Development of Super High Resolution Micro size Magnetic Sensors and Their Highlights Applications

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The trend of big data in Fig.1 creates the big progress of sensors towards to like bio sensors. Like bio sensors must have high performance in super high resolution, micro size, low power consumption, real-time, low cost and mass production. The like bio sensors must be archived by combination of sensor innovation and the sensor fusion smart system. In the field of magnetic sensors the developments of high resolution micro size magnetic sensors and their new applications such as wearable computer in Fig.2, medical applications in Fig.3, automotive driving systems, smart grid has been dramatically progressed.

MI sensor which consists of amorphous wire and MEMS coil must be most promising super high resolution micro size magnetic sensors. Recently the remarkable progress on MI sensor improved by pulse stimulation from MHz to GHz and fine pithed MEMS coil from 30 μm to 5μm in Fig.4 which gives the 100 times increase in sensitivity compared to that of MHz type MI sensor is reported. I propose GHz type MI sensor as GHz-spin rotation sensor (GSR sensor1)). This GSR sensor must measure the earth magnetism easily and apply to gyro compass which is used as motion sensor for wearable computer. Moreover it can detect bio magnetism of Pico tesla level and apply to heart magnetic cardiogram and magnetoencephalography.

The keynote speech will introduce the recent developments in super high resolution micro size magnetic sensors and their high light applications challenged in Silicon Valley.

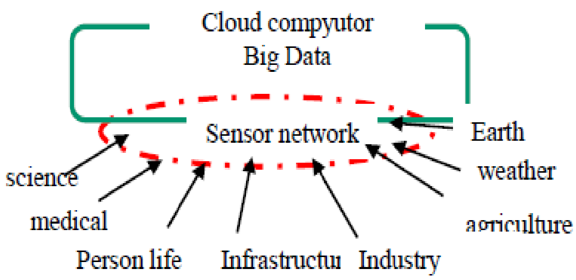

Fig.1 the ages of Big Data and the role of sesnors
Market will increase from 10 B pices /year to 100B pieces / year in 2020

Fig.2 Motion Fusion sensor
size 4×4×1mm

Fig.3 magntocadio graph using SQUID

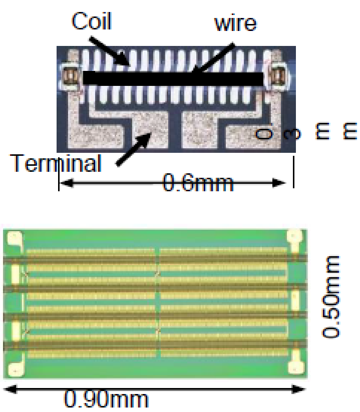

Fig.4 MI Element and coil pitch
Numbers of coil increased form 25 to 620 turns /mm

Reference
1) Y. Honkura; Nano plat form consortium symposium (2015).

High Sensitive Magnetic Field Sensor Using Amorphous Wire and Micro-fabricated Fine Pitch Coil

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There were various types of magnetic field sensors available at present to measure the magnetic fields from electromagnet, motor, earth field, and bio-magnetic field. Among these sensors, only a SQUID magnetic field sensor is used to detect quite small magnetic field from biological activity, e.g., human brain and heart fields. However, low temperature facilities are required to operate SQUID sensors, and thus high sensitive magnetic field sensors operated at room temperature are desirable to detect the small bio-magnetic signals without large medical facilities. One of the candidates is a magneto-impedance sensor[1)] which is comprised of an amorphous ferromagnetic wire and winding coils; we refer to this sensor as an amorphous wire sensor.

The amorphous wire for the magnetic field sensor is known to have a special domain structure due to its induced magnetic anisotropy and shape anisotropy, i.e., magnetization in the wire surface layer points in the circumferential direction and one in the wire center points along the wire axis. When the wire is placed in the magnetic field, the surface magnetization canted slightly along the field direction. The pulse current flowing along the wire tends to rotate back the surface magnetization in the circumferential direction, which induce the induction voltage to the coil winding the wire. The ultimate sensitivity of the amorphous wire sensor will be the thermal stability of the domain structure. For the detection of the bio-magnetic field of around 1 pT, the thermal stability factor K_uV should be larger than M_s × 1 pT, where K_u, V, and M_s are the uniaxial anisotropy, volume, and magnetization of the wire, respectively. If we assume the K_u = 1 kerg/cc and M_s = 1000 emu/cc, which corresponds to saturation field of 2 Oe, the necessary dimension to have sufficient K_uV for the detection of 1 pT is estimated to be 4 μmϕ x 500 μm, which is smaller than the present amorphous wire sensor.

The present amorphous wire sensor utilizes the wire of 15 μmϕ × 500 μm and winding coil with a turn number N of 16 (coil pitch of 30 μm), and it is reported to detect the magnetic field of 10 nT[2)]. Since the sensitivity of the wire is roughly proportional to NL^2 / D^2, where L and D are the wire length and diameter, respectively, the wire dimension of 5 μmϕ × 900 μm and winding coil with a coil pitch of 2 μm, corresponding to turn number of ~400, are estimated to be required. In this talk, we describe the micro-fabrication of the amorphous wire sensor with a coil pitch of 5.5 μm, and report the output of the sensor by flowing the pulse current in the wire under an external magnetic field. Figure 1 shows the optical micrograph of the micro-fabricated amorphous wire sensor with a wire dimension of 15 μmϕ × 420 μm and coil turn number of 42. The output signal of this sensor was confirmed to have 3 times larger amplitude than that of commercially available magneto-impedance sensor which has a coil turn number of 16.

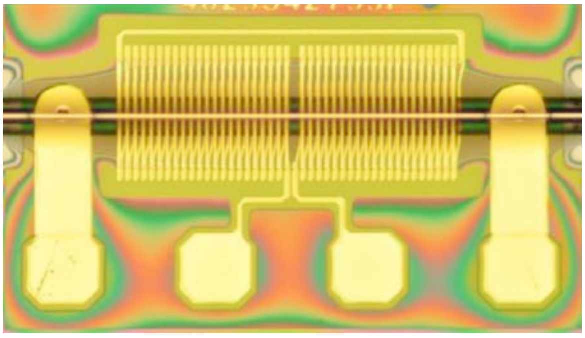

Fig. 1 Optical micrograph of the micro-fabricated amorphous wire sensor with a wire of 15 μmϕ × 420 μm and winding coil with a pitch of 5.5 μm.

Reference
1) L. V. Panina *et al*., Appl. Phys. Lett., **65**, 1189 (1994).
2) N. Hamada *et al*., PIERS Proc. 860 (2014).

Micromagnetic analysis of dynamic magnetization process in an amorphous wire for MI sensors

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MI sensors based on the magneto-impedance effect in amorphous wires are nowadays widely used in electric compasses, thanks to their small size and high sensitivity [1]. Recently, MI sensors with ultrahigh sensitivity have been studied for application to wearable computers and medical devices [2]. To realize these applications, it is of prime importance to analyze dynamic magnetization process in amorphous wires. In this symposium, we introduce micromagnetic analysis of dynamic magnetization process in an amorphous wire by using Landau-Lifshitz-Gilbert (LLG) equation taking into account the eddy current.

A schematic structure of an MI sensor is shown in Fig.1. A pickup coil is wounded around an amorphous wire. The amorphous wire has a circular magnetic anisotropy arising from the coupling between negative magnetostriction and frozen-in stress. Without external magnetic field H_{ex}, the magnetization in the wire forms the vortex structure in the *yz* plane, as shown in Fig.1. When H_{ex} is applied, the magnetization is tilted to the *x* direction by the field. As the pulse current whose change rate is in the order of MHz-GHz is applied, the magnetization turns back into the *yz* plane due to the Oersted field generated by the current. Simultaneously, the pickup coil detects the change in magnetic flux that arises from the rotation of the magnetization. Because of the high frequency of the current, it is necessary to take into account the eddy current effect in the wire to accurately calculate the dynamics of the magnetization process.

In the LLG simulation, the amorphous wire is treated by a 2D model, assuming that the magnetization distribution in the *x* direction is uniform. It is because their typical length (several hundred μm) is much larger than their diameter (~10 μm), and can be approximated as infinite. The pulse current field including the eddy current effect is incorporated into the effective field in the LLG equation. Fig.2 shows the magnetization process with and without the eddy current effect in the wire. The diameter of the wire is 10 μm, and the mesh size is 20 nm to compute the magnetic domain structures accurately. Saturation magnetization M_s, circular magnetic anisotropy H_k, and resistivity ρ are 1 T, 500 A/m, and 130 μΩcm, respectively. The pulse current height is 0.39 A and the rise time is 0.8 ns. The initial magnetization is aligned in the axial (*x*) direction. The magnetization rotates toward the *yz* plane due to the circular anisotropy and the pulse current field. As shown in Fig.2, the eddy current affects the motion of the magnetization drastically. In this symposium, we will show some simulation results to understand the phenomena in the amorphous wire.

Reference
1) http://www.aichi-mi.com/mi-technology/.
2) T. Uchiyama *et al*., IEEE Trans. Magn., 48, 3833 (2012).

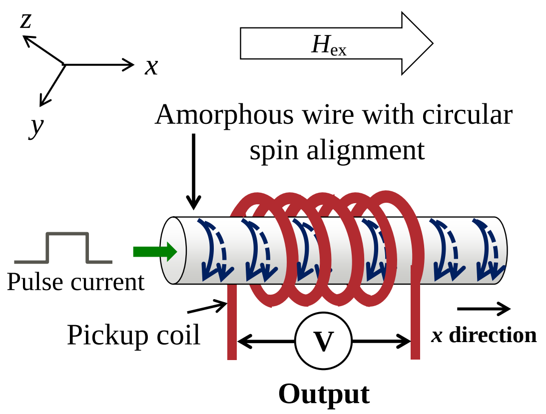

Fig.1 Structure of the MI sensor element

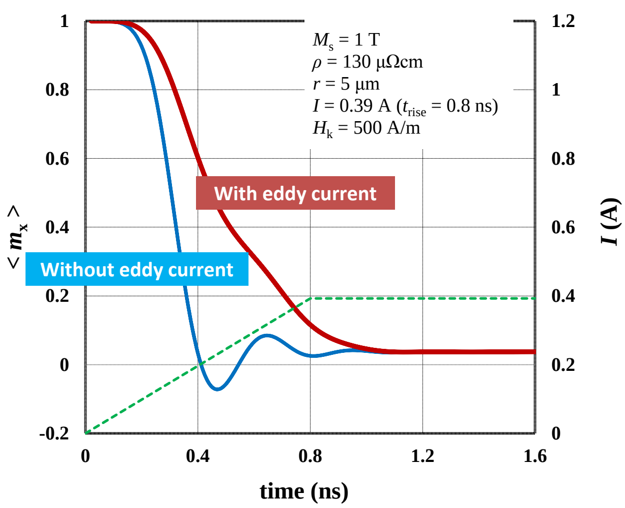

Fig.2 Response of magnetization in the wire to the pulse current with/without the eddy current effect

Signal-Noise Ratio Improvement of Magnetic Tunnel Junctions for Detection of Bio-Magnetic Field

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The discovery of large tunnel magneto-resistance (TMR) effect at room temperature in magnetic tunnel junction (MTJ) has spurred intensive investigation of MTJ applications for spin-electronics devices, such as magnetic random access memory and various magnetic field sensors. For sensor applications, low power consumption and small device size of MTJ make them prime candidates for next generation magnetic field sensor. In addition, from the feature that operate at room temperature, MTJ enables detection of bio-magnetic field (e.g. magnetocardiogram (MCG), magnetoencephalogram (MEG)) without liquid He (Fig.1). However, sensitivity and noise reduction are insufficient in MTJs have been developed. In this work, we fabricated MTJ with antiferromagnetic coupled bottom free layer for high sensitivity, and MTJs were connected series-parallel to reduce noise.

MTJ films were deposited on to thermally oxidized Si (001) wafers using DC/RF magnetron sputtering system. MTJs were micro-fabricated by photolithography process and Ar-ion milling. After micro-fabrication, MTJs were annealed 260 - 350 ^{o}C with applied magnetic fields of various directions. Fig.2 shows *R-H* curves of MTJ with CoFeSiB/Ru/CoFeB antiferromagnetic coupled free layer. High sensitivity of 115%/Oe was observed in single MTJ[1)].

Fig.3 shows a schematic image of signal and noise measurement. Series-parallel connected MTJs were placed in the center of the Helmholtz coil, the output voltage was amplified by the 100 dB amplifier and input to the oscilloscope. Fig.4 shows MgO barrier thickness dependence of signal voltage, noise voltage and S/N ratio measured from 18 Hz, 120 $nT_{p\text{-}p}$ input magnetic field. Both signal and noise decreased with decreasing MgO thickness. From this relation of signal and noise, maximum 154 S/N ratio was acquired by 2.2 nm MgO thickness. The Detectivity *D* (*D* = noise/signal) of MTJs with 2.2 nm MgO barrier was 0.8 nT, this value is possible to measure cardiac magnetic field by performing integration of the order of 100 times.

Acknowledgment This work was supported by the S-Innovation program, Japan Science and Technology Agency (JST) and Center for Innovative Integrated Electronic Systems, Tohoku University.

Reference 1) D. Kato *et al.*, APEX, **6** (2013) 103004.

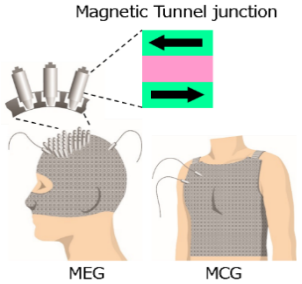

Fig.1 Schematic image of bio-magnetic field sensor using magnetic tunnel junctions.

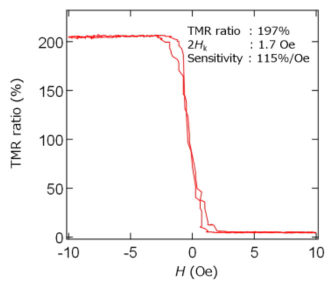

Fig.2 *R-H* curve of MTJ with CoFeSiB/Ru/CoFeB synthetic coupled free layer.

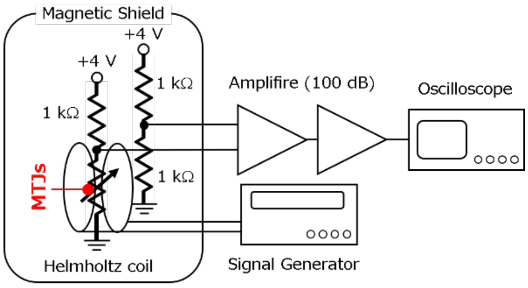

Fig.3 Schematic image of signal and noise measurement system.

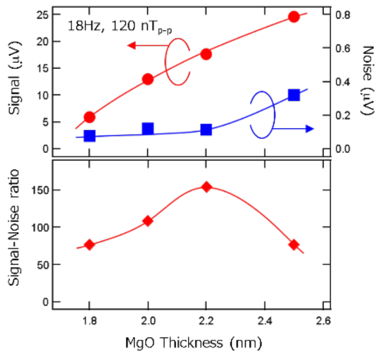

Fig.4 MgO barrier thickness dependence of signal voltage, noise voltage and

Development of pT resolution magnetic sensor utilizing MI element towards medical use

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(Nagoya University)

Magnetization dynamics by pulse excitation in amorphous wire is limited in the surface layer by skin effect due to magnetic rotation. We have constituted highly sensitive linear micro magnetic field sensors utilizing Off-diagonal Magneto-Impedance (MI) effect. Recently we have succeeded in producing pico-Tesla (10^{-8}Oe) resolution MI sensors due to ultra-low intrinsic magnetic noise of amorphous wire [1].

Superconducting quantum interference deice (SQUID) have ultrasensitive, which have been utilized for bio-magnetic signals. For example, magnetocardiography (MCG) is a noninvasive technology that measures the magnetic field of the heart. It was developed for general-purpose use as a noninvasive, noncontact diagnostic tool for detecting obstructive coronary artery disease (CAD), and especially for detecting cardiac ischemia. Recently, MCG study using highly sensitive magnetic sensors, which can operate at room temperature, have been reported [2),3)].

We have tried to measure MCG signal using MI gradiometer. Fig.1 shows magnetic signal along with ECG sensor at 4 cm left the pit of the stomach. The subject was a man. A distance between from sensor head to a body surface is about 3 mm. The magnetic signal shown was averaged for ten times. The magnetic wave form was confirmed that is similar to the ECG wave form. By contacting sensor head to on shirts we recorded cardiac magnetic field of premature ventricular contraction as shown in Fig.2.

The SQUID has been also used to measure the human brain. The application of brain signals detection was developed in various fields. In medicine area, it could be implemented in such as brain injury inspection, diagnosis of neocortical epilepsy, telemedicine or cognitive functions research. And with advances in sensing technology, neuroprosthetics applications based on brain computer interfacing (BCI) could be improved and used to restore damaged hearing, sight or movement.

Event-related potentials (ERP) is one of the important biosignals of the brain which has a wide application in examining brain activity and cognitive functions. The P300 (or P3) is one of the ERP components which normally elicited in the process of making decisions. We have recorded of the waveforms of mean P300 magnetic field in occipital region elicited by audio stimuli, for several subjects. Brainwave measurement results of MI sensor will be presented and the results will be compared to SQUID's or EEG's results.

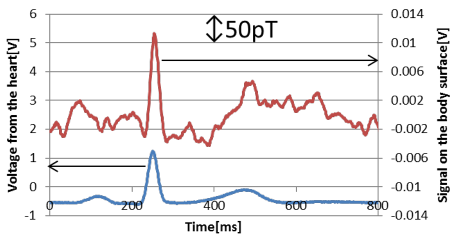

Fig.1.Voltage from the heart and Signal on the body surface at 4cm on the left of the pit of the stomach.

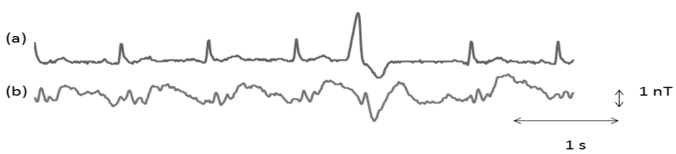

Fig.2. Recorded premature ventricular contraction of ECG in (a) and MCG by MI in (b).

Reference

1) T. Uchiyama, K. Mohri,Y. Honkura, L.V .Panina, *IEEE Trans. Magn.*48(10), 3833-3889, (2012).

2) H. Karo and I. Sasada, *J. Appl. Phys.* 117, 17B322 (2015).

3) S. Yabukami, K. Kato, T. Ozawa, N. Kobayashi and K.I. Arai, *J. Magn. Soc. Jpn.*, 38, 25-28 (2014) .

Thermally stable magnonic sensors using spin wave differential circuits

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Magnetic field sensors using spin wave propagating in the yttrium iron garnet (YIG) was proposed[1)]. Experimentally its high sensitivity, ~38 pT/Hz, was demonstrated with the artificial magnetic lattice (AML) composed of copper stripes onto YIGs2,3), but the thermal instability of magnetization of YIGs prohibited spin waves from moving to device steps. To solve this issue, we used the spin wave differential circuit (SWDC) comprising two YIG films magnetized in opposite directions. Figure 1 shows the fabricated SWDC. This setup was put into the thermostat chamber and the magnetic-field sensitivity was measured by changing the applied field by Helmholtz coil. Figure 2 shows the thermal sensitivity of circuit A alone, B alone and SWDC. The obtained thermal stability of SWDC was -9.5×10^{3} ° K^{-1}. This was about 2×10^{3} times better than single circuits. The sensitivity to the change of magnetic field was same with single circuit. This prototype of spin wave magnetic-field sensor can be minitualized with decreasing of the thickness and wavelength of spin waves. Details of measurement setup, tuning method of actual device, and fundamental properties of magnonic crystals modulating propagation properties of spin wave will be discussed in the symposium.

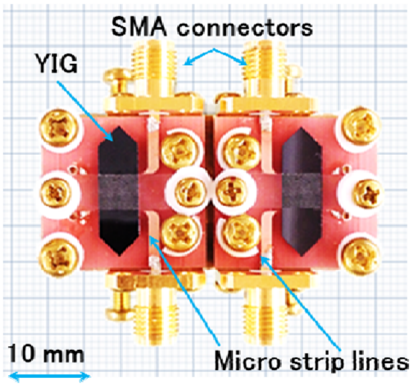

Fig. 1 Top view of the spin wave differential circuit composed of two YIG films placed onto four microstrip lines. Two YIGs are magnetized in opposite direction each other by bulk $Nd_2Fe_{14}B$ magnets embedded in jig composed of brass. Four microstrip lines are electrically connected to the vector network analyzer.

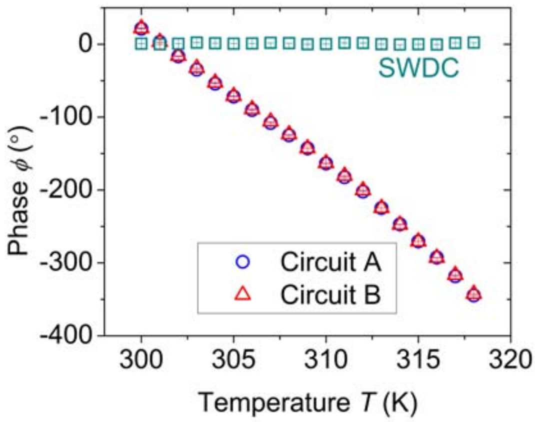

Fig. 2 Phase of spin wave versus temperature. Blue circles and red triangles show that of circuit A and B, respectively. Green squares show that of spin wave differential circuit.

Reference

1) M. Inoue, A. Baryshev, H. Takagi, P. B. Lim, K. Hatafuku, J. Noda, and K. Togo, *Appl. Phys. Lett.* 98, 132511 (2011).
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