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Sensors and Actuators A 63 (1997) 163–168

SENSORS AND ACTUATORS A PHYSICAL

An IC-compatible polyimide pressure sensor with capacitive readout

M. Pedersen *, M.G.H. Meijerink, W. Olthuis, P. Bergveld

MESA Research Institute, University of Twente, PO Box 217, NL-7500 AE Enschede, Netherlands

Received 27 August 1996; revised 16 January 1997; accepted 30 January 1997

Abstract

A capacitive differential pressure sensor has been developed. The process used for the fabrication of the sensor is IC-compatible, meaning that the device potentially can be integrated on one chip with a suitable signal-conditioning circuit. A sensor for a differential pressure of ± 1 bar has been fabricated and tested with a frequency-modulated detection circuit, and good agreement is found with the theoretical model of the sensor. A nominal sensitivity $\Delta C/C$ of 17% has been measured for a positive differential pressure of 1 bar. The resolution of the complete detection system is 2.5 mbar (250 Pa). © 1997 Elsevier Science S.A.

Keywords: Capacitive sensors; Differential sensors; Integrated sensors; Polyimide; Pressure sensors

1. Introduction

The development of integrated capacitive pressure sensors fabricated by means of micromechanical processes [1–8] has until now been hampered by the complexity of the structures and the fabrication process. It is well known that the capacitive detection principle is supreme, concerning sensitivity and power consumption. However, since the electrical capacitances are normally very small, the electrical connections to the sensor are very sensitive to parasitics and noise. Therefore, it is desirable to make the connections as short and well-defined as possible. The ultimate solution to this problem is to integrate the sensor directly on the same chip as the signal-conditioning circuit, whereby the physical distance between the two elements is both short and well defined. The basic problem of integrating a sensor and an integrated circuit is that the fabrication processes have to be compatible. Since the fabrication processes used for electronic circuits are very complex and sensitive to even small changes or modifications, the introduction of a sensor process has to be considered carefully. Previously, many suggestions how to approach this problem have been given.

One of the first integrated capacitive pressure sensors was presented by Sander et al. [1]. This sensor was fabricated by bonding a glass plate, containing the counter electrode, to the silicon wafer, in which a diaphragm was etched. This approach laid the foundation for many later developments [2–6] of capacitive pressure sensors with different integrated signal-conditioning circuits. Lately, single-substrate sensors made by surface micromachining have been proposed [7,8], whereby the need to bond the silicon substrate to another substrate has been eliminated. This must be considered as an improvement, since the bonding processes until now have been difficult to control, and therefore have had a relatively low yield. Since this process is normally one of the last in the complete process line, a yield as close to 100% as possible is absolutely essential. The integrated single-chip pressure sensors of Kung and Lee [7] and Dudaicevs et al. [8] both had a polysilicon membrane, which was formed by introducing extra process steps in a standard CMOS process. Unfortunately, this approach may have an influence on the characteristics of the electronic circuitry, which has to be determined. In this paper we report on a fabrication process for a single-chip capacitive pressure sensor, which can be carried out as a post-process after the completion of the electronic circuit at a relatively low process temperature. No modifications of the delicate IC process are required, because the sensor can be formed directly on the completed IC substrates. It will be demonstrated that the introduction of polymer layers greatly improves the compatibility of the fabrication process.

2. Sensor design

The structure of the pressure sensor, shown in Fig. 1, has been derived from previous developments in the field of silicon microphones [9,10]. The sensor basically consists of

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* Corresponding author. Tel.: +31 53 489 27 22. Fax: +31 53 489 22 87.

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PII S0924-4247(97)01507-0

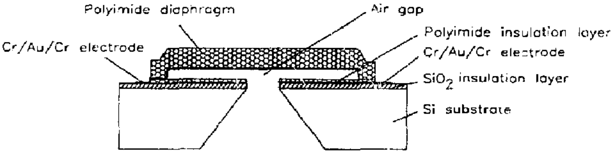

Fig. 1. Cross-sectional view of the capacitive differential pressure sensor.

a polyimide diaphragm under which a metal electrode is placed. On the silicon substrate, a counter electrode is deposited, and a second polyimide layer is used to provide electrical insulation between the two electrodes. The air gap in the device is created by means of a sacrificial-layer technique in which an aluminium layer is deposited and subsequently etched away. The opening to the sacrificial layer on the backside is made by combined etching of the silicon with potassium hydroxide (KOH) and reactive ion etching (RIE). Since the whole sensor fabrication process contains only low-temperature (<300°C) IC-compatible steps, the process can be carried out as a post-process on a substrate where integrated circuits have already been completed. By designing the air gap in the device correctly, the sensor may be used for positive as well as negative pressure differences.

3. Theory of operation

A capacitive pressure sensor is a transducer that converts the deflection of a structure, caused by a pressure load, into a change of electrical capacitance. Therefore, the model of transduction may be split into two separate parts: one part concerned with the mechanical properties, which determines the deflections in the structure, and one part concerned with the variation of electrical capacitance due to the deflection.

For the polyimide, which is used for the diaphragm (Fig. 1), the intrinsic tensile stress has been determined to be approximately 40 MPa. Since the Young's modulus of the polyimide is relatively low (≈ 7 GPa) it is assumed that bending may be neglected. If deflections are small compared with the thickness of the diaphragm, and if the diaphragm is under strong influence of intrinsic stress, the deflection profile of the square diaphragm can approximated by [11]

$$w(x,y) = w_0 \cos\left(\frac{\pi x}{2a}\right) \cos\left(\frac{\pi y}{2a}\right) \tag{1}$$

where a is half of the side length, x and y are the principal directions on the diaphragm with origin in the centre, and w_0 is the centre deflection given by

$$w_0 = 0.3284 \frac{pa^2}{\sigma h_d} \tag{2}$$

in which σ is the intrinsic stress, h_d is the thickness of the diaphragm, and p is the applied pressure load on the diaphragm.

The neglection of the bending, which is required to assume the deflection profile (Eq. (1)) introduces an error, but since the diaphragm is assumed to be in the linear range of deflection, it is possible to introduce a correction factor K in Eq. (2), which accounts for this error. Hereby, an approximated profile with the correct centre deflection is defined:

$$w_0 = K 0.3284 \frac{pa^2}{\sigma h_d} \tag{3}$$

The matching factor can be determined by comparing the centre deflection obtained from Eq. (2) with the centre deflection calculated from the combined action of intrinsic stress and bending [12]. For a diaphragm with a side length 700 μm and a thickness of 16 μm, this yields a matching factor $K = 0.57$.

The deflection function given in Eq. (1) may be used to calculate the electrical capacitance of the sensor. Assuming that the gap between the diaphragm and the counter electrode is filled partly with air and partly with the polyimide insulation layer, the sensor capacitance C_{sensor} can be derived by integrating over the deflection profile:

$$C_{\text{sensor}} = \epsilon_i \epsilon_0 \int_{-a}^{a} \int_{-a}^{a} \frac{1}{h_i + \epsilon_i [h_g + w(x,y)]} \, dx dy \tag{4}$$

where ϵ_i is the relative permittivity of the polyimide insulation layer, ϵ_0 is the permittivity in vacuum, h_i is the thickness of the polyimide insulation layer and h_g is the height of the gap.

For the structure in Fig. 1, an air gap (h_g) of 5 μm and a diaphragm thickness (h_d) of 16 μm were selected. The thickness of the polyimide insulation layer was chosen to be 0.5 μm. With the desired pressure range of the sensor being ±1 bar, a maximum side length of 825 μm where $w_0 < 5$ μm, can be calculated from Eq. (3). Consequently, a side length of 700 μm was chosen, which gives a deflection of 3.6 μm for a pressure difference of 1 bar. The size of the electrodes was chosen to be 600 μm, leaving a ring of 50 μm around the diaphragm electrode for verification of the removal of the sacrificial layer. The initial capacitance of the sensor with no pressure applied was calculated to be 0.62 pF. A finite grid of points on the diaphragm was used to calculate the sensor capacitance at different pressure loads, thereby allowing analysis of the situation where the diaphragm is only partly covered with the electrode [13]. In Fig. 2, the calculated capacitance of the sensor is shown as a function of the applied differential pressure. A decrease of 0.14 pF or 22% is observed over a pressure range of 1 bar.

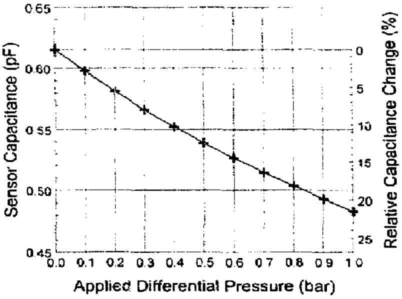

Fig. 2. Simulated sensor capacitance vs. applied differential pressure.

4. Fabrication process

The pressure sensors were made on a 3″, < 100 >, 400 μm thick, 5 Ω cm, p-type silicon substrate (Fig. 3). First, a layer of silicon dioxide with a thickness of 1.5 μm was grown thermally at 1150°C. The silicon dioxide was patterned on the back, and subsequently used as etch mask for etching of the silicon. The substrate was etched in a KOH solution (33 wt.%, 73°C), whereby a reverse pyramid was formed on the sensor backside (Fig. 3A). Thereafter, a chromium/gold/chromium electrode with a thickness of 4/20/4 nm was deposited on the front and patterned using resistive evaporation and a standard lift-off process with photoresist. A layer of polyimide was then deposited over the electrode (Fig. 3B). The polyimide resin used was a 4:1 solution of the HTR3-200 photosensitive polyimide from OCG Microelectronics Inc. and the solvent NMP (*N*-methylpyrrolidone). The polyimide solution was spun on to the substrate with a spin speed of 4000 rpm for 90 s, yielding a final layer thickness of the polyimide of ≈0.5 μm. To improve the adhesion of the polyimide on the silicon oxide surfaces, a γ-APS promoter (aminopropyltriethoxysilane) was used previous to the application of the polyimide. After spinning, the polyimide was baked at 90°C for 25 min to remove the solvent in the film. The layer was then partly exposed to 350 nm ultraviolet light with an energy of 15 mW cm^{-2} for 30 s. An intermediate bake at 90°C for 10 min was applied, to enhance the pre-polymerization of the exposed areas of the polyimide. The polyimide layer was subsequently developed for 3 min using the QZ 3301 Polyimide Developer from Ciba Geigy and rinsed in IPA (isopropyl alcohol), leaving the exposed

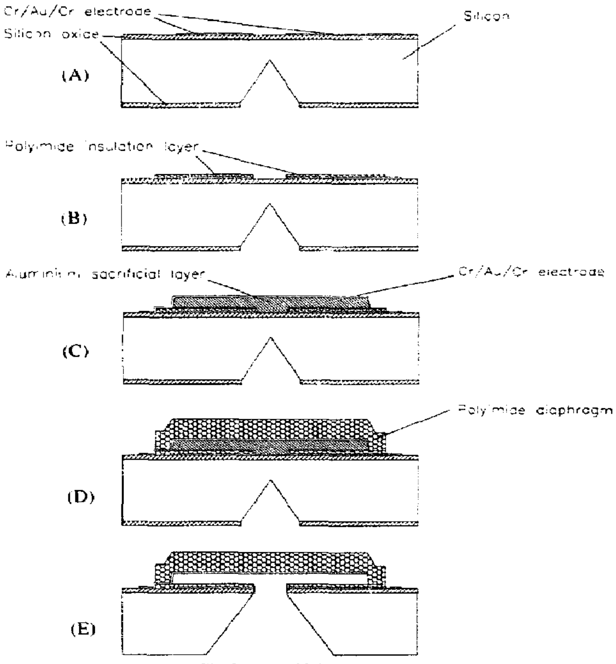

Fig. 3. Sensor fabrication process.

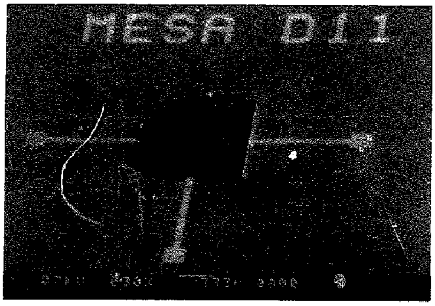

Fig. 4. SEM photograph of a completed sensor.

parts of the layer. Lastly, the layer was cured in an N_2 atmosphere at 300°C for 1 h.

An aluminium sacrificial layer was then deposited and patterned (Fig. 3C) using electron-beam evaporation and a standard aluminium etch solution, containing phosphoric acid, nitric acid and acetic acid. The thickness of the sacrificial layer was 5 μm. Subsequently, a chromium/gold/chromium electrode layer with a thickness of 10/300/10 nm was deposited and patterned with lift-off. This sandwich layer proves a good compromise between the low intrinsic stress of gold and the supreme adhesion properties of chromium to polyimide [14]. The polyimide diaphragm was then completed using a process similar to that described above (Fig. 3D). A spin speed of 1800 rpm for 20 s with a pure solution of the HTR3-200 polyimide yielded a 15 μm thick diaphragm after curing. Finally, a 50 μm × 50 μm opening to the sacrificial layer was made on the backside, by etching of the remaining silicon in the reverse pyramid (Fig. 3E). This was done in an Electrotech PF 340 reactive ion etch reactor using an SF_6/O_2 plasma with a flow of 30/5 sccm, a chamber pressure of 75 mtorr and an r.f. power of 75 W. The silicon dioxide left in the top of the pyramid was etched using a CHF_3 plasma with a flow of 10 sccm, a chamber pressure of 20 mtorr and an r.f. power of 50 W. After etching of the sacrificial layer in the standard aluminium etch solution and rinsing, the structures were dried using a freeze-drying technique, in which the liquid in the air gap is changed to cyclohexane, which is then sublimated by cooling the structures to −5°C. With this method, the problems of sticking of the diaphragm to the substrate were eliminated. Pressure sensors with the electrode configuration and dimensions described above have been completed using this fabrication process. In Fig. 4, a front-view SEM photograph of a completed sensor is shown.

5. Measurements and results

The sensors were individually mounted on a set-up in which a pressure could be applied to the backside of the sample. The pressure was regulated, using a pressure regulator (Wallace and Tierman Chlorator, type FA-235-6) with manometer. In this set-up, pressures of up to 2.5 bar can be applied.

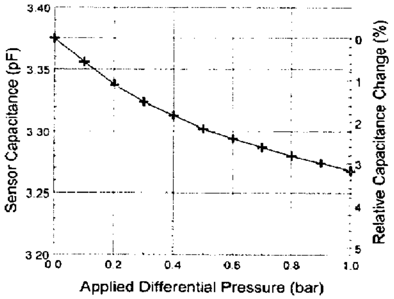

Fig. 5. Measured sensor capacitance vs. applied differential pressure.

First, the sensor was mounted on a steel support, and connected with bonding wires to a small piece of PCB (printed circuit board). From the PCB, further electrical connections to the detection electronics could easily be made. The absolute capacitance of the sensor was measured using a Hewlett-Packard 4194A Impedance/Gain-Phase Analyzer. In Fig. 5 the measured capacitance is shown as a function of the applied differential pressure. It can be seen that the capacitance decreases for increasing pressure load, meaning that the diaphragm deflects away from the substrate. Comparing the measurements with the simulations from Fig. 2, it is clear that the measured capacitances are much larger. This is believed to be caused by the parasitic capacitance of the electrical connections. As it can be seen, the relative change $\Delta C/C$ is only 3.2% over the full range of 1 bar. However, if the effect of the parasitic capacitance (2.7 pF) in parallel with the sensor is subtracted, the relative change $\Delta C/C$ becomes 17% for a pressure range of 1 bar. This is in reasonable agreement with the simulated value of 22%. The remaining differences may be explained by variations in film thicknesses and stresses. Especially the built-in stress in the polyimide diaphragm has a strong influence on the sensitivity.

Furthermore, the sensor was tested with a simple detection circuit, potentially suited for integration. The circuit (Fig. 6) is an astable multivibrator with an LF356 operational amplifier, and three external resistors [13]. The capacitive pressure

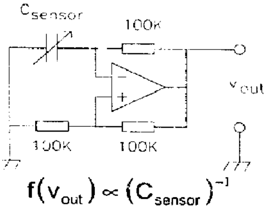

Fig. 6. Detection circuit with frequency-modulated output.

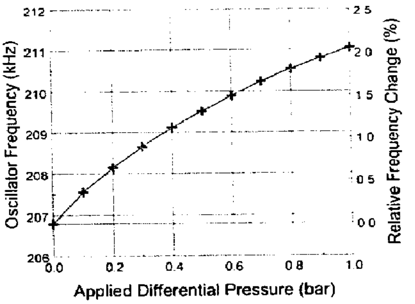

Fig. 7. Oscillator output frequency vs. applied differential pressure.

sensor is the frequency-determining capacitance C_{sensor}, which modulates the frequency of the voltage v_{out} on the output of the amplifier. In the circuit, all resistors were chosen to be 100 kΩ, yielding a base frequency of 207 kHz for the oscillator. In Fig. 7, the frequency of the oscillator is shown as a function of the applied differential pressure. The change of the frequency was 4 kHz for a pressure range of 1 bar, corresponding to a relative change $\Delta f/f$ of 2%. This sensitivity is again small compared with the theory, but it is still in good agreement with the capacitance measurements above, because the parasitic capacitance in this detection circuit can be larger than the 2.7 pF mentioned above. The jitter of the oscillator, measured with electrical shielding, was 10 Hz. Since the linearized sensitivity is 4 kHz bar^{-1}, this jitter corresponds to a maximum resolution of 2.5 mbar (250 Pa). The resolution, however, can be increased considerably by reducing the parasitic capacitances, i.e., by integration of the signal detection circuit.

6. Conclusions and discussion

A new capacitive differential pressure sensor has been developed, fabricated and tested. The fabrication of the single-substrate sensor is based on the use of a polymer (polyimide) for the pressure-sensing diaphragm. The introduction of this new material in mechanical sensors has greatly improved the IC-compatibility of the entire sensor fabrication process. Consequently, the sensor can be made directly on substrates already containing integrated circuits, and no attention has to be paid to the exact nature of the complex IC process.

The performance of the pressure sensor has been shown to be in good agreement with the theory, and from the measurements it is clear that the presence of parasitics hampers the sensitivity of the sensor. This can be greatly reduced by integrating the detection circuit with the sensor, and it is expected that the sensitivity of the sensor thereby will be close to the theoretical values.

The introduction of a polymer as pressure-sensing diaphragm might also bring problems, especially regarding creep and relaxation. It is well known that polymers possess viscoelastic properties, and that some relaxation will occur. However, since polyimide is one of the polymers with the highest glass transition temperature (≈400°C), these effects are expected to be very slow. Furthermore, the stress generated from the pressure load is very small (<0.5 MPa) compared to the built-in stress in the film. Accordingly, no drift relating to the sensor has been detected for a pressure load of 1 bar over a period of one day. The problem of relaxation of the built-in stress in the polyimide film may be dealt with by applying an environmental burn-in period similar to that used in the IC technology. The sensitivity to temperature and humidity of the sensor is also an important issue. First, the thermal stability is affected by the mismatch of the coefficients of thermal expansion (CTE), which is ≈50 ppm K^{-1} for polyimides and ≈3 ppm K^{-1} for silicon. This will cause a reduction of the built-in stress in the diaphragm, and hence an increase in sensitivity for increasing temperatures. Recent developments in polymer science, however, have demonstrated the possibility of synthesizing polyimides with thermal properties closely matched to silicon [15,16]. Therefore, in the future it will be possible to realize structures having very little sensitivity to temperature. Regarding humidity, it is well known that polyimide adsorbs water, leading most prominently to a change of the dielectric constant by as much as 35% over the full humidity range [14]. Considering, however, the structure in Fig. 1, only the thin polyimide insulation layer is electrically involved in the sensor. Since this layer is 10 times thinner than the air gap, and the dielectric constant is at least three times larger, the change of the sensor capacitance will be small. A calculation of the structure with the dimensions given in this paper shows that a change of less than 1% of the sensor capacitance over the full range of humidity will be caused by the polyimide layer.

Acknowledgements

The authors are indebted to Johan Bomer for assisting with the processing of the samples, Bert Otter for providing the SEM photographs and the Dutch Technical Foundation (STW) for financial support.

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Biographies

Michael Pedersen was born in Holbæk, Denmark, on November 29, 1969. He received the M.Sc. degree in electrical engineering from the Technical University of Denmark in 1993. Currently he is working on a Ph.D. project in the Biosensor Technology Group of the MESA Institute, at the University of Twente. His research is concerned with the development of fully integrated silicon condenser microphones.

Marco G.H. Meijerink was born in Deventer, The Netherlands, on September 8, 1972. He received the M.Sc degree in electrical engineering from the University of Twente, The Netherlands in 1996. Currently he is working on a Ph.D. project in the Sensors, Actuators and Microsystems Laboratory of the Institute of Microtechnology at the University of Neuchâtel, Switzerland.

Wouter Olthuis was born in Apeldoorn, The Netherlands, on October 23, 1960. He received the M.Sc. degree in electrical engineering from the University of Twente, The Netherlands, in 1986, and the Ph.D. degree from the Biomedical Engineering Division of the faculty of Electrical Engineering, University of Twente, in 1990. Currently he is working as an assistant professor in the Biosensor Technology Group of the MESA Institute, at the University of Twente.

Piet Bergveld was born in Oosterwolde, The Netherlands, on January 26, 1940. He received the M.Sc. degree in electrical engineering from the University of Eindhoven, The Netherlands, in 1965 and the 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, the actual invention of the ISFET, since then also investigated by many international research groups of Universities as well as industry. Since 1965 he has been a member of the Biomedical Engineering Division of the Faculty of Electrical Engineering (University of Twente) and was in 1984 appointed as 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 ISFET technology as well as physical sensors for biomedical and environmental applications, resulting up to now in more than 200 papers.