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A novel capacitive pressure sensor structure with high sensitivity and quasi-linear response

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Abstract

This paper describes a new capacitive structure of pressure sensor to increase simultaneously the sensitivity and the linearity of the transducer. This structure contains two capacitors which change in response to pressure, but in opposite senses. To increase even more the sensitivity of each capacitor, the pressure sensitive diaphragm carries a central boss. The optimal position and the length of the boss are also calculated. ***To cite this article: A. Ettouhami et al., C. R. Mecanique 332 (2004).***

Résumé

Une nouvelle structure de capteur de pression capacitif avec haute sensibilitée et réponse quasi-linéaire. Une nouvelle structure de capteur de pression capacitif permettant d'augmenter simultanément la sensibilité et la linéarité du transducteur a été proposée. Cette structure contient deux condensateurs qui varient avec la pression mais dans des sens opposés. Pour augmenter davantage la sensibilité de chaque condensateur, la membrane sensible à la pression porte une bosse au centre. La position optimale et la longueur de la bosse sont également calculées. ***Pour citer cet article : A. Ettouhami et al., C. R. Mecanique 332 (2004).***

Keywords: Control; Capacitive pressure sensor; Linearity; Sensitivity

Mots-clés : Automatique ; Capteur de pression capacitif ; Linéarité ; Sensibilité

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1. Introduction

The development of new techniques compatible with silicon integrated-circuit technology has pushed further the measuring limits. In fact, anisotropic etching of silicon and silicon–glass electrostatic seal allowed us to obtain small cavities and high-yield diaphragms whose thickness is accurately controlled. The capacitive pressure sensor has benefited from these recent techniques and its fabrication on silicon has become possible. This permits, on the one hand to improve performances and decrease fabrication cost, and on the other hand to expand the application spectrum including health care, transportation and industrial process control.

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The capacitive pressure sensor allowed us to solve some problems inherent in piezoresistive sensor, in particular the temperature sensitivity and the power consumption. In addition, it is very sensitive to pressure. However, in the most cases, the major problem of this structure (as will be seen later) is the nonlinearity of its response.

2. Background

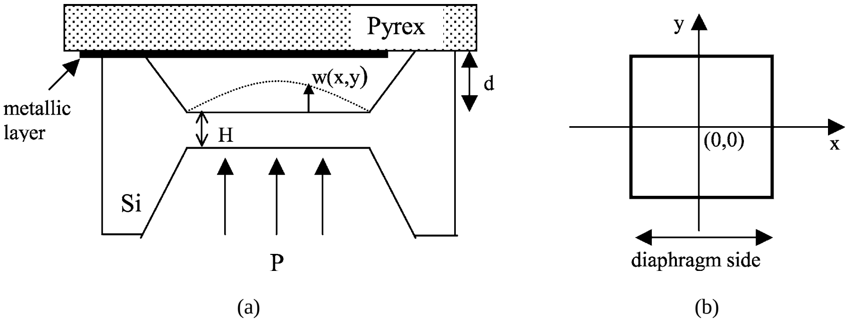
A thin diaphragm realized by anisotropic etching of thicker starting silicon wafer constitutes the movable plate of a parallel-plate capacitor. The second plate is formed by a thin metallic layer deposited on the Pyrex support (Fig. 1). When a differential pressure is applied, the silicon diaphragm warps and produces a capacitance variation [1,2]:

$$C - C_0 = \int_S \frac{\varepsilon \, \mathrm{d}S}{d - w(x, y)} - \frac{\varepsilon S}{d}$$

where C is the capacitance corresponding to the applied pressure P, C_0 is the zero-pressure capacitance, S is the diaphragm area, ε is the dielectric constant of trapped gas between the plates (usually the air) and d is the zero-pressure plate separation.

The study of the sensor response leads to determine the silicon diaphragm deflection $w(x, y)$ as a function of the applied pressure P. By using the theory of small deflections of thin plates [3], the equilibrium of the diaphragm is given by a differential equation which has no analytical solution, especially when the diaphragm thickness is not constant. We have solved it numerically by the finite-difference method. The principle of this method consists in replacing the partial derivative by equations expressed in terms of finite differences, at each point of the partitioned diaphragm. Hence the equation and the boundary conditions are transformed to a linear equation system. The method of Gauss allows the resolution of the system with high accuracy. Once the deflections are known, the capacitance is numerically calculated from the above relation. Based on theses equations and methods, we have developed a simulation program of the sensor response and its statical characteristics (sensitivity, linearity, dynamic range,...) [4,5].

An example of capacitive pressure sensor response is illustrated in Fig. 2. The simulated sensor has 2 mm of diaphragm side (a) and 3 µm of zero-pressure plate separation. The curve corresponding to 28 µm of diaphragm thickness (H) shows that the device is very sensitive to pressure. However this intrinsic sensitivity is not constant, it is of 1300 ppm/mmHg for small pressures and reaches 4400 ppm/mmHg when pressures approach the pressure that causes the two electrode plates to contact each other. The sensitivity corresponding to $H = 30$ µm varies between 950 ppm/mmHg and 2100 ppm/mmHg. The other curve shows that the linearity can be improved by increasing the diaphragm thickness, but this decreases also the sensitivity.



(a) (b)

Fig. 1. (a) Cross section of a capacitive pressure sensor. (b) Square diaphragm with built in edges.

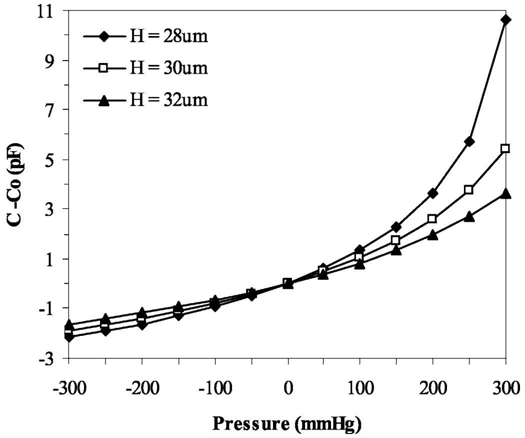


Fig. 2. Capacitance variation as a function of applied pressure for various diaphragm thicknesses ($a = 2$ mm, $d = 3$ µm).

The variation of capacitance can be determined by a signal-detecting circuit. For miniature pressure transducers, the change of capacitance is very small, of the order of picofarads. This necessitates the integration of the detecting circuit on the same chip of the capacitor. Capacitance is converted to frequency [6–8] or to voltage [9–11]. In the first case, the capacitor is, generally, a part of an oscillator whose frequency is proportional to $1/C^n$ ($n = 1$ or $1/2$). In the second case, the capacitor is a part of an impedance bridge and the output voltage is proportional to $C - C_r$, where C_r is a fixed reference capacitor, generally, equal to C_0 ($C_r = C_0$). In the two cases, the transducer response (sensor + signal-detecting circuit) is nonlinear (because of the sensor nonlinearity).

3. Proposition of a new capacitive structure

Several solutions have been proposed to reduce this nonlinearity: (a) allowing the central part of the diaphragm to touch the bottom of the cavity during the pressure range of interest [12]; (b) corrugation or weakening of parts of the diaphragm [13,14]; (c) a structure using comb-shaped diaphragm and cavity bottom[15]. A combination of these methods is also used.

The most of these structures use a nonuniform diaphragm thickness (generally more thicker at the center) to obtain approximately the same deflections for the all points of the central part of the diaphragm ($w(x, y) \approx W$). In this case $1/C \approx (d - W)/(\varepsilon S) \approx (d - kP)/(\varepsilon S)$ is a linear function of the pressure, and by using a detecting circuit which converts capacitance to frequency, the transducer response becomes linear. The integrated circuit technology and the advanced techniques of anisotropic etching allow the realization of such sensors (with nonuniform diaphragm thickness) with high accuracy [14,16,17].

The linearization of $C - C_0$ (as seen above) can be made by increasing the diaphragm thickness, but this is made to the detriment of the sensitivity.

To increase simultaneously the sensitivity and the linearity, we have proposed a new capacitive structure where the reference capacitor C_0, changes in response to pressure, but in the opposite sense of C. The principle scheme of this structure is represented in Fig. 3. When the pressure increases, the capacitor C changes in the positive sense, whereas C_0 changes in the negative sense.

Fig. 4 shows a comparison of responses of two transducers. The first one corresponds to the classical sensor where only one capacitor changes in response to pressure. The second one is that of Fig. 3 where the two capacitors change simultaneously. We remark that the linearity is significantly improved (the error of nonlinearity decreases from 6.4% to 3.8%) and the sensitivity is also increased (2000 ppm/mmHg instead of 950 ppm/mmHg). This can be explained as follow:

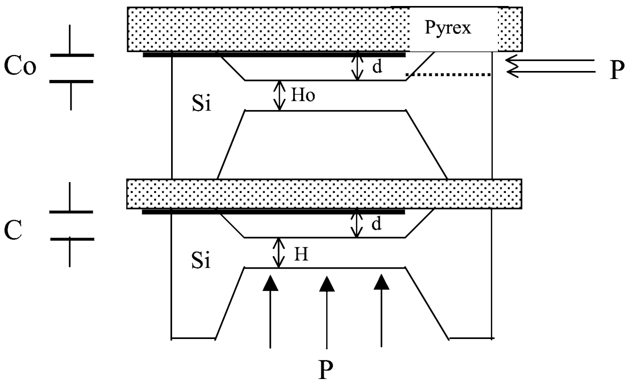


Fig. 3. Principle scheme of the proposed capacitive pressure sensor.

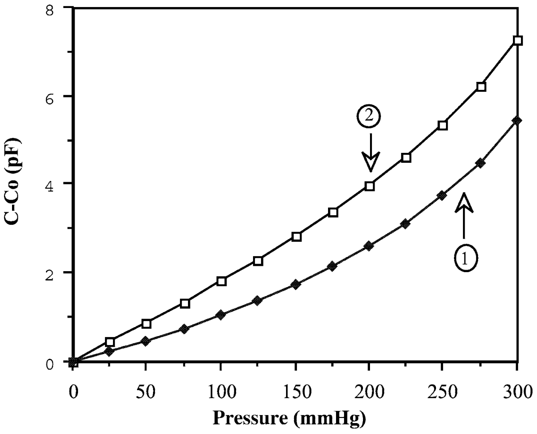


Fig. 4. The response of the transducer ($a = 2$ mm, $d = 3$ µm). 1: C_0 is constant, $H = 30$ µm. 2: C_0 is variable, $H = H_0 = 30$ µm.

the absolute sensitivity of the transducer (at a given pressure P_0) is represented by the slope of the transducer response curve:

$$S_T = \left[\frac{\Delta(C - C_0)}{\Delta P}\right]_{P_0} = \left[\frac{\Delta C}{\Delta P}\right]_{P_0} - \left[\frac{\Delta C_0}{\Delta P}\right]_{P_0}$$

Since C_0 is negative (Fig. 3):

$$S_T = \left[\frac{\Delta C}{\Delta P}\right]_{P_0} + \left[\frac{|\Delta C_0|}{\Delta P}\right]_{P_0} = S + S_0$$

where S and S_0 represent respectively the slopes of the curve of Fig. 2 for positive and negative pressures.

When P_0 increases, S increases but S_0 decreases (see Fig. 2) and therfore S_T which is the sum of S and S_0 does not increase by the same manner (in comparison with the classical sensor) and remains nearly constant allowing to decrease the nonlinearity.

The linearity and the sensitivity can be even more improved if the change of C_0 in the negative sense approaches (in absolute value) the change of C in the positive sense. This is possible by choosing a feeble diaphragm thickness of capacitor C_0 (H_0) in comparison with that of C. Fig. 5 shows that if the diaphragm thickness of C_0 is reduced to 20 µm, the sensitivity increases to 2600 ppm/mmHg and the error of nonlinearity decreases to 1.5%.

4. Sensor with nonuniform diaphragm thickness

The maximum sensitivity of capacitive pressure sensor, in a dynamic range [0...Pmax] is obtained when the diaphragm center approaches the second plate, in response to pressure Pmax ($w(0,0) \approx d$). In this case, the contribution of diaphragm edges to capacitance variation is weak. To improve the contribution of edges and hence the sensor sensitivity, once decreases the thickness of diaphragm edges. The resulting diaphragm has a square boss at the center (Fig. 6). The resolution of deflection equations has been made in taking into account of a nonuniform diaphragm thickness [18].

The optimal size leading to a maximum contribution of the all points of the diaphragm is illustrated by Fig. 7 which represents the normalised mean deflection $w_{\mathrm{moy}}/w(0,0)$ as a function of the normalised boss side *rl* for various values of *rh*, where: $w_{\mathrm{moy}} = \int_S w(x,y)\,\mathrm{d}x\,\mathrm{d}y$, S is the diaphragm area, *rl* is the ratio of the boss side to the diaphragm side, *rh* is the ratio of the boss thickness to the diaphragm thickness.

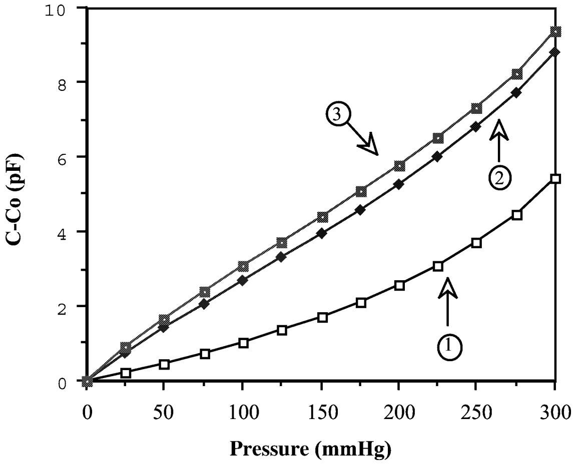


Fig. 5. The improved linearity and sensitivity of the transducer ($a = 2$ mm, $d = 3$ µm). 1: C_0 is constant, $H = 30$ µm. 2: C_0 is variable, $H = 30$ µm, $H_0 = 22$ µm. 3: C_0 is variable, $H = 30$ µm, $H_0 = 20$ µm.

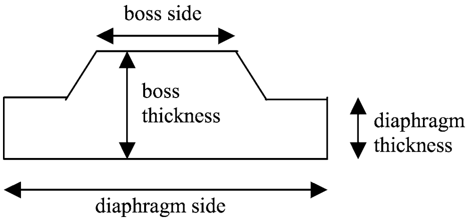


Fig. 6. Cross section of square diaphragm with a square central boss.

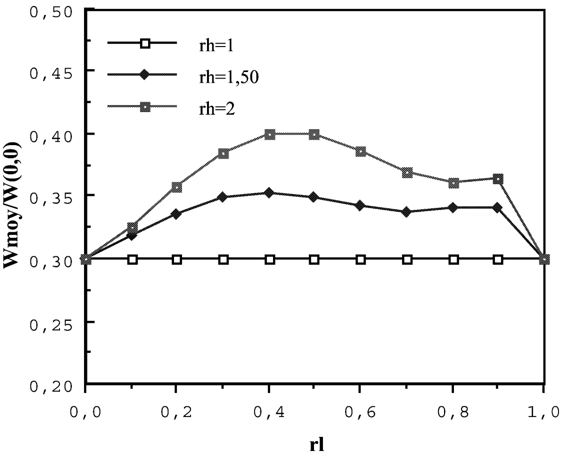


Fig. 7. Normalised mean deflection versus normalised boss side for various values of *rh*.

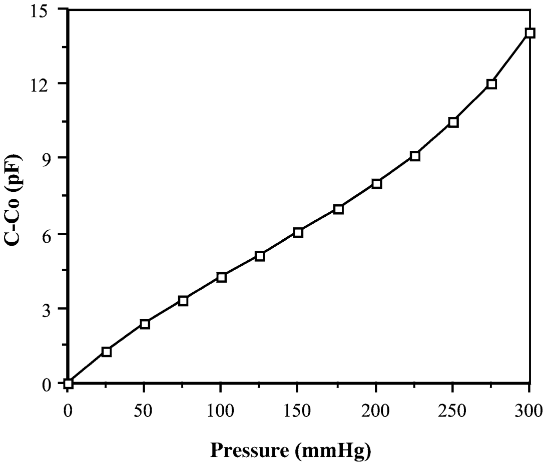


Fig. 8. Response of the transducer with a central boss ($a = 2$ mm, $d = 3$ µm, $rl = 0.4$, $H = 22$ µm, $H_0 = 15$ µm).

We remark that maximum sensitivity is obtained when $0.4 \leqslant rl \leqslant 0.5$, i.e., by choosing a square central boss occupying between 16% and 25 % of the diaphragm area.

If every capacitor of the above structure (Fig. 3) contains a diaphragm with a central boss at the optimal position, the sensitivity of the transducer is more increased. Fig. 8 shows that if $rh = 2$, the pressure sensitivity increases to 4000 ppm/mmHg and the response remains quasi-linear (the error of nonlinearity is 2.7%).

5. Conclusion

A new structure of capacitive pressure sensor is proposed. This structure contains two capacitors which change in response to pressure, but in two opposite senses. This allows us to improve simultaneously the sensitivity and the linearity of the sensor when an electronic circuit allowing the measurement of the difference between the two capacitors is incorporated on the same chip. To increase even more the sensitivity of every capacitor, the diaphragm must carry a central boss occupying about 20% of the diaphragm. The realization of such structures will profit from the same techniques used in classical capacitive pressure sensors: integrated circuit, etching of silicon and glass-silicon electrostatic seal.

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