Detection of Magnetic Field Distribution from Nerve Action Model With Needle Type SV-GMR Sensor

学術論文

Detection of Magnetic Field Distribution from Nerve Action Model With Needle Type SV-GMR Sensor

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Measurements of magnetic fields from nervous cells can transpire to be significant in not only diagnostics but also treatment of neurological diseases. The sensor for nerve magnetic field measurements must be capable of detecting very low signals in order of Pico/Femto Tesla and the measurements must be as non-invasive as possible. For this purpose needle type spin valve giant magnetoresistance (SV-GMR) sensor was fabricated. Thin wire of 15 μm radius with supplied pulse wave was used as a model of the nerve. External magnetic field created by current pulses in the nerve model can be measured by touching the needle of the sensor to the model. The proposed sensor is much easier and better adjustable to surgical conditions than so far suggested measuring techniques utilizing super conducting quantum interference devices (SQUIDs). Experiments show that pulse signals as low as 1 μA can be measured.

Keywords: nerve action, field distribution from nerve, GMR sensor, nerve model.

1 Introduction

The brand new idea of needle-type sensor of very small magnetic fields is highly likely to pave the way for innovative diagnostic and treatment techniques in medicine. The magnetic flux density created by human body cells and organs are almost on the verge of detectability for up-to-date sensors, in the region of nano, pico and femtotesla [1,2]. Diseases of the central and peripheral nervous sytem or neurogical disorders are critical for the patient in most cases.

Some of the common disorders/syndromes of the nervous system are Alzheimer disease, Huntington disease, Weber syndrome, Parkinson disease, Wilson disease and multiple sclerosis amongst many others. The magnetic fields used for treatment of various diseases have to be chosen carefully and are mostly small in order to treat and not to jeopardize patient's health [3]. Furthermore, operating in the living organism presents a lot of difficulties [4]. The measurements have to be very accurate, low-invasive, uncomplicated and convenient for surgeon and finally inexpensive.

The sensor presented in this paper seems to fulfill the imposed expectations. Small and light probe is tipped with micro meters thin, ceramic needle. The SV-GMR sensing element is placed on tip of the needle [5].

SV-GMR sensors are a newly introduced technique of measuring small magnetic fields. They are highly sensitive and accurate. What is more, the equipment necessary to process, read out and interpret the output signals from the probe is not very complicated or expensive. The needle is easy to use. The measurements can be conducted in real time.

The above paper presents one of the potential applications of the needle-type SV-GMR sensor which is neurological measurement of nerve action potentials in nervous cells.

The measuring techniques utilizing SQUIDs [6-8] or low-noise, low input impedance amplifiers that were suggested so far, are able to detect low nerve magnetic fields. However, non-invasive SQUIDs mostly measure compound action currents of the whole nerve (neuron bundles) and roughly estimate the currents [7]. This would be useful maybe in nerve reconstruction. Needle-type SV-GMR sensor on the other hand has the potential to measure the magnetic field of a single axon and is much easier and convenient in application. The idea is to touch the sensor's thin needle to a lateral surface of an axon of a nervous cell. SV-GMR sensor used in our experiment can detect magnetic fields with sensitivity of 12.5 μV/μT and maximum resistance change of 15-20 % [9].

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2 Background and methodology

Nervous cells in living organisms are transmitters of electrical signals. They conduct action potentials from dendrites through long axon to other neurons as shown in Fig. 1. Typically, nerve diameter may vary from 1 – 20 μm, for type C fibers even lower [10]. Action impulse travels along the nerve at speeds of 0.6 – 120 m/s. Action current is not higher than 1 μA.

Signals are traveling along neurons as waves of electrical discharge with frequency of about 1 kHz [10]. According to the above mentioned features long axon can be modeled as a thin wire with pulse signals of 1 kHz supplied to it. Magnetic field created around long thin conductor can be measured with sensor placed in the proximity to the wire's lateral surface. Fig. 2 shows the idea of such measurement.

Magnetic field originating from current flowing in a long thin conductor can be calculated by the following equation, derived from Ampere's law:

$$B = \mu \frac{I}{2\pi r} \tag{1}$$

where: I – current flowing in the wire [A],
r – distance from centre of the wire [m],
μ – magnetic permeability [H/m],
B – magnetic flux density [T].

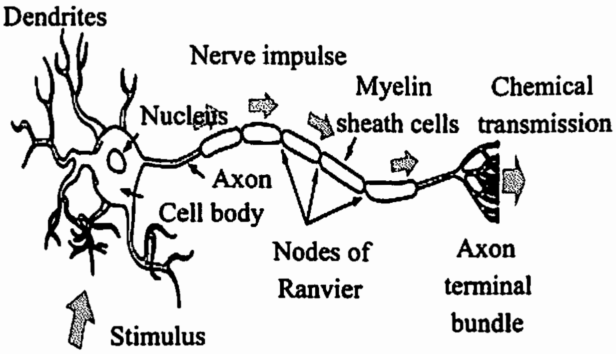


Fig. 1. Structure of nervous cell.

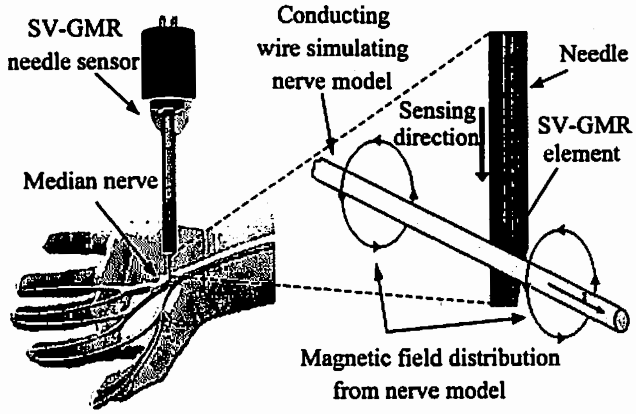


Fig. 2. Measurement of action currents in nerve model.

3 Description of the model.

3.1 Sensor

The needle-type GMR sensor was fabricated especially, for biological measurements [5,9]. The needle can be easily injected in to a body and touched to an axon's lateral surface. Fig. 3 shows the structure of the probe. The GMR element, with sensing area of 75 μm × 40 μm, is placed on the tip of the needle. The size of the needle of 15 mm is especially designed to be minimally invasive in potential medical applications.

The sensing direction is parallel to the needle. Fig. 4 illustrates the sensitivity of the SV-GMR element in all directions. SV-GMR probe is supplied with constant current of 5 mA. Sensitivity of the

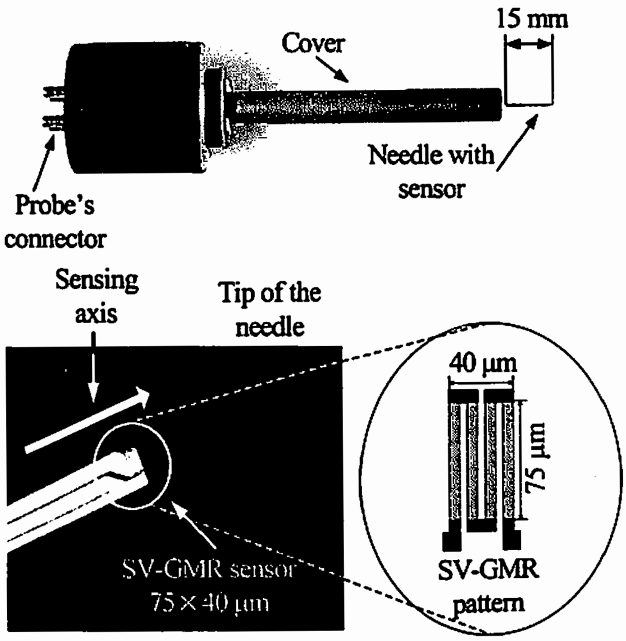


Fig. 3. Needle-type SV-GMR sensor structure.

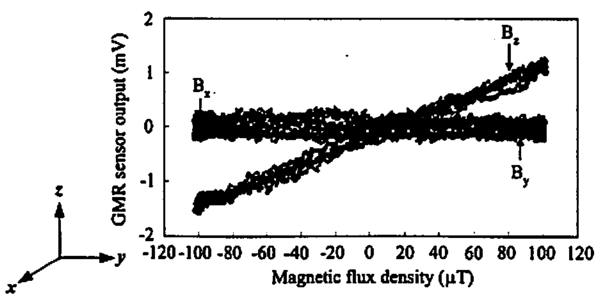


Fig. 4. Small signal characteristics of the SV-GMR sensor at 1 kHz in all directions.

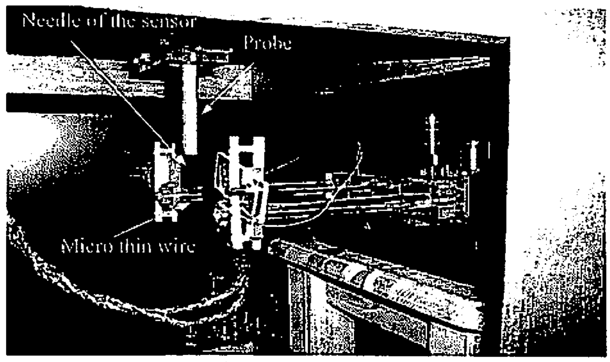


Fig. 6. Experimental setup.

SV-GMR element is 12.5 μV/μT. Normal resistance of the sensor is 1.3 kΩ, bias current amounts to 0.4 mA.

3.2 Experimental setup

As a model of the nerve thin wire of 15 μm radius was applied. The wire was supplied with action current resembling signal appearing in real neurons. Action current was modeled as a pulse signal with 10 % duty cycle at frequency of 1 kHz as shown in Fig. 5.

Fig. 6 shows the actual experimental setup used for obtaining results. Needle-type SV-GMR sensor touches the micro thin model of the nerve placed in non magnetic yokes. Output signal from the probe was amplified 1000 times before forwarding it to oscilloscope or locking amplifier. Oscilloscope was used for measurements of pulse signals as low as 1 μA. For signals lower than 1 μA sine wave was supplied and locking amplifier was applied.

Configuration of the circuit is presented in Fig. 7.

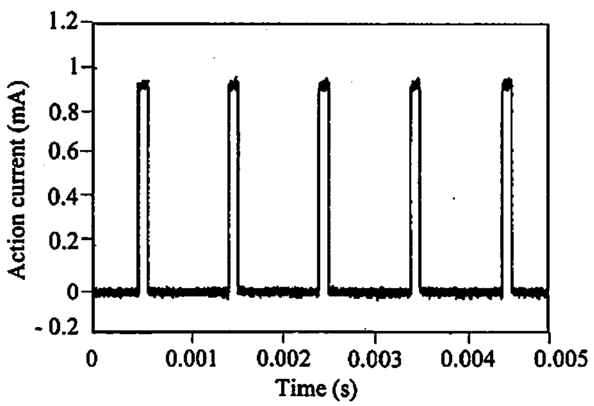


Fig. 5. Action signal of 1 kHz frequency used in the experiment.

The SV-GMR sensor has a bridge circuit design. There is a SV-GMR sensing element at the tip of the needle. The tip of the needle touches the thin wire during experiments. Amplification was implemented with use of precision instrumentation amplifier AD524 of a very low noise. During experimentation a gain of 1000 was employed to analyze the output signal that is obtained by the needle-type SV-GMR sensor.

All equipment was placed in a shielded area. Due to high sensitivity the SV-GMR sensor can easily detect other undesirable signals (noise). The shielding room used for experimentation was magnetically and electrically shielded. The attenuation of noise signals of frequency over 120 Hz is 1/100.

4 Measurement's results

4.1 Basic measurements

The measured signal can be observed in a form of pulse wave. The amplitude of the pulse is proportional to the measured magnetic field. Pulse output is in phase with input action current. Signal for supplied 400 μA is illustrated in Fig. 8. In spite of using additional shielding the output contains quite a lot of noise. Hence, multi-signal averaging technique of at least 128 times was applied.

The characteristics can be obtained by estimating the amplitudes of output signals versus input current. Comparing the above mentioned characteristic with the theoretically calculated values of magnetic flux density for the same values of current, we observe that

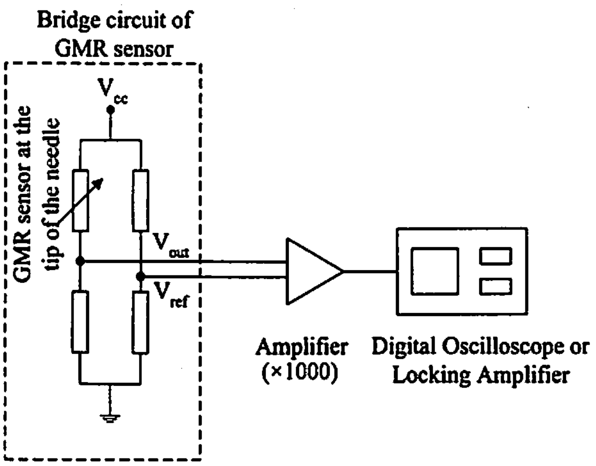


Fig. 7. Configuration of test circuit.

both plots are linear and parallel to each other. This is shown in logarithmic plot in Fig. 9. To distinguish lower signals and estimate their amplitudes higher averaging is necessary. This is due to a relatively greater noise level. Averaging of 2048 times was applied for signals lower than 50 μA and 4096 for signals not higher than 10 μA.

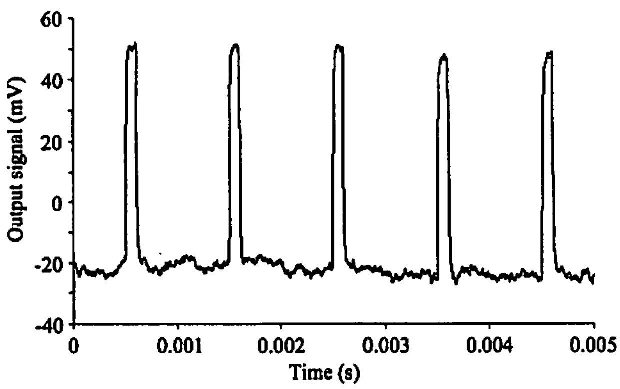


Fig. 8. Output signal with averaging of 128 times for action current of 400 μA.

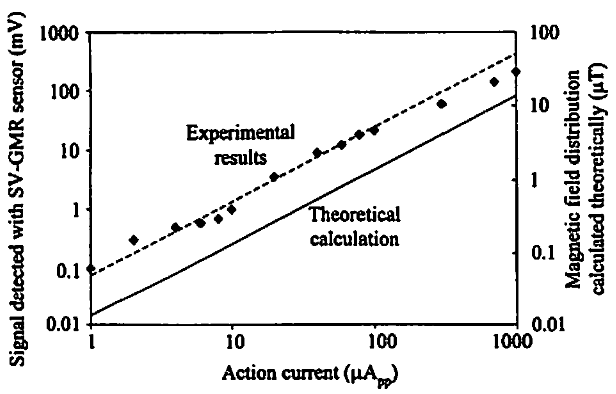


Fig. 9. Detected signal and calculated magnetic flux density versus action current.

4.2 Measurement distance

Detection of modeled nerve action currents with bare eye transpired to be quite difficult considering micro sizes of the wire and SV-GMR sensor on the needle. That is why further measurements were conducted. The purpose was to find in what distance of the nerve model from the sensing element the signal is still recognizable. First, the detectability was checked in vertical and horizontal direction.

Fig. 10 shows the situation where the nerve is moved in the vertical and horizontal direction. In this case r, with reference to Eq. (1), is calculated as follows:

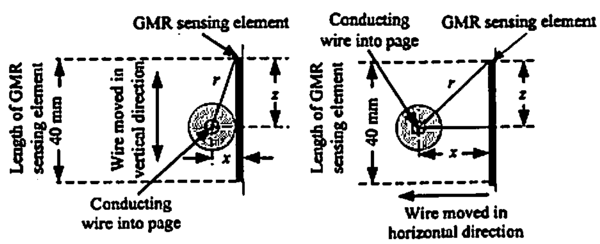
$$r = \sqrt{x^2 + z^2} \tag{2}$$

where: z – vertical height from conductor to point of interest [m]

x – radial distance from conductor [m]

For the vertical direction measurements the sensor needle is touching the conducting wire as shown in Fig. 10(a) effectively making, x negligible. In this situation we assume that x is equal to z. In Fig. 10(b) the conducting wire is moved away from the needle so x is significant. Fig. 11 presents the results of these measurements in vertical direction at 100 μA.

The experimental results are compared with theoretical data. The size of the sensor is in the order of 40 μm. The area of the recognizable signal is about 160 μm. This means it is about 4 times bigger than the size of sensor itself. Output signals taken into account were above 5 mV for 100 μA.



(a) Vertical direction setup (b) Horizontal direction setup

Fig. 10. Magnetic field measurement in vertical and horizontal direction from the nerve.

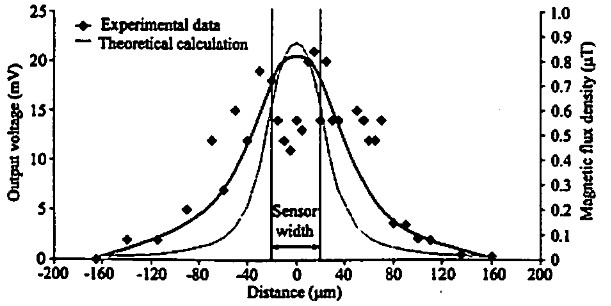


Fig. 11. Output signal measured in vertical direction for 100 μA.

The signal in the detecting region is not uniform. This can result from the fact that the sensor itself comprises 4 thin elements that create the entire sensing element. It can appear also due to the fact that in order to take each measurement we have to move the nerve model backward and forward which can introduce errors.

Measurements in horizontal direction involved finding the best output signal and afterwards moving the nerve model backward from the needle until the signal disappears. Characteristics that were measured are differing. Taking into consideration many experimental results, we can assess that, on average, the distance for which the signal can be still detected is about 750 μm. Fig. 12 presents an example of such characteristics. The considered plot should be inversely dependent on the distance of the centre of the wire from the sensor. However, the measured characteristic demonstrates a rather exponential function.

As a next step signals were measured through layers of polyimide foil of different thicknesses. This was to illustrate how the detectability would decrease while measuring the signals through body tissues. Fig. 13 illustrates the reduction of the detected signal versus increasing thicknesses of polymide layers.

Characteristic was checked for action current of 1000 μA. Analysis of a graph in Fig. 13 indicates that detected signal decreases proportionally to increasing layer thicknesses in accordance with Eq. (1).

4.3 Measurements of lower signals

The signals of interest are in order of nano Amperes. The results obtained in Figs. 11-13 are for action currents higher than 1 μA. The reason for this is that it is very difficult to distinguish between signals obtained at each distance for lower action currents. Hence, it is very difficult to show a clear relationship between output voltage and distance in the vertical or horizontal directions. Owing to the fact that measurements of lower currents than 1 μA with use of oscilloscope transpired to be difficult another technique was applied. This is because the output signal was lower than 2 mV which was the lowest division of the oscilloscope. Instead of pulse signal sinusoidal wave was supplied and locking amplifier was used. The utilization of this technique paved the way for the signals as low as 100 nA to be measured. Fig. 14 shows the plotting of averaged output signals versus input currents from 10 μA to 100 nA.

Fig. 15 presents the sine shaped output signal for

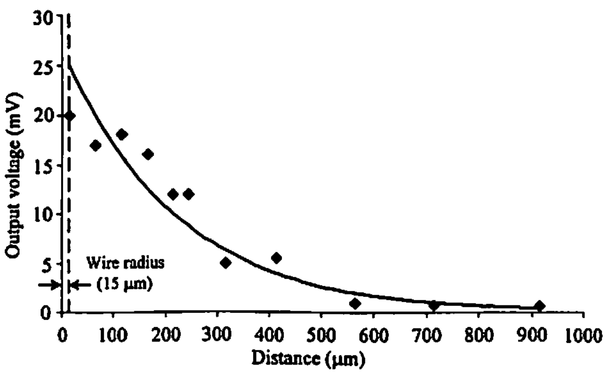


Fig. 12. Output signal measured in horizontal direction for 100 μA.

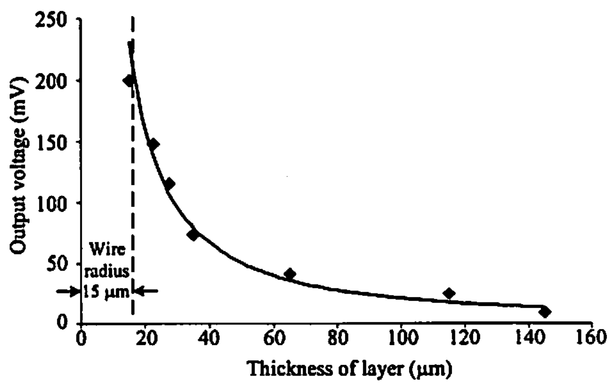


Fig. 13. Output voltage versus thickness of polymide layers placed between wire and sensor, for 1000 μA.

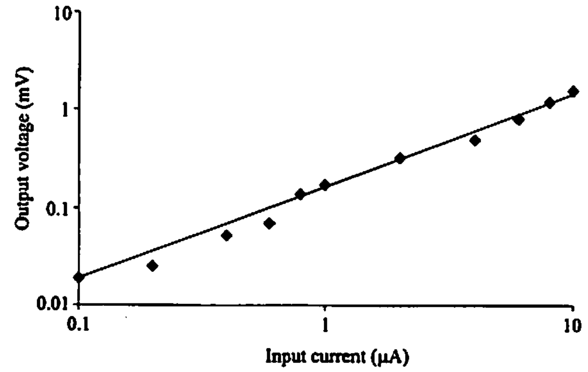


Fig. 14. Averaged output signals versus input currents.

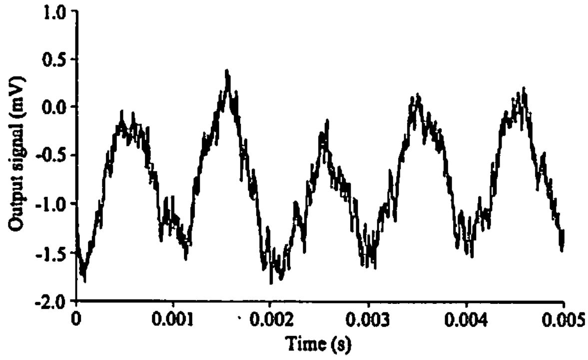


Fig. 15. Sine shaped output signal for 6 μA.

action current supplied to the nerve model of 6 μA. Even though the output signal is very small and slightly misshaped we are still able to estimate the average peak to peak amplitude. This result proves that measurements of currents in order of nano Amperes are possible.

5 Summary

First measurements of action currents in the model of the nerve with needle-type SV GMR sensor transpires to give expected results. The results presented in this paper show that measurement of nerve pulse currents as low as 1 μA are possible. Signals in some distance from the sensor can be measured as well as through the layers covering the nerve. Further measurements indicate that with use of locking amplifier currents as low as 100 nA can be measured. However, for effective detection of magnetic field distribution for action currents in the order of nano amperes, analysis methodology should be improved by signal processing techniques to clearly detect and measure pulse signals of low amplitudes. There is also necessity to facilitate operation on micro-size elements.

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