Piezoelectric MEMS Transducer as Audio Prosthesis

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This project develops a piezoelectric microelectromechanical system (MEMS) transducer for *in vivo* implantation as audio prosthesis. Through reduced size and increased biocompatibility, our transducer can be included in integrated circuits (IC) and is suitable to both humans and animals.

Our device replaces the ossicular chain of the middle-ear, which serves to transfer acoustic waves from the air into the cochlear fluid of the inner-ear. Previously, a study from a research team (Campanella et al.) from the Institute of Microelectronics at the National Center for Microelectronics in Barcelona, Spain, revealed such a device for human use. Actuating directly on the oval window of the inner ear, the device replaces the ossicular chain while performing patient-specific equalization and impedance matching. To ensure normal operation, the main design criterion is to have the first resonance above 20kHz, the upper limit of the human hearing range. The research team did not study the possibility of increasing further the frequency of the first resonance, so we propose a new device that increases the lowest natural frequency and extends its application to animals with similar prosthetic needs.

An external microphone sends the sound signal to our device (Fig. 1(a)), which is enclosed in titanium, a biocompatible material, due to the high cytotoxicity of the silicon. The screw-like shape increases the stability of the actuation on the inner ear. The acoustic cavity provides external mechanical isolation and contains the IC that performs pre-programmed equalization and impedance matching. Fig. 1(b) shows a 3D structure of the proposed device. Above the silicon wafer, a layer of silicon dioxide, deposited through PECVD, provides electrical isolation from the electrodes. Two layers of platinum serve as electrodes and encase the active material of our transducer, a thin layer of AlN. The passivation bilayer of Si3N4 and Si02 protects conduction paths from oxidation, aging, and detrimental alterations. Not represented, a thin layer of titanium eases the adherence of the platinum layer. Fig. 3 represents the fabrication process.

Using ANSYS, we aimed at increasing the 1st resonance while maximizing the deflection of the transducer. Using simulations based on Finite Elements Method (FEM), we looked at the modal properties of the transducing layer (Fig. 2 (a) and (b)) and specifically the lowest natural frequency, as a function of the thickness of our active piezoelectric AlN layer as well as the radius of the central layers (Pt, AlN, Si3N4, Si02). Fig. 4 (a) summarizes the results at a fixed wafer radius of 500µm. The results are also represented as a 3D graph in Fig. 4 (b).

The first conclusion is that changing the thickness of the AlN layer has a smaller impact than changing the radius of the central layers. The second conclusion is that a larger radius of the central layer increases the frequency of the first resonance. The highest value we achieved is 71.45kHz. This frequency is suitable for dogs and horses as shown in Fig. 5. We could not significantly improve the first resonance frequency by increasing the radius of the silicon wafer and trying other combinations of radii. We reproduced the results from Campanella et al., which correspond to radius of AlN layer = 400µm, radius of Si wafer = 500µm and thickness of AlN layer = 1.5µm.

In this project, we successfully modeled a piezoelectric transducer for audio prosthesis that replaces the ossicular chain's function of transmitting sound waves from the outer-ear to the inner-ear. Our simulations demonstrated proper performance of the device for extended frequency ranges. In addition to the device size, low power consumption, and CMOS / IC compatibility, our study suggest that our device is suitable for *in vivo* applications in both humans and animals. Future studies will conduct research on the biocompatibility of the device, in order to ensure that it is adapted to long-term use.

Word Count: 631

References

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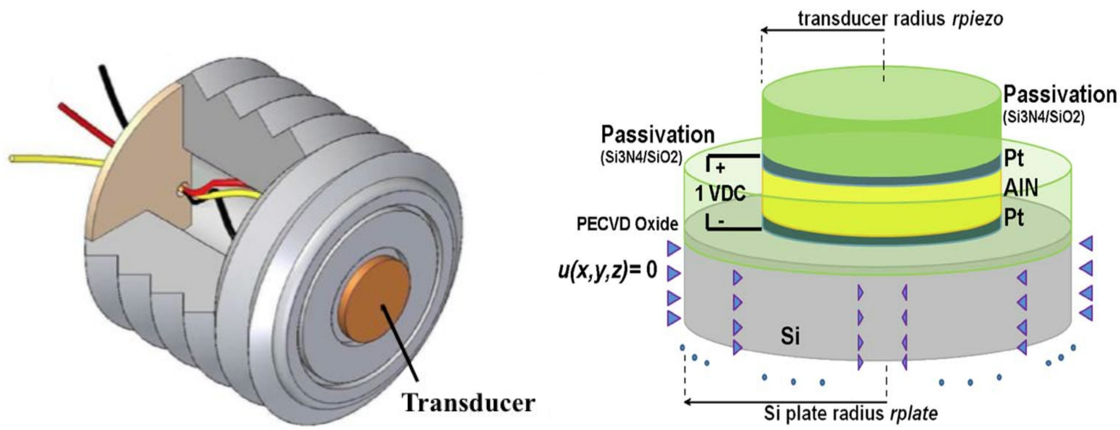

Figure 1. (a) Device Overview (b) Geometry and Layering of Transducer

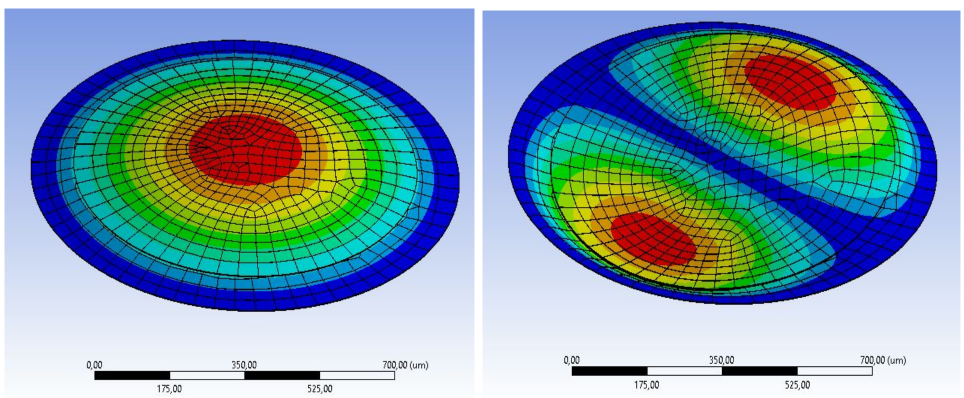

Figure 2. (a) First mode shape Figure 2. (b) Second mode shape

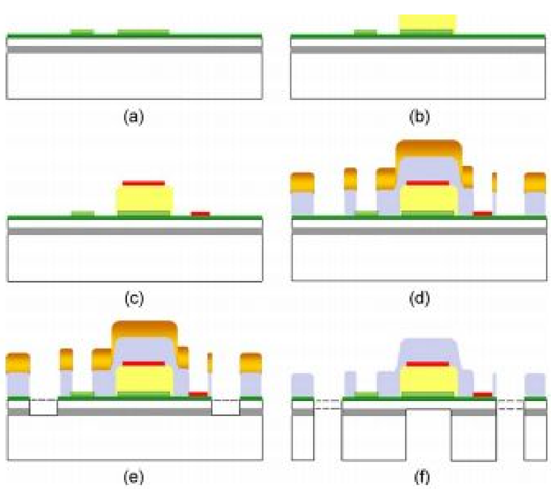

Fig. 3. Fabrication process of the piezoelectric transducer (as of cross section along the $A-A'$-axes in Fig. 2): (a) Isolation SiO_2 layer and first metal layer; (b) AlN sputtering and patterning; (c) second metal layer; (d) passivation deposition and patterning; (e) front-side RIE of the DEV layer; (f) DRIE of the bulk Si and wet etching of the BOX layer.

Radius of AlN layer --> Thickness of AlN layer	100 µm	200 µm	300 µm	400 µm	500 µm
0.5 µm	31676 Hz	31454 Hz	35808 Hz	40500 Hz	52735 Hz
1 µm	31333 Hz	31219 Hz	37042 Hz	45196 Hz	59191 Hz
1.5 µm	30947 Hz	30078 Hz	37609 Hz	49402 Hz	65406 Hz
2 µm	30544 Hz	30244 Hz	37729 Hz	53096 Hz	71450 Hz

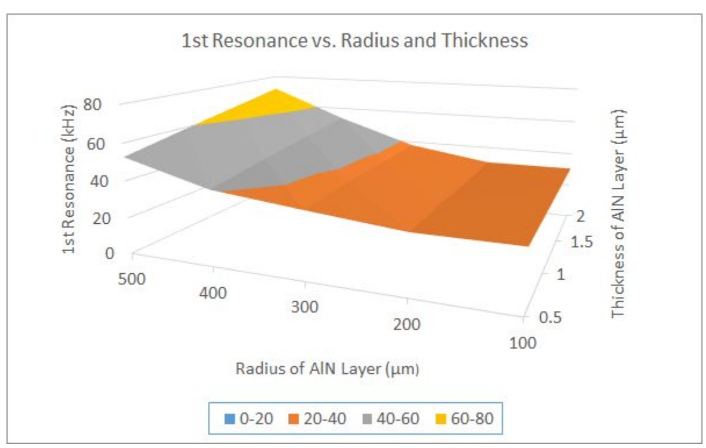

Figure 4. (a) 1st Resonance varying parameters
(b) Complementary Graph

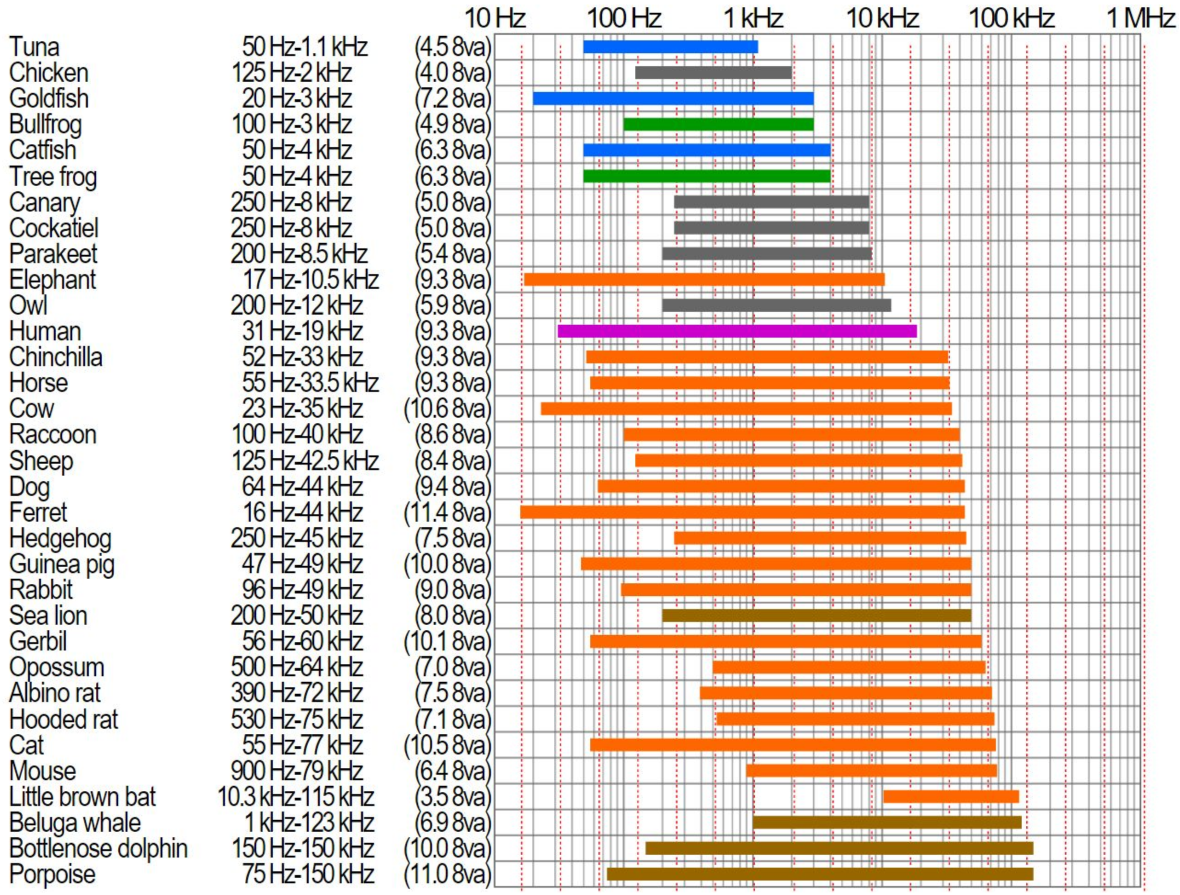

Figure 5. Hearing range of some animals.

Appendix: Piezoelectric equations

Modes of Vibration

Frequency Constant

$$N = f_0 \cdot L$$

Capacitance

$$C = \frac{\epsilon_r \cdot \pi \cdot r^2}{4 \cdot L}$$

Static voltage

$$V = \frac{g_{zz} \cdot F_z \cdot L}{\pi \cdot r^2}$$

Static displacement

$$\Delta L = d_{zz} \cdot V$$

$f_0 = Resonance\ Frequency$
$L = Length\ of\ Cylinder$
$\epsilon_r = Dielectric\ Constant\ (AlN = 8.5)$
$r = Radius\ of\ Cylinder$
$d_{zz} = Piezoelectric\ Charge\ Constant$
$V = Applied\ Voltage$
$g_{zz} = Piezoelectric\ Voltage\ Constant$
$F_z = Force\ in\ Z - Direction$

Coupled Equations

Linear Electric and Elastic Behavior

$$S = s^E \cdot T + d \cdot E$$
$$D = d \cdot T + \varepsilon^T \cdot \mathrm{E}$$

Static deflection at center of membrane

$$U(z) = -\frac{r^2}{D}\frac{I_e}{I_m}e_{31,f}z_pV$$

$D = Flexural\ Rigidity\ for\ Membrane$
$I_e = Equivalent\ Electrical\ Current$
$I_m = Equivalent\ Piezoelectric\ Moment\ Current$
$z_p = AlN\ Midplane\ to\ Neutral\ Plane$
$e_{31,f} = Transverse\ Piezoelectric\ Stress\ Coefficient$