Integration of High-Frequency Carrier-Type Thin-Film Magnetic Field Sensor with SmCo Thin-Film Bias Magnet

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***Abstract*—A bridge-connected high-frequency carrier-type thin-film magnetic field sensor is fabricated on a SmCo magnetic thin-film which provides an in-plane dc bias magnetic field to the sensor. The dc bias field of 320 A/m was achieved by using a 3 μm thick SmCo underlayer. The sensitivity obtained was 8.4 mV/Oe which was 12 times as large as the sensitivity without the SmCo thin-film magnet.**

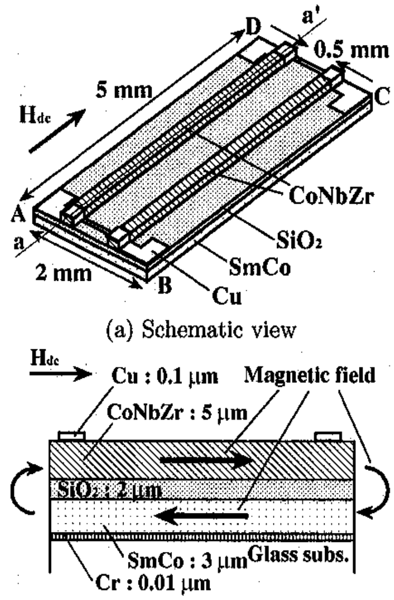
***Index Terms*—SmCo thin-film magnet, high-frequency carrier-type thin-film magnetic field sensor, non-uniform bridge-connected sensor, GMI sensor**

I. Introduction

THIS paper proposes an utilization of a thin-film magnet to give an in-plane dc bias field in micro-magnetic devices. Our main idea is to magnetize the thin-film magnet to in-plane direction, which gives an in-plane dc bias field to integrated soft magnetic materials in the same device. Permanent magnet bias eliminates a need for external power source, ease microfabrication and simplify the device structure. This idea has been applied in this paper to high-frequency carrier-type thin-film magnetic field sensor [1]–[3] (or so-called GMI sensor). The sensor needs the in-plane dc bias field of the intensity of nominally the anisotropy field of the soft magnetic film used.

II. Experimental Procedures

A non-uniform bridge-connected high-frequency carrier-type magnetic field sensor [3] is fabricated on an amorphous $Sm_{16}Co_{84}$ magnetic thin-film which gives a dc bias magnetic field as shown in Fig. 1. The bridge-connected sensor consists of a pair of parallel $Co_{85}Nb_{12}Zr_3$ magnetic legs and two Cu conductive legs. Cross-talk between the magnetic legs are negligible because these are separated by non-magnetic legs. We applied a high frequency carrier voltage of 1 V_{p-p} to the electrodes A and C in Fig. 1(a), and measured the output voltage, V_{out}, between the electrodes B and D with FET probes and an oscilloscope. The bridge-connected sensor was subjected to an external dc field, H_{dc}, generated by a Helmholtz coil.



(a) Schematic view

(b) Cross sectional view through a-a'

Fig. 1. Structure of the proposed integrated sensor.

A stacked film of 1 μm thick CoNbZr and 3 μm thick SmCo film with a 60 nm thick Cr layer in between was deposited on a glass substrate. The easy axis of the CoNbZr film was the same as that of the SmCo film in the stacked film. The film was etched using wetchemistry to a size of 3 mm × 3 mm size. The magnetization curve was measured by using a vibrating sample magnetometer.

III. Structure and Microfabrication

A. Annealing Temperature

Rather than a great energy product, the hard magnetic film requires a large anisotropy field and good squareness ratio of hysteresis loop. This demand is caused by the bias point of the proposed sensor to be very close to the point

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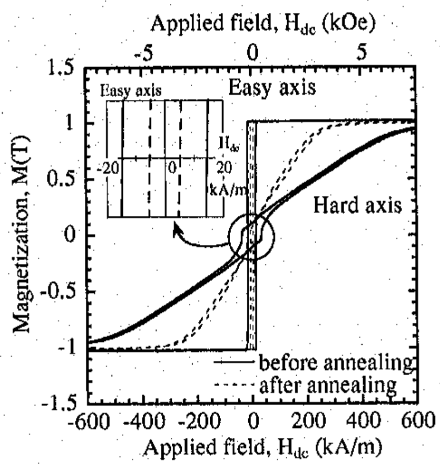


Fig. 2. Magnetization curve of the SmCo film.

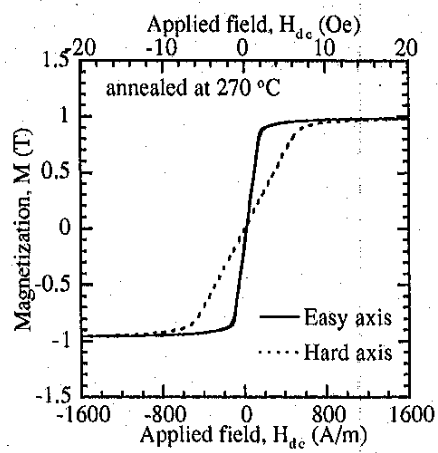


Fig. 3. Magnetization curve of the CoNbZr film.

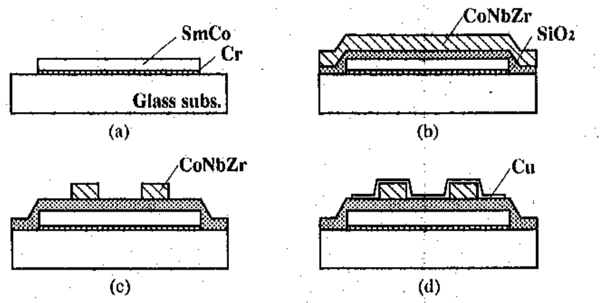


Fig. 4. Fabrication steps of the integrated sensor: (a) sputter and ion milled SmCo/Cr layer; (b) sputter CoNbZr/SiO_2 layer; (c) ion mill CoNbZr layer; (d) sputter Cu legs.

of residual induction of the M-H loop. The field deposited amorphous SmCo film [4], [5] is good for this purpose and we can expect a dc bias field of 24 to 800 A/m although the coercive force is low as 8 to 240 kA/m.

Fig. 2 shows the magnetization curve of the $Sm_{16}Co_{84}$ film whose composition maximize the coercive force and anisotropy energy [6]. The solid line is before annealing and the dashed line is after annealing at 360°C. The residual magnetization was about 1.0 T, coercive force was 16 kA/m, and squareness ratio was $B_r/B_s = 0.9$ along easy axis direction, the anisotropy field was about 500 kA/m before annealing. Obviously, the large uniaxial anisotropy was obtained before annealing. When the film was annealed at 360°C, the film remained still anisotropic although the anisotropy field was down to 300 kA/m. With the further increase of annealing temperature, the SmCo film is crystallized and the uniaxial anisotropy energy is degraded [7]. Consequently, the annealing temperature of the CoNbZr film should be lower than the crystallization temperature of the SmCo film. This exactly means the highest possible annealing temperature of the CoNbZr film is 360°C.

In our previous study [2], the $Co_{85}Nb_{12}Zr_3$ film exhibited an anisotropy filed large enough to the sensor application at an annealing temperature of 400°C. This temperature is higher than the highest possible annealing temperature. Therefore the annealing temperature dependence of the anisotropy field was studied carefully based on the known report that the anisotropy field decreases with an decrease of annealing temperature [8]. Then, in Fig. 3, it is seen that the anisotropy field annealed in a static filed at 270°C was still compatible to that annealed at 400°C. Therefore the sensor element was annealed at 270°C.

B. Microfabrication

Fabrication steps for the integrated sensor are summarized in Fig. 4. Firstly the 10 nm thick Cr underlayer and the 3 μm thick amorphous SmCo film were deposited on a soda glass substrate by rf-sputtering in a static field of 16 kA/m. Next, the 5 mm long and 2 mm wide SmCo film patterns were obtained by ion milling with their easy axis orientation along the length direction of the specimen, as shown in Fig. 4 (a). After sputtering the 2 μm thick SiO_2 film, the 5 μm thick amorphous soft magnetic $Co_{85}Nb_{12}Zr_3$ film was rf-sputter deposited, as shown in Fig. 4 (b). The specimen was annealed at 270°C in a magnetic field of 40 kA/m. For the first two hours the field was rotated at 60 rpm, followed of one hour of stationary field in order to induce uniaxial magnetic anisotropy for the CoNbZr film. After the annealing, the CoNbZr film was ion milled to two parallel rectangles with their easy axis along the width direction. The length of the CoNbZr leg was 5 mm, the width was 100 μm and the space between two legs was 0.5 mm. The anisotropy field of the sensor element was 400–480 A/m. Finally another two legs of the bridge and electrodes were made by a lift-off process of the 0.1 μm thick Cu film. The length of the Cu leg was 0.5 mm and the width was 10 μm. The Cu leg was designed so that the impedance of the leg is equal to the impedance of the CoNbZr leg at the bias point.

IV. Results and Discussion

Fig. 5 shows the minor loop of a SmCo/CoNbZr stacked film in the loop range of −3.2 to 3.2 kA/m along the easy axis direction of the stacked film. The CoNbZr film clearly was affected the bias field of 560 A/m from the SmCo film.

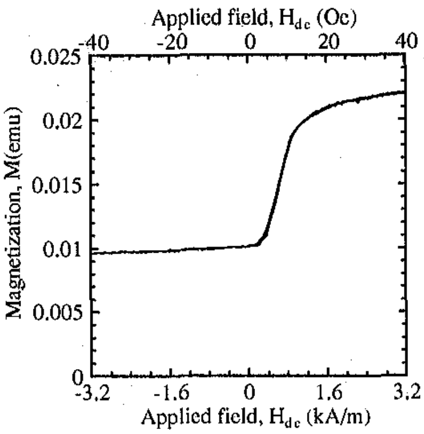
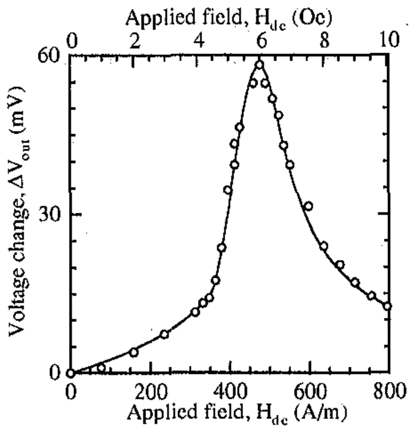
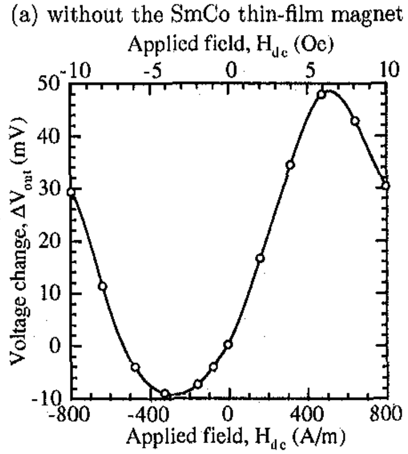


Fig. 5. Magnetization curve of CoNbZr/SmCo bilayer film.



(a) without the SmCo thin-film magnet



(b) with the SmCo thin-film magnet

Fig. 6. Dependence of the magnitude of the ac output voltage change on the external dc field for the bridge-connected sensor.

Fig. 6(a) shows the dependence of the magnitude of the output voltage change, ΔV_{out}, on the external magnetic field for the non-uniform bridge-connected sensor without the SmCo thin-film magnet at a carrier frequency of 10 MHz. The magnitude of voltage change was maximum when the dc magnetic field was nearly equal to the anisotropy field of the CoNbZr magnetic film [9], [10]. The sensitivity of the element around 0 A/m was 0.7 mV/Oe.

In the case of the integrated sensor of Fig. 1, the dc bias field of 320 A/m was apparently achieved by using SmCo film, as shown in Fig. 6(b). The sensitivity of the sensor was 8.4 mV/Oe. This is 12 times as large as the sensitivity of the sensor around 0 A/m without the SmCo bias field.

V. Conclusions

We investigated the integrated sensor consisting of a non-uniform bridge-connected high-frequency carrier-type magnetic sensor deposited on the SmCo thin-film magnet. The high sensitivity of 8.4 mV/Oe was achieved with the help of the dc bias magnetic field of 320 A/m provided by the 3 μm thick SmCo film.

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