Simulation and Fabrication of Wireless Passive MEMS Pressure Sensor

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Abstract:A wireless passive pressure sensor and the measurement system were designed and simulated using COMSOL 4.3. The sensor is based on MEMS capacitor attached to a planar inductor for wireless powering and readout. An external coil (antenna) is used for the measuring system. The pressure to be measured compresses the MEMS capacitor and changes the resonance frequency of the sensor. The complete system requires an electromagnetic and a mechanical model simulation; COMSOL 4.3 was used for the analysis of the two physics interactions. The Electromagnetic Waves module was used to simulate the antenna response and the effect of a coupled sensor in the frequency domain. Solid Mechanics module was used for the simulation of the compression of the sensor caused by an external pressure. Data obtained from the fabricated sensor were consistent with the simulation results, the differences were caused by the sensor's fabrication processes.

Keywords: wireless sensor, passive sensor, electromagnetic field, multiphysics simulation, COMSOL 4.3.

1. Introduction

Wireless passive sensors allow constant remote measurements for long periods of time without the need of a battery or maintenance. The advantages of such devices permit the implantation of a sensor in hazardous or fragile places for example sensing inside the human body [1] or inside a sealed environment [2]. The LC resonators have been used for sensing chemical and physical parameters as a wireless passive sensor for sensing pressure [3], humidity [2] and chemical compounds [4]. The sensing process is based on changes on the system's capacitor which represents a variation on the sensor's natural resonance frequency. An external coil (antenna) is used for the measuring system. An electromagnetic field is produced by the antenna which couples with the sensor, inducing currents in it. On this paper a wireless passive pressure sensor and the measurement system were designed and simulated using COMSOL 4.3.

2. COMSOL Multiphysics Simulation

The sensor study was made with a multiphysics simulation using the RF Module and the Structural Mechanics Module. The model was elaborated in 3D because no symmetry planes were present on the design and non-uniform changes on the sensor's geometry had to be taken into account, because they represent mayor variations on sensor sensibility and response. The sensor is based on MEMS capacitor attached to a planar inductor for wireless powering and readout. The pressure to be measured compresses the MEMS capacitor and changes the resonance frequency of the sensor. Figure 1 shows the sensor schematic diagram and the antenna-sensor system.

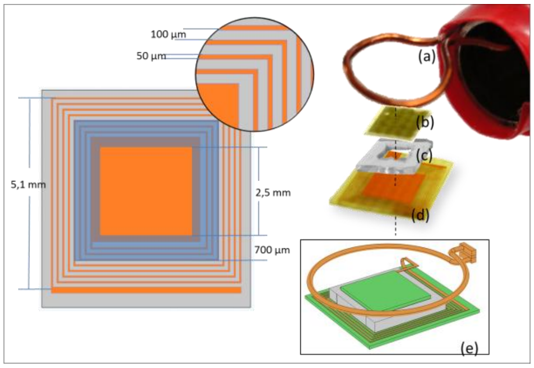

Figure 1. Wireless Passive MEMS pressure sensor system. (a) Antenna (b) Capacitor top plate (c)PDMS cavity (d) Planar inductance and Capacitor bottom plate (e) COMSOL 4.3 simulation model.

2.1 RF Module

The measurement of the wireless passive pressure sensor is based on a coupled sensor and antenna system. The coupling process is described as the induced voltage in the sensor caused by a change of the magnetic flux driven by the antenna and vice versa in steady state. This process can be measured in the antenna impedance and depends on the sensor, and as a consequence an effect of the sensor's resonance frequency can be detected. The RF Module allows the time-harmonic simulation of those physics with the Electromagnetic Waves module (emw).

The use of Maxwell's equations makes possible to simulate the electromagnetic waves interaction between the antenna and the pressure sensor in steady state. An air sphere is used to contain the sensor and the antenna. The following equation describes the electric field E inside the air sphere and the non-metallic elements like the substrate (FR4) and PDMS:

$$\nabla \times \mu_r^{-1}(\nabla \times E) - {k_0}^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \quad (1)$$

were μ_r denotes the relative permeability tensor, ω the angular frequency, σ the conductivity tensor, ε_0 the permittivity of the vacuum, ε_r the relative permittivity tensor, and k_0 is the free space wave number. Outside the air sphere, Perfectly Matched Layers are defined to reduce the reflections at the interface letting the generated waves propagate to infinity.

The simulation of metallic elements like the antenna and the sensor both made of copper is achieved by using the impedance boundary condition, the follow equation describe the source electric field E_s and the electromagnetic field generated by the induced current on the boundary surface:

$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_c}}\, n \times H + E - (n \cdot E)n = (n \cdot E_s)n - E_s (2)$$

A lumped port is used to apply a current excitation on the antenna; the two terminals of the antenna are connected using the boundaries of a box. The port is assigned with 50 Ω impedance and with a 1 A driven current. The 1 A driving current does not affect the resonance frequency of the coupled sensor.

2.2 Solid Mechanics

The compression on the sensor was simulated using the solid mechanics module; an external pressure was applied on the MEMS capacitor top plate using the Bondary Load condition. The substrate was set as a fixed constrain for the sensor. The compression was simulated using the Linear Elastic Material Model, the Young's modulus and Poisson's ratio of the FR4 and copper were included on the material library of COMSOL 4.3. The PDMS constants used were Young's modulus 360 KPa, Poisson ratio 0.5 and Mass density 0.97 kg/m^3 [5]. The Poisson ratio defines the PDMS as a Nearly incompressible material, the simulation was stationary in order to get the complete deformation caused by the external pressure on the sensor.

$$\varepsilon = \frac{1}{2}(\nabla u + \nabla u^T)(3)$$

2.3 Meshing

In order to reduce the simulation time, the meshing process was customized taken in consideration the best properties for every domain and boundary in the model. For the solid mechanics simulation only the sensor was meshed, that includes: the FR4 substrates, the coil and MEMS capacitor metallic parts, the PDMS cavity and the air cavity inside the PDMS.

The metallic parts of the pressure sensor and the antenna need a good mesh distribution for a proper electromagnetic simulation, a Free Triangular mesh was used in the external boundaries with a minimum element size of 120 µm. The interior on the metallic domains were not meshed for this model simulation since they were defined under the impedance boundary condition. The connections between the bottom and top plate of the MEMS capacitor and the connections between the two terminals of the coil were simplified; the geometries are shown in figure 2. The metallic parts on the pressure sensor unions and the PDMS cavity preserves the interior boundaries in order to avoid meshing problems.

The air sphere domain was meshed using a little initial step and a high growth rate for the mesh, because the calculated deformation in most cases was in units of micrometers which caused meshing problems.Finally the external air sphere used in the Perfectly Matched Layers condition was meshed using a swept distribution. Figure 3, show the meshed model.

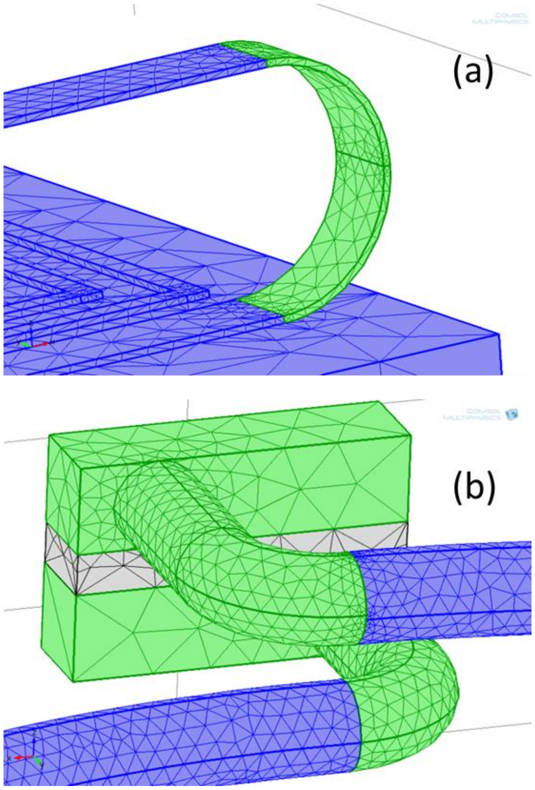

Figure 2.(a) Connections between the bottom and top plate of the MEMS capacitor (b)Connections between the two terminals of the coil.

3. Sensor Fabrication

The pressure sensor was design with a resonance frequency of 200 MHz, the MEMS capacitor had a 2750 µm side, the capacitor has an internal PDMS support which gives structural support and mechanical memory to the sensor. The width on the PDMS walls was 700 µm. A planar inductor attached to the capacitor was design using turn widths of 50 µm and turn separation of 100 µm, the coil had 8 turns and the total length of the sensor was 5.1mm. The sensor was fabricated using fiber glass substrate (FR4) with a 30 µm copper layer; a PDMS layer of 1000 µm was used as dielectric for the capacitor with an internal air cavity of 2.5 mm x 2.5 mm. All the fabrication and characterization processes were carried out at the clean room of the Universidad de los Andes.

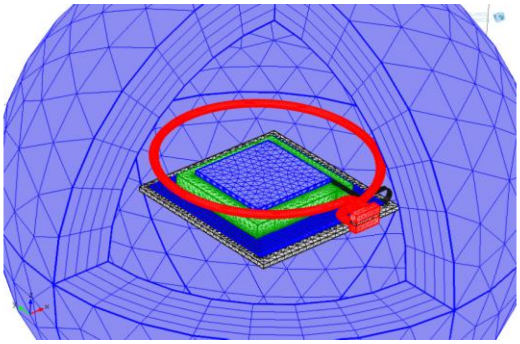

Figure 3. Mesh of the system. The antenna is show in red; the PDMS is shown in green; the sensor is show in blue and gray; the sensor and the antenna had a high density mesh.

The fabrication processes of the copper patterns for the sensor were based on techniques of softlitography and chemical wet etching. A maskless micro-patterning SF100 projector (Intelligent, UK) was used for transfer the sensor schematics into the substrate coated with positive photoresist SC1827 (Microchem, USA), ferric chloride was used in the copper chemical wet etching process. The PDMS (Sylgard,USA) cavity was build using glass molds covered with oil, a 10:1 base with curing agent PDMS mixture were deposited into the molds, after a curing process at 80 °C for 2 hours the PDMS cavity was removed. A thin PDMS layer of 25-30 µm was deposit on the PDMS cavity for bonding it with the planar inductance and capacitor bottom

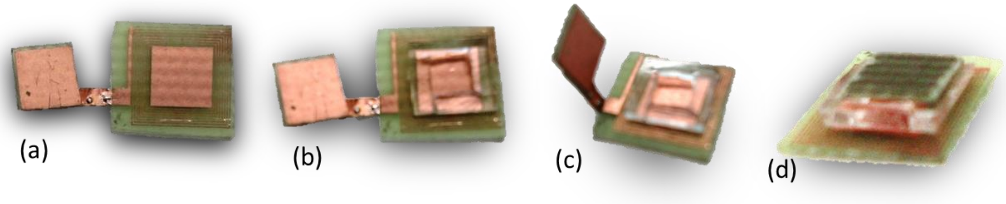

Figure 4. Pressure sensor assembling process. (a) MEMS capacitor and planar coil, (b) PDMS cavity bounded to the bottom plate of the sensor, (c) assembling of the sensor, (d) wireless pressure sensor.

plate the union was cured at 60 °C for 4 hours. The final assembly process was done by depositing a thin PDMS layer on the capacitor's top plate, the sensor was cured over the night at 60 °C, the fabrication process is shown on Figure 4.

4. VNA Measurements

Measurements were done using a Vector Network Analyzer (VNA) Master (Anritsu, Japan). The resonance frequency was taken from the real part of the impedance magnitude of the antenna coupled with the sensor. The setup used for the measurement is shown on Figure 5, a water barometer is used to generate and measure a constant pressure over the sensor placed in the bottom of the 10mm tube. Compressed air was used to increase the pressure inside the barometer, the pressure variations were measured using a camera and a measuring tape. Data was saved in the VNA immediately after a change in the pressure.

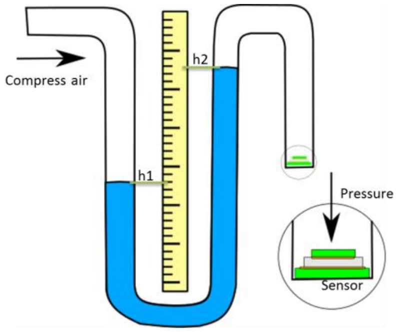

Figure 5. System used for the pressure measurement, the sensor is placed in the bottom of the tube.

5. Results and Discussion

Mechanical simulations are shown in Figure 6. The deformation caused by a constant pressure over the MEMS capacitor top plate was almost uniform; the displacement values were used on the electromagnetic simulation for the analysis on the resonance frequency caused by an external pressure. The displacement on the z axis was calculated evaluating the global displacement on the points of the boundary where the pressure was applied. For this study, a maximum pressure of 75 Torr was used; the deformation on the sensor after simulation with this pressure was of 26 µm in average.

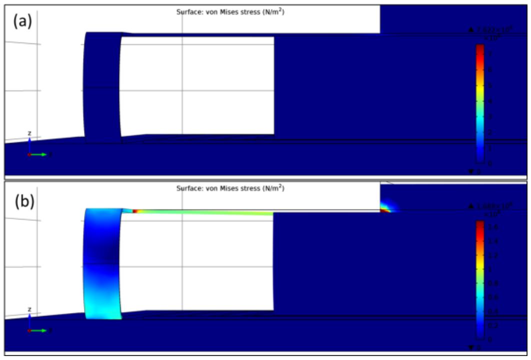

Figure 6. Deformation caused by an external pressure applied to the sensor. (a) Pressure of 3 torr applied (b) Pressure of 75 torr.

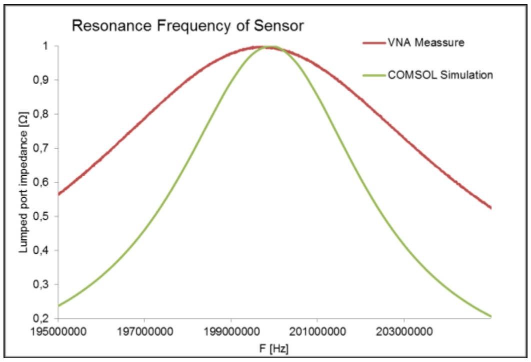

Figure 7. Normalized simulated and measured resonance frequency of the sensor.

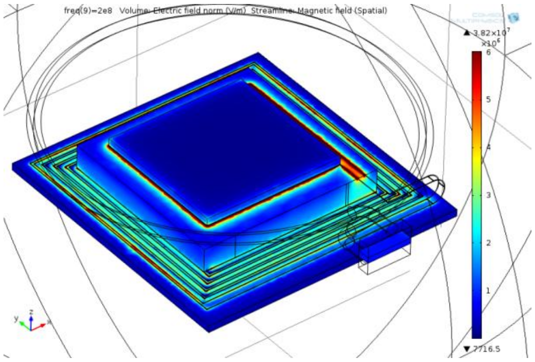

Figure 8. Energy induced on the sensor.

Figure 7 shows the simulated sensor impedance and the measurement registered with the VNA. The coupling effects caused by the sensor were similar in both real and simulated data. The resonance frequency of the simulated sensor was of 200.00 MHz, and the measured frequency was of 199.72 MHz. Figure 8 shows the energy induced on the sensor.

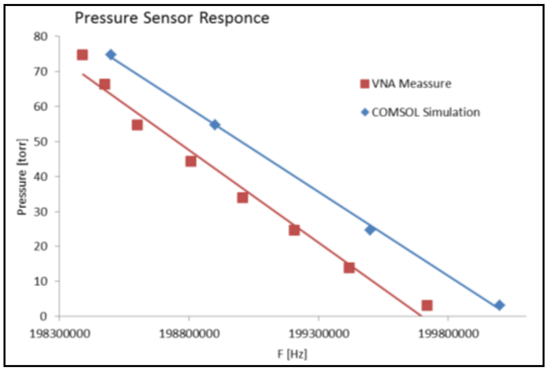

Figure 9. Resonance frequency of the sensor with different pressures. Simulated data is shown in blue and measured data in red.

The resonance frequencies were used to obtain the pressure measurements. Figure 9 shows the relation between the pressure applied and the resonance frequency. The electromagnetic simulation was carried out using the displacement value calculated from the solid mechanics simulation. The PDMS layer height was reduced to simulate the compression caused by the external pressure on the sensor. The changes caused on the PDMS cavity show the same behavior in the frequency displacement of the sensor in both simulated and experimental data.

6. Conclusions

COMSOL Multiphysics was used for the simulation of a wireless passive pressure sensor. The RF module show the behavior of the antenna coupling the sensor, the resonance frequency of the sensor had a 0.14% relative error caused by the fabrication processes. The compression on the sensor caused by an external pressure was simulated, the calculated displacement on the MEMS capacitor was approximated and the results of the sensor were consistent with the experimental results.

8. References

1. Po-Jui Chen; Dodger, D.C.; Saati, S.; Humayun, M.S.; Yu-Chong Tai, “Microfabricated Implantable Parylene-Based Wireless Passive Intraocular Pressure Sensors,” *Microelectromechanical Systems*,**Volume 17, no. 6**, page.1342-1351 (2008)

2.Tan, E.L.; Ng, W.N.; Shao, R.; Pereles, B.D.; Ong, K.G. A “*Wireless, Passive Sensor for Quantifying Packaged Food Quality”, Sensors*, **Volume 7, no. 9**, page. 1747-1756. (2007)

3.Nabipoor, M.; Majlis, B.Y.; "*A passive telemetry LC pressure sensor optimized for TPMS,*" *Semiconductor Electronics*. ICSE 2004.IEEE International Conference on, **Volume**.**1**, page. 5.(2004)

4. García-Cantón, J.Merlos, A.Baldi A., *“A wireless LC chemical sensor based on a high quality factor EIS capacitor”*, *Sensors and Actuators B: Chemical*, **Volume 126**, Issue 2, Pages 648-654. (2007)

5. *“Material: PDMS (polydimethylsiloxane)”, Material Property Database*, Available on: http://www.mit.edu/~6.777/matprops/pdms.htm

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