ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

ANALYSIS, DESIGN, FABRICATION AND OF MEMS CAPACITIVE MICROPHONES

Hong-Ching Her[1], Chuan-Hsien Cheng[2], Hsien-Kuang Liu[1], and Jin H. Huang[1]

[1]Department of Mechanical and Computer-Aided Engineering, Feng Chia University, Taichung 40724, Taiwan
[2]Merry Electronics Co., Taichung Industrial Park, Taichung 407, Taiwan
jhhuang@fcu.edu.tw

Abstract

Condenser microphones with considerably higher sensitivity and low power consumption offer an innovative design for sound pressure micro sensors. Polysilicon with smooth surfaces and incredibly by low residue stress is used for the diaphragm of the capacitive microphone. Two methods—equivalent circuit method and finite element method—have been applied in this research to achieve the highest sensitivity of the capacitive microphone. Optimal parameters, such as the dimension of the diaphragm, the air gap distance, the volume of front and back chambers, and the hole fraction in the backplate, have been determined through analyzing and simulating the MEMS condenser microphone, understanding the variation of parameters, and dissecting the impact among sensitivity, frequency response and electric field. Consequently, the valuable design parameters are able to be provided for the best choice of condenser microphones among different materials. In addition, the results can improve and control the performance and dimensions of the microphone. Furthermore, the microphone is fabricated using a combination of surface and bulk micromaching techniques which has the favourable integrated capability of CMOS (Complementary Metal-Oxide Semiconductor). The device and techniques are promising for their future production.

1. INTRODUCTION

Recently, MEMS attracts a great amount of attention in technology development because it can reduce volume of products as well as increase performance, reliability, and additional values. During the past decade numerous novel sensor devices based on MEMS technologies have been made: accelerometers, MEMS mirror arrays, inkjet printer heads, and tire pressure gauges. Due to extensive use of mobile phones, notebooks, and consumer products with audio input such as video recorders, digital cameras, dictation devices, and PDA in the world, researchers are developing digital MEMS microphones for this hot market. In addition, two major areas drive the interest in MEMS microphones: hearing aids where small size and integration with signal processing are important and consumer devices where there is interest in reducing costs by integrating a complete systems solution on an integrated circuit and packaging of devices [1, 2]. Therefore, it is believed that MEMS microphones would be the next successful MEMS device in the market. Micromachined microphone chips can match and extend the performance of existing devices and improve manufacturing methods with advantages of reliability, low consumption of materials and energy, high precision, low sensitivity to vibration, and robustness. The use of MEMS techniques developed from semiconductor manufacturing can further produce large numbers of microphones with uniform quality, compatibility with CMOS processing, and ease of integration as a SOC (System On Chip). Therefore, it offers additional functionality such as multiple microphones for noise suppression and beam forming. Based on state-of-the-art development, novel applications will soon emerge such as tiny microphones for spying, arrays of tiny speakers on flexible substrates to make surround sound wallpaper, an in-ear MP3 player, and an in-ear translator.

2. FABRICATION

The substrate material used for the condenser microphone is a six-inch single crystal silicon *N* type (100) wafer with thickness 625 μm. The direction of orientation flat is <110> and resistivity is 1~100Ω-cm. Table 1 shows process steps for fabricating the condenser microphone by the SMART (Surface Micromachining for Applications and Research Technology Platform) procedure developed in Taiwan [3]. There are eleven steps in the process. The back chamber and air gap are implemented by bulk micromachining and release processes. In addition, MEMS chip and amplifier chip are assembled in a packaged housing which has one or more air inlet holes. Accordingly, the present MEMS condenser microphone possesses a MEMS chip, an IC chip and a package with an electronic shielding housing.

3. EQUIVALENT CIRCUIT MODEL

A well-designed MEMS condenser microphone should be easy to manufacture, deliver a high sensitivity despite its small size and have a flat frequency response, and have a low distortion. In order to fully realize the performance of the microphone, a complete sound level analysis will be performed. Figure 1 shows the analogous circuit incorporating electrical, mechanical and acoustic domains for the packaged MEMS condenser microphone, in which all acoustical and mechanical properties of the microphone can be defined as elements in an equivalent electrical circuit. The transduction factor ϕ and acoustical elements included in the circuit are brief introduced below.

3.1 The Transduction Factor

The transduction factor that converts electrical domain to acoustical domain is defined as

$$\phi = \frac{U_2}{i(t)} = \frac{hA_d}{i\omega(C_0 + C_P)e_0} \qquad (1)$$

where C_0 represents the static capacitance, C_p is the parasitic capacitance, e_0 is the static voltage, A_d is diaphragm area, and h is air gap distance.

3.2 Acoustic Elements

Acoustic radiation resistance and mass of the diaphragm is approximated by

$$Z_{a-rad} = \frac{\rho_0 c}{\pi a^2}(\Re + j\chi) \tag{2a}$$

where

$$\begin{aligned} \Re &= 1 - \frac{J_1(2ka)}{ka} \\ \chi &= \frac{4}{\pi}\int_0^{\pi/2} \sin\left[2ka\cos(\xi)\right]\sin^2(\xi)d\xi \end{aligned} \tag{2b}$$

with J_1 being the first kind Bessel function of order one, a the radius of the circular diaphragm, ρ_0 the density of air, c the speed of sound in air, and k the acoustic wavenumber. For small ka, $\Re \to \frac{1}{2}(ka)^2$ and $\chi \to \frac{8}{3\pi}ka$, while $\Re \to 1$ and $\chi \to \frac{2}{\pi}\frac{1}{ka}$ as $ka \gg 1$.

If the air inside small diameter holes of the microphone housing or backplate is a laminar flow, it can be described by an acoustic resistance and mass [4]:

$$R_a = \begin{cases} \dfrac{\ell}{\pi a^3}\sqrt{2\mu\omega\rho_0} & \text{for } ka > 10 \\ \dfrac{8\mu\ell}{\pi a^4}\sqrt{1 + \dfrac{(ka)^2}{32}} & \text{for } 1 < ka < 10 \\ \dfrac{8\mu\ell}{\pi a^4} & \text{for } ka < 1 \end{cases} \tag{3a}$$

$$m_a = \begin{cases} \dfrac{\rho_0\ell}{\pi a^2} & \text{for } ka > 10 \\ \dfrac{\rho_0\ell}{\pi a^2}\left[1 + \left(3^2 + \dfrac{(ka)^2}{2}\right)^{-1/2}\right] & \text{for } 1 < ka < 10 \\ \dfrac{4}{3}\dfrac{\rho_0\ell}{\pi a^2} & \text{for } ka < 1 \end{cases} \tag{3b}$$

with t being the thickness of acoustic holes, r the radius of holes, and μ the viscosity coefficient. In general, the air gap in the silicone condenser microphone is very small. f there are n holes in a perforated backplate, the acoustic impedance is approximately equal to $1/n$ times that for one hole.

The streaming of the air in the thin gap thereby induces the acoustic resistance given by [5]

$$R_{a-g} = \frac{12\mu}{\pi n h^3 A_b}\left(\frac{\alpha}{2} - \frac{\alpha^2}{8} - \frac{\ln\alpha}{4} - \frac{3}{8}\right) \tag{4}$$

where h denotes the air gap distance, n is the hole density in the backplate, and α is the surface fraction occupied by the holes.

When the microphone is mounted in a closed chamber of internal net volume V and the air in the chamber is compressible, the acoustic impedance in the front or back chamber is identified as an acoustic compliance

$$C_a = \frac{V}{\rho_0 c^2} \tag{5}$$

The mechanical compliance and mass of the backplate can be defined as

$$C_i = \frac{1}{A_i}\left(\Delta w / \Delta p\right)_i, \qquad m_i = \rho_i A_i t_i \tag{6}$$

where the subscript i denotes the plate configuration: b (backplate) or d (diaphragm), $\Delta w / \Delta p$ stands for the average deflection of plate per unit sound pressure, t is the thickness, and ρ is the density of plate. In the present work, the average deflection for plate is calculated from finite element software ANSYS.

3.3 Loop Equations

The loop equations is readily obtained from Fig. 1 as

$$\begin{bmatrix} Z_{a-rad} + Z_{a-fc} + Z_{a-h} & 0 & -Z_{a-fc} \\ 0 & Z_{a1} + Z_e + Z_b & -Z_b \\ -Z_{a-fc} & -Z_b & Z_b + Z_d + Z_{a2} \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} p \\ 0 \\ 0 \end{Bmatrix} \tag{7}$$

where

$$\begin{aligned} & Z_{a-rad} = \frac{i\omega R_{a-rad} m_{a-rad}}{R_{a-rad} + i\omega m_{a-rad}}, \qquad Z_{a-h} = R_{a-fh} + i\omega m_{a-fh}, \qquad Z_{a-fc} = \frac{1}{i\omega C_{a-fc}}, \\ & Z_d = \frac{(i\omega m_d + \frac{1}{i\omega C_d})}{A_d{}^2} \qquad Z_b = \frac{1}{A_b^2}(i\omega m_b + \frac{1}{i\omega C_b}), \qquad Z_{a1} = R_{ag} + R_h, \\ & Z_{a2} = \frac{1}{i\omega C_{bc}}, \qquad Z_e = \frac{1}{i\omega (C_0 + C_P)\phi^2}. \end{aligned} \tag{8}$$

The sound pressure p can be factored from the left hand side of Eq. (11) and the equation is rewritten as

$$U_2 / p = \{0 \quad 1 \quad 0\} \mathbf{Z}^{-1} \{0 \quad 1 \quad 0\}^T \tag{9}$$

This equation in combination with Eq. (1) can be used to investigate the sensitivity of the condenser microphone.

4. ANALYSIS RESULTS

To demonstrate how the design parameters, such as the dimension of the diaphragm, the air gap, the volume of front and back chambers, and the hole fraction in the backplate, affect the microphone sensitivity, following are discussed the numerical results for a condenser microphone whose pertinent dimensions and the parameters used for the microphone model are listed in Table 2. As shown in Fig. 2, the numerical predictions of sensitivity obtained by the proposed equivalent circuit model for packaged MEMS microphone agree well with experimental measured results. The difference between predicted and measured results is less than 2dB. The figure also demonstrates that the curves for packaged and unpackaged (without front chamber) MEMS microphone correlate well with measured results. However, discrepancies of the sensitivity for unpackaged microphone simulations are found in the high frequency range. These discrepancies are caused due to the lack of taking the volume of front chamber into account.

The effects of the diaphragm diameter and air gap distance h on the sensitivity of the packaged microphone are shown in Figs. 3 and 4, respectively. For the microphone studied herein, Figure 3 indicates that sensitivity increases in a monotonic way with the diaphragm diameter from 400μm to 800μm since the area of the diaphragm is increased. In contrast to the effect of the diaphragm diameter, the sensitivity of the packaged microphone is significantly increased when the air gap distance decreases as shown in Fig. 4. The smaller the air gap is, the higher its sensitivity is, but the over-small air gap may lead to pull-in. The reason is that the open circuit voltage which is inversely proportional to the air gap increases when the air gap diminishes. Therefore, the option and controlling over air gap is crucial.

The influence of the acoustical holes on the performance of the microphone is shown in Fig 5. From this figure it is clear that increasing the hole fraction results in the lower viscous loss. Due to the hole fraction increasing, the capacitance of the microphone is decreased and the contribution to the input noise from the amplifier is increased. Therefore, an optimized value 29% for the hole fraction is suggested in the present design.

5. CONCLUSIONS

We have designed, analyzed, and fabricated a high sensitivity MEMS condenser microphone through SMART process. In theoretical part, an accurate model for MEMS microphone has been presented. The model calculates acoustical sensitivity from the design and process parameters, such as the size of the diaphragm, the air gap, the front chamber volume, and the perforation. A high mechanical sensitivity to a dynamic pressure is the result if a low stress diaphragm material, a low backplate hole fraction, a large diaphragm area and a small air gap is used. Low streaming losses in the air gap can be achieved with acoustic holes in the backplate.

ACKNOWLEGEMENT

One of the authors (JHH) would like to thank Mr. Leo Liao and Mr. Jack Wei of Merry Electronics Co. for their encouragements and suggestions. The National Science Council of

Taiwan (Contract Nos. NSC 95-2221-E-035-013-MY3 and95-2221-E-035-087) has also supported this research. We thank Listen Inc. for supplying SoundCheck measurement.

Table 1 Process steps for fabricating the MEMS condenser microphone.

Step	Description
Starting material	6” silicon wafer
1. ThOX	Thermal oxidation to obtain 0.5μm SiO_2
2. LS SiN 0	LPCVD to deposit 0.5μm low intrinsic stress Si_3N_4
3. Patterned Poly 0	LPCVD to deposit 0.5μm polysilicon followed by doping phosphorus and patterned by mask 1 and RIE (lower electrode)
4. Patterned SiN	LPCVD to deposit 0.5μm Si_3N_4 and patterned by mask 2 and RIE
5. LTO 1	Low temperature oxidation to get 1.75μm SiO_2 as sacrificial layer patterned by mask 3
6. Poly 1	LPCVD to deposit 2.0μm polysilicon followed by doping phosphorus and patterned by mask 4 and RIE
7. LTO 2	Low temperature oxidation to get 1.75μm SiO_2 as sacrificial layer patterned by mask 5
8. Poly 2	LPCVD to deposit 2.0μm polysilicon and patterned by mask 6 and RIE as backplate
9. Metal (Cr/Au)	Life off and pattern Cr/Au with 0.01/0.5 μm (upper electrode)
10. Substrate	KOH etches Si from back side to a required thickness
11. ThOX	BOE to remove LTO 1 and LTO 2

Table 2 Parameters of MEMS microphone.

Membrane diameter	670 μm	Inlet hole diameter	0.4 mm
Membrane thickness	1 μm	Density of membrane	2330 Kg/m^3
Back plate diameter	560 μm	Young’s module of membrane	130 GPa
Back plate thickness	1.2 μm	Residual stress of membrane	0 MPa
Air gap distance	4 μm	Density of back plate	2843 Kg/m^3
Air hole diameter	4 μm	Young’s Module of back plate	160 GPa
Air hole number	6610	Residual stress of back plate	100 MPa
Air hole ratio	29 %	Density of air	1.8 Kg/m^3
Back chamber height	450 μm	Viscosity of air	1.73×10^{-5} N s/m2
Front chamber volume	10^{-9} m^3	Bias voltage	5 V
Housing thickness	0.2 mm	Parasitic capacitor	1 pF

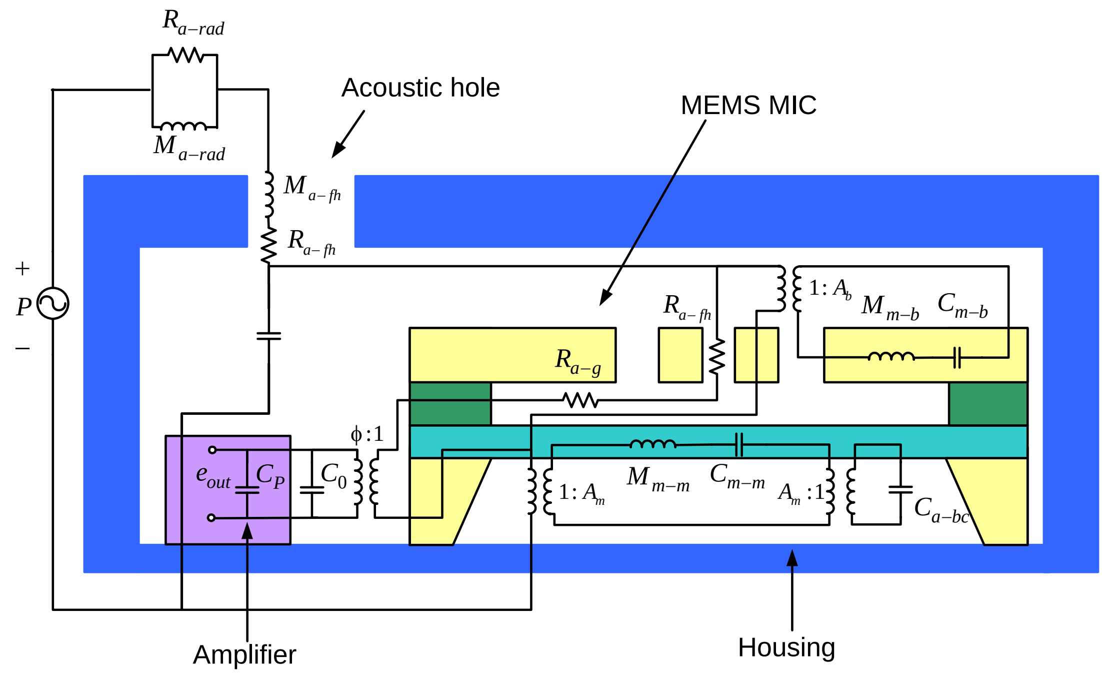

Fig.1 Equivalent circuit for the packaged MEMS condenser microphone.

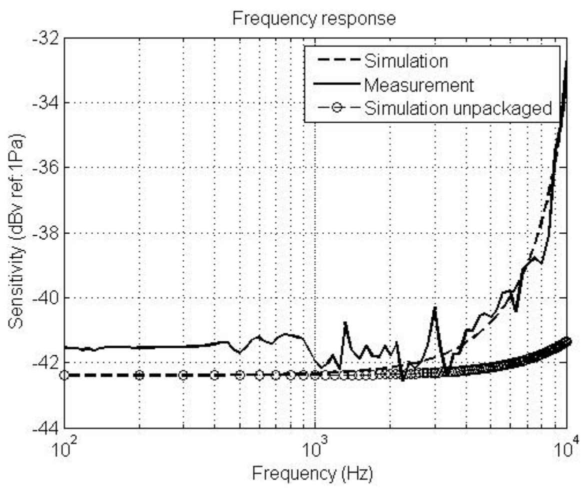

Fig.2 MEMS microphone simulation and measurement.

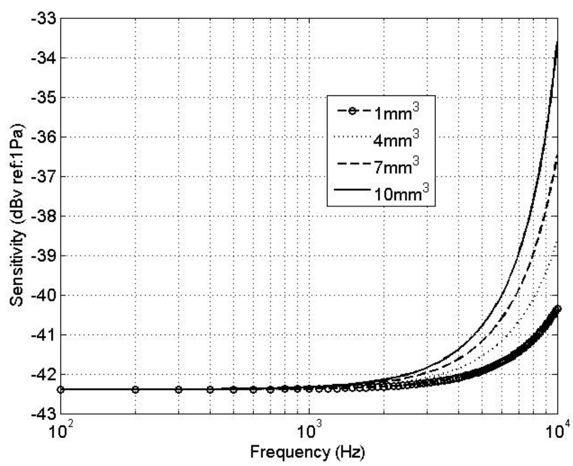

Fig.3 Diaphragm diameter vs. frequency response.

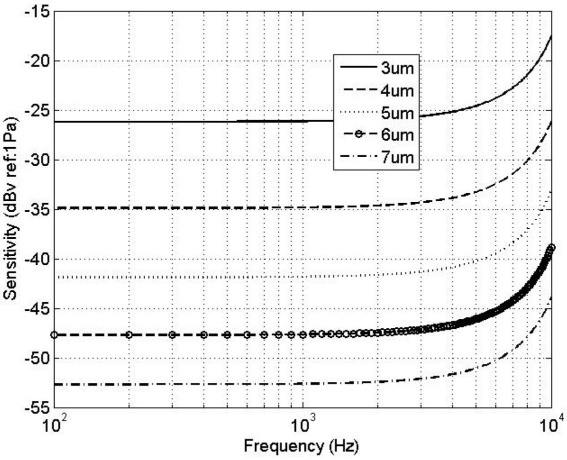

Fig.4 The effects of the air gap distance on the sensitivity

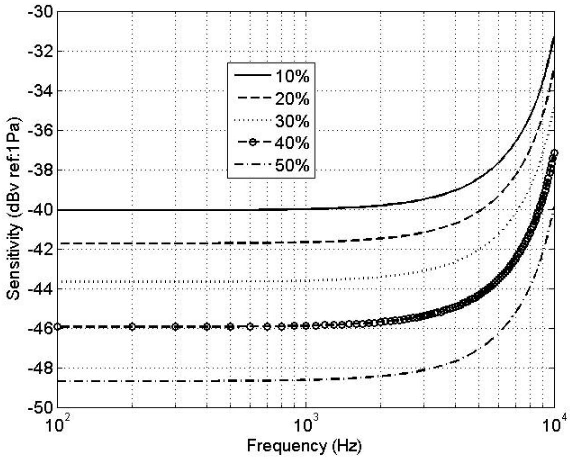

Fig.5 The influence of the acoustical holes on the performed backplate.

REFERENCES

[1] A. Dehé, "Silicon microphone development and application," *Sensors and Actuators A* **133**, 283-287 (2007).

[2] M. Pedersen, W. Olthuis, and P. Bergveld," *Journal of microelectromechanical systems* **7**, 387-394 (1998).

[3] Y. P. Ho, P. T. Liu, C Lo, and H. Y. Lin, "Surface Micromachining for applications and research technology platform," *Design Handbook*, Reversion 3.0, 2003.

[4] D.Y. Maa, "Potential of micro perforated panel absorber," *Journal of Acoustic Society* of *America* **104**, 2861-2866 (1998).

[5] Z. Skvor, "On the acoustical resistance due to viscous losses in the air gap of electorostatic transducers," *Acustica* **19**, 292-299 (1968).