Finite Element Analysis of Capacitive Silicon Pressure Sensors

용량형 실리콘 압력 센서의 유한요소 해석

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Abstract

Capacitive micro pressure sensor is simulated with finite element methods to analyze the effect of geometrical variation on its performace. Sensor material is the silicon single crystal. The sensor consists of a disk type diaphragm and several bridges connected to a rigid frame. Structural variables in consideration are the thickness of the diaphragm and the bridges, radius of the circular plate, and the number of bridges. Results of static, dynamic and sensitivity analyses reveal the best structure of the sensor among the fifteen cases under investigation.

요 약

용량형 압력센서의 거동을 유한요소법으로 해석하였다. 센서는 원형박막과 이를 강성지지대에 연결하는 몇개의 다리들로 구성이 되며, 센서재료는 실리콘 단결정이다. 성능에 영향을 미치는 센서구조의 형상변화를 유한요소 해석법을 이용하여 알아보았는데, 고려한 변수들은 원형박막의 직경 및 두께, 그리고 다리의 개수 등이다. 이들 변수의 변화에 따른 마이크의 정적거동해석, 동적 거동해석, 그리고 감도해석 등의 결과를 분석하여 제작하고자 하는 총 15개의 미소형 압력센서 구조중 최선의 것을 결정하였다.

Ⅰ. Introduction

Over the decade, silicon pressure sensors have undergone a significant growth[1]. The miniature capacitive pressure sensors are possible due to the development of the micromachining techniques. They are based on the piezoelectric, piezoresistive and capacitive principles [2, 3]. A capacitive pressure sensor usually consists of a thin, flexible diaphragm mounted on a rigid backplate, constituting the movable electrode in a parallel plate capacitor. The pressure dependence of the sensor is obtained by letting the pressure deflect the diaphragm, thus changing the capacitance to the bottom of the enclosed cavity. The pressure-capacitance relationship thus obtained has an apparent nonlinearity. Capacitive pressusre sensors are more nonlinear in their pressure response than their piezoresistive counter parts, but they are significantly more sensitive to pressure and less sensitive to temperature. Other nonlinearities are due to nonlinear materials, large deflections, deflections in undesired directions, deflections varying over the membrane or to stray capacitances. Two appreciated properties are high stability and flat frequency response. These sensors with large sensitivity are suitable for low pressure measurements, which complement the conventional piezoresistive pressure sensors.

This study is aimed to design capacitive micro pressure sensors which can replace conventional microphones. So far, their sensitivity has not been inproved so much as to replace current electromagnetic microphones. However, due to their small sizes, robustness and the ease of composing an array, they can find appropriate applications such as high pressure range applications and high resolution acoustic

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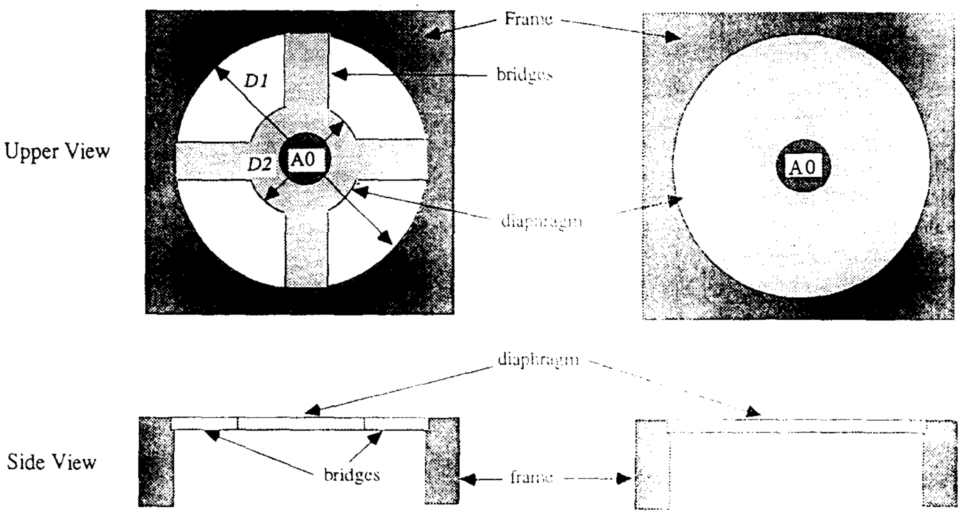
pressure ranging(similar to high pixel imaging). The sensors are supposed to work under the pressure range of less than 10 MPa over audio frequencies. In a usual sense, the acoustic pressure of 115dB corresponds to the application of 10 Newton force over 1 m^2. The design principle in this paper is that each sensor must withstand that much force. The sensor in mind sizes about 1 mm^2. Hence the application of 10 Newton force to each sensor corresponds to the pressure of 10 MPa. Design considerations are (1) statically it should be as robust as possible with respect to external pressure, (2) dynamically it should have high enough resonant frequencies so that the sensor can have a flat response over the operating frequency range, and (3) it should have as high and linear sensitivity as possible. In the past, lots of work has been done on the design of capacitive micro pressure sensors [4, 5]. However most of their structures consist of rectangular diaphragms. Part of the reasons is the ease of silicon crystal etching processing. The diaphragm in this study takes the form of a circle. Further, most of the previous researches has focused on specific behavior, either static, dynamic, or other) of the sensor [6]. This constitutes the motivation of the study in this paper. We are testing several realizable circular diaphragm types of the sensor structure. The selection has been made in consideration of the easiness in silicon wafer processing. Through computer simulation, we evaluate the above mentioned properties for each structure, and determine the best one to meet all the requirements. Finite element method is employed for the analysis with a commercial package, ANSYS [7, 8].

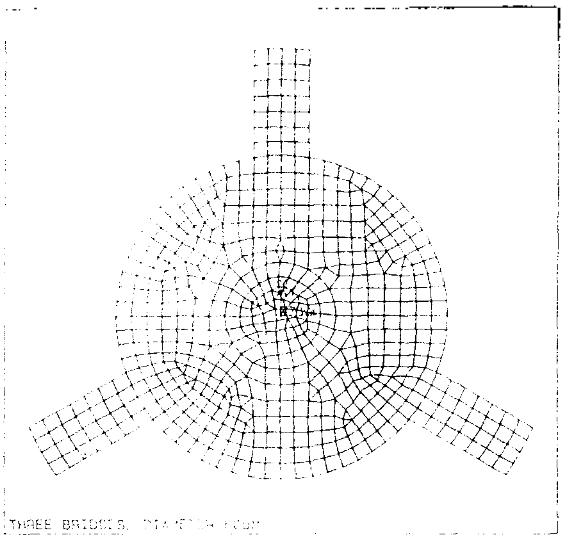
II. Analysis

Figure 1 is the schematic diagram of the model to be investigated, while Fig. 2 is its FEM mesh diagram. The sensor is composed of silicon single crystals. Circular disk(diaphragm) works as the upper capacitor plate, while it is supported by several bridges. The bridges do not work as the capacitor electrodes. The bridges are attached to a rigid frame that does not allow any displacements. Figure 1 b denotes a rather special case where the diaphragm is in direct contact with the frame without the help of any bridges. Outer radius D_1 is 100 μm, and the bridges are 10 μm wide. As the variables of the sensor structure, we have thickness of the diaphragm and the bridges, radius D_2 of the circular plate, and the number of bridges. We are testing fifteen different strucutres of the pressure sensor by investigating the effect of these three variables. However, we can not check all the possible combinations of those three variables. It is quite time consuming and costs a lot. Further we have certain limitations in the combination due to the difficulty in silicon crystal processing. Hence we select only the types of practical realizability [9]. Table 1 lists fifteen variations of the factors to be analyzed. Properties of the silicon single crystal is as

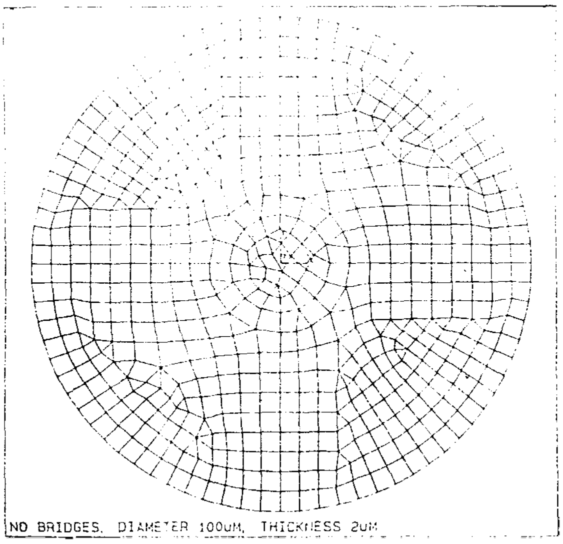


(a) general type with bridges (b) special type with no bridges

Fig 1. Schematic view of the silicon pressure sensors



(a) with bridges



(b) without bridges

Fig 2. Illustrative finite element models of the pressure sensor

Table 1. The 15 models investigated in FEM analysis

	No. of bridges	D2	diaphragm thickness
Model 1	0	100	2
2	0	100	5
3	0	100	10
4	3	40	2
5	3	60	2
6	3	80	2
7	4	40	2
8	4	60	2
9	4	80	2
10	6	40	2
11	6	60	2
12	6	80	2
13	8	40	2
14	8	60	2
15	8	80	2

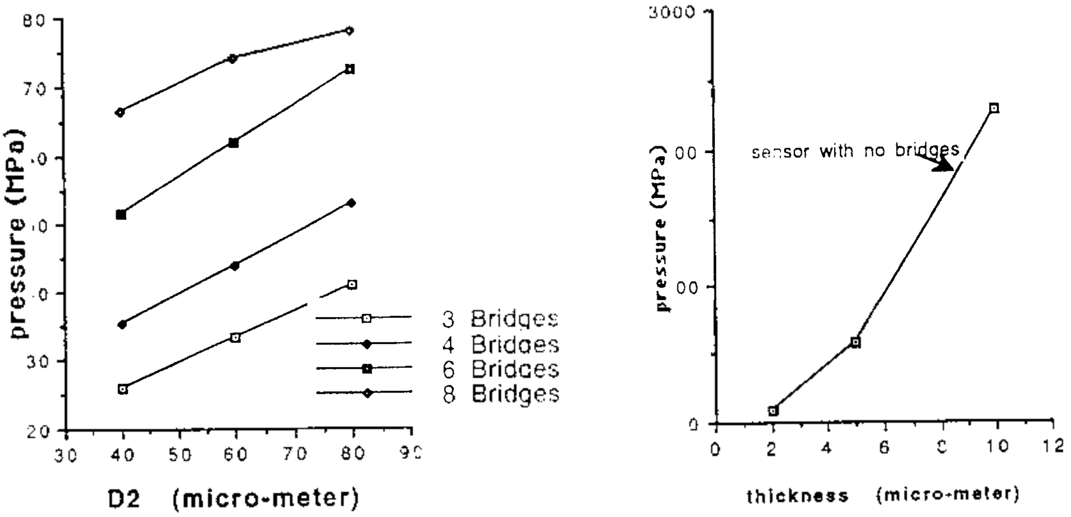
follows [10]. The properties are for the particular crystal cut, i.e. ⟨110⟩ cut, of the silicon wafer.

Young's modulus	130 GPa
Shear modulus	79 GPa
Poisson's Ratio	0.29
Density	2300 Kg/m^3
Tensile Strength	7.0 MPa

2.1 Static Analysis

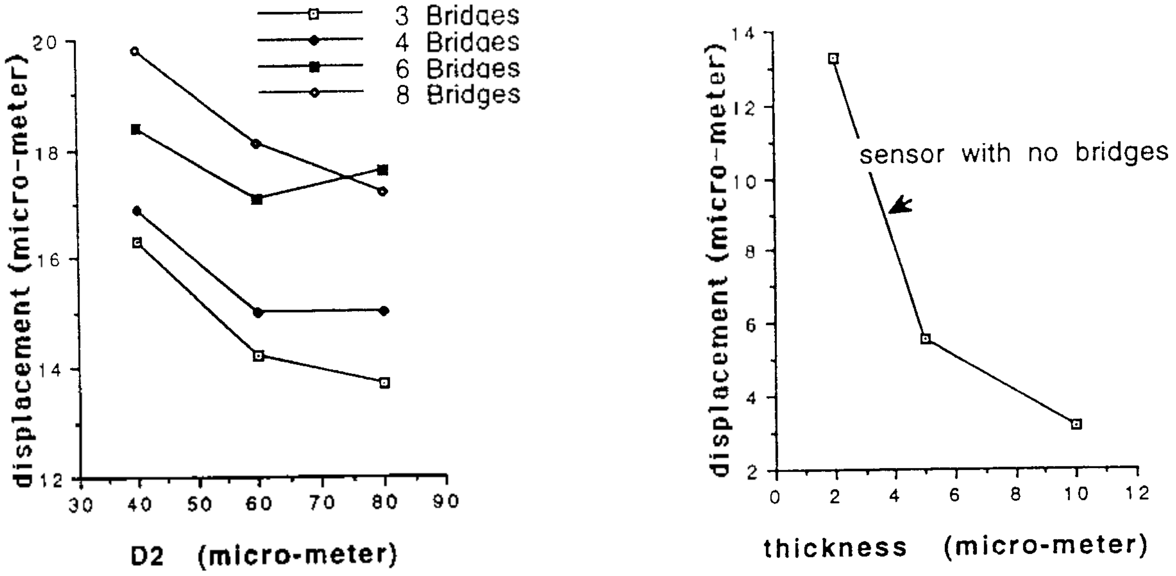
The range of pressure to which the sensor is normally to be exposed is less than 10 MPa. However, in some severe situations, it may suffer from an extraordinarily large pressure even though unwanted. High enough safe factor should be considered for long life operation of the sensor. Hence the maximum allowable magnitude of pressure is calculated, which corresponds to yield strength of each structure. In this model, the pressure is assumed to be applied only to the central circular area A_0. Figure 3 shows the results. In all the cases, the fracture cracks initiate at the intersections of either the bridges and the circular diaphragm or the bridges and the rigid frame. The maximum allowable pressure increases with the number of bridges and the radius of the diaphragm. The maximum pressure also increases with the diaphragm thichness. The lowest value of the yield pressure is observed when the diaphragm radius is 20 μm, its thickness is 2 μm, and the number of the bridges is three. However the lowest values, 25.8 MPa, is still about two times higher than the operation limit of the sensor under study. Hence the criterion of high enough static strength does not put any restricition on the structural variation.

The maximum pressure loading will lead to the maximum deflection of the diaphragm. The results can be referenced to determine the initial gap between the diaphragm and the backplate. Usually the amount of the initial gap is limited by the difficulty in silicon crystal processing. Too large initial gap is undesirable for the processing. Maximum pressure induced displacements corresponding to the Fig. 3 are shown in Fig. 4. They are increasing with the number of bridges while decreasing with the radius of the diaphragm. The maximum displacements also decrease with the diaphragm thickness. The highest value of 19.3 μm is observed when the diaphragm is 2 μm thich and its radius is 100 μm (no bridges). The lowest value of 4.36 μm occurs when the diaphragm is 10 μm thich and its radius is 100 μm (no bridges). Considering that, in practice, it is very difficult to have the initial gap more than 4 μm, the models of No. 4, 5 and 7 should be excluded [10]. Theses maximum displacements are given by the tensile yield strength of each sensor structure. Therefore the largest maximum displacement has nothing to do with the sensitivity of the sensors. It just means that the structure can endure that much deflection of the diaphragm.



(a) (b)

Fig 3. Variation of the maximum allowable pressure with (a) D_2 and (b) thickness



(a) (b)

Fig 4. Variation of the maximum allowable displacement with (a) D_2 and (b) thickness

2.2 Modal Analysis

There are in general two design rules for acoustic sensors. The first is to make use of natural frequencies of the sensor to increase its sensitivity. This method is quite useful when the sensor is expected to work over a narrow frequency range because the sensor response is valid only within the bandwidth of the specific mode. The second is to make use of the region below the fundamental natural frequency. At the expense of sensitivity, this method can achieve a wide operating frequency range. The sensor under study is supposed to work over the audio frequency range (20-20,000 Hz). For this low and wide operation range, we have no other way but to take the second method. However, to achieve the flat response, the fundamental natural frequency should be as high as possible so that the operation response could be free from any resonance effect. With this requirement, modal analyses are performed for the fifteen models and the results are shown in Fig. 5. The natural frequency of the fundamental mode increases with the number of bridges, and the thickness of the diagphragm. On the other hand, it decreases with the radius of the diaphragm. Of all the occasions, we could observe the lowest value of the fundamental resonance frequency when the diaphragm radius is 20 μm, its thickness is 2 μm, and the number of bridges is three. The highest value occurs when the diaphragm radius is 100 μm (no bridges) and the diaphragm is 10 μm thick. The lowest value of 1.49 MHz is still high enough that no resonance effect is considered to be imposed on the operation response.

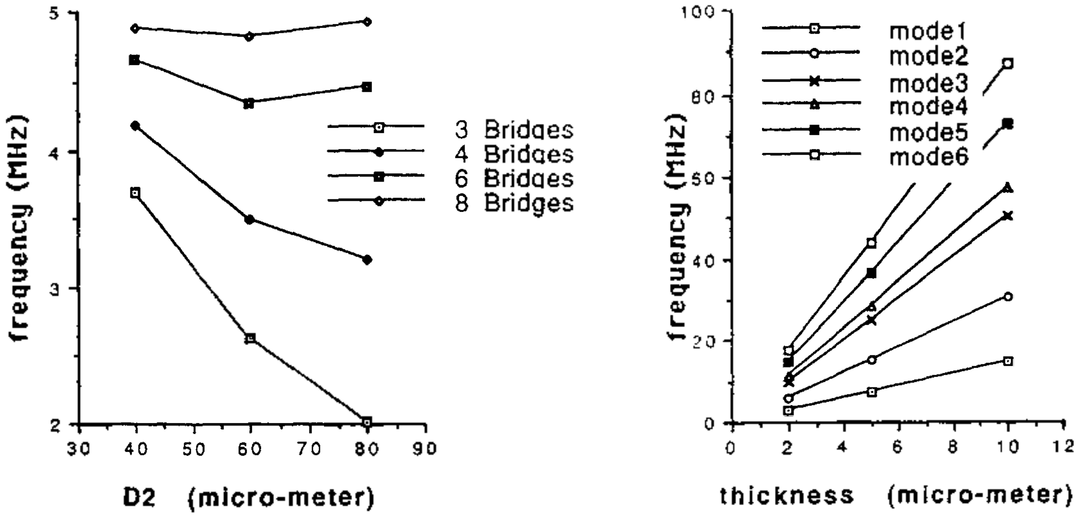
2.3 Sensitivity Analysis

The sensitivity of a capacitive pressure sensor is determined by the amount of capacitance change to the pressure variation. For a given magnitude of pressure, corresponding capacitance and sensitivity is calculated with the following equations [11]:

$$\text{capacitance } C(P) = \int_0^{2\pi}\int_0^{r} \frac{\varepsilon}{d-w(r,\theta,P)}\, r\,dr\,d\theta \text{ (Farad)} \tag{1}$$

$$\text{sensitivity } S(P) = \frac{\partial C(r,q,P)}{\partial P} \quad \text{(Farad/Pa)}$$

where ε is the permittivity of the material between the diaphragm and the backplate, usually air, d is the initial gap, and w is the calculated diaphragm deflection for a given pressure, P. For good sensors, the sensitivity should be as high and linear as possible over the frequency range of interest. Figure 6 shows the results. Sensitivity is increasing with the diaphragm radius and number of bridges, while decreasing with diaphragm thichness. According to the results, the sensor composed of 2 μm thick diaphragm with no bridges(D_2 is 50 μm) gives the highest and most linear



(a) (b)

Fig 5. Variation of (a) the first mode natural frequency with D_2, and (b) all the natural frequencies with diaphragm thickness response.

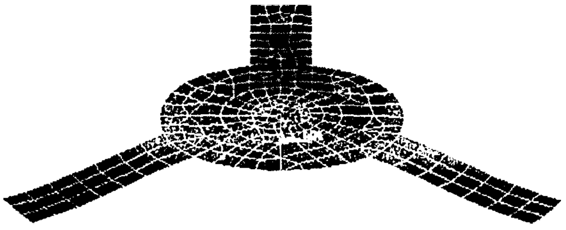


Fig 6. Illustrative mode shape of the first mode of the pressure sensor. The sensor has three bridges, diaphragm is 2μm thick, and its radius is 20μm.

III. Conclusion

For development of capacitive silicon miniature pressure sensors, we analyzed the effect of geometrical variation on their performance with fifteen different structure models. The sensors consisted of a disk type diaphragm and a number of bridges connected to a rigid frame, working within the pressure range of 10 MPa over the audio frequencies. Variables in consideration were the thickness of the diaphragm and the bridges, radius of the circular plate, and the number of bridges. Results of all the analyses revealed that the geometry of 2 μm thick diaphramg having the radius of 50 μm (no bridges) was the most suitable structure for the application.

Acknowledgement

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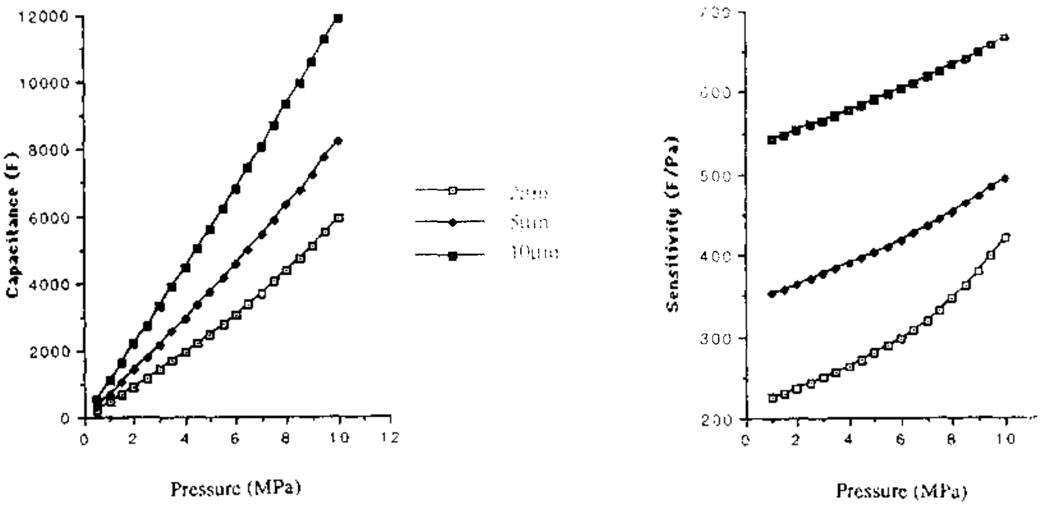

Fig 7. Variation of the capacitance and the sensitivity with D2 (diaphragm radius) for the illustrative case of three bridges

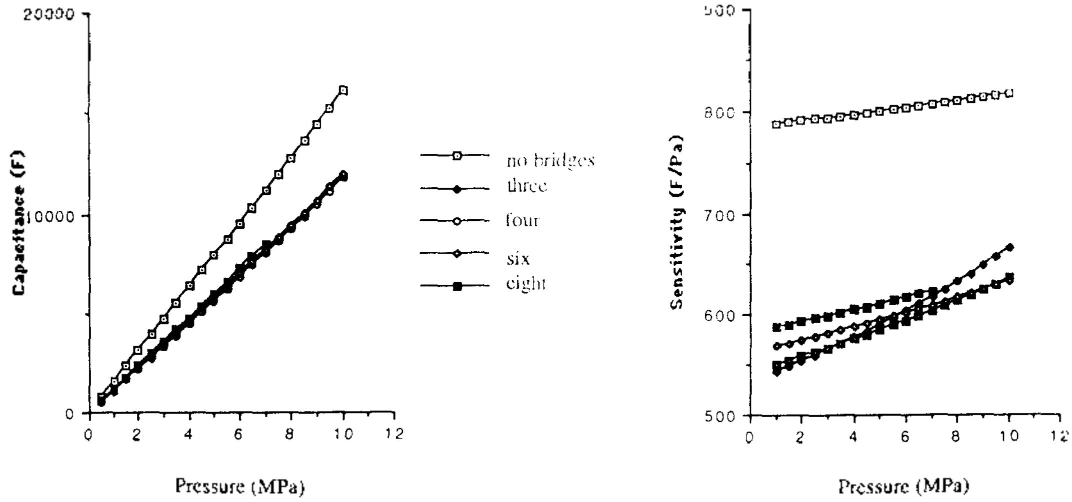

Fig 8. Variation of the capacitance and the sensitivity with the number of bridges

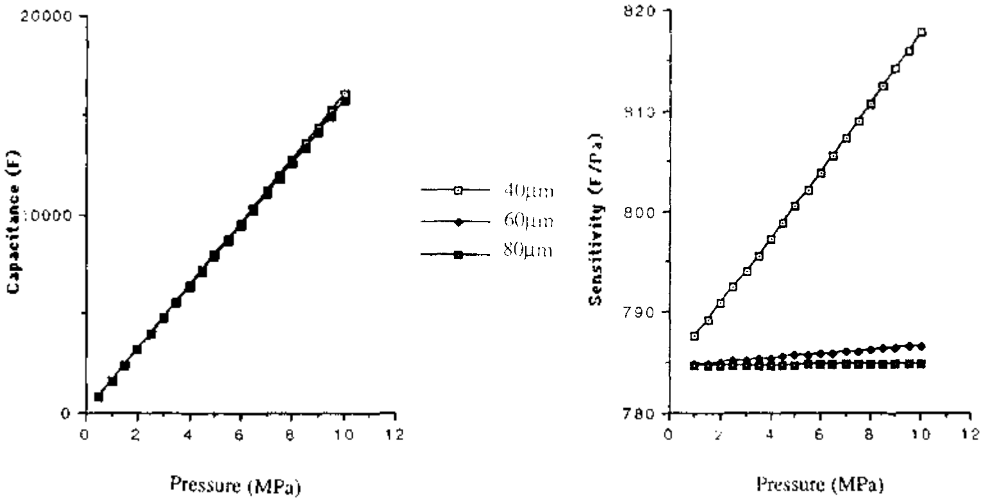

Fig 9. Variation of the capacitance and the sensitivity with diaphragm thickness

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