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High Frequency Carrier Type Bridge-Connected Magnetic Field Sensor

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Abstract—**This paper discusses the enhancement of the sensitivity of high frequency carrier type magnetic field sensors by using bridge connection of the sensor elements. A high sensitivity of 2.0 V/Oe was achieved at a carrier freqeuency of 15 MHz.**

I. Introduction

Recently, thin-film magnetic field sensors using impedance change of soft magnetic thin-films at high frequencies have been studied because the sensors have high sensitivity, coilless configuration, etc [1]–[6]. The sensing principle is based on skin effect and permeability change of soft magnetic thin films when subjected to the external magnetic field to be sensed, as in the case of bulk devices [7], [8].

We have already clarified how the permeability changes with external magnetic field, and that the occurrence of a peak in the impedance vs. external magnetic field relationship can be explained by the bias susceptibility theory [9], [10]. These studies clarified that the resistance of the thin-film type sensor is relatively large comparing with the bulk type sensor because of the thinness of the film. This masks the impedance changes.

In order to solve this problem, we propose a new brideconnected magnetic field sensor. The sensor can cancel the dc resistance, which enhances the sensitivity very much.

II. Experimental Procedures

Fig.1 shows the schematic view of the fabricated bridge-connected sensor. The element consists of four rectangular legs of amorphous $Co_{84.85}Nb_{12}Zr_{3.15}$ thin-films. The CoNbZr thin-films were deposited on a glass substrate by rf sputtering. The 6 μm thick films were micromachined into the sensor element by using photolithography and ion milling techniques. The length of the single rectangular leg is 5 mm and the width is 100 μm. The sensor element 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 in order to induce uniaxial magnetic anisotropy. The anisotropy field, H_k, of the sensor element was 400–480 A/m. The legs AB and CD are with the orientation of the easy axis of magnetization along the width direction, and BC and AD have the easy axis along the length direction.

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As shown in Fig.2, we applied a high frequency carrier voltage of 1 V_{p-p} to the electrodes A and C, and we measured the output voltage, V_{out}, between the electrodes B and D by the use of FET probes and a oscilloscope. The bridge-connected sensor was subjected to an external dc field, H_{dc}, generated by a helmholtz coil. The differential amplifier was used to give the ac output voltage of the bridge. The gain of the amplifier is 4.7. The ac output voltage, V_{ac}, was rectified and amplified into the dc output voltage, V_{dc}, of the element.

After the bridge-connected measurements, the sensor was cut off by a Focused Ion Beam (FIB) into single rectangular elements, as shown in Fig.3. The impedance of four cut elements was measured with a network analyzer (HP8752A) when the dc field was applied.

III. Operating Principle of the Bridge-Connected Sensor

The impedances Z_{AB} and Z_{CD} in Fig.2 increase with the increase of the dc magnetic field, and are maximum when the dc field, H_{dc}, nearly equals the anisotropy field, H_k, of the magnetic films, as shown in Fig.4. On the other hand, the impedances Z_{BC} and Z_{AD} are roughly constant [9].

The output voltage, V_{ac}, of the element is given as fol-

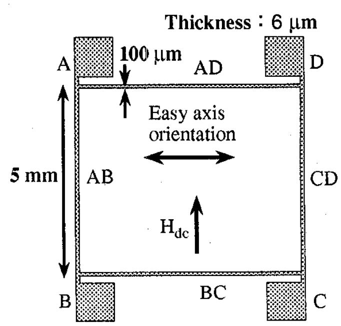

Fig. 1. Schematic diagram of the bridge-connected thin-film magnetic sensor element.

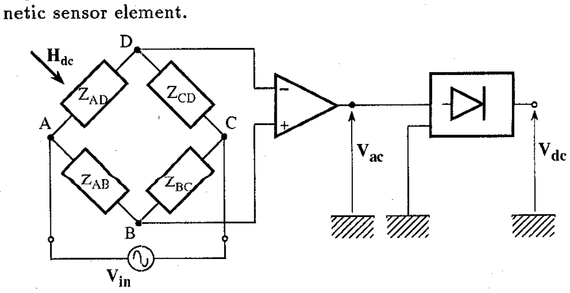

Fig. 2. Measurement system of the sensor element.

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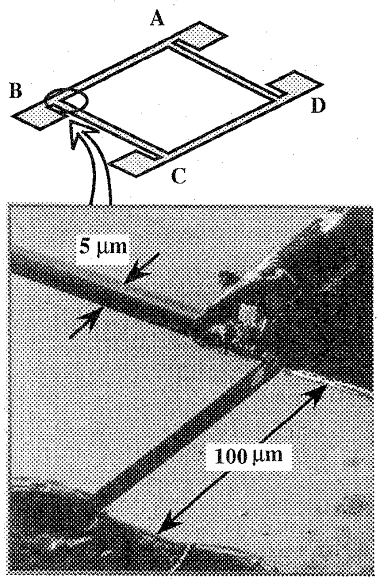

Fig. 3. Photograph of the cut elements by FIB.

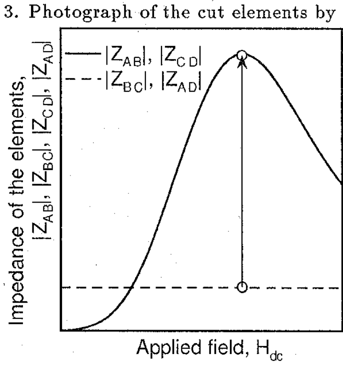

Fig. 4. Dependence of the impedance on the external dc field for the rectangular elements.

lows.

$$V_{ac} = K\frac{Z_{AB}Z_{CD} - Z_{BC}Z_{AD}}{(Z_{AB}+Z_{BC})(Z_{CD}+Z_{AD})}V_{in} \quad (1)$$

Where, K is the gain of the differential amplifier (K = 4.7). Given that Z_{AB} equals Z_{CD} and Z_{BC} equals Z_{AD} as (2) and (3), the output of the element can be expressed by (4).

$$Z_{AB}=Z_{CD} \equiv Z_a \quad (2)$$

$$Z_{BC}=Z_{AD} \equiv Z_b \quad (3)$$

$$V_{ac} = K\frac{Z_a - Z_b}{Z_a + Z_b}V_{in} \quad (4)$$

If Z_a equals Z_b, the output voltage becomes zero. Our final goal is to realize this state when the dc field is zero. However it is difficult to equalize the real parts and the imaginary parts simultaneously. This problem could be overcome by using non-magnetic elements for either Z_a or Z_b, which will be discussed in future work.

Anyway there is the dc offset voltage, V_{ac0}, at $H_{dc} = 0$. Therefore we use the output voltage change, ΔV_{ac}, ΔV_{dc} defined as,

$$\Delta V_{ac}=V_{ac} - V_{ac0} \quad (5)$$

$$\Delta V_{dc}=V_{dc} - V_{dc0} \quad (6)$$

Where, V_{ac} and V_{ac0} are the ac output voltages of the element with and without the external dc magnetic field, and V_{dc}, V_{dc0} are the dc output voltages.

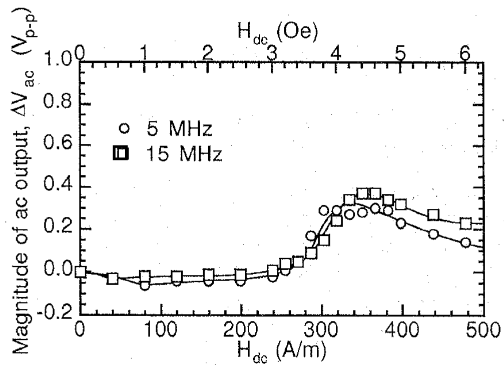

Fig. 5. Dependence of the magnitude of the ac output voltage change on the external dc field for the bridge-connected sensor element.

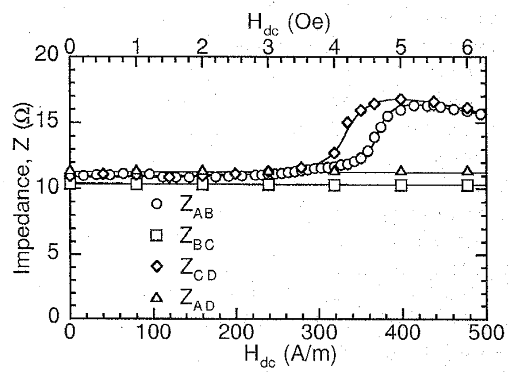

Fig. 6. Dependence of the impedance on the external dc field for the rectangular elements.

IV. Results and Discussion

Fig. 5 shows the dependence of the magnitude of the ac voltage change, ΔV_{ac}, on the external magnetic field, H_{dc}, at carrier frequencies of 5 MHz and 15 MHz. The magnitude of the voltage change was maximum when the dc magnetic field, H_{dc}, was nearly equal to the anisotropy field, H_k, of the magnetic films. The maximum ΔV_{ac} was 0.30 V_{p-p} and 0.37 V_{p-p} at 5 MHz and 15 MHz, respectively. The offset voltage, V_{ac0}, without the dc field was 1.61 V_{p-p} and 1.65 V_{p-p} at carrier frequencies of 5 MHz and 15 MHz.

Fig. 6 shows the dependence of the impedance, Z_{AB}, Z_{BC}, Z_{CD}, and Z_{AD} of the cut rectangular elements at 15 MHz. The impedances Z_{AB} and Z_{CD} were maximum at around $H_{dc} = H_k$ and the maximum magnitude of change was about 6 Ω. The impedances Z_{BC} and Z_{AD} were insensitive to the external dc field, and the Z_{BC} nearly equaled

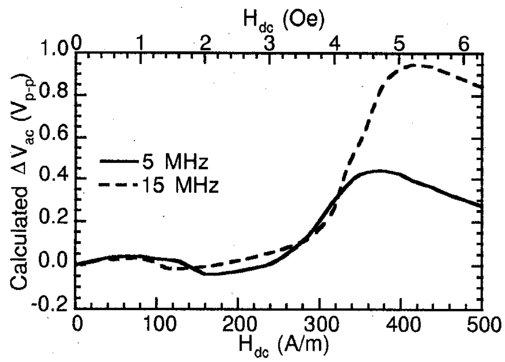

Fig. 7. Dependence of the magnitude of the calculated ac output voltage change on the external dc field for the bridge-connected element.

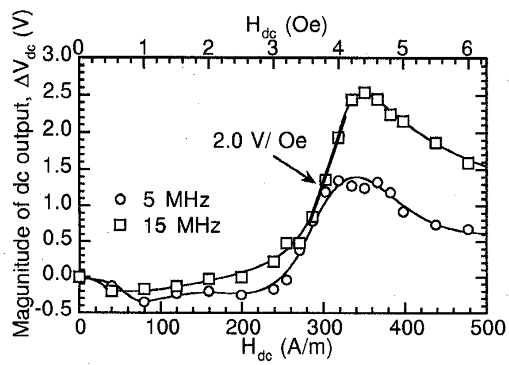

Fig. 8. Dependence of the magnitude of the dc output voltage change on the external dc field for the bridge-connected sensor element.

the Z_{AD}.

Fig. 7 shows the external dc field dependence of the calculated ΔV_{ac} based on (1), in which the impedances measured in Fig. 6 were used for calculation. The calculated values were maximum at $H_{dc} \simeq H_k$. The maximum calculated ΔV_{ac} was 0.44 V_{p-p} and 0.95 V_{p-p} at 5 MHz and 15 MHz. The calculated values roughly agreed with the measured values of Fig. 5 at the carrier frequency of 5 MHz. However the maximum calculated ΔV_{ac} nearly doubled the measured value at 15 MHz. It was due to the inductance of lead wires which connects the sensor element and oscillator. Since the reactance of wires becomes large at a high frequency, the input voltage, V_{in} in (1) at 15 MHz would be smaller than V_{in} at 5 MHz.

Therefore, the output voltage of the element can be estimated qualitatively on the impedance change of the cut rectangular elements.

Fig. 8 shows the dependence of the magnitude of the measured dc voltage change, ΔV_{dc}, on the external field at carrier frequencies of 5 MHz and 15 MHz. The maximum sensitivity of the element at 15 MHz was 2.0 V/Oe between 270 A/m to 335 A/m, which was about 10 times greater than the value obtained with conventional high frequency carrier type thin-film sensors [2]–[5]. Linearity within this range was 3.3 %.

The specification should be enough for sensing the position of buried magnets under the road, being used for Intelligent Transport Systems which would guide cars automatically on highways.

V. Conclusions

We investigated a bridge-connected magnetic field sensor element and achieved a high sensitivity of 2.0 V/Oe at 15 MHz. The output voltage of the bridge-connected sensor element can be estimated qualitatively on the impedance change of the micromachined soft-magnetic thin-film rectangular elements.

Acknowledgment

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