Available online at www.sciencedirect.com

ScienceDirect

Sensors and Actuators A 144 (2008) 367–373

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Piezoelectric microphone built on circular diaphragm

Woon Seob Lee*, Seung S. Lee

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology,
373-1 Guseong-dong, Yuseong-gu, Daejeon, Republic of Korea

Received 1 October 2007; received in revised form 25 January 2008; accepted 4 February 2008

Abstract

This paper describes a piezoelectric microphone built on a circular diaphragm (CD), which is fabricated using the boron etching stop method. ZnO was used as the piezoelectric material, and the diaphragm material is low-stress Si_xN_y. The diameter and thickness of the circular diaphragm are 2 mm and 1 μm, respectively. The thickness of the boron-doped layer – a support layer for the circular diaphragm – is approximately 7.4 μm. Based on ANSYS simulations, the sensitivity increment of the CD microphone was comparable to that of a square diaphragm (SD) microphone. The sensitivity of the CD microphone increased to 197% of that of a SD microphone, as expected from the simulation results. The first resonance frequency of the CD microphone is 54.8 kHz. At 1 kHz, the displacement of the CD microphone and SD microphone are 3.96 nm and 1.54 nm, respectively. The fabricated CD microphone was connected to an amplifier system to confirm the ability to reproduce a human voice. The gain of the amplifier system is 200.

Keywords: Piezoelectric microphone; Circular diaphragm; ZnO; Boron etch stop method; MEMS

1. Introduction

During the last few decades, micromachining technology has been explored to fabricate various acoustic transducers including microphones [1–7]. The advantages of micromachined microphones are accurate dimension control, a high degree of miniaturization, and low cost due to batch processing. Recently, many trials have focused on the applications of micromachined microphones to hearing-aid cellular phones, micropersonal digital assistants, and so on [6].

Microphones are basically pressure sensors that detect airborne pressures generated by sound having pressures with 10 orders of magnitude lower than the ambient pressure. Hence, a microphone requires an extremely compliant diaphragm to increase its sensitivity. Several types of microphones have been reported to be fabricated using different methods and principles including three major transduction principles, that is, condenser, piezoelectric, and piezoresistive microphones. Condenser microphones are more popular than the others. However, they require a high DC bias voltage [11]. Piezoelectric microphones are simpler ones to be fabricated, free from polarization–voltage requirement, and responsive over a wider dynamic range [5–10]. However, as a microphone, they exhibit relatively low sensitivity [9,10]. In order to increase the sensitivity, some researchers have attempted to reduce the tensile residual stress of a transducer diaphragm using a cantilever with a nitride film [7] or a wrinkled diaphragm with a compressive nitride film [10], for example.

Micromachined microphones fabricated form a single crystal silicon wafer using bulk micromachining bear an intrinsic limitation with regard to the shape of the diaphragm due to the anisotropic etch property. Therefore, most of diaphragms adopted for microphones are quadrangular. Circular diaphragms (CDs) almost have not been reported to be fabricated primarily because it is difficult to fabricate them using traditional bulk micromachining processes. Deep reactive ion etching (RIE) is a possible process to fabricate such diaphragms so far. Polcawich et al. reported a CD microphone using deep RIE process [12]. Deep RIE is now an economical and cost effective process with high yield, no sticktion/contamination, and easy and accurate dimensional control. Structures with very high aspect ratio and smooth side wall can be obtained also through deep RIE. Furthermore, selective etching and anisotropic etch control are another important merits of this process. However, deep RIE relatively

---

* Corresponding author. Tel.: +82 42 869 3086; fax: +82 42 869 5046.
E-mail address: wslee73@kaist.ac.kr (W.S. Lee).

0924-4247/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2008.02.001

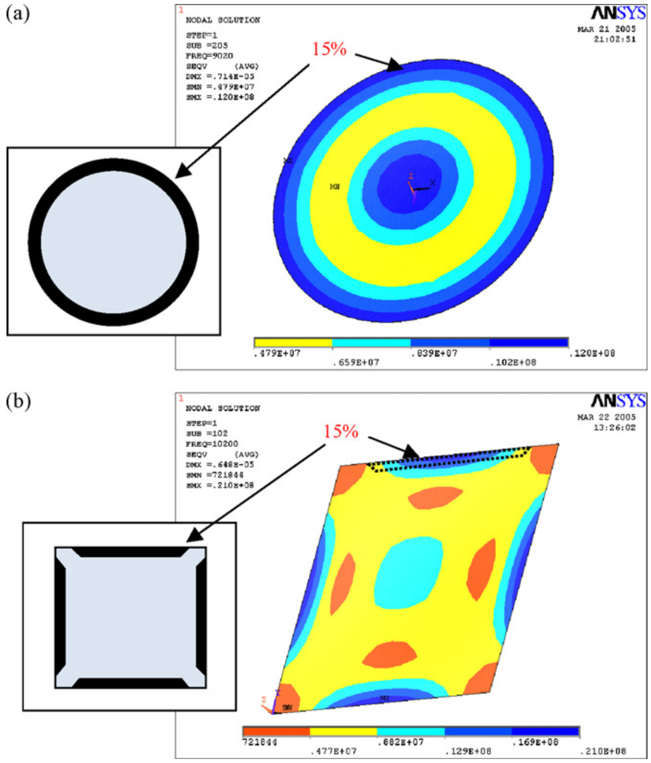


Fig. 1. Simulation results comparing stress distributions of a circular diaphragm (a) and a square diaphragm (b), and the small square boxes show areas of effective electrodes.

costs more than wet bulk etching process. In addition, isotropic etching has another flexible application area although it is difficult to control the dimension and shape of a diaphragm and maintain the reproducibility.

In this paper, the boron etch stop method is used to fabricate a circular diaphragm [13–17]. A circular diaphragm has uniform stress distribution that contributes to increasing the sensitivity when applied to a piezoelectric microphone.

2. Simulation and design

Finite element modeling with ABAQUS software and ANSYS has been performed to study the difference between the mechanical behavior and stress distribution of circular and square diaphragms (SDs) and to determine whether changing the shape of the diaphragm will increase the sensitivity or not.

Static analysis has been performed to obtain the stress distribution in the circular and square diaphragms under uniform pressure load (1 Pa), as shown in Fig. 1. The diameter of the circular diaphragm is 2 mm and its thickness is 1 μm; the SD has the same area and thickness as the circular diaphragm. Table 1 shows the material properties used in these simulations. The distribution of the maximum stress is uniform along the circumference of a circular diaphragm, while that of a square diaphragm is distributed along a part of the edges. It is possible to locate the electrode on the circumference in case of a circular diaphragm. The circular diaphragm could be expected to have greater sensitivity than the square one even if the electrode is fabricated on the same area over the maximum stress area because the sensitivity of a piezoelectric microphone follows [12]:

$$\text{sensitivity} = \frac{A_{\text{piezo}}\sigma d_{31}}{C_{\text{load}} + C_{\text{piezo}}} \qquad (1)$$

A_{piezo} denotes the area of the piezoelectric; σ, the applied stress; d_{31}, the transverse piezoelectric coefficient; C_{load}, the load capacitance; C_{piezo}, the capacitance of the piezoelectric. The effective electrode area was divided into three parts – 15%, 30%, and 40% of the diaphragm area – to calculate the increase in sensitivity, as shown in Fig. 2. Table 2 shows the ratio of σ_{circular} to σ_{square} according to the increase in the effective electrode area. The ratio of σ_{circular} to σ_{square} increased with an increase in the area of the electrode: 150%, 168%, and 186%. 30% of the diaphragm area was chosen as the electrode area, as mentioned in Table 2.

Table 1
Material properties used in analysis

Material	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Si_xN_y	85	0.25	3100
Si	125	0.22	2330

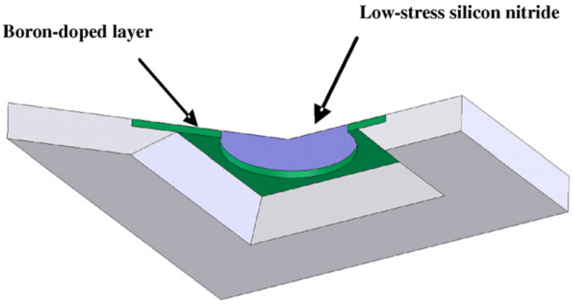
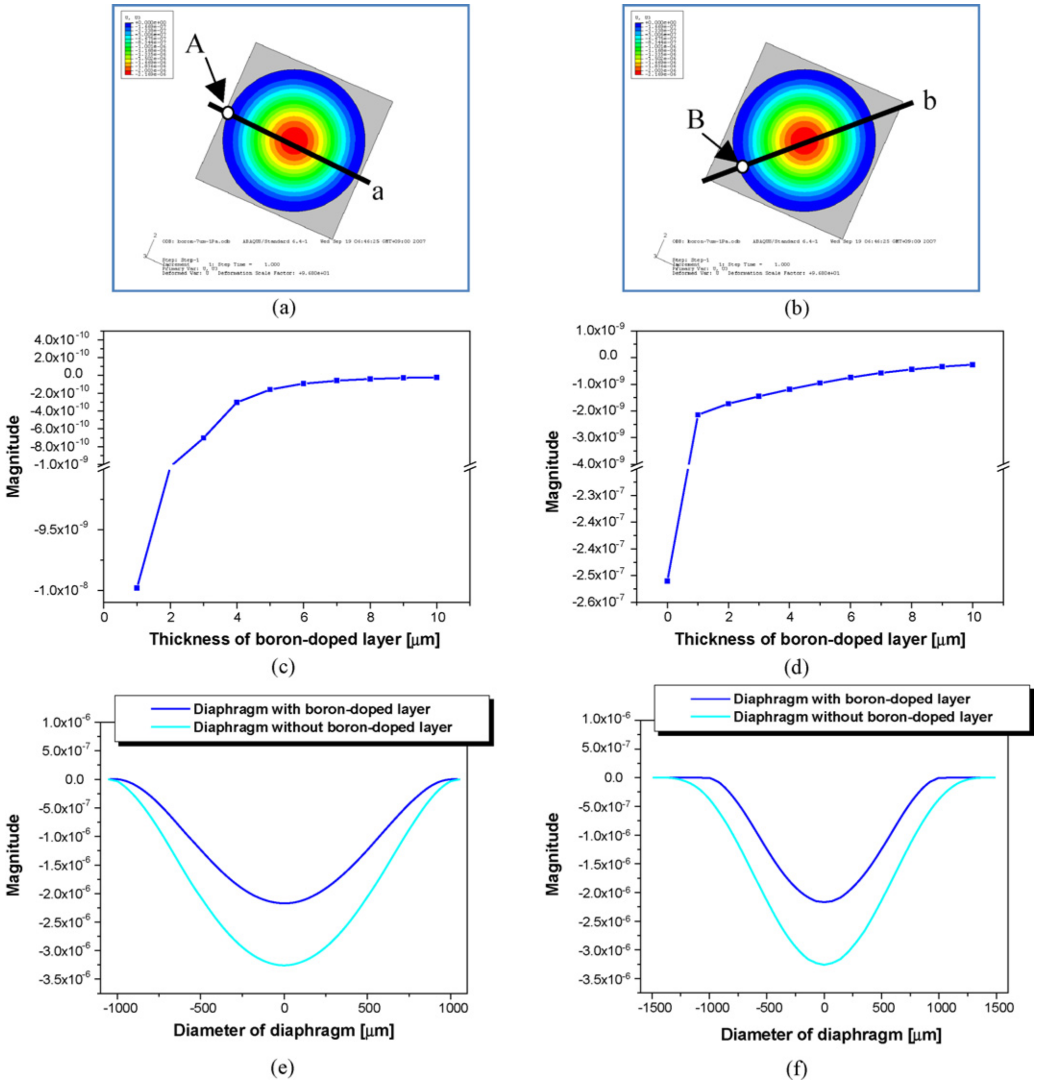


Fig. 2. Schematic diagram of the structure of a circular diaphragm.

Boron etch stop method was used to fabricate a circular diaphragm as shown in Fig. 2. Simulation has been performed to determine the thickness of boron-doped layer. Static analysis has been performed to obtain the displacement in circular diaphragms by the change of the thickness of boron-doped layer under uniform pressure load (1 Pa), as shown in Fig. 3. The size of a side of boron-doped layer which is open is 2.1 mm, and the circular diaphragm is located inside of the boron-doped layer. The diameter and thickness of the circular diaphragm are same as designed previously. Fig. 3 shows the results of simulations. When the thickness of the boron-doped layer is over 6 μm, the displacement, when doped, is approximately 1/1000 that of the undoped membrane as the same load applied. Therefore, the thickness of the boron-doped layer is designed to be over 7 μm

Table 2
The ratio of σ_{circular} to σ_{square} according to the increase in area under the stressed region

Effective electrode area/diaphragm area (%)	$\sigma_{\text{circular}}/\sigma_{\text{square}}$ (%)
15	150
30	168
40	186



(a) (b)

(c) (d)

(e) (f)

Fig. 3. The magnitude of displacement of a boron-doped layer according to the change of the thickness of a boron-doped layer. (a) and (b) The simulation results of the diaphragm displacement; (c) and (d) the displacement on points of A and B, respectively; (e) and (f) the change of displacement through line a and b, respectively.

in this fabrication. Fig. 3(e) and (f) shows the magnitude of displacement of two cases; the first one has a boron-doped layer of which the thickness is 7 μm and the second one does not have a boron-doped layer. The displacement of the doped membrane is approximately 1/10,000 that of the undoped membrane as shown in Fig. 3.

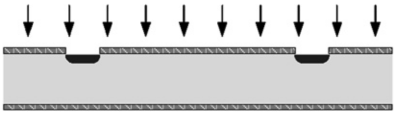
3. Device fabrication

Microphones were fabricated simultaneously on circular and square diaphragms to compare the functional differences of the microphones based on each type of diaphragm.

Fig. 4 shows the fabrication process of the microphones. The circular diaphragm microphone was fabricated on the circular diaphragm, as shown in Fig. 4(a)–(e). In the fabrication process, a 4-in. p-type silicon (Si) wafer was covered with a silicon oxide (SiO_2) layer of 1 μm thickness by thermal oxidation to prevent boron from diffusing into silicon. The SiO_2 layer was patterned to guide the desired high doping of boron. Boron diffused from the solid source for 15 h at 1100 °C in N_2 environment. SiO_2 was removed immediately after boron doping. Subsequently, another SiO_2 layer with a thickness of 0.2 μm was deposited by LPCVD to prevent boron from diffusing into the SiO_2 layer during thermal oxidation. An LPCVD low-stress silicon nitride (Si_xN_y) layer was deposited with a thickness of 1 μm as a membrane material. An anisotropic etchant, 20 wt.% of tetramethyl ammonium hydroxide (TMAH), was used to expose the silicon nitride diaphragm for 12 h at 90 °C by etching the Si wafer from the backside (bottom side in Fig. 4(e)). A photograph and scanning electron microscopy (SEM) image of the completed circular diaphragm are shown in Fig. 5(a) and (b), respectively. The measured diameter of the diaphragm is 2 mm, as designed. The thickness of the boron-doped layer, measured by SEM and a 3D surface profiler, is approximately 7.5 μm, as shown in Fig. 5(c) and (d).

The fabrication of circular diaphragm microphones commenced with the circular diaphragm. A 0.3-μm thick aluminum (Al) layer was formed by evaporation with an E-beam evap-


(a) Thermal oxidation (1 μm) and patterning


(b) High doping of boron

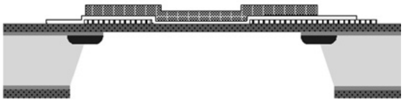

(c) Removal of oxide layer

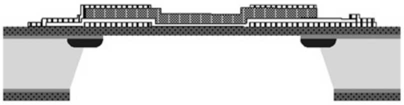

(d) Deposition of LPCVD silicon nitride (1 μm)


(e) Back side etching


(f) Aluminum evaporation (0.3 μm) and patterning


(g) Depostion of PECVD Silicon oxide (0.2 μm) and patterning


(h) Zinc Oxide deposition (1 μm) and patterning


(i) Aluminum evaporation (0.3 μm) and patterning

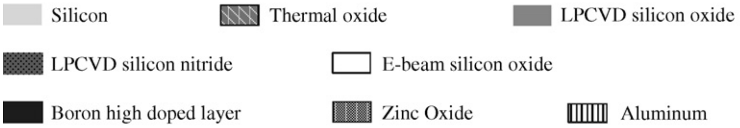


Fig. 4. Fabrication process of the piezoelectric microphone: (a)–(e) circular diaphragm and (f)–(i) piezoelectric microphone.

orator as a bottom electrode. The bottom electrode was patterned on LPCVD low-stress silicon nitride. A thick silicon oxide layer – 0.2 μm thick – was deposited by PECVD in order to form an electrical passivation layer. RIE was used to etch SiO_2. Subsequently, a 0.8-μm thick zinc oxide (ZnO) layer was deposited by sputtering in an RF sputter for 2 h. Al was evaporated on this ZnO layer to form a 0.3-μm thick layer. The Al layer was patterned to form the top electrodes. Fig. 5(e) shows the fabricated piezoelectric microphones.

4. Experimental results

4.1. Displacement of diaphragm

The displacement and resonance frequency at the center of the diaphragms was measured with a laser Doppler vibrometer (LDV) in the 100–200 kHz range to supply $1V_{pk}$ to the microphones. Fig. 6 shows the characteristics of the displacement at the center of the diaphragm. From these results, the first resonance frequencies of the CD microphone and SD microphone were 54.8 kHz and 56.1 kHz, and their displacements were 77 nm and 82 nm, respectively. The displacements of these devices were 3.96 nm and 1.54 nm at 1 kHz, as shown in Fig. 6. Therefore, these results show that the displacement of the CD microphone is larger than twice that of the SD microphone.

4.2. Sensitivity of the microphone

The fabricated devices were tested to examine the characteristics of the output voltage for input acoustic pressure by the FFT analyzer. A dynamic speaker was used as the input acoustic pressure source for the fabricated microphones, and the B&K 4190 microphone was used as a reference microphone. Fig. 7 shows the unamplified output voltages of the circular and square diaphragm microphone in the 400 Hz to 10 kHz range using a supply voltage of $1V_{pk}$ of dynamic speaker. The average sensitivity of the circular diaphragm microphone (S_c) and square diaphragm microphone (S_s) was 39.6 μV/Pa and 20.1 μV/Pa, respectively. S_c/S_s was 197% as expected from the simulation results. The difference between the measurement results and simulation ones was within the error margin. This shows that S_c was stable in the entire range. The response characteristics of the unamplified CD microphone were compared with those of the B&K 4190 reference microphone as shown in Fig. 8. Both microphones showed similar sensing abilities.

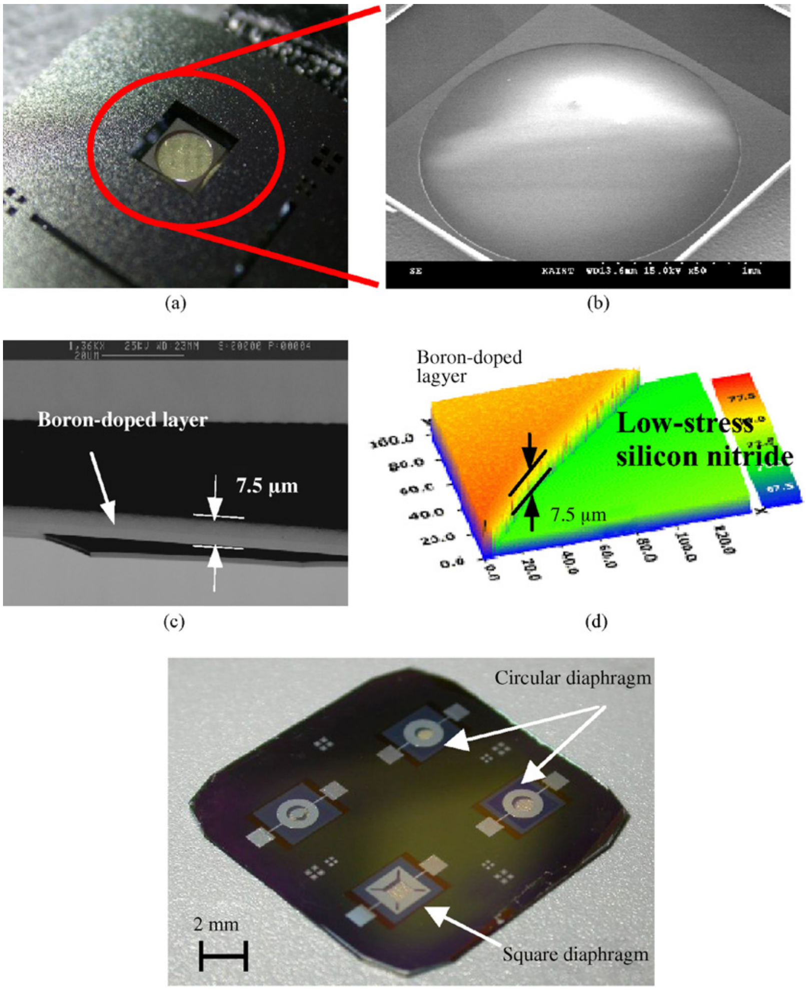


Fig. 5. Pictures of circular diaphragms and microphones: (a) and (b) circular diaphragm, (c) and (d) thickness measurement results of boron-doped layer, and (e) fabricated microphones.

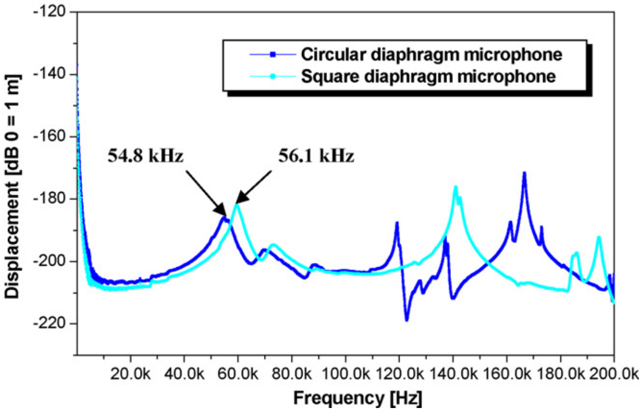


Fig. 6. Displacements of the circular and square diaphragm microphone in 100 Hz to 200 kHz range.

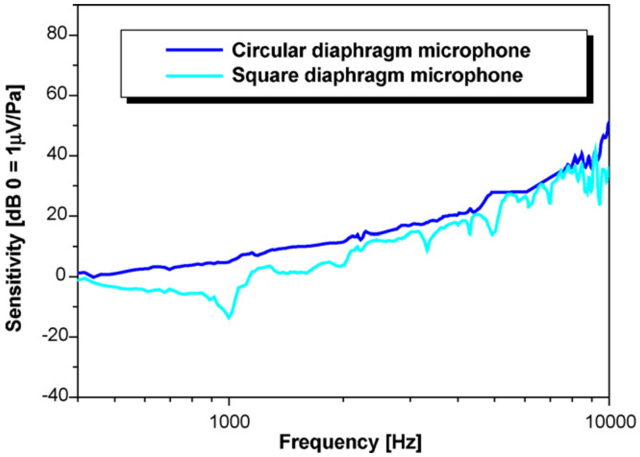


Fig. 7. Unamplified sensitivities of the circular and square diaphragm microphone in the audio-frequency range.

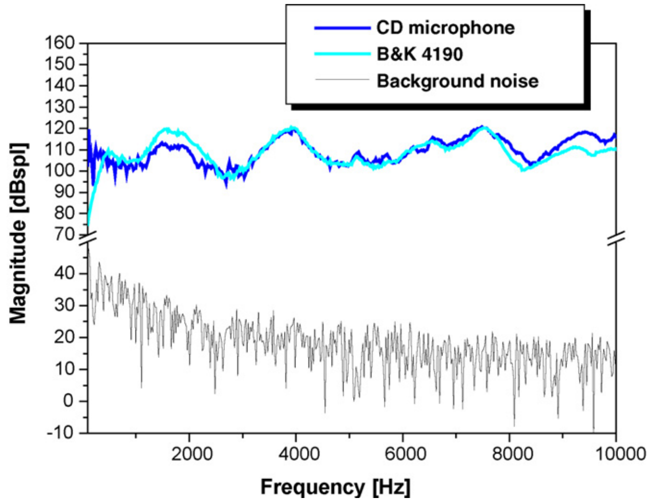


Fig. 8. Response characteristic of the circular diaphragm microphone in the audio-frequency range.

Fig. 9 shows the amplifier circuit for testing the response characteristics to a human voice. The function of the CD microphone was tested by using this circuit, which was packaged in a metal box to isolate from electric noise. The gain of the amplifier is 200. The sensitivity of the CD microphone with this amplifier was 8.1 mV/Pa on average using a supply voltage of $1V_{\mathrm{pk}}$. The system shown in Fig. 9(c) was able to clearly reproduce the human voice. The response characteristics of the CD microphone system were compared with those of the B&K 4190 reference microphone, as shown in Fig. 10. Both microphones showed similar sensing abilities. The white noise which existed below 500 Hz, as shown in Fig. 8, was removed with the amplifier system.

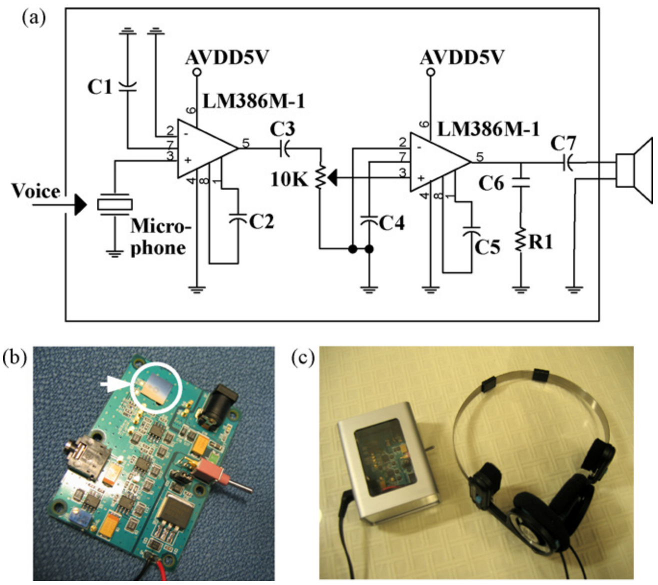


Fig. 9. Circuit of the amplifier and portable package: C1–C5 = 10 μF, C6 = 0.047 μF, C7 = 220 μF, and R1 = 10 Ω.

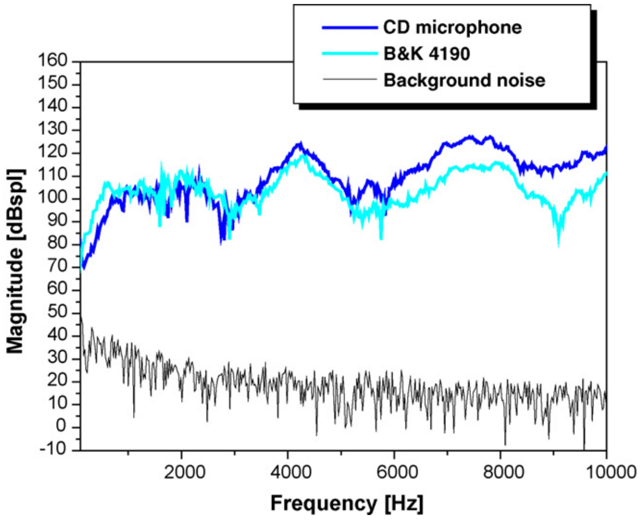


Fig. 10. Response characteristic of the circular diaphragm microphone system in the audio-frequency range.

5. Conclusion

A piezoelectric microphone built on a circular diaphragm was designed, fabricated, and verified. The circular diaphragm was fabricated by using the boron etching stop method. The thickness of the boron-doped layer was approximately 7.5 μm. It was confirmed experimentally that its boron-doped layer could be used as a support layer for the diaphragm. Based on simulations, the sensitivity was expected to increase on changing the shape of the diaphragms. Compared with the sensitivity of the SD microphone, that of the CD microphone increased, as expected from the simulation results; furthermore, the output of the CD microphone was very stable. The CD microphone system with an amplifier was also confirmed to have a similar sensing ability of that of the B&K 4190 reference microphone.

Acknowledgments

This research was supported by the center for intelligent robotics, which carries out one of the 21st century's Frontier R&D Projects sponsored by the Korea Ministry of Commerce, Industry and Energy. We would like to thank Dr. S.C. Ko and C.H. Choi for their experimental assistance.

References

[1] M. Royer, J.O. Holmen, M.A. Wurm, O.S. Aadland, M. Glenn, ZnO on Si integrated acoustic sensor, Sens. Actuators A 4 (1983) 357–362.
[2] R. Schellin, G. Hess, A silicon subminiature microphone based on piezoresistive polysilicon strain gauges, Sens. Actuators A 32 (1992) 555–559.
[3] D. Hohm, R. Gerhard-Multhaupt, Silicon-dioxide electret transducer, J. Acoust. Soc. Am. 75 (4) (1984) 1297–1298.
[4] P.R. Scheeper, A.G.H. van der Donk, W. Olthuis, P. Bergveld, A review of silicon microphones, Sens. Actuators A 44 (1994) 1–11.
[5] M.N. Niu, E.S. Kim, Piezoelectric bimorph microphone built on micromachined parylene diaphragm, J. Microelectromech. Syst. 12 (6) (2003) 892–898.
[6] S.C. Ko, Y.C. Kim, S.S. Lee, S.H. Choi, S.R. Kim, Micromachined piezoelectric membrane acoustic device, Sens. Actuators A 103 (2003) 130–134.

[7] S.S. Lee, R.P. Ried, R.M. White, Piezoelectric cantilever microphone and microspeaker, J. Microelectromech. Syst. 5 (4) (1996) 238–242.

[8] W. Kuhnel, G. Hess, Micromachined subminiature condenser microphones in silicon, Sens. Actuators A 32 (1992) 560–564.

[9] C.H. Han, E.S. Kim, Fabrication of dome-shaped diaphragm with circular clamped boundary on silicon substrate, in: Proceedings of the IEEE Conference MEMS, Orlando, USA, 1999, pp. 505–510.

[10] S.H. Yi, E.S. Kim, Piezoelectric microspeaker with compressive nitride diaphragm, in: Proceedings of the IEEE Conference MEMS, Las Vegas, USA, 2002, pp. 260–263.

[11] J.J. Neumann Jr., K.J. Gabriel, CMOS-MEMS membrane for audio-frequency acoustic actuation, Sens. Actuators A 95 (2002) 175–182.

[12] R.G. Polcawich, M. Scanlon, J. Pulskamp, J. Clarkson, J. Conred, D. Washington, R. Piekarz, S. Trolier-Mckinstry, M. Dubey, Design and fabrication of a lead zirconate titanate (PZT) thin film acoustic sensor, Integr. Ferroelectr. 54 (2003) 595–606.

[13] J.C. Greenwood, Ethylene diamine–cathechol–water mixture shows preferential etching of p–n junction, J. Electrochem. Soc. 116 (1969) 1325–1326.

[14] O.C. Jeong, S.S. Yang, Fabrication and test of a thermopneumatic micropump with a corrugated p+ diaphragm, Sens. Actuators A 83 (2000) 249–255.

[15] M. Gel, I. Shimoyama, Sub-micron thick high sensitive piezoresistive contilevers by boron etch stop and argon implantation, in: Proceedings of the IEEE Conference MEMS, Kyoto, Japan, 2003, pp. 494–497.

[16] M.J. Madou, Fundamentals of Microfabrication, 2nd ed., CRC Press LLC, New York, 2002.

[17] E. Manea, I. Cernica, V. Dolocan, R. Muller, Residual stress analysis in thin membranes obtained by boron diffusion processes, in: Proceedings of Semiconductor Conference, Sinaia, Romania, 2000, pp. 471–474.

Biographies

Woon Seob Lee He received his BS and MS degrees in the Department of Materials Science and Engineering of the Soonchunhyang University, Korea, in 2000 and 2002, respectively. He was a researcher in the Department of Mechanical Engineering at POSTECH from 2002 to 2003. He has been a PhD candidate in the Department of Mechanical Engineering from the Korea Advanced Institute of Science and Technology (KAIST) from 2003. He is interested in MEMS devices including acoustic transducers and display systems.

Seung S. Lee He received BS degree from Seoul National University, Korea in 1984 and the MS degree in mechanical engineering of University of California, Berkeley, USA in 1989. After his MS degree, he joined Berkeley Sensor and Actuator Center (BSAC) and got his PhD degree there in 1995. After 1 year at Samsung Advanced Institute of Technology (SAIT) in Kiheung, Korea, he joined the Faculty of the Department of Mechanical Engineering of Pohang University of Science and Technology (POSTECH), Korea, in 1997 and became an associate professor there in 2003. He moved from POSTECH to the Korea Advanced Science and Technology (KAIST) in 2003 as an associate professor of the Department of Mechanical Engineering and currently working in KAIST as a professor. His recent research area includes HARMST with LIGA process, Bio-MEMS, Microfluidics, and piezo-MEMS.