Fabrication and application of a wireless inductance-capacitance coupling microsensor with electroplated high permeability material NiFe

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Abstract. A fully integrated wireless inductance-capacitance (LC) coupling microsensor was designed and fabricated by MEMS technology. The sensing loop was formed by connecting a deformable parallel-plated capacitor and a planar spiral inductor with a Ni(80)Fe(20) core. Polyimide and PMMA were used to isolate and package the devices. Typical dimension of the sensors was 5 × 5 mm² × 0.77 mm. Different electroplated inductive coils (30, 40, and 60 turns) were fabricated to connect with a 4 × 4 mm² plate capacitor in series. The LC sensing module for measuring liquid-level induced frequency responses was setup. Experimental results show that frequency response decreased as liquid level increased and sensitivity is about 7.01 kHz/cm with deviation less than 2%. Developed planar spiral inductor with high permeability magnetic core can provide a wide range of frequency variation in LC sensing applications.

1. Introduction
The monitoring and control of liquid level is of critical importance in a variety of industrial processes. Many measurement methods were in wide use exclusively based on hydrostatic pressure, visual inspections, mechanical floats, ultrasonics, fiber optics or capacitive sensor. The power delivery, data acquisition, deep depth and far distance measurement were always limited while traditional methods used. The demand for more potable devices continues to increase rapidly. A wireless fluid-level measurement technique using magnetic response and capacitive sensors for various substance levels were presented [1]. The integrated inductors with high permeability core to have large inductance density and low coil resistance show a great potential in various application such as filter, power conversion, and electromagnetic interference noise reduction [2-5]. The performance of a variety of magnetic thin films (nickel-iron and cobalt-iron-copper alloys) for magnetic components has been characterized [6]. Capacitive pressure sensors developed to meet critical required for reliable, low cost, high performance pressure measurements [7-9]. In this paper, an LC-coupling wireless microsensor was developed with electroplating NiFe core by MEMS-based compatible technology. A planar inductor shows high inductance enhancement over the air core equivalent and small area consumption.
An application of the device was achieved by signal processing technique using transmitting and receiving antennas, a signal function synthesizer, and a spectrum analyze. The various detected signal in the sensor arises from a change in effective electrode area. The LC-coupling wireless microsensor can be reliably fabricated for various applications to realize RF integrated electronics.

2. Principle of operation
The LC coupling microsensor consists of a variable capacitive element and a reliable inductive element to form a wireless resonance circuit. Its operation principle is by detecting the resonance frequency variation due to the deformation of capacitive electrode. Based on inductance and capacitance variation ($\Delta L$ and $\Delta C$), the resonance frequency variation $\Delta f$ of the LC coupling microsensor is given by equation (1), and $f_0$, $L_0$ and $C_0$ are the resonance frequency, inductance and capacitance in equilibrium, respectively.

$$\Delta f = f_0 \mp f = \frac{1}{2\pi \sqrt{L_0 \cdot C_0}} - \frac{1}{2\pi \sqrt{(L_0 + \Delta L) \cdot (C_0 + \Delta C)}}$$

(1)

In general with permittivity $\varepsilon$, electrode area $A$ and electrode separation $d$ can change if the parallel-plated type capacitor is pressured so that the change ratio in capacitance $\Delta C / C$ is given by equation (2). For a capacitor with a constant permittivity, the pressure-induced plate variable area will dominate the capacitance variation ratio. For a capacitive sensor, the capacitance variation due to membrane deflection is given by equation (3), where $w(x, y)$ is the deflection at the point $(x, y)$, and the product of $\varepsilon_0$ and $\varepsilon_r$ is permittivity $\varepsilon$ between plates [7]. Equation (4) is given to calculate the inductance $L$ with a planar spiral rectangular coil [8], where $N$ is the number of turns, $\mu$ is permeability, $L_{eff}$ and $W_{eff}$ are effective length and width respectively, $h$ and $w$ are coil thickness and line-width respectively, $k_1$ and $k_2$ are constant.

$$\frac{\Delta C}{C} = \frac{\Delta \varepsilon}{\varepsilon} + \frac{\Delta A}{A} - \frac{\Delta d}{d}$$

(2)

$$\Delta C = C - C_0 = \frac{\varepsilon_0 \cdot \varepsilon_r}{d} \int \int_{\Omega} dx \cdot dy \left[ \frac{1}{1 - \frac{w(x, y)}{d}} \right] - \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

(3)

$$L = 9.21 \times 10^{-7} N^2 \cdot \mu \left[ \left( L_{eff} + W_{eff} \right) \cdot \log \left( \frac{8L_{eff} \cdot W_{eff}}{N(h + w)} \right) - k_1 - k_2 \right]$$

(4)

3. Design and simulation
The microstructure is designed as an LC resonated circuit which one electrode of the capacitor is a fixed metal film to connect the planar spiral inductor with high permeability core in series, the other is flexible flat rectangular membrane clamped around its circumference, dielectric are polyimide and air. To achieve magnetic measurement with high inductance, some electrodeposited magnetic materials, FeTaN ($\mu_r = 200 \sim 500$), NiFe ($\mu_r = 2000$), CoTaZr ($\mu_r = 600$) and CoFeCu ($\mu_r = 300$), were used as inductor core [5-7]. Compared with these thin film materials, the NiFe for magnetic core was chosen and fabricated to develop device with high permeability, high saturation flux, high resistivity and low coercivity. The core resistance is proportional to both the frequency and the permeability ratio, but do not influence by resistivity of the core. The resistance of the inductor with a NiFe core sources from the materials of coil and core, and it keeps a constant in the frequency range of 8 - 12 MHz [5]. By developing compatible fabrication process, the inductor has a stable inductance 24.1$\mu$H that shows large inductance and Q-factor to enhance sensor quality for various capacitance operations with high frequency response. The Q-factor can be increased by reducing coil resistance and by increasing coil thickness. The sensing membrane is an elastic element which is bent into a curve by the applied pressure. A deformation of the electrode plate means that the average separation of the plates is reduced, the resulting increases in capacitance. The sensing capacitance was determined by Equation
For the application of liquid-level measurement, the liquid-depth related resonant frequency change is proportioned to fluidic pressure. The LC coupling microsensor has completed using (100)-orientation silicon wafers. The designed sensor has two parts, the upper and the lower structures. The upper structure is designed as a sensing part contains a flexible sensing membrane with a metal electrode and an isolated dielectric polyimide film. The lower structure consists of a fixed electroplated electrode and a planar spiral inductor that connect together in series as a passive resonated circuit. The integrated microsensor keeps a deformable sensing capacitance and a robust inductor with high permeability NiFe core that can reduce structure area effectively. To protect the inductor and the magnetic core, thick polyimide and PMMA are used to package the device for preventing device from leakages and damages. Simulation of the micro structures was analyzed using software ANSYS 10.0, and simulation of the liquid-level measurement with the effective capacitor electrode of 4 × 4 mm², 5 μm thick polyimide and 30 μm air gap. The simulation results indicated the thicker sensing membrane with the electrode area of 4 × 4 mm², and air gap of 30 μm, can sense the larger range of pressure, but sensitivity is reduced as shown in Figure 1. Where, the sensitivity is defined as the ratio of resonate frequency variation (kHz) to liquid level (cm). For the robust inductor designed, the higher the capacitance variation is, the higher the resonant frequency variation is, and then the higher the sensitivity has. Higher sensitivity can be achieved by increasing metal thickness of the sensing electrode. With a constant sensing gap between two electrodes of the capacitor, a result shows the sensitivity increased by increasing polyimide thickness because of its high permittivity. As the space increases between capacitor electrodes, the sensitivity decreases. The capacitance change is proportional to the electrode area of capacitor. Two different sizes, 5 × 5 mm² and 4 × 4 mm², were compared shown in Figure 2. All results show that the sensing capacitance is proportional to liquid-level pressure. The inductance was affected evidently by coil turns and permeability of magnetic core, but the influence from coil thickness can be neglected. The planar spiral inductors were fabricated and inductance at the line-width and space of 20, 30, 40, and 50 μm, were calculated by equation (4) [8].

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** Capacitance variation related liquid-level on different separations of dielectric space. **Figure 2.** The liquid-level dependent capacitance variation in various sensing electrode area.

### 4. Fabrication

A six-mask process has been developed to fabricate the LC coupling microsensor with major process flow shown in Figure 3. The fabrication processes have two parts, the upper and the lower structure processes. The lower substrate was fabricated on 4 inch (100), 250 μm thick, p-type Si wafer with thermal-growth silicon dioxide thickness of 1.2 μm shown in Figure 3(a). The backside SiO₂ was patterned by photolithography and wet etching. The Si substrate was etched anisotropically using 20% KOH to define conductive through holes shown in Figure 3(b). The SiO₂ was patterned again to define a location for the planar inductor shown in Figure 3(c). The topside SiO₂ was patterned and etching to define a location for the parallel-plated capacitor, then the Si substrate was double-sided etching away to connect the conductive holes shown in Figure 3(d). The chromium-nickel-based seed layer was deposited to increasing adhesion of electroplate nickel film, and photo-lithographic defined planar inductor and then electroplating shown in Figure 3(e-g). The Ni-Fe alloy as the magnetic core was electroplated as Figure 3(h). The electroplated NiFe has high permeability (≈ 2000) used as magnetic core to keep inductor stable [4]. The upper substrate was fabricated on 4 inch (100), 525 μm thick, p-
type Si wafer with thermal-growth silicon dioxide thickness of 1.2 μm shown in Figure 3(i). The topside SiO₂ was patterned by photolithography and wet etching to open Si etching windows, then Si was etched anisotropically using KOH to define deformable membrane shown in Figure 3(j). A Ni electrode was deposited and a 5μm thick polyimide was spun and cured as an insulator and then was patterned to open electrical connection windows shown in Figure 3(k-l). Each device of the lower and the upper structure was aligned to each other and bonded together to assemble a sensing LC chamber that was a crucial step. The packaging was completed using PMMA as protection material and the sensing area was exposed for satisfying environmental measurements. The whole schematic diagram of a fully-integrated wireless LC coupling microsensor was shown in Figure 3(m).

Figure 3. Fabrication processes of the LC coupling microsensor: (a)-(h) lower structure processes, (i)-(l) upper structure processes, and (m) assembly with packaging.

5. Experimental result and discussion
Preliminary experiments were performed to evaluate the performance of the fabricated LC coupling microsensor for the liquid-level measurements. An experimental apparatus consists of a signal function synthesizer, amplifiers, antennas, a spectrum analyzer, a computer and the microsensor. The waveforms generated by an arbitrary waveform generator were used as a signal which was amplified. Amplified signal was transmitted by a transmit antenna at a fixed position exciting the LC sensor to generate sensing resonant waveform. The inductor was characterized by RLC meter. The fluid-level related resonant frequency was received by an antenna for analyzing by a spectrum analyzer shown as Figure 4. In this work, the 5 × 5 mm² capacitor consists of two parallel 5 μm thick electrodes with a 30 μm separation and a 5 μm thick polyimide isolation layer. For the fixed device dimension, design parameters of a planar spiral inductor are composed of magnetic core material, coil line width (W) and separation (d), and coil turns (N). The W and d were designed and tested in 30, 40, and 50 μm, respectively. The different Ns were tested in 60, 40, and 25 turns. The experimental results by measuring resonant frequency response with different W, d and N in the liquid-level range from 0 to 100 cm were shown in Figure 5. To electroplate NiFe core must be cared because the seed layer may not attach well

Figure 4. An experimental setup for measuring various liquid levels.
to deeply etched substrate due to more than 30 μm roughness on silicon surface. And the capacitance was also affected from the wet etching that induced lower measured resonant frequency than the simulation value. The sensitivity of 7.01 kHz/cm for liquid-level measurement is shown in Figure 6.

![Figure 5](image1.png)  
**Figure 5.** Frequency response versus liquid-level, the inductor has 60 × 20 μm² winding area, 20 μm line spacing, and widths as 50, 40, 30 and 20 μm.

![Figure 6](image2.png)  
**Figure 6.** The sensitivity versus coil width with an equal separation between adjacent coils.

6. Conclusion

A high performance LC-coupling microsensor integrated wireless transmitting module has been developed using MEMS technology. A polyimide film is coated between deformable electrodes as an insulator to prevent short-circuited problem. The silicon-based microsensor (5 × 5 mm² × 0.77 mm) formed by a planar inductor with electroplated Ni-Fe core connected an electrode-deformable capacitor in series. The inductance 24.1 μH with coil resistance less than 1 Ω and capacitance 6 pF are obtained, corresponding to the inductance enhancement of 18 times over the air core equivalent. A wireless sensing and communication module achieves room temperature operations over a telemetry distance of 2 meters with a power consumption of 160 μW. The liquid-level measurements have been executed by measuring variation of resonant frequency with achieved sensitivity 7.01 kHz/cm and deviation less than 2% in range of 0 - 100 cm. The proposed LC coupling microsensor shows a great potential for various application in pressure-related measurements. Further work into a real-time automatic measurement system is to be performed using developed microdevice to integrate a human machine interface.

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7. References

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