Design:

Current cochlear replacement devices have dramatically impacted users with significant hearing loss, but they also have significant drawbacks. These include the fact that they are uncomfortable and need to be externally mounted due to their size and need for significant external power supplies. They also have a limited number of sensors, and thus do not restore a full range of hearing, although they do allow for most users to regain speech recognition.
The advantages of using nano-devices for this type of application would include the possibility that the device could generate its own electrical signals without a separate power supply. If made small enough and flexible enough, it could be fully internalized. The possibility of having a larger number of sensors would also improve the range of sounds that could then be interpreted by the user.
as the vibration of the basilar membrane in the human cochlea. The use of inorganic piezoelectric crystals can generate an electrical output sufficient to trigger the neuronal systems in a manner similar to native hair cells. The opportunity to connect the device to the existing nervous system was not explored in the research paper presented above, but in general, such connections can be done in the manners presented in the diagram below.

4. Fabrication

The fabrication of the nanosensor follows these steps: Initially a 0.4M solution of Pb $\text{[Zr}_{0.52}\text{Ti}_{0.48}]$ O$_3$ (PZT) is taken and spin-coated on a wafer at 2500rpm for 25sec. Then thermally treated by rapid thermal annealing at 450°C for 10min to remove organic components. This processes is repeated 20 times, to get a thickness of 2µm (100nm added each time). The second step is taking the PZT film, which was created last step, and thermally treat it at 650°C for 45min for its crystallization. After the crystallization, a flexible supporting plastic substrate is bounded to the top of the PZT film by an ultraviolet curable polyurethane (PU), and then lighted by UV light to strongly connect between the substrate and the PZT film. With this step we ensure having the needed mechanical capabilities to our device. The third step is removing the sapphire wafer from the film, because it isn’t needed anymore and to create space for the interdigitated electrodes (IDE). The removal preformed with XeCl laser beam with 308nm wavelength and energy of 420mJ/cm$^2$. The forth step is Cr/Au deposition on the film, creating the IDEs pattern on the PZT film by radio frequency sputtering, grating the device its electrical properties, creating the final form of the inorganic piezoelectric acoustic nanosensor (iPAN). The last step is implementing the iPAN on a trapezoidal silicon-based membrane having a frequency separator intended to separate incoming sound frequencies that are used as the main function of the device.
Those steps can be seen in the following figure:

5. Characterization

The device as designed was able to distinguish between sounds in a range of 100Hz to 1600Hz. While this is not as broad a range as normal human hearing, this represents the low frequency end of the range, and that is the range that most frequently has hearing damage due to the effects of old age or loud noise exposure. The device was also able to generate piezo-electrical signals of 54.8 microvolts at 500 Hz, 46.6 microvolts at 600 Hz and 59.7 microvolts at 1,000 Hz, which would be sufficient to allow these events to be perceived. The device was also determined to be flexible enough and robust enough to be manipulated for implantation without damaging the device.
Current limitations of this device include that it is still somewhat large to be implanted, and that the natural membrane vibrates at 10 orders higher levels than the currently designed device. Further efforts to make this device even smaller will allow for even more flexible substrates and the use of more of the smaller iPANs, both of which will not only make the device easier to implant, but will increase the range of frequencies detected.

6. Application

Such a device has great potential to help with people who have hearing impairments, especially at the lower frequencies of the hearing range, which are most often impacted. While promising, it is not yet ready for the end users, but there are clear pathways identified for further research that can build upon the early successes of this prototype.
7. Summary

This particular device is very interesting, as it tries to replicate the natural cochlea in its use of a base membrane that varies in width across the membrane, and therefore, is subject to vibrational resonance at different locations across the device. The use of a series of iPANs constructed of inorganic piezoelectric crystals allows for this device to generate electrical signals without an external power supply, and in this aspect, it also mimics the electrical signal generation that is created by the inner hair cells of the ear. Although the currently proposes device is too large and somewhat limited in the range of frequencies detected, this early work lays out the pathway for future device improvements. It is important to remember that such a device can be a very success aid to human hearing even if it only allows for the recovery of hearing at the lower frequency aspects of the normal human hearing range, as it is these frequencies that are most often lost to damage cause by age or exposure to loud noises.

8. Literature Review

Background information on the cochlea in the Introduction/Project Goal sections, including the two diagrams, was taken from the following sources:
Peggy Mason, PhD, Medical Neurobiology, Oxford University Press, 2011. Pages 399 to 415.

“Understanding the Brain: The Neurobiology of Everyday Life”, Coursera Class taught by Peggy Mason, PhD of the University of Chicago (02/23/2015 to 05/27/2015), especially lecturers for Week 5 (“The Inner Ear: Hearing and Communications”)

Background information on the artificial cochlea in the Introduction section was taken from the following sources:
Information on the nanodevice artificial cochlea in the Design / Fabrication / Characterization / Application sections, including the diagram, was taken from the following source:


Information on the nerve interface in the Design section, included in the diagram, was taken from the following source:

www.newscientist.com/data/images/archive/2754/27546201.jpg

Related Literature:


Kumar, A. et al, Piezoelectric materials selection for sensor applications using finite element and multiple attribute decision-making approaches, Journal of Advanced Dielectrics 03/2015; 05(01):1550003. DOI: 10.1142/S2010135X15500034


Related Videos:

On Nanodevice Artificial Cochlea
https://www.youtube.com/watch?v=LpzbYpbpjSc

On Human Cochlea
https://www.youtube.com/watch?v=PeTriGTENoc