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

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

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. 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, $d\omega$, resulting from an increase in the pressure, $dP$, acting on the diaphragm.

$$S_m = \frac{d\omega}{dP}$$  \hspace{1cm} (1)

Note that $d\omega = -ds_{ao}$, 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]

$$S_m = \frac{R^2}{8\alpha \sigma h_d}$$  \hspace{1cm} (2)

where $R$ is the radius of the diaphragm, $\sigma$ the diaphragm stress and $h_d$ the diaphragm thickness. In eqn (2) it is assumed that the compression of air in the back-chamber 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, $ds_{ao}$, and the resulting change in the voltage across the air gap, $dV$, is given by the electrical sensitivity of the microphone.

$$S_e = \frac{dV}{ds_{ao}}$$  \hspace{1cm} (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

$$ S_e = E_a = \frac{V_b}{S_{s0}} \tag{4} $$

where $V_b$ is the d.c. bias voltage of the microphone.

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

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

Note that a minus sign has been introduced in eqn (5), because $dS_m = -d\omega$. 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 $S_{\text{meas}}$ is equal to

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

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]

$$ V_{\text{max}} = \left( \frac{64 \sigma_d h_s e_0}{27 e_0 R^2} \right)^{1/2} \tag{8} $$

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 analogs, 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 $R_c$ describes the frictional force due to radiation of sound back into the surrounding medium. The inductance $L_c$ 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
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 Skvor [24]

$$R_a = \frac{12 \eta_a}{\pi^2 R^2 n^2 s_{a0}} B(A)$$  \hspace{1cm} \text{(9)}$$

with

$$B(A) = \frac{1}{4} \ln \left( \frac{1}{A} - \frac{3}{8} + \frac{1}{2} A - \frac{1}{8} A^2 \right)$$  \hspace{1cm} \text{(10)}$$

where $\eta_a$ is the viscosity of air ($17.1 \times 10^{-6}$ 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 ($0 < A < 1$).

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 $f_c$.

$$f_c = \frac{n s_{a0}^3}{24 \eta_a B(A) (S_{m d} + S_{m bp})}$$  \hspace{1cm} \text{(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 Kjaer 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 Kjaer 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 $1 \times 10^6$ and $1.5 \times 10^6$ 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 5 Measured frequency responses of the three microphones with a 2 mm x 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 15, 40 and 80 V, respectively.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Microphone</th>
</tr>
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<tbody>
<tr>
<td>σ₀ (×10⁷ N m⁻²)</td>
<td>0.26 1.8 1.8 1.8</td>
</tr>
<tr>
<td>hₐ (μm)</td>
<td>1.0 1.0 0.24 0.24</td>
</tr>
<tr>
<td>n (mm²⁻)</td>
<td>121 121 121 242</td>
</tr>
</tbody>
</table>

*Fixed parameters for all microphones are diaphragm area 2 mm x 2 mm, diaphragm stress σ₀ = 1.5×10⁷ N m⁻², backplate thickness hₐ = 1 μm, air-gap thickness s₀ = 31 μm and acoustic hole area 40 μm x 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 (18 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 2.6×10⁷ N m⁻² and 1.8×10⁷ 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 110 and 40 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 10 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
The measured frequency responses of type B and C microphones (a) type C, 50 V dc bias, (b) type B, 110 V dc bias.

The measured frequency responses of type C and D microphones (a) type D, 50 V dc bias, (b) type C, 5 V dc 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 50 V dc bias voltage. The collapse voltage of the type D microphone is 80 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 50 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 (50 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 10 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 x 200 μm bondpad (20 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 x 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 15 mm x 15 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 mi-
microphones show a sensitivity of 50 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 50 V, which is about 60% of the collapse voltage A 50 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

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
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
32 P R Scheeper, W Oltius and P Bergveld, The design, fabrication and testing of corrugated silicon nitride diaphragms, *IEEE J Microelectromech. Sys.*, accepted for publication
34 A J Sprenkels, A silicon subminiature electrrect microphone, *Ph D Thesis*, University of Twente, 1988

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**Pet 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