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A silicon condenser microphone with polyimide diaphragm and backplate

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Abstract

A new technology for the fabrication of silicon condenser microphones is presented. The technology, which is based on the use of polyimide, can be performed entirely as a post process on substrates already containing integrated circuits. Microphones with an open-circuit sensitivity of 8.1 mV Pa^{-1}, and a flat frequency response (±2 dB) between 100 Hz and 15 kHz have been fabricated with this technology. The bias voltage used in these measurements is 15 V, and the measured noise level with zero bias is 24 dB SPL, which is sufficient for most acoustic applications, including hearing aids. © 1997 Elsevier Science S.A.

Keywords: Silicon condenser microphones; Polyimide; IC-compatible sensors

1. Introduction

The condenser microphone is one of the classical capacitive sensors, of which few devices have been presented with on-chip detection circuitry [1,2]. Even though the advantages of integration, notably smaller parasitic capacitances, higher sensitivity [2], and lower noise generation [3], are desirable, the silicon condenser microphones prove difficult to combine with electronic fabrication technologies. Ever since the first developments of silicon-based condenser microphone structures, by Hohm and Hess [4], efforts have been made to improve the performance and flexibility of these devices. The result has been the evolution of several different microphone structures [5–9]. Common for all these designs is the small air gap between the diaphragm and the backplate, whereby the required d.c. bias voltage (V_b) has been reduced from > 100 V to 10–20 V. However, since all these devices consist of two separately processed parts, which are later bonded or glued together, they are considered to be less suitable for integration with electronic circuitry. One of the first condenser microphones made on a single chip was presented by Scheeper et al. [10]. This design comprised a thin-film diaphragm and backplate made with a combined bulk- and surface-micromachining process. Later, condenser microphones with a similar structure, but with different thin-film materials were demonstrated [1,11,12].

In this paper, a new condenser microphone structure is presented. The structural design is similar to that of Scheeper et al. [10], however, the materials and the fabrication process are different. Since the fabrication process only consists of low-temperature (<300°C) spin-on, baking, evaporation and etching processes, it is believed that the process may be performed as a post-process on substrates where electronic circuits have already been completed. The advantage of this approach is that the structures can be integrated with any electronic process, without any adaptation required of the complex IC fabrication process. In the following it will be shown that the introduction and use of polyimide for the mechanical parts of the microphone improves the IC compatibility of the whole fabrication process. Polyimide has previously been applied in micromechanical structures [13,14], and polymer diaphragms have already been applied in silicon electret microphones by Sprenkels et al. [15].

2. Device technology

The microphone structure (Fig. 1) is in principle similar to that of Scheeper et al. [10], where the backplate is placed

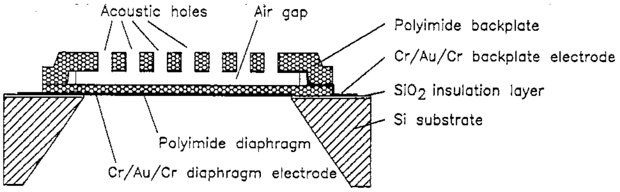

Fig. 1. Cross-sectional view of a condenser microphone with polyimide membrane and backplate.

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on top of the diaphragm with a sacrificial layer in between, which is etched away to create the air gap, and where the etch holes in the backplate function as the necessary acoustic holes in the finished microphone.

In contrast to previous designs of this structure, the diaphragm and backplate are made of a polymer (polyimide). The use of this material offers several advantages over more conventional micromechanical materials. First, and most important, the processing of the material is very simple. If a photosensitive polyimide is used, the process of deposition and patterning is like a conventional lithographic process followed by a low-temperature (300°C) curing of the polyimide. Secondly, the polyimide can be made with thicknesses from < 1 μm to > 30 μm, which makes it possible to produce thin diaphragms as well as thicker backplates with one and the same technology. The lack of this possibility has until now been one of the problems of the single-chip microphone structure. By placing the backplate electrode under the backplate, problems with step coverage over the thick backplate can be eliminated. Lastly, the polyimide layers can generally be made with lower built-in stress than conventional materials, yielding microphones with higher sensitivities.

For the metal electrodes in the structure, Cr/Au/Cr multilayers were chosen. These layers comprise the good combination of the relatively low stress of Au and the supreme adhesion of Cr on polyimide [16]. Since the cured polyimide is chemically very stable in acid solutions, layers of Al or Ag may be used for the sacrificial layer, and subsequently etched very selectively. The etching of the silicon substrate is first carried out with KOH, until ≈ 50 μm of silicon remains in the sensor area. The remaining silicon is then etched with reactive ion etching (RIE), where the Cr/Au/Cr diaphragm electrode acts as an etch stop.

3. Theory of operation

The normal way to operate the condenser microphone is to apply an electrical field between the diaphragm and the backplate, by means of a d.c. bias voltage. Consequently, any movement of the diaphragm with respect to the backplate may be detected as a change of potential across the microphone.

3.1. Dynamic model

The dynamic properties of the transducer can be derived by applying the analogy between the acoustic, mechanical and electrical domains [17], and the mechanical equivalent circuit is shown in Fig. 2. The mechanical source represents the force applied by the harmonic sound pressure p, acting on the square diaphragm with side length L. The mechanical resistance $R_{\mathrm{r}(\omega)}$ and inductance M_{r} account for the radiation impedance of the diaphragm, and are given by

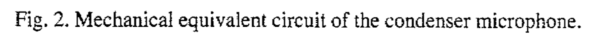

Fig. 2. Mechanical equivalent circuit of the condenser microphone.

$$R_{\mathrm{r}(\omega)}=\frac{0.1886}{\pi^3}\frac{L^6\rho_0\omega}{c^3}\quad M_{\mathrm{r}}=\frac{2.67L^3\rho_0}{\pi\sqrt{\pi}} \tag{1}$$

where ρ_0 is the density of air, ω is the angular frequency and c is the speed of sound in air.

If the flexural rigidity of the diaphragm and the backplate is assumed to be dominated by the intrinsic stress, the compliances C_{d} and C_{b} are defined as

$$C_{\mathrm{d}}=\frac{1}{30\sigma_{\mathrm{d}}h_{\mathrm{d}}}\quad C_{\mathrm{b}}=\frac{1}{30\sigma_{\mathrm{b}}h_{\mathrm{b}}\sqrt{1-\frac{4a^2}{b^2}}} \tag{2}$$

in which the σ_{d}, σ_{b} and h_{d}, h_{b} are intrinsic stresses and thicknesses of the diaphragm and the backplate, and $2a$ and b are the size and centre-to-centre distance of the acoustic holes in the backplate. The mass of the diaphragm and the backplate are given by

$$M_{\mathrm{d}}=\rho_{\mathrm{d}}h_{\mathrm{d}}L^2\quad M_{\mathrm{b}}=\rho_{\mathrm{b}}h_{\mathrm{b}}L^2\sqrt{1-\frac{4a^2}{b^2}} \tag{3}$$

where ρ_{d} and ρ_{b} are the densities of the diaphragm and the backplate.

The mechanical impedance caused by air streaming in the narrow air gap between the diaphragm and the backplate has been derived by Skvor [18] for a non-compressible laminar flow and is given by

$$R_{\mathrm{a}}=\frac{1.22\eta\pi L^2b^2}{h_{\mathrm{a}}^3}B\quad M_{\mathrm{a}}=\frac{0.102\rho_0\pi L^2b^2}{h_{\mathrm{a}}}B \tag{4}$$

where η is the dynamic viscosity of air, h_{a} is the height of the air gap, and B is defined as

$$B=\frac{1}{4}\ln\left(\frac{0.160b^2}{a^2}\right)-\frac{3}{8}+3.133\frac{a^2}{b^2}-4.907\frac{a^4}{b^4} \tag{5}$$

Furthermore, the streaming of air in the acoustic holes in the backplate causes an impedance described by R_{h} and M_{h}. By considering the holes as narrow slits [19], this impedance can be expressed by

$$R_{\mathrm{h}}=\frac{12\eta h_{\mathrm{b}}L^2}{b^2}\quad M_{\mathrm{h}}=\frac{24\rho_0h_{\mathrm{b}}a^2L^2}{5b^2} \tag{6}$$

The enclosed volume in the backchamber, which is required to provide the dynamic pressure difference across the diaphragm, gives rise to the mechanical compliance C_{bc}. If the air in the backchamber is assumed to be an ideal gas, the compliance is given by [19]

$$C_{\mathrm{bc}}=\frac{V}{\rho_0c^2L^4} \tag{7}$$

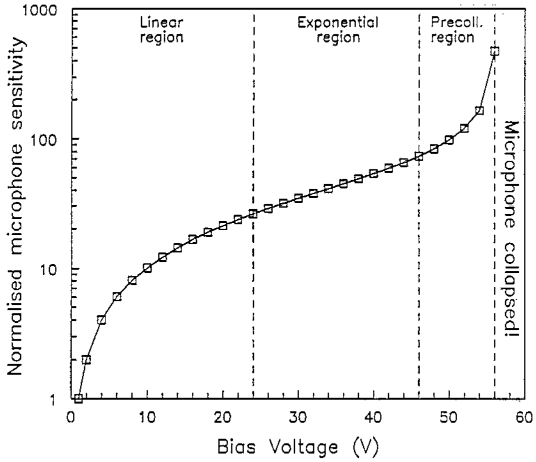

Fig. 3. Typical result of the quasistatic analysis. Normalized sensitivity vs. d.c. bias voltage.

where V is the volume of the backchamber. In the measurements presented later in this paper, however, the volume, and consequently the compliance of the backchamber, was assumed to be infinitely large.

By calculating the flows v_d and v_b in the mechanical equivalent circuit, the velocities of the diaphragm and the backplate may be determined. If the applied sound pressure is harmonic, the displacement of the diaphragm and backplate can be derived simply by dividing the velocities by the angular frequency ω. For frequencies below the resonance frequencies of the diaphragm and the backplate, the two displacements will be in phase and must consequently be subtracted to attain the effective variation of the air gap x_a. The output signal of the microphone is calculated by multiplying the electrical field in the air gap by the differential displacement:

$$v_{\text{out}} = Ex_a = E(x_d - x_b) = E\frac{v_d - v_b}{\omega} \qquad (8)$$

Considering the structure in Fig. 1, the effective electrical field in the air gap is given by

$$E = K\frac{\epsilon_d V_{\text{bias}}}{\epsilon_d h_a + h_d} \qquad (9)$$

where ϵ_d is the relative dielectric constant of the diaphragm material, V_{bias} is the applied bias voltage and K is a factor accounting for the field reduction due to the holes in the backplate. The sensitivity of the microphone is given by dividing the output signal by the applied acoustic sound pressure, yielding the following expression:

$$S = \frac{v_{\text{out}}}{p} = K\frac{\epsilon_d(v_d - v_b)}{p\omega(\epsilon_d h_a + h_d)}V_{\text{bias}} \qquad (10)$$

3.2. Quasistatic model

Another important aspect of the condenser microphone is the stability. The problem of stability is mainly caused by the electrostatic forces induced by the bias voltage. This attraction force between the diaphragm and the backplate may cause a collapse of the structure if the bias voltage or consequently the electrical field is too high. The stability of this non-linear system can be analysed in the quasistatic situation for frequencies far below roll-off and/or resonances, where the deflection of the diaphragm and the backplate can be described by a non-linear coupled differential equation system [20], the stability of which coincides with the stability of the microphone. A detailed description of the theory and simulation of this system can be found elsewhere in the literature [20,21], and will only be illustrated here by a typical result of such an analysis. In Fig. 3, the normalized quasistatic sensitivity is shown as function of the applied d.c. bias voltage. As can be seen, it is possible to divide the mode of operation into four different regions. In the first linear region, the electrostatic forces are insignificant and the sensitivity consequently increases linearly with the increase of the electrical field. In the exponential region the electrostatic forces become more significant, causing an exponential dependence of the sensitivity on the bias voltage. For higher voltages in the pre-collapse region, the electrostatic forces are very dominating, whereby the dependence becomes stronger than exponential. Finally, above the critical bias voltage the structure collapses, and no solution to the quasistatic equation system exists.

The material parameters and dimensions of the two realized microphone structures are given in Table 1, and the behaviour has been simulated with both the dynamic and quasistatic models. The built-in stress in the polyimide was

Table 1
Material parameters and microphone dimensions

Young's modulus (diaphragm/backplate)	7 GPa
Poisson's ratio (diaphragm/backplate)	0.45
Density (diaphragm/backplate)	1430 kg m^{-3}
Relative dielectric constant (diaphragm)	3.4
Intrinsic stress in diaphragm	70 MPa
Intrinsic stress in backplate	40 MPa
Thickness of diaphragm	0.9 μm
Thickness of backplate	18 μm
Air gap	1.5 μm
Side length	1.6 mm (**A**), 2.1 mm (**B**)
Acoustic hole size in backplate	75 μm × 75 μm (**A**), 100 μm × 100 μm (**B**)
Acoustic hole fraction in backplate	36% (**A**), 44% (**B**)

measured separately with the wafer bending method, from which a tensile stress of 40 MPa was determined. In the thin polyimide diaphragm, the tensile stress in the Cr/Au/Cr electrode layer is also significant, and has been measured to be as high as 1 GPa. For a 0.9 μm thick polyimide diaphragm with a 30 nm thick Cr/Au/Cr electrode, this yields an overall stress of approximately 70 MPa. In Fig. 4, the simulated dynamic response of the two microphones is shown for a d.c. bias voltage of 15 V. It can be seen that both responses are flat in the frequency range between 100 Hz and 15 kHz, which implies that the hole fraction in the backplate is sufficient. From the calculations open-circuit sensitivities of −44.1 dBV Pa^{-1} (6.2 mV Pa^{-1}) and 40.2 dBV Pa^{-1} (9.8 mV Pa^{-1}) are predicted for type **A** and **B**, respectively. Furthermore, the resonance frequencies of the diaphragm and the backplate were calculated to be 91.3 and 100.0 kHz for type **A**, and 66.3 and 77.8 kHz for type **B**. The open-circuit sensitivity was also simulated as a function of the d.c. bias voltage with the quasistatic model, yielding the curves in Fig. 5. From these simulations a critical bias voltage of 23.5 V for type **A** and 19.0 V for type **B** was calculated.

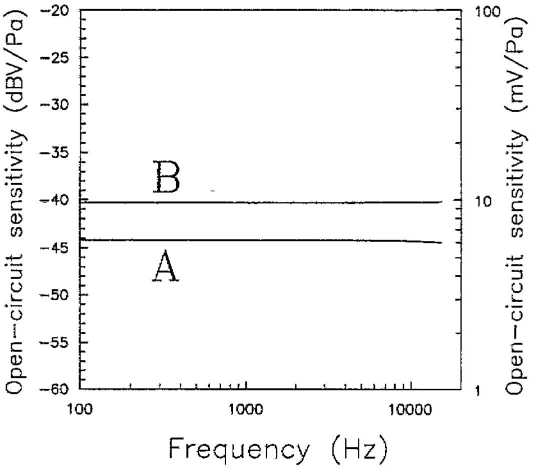

Fig. 4. Simulated frequency response of the two polyimide condenser microphones (**A**: 1.6 mm, **B**: 2.1 mm) with $V_{bias} = 15$ V.

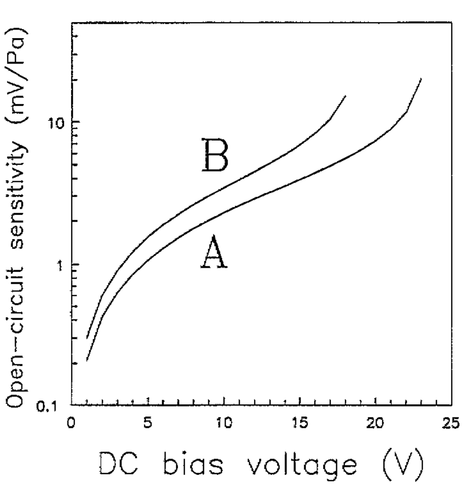

Fig. 5. Simulated open-circuit sensitivity vs. d.c. bias voltage for the two polyimide condenser microphones (**A**: 1.6 mm, **B**: 2.1 mm).

4. Device fabrication

Microphones have been fabricated using the process shown in Fig. 6. The silicon substrates used were 3″, ⟨100⟩, p-type, 5 Ω cm wafers. The thickness of the substrates was 400 μm. First, a 1.5 μm thick layer of SiO_2 was grown by wet oxidation at 1150°C. The SiO_2 was subsequently etched in BHF to define the active sensor area on the backside of the substrate. During the etching, the front was protected with photoresist. The substrate was then etched in a KOH solution (33 wt.%, 73°C) until the thickness in the sensor area was reduced to approximately 50 μm (Fig. 6(a)). After rinsing, a thin diaphragm electrode was evaporated and patterned on the front, using a standard lift-off process with photoresist. The electrode was a Cr/Au/Cr multilayer, with a thickness of 4/20/4 nm.

The first layer of polyimide, which is later to be the diaphragm, was then spun on the front. The photosensitive polyimide was HTR3-200 from OCG Microelectronics, and in order to obtain a sufficiently thin layer, a 5:1 solution of polyimide and the solvent NMP (*N*-methylpyrrolidone) was used. To improve the adhesion on the SiO_2 surface, a γ-APS (aminopropyltriethoxysilane) promoter was applied before the spinning of the polyimide. For the polyimide layer, a speed of 4000 rpm and a time of 1 min were used, yielding a layer with an approximate thickness of 1 μm. After a prebake for 25 min at 90°C to remove the solvent, the layer was exposed to 350 nm UV light with an energy of 15 mW cm^{-2} for 15 s, and baked for 10 min at 90°C. This intermediate bake was done to enhance the prepolymerization of the exposed areas. Thereafter, the layer was developed for 1 min in HTRD-3 polyimide developer from OCG Microelectronics, and subsequently rinsed in IPA (isopropyl alcohol). The polyimide was then cured for 1 h at 300°C in an N_2 atmosphere, and the thickness of the polyimide diaphragm was measured with a SLOAN-DEKTAK Surface Profiler to be 0.8–0.9 μm. An Al sacrificial layer was then deposited and patterned, using electron-beam evaporation and a standard

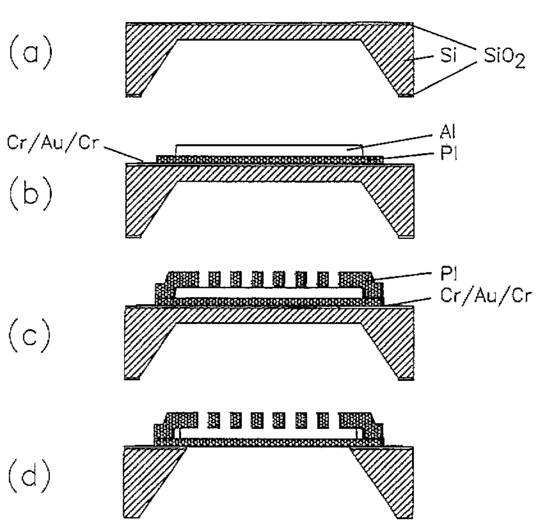

Fig. 6. Fabrication process of the microphone.

Al etch solution. The thickness of the sacrificial layer was 1.5 μm (Fig. 6(b)).

Subsequently, the backplate electrode was deposited and patterned using resistive evaporation and lift-off. The thickness of the Cr/Au/Cr multilayer electrode was 10/200/10 nm. After rinsing the substrate, the polyimide backplate layer was spun on to the front using a process similar to that described for the diaphragm. However, for this layer a pure solution of the photosensitive polyimide HTR3-200 was used, and with a spin speed of 2500 rpm for 20 s a layer thickness ≈ 18 μm was realized after curing. The sacrificial Al layer was then etched for 3 h using the standard Al etch solution (Fig. 6(c)).

After rinsing, the structures were dried using a freeze-drying technique, in which the substrate was first soaked in IPA for 1 h, thereafter in cyclohexane for 30 min, and was finally frozen in an N_2 atmosphere until all of the cyclohexane was sublimated. This process, which is standard for polysilicon and silicon nitride structures, is normally used to reduce the problem of sticking in the structures. Later experiments, however, showed that the problem of sticking is much smaller for the polyimide structures than for comparable silicon nitride structures, and a simple drying of the structures by heating may therefore be applied. The final step in the fabrication process was to release the polyimide diaphragms by etching the remaining silicon under the diaphragm. This was done in an Electrotech PF 340 reactive ion etch reactor using an SF_6 plasma with a flow of 12 sccm, a pressure of 120 mtorr and an r.f. power of 75 W. During the etching, the areas around the sensor were not protected, meaning that the substrate was thinned down to approximately 300 μm (Fig. 6(d)). The precision of the side length of the diaphragms is determined by the thickness variation of the silicon substrate, in combination with the uniformity of the dry etch process. In the realized devices, deviations of less than 5% were measured.

With this fabrication process condenser microphones with side lengths of 1.6 mm (type **A**) and 2.1 mm (type **B**), have been fabricated. The SEM photograph in Fig. 7 shows the front of a completed microphone. Clearly visible are the perforated backplate and the two bond pads for electrical connection. In Fig. 8, a close-up of one of the acoustic holes is shown, and the air gap between the backplate and the polyimide diaphragm may be distinguished.

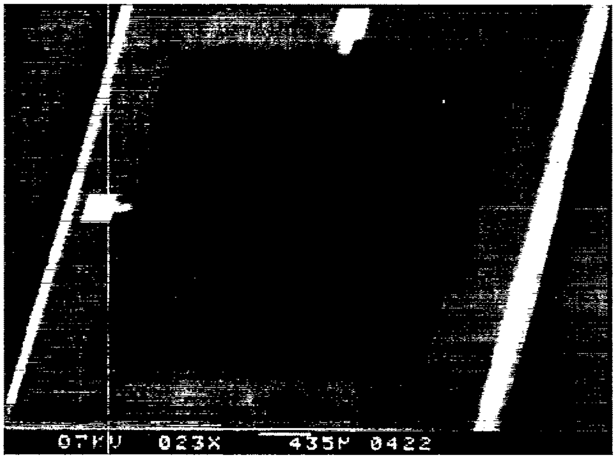

Fig. 7. SEM photograph of the front of the polyimide condenser microphone.

Fig. 8. Close-up SEM photograph of the polyimide backplate.

5. Measurements and results

For the characterization of the devices a set-up was used which allows acoustoelectric measurements to be made directly on wafer scale. This greatly improves the turnover time, since a precise acoustic measurement can be done without having to separate and mount the microphones. The acoustic set-up, which has been described in greater detail elsewhere [22], basically consists of a loudspeaker and a reference microphone. The volume inside the sealed acoustic chamber is very small, thereby allowing closed-field measurements. In the top of the chamber a small opening is made, over which one of the microphones (MUT) on the wafer under test can be placed. The electrical connections to the device are made with standard probe needles, and a small hybrid preamplifier is used to minimize the electrical loading of the connections. The set-up is controlled by a Hewlett-Packard 35670A Dynamic Signal Analyzer, which drives the loudspeaker and measures the output of the reference microphone and the MUT.

The acoustic measurements were done with the swept sine option with auto levelling on the HP Analyzer. In this mode the analyzer performs individual measurements at a number of frequencies within the specified frequency range, and uses the signal from the reference microphone in a feedback loop to adjust the output of the loudspeaker to the specified sound pressure. The advantage of this method over measurements with random noise is that the frequency characteristic of the loudspeaker can be compensated for, thereby ensuring the best signal-to-noise ratio in the specified frequency range. The sound pressure used in the measurements was 2 Pa (100 dB SPL), and the average parameters measured from four samples of each type are given in Table 2.

Table 2
Microphone specifications

	Type **A**	Type **B**	Conditions
Size	1.6 mm	2.1 mm	
Capacitance	14.9 pF	18.5 pF	
Open-circuit sensitivity	-45.8 dBV Pa^{-1} (5.1 mV Pa^{-1})	-41.8 dBV Pa^{-1} (8.1 mV Pa^{-1})	f= 1 kHz bias voltage: 15 V
Critical bias voltage	23 V	21 V	sound pressure: 100 dB SPL
A-weighted noise voltage	2.5 μV_{rms}	25 μV_{rms}	bias voltage: 0 V
	5.5 μV_{rms}	8.0 μV_{rms}	bias voltage: 15 V
Equivalent noise level	28 dBA SPL	24 dBA SPL	bias voltage: 0 V
	35 dBA SPL	34 dBA SPL	bias voltage: 15 V

A correction function was measured by placing a 1/8″ Bruel and Kjær reference microphone (4138) over the small opening. This correction function was later used to remove effects generated by the set-up from the measured spectra. Furthermore, since the output impedance of the microphone is very high, the parasitic capacitances in the set-up will load the microphone, which reduces the measured sensitivity. To calculate the open-circuit sensitivity of the microphone, which is a more general parameter, the electrical loading must be determined. To measure this, the d.c. voltage source for the biasing of the microphone was replaced by a 100 mV a.c. source, and the analyzer was used to measure the amplification/loading of the set-up [22]. The measured amplifications at 1 kHz were -10.8 dB for **A** and -9.8 dB for **B**. Furthermore, the capacitances of the microphones were determined with a Hewlett-Packard 4194A Impedance Analyzer. The measured values, 14.9 pF (**A**) and 18.7 pF (**B**), are in reasonable agreement with the calculated values 12.3 pF (**A**) and 21.2 pF (**B**). The differences may be explained by deviations in the height of the air gap, and residues of the Al sacrificial layer at the boundaries of the structure.

In Fig. 9, the corrected open-circuit frequency responses (V_b = 15 V) of two microphones of the type **A** and **B** are shown. From the Figure it may be seen that open-circuit sensitivities of -45.8 dBV Pa^{-1} (5.1 mV Pa^{-1}) and -41.8 dBV Pa^{-1} (8.1 mV Pa^{-1}) were measured at 1 kHz for **A** and **B**, respectively. Furthermore, the frequency responses appear to be flat within ±2 dB in the range between 100 Hz and 15 kHz. The small slope of the responses is believed to be caused by leakage from the acoustic chamber, and not by an effect in the microphones.

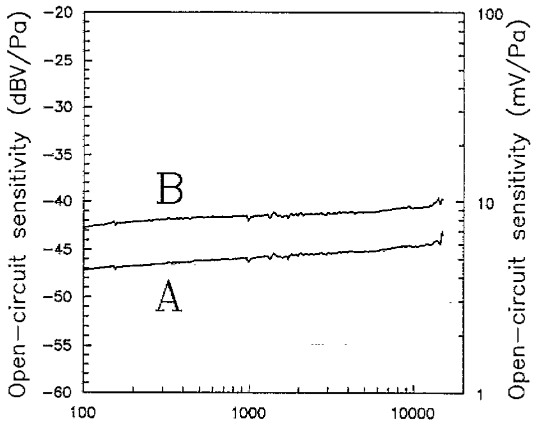

Fig. 9. Measured frequency responses of two polyimide condenser microphones (**A**: 1.6 mm, **B**: 2.1 mm) with V_{bias} = 15 V.

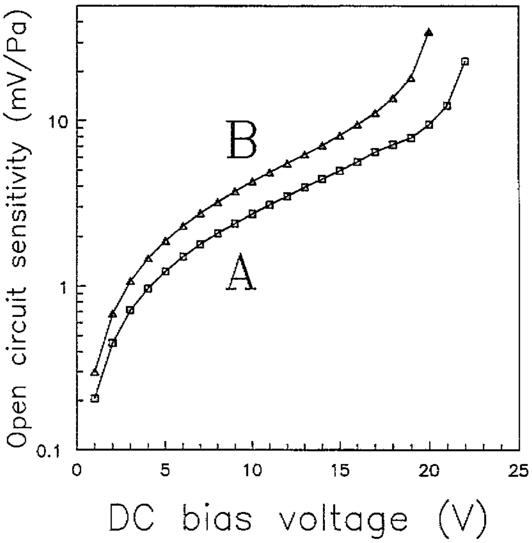

Fig. 10. Measured open-circuit sensitivity vs. d.c. bias voltage for two polyimide condenser microphones (**A**: 1.6 mm, **B**: 2.1 mm).

The stability of the microphones has been investigated for different d.c. bias voltages. In Fig. 10, the open-circuit sensitivities of **A** and **B** are plotted as a function of the bias voltage, and the critical bias voltage was measured to be ≈22 V for **A** and ≈20 V for **B**. Furthermore, experiments show that the devices are able to recover from collapse by removing the bias voltage, and since the electrodes are always insulated, the input of the preamplifier is protected against the d.c. bias voltage, even if a collapse occurs. Comparing the measurements in Fig. 9 and Fig. 10 with the simulations from Fig. 4 and Fig. 5, excellent correlation is found between the theory and the experiments.

The noise, which has previously been shown to be dominated by the preamplifier [3], was measured using a Brüel and Kjær 2610 Measuring Amplifier. The A-weighted noise at the output of the preamplifier was -112 dBV$_{rms}$ (2.5 μV_{rms}). This was measured with zero bias voltage, because the acoustic noise level around the set-up was not sufficiently low (≈35 dBA SPL). If the microphones are used with a d.c. bias voltage of 15 V, the equivalent noise level is 28 dBA SPL for **A** and 24 dBA SPL for **B**, which can be considered to be the ultimate performance.

6. Conclusions

In this paper, a new fabrication technology for silicon condenser microphones has been presented. The technology, which is based on the use of polyimide to create diaphragms as well as backplates, contains only low-temperature (<300°C) process steps that are all in principle compatible with preprocessed integrated circuits. This means that the microphone process can be carried out on substrates on which electronic circuits have been completed. This approach proves to be flexible, because the fabrication of the microphone does not depend on the selection of the electronic circuit process, and vice versa. A remaining issue of compatibility is the etching of the substrate, which if performed with wet chemical etching (e.g., KOH) will require physical protection of the electronic circuits on the substrate. This can be achieved by utilizing a special fixation during the etching, in which the front of the substrate is not in contact with the etching liquid. A different approach, which is currently being adopted, is to eliminate the wet chemical etching all together, and to etch through the substrate by means of dry etching, utilizing an anisotropic etch process [23]. In that case, no special protection of the substrate is required and the etch mask on the backside can be an evaporated metal (i.e., Cr).

The use of polyimide offers some advantages, compared to existing technologies, concerning the microphone performance. First, the elastic modulus and the built-in stress are relatively low, potentially yielding diaphragms with a larger mechanical sensitivity than silicon nitride. Secondly, the polyimide layers can be made with thicknesses from < 1 μm to > 30 μm, meaning that the backplate can be thicker than what can be made with most thin-film technologies. The performance of the realized microphones is encouraging, especially concerning the noise levels. A major reason for this is that the source capacitance of these microphones is relatively large.

The sensitivity to humidity is a well-known feature of polyimide, and is caused by absorption of water molecules in the film. This leads to a change of relative permittivity of up to 35% over the full humidity range [16]. However, assuming a 35% change of the dielectric constant in the dynamic model described above yields a change of sensitivity of less than 0.5 dB, and may therefore be disregarded. The coefficient of thermal expansion (CTE) of conventional photosensitive polyimide is typically 40–50 ppm $^\circ C^{-1}$ [16], which is significantly larger than that of the silicon substrate (3.2 ppm $^\circ C^{-1}$). For increasing temperatures, the stress in the diaphragm will therefore decrease, and for a Young's modulus of the diaphragm of 3 GPa, the stress reduction will be approximately 0.25 MPa $^\circ C^{-1}$. A reduction of the stress leads to an increase of the microphone sensitivity, which was calculated with the dynamic model to be 2.9 dB for an increase from room temperature (20°C) to 100°C. The introduction of new polymides with lower CTE [24] may in the future help to improve the thermal stability of the devices.

In conclusion, it can be stated that the use of polyimide has been shown to be useful for microphones, and it is currently being applied in the fabrication of microphones on substrates containing CMOS circuits. Furthermore, investigations into other applications, such as pressure sensors and accelerometers, are being carried out, and it is believed that the technology may provide a useful alternative to the fabrication of these devices, with or without on-chip electronic circuitry.

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