Improvement of the performance of microphones with a silicon nitride diaphragm and backplate*

P.R. Scheeper**, W Olthuis and P Bergveld
MESA Research Institute, University of Twente, P O Box 217, 7500 AE Enschede (Netherlands)

(Received May 25, 1993, accepted September 14, 1993)

Abstract

The performance of a single-wafer fabricated silicon condenser microphone has been improved by increasing the stress and the acoustic hole density of the backplate and by decreasing the diaphragm thickness The best microphones show a sensitivity of 5 0 mV Pa^{-1}, which corresponds to an open-circuit sensitivity of 10 mV Pa^{-1} for a microphone capacitance of 6 6 pF The measured frequency response is flat within ±2 dB from 100 Hz to 14 kHz, which is better than the requirements for a hearing-aid microphone. The operating voltage of these microphones is only 5 0 V, which is about 60% of the collapse voltage The measured noise level of the microphones is 30 dBA SPL, which is approximately as low as required for a hearing-aid microphone (<29 5 dBA SPL)

1. Introduction

Since 1983, silicon micromachining techniques have been applied for the fabrication of miniature microphones in silicon [1–17] Piezoelectric microphones have been developed using zinc oxide [1,2] and aluminium nitride [3] as the piezoelectric material The measured sensitivities were 250 μV Pa^{-1} [1], 1000 μV Pa^{-1} [2] and 25 μV Pa^{-1} [3], respectively A piezoresistive microphone with a sensitivity of 25 μV Pa^{-1} was presented by Schellin and Hess [4] A recent development is a silicon condenser microphone with an integrated field-effect transistor [5,6]

Most of the silicon microphones presented in the literature are based on the capacitive principle [7–17] The capacitive microphones can be divided into electret microphones [7–9], which are biased by a built-in charge, and condenser microphones [10–17], which have to be biased by an external voltage source

A capacitive microphone consists of a thin, flexible diaphragm that is mounted on a rigid backplate The backplate is provided with one or more acoustic holes to allow air to flow in and out of the air gap Various methods have been applied for fabricating the capacitor structure In the microphones of Hohm and Gerhard-Multhaupt [7], Sprenkels *et al* [8] and Murphy *et al* [9], the diaphragm is a thin Mylar foil The Mylar foil is attached manually on the silicon wafer with the backplates and fixed by a polymer spray [8] In other microphones, the diaphragms and backplates are fabricated on separate wafers, which have to be sealed together later on In this way, thin film diaphragm materials can be used as a diaphragm Hohm and Hess [10] used a 150 nm thick low-pressure chemical vapour deposited (LPCVD) silicon nitride diaphragm, the tensile stress of which was controlled using ion implantation Bergqvist *et al* [11,12] fabricated silicon diaphragms by applying the electrochemical etch-stop technique, whereas Bourouina *et al* [13] fabricated silicon diaphragms by using the p^+ etch-stop technique

In all these capacitive microphones, the diaphragm and the backplate are fabricated separately Thus some kind of assembly technique is necessary in order to obtain a complete microphone

The final assembly step can be avoided by fabricating the microphones on a single wafer, as originally proposed by Hohm and Sessler [18] This process is based on the well-known sacrificial layer etching technique With this technique, the thickness of the air gap is determined by the thickness of the sacrificial layer, which is typically between 1 and 3 μm We found that the narrow air gaps resulted in a very high air streaming resistance, thus causing a bad microphone sensitivity for audio frequencies [14,15] Other authors have solved this problem by etching grooves or holes in the backplate [16,17], or by providing the backplate with a large number of acoustic holes [12,16] We proposed and developed such a microphone using a single-wafer fab-

*Paper presented at the Micromechanical Acoustic Sensors Meeting, Saint-Louis, France, February 18–19, 1993

**Present address Brüel and Kjær, Skodsborgvej 307, 2850 Nærum, Denmark

SSDI 0924-4247(93)00773-W

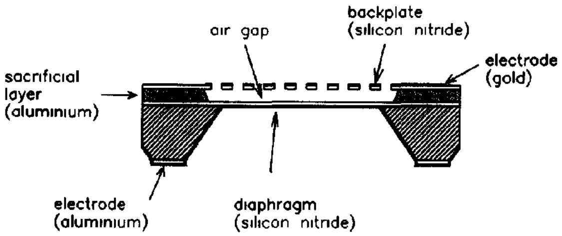

Fig 1 Schematic cross-sectional view of a single-wafer fabricated silicon condenser microphone with a thin, highly perforated backplate

rication process [15] This microphone design is shown schematically in Fig. 1 A similar construction is found in the capacitive pressure sensor design of Petersen [19] The diaphragm is a 1 μm thick LPCVD silicon nitride film The backplate is a 1 μm thick plasma-enhanced chemical vapour deposited (PECVD) silicon nitride film, which is provided with 120–525 acoustic holes per mm^2 The air-gap spacing is between 1 and 3 μm A sensitivity of about 1 mV Pa^{-1} and a flat frequency response between 100 Hz and 14 kHz have been measured The equivalent noise level was about 40 dBA SPL

The condenser microphone, which is being developed at the University of Twente, is meant for application as a hearing-aid microphone For this application, the measured sensitivity at the output of the preamplifier should be 10 mV Pa^{-1}, the noise level should be lower than 29 5 dBA SPL and the frequency response should be flat from 100 Hz to 7 kHz [20] It can be concluded that the recently developed condenser microphones, as described in ref 15, do not meet these specifications

The objective of this paper is to show the systematic improvement in the performance of the microphones First, the effect of microphone parameters on the sensitivity and the frequency response is discussed (Section 2) In Section 3, the improvement in the microphones due to systematic changes in the microphone parameters is demonstrated Finally, conclusions are drawn in Section 4

2. Theory

The open-circuit sensitivity of the condenser microphone shown schematically in Fig 2(a) is considered to consist of the two components S_m and S_e, which are the mechanical and the electrical sensitivity of the microphone, respectively

The mechanical sensitivity is defined as the increase in the deflection of the microphone diaphragm, dw, resulting from an increase in the pressure, dP, acting on the diaphragm

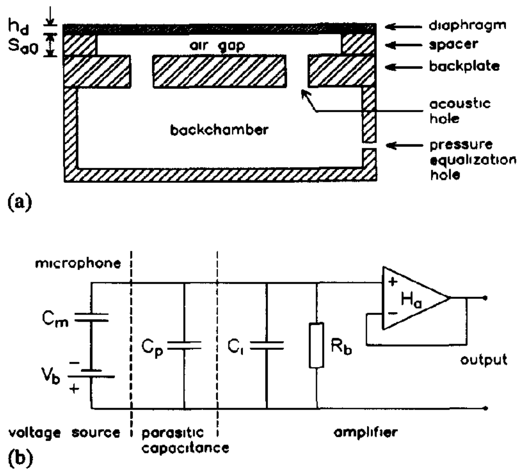

Fig 2 (a) Schematic cross-sectional view of a condenser microphone (b) The condenser microphone, connected to an external d c bias voltage source, loaded by a parasitic capacitance C_p, a bias resistor R_b and a preamplifier with an input capacitance C_i

$$S_m = \frac{dw}{dP} \tag{1}$$

Note that $dw = -ds_{a0}$, because a diaphragm displacement decreases the air-gap thickness The microphone diaphragm is a stressed membrane with a negligible bending stiffness By integrating the membrane amplitudes over the surface and taking the average, an equivalent rigid piston can be defined that behaves the same acoustically The mechanical sensitivity of the piston is equal to [21]

$$S_m = \frac{R^2}{8\sigma_d h_d} \tag{2}$$

where R is the radius of the diaphragm, σ_d the diaphragm stress and h_d the diaphragm thickness In eqn (2) it is assumed that the compression of air in the backchamber does not influence the diaphragm movement

Note that eqn (2) describes a circular microphone, whereas the actual microphones have a square geometry However, a model of a square microphone would qualitatively give the same results, but would lead to more complicated equations that have to be solved numerically

The relation between a change in the thickness of the air gap, ds_{a0}, and the resulting change in the voltage across the air gap, dV, is given by the electrical sensitivity of the microphone

$$S_e = \frac{dV}{ds_{a0}} \tag{3}$$

The microphone capacitance changes with the diaphragm movements Hence, if the charge is kept constant (which is the case for fast diaphragm movements), the voltage across the condenser plates varies with the diaphragm movements Note that in the case of a piston diaphragm, the electric field strength E_a in the air gap is homogeneous The electrical sensitivity is then given by

$$S_e = E_a = \frac{V_b}{s_{a0}} \tag{4}$$

where V_b is the d c bias voltage of the microphone

The quasi-static open-circuit sensitivity S_{open} of a condenser microphone is defined as

$$S_{open} = -S_m S_e \tag{5}$$

Note that a minus sign has been introduced in eqn (5), because $ds_{a0} = -dw$ Thus the microphone sensitivity has a negative value For clarity, when we compare microphone sensitivities, we shall compare the absolute values of the sensitivities

To measure the sensitivity, the microphone is connected to a preamplifier, which acts as an impedance converter (see Fig 2(b)) The source follower is a commonly used preamplifier It has a gain H_a, which is close to unity, and an input capacitance C_i The measured microphone sensitivity S_{meas} is equal to

$$S_{meas} = -S_m S_e H_c H_a \tag{6}$$

where H_c is the capacitive signal attenuation due to the input capacitance of the preamplifier and the parasitic capacitance C_p, which is due to the bondpad of the microphone

$$H_c = \frac{C_m}{C_m + C_i + C_p} \tag{7}$$

where C_m is the microphone capacitance

Thus the measured value of the microphone sensitivity is also determined by the gain and the input capacitance of the preamplifier Therefore, a more reasonable comparison of microphones can be made if open-circuit sensitivities are compared However, in that case the microphone capacitance must also be given, so that every author can calculate the capacitive signal attenuation for his or her specific preamplifier

As can be seen from eqn (4), the electrical sensitivity, and thus the open-circuit microphone sensitivity, increases if the bias voltage increases However, the d c bias voltage cannot be increased without limit At a certain bias voltage, the microphone diaphragm collapses to the backplate For a piston diaphragm, with a mechanical sensitivity given by eqn (2), the collapse voltage is equal to [22]

$$V_{max} = \left(\frac{64\sigma_d h_d s_{a0}^3}{27\epsilon_0 R^2}\right)^{1/2} \tag{8}$$

Note that the collapse voltage is inversely proportional to the square root of the mechanical sensitivity Thus, if the sensitivity of a condenser microphone is improved by increasing the mechanical sensitivity of the diaphragm, this gain is partially reduced because the collapse voltage has decreased If the d c bias voltage is always kept at a fixed fraction of the collapse voltage, it can be concluded from eqns (2), (4), (5) and (8) that the open-circuit sensitivity of a condenser microphone is proportional to the square root of its mechanical sensitivity

Note that in eqn (8) it is assumed that the backplate is rigid For microphones with a thin backplate [12,15,16] that is not perfectly rigid, the collapse voltage is lower than that predicted by eqn (8)

A well-known method for calculating the frequency response of a mechanical–acoustical system involves using an analogous electrical circuit Current is then analogous to volume flow and voltage is analogous to pressure Properties such as mass, friction and compliance (the inverse of the mechanical sensitivity) are represented by their electrical equivalents, i e, inductance, resistance and capacitance, respectively [23]

The equivalent circuit of the microphone shown in Fig 1 is given in Fig. 3 The resistance R_r describes the frictional force due to radiation of sound back into the surrounding medium The inductance L_r describes the mass of the air close to the diaphragm that is vibrating in phase with the diaphragm [23]

In our experiments, the microphones are not mounted on small backchambers and thus the backchamber volume can be considered to be infinitely large In the analogous electrical circuit, the capacitance C_{bc} can thus be shortcircuited Note that the thin backplate is modeled as a thin diaphragm with a large initial stress Therefore, the mechanical sensitivity of the backplate is given by eqn (2)

Note that no shunt capacitance is added to account for compression of air in the air gap, as can be found for instance in the microphone model of Bergqvist *et al* [12] This capacitance has been omitted, since it is

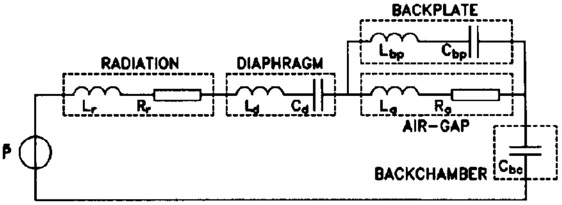

Fig 3 Analogous electrical circuit of a condenser microphone with a thin backplate, mounted on a backchamber

in contradiction with the assumption of incompressible air, which has been made in order to calculate the air-streaming resistance of the air gap [24]. Since the typical air-gap volumes are very small, the shunt capacitance would be very small. Only negligible currents would flow through this capacitance for audio frequencies, thus having no effect on the calculated frequency responses.

It can be shown that the impedances of C_d, C_{bp} and R_a are dominating and determine the frequency response of the microphone [25]. C_d and C_{bp} represent the compliance of the diaphragm and the backplate, respectively. R_a represents the air-streaming resistance of the air gap. The value of R_a has been calculated by Škvor [24]

$$R_a = \frac{12\eta_a}{\pi^2 R^2 n s_{a0}^3} B(A) \tag{9}$$

with

$$B(A) = \left[\frac{1}{4}\ln\frac{1}{A} - \frac{3}{8} + \frac{1}{2}A - \frac{1}{8}A^2\right] \tag{10}$$

where η_a is the viscosity of air (17.1×10^{-6} Pa s), n is the number of acoustic holes per unit area (acoustic hole density) and A is the ratio of the area of the acoustic holes to the total backplate area ($0 \leqslant A \leqslant 1$).

Note that the system is a second-order system operating below its resonance frequency. However, since the microphone is strongly damped, it shows the frequency dependence of a first-order system with a cutoff frequency f_c

$$f_c = \frac{n s_{a0}^3}{24\eta_a B(A)(S_{m\,d} + S_{m\,bp})} \tag{11}$$

where $S_{m\,d}$ and $S_{m,bp}$ are the mechanical sensitivity of the diaphragm and the backplate, respectively. It can be concluded from eqn. (11) that a thin, movable backplate causes a decrease in the cutoff frequency. The cutoff frequency can be improved by increasing the acoustic hole density n or the air-gap thickness s_{a0}. Since an increase in the mechanical sensitivity of the diaphragm, $S_{m\,d}$, causes a decrease in the cutoff frequency, an optimum must be found between sensitivity and frequency response of the microphone.

3. Measurements

The frequency responses of the microphones were measured with a Bruel and Kjær 4219 'artificial voice', at a sound pressure of 4 Pa. The bias voltage was provided by a d.c. voltage source in series with the microphone. The microphone signal was measured using a source follower with an input capacitance of 2.5 pF and a gain of 0.83, and a Bruel and Kjær 2610 measurement amplifier.

All measurements were performed on microphones that were still part of a complete wafer. The wafer was placed directly on the 'artificial voice' with a silicone rubber seal, guaranteeing a negligible air leak.

The performance of the microphone shown in Fig. 1 is improved by systematically changing its parameters. The starting point is a batch of microphones with 2 mm×2 mm diaphragms and with air-gap thicknesses of 1, 2 and 3 μm. The dependence of the quasi-static sensitivities of three microphones, with different air-gap thicknesses, on the d.c. bias voltage is shown in Fig. 4. The thicknesses of the diaphragm and backplate were 1 μm. The backplate and diaphragm stresses were about 1×10^8 and 1.5×10^8 N m^{-2}, respectively.

It can be seen that the microphone sensitivity increases close to the d.c. bias voltage where the diaphragm collapses owing to electrostatic attraction between the diaphragm and the backplate. Collapse occurred at d.c. bias voltages of 2.5, 7.2 and 13.2 V, respectively. The characteristics are strongly dependent on the air-gap thickness of the microphone. It can be concluded that the sensitivities of different microphones cannot be compared fairly when all microphones are biased with the same voltage, although this is often done in the literature [13,16]. A more reasonable comparison is made when the microphones are biased at the same fraction of the collapse voltage. Commercially available microphones are biased at about 60% of the collapse voltage [26]. This relative bias voltage is used for all of the following measurements.

Figure 5 shows the typical measured frequency responses of the three microphones. The microphones are biased with 1.5, 4.0 and 8.0 V, respectively. It can be seen from Fig. 5 that the frequency responses of the microphones show the expected behaviour of a first-order system, with a slope of −6 dB/oct for higher frequencies. The measured cutoff frequencies of the

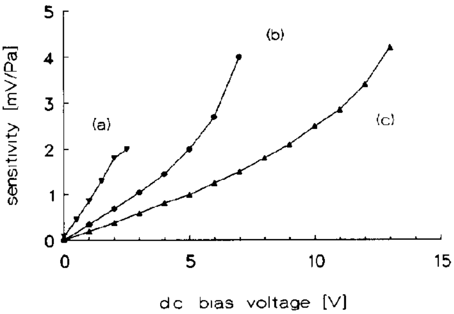

Fig. 4. The measured sensitivity of microphones with a 2 mm×2 mm diaphragm as a function of the d.c. bias voltage for different air-gap thicknesses: (a) 1 μm, (b) 2 μm, (c) 3 μm.

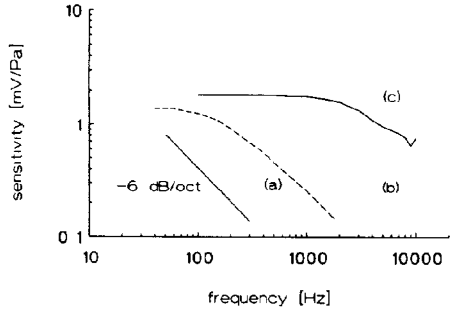

Fig 5 Measured frequency responses of the three microphones with a 2 mm×2 mm diaphragm with air-gap thicknesses of (a) 1 μm, (b) 2 μm and (c) 3 μm, applying a d c bias voltage of 1 5, 4 0 and 8 0 V, respectively

TABLE 1 The parameters of the microphones of type A, B, C and D

Parameter	Microphone			
	A	B	C	D
σ_{bp} ($\times 10^8$ N m^{-2})	0 26	1 8	1 8	1 8
h_d (μm)	1 0	1 0	0 24	0 24
n (mm^{-2})	121	121	121	242

*Fixed parameters for all microphones are diaphragm area 2 mm×2 mm, diaphragm stress $\sigma_d = 1\ 5\times10^8$ N m^{-2}, backplate thickness $h_{bp} = 1$ μm, air-gap thickness $s_{a0} = 3\ 1$ μm and acoustic hole area 40 μm×10 μm

microphones with air-gap thicknesses of 1, 2 and 3 μm are 175 Hz, 1 7 kHz and 3 2 kHz, respectively

It can be concluded from Fig 5 that the microphone with the 3 μm air gap shows the highest sensitivity (1 8 mV Pa^{-1}) as well as the highest cutoff frequency (3 2 kHz) However, both values are too low for a hearing-aid microphone

The performance of this type of microphone is improved by systematically changing the backplate stress, the diaphragm thickness and the acoustic hole density of the backplate For this purpose, a new batch of microphones was made The parameters of the different microphones, which are indicated by A, B, C and D, are given in Table 1

Microphone A was made under the same experimental conditions as the previous batch Microphone B was provided with a backplate having a higher stress The stress of the backplates was measured with the bulge test [27,28] on silicon nitride diaphragms on separate dummy wafers and was found to be 2 6×10^7 N m^{-2} and 1 8×10^8 N m^{-2} for the low- and high-stress silicon nitride, respectively

The collapse voltage of the microphones with the low-stress backplates was 7 V, whereas 18 V was measured for the microphones with high-stress backplates In Fig 6 the measured frequency responses are shown for two microphones with a high- and low-stress backplate, indicated by curves a and b, respectively The measured quasi-static sensitivities of the microphones were 2 5 mV Pa^{-1} (curve a) and 0 7 mV Pa^{-1} (curve b) at d c bias voltages of 11 0 and 4 0 V, respectively The measured cutoff frequency was 2 kHz for the microphone with the low-stress backplate, whereas the microphone with the high-stress backplate showed a cutoff frequency higher than 14 kHz

It can be concluded that increasing the stress of the backplate increases the collapse voltage, thus increasing the electrical sensitivity of the microphones Furthermore, the cutoff frequency increases if the backplate stress is increased

Note that the collapse voltage (7 V) and the cutoff frequency (2 kHz) of microphone A were both lower than the values for the corresponding microphones of the previous batch (13 2 V and 3 2 kHz, respectively) This may be due to nonreproducibility of the backplate deposition process, which causes changes in the backplate stress

The sensitivity of microphone B, with a 1 μm thick diaphragm, is improved by using a 0 24 μm thick diaphragm (microphone C) Microphone C is also provided with a high-stress backplate The frequency responses of microphones B and C are shown in Fig 7 The low-frequency sensitivity has been increased from 2 5 to 5 4 mV Pa^{-1} However, the cutoff frequency of microphone C has decreased to 3 kHz, and the collapse voltage decreased to 8 6 V

According to eqn (2), the mechanical sensitivity of microphone C is four times larger than that of microphone B, because the diaphragm thickness has been decreased from 1 0 to 0 24 μm The observed increase in the microphone sensitivity by a factor of two is in good agreement with the expectation that the microphone sensitivity increases with the square root of the mechanical sensitivity According to eqn (11), a strongly decreased cutoff frequency is expected, because of the

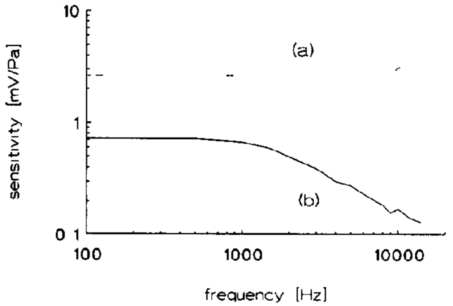

Fig 6 The measured frequency responses of type A and B microphones (a) type B, 11 0 V d c bias, (b) type A, 4 0 V d c bias

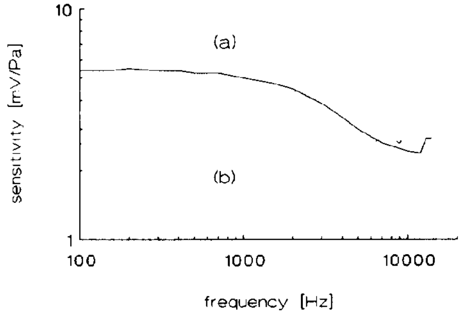

Fig 7 The measured frequency responses of type B and C microphones (a) type C, 5 0 V d c bias, (b) type B, 11 0 V d c bias

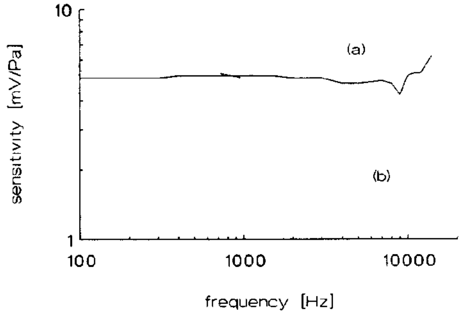

Fig 8 The measured frequency responses of type C and D microphones (a) type D, 5 0 V d c bias, (b) type C, 5 V d c bias

increase in the mechanical sensitivity by a factor of four

The frequency response of microphone C is improved by using a backplate with a higher acoustic hole density (microphone D) In Fig 8 the measured frequency responses are shown for type C and type D microphones Both microphones are provided with a 5 0 V d c bias voltage The collapse voltage of the type D microphone is 8 0 V The effect of making the backplate acoustically more transparent can be seen in Fig 8 The type C microphone has a cutoff frequency of 3 kHz (curve b), whereas the type D microphone shows a frequency response that is flat from 100 Hz to 14 kHz within ± 2 dB (curve a) For none of the six type D microphones tested did the sensitivity deviate more than 10% from the value of 5 0 mV Pa^{-1} that is shown in Fig 8 Note that the quasi-static sensitivity of the type C microphone (5 4 mV Pa^{-1}) is slightly higher than that of the type D microphone (5 0 mV Pa^{-1}) This was observed for all microphones tested This is due to the fact that the capacitance of the type C microphones is higher than that of the type D microphones, because the area occupied by the acoustic holes is smaller (about 20% and 40% of the total backplate area for types C and D, respectively) Consequently, the capacitive attenuation of the microphone signal is smaller for the type C microphones, resulting in a slightly higher low-frequency sensitivity

The sensitivities that have been discussed up to now were measured at the output of the source follower The capacitive attenuation can be calculated if the microphone capacitance is known The capacitance of a type D microphone, which is provided with a 3.1 μm air gap and dielectric layers of 0 24 and 1 0 μm, respectively, with a relative dielectric constant of 7, is about 6 6 pF The reduction of the microphone capacitance by the 40% acoustic hole area is taken into account With the capacitance of the 200 μm$\times$200 μm bondpad (2 0 pF) the theoretical microphone capacitance becomes 8 6 pF Since the input capacitance of the source follower is 2 5 pF, the capacitive attenuation becomes 0 59, according to eqn (7) With the source follower gain of 0 83, the total signal attenuation is 0 49 Thus the open-circuit sensitivity of microphone D is 10 mV Pa^{-1}

In previous experiments, noise measurements were carried out on microphones that were mounted on epoxy carriers [15] One disadvantage of this method was that extra parasitic capacitances were introduced Another disadvantage was that the solidity of the largest microphones, with 2 mm$\times$2 mm diaphragms, did not allow mechanical dicing of the wafer and their mounting on the epoxy carriers Therefore, it was decided to glue a source follower on the wafer The gate is connected to the microphone bondpad with a thin gold wire The noise measurements were carried out in a shielded environment

The noise of a condenser microphone that is connected to a source follower is found to be dominated by the noise of the source follower [12,13] In this case, the only microphone parameter that determines the noise is the microphone capacitance [29] The measured noise of the type C and D microphones was 2 9 and 3 3 μV(A), respectively With the sensitivities being 5 4 and 5 0 mV Pa^{-1}, the equivalent noise levels become 29 and 30 dBA SPL, respectively The measured equivalent noise level of microphones with 1 5 mm$\times$1 5 mm diaphragms, having a smaller capacitance, was typically 33 dBA SPL

4. Discussion and conclusions

The single-wafer fabricated silicon condenser microphone, which was introduced in 1992 [15], showed promising results for application as a hearing-aid microphone The performance of this microphone has been improved by increasing the backplate stress, decreasing the diaphragm thickness and increasing the acoustic hole density of the backplate The best microphones show a sensitivity of 5 0 mV Pa^{-1}, which corresponds to an open-circuit sensitivity of 10 mV Pa^{-1} for type D microphones with a capacitance of 6 6 pF The measured frequency response was flat within ±2 dB from 100 Hz to 14 kHz, which is better than the requirements for a hearing-aid microphone

The operating voltage of the microphones is only 5 0 V, which is about 60% of the collapse voltage A 5 0 V d c bias voltage can also be obtained from a 1 2 V battery, as commonly used in hearing aids, using a CMOS voltage multiplier [30] Therefore, the condenser microphones presented do not need an electret and will therefore not suffer from the problem of long-term instability due to charge decay in the electret In addition, the technological difficulties that are involved in the fabrication and charging of an electret in an all-silicon condenser microphone are avoided

The sensitivity at the output of the source follower should be increased by a factor of two to meet the requirements for hearing-aid microphones This can be achieved by further increasing the mechanical sensitivity using thinner diaphragms or diaphragms with a lower tensile stress Another possibility for increasing the mechanical sensitivity may be the application of a corrugated microphone diaphragm These diaphragms have been shown to have a larger mechanical sensitivity than flat diaphragms of equal size and thickness [31,32]

Furthermore, the sensitivity can also be increased by nearly a factor of two by decreasing the area of the backplate electrode, as shown by several authors [33–35] The capacitance changes are much smaller near the edge of the diaphragm than in the centre, since the vibration amplitude is largest in the diaphragm centre Therefore, the electrode near the diaphragm edge acts as a capacitive loading of the active diaphragm centre capacitance Reduction of the electrode area leads to a reduction of this loading capacitance Of course this electrode reduction must be optimized, to avoid excessive signal attenuation caused by the (external) parasitic capacitance The backplates of the microphones that have been tested were metallized over about 90% of the total backplate area

The measured noise level of the microphones was 30 dBA SPL, which is nearly that required for a hearing-aid microphone (<29 5 dBA SPL) If the microphone sensitivity is increased by a factor of two, the noise level will become 6 dB lower, which is much better than required

Summarizing, the performance of the silicon microphones has been improved considerably The sensitivity needs to be increased by a factor of two, enough tools are available for this If the sensitivity is increased by this factor of two, the noise level will be lower than the requirement for commercially available hearing-aid microphones Therefore, we think that it is possible to fabricate silicon condenser microphones for hearing aids that can compete with the present conventionally fabricated ones

References

1 M Royer, J O Holmen, M A Wurm, O S Aadland and M Glenn, ZnO on Si integrated acoustic sensor, *Sensors and Actuators, 4* (1983) 357–362

2 E S Kim, J R Kim and R S Muller, Improved IC-compatible piezoelectric microphone and CMOS process, *Proc 6th Int Conf Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA, June 24–28, 1991*, pp 270–273

3 W Kühnel, J Franz, D Hohm and G Hess, Silicon subminiature microphones for airborne sound, *Acustica, 73* (1991) 90–99

4 R Schellin and G Hess, A silicon subminiature microphone based on piezoresistive polysilicon strain gauges, *Sensors and Actuators A, 32* (1992) 555–559

5 W Kühnel, Silicon condenser microphone with integrated field-effect transistor, *Sensors and Actuators A, 25–27* (1991) 521–525

6 E Graf, W Kronast, S Dühring, B Müller and A Stoffel, Silicon membrane condenser microphone with integrated field-effect transistor, *Sensors and Actuators A, 37–38* (1993) 708–711

7 D Hohm and R Gerhard-Multhaupt, Silicon-dioxide electret transducer, *J Acoust Soc Am*, *75* (1984) 1297–1298

8 A J Sprenkels, R A Groothengel, A J Verloop and P Bergveld, Development of an electret microphone in silicon, *Sensors and Actuators, 17* (1989) 509–512

9 P Murphy, K Hubschi, N de Rooij and C Racine, Subminiature silicon integrated electret capacitor microphone, *IEEE Trans Electron Instr*, *EI-24* (1989) 495–498

10 D Hohm and G Hess, A subminiature condenser microphone with silicon nitride membrane and silicon backplate, *J Acoust Soc Am*, *85* (1989) 476–480

11 J Bergqvist and F Rudolf, A new condenser microphone in silicon, *Sensors and Actuators, A21–A23* (1990) 123–125

12 J Bergqvist, F Rudolf, J Maisano, F Parodi and M Rossi, A silicon condenser microphone with a highly perforated backplate, *Proc 6th Int Conf Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA, June 24–28, 1991*, pp 266–269

13 T Bourouina, S Spirkovitch, F Baillieu and C Vauge, A new microphone with a p^+ silicon membrane, *Sensors and Actuators A, 31* (1992) 149–152

14 P R Scheeper, W Olthuis and P Bergveld, Fabrication of a subminiature silicon condenser microphone using the sacrificial layer technique, *Proc 6th Int Conf Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA, June 24–28, 1991*, pp 408–411

15 P R Scheeper, A G H van der Donk, W Olthuis and P Bergveld, Fabrication of silicon condenser microphones using single wafer technology, *IEEE J Microelectromech Syst*, *1* (1992) 147–154

16 W Kühnel and G Hess, Micromachined subminiature condenser microphones in silicon, *Sensors and Actuators A, 32* (1992) 560–564

17 W Kühnel and G Hess, A silicon condenser microphone with structured back plate and silicon nitride membrane, *Sensors and Actuators A, 30* (1992) 251–258

18 D Hohm and G M Sessler, An integrated silicon-electret condenser microphone, *11eme Congrès International d'Acoustique, Paris, France, 1983*, Vol 6, pp 29–32
19 K E Petersen, Capacitive pressure transducer, *US Pat No 4 332 000* (May 1982)
20 Microtel B V, Specifications of electret microphone model 32, Amsterdam, June 1986
21 G M Sessler, *Electrets*, Topics in Applied Physics, Vol 33, Springer, Berlin, 1st edn, 1980, p 349
22 H C Nathanson, W E Newell, R A Wickstrom and J R Davis, The resonant gate transistor, *IEEE Trans Electron Devices, ED-14* (1967) 117–133
23 P Morse and K U Ingard, *Theoretical Acoustics*, McGraw-Hill, New York, 1st edn, 1968, pp 383–394 and 474–490
24 Z Škvor, On the acoustical resistance due to viscous losses in the air gap of electrostatic transducers, *Acustica, 19* (1967) 295–299
25 P R Scheeper, A silicon condenser microphone materials and technology, *Ph D Thesis*, University of Twente, 1993
26 A J Sprenkels (Siemens Nederland N V, Dept Audiological Components), personal communication
27 E I Bromley, J N Randall, D C Flanders and R W Mountain, A technique for the determination of stress in thin films, *J Vac Sci Technol B, 1* (1983) 1364–1366
28 M Mehregany, M G Allen and S D Senturia, The use of micromachined structures for the measurement of mechanical properties and adhesion of thin films, *Proc IEEE Solid-State Sensors and Actuators Workshop, Hilton Head Island, SC, USA, 1986*
29 A G H van der Donk, P Bergveld and J H Voorthuyzen, Optimal design of electret microphone MOSFET preamplifier, *J Acoust Soc Am, 91* (1992) 2261–2269
30 A G H van der Donk, A silicon condenser microphone modelling and electronic circuitry, *Ph D Thesis*, University of Twente, 1992
31 Y Zhang and K D Wise, Performance of non-planar silicon diaphragms under large deflections, *Proc IEEE Microelectromechanical Systems Workshop, Fort Lauderdale, FL, USA, Feb 7–10, 1993*, pp 284–288
32 P R Scheeper, W Olthuis and P Bergveld, The design, fabrication and testing of corrugated silicon nitride diaphragms, *IEEE J Microelectromech. Syst*, accepted for publication
33 W H Ko, M -H Bao and Y -D Hong, A high-sensitivity integrated-circuit capacitive pressure transducer, *IEEE Trans Electron Devices, ED-29* (1982) 48–56
34 A J Sprenkels, A silicon subminiature electret microphone, *Ph D Thesis*, University of Twente, 1988
35 J A Voorthuyzen, A.J Sprenkels, A G H van der Donk, P R Scheeper and P Bergveld, Optimization of capacitive microphone and pressure sensor performance by capacitor-electrode shaping, *Sensors and Actuators A, 25–27* (1991) 331–336

Biographies

Patrick Richard Scheeper was born in Nieuw-Vennep, The Netherlands, on October 25, 1965 He received his B S degree in applied physics from the Rooms Katholieke Hogere Technische School Rijswijk, Rijswijk, The Netherlands, in 1988 In the same year he joined the Biomedical Engineering Division, Department of Electrical Engineering, University of Twente, The Netherlands, where he received his Ph D degree in 1993 The subject of his dissertation was the development of a condenser microphone based on silicon technology for use in hearing aids He is currently employed by Bruel and Kjær, Nærum, Denmark

Wouter Olthuis was born in Apeldoorn, The Netherlands, on October 23, 1960 He received his M S degree in electrical engineering from the University of Twente, Enschede, The Netherlands, in 1986 In the same year he joined the Biomedical Engineering Division of the Faculty of Electrical Engineering, University of Twente, Enschede, The Netherlands, where he received his Ph D degree in 1990 He is currently working as an assistant professor in the Biosensor Technology Group of the University of Twente

Piet Bergveld was born in Oosterwolde, The Netherlands, on January 26, 1940 He received his M S degree in electrical engineering from the University of Eindhoven, The Netherlands, in 1965 and his Ph D degree from the University of Twente, The Netherlands, in 1973 The subject of his dissertation was the development of ISFETs and related devices, including the actual invention of the ISFET, since then also investigated by many other international research groups at universities as well as in industry Since 1965 he has been a member of the Biomedical Engineering Division of the Faculty of Electrical Engineering (University of Twente) and in 1984 was appointed full professor in biosensor technology He is one of the project leaders in the MESA Research Institute His research subjects still concern the further development of ISFETs and biosensors based on ISFET technology as well as silicon microphones, and have resulted up to now in more than 150 papers