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A silicon microspeaker for hearing instruments

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Abstract
A micromachined loudspeaker for audible acoustic instruments is designed, fabricated and tested. A single loop voice coil on a flexible polyimide membrane is conceived to serve as the sound generating plate, and is driven by electromagnetic actuation. The diameter of the microspeaker is 5 mm × 5 mm, and it is fabricated by a low temperature micromachining process. At a driving voltage of as low as 1.5 V, the microspeaker output sound pressure level is 93 dB at 5 kHz when measured in a 2 cc volume.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Since the early 1980s, there has been significant interest in the micromachining of miniature microphones [1]. The advantages of micromachining over conventional fabrication include precise dimensional control, the integration of on-chip circuits and potential low cost owing to batch fabrication.

However, using the MEMS technology to fabricate micro loudspeakers for hearing instruments is challenging because of certain critical requirements, including their small size, low driving voltage, high output sound pressure level, flat frequency response and low energy consumption. Several research groups have studied the feasibility of silicon microspeakers, using either electrostatic [2], piezoelectric [3, 4], or electromagnetic force [5, 6]. A small in size, lightweight, and low-cost microspeaker is demanded for applications such as cellular phones and hearing aids.

The aim of this work is to develop an integrated micromachined electromagnetic loudspeaker using silicon microfabrication batch processing. The microspeaker uses the moving-coil driver, which is common in today’s conventional macroscopic hearing instruments, and is implemented by a low temperature micromachining process (<300 °C). The low temperature fabrication process allows post processes on substrates where the electronic circuits have already been completed. The finite-element method (FEM) and equivalent circuit model are utilized to simulate the mechanical and acoustic behavior of the microspeaker.

2. Design of the microspeaker
2.1. Working principle
A schematic view of the micromachined loudspeaker is shown in figure 1. The device consists of a micromachined membrane in a silicon wafer with an electroplated coil bonded to a back plate with a small magnet. Electromagnetic actuation is chosen in this design because of its large driving force over a large air gap and a low driving voltage. When the current flows through the coil, a force is generated which actuates the membrane to move and radiates sound. The Lorentz force determines the driving force in the current-carrying coil, and is given by

$$\vec{F} = I \vec{l} \times \vec{B}, \quad (1)$$

Since the dimension of the microspeaker and ear cavity is small compared to the wavelength of sound, the sound pressure is distributed uniformly in the volume. The pressure change is proportional to the volume displacement of the diaphragm, and is expressed by

$$dP = -\frac{4P_0}{V_0} dV, \quad (2)$$

where $P_0$ is the pressure of the atmosphere and $V_0$ is the volume of the ear cavity (which is about 2 cc). The generated sound pressure level (SPL) is defined as

$$SPL = 20 \log_{10} \left( \frac{dP}{P_{ref}} \right) (dB), \quad (3)$$
Figure 1. The schematic view of the microspeaker.

2.2. The mechanical model

The vibration of diaphragm of the loudspeaker behaves like a second-order system, and is described by [7]

\[ M \frac{d^2 w}{dt^2} + R \frac{dw}{dt} + \frac{w}{C} = F, \]  

(4)

where \( M \) is the total mass including the coil, the diaphragm and air load, \( R \) is mechanical resistance due to dissipation in the air load, and \( C \) is compliance of the suspension system.

When the coefficients \((M, R, C)\) are constant and the system is subjected to a harmonic force \( F = F_0 \cos \omega t \), a particular solution to equation (4) is obtained [7]

\[ w = w_0 \cos(\omega t - \phi), \]  

(5)

where the displacement of the vibration \( w_0 \) has phase lag \( \phi \), and is expressed by

\[ w_0 = \sqrt{\left(1/C - M\omega^2\right)^2 + \left(\omega/R\right)^2}, \]

(6)

\[ \phi = \tan^{-1} \left(\frac{C\omega}{R(1 - M\omega^2)}\right). \]

However, in real cases, \( C \) and \( F \) change with displacement \( w \), caused by the nonlinear behavior of the mechanical suspension, inhomogeneous distribution of the magnetic flux, or nonlinear vibration modes at high frequency. The nonlinear vibration will produce undesired harmonic components when a sinusoidal signal is applied, and make the acoustic output distorted. Harmonic distortion should be avoided in the design.

2.3. Magnetic field analysis

For a cylindrical magnet of length \( z_0 \) and radius \( a \), magnetized with a uniform dipole moment \( M \) (per unit volume) in the \( z \)-direction, the external field distribution \( B \) at the point \((r, \theta, z)\) could be derived by the equivalent surface current \( J = \nabla \times M \) [8].

\[ B_r = \frac{\mu_0 J}{2\pi} \int_{-z_0/2}^{z_0/2} \frac{1}{[(a + r)^2 + (z - z')^2]^{1/2}} \times \left[ \frac{a^2 - r^2 - (z - z')^2}{(a - r)^2 + (z - z')^2} E(k) + K(k) \right] dz'. \]  

(7)

where \( K(k) \) and \( E(k) \) are the complete elliptic integrals of the first and second kinds with

\[ k = \sqrt{\frac{4ar}{(a + r)^2 + (z - z')^2}}. \]

Figure 2 shows the magnetic induction along the radial line from the center, 50 \( \mu m \) above the top of a 2.6 mm \( \times \) 2.6 mm \( \times \) 3 mm Neodymium–Iron–Boron (Nd–Fe–B) magnet with a magnetization of 0.6 T, by the electromagnetic simulator ANSOFT. The radial component of the magnetic induction \( B_r \), which contributes to the levitation force of the diaphragm, has a maximum right above the edge of the magnet, and decays with distance \( r \) approximately as \( r^{-3} \). Since the product \( Bl \) varies with the position on the diaphragm, the force will not be proportional to the current, and distortion will be produced. In our design, only a single loop of voice coil is used to drive the diaphragm. The wider the coil width the greater the diaphragm excursion and the better the heat dissipation; nevertheless, the tradeoff is the generation of harmonic distortion.

To maximize and provide a uniformly distributed driving force on the coil, both soft and permanent magnets were integrated into our device to induce magnetic flux to be perpendicular to the current-carrying coil as shown in figure 3. The high permeability of the soft magnet formed a low reluctance path, and thus focused the magnetic flux through the air gap. The cross section area of the soft magnet was designed to be large enough to avoid the saturation of flux density. As the typical simulation value of the magnetic flux density is 0.1 T, the calculated force is 205.8 \( \mu N \) when the current is 214 mA.

2.4. Load-deflection of the diaphragm

The loudspeaker diaphragm is made from polyimide because of its excellent properties, including high breakdown voltages, high thermal stability and low thermal expansion coefficient. Compared to the conventional membrane materials such as nitride, polysilicon and silicon, polyimide has smaller Young’s modulus (i.e. 60 to 100 times smaller), and the simple and low temperature fabrication processing steps.

For better frequency response and efficiency, the mass of the moving part of the loudspeaker needs to be minimized. In our design, only a thin flexible membrane with a single coil formed the sound generation plate, and the relatively heavy magnets were located on the static part of the device. Figure 4 shows the typical deformed shape of the microspeaker when the polyimide diaphragm is of thickness 5 \( \mu m \) and a diameter 3.5 mm, with voice coil of thickness 5 \( \mu m \), and width 100 \( \mu m \) subjected to 205.8 \( \mu N \) simulated by the ANSYS finite-element simulator. The diaphragm is stretched flat across the stiff voice coil, and behaves like a piston when loaded. The resonance frequency is designed about 2.8 kHz since it is the frequency of the natural canal resonance [9].

The load-deflection characteristic of the microspeaker diaphragm is shown in figure 5. The relation is linear for
small deformation, but becomes nonlinear for a large applied force. The load-deflection could be expressed by
\[ C_1 w + C_2 w^3 = F, \] (9)
where \( C_1 \) and \( C_2 \) are constants. The nonlinear \( (w^3) \) term arises from the fact that the rigidity of the diaphragm increases with the load. This nonlinear term is not preferred for loudspeakers because it would cause harmonic distortion \( (\cos 3\omega t) \).

The introduction of the corrugation design could extend the linear range of load-deflection of the diaphragm. The corrugation diaphragm is stiffer than the flat one, and the increased length of cross-sectional length of the diaphragm allows large deformation. The corrugation membrane was integrated in micromachined microphones to release the stress of the membrane, and increased the mechanical sensitivity of the device. The method of corrugation membrane fabrication for microspeaker application can be found in our work [10].

2.5. Electroacoustic model

The dynamic response of microspeakers can be calculated using an equivalent analog electrical circuit shown in figure 6 [11]. The acoustic pressure and volume flow are modeled as an equivalent voltage and an equivalent current, respectively. The electrical impedance \( Z_E \) includes the resistance and inductance of the coil. The compliance \( C_m \) represents the mechanical compliance of the diaphragm suspension derived from the ANSYS simulation, while the mass \( M_m \) models the mass of the diaphragm and coil
\[ C_m = \frac{\Delta w}{\Delta F}, \quad M_m = \frac{1}{C_m(2\pi f_r)^2}. \] (10)

The coupling coefficient between the mechanical system and acoustic circuit is \( S^2 \), where \( S = \pi a^2 \) is the area of the movable diaphragm upon which the sound pressure is generated.
The acoustic impedances $Z_{AF}$ and $Z_{AB}$ model the acoustic air load impedance on the front and the back of the diaphragm. Since the pressure is evenly distributed behind the membrane, the back chamber is modeled as a single equivalent compliance

$$Z_{AB} = C_{AB} = \frac{V_b}{\rho_0 c^2}, \quad (11)$$

where $\rho_0$ is air density, $c$ is the speed of the sound and $V_b$ is the volume of back chamber (approximately, subtraction of the volume of the magnet from the volume of the silicon cavity, $20 \text{ mm}^3$). Since $C_{AB}$ is smaller than the compliance of the 2 cc coupler and that of the membrane, the frequency response is dominated by $M_m$ in series with $C_{AB}$.

Depending on the applications, the front acoustic impedance $Z_{AF}$ could be expressed as follows.

(1) To a 2 cc coupler: the air of the 2 cc coupler is modeled by an equivalent compliance,

$$Z_{AF} = C_{AF} = \frac{V_{2cc}}{\rho_0 c^2}. \quad (12)$$

(2) To air: the acoustic impedance of the air with the vibrating diaphragm is expressed by a radiative resistance and mass [11],

$$Z_{AF} = R_{AF} + j\omega M_{AF} = \frac{128\rho_0 c}{9\pi^2 a^2} + j\omega \frac{8\rho_0}{3\pi^2 a}. \quad (13)$$

When the leakage path exists between the ear cavity and the device, the air is allowed to move in and out. With a slit
hole of width $b$, height $d$ and length $l$, the acoustic resistance is expressed by

$$R_{\text{leakage}} = \frac{12\eta_0 l}{bd^3}, \quad L_{\text{leakage}} = \frac{6\rho_0 l}{\pi d},$$

where $\eta_0$ is the viscosity of the air. The leakage of the microspeaker packaging can be attributed to the electrical interconnect lead and space between the microphone and the coupler, and improper backchamber sealing as shown in figure 7. The leakage path renders the low frequency response since the out-of-phase sound in the backchamber would cancel the sound in the front. The parameters in the analogy circuit model are listed in the appendix.

Figure 8 shows the calculated frequency response of a 3.5 mm microspeaker to the 2 cc coupler and to the air. If the packaging is perfectly sealed, the flat frequency response (81 dB) is expected in the 2 cc coupler. When the leakage path exists in the 2 cc coupler, the low frequency response will be attenuated. The air in the leakage path and the compliance of the 2 cc coupler form a Helmholtz resonator and the resonance frequency is about 5 kHz [11]. When the speaker is operated in the air, the sound pressure level is calculated at 2 cm from the source, and is proportional to the frequency because the radiation resistance of the air on the diaphragm is...
proportional to the square of frequency. The two resonance peaks can be attributed to the Helmholtz resonators formed by both backchamber/leakage and the air/leakage.

3. Fabrication

The main fabrication process flow of the microspeaker is shown in figure 9. (a) The membrane area is defined on the backside and silicon substrate is etched until a 30 µm thick diaphragm is left. (b) Polyimide is spun onto the wafer and then is cured. A thin film of Ti/Cu is evaporated to serve as a seed layer for electroplating. (c) The mold for copper electroplating is patterned with double-sided alignment and exposure. Copper coil is electroplated in copper sulfate acid bath. (d) Remove photoresist, and define a thick photoresist mold for Ni/Fe soft magnet electroplating. The Ni/Fe is electroplated in the aqua solution mixture of NiSO₄/NiCl₂/FeSO₄/additives. (e) Remove photoresist plating mold and the seed layer. Membrane is released from the backside by dry etching. (f) A thin film of Au/Cr is deposited and patterned on the glass substrate to serve as the etching mask. Acoustic holes are etched in HF solution. (g) Strip Au/Cr layer, and mount a rare earth magnet on the glass substrate. (h) The wafers are glued together by High super5 adhesive to form the sealed cavity.

Since all the processes are carried out at low temperature, the microspeakers are suitable for post-CMOS processing, and are potentially possible to integrate with integrated circuit and condenser polymer microphone [12]. Shown in figure 10 are the fabricated devices of different designs, in which the copper coil was electroplated on the polyimide membrane, and surrounded by a thick plated Ni/Fe soft magnet.

4. Measurement results

Figure 11 shows the measured performance of a micro silicon loudspeaker. The loudspeaker was made of a 5 µm thick, 3.5 mm in diameter polyimide membrane, an electroplated copper coil and a soft magnet, and a 3 mm × 3 mm × 1.8 mm rare-earth NdFeB hard magnet mounted on a backing plate. The static displacement of the coil under dc drive was measured using a WYKO interferometer and the result is shown in figure 11(a). The movement could be bidirectional, and was determined by the current direction. In figure 11(b), the displacement of the coil was measured using the laser Doppler instrument, and its real-time wavefront under sinusoidal drive is shown in figure 12. The vibrational amplitude of 3 µm was obtained even under 1.5 V driving. The first resonant frequency was...
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Table 1. Comparison of miniature loudspeakers.

<table>
<thead>
<tr>
<th>Actuation</th>
<th>Diaphragm area (mm)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
<th>SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neumann [2]</td>
<td>Electrostatic 0.5 × 0.5</td>
<td>67 (dc) + 10.1 (ac)</td>
<td>NA</td>
<td>82 dB</td>
</tr>
<tr>
<td>Lee [3]</td>
<td>Piezoelectric 2 × 2</td>
<td>6 (zero-peak)</td>
<td>NA</td>
<td>100 dB at 4.8 kHz, 2 cm³</td>
</tr>
<tr>
<td>Han [4]</td>
<td>Piezoelectric 5 × 5</td>
<td>17.6 (rms)</td>
<td>NA</td>
<td>94 dB at 2.1 kHz, 2 cm³</td>
</tr>
<tr>
<td>Hwang [13]</td>
<td>Electromagnetic 15 × 15</td>
<td>NA</td>
<td>600</td>
<td>87 dB, 1000 cm³</td>
</tr>
<tr>
<td>This work</td>
<td>Electromagnetic 3.5 × 3.5</td>
<td>1.5</td>
<td>320</td>
<td>93 dB at 5 kHz, 2 cm³</td>
</tr>
</tbody>
</table>

Figure 12. The vibrational wavefront of the microspeaker at (a) 1 kHz and (b) 12 kHz.

Figure 13. The measurement setup for sound testing.

Figure 14. The measured frequency response of the 3.5 mm microspeaker.

The performance of the microspeaker is compared with other works of miniature loudspeakers in Table 1.

5. Conclusion

We report a silicon electromagnetic loudspeaker for audible acoustic instrument applications. The device consists of a micromachined polyimide membrane as the sound generating plate, and a back plate with a permanent magnet and acoustic holes bonded together. The diameter of the microspeaker is 5 mm × 5 mm, and it is fabricated by a low temperature micromachining process. At a driving voltage of as low as 1.5 V, the microspeaker output sound pressure level (SPL) is 93 dB at 5 kHz when measured in a 2 cc volume. The finite-element method (FEM) and equivalent circuit model are utilized to simulate and optimize the mechanical and acoustic behavior of the microspeaker.

about 3 kHz. Audible sound for frequencies higher than 3 kHz could clearly be heard at 2 m away from the source.

Figure 13 shows the measurement setup for the sound pressure. The microspeaker was tested in a closed chamber (volume 2 cc) with a sinusoidal input (1.5 V), and the sound output was measured by a reference microphone. In the measurement of sound output in the air, the reference microphone was placed at 2 cm above the microspeaker without the coupler. Figure 14 plots the measured sound pressure level versus frequency. The maximum sound output of 93 dB was available when the microspeaker was driven at 5 kHz in the 2 cc coupler. The available acoustic pressure in the 2 cc coupler was larger than in the free air by 10 dB before 10 kHz. The loss of the bass response in the 2 cc coupler was attributed to the air leakage of the package since the sound pressure is proportional to the square of the frequency. The
Acknowledgments

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Appendix

The polyimide: density $\rho = 1200 \text{ kg m}^{-3}$, Young’s modulus $5 \text{ GPa}$, stress $25 \text{ MPa}$.

The copper: density $\rho = 8960 \text{ kg m}^{-3}$, Young’s modulus $128 \text{ GPa}$.

Driving voltage $V = 1.5 \text{ V}$.

Area of piston $S = \pi a^2 = 9.616 \times 10^{-6} \text{ m}^2$.

$IB$ product $IB = 9.11 \times 10^{-4} \text{ Tm}$.

$R_E = 75 \Omega$.

The mechanical compliance and mass of the diaphragm

$$C_m = \frac{\Delta w}{\Delta F_{\text{ANSYS}}} = 0.16 \text{ m N}^{-1}$$

$$M_m = \frac{1}{C_m(2\pi f_0)^2} = 2.07 \times 10^{-8} \text{ kg}.$$

The acoustic impedance of the 2 cc coupler and back chamber ($V_b = 20 \text{ mm}^3$)

$$C_{AF} = \frac{V_{2cc}}{\rho_0 c} = 1.408 \times 10^{-11} \text{ m}^4 \text{s}^2 \text{kg}^{-1}$$

$$C_{AB} = \frac{V_b}{\rho_0 c} = 1.408 \times 10^{-13} \text{ m}^4 \text{s}^2 \text{kg}^{-1}.$$

To air $M_{AF} = \frac{8M_n}{\pi^2\nu} = 199.632 \text{ kg m}^{-4}$

$$R_{AF} = 128\rho_0 c \left(\frac{9\pi^2a^4\nu}{u^4}\right) = 1.964 \times 10^7 \text{ kg m}^{-4} \text{s}^{-1}.$$

The leakage $M_l = 75H$, $R_l = 5 \times 10^5 \Omega$.

References


