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Review Paper

A review of silicon microphones

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Abstract

Silicon micromachining has successfully been applied to fabricate piezoelectric, piezoresistive and capacitive microphones. The use of silicon has allowed the fabrication of microphones with integrated electronic circuitry and the development of the new FET microphone. The introduction of lithographic techniques has resulted in microphones with very small (1 mm^2) diaphragms and with specially shaped backplates. The application of corrugated diaphragms seems a promising future development for silicon microphones. It is concluded from a noise consideration that the FET microphone shows a high noise level, which is mainly due to the small sensor capacitance. From this noise consideration, it can be shown that integration of a capacitive microphone and a preamplifier will result in a further reduction of the noise.

1. Introduction

Microphones are transducers that convert acoustic energy into electrical energy. Many transduction principles have been developed, including the electrodynamic, the piezoelectric, the piezoresistive, the capacitive and the contact microphone (carbon microphone) [1]. These transduction principles were already known at the end of the nineteenth century and the beginning of the twentieth century. In 1978 a new type of microphone was introduced that was based on optical waveguides [2].

Royer et al. presented the first microphone to be fabricated using silicon micromachining techniques in 1983 [3]. The introduction of silicon technology allows accurate control of the dimensions, a high degree of miniaturization, and batch fabrication of microphones at low cost and with good reproducibility [4]. Furthermore, integration of electronic circuitry with the microphone is possible, as in, for example, the piezoelectric microphone of Royer et al. [3] and Kim et al. [5] and the FET microphone (condenser microphone with integrated field-effect transistor) of Kühnel [6] and Graf et al. [7].

The transduction principles that are most convenient for realization with micromachining techniques are the piezoelectric, piezoresistive and condenser microphones.

In this paper, a review of silicon microphones is given. The piezoelectric and piezoresistive microphones will be discussed briefly in Sections 2 and 3. Since most of the silicon microphones are based on the capacitive principle, a more extensive review on this type of microphone is given in Section 4. The effect of the parameters on the performance of the capacitive microphones is discussed in Section 4.1. The development of the silicon capacitive microphones is given in Section 4.2. In Section 4.3, the FET microphone is discussed separately. The expected future developments of silicon microphones are discussed in Section 5. Conclusions are drawn in Section 6.

2. Piezoelectric microphones

A piezoelectric microphone consists of a thin diaphragm that is either provided with a piezoelectric material or mechanically connected to a bimorph bender, which is a cantilever beam of two layers of piezoelectric material having opposite polarizations. The movement of the diaphragm causes stress in the piezoelectric material, which generates an electric voltage.

Royer et al. presented the first piezoelectric microphone realized using silicon micromachining techniques in 1983 [3]. The microphone consists of a 30 μm thick silicon diaphragm, having a diameter of 3 mm, with a

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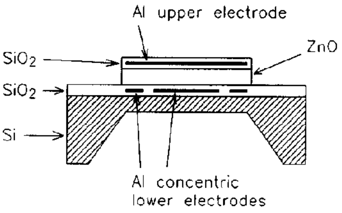


Fig. 1. Schematic cross-sectional view of the piezoelectric microphone of Royer et al. [3].

3–5 μm ZnO layer on top, sandwiched between two SiO_2 layers which contain the electrodes (see Fig. 1). Some microphones were provided with an integrated MOSFET preamplifier. A sensitivity of 50–250 μV Pa^{-1} and a frequency response of 10 Hz to 10 kHz, which was flat within 5 dB, were measured.

Other authors also presented piezoelectric silicon microphones [5,8,9]. The sensitivity of these microphones was between 0.025 mV Pa^{-1} [2,8] and 1 mV Pa^{-1} [5]. A disadvantage of the piezoelectric microphones is the relatively high noise level, which is between 50 dBA SPL[1] [5] and 72 dBA SPL [2].

3. Piezoresistive microphones

A piezoresistive microphone consists of a diaphragm that is provided with four piezoresistors in a Wheatstone bridge configuration. Two resistors are placed in the middle and two are placed at the edge of the diaphragm for polycrystalline silicon. If the diaphragm deflects, the strains at the middle and the edge of the diaphragm have opposite signs, thus causing an opposite resistance change of the piezoresistors. An advantage of the piezoresistive microphone is the relatively low output impedance.

Schellin and Hess presented a piezoresistive silicon-based microphone in 1992 [10]. The microphone diaphragm is 1 μm thick highly boron-doped silicon with an area of 1 mm^2. The diaphragm is provided with 250 nm thick p-type polysilicon resistors, which are isolated from the diaphragm by a 60 nm silicon dioxide layer (see Fig. 2).

Using a supply voltage of 6 V, the microphone showed a sensitivity of 25 μV Pa^{-1} and a frequency response of 100 Hz to 5 kHz ($\pm$3 dB). The sensitivity was lower than expected by more than a factor of 10, which was explained by the initial (static) stress in the highly boron-doped silicon diaphragm.

[1]This is the noise level that is measured using an A-weighing filter, in dBs relative to 2×10^{-5} Pa, which is the lowest sound level detectable by the human ear. The A-weighing filter corrects for the frequency characteristic of the human ear, thus providing a measure of the audibility of noise.

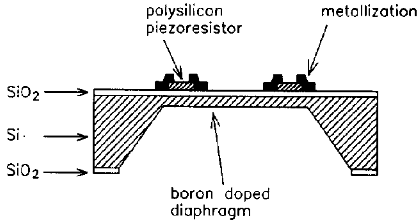


Fig. 2. Schematic cross-sectional view of the piezoresistive microphone of Schellin and Hess [10].

The piezoresistive coupling factor of the polysilicon, to which the microphone sensitivity is proportional, has been optimized by the authors. The only remaining design factor that enhances the sensitivity of this type of microphone is increased diaphragm area.

4. Capacitive microphones

The majority of silicon microphones are based on the capacitive detection principle. Therefore, this type of microphone will be treated in more detail. In Section 4.1 the principle of operation of the capacitive microphone is discussed, in order to understand the effect of the parameters of the microphone and its preamplifier which determine the microphone performance. In Section 4.2 an overview of capacitive microphones in silicon is given. In Section 4.3 the recently developed capacitive microphone with an integrated field-effect transistor is discussed.

4.1. Principle of operation

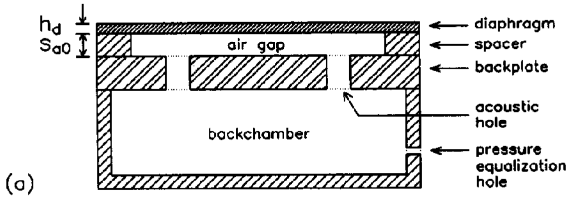
Microphone sensitivity

The open-circuit sensitivity of a condenser microphone, as shown schematically in Fig. 3(a), is considered to consist of two components, S_m and S_e, i.e., the mechanical and electrical sensitivity of the microphone, respectively [11,12].

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:

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

Note that $dw = -ds_{a0}$, where s_{a0} is the thickness of the air gap between the two plates. It is assumed that the diaphragm moves like a rigid piston, with the average movement of an actual microphone diaphragm. If the microphone is provided with a circular diaphragm with a large initial tensile stress, the mechanical sensitivity of the piston diaphragm is equal to [13]



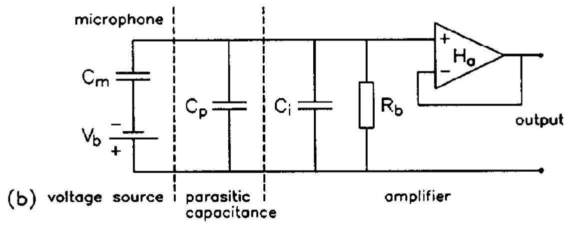


Fig. 3. (a) Schematic cross-sectional view of a condenser microphone. (b) The condenser microphone, connected to an external d.c. bias voltage source, loaded by a parasitic capacitance C_p, a bias resistor R_b and a preamplifier with an input capacitance C_i.

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

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

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:

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

Note that in the case of a piston diaphragm, the electric field strength E_a in the air gap is homogeneous. For fast diaphragm movements, the charge on the plates of the microphone remains constant. Consequently, the electric field strength between the plates remains constant. 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 electric field in the air gap can also be supplied by built-in charge. In this case, the backplate is provided with a thin dielectric layer, which is charged. The charged layer is the so-called electret. The electric field strength in the air gap is then given by

$$S_a = \frac{\dfrac{\sigma_e s_e}{\epsilon_0 \epsilon_e}}{s_{a0} + \dfrac{s_e}{\epsilon_e}} = \frac{V_e}{s_{a0} + \dfrac{s_e}{\epsilon_e}} \tag{5}$$

where s_e and ϵ_e are the thickness and the relative dielectric constant of the electret, σ_e is the charge density and ϵ_0 is the dielectric constant of a vacuum. The voltage V_e is the resulting electret voltage of the charge σ_e.

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

$$S_{open} = -S_m S_e \tag{6}$$

Note that a minus sign has been introduced in Eq. (6), because $ds_{a0} = -dw$. Thus the microphone sensitivity has a negative value. For clarity, if we compare microphone sensitivities, we will compare the absolute values of the sensitivities.

The open-circuit microphone signal, e_m, can be described as

$$e_m = S_m S_e p \tag{7}$$

where p is the sound pressure.

When the sensitivity is measured, the microphone is connected to a preamplifier, which acts as an impedance converter (see Fig. 3(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

$$S_{meas} = -S_m S_e H_c H_a \tag{8}$$

where H_c is the capacitive signal attenuation due to the input capacitance of the preamplifier and the parasitic capacitance C_p:

$$H_c = \frac{C_m}{C_m + C_i + C_p} \tag{9}$$

where C_m is the microphone capacitance.

For a source follower, the gain is given by [11,14,15]

$$H_a = \frac{g_m R_s}{1 + g_m R_s} \tag{10}$$

where g_m is the transconductance of the field-effect transistor (FET) and R_s is the value of the source resistor.

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 specific preamplifier.

As can be seen from Eq. (4), the electrical sensitivity, and thus the open-circuit microphone sensitivity, increases if the bias voltage is increased. 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 Eq. (2), the collapse voltage is equal to [16]

$$V_{\max}=\sqrt{\frac{64\sigma_d h_d s_{a0}^3}{27\epsilon_0 R^2}}=\sqrt{\frac{1}{S_m}\frac{8s_{a0}^3}{27\epsilon_0}} \qquad (11)$$

Note that the collapse voltage is inversely proportional to the square root of the mechanical sensitivity. Thus, improving the sensitivity of a condenser microphone by increasing the mechanical sensitivity of the diaphragm is limited, because the collapse voltage is decreased. If the d.c. bias voltage is always kept at a fixed fraction of the collapse voltage, it can be concluded from Eqs. (2), (4), (6) and (11) that the open-circuit sensitivity of a condenser microphone is proportional to the square root of its mechanical sensitivity.

Note that in Eq. (11) it is assumed that the backplate is rigid. For microphones with a thin backplate [17–19] that is not perfectly rigid, the collapse voltage is lower than that predicted by Eq. (11).

Eq. (11) is an approximation that is valid for a piston diaphragm. Warren [20] has presented more accurate calculations for microphone diaphragms. Warren assumed that the diaphragm is very thin and has a high initial stress. The fact that the electrostatic force is not distributed uniformly across the diaphragm was taken into account. The collapse voltage that was numerically calculated by Warren is 18% lower than the value given by Eq. (11).

Frequency response of a capacitive microphone

A well-known method for calculating the frequency response of a mechanical–acoustic system is to describe it 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: inductance, resistance and capacitance, respectively [21].

Fig. 4 gives the equivalent circuit of the microphone shown 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 [21]. C_d and C_{bp} represent the compliance of the diaphragm and the backplate, respectively. Note that the thin backplate is modelled as a thin diaphragm with a large initial stress. Therefore, the mechanical sensitivity of the backplate is also given by Eq. (2).

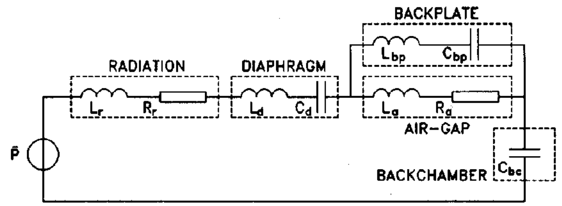


Fig. 4. Analogous electrical circuit of a condenser microphone with a thin backplate, mounted on a backchamber.

The air-streaming resistance of the air gap, R_a, has a large effect on the frequency response of the microphone. The value of R_a has been calculated by Škvor [22]:

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

with

$$B(A)=\left(\frac{1}{4}\ln\frac{1}{A}-\frac{3}{8}+\frac{1}{2}A-\frac{1}{8}A^2\right) \qquad (13)$$

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 ($0\leqslant A\leqslant 1$).

Noise performance of a capacitive microphone

Another important property of condenser microphones is the noise performance. The most significant noise is produced in the bias resistor, the preamplifier and the impedance of the package (housing) of the microphone and the preamplifier [12,14,15]. A more detailed diagram of the condenser microphone and the source follower, extended with the noise sources, is shown in Fig. 5. The open-circuit output voltage of the microphone is given by e_m, as described by Eq. (7).

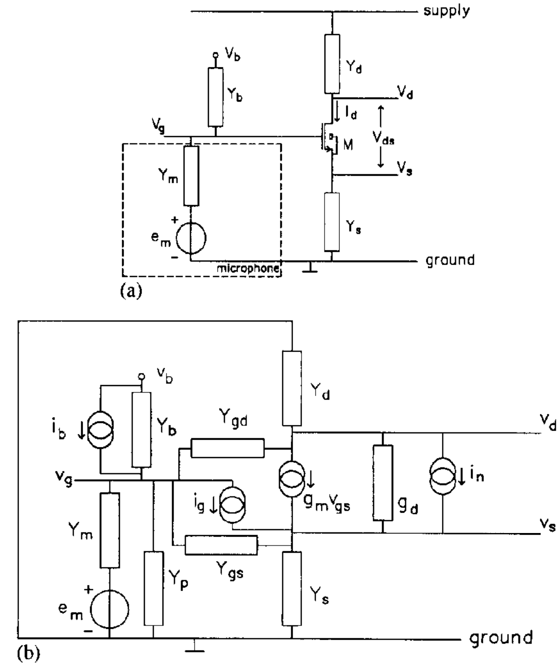


Fig. 5. (a) General model of an FET preamplifier, connected to a capacitive microphone. (b) Small-signal circuit with noise sources.

The noise in the bias resistor and the package gate impedance can be modelled by the current sources i_b and i_g, respectively, and the noise of the FET by a current source i_n. The admittances in Fig. 5 can be described in more detail as follows:

$Y_m = j\omega C_m$ (output capacitance microphone)
$Y_p = j\omega C_p$ (parasitic gate-to-ground capacitance)
$Y_b = 1/R_b + j\omega C_p$ (bias element)
$Y_{gs} = j\omega C_m$ (gate-to-source capacitance)
$Y_{gd} = j\omega C_p$ (gate-to-drain capacitance)

The admittances Y_s and Y_d are resistive. The effect of all noise sources on the output of the preamplifier has been calculated by van der Donk et al. [14]. An expression for the squared equivalent input noise density N_i^2 was obtained, which can be considered as a noise generator with a value of N_i V $\mathrm{Hz}^{-1/2}$ in series with the signal source e_m. N_i^2 is given by [14]

$$N_i^2 = \frac{(C_m + C_p + C_b + C_{gs} + C_{gd})^2}{C_m^2} \left(\frac{K}{f} + \frac{8kT}{3g_m}\right) + \frac{4kT(1/R_b + 1/R_g)}{\omega^2 C_m^2} \qquad (14)$$

where K is the flicker noise coefficient, which strongly depends on the technology used to fabricate MOSFETs [14], f is the frequency, $k = 1.38 \times 10^{-23}$ J K^{-1} (the Boltzmann constant) and T is the absolute temperature.

The first term in Eq. (14) represents the contribution of the channel noise of the FET. The second term represents the thermal noise of the bias element and the packaging leakage resistance. Eq. (14) is valid if either the source or the drain is used as the output.

It can be concluded from Eq. (14) that the ratio of noise to signal can be minimized by choosing C_m, R_b and R_g as large as possible. Note that R_g is not a component, but an unwanted effect of the packaging of the preamplifier and the microphone. The noise caused by this resistance may be considerable [14]. The design and fabrication of the MOSFETs can be optimized to reduce the channel noise [14].

4.2. Capacitive microphones in silicon

An overview of the most significant dimensions, the capacitance, the measured sensitivity, the noise level and the frequency range of capacitive silicon microphones (if mentioned), as reported by several authors, is given in Table 1.

Hohm and Gerhard-Multhaupt [23] in 1984 presented the first electret microphone that was based on silicon technology (see Fig. 6). The backplate was 1 cm × 1 cm silicon and was provided with one circular acoustic hole, with a diameter of 1 mm, which was fabricated by sand blasting. A 2 μm thick SiO_2 layer was used as electret and was charged to about −350 V. The diaphragm was a metallized 13 μm thick Mylar foil, with a diameter of 8 mm. A 30 μm Mylar foil was used as a spacer, thus yielding an air gap with the same thickness.

Polymer foil diaphragms were also applied by Sprenkels [11] in 1988 and by Murphy et al. [24] in 1989. The microphone fabrication process was made more compatible with standard thin-film technology by using anisotropic etching with KOH for fabrication of the backplate. In the microphone of Sprenkels [11] the Mylar foil was glued directly on the backplate wafer (see Fig. 7). In the microphone of Murphy et al. [24] the foil diaphragm was mounted on a support wafer for the microphone assembly. Sprenkels showed that silicon microphones with Mylar diaphragms can show very high sensitivities of 19 mV Pa^{-1} (25 mV Pa^{-1} open-circuit) [25,26].

Hohm improved the microphone fabrication process in 1986 [27,28] by using anisotropic etching and replacing the Mylar foil diaphragm by a 150 nm thick low pressure chemical vapour deposited (LPCVD) silicon nitride film. The microphone design is shown in Fig. 8. The diaphragm and the backplate were fabricated on separate wafers. The diaphragm stress was controlled by implantation with nitrogen ions. Owing to the smaller size of the microphone diaphragm (0.8 mm × 0.8 mm), the open-circuit sensitivity and the capacitance decreased from 8.8 mV Pa^{-1} [23] to 4.3 mV Pa^{-1} [27,28] and from 9 to 1.4 pF, respectively.

Bergqvist and Rudolf [29] showed in 1990 that silicon-based solid-state microphones also can show a high sensitivity. Microphones with a 2 mm × 2 mm diaphragm showed an open-circuit sensitivity of 1.4–13 mV Pa^{-1}. The 5–8 μm thick silicon diaphragm was fabricated using anisotropic etching in a KOH solution and applying an electrochemical etch-stop. The backplate was a glass plate, which was thinned by mechanical polishing (see Fig. 9). The backplate wafer was bonded together with the diaphragm wafer and another silicon and glass wafer. This sandwich of four wafers forms a condenser microphone with a backchamber.

A disadvantage of many silicon condenser microphones appeared to be the decreased sensitivity for high frequencies due to the air-streaming resistance of the narrow air gap. The first microphones with polymer diaphragms were provided with relatively thick air gaps of 20 to 95 μm [11,23,24]. The microphones with silicon nitride and silicon diaphragms were provided with air gaps of 2 μm [27,28] or 4 μm [29]. According to Eq. (12), the air-streaming resistance increases considerably if the air-gap thickness is reduced. Consequently, the frequency response of these microphones was limited to 2 kHz [27,28] and 4 kHz [29] for the most sensitive types, in contrast to flat frequency responses up to 15 kHz for microphones with thicker air gaps [11,24].

TABLE 1. Overview of relevant properties of condenser microphones, fabricated in silicon

Author (year)	Diaphragm area (mm^2)	Air-gap thickness (μm)	Capacitance (pF)	Sensitivity (mV Pa^{-1})	Noise level (dBA SPL)	Upper frequency (kHz)
Hohm [23] (1984)	50	30	9	8.8[a]		8.5[b]
Hohm [27] (1986)	0.64	2	1.4	0.2[a]		>20
	0.64	2	1.4	0.6[a]		20
	0.64	2	1.4	1.6[a]		7
	0.64	2	1.4	2.9[a]		2
	0.64	2	1.4	4.3[a]		2
Sprenkels [25] (1989)	6.0	20	2	25[a]		>15
Murphy [24] (1989)	≈4	25–95	2	4–8		>15
Berqvist [29] (1990)	4	8	3.5	1.4[a]		>16
	4	5	3.5	13[a]		4
Berqvist [17] (1991)	4	2	5	1.6	40	>20
Scheeper [36] (1991)	4	1	≈20	1.4		<0.04
Kühnel [30] (1992)[c]	0.64	2	1–1.2	0.44–10[a]	43	5–20
Kühnel [18] (1992)[d]	1	2		3		16[b]
Bourouina [33] (1992)	0.25	5		0.4		20
	0.5	5		2		7
	1	5		3.5		2.5
	1	7.5		2.4	38	10
Scheeper [37] (1993)	4	3	≈8.6	7.8[a]	30	>14

[a]Open-circuit sensitivity.
[b]For these microphones, the resonance frequency is indicated. For other microphones, the −3 dB cutoff frequency is given.
[c]Backplates with holes or grooves.
[d]Microphone with highly perforated backplate.

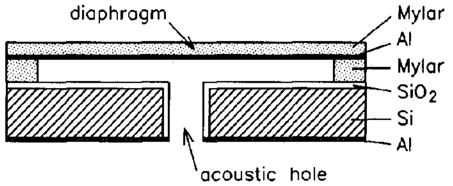


Fig. 6. Schematic cross-sectional view of the silicon electret microphone of Hohm and Gerhard-Multhaupt [23].

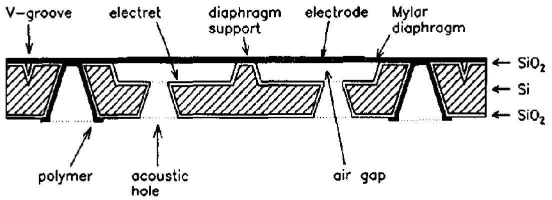


Fig. 7. Schematic cross-sectional view of the silicon electret microphone of Sprenkels [11].

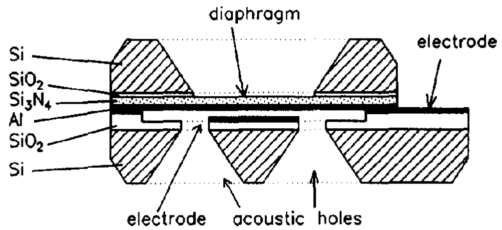


Fig. 8. Schematic cross-sectional view of the silicon condenser microphone of Hohm [27].

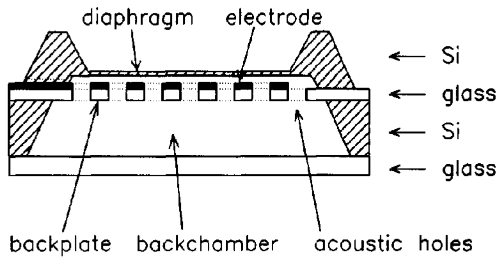


Fig. 9. Schematic cross-sectional view of the silicon condenser microphone of Bergqvist and Rudolf [29].

According to Eq. (12), the air-streaming resistance can be decreased by using a very large number of acoustic holes in the backplate. Bergqvist et al. [17] presented a microphone in 1991 with a thin (≈ 10 μm) backplate, which was provided with 640–4000 acoustic holes per mm^2 (see Fig. 10). The frequency response was flat between 2 and 20 kHz. Kühnel and Hess [18,30] presented condenser microphones with specially designed backplates to reduce the air-streaming resistance. The microphone fabrication process is based on the technology that was developed by Hohm [27,28]. The backplates were provided with anisotropically etched

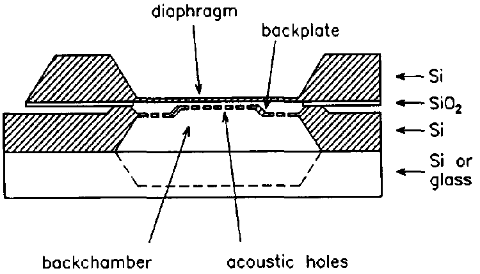


Fig. 10. Schematic cross-sectional view of the silicon condenser microphone of Bergqvist et al. [17].

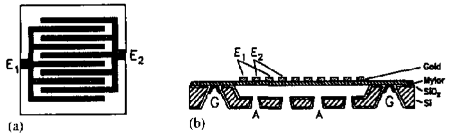


Fig. 11. (a) Top view of the diaphragm and the electrodes of the feedback silicon condenser microphone of van der Donk [31]. (b) Schematic cross-sectional view of the microphone.

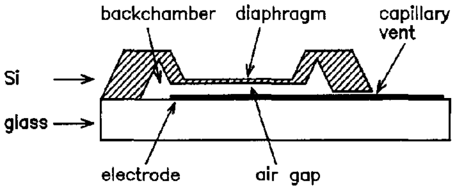


Fig. 12. Schematic cross-sectional view of the silicon condenser microphone of Bourouina et al. [33].

holes [18,30], plasma-etched grooves [18,30] or highly perforated backplates [18]. Flat frequency responses up to 20 kHz were obtained with these microphones.

The problem of the poor frequency response can also be solved by application of an electromechanical feedback system, which reduces the movement of the diaphragm, as proposed by van der Donk et al. [31,32]. The microphones (see Fig. 11) were fabricated according to the technology developed by Sprenkels [11], but with a narrowed air gap (2–3 μm). Furthermore, the diaphragm was provided with two interdigitated electrodes (E_1 and E_2). One interdigitated electrode was used as the normal sensor electrode. The other one was used as actuator electrode for a feedback signal. Using the microphone in a normal way, the cutoff frequencies of the microphones were 20, 30 and 400 Hz, depending on the dimensions. These low cutoff frequencies were caused by the narrow air gap. Using the feedback system, the cutoff frequencies could be increased to 400, 200 and 8000 Hz, respectively.

In 1992, Bourouina et al. [33] presented a new condenser microphone design without acoustic holes, shown schematically in Fig. 12. In order to keep the air-streaming resistance low, a relatively thick air gap was used (5–7.5 μm). The diaphragm was made of p^+ doped silicon. A glass wafer with the counter electrode was bonded to the diaphragm wafer. The backchamber volume was etched in the diaphragm wafer, close to the diaphragm. One of the microphones, with a 7.5 μm air gap, showed a flat frequency response up to 10 kHz.

For all of the capacitive microphones that have been discussed up to now, the diaphragm and backplate were fabricated separately. Some kind of assembly step is necessary to complete the fabrication process. In the microphones of Hohm and Gerhard-Multhaupt [23] and Sprenkels [11], a Mylar foil must be attached to the silicon backplate. In the other microphones, the diaphragm and the backplate are fabricated in different wafers. Sometimes, the wafers are diced first and then the microphones are assembled individually [18,24,28, 30]. This process is not very suitable for series production. Therefore, some authors first bond the backplate and the diaphragm-containing wafer before they are diced into the individual microphones [17,29,33]. However, this process still requires a critical and labour-intensive wafer-alignment before the bonding process. Several wafer bonding methods have been presented [17,34]. Most wafer bonding processes involve high-temperature treatments [17] or high electric field strengths [34]. Such bonding processes may negatively affect the integrated electronics, change properties of temperature-sensitive materials or discharge an electret [11].

The disadvantages of a two-wafer fabrication process can be avoided by using a single-wafer process, as proposed by Hijab and Muller [35]. This fabrication process is based on the sacrificial layer etching process, as originally presented by Nathanson et al. [16].

Microphones that were fabricated using the single-wafer process of Hijab and Muller were presented by Scheeper et al. in 1991 [36]. More results for this type of microphone were presented in 1992 [19]. Owing to the thin air gap (0.8 μm), the measured cutoff frequencies were lower than 100 Hz. Therefore, a new microphone design (shown in Fig. 13) was presented with a high density of acoustic holes (120–525 mm^{-2}) in a thin backplate (1 μm) [19]. In 1993, improved

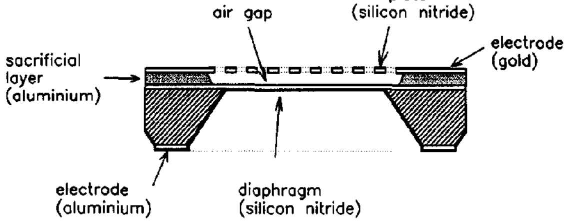


Fig. 13. Schematic cross-sectional view of the single-wafer fabricated silicon condenser microphone of Scheeper et al. [19].

microphones were presented showing an open-circuit sensitivity of 7.8 mV Pa^{-1}, a capacitance of 8.6 pF and a frequency response of 100 Hz to 14 kHz (± 2 dB) [37,38]. Owing to the narrow air gap, these microphones could operate at a relatively low bias voltage, making an electret superfluous.

An advantage of the application of silicon micromachining techniques for the fabrication of capacitive microphones is the possibility to increase the sensitivity by reducing the area of the diaphragm electrode [11,39,40]. Since the deflection near the edge of the diaphragm is very small, the part of the electrode in this area mainly contributes to the parasitic capacitance loading the microphone. Consequently, if this part of the electrode is omitted, the capacitive signal attenuation is reduced, thus increasing the sensitivity.

Silicon condenser microphones for special applications have also been developed, as for instance the microphone for ultrasonic applications of Suzuki et al. [41] and the condenser hydrophone (microphone for underwater acoustic detection), which was presented by Bernstein [42].

4.3. The FET microphone

A silicon condenser microphone with an integrated field-effect transistor was developed by Kühnel in 1991 [6]. A schematic cross-sectional view of the microphone is shown in Fig. 14. The metallized diaphragm served as the movable gate of the field-effect transistor. The microphones showed a sensitivity of 0.2–0.6 mV Pa^{-1} and a flat frequency response between 100 Hz and 30 kHz. In 1992, an improved FET microphone with a sensitivity of 5 mV Pa^{-1} was presented by Kühnel and Hess [18]. An FET microphone with a sensitivity of 38 mV Pa^{-1} was presented by Graf et al. in 1992 [7]. However, this reported sensitivity was measured at the resonance frequency of 7 kHz. At 1 kHz, the sensitivity was about 6 mV Pa^{-1}. This non-flat frequency response is partially caused by the fact that some of these microphones are of the gradient type.

An advantage of the FET microphone is the low output impedance, because the preamplifier is integrated with the microphone. A disadvantage of this type of microphone is the absence of a bias element, which defines a stable gate potential of the FET. Therefore, the long-term stability of the microphones will be affected by drift. Another typical disadvantage of the FET microphones is their relatively high noise levels (62 dBA SPL [18] and 58 dBA SPL [42], respectively).

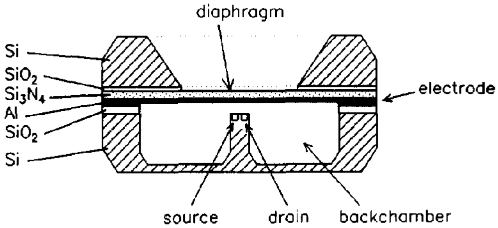


Fig. 14. Schematic cross-sectional view of the FET microphone of Kühnel [6].

Noise measurements of Kühnel [6] have shown that the noise voltage of the FET microphone shows a $1/f^{1/2}$ dependence, indicating that the main source of noise is flicker noise in the channel of the FET. This noise source is described in the first part of the first term of Eq. (14). It can be seen from this equation that the contribution of the channel noise is determined by the ratio of the microphone capacitance and all other parasitic capacitances that are connected to the gate. In the case of the FET microphone, the microphone capacitance C_m is defined by the small part of the diaphragm area above the gate of the FET. The capacitance of the bias element, C_b, which is absent, is zero and the parasitic capacitance C_p is negligibly small. However, owing to the construction of the microphone, the gate-to-source and gate-to-drain capacitances, C_{gs} and C_{gd}, are relatively large. Consequently, it is not surprising that a high noise level is found.

5. Future development of silicon microphones

In order to be competitive with conventionally fabricated microphones, the micromachined silicon microphones should have a low noise level and a high sensitivity, and should be made reproducibly. It is expected that the noise level can be reduced by integration of the microphone with the preamplifier. The parasitic capacitance can be reduced by integration, because a relatively large bondpad can be omitted. Furthermore, the packaging leakage resistance is eliminated. Therefore, according to Eq. (14) integration is expected to result in a lower noise level of the microphone and preamplifier.

A method for increasing the sensitivity of the silicon microphones may be the application of corrugated diaphragms. It has been shown that corrugated diaphragms can have a considerably larger mechanical sensitivity than flat diaphragms of equal size and thickness [43,44]. These diaphragms can easily be made using micromachining techniques. The reproducibility of the deposition process of the diaphragm material is not expected to be critical for the mechanical sensitivity of corrugated diaphragms, in contrast to flat diaphragms [44]. Another advantage of corrugated diaphragms is that the influence of temperature changes and packaging stress on the microphone is greatly reduced [45,46].

Thus, the use of corrugated diaphragms is expected to increase the mechanical sensitivity of microphones, improve the reproducibility of the fabrication process and reduce the influence of temperature and packaging on microphones. Therefore, it is believed that the performance of new silicon microphones can be improved considerably by providing them with corrugated diaphragms.

6. Conclusions

The application of silicon micromachining for the fabrication of microphones has resulted in miniature piezoelectric, piezoresistive and capacitive microphones. Special silicon microphones have been developed for ultrasonic [41] and underwater [42] applications.

The use of silicon as constructional material has resulted in the development of the new FET microphone [6,7] and the integration of microphones with preamplifiers [3,5]. The lithographic techniques have allowed the fabrication of miniature microphones with diaphragms having an area of less than 1 mm^2. Furthermore, silicon micromachining offers the opportunity to fabricate specially shaped backplates [30] and electrodes [11,40] to optimize the sensitivity and the frequency response. Silicon condenser microphones with narrow air gaps have been developed that show a reasonable sensitivity at a low operating voltage (5 V) [17,38]. Consequently, this type of silicon condenser microphone can operate without an electret.

A noise consideration has shown that integration of a capacitive microphone and a preamplifier will result in a reduction of the noise. From this noise consideration, it has also been concluded that the FET microphone shows a high noise level, which is mainly due to the small sensor capacitance with respect to all other parasitic capacitances.

The performance of silicon condenser microphones can be improved further by providing them with corrugated diaphragms and by integration of the microphones with a preamplifier. These developments are believed to be important for future silicon condenser microphones.

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References

[1] O. Brosze, Aufbau und Wirkungsweise elektroakustischer Wandler, *Fernmelde-Ing.*, *35* (6) (1981) 1–36; *35* (7) (1981) 1–35.

[2] G.M. Sessler, Acoustic sensors, *Sensors and Actuators A, 25–27* (1991) 323–330.

[3] 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.

[4] K.E. Petersen, Silicon as a mechanical material, *Proc. IEEE, 70* (1982) 420–547.

[5] 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.

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

[7] 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.

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

[9] R. Schellin, G. Hess, W. Kühnel, G.M. Sessler and E. Fukada, Silicon subminiature microphones with organic piezoelectric layers, *IEEE Trans. Electr. Insul., EI-27* (1992) 867–871.

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

[11] A.J. Sprenkels, A silicon subminiature electret microphone, *Ph.D. Thesis*, University of Twente, 1988.

[12] F. Fraim and P. Murphy, Miniature electret microphones, *J. Audio Eng. Soc., 18* (1970) 511–517.

[13] G.M. Sessler, *Electrets*, Topics in Applied Physics, Vol. 33, Springer, Berlin, 1st edn., 1980, p. 349.

[14] A.G.H. van der Donk, J.A. Voorthuyzen and P. Bergveld, Optimal design of electret microphone MOSFET preamplifier, *J. Acoust. Soc. Am., 91* (1992) 2261–2269.

[15] A.G.H. van der Donk, J.A. Voorthuyzen and P.Bergveld, General considerations of noise in microphone preamplifiers, *Sensors and Actuators A, 25–27* (1991) 515–520.

[16] 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.

[17] 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.

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

[19] 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.

[20] J.E. Warren, Capacitance microphone static membrane deflections: Comments and further results, *J. Acoust. Soc. Am., 58* (1975) 733–740.

[21] P. Morse and K.U. Ingard, *Theoretical Acoustics*, McGraw-Hill, New York, 1st edn., 1968.

[22] Z. Škvor, On the acoustical resistance due to viscous losses in the air gap of electrostatic transducers, *Acustica, 19* (1967) 295–299.

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

[24] P. Murphy, K. Hübschi, N. De Rooij and C. Racine, Subminiature silicon integrated electret capacitor microphone, *IEEE Trans. Electr. Insul., EI-24* (1989) 495–498.

[25] 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.

[26] J.A. Voorthuyzen, P. Bergveld and A.J. Sprenkels, Semiconductor-based electret sensors for sound and pressure, *IEEE Trans. Electr. Insul., EI-24* (1989) 267–276.

[27] D. Hohm, *Kapazitive Silizium-Sensoren für Hörschallanwendungen*, Fortschritt-Berichte VDI, VDI, Düsseldorf, 1986.

[28] D. Hohm and G. Hess, A subminiature condenser microphone with silicon nitride membrane and silicon back plate, *J. Acoust. Soc. Am., 85* (1989) 476–480.

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

[30] 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.

[31] A.G.H. van der Donk, A silicon condenser microphone: modelling and electronic circuitry, *Ph.D. Thesis*, University of Twente, 1992.

[32] A.G.H. van der Donk, P.R. Scheeper, W. Olthuis and P. Bergveld, Amplitude-modulated mechanical feedback system for silicon condenser microphones, *J. Micromech. Microeng., 2* (1992) 211–214.

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

[34] G. Wallis and D.I. Pomerantz, Field-assisted glass–metal sealing, *J. Appl. Phys., 40* (1969) 3946–3949.

[35] R.S. Hijab and R.S. Muller, Micromechanical thin-film cavity structures for low-pressure and acoustic transducer applications, *Proc. 3rd Int. Conf. Solid-State Sensors and Actuators (Transducers '85), Philadelphia, PA, USA, June 7–11, 1985*, pp. 178–181.

[36] 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.

[37] P.R. Scheeper, A silicon condenser microphone: materials and technology, *Ph.D. Thesis*, University of Twente, 1993.

[38] P.R. Scheeper, W. Olthuis and P. Bergveld, Improvement of the performance of microphones with a silicon nitride diaphragm and backplate, *Sensors and Actuators A, 40* (1994) 179–186.

[39] W.H. Ko, M.-H. Bao and Y.-D. Hong, A high-sensitivity integrated-circuit capacitive transducer, *IEEE Trans. Electron Devices, ED-29* (1982) 48–56.

[40] 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.

[41] K. Suzuki, K. Higuchi and H. Tanigawa, A silicon electrostatic ultrasonic transducer, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control, UFFC-36* (1989) 620–627.

[42] J. Bernstein, A micromachined condenser hydrophone, *Proc. IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, USA, June 22–25, 1991*, pp. 161–165.

[43] Y. Zhang and K.D. Wise, Performance of non-planar silicon diaphragms under large deflections, *Tech. Digest, IEEE Micro Electromechanical Systems Workshop, Fort Lauderdale, FL, USA, Feb. 1993*, pp. 284–288.

[44] P.R. Scheeper, W. Olthuis and P. Bergveld, The design, fabrication and testing of corrugated silicon nitride diaphragms, *IEEE J. Microelectromech. Syst.*, submitted for publication.

[45] V.L. Spiering, S. Bouwstra, R.M.E.J. Spiering and M. Elwenspoek, On-chip decoupling zone for package-stress reduction, *Tech. Digest, 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA, June 24–28, 1991*, pp. 982–985.

[46] H.L. Offereins, H. Sandmaier, B. Folkmer, U. Steger and W. Lang, Stress free assembly technique for a silicon based pressure sensor, *Tech. Digest, 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA, June 24–28, 1991*, pp. 986–989.

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