Characterization of tunable magnetic sensor using bias magnetic field of a hard magnetic film magnetized by pulsed-magnetic field

Makoto Sonehara[1], *Member, IEEE*, Hiroki Kamada[1], Satoko Iida[2,1], and Toshiro Sato[1], *Member, IEEE*

[1]Spin Device Technology Center, Shinshu University, 4-17-1 Wakasato, Nagano 380-8553, Japan
[2]Kisarazu National College of Technology, 2-11-1 Kiyomidaihigashi, Kisarazu, Japan

A tunable MR sensor with variable sensitivity and measuring range is fabricated and characterized. The sensor has been fabricated using a combination of Ni-Fe soft magnetic film, Fe-Co-Sm hard magnetic film. The sensor is placed in a magnetizing coil for the process of magnetizing the hard magnetic film. The sensitivity and the measuring range of the sensor are tuned by bias magnetic field produced by the magnetic poles of the hard magnetic film. The sensitivity change was about 60 %, and the measuring range change was about 30 % in the tunable MR sensor from the experimental results. The bias magnetic field is controlled by changing amplitude of the pulsed magnetic field in the magnetizing for the hard magnetic film. The control power for one time tuning is about 18 μWh.

Index Terms— **Tunable magnetic sensor, variable sensitivity and measuring range, hard magnetic film, soft magnetic film, pulsed magnetic field magnetizing method.**

I. INTRODUCTION

The magnetic sensors with the soft magnetic film such as magnetoresistance (MR) and giant magnetoresistance (GMR) sensors are used for the current sensors, electric compasses, magnetic heads, etc [1]-[3]. Recently, an optical probe current sensor for electric vehicles (EVs) and the hybrid electric vehicles (HEVs) using the Kerr effect of a soft magnetic film was fabricated and characterized [4],[5]. Its advantage is high noise immunity and electrical insulation. The magnetic sensors with high sensitivity and wide measuring range are required for EVs/ HEVs application. For the safety, wide measuring range is required at high load current of electric motor such as sudden acceleration, and high sensitivity is required at low load current such as low speed driving in a traffic jam. However, there is a reciprocal relationship between the sensitivity and the measuring range of the magnetic sensors. Both the sensitivity and the measuring range dependents on the internal energy which include the anisotropy energy of the soft magnetic film [2]. It is difficult to control the internal energy of the sensor using the soft magnetic film only.

Thus a method to apply external energy to the soft magnetic film has been suggested. For example, B. K. Kuanr et al. reported a tunable FMR (ferromagnetic resonance) filter using bias magnetic field applied in easy magnetization direction of the magnetic film [6]. The control power for changing FMR frequency becomes large in case of using dc current for generating bias magnetic field. Moreover, the dc current for the external magnetic field energy (the Zeeman energy) must be kept a constant value in order to maintain the fixed FMR frequency.

In this study, a hard magnetic film based magnetic field biasing the tunable magnetic sensor was proposed. The magnetic sensor has a combination of the soft and hard magnetic combination films. Therefore the sensitivity and the measuring range in the magnetic sensor are tuned by the Zeeman energy from bias magnetic field in hard magnetic film.

This paper describes a development and characterizations of the tunable MR sensor with Ni-Fe soft magnetic film and Fe-Co-Sm hard magnetic film as fundamental experiment of the optical probe current sensor.

II. BASIC PRINCIPLE OF TUNABLE SENSOR

A. Tunable method of bias magnetic field by hard magnetic film in soft/hard magnetic films

Figure 1, 2 and 3 show a basic principle of the internal energy control for the soft magnetic film using a bias magnetic field of the hard magnetic film. Figure 1 shows a schematic explanation of tunable MR sensor with soft/hard magnetic combination films and applying bias magnetic field from the hard magnetic film. As shown in Fig. 2, the hard magnetic film is magnetized by the pulsed magnetic field magnetizing method. The first pulsed-current I_{p1} for saturating magnetization has constant amplitude in order to erase the hysteresis of the magnetization. The second pulsed-current I_{p2} has variable amplitude to change the remanent magnetization M_r of the hard magnetic film. The range of the remanent
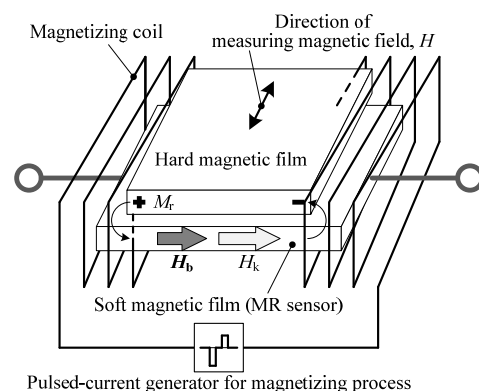

Fig. 1. Schematic explanation of tunable MR sensor with soft/hard magnetic combination films and applying bias magnetic field from hard magnetic film.
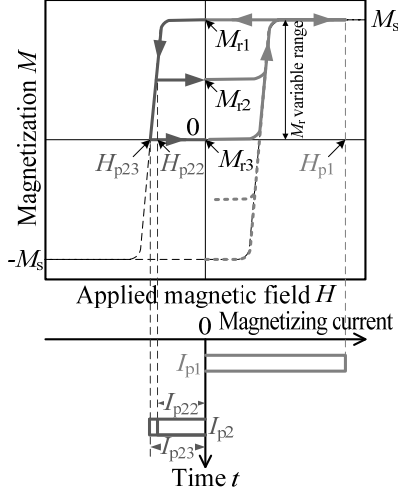
Fig. 2. Schematic hysteresis curve with varying remanent magnetization M_r in hard magnetic film using a pulsed magnetic field magnetizing method in the tunable sensor.
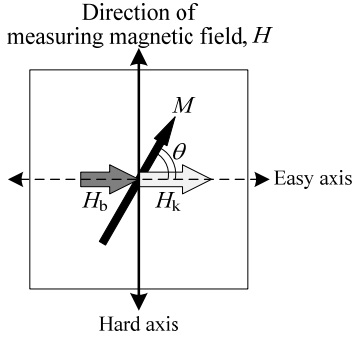

Fig. 3. Schematic top view of relation between the magnetization M, the uniaxial anisotropy field H_k, the bias magnetic field H_b, the measuring magnetic field H, and the angle θ in soft magnetic film.

magnetization M_r is approximately $-M_s$ to M_s, when the hard magnetic film has high squareness ratio. In case of $I_{p2} = 0$, M_r and H_b are maximum. When decreasing I_{p2} as shown I_{p22} in the Fig. 2, M_r and H_b are decreased. In case of $I_{p2} = I_{p23}$, M_r and H_b are 0. On the other hand, a magnetic pole is reversed in $I_{p2} < I_{p23}$, namely, the relation between M_r or H_b and $I_{p2} - I_{p23}$ are expressed to an even function.

The bias magnetic field H_b applied in easy axis of the soft magnetic film can be controlled by changing M_r, and then the internal energy E of the soft magnetic film can be tuned as shown Eq. (1);

$$E = M_s \left(\frac{H_k}{2} \sin^2 \theta - H_b \cos \theta - H \sin \theta \right) \qquad (1)$$

where M_s is the saturation magnetization, and H_k is the uniaxial anisotropy field in the soft magnetic film, θ is the angle of magnetization M from the easy axis in the soft magnetic film as shown in Fig. 3, and H is the measuring magnetic field.

The angle θ is decided by Eq. (1) and (2):

$$\frac{\partial}{\partial \theta} E = 0, \qquad \frac{\partial^2}{\partial \theta^2} E > 0 \qquad (2)$$

B. Tunable MR sensor

Figure 4 shows a relation between an absolute angle $|\theta|$ and $|H| / H_k$. When the bias magnetic field H_b is 0, the absolute angle $|\theta|$ equals to 90° in $|H| \geq H_k$. The output of the MR sensor is dependent on the angle θ as following Eq. (3), and the output of the optical probe current sensor is dependent on the angle θ, too [4], [5]. Therefore the measuring range of the sensor is limited in $|H| = H_k$ in this case.

$$\rho = \rho_0 + \Delta\rho \cos^2 \theta \qquad (3)$$

On the other hand, when the bias magnetic field H_b is applied, the measuring range of the sensor is unlimited. The sensitivity of the sensor is decreased when increasing the bias magnetic field H_b.

III. FABRICATION OF SOFT/HARD MAGNETIC FILMS

Figure 5 shows a schematic and dimension of the fabricated tunable MR sensor using bias magnetic field of the hard magnetic film magnetized by the pulsed magnetic field magnetizing method. First, a photo resist pattern with 50 μm width air-gap like as lattice pattern and 200 μm length segment for hard magnetic film was formed on a glass substrate in order to improve the spatial distribution of bias magnetic field in the soft magnetic film [7]. Then 1 μm thick $Fe_{56.7}Co_{36.7}Sm_{6.6}$ (at.%) amorphous hard magnetic film with 1.4 T of M_s, and then 50 nm thick SiO_2 film for anti-oxidation barrier layer were deposited by r.f. magnetron sputtering. Then the photo resist was removed by lift-off method. Second, 50 nm thick $Ni_{78}Fe_{22}$ (at.%) soft magnetic film for the MR sensor
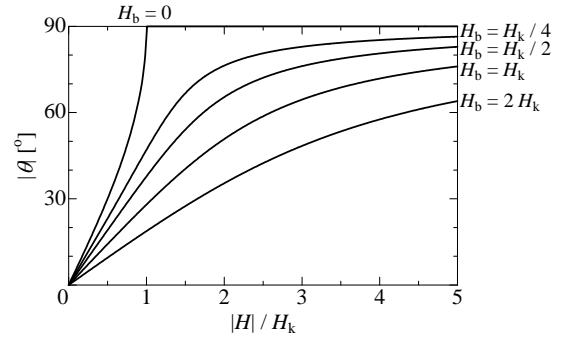

Fig. 4. Relation between the absolute angle $|\theta|$ and $|H| / H_k$ in an uniaxial anisotropy magnetic film with the bias magnetic field.
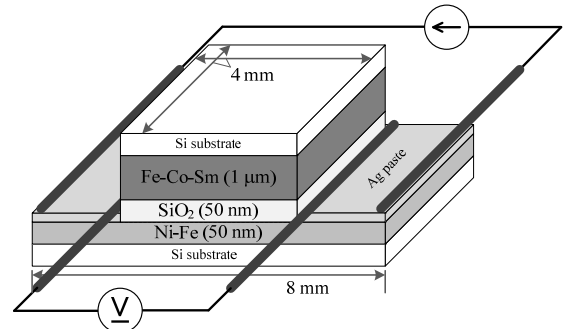

Fig. 5. Schematic and dimension of fabricated tunable MR sensor with Ni-Fe soft/Fe-Co-Sm hard magnetic combination films.

with 3.2 kA/m of H_k and 1 % of MR ratio was deposited by r.f. magnetron sputtering on another glass substrate. Third, the SiO_2/Fe-Co-Sm hard magnetic film and the Ni-Fe soft magnetic film were diced to 4 mm square size and 4 mm x 8 mm size respectively by using a dicer. Finally, two films were joined, and then Cu wires for the four-terminal method were connected by using Ag paste on the soft magnetic film as shown Fig. 5 [8].

IV. Measurement

The tunable MR sensor was put in the center of a magnetizing solenoid coil with 18 mm of length, 10 mm of mean diameter, and 568 turns as shown Fig. 1. The magnetizing solenoid coil connected to a handmade pulse current generator. A relation between the magnetizing field H_p and the pulsed-current I_p from the dc supply is following equation; $H_p = 7.14\,I_p$ [kA/m]. The first pulsed-current with constant amplitude I_{p1} was kept to 7.5 A ($H_{p1} = 53.5$ [kA/m]) in order to saturate the Fe-Co-Sm hard magnetic film. On the other hand, the second pulsed-current with variable amplitude I_{p2} were established $-6.0 \le I_{p2} \le 0$ [A] (i.e. $-43 \le H_{p2} \le 0$ [kA/m]). The current pulse-width was about 1 ms in this experiment.

The sensor and the magnetizing coil were put in a solenoid coil with 95 mm of length, 103 mm of mean diameter, and 1150 turns for the applied magnetic field H which connected to a dc supply (KENWOOD; PR18-1.2A). A relation between the applied magnetic field H and the current I from the dc supply is following equation; $H = 8.16\,I$ [kA/m].

A variation of a resistivity in the tunable MR sensor with the applied magnetic field H was measured by four-terminal method using a digital multi meter (ADVANTEST; R6871E-DC).

V. Results and Discussion

A. Relation between remanent magnetization and pulsed-current in Ni-Fe/Fe-Co-Sm films for tunable sensor

Figure 6 shows the relation between the remanent magnetization M_r in the Fe-Co-Sm hard magnetic film, the second pulsed-current with variable amplitude I_{p2}, and the variable magnetizing field H_{p2} in the Ni-Fe/Fe-Co-Sm
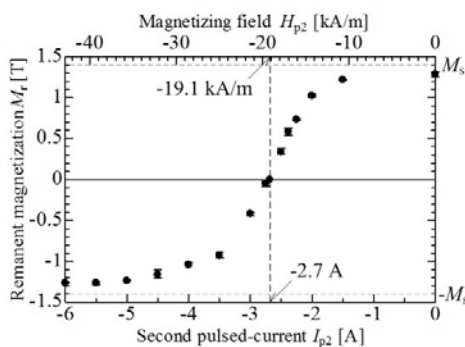
combination films of the tunable MR sensor. The remanent magnetization M_r was measured by using a vibrating sample magnetometer (VSM, Riken Denshi; BHV-55). From Fig. 6, the remanent magnetization M_r is equal to 0 [T] at $I_{p2} = -2.7$ [A] ($H_{p2} = -19.1$ [kA/m]), so then bias magnetic field $H_b = 0$ is expected. M_r increases when I_{p2} increases. M_r is approximately saturated in $I_{p2} > -1.3$ [A]. On the other hand, M_r deceases when I_{p2} decreases. M_r is approximately saturated in $I_{p2} < -5$ [A]. These results follow by the Section II A and Fig. 2.

B. Relation between a change in resistivity and applied magnetic field in tunable MR sensor with Ni-Fe/Fe-Co-Sm combination films

Figure 7 shows the relation between a change in resistivity $\Delta\rho/\rho$, the applied magnetic field H, and the typical variable magnetizing field H_{p2} in the tunable MR sensor. Furthermore the relation between a change in resistivity $\Delta\rho/\rho$ and the applied magnetic field H of a MR sensor without hard magnetic film was described in Fig. 7. In addition, the calculated results were estimated by Eq. (1)-(3). The bias magnetic field H_{be} used for the calculation were fitted by the measured results.

From Fig. 7, the sensitivity decreases, and the measuring range increases when H_{p2} increases. The calculated results agree well with the measurements in the low field H region ($H < 3$ [kA/m]). However, the calculated results are inconsistent with the measurements in the vicinity of saturating $\Delta\rho/\rho$. The authors considered that the main reason is an effect of anisotropy dispersion in the soft magnetic film.

The measured result at $H_{p2} = -19.1$ [kA/m] is inconsistent with that of without hard magnetic film, and the bias magnetic field H_{be} was estimated about 0.7 kA/m from the results. The reason is currently not clear. However, the authors observed many stripe magnetic domains in the hard magnetic film at $H_{p2} = -19.1$ [kA/m]. Therefore it is expected that 0.7 kA/m of microscopic bias magnetic field was occurred by the magnetic poles in the magnetic domains. The authors examine and research a mean of $H_{be} = 0$.
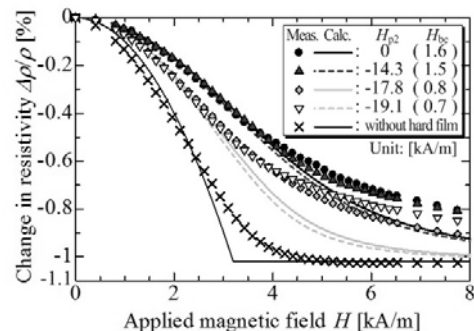

Fig. 6. Relation between the remanent magnetization M_r in Fe-Co-Sm hard magnetic film, the second pulsed-current with variable amplitude I_{p2}, and the variable magnetizing field H_{p2} in Ni-Fe/Fe-Co-Sm combination films for the tunable MR sensor.

Fig. 7. Relation between change in resistivity $\Delta\rho/\rho$, applied magnetic field H, and typical variable magnetizing field H_{p2} from hard magnetic film in the tunable MR sensor.
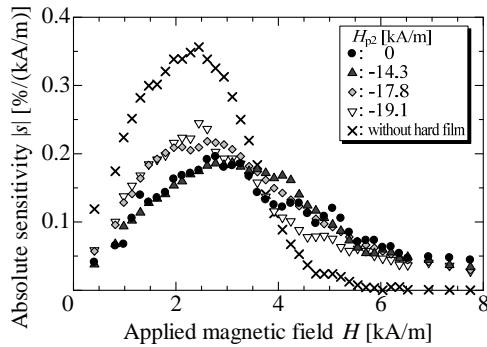
Fig. 8. Relation between change in absolute sensitivity $|s|$, applied magnetic field H, and variable magnetizing field H_{p2} from hard magnetic film in the tunable MR sensor.
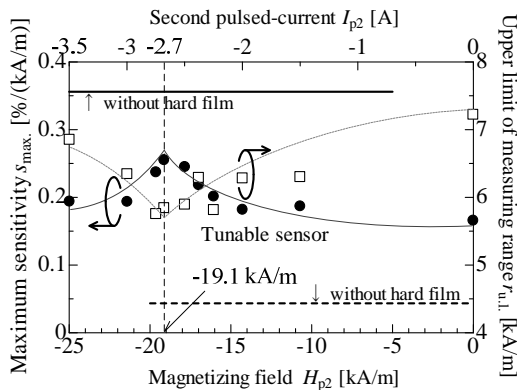

Fig. 9. Relation between maximum sensitivity $s_{max.}$, upper limit of measuring range $r_{u.l.}$, variable magnetizing field H_{p2} from hard magnetic film, and second pulsed-current I_{p2} in the tunable MR sensor.

C. Variable sensitivity and measuring range in tunable MR sensor with Ni-Fe/Fe-Co-Sm combination films

Figure 8 shows the relation between an absolute sensitivity $|s|$, the applied magnetic field H, and the typical variable magnetizing field H_{p2} from hard magnetic film in the tunable MR sensor. The absolute sensitivity $|s|$ [%/(A/m)] was defined by $|d(\Delta\rho/\rho) / dH|$ and calculated from Fig. 7.

Figure 9 shows the relation between a maximum sensitivity $s_{max.}$ in each data, an upper limit of measuring range $r_{u.l.}$, the variable magnetizing field H_{p2}, and the second pulsed-current I_{p2} in the tunable MR sensor. The upper limit of measuring range $r_{u.l.}$ is defined at $|s| = 0.05$ [%/(kA/m)] in Fig. 8.

From Fig. 8 and 9, the sensitivity s decreases when H_{p2} increases. The sensitivity in the tunable MR sensor was tuned about 60 %. If some problems such as the anisotropy dispersion in soft magnetic film were solved, the result of the tunable MR sensor with $M_r = 0$ will correspond to that of the sensor without hard magnetic film, so then a change in sensitivity is expected about 110 %.

On the other hand, from Fig. 9, the upper limit of measuring range $r_{u.l.}$ increases when H_{p2} increases. $r_{u.l.}$ in the tunable MR sensor was tuned about 30 %. A change in $r_{u.l.}$ is expected about 60 % for the reason mentioned above.

VI. CONCLUSIONS

This paper describes a development and characterizations of the tunable MR sensor using a bias magnetic field of the hard magnetic film magnetized by pulsed magnetic field magnetizing method. The results obtained are as follows:

(1) The remanent magnetization M_r of the Ni-Fe/Fe-Co-Sm magnetic combination films in the tunable MR sensor is changed from –1.3 to 1.3 [T] by variable bias magnetic field of the Fe-Co-Sm hard magnetic film. M_r is equal to 0 [T] at $I_{p2} = -2.7$ [A] ($H_{p2} = -19.1$ [kA/m]).

(2) The sensitivity decreased, and the measuring range increased when increasing H_{p2} in the tunable MR sensor with the Ni-Fe/Fe-Co-Sm magnetic combination films.

(3) The sensitivity change was about 60 %, and the measuring range change was 30 % in the tunable MR sensor. The potential variable values of the two parameters were expected about 110 % and 60 %, respectively.

Thus the tunable sensor using a bias magnetic field of a hard magnetic film magnetized by the pulsed magnetic field magnetizing method is demonstrated as a part of fundamental experiment of the optical probe current sensor.

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