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LC공진을 이용한 원격측정용 압력센서의 제작 및 실험

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A Telemetry Silicon Pressure Sensor of LC Resonance Type

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Abstract - This paper presents an implantable telemetry LC resonance-type pressure sensor to measure the cerebral ventricle pressure. The sensor consists of an inductor and a capacitor. The LC resonant circuit consists of the sensor and an external antenna coil that are coupled magnetically. The resonance frequency of the circuit decreases as the applied pressure increases the capacitance of the sensor. The sensor is designed in consideration of the biocompatibility and long lifetime for continuous monitoring of the ventricle pressure. The sensor is simple to fabricate and small in comparison with others reported previously. The inductor is fabricated by electroplating and the variable capacitor is constructed with a flexible p+ diaphragm. Also, the deflection of the diaphragm, the variation of the capacitance and the resonance frequency are analyzed and calculated.

1. INTRODUCTION

Recently, the pressure sensors have been developed for the biomedical use. The implantable pressure sensors must be small, biocompatible, and wireless. In this paper, the telemetry pressure sensor is designed and fabricated for the detection of cerebral ventricle pressure. The telemetry pressure monitoring system via data communication includes integrated circuits for the transmission of the power and the signal. Also, the system is fabricated by complicated processes and assembly of many parts such as pressure sensor, rechargeable battery, transmission system, coils, and signal processor, etc. In the case of inductor-capacitor (LC) resonance type pressure sensor, the sensor is simple and small [1,2]. Another advantages of this type are the high resolution and the simplicity in the design for the wide range of pressure and temperature [3]. An LC resonator that is composed of a capacitive pressure sensor and an inductor can be implanted in the patient's cranium and transmits pressure information to an external detector. A pressure ranging from 0 to 60 cmH_2O must be monitored in this application. In This paper, the inductor and the capacitor are fabricated by micromachining for the miniaturization. The variable capacitor has a flexible p+ diaphragm subject to the pressure. This paper presents the calculation of the diaphragm deflection, the capacitance, and the resonance frequency for the applied pressure frequency characteristic. The fabricated sensor is measured.

2. THE STRUCTURE OF SENSOR

Fig. 1 shows the structure of the telemetry pressure sensor. It consists of two substrates. One is fabricated with a Pyrex glass substrate, and the other is fabricated with a silicon substrate. The micro copper coil on the Pyrex glass has self-inductance. The p+ diaphragm fabricated on the silicon substrates and the Cr/Au electrode fabricated on the glass substrate constitute a variable capacitor. The variable capacitance depends on the gap between the fixed electrode and the flexible diaphragm subject to the applied pressure. The inductor and the capacitor are connected to make a LC circuit. The total size of the sensor is 8.05 mm × 7.8 mm. The coil is 10㎛ thick, and 50㎛ wide and the total length is 4900㎛. The number of turns of the coil is 13. The gap between the Cr/Au electrode and the diaphragm is 10㎛. The thickness of the diaphragm is about 1.5 mm and the size is 3 mm × 3 mm. The diaphragm has corrugations to release the residual stress and to increase the sensitivity. After anodic bonding the vent is sealed with epoxy. For the self-alignment there are 20㎛-deep grooves on the silicon substrate and 10 ㎛ high protrusions on the glass substrate.

Fig 1 The structure of the telemetry pressure sensor.

3. ANALYSIS AND CALCULATION

The calculation of the deflection of the diaphragm is necessary to the simulation of the capacitive pressure sensor. The center deflection of the flat diaphragm can be given.

$$\frac{Pa^4}{Eh^4}=\frac{3.14a^2}{Eh^2}\sigma\left(\frac{y}{h}\right)+\frac{1.98(1-0.295\nu)}{1-\nu}\left(\frac{y}{h}\right)^3$$

where P is the pressure applied on the diaphragm, and y is the diaphragm center deflection, and E, ν, σ, a, H and h are Young's modulus, Poisson's ratio, the residual stress, the size, the height of the corrugation and the thickness of the diaphragm, respectively. Let $w_0 = y$, the 3-dimensional deflection analysis of the square diaphragm can be impossible using Eq. Fig. 2 shows the 3-dimensional deflection of the flat diaphragm at 60cmH$_2$O when $w_1=w_0\times0.401$, $w_2=w_0\times1.1611$.

$$\omega(x,y)=\left(\omega_0+\omega_1\cdot\frac{x^2+y^2}{a^2}+\omega_2\cdot\frac{x^2y^2}{a^4}\right)\cdot\cos\frac{\pi x}{2a}\cdot\cos\frac{\pi y}{2a}$$

To calculate the capacitance when the diaphragm is deflected, the 3 mm×3 mm-sized diaphragm is divided into 30×30 pieces for the calculation with Matlab software package. The deflection of each piece is calculated. The capacitance of each piece is calculated from the calculated deflection and total capacitance.

Fig. 3 shows the resonance frequency for the applied pressure. The sensitivity at 60cmH$_2$O are 2.17 MHz/cmH$_2$O for the corrugated diaphragm and 0.83 MHz/cmH$_2$O for the flat diaphragm.

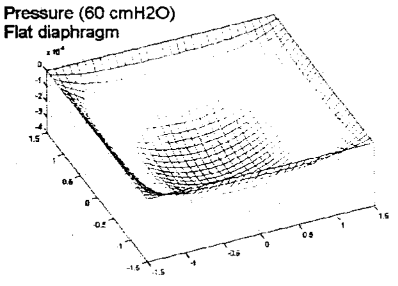


Fig 2 The 3D profile of the flat diaphragm

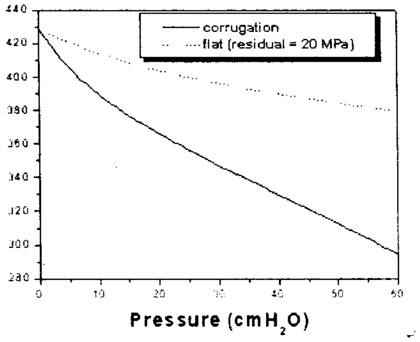


Fig 3 The resonance frequency vs. the pressure

4. THE EQUIVALENT CIRCUIT

Fig. 4 is the measurement circuit including the sensor and the antenna linked via inductive coupling. We simplify the inductively coupled circuit to an equivalent circuit using some assumptions

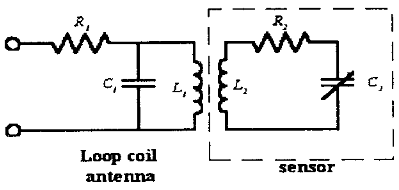


Fig 4 The inductively coupled circuit

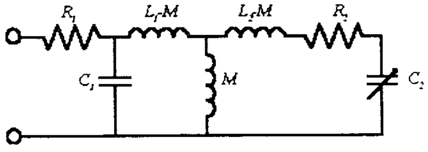


Fig 5 The equivalent circuit

The inductance, L_{squ}, of a flat squared coil is calculated theoretically as

$$L_{squ}[H]=\frac{\mu_0 D^3}{4\pi p^2}(1-\alpha^2)(1-\alpha)\times\left[\ln\frac{(1+\alpha)}{(1-\alpha)}+0.2235\frac{(1-\alpha)}{(1+\alpha)}+0.726\right]$$

The equivalent circuit impedance, Z_{eq}, including the mutual inductance and the impedance of the sensor is given by.

$$Z_{eq}(\omega)=R_1+j\omega L_1+\frac{1}{j\omega C_1}+\frac{\omega^2M^2}{Z_s(\omega)}$$

When the pressure is applied to the diaphragm of the sensor, the capacitance increases and the resonance frequency decreases. Fig. 6 shows the magnitude of signal for the frequency and the phase. The resonance frequency is the frequency where the phase cross 0° in Fig. 6.

From the resonance frequency, we can find capacitance of the sensor, and the pressure.

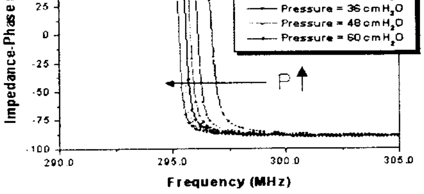


Fig 6 The frequency characteristic of the equivalent circuit.

5. THE FABRICATION OF THE SENSOR

Fig. 7 is the fabrication process of the upper substrate. First, a 0.8-μm-thick thermal oxide layer for an etch mask is grown. For the fabrication of the air cavity, the front side of the wafer is etched 30μm with TMAH solution shown in fig. (b). The silicon oxide patterned and the silicon is etched 10 μm with TMAH to form concentric circular and rectangular corrugations shown in fig (c). Boron is diffused into the surfaces to make p+ etch stop layers. The backside of the wafer is etched with EPW solution to fabricate the diaphragm.

Fig. 8 is the fabrication process of the lower substrate. The inductor is fabricated on the Pyrex glass by the Cu electroplating. An inductor with line/space width of 50/50 μm and thickness of 10μm is formed using 20-μm-thick PR AZ-4620 molds. The electroplating is performed with the solution ($CuSO_4$-$5H_2O$: H_2SO_4 : D.I Water 150 g : 20 mℓ : 1 ℓ) at room temperature. When the current density of electroplating is 10 mA/cm^2, the thickness of the copper electroplated for 30 minute is about 10μm. Fig 9 shows the fabricated sensor.

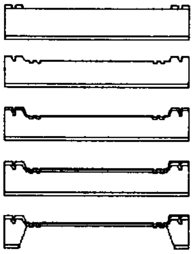


Fig 7 The fabrication process of the silicon

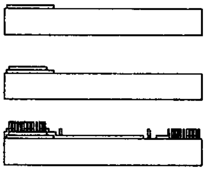
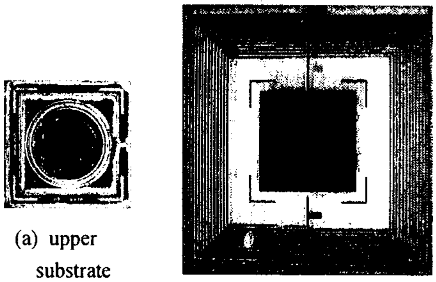


Fig 8 The fabrication process of the glass substrate



(a) upper substrate

(b) lower substrate

Fig 9 The photograph of the fabricated sensor

2.5 EXPERIMENT

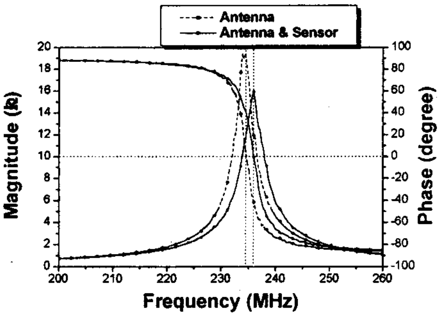


Fig 10 The impedance of the circuit

In order to measure the characteristic of the fabricated sensor, we measure inductance and resistance of the sensor and the antenna coil using LCR meter. The inductance and resistance of the sensor are 3.2 μH and 14.5Ω, respectively. And the inductance and the resistance of the antenna coil are 18.7 μH and 60 mΩ, respectively. Using an impedance analyzer (HP4194A), the magnitude and the phase of the antenna coil impedance is measured against the frequency. Fig 10 shows the measured data. The resonance frequency of the antenna coil is 234.7 MHz. This shows that it has the parasitic capacitance. When the sensor is put over the antenna coil 5 mm high, the resonance frequency is 235.9 MHz. The resonance frequency shift due to sensor is about 1.2 MHz.

6. CONCLUSION

In this paper, the LC resonance type pressure sensor has been designed, and the resonance frequency to the applied pressure has been calculated by analysis. The sensitivity of corrugated diaphragm is 2.17 MHz/cmH_2O, which is 2.6 times that of the flat diaphragm.

The LC resonance pressure sensor for telemetry has been fabricated by micromachining. The impedance of the antenna coil itself and that of the antenna coil with the LC sensor have been measured. The resonance frequency shift is 1.2MHz. In the near future, the resonance frequency shift by the applied pressure will be measured with the phase-detecor.

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