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A silicon condenser microphone with a silicon nitride diaphragm and backplate

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Abstract. A new condenser microphone design, which can be fabricated using the sacrificial layer technique, is proposed and tested. The microphone backplate is a 1 μm PECVD silicon nitride film with a high density of acoustic holes (120–525 holes mm^{-2}), covered with a thin Ti/Au electrode. Microphones with a 1.5 × 1.5 mm diaphragm show a flat frequency response between 100 Hz and 14 kHz and a sensitivity of about 2 mV Pa^{-1} using a bias voltage of 16 V. These values are comparable to those of other silicon microphones with highly perforated backplates. The major advantage of the new microphone design is that it can be fabricated on a single wafer so that no bonding techniques are required.

1. Introduction

Several condenser microphones have been fabricated on silicon wafers using micromachining techniques [1–4]. One of the microphones, an electret hearing-aid microphone which was 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]. In other laboratories, microphones were fabricated by means of IC-compatible technologies and materials [2–4]. The backplate and the diaphragm of these microphones were fabricated on separate wafers. The microphones were assembled by means of wafer-bonding techniques. Wafer bonding always requires laborious alignment of the two wafers. Another serious drawback is that most wafer-bonding techniques require exposure of the wafers to high electric fields or high-temperature steps. This may also cause difficulties with future integration of microphones and pre-amplifiers.

An alternative production process may be the application of the sacrificial layer technique for the diaphragm fabrication. A microphone can be fabricated by using anisotropically etched holes in the silicon wafer as access holes to etch the sacrificial layer, as proposed by Hijab and Muller [5]. These access holes will act as acoustic holes during normal operation of the microphone.

A microphone fabricated by means of this method has already been presented [6]. A cross-sectional view of the microphone is shown in figure 1. The microphones are fabricated on three-inch ⟨100⟩ silicon wafers, with a thickness of 380 μm. The silicon backplate is provided with 450 nm SiO_2. The diaphragm consists of plasma-enhanced chemical vapour deposited (PECVD) silicon nitride with a thickness of 1.3 μm. The sacrificial layer is made up of evaporated aluminium, leaving a 1 μm air gap after sacrificial layer etching. The electrode consists of a 30 nm gold and a 30 nm titanium adhesion layer. More details concerning the fabrication process have been presented earlier [6]. The measured frequency response, which decreased by 3–4 dB/octave, showed that this microphone was strongly damped. The sensitivity for the lowest frequency (20 Hz) was 1.4 mV Pa^{-1}.

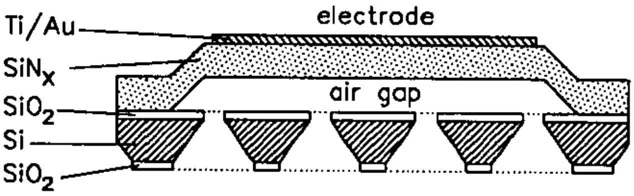

Figure 1. Schematic cross-sectional view of a silicon condenser microphone, according to the original design, as proposed by Hijab and Muller [5].

For application as a hearing-aid microphone, a sensitivity of 10 mV Pa^{-1} and a flat frequency response of between 100 Hz and 7 kHz are required. The major drawback of the previously presented microphone is the frequency response. Thus, the objective of our present research is to improve the frequency response of microphones, fabricated by means of the sacrificial layer technique. Therefore, in this paper, a new microphone design will be presented and tested.

2. Dynamic behaviour of a condenser microphone

A condenser microphone can be modelled as a movable mass M, connected to a spring with a stiffness constant K and a damping with a resistance R_a. The mass M

represents the diaphragm mass, the stiffness constant K represents the low-frequency sensitivity of the diaphragm, and the resistance R_a represents the damping due to the lateral flow of air in the air gap. This system behaves like a second-order system and can be described by (1):

$$M\frac{d^2w}{dt^2} + R_a\frac{dw}{dt} + Kw = F(t) \qquad (1)$$

where w is the diaphragm deflection and $F(t)$ is the force on the diaphragm that is caused by the sound pressure. The resistance R_a was calculated by Škvor [7], assuming a laminar flow in the air gap. For a circular microphone with radius R, the damping resistance, R_a, is

$$R_a = \frac{12\eta_a R^2}{n s_{a0}^3}\left(\frac{1}{4}\ln\frac{1}{A} - \frac{3}{8} + \frac{1}{2}A - \frac{1}{8}A^2\right) \qquad (2)$$

where η_a is the viscosity of air, n is the number of acoustic holes per unit area (acoustic hole density), s_{a0} is the thickness of the air gap and A is the fraction of the backplate area that is occupied by the acoustic holes. If the microphone is strongly damped, the system behaves like a first-order system. The bandwidth of the microphone then becomes

$$f = K/2\pi R_a. \qquad (3)$$

It can be seen from (3) that the bandwidth of the microphone is proportional to the stiffness constant, K, and inversely proportional to the damping resistance, R_a. It can be concluded that the ratio K/R_a of the previously presented microphones is too small [6]. Increasing the stiffness constant, K, is unacceptable, because the sensitivity of the microphone is then decreased too. A better approach is to reduce the damping of the air gap. However, increasing the thickness of the air gap causes problems with the step coverage of the silicon nitride over the aluminium sacrificial layer, as can be seen from figure 1. A good alternative is to increase the acoustic hole density, n, as (2) predicts. One problem of the original microphone design (figure (1)) is that an increase of the acoustic hole density is limited, because of the shape of anisotropically etched holes, with the typical angle of 54.7° for ⟨100⟩ silicon. Decreasing the damping by etching lateral grooves in the backplate, as proposed by Kühnel and Hess [4], is too complicated to be combined with the sacrificial layer technique. In order to get around all these difficulties quite another microphone design is proposed that can be realized using the sacrificial layer technique.

3. A new microphone design

The starting point of the new design is that the damping should be minimized using a high acoustic hole density. The fabrication process is shown in figure 2(a), (b) and (c). Note that the result is similar to the design of Bergqvist *et al* [3] and Kühnel and Hess [4], who used a relatively thin ⟨100⟩ silicon backplate (10–15 μm) with a very high acoustic hole density. Instead of using a silicon backplate, in our design the backplate is composed of a metallized 1 μm PECVD silicon nitride layer, provided with about 120–525 holes mm^{-2}.

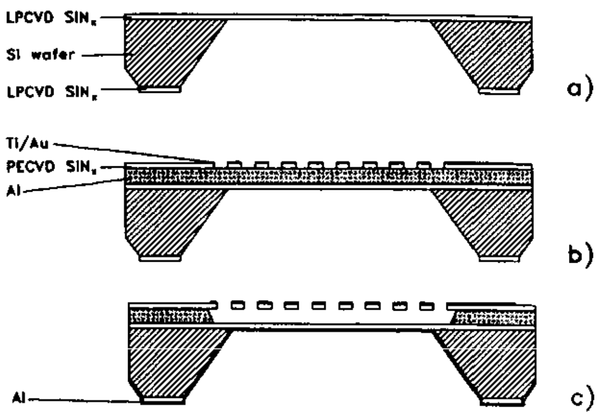

Figure 2. Schematic representation of the alternative microphone fabrication process. (a) Growth of 1 μm LPCVD silicon nitride, patterning and anisotropic etching of V-grooves and diaphragm in 33 wt.% KOH solution (73 °C). (b) Evaporation of 3 μm aluminium, growth of 1 μm PECVD silicon nitride, evaporation and patterning of a 30 nm titanium adhesion layer and a 30 nm gold electrode, etching of access/acoustic holes in Ti/Au and PECVD silicon nitride. (c) Etching of aluminium sacrificial layer, drying and evaporation of 100 nm aluminium on silicon/silicon nitride on the reverse side (counter electrode).

4. Measurements

The frequency response has been measured with a Brüel & Kjaer 4219 'artificial voice', using a sound pressure of 4 Pa. The bias voltage was provided by a DC voltage source in series with the microphone. The microphone signal was measured using a source follower with an input capacitance of about 2 pF and a Brüel & Kjaer 2610 measurement amplifier. Figure 3 shows the measured frequency response of five microphones (of two

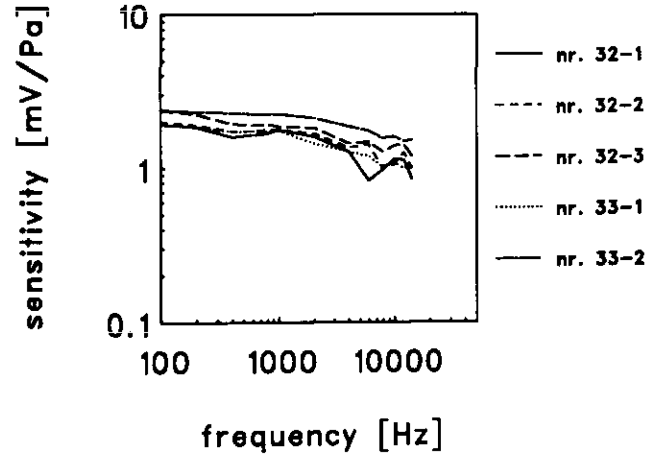

Figure 3. Measured frequency response of five microphones of the design shown in figure 2. Diaphragm 1.5 × 1.5 mm; thickness 1.0 μm; air gap 3.3 μm. Backplate with 174 holes mm^{-2}; Bias voltage 16 V. Numbers 32 and 33 refer to different wafers.

different wafers) with a 1.5 × 1.5 mm diaphragm. The acoustic hole density has been increased by a factor of more than 100 and the air-gap thickness by a factor three with respect to the original design, as shown in figure 1. Therefore the resistance R_a is decreased by a factor 2700. As can be seen from figure 3, the bandwidth of the microphones is at least 14 kHz. The reproducibility is also good wafer-to-wafer. The sensitivity is about 2 mV Pa^{-1} (1 kHz) for a bias voltage of 16 V. This value has not been corrected for the attenuation of the source follower. Collapse of the diaphragm, due to electrostatic attraction between the diaphragm and the backplate, occurred at a bias voltage between 17 and 20 V.

The measured sensitivities (2 mV Pa^{-1}) are roughly equal to the values presented by Bergqvist *et al* [3] (1.6 mV Pa^{-1}) and by Kühnel and Hess [4] (3 mV Pa^{-1}).

5. Conclusions

A new condenser microphone design, that can be fabricated using the sacrificial layer technique, has been proposed and tested. Microphones with a flat frequency response between 100 Hz and 14 kHz have been fabricated in a reproducible way. The measured sensitivities are comparable to values presented in literature for silicon microphones [3, 4]. The major advantage of the new microphone design is that it can be realized on a single wafer and therefore no bonding techniques are required. Further work will be focused on optimization of the sensitivity in order to achieve values of about 10 mV Pa^{-1}.

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References

[1] Sprenkels A J, Groothengel R A, Verloop A J and Bergveld P 1989 Development of an electret microphone in silicon *Sensors Actuators* **17** 509–12

[2] Hohm D and Hess G 1989 A subminiature condenser microphone with silicon nitride membrane and silicon backplate *J. Acoust. Soc. Am.* **85** 476–80

[3] Bergqvist J, Rudolf F, Maisano J, Parodi F and Rossi M 1991 A silicon condenser microphone with a highly perforated backplate *Transducers '91 (San Francisco, USA, 1991)* Technical digest pp 266–9

[4] Kühnel W and Hess G 1992 Micromachined subminiature condenser microphones in silicon *Sensors Actuators* A **32** 560–4

[5] Hijab R S and Muller R S 1985 Micromechanical thin-film cavity structures for low-pressure and acoustic transducer applications *Transducers '85 (1985)* Technical digest pp 178–81

[6] Scheeper P R, Olthuis W and Bergveld P 1991 Fabrication of a subminiature silicon condenser microphone using the sacrificial layer technique *Transducers '91 (San Francisco, USA, 1991)* Technical digest pp 408–11

[7] Škvor Z 1967 On the acoustical resistance due to viscous losses in the air gap of electrostatic transducers *Acustica* **19** 295–9