FABRICATION OF A SUBMINIATURE SILICON CONDENSER MICROPHONE USING THE SACRIFICIAL LAYER TECHNIQUE

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Abstract

The application of the sacrificial layer technique for the fabrication of a subminiature silicon condenser microphone with a silicon nitride diaphragm has been investigated. Square diaphragms with dimensions from 0.6 to 2.6 mm and a thickness of 1 μm have been realized. Measurements on a microphone with a 2 x 2 mm diaphragm and a 1 μm air-gap have shown that a sensitivity of 1.4 mV/Pa for low frequencies can be achieved with a low bias voltage (-2 V). The sensitivity decreases for high frequencies. This effect is likely due to the small air-gap. Therefore microphones with wider air-gaps have to be developed to achieve a flat frequency response for the entire audio frequency range.

Introduction

Silicon micromachining has been successfully applied to the fabrication of miniature microphones on silicon wafers [1-3]. The first generation of the silicon-based hearing-aid microphone, developed at the University of Twente, consists of an anisotropically etched silicon backplate and a commercially available Mylar diaphragm, which is attached manually per wafer and fixed by means of glue [1]. At present, research is directed towards the development of a second generation of the silicon-based microphone, in which diaphragms are fabricated by means of IC-compatible technologies and materials, as for instance presented by Hohm and Hess [2] and Bergqvist and Rudolf [3]. These authors have fabricated the backplate of the microphone and the diaphragm on separate wafers. The microphone is assembled by means of a wafer bonding technique. This technique requires laborious wafer alignment and exposure of the wafers to high electric fields or high-temperature steps. An alternative production process may be the application of the sacrificial layer technique for the diaphragm fabrication. Experiments have shown that 300 x 300 μm silicon nitride diaphragms with a thickness of 1 μm can be produced with this technique in a reproducible way. Evaporated aluminium has been used as sacrificial layer and plasma-enhanced chemical vapour deposited (PECVD) silicon nitride as diaphragm material. The access holes for the etchant have been etched in the diaphragm [4].

A more appropriate technique to fabricate a microphone is the use of access holes in the silicon backplate, as proposed by Hijab and Muller [5]. The access holes will act as acoustic holes during normal operation of the microphone. The objective of our present research is to investigate the effect of the number and dimensions of these holes on the fabrication and the dynamic behaviour of the microphones. First, the sensitivity of the microphones will be calculated using a quasi-static model. Next, the fabrication process will be described and finally, technological results and some preliminary measurements will be presented.

Microphone design

The dimensions which are required for a hearing-aid microphone can be estimated using a quasi-static model. The (open-loop) sensitivity of a condenser microphone can be written as :

$$\frac{\partial V}{\partial P} = \frac{\partial V}{\partial s_a}\,\frac{\partial s_a}{\partial P} \qquad (1)$$

where V is the voltage across the air-gap, ∂P is the sound pressure and ∂s_a is the change of the air-gap thickness. $\partial s_a/\partial P$, the mechanical sensitivity of the diaphragm, is the change of the air-gap thickness as a result of the sound pressure ∂P. $\partial V/\partial s_a$, or the electrical sensitivity, is the change of the voltage across the air-gap due to a change of the air-gap thickness ∂s_a and can be written as :

$$\frac{\partial V}{\partial s_a} = \frac{V_b}{s_a}\left[\ln^{-1}\left(\frac{s_{a0}}{s_a}\right) - \left(\frac{s_a}{s_{a0}-s_a}\right) \right] \qquad (2)$$

where s_{a0} is the thickness of the air-gap without any external force applied to the diaphragm and V_b is the bias voltage. For small diaphragm deflections, $s_a \approx s_{a0}$, the expression between brackets approximates 1/2 and equation (2) can then be written as :

$$\frac{\partial V}{\partial s_a} = \frac{1}{2}\,\frac{V_b}{s_{a0}} \qquad (3)$$

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For a circular diaphragm the mechanical sensitivity, $\partial s_a/\partial P$, is equal to:

$$\frac{\partial s_a}{\partial P} = \frac{R^2}{4 \sigma_0 h} \tag{4}$$

where R is the radius and h is the thickness of the diaphragm; σ_0 is the stress in the diaphragm material. Note that in this equation it is assumed that the sensitivity of the diaphragm is determined by the stress and not by the Young's modulus of the diaphragm material.

For a microphone with a diaphragm radius of 1 mm and a thickness of 1 μm, an air-gap thickness of 1 μm and a diaphragm stress of 10^8 Pa, the mechanical sensitivity is 2.5×10^{-9} m/Pa. A diaphragm stress of 10^8 Pa is a typical value for the stress of the plasma-enhanced chemical vapour deposited silicon nitride films that will be used as diaphragm material [4]. Some calculated values of the electrical sensitivity, according to equation (3), and the open-loop sensitivity, according to equation (1), as a function of the bias voltage are shown in table 1.

Table 1. The calculated electrical sensitivity $\partial V/\partial s_a$ and open-loop sensitivity $\partial V/\partial P$ as a function of the bias voltage of a circular microphone with a radius of 1 mm, air-gap thickness of 1 μm, diaphragm stress of 10^8 Pa and diaphragm thickness of 1 μm.

Bias Voltage $[V_b]$	$\partial V/\partial s_a$ $[10^6$ V/m$]$	$\partial V/\partial P$ [mV/Pa]
0.5	0.25	0.63
1.0	0.50	1.25
1.5	0.75	1.88
2.0	1.00	2.50
2.5	1.25	3.13
3.0	1.50	3.75

The calculated open-loop sensitivities are smaller than the sensitivity of the microphone with the Mylar diaphragm (typically 25 mV/Pa) [1]. However, the capacitance of the microphone with the silicon nitride diaphragm will be about 22 pF, whereas the capacitance of the microphone with the Mylar diaphragm is only 3 pF [1]. Therefore the signal of the microphone with the silicon nitride diaphragm will be less attenuated by the input capacitance of the measuring amplifier (typically 2 pF), which will partly compensate for the lower open-loop sensitivity.

The microphones that are fabricated have diaphragms of 0.6, 1.0, 1.5, 2.0 and 2.6 mm square. Different numbers and configurations of the holes, square or rectangular (slits), in the backplate are used to study the effect on sacrificial layer etching and can also be used to study the effect on the frequency response of the microphones.

Microphone fabrication process

The microphone fabrication process is shown in figure 1. First the reverse side of a <100>-silicon wafer is covered with 1.8 μm and the polished side with 0.45 μm thermal silicon dioxide. Square windows are etched in the oxide on the reverse side. 1 μm aluminium is evaporated on the polished side of the wafer and patterned, followed by plasma-enhanced chemical vapour deposition of 1 μm of silicon nitride (1). Holes are anisotropically etched from the reverse side of the wafer in a 33 wt.% KOH solution, saturated with isopropanol, at a temperature of 73°C (2). After the KOH etching has been completed, the SiO_2 etch-stop is removed in buffered HF. The aluminium sacrificial layer is etched in a H_3PO_4/ HNO_3/ CH_3COOH/ H_2O-mixture at a temperature of 50°C. Completion of sacrificial layer etching was determined by optical inspection. An indication of the time that was required to complete etching of some of the diaphragms is shown in table 2. Note that relatively large 2.6 mm diaphragms with four slits can be etched in 13 hours, whereas 0.6 mm diaphragms with one hole require about 22 hours etching.

The microphone fabrication process is completed by evaporation of a 20 nm titanium adhesion layer and a 40 nm gold electrode on top of the diaphragms by application of a shadow mask (3).

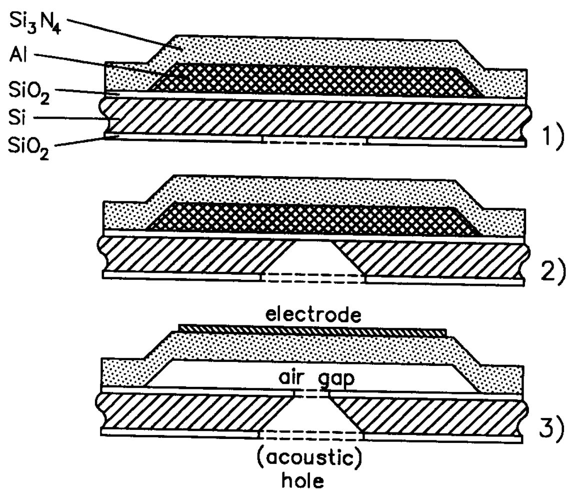

Figure 1. Schematic drawing of the microphone fabrication process.

Table 2. The time required to complete etching of the aluminium sacrificial layer for diaphragms with different dimensions and different numbers of slits or holes in the silicon wafer.
Etchant: 80% H_3PO_4/ 5% HNO_3/ 5% CH_3COOH/ 10% H_2O, temperature 50°C, no stirring.

diaphragm [mm]	slits/holes [number]	time [hrs]
0.6	1 hole	22
1.0	4 holes	22
1.5	2 slits	13
2.0	3 slits	16
2.6	16 holes	22
2.6	4 slits	13

Figure 2 shows a photograph of a 2.0 x 2.0 mm diaphragm after completion of sacrificial layer etching. The three slits in the backplate are visible through the silicon nitride diaphragm.

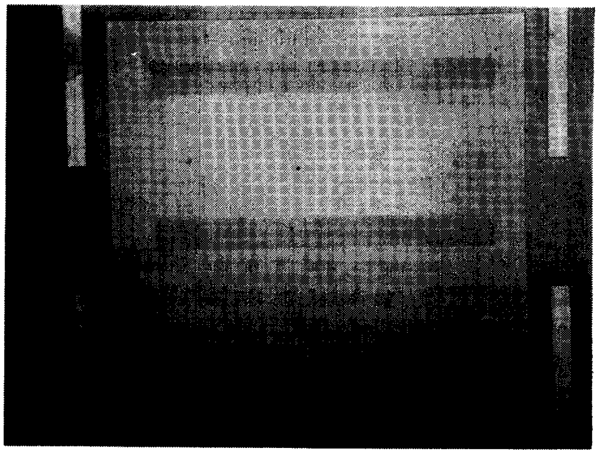

Figure 2. Photograph of a 2.0 x 2.0 mm diaphragm after completion of etching.

Preliminary measurements

The frequency response of a microphone with a 2.0 x 2.0 mm diaphragm and a backplate with 3 slits has been measured using a Brüel & Kjaer 4219 'artificial voice'. The bias voltage is provided by an external voltage source in series with the microphone (silicon substrate negative). The measured frequency response as a function of the bias voltage is shown in figure 3.

The measured frequency response of the microphone, as shown in figure 3, is not flat, but decreases with a slope of 3.4 dB/oct. The cut-off frequency of the microphone apparently is lower than 40 Hz, which could however not be measured with our setup.

The measured sensitivities for low frequencies are close to the theoretically predicted values, as shown in table 1. Using a bias voltage of -2.5 Volt, the diaphragm collapsed due to the electrostatic attraction.

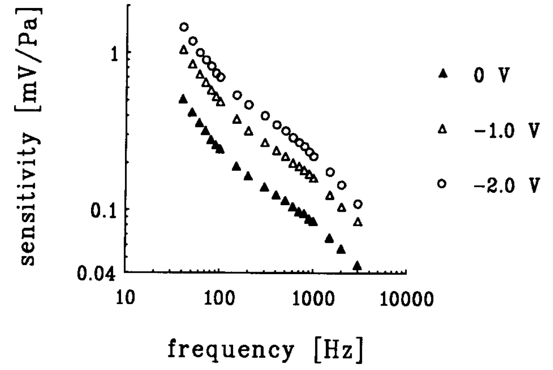

Figure 3. The measured frequency response of a microphone with a 2 x 2 mm diaphragm as a function of the bias voltage (substrate at a negative potential).

Note that for an external bias of 0 Volt a sensitivity of 0.5 mV/Pa (40 Hz) has been measured. This effect may be due to a built-in negative charge in the oxide of the backplate or positive charge in the silicon nitride diaphragm. This has been proven by using a bias voltage of +1.0 V (silicon substrate positive). The sensitivity then showed a minimum value of 0.068 mV/Pa (40 Hz), from which it may be concluded that the microphone has a built-in potential of -1 Volt. For higher positive bias voltages, the microphone sensitivity increased.

Conclusions and discussion

Condenser microphones with plasma-enhanced chemical vapour deposited (PECVD) silicon nitride diaphragms can be fabricated using the sacrificial layer technique. The measured sensitivity for low frequencies (1.4 mV/Pa) is in agreement with the theoretically predicted values and can be achieved with a low bias voltage (-2 V). It is important to note that this bias voltage can be achieved without the application of an electret and directly be supplied by a hearing-aid battery.

A drawback of the microphone is that the sensitivity decreases for high frequencies, which is likely due to the damping caused by the small air-gap, even with the maximum acoustic hole surface (3 slits). With an air-gap of 2 μm, a cut-off frequency of 2 kHz has been measured by Hohm and Hess [2]. Bergqvist and Rudolf [3] measured cut-off frequencies between 5 kHz and 16 kHz for microphones with an air-gap of 4 μm. Using an air-gap of 30 μm, the cut-off frequency is above 15 kHz [1]. It can be concluded that microphones with wider air-gaps have to be developed to achieve a flat frequency response for the entire audio frequency range.

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