Fabrication of Silicon Condenser Microphones using Single Wafer Technology

P. R. Scheeper, A. G. H. van der Donk, W. Olthuis, and P. Bergveld

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 flat frequency response between 100 Hz and 14 kHz and a sensitivity of typically 1–2 mV/Pa have been fabricated in a reproducible way. These sensitivities can be achieved using a relatively low bias voltage of 6–16 V. The measured sensitivities and bandwidths 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.**

I. Introduction

Silicon micromachining techniques have been applied successfully for the fabrication of miniature microphones on silicon wafers [1]–[10]. These silicon microphones were based on the piezoelectric [1], [2], piezoresistive [3] and capacitive principle [4]–[12]. The capacitive microphones can be divided into electret microphones [4]–[6], which are biased by built-in charge, and condenser microphones [7]–[12], which have to be biased by an external voltage source. The piezoelectric microphones showed a sensitivity of 250 μV/Pa [1] and 1000 μV/Pa [2]. The sensitivity of the piezoresistive microphone was 25 μV/Pa [3]. Sensitivities up to 25 mV/Pa have been obtained with the capacitive microphones [5]. A recent development is a silicon condenser microphone with an integrated field-effect transistor, having a sensitivity of 5 mV/Pa [10].

A capacitive microphone usually consists of a thin, flexible diaphragm mounted on a rigid backplate. The backplate is provided with acoustic holes to allow air to flow in and out of the air gap. The backplate of conventional microphones consists of stainless steel, but of the modern versions it is fabricated from glass [8], [12] or from ⟨100⟩ silicon wafers [5]–[7], [9]–[11]. In the latter case anisotropic etching in a KOH solution is used to form the air gap and the acoustic holes. The diaphragm of the silicon microphone of Sprenkels *et al.* [5] consists of a thin Mylar foil, which is attached manually on the backplate and fixed by a polymer spray. With other microphones, the diaphragm and backplate are fabricated on separate wafers and have to be sealed together later on. Murphy *et al.* [6] used a polyester diaphragm that was mounted on a separate support wafer before microphone assembly, in contrast to the diaphragm of the microphone of Sprenkels *et al.* [5] that was mounted directly on the backplate wafer. Hohm and Hess [7] and Kühnel and Hess [10], [11] used 150-nm-thick low pressure chemical vapor deposited (LPCVD) silicon nitride films as a diaphragm. Bergqvist *et al.* [8], [9] fabricated silicon diaphragms by applying the electrochemical etch-stop technique, whereas Bourouina *et al.* [12] fabricated silicon diaphragms by using the p^+ etch-stop technique.

With the microphones of Murphy *et al.* [6], Hohm and Hess [7] and Kühnel and Hess [10], [11], the wafers are diced first and then the microphones are assembled individually. This process is less attractive for series production. In a more advanced process, the diaphragm-containing wafer and the backplate wafer are bonded first, and then the bonded wafers are diced into the individual microphones. This process is applied by Bergqvist *et al.* [8], [9] and Bourouina *et al.* [12]. However, the last process still requires a critical and labor-intensive alignment of the two wafers before they can be bonded. Furthermore, most bonding processes involve high-temperature treatments [9] or strong electric fields [13]. Therefore, the bonding process may affect integrated electronics or change properties of temperature-sensitive materials.

The solution may be the realization of microphones in a single wafer process, as originally proposed by Hijab and Muller [14]. This process is based on the well-known sacrificial layer etching technique. The sacrificial layer is etched through access holes that are anisotropically etched from the reverse side of the wafer. These access holes will act as acoustic holes during normal operation of the microphone. Some preliminary results of our design of this type of microphone have been presented earlier [15].

The objective of this paper is to further investigate the fabrication of single-wafer silicon condenser microphones, for application in hearing aids. Hearing-aid microphones should have a sensitivity of about 10 mV/Pa and a −3 dB upper cutoff frequency of 7 kHz. Because no experimental frequency responses were available in literature, microphones will be fabricated according to the design of Hijab and Muller [14]. Measurements will show

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that with this design it is very difficult to fulfill the requirements of a hearing-aid microphone. Modeling the microphone as a strongly air-damped second-order system, it will be shown that the microphone must be provided with more acoustic holes. Therefore, a new microphone design will be presented that can be fabricated using a single-wafer technology. Measurements of the relation between shape, dimensions, and related properties of the microphone and its performance show that this design approaches the requirements for a hearing-aid microphone better than the original design.

II. The Original Microphone Design

A. Fabrication Process

The microphone fabrication process, as proposed by Hijab and Muller [14], is shown in Fig. 1(a), (b) and (c). This process is applied to 3-in., 380-μm thick ⟨100⟩ silicon wafers, in the following sequence:

a) The reverse and polished sides of the wafer are covered with 1.8 μm and 0.45 μm thermal silicon dioxide, respectively. Square windows are etched in the oxide on the reverse side. Aluminium of 1 μm is evaporated on the polished side of the wafer and patterned, followed by plasma-enhanced chemical vapor deposition (PECVD) of 1.3 μm of silicon nitride. The recipe of the PECVD process is shown in Table I. The tensile stress of the silicon nitride layer that is fabricated with this process is 1.1×10^8 N/m^2 [16].

b) Holes and V-grooves are etched anisotropically from the reverse side of the wafer in a 33 wt.% KOH solution, saturated with isopropanol, at a temperature of 73°C. The V-grooves are etched to simplify the dicing of the wafer after the fabrication process has been finished. During the KOH etch, the polished side of the wafer is protected against the etchant by a Teflon holder. The diaphragm is provided with a 30-nm titanium adhesion layer and a 30-nm gold electrode.

c) 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 on a dummy sample.

The time that was required to complete the release of the diaphragms varied between 13 and 22 h, depending on both the diaphragm and access-hole size. Diaphragms of 0.6, 1.0, 1.5, 2.0, and 2.6 mm square have been fabricated this way.

Fig. 2 shows a SEM photograph of a detail of the cross section of a microphone. A part of an acoustic hole is shown on the right and a piece of the backplate on the left. Also the air gap and the diaphragm are shown.

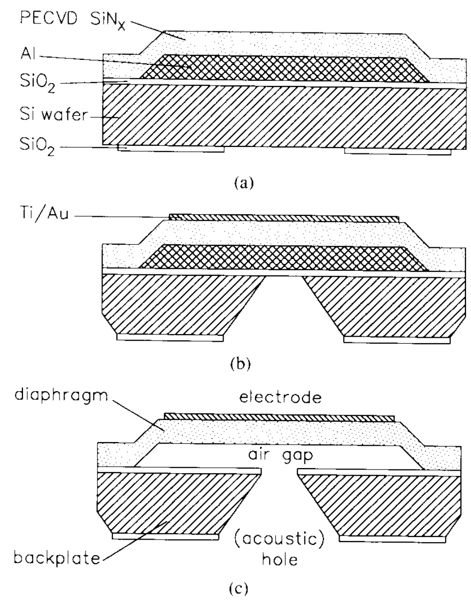

Fig. 1. Schematic representation of the original microphone fabrication process (see text), according to Hijab and Muller [14].

TABLE I
THE DEPOSITION CONDITIONS OF THE PECVD SILICON NITRIDE

Reactor	Parallel plate (Electrotech PF 310)
Temperature	300°C
Pressure	650 mTorr
Power	20 W
Frequency	13.56 MHz
SiH_4/N_2 (2%)	2000 sccm
NH_3	10/19 sccm[a]

[a] 10 sccm NH_3 results in stress of 1.1×10^8 N/m^2, 19 sccm NH_3 results in stress of 2.3×10^8 N/m^2.

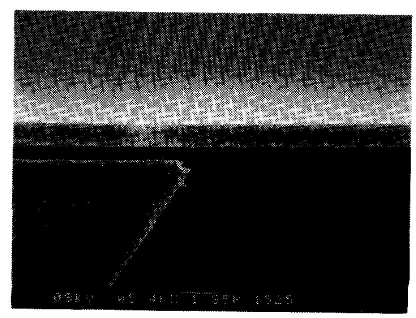

Fig. 2. SEM photograph of the cross section of a silicon condenser microphone, according to the design of Hijab and Muller [14], showing a detail of an acoustic hole (right), the backplate (left), the air gap, and the diaphragm.

B. Measurements

The frequency response of the microphones has been measured with a Brüel & Kjaer 4219 "artificial voice," using a sound pressure of 10 Pa. The bias voltage was provided by a dc voltage source in series with the micro-

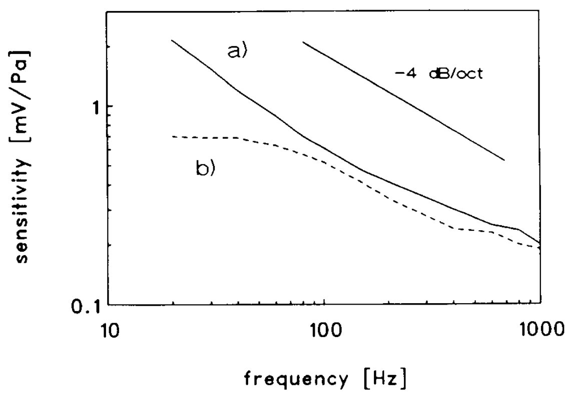

Fig. 3. Measured frequency response of a microphone of the original design with a 2.6 × 2.6 × 1.3 μm diaphragm (curve a) and a 0.6 × 0.6 × 1.3 μm diaphragm (curve b). Air-gap thickness 0.8 μm. DC bias voltage 3.0 V (curve a) and 10 V (curve b).

phone. The microphone signal was measured using a source follower with an input capacitance of about 2 pF and a Brüel & Kjaer 2610 measurement amplifier. All measurements were performed on complete wafers with microphones. The wafer was placed directly on the "artificial voice" with a silicone rubber seal, guaranteeing a negligible air leak. Because the microphones were not mounted on a special housing, the rear volume can be considered infinitely large.

Fig. 3 shows the measured frequency response of microphones with a 2.6 × 2.6 mm (curve a) and a 0.6 × 0.6 mm (curve b) diaphragm. The backplates are provided with four rectangular acoustic holes of about 2000 × 150 μm (curve a) or one acoustic hole of about 150 × 150 μm (curve b). Both values are the size of the holes on the polished side of the wafer.

The measured sensitivity of the microphone with a 2.6 × 2.6 mm diaphragm (curve a) is 2.1 mV/Pa at a frequency of 20 Hz and a dc bias voltage of 3.0 V. With our measurement setup, measurements below 20 Hz could not be performed. Three other microphones of the same dimensions showed a similar frequency response and a sensitivity of 1.4–2.0 mV/Pa. All measured sensitivities have 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 of 3.1–3.2 V. It can be seen from Fig. 3 that the measured frequency responses show a slope of −4 dB/oct.

The measured sensitivity of the microphone with a 0.6 × 0.6 mm diaphragm (curve b) was 0.7 mV/Pa at frequencies of 20–40 Hz, applying a bias voltage of 10 V. Collapse of the diaphragm occurred at a bias voltage of 16.7 V. It can be seen from Fig. 3 that the −3 dB cutoff frequency of the microphone is 100 Hz.

The measurements on microphones, according to the design of Hijab and Muller [14], show that microphones can be fabricated reproducibly and with a sensitivity of about 1 mV/Pa at a relatively low bias voltage. However, a drawback of the fabricated microphones is the small bandwidth. The microphone with the 0.6 × 0.6 mm diaphragm showed a cutoff frequency of 100 Hz. Microphones with a diaphragm of 2.6 × 2.6 mm show a cutoff frequency lower than 20 Hz. Similar results have been obtained for microphones with a diaphragm of 2.0 × 2.0 mm [15].

As mentioned previously, a hearing-aid microphone should have a sensitivity of about 10 mV/Pa and a cutoff frequency of 7 kHz. From the measurements, it can be concluded that the major drawback of the fabricated microphones is the very small bandwidth. To investigate this phenomenon, a simple model will be treated that describes the dynamic behavior of the microphones. This model will indicate how the microphone design can be improved.

III. Dynamic Behavior of a Condenser Microphone

A condenser microphone can be modeled as a movable mass M, connected to a spring with a stiffness constant K in parallel with a damper with a mechanical 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 of the diaphragm movement 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)

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

where w is the diaphragm deflection, and $F(t)$ is the force on the diaphragm caused by the sound pressure. The resistance R_a was calculated by Škvor [17], assuming a laminar flow in the air gap. For a microphone with a square diaphragm with side a, the air streaming resistance R_a is

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

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 at zero pressure, and A is the fraction of the backplate area occupied by the acoustic holes.

By solving the differential equation that describes the deflection of a square membrane with clamped edges loaded by a homogeneous pressure [18], it can be shown that the stiffness constant of the microphone diaphragm K is

$$K = 13.57\sigma_d h_d \tag{3}$$

where σ_d and h_d are the stress and the thickness of the diaphragm, respectively. If a second-order system is strongly damped, the system can be considered as two first-order systems in series. This consideration is justified for the condenser microphone, if the following condition is fulfilled:

$$0.5\, R_a(MK)^{-1/2} \geq 1. \tag{4}$$

Typical values for the original microphone design from Fig. 1 are

$$a = 1 \text{ mm}$$
$$h_d = 1\ \mu\text{m}$$
$$\sigma_d = 1.1 \times 10^8 \text{ Nm}^{-2}$$
$$s_{a0} = 1\ \mu\text{m}$$
$$n = 1 \text{ mm}^{-2}$$
$$A = 0.1.$$

For $\rho_{Si3N4} = 3 \times 10^3$ kg $\times$ m^{-3} and $\eta_a = 17.1 \times 10^{-6}$ Pa $\times$ s, the value of $0.5\ R_a\ (MK)^{-1/2}$ becomes 4×10^3. Therefore the microphone can be considered as two first-order systems in series. The system with the highest time constant determines the cutoff frequency of the microphone, which then becomes

$$f = \frac{K}{2\pi R_a} \tag{5}$$

which also follows from (1), with $M = 0$. Above the frequency f the sensitivity of the microphone decreases with 6 dB/oct. For very high frequencies, the diaphragm mass M will no longer be negligible and the sensitivity will decrease with 12 dB/oct. However, this effect is of no practical interest, because the bandwidth is limited by the cutoff frequency f, as given by (5).

For the two microphones that have been tested (see Fig. 3) the stiffness constant is 1.9×10^3 N/m. The air streaming resistances are 5.8 and 33 Ns/m, resulting in cutoff frequencies of 54 and 9.3 Hz for the microphones with a 0.6×0.6 mm^2 and a 2.6×2.6 mm^2 diaphragm, respectively (data from the previous section have been used). This agrees well with the measured frequency responses in Fig. 3.

It can be seen from (5) that the cutoff frequency of the microphone is proportional to the stiffness constant K and inversely proportional to the air streaming resistance R_a. It can be concluded that the ratio K/R_a of the originally designed microphones presented in the previous section is too small. Increasing the stiffness constant K is unacceptable, because also the sensitivity of the microphone is then decreased. A better approach is to reduce the damping of the air gap. One way to achieve this is by increasing the thickness of the air gap s_{a0} as (2) predicts. This, however, would cause problems with the step coverage of the silicon nitride over the aluminium sacrificial layer, as can be seen from Fig. 1. A good alternative is to increase the acoustic hole density n. It can be seen from (2) and (5) that the cutoff frequency f is proportional to the acoustic hole density n. Therefore, it is expected that increasing the acoustic hole density with a factor 100–1000 will result in an adequate frequency response.

Microphones with a high acoustic hole density have been realized successfully by Bergqvist *et al.* [9] and Kühnel and Hess [10], using a two-wafer microphone fabrication process. A problem of the original microphone design (Fig. 1) is that an increase of the acoustic hole density is limited by the shape of anisotropically etched holes, with the typical angle of 54.7° for ⟨100⟩ silicon. Decreasing the damping by etching lateral grooves or holes in the backplate, as proposed by Kühnel and Hess [10], [11], is too difficult to be combined with the sacrificial layer technique. In order to get around all these difficulties, quite another microphone design is proposed, which can be realized using the sacrificial layer technique.

IV. A New Microphone Design

A. Fabrication Process

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 Fig. 4(a), (b), and (c).

Note that the backplate, which was originally the silicon wafer, is now replaced by a 1-μm-thick metallized perforated PECVD silicon nitride layer.

The deposition conditions of the LPCVD process are listed in Table II. The produced LPCVD silicon nitride layers exhibit a tensile stress of 1.5×10^8 N/m^2.

The thin diaphragm and backplate can easily stick together during drying of the wafer after completion of the sacrificial layer etching process. In order to avoid this undesirable phenomenon, the diaphragm is provided with small supports (fabrication step b), which have to maintain a distance of about 0.5 μm between the diaphragm and the backplate during the drying process. In spite of the presence of the diaphragm supports, it was observed that sticking sometimes still occurred. The yield of the drying process was improved by applying the freeze-drying process, as described by Guckel *et al.* [19].

An advantage of the new fabrication process is that it is a planar process. The absence of step coverages makes the diaphragm less vulnerable and allows the designer to choose any combination of the thicknesses of the sacrificial layer, the diaphragm, as well as the backplate.

Six types (three sizes, two different acoustic hole densities) of microphones have been fabricated. Characteristic dimensions are listed in Table III. The thickness of the diaphragms is 1 μm. Note that the fabricated PECVD silicon nitride backplates have the same dimensions as the diaphragm. Three values of the air-gap thickness have been realized: 1.1, 2.2, and 3.3 μm. Furthermore, the backplate stress was varied. Backplates with a tensile stress of 1.1×10^8 N/m^2 and 2.3×10^8 N/m^2 have been fabricated.

Fig. 5 is an SEM photograph of the backplate of a microphone of type 3. Fig. 6 is an SEM photograph of a microphone, as seen from the reverse side of the wafer, showing the silicon nitride diaphragm and the V-grooves around the microphones, which are used to simplify dicing the wafer after the fabrication process has been completed.

B. Measurements

The same measurement setup as described in the previous section has been used. The frequency response has been measured using a sound pressure of 4 Pa. The mea-

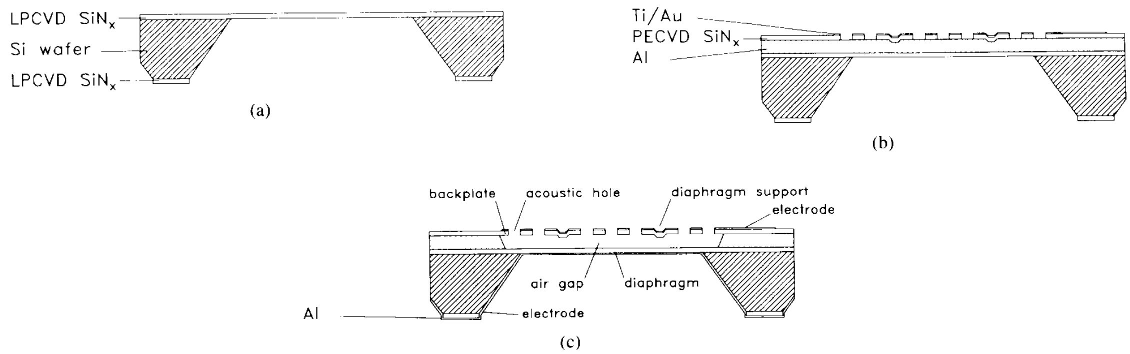

Fig. 4. Schematic representation of the alternative microphone fabrication process: (a) growing of 1 μm Low Pressure Chemical Vapor Deposited (LPCVD) silicon nitride, patterning and anisotropic etching of V-grooves and diaphragm in 33 wt.% KOH solution (73°C) from the unpolished side of the wafer; (b) evaporating 1–3 μm aluminium sacrificial layer, etching of 0.5 μm deep holes in the aluminium layer to form diaphragm supports, growing of 1 μm PECVD silicon nitride, evaporating and patterning a 30-nm titanium adhesion layer and a 30-nm gold electrode, etching of access/acoustic holes in Ti/Au and PECVD silicon nitride; and (c) etching of the aluminium sacrificial layer, drying and evaporating 100 nm aluminium on the silicon/silicon nitride on the reverse side (diaphragm electrode).

TABLE II
THE DEPOSITION CONDITIONS OF THE LPCVD SILICON NITRIDE

Temperature	850°C
Pressure	200 mTorr
SiH_2Cl_2	70 sccm
NH_3	18 sccm

TABLE III
CHARACTERISTIC DIMENSIONS OF DIFFERENT TYPES OF MICROPHONES. THE RELATED ACOUSTIC HOLE DENSITY n AND THE PARAMETER A, THE FRACTION OF THE BACKPLATE AREA THAT IS OCCUPIED BY ACOUSTIC HOLES, ARE ALSO SHOWN

Type	Diaphragm size (mm)	Number of supports	Acoustic hole size (μm)	Number of acoustic holes	n (mm^{-2})	A
1	1.0 × 1.0	64	20 × 20	256	256	0.10
2	1.0 × 1.0	100	20 × 20	525	525	0.21
3	1.5 × 1.5	49	30 × 30	392	174	0.16
4	1.5 × 1.5	100	30 × 30	800	356	0.32
5	2.0 × 2.0	121	40 × 40	484	121	0.19
6	2.0 × 2.0	121	40 × 40	968	242	0.39

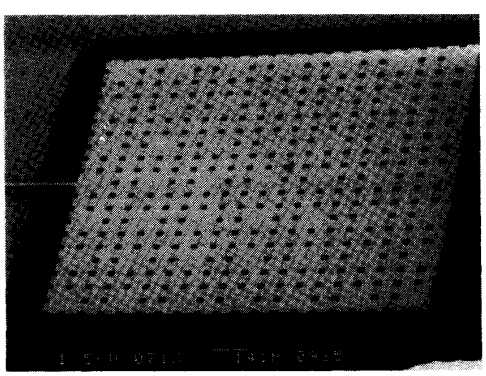

Fig. 5. SEM photograph of a microphone of type 3 (see Table III), showing the backplate with the acoustic holes, diaphragm supports (at places where no acoustic hole is present) and the electrode.

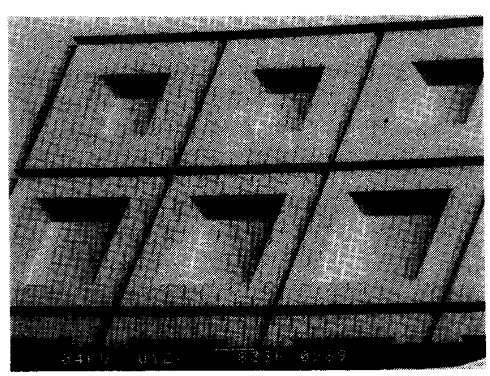

Fig. 6. SEM photograph of microphones, as seen from the reverse side of the wafer, showing the silicon nitride diaphragm and the V-grooves around the microphones.

sured sensitivities have not been corrected for the attenuation of the source follower. The frequency responses have been measured on wafer, as explained before. For the capacitance and noise measurements, some microphones were mounted on epoxy carriers.

Fig. 7 shows the measured frequency response of three microphones of type 4 (see Table III) with an air-gap thickness of 1.1, 2.2, and 3.3 μm, respectively. The microphones are biased with 2.5, 6.0, and 12.0 V, respectively. Collapse of the diaphragm, due to electrostatic attraction between the diaphragm and the backplate, occurred at a bias voltage of 3, 7.8, and 16 V, respectively. The stress of the diaphragm and the backplate have been determined from separate wafers using the wafer-bending method and are 1.5×10^8 N/m^2 and 1.1×10^8 N/m^2, respectively.

It can be seen from Fig. 7 that the frequency response of the microphone with the 1.1 μm air gap shows the behavior of a first-order system, with a slope of −6 dB/oct for higher frequencies. The cutoff frequencies of the microphones with an air-gap thickness of 1.1 μm and 2.2 μm are 600 Hz and 2 kHz, respectively. The bandwidth of the microphone with a 3.3 μm air gap is more than 14 kHz, which is more than enough for a hearing-aid microphone.

Fig. 8 shows the frequency response of five microphones of type 3, with the diaphragm and backplate having the same thickness and stress as the microphones mentioned above. The microphones are biased at 16.0 V. Collapse of the diaphragms occurred at a bias voltage between 17 and 20 V. The numbers 32 and 33 refer to two different wafers. It can be concluded that the reproducibility of the first batch of microphones is good.

The dependence of the microphone sensitivity on the dc bias voltage is shown in Fig. 9. The measurements were performed on a microphone of type 3 as described above (number 32-2 from Fig. 8). Collapse of the diaphragm occurred at a dc bias voltage of 18.5 V. Above 12 V the sensitivity increases very rapidly. Close to the diaphragm collapse, a sensitivity of 4 mV/Pa has been measured.

More detailed calculations of the dynamic behavior of the microphones have shown that the bandwidth is limited by the flexibility of the backplate. At higher frequencies, the air flowing in an out of the air gap causes the thin backplate to vibrate in phase with the diaphragm. The vibration amplitude increases with increasing frequencies, thus decreasing the microphone output signal, resulting in a −6 dB/oct slope of the frequency response. The bandwidth can be increased by stiffening the backplate. This can be realized by increasing the backplate thickness and/or stress.

Fig. 10 shows the influence of the backplate stress on the measured frequency response of two microphones of type 4. The backplate stress is 1.1×10^8 N/m^2 for curve a and 2.3×10^8 N/m^2 for curve b. The microphones are provided with a dc bias voltage of 6.0 V (curve a) and 8.0 V (curve b), respectively. The air-gap thickness of both microphones is 2.2 μm. The thickness of the backplate and the diaphragm is 1 μm. The diaphragm stress is 1.5×10^8 N/m^2. It can be seen from Fig. 10 that the microphone with the lowest backplate stress (1.1×10^8 N/m^2), represented by curve a, has a cut-off frequency of 3 kHz. Increasing the backplate stress to 2.3×10^8 N/m^2 (curve b) increases the cutoff frequency to more than 14 kHz. Furthermore, due to the higher backplate

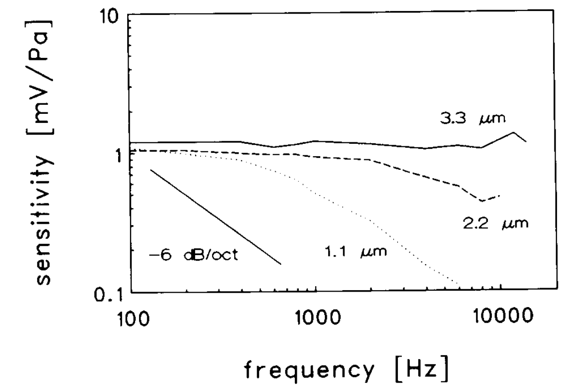

Fig. 7. Measured frequency response of three microphones of type 4 (see Table III), with an air-gap thickness of 1.1, 2.2, and 3.3 μm. DC bias voltage 2.5, 6.0 and 14.0 V, respectively. Diaphragm and backplate stress 1.5×10^8 N/m^2 and 1.1×10^8 N/m^2, respectively, and thickness of 1 μm.

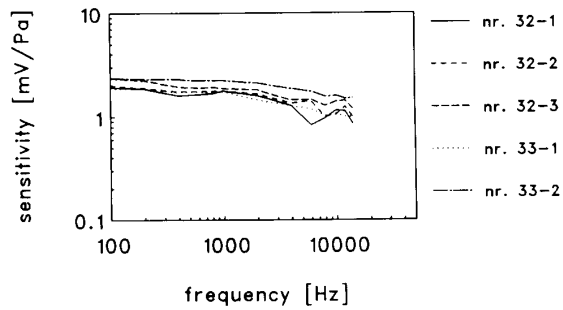

Fig. 8. Measured frequency response of five microphones of type 3 (see Table III). Diaphragm and backplate stress 1.5×10^8 N/m^2 and 1.1×10^8 N/m^2, respectively, and thickness of 1 μm. Air-gap 3.3 μm. DC bias voltage 16 V. Numbers 32 and 33 refer to different wafers.

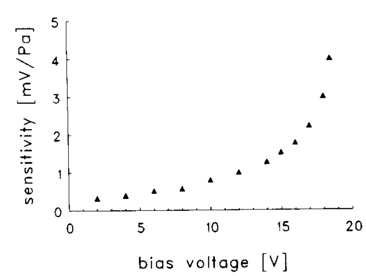

Fig. 9. The measured sensitivity, at a frequency of 1 kHz, as a function of the dc bias voltage for a microphone of type 3. Air-gap thickness 3.3 μm. Diaphragm and backplate stress 1.5×10^8 N/m^2 and 1.1×10^8 N/m^2, respectively, and thickness of 1 μm.

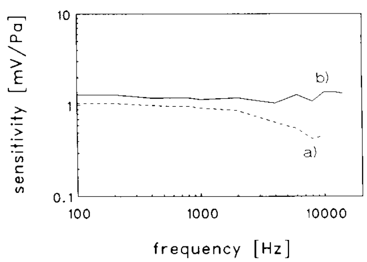

Fig. 10. Measured frequency response of two microphones of type 4 (see Table III), with an air-gap thickness of 2.2 μm. Stress backplate 1.1×10^8 N/m^2 (curve a) and 2.3×10^8 N/m^2 (curve b). DC bias voltage 6.0 V (curve a) and 8.0 V (curve b). Diaphragm stress 1.5×10^8 N/m^2 and thickness 1 μm.

stress, a higher dc bias voltage is allowed. The maximum allowable bias voltage was 7.8 V for the microphone with the lowest backplate stress, and 14.2 V for the microphone with the highest backplate stress.

The measured capacitance of microphones of type 3 and 4, that were mounted on epoxy carriers, was 10–11 pF. Taking the parasitic capacitances of the mounted microphones into account, the microphone capacitance is 5–7 pF, which corresponds reasonably with the calculated value of 5.5 pF.

The noise voltage was measured of three microphones of type 3. The microphones had an air-gap thickness of 3.3 μm. For the noise measurements, an A-weighing filter was used. It was found that the measured noise voltage, 2.2–2.5 μV (A), was dominated by the preamplifier noise. For a sensitivity of 1–2 mV/Pa, the equivalent noise level becomes 35–42 dB(A). For comparison, the noise level of two microphones with a Mylar diaphragm was measured. These microphones have also been developed at the University of Twente and were described earlier [5]. Using the same preamplifier, the measured equivalent noise level was only 22 dB(A), mainly due to the high sensitivity of the microphones (typically 25 mV/Pa).

V. Discussion

The original microphone design, as proposed by Hijab and Muller [14], showed a reasonable sensitivity, typically 1 mV/Pa for low frequencies, using a low bias voltage. However, a drawback of this design is that the bandwidth is too small for application as a hearing-aid microphone.

As shown in Fig. 3, the measured frequency characteristics of our original microphone design showed a slope of −4 dB/oct above the cutoff frequency. This value has also been measured by Hohm and Hess [7] for strongly damped condenser microphones. They explained this unusual slope by assuming that the air streaming resistance of the air gap is a function of frequency, according to $R_a \sim \omega^{-1/3}$.

With the new microphone design, the acoustic hole density has been increased by a factor of more than 100 and the air-gap thickness by a factor 1–3 with respect to the original design. Therefore the resistance R_a is decreased by a factor 100–2700. This corresponds well to the measured cutoff frequencies ranging from 600 Hz to more than 14 kHz, for microphones with an air-gap thickness of 1.1 and 3.3 μm, respectively.

The measured sensitivities (1–2 mV/Pa) are roughly equal to the values presented by Bergqvist *et al.* [9] (1.6 mV-Pa) and by Kühnel and Hess [10] (3 mV/Pa) for their microphones with thin and highly perforated backplates.

The measured noise level (35–42 dB(A)) corresponds well with the measurements of Bergqvist *et al.* [9] (37–44 dB(A)). Because the noise is dominated by the microphone preamplifier, the signal-to-noise ratio of the silicon microphones can only be optimized by increasing the sensitivity. Therefore, microphones with a Mylar diaphragm, having a sensitivity of typically 25 mV/Pa, showed a low noise level (22 dB(A)).

The sensitivity of the microphones can be optimized by decreasing the stiffness constant K (see (1)), that determines the low-frequency sensitivity of the diaphragm. This can be realized by decreasing the diaphragm stress and/or the diaphragm thickness. In order to maintain the same bandwidth, the air streaming resistance should then be decreased as well, as can be seen from (3). In the new microphone design, this can easily be realized by increasing the air-gap thickness.

It has been shown that the bandwidth of the microphones can be further improved by increasing the stress of the backplate.

VI. Conclusions

A new condenser microphone design, which 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 effect of the air-gap thickness and the backplate stress on the frequency response of the microphones has been demonstrated. The measured sensitivities are comparable to values presented in literature for silicon microphones (1–2 mV/Pa). 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 research will be focused on optimization of the sensitivity, in order to achieve values of about 10 mV/Pa.

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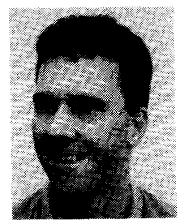

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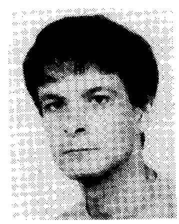

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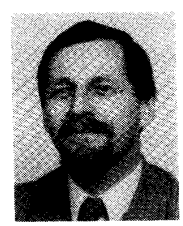

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