ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 7, January 2018

Magnetic response characteristics of magneto resistive sensors with superconducting magnetic focusing thin film

Tetsuro Hirata, Yoshihiro Nakamura, Yatsuse Majima, Kaoru Amano, Kenji Sakai, Toshihiko Kiwa, Keiji Tsukada

Abstract*— Magnetic sensors such as magneto resistive (MR) sensors and superconducting quantum interference devices (SQUIDs) are used for various applications, such as nondestructive evaluation of metallic materials and magnetic immunoassays. MR sensors are relatively inexpensive and are widely used in consumer products, although their sensitivity is extremely low compared to that of SQUIDs. In this study, we developed a hybrid magnetic sensor by combining an anisotropic MR (AMR) sensor with two high-temperature superconducting (HTS) plates made from YBCO to achieve a sensitivity that is intermediate to those of MR sensors and SQUIDs. The AMR sensor was installed inside a slit between two magnetic-focusing HTS plates. The magnetic sensitivity of the AMR sensor without HTS plates decreased from room temperature (RT) to liquid N2 temperature because the electrical resistivity of the thin ferromagnetic film reduced upon cooling. On the other hand, the AMR sensor with two HTS plates (i.e., hybrid magnetic sensor) showed higher overall magnetic sensitivity at liquid N_2 temperature than at RT, although its sensitivity decreased. We also succeeded in improving the magnetic resolution and magnetic sensitivity and controlled the magnetic sensitivity and magnetic resolution of the AMR sensor by changing the relative position of the AMR sensor and the HTS plates or the slit width of the HTS plates.

***Index Terms*—magneto resistive sensor, high temperature superconducting plates, magnetic sensitivity.**

I. INTRODUCTION

Magnetic sensors can be used for measuring various magnetic phenomena. Among these, magneto resistive (MR) sensors are very popular in consumer products because they are relatively inexpensive. In particular, SQUIDs are widely used as magnetic sensors because of their relatively high magnetic sensitivity. SQUIDs are devices based on superconducting loops containing a Josephson junction. There are two types of SQUIDs, low-Tc SQUID[1] and high-Tc SQUID[2], depending on the critical temperature (Tc) of the superconducting material. Low- and high-Tc SQUIDs are operated with liquid helium (4.2 K) and liquid N_2 (77 K), respectively. Both are very sensitive to magnetic signals, with sensitivity of the order of femtoteslas. This makes it possible to detect extremely low magnetic signals such as biomagnetism, and it enables applications such as magnetic immunoassays [3] with magnetic nanoparticles. MR sensors use the magnetoresistance, that is, the tendency of a ferromagnetic material to change its electrical resistance under an external magnetic field. Various types of MR sensors have been developed, such as anisotropic MR (AMR) sensors, giant MR (GMR) sensors, and tunnel MR (TMR) sensors. These sensor types have different ferromagnetic thin film structures, and they are used for various purposes such as the nondestructive evaluation of metallic materials. MR sensors have some advantages in that their cost is lower and device size is smaller than that of other magnetic sensors, although their sensitivity (of the order of nanoteslas) is lower than that of SQUIDs. We have developed a hybrid magnetic sensor by combining an AMR sensor (Honeywell HMC1001) with two high-temperature superconducting (HTS) plates to achieve an intermediate sensitivity between that of MR sensors and SQUIDs for high magnetic sensitivity applications such as low-frequency nondestructive testing[4]. By installing an AMR sensor between two magnetic-focusing HTS plates, we focused the magnetic flux into the AMR sensor to improve its magnetic sensitivity and magnetic resolution. We also optimized the characteristics of the hybrid sensor by changing the slit width of the HTS plates or relative position of the AMR sensor and the HTS plates to control its sensitivity for various applications.

II. METHODS AND MEASUREMENTS

A. *Magnetic focusing method*

Magnetic flux avoids a superconductor because of the Meissner effect. Figure 1 shows a conceptual diagram of magnetic focusing. When two superconductors are arranged, the magnetic flux avoids them and therefore gets concentrated between them. Because the magnetic flux density between the two superconductors increases, the sensitivity of AMR sensors can be improved by placing them between two HTS plates. We used YBCO, which can be used with liquid N_2, as the superconducting material for the HTS plates.

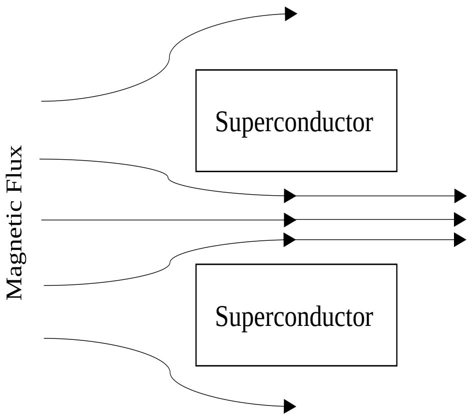


Fig.1. Magnetic focusing method

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 7, January 2018

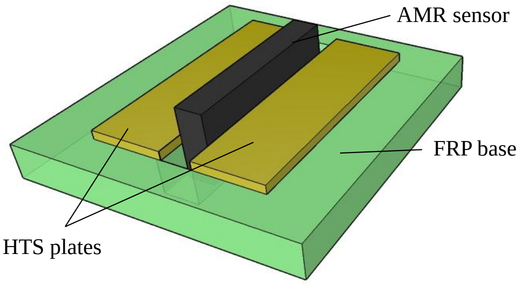


Fig.2. Schematic of the hybrid magnetic sensor

B. Hybrid magnetic sensor

We developed a hybrid magnetic sensor by combining an AMR sensor with two HTS plates, as shown in Fig. 2. Fiber-reinforced plastic (FRP) is used as a base because it is light and durable. Two HTS plates were attached on the FRP base as a slit. These rectangular-shaped HTS plates were 10 mm long and 4 mm wide and were made of YBCO (500 nm) on a MgO (0.5 μm) substrate. A hole for the AMR sensor was bored at the center of the FRP base, and an AMR sensor was installed inside a slit between two magnetic-focusing HTS plates.

After fabricating the hybrid magnetic sensor, we optimized the positional relationship between the AMR sensor and the two HTS plates to control its sensitivity. First, the relative height of the AMR sensor toward two HTS plates was changed. The datum level was defined at the same height as the bottom face of the HTS plates. The relative height shows the distance between the datum level and the bottom face of the AMR sensor. We changed the relative height (±0 mm, +1.5 mm, −1.5 mm) of the AMR sensor to evaluate the relative height dependence of the magnetic response of the AMR sensor. In this measurement, the slit width of the two HTS plates was kept constant.

We also evaluated the slit width dependence of the magnetic response of the AMR sensor by changing the slit width (1.5 mm, 2.5 mm, 3.5 mm) of the two HTS plates, as shown in Fig. 4. In this measurement, the relative height of the AMR sensor was kept constant.

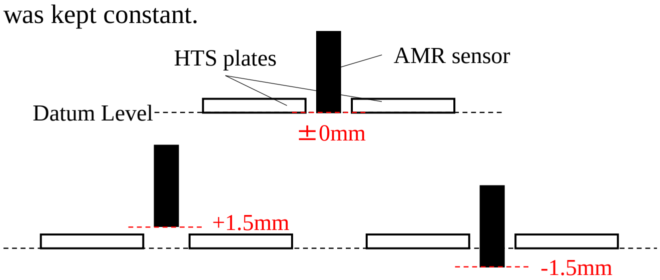


Fig.3. Relative height of AMR sensor

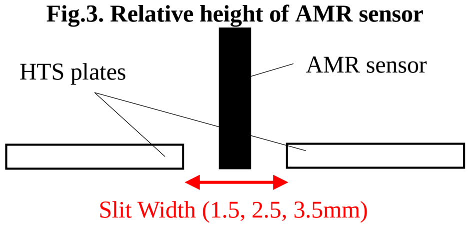


Fig.4. Slit width of two HTS plates

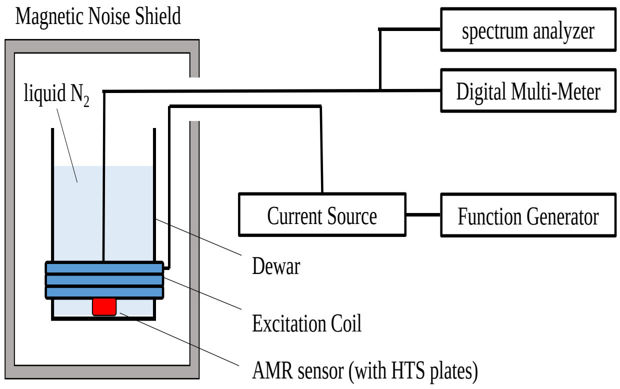


Fig.5. Schematic of measurement system

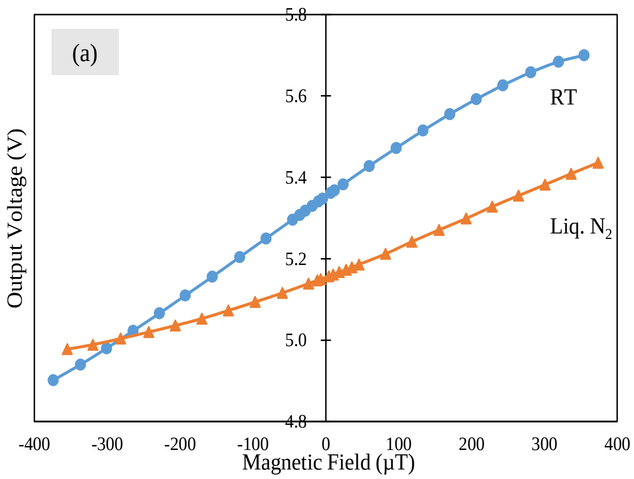
C. Method and system of measurement

Firstly, we evaluated the magnetic sensitivity and magnetic resolution of the AMR sensor without HTS plates at RT and liquid N_2 temperature because it is necessary to compare the data with or with HTS plates for proving magnetic flux focusing. Figure 5 shows the measurement system that we used in this study; the magnetic sensitivity and magnetic resolution of the AMR sensor were evaluated in a three-layer environmental magnetic noise perm alloy shield. The AMR sensor was placed at the center of the bottom of a dewar. The magnetic sensitivity was estimated by measuring the changes in the external magnetic field applied by a magnetic coil (120 mm in diameter) wound around the dewar, and the magnetic resolution was measured using a spectrum analyzer.

III. RESULTS

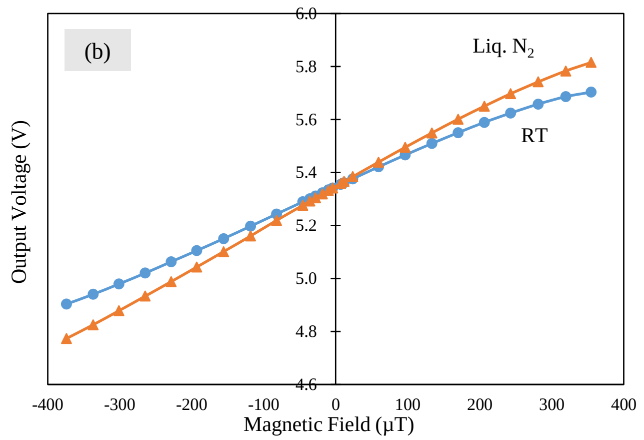
A. Magnetic response of AMR sensor

Figure 6(a) shows the magnetic sensitivity of the AMR sensor without HTS plates at RT and liquid N_2 temperature. A comparison of the magnetic response at RT and liquid N_2 temperature indicates that both characteristics show linearity. The magnetic sensitivity of the AMR sensor decreased from 1.17 mV/μT at RT to 0.65 mV/μT at liquid N_2 temperature. The electrical resistance of the ferromagnetic thin film in the



(a)

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 7, January 2018



(b)

Fig.6. Magnetic response of the AMR sensor (a)without and (b)with HTS plates.

AMR sensors changed with the external magnetic field because of the magnetoresistance, and this change led to a change in the output voltage of the AMR sensors. Therefore, the output voltage decreased because the electrical resistance of the ferromagnetic thin film decreased upon cooling with liquid N_2. This is because the magnetic sensitivity of the AMR sensor decreased from RT to the liquid N_2 temperature.

Figure 6(b) shows the magnetic sensitivity of the AMR sensor combined with the HTS plates at RT and liquid N_2 temperature. The magnetic sensitivity of the AMR sensor increased from 1.17 mV/μT at RT to 1.48 mV/μT at liquid N_2 temperature. This is because the two HTS plates focused the magnetic flux upon cooling, and this led to an increase in the magnetic flux that the AMR sensor can detect. According to Fig. 6(a) and (b), although the magnetic sensitivity of the AMR sensor without HTS plates decreased upon cooling, the AMR sensor combined with the HTS plates showed higher sensitivity at liquid N_2 temperatures than at RT because of the focusing of the magnetic flux by the HTS plates. This result shows that our magnetic focusing method is effective for improving the magnetic sensitivity of MR sensors.

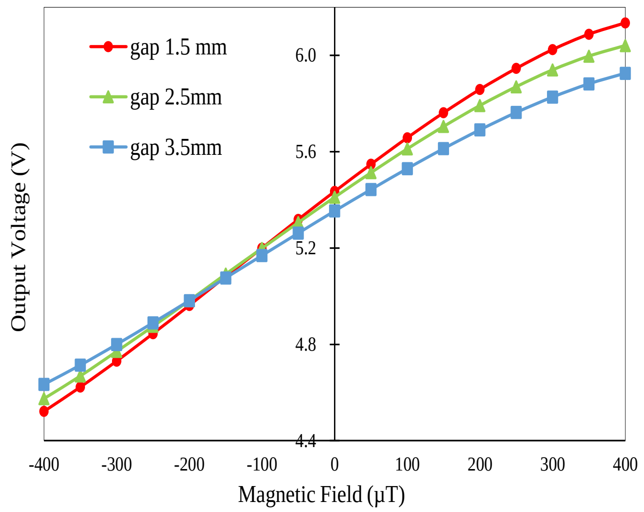


Fig.7. Magnetic response of the AMR sensor with different relative height.

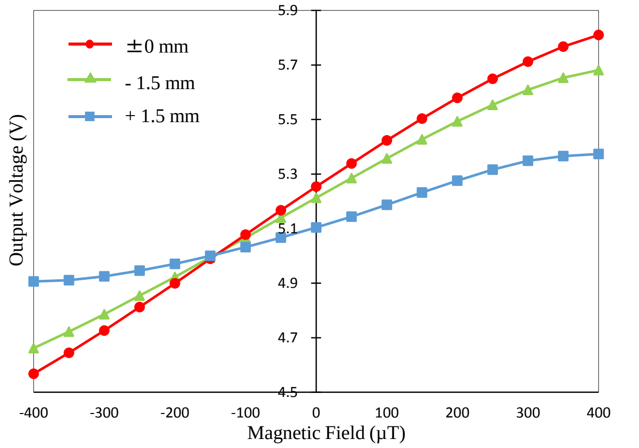


Fig.8. Magnetic response of the AMR sensor with different slit widths.

B. Change of relative height

Figure 7 shows the relative height dependence of the magnetic response of the AMR sensor at liquid N_2 temperature. According to Fig. 7, the slope of the linear region varied with each relative height (±0 mm, +1.5 mm, −1.5 mm). This result shows that the magnetic sensitivity can be controlled by changing the relative height. It is assumed that the sensing part of the AMR sensor is closest to the two HTS plates when the relative height is ±0 mm. Therefore, at ±0 mm, the slope of the linear region was the largest and the magnetic sensitivity had its highest value of 1.67 mV/μT.

C. Change in slit width of HTS plates

Figure 8 shows the magnetic sensitivity of the AMR sensor with different slit widths of the HTS plates at liquid N_2 temperature. In this measurement, the relative height of the AMR sensor was kept at ±0 mm because we obtained the highest sensitivity at ±0 mm for the optimization of the relative height. According to Fig. 8, the slope of the linear region varied with each slit width (1.5 mm, 2.5 mm, 3.5 mm). This result shows that the magnetic sensitivity can be controlled by changing the slit width. The sensitivity had the highest value of 2.11 mV/μT when the slit width was the narrowest (1.5 mm). This is because the narrower the slit width, the larger is the magnetic flux density inside the slit.

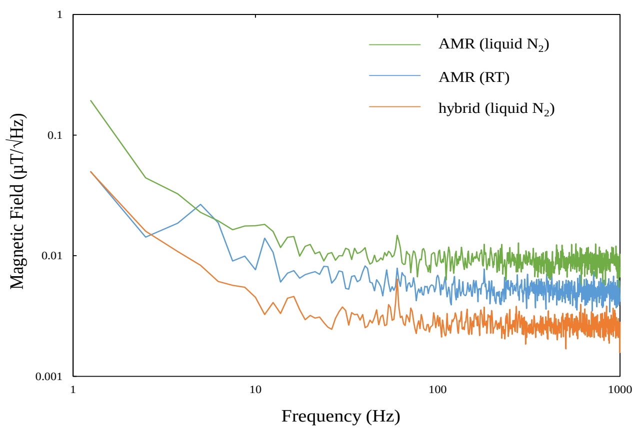


Fig.9. Noise characteristic of the AMR sensor.

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 7, January 2018

D. Noise characteristics

The magnetic resolution of the AMR sensor without HTS plates and with HTS plates (i.e., hybrid magnetic sensor) were evaluated at liquid N_2 temperature, as shown in Fig. 9. In this measurement, for the hybrid magnetic sensor, we set the relative height as ±0 mm and slit width as 1.5 mm because the magnetic sensitivity was the highest under these conditions. It is assumed that the thermal noise decreased when operating the AMR sensor at liquid N_2 temperature. However, because the output of the AMR sensor comes from the output voltage, the electrical resistance of the ferromagnetic thin film decreased upon cooling, and this led to a decrease in the output of the AMR sensor. This is because the magnetic resolution of the AMR sensor at liquid N_2 temperature (10.8 nT/$\sqrt{}$Hz at 100 Hz) was lower than that at RT (6.6 nT/$\sqrt{}$Hz at 100 Hz), as can be seen from the higher noise spectral density. Conversely, although the noise characteristics of the AMR sensor worsened, the magnetic resolution of the hybrid magnetic sensor (2.6 nT/$\sqrt{}$Hz at 100 Hz) was improved overall because the magnetic sensitivity of the AMR sensor was improved by the magnetic focusing effect.

IV. CONCLUSION

Although the magnetic sensitivity of the AMR sensor without HTS plates worsened at liquid N_2 temperature, we could improve the magnetic sensitivity of the AMR sensor by combining it with HTS magnetic-focusing plates and control the performance of the AMR sensor by changing the positional relation between the AMR sensor and the HTS plates.

This study is a preliminary trial of improving sensitivity of AMR sensor using magnetic focusing method with superconductor. It is speculated that higher sensitivity will be achieved via the change of size or shape of HTS plates.

ACKNOWLEDGMENT

This work was supported by the Council for Science, Technology and Innovation and Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management (funding agency: JST).

REFERENCES

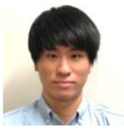
[1] J. Clarke and A. I. Braginski, The SQUID Handbook, Wiley-Vch Verlag GmbH&Co. KGaA, Weinheim, 2004.

[2] S. Adachi, K. Hata, T. Sugano, H. Wakana, T. Hato, Y. Tarutani, and K. Tanabe, "Preparation of multilayer films for integrated high-Tc SQUIDs with ramp-edge Josephson junctions," Physica C, vol. 468, pp.1936-1941, 2008.

[3] R. Kotitz, H. Matz, L. Trahms, H. Koch, W. Weitschies, T. Rheinlander, W. Semmler, and T. Bunte, "SQUID based remanence measurements for immunoassays," IEEE Trans. Appl. Supercond., vol. 7, pp. 3678-3681, 1997.

[4] K. Tsukada, Y. Haga, K. Morita, N. Song, K. Sakai, T. Kiwa, and W. Cheng, "Detection of inner corrosion of steel construction using magnetic resistance sensor and magnetic spectroscopy analysis," IEEE Trans. Magn., vol. 52, 6201504, 2016.

AUTHOR BIOGRAPHY



Tetsuro Hirata received the B.S. degree from Okayama University in 2017. He is a currently graduate student in the Graduate School of Natural Science and Technology, Okayama University, Japan. His subject includes magnetic measurement system.

Yoshihiro Nakamura received the B.S. degree from Okayama University in 2016. He is a currently graduate student in the Graduate School of Natural Science and Technology, Okayama University, Japan. His subject includes magnetic measurement system.

Yatsuse Majima received the B.S. degree from Okayama University in 2016. He is a currently graduate student in the Graduate School of Natural Science and Technology, Okayama University, Japan. His subject includes magnetic measurement system.

Kaoru Amano received the B.S. degree from Okayama University in 2016. He is a currently graduate student in the Graduate School of Natural Science and Technology, Okayama University, Japan. His subject includes magnetic measurement system.

Kenji Sakai received Dr. Eng. degree from Doshisha University in 2010. After that, he was a Research Fellow of the JSPS at Doshisha University. He is currently an assistant professor of Okayama University. He is now involved in the research of magnetic sensor and SQUID devices and their applications, non-destructive evaluation system, and gas sensor.

Toshihiko Kiwa received Dr. Eng. degree from Osaka University in 2003. After that he worked for one year as a JSPS fellow at the Research Center for Sueprconductor Photonics, Osaka University, where he was involved in the development of terahertz and superconductor devices. Currently, he is an associate professor of Graduate school of natural science and technology, Okayama University. His research interests include chemical sensors, magnetometric sensors, and terahertz devices.

Keiji Tsukada received Dr. Eng. and the Ph. Dr. degrees from Tsukuba University in 1990, and 2001, respectively. He joined the Central Research Laboratory, Hitachi Ltd. in 1982, where he was involved in the study of integrated solid-state chemical sensor for blood analyses. He was with the Superconducting Sensor Laboratory from 1991-1996. He was involved in the research and development of SQUID's and multichannel SQUID system. He was with the Central Research Laboratory, Hitachi Ltd. from 1996-2003. He was a Project Leader of the SQUID application research group. He is presently a Professor of Department of Electrical and Electronic Engineering, Okayama University. He is involved in the research of chemical sensor, magnetic sensor and superconducting sensor devices, and their applications.