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Design, Fabrication and Characterization of Electrodynamically Actuated MEMS-Speaker

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This paper describes the fabrication and characterization of an electrodynamics MEMS speaker. The miniaturized electrodynamics MEMS Speaker includes a single turn coil suspended onto a 25 mm thick polyimide diaphragm, with 2.5 mm diameter and a small volume permanent magnet made of Neodymium-Iron-Boron (Nd-Fe-B). The structure was supported using a silicon frame and fabricated using MEMS technology. The measurement was performed using FineSPL-Loudsoft software in a standard acoustic chamber in two conditions. In sealed condition, the significant and best performance in terms of frequency response to sound pressure level of the MEMS-speaker when measured in the ear canal application using 1500 mm^3 silicon rubber tube, resulting in peak amplitude of around 90 dB-SPL at frequencies of 1 kHz, 5 kHz and 10 kHz and experiencing boosting level of around 25 to 30 dB at frequency below 1 kHz. The peak level was achieved at 200-500 Hz, 92.5 dB-SPL and at 20-60 Hz, 110 dB-SPL. Our MEMS speaker prototype performance has been tested for hearing music and speech and will benefit in the development of future micro speakers for hearing aid applications.

Keywords: MEMS-Speaker, polyimide diaphragm, permanent magnet, electrodynamics, Neodymium-Iron-Boron

I. INTRODUCTION

Micro electro-mechanical systems (MEMS) technology has allowed the fabrication of micromechanical structures for micro sensor and actuator with small in size, lightweight, low power consumption, and low production cost (Madou, 2002). Driven by the development of small and slim multimedia devices and mobile consumer electronic products such as smartphones, tablet, music player and hearing aids, the research efforts to fulfill the demand of reducing the size of micro speakers using MEMS technology has become an exciting investigation. The biggest challenge in the development of microspeakers using MEMS technology or MEMS-speaker, in which the device has a relatively small area is how to produce a significant sound for high sound pressure and quality performances. The work on MEMS-speakers has been previously demonstrated with different actuation mechanisms that are also functioning for various biomedical devices, such as micropump, micromixers and microvalve (Johari *et al.*, 2009; Hamid *et al.*, 2017; Pawinanto *et al.*, 2019). The diaphragm actuation of the microspeaker is basically working through electrostatic (Neumann & Gabriel, 2002), piezoelectric (Ren *et al.*, 2006; Seo *et al.*, 2007), electromagnetic (Harradine *et al.*, 1997; Jörg *et al.*, 2001) and electrodynamics (Ayatollahi & Majlis, 2008; Chen & Cheng, 2011; Ming-Cheng *et al.*, 2004; Shahosseini *et al.*, 2012; Sugandi & Majlis, 2011) actuation mechanism that enables to produce air pressure on the diaphragm surface.

The conventional speakers have been developed since decades (Everest, 2001) and technology to fabricate the device has been matured in which the electromagnetic

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*Corresponding author's e-mail: gandi511@yahoo.com induction of the membrane actuator was the most effective technique to create voice pressure. However, the devices suffer from large size and heavy-weight that is not suitable for mobile biomedical instrumentation.

In this work, a MEMS-speaker with electro-dynamic actuation using silicon microfabrication technique is developed that is predicted to solve the problems in size, weight and performance of the microspeaker. The structure of the MEMS-speaker consisted of a planar micro coil driver deposited onto a flat flexible polyimide diaphragm and a small size disc permanent magnet, in which the whole parts were fabricated and bonded on a silicon wafer. In this type of actuator, the mechanism of the generated force to actuate the diaphragm vibration resulted from the interaction of electrical current flowing through the coil and the surrounding magnetic field generated by a permanent magnet. The force is well known as the Lorentz force.

In this paper, the design, fabrication and characterization of the MEMS-speaker will be discussed in detail. Since the dimension of MEMS speaker is much smaller compared to the wavelength of sound, we have restricted our study of the speaker performance for in-ear canal application. The design concept of MEMS speaker for in-ear canal application is quite different compared with the design for free field application. The change of sound pressure in-ear canal is distributed uniformly and proportional to the volume displacement of the diaphragm. In this case, the ear essentially acts as a pressure detector. The microfabrication process and performance test of the sound pressure level MEMS speaker was implemented in a standard acoustic chamber and analyzed using FineSPL-LoudSoft software.

II. THEORETICAL BACKGROUND

As mentioned before, the structure of the MEMS Speaker is smaller compared to the wavelength of sound and so the design was restricted to in-ear canal application. The schematic of the MEMS speaker is shown in Figure 1. The design of the MEMS-speaker consists of two silicon wafers, where the first wafer functioned as a micromachined flat flexible diaphragm onto which a metal planar micro coil was deposited, and the second wafer functioned as a platform for a bonded permanent magnet.

The working principle of electro dynamically actuated MEMS speaker is based on the generation of the driving force on the flat flexible diaphragm, that results from an interaction between the current-carrying coil and the magnetic field surrounding the coil. The generated force actuates the diaphragm to mechanically vibrate and radiate sound waves around the front of the diaphragm, the force well known as the Lorentz force. A disc permanent magnet with its north pole up is placed along the symmetric axis below a planar single turn microcoil. At the location of the coil, the magnetic field makes an angle θ with the vertical, the total Lorentz force acting on the current-carrying planar coil is generally given by (Shahosseini *et al.*, 2010):

$$\vec{F} = \sum_{i=1}^{N} 2\pi R_i \, I \times \overrightarrow{B_r}(R_i) \times \sin\theta \tag{1}$$

where I is the coil current, R_i the radius of each turn coil, B_r the radial component of the magnetic field in the coil plane, and θ angle direction of the magnetic field to the vertical axis. Therefore, the total force for a single turn coil is given by:

$$\vec{F} = Il \times \overrightarrow{B_r} \times \sin\theta \tag{2}$$

with l a total length of single turn coil in radius r. Using both equations, we can see where the force vector direction acts.

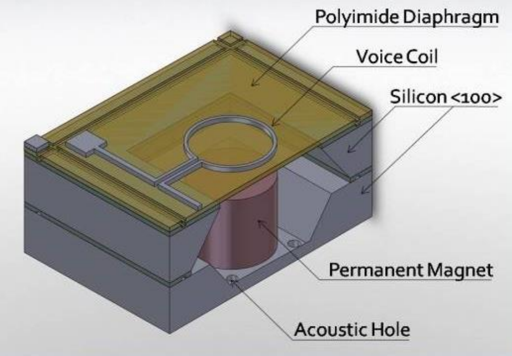

Figure 1. The schematic structure of the 3D MEMS speaker [14]

According to [12], the dimension of MEMS speaker and ear canal is small compared to the wavelength of sound, therefore the sound pressure is distributed uniformly in the volume. The pressure change is proportional to the volume displacement of the diaphragm and the equation for determining the pressure change in the canal is given by:

$$\Delta P = -\frac{1.4 \times P_0}{V_0}\,\Delta V \qquad (3)$$

where P_0 is the pressure of the atmosphere, and V_0 is the volume of the ear canal about 2000 mm³ (2 cm³). The generated sound pressure level (SPL) of MEMS speaker in-ear canal application is expressed by

$$SPL = 20\log\left[-\frac{1.4\,p_0}{p_{ref}}\frac{\Delta V}{V_0}\right](dB) \qquad (4)$$

where Pref is 20 µPa. Based on equations (3) and (4), the prediction of volume displacement and peak pressure of diaphragm corresponding to the generated sound pressure level in the volume ear canal of 2 cm³, the calculation is given by:

$$\Delta V = \frac{10^{SPL/20}p_{ref}V_0}{1.4\,p_0}\,(mm^3) \qquad (5)$$

Figure 2 shows the calculation results of volume displacement and peak pressure of diaphragm versus generated sound pressure in dB SPL. For the design of MEMS speaker, the maximum value of the generated sound pressure level should be first determined. Using this curve we can estimate the volume displacement and peak pressure for generated sound output pressure in ear canal volume of approximately 2 cm³.

For example, in order to generate sound pressure about 90 dB SPL in the volume of the ear canal of 2 cm³, it has to be increased by volume displacement about 0.0128 mm³ that corresponds to the peak pressure of 0.894 Pa. In loudness level about 90 phons based on the Robinson-Dadson curve [15], the human ear is relatively flat to the response of frequencies in the range of 20 to 6000 Hz and sensitive between 1000-6000 Hz, it means that 90 phons of loudness are essentially equal to dB SPL at all volumes displacement.

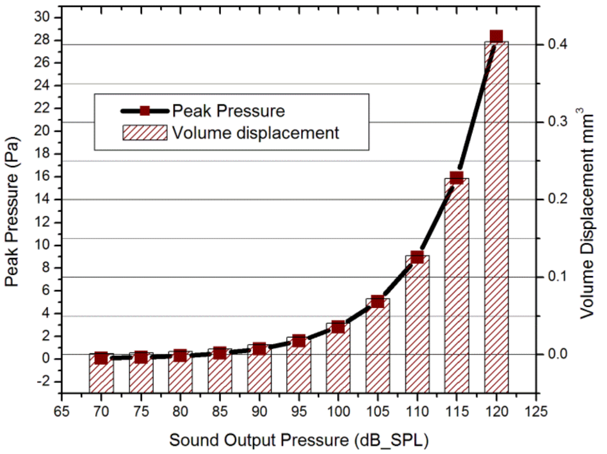

Figure 2. The curve of calculation results of generated SPL versus Volume displacement and Pressure change of diaphragm in the chamber 2 cm³ using equation (5)

III. MEMS MICROSPEAKER FABRICATION

The fabrication of the microspeakers started with the preparation of the physical structure of the device. Here, the silicon wafer with <100> orientation is cut to a size of 5x5 mm². The 2.5x2.5 mm² polyimide layer is used as the diaphragm with thickness of 25 µm and the electromagnetic field generator is made of single turn planar microcoil having the length, thickness of sputtered gold and width of 5mm, 1 µm and 75 µm, respectively. Finally, a permanent magnet N52 (Neodymium-Iron-Boron, NdFeB from K&J Inc.) with a diameter of 1.6 mm, 0.8 mm thickness, and remnant flux 1.4 T was attached on to the substrate for creating the induction and magnetic force. The gap between the magnet and the micro coil was about 100 µm.

The MEMS-based microspeaker device was constructed from two main components: the first component is the silicon wafer frame with planar coil suspended on polyimide membrane, and the second component is the acoustic hole with attached permanent magnet NdFe. Each component was fabricated separated using MEMS technology, and assembled together by adhesive bonding at the final step of the process. The main process techniques for the fabrication of each component, includes photolithography, anisotropic wet etching, deposition metal using sputtering and lift-off process. The process steps of the device fabrication are shown in figure 3 below.

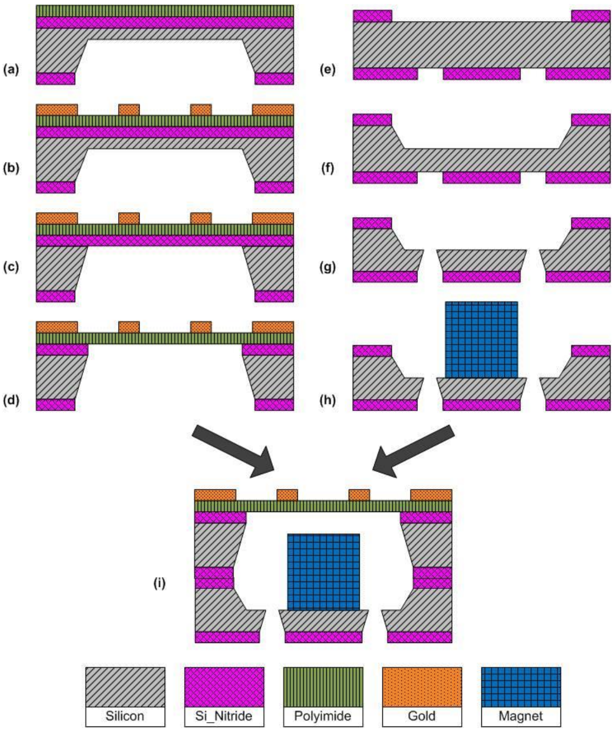

Figure 3. Schematic fabrication processes of electrodynamics MEMS-Speaker

A silicon wafer <100> with a thickness of 650 µm and a 200 nm thick silicon nitride (Si_3N_4) coating layer was used as the starting substrate. A silicon diaphragm is then fabricated using an anisotropic wet etching followed with the coating a cover layer made of 25 µm thick polyimide, as shown in figure 3(step-a). A 1 mm thick sputtered Ti/Au metal coil was then patterned by photolithography, which is immediately followed by the lift-off process, as shown in Figure 3(step-b).

The silicon diaphragm was then released from the backside by continuing the anisotropic wet etching, as shown in Figure 3(step-c). The remained etch-stop silicon nitride was removed by buffer HF or BOE solution, as shown in Figure 3(step-d). This step results in the creation of the moving diaphragm with an electromagnetic coil.

On another part, the second silicon wafer was processed by simultaneously anisotropic wet etching at the top and bottom silicon surface to create the spacer, air cavity and for bonding the permanent magnet platform, as shown in Figure 3(step-e to g). The permanent magnet was finally bonded in the center of the second wafer using glue, as shown in Figure 3(step-h). Finally, both wafer silicons were bonded together by adhesive glue (Figure 3, step-i). Figure 4 shows the photograph of the MEMS-speaker which was packaged in an earphone shell.

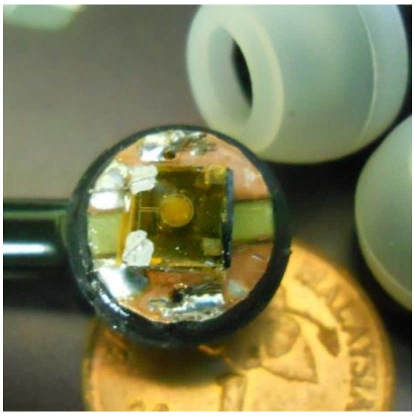

Figure 4. The photograph of MEMS-speaker in an earphone package

IV. MEASUREMENTS

The electro-acoustic performance of the fabricated MEMS Speaker was measured in a standard voice chamber with the measurement setup as shown in Figure 5. The sinusoidal signal input with various audible frequencies in the range of 20 Hz to 20 kHz were generated using FineSPL-loudsoft software on PC via internal sound card output of PC. The input signal was amplified using an audio power amplifier and fed to the MEMS Speaker. Various generated acoustic signal of the speaker in 1500 mm^3 silicon rubber tube was measured using a microphone at one end of the tube. The electrical signal from the microphone was fed to the input of the sound card, then the collected data was processed in software to form sound pressure level in the range of audible frequency.

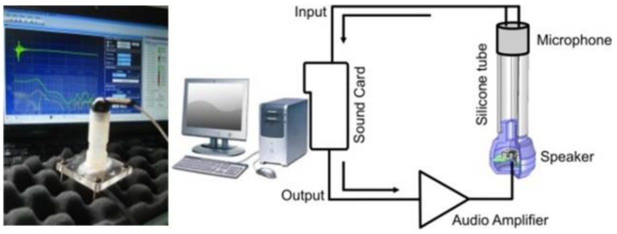

Figure 5. The measurement setup of characterization of MEMS Speaker in silicon rubber tube with 1500 mm3 of volume chamber

The measurement was done in two conditions, in which the MEMS speaker was put within sealed and unsealed tube condition. The audio power amplifier was biased with 3.3

volt and 100 mA maximum current fed to the coil with a total power consumption of 110 mW. The measurement result of frequency response versus sound pressure level of MEMS speaker can be seen in Figure 6.

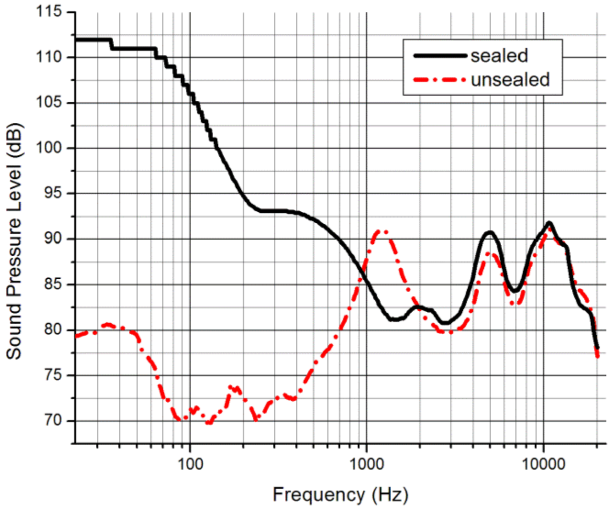

Figure 6. Measured results of the frequency response versus sound pressure level of the MEMS Speaker in sealed and unsealed condition

It is seen in the unsealed condition, that 3 peak amplitude maximums, of 91 dB, 88 dB and 92 dB SPL at frequencies of around 1.2 kHz, 5 kHz and 10 kHz were revealed. At frequency below 1kHz down to 100 Hz the sound pressure level dropped until 70 dB and raised to 80 dB at frequency of 50 to 20 Hz. While in the sealed condition, the generated first peak in unsealed condition disappeared, what remains are 2 peaks amplitude at frequencies of 5 kHz and 10 kHz with sound pressured level raised to 91 and almost 92.5 dB respectively. In this perfectly tight condition, compared to the unsealed condition, the sound pressure level at frequencies below 1 kHz experienced boosting sound pressure fantastically about 25 dB at frequency of 200 Hz and more than 30 dB at frequency of 50 Hz. The peak level was achieved at 200-500 Hz 92.5 dB-SPL and at 20-60 Hz 110 dB-SPL.

V. CONCLUSION

In summary, we report the miniaturization of an electrodynamics MEMS Speaker including single turn coil suspended onto a thick polyimide diaphragm and small volume permanent magnet with supporting silicon frame that is integrated using MEMS fabrication processes. The significant and fantastic performance of frequency response to sound pressure level of the MEMS-speaker for in-ear canal application was measured in 1500 mm^3 silicon rubber tube resulted in peak amplitude around 90 dB-SPL at frequency range 1, 5 and 10 kHz and experienced boosting level around 25 to 30 dB SPL at frequency below 1 kHz compare to the unsealed condition. The peak amplitude of sound pressure level achieved at 200-500 Hz was 92.5 dB-SPL and at 20-60 Hz 110 dB-SPL. The characteristics of this MEMS speaker has been found as the best performance for covering the hearing headset of music player and hearing aids application.

VI. ACKNOWLEDGMENT

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