High Spatial Resolution Non-contact Measurement of Low Current Signal by Needle-Type GMR Probe

Regular Paper

High Spatial Resolution Non-contact Measurement of Low Current Signal by Needle-Type GMR Probe

H. HOANG[*1], M. KAKIKAWA[*1], S. YAMADA[*1]

Miniaturization of electronic devices has making progress, resulting in smaller current flowing in extremely high-density LSI (large scale integration) or PCB (printed circuit board). However, measurements of such low local current have still been confronted with many difficulties because of the limitation on size of relatively large and cumbersome typical current sensors, lead to detecting general signals of a wide area. In this research, we propose the novel micron size and high sensitivity needle-type GMR probe in applications of non-contact measuring low currents coming from area narrower than 10^{-6} m^2 with small signal crosstalk such as PCB current measurement and low bio magnetic signal detection. Low current of hundreds μA in high-density PCB tracks of 4×10^{-4} m pitch was measured with the signal crosstalk less than 10% and 5×10^{-6} A of nerve signal model was possible to be detected by micron size GMR probe.

Keywords: giant magnetoresistive sensor, GMR, low current, high spatial resolution, PCB track, nerve signal model.
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1. Introduction

Detection and measurement of low current signals have been studied for years in medical as well as in industrial applications. Nowadays with the development of advanced technologies in industry, the miniaturization of electronic devices has made progress as well resulting in lower currents flowing in extremely dense LSI or PCB. Requirements of such low local current measurement for circuit operation testing, electromagnetic noise source and path investigation or simulation in circuit designs become more difficult [1].

Furthermore, in order to reduce the influences to circuit conditions, non-contact measurement is a practical method where relatively large and cumbersome magnetometers such as Hall sensor, Squids, current clamp, etc… are used for monitoring magnetic signals generated from the current sources. However, due to the limitation on size of those typical current sensors, relatively far distance away from the target objects is required resulting in general signals of a wide area.

In this research, we propose the possibility of the novel micron size and high sensitivity GMR probe to the applications in non-contact measurement of low current in extraordinarily narrow operating space (less than 10^{-6} m^2) with low signal crosstalk such as high-density PCB current measurement and low bio magnetic signal detection.

2. Low Current Measurement System

2.1 Novel Needle-type GMR Probe

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Fabricated GMR probe(shown in Fig. 1) with a needle consisting of miniature sensing element (40 ×40 μm) deposited only 8×10^{-6} m from the bottom edge at the tip allows it to be placed very close proximity (less than 10^{-4} m) to the current source.

The ceramic needle has a square cross-section of 400 × 400 μm and length of 0.03 m. The tip of the needle was cut in to U-shape to be easier for positioning. As a result, this type of probe is expected to be able to detect such high-density low current signals locally with high spatial resolution of 10^{-5} m order, which was considered to be difficult for the other conventional types of sensors.

Wheatstone bridge structure formed by two GMR elements and resistors helps miniaturizing thermal fluctuation due to low DC offset voltage. Another GMR element (GMR2) at the top of the needle composed with

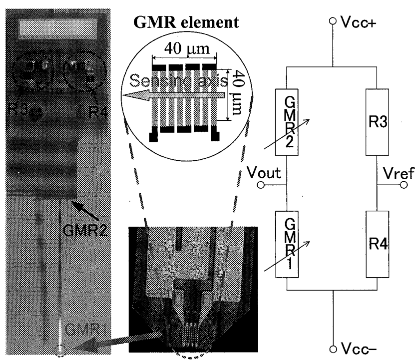

Fig. 1. Needle-type GMR probe.

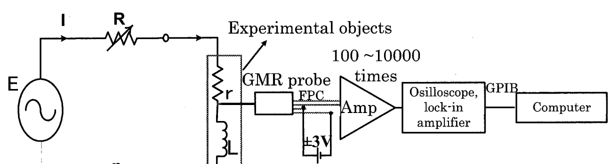

Fig. 2. Magnetic measurement system.

the sensing one(GMR1) giving differential output which results in the environmental magnetic noise canceling.

Extremely small size but high sensitivity and one sensing axis enable the probe to operate in confined and difficult to access spaces.

2.2 Low Current Measurement Set-up

Non-contact low current measurement system is demonstrated in Fig. 2. Low currents applied into experimental objects are produced by a considerably ideal low current source, which is supplied by function generator (WF 1974, NF) connected to 10^5 Ω resistors, in order to reduce unwanted noise from power supply. Output voltage of the probe is amplified 1000~5000 times by amplifier (CDV-700A, Kyowa) before being forwarded to either the digital oscilloscope (DS-5314, Iwatsu), which averaged the experimental data at about 256 times, or the very low noise lock-in amplifier (5610B, NF Electronics,). Additionally, micrometre is installed to adjust a lift-off height from the tip of needle to PCB surface, and video camera is installed for precisely detecting the x and y positions of the needle. Experiments were performed inside the shielding room to prevent undesirable magnetic noise.

3. Non-contact Low Current Measurement

3.1 PCB Track's Current Analysis

PCB is a ground plane consisting of dense printed wires and a lot of electronic components different from individual wires which requires a special structure device for its current measurement. Current measurement of dense printed wires on the PCB is suggested as high spatial resolution detectable ability of the GMR probe. Measured PCB tracks whose 2×10^{-4} m width and 4×10^{-4} m pitch are shown in Fig. 3.

Theoretical values of the magnetic flux density of the measured objects can be calculated by the following equation from law of Bio-Savart:

$$d\boldsymbol{B} = \frac{\mu I}{4\pi}\frac{d\boldsymbol{l}\times\boldsymbol{r}}{r^3} \qquad (1)$$

where $\boldsymbol{B}$ is magnetic flux density, product of I and $\boldsymbol{l}$ is current element, $\boldsymbol{r}$ is distance from the axis of wire to the target point.

$$B_{1y} = \frac{\mu I_1}{4\pi a_1}(\theta_1 - \theta_2) \qquad (2)$$

When thickness of the wire is considered to be extremely smaller than its width, Eq. (2) is derived from Eq. (1) [2].

As it is shown in Fig. 3 that in z direction, magnetic flux density generated by current in wire no.1, B_{1z}, is almost as high as magnetic density generated by current in wire no.2, B_{2z}; while in y direction, B_{1y} is definitely much higher than B_{2y}, as shown clearly in "Area 1" in Fig. 4.

This difference in amplitude of the two vectors B_z is bigger and bigger as the distance between measured point and PCB surface (the lift-off height) is smaller and smaller as shown in Fig. 5.

Lift-off height less than 10^{-4} m gives signal crosstalk less than 10 % while that more than 2 mm gives a high signal crosstalk up to nearly 100 %.

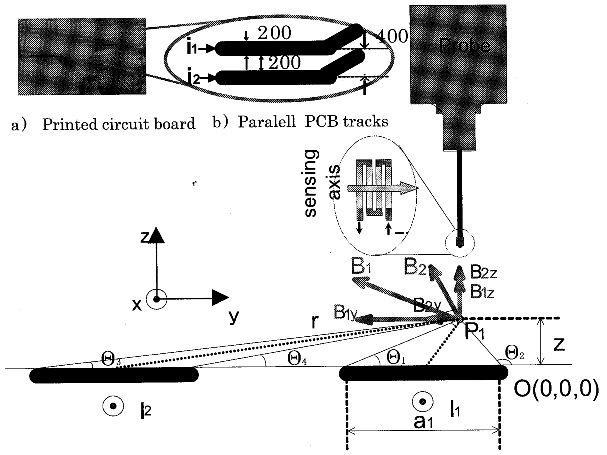

Fig. 3. Cross-section of the needle and magnetic flux density vector of PCB track's adjacency.

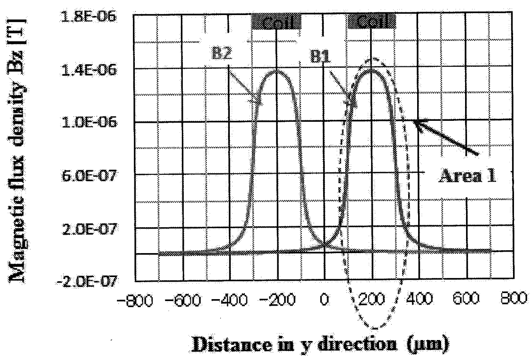

Fig. 4. Dependence on PW's width direction. (z = 20 μm, I = 0.5 m A)

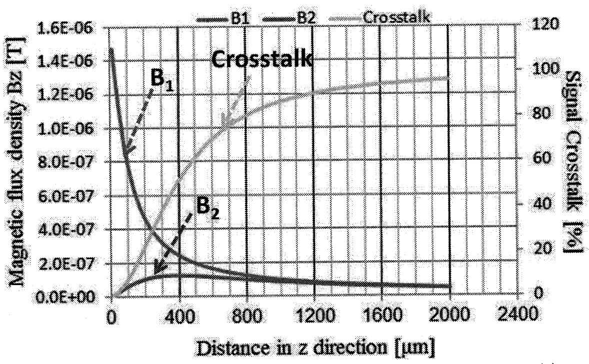

Fig. 5. Dependence on lift-off height. (I = 0.5 mA)

Taking into account of this, by using one-direction sensing probe whose ability to approach very close to the PCB surface is superior, low current measurement of individual PCB track became possible.

3.2 PCB Track's Current Measurement

Low current of $10^{-4} \sim 10^{-3}$ A at 10^5 Hz was applied to PCB tracks. Experimental data were received from the lock-in amplifier. The probe was placed expectedly perpendicular to the PCB plane and positioned just above the target track (no.1) while lift-off height (distance in z direction from the PCB conductor to GMR sensing element) was set to 2×10^{-5} m as the probe tip is touch the PCB surface. Here we consider the solder resist on the PCB track conductor is approximate 10^{-5} m. Experimental result shown in Fig. 6 indicates that the output voltage of the probe is proportional to input current of the target PCB track. The signal crosstalk achieved was about 5 %~10 %.

The spatial distribution of magnetic flux density generated by two PCB currents depends on track's width direction (y direction) was obviously observed from Fig. 7. Currents of 5×10^{-4} A were input separately into two tracks at 10^5 Hz.

In the performed experiment, GMR probe was precisely moved along the horizontal y axis in 5×10^{-5} m steps when lift-off height was adjusted to be constant at 2×10^{-5} m. The amplitude of output signals displayed was after the AC offset voltage subtraction.

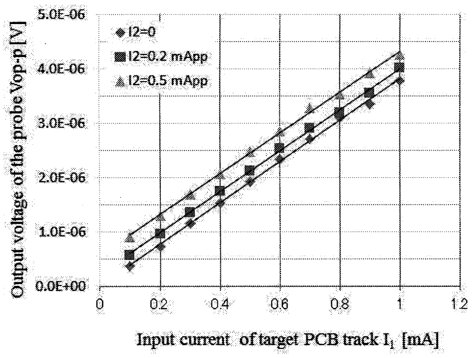

Fig. 6. Proportional relation and signal crosstalk.

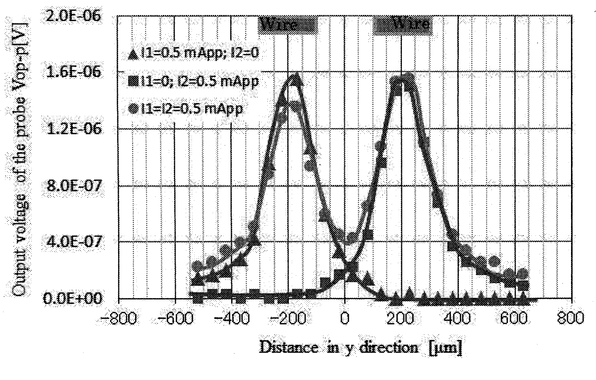

Fig. 7. Magnetic field distribution of the PCB tracks.

Monitoring PCB tracks when one by one current input gave almost the same spatial distribution of the two. In contrast, when two currents were applied simultaneously, slight difference was found between the peak amplitudes due to unexpected incline of the probe toward the PCB surface.

Consequently, magnetic field distribution of currents in high density PCB tracks had been performed by the GMR probe with scanning steps as small as 5×10^{-5} m and lift-off height of 2×10^{-5} m.

In Figs. 8, 9 and 10, some examples of output signal waveforms were displayed. The probe tip was set over wire No. 1. Both sinusoid and square current signals of different frequencies ($10^3 \sim 10^5$ Hz) were detected by the probe. When currents in both tracks were applied at the same time, the output signal was the same frequency with the target input signal without phase difference as shown in Figs. 8 and 9.

Although the current flowing in adjacent track has the amplitude twice bigger than that in the target track, only ignorable small disturbance could be seen from the output signal. At frequency of 10^5 Hz, phase delay of about 30° occurred but still observed sinusoid wave.

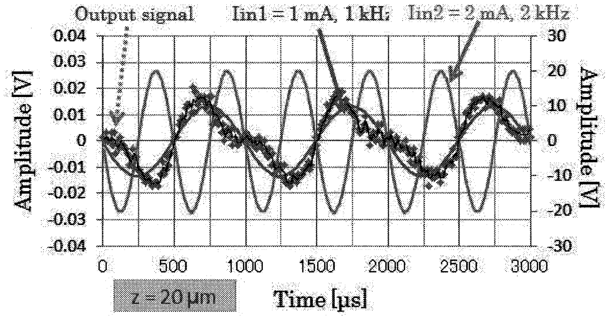

Fig. 8. Detected sinusoid signal waveform. (z = 20 μm)

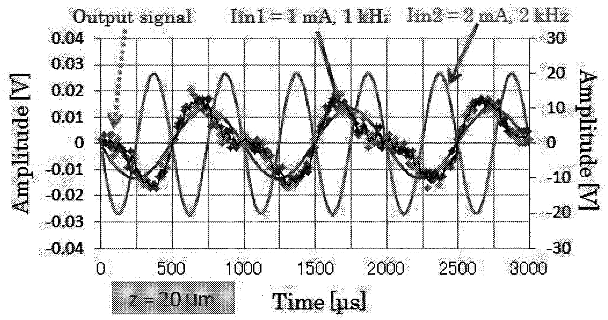

Fig. 9. Detected square signal waveform. (z = 20 μm)

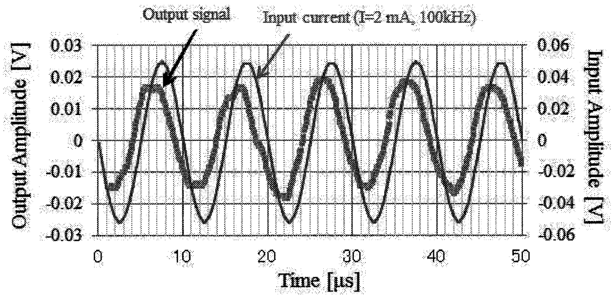

Fig. 10. Detected signal waveform. (z = 20 μm)

3.3 Nerve Signal Model's Current Measurement

Additionally, we propose a model of nerve signals propagation for extremely low current signals as one example of applications in bio magnetic fields detecting, which minimal invasive measurement is required or operations using large size magnetometers are difficult. For this low level local current detection, distance between the sensing element and the measured objects is required to be as small as possible, resulting in the possibility of giving a larger output signal [3,4].

Many research from early days on nerve signal discovered that when the nerve is stimulated, the action potential consisting of depolarization and repolarization occurs and be propagated along axon. This nerve signal propagating process can be assumed as the chain of two current dipoles in opposite directions flowing in nerve axon as shown in Fig. 11 [4-6]. The peak action currents are about $5\times10^{-6}\sim10\times10^{-6}$ A [6-7].

Considering characteristics of nerve axon as well as its action current, we developed a nerve model which is a wire of 2×10^{-5} m diameter knitted into holes of 2×10^{-4} m diameter on a silicon plate (wire is indicated as the black broken line, while s is the diameter of the hole in Fig. 12). d is the thickness of the silicon plate, l is the distance between holes and y_0 is lift-off height. When current I is applied into the wire, current dipoles in alternately opposite directions were generated.

Action current was modelled by a rectangular current (20 % duty, 10^3 Hz) and amplitude in order of few 10^{-6} Ap-ps supplied to the nerve model. This field is detected by the micro size GMR probe which is placed in a distance of about 2×10^{-5} m from the nerve model. Low magnetic flux density of approximate 3×10^{-8} T was detected with the pulse input current as small as 5×10^{-6} A, shown in Fig. 13.

Agreeing quite well with the theoretical calculation, experimental results show that the magnetic flux density is highest at the middle of current dipole and decreases at the area between the two opposite current dipoles (area around the holes) because the cancelling of flux density vector.

4. Conclusion

Experimental results demonstrated that low current measurement of PCB tracks of about 2×10^{-4} m width and 4×10^{-4} m with signal crosstalk less than 10% was materialized. Furthermore, magnetic field of few 10^{-8} T generated by current signals as small as 5×10^{-6} A order can be detected with the spatial resolution of few 10^{-5} m.

Therefore, take into account of the experimental results, we can point out that our extremely small size and specific construction of novel needle type GMR probe is a super tool in proposed high spatial resolution non-contact measurement of small current.

The GMR sensor has the advantages of a wide range frequency from DC to GHz of GMR element and instinct noise of less than 10^{-8} V/√Hz, so with the improvement of measurement circuit (cables, low noise amplifier, etc.), PCB track's low current at high frequency up to MHz is expected to be possible to measure.

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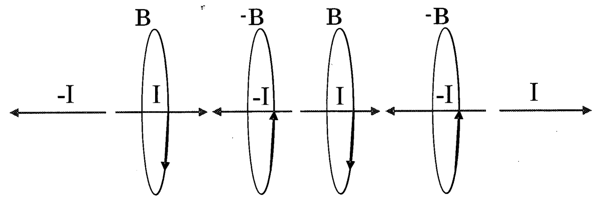

Fig. 11. Nerve signal propagation.

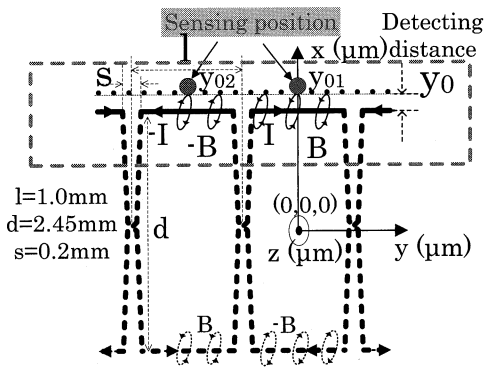

Fig. 12. Nerve signal modelling.

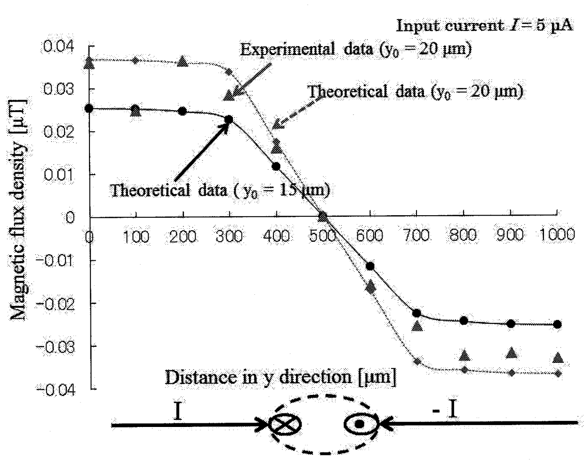

Fig. 13. Current measurement of nerve model.

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