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MICRON SIZE GMR MAGNETIC SENSOR WITH NEEDLE STRUCTURE

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ABSTRACT. The work presents inimitable shaped needle type probe with spin valve giant magnetoresistance (SV-GMR) elements. Sensitive elements with 75 µm width are connected in the Wheatstone bridge structure. The length of the needle is 20-30 mm and its cross section is square. The magnetic sensor probe has the advantage of micron order spatial resolution. The needle type probe works as a gradient meter which concurrently suppresses the influence of externally applied field and detects magnetic fields emanating from nano or micro order size sources. Sensing elements present high sensitivity 260 µV / µT and are capable of detecting the magnetic fields in order of few nT. SV-GMR elements present flat amplitude and phase characteristics in wide frequency range. The novel characteristicsof the probe allow it to be utilized in detection of the in-phase and out of phase signal components.

An additional merit of this design is extremely small liftoff height between sensing element and the source of magnetic field. The SV-GMR elements are isolated only by very thin protection layer (a few µm), that gives opportunity to apply the probe in biological (*in vivo*) experiments, and in non destructive evaluation of current detection. The needle shape allows the sensing element toapproach the examined materials in a distance of few ten µm.

Keywords: Giant Magnetoresistance, Needle Structure, Micro Sensor, Nanoparticles, Current Detection
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INTRODUCTION

It has been over 20 years since the discovery of the GMR effect took place. Since then, the technology involved in production of thin films has developed greatly. One of the most common applications of GMR is in magnetoelectronic devices such as magnetic field sensors [1], magnetoresistance random access memories, magnetoresistance transistors. GMR sensors have found applications in hard drives [2-4], position detection, non-destructive evaluations [5-7], and conductive microbead detection [8]. Applications in utilization of GMR chips whose surface is bound with biological tagged markers can be found in [9-12]. Any movement of charge produces magnetic field therefore detection of current flowing in conductors is possible by magnetometers andproposition of utilization of GMR sensors is described in [13]. GMR based sensor was also applied in detection of signals produced from nerve model based on principle of axon potential in neuron [13,18].

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Biological application of GMR, in estimating volume density of magnetic fluid, was successfully performed in [11,14]. Nowadays, it is possible to build vibration detectors with commercially available sensors as well [15].It is not questionable that the evolution of the sensors pushes the industrial world forward.Due to improvement of the sensors, it is possible to measure various features more precisely and accurately. Evolution of the magnetic sensors helps to evolve new medical techniques like electroencephalography, fetal magnetography, and magnetocardiography. Magnetic sensors are currently applied in various fields. The article presents two designs of the needle sensors which are applied in detection and estimation of the weight density of injected fluid in hyperthermia treatment and in liquid phase immunoassay. Furthermore, utilization of the probes in non-contact measurement of small currents with high spatial resolution and detection of low biomagnetic signals is described. Firstly the structure and characteristics of the probe are discussed, and then applications are described.

NEEDLE TYPE SV-GMR PROBE

The probe designed in the laboratory has a straight needle shape similar to an acupuncture needle. The acupuncture needle is placed inside the body and can be removed causing no pain. The same idea was on the mind of the inventors of the needle type probe. The main aim is to place the sensor inside an examined object without causing any detriment of one's health. This type of design was chosen for biomedical applications or non-destructive evaluations. The sensing element at the tip of the needle allows us to measure magnetic fields inside the object of interest orto place the sensor in uneasily accessible places. Therefore, considering previously mentioned aspects, the shape of the needle, its cross section and length was chosen correspondingly to fulfill requirements of various possible applications.

Initial Design of the Needle Probe

The length of the initial probe utilized in experiments was equal to 20 mm as shown in Fig.1(a). This distance is long enough to limit influences of variety of examined objects on reference sensing elements. On the other hand, it is short enough to assure that the uniform magnetic field generator produces field variance at a distance of 20 mm smaller than few nT. The needle's cross section is square. This shape allows us to easily deposit a sensor element on one wall of the needle prism. The cross section of the first designed needle is 250 μm x 250 μm. Notwithstanding rod of thin shape, the strength of

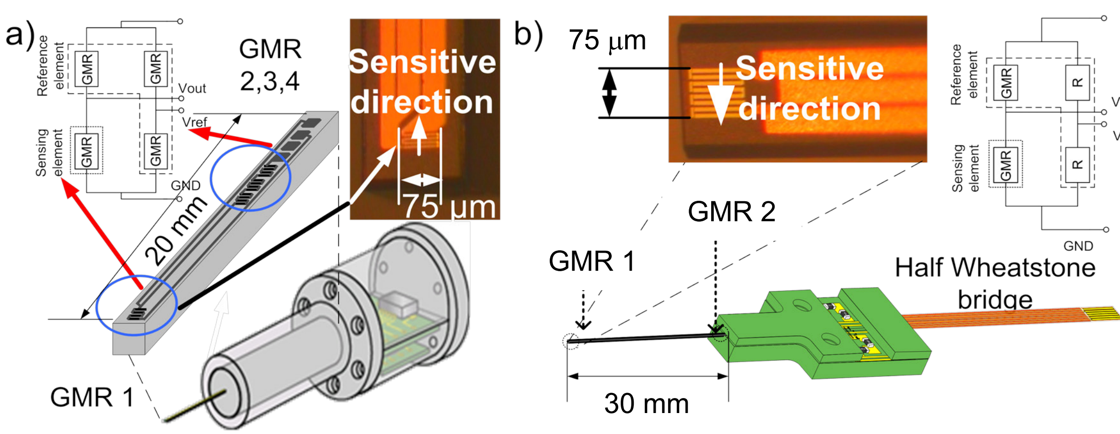

FIGURE 1. (a) First and (b) second design of the needle probes.

the needle is guaranteed by a special material. The needle is constructed from aluminum titanium carbon (AlTiC), produced by sintering the aluminum oxide (Al_2O_3) and titanium carbon (TiC). The hardness is 9-9.5 on Mohs scale. This material causes that the needle not to be susceptible to a force applied in the direction parallel to its length.

The needle has four spin valve type GMR thin film elements placed at the substrate, four bonding pads and lead conductors for electrical connections of sensing elements and bonding pads. After sensing elements are placed, the needle is covered by a film protection layer which is biocompatible and is resistant to chemical substances. In the present design of the probe, one sensing element is placed at the tip of the needle. Three other sensing elements are located close to the bonding pads (as shownin Fig. 1(a)). Sensing element at the tip is used to detect magnetic fields emanating from examined objects. Three other elements located at the second end of the needle are used as a reference elements detecting exciting magnetic field. All the sensing elements of the probe are connected into Wheatstone bridge as shown in Fig.1(a). The Wheatstone bridge structure suppresses the fluctuations due to the temperature, andcancels external magnetic fields and noise.The sensing elements of the probe are shaped in meander style. Each element is build from spin valve giant magneto-resistive thin film. Example of one utilized design of the meander style is shown in Fig. 2. The length of the meander is equal to 75μm and the width is equal to 45 μm. Detailed arrangement of thin film strays is presented in Fig. 2. The characteristics of the sensing element placed in the DC field ranging from ±4 mT are presented in Fig. 2. The characteristics show that sensing element has very small remanence and coercive force what assures that measurement with various frequencies are not affected by the hysteresis effect of the sensing element. The first design of the needle has SV-GMR elements aligned to have the sensitive direction along the longer side of the needle. Connection of the sensing elements into the Wheatstone bridge structure, which one of the sensing elements is placed at the tip of the needle and the other ones are in another position, creates first order gradient meter. Because it is difficult to operate precisely with very thin and short element (needle 20mm in length),a special case was designed. The case has a place for preamplifier and connecting boards. The case of the probe is made from nonmagnetic material in order not to influence precise magnetic measurements.

Second Design of the Needle Probe

The second probe has a length equal to 30mm and the cross-section of the needle equal to 400 μm x 400 μm. The length of the needle was increased in order to allow measurements of bigger objects. The cross section of the needle was enlarged in order to

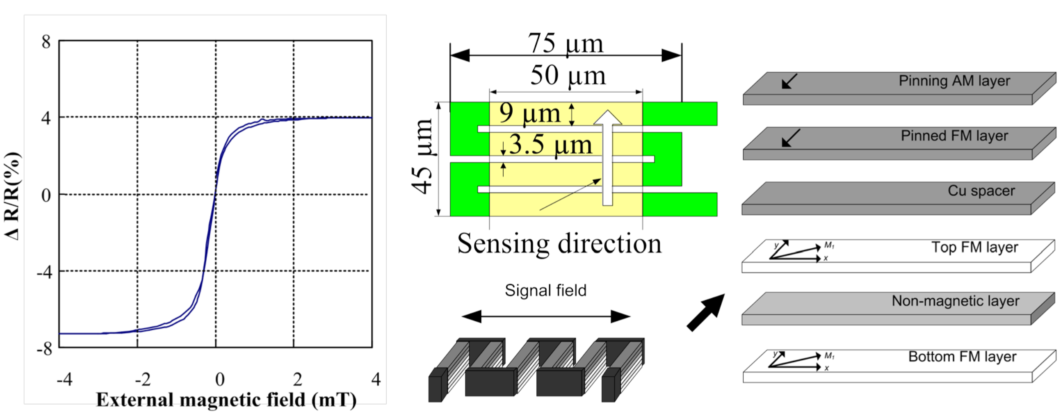

FIGURE 2. Characteristics of spin valve type giant magnetoresistance sensor.

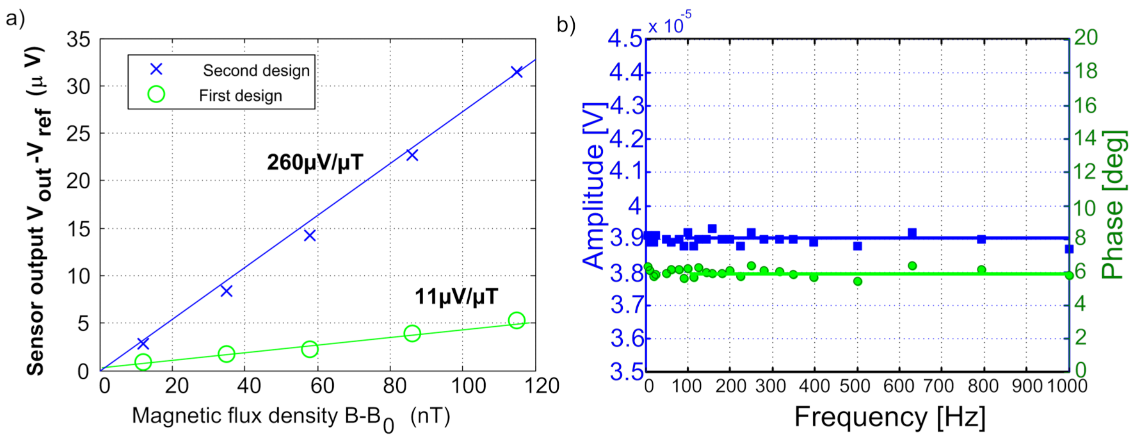

FIGURE 3. (a) AC sensitivity characteristics and(b) frequency characteristic of the GMR probes.

assure bigger stiffness of the needle. The secondly designed probe differs from the initial one in the electrical connection schema. The needle has two SV-GMR elements and two resistors connected into Wheatstone bridge structure. The connection of the elements creates half bridge SV-GMR structure. One sensitive element is at the tip of the needle whereas the second one is distanced30mm and placed at the opposite end of the needle. This type of connection creates gradient meter which detects difference in fields rather than magnitude. This allows us to precisely measure the difference between magnetic flux densities at two locations (tip and opposite side of the needle). The sensitive direction of SV-GMR elements is perpendicular to needle length as shown in Fig. 1(b). Changing arrangement of the sensing elements allows us to detect magnetic flux densities in direction perpendicular to the needle length. The weight of the needle and the connection board was decreased to 3.0 g. Moreover, the size of the sensing elements was changed, secondly designed probe has a sensitive elements with size equal to 75 µm x 75 µm. The characteristics of gain and phase are shown in Fig.3.

Characteristics of the Needle Probes

A setup consisting of two coils with Helmholtz arrangement can be used for characterization of the SV-GMR needle probe. The currents at each coil flow in opposite directions causing the generation of the magnetic gradient fields along the distance between them. In the geometrical center of the coils there is the point where magnetic flux density should be equal to zero. Placing the probe tip in the geometrical centre of the coils causes one sensing element to be in zero magnetic fields. Three other elements are placed at a distance of 20 (or 30) mm from the tip, i.e. in a generated gradient field. It is possible to obtain the sensor’s output voltage, in a given gradient. By increasing the gradient field and recording the sensor output voltage, it is possible to determine information about the probe’s sensitivity factor. Firstly designed probe has sensitivity equal to 11 µV/µT, whereas the secondly designed probe has sensitivity equal to 260 µV/µT.

APPLICATIONS OF NEEDLE PROBE TO BIOLOGICAL FIELDS

Estimation of the Concentration of Magnetic Fluid in Hyperthermia Treatment

Currently magnetic fluids are used in a numerous clinical applications such as magnetic drug targeting (MDT), magnetic resonance imaging (MRI), hyperthermia therapy and others [16,17]. Especially in hyperthermia treatment based on induction heating,proper estimation of magnetic fluid concentration is crucial for successful therapy [17]. On the hyperthermia treatment the magnetic fluid is directly injected into the cancer cells. Magnetic fluid consisting of nanoparticles can be used as a heating agent causing apoptosis of cancer cells [17]. Weight density of the magnetic fluid is a crucial parameter to apply proper heating during hyperthermia treatment. When the uniform external magnetic flux density B_0 is applied to magnetic fluid in the specific embedded cavity (Fig. 4(a)) and the magnetic flux lines converge at the cavity within the magnetic fluid. Inside tissue with magnetic nanoparticles the magnetic flux density changes to B_1.It is known that the relative permeability (magnetic susceptibility) is proportional to the magnetic fluid weight density [6].Therefore, magnetic flux density changes proportionally to weight density of fluid D_w. Then by monitoring the magnetic flux density change ratio δbetween the magnetic flux B_1 and B_0, it is possible to obtain weight density of fluid or its relative permeability and relative susceptibility χ*:

$$\delta = \frac{B_1 - B_0}{B_0} = \frac{(1-N)C_d D_w}{\gamma_f} = \frac{(\mu^* - 1)(1-N)}{\mu^*} \approx (1-N)\chi^* . \quad (\mu^* \approx 1) \qquad (1)$$

where B_1 is the magnetic flux density inside the tissue,B_0 is the magnetic flux density of the externally applied field,N is the demagnetizing factor, and μ^* is the relative permeability of the tissue. It is possible to estimate concentration of tissue with the magnetic fluid when the change of the ratio δ is measured and the dependence of the relative permeability on weight density of fluid and the shape ratio of a cavity is known.

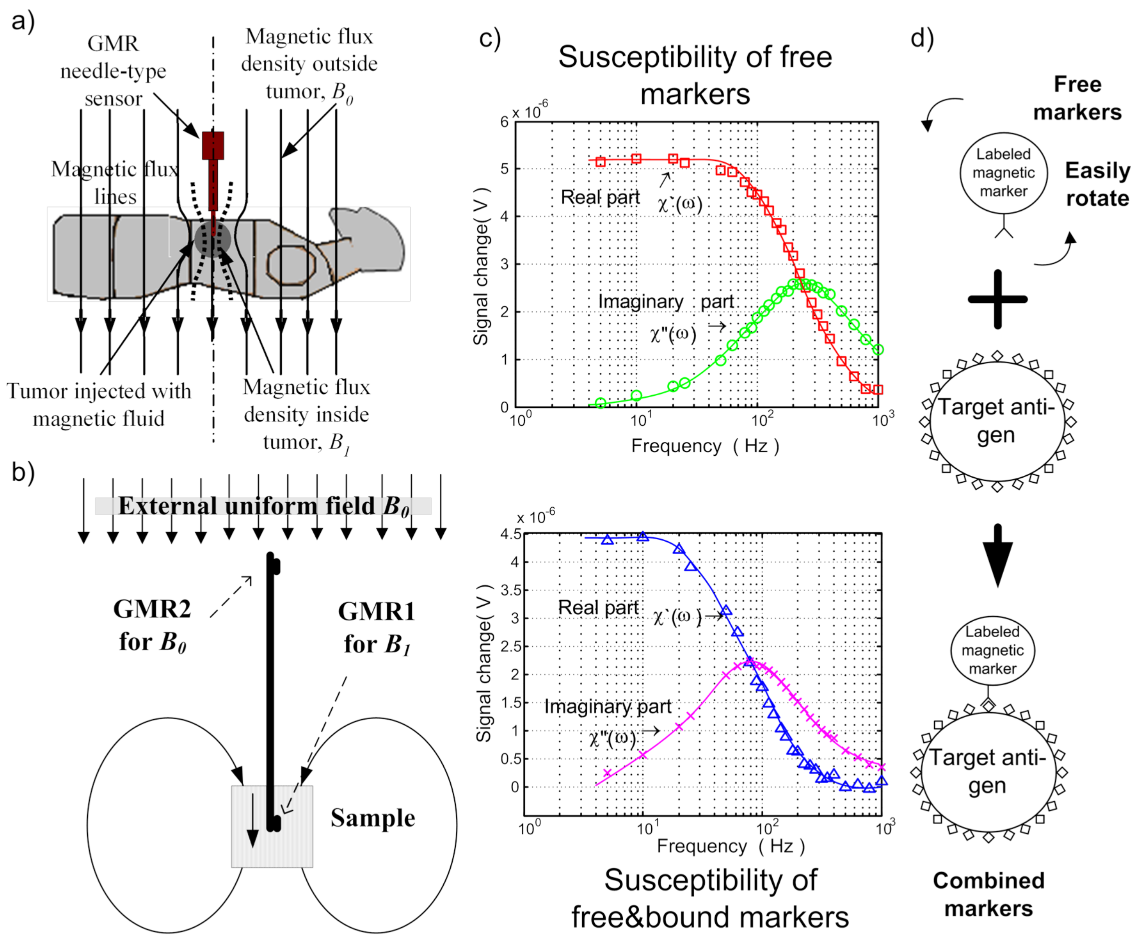

FIGURE 4. Applications of designed probes (a) estimation of weight density in hyperthermia treatment, (b) immunoassay detection of biological targets.

Spectroscopic Studies of Ferrofluid–Magnetic Immunoassay

Immunoassay is well-known as an extremely sensitive test checking presence of biologically active substances. One type of immunoassay tests is a magnetic immunoassay. This specific test employs biologically activated magnetic markers. It is possible to cover surface of small particles consisting of magnetic materials with antibody capable of binding antigen. These particles commonly known as magnetic markers can be used to combine with antibodies. The principle of the immunoassay is shown in Fig.4(d).The presence of external magnetic field applied to the ferrofluid particles, whose single magnetic domain tends to align along the applied field, leads to a net magnetization. This particular situation allows us to treat the ferrofluid like a superparamagnetic system. The AC susceptibility response of the system on applied magnetic field varying in time should occur in specific frequency characteristic. If nanoparticles are treated like ultra small size magnets their magnetic moment can influence on the external field. The changes caused by the particles binding to biological targets are small, so it is difficult to measure them. Yet these specific changes can be measured inside the sample in parallel direction to the applied field or outside the sample in perpendicular direction to the applied field.

The utilization of the SV-GMR needle probe in examination of such frequency characteristic of magnetic nanoparticles was proposed and verified in Fig. 4(b),(c)[14]. The outline of the measurement method is following: when the ferrofluid is placed in the external field, the sample magnetization causes the change of the magnetic flux density. The Wheatstone bridge structure allows us to measure simultaneously the signal change (B_1-B_0) caused by sample and to eliminate the influences of the external fields. Such configuration allows obtaining the changes of the flux density inside a sample (B_1) and applied field (B_0) as shown in Fig. 4(b).The relationship between the measured value (B_1-B_0) and the susceptibility $\chi=\chi'+i\chi''$ can be easily derived from the equation (1). Taking into consideration the fact that the susceptibility change is proportional to the probe signal, it is possible to state that the in phase component of the signal is proportional to the real part of the susceptibility and the quadrature component is proportional to the imaginary part of the susceptibility. Monitoring the changes of the real and imaginary part of the signal allows us to find linear dependence between the number of magnetic markers in liquid sample and the number of biological targets [14].

Non-Contact Measurement of Small Current Signal with High Spatial Resolution

Detection and measurement of low-level current have been studied for years in medical as well as in industrial applications where relatively large and cumbersome magnetometers are used for monitoring magnetic signals. However, the typical current sensors have the limitation in size so that they need to be placed at a specific distance, relatively far away from the target objects, that results in general signals of a wide area. Current measurement of dense printed wires on the PCB is suggested as an example of high spatial resolution detection ability. Small current of 100 μA ~ 2 mA is applied to printed wires with pitch and width equal to 200 μm as shown in Fig. 5(a). The example of detected magnetic flux density distribution generated by currents of two printed wires is included in Fig. 5(b). The currents with amplitude 2 mA and 1 mA were fed into wires. Output of the sensing element, located 30 μm above the wire, after 100 times amplification, shows that current flowing in the first wire is approximately twice the current in the second wire. Distribution of currents in high spatial density printed wires is performed by the needle type GMR probe with scanning steps as small as 50 μm.

Additionally, we propose a model of propagating nerve signal for extremely small current signal detection as an example of biomagnetic application [18]. Many researchers working on nerve signal, discovered that when the nerve is stimulated, the action potential propagates along axon. The process of propagating nerve signal can be assumed as the chain of two current dipoles in opposite directions flowing in nerve axon [19-21]. Considering characteristics of nerve axon and the action current, we developed a nerve model which is a wire of 20 μm diameter knitted into holes giving opposite direction of current dipoles as shown in Fig. 5(c). Action current was modeled by a rectangular current (20% duty, 1 kHz) and amplitude in order of few $\mu A_{p\text{-}p}$ was supplied to the nerve model. The magnetic field is detected by the micro needle-type GMR probe placed in distance of 20 μm from the nerve model. Low magnetic flux density of approximate 30 nT was detected with the pulse input current as small as 5μA, (see Fig. 5(d)). Experimental results agree quite well with the theoretical calculation and prove that the magnetic flux density is the highest at the middle of current dipole and decreases at the area between the two current dipoles because flux density cancels each other.

CONCLUSIONS

Typical commercial sensors have the limitation in size, therefore they have to be placed a little bit away from the target objects what results in detecting signals from wider area. For extremely small dimensions of measured objects, sensing distance is required to be as small as possible. Therefore, needle sensors with miniature sensing elements can be a good solution. Both probes are characterized by high spatial and time resolution. As being described in article,probes present flat amplitude and phase in wide frequency range. The construction of the probes is unique around the world.We evaluate the sensitivity of each probe for DC and AC magnetic fields.The frequency characteristics of the probe in AC fields are achieved in order to assure that the measurements of the magnetic markers can be accurately performed.Owing to the specific features of the probe, it is possible to detect

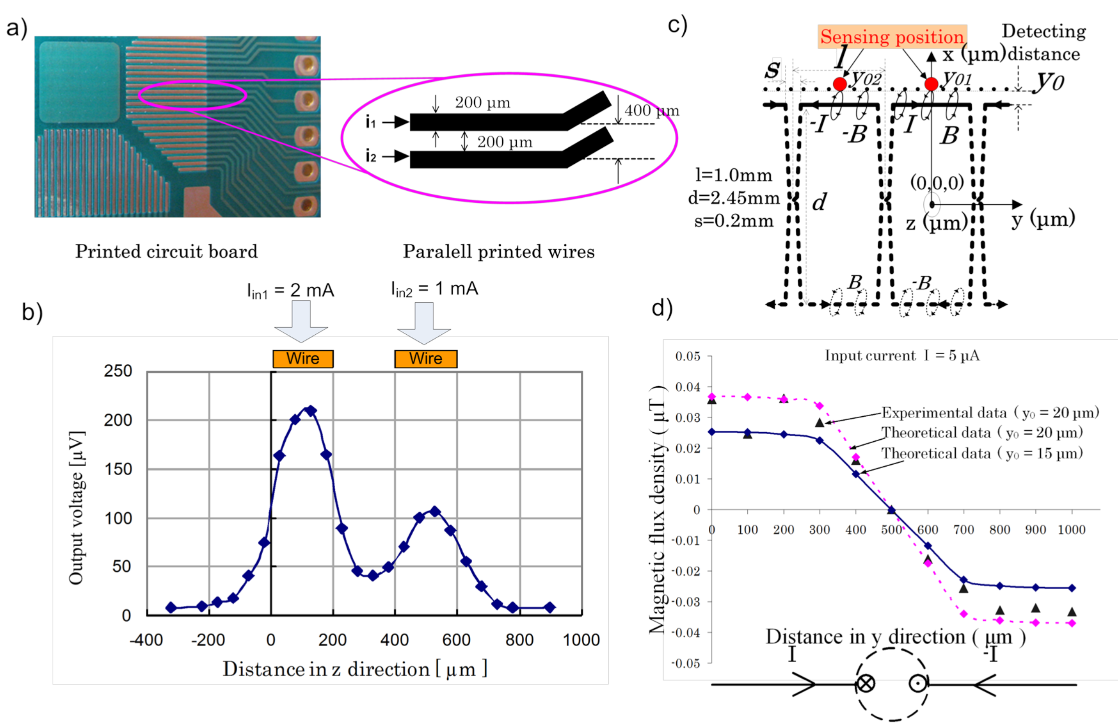

FIGURE 5. Applications in non-contact current measurement (a), (b), PCB's current measurement; (c), (d) nerve signal model measurement.

changes in signal of samples before and after connection with biological targets and estimate the number of biological targets in the samples. It is also possible to estimate concentration of magnetic fluid inside tissue as well.The described needle probes are powerful in detection and measurement of small current in medical as well as in industrial applications.

The experiment results demonstrate that small current of high spatial printed circuit wires of about 200 μm pitch are measureable. Furthermore, magnetic field of few ten nT generated by current signals as small as μA order can be detected with the spatial resolution of few ten μm. Therefore, taking into account the experimental results, we can point out that our extremely small size and specific construction of novel needle type GMR probe is anexcellent tool for high spatial resolution non-contact measurement of small currents.

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