Modeling and Simulation of Dual Application Capacitive MEMS Sensor

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Abstract: Capacitive MEMS sensors offer high spatial resolution, sensitivity and good frequency response. In this paper, we present a circular membrane capacitive MEMS device that finds use both as capacitive micromachined ultrasonic transducer (CMUT) and pressure sensor. The MEMS device is first designed and simulated to work as a CMUT operating at about 5 MHz. The device can also function as a highly sensitive pressure sensor. The paper describes the design considerations and COMSOL simulation results.

Keywords: Capacitive MEMS sensor, Capacitive Micromachined Ultrasonic Transducer (CMUT), Pressure sensor, COMSOL Multiphysics.

1. Introduction

Capacitive MEMS devices offer several advantages due to their size, cost and ease of integration with CMOS circuitry. The ultrasonic transducer and the pressure sensor discussed in this paper are based on capacitive sensing transduction mechanism. The CMUT has applications in non-destructive evaluation of materials, fingerprint sensing, medical imaging and therapy, and the absolute pressure sensor can be used as altitude, tactile and automobile pressure sensors.

CMUTs are silicon-based microtransducers that offer several advantages over traditional piezoelectric transducers, which includes wider bandwidth, ease of large array fabrication, higher transduction efficiency and operation over wide range of temperatures [1]. A CMUT generally consists of a membrane suspended over a cavity that is just above the bottom electrode. In transmit mode, a small AC signal is superimposed on a DC bias voltage that leads to electrostatic deflection of the membrane and simultaneous transmission of ultrasonic waves. In receive mode, incoming acoustic wave will induce vibrations in the membrane leading to a change in capacitance, that is sensed out using a read-out circuit [1,3].

Capacitive pressure sensors work on the principle of mechanical deformation of thin membranes induced by pressure difference across the diaphragm. The mechanically induced diaphragm deformation leads to a change in capacitance which can be detected using a read out circuit.

The organization of the paper is as follows: section 2 describes the design consideration of the CMUT and gives a brief description of its fabrication. Simulation of CMUT and pressure sensor using COMSOL Multiphysics tool is described in Section 3, and Section 4 provides our conclusions.

2. Design considerations

Our goal was to design a CMUT that can operate at about 5MHz. We wanted the materials used to fabricate the CMUT and capacitive sensor to be CMOS materials, to allow for fabrication in a standard cleanroom with small modifications to standard CMOS. Silicon is chosen as the membrane material, Aluminum as the metal layer and silicon dioxide for posts.

For the membrane material of density ρ, Young's modulus E and Poisson's ratio υ, the resonant frequency is given by [3]

$$f = \frac{0.47\,t}{a^2}\sqrt{\frac{E}{\rho\,(1-\upsilon^2)}}$$

Calculation of pull-in or collapse voltage is an important design parameter for CMUT [1,5]. By substituting γ = 0.82 for half metallization, collapse voltage is calculated using

$$V_{col} = \gamma\sqrt{\frac{128\,(E-T)\,t^3 d^3}{27\,\varepsilon\,(1-\upsilon^2)a^4}}$$

Table 1. CMUT design parameters

Thickness of membrane (t)	3.26 µm
Radius of membrane (a)	50 µm
Gap between electrodes (d)	100 nm
Resonant frequency (f)	5 MHz
Collapse Voltage (V_{col})	17.56 V

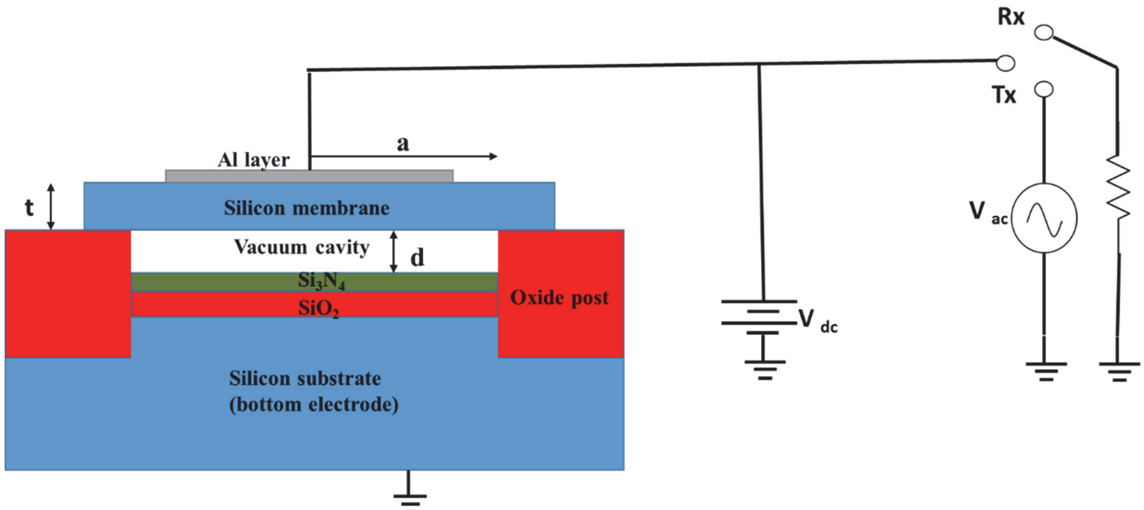

Figure 1. Circular Membrane CMUT structure

For a CMUT operating at 5 MHz frequency, the design parameters obtained using the above two equations are listed in table 1. The capacitive MEMS structure can be fabricated based on LOCOS process and direct wafer bonding technique. By following this technique, a vacuum cavity is created between the electrodes. Park et al. report that this fabrication technique can improve the device reliability and performance [2]. A schematic of the capacitive MEMS sensor is shown in figure 1.

3. Use of COMSOL Multiphysics

The capacitive MEMS sensor was modeled in 3D using COMSOL Multiphysics. Simulation of the CMUT was carried out followed by that of the pressure sensor.

3.1 Simulation of CMUT

The CMUT was simulated for resonant frequency and membrane deflection at collapse voltage.

Eigen frequency analysis was used to simulate the resonant frequencies of the membrane structure. By fixing the edges of the membrane and the posts, boundary condition was applied. The Eigen frequencies for the first two modes were found to be 4.56 MHz and 9.5 MHz.

However for CMUTs, the first mode frequency is the frequency of operation. Figures 2 (a) and (b) show the COMSOL simulation results. Next, the CMUT structure was modeled to study membrane deflection at collapse voltage. Solid mechanics and electrostatics physics were chosen with stationary analysis for the simulation.

Voltage of 17.56 V was applied to the Al metal layer and the silicon substrate was grounded.

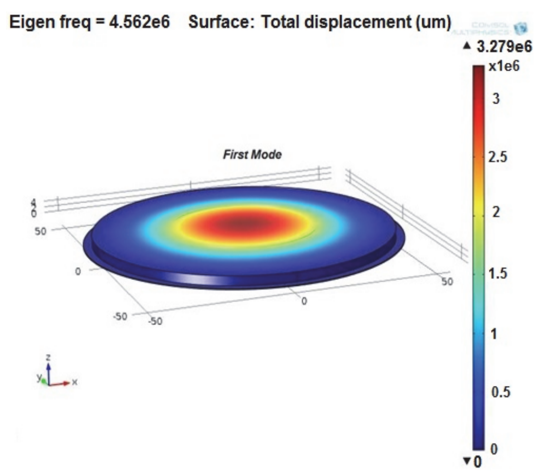

Figure 2 (a). Eigen frequency analysis – mode 1

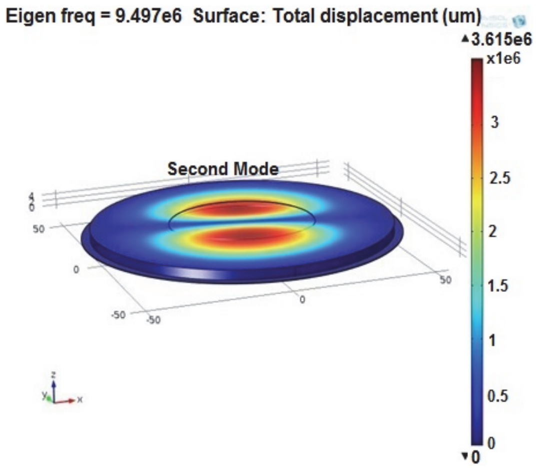

Figure 2(b). Eigen frequency analysis – mode 2

Theoretically, the total pressure applied is given by

$$P = P_{atm} + \frac{F_{elec}}{Mem\ Area};$$

where,

$$\frac{F_{elec}}{Mem\ Area} = \frac{\varepsilon V^2 A}{2\, A\, d^2}$$

The maximum membrane deflection only due to electrostatic force at collapse voltage is theoretically $1/3^{rd}$ the distance between the two electrodes. Membrane deflections for total pressure with and without P_{atm} were analyzed and are presented in table 2. Figure 3 shows the COMSOL simulation result for pressure only due to the electrostatic force.

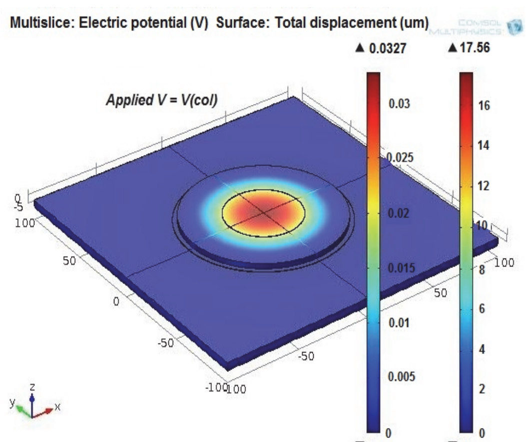

Figure 3. Membrane deflection at collapse voltage.

Table 2. Membrane deflection analysis

Applied voltage	Mem. deflection (with P_{atm})	Mem. deflection (without P_{atm})
17.56 V	0.057 µm	0.0327 µm

3.2 Simulation of Pressure Sensor

The membrane deflections for various pressures were simulated using stationary analysis coupled with solid mechanics physics. For computation purpose, the substrate layer is removed and the pressure is applied to the top surface of the membrane as shown in figure 4. The theoretical membrane deflection can be calculated using [6]

$$w = \frac{P\, a^4}{64\, D};$$

where, flexural rigidity (D) is given by

$$D = \frac{E\, t^3}{12\,(1 - \upsilon^2)}$$

Table 3 shows the membrane deflections for various applied pressures. The simulation results are graphically compared with theoretical values, and are shown in figure 5.

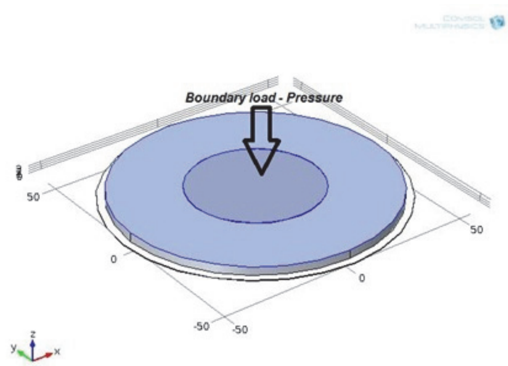

Figure 4. Pressure is applied to the top surface of the membrane.

Table 3. Maximum membrane deflection for different applied pressures.

Applied pressure (1E5 Pa)	Membrane deflection from COMSOL simulation (µm)
1.01325	0.025
1.885	0.0465
2.756	0.0679
3.628	0.0893
4.50	0.1108

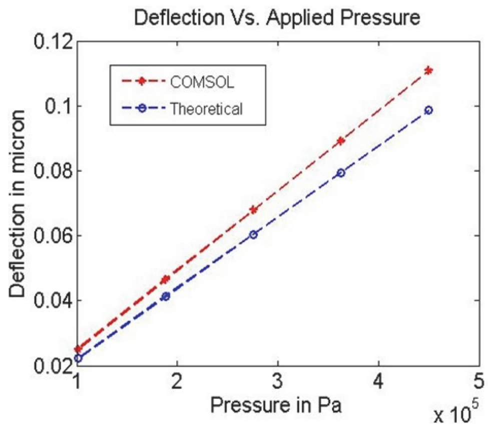

Figure 5. Comparison of maximum membrane deflections

4. Conclusion

Capacitive MEMS sensors are one of the widely used sensing technologies today. A capacitive MEMS sensor that can be used both as a CMUT operating at about 5MHz frequency and as an absolute pressure sensor is presented. The CMUT operating at around 5 MHz frequencies find applications in medical imaging, biometrics, non-destructive evaluation and navigation, and the highly sensitive pressure sensor described can be used as altitude, tactile and automobile pressure sensors. COMSOL Multiphysics was used to simulate the sensors and study the membrane deflections for different applied pressures. Further, it is shown that the simulation results match closely with the theoretical analyses of the CMUT and pressure sensor.

5. References

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