An Engineering Approach for Modeling and Design of a Diaphragm Based Comb Drive Capacitive Pressure Sensor

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Abstract: The Microelectromechanical (MEMS) diaphragm based comb drive capacitive pressure sensor has two stages, Mechanical (Diaphragm) and Capacitive (Comb Drive). The diaphragm displaces in response to apply pressure and the displacement moves the movable comb structure. The two most common architectures of comb drive are single side comb structure and double fold comb structure. In this paper, an impressive technique for designing and modelling of single side comb structure capacitive pressure sensor is being presented. A mathematical model of the sensor is derived and the model simulates the designed structure with the COMSOL Multiphysics Simulator. The Mechanical Sensitivity, Electrostatic sensitivity and Overall Sensitivity are studied for the designed structure. A comparative study of the mathematic analytical values and simulated output values are examined and are found very much closed to each other. The various parameter like Young's Modulus, Poisson's Ratio, Dimensions and Structure of the pressure sensor, number of comb fingers and dimension of the comb finger affecting the sensitivity is widely discussed.

Keywords: coupler, fringing effect, electrostatic sensitivity, mechanical sensitivity.

1. Introduction

There are various pressure sensors viz. Piezo-resistive Strain Gauge, Capacitive, Electromagnetic, Piezo-electric, Strain Gauge, Optical, Potentiometric, Resonant, Thermal (Pirani Gauge) and Ionization but few of them are applicable for MEMS design. The advantages of MEMS technology are: small in size, volume and mass, low power consumption, low cost, compatible with silicon technology, low heating effect, parallelism etc. The capacitive pressure sensor is an active sensor as it requires an external power source to operate. It is one of the common in MEMS design. MEMS-based comb drive capacitive pressure sensors are miniaturized, consume less power and more efficient. Such sensors have wide application in the field of pressure monitoring, safety purpose, controlling etc. The capacitive has a wide application in various fields in monitoring, LC tank circuit, high pressure sensing, harsh environment, biomedical, measuring plantar pressure, measuring bowel state, microphone, and ultralow pressure detection [1–10]. Capacitive pressure sensor can be developed with silicon micromachining fabrication technique [11]. Many researchers use ANSYS and COMSOL finite element method multiphysics simulator for simulation [6,12,13]. Some researchers have proposed a diaphragm based comb drive pressure sensor but their study is the effect of different material properties on the sensitivity [14]. In this study, the systematic design approach for comb drive is being studied.

The working principle of comb drive capacitive pressure: the measuring pressure is applied at the mechanical sensing structure, common structures are diaphragm, bridges or cantilever, and deflect. The deflection is coupled with the coupler to translate into linear displacement and displaced the comb position resulting in the changes in capacitance.

2. Sensor Design Structure

In this paper, diaphragm-based comb drives capacitive pressure sensor has four main structures i.e. diaphragm structure, mechanical coupler, movable comb structure and fixed comb structure as is shown in fig1. The diaphragm is the structure where the pressure (stimulus) is applied and converts pressure into deflection or displacement. A square diaphragm with dimension is 200µmX200µmX5µm is considered for the design. Mechanical coupler is to translate the diaphragm deflection into linear displacement and couples to movable comb drive. Since the maximum deflection of the square diaphragm is at the centre, mechanical coupler is connected at the centre of the diaphragm and at the other end movable comb drive. The dimension of the coupler is 6µmX6µmX10µm. A comb structure having ten fingers on both side with a gap of 15µm in between the two fingers. The dimension of a finger is 200µmX40µmX5µm. The length of the finger G_1 is 40µm, the gap between the two plates G_2 is 80µm and the gap between the two adjacent fingers of movable and fixed comb G_3 is 5µm.

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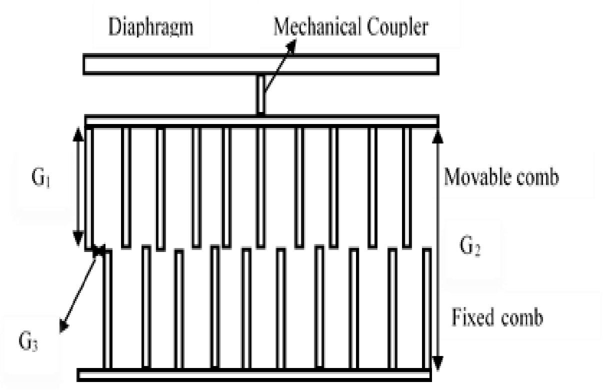

Fig. 1 *Schematic Diagram of Comb Drive.*

3. Mathematical Modelling

The diaphragm based comb drive capacitive pressure sensor has a combination of mechanical and electrostatic. In mechanical modelling, the pressure or force is applied at the diaphragm and deflects the diaphragm. The generalized equation of square diaphragm deflection W is eqn. 1[15,16]. Where, D is the flexure rigidity given by eqn.2.

$$W(x,y)=(0.0213pa^4/D)(1-x^2/a^2)^2(1-y^2/a^2)^2. \quad (1)$$

$$D=Eh^3/(12(1-v^2)). \quad (2)$$

Where,

E: is the Young's Modulus,

h: is the thickness of the diaphragm,

v: is the Poisson's Ratio,

a: is the half length of the square diaphragm,

x,y: is the coordinate of the diaphragm from the centre as an origin.

The maximum deflection occurs at the centre of the diaphragm i.e. x=a, y=a. The maximum deflection is given by eqn.3.

$$W(x,y)_{max} = W(0,0) = pa^4/47D. \quad (3)$$

Mechanical sensitivity, S_M, is given by the ratio of change in deflection to change in the applied pressure. It is given by the eqn.4.

$$S_M = \delta w/\delta p. \quad (4)$$

Where,

δw is the change in deflection with respect to applied change in pressure δp.

The deflection and mechanical sensitivity of the diaphragm depends on many parameters such as Young's modulus, Poisson's Ratio of the materials, length, breadth and thickness of the diaphragm.

3.1. Electrostatic modeling

In electrostatic, the capacitance, C, of a parallel plate capacitor is given by eqn. 5

$$C = \varepsilon A/g \quad (5)$$

Where, ε is the relative permittivity, A is the area of the plate and g is the gap between the plates.

To calculate the capacitance value of the comb drive, there are 5 (five) parallel plate capacitances and fringing capacitance, which connected in parallel in a simple comb structure as shown in fig. 2. Parallel plate capacitances C_3, C_4 and C_5 are same value and Capacitance C_1 and C_2 has same value since they have same gabs, area and dielectrics.

The overall parallel plate capacitance, $C_{parallel}$, of the simple comb drive is given by eqn. 6.

$$C_{parallel} = C_1 + C_2 + C_3 + C_4 + C_5 \quad (6)$$

$$C_{parallel} = 2C_1 + 3C_3 \quad (7)$$

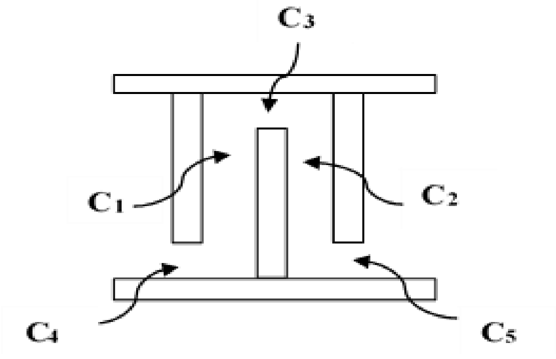

Fig. 2 *Various capacitance in comb drive.*

Considering, the design structure dimensions, the capacitance C_1 and C_3 values will be given by eqn. 8 and eqn. 9 respectively.

$$C_1=\varepsilon l(\delta w)/G_3 \quad (8)$$

$$C_3 = \varepsilon tl/(G_1 - \delta w) \quad (9)$$

Where, ε is the relative permittivity, *l* is the length of the finger, *t* is the thickness of the finger, G_3 is the gap between the two finger, G_1 is the gap between the tips of the finger and base of the opposite comb and δw is the change in displacement of the finger. N_3 is the total number of fringing area.

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The total capacitance of the design comb drive can be express by eqn. 10.

$$C_{parallel} = N_1C_1 + N_2C_3 \quad (10)$$

The fringing effect capacitance is given by eqn. 11.

$$C_{fringing} = N_3\, \varepsilon(G_1 - \delta w)l/\, G_3 \quad (11)$$

$$C_{total} = C_{parllel} + C_{fringing.} \quad (12)$$

The electrostatic sensitivity of the sensor is the sensitivity which is the ration of change in capacitance to change in deflection. It is given by eqn. 13.

$$S_E = \delta C_{total}/\delta w \quad (13)$$

The overall sensitivity is the sensitivity which is the ratio of change in capacitance to change in applied pressure. It is given by eqn.14.

$$S_{Total} = \delta C_{total}/\delta w = (\delta w/\delta p)(\delta C_{total}/\delta w) = S_M S_{E.} \quad (14)$$

The overall sensitivity is equal to the product of mechanical sensitivity and electrostatic sensitivity.

4. FEM Simulation

The proposed 3D meshing model is designed in the COMSOL Multiphysics simulator as it illustrated in the fig.3. The device has ten fingers in each, movable comb drive and fixed comb drive. The material used is gold (Au) from the inbuilt COMSOL material for the fingers and diaphragm. The gap between the combs is filled with air as a dielectric. A voltage of positive one volt is given in the movable plate and ground on the fixed plate. The physics for simulation is Electromechanics (emi) and the study is stationary. The meshing is done with Free Tetrahedral and number of elements is 1164398.

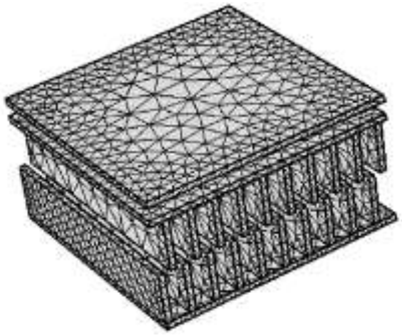

Fig. 3 *Mesh model of comb drive.*

Table 1. Gold (Au) properties.

Properties	Value	Unit
Density	19300	Kgm^{-3}
Young's Modulus	70	GPa
Poisson's Ratio	0.44	1

5. Comparisons of Simulated values and analytical values

Various comparisons are made between the analytical and simulated values. The mathematical model equations are realized in MATLAB and simulation in COMSOL Multiphysics. The graph between the deflections and the applied pressure in Fig. 5 shows linearly varying. The Mechanical Sensitivity (S_M) of the analytical and simulated are 0.023 µm/KPa and 0.020 µm/KPa.

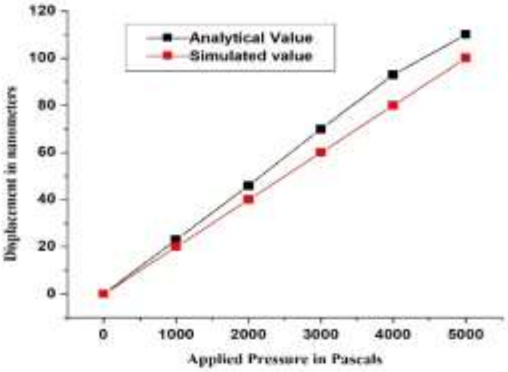

Fig. 5 Applied pressure Vs *Displacement*

The comparison is made between the analytical and simulated value of capacitance for the set of applied pressure in table 2.

Table 2. Analytical and Simulated value of Capacitance for applied pressure.

Applied Pressure (KPa)	Analytical Capacitance (pF)	Simulated Capacitance (pF)
0	0.073413	0.071560
1	0.073430	0.071570
2	0.073447	0.071580
3	0.073464	0.071590
4	0.073481	0.071600
5	0.073498	0.071610

The overall Sensitivity (S_{total}) of analytical and simulated are 0.000017 pF/KPa and 0.000010 pF/KPa respectively. The electrostatic sensitivity (S_E) of analytical and simulated are 0.000739 pF/µm and 0.000500 pF/µm respectively.

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6. Conclusion

From this study, the sensitivity of diaphragm-based comb drive capacitive pressure sensor depends on the material properties and dimension of the diaphragm and the structural design of the comb drive. The capacitance of the sensors is increased linearly with an increase in pressure. For this particular design, the sensitivity is found to be 0.000017 pF/KPa and 0.000010 pF/KPa for analytical and simulation respectively.

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