2013

Piezoelectric-Based, Self-Sustaining Artificial Cochlea

Jared Evans

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Piezoelectric-Based, Self-Sustaining Artificial Cochlea

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

By

JARED EVANS
B.S.E.E., Wright State University, 2012

2013
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Jared Evans ENTITLED Piezoelectric-Based, Self-Sustaining Artificial Cochlea BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

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ABSTRACT

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Hearing loss is a prevalent issue, affecting all ages in innumerable occupations. Cochlear implants are one solution to sensorineural hearing complications; and though they are commonly used, the electronic devices have limitations in power consumption and external equipment. Piezoelectric films emulate the relationship between the basilar membrane and inner hair cell structures of the human cochlear epithelium, inducing a potential difference in response to sound pressure. Through proper MEMS fabrication and material selection, an artificial cochlear can be developed utilizing piezoelectrics, which is self-sustainable and functions naturally with the mechanisms of the human ear.

This research investigates the feasibility of piezoelectric films in achieving adequate voltage output and frequency selectivity to replace the human cochlea. Piezoelectric samples were manufactured for different resonant frequencies and subjected to air vibrations, after which the resulting voltage was recorded. Through both simulated and experimental data, the necessary 5-10mV to stimulate nerve bundles connected to the hearing centers of the brain was realized. The response spanned the human speech register of 500 to 8000 Hz.
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Chapter 1 – Introduction

1.1 Introduction to Hearing Complications and Solutions

1.1.1 Prevalence of Auditory Issues

Hearing loss is a widespread problem, affecting all ages in multitudes of occupations. Though 3 in every 1,000 children are born deaf or hearing impaired, a direct link is also formed between hearing loss and age; 18% of adults between 45 and 54 have ear damage, increasing to 47% above 75 years of age. Overall, 1 in 5 Americans has some form of hearing loss in at least one ear, severe enough to hinder communication. The mechanisms which produce auditory issues are not limited to sudden, powerful sounds, but can arise from long-term exposure to moderate noise at the work place or during leisurely activities. Hearing loss is especially prominent in military service, where 60% of deployed personnel have some degree of ear damage. Disease, such as Ménière's disease and Otosclerosis, and physical trauma to the head additionally account for loss of hearing [4].

1.1.2 Human Ear Anatomy

In light of the auditory statistics of Section 1.1.1, understanding the functionality of the ear is essential to remedying the ailment. The human ear consists of three sections, the outer ear, the middle ear, and the inner ear as shown in Figure 1.1. The outer ear functions to collect sound waves and funnel them to the middle ear mechanisms. Sound waves travelling through the air are captured by the auricle and intensified by the ear canal, inciting vibrations of the ear drum. These vibrations excite the three bones of the middle ear, the ossicles, which serve to mechanically amplify the sound. The mechanical oscillations transfer the waves to the inner ear.
The inner ear houses the components which convert sound waves to electrical signals and stimulate the hearing centers of the brain. After amplification by the ossicles, compression waves are generated in the endolymph and perilymph fluids of the spiral-shaped cochlea; these fluids are characteristically similar to silicone oil in viscosity and density. The fluid displacement stimulates a structure termed the basilar membrane, housed in the length of the spiral structure. The basilar membrane reacts differently based on the frequency of the incoming signal, due to its varying stiffness. It responds to higher frequencies near the base and lower frequencies near the apex, as represented in Figure 1.2. The total length of the basilar membrane is approximately 30mm.

As pressure displaces the basilar membrane, the movement stimulates receptors called hair cells, which convert the vibrations to electrical signals. The movement of the inner hair cells due to the basilar membrane creates a potential difference, between 5-10 millivolts from the resting state [12], while outer hair cells act to control the total output.
The resulting electrical signal stimulates nerve bundles connected to the brain, leading to what is perceived as hearing.

Figure 1.2 – Basilar membrane structure and frequency characteristics

Two classifications can be used to describe hearing loss, regarding which section of the ear is impaired: conduction deafness and sensorineural deafness. Conduction deafness refers to problems originating in the outer and middle ear, including blockage of the ear canal, damage to the tympanic membrane, ear infections, and decreased movement of the ossicles. Sensorineural deafness results from complications in the inner ear, such as impairment of the hair cells, damage to nerve fibers, and injury to the brain.

1.1.3 Cochlear Implants

Conduction and sensorineural deafness can be treated with hearing aids, which amplify sounds entering the outer ear, or cochlear implants, which directly stimulate the
nerves of the inner ear; however, for significant nerve deafness and damage to the inner ear, cochlear implants can provide a wider range of benefits.

The inception of the theory for cochlear implants began 1800, after Allessandro Volta successfully stimulated his inner ear using electric current. With new technological and medical advances, the experiment was expanded upon in 1950 when Lundberg was able to directly excite an auditory nerve. Further research then lead to a working implant in 1956 and wearable signal processor in 1972. The FDA began testing to ensure safe and effective functionality of cochlear implants in 1980, with the first clinically approved device released 4 years later. As of December of 2010, 219,000 people worldwide have received cochlear implants, consisting of both born-deaf children and severely hard-of-hearing or deaf adults [8].

Currently, the primary approved manufacturers of cochlear devices in the US are Cochlear Limited, Advanced Bionics, and Medical Electronics, each utilizing a similar procedure for digitalizing sound and applying it to the nerves of the inner ear. In contrast, each have different benefits towards size, reliability, electrode quantity, and water resistance of the devices. The technology consists of two major components, the signal processor and the electrode array. The signal processor utilizes a microphone to collect sound waves and software to process the relevant frequencies and intensities, digitally encoding this data. These signals are then wirelessly transmitted to an electrode array surgically deposited in the spiral turn of the cochlea. Based on the algorithms within the signal processor, the electrodes electrically stimulate the relevant neurons. The process of implanting the electrode array almost always destroys any remnant hearing and therefore is typically only used for extreme cases of hearing loss.
Though the success of these implants is documented, both external power sources and digital sound equipment are required to be present on the user’s self. The aforementioned power supply grants problems of charge depletion and recharging of the device. The external nature of the device furthermore limits activities of which the user can partake. As shown in Figure 1.4, cochlear implants utilize both external and internal equipment, where the process stimulating the inner ear results in a bypass of the middle and outer ear mechanisms.
1.2 Artificial Cochlea

1.2.1 Proposed Device

This paper proposes a totally implantable, self-sufficient artificial cochlea to supplement individuals with sensorineural hearing loss. In particular, the proposed device mimics the frequency selectivity of the basilar membrane of the cochlea and the electrical output of the hair cells of the organ of Corti through a fabricated piezoelectric structure; the device stimulates the cochlear nerves with an intensity that is re-adjustable through signal processing, powered by energy sources available in the human body.
1.2.2 Approach and Structure

This research strives at fashioning a piezoelectric membrane with key attributes of sufficient output to stimulate the inner hair cells and selective response to human speech frequencies. The number of frequency channels will be based on the quantity of electrodes on the film. Research performed by Shintaku et al. describes an approach using piezoelectric membranes to achieve frequency-dependent output; yet, voltage generation of the films was insufficient, requiring 1000 fold amplification [5].

In the paper, piezoelectric material was subjected to sound pressure whilst sealed over a trapezoidal slit. The varying width of the cavity brought about resonance at diverse locations along the length of the material; electrodes were evenly fabricated on the film to store the manifested charge [5]. However, the displacement of the film was not precisely isolated to the electrode sites, which produces the issue of one frequency response agitating multiple electrodes. Figure 1.5 shows displacement amplitudes of the film in air at (a) 4kHz, (b) 6kHz, (c) 9kHz, and (d) 12kHz. Though the resonant regions visibly change with frequency, the high points of vibration span sizable portions of the film. The pinnacle of the Shintaku et al. research involved in vitro studies, performed with a one channel embodiment of the device. The film, implanted into guinea pig cochleas, garnered an animal response upon sound stimulation of 104.4 dB [7].
The Shintaku investigation verified piezoelectrics as a possible measure for frequency-based nerve stimulation, though the issue of adequate channel isolation deserves examination. To address channel isolation, the viability of the piezoelectric film shown in Figure 1.6 will be explored. MEMS technology will be confirmed in crafting trenches in the piezoelectric film to isolate the segments, having varied widths which change the resonance characteristics. The piezoelectric membrane negating any fabrication is shown in Figure 1.6a. Trenches are etched on the top for isolation and on the bottom for increased membrane displacement, and then electrodes are deposited as given in Figures 1.6b and 1.6c, respectively. Finally, this device will be exposed to fluid interactions similar to the inner ear mechanisms. Figure 1.6d shows the etched membrane secured over a fluid channel (yellow).
In the preferred embodiment of the device, the transducer elements will be mechanically isolated from each other and give enhanced yield due to the thinned material. The topside incisions will be thin and cover the entire width of the membrane, reducing undesired output and providing local stimulation to the nerves connected to the implant. The etching can potentially be done with dimethyl acetamide (DMA), a polymer etching agent tested with PVDF [3].

![Figure 1.6 – Proposed artificial cochlea device fabrication (a) original membrane (b) etched membrane (c) etched membrane with electrodes (d) sealed membrane with fluid chamber](image)

Referencing the basilar membrane structure, larger segments will respond more readily to lower frequencies in this design, as the size endows increased loading to the segment, reducing the resonant frequency. Likewise, high frequencies will resonate more readily on narrower sections. Adjustable thickness for each segment permits tuning the resonant frequency of each individual structure. Ideally, thinner segments result in higher vibrational amplitude and will be targeted, resulting in greater output voltage; however, care has to be taken in maintaining structural integrity of the device. A simulated model of the potential piezoelectric membrane is given in Figure 1.7.
1.2.3 Benefits

The benefits of this device stem from the use of piezoelectric material, carefully chosen to respond ideally in the environment of the inner ear; the nerves controlling hearing can be stimulated in a more natural approach. The material acts as a replacement for failing basilar membrane or hair cells of the cochlea, working with the outer and middle ear mechanism, which can provide additional amplification. As opposed to relying on software to generate electric signals and determine frequency, all is done simultaneously on the film. The structure offers a totally implantable solution, eliminating the need for external equipment and signal strengthening. If supplementary power is required, human body-based power sources will be explored for auxiliary functionality. This auxiliary function includes a signal processing device to control the output of the film and tune the device based on the individual.

This device will be implanted in a select portion of the cochlear turn and function by stimulating a small region of the nerves in the inner ear, resulting in a less intrusive measure than the currently used series of electrodes; the device is completely contained within the
cochlea whereas current models necessitate connectors between the electrode array and receiver structure, as shown in Figure 1.4. The design of the structure can accommodate future electrode technology to achieve improved hearing resolution.

1.3 Summary

With the prevalence of hearing issues, artificial cochleas have arisen to deal with the most profound cases. However, these devices have their limitations due to external equipment and power requirements. To resolve these limitations, an artificial cochlear device was proposed, consisting of an etched piezoelectric membrane to mimic the frequency selectivity of the basilar membrane and electric output of the inner hair cells.

This research aims to develop an artificial cochlear that is self-sufficient, based on piezoelectric materials. Current research endeavors towards verifying both the output potential and resonance properties of select piezoelectric films. Presently, the voltage generation of the piezoelectric films has been proved in response to sound pressure at adequate levels, and the frequency dependence on film width and length has been documented.
2.1 Piezoelectric Properties

2.1.1 Introduction to Piezoelectrics

Piezoelectrics are transducers, devices that convert one form of energy to another. A piezoelectric device proportionally produces an electrical output upon application of mechanical stress. Conversely, deformation can be produced with electrical stimulation. The generation of voltage from mechanical motion or vice versa is named the piezoelectric effect. This effect was first discovered in 1880 by Jacques and Pierre Currie. By securing a sample of quartz with two sheets of tin (as electrodes) on opposite sides of the crystal, an electric potential change was observed upon tightening the vice holding the material [2]. This effect was originally shown in simple asymmetric crystals, such as tourmaline, quartz, topaz, cane sugar, and Rochelle salt; however, upon their discovery, man-made piezoelectric ceramics were widely used due to their excellent piezoelectric constants and durable composition. These ceramics were given piezoelectric properties through polarization, where a high DC voltage is applied to the material at controlled temperatures. Whereas most manufactured piezoelectrics initially were ceramics, in 1969 Kawai discovered a highly noticeable piezoelectric effect in polymers, such as polyvinylidene difluoride (PVDF).

These man-made piezoelectrics had the advantage of being physically strong, chemically inert, and inexpensive; they could additionally be molded to fit many shapes and survive at higher temperatures. Although the output magnitude often requires amplification, piezoelectric materials have been adapted to an impressive range of
applications, including sensors, actuators, acoustic transducers, medical equipment, and motors. Generally, the voltage output is large, but current is miniscule, limiting many power-driven applications.

2.1.2 Piezoelectric Principles

The piezoelectric effect occurs due to the arrangement of atoms within the crystal structure; under mechanical stress, dipoles form in the material, a separation of positive and negative charges. The Weiss domains, which are collections of dipoles with similar orientations, are randomly oriented under normal conditions within a material; these garner no net charge. Yet, as stress is applied, the atomic structure changes and the dipoles align, resulting in the net voltage. In natural piezoelectrics, like quartz, the dipoles form when there is no center of symmetry due to ion reconfigurations in the crystalline structure. Figure 2.1 shows the altered center of symmetry resulting in piezoelectric effect (a) and stretched structure and the normal positioning of the ion (b).

![Figure 2.1 – (a) Normal positioning of crystal structure and (b) lack of symmetry resulting in piezoelectric effect](http://www.intechopen.com/source/html/19252/media/image3.png)
Potentially, non-piezoelectric materials can be forced to be piezoelectric by a process termed poling. Below a certain temperature, known as the Curie point, a non-polar material can undergo a structural transformation, having an induced electric polarization. The Weiss domains in a material can be aligned by exposing the element to a strong, direct current electric field, usually at a temperature slightly below the Curie point. Through this poling treatment, the crystal element lengthens in the direction of the field similar to Figure 2.1b. When the electric field is removed, a majority of the dipoles are locked into a configuration of near alignment, resulting in a permanent polarization. Raising the material above its Curie will remove this effect. The random dipoles of an un-poled material, the dipoles after DC voltage application, and the remnant dipoles after the field is removed are shown in Figure 2.2.

![Figure 2.2 – Poling effect of piezoelectric material](http://piezokeramika.wcz.cz/images/2piezo.gif)

Once a material exhibits a piezoelectric effect, multiple parameters are used to describe the quality of the transducer. The terms give detail into what vibrational amplitude and voltage can be generated by different materials. The most influential are the piezoelectric coefficients for charge (“d”), voltage (“g”), Young’s modulus, density, and
Poisson’s ratio. The terms “d” and “g” are most widely used when designing piezoelectric transducers.

Piezoelectricity is the combined effect of the electrical behavior of the material and Hooke’s Law:

\[
D = \varepsilon \cdot E \quad \text{(Equation 2.1)}
\]

\[
S = s \cdot T \quad \text{(Equation 2.2)}
\]

where \(D\) is the electric displacement, \(\varepsilon\) is permittivity, \(E\) is electric field strength, \(S\) is the strain, \(s\) is the compliance, and \(T\) is the stress. These may be combined into so-called coupled equations, of which the strain-charge form is:

\[
S = sE \cdot T + d \cdot E \quad \text{(Equation 2.3)}
\]

\[
D = dt \cdot T + \varepsilon T \cdot E \quad \text{(Equation 2.4)}
\]

These equations describe the stress developed when the piezoelectric is subjected to an electric field, and the potential developed due to pressure on the piezoelectric, respectively. "d" coefficients are generally obtained by measuring the density of charge which appears on the surfaces of the film when a mechanical stress is applied. These coefficients have subscripts, such that \(d_{33}\) indicates that a stress in the 3 direction, using the definitions given in Figure 2.3, produces charge in the same direction. Likewise, a \(d_{31}\) constant indicates that a stress in the 1 direction will produce a charge in the 3 direction. Greater “d” coefficients thus correlate to a higher strain in the material.
Moreover, if the variation in the electric field is measured per unit of stress, the “g” coefficients are obtained. These are related to “d” terms by the correlation in Equation 2.5, where $\varepsilon$ is the dielectric constant which depends on the thickness of the film.

$$g = \frac{d}{\varepsilon} \quad (\text{Equation 2.5})$$

**Figure 2.3 – Definition of subscripts for force direction of constants**

As with all solids, piezoelectric materials have mechanical stiffness properties described as Young's modulus. Young's modulus is the ratio of stress to strain, or force applied to length displaced. Compliance is the inverse of Young’s Modulus. This parameter gives insight into the stiffness or elasticity of a material.

$$Y = \frac{\text{Stress}}{\text{Strain}} \quad (\text{Equation 2.7})$$

Poisson’s ratio is the ratio of transverse to axial strain. This term describes the material effect where compression in one direction results in the expansion in perpendicular directions.
Finally, the density is given as the ratio of the mass to volume in the material:

\[ \rho = \frac{\text{mass}}{\text{volume}} \]  

(Equation 2.9)

The piezoelectric properties described above are defined for ideal shapes measured under ideal mechanical and electrical boundary conditions. In practical applications, boundary conditions and other parameters contribute losses due to such things as standing waves, interfering vibrational modes, pseudo-clamping, and stray electric and dielectric resistances.

Piezoelectrics can degrade their induced polarization under different circumstances. Mechanical depolarization occurs when the mechanical stress on a piezoelectric element becomes high enough to destroy the alignment of the dipoles. Additionally, if a piezoelectric element is heated to its Curie point, thermal depolarization can occur as the domains become disordered [10].

2.1.3 Piezoelectric Plastics and Copolymers

Quartz crystals were the first widely used piezoelectric material, which gave way to barium titanate ceramics as man-made piezoelectrics became widely accepted. PZT ceramics were discovered in 1954 and overtook barium titanate on account of its higher electromechanical coupling factor, good frequency-temperature characteristics, and suitable quality factor [2]. In time, piezoelectric properties were discovered in certain man-
made plastics, granting increased flexibility in applications. As opposed to the reorientation of ions within the crystals of ceramic elements, the reorientation of molecular groups forms the dipoles in polymer devices.

![Figure 2.4 – Metallic-coated P(VDF-TrFE) films](http://www.piezotech.fr/image/products/news-31-p-vdf-trfe-piezoelectric-films-2_xs.jpg)

Polyvinylidene difluoride (PVDF) is an example of a plastic material capable of such piezoelectric properties. The material must undergo multiple procedures and phases to display the piezoelectric effect. Crystallization from the cooling of resins or powders, after melting the materials into a defined shape, forms a non-polar $\alpha$-phase, which can be converted into the polar $\beta$-phase by a uniaxial or biaxial drawing operation. The stretching of the material results in dipole formation. The resulting dipoles are then reoriented through electric poling. Large sheets can be manufactured and thermally formed into complex shapes.

The copolymerization of vinilylde difluoride with trifluoroethylene (TrFE) results in a random copolymer (PVDF-TrFE) with a stable, polar $\beta$-phase, which can then be poled directly. The copolymer has larger piezoelectric response due to increased crystallinity.
Although the piezoelectric “d” constants of plastics are lower than ceramics, as shown in Table 2.1, piezoelectric polymers have the following benefits: light weight and soft elasticity, leading to good acoustic impedance matching with water or the human body; a low mechanical quality factor Q, allowing for a broad resonance band width, high mechanical strength; balanced piezoelectric activity; and stability up to approximately 90°C. The voltage coefficients are also superior due to low dielectric constant.

In regards to this project, the light weight and elasticity is preferable for conforming to the spiral turn of the cochlea, whereas ceramics would have a greater change of damaging tissue due to stiffness. Biocompatibility of P(VDF-TrFE) is observed [6] whereas PZT-based ceramics contain lead, which has noted toxicity. Furthermore, perilymph fluids are present in the implantation environment; thus, polymers will have lesser output dampening due to the acoustic impedance similarity. Based on these characteristics, P(VDF-TrFE) was chosen for the artificial cochlear membrane in this research, initially with a 70/30 molar blend.
2.2 Resonant Frequency

To achieve maximum output from a piezoelectric device, the ideal operating frequency is about a point called the resonant frequency. This is the frequency at which objects vibrate most readily and naturally, as determined by its physical parameters. Alternatively, it is where mechanical pressure is converted to electrical energy at the highest efficiency. As there is less resistance to vibration, this will cause the piezoelectric to oscillate at higher amplitudes, leading to greater voltage output. There are multiple resonant frequencies for each device, occurring at different harmonics offset by specific intervals.

Based on the size of the film, its thickness, loading due to how the film is secured, and other material properties, the resonance region can be intelligently altered. As mentioned before, designing the material around this parameter will ensure optimal output, but moreover isolate the responses of the membrane to select segments, as described in Section 1.2.3. Each segment will be constructed for a unique, narrow bandwidth; thus, the resonant frequency is the basis for creating the frequency-selective artificial cochlear.

2.3 CoventorWare

CoventorWare is an industry standard software with the capability to design MEMS systems and analyze their mechanical, thermal, and electric characteristics. In particular to this research, it has a module that can simulate the displacement and potential generation of piezoelectric devices. The software uses the mathematical approach, finite element method (FEM), to solve complex boundary conditions, dividing an intricate structure into numerous manageable pieces. This method is used due to its ability to create an accurate
representation of complex geometry, analyze dissimilar material properties, and capture local stress effects. In addition to modal and harmonic analyses for frequency experimentation, the software is capable of modeling damping due to material contact; this benefits in observing fluid interactions.

From data sheets of the piezoelectrics used in this research, a material definition for P(VDF-TrFE) was created in the software, having the proper thermal, piezoelectric, mechanical, and electric characteristics. The piezoelectric properties described in Section 2.1.2 were accurately modeled in the software. The device was then built layer for layer in the same MEMS manner that the actual device can be fabricated, by defining masks, etching layers, and depositing new materials subsequently. With the layers and masks managed, a 3D image of the device was rendered, containing the piezoelectric membrane and defined electrodes. The models were then meshed, setting up boundary conditions for the FEM simulation.

With the preliminary steps completed, the models were analyzed through the MemMech solver, simulating the mechanical and piezoelectric response of the membrane. Results were tabulated for the charge output, resonant frequency, and displacement of the device, as well as the stress tolerance of the film.

Mesh creation for the simulation was an issue, as it was difficult to find proper division size for both accurate results and manageable simulation times. Thus initial simulations used a much smaller model to get quantitative results. The outcome gave insight into how resonant frequency and film displacement were affected by dimension alterations.
2.4 Simulation Results

2.4.1 Width and Length Dependency

Through the procedures described in Section 2.3, simulations for the experimental devices, described later in Section 3, were performed over the typical frequency range for human speech, 500 to 8500 Hz, at increments of 50 Hz. The pressure applied uniformly to the film was the equivalent of 78 dB SPL, the same pressure to which the experimental samples were exposed. The substrate model dimensions were 20mm by 50mm and contained a slit in the center, which was varied in width and length. The substrate model is shown in Figure 2.5a, with the deposited film and electrode shown in Figure 2.5b. Cavity widths of 3mm, 3.5mm, 4mm, 4.5mm, 5mm, 5.5mm, and 6mm at slit lengths of 30mm were examined; lengths of 15mm and 8mm were also simulated.

Changes in Young’s modulus and Poisson’s ratio were likewise examined due to expected error presented in the material datasheets. For example, the value for Young’s modulus had a possible error of 20%. After a preliminary run through the defined frequency
range, an additional analysis was performed about the highest response at 1 Hz increments; this was done to uncover the peak magnitude for each film size, as the bandwidth of the simulated results is extremely narrow. The results of the width changes are shown in Table 2.2.

<table>
<thead>
<tr>
<th>Film Width</th>
<th>3mm</th>
<th>3.5mm</th>
<th>4mm</th>
<th>4.5mm</th>
<th>5mm</th>
<th>5.5mm</th>
<th>6mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output (µm)</td>
<td>1.618</td>
<td>4.87</td>
<td>4.534</td>
<td>3.75</td>
<td>4.35</td>
<td>3.21</td>
<td>4.17</td>
</tr>
<tr>
<td>Frequency</td>
<td>6427</td>
<td>4562</td>
<td>3387</td>
<td>2980</td>
<td>2535</td>
<td>2292</td>
<td>1652</td>
</tr>
</tbody>
</table>

Table 2.2 – Simulated results based on film width at constant 40µm thickness and 30mm length

Table 2.3 details the changes to output magnitude and resonant frequency on account of specific parameter alterations. The film width was constant at 4mm while the length, Young’s modulus, and Poisson’s ratio were changed from the control sample (30mm length). According to the results of Tables 2.2 and 2.3, greater film widths and longer lengths reduced the resonant frequency; the increased film size introduced a greater load. Errors in Young’s modulus were additionally found to have a profound effect on the output.

<table>
<thead>
<tr>
<th>Film Parameter</th>
<th>30mm length (Control)</th>
<th>15mm length</th>
<th>8mm length</th>
<th>Young’s Raised 20%</th>
<th>Young’s Lowered 20%</th>
<th>Poisson Lowered 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output (µm)</td>
<td>4.534</td>
<td>3.503</td>
<td>3.589</td>
<td>5.66</td>
<td>7.722</td>
<td>4.02</td>
</tr>
<tr>
<td>Frequency</td>
<td>3387</td>
<td>6666</td>
<td>7229</td>
<td>2504</td>
<td>3599</td>
<td>3254</td>
</tr>
</tbody>
</table>

Table 2.3 – Length and material property effects on 4mm wide films at constant 40µm thickness
Conclusively, these CoventorWare simulations suggest that the resonant frequency of the piezoelectric material under investigation can predictably be controlled by changing the width and length of the material. Furthermore, specified error in key parameters, such as Young’s modulus, substantially alters the performance and should be accounted for in experimental error.

2.4.2 Film Thickness

As described in Section 1.2.3, thinning the film is one of the key concepts for increasing the voltage output, while simultaneously reducing the interference from different segments. The thinner film theoretically produces superior voltage as the membrane is less resistant to displacement; therefore, the film will deform more readily and create a higher potential difference.
The simulations were originally run in Section 2.4.1 using 40 micron-thick films. A visual representation of the 40 micron response is shown in Figure 2.6. In the simulation shown in Figure 2.7, the thickness was changed to 20 microns, while the sample holder dimensions, electrode size, and fixed boundaries remained unaltered. Over the same frequency range, the maximum output of the 20 micron film is given in Figure 2.6 at a displacement of 18.416 microns, compared to 4.5 microns produced by the 40 micron film. The 20 micron-thick film produced an output over 4 times larger than the 40 micron-thick counterpart.
2.4.3 Frequency Selectivity

Simulations were furthermore performed to grant insight into changes resulting from etching the piezoelectric film as described in section 1.2.3. As more complexity was introduced in the models, the simulations required excessive run-time. To counteract this hindrance, the size of the model was reduced, thus generally increasing the resonant frequency and reducing the output magnitude.

Regardless, the segments were shown to preferably react to different frequencies, while the etches in the film reduced the output of neighboring segments, as given by Figure 2.8. The simulation confirmed that the proposed structure can offer isolation and frequency selectivity determined by the dimensions of the segments.

Figure 2.7 – Simulated frequency selectivity of proposed structure
2.5 Summary

PVDF-TrFE has been chosen as the experimental material due to a few key characteristics. Although ceramics have improved piezoelectric responses, they lack flexibility and compatibility with the human body, whereas PVDF-TrFE additionally has an acoustic impedance similar to water, giving a better response in the fluids of the cochlea. Coventorware software FEM simulations were run to determine frequency and output characteristics of the film.

Simulated results were provided for frequency response based on size of the film, thickness of the film, and the effects of the film etching to provide frequency selectivity. The results verified the theory that film size can control the resonant frequency, and that potential output grows with decreased material thickness. The output of a 20 micron thick film was over 4 times larger than a 40 micron thick film. A summary of width vs. resonant frequency is given in Figure 2.9 for constant 30mm length.

![Figure 2.9 – Resonant Frequencies for 30mm long films with varied widths](image-url)
Chapter 3 – Piezoelectric Film Characterization

Though simulations give a general description of the performance of the device, it does not account for the experimental complications, such as imperfect bonding between the substrate and piezoelectric, electrode and wiring issues, and interference from outside sources. Consequently, experimental data is required to survey these topics. There are three major portions to the measurement procedure in this research: sample preparation, output measurement, and results interpretation. The general setup used for this project is shown in Figure 3.1.

![Diagram of experimental setup](image)

**Figure 3.1 – Diagram of experimental setup**

3.1 Sample Preparation

3.1.1 Metal Deposition

Metal deposition is the chemical or physical process by which thin electrodes can be formed on the piezoelectric film. These electrodes are necessary as a common region
for charge generated by film displacement to collect. If the electrodes are placed on opposing sides of the sheet at the same location, then a potential difference can be measured on the film. However, if these metal layers are too thick or extensive, excessive loading will dampen the film, affecting the output. Common methods for metal deposition are chemical vapor deposition, physical vapor deposition, and sputtering.

Initially in the project, silver epoxy was used to form electrodes on the film; yet by hand, the thickness of the metal was overbearing, compared to the smaller thickness of the piezoelectric sheet. As a result, no output was identifiable. Cleanroom sputtering, where atomic high speed collisions on a target material (metal) causes atoms to form a thin layer on the substrate (PVDF), was then used on the PVDF samples. The sputtering allowed electrodes to form that were orders of magnitude thinner than the piezoelectric membrane. With these electrodes in place, output from the film was visible on the spectrum analyzer. Subsequent piezoelectric materials were purchased pre-coated with a metallic layer, as adequate equipment for metal deposition was not available. The task then was to remove the metal from the film, leaving desired electrode patterns.

3.1.2 Chemical etching

Chemical etching is the process through which a layer of material is selectively removed from another through chemical erosion. The chemical composition of the etchant determines what material will be removed. In this case, the etchant was chosen specifically to remove the metal layers present on the piezoelectric. The process is furthermore isotropic, denoting that the etching occurs in all directions.
For the P(VDF-TrFE) samples used in this research, the electrode composition was 70Å chromium (Cr) deposited directly to the sheet with 1000Å aluminum (Al) deposited on top of the Cr, for the 20μ and 40μ thick films. This was altered to 50Å Cr deposited first with 220Å Al on top, for the 9μ thick film. Al can potentially be etched by both acidic and basic solutions; however, another requirement was for the etchant to not affect plastics, thus dissolving the film. Consequently, two candidates for the etching process were sodium hydroxide and hydrochloric acid.

A mask was likewise needed to maintain the desired electrode size. To achieve this selectivity, transparent adhesive tape was cut and applied to each side of the film. For these tests, the mask was always placed in the center of the film, spanning the entire film with a width of 2mm. Precaution was needed when handling the films, as any residue present could act as a mask, leaving unetched regions.

Figure 3.2 – Effect of etching techniques on the film (a) no etch (b) NaOH etch (c) HCl etch
Initially, the basic NaOH solution was examined. Although large segments of the metal were fully removed, small patches of material still remained, which would not erode post 30 minutes of etching. The HCl solution mixed was 6:14 parts HCl to water. Between 9 and 11 minutes proved long enough to completely etch the films, though care had to be taken when removing the mask, as the thin film easily sheared. The stages of etching are shown in Figure 3.2. A magnified view of the etched film is shown in Figure 3.3 at the border of the masked electrode and etch.

![Etched region](image)

**Figure 3.3 – Magnified view of electrode etch boundary**

With these electrodes present, wires could interface the metal, allowing external equipment to access the potential.

### 3.1.3 Electrode Preparation

Due to the film’s Curie temperature of approximately 90° C and plastic composition, soldering could not be used to attach wires to the electrodes. As an alternative,
silver conductive epoxy with a resistivity of 0.18 Ω·cm (MG Chemicals) was utilized to provide the required connectivity. 0.003” nickel wire was held firmly to the sample film while a bead of the silver conductive epoxy was placed to envelope the wire and electrode. A close-up of the connection is shown in Figure 3.4.

![Figure 3.4 – Magnified wire-electrode connection](image)

The samples used in this experiment were purchased in sheet quantity; thus, different regions on the same sheet might have slight manufacturing differences providing errors in conductivity.

### 3.1.4 Sample Holder Characteristics

These wire-melded samples were then sealed to identically-produced PVC sample holders, each having varying slot widths to test for frequency resonance. The sealing agent
used was a clear quick-drying epoxy. Ideally, the film would be completely secured around the edges, keeping the film completely flat and without strain, only permitting the region above the slot to vibrate. However, the small beads of silver epoxy restricted the film from being completely flat, and could potentially generate additional strain. Two samples fastened to the substrates are shown in Figure 3.5.

![Image of sample holders](image)

**Figure 3.5 – 6mm sampler holder (left) and 4mm sample holder (right) with attached piezoelectric film**

Additionally, the clear epoxy formed issues, introducing unexpected output and resonance characteristics. Upon application, the epoxy could flow minimally into the slot after applying pressure to the film or during alignment. This would artificially make the slot narrower by restricting the film movements in unintended regions. The effect is presented in Figure 3.6, where the overflowed epoxy is nearly 1mm.
3.2 Amplification

Due to the small dimensions of the piezoelectric film and relative low levels of sound pressure applied, amplification was obligatory to perceive the microvolt and millivolt scale signals in a straightforward manner; otherwise, the signals could easily be masked by noise. Initially, this was especially beneficial as the output quality of the film was unknown. Additionally, the amplifier appropriated inputs from both negative and positive terminals of the film, resulting in the potential difference between the electrodes. An instrumental amplifier, AD8226 (Analog Devices) was chosen to amplify the signal, having both the differential capacity and an adjustable gain. The gain was set to generate approximately 100 times amplification.
Surface mount components were soldered on a printed circuit board in order to keep the system compact and ensure no connection issues. This furthermore reduced complicated wiring, which could collect additional interference or result in loses. The samples were connected to the amplifier by small clip leads, soldered to the amplifier circuitry. The clips were chosen as soldering the electrode wires directly was unsavory. It not only greatly increased the time needed to change samples, but reduced connectivity as the nickel wires did not easily meld through soldering.

![Amplifier device with internal battery and clips](image)

**Figure 3.7 – Amplifier device with internal battery and clips**

From the first version of the amplifier, issues were present in that the gain at low frequencies was only 50 times, drastically reducing as frequency grew. The cause of this was found to be fluctuating voltage levels from the power source. Changes were made to this amplifier in order to regulate the incoming voltage and moreover change the rails to -3.3V and 3.3V. This gave a constant gain regardless of the varying input voltage and also served to better control miniscule voltage yield, as opposed to when the lower rail was 0V.
The maximum output of the amplifier with this setup is approximately 65mVp-p and can accurately track towards zero. The amplifier structure is shown in Figure 3.7.

A low-pass filter with a bandwidth of 10 kHz was connected to the output, eliminating high frequency signals on the system, produced by the amplifier. Consequently, the system had losses as the frequency approached the cutoff value, where the reduction at 10 kHz is approximately 20%. These are generally characterized in Table 3.1. In future experiments, the filter should be altered for a cut-off frequency of 20 kHz.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>1000</th>
<th>5000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output (Vrms)</td>
<td>1.702</td>
<td>1.596</td>
<td>1.344</td>
</tr>
</tbody>
</table>

**Table 3.1 – Output when 17.65mVrms applied**

Whereas the amplifier is utilized to improve the visibility of the output from the film, additional equipment was developed for exciting the piezoelectric effect of the film.

### 3.3 Experimental Setup

#### 3.3.1 Signal Generation

The piezoelectric films required physical pressure to deform and thus produce a potential difference. To apply this principle, a speaker and signal generator (Agilent 33120A) were used to form a constant pressure on the surface of the device. At this time, only pressure produced perpendicular to the film was examined. The quality of constant pressure was determined by the Sound Pressure Level (SPL) emanating from the speaker.
As SPL is weighted with frequency, an SPL meter detected the emanating levels from the speaker, between the frequency range of 500 and 8500 Hz. The voltage driving the speaker was then adjusted in order to maintain a constant 78dB SPL. This output was chosen due to the limitations of the speaker and signal generator, though this SPL adhered to the Environmental Protection Agency’s standard of probable hearing loss. 70dB SPL is the maximum recommended exposure to avoid hearing loss, whereas subjugation to 85 dB SPL can cause hearing damage over long-term exposure. For each sample point, the voltage of the signal generator was adjusted accordingly and monitored with the meter. SPL variations due to changes in frequency and voltage applied to the speaker vs. frequency are given in Figures 3.8 and 3.9, respectively. The speaker was secured 10 inches above the film.
3.3.2 Output Capture and Measurement

The voltage differential generated from the applied pressure was measured through two different mediums, a spectrum analyzer (Agilent N9320B) and an AC multimeter (Agilent U1242A).

The spectrum analyzer gave a clear representation of the output at different frequencies, displaying real-time peaks of the output and any related harmonics. This output was in terms of power, but could be converted to voltage by first changing the power from dBm to watts, through Equation 3.1.

\[
P(w) = 10^{\frac{P_{dBm} - 30}{10}} \quad \text{(Equation 3.1)}
\]

A network analyzer (Agilent E5061B) was used to determine the resistance at each of the examined frequencies. The resistance nearly matched the data sheet given value for
electrical impedance, 1000Ω. The power measurements could then be converted from watts to volts with Equation 3.2.

\[ P(w) = \frac{v^2}{2R} \]  
(Equation 3.2)

The true voltage generated by the film can then be uncovered after dividing by 100 to account for the amplifier.

Measurements were systematically taken by starting the signal generator at the lowest frequency and simultaneously applying the voltage correction for proper SPL as frequency increased; this process was then repeated for each frequency up to the maximum of 8500 Hz.

![Figure 3.10 – Spectrum analyzer noise](image-url)

Figure 3.10 – Spectrum analyzer noise
One issue with this spectrum analyzer was the considerable amount of noise near lower frequencies, as shown in Figure 3.10, which is only resolved above 9000 Hz. This additive noise primarily disrupts readings at low frequencies; however, in most cases the output from the piezoelectric film was far greater than the raised noise floor. Regardless, averaging was used to determine the noise floor due to this low frequency interference, and in subsequent experimental readings, the noise was subtracted from each data point.

The output was subsequently verified with an AC multimeter. This device was able to display the after-gain voltage as well as the frequency recorded, which matched the spectrum analyzer readings.

3.3.3 Interference Protection

After initial testing, interference from the signal generator was found to be problematic; the electromagnetic radiation was overpowering the piezoelectric response as the wires and components comprising the amplifier acted as antennas. To reduce the masking of the film output, a conducting shield needed to be constructed to block the radiation.

Low frequency electric signals have long wavelengths, penetrating further into materials. Skin effect describes the tendency for AC signals to be distributed near the surface of a conductor; the skin effect depth is reduced as material thickness increases. Therefore, based on Figure 3.11, for the frequency range relevant to this research, a conductor should be approximately 4mm to block the interference if aluminum is used.
A 3mm aluminum box was constructed to house the power source, amplifier, and sample holder with attached film. This structure contained a BNC connector on one side for instrument connection and a rectangular hole in the top to allow the sound pressure to affect the film. This hole was later reduced in size as the width of test samples was decreased.

Further testing verified that the output emanating from the piezoelectric film was free of any contaminant signals. Claps, whistles, and speech could be picked up on the spectrum analyzer to ensure mechanical vibrations were causing the output. Furthermore, the cables powering the speaker were moved proximal to the box, which resulted in no interference compared to the substantial effect without the housing. These tests were repeated each time to ensure that the output was from the expected source.
3.4 Characterization of Piezoelectric Response

3.4.1 Measurements without Interference Protection

Preliminary measurements done with the test system had the problem of outputting results when no sound was applied. The effect from this is shown in Figure 3.12, and the output was fairly flat, producing no clear peaks. Although output from pressure was still visible on the spectrum analyzer, output from interference sources described in Section 3.3.3 were significant enough to disrupt the reading. This was discovered when the signal generator was set to its maximum voltage output, and the cable attaching it to the speaker was unplugged and moved towards the amplifier and sample. Once the aluminum box described in section 3.3.3 was introduced in order to reduce the EM effects, measurements were found to not have any additional effect from interference, and all signals emanating from the system were caused solely by mechanical vibrations.

Figure 3.12 – Flat output shown on spectrum analyzer due to interference
3.4.2 Sample Size Determination

Sample holders originally had a fluid chamber, as described in the papers by Shintaku et al. These were developed in order to include fluid interactions in the subsequent measurements. However, the size of these fluid chambers may have initially been too large. The sample holder is shown in Figure 3.13.

![Initial Sample holder device (30mm cavity)](image)

**Figure 3.13 – Initial Sample holder device (30mm cavity)**

As a result, the size of the film within the freely-vibrating region was potentially too wide, loading the film excessively. As shown in Figures 3.14 and 3.15, the output was broad, not displaying any clear resonance and one frequency. This was likely a consequence of the resonant frequency being too low and not visible on the spectrum analyzer, as 500 Hz was the minimum tested frequency point.

![Frequency dependence response of 30mm long, 21mm wide film](image)

**Figure 3.14 – Frequency dependence response of 30mm long, 21mm wide film**
To bring the output into the desired frequency spectrum, the width of the films was reduced from 21mm to the range of 3mm to 6mm; samples were also made at 8mm and 14mm, yet were not repeatable and had low output although peaks were found. The 8mm film output is shown in Figure 3.16. With the smaller widths of samples, data was obtained that showed improvements over the flat response shown before, yet the amplitudes of the peaks were not vastly different from other peaks found during the experiment and the results were not systematic. Therefore, the next step was to utilize etching techniques in order to remove the metal that covered the entire film, and potentially reduce the stiffness and loading.

**Figure 3.15 – Frequency dependence response of 30mm long, 21mm wide film**

**Figure 3.16 - Frequency dependence response of 30mm long, 8mm wide film**
3.4.3 Etched Measurements

Section 3.1.2 described the etching steps taking to make narrow electrode strips on the films. These electrodes were chosen to initially be 2mm wide and span the width of the film. Uniform sample holders were produced that had variable widths for the cuts made in the holder, which allowed vibration to a select region of the sample.

Experiments were performed at 3mm, 3.5mm, 4mm, 4.5mm, 5mm, 5.5mm, and 6mm sizes, which were simulated in section 2.4.1. Although 3 samples of each variant were used, only a few of these garnered sufficient output to be considered acceptable. Criteria were based on the potential difference generated, resonant frequency due to width, and distance between each harmonic; wider films should have lower resonant frequencies and less distance between each harmonic. The results are shown in Figures 3.17, 3.18, and 3.19. The widths of 3.5mm and 4mm gave acceptable results, while the 6mm matched the frequency expected but output was lackluster. The maximum output as recorded from the 4mm wide film was 10.4mV.

![Figure 3.17 – 3.5mm wide film frequency response](image-url)
The issues in output for Figure 3.19 could be due to the sealing agent used to holster the films in place, as well as the connections made by the electrodes and wires. An improper mixture of the silver epoxy agent would greatly increase the resistance of the system,
reducing the output. The thin wires additionally could have been damaged to once again increase this resistance.

For the other rejected samples, as described in Figure 3.6, the sealing agent was potentially applied in excess, causing epoxy to flow under the film and artificially reduce the film width, changing the output and frequency properties. This would be an explanation for the unexpected resonant frequencies given by the tests. As a result, a new piezoelectric sealing method will need to be researched to reduce the effect of the boundary problems.

Another issue might have resulted from the temperatures and humidity in the testing room. For a few of the samples, the resonant frequency and output voltage were moderately altered as the samples were retested after a long period of time. In the future, a testing system will need to be established to control these environmental uncertainties.

3.4.4 Film Thickness Impact

Three thicknesses of PVDF-TrFE films were tested in this experiment to demonstrate earlier given theory. With width constant at 4mm and length constant at 30mm, comparing 40 micron thick films (Figure 3.20) vs. 20 micron thick films (Figure 3.18), verified that the output was decreased as the film thickness increased. The 40 micron film was shown to be approximately 4dBm smaller in output than the 20 micron thick version. However as the test system is not completely systematic, this relationship will have to be further experimented upon on account of the epoxy issues.
Figure 3.20 – 4mm wide frequency response (40μm thick)

9 micron thick films were likewise examined in this research, yet their potential output could not be verified due film damage during testing. The output of the film showed no definite peak at any frequency, and the output was substantially lower than the other films. Upon examining the sample holders, the film seemed to have a plastic deformation around the boundary of the slit. Potentially, this implies that the sound pressure applied by the speaker was too much for the thin film to handle, resulting in a permanent deformation. This observation necessitates further exploration.

3.5 Summary

Experimental work done in this research has been targeted towards verifying the electrical output and frequency response of piezoelectric film, altered in width, thickness, and length. An experimental system consisting of a speaker powered by a function generator, an aluminum box to reduce EM interference which houses an amplifier and
piezoelectric film, and spectrum analyzer and multimeter for measuring the response was used in this research.

Width selection for the targeted frequency range was determined from this work as well as the electrical output associated with these films. The maximum output of the films was found to be 10.4mV and three films were produced which had resonant frequencies at 1700, 4100, and 6400 Hz at widths of 3.5mm, 4mm, and 6mm, respectively.
Chapter 4 – Conclusions and Future Works

4.1 Conclusion

Piezoelectrics are very promising for artificial cochlear implants, due to their biocompatibility, sufficient voltage output, and potential frequency selectivity through MEMS processing. This research works towards developing a cochlear implant, which is self-sustaining and uses the natural functions of the human outer and middle ear; the device will target sensorineural hearing loss.

In this work, experimental and simulated data based on the output of fabricated piezoelectric films was determined. Fabricating the piezoelectric samples proved troublesome due to the delicacy of the films and unintentional loading on the devices. The measurement system targeted towards reading the output voltage additionally was adversely affected by electromagnetic interference. As a result of this research, the potential of fabricating frequency selective piezoelectric segments has been verified, and their voltage generation at resonance is within the necessary bounds at a maximum of 10.4 mV.

With these confirmations, work can now begin on developing the targeted device and starting both in vivo and further in vitro testing.

4.2 Future Works

4.2.1 Future Test System

Due to the current errors in the test system and need for a more accurate approach when fabricating the frequency selective device, a new test system is planned for this
research. Software to maintain a constant SPL and a microphone system for active feedback can reduce the errors in maintaining mechanical pressure. The sample will also be housed in an anechoic chamber to reduce noise from external sources and environmental effects. This setup will allow quicker and more accurate measurements, also granting more resolution in frequency changes. The accuracy will become especially useful when etching of the piezoelectric necessitates precise measurement of resonant frequencies.

Research into a new mounting procedure for the film will also have to be uncovered, as the yield of samples experimented upon was unsavory, likely due to the securing of the film and epoxy leaking. As opposed to sealing down the samples with epoxy, MEMS processes can produce electrode networks on a substrate, making direct contact with the electrodes on the film when another structure holds down the film; this will eliminate the need for wires and silver epoxy as well. However, these surfaces will have to be extremely flat to secure the thin films.

Once a more adequate testing system is in place, more experimentation can commence into other possible parameters of the film. As only size and thickness of the film have been experimented upon so far, additional work will go into investigating effects of electrode placement, electrode size, and edge placement for sealing down the films, as potentially in the cochlea the device will not be able to be secured on all edges.

4.2.2 Fluid Testing

Due to the fluid-filled conditions of the human inner ear, used to conduct the sound waves, testing needs to be done with the sample devices in a fluid environment. This will likely be done using silicone oil, due to its density and viscosity properties. The resistance
to deformation given by liquid interactions potentially will reduce the output voltage and lower the resonant frequency, which needs confirmation. A simple system for emulating the outer, middle, and inner ear fluid interactions is shown in Figure 4.1.

![Figure 4.1 – Fluid effect test system](image)

4.2.3 Membrane Etching

The testing done up to this point has only included larger samples in which the widths and lengths were altered. To produce the projected device, chemical etching performed on the piezoelectric membranes will induce the different sized segments for selectivity by forming trenches for separation as described in section 1.2.3. Additionally, the actual implantable device will be nearly an order of magnitude smaller than the tested segments so far; these reduced structures will likely decrease the amplitude and increase the resonant frequency; however, the fluid interactions can potentially allow the frequency to remain in the desired range.
Nano-wire structures to increase displacement will also be researched to increase the output. These can be distributed on the surface of the film through etching procedures and further the strain [1].

4.2.4 In-Vivo Testing

To ensure that the piezoelectric membrane and the associated materials are biocompatible, in vivo testing will begin to collect data on any cytotoxic effects. Initially, the experiment will be limited to implanting the materials and later performing a histology study, where cochlea sections would be stained/viewed under a microscope to see if there is any cellular damage. Once tested over the course of months, a simple version of the actual device can then be used in animal testing to determine if a single channel can stimulate the nerves of the hearing centers of the brain.

4.2.5 Power Sources

As the effect of the fluids and smaller film sizes could potentially reduce the output of the piezoelectric film, amplification could be required after the damping effects are found. Due to this, research into human body-available power sources is planned. These power sources can include thermal, vibrational, or electrochemical means, such as through the stria vascularis [11].
The electrical output of the etched PVDF film is expected to be only a couple of magnitudes lower than that required to stimulate the nerves in the human ear, thus, a minimal power amplifier can be used to reach the necessary output. This class of amplifier can run from μW of power, which can be generated by a simple thermal source, whose generation potential is shown in Figure 4.2 and structure in Figure 4.3.
REFERENCES


