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著者	Miyata H., Yamamoto R., Morimoto Y., Takezawa M.
journal or publication title	IEEE Transactions on Magnetics
volume	50
number	11
page range	1-4
year	2014-12-02
URL	http://hdl.handle.net/10228/5876

doi: info:doi/10.1109/TMAG.2014.2332348

Relationship between Output of a Fluxgate Sensor and Magnetization Process of its Core

Hiroshi Miyata[1], Ryoma Yamamoto[2], Yuji Morimoto[2], and Masaaki Takezawa[2]

[1]MTI Co., Ltd., 2-1-15, Edamitsu, Yahatahigashi-ku, Kitakyushu, Fukuoka 805-8503, Japan
[2]Faculty of Engineering, Kyushu Institute of Technology, 1-1, Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka 804-8550, Japan

Motivated by the need to miniaturize fluxgate sensors, we investigated the dependence of the sensitivity of fluxgate sensors on the saturation flux density and magnetostriction of an amorphous ribbon core. In addition, the relationship between the sensing properties and the magnetization process of its core was investigated with a Kerr microscope. We found that the sensitivity decreased with an increase in magnetostriction. Highly magnetostrictive amorphous ribbons exhibited maze domains that were difficult to move by applying a low magnetic field of a few hundred amperes per meter. This effect caused a decrease in the sensitivity of the sensors.

Index Terms—**Magnetic sensors, Magnetic domains, Magnetostriction, Fluxgate sensors, Kerr microscope**

I. INTRODUCTION

FLUXGATE sensors are extremely accurate magnetic sensors. They are sensitive to the field direction in a range of up to 1 mT, with achievable resolution down to 10 pT [1]. A fluxgate sensor can work at room temperature, and its temperature stability allows its use as a popular high-sensitivity magnetic sensor.

A fluxgate sensor consists of a magnetic bulk or ribbon core and electrical windings, which act as both excitation and detection coils around the magnetic core. The dual nature of the winding makes the miniaturization of the sensor head difficult. Researchers have developed several micro fluxgate sensors that can be directly integrated on Si wafers [2]-[5]. However, they utilized thin films as the fluxgate sensor element, which is more expensive than the traditional magnetic bulk element.

In this manuscript, we seek to understand the underlying physics that would allow the development of a commercially viable fluxgate sensor containing a miniaturized head. This is not a simple task since decreasing the sensor head size causes a decrease in its sensitivity. However, a sensor having low noise and high sensitivity has been developed using either a heat-treated permalloy (with 78%–81% nickel) or an amorphous ribbon with low magnetostriction [5]. The output from the pick-up coil is induced by a change in magnetic flux. Therefore, using amorphous ribbons with a high saturation flux density B_s as the core material is one of the possibilities for miniaturizing a sensor head while retaining high sensitivity. However, amorphous ribbons with a high B_s generally have a large magnetostriction, which produces low sensitivity because of change in magnetic domain structure and magnetization process. Little is known about their magnetic domains and magnetization process, which are important properties for the sensitivity of the fluxgate sensor [6], [7]. To address this issue, we seek to elucidate the magnetization process and how the magnetic domain changes in the sensor head when the sensor is excited by an AC magnetic field.

In this study, we dynamically observed the domain structure of the sensor head using a Kerr microscope when an AC magnetic field was applied. We investigated the relationships between the sensing properties and the domain structure because the sensing properties are related to the domain structure and magnetization process of the core material. We examined the dependence of the sensitivity of fluxgate sensors on saturation flux density by using different types of amorphous cores having different B_s values. In this experiment, the output voltage of the sensor output from the three cores was observed and the B_s dependence of the sensor output was investigated.

II. EXPERIMENT PROCEDURE

1) *Measurement of the sensor output*

A schematic of the sensor element, consisting of a conventional parallel-type fluxgate structure, is shown in Fig. 1. The excitation coil is wound on an amorphous magnetic ribbon and consists of 400 turns. The excitation current I_{exc} flowing through the excitation coil produces a field that periodically saturates (in both directions) in the soft magnetic material of the sensor core. When a measurable field is present, voltage is induced in the sensing pick-up coil at the second (and higher) harmonic(s) of the excitation frequency [1].

In this study, we used three types of amorphous ribbons,

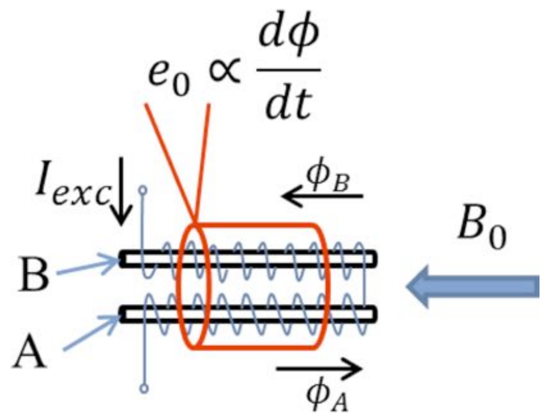

Fig. 1. Schematic of a sensor head.

Manuscript received March 7, 2014. Corresponding author: M. Takezawa(e-mail: take@ele.kyutech.ac.jp).
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manufactured by Hitachi Metals Ltd. The composition, saturation flux density B_s, and magnetostriction λ_s of the core materials are shown in Table 1. The materials used are as follows: a Co-based ribbon (2714A), a Ni-based ribbon (2826MB), and a Fe-based ribbon (2605SC). The Fe-based ribbon has the highest B_s = 1.6 T and $\lambda_s = 30 \times 10^{-6}$ and the Co-based ribbon has the lowest B_s = 0.57 T and $\lambda_s << 1 \times 10^{-6}$. The samples are 1 mm wide, 20 mm long, and 15–20 µm thick.

The *B-H* loop of each sample is measured at 15 kHz with a *B-H* analyzer (SY-8232 by IWATSU), and the results are shown in Fig. 2. The flux density at 800 A/m of the Co-based, at 1600 A /m of the Ni-based and at 2400 A/m of the Fe-based ribbons are 524, 746, and 1247 mT, respectively. The coercive force of the Co-based, Ni-based, and Fe-based ribbons is 27.8, 100.7, and 138.3 A/m, respectively.

A sine wave is produced by a function generator, and is diverted to an excitation coil as an excitation current. The excitation frequency is 5 kHz. The AC sensor output voltage is measured with a voltmeter. We simply considered the RMS value of the AC voltage induced in the pick-up coil in this study.

B. Magnetic domain observation

Magnetic domains of the three core materials of the fluxgate sensor are examined with a Kerr microscope. The observed sample is fixed with an adhesive on a glass substrate, and the magnetic domain of the sample's center area is observed. Dynamic domain observation is performed during the AC magnetization process by applying an AC field of ±288 A/m at 20 kHz along the longitudinal direction of the ribbon. Figure 3 shows the observation method of the AC magnetization process. A change in the domain image is extracted by subtracting a reference image in an AC applied field using an image processor [8]. A domain pattern in a remnant state is applied as the reference image, and we integrate 128 times every 1/30 s. By this process, magnetization rotation and wall displacement can be identified from their images, as schematically shown in Fig. 3. Moreover, the observation method can be compared to the mobility of the magnetic domain wall.

TABLE I
Parameters of the amorphous ribbons for the sensor core.

	Composition	B_s [T]	$\lambda_s \times 10^{-6}$
2714A Co-based	$Co_{66}Fe_4Ni_1Si_{14}B_{15}$	0.57	<< 1
2826MB Ni-based	$Fe_{40}Ni_{38}Mo_4B_{18}$	0.86	12
2605SC Fe-based	$Fe_{81}B_{13.5}Si_{13.5}C_2$	1.60	30

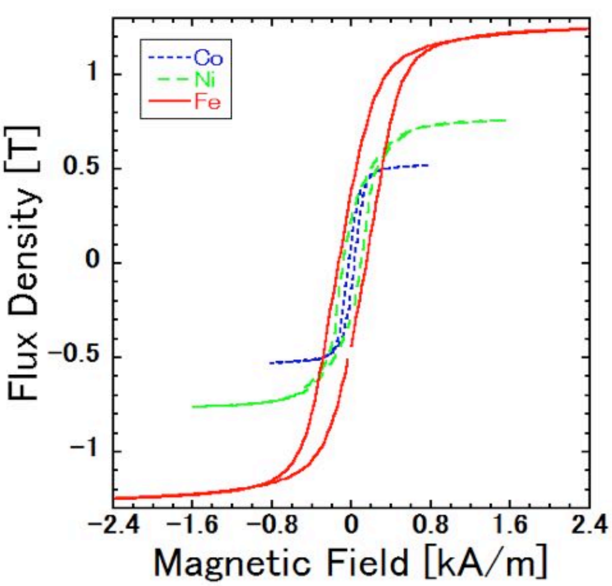

Fig. 2 B-H curves of amorphous cores.

III. Result and discussion

Figure 4 shows the excitation current dependence of the sensitivity defined by the output voltage gradient of the detection coil at 80 A/m. The excitation current changes from 1 to 20 mA. In the case of low excitation current that promotes non-saturated state, sensor output is small. When the excitation current changed high enough to saturate the cores, the sensitivity of the sensors increases with excitation current, as shown in Fig. 4. The highest sensitivity is obtained in the Co-based ribbon.

Figure 5 shows the frequency dependence of the sensitivity defined by the output voltage gradient of the detection coil at 80 A/m. The frequency changes from 1 to 20 kHz. The sensitivity of the sensor increases with excitation frequency, as shown in Fig. 5. The highest sensitivity is obtained in the Co-based ribbon despite its low B_s.

Figure 6 shows the magnetic domain images of the three types of amorphous ribbons. The left images show the static magnetic domain structure at a remnant state. The bright and dark domains are magnetized in the upward and downward directions, respectively. Wide stripe domains having an approximately 100-µm-wide stripe and narrow maze domains having an approximately 10-µm-wide stripe are observed in all the ribbons, as shown in Fig. 6(a), 6(c), and 6(e). The

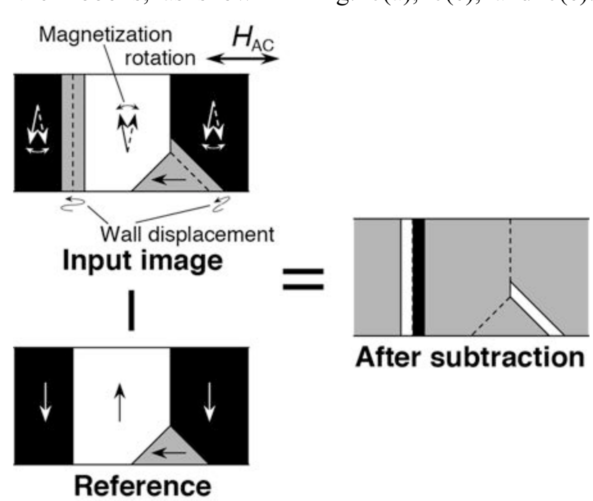

Fig. 3 Principle of domain subtraction using an image processor.

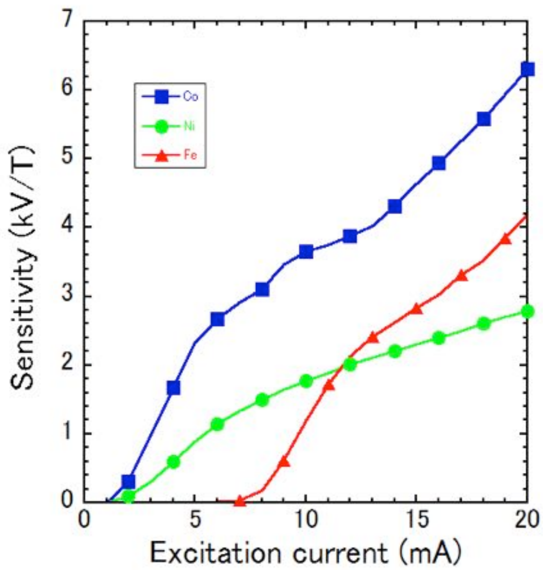

Fig. 4 Excitation current dependence of sensitivity.

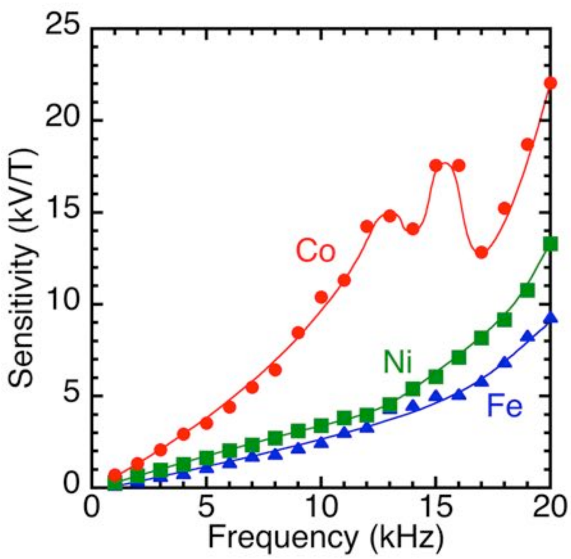

Fig. 5 Frequency dependence of sensitivity.

narrow maze domains are formed by local stress being induced at the bonding boundary with the substrate. The right images show the dynamic magnetic domain obtained by applying an AC field of ±288 A/m at 20 kHz. Wall displacement is observed in all the ribbons. However, wall motion in narrow maze domains is negligible in Ni- and Fe-based ribbons, as shown in Fig. 6(d) and 6(f), respectively.

On the other hand, wall displacement in the narrow maze domains is observed only for the Co-based ribbon, as shown in Fig. 6(b). Although the domain patterns same, smooth domain wall motion occurred only at Co-based ribbon. Because the output voltage of pickup coil depends on $d\Phi/dt$, the large dB/dH at Co-based ribbon due to smooth wall motion promotes high sensitivity of the fluxgate sensor. Moreover, the smooth wall motion causes lower Barkhausen noise.

As a result, sensitivity of the core material increases with a

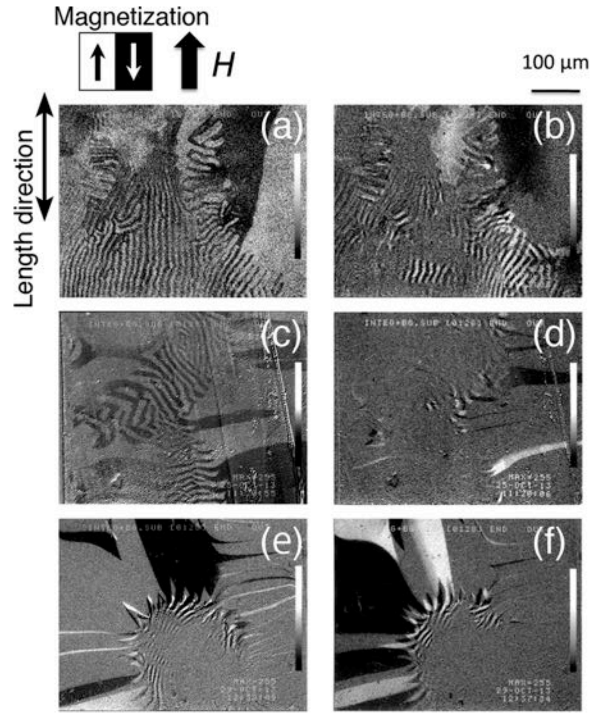

Fig. 6 Static and dynamic magnetic domain images: (a) static image of Co-based core, (b) dynamic image of Co-based core, (c) static image of Ni-based core, (d) dynamic image of Ni-based core, (e) static image of Fe-based core, and (f) dynamic image of Fe-based core.

decrease in magnetostriction. Furthermore, the local stress produced by the substrate causes pinning sites of the domain wall motion in the case of high magnetostrictive ribbons.

IV. Conclusion

In this study, we investigated the dependence of the sensitivity of fluxgate sensors on the saturation flux density and magnetostriction of an amorphous ribbon core. In addition, the relationship between the sensing properties and the magnetization process of its core was investigated with a Kerr microscope. The sensitivity decreased with an increase in magnetostriction. Highly magnetostrictive amorphous ribbons exhibited maze domains that were difficult to move by applying a low AC magnetic field of a few hundred amperes per meter. This effect caused a decrease in the sensitivity of the sensors. In our future work, we will improve to control magnetic domain structure of the amorphous core for reduction of maze domains, which can realize miniaturization of the fluxgate sensor.

References

[1] P. Ripka, “Advances in fluxgate sensors” *Sensors and Actuators A*, vol. 106, pp. 8-14, 2003..

[2] T. Munaka, K. Yoshimi, H. Nakanishi, K. Iijima, and Y. Yamada, “Fabrication of a Thin-Film Fluxgate Magnetic Sensor” *J. Magn. Soc Jpn.*, vol. 20, pp. 561-564, 1996.

[3] T. M. Liakopoulos and C. H. Ahn, “A micro-fluxgate magnetic sensor using micromachined planar solenoid coils” *Sens. Act.,* vol. 77, pp. 66-72, 1999.

[4] P. Kejik, L. Chiesi, B. Janossy, and R. S. Popovic, “A new compact 2D planar fluxgate sensor with amorhous metal core” *Sens. Act.,* vol. 81, pp. 180-183, 2000.
[5] O. Dezuari, E. Belloy, S. E. Gilbert, and M. A. M. Gijs, “Printed circuit board integrated fluxgate sensor” *Sens. Act.*, vol. 81, pp. 200-203, 2000.
[6] K. Zaveta, O. V. Nielsen, and K. Jurek, “A domain study of magnetization processes in a stress-annealed metallic glass ribbon for fluxgate sensors” *J. Magn. Mater*., vol. 117, pp. 61-68, 1992.
[7] R. H. Koch and J. R. Rozen, “Low-noise flux-gate magnetic-field sensors using ring- and rod-core geometries” *Appl. Phys. Lett*., vol. 78, pp.1897-1899, 2001.
[8] M. Takezawa and J. Yamasaki, “Dynamic domain observation narrow thin films” *IEEE Trans. Magn.*, vol. 37, pp. 2034-2037, 2001.