Fabrication of Circular Diaphragm for Piezoelectric Acoustic Devices

Woon Seob Lee, Yong Chul Kim, Jin Seung Lee, Seok Woo Lee, and Seung S. Lee

Abstract—**This paper describes a fabrication method of a circular diaphragm using boron etching stop method. It will be applied to acoustic transducers such as microphones or microspeakers and so on. The sensitivity is expected to be increased with the circular diaphragm through the simulation results to compare with a general rectangular diaphragm. The boron-doped layer which is doped with solid source is sufficient for achieving an etching stop in 20 wt% TMAH, and the thickness is about 7.4 µm. The diameter of the circular silicon nitride diaphragm was measured to be 2 mm with 1 µm thickness. The fabrication of piezoelectric acoustic devices was completed.**

Index Terms—**Boron doping, Circular diaphragm, Microphone, Microspeaker**

I. Introduction

During the last decades, micromachining technology has been explored to fabricate various acoustic transducers such as microphones and microspeakers [1-11]. The advantages of micromachined microphones and microspeakers are accurate control of the dimensions, high degree of miniaturization, and low-cost as a result of batch processing. Recently, a lot of trials are focused on applications of the micromachined microphones and microspeakers to hearing-aid cellular phones, micro-personal digital assistants, earphones, and so on [7].

Microphones are basically pressure sensors detecting airborne pressures which are generated by sound with ten orders of magnitude lower than ambient pressure. Hence a microphone needs an extremely compliant diaphragm to increase its sensitivity.

Several types of microphones have been reported to be fabricated by variable methods and principles including three major transduction principles, that are the condenser, piezoelectric, and piezoresistive microphones. A condenser microphone is more popular than others, but it requires high DC bias voltage [5]. The piezoelectric microphones are simple to be fabricated, free from polarization-voltage requirement, and responsive over a wider dynamic [6-11]. However, they show relatively low sensitivity as a microphone and low output pressure as a microspeaker [10,11]. To increase sensitivity, some researchers have tried to reduce tensile residual stress of the transducer diaphragm such as cantilever with a nitride film [8], dome-shaped microspeaker with a Parylene film [10], or wrinkled diaphragm microspeaker with a compressive nitride film [11].

Micromachined microphones and microspeakers based on single crystal silicon wafer using bulk micromachining have innate limitation of the shape of diaphragm due to the anisotropic etching property. Therefore, most of the diaphragms for microphones and microspeakers have been limited to have rectangular shapes.

In this paper, we report a novel fabrication process of circular diaphragm using boron etching stop method for piezoelectric acoustic devices. This fabrication method can be applied to manufacturing any shape of membrane from single crystal silicon wafer. A circular diaphragm with a

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uniform stress distribution will contributes to increased sensitivity if it is applied for acoustic transducers.

II. Design and Fbrication

A circular diaphragm has the limitation to be fabricated using traditional bulk micromachining processes. Some techniques, such as isotropic etching and deep-RIE (reactive ion etching), may be adopted to fabricate a circular diaphragm. However, it is difficult to control the dimension and shape of a diaphragm and the reproducibility in isotropic etching. Deep-RIE is so expensive and it is difficult to prevent the fracture of diaphragm during the process. Therefore, we devised the application of boron etching stop method to fabricate circular diaphragms.

After Greenwood's first report about the boron etching stop [12], it has been used for manufacturing thin cantilever, membrane, beam, or nozzle in MEMS field [13-16]. A silicon oxide layer or a silicon nitride layer functions as a protection layer for boron-doped layer during general anisotropic bulk etching. Silicon nitride layer, however, is a membrane, and boron-doped layer is just a supporting structure for the circular diaphragm fabrication. Fig. 1 shows the schematic diagram of a circular diaphragm. Microphones were fabricated simultaneously on the circular diaphragm and rectangular one with the same dimension, 3.14 mm^2, to compare the functional differences of microphones.

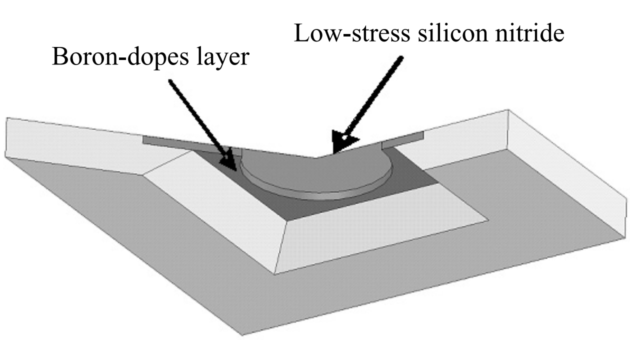


Fig. 1. Schematic diagram of the circular diaphragm

The first and second modes of the circular diaphragm were created at 8.6 kHz and 17.2 kHz by using finite element method (the rectangular diaphragm : 9.2 kHz, 18.8 kHz). The electrode patterns are designed based on the stress distribution.

1. Circular Diaphragm Fabrication

Fig. 2 shows the process flow to fabricate a circular diaphragm. The fabrication started with 4-in. p-type silicon wafers. The wafer was covered with a silicon oxide layer of 1 μm thickness by thermal oxidation to protect boron from diffusing into silicon. The silicon oxide layer was patterned to guide the desired boron high doping. Boron was diffused from the solid source for 15 hr at 1100 °C in N_2 environment. The silicon oxide was removed right after boron doping. Then another silicon oxide layer with 0.2 μm thickness was deposited by LPCVD to prevent boron from diffusing into silicon oxide layer during the

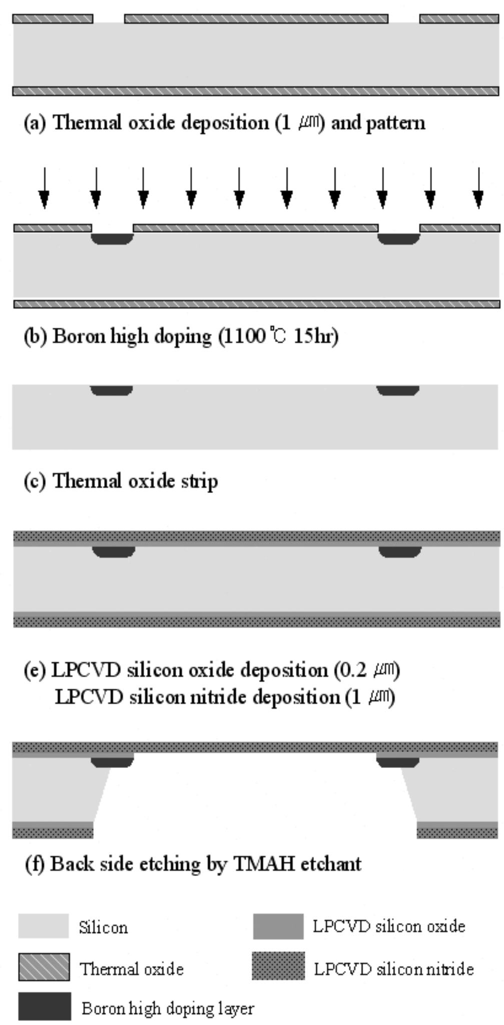


Fig. 2. Fabrication process for circular diaphragm

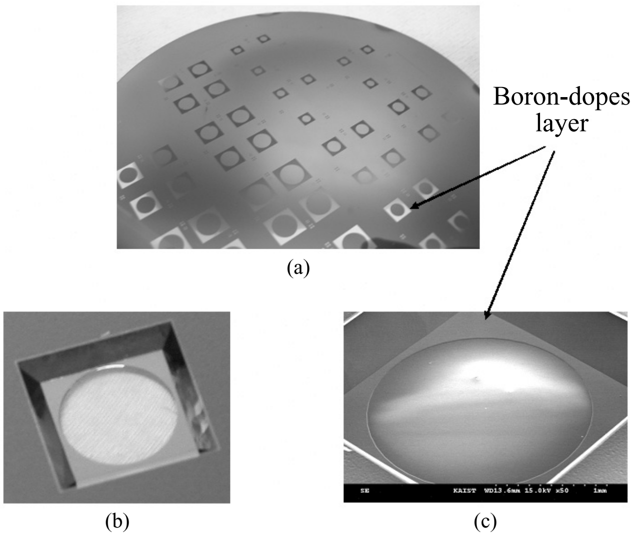


Fig. 3. Picture of circular diaphragm. (a) before etching, (b) and (c) after etching (diaphragm size : 2mm)

following thermal oxidation. A LPCVD low-stress silicon nitride layer was deposited with 1 μm thickness as a material of membrane. An anisotropic etchant, 20 wt% of TMAH (Tetramethyl Ammonium Hydroxide), was used to expose the silicon nitride diaphragm for 12 hr at 90 °C by etching the silicon wafer from the backside (bottom side in Fig. 2). Arrayed patterns of boron-doped layers are shown in Fig. 3(a). A picture and SEM (scanning electron microscopy) back side image of the completed circular diaphragm are also shown in Fig. 3(b) and 3(c), respectively. The diameter of the diaphragm was measured to be 2 mm as designed.

2. Microphone Fabrication

Fig. 4 shows the fabrication process of piezoelectric microphone. A 0.4 μm-thick aluminum(Al) layer was formed by evaporation with E-beam evaporator as a bottom electrode. The bottom electrode was patterned on a LPCVD low-stress silicon nitride. A thick silicon oxide layer with 0.2 μm thickness was evaporated with E-beam in order to form a electrical passivation layer. RIE was used to etch the evaporated silicon oxide. Then a 0.8 μm of ZnO layer was made by sputtering in RF sputter for 2 hr. Aluminum was evaporated on this ZnO layer to for a 0.4 μm of layer. The aluminum layer was patterned to form the top electrodes. Finally, gold wire was connected with bond pads. Fig. 5 shows the fabricated piezoelectric microphone.

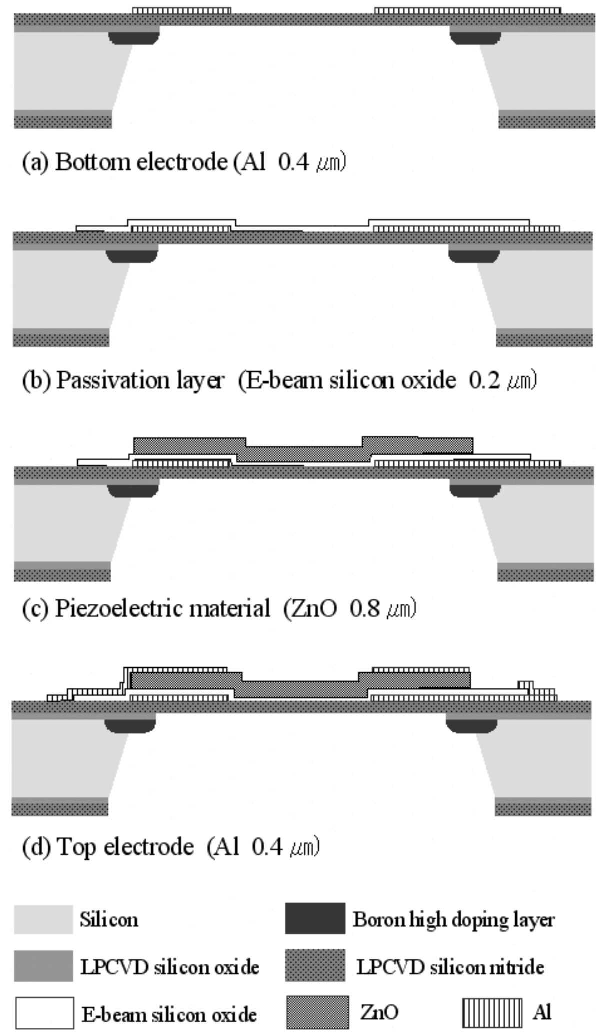


Fig. 4. Fabrication process of microphone

III. Simulation and Results

Finite element modeling with I-Deas software has been performed to study the difference of the mechanical behavior and stress distribution of the circular and rectangular diaphragm.

Static analysis, a 1 Pa pressure load, and dynamic mode shape of the diaphragms have been investigated. The model considered the diaphragm as being fixed on the silicon substrate. The material properties used in the analysis are listed in the Table 1. Static analysis has been performed to obtain the stress distribution in the diaphragms under a uniform pressure load, 1 Pa, as shown in Fig. 6. The circular diaphragm showed a uniform stress distribution while the stress in the rectangular diaphragm

Table. 1. Material properties used in analysis

Material	Thickness	Material Properties		
		Young's Modulus	Poisson's Ratio	Density
Si_xN_y	2 μm	272GPa	0.25	3100kg/m³

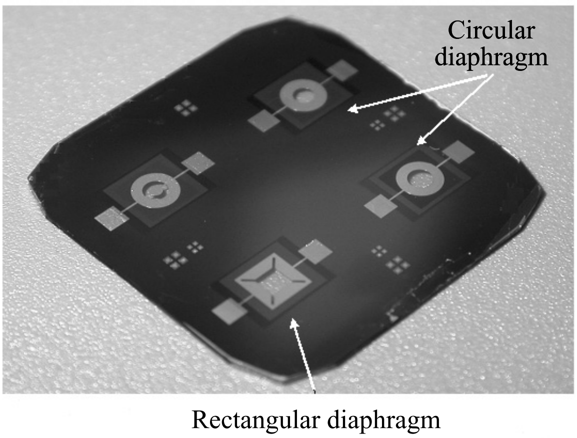
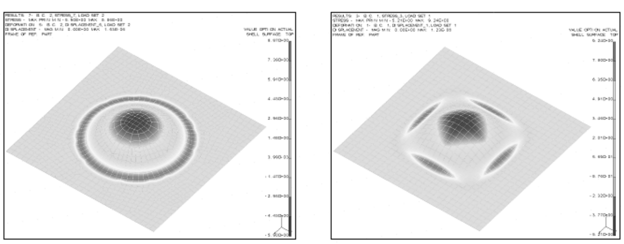


Fig. 5. Picture of the fabricated microphone



(a) (b)

Fig. 6. The stress distribution under 1 Pa uniform pressure load. (a) Circular diaphragm, (b) rectangular diaphragm.

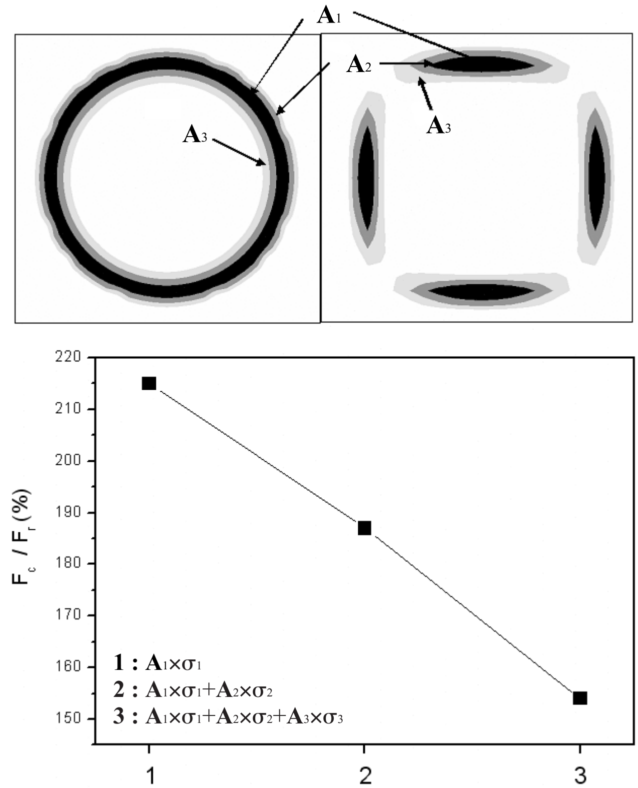
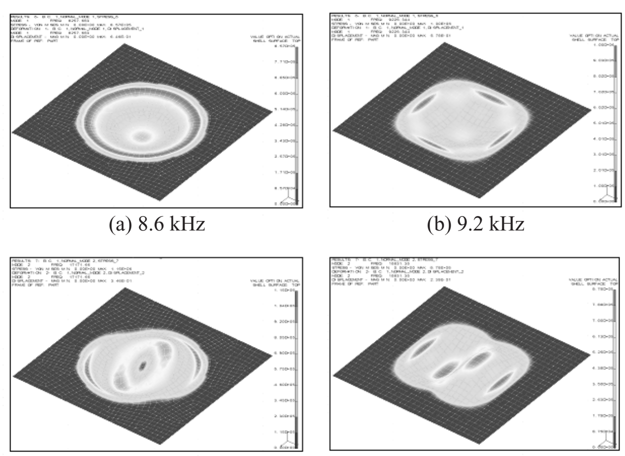


Fig. 7. The ratio of F_c over F_r according to the increase of area under stressed region



(a) 8.6 kHz (b) 9.2 kHz

(c) 17.2 kHz (d) 18.8 kHz

Fig. 8. Results of modal analysis for the circular and rectangular diaphragm.
(a) The first mode and (b) The second mode of circular diaphragm, (c) The first mode and (d) The second mode of rectangular diaphragm

distributed on the edges.

The area of stressed region was divided to three major parts, 50 %, 75 %, and 100 % of the tensile stress area, to compare the force transferred to ZnO by the stress on the circular diaphragm, F_c, and rectangular diaphragm, F_r. Fig. 7 shows the ratio of F_c over F_r according to the increase of the area of stressed region. The ratio of F_c over F_r decreased as the area of tension increased; 215 %, 187 %, and 154 %. However, the force of the circular diaphragm was still bigger than the rectangular one. Therefore, a sensitivity of the circular diaphragm will be better than the rectangular one when it is applied to piezoelectric acoustic transducers.

Modal analysis has been performed to determine the vibration characteristics. Fig. 8 shows the results for the first and second modes of the circular and rectangular diaphragm. For both of the circular and rectangular diaphragm, the first mode shape showed the symmetric up-and-down mode, and the second mode had a kind of tiling shape.

The fabrication of a circular diaphragm using boron

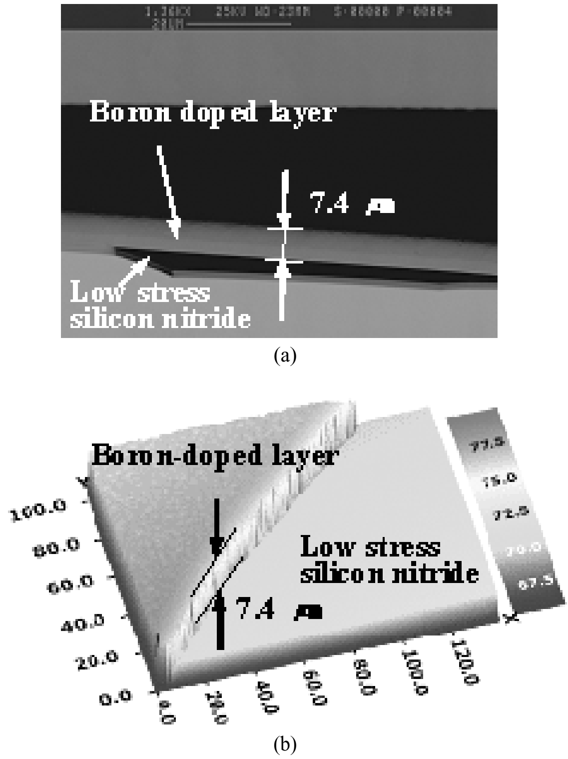


Fig. 9. Thickness of boron-doped layer.
(a) SEM, (b) 3D coordinate measurement system

etching stop method was accomplished. Boron was deposited using a solid source for 15 hr at 1100 °C. The wafer was etched in 20 wt% TMAH for 12 hr. The diameter of the diaphragm was measured to be 2 mm as designed, which means complete resistance and preservation of boron-doped layer against etchant. The thickness of boron-doped layer was measured by SEM and 3D coordinate measurement system. The thickness is about 7.4 μm. Fig. 6 shows the image of the boron-doped layer.

IV. Conclusions and Future Work

The circular diaphragm was fabricated using boron etching stop method. The shape and dimension of a diaphragm can be controlled. The diameter of the silicon nitride circular diaphragm was 2 mm, and the thickness of boron-doped layer was measured to be about 7.4 μm which can be used as diaphragms of piezoelectric acoustic transducers. It is expected that the sensitivity of piezoelectric transducers will increase by applying the circular diaphragm rather than the rectangular diaphragm. We are currently fabricating piezoelectric acoustic transducers with this circular diaphragm, and it will be compared with some rectangular diaphragm in the next step.

Acknowledgments

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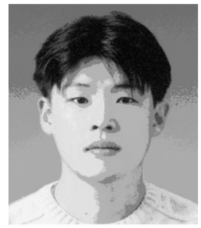

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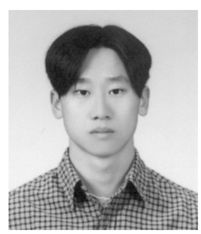

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