Micro magnetic thin-film sensor using LC resonance

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Micro Magnetic Thin-Film Sensor Using LC Resonance

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Abstract—**This paper reports the performance of a new micro magnetic thin-film magnetic field sensor, which makes use of LC resonance of the sensor element as well as the impedance change due to the permeability change of the magnetic film. A large impedance change of 105% was achieved at a carrier frequency of 100 MHz. The large change was realized when the LC resonance frequency of the sensor element was lower than the frequency at which the eddy-current losses increased.**

I. INTRODUCTION

Recently, micro-sized magnetic sensors with high-sensitivity and quick response are required by high density magnetic recording systems and various sensing systems. In order to meet this requirement, an MR sensor, a GMR sensor, and a fluxgate sensor have been investigated as well as micro magnetic thin-film sensors utilizing impedance changes caused by magnetic field dependence of permeability and skin effect at high frequencies [1]–[5]. These sensors are based on magnetic thin-film technology and micro-fabrication technology. However, the development of more sensitive micro magnetic sensors at room temperature is urgently necessary for biomagnetic instrumentation and future magnetic recording system, etc.

In order to solve this problem, we have briefly proposed a new micro magnetic thin-film magnetic field sensor making use of the impedance change due to not only the permeability change of the magnetic film but also LC resonance of the sensor element [6]. In this work, we discuss the details of the frequency dependence of impedance, resistance, and reactance of the sensor element, and found that a large impedance change was achieved when the LC resonance frequency of the sensor element was lower than the frequency at which the eddy-current losses increased.

II. EXPERIMENTAL PROCEDURES

Fig. 1 shows the schematic diagram of the closed magnetic circuit type sensor element used in this work. The main body of the sensor is a thin-film inductor of single leg inner-coil type fabricated on a Si substrate. The sensor consists of CoZrNb amorphous magnetic films, SiO_2 insulating films and Cu conductive film. The thickness of each CoZrNb layer is 1 μm and the width is 4 mm, and the length is 14 mm. The thickness of each SiO_2 layer is 1 μm and the width is 3 mm, and the length is 16 mm. The thickness of the Cu layer is 1 μm and the width is 2 mm, and the length is 20 mm. The films were deposited on the water cooled substrate using rf sputtering. In order to induce uniaxial magnetic anisotropy along the width direction of the sensor, the sensor was annealed for 2 hours at 400 ℃ in a 60 rpm rotating magnetic field of 40 kA/m, followed by 1 hour at 400 ℃ in a static magnetic field of 40 kA/m. The anisotropy field, H_k, of the sensor element was 520 A/m. And then, the sensor was set on the ground plane of a microstrip line. In this work, Si substrate was used as dielectric layer to obtain low LC resonance frequency. A static external magnetic field, H_{dc}, was applied with a Helmholtz coil, and a high frequency (1 MHz $\sim$ 500 MHz) current was supplied to the Cu conductor. The impedance of the sensor was measured with a network analyzer (HP8752A).

III. SENSITIVITY OF SENSOR USING LC RESONANCE

Fig. 2 shows a simple equivalent circuit of the sensor element. The resistance and inductance of the sensor are represented by R_0 and L_0, while the stray capacitance appearing between the conductor and the ground plane of the microstrip line is represented by C. The impedance ($Z = R + jX$) of the circuit is given as follows.

$$R=\frac{R_0}{2}+\frac{2R_0}{\omega^4 L_0^2 C^2+\omega^2(R_0^2 C^2-4L_0 C)+4} \tag{1}$$

$$X=\frac{\omega L_0}{2}+\frac{\omega(2L_0-R_0^2 C-\omega^2 L_0^2 C)}{\omega^4 L_0^2 C^2+\omega^2(R_0^2 C^2-4L_0 C)+4} \tag{2}$$

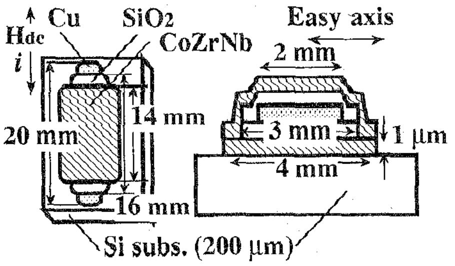

Fig. 1. Schematic diagram of the closed magnetic circuit type sensor element.

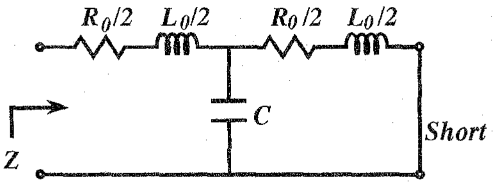

Fig. 2. Equivalent circuit of the sensor element.

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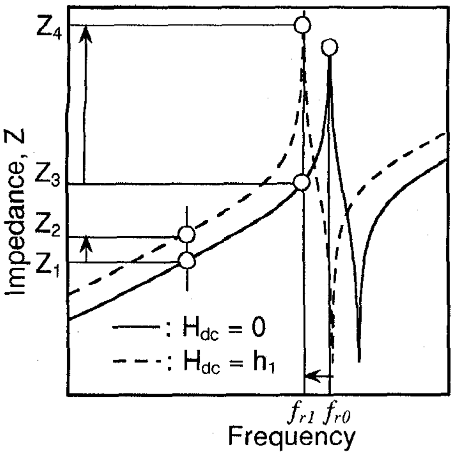


Fig. 3. Frequency dependence of the impedance of the equivalent circuit.

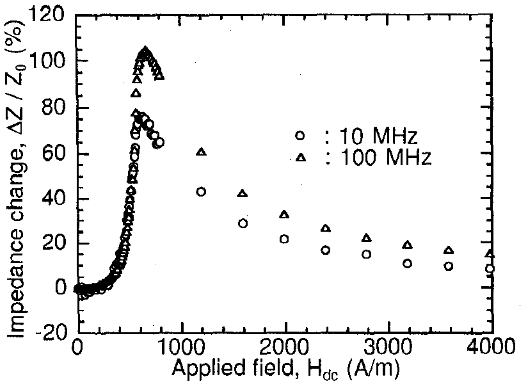


Fig. 4. Dependence of the relative change of the impedance on the applied field for the sensor element.

$$|Z| = \sqrt{R^2 + X^2} \tag{3}$$

The LC resonance frequency of the circuit is given as follows.

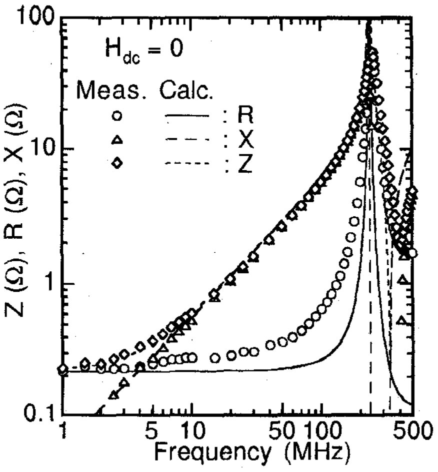
$$f_r = \frac{1}{2\pi}\sqrt{\frac{2}{L_0 C}} \tag{4}$$

The frequency role of the impedance is shown conceptually in Fig. 3. When the dc field is zero, the resonance frequency is f_{r0}. When the dc field, h_1 ($\leq H_k$), is applied to the length direction of the sensor, the permeability of the magnetic layer increases [7] and therefore the inductance, L_0, becomes larger. In this case, the LC resonance frequency goes down to f_{r1} as shown by the broken line. If the carrier frequency is far lower than the resonance frequency, the impedance changes only from Z_1 to Z_2. Besides, adjusting the carrier frequency to the resonance frequency (either of f_{r0} or f_{r1}), magnitude of the impedance change will be extremely enhanced. In Fig. 3, the impedance changes from Z_3 to Z_4 at the resonance frequency of f_{r1}, for example. We set $h_1 = H_k$ in this work.

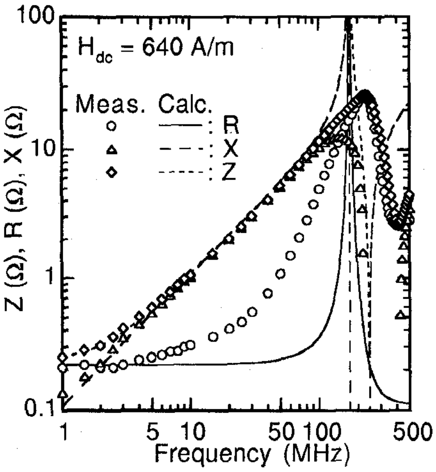
The relative change of the impedance is defined as,

$$\frac{\Delta Z}{Z_0} = \frac{Z_{H_{dc}} - Z_0}{Z_0} \tag{5}$$

Where, $Z_{H_{dc}}$ and Z_0 are the impedance of the sensor with and without the external magnetic field. This definition corresponds to the MR ratio of a conventional MR sensor.



(a) $H_{dc} = 0$



(b) $H_{dc} = 640$ A/m

Fig. 5. Frequency dependence of the impedance, resistance, and reactance.

IV. RESULTS AND DISCUSSION

Fig. 4 shows the dependence of the relative change of the impedance on the external magnetic field, H_{dc}, at carrier frequencies of 10 MHz and 100 MHz. The sensitivity was maximum when the dc magnetic field, H_{dc}, equals the anisotropy field, H_k, of the magnetic films. The maximum value of $\Delta Z/Z_0$ is 105 % at 100 MHz, which is about 10 times greater than the value obtained with a conventional MR sensor [8].

Fig. 5 shows the frequency dependence of the resistance, R, reactance, X, and impedance, Z, of the sensor element in the case of $H_{dc} = 0$ and $H_{dc} \simeq H_k$. In the calculation, the values of R_0 and L_0 are fit to the measured values of R and X at 3 MHz, since the R and X of the element nearly equal R_0 and ωL_0 at low frequency according to the equation (1) and (2). The values used are $R_0 = 0.22\,\Omega$, $L_0 = 9$ nH at $H_{dc} = 0$ and 17 nH at $H_{dc} \simeq H_k$, and C =

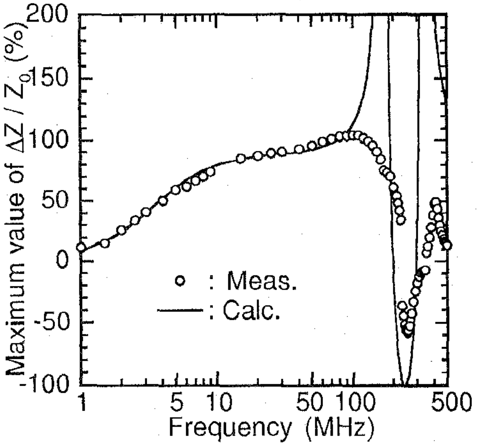


Fig. 6. Frequency dependence of the maximum value of the relative change of impedance.

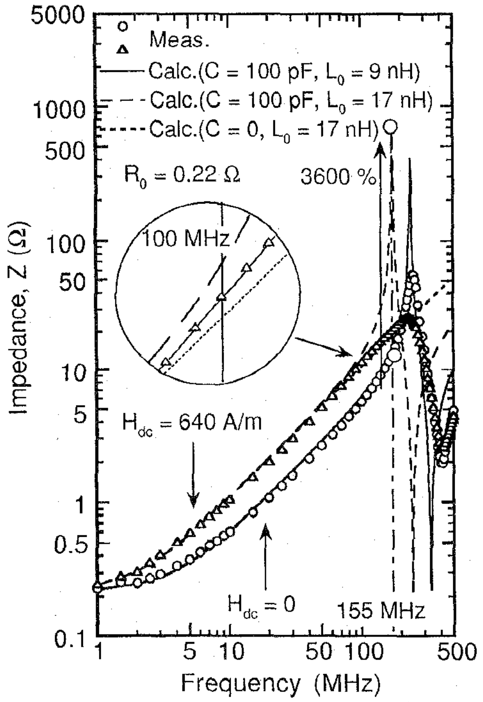


Fig. 7. Frequency dependence of the impedance.

100 pF. The value of C is obtained from the equation (4) assuming $f_{r0} = 240$ MHz and $L_0 = 9$ nH. We assumed that the R_0, L_0, and C, in the equivalent circuit were independent of the frequency.

Without the dc field, the measured values agreed with the calculated values as shown in Fig. 5(a). In detail, the measured value of R was larger than the calculated value because of eddy-current generation in the magnetic film. The LC resonance frequency was 240 MHz.

When the dc field was applied, the frequency profile turned out as shown in Fig. 5(b). The measured values roughly agreed with the calculated values. However we see a certain discrepancy around the resonance frequency. This is because of the skin effect, judging from the comparison of the resistance, R, in Figs. 5(a) and 5(b).

Fig. 6 shows the frequency dependence of the maximum value of $\Delta Z/Z_0$. Lower than 80 MHz, measured values agreed well with the calculated values. However the measured value was smaller than the calculated value in the frequency above 80 MHz because of the skin effect. The largest value of the $\Delta Z/Z_0$ was 105 % at 100 MHz.

To discuss the effect of the LC resonance on the increase of the impedance at 100 MHz, we calculated the impedance of the equivalent circuit with and without capacitance as shown in Fig. 7. The effect of the capacitance appeared over 80 MHz. The measured value around 100 MHz was larger than the calculated value without the capacitance. Therefore the impedance change is surely enhanced by the LC resonance although the frequency of 100 MHz is lower than the calculated LC resonance frequency. This result means the change of the impedance of this sensor element appeared not only by the permeability change of the magnetic films but also the LC resonance. If the eddy-current losses were avoidable, a large impedance change of 3600 % at 155 MHz could be obtained. This value means the sensitivity of this sensor element is extremely high as 5.6 %/(A/m) (450 %/Oe).

V. CONCLUSIONS

We investigated a new magnetic thin-film sensor elements using LC resonance and achieved a large impedance change of 105 % at a frequency of 100 MHz. By reducing the eddy-current losses, the change of the impedance will be 3600 %. This result reveals a great possibility for high sensitivity sensor element using LC resonance.

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