Virtual prototyping of a MEMS capacitive pressure sensor for TPMS using Intellisuite®

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Abstract— **Tire pressure monitoring system (TPMS) plays an important role in automobile safety. One of the important components of TPMS is a MEMS pressure sensor. This paper presents the virtual prototyping of TPMS which involves design, virtual fabrication and system level modelling of a square diaphragm based capacitive pressure sensor for a given stroke length. Intellisuite® MEMS design tool is used for obtaining the virtual prototype. The analytical expression for the sensitivity of square diaphragm in small deflection regime is derived and comparison of calculated results with simulated is presented.**

Keywords-TPMS, MEMS, Intellisuite, capacitive pressure sensor

I. INTRODUCTION

MEMS stand for MicroElectroMechanical Systems. It is a process technology used to create tiny integrated devices that combine mechanical and electrical components [1]. MEMS have been identified as one of the most promising technology for the 21st century and have the capability to reform both industrial and consumer products based microelectronics [2]. MEMS find application in automotive, medical, consumer, industrial, and aerospace sectors etc. The automotive sector has been a long growth market for MEMS sensors. Leading markets are ESP gyroscopes ($ 272 million), airbags ($ 260 million), followed by pressure with MAP and BAP (total $ 192 million), side airbags and TPMS [3]. Tire pressure monitoring system (TPMS) is one of the biggest automotive safety equipment required for safety on the road. Tire pressure monitoring systems (TPMS) are a way of warning a driver that the tire is incorrectly inflated, which will decrease the safety and performance of the vehicle, and increase the risk of an accident[2]. TPMS includes sensors for measuring pressure and temperature inside the tire, sensors to detect wheel speed and/or direction of rotation, controller with time base for periodic measurements, means to identify which tire is providing the data, data output to the vehicle chassis, command input for diagnostics and wake up and power source [5]. 99% of direct TPM systems currently use MEMS pressure sensors. TPMS pressure sensor is expected to reach $183M in 2012 from $168M in 2007[4]. The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) has mandated that all vehicles sold in the United States must be equipped with TPMS from the year 2012[6]. The MEMS pressure sensors can either be piezoresistive or capacitive. Capacitive pressure sensor has less power consumption, insensitivity to environmental (temp.) effect, high sensitivity near linear region in comparison with piezoresistive pressure sensor. It can also be easily be scaled down as there is no need to have resistor membrane [7]. This paper presents the virtual prototyping of TPMS which involves design, virtual fabrication and system level modelling of a square diaphragm based capacitive pressure sensor for a given stroke length. Intellisuite® MEMS design tool is used for obtaining the virtual prototype. The analytical expression for sensitivity of a square diaphragm based pressure sensor is also derived, as the literature survey revealed that the expression for the same has not been reported. The capacitance is also calculated numerically using Mathematica and by finite element modelling.

II. SENSOR DESIGN CONCEPT

A capacitive pressure sensor is composed of two plates which serve as top and bottom electrodes and a sealed cavity in the middle as shown in figure 1. The bottom electrode is fixed while the top electrode is composed of a deformable diaphragm. The deformation of the top diaphragm due to applied load pressure results in the variation or change in the capacitance, which can be measured with an interface circuit. The deformable diaphragm can either be circular or square or rectangular. The square diaphragm are preferred due to ease in fabrication and better yield [8]. According to the theory of diaphragm bending, the deflection of diaphragm/plate may fall in small deflection regime and large deflection regime depending upon whether the strain in the middle plane can be neglected or not respectively. The deflection regime is chosen as small as the deflection varies linearly in this case. The performance of capacitive pressure sensor is given by two important parameter sensitivity and non-linearity. The analytical expressions for sensitivity, non-linearity and small deflection regime are discussed below for the square geometry.

For square diaphragm small deflection at any point(x,y) is

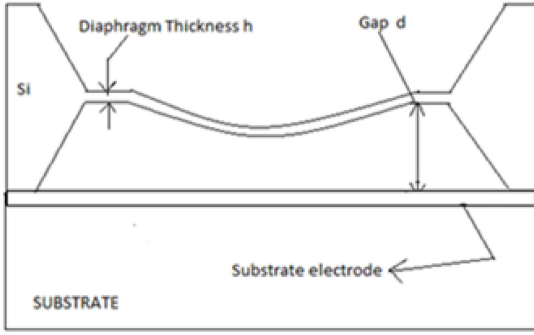

Figure 1. Capacitive pressure sensor

given by[9]:

$$w(x,y)=\frac{49Pa^4(x^2-a^2)(y^2-a^2)}{2304D} \quad (1)$$

Here a is the half side length and maximum deflection occurs at the center (x=0,y=0) is given by

$$w_0=\frac{0.216Pa^4}{Eh^3} \quad (2)$$

and the capacitance given as

$$C=\iint \frac{\in dxdy}{d-w(x,y)} \quad (3)$$

Eq. (3) is solved numerically using Mathematica®

For ***small deflection*** analytical expression of capacitance can be derived by expanding the denominator of equation (3) by using Taylor series expansion as given below:

$$C=\frac{\in}{d}\iint\left\{1+\frac{w(x,y)}{d}+\frac{w^2(x,y)}{2d^2}\right\}dxdy \quad (4)$$

Since it is small deflection case so higher order terms can be neglected. Then equation becomes:

$$C=\frac{\in}{d}\iint\left\{1+\frac{w(x,y)}{d}\right\}dxdy \quad (5)$$

Integrating the equation (5) by substituting w(x,y) from eq. (1), one gets

$$C=C_0\left(1+\frac{12.5Pa^4}{2025dD}\right) \quad (6)$$

where C_0 is the zero pressure capacitance and given by

$$C_0=\frac{\in 4a^2}{d}$$

Sensitivity is given as

$$S_A=\frac{dC}{dP} \quad (7)$$

Sensitivity can be calculated by differentiating equation (6) w.r.t to pressure P and is given as

$$S_A=\frac{49\in a^6}{2025d^2D} \quad (8)$$

Non-Linearity is given by

$$\frac{\Delta C_+-\Delta C_-}{2(C_{max}-C_{min})}100\% \quad (9)$$

III. VIRTUAL PROTOYPING

Virtual Protoyping involves following steps

1. Calculation of the structural parameters for a given stroke length and determination of sensitivity and non-linearity for a given pressure range
2. Virtual Fabrication of the structure using Intellifab®
3. Thermo-electromachanical simulation to analyse the behavior of the pressure sensor
4. Macromodel Extraction and current to voltage conversion using SNYPLE®

A. *Calculation of structural parameters*

The two parameters sensitivity and non-linearity are influenced by structural properties, material properties and the stroke length, where as stroke length is decided by the gap d. The stroke length is chosen because it decides the pressure range that can be traversed by the diaphragm. The gap d is the critical parameter in both surface micromachining and bulk micromachining devices, as it is decided by the thickness of sacrificial layer in surface micromachining and by etch stop in bulk micromachining [11]. The choice of material is also important. Si (E=130GPa, υ=0.3) is chosen as the device material here. Depending upon the choice of material and micromachining process gap d is taken as 5µm. The maximum pressure to be measured by the pressure sensor is equal to standard tire pressure of car i.e. 35psi or 241.29kPa. We have considered three different stroke lengths:

Case I: maximum stroke length is 1/3 of the gap.
Case II: maximum stroke length is 1/2 of the gap.
Case III: maximum stroke length is 3/4 of the gap.

Since the maximum deflection is always limited to one third of thickness, therefore, stroke length gives the following relation between h and d:

Case I: thickness of diaphragm is equal to the gap.
Case II: thickness of diaphragm is 1.6 times of gap.
Case III: thickness of diaphragm is 2.6 times of gap.

The other parameter is side length. The side length can be calculated either by deflection formula as given in (2) sensitivity formula as given in (8). The structural parameters and calculated sensitivity for three cases are given in table I-II.

TABLE I STRUCTURAL PARAMETER FOR THREE CASES

Case	Stroke length (µm)	D (µm)	h (µm)	Square (a) (mm)
I	1.5	5	5	0.146
II	2.5		8.3	0.244
III	3.75		12.5	0.367

TABLE II CALCULATED SENSITIVITY FOR THE THREE CASES

Case	Stroke length (µm)	Sensitivity (pF/kPa)
I	1.5	0.000065
II	2.5	0.00026
III	3.75	0.0009

B. *Virtual fabrication process*

For the virtual fabrication of capacitive pressure sensor IntelliFab is used. This paper includes the virtual fabrication steps of normal mode CPS using bulk micromachining and fusion bonding.The fig. 2 gives the process flow of capacitive pressure sensor of dimensions a=0.146mm, h=5µm, d=5µm in IntelliFab.

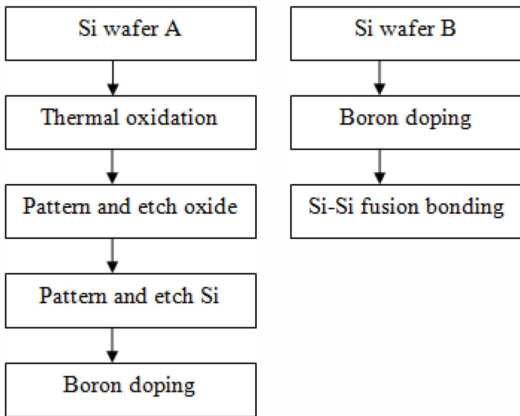

Figure 2. Process flow chart of fusion bonding

Figure 3 shows the process flow for virtual fabrication.

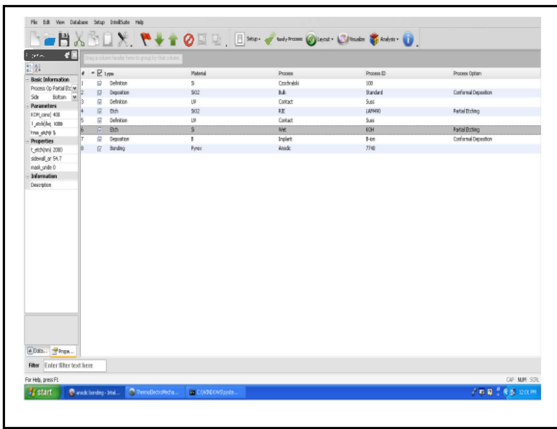

Figure 3. Process flow chart of fusion bonding

C. *Simulation using TEM*

Virtually fabricated sensor is analyzed using TEM module..The deflection and capacitance v/s pressure results are shown below in figures 4-6 and Table III.

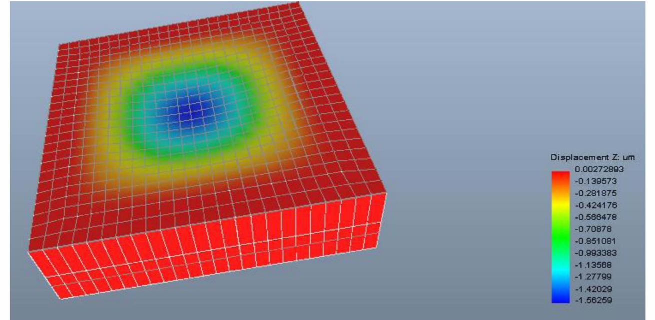

Figure 4. Result of simulation for square diaphargm

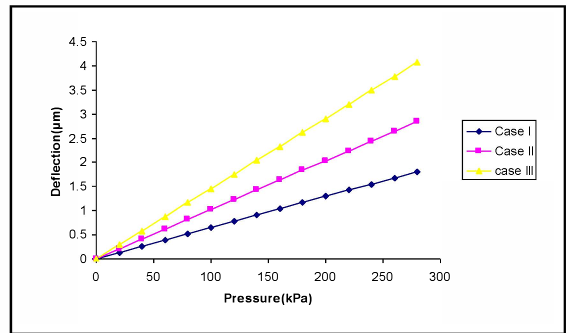

Figure 5. Combined graph for small deflection variation due to applied pressure

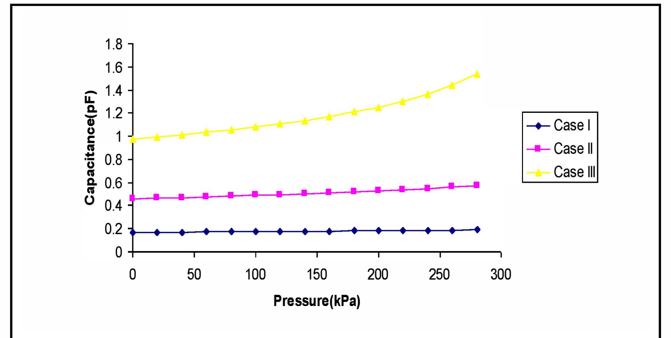

Figure 6. Combined graph for capacitance variation due to applied pressure for all three cases

TABLE III SIMULATED AND CALCULATED RESULTS FOR SMALL DEFLECTIONS

Case	Calculated sensitivity (pF/kPa)	Simulated sensitivity (pF/kPa)	Non-linearity in capacitance
I	0.000065	0.00007	3.2%
II	0.00026	0.0004	5.5%
III	0.0009	0.0018	8.6%

D. System level modeling

System-level modeling is that approach of simulation, where analytical or semi-analytical models of device components are placed and connected in a schematic of the device and the whole device is simulated. Figure 7 shows the dc analysis schematic obtained from SYNPLE

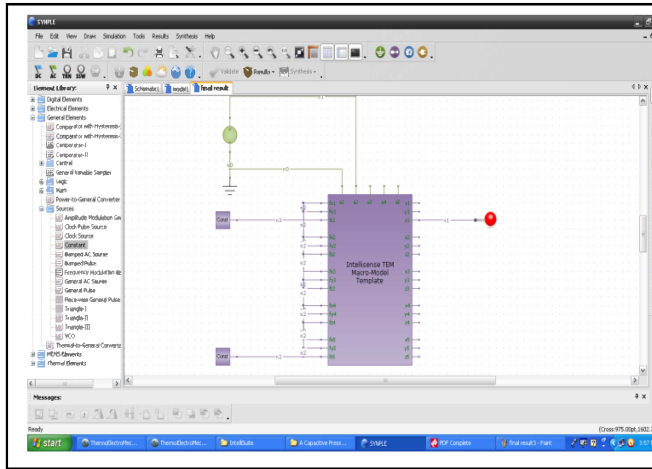

Figure 7. DC analysis schematic

E. Capacitance measurement circuit

In the capacitive pressure sensor whenever pressure is applied at the electrode which is free to move, there is change in gap between the electrodes leading to change in the capacitance . Capacitive Pressure sensor converts the diaphragm deformation, corresponding to pressure, into a change of capacitance and which is finally converted output electrical signal. To convert the capacitance into voltage, capacitance measurement circuit is used. There are various methods for the measurement of capacitance [12]. These range from measurement of capacitance using a capacitance bridge to excitation of the unknown capacitance by modulating it using a waveform and demodulating it. One of the commonly used capacitance to voltage converter is charge amplifier. The schematic of the charge amplifier is shown in Fig 8. Voltage sensitivity is -0.00003V/kPa

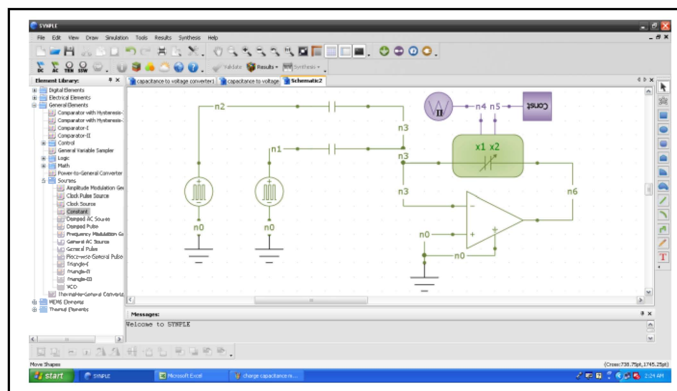

Figure 8. Capacitance measurement circuit

IV. Results and Discussions

Capacitive pressure sensor with square diaphragm was designed for for small deflection by taking three different stroke lengths and two performance parameters sensitivity and non-linearity were obtained from simulation and as well as calculations. The results obtained are summarized as follows:

- The expression for sensitivity was obtained for case of small deflection only and is given by

$$S_A = \frac{49 \in a^6}{2025 d^2 D}$$

- For a given gap, as the stroke length increases, the side length as well as thickness also increases by almost the same ratio.
- Sensitivity and non-linearity increases as stroke length increases
- The calculated and simulated values were found to be in good agreement for the capacitance as well as deflection.
- The virtual prototyping of pressure sensor was successfully done

Acknowledgment

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