Highly Sensitive CMOS Magnetoimpedance Sensor Using Miniature Multi-Core Head Based on Amorphous Wire

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We newly report a highly sensitive CMOS magnetoimpedance (MI) sensor based on a miniature multi-core head (~2 mm^2). The miniature head consists of 13 μm diameter amorphous wires and pick-up coils totaling 250 turns. In this paper, the sensitivity and noise level of the prototype sensor is investigated. We showed that the noise floor of the prototype sensor is lower than 100 pT/Hz$^{1/2}$ for the frequency range of 20–500 Hz. We estimated the peak-induced voltage at the pick-up coil on the basis of off-diagonal impedance theory. The results obtained in this paper will be useful for designing a highly sensitive MI sensor based on a miniature multi-core head with a CMOS pulse circuit.

***Index Terms*— Amorphous wire (a-wire), magnetic sensor, magnetoimpedance (MI) element, miniature head.**

I. INTRODUCTION

HIGHLY sensitive micro magnetic sensors, based on magnetoimpedance (MI) effect, have been developed [1]–[3]. The signal processing of this MI sensor relies on CMOS IC electronic circuits of to provide a sharp-pulse excitations [1]. Mass product magnetoimpedance IC (MI IC) sensors have been produced by Aichi Steel Corp. Those for the mobile phone and smart phone have been produced since 2002 and 2010, respectively. Recently, we have succeeded in producing picotesla (10^{-8} Oe) resolution MI sensors, utilizing ultra-low intrinsic magnetic noise of amorphous wire (a-wire) [3], [4]. We have proposed a four core head MI sensor, which has a machinery pick-up coil of three hundred turns, for the purpose of reducing magnetic noises [4]. A miniature head with a pick-up coil of several hundred turns is required to realize highly sensitive MI IC with picotesla resolution. Use of pick-up coil has an advantage to realize of high-performance linear magnetic field sensor [5], [6] is applicable in wide fields. There have been several reports about nonlinear MI sensors, which show extremely large impedance change with applying magnetic field [7], [8]. Utilizing high harmonic component of magnetic response, the nonlinear MI sensor system is considered to be suitable for very weak magnetic field detection. However, high harmonic wave signal detection system is more complicated than fundamental wave signal detection system, so application field of nonlinear MI sensor is likely limited.

In this paper, we newly present a prototype miniature multi-core head (~2 mm^2) consisting of 13 μm diameter a-wire and pick-up coils totaling 250 turns. Soft magnetic micro wires have been developed for sensors elements [9]. We also report the magnetic field detection characteristics of the CMOS MI sensor using the prototype miniature multi-core head for purpose of realizing highly sensitive MI IC of picotesla resolution.

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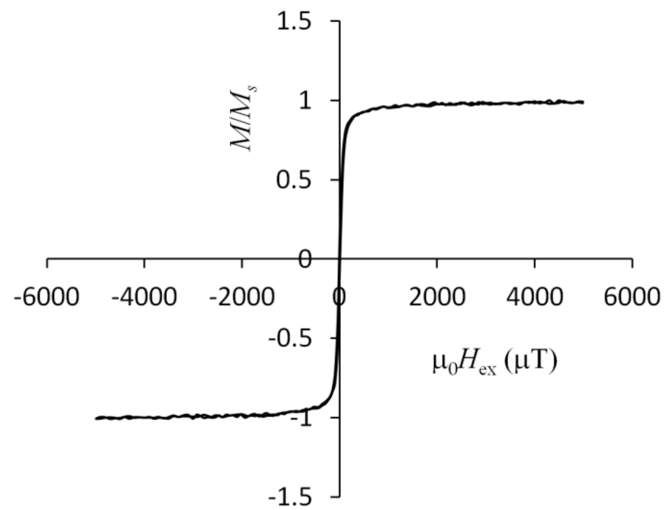

Fig. 1. B–H characteristics for amorphous wire having 13 μm in diameter.

II. MINIATURE MULTI-CORE HEAD

The features of MI effect resulting from the skin effect in a-wires with a circular domain structures have been utilized for micro magnetic sensor in combination with CMOS circuit [1]. The magnetization direction at the surface layer is controlled to be in circular direction by tension annealing.

Fig. 1 shows the B–H characteristics of a-wire (CoFeSiB) with a diameter of 13 μm. Assuming circumferential anisotropy in the outer shell, the anisotropy field $\mu_0 H_k$ is estimated to ~100 μT by the B–H loop measurement.

Pick-up coils placed on a-wire are applicable for signal detection in MI sensors [1], [3], [5], [6]. A sensitivity dependence on number of turns N of pick-up coils have been investigated for a-wire with 30 μm in diameter [3]. The normalized sensitivity was estimated to 249 V/T/turns for 1 cm length [3]. The sensitivity depends on wire diameter as well,

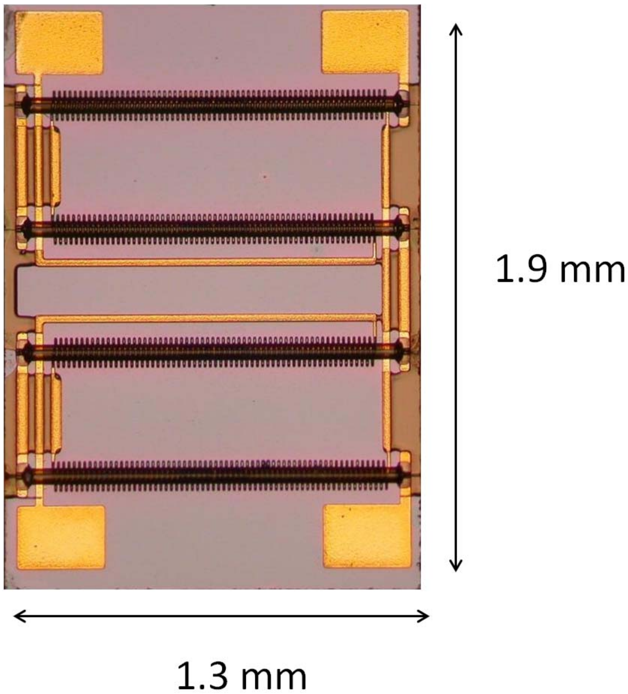

Fig. 2. Prototype miniature multi-core head, which is used in this experiment. The miniature head includes four a-wires with 1 mm length each and MEMS pick-up coils.

because the flux change volume in a-wire depends on wire diameter. For this reason, thinner wire than 30 μm diameter probably is not so effective for highly sensitive magnetic field sensor. However, thinner wire has a merit for coil fabrication due to plating.

Fig. 2 illustrates prototype miniature multi-core head construction used in this experiment. The miniature head consists of four a-wires with 1 mm length each and pick-up coils. The a-wire was placed on Si substrate. The pick-up coil fabrication is based on photolithography and plating. The line spacing of the coil process is 17 μm. The process temperature was ~200 °C. The pickup coil on each a-wire is connected in series, thus totaling turns are 250. After fabrication of the head, the anisotropy field $\mu_0 H_k$ of each a-wire was increased to 500–1000 μT.

III. CMOS MI Sensor

The principle CMOS MI sensor circuit is represented in Fig. 3. The sharp pulse current to the a-wire is supplied as a carrier by use of CMOS inverters (74AC04). The pulse current excitation method has been proposed for use of giant magnetoimpedance (GMI) [11] element in CMOS circuit.

Fig. 4 illustrates induced voltage at pick-up coils in the miniature multi-core head and also shows applied pulse current with a repeat frequency of 500 kHz. We can see that first induced voltage V_{p1} corresponds to rising up pulse current, and the next induced voltage V_{p2} corresponds to falling pulse current. Fig. 5(a) represents applied field dependence of both V_{p1} and V_{p2}, and Fig. 5(b) shows applied field dependence of peak-to-peak voltage V_{pp}. Both V_{p1} and V_{p2} have linear

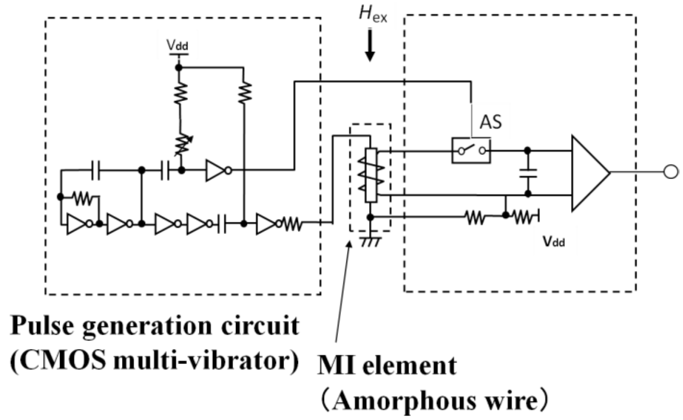

Fig. 3. Principle CMOS MI sensor circuit for linear magnetic sensor.

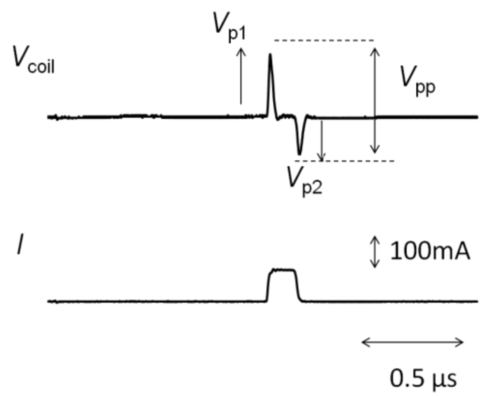

Fig. 4. Pulse wave forms for induced voltage at miniature coils and pulse current to the amorphous wire.

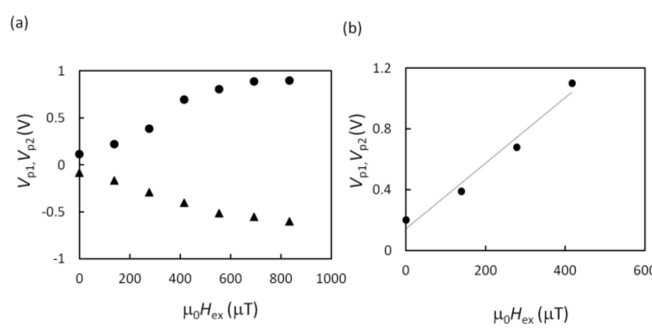

Fig. 5. (a) Closed circle: applied field dependence of V_{P1}. Closed triangle: applied field dependence of V_{P2}. (b) Applied field dependence of V_{pp}.

dependence on H_{ex}. Therefore, V_{pp} increases linearly with increasing applied magnetic field.

A signal detection circuit is consist of an analog switch, hold condenser, and timing circuit to control the analog switch, so that an output voltage E_{out} is proportional to applied external field H_{ex} [1]. In this paper, the signal detection circuit was adjusted to detect the first peak V_{p1} at the pick-up coil. The E_{out} versus H_{ex} characteristics of the CMOS MI sensor using prototype miniature multi-core head are shown in Fig. 6. Because input voltage range of analog switch used in this experiment is from 0 to 5 V, the voltage reference for coil

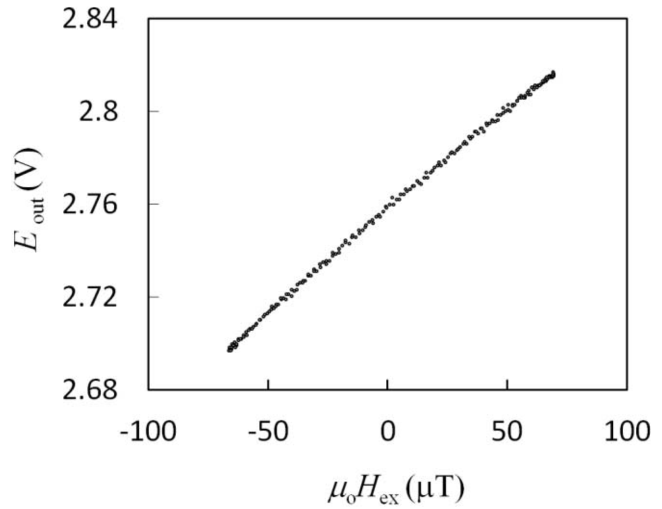

Fig. 6. Example of field detection characteristics of the CMOS MI sensor used in this experiment.

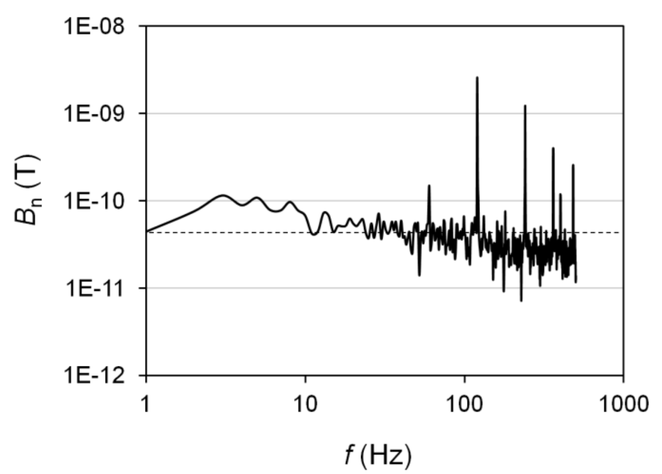

Fig. 7. Noise spectral density for the miniature multi-core head MI sensor in a shield box. Dashed line: noise floor for the relatively high-frequency range 70 pT/Hz$^{1/2}$.

termination was set to be ~2.5 V. A high field detection sensitivity of ~900 V/T and good linearity were obtained with almost no hysteresis characteristics. We also investigate the noise spectral density in the shielded box. E_{out} is amplified using an instrumentation amplifier ($A = 10\,000$), the sampling data are analyzed by a laptop computer. The sampling rate and resolution of the AD conversion system are 1 ms and 14 bits, respectively. Fig. 7 illustrates noise spectral density. It is found that the noise floor of the CMOS MI sensor with the prototype miniature multi-core head MI sensor is lower than 100 pT/Hz$^{1/2}$ for the frequency range from 20 to 500 Hz. The noise floor for the relatively high-frequency range >100 Hz is ~70 pT/Hz$^{1/2}$.

IV. Discussion

Fig. 8 represents pulse MI [1] characteristics of the wires having various H_k, which is determined by the B–H loop. Pulse height of this experiment is 50 mA and wire length is 10 mm. GMI theory for a-wire with circumferential

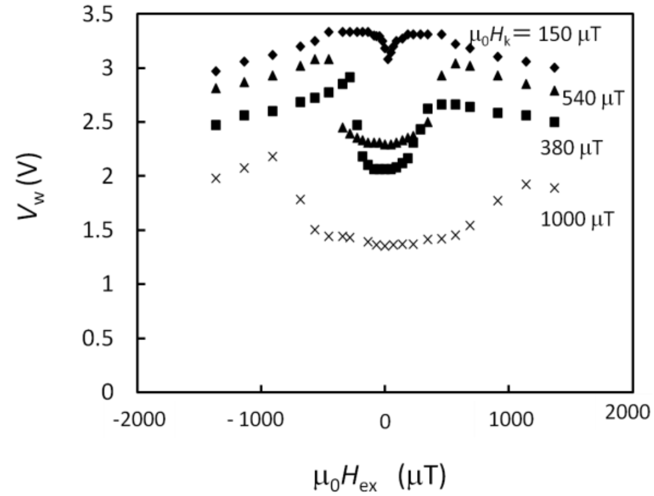

Fig. 8. Pulse MI properties of a-wires (13 μm) having different anisotropy field H_k.

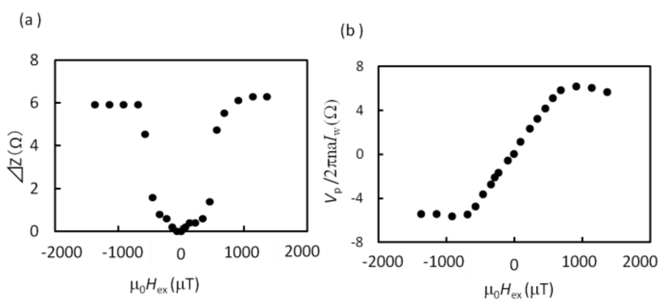

Fig. 9. (a) Pulse impedance properties of two-core miniature head. (b) Pulse off-diagonal impedance properties of two-core miniature head.

anisotropy predict that Z has a maximum at $H_{\text{ex}} \sim H_k$ [2], [11].

Peak voltage V_p at a pick-up coil, which is wound on the a-wire, can be estimated on the basis of off-diagonal impedance theory [12]. The dc uniform equilibrium magnetization M_0 in the surface of a-wire is inclined toward the wire axis by applying H_{ex}. In this case, the inclined angle θ is angle between equilibrium magnetization direction and circular direction (anisotropy direction of a-wire). Assuming effective permeability is independence of field, we can lead

$$\begin{aligned} V_w &\fallingdotseq |Z| I_w \cos^2\theta + Z_0 I_w \\ V_p &\fallingdotseq 2\pi n a |Z| I_w \sin\theta\cos\theta \end{aligned} \tag{1}$$

where V_w is the voltage between both ends of wire, Z_0 is wire impedance for case of no applied field, n is numbers of coil turns per unit length, and I_w is wire current. We investigated relation between wire impedance $Z_w = V_w/I_w$ and off-diagonal impedance V_{p1}/I_w using two-core head, which is half part of four-core head. Fig. 9(a) shows pulse impedance ($= V_w/I_p$) characteristics and Fig. 9(b) shows pulse off-diagonal impedance ($= V_{p1}/I_p$) characteristics with applying H_{ex}. Here, ΔZ is equal to $V_w/I_p - Z_0$ and I_p is pulse height. Before fabrication, $\mu_0 H_k$ of the a-wire was 130 μT. After fabrication of miniature head, Z has a maximum at $\mu_0 H_{\text{ex}}$ of ~500 μT. The increase of anisotropy field seems to

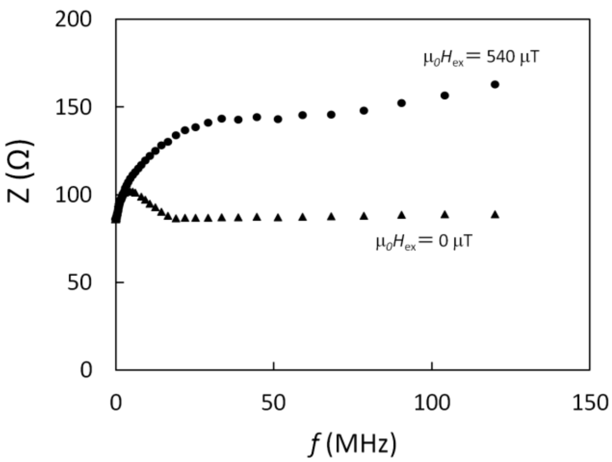

Fig. 10. Frequency dependence of impedance. The a-wire with 13 μm diameter and 10 mm length were used.

be due to increase of residual stress. The maximum absolute value of normalized off-diagonal impedance $V_{p1}/(2\pi naI_w)$ corresponds to $\Delta Z_{\max}$. This experimental results implies that miniature coil fabricated here can detect reasonable voltage from a-wire element. However, the coil voltage of four core head has not reached two times larger compared with coil voltage of two-core head. Voltage drop at dc resistance is considered to be one of the reasons for induced voltage drop in the miniature coil.

Fig. 10 illustrates impedance frequency characteristics for the wire having $\mu_0 H_k = 540$ μT. The length of wire is 10 mm. The pulse current (i_p) MI effect is considered to be equivalent to the high frequency current (i_{ac}) effect with a relation of $i_p = (I_p/2)(1 + \sin(2\pi/3t_r)t)$ [1], and t_r is pulse rising time. Typically, t_r of CMOS inverter current is 5–10 ns, which corresponds to frequency of 30–60 MHz. The maximum change in impedance with applying magnetic field is 50–60 Ω at frequency of 30–60 MHz. Pulse voltage V_w is considered to be nearly proportional to $(I_p/2)Z_w$, so maximum change in pulse impedance ($= V_w/I_p$) per 2.6 mm length was estimated to be 6.5–7.8 Ω. The estimated value roughly coincides with experimental results shown in Fig. 9.

V. Conclusion

We have developed a prototype miniature multi-core head ($\sim$2 mm^2) consisting of 13 μm diameter a-wire and pick-up coils totaling 250 turns. A high field detection sensitivity of $\sim$900 V/T and good linearity were obtained in combination with CMOS pulse circuit. It is found that the noise floor of the CMOS MI sensor with the prototype miniature multi-core head is lower than 100 pT/Hz$^{1/2}$ for a frequency range from 20 to 500 Hz. We estimated the peak voltage at a pick-up coil on the basis of off-diagonal impedance theory and compared with experimental data. The results obtained in this paper will be useful for designing a highly sensitive MI sensor based on a miniature multi-core head with a CMOS pulse circuit.

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