Application of MEMS Magnetic Sensors for MedTech Innovation

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In recent days, the advances of MEMS technology enble mass production and commerciallization of ultra-small and low-power MEMS magnetic sensor with ultra-high sensitivity of a few uT. Besides explosive growth in smart phone applications, those ultra-sensitive MEMS magnetic sensors are believed extrodenery important for medical technology innovations due to inherent characteristics of the magnetic field to human body.

Towards real time imaging of human organs during medical surgeries for organ excision or tumor care, i.e. laparoscopic hepatectomy, we have been engaed in developing a high-resolution location tracking system by using artificial magnetic field and 3D MEMS magnetic sensor nodes for years. In this talk, fundamental principle of the system will be prsented and demonstrated. Our preliminary results indicated that location reolution of a few mm can be achived when multi-pairs of electrical magnetics were applied to create a unique magnetic field, in which both DC and AC signals were combined for noise cancellation as well as for rotation recognition. Our experimental results also suggested that mapping of the whole magnetic filed, as an extension of simulation, may greatly improve positioning accuracy. Besides stability and repeatibility, many other specifications of the system were investigated and discussed in details.

In addition, a few other examples of using MEMS magnetic sensors will be given and discussed herein. Related works on integration and assembly of ultra-compact wireless implantable sensor nodes for animal monitoring as well as its wireless power supply system will be introduced too for better understanding technical issues for practical application of above technologies in MedTech Innovations.

Development of high-sensitive and wide-range linear magnetic field sensor

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Recently, there are increasing interests in high sensitive magnetic sensors from a view point of application to biomagnetic sensing and non-destructive analysis. For example, pT level or smaller value of magnetic detectivity is required for the detection of electrical activities in brain and heart. Spin-valve TMR sensor is one of the candidates to realize such high performance at room temperature without complicated equipment. High sensitive spin-valve TMR with bottom free layer structure has been reported[1, 2]. Nevertheless, in general, there are technical tradeoff between the magnetic sensitivity and the input range of the magnetic field.

In our study, an improved magnetic sensor structure with highly enhanced magnetic sensitivity has been developed by incorporating an optimally designed magnetic flux concentrators (MFC) with bottom free structured TMR. Also excellent linearity with wide input range has been successfully obtained by using magnetically balanced closed-loop system.

Figure 1 shows transfer functions of the magnetic sensor with MFC and that without MFC. The magnetic sensitivity is enhanced over 87 times larger than that without MFC. In order to make such high sensitivity compatible with wide input range, we utilized magnetically balanced closed loop system. The linearity of the closed loop sensor is better than ±0.1 % F.S. (Fig.2) in the range as much as ±100 μT, which is larger than the earth magnetic field. Figure 3 shows a sensor output signal spectrum in which an input sine wave signal of 354 pT rms at 10 Hz is detected with sufficient SNR.

This sensor device structure explained above is envisioned to become a key technology in realizing the magnetic sensing of pT level.

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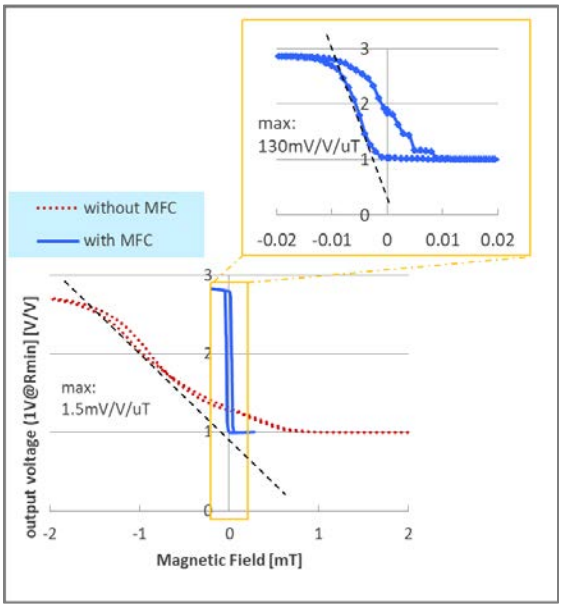

Fig. 1 transfer functions of the magnetic sensor

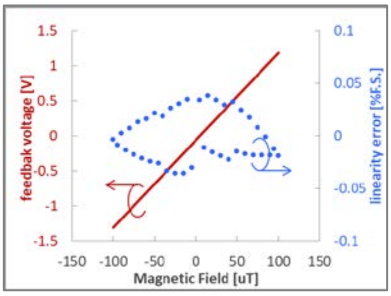

Fig. 2 Feedback voltage and linearity error

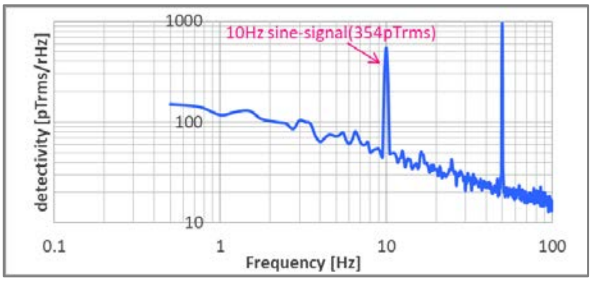

Fig. 3 Spectrum of the sensor output signal with 10Hz sine wave input

Magnetic Sensors for Automobile

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Magnetic Sensors for Automobile

In order to address the enhancement of emission regulations, “Electronicization of cars” including electronic control of engines has progressed rapidly and many semiconductor sensor devices have been adopted in automobile. Magnetic sensors, for detecting the rotation angle of Cam and Crank, the position of accelerator pedal, the speed of vehicle / wheel, and the current of battery etc., are mounted about 10 or more pieces in a car, and the quantity of them are increasing. In the future, electric vehicles such as PHEV/EV will increase due to global fuel efficiency regulations and EV strategy of European automobile manufacturers, and the amount of current sensors for inverters and/or EV batteries are expected to grow drastically.

The needs for these current sensors are

1) Miniaturize ; To correspond the space reduction due to increasing the number of battery cells
2) High precision ; To use up batteries for extending the EV cruising distance
3) High current detection : To drive the motor with high current.

In general, Hall sensor is used as magnetic detecting devices for automotive current. It has a magnetic yoke to improve sensitivity and noise tolerance[1]. Others, shunt resistance device and a flux gate device are used as more accurate detection applications. However, these devices have a disadvantage that the size is large.

Current Sensor using MTJ Element[2]

Therefore, we aimed to productionize the small (yokeless) and high precision current sensors, we developed the new type current sensors which detect the magnetic field without yoke using with the high sensitive magnetic tunnel junction (MTJ) element. To realize the high accuracy, we need to reduce the nonlinearity to 0.1% FS or less. In addition, currents to be monitored may be as large as 1,000A, it is estimated that the magnetic sensors should have a dynamic range as wide as the order of 1,000Oe.

For these reasons, we adopted a structure which have in-plane magnetized free layer and perpendicularly magnetized reference layer, compared to the conventional MTJ sensors which have in-plane magnetized free and reference layer of CoFeB / MgO / CoFeB MTJ. In reference layer, we applied the synthetic antiferromagnetic (SAF) structure due to the high exchange bias, the wide dynamic range of +/-2,500Oe. In free layer, in order to optimize the anisotropic magnetic field, we investigated the thickness dependence of it. When the thickness is 1.8 nm or more, it becomes in-plane magnetization, and when the film thickness becomes thick, the slope of minor $G – H$ curve decreases, it is equivalent to the decreasing the sensor sensitivity. This is consistent with the minor G - H curve calculated by the Slonczewski model[3]. As the result, we achieved the nonlinearity <0.1% FS within ± 1,000 Oe.

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A multi-channel SQUID system for biomagnetic measurements

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Biomagnetic measurement is a promising tool to investigate electrical activities in a living body noninvasively. A weak magnetic field induced from nerves or muscles is detected by highly sensitive magnetic flux sensors, and magnetic source analysis reconstructs the electrophysiological current distribution.

Superconducting quantum interference devices (SQUIDs) are typically applied to the detection of the biomagnetic signals whose intensity is on the order of 10^{-15}–10^{-12} T. The structure of the SQUID is a superconductor ring with a single or two Josephson junctions, consisting of two superconductors sandwiching a thin insulating or normal conducting layer to form a weak link. When a bias current larger than the critical current is applied to the ring, the SQUID induces a voltage (V). The voltage is modulated periodically depending on a magnetic flux (Φ) applied to the SQUID ring. The period is exactly equal to the magnetic flux quantum. This gives a large differential coefficient (dV/dΦ) that contributes to highly sensitive magnetic flux detection. The SQUID is connected to a flux-locked loop (FLL) [1] to linearize its output and improve its dynamic range. The flux quanta counting [2], thanks to the periodic characteristics of the Φ-V curve of the SQUID, also broadens the dynamic range. The SQUID sensors are usually equipped with a superconducting gradiometric pickup coil to cancel external magnetic flux disturbances. These make it possible to detect cardiac biomagnetic fields outside of a magnetically shielded room [3].

We developed a SQUID biomagnetic measurement system intended for the spinal cord, peripheral nerves, and muscles [4]. The system had two main characteristic features. The first one was the sensor array equipped with 44 vector-type gradiometric magnetometers arranged in an area of 110 mm × 160 mm. The vector-type gradiometric magnetometer was composed of one axial-type and two planar-type gradiometric pickup coils combined into a single bobbin. Each pickup coil was coupled with three individual SQUIDs and oriented perpendicular to each other so that three independent components of magnetic fields, not only the radial component but also the components tangential to the body surface, could be detected simultaneously. This is effective to extract the magnetic field information maximally from the narrow observation area, such as a neck or wrist. The second characteristic feature was the uniquely shaped cryostat to keep the SQUID sensors in their superconducting state. The cryostat had a cylindrical main body to reserve liquid helium (LHe) and a protrusion from its side surface. The sensor array was installed along the upper side in the protrusion so that the magnetic field could be detected from the bottom of the target pillowed on the protrusion. The cool-to-warm separation at the sensor array was approximately 10 mm.

Our SQUID system was equipped with closed-cycle helium recondensation using a pulse tube cryocooler [4]. In the past, high operational cost because of the LHe consumption to keep the superconducting state of the sensors prevented conventional SQUID systems from becoming widespread. However, the closed-cycle helium recondensation allowed us to recycle almost 100% of the LHe, so our SQUID system continued to be in operation for more than nine months without refilling the LHe, and the operational cost of the system was drastically reduced.

Using the SQUID system, we had already corrected spinal cords' or peripheral nerves' biomagnetic data from more than one hundred subjects. Neural current distributions were reconstructed from the obtained biomagnetic data using spatial filter analysis. Propagation of the neural signals along spinal cords or peripheral nerves was clearly visualized as a transition of the reconstructed current distribution. It was indicated that clinically significant information can be obtained by our SQUID system [5].

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Recent developments on magnetoimpedance sensor

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Sensitive micro magnetic sensors referred to as MI sensors1) are based on magnetoimpedance (MI) effect in amorphous wires and CMOS IC electronic circuits providing a sharp-pulse excitation. Micro sized mass production MI IC chips for electronic compasses have been supplied since 2002 for mobile phones and since 2010 for smart phones. Making use of ultra-low intrinsic magnetic noise in amorphous wires, pico-Tesla (10^{-8} Oe) resolution had been realized for developed MI sensor, in which several hundred turns pick-up coil was used for signal detection.

For measuring extremely weak magnetic field such as a bio-magnetic field, it is necessary for canceling the background uniform noises such as geomagnetic field. We have developed a gradiometer based on the MI sensor. The gradiometer is composed of a pair of MI elements: a sensing element and a reference element with distance between elements of 3 cm. The gradiometer has a good linearity and a high sensitivity of 1.2×10^5 V/T even for no amplification (Fig.1). The sensitivity difference in two heads is within 1%. As shown in Fig. 2, the noise level of the gradiometer is approximately 2 pT/Hz$^{1/2}$ at 1Hz. We have also demonstrated bio-magnetic field measurement using the high performance MI gradiometer2)-3).

Three principal advantageous features of the amorphous wire MI sensor in summarized are follows.

1) Sub-millimeter size sensor head is realized with a high sensitivity of several nT resolution. Utilizing this advantage, 3-axis electronic compass chips having 10 μm diameter amorphous wire heads are in producing; those are compatible with the advanced integrated circuitry for smart phones.
2) Ultra high sensitivity with a resolution of 1 pT without any magnetic shielding in a portable type MI sensor operating at room temperature have been realized.
3) Ultra quick response for magnetic field signal detection will be useful for micro size wireless receiver application.

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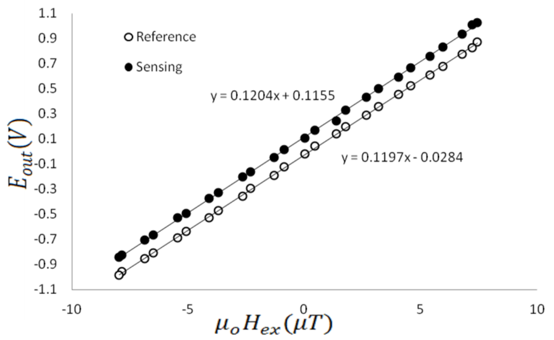

Fig.1 Field detection characteristics of the MI gradiometer. Number of turns of the pick-up coil is 600 and the length of the wire is 1 cm.

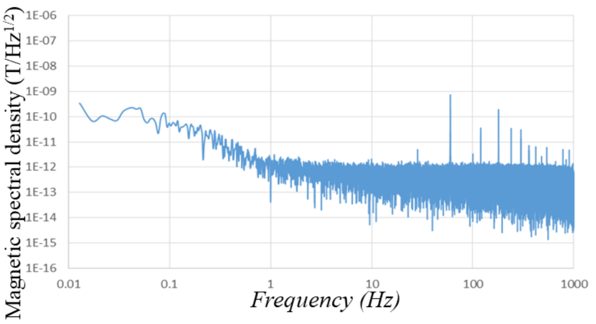

Fig.2 Magnetic noise spectral density of the MI gradiometer.

Measurement of Magnetoencephalography and Magnetocardiography using Tunnel Magneto-Resistance Sensor

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The electrical activity of the tissue of the human body creates magnetic field. Measurement of biomagnetic fields such as magnetoencephalography (MEG) and magnetocardiography (MCG) is useful for elucidation of biological functions and diagnosis of diseases from its non-invasiveness and high spatial resolution. However, such measurements requires the use of SQUIDs with high equipment and running costs, especially the price of liquid helium. We have been studying to measure these biomagnetic fields using tunnel magneto-resistance (TMR) sensor which is a room temperature operating device. In this study, we performed MCG and MEG measurement using low noise, high sensitivity TMR sensor and circuit system.

The Magnetic Tunnel Junction (MTJ) multilayer film constituting the TMR sensor was deposited on a thermally oxidized Si substrate. MTJs were micro-fabricated by photolithography and Ar ion milling. To reduce the $1/f$ noise, MTJs were connected in 870 series and 2 parallel1); the size of the integrated TMR sensors was 7.1 × 7.1 mm^2.

Fig. 1 shows the MCG signals using TMR sensor. The R peak of MCG was observed without averaging. This is the first demonstration of real-time MCG measurement using the TMR sensors. In addition, the Q and S peaks were clearly observed with 64 times averaging. Fig. 2 shows the MEG signal acquired by the TMR sensor. The signal was averaged 10,000 times with alpha wave as a trigger. Although there was a phase shift, the same 10 Hz signal as the brain wave was obtained in the MEG. The amplitude of the magnetic field was approximately 2 pTp-p, which is consistent with the reported value2); the correlation coefficient of the MEG with the EEG was as high as 0.7 or more.

This work was supported by the S-Innovation program, Japan Science and Technology Agency (JST) and Center for Spintronics Research Network, Tohoku University.

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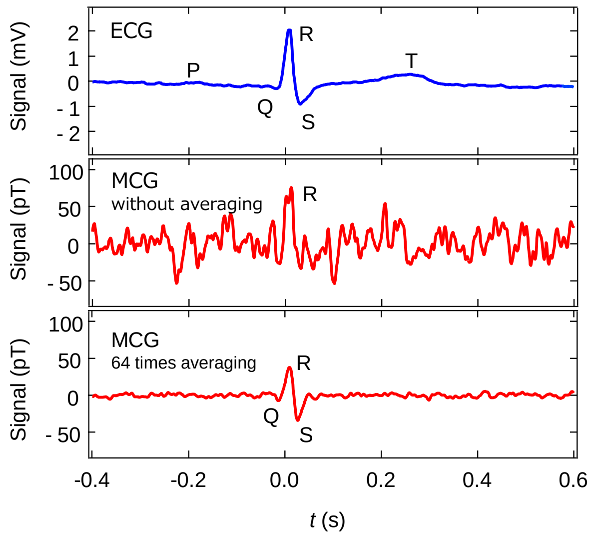

Fig. 1 Electrocardiography (ECG) and magneto-cardiography (MCG) using TMR sensor.

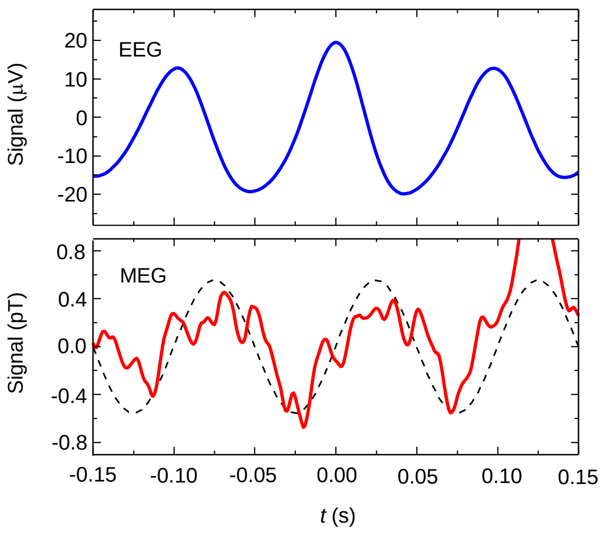

Fig. 2 Electroencephalography (EEG) and magneto-encephalography (MEG) using TMR sensor.

Optically Pumped Atomic Magnetometers: Perspectives for New Optical Biomagnetic Imaging Systems

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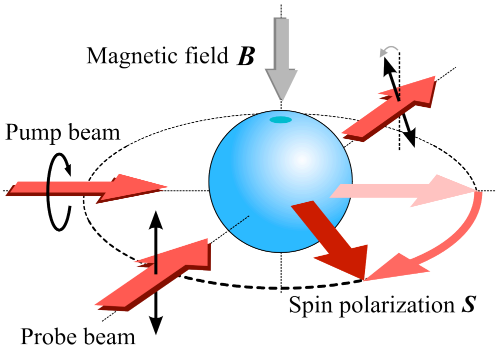

In recent years, **optically pumped atomic magnetometers** (**OPMs**) operating under **spin-exchange relaxation-free** (**SERF**) conditions have reached sensitivities comparable to and even surpassing those of superconducting quantum interference devices (SQUIDs) [1-3]. OPMs are based on the detection of electron spin precession in alkali-metal atoms contained in glass cells. In the pump-probe arrangement as shown in the right figure, a circularly polarized pump laser beam and a linearly polarized probe laser beam crossed orthogonally in the center of the glass cell including vaporized alkali-metal atoms. At present, the most sensitive OPM has sensitivity of 160 fT/Hz$^{1/2}$ in a gradiometer arrangement with a measurement volume of 0.45 cm^3 at the frequency range lower than 100 Hz. In addition, OPMs have the intrinsic advantage of not requiring cryogenic cooling. Therefore, OPMs are currently expected to overtake SQUIDs and the possibilities for using OPMs for biomagnetic field measurements and MRI have been demonstrated.

We have been developing OPMs with pump-probe arrangement since 2006 [3-6] and started to fabricate compact and portable potassium OPM modules in 2012 [7]. The figure at the bottom illustrates one of our OPM module reported in 2015 [8]. The sensitivity of the OPM module reached 21 fT/Hz$^{1/2}$ at 10 Hz, so that we carried out measurements of human magnetoencephalograms with it. Compared with the results obtained with SQUID-based magnetometers, we could successfully observe distinct features of event-related desynchronization in the 8-13 Hz (alpha) band associated with eyes open [8].

Meanwhile, we have also been challenging to detect NMR signals and MRI with OPMs [9] at ultra-low field (ULF) below several hundred μT. Since sensitivity of OPMs does not depend on frequency, OPMs are suitable to be used as receiving sensors for ULF-MRI systems. In 2017, for the first time, we have shown that MRI and NMR signals could be acquired with the same OPAM module described above operating at a Larmor frequency of 5 kHz without the use of any cryogenics [10].

We believe that the applicability of new ultra-sensitive optical biomagnetic imaging systems might provide important advancements in neuroscience and also improve the clinical diagnosis of neurological and psychiatric disorders.

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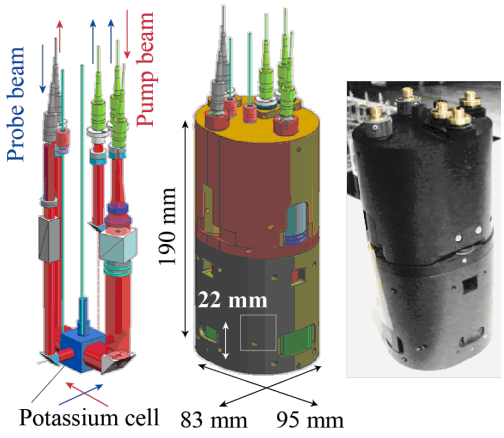

Possibilities of Diamond Quantum Sensors

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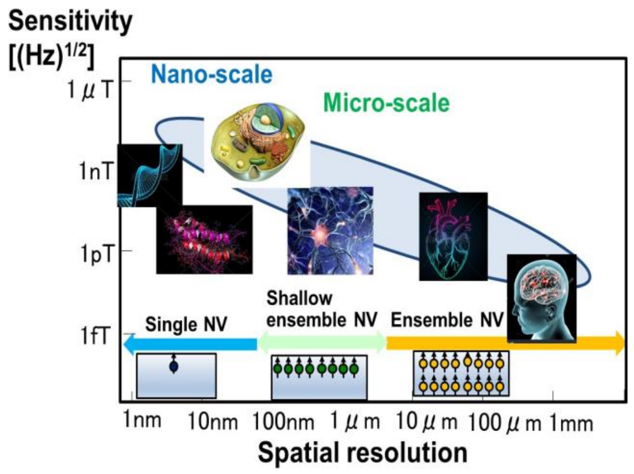
Nitrogen-vacancy (NV) centers in diamond have superior physical properties at room temperature for quantum sensing of magnetic field, electronic field, temperature, and pressure with scalable applications from atomic-scale to macroscopic range. We would like to introduce highly sensitive diamond sensors by applying advanced nano-device technologies, quantum sensing protocols and module system. For application, we will show the biological imaging, nano-scale NMR, and the device sensing. Advanced technologies for spintronics and electronics are needed for higher performance.



Potential on the scalable application of diamond quantum sensors