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Giant Magneto-Impedance Effect Microcurrent Sensor Based on MEMS Technology

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Giant Magneto-Impedance Effect Microcurrent Sensor Based on MEMS Technology

Siyuan Liu[1*], Tao Wang[1], Yufeng Luo[1]

[1]School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200444, China

[*]Corresponding author's e-mail: siyuan_liu@shu.edu.cn

Abstract. The performances of common magnetic sensors in the field of microcurrent detection are presented. The giant magneto-impedance (GMI) effect is summarized, and the possibility of picoampere microcurrent measurement using the GMI effect sensor is proved. The classical design scheme of the GMI effect current sensor is improved, and a GMI sensor chip model that can realize picoampere microcurrent measurement is preliminarily established, which lays a theoretical foundation for further development of GMI microcurrent sensor with high performance, small volume, and low cost.

1. Introduction

Microcurrent detection technology is a weak signal detection technology that can obtain target information by detecting the weak current of the target conductor. It has been widely used in the fields of military, nuclear engineering, aerospace, food safety, biomedicine, physics, chemistry, geology, magnetism, astronomy, and so on. For example, in the field of military, missile detectors are usually used to detect the running state of electric initiators on different parts of missiles. Since the electrical initiator is activated by current, small changes in current need to be accurately detected to prevent false activation during detection. In the field of nuclear engineering, self-sufficient energy detectors are usually used to control the power of nuclear reactors by monitoring neutron flux. As the output current of self-sufficient energy detectors will drop to a low level when the reactor power drops, a highly sensitive microcurrent sensor is needed to monitor the change of current. In the field of aerospace, in the space environment reliability test of satellites, space stations, and other spacecraft, the vacuum degree measurement needs to be realized by detecting the weak current from the microampere to the picoampere level. In the field of food safety, the detection of food components is often achieved by detecting the microcurrent in food. However, most of the current microcurrent detection devices use the contact current detection method. The contact current detection method is a method of estimating current by measuring parameters such as the voltage at a particular position in the circuit. The equipment using the contact method includes electrometers, picoammeters, etc. However, the signal circuit of such equipment is extremely complex, and the current flowing through the conductor for a long time not only causes continuous loss but also requires frequent calibration of the instrument [1]. The non-contact current detection method provides a new way to solve these problems. It is a method of measuring current indirectly by detecting signals such as magnetic fields generated by conductors with sensors. It has the advantages of strong anti-interference ability, simple circuit design, and low power consumption. The magnetic sensors commonly used in non-contact current detection are current transformers, Rogowski coils, Hall current sensors, fluxgate current sensors, and so on. Weigen Chen et al. [2] studied the measurement of microcurrent by the current transformer and realized the measurement of a 5 μA weak current by reducing the integral resistance. Pauline Verzele et al. [3] reported a Rogowski coil capable of measuring a weak current of less than 100 μA. Cosmin Cirstea et al. [4] constructed a microcurrent measurement system using two Hall current sensors and realized the measurement of μA level weak current. Nikolay Shtabel et al. [5] manufactured A fluxgate current sensor with amorphous nanometer soft magnetic material as core material and realized the measurement of a 10 μA weak current. However, the dynamic range of the current transformer is small, and the measurement accuracy is low. It is difficult to mass-produce Rogowski coils by the standard manufacturing process. Hall current sensor has low sensitivity and weak output signal. The preparation process of fluxgate current sensors is complex, and these problems limit the wide application of these traditional magnetic sensors in the field of non-contact microcurrent detection. The discovery of the GMI effect has made it possible to solve these problems. Compared with the traditional magnetic sensor, the GMI sensor has higher sensitivity (6500% / Oe), higher resolution (pT), and faster response speed (10 MHz). As shown in Table 1, the sensitivity, resolution, and response speed of the GMI sensors are almost ten times higher than the traditional magnetic sensors [6-9], which makes it has great potential applications in the field of microcurrent detection.

Table 1. Performance Comparison of Magnetic Sensors

Type	Sensitivity	Resolution	Response Speed
Hall	0.001 V/Oe	10^{-4} T	1 MHz
Fluxgate	1.462 V/Oe	10^{-11} T	5 kHz
GMR	0.028 V/Oe	10^{-5} T	1 MHz
GMI	10 V/Oe	10^{-12} T	10 MHz

2. Giant Magneto-Impedance Effect

The giant magneto-impedance (GMI) effect refers to that the alternating impedance of some materials will change rapidly with the applied axial magnetic field when alternating current is applied at a certain frequency. Figure 1 shows the commonly used measurement circuit for the GMI effect of soft magnetic alloy materials. U_s represents the alternating voltage source, R represents the standard resistance used to detect excitation current, I_{ac} represents the excitation current, U_{ac} represents the alternating voltage at both ends of the GMI sensitive material, and H_{ex} represents the applied magnetic field.

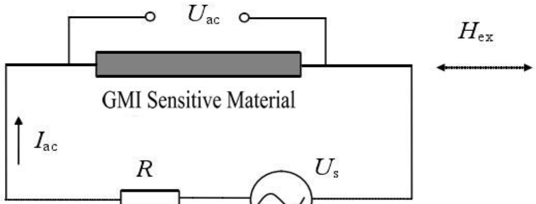

Figure 1. Common measurement circuit for the GMI effect of soft magnetic alloy materials

The GMI effect is usually expressed in terms of the GMI ratio, as shown in Equation (1). $Z(H_{ex})$ and $Z(H_{sa})$ represent the alternating impedance of materials with arbitrary external magnetic fields and saturated external magnetic fields, respectively[10].

$$GMI(\%) = \frac{\Delta Z}{Z}(\%) = \frac{Z(H_{ex}) - Z(H_{sa})}{Z(H_{sa})}(\%) \tag{1}$$

The magnetic field response sensitivity of the GMI effect can be expressed by Equation (2), where $FWHM$ represents the full width at half maximum [11]. That is, in a figure where the abscissa is the magnetic field and the ordinate is the GMI ratio, a line parallel to the horizontal coordinate axis is drawn through the midpoint of the peak height. The line intersects both sides of the peak at two points, which are separated by a distance of $FWHM$.

$$\xi(\%/Oe) = 2[GMI(\%)]_{max}/FWHM \tag{2}$$

In terms of working mechanism, the GMI effect is a form of electromagnetic effect. Under a weak magnetic field and at room temperature, the GMI effect sensor can achieve a magnetic field sensitivity of 10%-120%/Oe, which is one or even several orders of magnitude higher than the sensitivity of the traditional magnetic sensors. In addition, the GMI effect sensor also has the advantages of miniaturization, low power consumption, high-frequency response speed and no hysteresis. Therefore, the weak magnetic sensor made by the GMI effect makes up for the shortcomings of the traditional magnetic sensor.

3. Classic Design of GMI Effect Current Sensor

There are few current sensor designs based on the GMI effect. Figure 2 shows one of the most widely used designs.

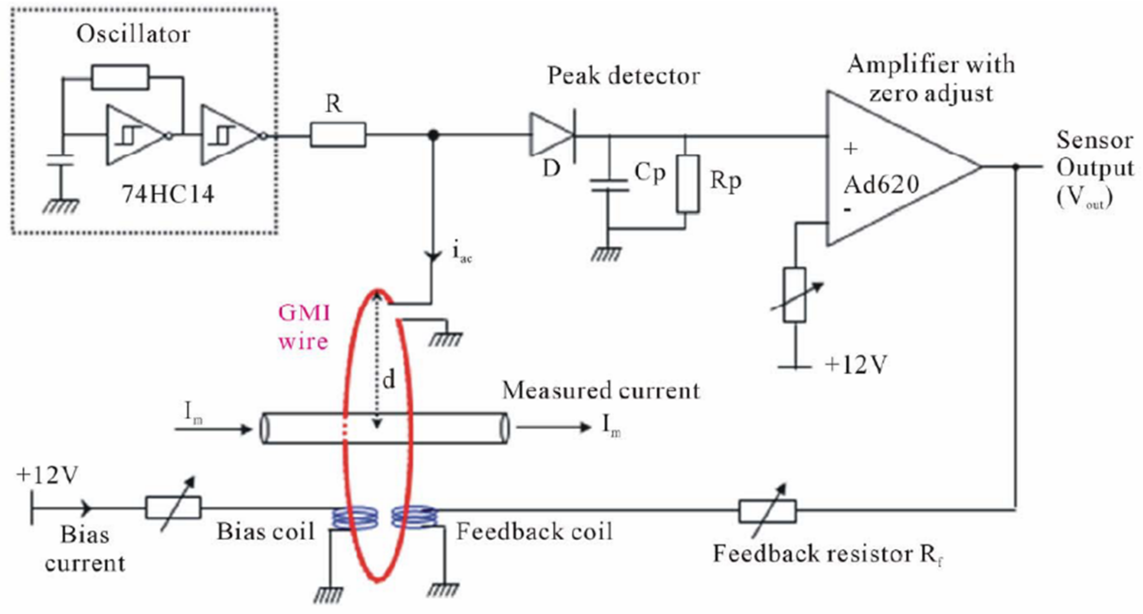

Figure 2. The classic design of GMI effect the current sensor

The design scheme was proposed by AkthamAsfour et al. [12], whose team designed a high dynamic range current sensor based on the GMI effect. The sensor uses a GMI sensing element with negative feedback. The sensing element is a cobalt-based amorphous filament with a diameter of 30 μm, shown in red in Figure 2. It is bent into a 2 cm diameter ring. The feedback coil and the bias coil are wound around the ring. The cylindrical conductor is passed through the center of the ring and is reattached to the central axis of the ring. The magnetic field generated by the conductor is applied to the GMI sensing element to obtain the asymmetric GMI effect. The circuit components mainly include an oscillator, a peak detector and an amplifier. In practice, the oscillator generates a high frequency square waveform, which is converted through the resistance R into a constant square waveform current (i_{ac}) and fed to the GMI element. The peak detector outputs a DC voltage proportional to the voltage amplitude of the GMI element. The DC voltage is output to the amplifier whose output can be measured by a voltmeter. The zero voltage of the amplifier output corresponds to the zero of the external magnetic field. The sensor realizes the measurement of DC and shows very good sensitivity and linearity. The response speed is fast. The linear error of the sensor is about 0.02%, the sensitivity is about 0.24V /A, and the dynamic range is up to ±40 A.

Similarly, R. Valenzuela et al. [13] used Co-Fe-Si-B amorphous wire to manufacture a GMI effect current sensor. The magnetic field applied by the solenoid valve causes the impedance change of the wire. The DC current can be measured indirectly according to the relation between the impedance and the magnetic field. Y.Wrheem et al. [14] built an asymmetric GMI effect current sensor. The sensor adopts annealed cobalt-based amorphous band as the sensor element, and its output voltage and input current have a highly linear dependence. The direction of current can be judged according to the asymmetry of the GMI effect.

Although the GMI effect sensor has many advantages such as miniaturization, no hysteresis, low power consumption, high sensitivity, high resolution, and fast response speed, there are few industrial achievements of the GMI effect current sensors. At present, the best GMI effect current sensor can only measure the current at the magnitude of μA (10^{-6} A). But theoretically, the magnetic induction intensity generated by a straight wire with pA (10^{-12} A) level weak current at the micron distance from the center of the circle is about pT (10^{-12} T) level, which belongs to the resolution range of the GMI sensor. AkthamAsfouret al. [15] analysed several influence factors that restrict the industrial application of the GMI current sensors were considered, including operating temperature, bending stress on the sensitive element, and the effect of magnetic disturbances. However, these factors can be circumvented by Micro-Electro-Mechanical-System (MEMS) technology. Therefore, the GMI effect sensor has the potential to realize the measurement of pA level microcurrent.

4. GMI Effect Microcurrent Sensor Based on MEMS Technology

For a planar current-carrying wire of any shape, the magnitude of the magnetic field at a point on the plane can be expressed by Equation (3), where θ represents the polar angle [16].

$$B = \frac{\mu_0 I}{4\pi} \oint_C \frac{d\theta}{r} \tag{3}$$

According to Equation (3), B is inversely proportional to r. In other words, the closer the conductor, the stronger the magnetic induction is. Combined with Equation (3), the analysis of the design scheme in Figure 2 shows that the resolution of the sensor can be further improved by shortening the distance between the current-carrying wire and the sensing element. The magnetic field resolution limit of GMI effect magnetic sensors is at the magnitude of pT (10^{-12} T), which is difficult to be further improved. Therefore, we assumed that the resolution of the sensor remains unchanged at the magnitude of pT. According to Equation (3), when I is at the magnitude of pA (10^{-12} A), the magnetic field generated at r = 1 μm is just at the magnitude of pT. In other words, pA-level microcurrent measurements are made by reducing the distance between the sensor element and the current-carrying conductor from 1 cm to 1 μm.

However, the ring with a radius of 1 μm is difficult to be bent by hand, and it is difficult to ensure that the current-carrying conductor and the central axis of the ring always coincide accurately after forming the ring. In the design scheme in Figure 2, the ring and the conductor are independent, and the relative position relationship is maintained by the support. This method is unreliable in the micro-distance measurement. Due to the existence of airflow, vibration, and other factors, there is still a possibility of relative movement between the ring and the conductor, which will lead to large measurement errors. To solve this problem, MEMS technology can be used to directly process the sensing element and current-carrying wire as a whole, that is, the GMI sensor chip can be directly processed by various micro-processing technologies such as electroplating, sputtering, and lithography. The proposed GMI sensor chip structure is shown in Figure 3, which theoretically can achieve accurate measurement of PA-magnitude microcurrent.

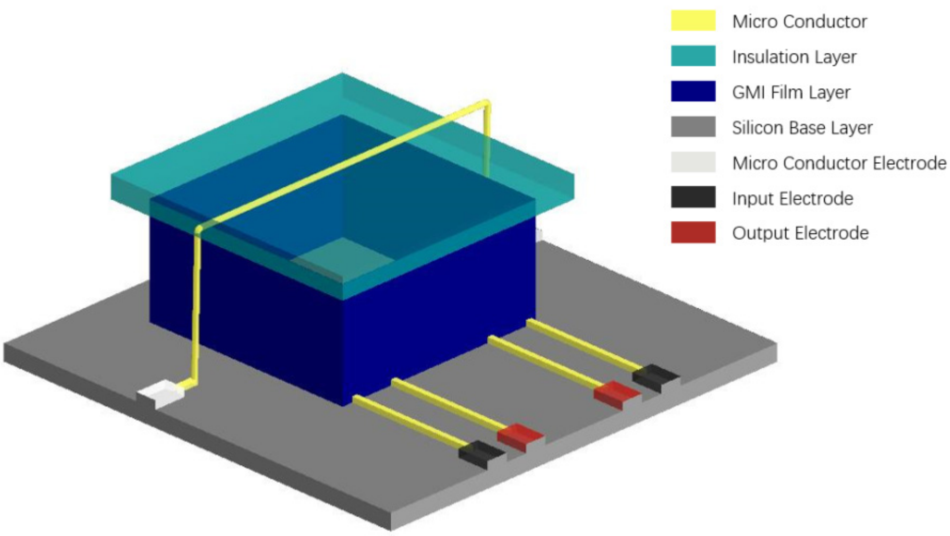

Figure 3. The GMI sensor chip manufactured by MEMS technology

The GMI film layer in Figure 3 is a kind of NiFe/Cu/NiFe sandwich film manufactured by MEMS technology. The GMI effect of the film has been studied in detail, and an impedance model has been established [17]. The difficulty in the design lies in how to realize the 1μm gap, and other structures can be realized by common MEMS processing technology. Considering that the conductor is too thin and may deform due to gravity and other factors, it is difficult to maintain the distance between itself and the GMI film layer as 1 μm everywhere. To prevent this from happening, a solid structure can be used to fill the 1 μm gap between the micro conductor and the GMI film layer to fully support the micro conductor. [18] provides us with a solution. Here, we can use MEMS sputtering technology to process an Al_2O_3 insulation layer with thickness of 1 μm between the micro conductor and the GMI film layer. Because of the non-contact magnetic field measurement of the sensor, Al_2O_3 material will not have any impact on the measurement.

In the actual measurement, the GMI microcurrent measurement module can be placed in a magnetic shield to eliminate the interference of the geomagnetic field and other external magnetic fields. The small size of the sensors based on MEMS technology significantly reduces the cost of magnetic shields. The micro conductor electrodes in the chip are connected to the pA level microcurrent source, and the input electrode and output electrode of the GMI film layer are respectively connected to the ac power source and the oscilloscope. When the microcurrent flows through the micro conductor, it can produce an annular magnetic field around the micro conductor, the magnetic field acts on the GMI film layer and leads to the change of its impedance. According to the impedance model of the chip [17], the value of microcurrent and impedance can be matched accurately, to realize the detection of picoampere-level microcurrent.

5. Conclusions

Compared with the traditional magnetic sensors, the GMI effect sensors have many advantages, such as miniaturization, no hysteresis, low power consumption, high sensitivity, high resolution, and fast response speed, which make them have great potential applications in the field of microcurrent detection. However, the existing GMI effect current sensors can only detect current at the magnitude of μA (10^{-6} A). The possibility of picoampere microcurrent measurement using the GMI effect sensor is proved in this paper. The classical design scheme of the GMI effect current sensor is improved, and a GMI sensor chip model that can realize pA (10^{-12} A) microcurrent measurement is preliminarily established, which lays a theoretical foundation for further development of GMI microcurrent sensor with high performance, small volume, and low cost.

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