Reserch Report

Thin Film Magnetic Field Sensor Utilizing Magneto Impedance Effect

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Abstract

Recently, a magneto impedance effect found in amorphous wires with soft magnetic properties has been noted as a new principle in the sensing magnetic field. According to this effect, the impedance of the wire in the range of high frequencies over 10 MHz changes remarkably with an external magnetic field. This effect is expected to be promising for magnetic field sensors with high sensitivity. Therefore, we have attempted to introduce this effect into amorphous thin films to extend the application fields, and a novel thin film sensor sensitive to a small magnetic field based on the magneto impedance effect has been proposed. The sensor consists of two individual detecting elements with FeCoSiB/Cu/FeCoSiB multi-layers which forms a half bridge. The detecting element exhibits a large impedance change ratio of more than 100% when an external magnetic field is applied. By optimizing of the operating point via a bias field and processing the signal with a synchronous rectifier circuit, no hysteresis, good linearity and good stability even with temperature variation as well as high sensitivity in the sensor characteristics have been achieved. The variation in the sensor output with the temperature is largely reduced to one-third, compared to the conventional thin film sensor we developed previously. A detection resolution of 10^{-3} Oe order higher than those of any other conventional thin film sensors is obtained.

Keywords Magnetic sensor, Magnetic thin film, Multi-layer, Amorphous, Impedance

1. Introduction

Recently, micro-sized sensors with high sensitivity, quick response and low cost are strongly required for magnetic sensing systems such as high density recording systems or various automobile control systems. In order to meet such requirements, magneto-resistance (MR) sensors, giant magneto-resistance (GMR) sensors and fluxgate sensors have been studied energetically. However, further subjects were left for practical applications. On the other hand, it was found that the amorphous ferromagnetic wires such as FeCoSiB and CoSiB exhibited remarkable changes in impedance caused by an external magnetic field in the range of high frequency over 10 MHz[1-3]. This phenomenon has been called a magneto impedance effect since then and has been expected to be a promising effect for magnetic field sensors with high sensitivity. However, wire forms resulting in difficulty in the installation and the poor repeatability of magnetic properties have prevented the extension of application areas as magnetic sensors. Consequently, great efforts have been devoted to develop thin film magnetic field sensors utilizing the magneto impedance effect by many researchers in order to eliminate these problems [4, 5]. We have developed a new type of thin film detecting element sensitive to an external magnetic field by introducing a magneto impedance effect into a thin film previously [6-8]. We also have reported that the thin film element exhibited an impedance change ratio of over 100% even at a low frequency of 1 MHz compared to that in a conventional wire element, and it was capable of detecting a magnetic field with high sensitivity.

Generally no hysteresis, good linearity and good stability against temperature variation as well as high sensitivity are important for sensors in various practical applications. Therefore, this work describes improvements in these performances of the thin film detecting element and the magnetic field sensor with high detection resolution achieved by using this thin film detecting element.

2. Thin film MI element

2. 1 Configuration of MI element

A schematic drawing of the detecting element with FeCoSiB/Cu/FeCoSiB multilayers on the substrate is shown in **Fig. 1**. The detecting element is composed of an inner layer of a non magnetic material such as Cu with good conductivity and two outer layers of the amorphous soft ferromagnetic material such as FeCoSiB with zero magnetostriction. The thickness of the Cu layer is 3 μm and the width is 0.1mm. On the other hand, the thickness of the FeCoSiB layer is 2 μm and the width is 0.2 mm. The total size of the element is 10 mm by 2 mm. To enhance the magneto impedance effect, two ferromagnetic layers are deposited to sandwich the copper layer and to form a magnetically closed loop structure. Furthermore, a magnetic unidirectional anisotropy is established in the transverse direction of the upper and lower magnetic films.

The films were deposited on a substrate of Corning glass No.7059 using the RF-magnetron sputtering method. The pattern of the element was formed by locating a slit metal sheet mask on the glass during sputtering. A constant DC magnetic field of about 100 Oe was applied parallel to the film surface during the deposition to establish a unidirectional anisotropy in the magnetic thin films, and the magnitude of the anisotropy field in the magnetic thin film was 20 Oe. The easy axis was induced in the direction parallel to the applied field, and typical stripe domain patterns were confirmed on the magnetic thin film surface using the Bitter method. It was found that the FeCoSiB thin film has an amorphous structure based on X-ray diffraction patterns. After the detecting element was fabricated on the glass substrate, the chip was annealed under a DC magnetic field of 1k Oe at 280 °C in Ar gas atmosphere.

2. 2 Characteristics of MI element

Fig. 2 shows the typical impedance change in the detecting element at 1 MHz. When an external magnetic field was applied in the longitudinal direction of the element, the impedance changed

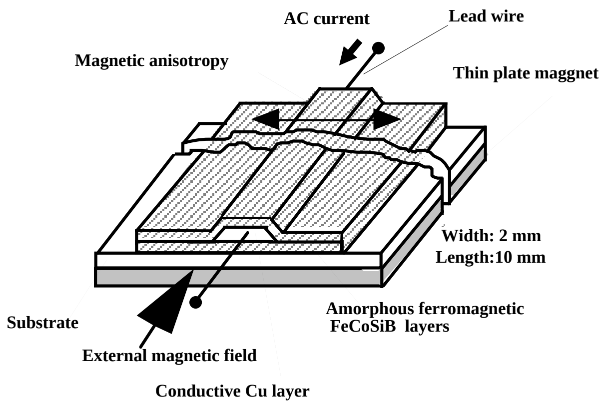


Fig. 1 Schematic drawing of thin film magnetic field detecting element.

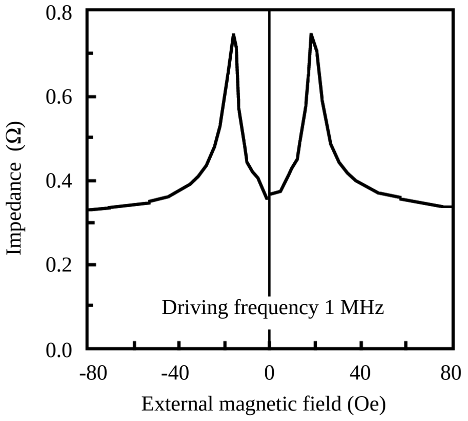


Fig. 2 Impedance change in detecting element versus external magnetic field.

remarkably due to the magneto impedance effect. The impedance change ratio is as high as 100%, and the maximum value of the impedance appears at a magnetic field of 20 Oe which is equal to the magnitude of the anisotropy field induced in the magnetic thin film. An interesting thing is that the detecting element shows the large impedance change even at a frequency of about 1 MHz much lower than that necessary for conventional wire detecting elements. The origin of the large change in impedance is based on the change in the AC permeability at 1 MHz caused by simultaneous magnetization in the upper and lower magnetic thin films. The change in impedance can be well explained in terms of the change in the AC permeability of the magnetic thin film in the transverse direction perpendicular to the applied magnetic field. The theoretical permeability calculated from the Landau-Lifshitz dynamic equation and the experimental one measured using a one-turn coil type of permeability meter are shown in **Fig. 3**. The two curves show profiles similar to the profile of the impedance change shown in Fig. 2. This result suggests that the behavior of the MI detecting element is dominated by the permeability in the magnetic thin film.

3. Magnetic sensor with thin film MI elemet

3. 1 Improvement in sensor performance

In this section, we focus on the improvement in the characteristics of the detecting element in terms of hysteresis, linearity and temperature dependence. Two interesting phenomena were observed and found helpful in the sensor performance improvement. First, the impedance of the detecting element can be divided into two components, the resistance and the inductance components. The dependence of resistance and inductance on the external magnetic field are shown in **Fig. 4**(a) and Fig. 4(b), respectively. The inductance component is related to the permeability of the magnetic thin film, and it is found that the inductance exhibits stable behavior without suffering from the influence of temperature variation, as shown in Fig. 4(b). Second, the profile of the inductance in the magnetic field range higher than 20 Oe (right side profile about peak) shows a significant difference from that in the range lower than 20 Oe (left side profile about peak). Generally the magnetization of magnetic material is caused by domain wall displacement and magnetization rotation. On the left side of the peak where the domain wall displacement is dominant,

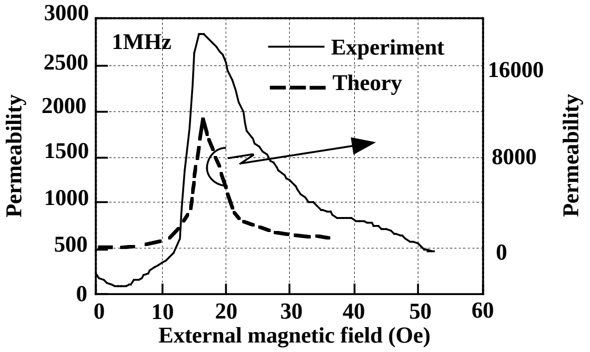
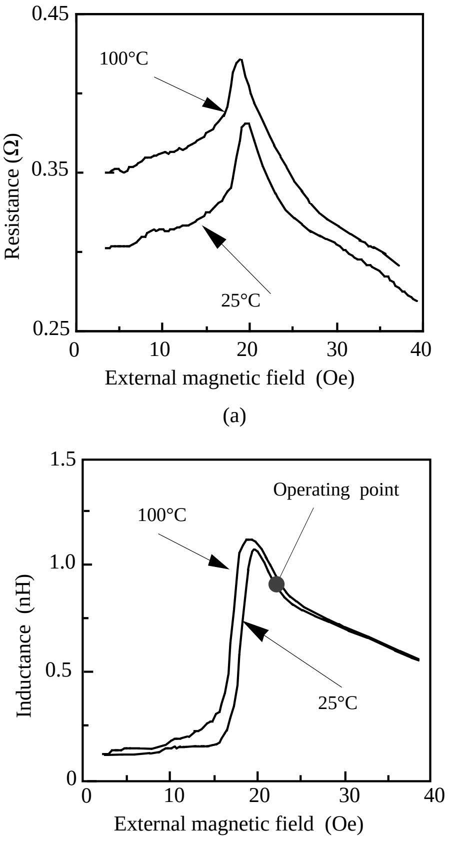


Fig. 3 Permeability of magnetic thin film versus external magnetic field.



(a)

(b)

Fig. 4 Characteristics of detecting element at 25°C and 100°C versus external magnetic field. (a) resistance component and (b) inductance component.

hysteresis, non-linearity and poor stability with temperature variation are exhibited. On the contrary, on the right side of the peak where the magnetization rotation is dominant, no hysteresis, good linearity and good stability are exhibited. Therefore, extracting of the inductance component from the impedance and shifting the operating point of the detecting element to the right side of the peak using a bias magnetic field as shown in Fig. 4(b) are effective in achieving good characteristics.

3. 2 Configuration of magnetic sensor

A thin plate FeCoCr metal permanent magnet was attached to the back side of the substrate to generate a bias magnetic field in the longitudinal direction of the magnetic films, as shown in Fig. 1. The magnitude of the bias magnetic field is optimized by adjusting the thickness of the thin plate permanent magnet so that high sensitivity and good linearity can be obtained. The optimum value was found to be 22 Oe, which could be obtained when the thickness of the thin plate permanent magnet was 50 μm.

Fig. 5 presents the schematic diagram of the developed magnetic field sensor and the processing circuit. To cancel the temperature dependence of the characteristics of the detecting element and obtain high detection resolution, a full bridge configuration consisting of two detecting elements and two resistances was adopted. An AC voltage with a driving frequency of 1 MHz is applied to the bridge. At a zero external magnetic field, the bridge is balanced electrically, and when an external magnetic field is applied to the individual detecting element, the bridge changes to an imbalance. The bridge output caused by the bridge imbalance is input to a synchronous rectifier circuit that extracts only the inductance component from the total impedance of the detecting element. Consequently, the output from the synchronous rectifier circuit provides the detecting signal corresponding to the external magnetic field.

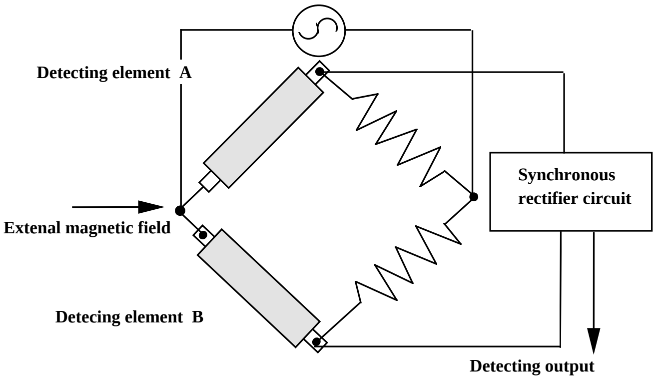


Fig. 5 Schematic diagram of sensor with bridge connection of individual elements, including circuit.

4. Results

4. 1 Characteristics of magnetic sensor

In the characteristic measurements, the sensor was fixed on a rotating stage as shown in **Fig. 6**. The terrestrial field, which is almost 0.3 Oe and is directed North, was used as the external field. When the stage is rotated, the magnitude of the field applied to the sensor changes sinusoidally with the rotation angle. **Fig. 7** shows the sensor output as a function of the direction. When the sensor was rotated in the horizontal plane, the sensor output changed sinusoidally with good symmetry. When the sensor was placed parallel to the northern direction, the applied magnetic field was the maximum value of about 0.3 Oe and the maximum sensor output appears. The sinusoidal decrease in

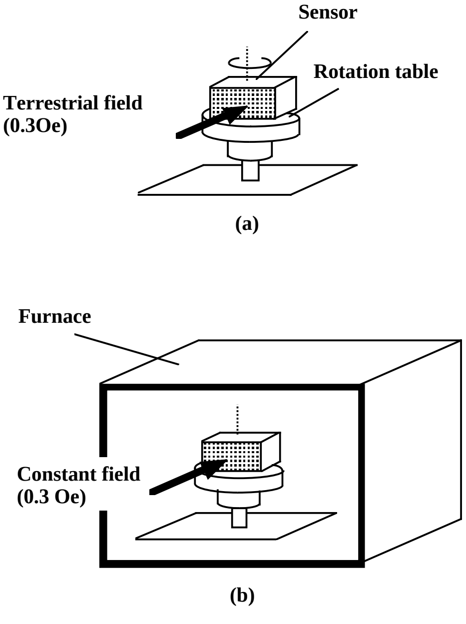


Fig. 6 Schematic illustration of the set up for measuring (a) output characteristics of sensor and (b) dependence of sensor outputs on temperature.

the sensor output was observed down to the minimum value at the southern direction where the applied field was -0.3 Oe. The symmetric sinusoidal behavior of the sensor output means that the characteristics of the sensor possess good linearity and no hysteresis, because it fits the symmetric sinusoidal variation of the terrestrial field with a rotation of the detecting direction in the horizontal plane. The noise level of the sensor output is shown in **Fig. 8**. The magnitude of the noise is about 60mV corresponding to about 9 m Oe. Thus the attained detection resolution of this sensor is approximately in the order of 10^{-3} Oe.

4. 2 Dependence of characteristics of sensor on temperature

The dependence of the sensor output on the temperature was measured by placing the sensor in a furnace and applying the external field of 0.3 Oe to the sensor. The ambient temperature in the furnace was varied from room temperature to 85°C. The sensor output was measured for applied fields of 0 Oe and 0.3 Oe. **Fig. 9** shows the dependence of the sensor output on the temperature. In this figure, the solid line is the sensor output at 0 Oe, while the broken line is that at 0.3 Oe. The gap between the solid line and the broken line corresponds to the change in the sensor output induced by the field of 0.3 Oe and can be regarded as the sensitivity of the sensor. The sensor output decreases gradually with the increase in the temperature, while the gap of the sensor outputs remains almost the same as 0.4 V in the range of room temperature to 85°C. This means that the sensitivity is maintained almost constant in the same range of temperature. The dependence of the outputs at zero field on temperature is plotted in **Fig. 10** for comparison with that of the single detecting element we developed previously. The variation in the sensor output with the temperature is reduced to one-third, compared to the single detecting element. The significant improvement in the temperature dependence is due to the cancellation of the output drifts by the bridge connection.

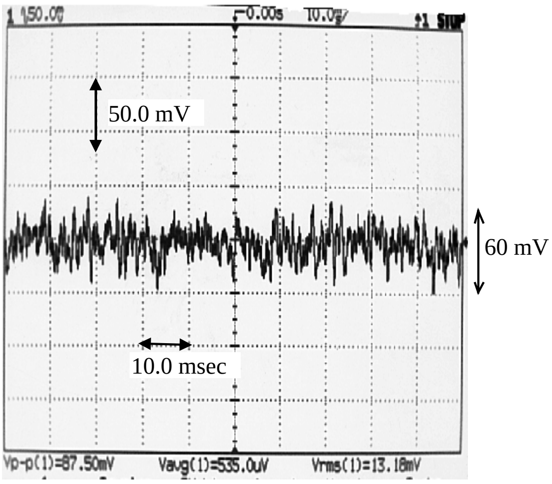


Fig. 8 Noise level in raw signal of sensor.

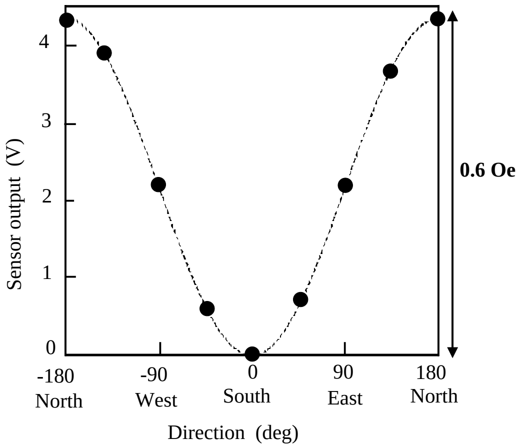


Fig. 7 Output characteristics of sensor versus applied field direction.

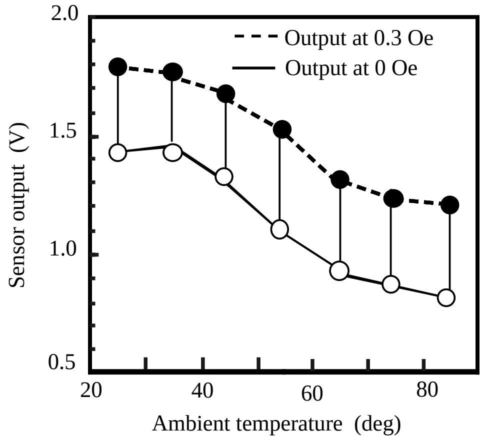


Fig. 9 Dependence of sensor output on temperature.

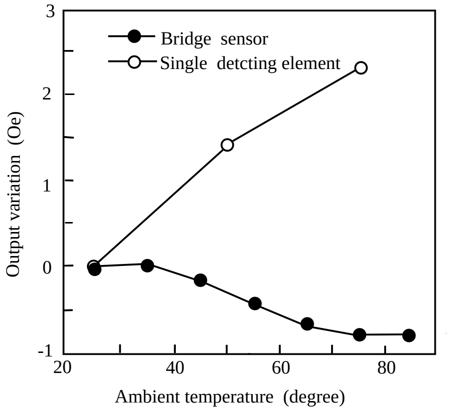


Fig. 10 Temperature dependence of outputs from bridge sensor and single detecting element at zero external magnetic field.

5. Conclusions

A new type of magnetic sensor has been developed using a thin permanent magnet plate to generate a bias field, a bridge connection of two individual elements and a synchronous rectifier to extract the inductance. This sensor is sensitive to a small field and is found to have no hysteresis, good linearity and good stability even with temperature variation as well as high sensitivity in the output characteristics. The attained detection resolution is in the order of 10^{-3} Oe and is higher than those of any other thin film magnetic field sensors such as a hall element and a magneto resistance element [9]. It will be useful for various applications such as direction, revolution and position sensing.

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