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A new passive telemetry LC pressure and temperature sensor optimized for TPMS

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Abstract. A new structure for a passive telemetry LC absolute pressure and temperature sensor is proposed, analytically simulated, and optimized to be used in a Tire Pressure Monitoring System (TPMS). This device is designed to measure a range of pressure from 0 to 100psi with an average sensitivity of 194.8KHz/psi and a wide temperature range of -100°C to more than $+300^{\circ}\text{C}$ with a sensitivity of $0.273\ \Omega/^{\circ}\text{C}$. The die size measures 6mm*6mm and the maximum working frequency is 56MHz.

1. Introduction

Continuous and accurate measurement of air pressure and temperature in next generations of tire pressure monitoring systems (TPMS) in automotive applications requires a wireless device to increase the portability and reliability. To serve as a long-term device, no battery must be used in such sensors due to the limitations of lifetime, power, and chemical stability. The idea of telemetry communication has been applied to some state of the art pressure sensors mostly designed to be implanted in human body in medical applications [1-3]. We applied this idea for higher pressure ranges to be used in automotive applications. Also we designed the sensor structure to sense the temperature in addition to pressure.

In this passive telemetry LC pressure and temperature sensor a pressure sensitive capacitor is used in parallel with a temperature sensitive inductor and together they make a LC tank circuit (figure 1). Changing the applied pressure affects the resonant frequency of the circuit while the temperature affects the bandwidth and amplitude of the impedance at this frequency.

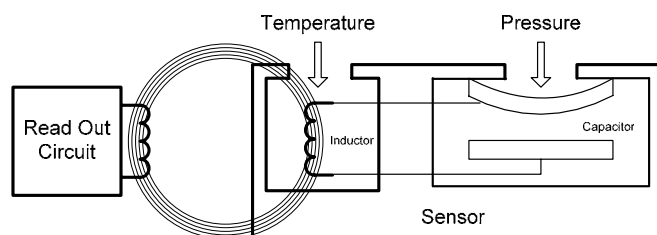


Figure 1. The working principle of the LC pressure and temperature sensor.

There would be another inductor in the external readout circuit which is coupled with the sensor inductor and the impedance of the sensor is reflected to the external circuit by induced electromagnetic field. The passive telemetry electrical circuit model is shown in figure 2 in which R_P and L_P are the resistance and inductance of readout circuit respectively, ω is the angular frequency and M is the mutual inductance. The circuit on the left is the direct model and the one on the right is its equivalent circuit in which the sensor impedance is reflected to the readout circuit. The amount of applied pressure and temperature could be determined by monitoring the amplitude and phase of the reflected impedance for different frequencies.

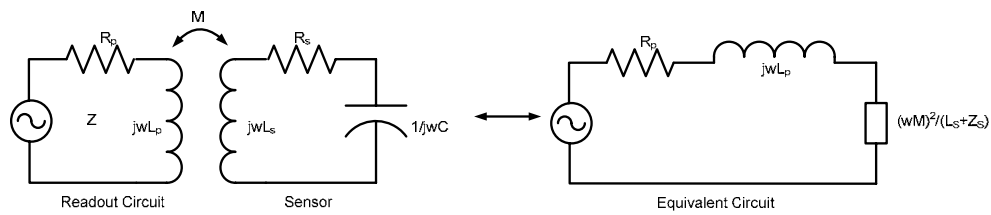


Figure 2. The electrical model of the sensor with readout circuit and its equivalent circuit.

The sensor structure and simplified fabrication process are briefly introduced in Section 2. Electromechanical analysis of the sensor parts (capacitor and inductor) are described in Section 3. Section 4 is about optimization of the sensor for automotive applications followed by conclusion Section.

2. Sensor structure

Figure 3 shows the cross section of the proposed sensor structure. Bottom electrode of the capacitor and the coil of the inductor are fabricated on a glass wafer. The capacitor top electrode is created in a 5 μ m square recess in silicon.

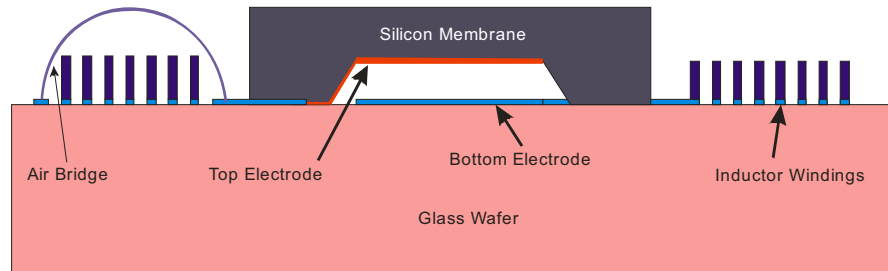


Figure 3. The cross section of the proposed structure for pressure and temperature sensor

The fabrication process starts with anisotropic etching of the silicon wafer in KOH to produce a (1mm*1mm*5 μ m) square recess as the gap between two capacitor electrodes. Then a thin (100-200 nm) Aluminum film is evaporated and patterned on this recess to form the capacitor top electrode. The next step is creating a deep recess by Deep Reactive Ion Etching (DRIE) to open the face of inductor metal to the air. On the glass wafer a double layer thin metal (Ti/Pt) is deposited and patterned to form the capacitor bottom electrode and the inductor's seed layer. The Ti/Pt layer has a good adhesion with glass [1]. A photoresist mold is then used for electroplating of thick copper layer of 25-turns square inductor spiral. The silicon and glass wafers are anodically bonded together. Then the backside of silicon wafer is etched to define the silicon membrane and also expose the inductor coil to the air. The last step is connecting the capacitor's top electrode to the outer end of the inductor using an air bridge.

3. Electromechanical analysis

The top view and cross section of a deflected square plate under a uniform pressure is shown in the following figure.

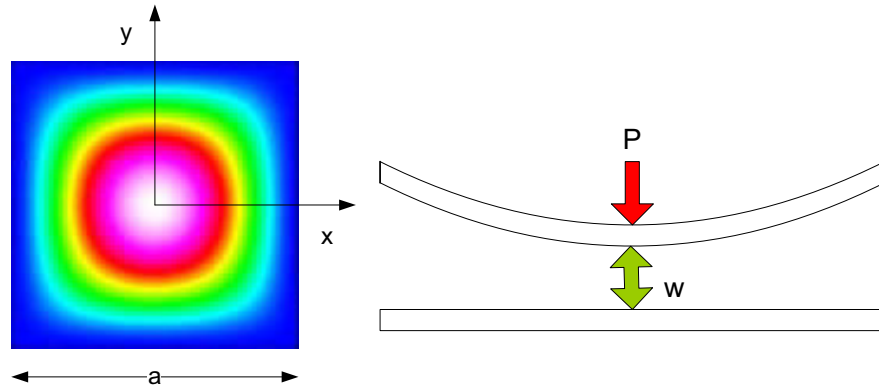


Figure 4. Top view and cross section of the capacitor top plate under a uniform pressure.

Based on the classical plate equations of small deflection theory [4], the deflection d of any point on a rectangular or square plate under uniform pressure P could be calculated by solving the following partial differential equation [5].

$$\nabla^4 d(x, y) = \frac{P}{D} \quad (1)$$

In which D , the bending stiffness of the plate, and the operator ∇^4 are defined as follows,

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

$$\nabla^4 = \frac{\partial^4}{\partial x^4} + 2 \frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4} \quad (3)$$

Where E is the Young's modulus and ν is the Poisson's ratio of the plate material and t is the thickness of the plate. The analytical method of solving (1) has described in literature [5].

Under a uniform pressure the maximum stress is applied to the center of each side near the surface and the centre of the plate gets the maximum displacement [6]. The maximum deflection and the maximum stress are defined by (4) and (5) [6].

$$d_{\max} = \frac{\beta P a^4}{Et^3} \quad (4)$$

$$\sigma_{\max} = \frac{\eta P a^2}{t^2} \quad (5)$$

β and η are constants which are ~ 0.0138 and ~ 0.31 respectively. To calculate the capacitance between two square plates one under uniform pressure and the other one fixed, the integration of (6) must be calculated over the plate area in which g is the gap size.

$$C = \int_{-a/2}^{a/2} \int_{-a/2}^{a/2} \frac{\epsilon_0 dx dy}{g - d(x, y)} \quad (6)$$

Numerical calculation is the best way to solve this integration because the deflection equation has a very complicated form.

A good inductor model should represent its parasitic components such as series resistance, skin effect, parasitic capacitances and substrate losses as well as its inductance. There has been done a lot of works on modeling micro inductors [7-9]. A glass substrate is a very good isolator and the substrate losses are negligible for the inductors fabricated on glass. The top view and electrical model of a planar inductor over the glass wafer is shown in figure 5.

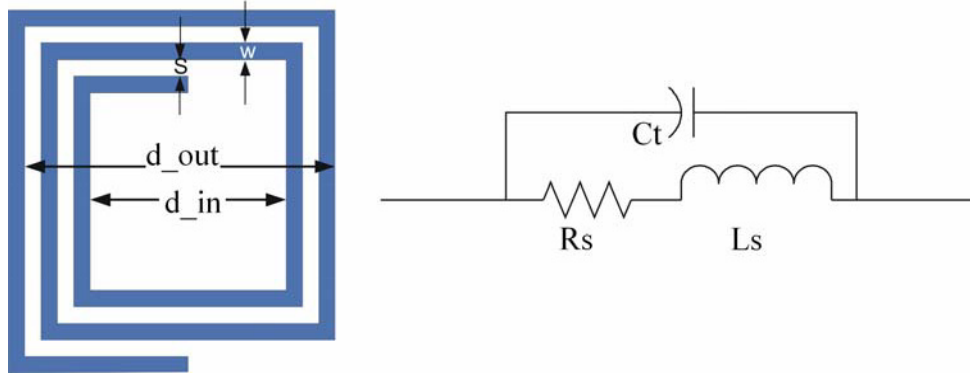


Figure 5. Top view and electrical model of a planar inductor on glass substrate.

L_s is the inductance of the coil in low frequencies, R_s is the temperature dependent series resistance which models the DC resistance of the coil as well as its skin effect in high frequencies, C_t is the capacitance between the turns of the inductor windings.

Simplified equations for calculating L_s and R_s of a square spiral wire with rectangular cross section are (7) and (8) defined in [8] and [1].

$$L_s[H] = \frac{2\mu \cdot s}{\pi} N^2 \left[\ln \frac{s}{N \cdot (w+s)} + 0.2235 \frac{N \cdot (w+s)}{s} + 0.726 \right] \quad (7)$$

$$R_s = \frac{\rho l}{w \delta (1 - \exp(-\frac{h}{\delta}))} \quad (8)$$

$$\delta = \sqrt{\frac{\rho}{\mu \pi f}} \quad (9)$$

In which μ is the relative permeability of air, s is the distance between two wires, N is the number of turns, ρ is the resistivity of the metal, l is the total length of inductor, w is the width and h is the height of the wire, δ is the skin depth and f is the working frequency.

There is a parasitic capacitance between each turn of the inductor and the adjacent turn. Equation (9) defines this capacitance for i^{th} turn and its next turn. C_t which is defined by (10) is the equivalent total capacitance of these capacitors which are connected together in series.

$$\frac{1}{C_i} = \int_{d_{in}+i(w+s)-s}^{d_{in}+i(w+s)} \frac{dr}{8\epsilon_0 r h} = \frac{\ln(d_{in} + i(w+s)) - \ln(d_{in} + i(w+s) - s)}{8\epsilon_0 r h} \quad (10)$$

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_{N-1}} \quad (11)$$

In above equations, ϵ_0 is the permittivity of air.

4. Design for TPMS

The pressure range in TPMS applications is from zero to 100psi and the pressure sensor should tolerate another 100psi overload pressure and the temperature range is from -40°C to $+100^{\circ}\text{C}$.

4.1. Pressure dependency

In (6) the capacitance is related to the membrane size, the gap size, and the membrane deflection. The deflection itself is a function of other parameters including pressure, membrane length, thickness and material. The capacitor must have a small gap size and a thin membrane to have higher pressure sensitivity. The ultimate stress of silicon ($\sigma_u \sim 600\text{MPa}$ [6]) determines the ratio of membrane length over thickness (equation 5). Also the sensor capacitance should be much higher than the inductor parasitic capacitance. This structure is designed to work in non-contact electrode mode. It means that the maximum deflection of the plate under full pressure range which is defined by (4) should be smaller than the gap size between two plates.

4.2. Temperature dependency

The resistivity of metals is a temperature dependent parameter and its general form is shown in (12).

$$\rho = \rho_0 + \alpha T \quad (12)$$

In which, ρ_0 is the absolute resistivity of the metal, α is a constant, and T is temperature in Kelvin. For high frequencies where the skin effect comes into account, the resistance value is a frequency dependent parameter. To have a temperature dependent only resistance, the working frequency and inductor dimensions should be carefully chosen to avoid skin effect. Increasing the inductor length and decreasing the wire width and height increases the temperature sensitivity of the sensor.

Table 1 shows the sensor dimensions considering all the above mentioned issues and also some process limitations.

Table 1. Dimensions of TPMS LC pressure and temperature sensor [μm]

a	t	g	w	s	d_{out}	N
1000	24	5	18	6	4000	25

The following graphs show the changes of the capacitance versus applied pressure and the changes of the inductor resistance versus temperature.

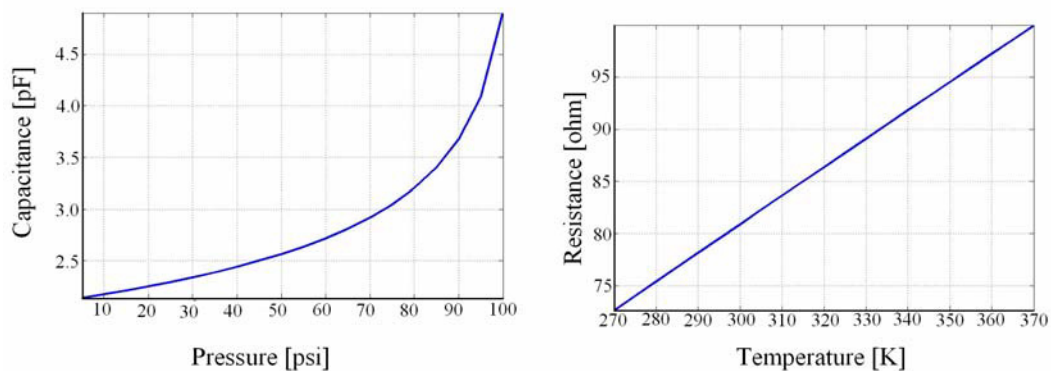


Figure 6. The changes of the capacitance and resistance of the sensor versus pressure and temperature

The impedance of the sensor versus frequency for different pressures and temperatures are graphed in the following figure.

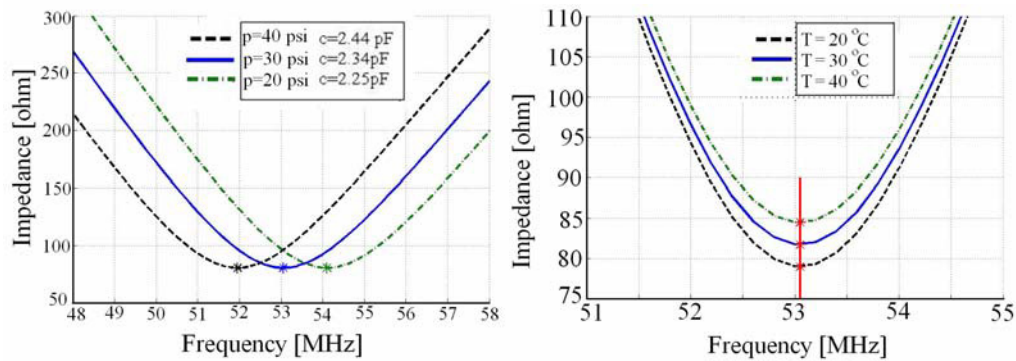


Figure 7. The impedance of the sensor versus frequency for different pressures and temperatures.

The resonant frequency is changed from 55.91MHz to 36.43MHz when the pressure is changed from zero to 100psi and the impedance is changed from 72.62 Ω to 99.95 Ω when the temperature is changed from zero to 100°C. So the sensor's average pressure sensitivity is -194.8 KHz/psi and its temperature sensitivity is 0.273 $\Omega/^{\circ}\text{C}$.

5. Conclusion

A passive telemetry LC structure was used to sense the pressure and temperature for automotive applications. A new structure and a simple fabrication process were proposed for this structure. The analytical model and design consideration of this sensor were studied and the sensor structure was optimized for TPMS application.

Acknowledgment

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