A MEMS Vertical Fringe Comb Capacitive Pressure Sensor for Biomedical Application


Center of Telecommunication and Microelectronics
Victoria University, P.O.Box 14428, Melbourne City
MC8001, Victoria, Australia, hai@ee.vu.edu.au.

ABSTRACT

This paper presents the design and implementation of a Micro Electromechanical Systems (MEMS) vertical fringe comb capacitive pressure sensor for biomedical application. MEMS sensors are widely used in biomedical application due to its advantages of miniaturisation, low power consumption, ease of measurement and telemetry. In this design, a vertical fringe capacitor structure is employed to reduce the system area, increase the system linearity and have larger full scale change in capacitance compared to its parallel plate counterparts, which are used conventionally. The designed pressure sensor is coupled with a CMOS Radio Frequency (RF) oscillator working in frequency range of 2.4GHz to 2.54GHz as the system signal conditioning circuit. Results show that for the pressure range of 0 to 300mmHg the device capacitance range of 1.31pF to 1.98pF is achieved which results in a frequency sweep of 2.54GHz to 1.95GHz with good linearity over the whole range.

Keywords: MEMS, biomedical sensor, capacitive sensing, co-simulation, vertical fringe capacitor.

1 INTRODUCTION

Biomedical application of sensors requires the devices to be small, low powered and ease of being telemetered [1][2]. Pressure sensor is one of the few devices that have been widely used in biomedical applications. Amongst different types of pressure sensors parallel plate capacitive pressure sensors is one of the most widely studied devices in terms of device physics, performance and reliability [3]. Designers have been concerned about non-linearity issues of parallel plate capacitive pressure sensors and have addressed them by using proper signal conditioning circuits [4][5][6]. Recently MEMS (Micro Electro Mechanical Systems) and CMOS technologies have enabled the implementation of a complete sensor with signal conditioning circuits for better accuracy and reliability [7]. With recent advancements in MEMS technology now it is possible to fabricate devices with high aspect ratios which give designers and extra edge to try different models of capacitors. In this design, vertical fringed capacitor is employed to achieve the advantages of reduction in system area, increase system linearity and have larger full scale change in capacitance compared to parallel plate counterparts. Sensor is required to operate in the range of 0 to 300mmHg, as it is targeted for blood pressure sensing and heart beat rate sensing. CMOS circuits offer low power consumption and high speed characteristics and use of RF (Radio Frequency) CMOS gives the needed edge of telemetry to the sensor [8]. In this design, the sensor is coupled with CMOS RF oscillator as signal conditioning circuit. Oscillator uses the upper ISM (Industrial, Scientific and Medical) Band of frequencies of 2.4GHz to 2.54GHz to take the advantage of on-chip antenna for signal transmission for telemetry, smaller capacitance value required, smaller system, low power, etc.

2 DESIGN OF VERTICAL FRINGE CAPACITOR.

Figure 1 presents the structural diagram of the proposed pressure sensor. The top diaphragm has thickness of 5µm with area of 200µm x 300µm supported from each side by 2 cantilevers as spring supports. Actual structure consists of 25 fringes, 3µm thick and separated by distance of 1µm.

![Figure 1: Structural diagram of Capacitive pressure sensor](image)

A multi fringed comb capacitor structure is utilised to minimise the area on which the pressure to be measured is applied. The total capacitance \( C_{\text{total}} \) for N number of fringes with Overlap height \( O_h \), Overlap Width \( O_w \), Fringe gap \( F_g \), Dielectric Thickness \( D_t \) and Dielectric constant \( \varepsilon_r \) is given as:

\[
C_{\text{total}} = N \times \frac{D_t \times \varepsilon_r}{F_g} \]
The overlap height changes with pressure applied. The theory of thin plates is applied to determine the deflection of top plate under applied uniform pressure. Deflection in Z-direction ($d_z$) is a function of uniform pressure applied ($q$) and flexure rigidity ($D$) of plate. It obeys the following 4th order differential equation (2) [9]:

$$\nabla^4 d_z = \frac{\partial^4 d_z}{\partial^4 x} + 2 \frac{\partial^4 d_z}{\partial^2 x^2 \partial^2 y} + \frac{\partial^4 d_z}{\partial^4 y} = \frac{q}{D}$$

(2)

Where, $D$ is a function of Young’s modulus ($E$) of material of diaphragm, Poisson’s ratio ($\nu$) and thickness of the plate ($t$) and is given as in equation (3):

$$D = \frac{Et^3}{12(1-\nu^2)}$$

(3)

Proper Boundary conditions applied to equation (2) determines the solution for $d_z$. Maximum value of $d_z$ is at the centre of the plate where moments of inertia are maximum. Actual capacitance at certain pressure can be determined obtaining the value of $d_z$ at that pressure, and then calculating the total capacitance from equation (4).

$$C_{total}(dz) = \frac{(N-1)\varepsilon_0 (O_h + dz)O_w}{F_g + \frac{Dt}{\varepsilon_r}}$$

(4)

Capacitance of 1.3pF can be achieved with 44 fringes, $L=200\mu$m, $W=300\mu$m, $O_h=10\mu$m, $O_w=200\mu$m, $F_g=0.8\mu$m, $D_t=0.2\mu$m, $\varepsilon_r=7$ for aluminium. Fringing effects are considered to be minimum.

### 2.1 Boundary conditions

The 4th order differential equation (2) has different solutions under the different boundary conditions of support given to this plate to oppose the applied uniform load on top surface of the plate. The case discussed here is of a corner supported Plate by a cantilever support at each corner. The boundary conditions for solution of above equation will be derived from figure 2 [9].

The shaded section is the plate area over which a uniform load $q$ is applied. The metal plate, presented in figure 2, is symmetry about both X-axis and Y-axis. Therefore, boundary conditions can be reduced and are defined in equations (5), (6), (7), (8), (9) and (10).
of plate at different points on the surface with maximum deflection at the centre of the plate.

3 DESIGN OF SIGNAL CONDITIONING OSCILLATOR

The frequency of oscillation of the signal conditioning circuit is required to be 2.4GHz to 2.54GHz. The required capacitance values corresponding to these frequencies are very small and its range is constrained by two criteria (A) Range of Pressure to be measured (B) Range of Frequency of operation of system. With pressure range from 0 to 300mmHg, frequency of operation range from 2.4GHz to 2.54GHz and fixed inductance value of 4.846nH, the required range of the capacitance is from 1.31pF to 1.46pF. Since the capacitance to be sensed is very small a differential oscillator is chosen with one capacitive pressure sensor connected to each branch. Figure 3 presents the schematic diagram of the circuit.

4 DEVICE MODELLING AND SIMULATION

The MEMS sensor, presented in Figure 1, has been implemented in Coventorware and its Reduced Order Models (ROM) are extracted. Electrical behaviour of device is modelled as change in capacitance with respect to change in distance between the two metal plates. Mechanical behaviour of device is modelled as spring constant ‘k’ of the system by relating amount of reaction force offered by the rigid supports when uniform pressure is applied on top moving plate to achieve desired deflection. The connecting link between these two models is the Mass model that encapsulates the Moments of Inertia at different

5 RESULTS

The capacitance was designed to have 25 fringes connected as 13 on bottom plate and 12 on top plate. Maximum displacement was allowed to be 0.8μm and it has been found that at maximum pressure the displacement of only 0.7μm. The required capacitance range is from 1.3pF to 1.46pF but the final capacitance range achieved is from 1.31pF to 1.98pF. This leads to a significant reduction of the lower limit of operation frequency from 2.54GHz to 1.98GHz. Figure 5, 6 and 7 presents the mechanical behaviour of device, the electrical behaviour of device and the relationship between pressure and frequency respectively.

6 CONCLUSION

Deflection \( d_z \) varies at different locations on the surface of plate but it was found that for the plate area to which the fringes are connected the deflection \( d_z \) is almost same. Hence a bit of difference is found between designed capacitance and practical value. The non-linearity seen in displacement to capacitance relationship is taken care of by the signal conditioning oscillator and the relation between

Figure 3: Differential Oscillator schematic diagram.

Figure 4: Sensor model in Cadence

Pressure and Frequency is found to be fairly linear over the whole range of operation.

Results show that for the pressure range of 0 to 300mmHg the device capacitance range of 1.31pF to 1.98pF is achieved which results in a frequency sweep of 2.54GHz to 1.95GHz. A full-scale change in capacitance of 680fF was obtained.

A remarkable change in range of capacitance value was found due to fringing effects dominating at smaller distance between the plates. Device sensitivity as determined from the Pressure vs Capacitance graph is found to be 0.25fF/mmHg which is really good enough compared parallel plate counterparts of similar size.

REFERENCES


