Silicon microphone with wide frequency range and high linearity

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Abstract

This paper reports a silicon microphone with a wide frequency range and high linearity and its novel fabrication process. The transducer has a monolithic structure and is simply fabricated from a bonded silicon wafer. A frequency range from 30 Hz to 20 kHz, which covers the audio frequency, and a total harmonic distortion less than 0.3% at a sound pressure level of 20 Pa (120 dB SPL) are obtained. The measured sensitivity of the transducer is $-52 \text{dBV/Pa}$ (1 kHz), which is in good agreement with the calculated value.

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1. Introduction

High-performance microphones currently used for broadcasting have superior acoustic characteristics such as wide frequency range, high linearity and high sensitivity. These microphones require, however, a complicated fabrication process, which includes assembly and adjustment of many miniature components. Such microphones have high production costs and are rather fragile. The demand for low-cost high-performance microphones is, therefore, strong.

Micromachined condenser silicon microphone may be an attractive alternative to the conventional high-performance microphone. A large number of studies have been reported [1–7], some dealing with a surface micromachining process that fabricates a transducer including a diaphragm out of deposited films such as polysilicon and/or silicon nitride. Such a process is suitable for fabricating a structure with a diaphragm of sub-micrometer thickness and a narrow air gap of under few micrometers, which enables low-voltage operation. However, a microphone with a narrow air gap has difficulty in obtaining high linearity at a higher sound pressure level, because the diaphragm sticks to the backplate at higher sound pressure levels owing to its narrow air gap. Also, the backplate is often formed of deposited film, for which the stiffness may not be large enough. Sound pressure vibrates a backplate without sufficient stiffness, and this causes undesired resonance that disturbs the frequency response. For these reasons, the surface micromachining process is not appropriate for fabricating high-performance microphones for professional applications such as broadcasting.

A wide air gap and a non-vibrating stiff backplate are required for securing high linearity and a wide frequency range. Scheeper et al. [8] adopted a bulk micromachining process to fabricate a wide air gap of 20 $\mu$m, which resulted in a high-performance measurement microphone. This transducer, however, required a complicated fabrication process. The diaphragm and backplate were formed on separate wafers by etching processes, followed by a wafer bonding process and a second etching process. Mass production of this microphone at a reasonable cost, therefore, is difficult.

To overcome the above-mentioned difficulties, we have developed a novel bulk micromachining process for fabricating a silicon condenser microphone using a bonded wafer [9]. The transducer is fabricated of monocrystalline silicon as one body with a wide air gap and a stiff backplate. The process is very simple, and it would contribute to reduce the production cost. This paper describes the fabrication process and the performances of a fabricated transducer and prototype microphone.
2. Structure

Fig. 1 shows a cross-sectional view of the transducer. A thin diaphragm, which is vibrated by sound pressure, and a fixed backplate make up the condenser, which is charged by an external bias voltage. The amount of charge is kept constant during the vibrating period of the diaphragm, in which the capacitance change caused by sound pressure is converted into a voltage change between the diaphragm and the backplate. Acoustic holes perforate the backplate to reduce the squeeze-film air damping applied to the diaphragm.

The diaphragm is formed with its frame as one body out of monocrystalline silicon, which has excellent durability. The backplate is also formed of monocrystalline silicon and is much thicker than the diaphragm. This ensures sufficient stiffness, which in turn prevents undesired resonances that disturb the frequency response.

3. Process

Fig. 2 shows the fabrication process. Two (001)-oriented silicon wafers, which are called a handle wafer and a base wafer, were used to fabricate the transducer. A highly concentrated boron etch-stop layer, which controlled the diaphragm’s thickness, was formed on the handle wafer by solid source diffusion in nitrogen atmosphere (Fig. 2(a)). A BSG layer, which consisted of fine particles, was formed on the base wafer by chemical vapor deposition. The handle and base wafers were bonded at high temperature, which resulted in a void-free bonded wafer because the BSG particles were condensed during the bonding. After that, the base wafer was polished to the thickness of the backplate (Fig. 2(b)). Thermal oxide layers were grown on both sides of the bonded wafer and were patterned as etching masks for forming the diaphragm and backplate (Fig. 2(c)). The diaphragm and backplate were formed by anisotropic wet etching with a tetra methyl ammonium hydroxide (TMAH) solution. Etching of the handle wafer and base wafer was stopped by the boron etch-stop layer and the BSG layer, respectively (Fig. 2(d)). The BSG layer between the diaphragm and backplate was removed through the acoustic holes of the backplate with hydrofluoric acid. The BSG layer remained under the peripherals of the backplate consisting of the insulators between the diaphragm and the backplate (Fig. 2(e)). The transducer was completed by depositing alu-
minum electrodes on both sides of the wafer (Fig. 2(f)). For simplicity, patterning of the electrodes was not performed.

4. Fabrication

4.1. Diaphragm

The boron etch-stop layer was formed by a 4-h diffusion in a nitrogen atmosphere at 1200 °C. Fig. 3 shows the measured initial boron concentration profile before the wafer bonding. Silicon etching was performed with a 25% TMAH solution at 80 °C. The etch-stop was effective, and an 8-μm-thick diaphragm was formed, although, throughout the wafer bonding and successive oxidation, the boron concentration would change from the initial profile. The thicknesses of the aluminum electrodes on both sides of the wafer were 200 nm. Part of the aluminum was deposited on the backside of the diaphragm where the diaphragm was not covered with the backplate (under the acoustic holes and peripheral area of the diaphragm). Since the aluminum electrodes were sufficiently thinner than the diaphragm, the surface of the diaphragm was flat, and no buckling of the diaphragm was observed after forming the electrodes. Fig. 4 shows SEM photographs of the diaphragm.

4.2. Backplate

Fig. 5 shows an optical microscope photograph of the backplate. To reduce parasitic capacitance, the backplate supports (BSG insulators) were located under four small peripheral areas of the backplate. The acoustic holes were each approximately 10 μm × 10 μm, and the backplate was 50 μm thick.

Fig. 3. Initial boron concentration profile before the wafer bonding.

Fig. 4. SEM photographs of the diaphragm: (a) surface; (b) cross-section. The surface of the diaphragm was flat, and no buckling of the diaphragm was observed. The thickness of the diaphragm was 8 μm.

Fig. 5. Optical microscope photograph of the backplate. The acoustic holes were each approximately 10 μm × 10 μm, and the backplate was 50 μm thick.
4.3. Transducer

Fig. 6 shows the transducer. The size of the transducer was 4.4 mm × 4.4 mm, and the diaphragm’s area and air gap length were 2.1 mm × 2.1 mm and 10 μm, respectively.

4.4. Prototype microphone

The prototype microphone was fabricated by encapsulating the transducer in a small metal package (Fig. 7). To avoid a packaging stress, the transducer was mounted in the package with silicone sealant at room temperature. The package measured 13 mm × 5.7 mm × 3 mm and included a discrete unity gain preamplifier circuit for impedance conversion. The back-chamber volume was approximately 0.07 cm³. The external bias voltage applied to the transducer was 39 V, which was restricted by the endurance voltage of the preamplifier circuit.

5. Measurements

5.1. Pressure versus capacitance change characteristics

Fig. 8 shows the pressure versus capacitance change characteristics of the transducer. The capacitance change of the transducer from the initial value (without static pressure or bias voltage) was measured under static pressure by using a capacitance bridge [9]. Bias voltage ($V_b$) of 0 or 39 V was applied to the transducer during the measurement. Linearity up to 100 Pa (134 dB SPL), which is the upper pressure limit of the measurement apparatus, was confirmed under a bias voltage of 39 V (0 V). Measured total harmonic distortion of the prototype microphone was less than 0.3% at a sound pressure level of 20 Pa (120 dB SPL). The sound pressure applied to a microphone under normal conditions, such as during an orchestra recording session, is less than a few Pascals. Thus, the prototype microphone guarantees very good linearity.

5.2. Bias voltage versus capacitance change characteristics

Fig. 8. Pressure vs. capacitance change characteristics of the transducer. Linearity up to 100 Pa was confirmed.
5.3. Frequency response

Fig. 10 shows the frequency response of the prototype microphone. The measurement was performed in an anechoic room, and the sound field was calibrated with a reference microphone. The frequency response was almost flat from 30 Hz to 20 kHz, which covers the audio frequency. The resonant frequency of the diaphragm was 27 kHz. No resonance of the backplate was observed up to 30 kHz. The measured sensitivities of the transducer and of the prototype microphone were $-52$ dBV/Pa (1 kHz) and $-62$ dBV/Pa (1 kHz), respectively. The lower sensitivity of the prototype microphone was due to the loss from the input parasitic capacitance of the unity gain preamplifier circuit. Measured equivalent noise level of the microphone was 47 dB (A-weighted). Table 1 summarizes the specifications and measured performance of the transducer and the prototype microphone.

6. Discussion

The sensitivity of the transducer and the possibility of its improvement are discussed on the basis of the measured performance. The sensitivity of the transducer is given by

$$S = \frac{V_b}{d} S_m \frac{C_m}{C_m + C_p} \quad (1)$$

where $V_b$ and $d$ are the bias voltage and air gap length, respectively, $S_m$ the mechanical sensitivity, which is defined as the average displacement of the diaphragm per unit pressure, $C_m$ the capacitance between the diaphragm and the backplate and $C_p$ is the parasitic capacitance of the backplate supports. Supposing a linear piston motion of the diaphragm, $S_m$ is approximately given by

$$S_m = \frac{A}{8\pi \rho h} \quad (2)$$

where $A$ and $h$ are the diaphragm’s area and thickness, respectively. $\sigma$ is the diaphragm’s internal tensile stress, which is given by

$$\sigma = 2A\rho f_0^2 \quad (3)$$

where $\rho$ (2330 kg m$^{-3}$) and $f_0$ are the diaphragm’s density and resonant frequency, respectively. Substituting the diaphragm’s area (2.1 mm $\times$ 2.1 mm) and the measured resonant frequency (27 kHz) into Eq. (3) yields $\sigma = 15$ MPa, which is the average internal tensile stress of the diaphragm. Eq. (2) thus gives $S_m = 1.2 \times 10^{-9}$ m Pa$^{-1}$. Substituting this value into Eq. (1) yields $S = -53$ dBV/Pa, which shows good agreement with the measured value. $C_m$ and $C_p$ were 2.3 and 2.2 pF, as calculated from the geometric shape of the backplate. The pull-in voltage (bias voltage at which the diaphragm sticks to the backplate) is approximately given by

$$V_p = \sqrt{\frac{8d^3}{27\varepsilon_0 S_m}} \quad (4)$$

where $\varepsilon_0$ is permittivity in air. By substituting the values of $d$ (10 $\mu$m) and $S_m$ into Eq. (4), $V_p$ of 170 V is obtained.

The prototype microphone had good linearity and a wide frequency range; however, the sensitivity was not equal to those of current high-sensitivity professional microphones, which have sensitivities of higher than $-45$ dBV/Pa. Still, improvement of the sensitivity is feasible, because the pull-in voltage was much higher than the bias voltage. Note that pull-in voltage rapidly drops as the air gap decreases. Therefore, to achieve higher sensitivity, greater mechanical sensitivity is more appropriate than narrowing the air gap. Mechanical sensitivity can be increased by thinning the diaphragm and decreasing its internal tensile stress. To form a thinner diaphragm, shallow boron doping and strict
control of the subsequent thermal processes during wafer bonding and oxidation would be required. In order to decrease internal tensile stress of the diaphragm, the thermal process should also be controlled, and packaging stress should be considered as well.

7. Conclusion

A micromachined condenser silicon microphone was fabricated using a bonded silicon wafer. The transducer showed good linearity and a flat frequency response within the audio frequency range. The sensitivity of the transducer was in good agreement with the calculated value. Our future work will include controlling the thickness and the internal tensile stress of the diaphragm to produce a professional microphone with sufficient sensitivity.

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References


