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Simulation and Modeling of a High Sensitivity Micro-electro-mechanical Systems Capacitive Pressure Sensor with Small Size and Clamped Square Diaphragm

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ABSTRACT

This paper proposes a Micro-electro-mechanical (MEMS) capacitive pressure sensor that relies on the movable electrode displaced like a flat plate equal to the maximum center deflection of diaphragm. The diaphragm, movable electrode and mechanical coupling are made of polysilicon, gold and Si_3N_4, respectively. The fixed electrode is gold and the substrate is Pyrex glass. This proposed method increased the effective surface of capacitor and the displacement of movable electrode. The size of this sensor is 250×250 μm^2 and the thickness of diaphragm is 1μm with 1 μm air gap. According to the results the sensitivity of sensor is $58.5\frac{fF}{mmHg}$.

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1. INTRODUCTION

In the past years MEMS capacitive pressure sensors have received increasing attention due to several advantages such as: low temperature sensitivity, good DC response and stability, low power consumption [1-3]. The capacitive pressure sensor is used for advanced industrial, military, automotive, medical applications, control systems and process control. During these years many different designs have been proposed for increasing sensitivity based on the reduction of diaphragm stiffness with different structures and different materials. The common shape of diaphragms are square and round. But in general, the capacitive pressure sensors contain a thin flexible plate as a diaphragm and a fixed plate as a second electrode of capacitive that these plates are separated each other by a small air gap for pressure sensing [3-7].

In MEMS capacitive pressure sensor when the external pressure is applied on diaphragm, the diaphragm is deflected and changes the air gap between two plates. So, deflection of the diaphragm due to the applied pressure is sensed and translated into an electrical capacitance change. Then, the appropriate microelectronic circuits convert the capacitance change of capacitor to a useful voltage signal [8].

Generally, the pressure sensitivity of capacitive pressure sensor is increased by reducing diaphragm thickness and air gap, increasing diaphragm size. But some of these elements are limited in different devices that deployed in medical applications. Analyses of capacitance changes are so effective on sensitivity of capacitive sensor in the different designs. Therefore, modeling of capacitance is necessary that it requires more knowledge about mechanical deflection of sensor's structure. The behaviors of the flat clamped diaphragms are investigated using the classical Timoshenko plate theory [9]. Also, during many years, many researchers have improved small and large deflection analysis for plates [2, 3, 10].

In this paper a MEMS capacitive pressure sensor with clamped square diaphragm are proposed that the

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sensor sensitivity and the mechanical analysis prove the simulation results.

2. SENSOR DESIGN

A new design of MEMS capacitive pressure sensor with square diaphragm is shown in Figure 1. This pressure sensor consists of a thin diaphragm with clamped edges for sensing pressure and a pair of plates, one free edges movable electrode and one fixed electrode, for capacitance sensing.

As shown in Figure 1, the h, d_0, 2a are the diaphragm thickness, the distance between the pair of capacitor plates and the diaphragm side length, respectively.

2. 1. Mechanical Analysis According to Figure 2, the boundary conditions for the square diaphragm with clamped edges can be expressed as follows [9]:

$$W(x=a;\ y) = 0,\quad W(x;\ y=a) = 0,\quad \frac{\partial w}{\partial x}(x=a;\ y) = 0,\quad \frac{\partial w}{\partial x}(x; y = a) = 0 \tag{1}$$

Under these conditions the central deflection, W_0, of a clamped square diaphragm with residual stress due to pressure, P, is given in literature [2]:

$$P= [3.45\frac{\sigma_0 h}{a^2} +4.06\frac{\tilde{E}h^3}{a^4(1-\nu^2)}]\, w_0+ [1.994\, f_s(\nu)\frac{\tilde{E}h}{a^4}]\, w_0^3 \tag{2}$$

where σ_0 and υ are the residual stress and the poisson ratio that depend on the diaphragm material.

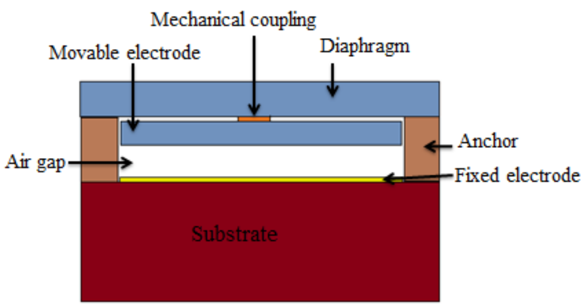


Figure 1. Cross section view of pressure sensor

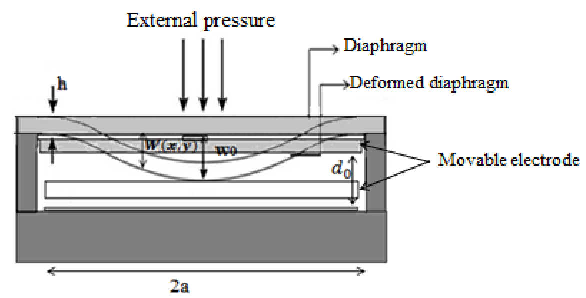


Figure 2. Cross section view of diaphragm and movable plate

The effective young's modulus, $\tilde{E}$, and the poisson ratio dependent function, f_s, expressed as:

$$\tilde{E} = \frac{E}{1-\nu^2} \tag{3}$$

$$f_s(\nu)= \frac{1-0.271\nu}{1-\nu} \tag{4}$$

At this design, the initial capacitance between the fixed and movable electrode is given by:

$$C_0= \frac{\varepsilon A}{d_0} \tag{6}$$

where ϵ is the dielectric constant and A is the effective area of the electrodes. Generally the capacitance of pressure sensor that made of two parallel electrodes with clamped diaphragm due to external pressure is given in literature [9]:

$$C=\iint \frac{\varepsilon}{d-w(x,y)}dx\, dy \tag{7}$$

where w(x,y) is the diaphragm deflection. But at this new design, the free edges movable electrode attached to diaphragm with mechanical coupling, displaced like a flat plate. This displacement is linear and equal to the deflection at the center of the diaphragm. Therefore the capacitance at this new design due to external pressure is given by:

$$C= \frac{\varepsilon A}{d_0-w_0} \tag{8}$$

For pressure sensor, the capacitance sensitivity can be defined as following:

$$S_c = \frac{\Delta C}{\Delta P} \tag{9}$$

where Δc is the change in capacitance that given by:

$$\Delta C= C - C_0 = \frac{\varepsilon A}{d_0-w_0} - \frac{\varepsilon A}{d_0} \tag{10}$$

2. 2 Sensor Structure The new sensor is consist of the polysilicon diaphragm, gold movable electrode and fixed electrode. The properties of the polysilicon that used as the diaphragm material is shown at Table 1 [2, 11]. The mechanical coupling material is Si_3N_4. Mechanical coupling attached the center of the movable electrode and diaphragm mechanically but electrically isolated from each other. Also the dimension of diaphragm is 250×250×1 μm^3 . The height of air gap is 1μm and the size of the mechanical coupling is small enough to ignoring the effect on the diaphragm deflection, 5×5×0.1 μm^3.

TABLE 1. The properties of diaphragm material

Diaphragm material	Young modulus	Poisson's ratio	stress
polysilicon	169(Gpa)	0.3	20(Mpa)

3. SIMULATION OF THE CAPACITIVE PRESSURE SENSOR

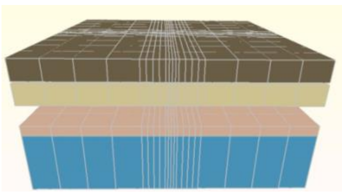
Intellisuite software is used for simulating MEMS capacitive pressure sensor to improve performance and reduce the time of fabrication process. The analysis type is thermo-electro-mechanical relaxation, iteration accuracy is 0.001 and a maximum mesh size is $4\mu m$. Figure 3 shows the simulated sensor with this setup. As shown in Figure 3, the edges of the diaphragm are fixed and movable electrode has free edges. By applying pressure on diaphragm, the movable electrode linearly approaches the fixed electrode.

4. RESULTS AND DISCUSSION

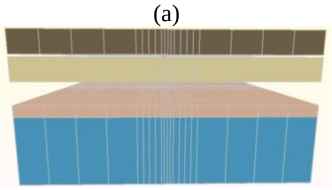
The sample of MEMS pressure sensor, under 40mmHg pressure, is shown in Figure 4. As shown in this figure, when pressure is applied, maximum deflection is in the center of clamped diaphragm. The attachment of movable electrode with free edges and the center of the diaphragm through mechanical coupling cause displacement of the movable electrode without any deflection, like a flat plate, equal to maximum diaphragm displacement.

When pressure is applied, maximum stress is created at the fixed corners of the plates. As can be seen from Figure 4, the corners of the movable electrode are not fixed. Then, this maximum stress does not exist in the edges of movable plate. In this design, this stress only exists at the fixed corners of the diaphragm and fixed electrode. Therefore, this stress does not have an important influence on the displacement of the movable electrode.

This reason increases the effective surface of movable electrode that makes capacitor. On the other hand, since the diaphragm is decoupled from movable electrode by the mechanical coupling, the movable

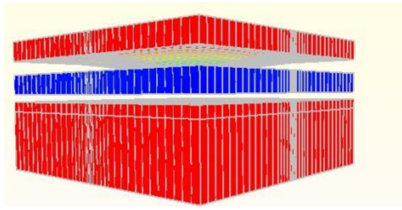


(a)

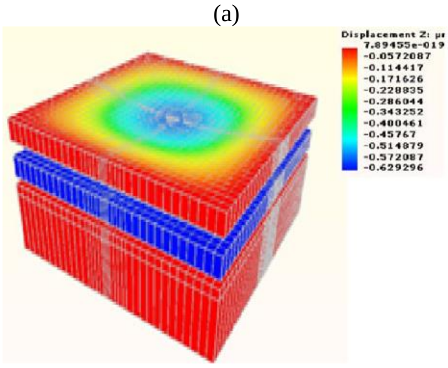


(b)

Figure 3. Simulation setup for MEMS capacitive pressure sensor (a) top view (b) side view



(a)



(b)

Figure 4 MEMS capacitive pressure sensor under 40mmHg pressure (a) side view (b) top view

electrode is displaced equal to center deflection of diaphragm then in addition to increase the effective surface of capacitor, the displacement of the movable electrode increased as well. Therefore, measured capacitance will increase.

Figure 5 shows the movable electrode displacement, for the range of pressure applied. As can be seen from Figure 5 the simulation results is found to be very close to the theoretical results that are according to Equation (2). Figure 6 shows the simulation and theoretical values of the capacitance between two electrodes due to applying pressure to the diaphragm. The theoretical values are according to Equation (8).

Considering Figure 5, when the applied pressure on the diaphragm is increased, diaphragm deflection is increased too. Figure 6 shows that the capacitance between two electrodes is increased as the air gap is reduced. In this design, according to Equations (9) and (10) and Figure 6, the sensor sensitivity is equal to 58.5 $\frac{fF}{mmHg}$.

In the following, the effects of diaphragm thickness and diaphragm size on capacitance for a given pressure load 40mmHg are shown in Figures 7 and 8, respectively. It can be seen in Figure 7 that by increasing the thickness of the diaphragm, the capacitance has reduced, due to increasing diaphragm stiffness. According to Figure 8, by increasing the dimensions of diaphragm, the capacitance has increased because of decreasing the diaphragm stiffness and increasing the effective surface of capacitor. Also, all results show that the analytical model of capacitance for MEMS sensor is very close to the simulation results.

Therefore, the model is verified to design and analysis of new MEMS capacitive pressure sensor.

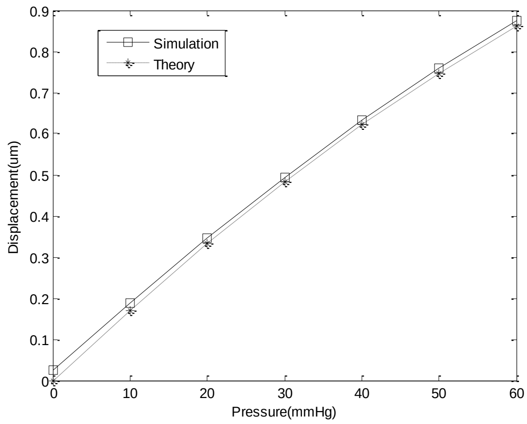


Figure 5. Displacement of movable electrode vs. pressure

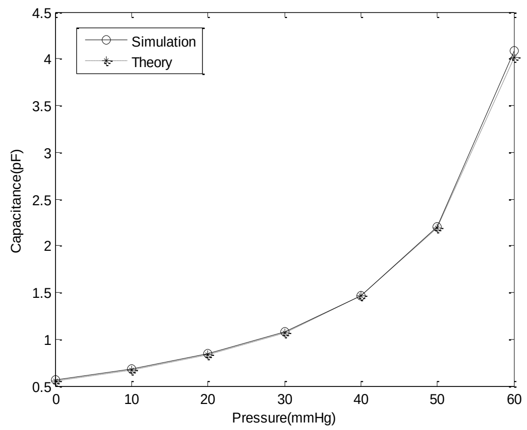


Figure 6. Capacitance vs. pressure

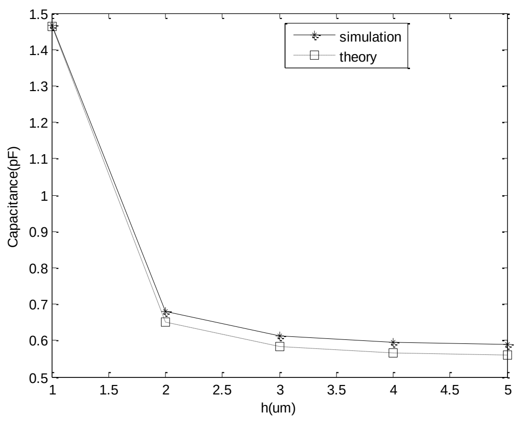


Figure 7. Capacitance vs. diaphragm thickness

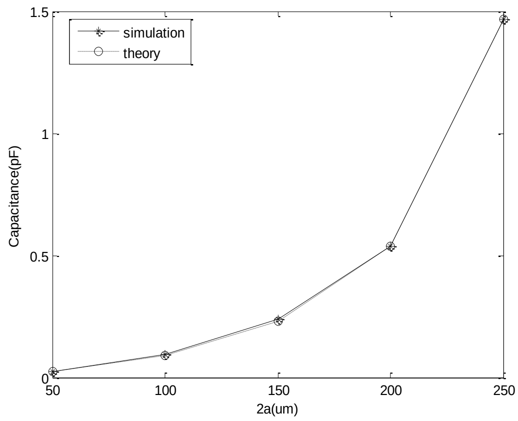


Figure 8. Capacitance vs. diaphragm size

5. CONCLUSIONS

This paper proposed the MEMS capacitive pressure sensor with high sensitivity and small size. In this design, the diaphragm and movable electrode are separated and decoupled to each other with mechanical coupling. Also, no stress exists at the free edges of movable electrode.. Therefore, the movable electrode displaces like a flat plate and has excellent linear variation equal to center deflection of the diaphragm over the pressure.

The device used a polysilicon square clamped diaphragm, the movable and fixed electrodes are gold. Also, the substrate material is Pyrex glass and mechanical coupling is Si_3N_4.

Structure design model and sensitivity analysis was carried out with simulation and mechanical analysis results. The results show that the theoretical results are close to the simulation results. The size of this sensor is 250×250 μm^2 and the thickness of diaphragm is 1µm with 1μ air gap. According to the results, the sensitivity of sensor is $58.5\frac{fF}{mmHg}$.

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چکیده

این مقاله حس‌گر فشار خازنی MEMS را ارائه داده است. در این طراحی الکترود متحرک مانند یک صفحه ثابت حرکت می‌کند که میزان جابه‌جایی آن برابر با حداکثر جابه‌جایی مرکزی دیافراگم است. جنس دیافراگم، الکترود متحرک و کوپلینگ مکانیکی به ترتیب پلی سیلیکون، طلا و Si_3N_4 است. همچنین، الکترود ثابت از طلا و زیر لایه از شیشه‌ی پیرکس تشکیل شده است. روش پیشنهادی موجب افزایش سطح موثر صفحات خازن و افزایش جابه‌جایی الکترود متحرک می‌شود. اندازه‌ی این حس‌گر برابر است با ۲۵۰×۲۵۰ میکرومترمربع، ضخامت دیافراگم ۱ میکرومتر و فاصله‌ی هوایی ۱ میکرومتر می‌باشد. مطابق با نتایج حساسیت حس‌گر $58.5\frac{fF}{mmHg}$ است.

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