The Development of a High Sensitive Micro Size Magnetic Sensor Named as GSR Sensor Excited by GHz Pulse Current

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Abstract— We observed GSR (GHz-Spin-Rotation) effect exhibiting high sensitivity which is related to the GHz speed spins rotation in the surface circular magnetic domain. GSR effect gives output coil voltages to increase with the increase with pulse frequency up to 3 GHz and the relationship between with the coil voltage V and the magnetic field H expressed by $V = V_o \sin(\pi H/2Hm)$. GSR effect gives non hysteresis and low noise. These futures are explained by the spins rotation not accompanied with domain wall movements. We produced various ASIC (Application-Specified integrated circuit) type GSR sensors and demonstrated better performance than that of commercial GMI sensors. Developed GSR sensor can be suitable for the automotive and medical applications.

1. INTRODUCTION

Super high sensitive micro magnetic sensors such as GMI (Giant Magne to Impedance) sensor [1–5], tMR sensor and so on has been developed toward to IOT (Internet of Things) age. In the process to improve GMI sensor we discovered a new type magnetic sensor named as GSR (GHz-Spin-Rotation) sensor [6] and developed ASIC type GSR sensors to have good magnetic performance.

The GMI effect [3] based on movement of 90 degree magnetic wall close to the surface was discovered using amorphous ribbon by Prof. V. E. Makhotkin [7] in 1991. Prof. Mohri [8] improved the performance using amorphous wire and a negative feedback circuit in 1993 and developed a coil pickup type of GMI sensor [9] to equip a good temperature stability in 1999.

In 2006 ASC type GMI sensor [10] combined with a micro size element and ASIC was developed and widely used as electronics compass for mobile phones. GMI sensor has advantages in super high sensitivity, high ODR (output data rate) and low consumption power but a lot of disadvantages on some magnetic properties such as narrow measuring range, nonlinearity, hysteresis, big noise and on poor cost performance compared to semiconductor type magnetic sensors. Many studies has been carried out to improve the total performance on GMI sensors, but they meets difficulty.

The principle of coil pick up type GMI effect [3, 5, 6, 10, 15] performed by amorphous wires with zero magnetostriction is based on the skin effect induced by high frequency current or pulse current of about 10 MHz. The wire presents a specific magnetic domain structure which consists of surface magnetic domains with circular magnetization orientation and the inner magnetic domains with axial direction magnetization separated by 90 degree domain walls. The wall is moved from the surface to the inner side of the wire by pulse current of MHz frequency. The movement makes rotation of axial direction magnetization and the coil voltage of $\Delta\phi(= \Delta B \cdot S)/\Delta t$. By integrating the voltage, $B(= \int \Delta B \Delta t)$ and the magnetic field $H(= B/\mu)$ are obtained.

Authors started to study the improvement of GMI sensor based on a hypothesis that a coil voltage might be increased by the pulse current of GHz frequency [5, 6] if spins existing in circular magnetic domains can be rotated at GHz high speed and the magnetic properties characterized by low magnetic noise, no hysteresis and good linearity might be obtained if the domain wall movement cannot be made by the pulse current of GHz frequency.

However it was predicted that the rotating magnetization produced by spin rotation might has a small value compared to that of GMI effect. We made an effort to increase the electromagnetic interaction between the wire surface and the coil by decreasing the gap between the wire and the coil from 20 µm to 3 µm. We developed a new technology named as 3 dimensional photolithography technique [1] and produced GSR elements with micro coils on Si wafer which equips 3 µm gap between the surface and inner diameter of the coil and the coil pitch of 5.5 µm. Current GMI sensor has the big gap of 20 µm and the rough coil pitch of 30 µm.

In 2015 we found using micro type elements that the coil voltage is increased with GHz pulse current and that the relationship between magnetic field and coil voltage was expressed by a sin

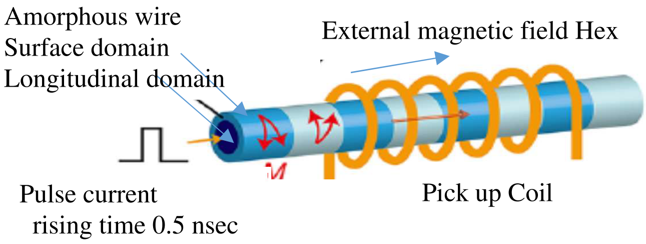


Figure 1: Principle of GSR effect.

function [1, 6]. And we found to show no hysteresis. We thought these futures of GSR sensor might be caused by new electromagnetic phenomena to make magnetization rotation forced by spin rotation with GHz speed excited by GHz pulse current not accompanied with movement of magnetic walls and we named it as GSR (GHz-Spin-Rotation) effect [1, 5, 6].

We presented the interesting results in IWMW2015 held in Spain and got US patent [6] in 2018 and then produced prototype samples of ASIC type GSR sensor suitable for Automotive use, compass use and medical use. The present paper reports the characteristic of GSR effect and the performance of ASIC type GSR sensors.

2. EXPERIMENTAL PROCEDURE

2.1.

The principle of GSR effect induced in amorphous wires with zero magneto-striction is based on the spin rotation in the surface domain driven by GHz pulse current shown in Fig. 1. The wire has a special magnetic domain structure which consists of surface domains with circular spin, axis magnetic domains and 90 degree magnetic wall existing between two domains. When external magnetic field is applied to the wire along axis direction, electronic spins in surface domains tilt toward the axis direction with the angle dependent on the magnetic field strength accompanied with an axis direction magnetization in the surface domain. The axis magnetic domains induce axis direction magnetization. GHz pulse current passes through the wire to make strong circular magnetic field and makes only spin rotation with GHz angular velocity but no movement of the magnetic wall because of strong skin effect induced by GHz current pulse.

2.2.

The present GSR element uses a glass coated amorphous wire [14] with a diameter of 10 µm produced by Talor-Ulitovky technique. This wire has a composition of $Co_{50.7}Fe_{8.1}B_{13.3}Si_{10.3}$ and permeability of 1800. The element is produced through a following process shown in Fig. 2. First step is to form a groove with a width of 18 µm and a depth of 7 µm on the Si wafer by etching. Second step is to produce a bottom coil pattern with a coil pith of 5.5 µm using 3 dimensional photolithography on the Si wafer coated by resist. Third step is to set the amorphous wire along the groove by an aliment machine. Fourth step is to mold the wire using an adhesive resist. Fifth step is to produce a upper coil pattern with a coil pith of 5.5 µm using 3 dimensional photolithography on the adhesive resist.

Various GSR elements in the experiments have the length of 0.16 mm, 0.45 mm and 0.96 mm, wire resistance of 3 Ω, 8 Ω, 4.5 Ω and 13 Ω, coil turn numbers of 14, 32, 66 and 148 and coil resistance of 80 Ω, 210 Ω, 360 Ω and 810 Ω respectively are shown in Figs. 3(a) and (b).

2.3.

The Block diagram of ASIC electronics circuit is same to a conventional GMI circuit [1, 2, 10] but any block is improved as follows. The pulse generator can generate some kinds of pulse currents with frequency of 1 GHz to 3 GHz defined by $f = 1/2\Delta t$, (where Δt are the rising time or falling time) and with the amplitude of 200 mA and the interval time of 10 nsec. An electronic switch can operate with a very small interval of 0.1 nsec between on and off. An adjustment circuit can control a detection timing from 0 to 40 nsec by interval of 0.1 nsec. AD converter has 16 bits. The I2C communication is used to send data to MCU. Consumption current is about 0.4 mA @ ODR of 5 KHz.

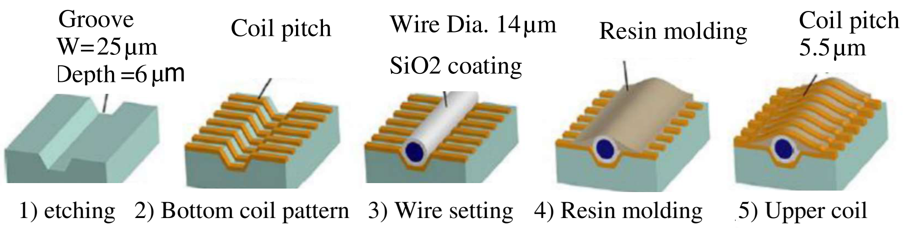


Figure 2: Production process to produce GSR element.

2.4.

The experiments using GSR sensor produced by connecting with ASIC and GSR elements by wire bonding (Fig. 3(c)) are carried out to examine the effects of pulse frequency, detection timing, coil turn numbers and wire permeability on magnetic properties such as sensitivity, relationship between magnetic field and col voltage, measuring rage, linearity, noise and hysteresis. The effect of frequency is examined by changing transition time of pulse current Δt from 0.2 nsec to 1 nsec where pulse frequency f is defined by $f = 1/2\Delta t$.

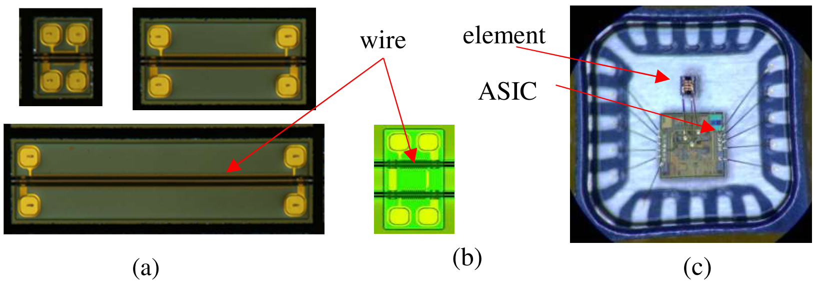


Figure 3: Various types of GSR elements and ASIC used in experiments. (a) One wire types with length of 0.16 mm, 0.45 mm, 0.96 mm. (b) Two wire type with 0.16 mm. (c) ASIC connected with a GSR element.

3. RESULTS AND DISCUSSIONS

3.1. Coil Voltage of GSR Sensor [6]

A coil voltage of GSR sensor observed under a frequency of 1.5 GHz under applied magnetic field of ± 720 A/m is shown in Fig. 4. It takes a maximum value about the time of 1 nsec and then decreases. The maximum value increases with increase of magnetic field and takes opposite value by positive and negative. It is noted that the coil voltages at $H = 0$ A/m are under 4% compared to the magnetic signal at $H = 720$ A/m.

On contrary GMI Sensor has a big electric signal voltage of roughly 30% compared to the magnetic signal voltage. That signal suffers the temperature stability of GMI sensor because the electric signal voltage caused by parasitic capacitance is dependent on temperature.

A relationship between the coil voltage and the magnetic field at the detection timing to show the maximum voltage of the falling process is shown in Fig. 5. There is a surprising result that the relationship ship has a sin function expressed by an equation as $V = V_0 \cdot \sin(\pi H/2Hm)$. Where Hm is defined as the magnetic field strength according to the maximum coil voltage V_0. The experimental data results that Hm is nearly equal to the anisotropy Hk of the amorphous wire, that is, $Hm = 0.96Hk$. When the wire length makes short, the effective anisotropy Hk increases accompanied with the increase of Hm resulting in the extension of the measurement range.

3.2. Sensitivity of GSR Sensor

The effect of pulse current frequency on the sensitivity of GSR sensor type of length = 0.26 mm is studied by changing from 1 GHz to 3 GHz as shown in Fig. 6, where the sensitivity (mV/G) is defined as coil voltage (mV) by magnetic field(G). The experimental result shows the coil voltage increases with the increase of frequency following saturation up to over 3 GHz and correspond to the theoretical effect that the coil voltage increase in proportion to the square of the frequency $\sqrt{f}$. The spins existing the surface magnetic domain which has circular spin aliments can rotate at the angular velocity $\omega(= 2\pi f)$ driven by GHz pulse current and the high speed spin rotation

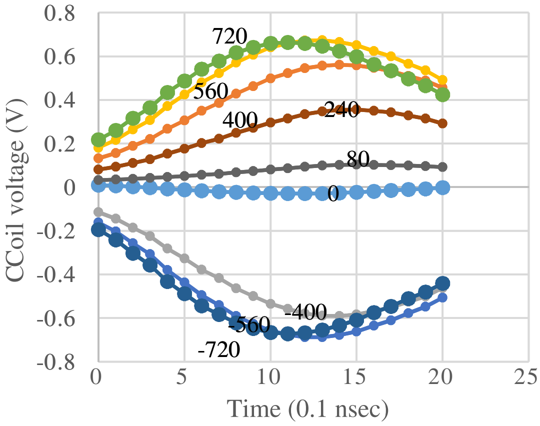


Figure 4: Coil voltage wave vs magnetic filed (A/m).

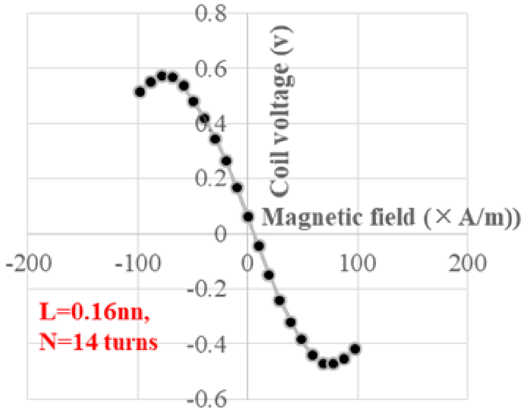


Figure 5: Coil voltage vs magnetic field.

causes the big coil voltage $V(= -\Delta\varphi/\Delta t)$. By the way, the reason to take saturation over 3 GHz is probably because the angular velocity of spin of $2\pi f$ forced by pulse frequency f might decrease due to influence of the eddy current.

On the contrary, the output $\Delta Z/Z_0$ of GMI sensor has a maximum value of around 10 MHz and comes close to zero over 100 MHz [3]. The GMI effect is caused by movement of 90 degree domain wall existing between surface circular domain and axial domain at the frequency of 10 MHz which produces big skin effect proportional to magnetic field strength. When the frequency increases over 100 KHz, the wall moves only slowly due to the influence of big eddy current resulting in the decrease of $\Delta Z/Z_0$. The GSR sensor based on GHz pulse has a very deferent effect of frequency on the sensitivity.

Rising detection [1, 2] makes 40% higher sensitivity than that of falling detection as shown in Fig. 7. In rising process, spins in surface domain tilted with angle $\theta(= \tan^{-1} H/Hm)$ toward the axial direction by magnetic field are rotated toward the circular direction driven by GHz pulse current. This process makes high speed rotation of spins. In falling process, the spins align toward the circular direction and then rotate spontaneously or without the forced circular magnetic field to a balanced state of angle θ so that falling process has somewhat slow spin rotation speed compared to that of rising process.

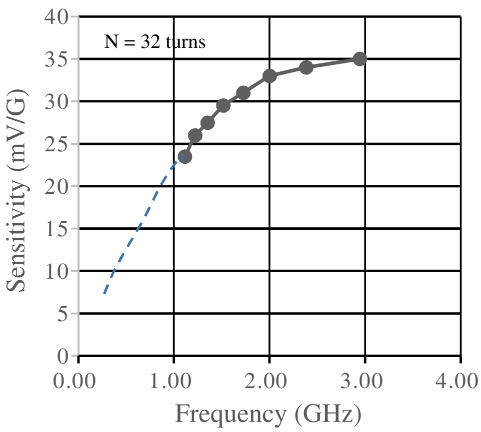


Figure 6: Effect of frequency on sensitivity.

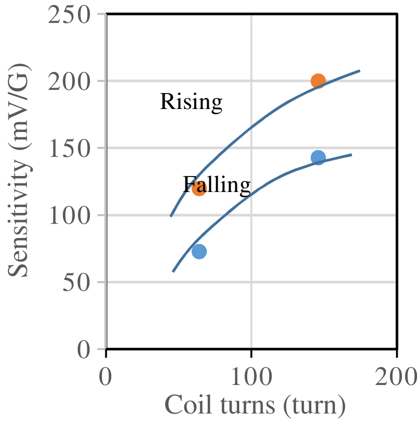


Figure 7: Sensitivity of falling and rising.

The sensitivity increases proportional to coil turn numbers as shown in Fig. 8, where coil turn numbers change from 16 turns to 148 turns keeping same wire length of 0.96 mm. The influences of increase of coil resistance and parasitic capacitance accomplished with increase of coil turn numbers are not observed as long as present test conditions. The sensitivity increases proportional to effective permeability as shown in Fig. 9, where wires tested with intrinsic permeability of 1800 and the diameter of 10 µm has effective permeability of 150 and 460 controlled by wire length of 0.16 mm and 0.26 mm respectively.

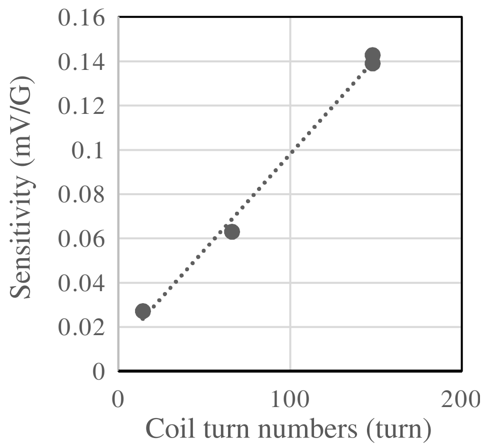


Figure 8: Effect of coil turn numbers on sensitivity.

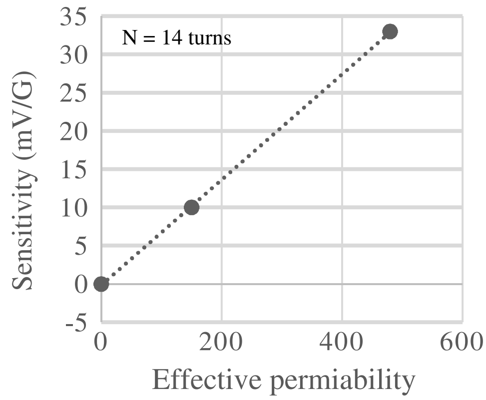


Figure 9: Effect of permeability on sensitivity.

It is found that the sensitivity of GSR sensor is effected by pulse frequency, detection type of falling or rising, coil turn numbers and effective permeability.

3.3. Other Magnetic Properties

Figure 10 shows both linear lines of an inversed voltage by $\pi H/2Hm = \arcsin(V/V_0)$ and a regression line. It is found the linear relationship [6] between coil voltage and magnetic field gives good linearity of 0.5% FS and an extension of the measuring range of from 960 A/m (linear approximation) to 7200 A/m (dependent on Hm). On the contrary GMI sensor output is based on BH curve of amorphous wire not characterized by some kind of mathematical equation so that a collinear approximation of BH curve cannot extend the measuring range. The narrow measuring range of GMI sensor is one of big disadvantage.

Figure 11 shows the result that rising detection of GSR sensor makes no hysteresis as well as falling detection. GSR effect detects only spin rotation around the wire surface so that hysteresis does not occur. On the contrary, GMI sensor makes a big hysteresis [11] in the case of rising detection but falling detection gives almost no hysteresis due to the effect of pulse annealing which causes an initial magnetic state with no hysteresis. Rising detection is important for developing high ODR type GSR sensor of over 1 MHz. It means GSR sensor has bigger potential ability than GMI sensor.

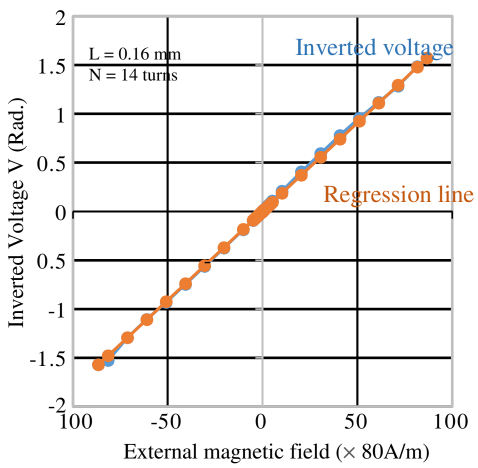


Figure 10: Inverted coil voltage vs regression line.

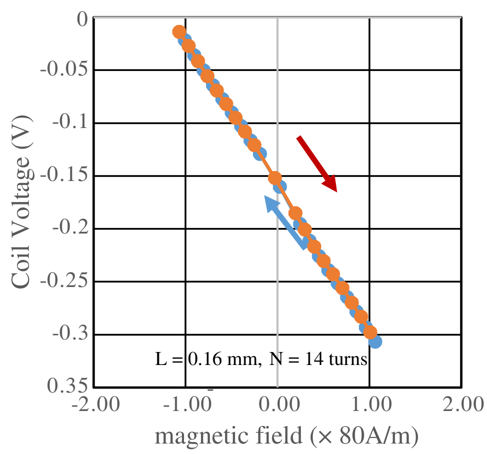


Figure 11: Hysterisis of GSR sensor under pulse rising detection.

Figure 12 shows the result that σ-noise becomes small to 40 µV under $H = 7200$ A/m when falling detection is carried out around peak position of the coil voltage. It means magnetic noise of GSR sensor occurs only 10 µV because the ASIC has own noise of 30 µV. The frequency of pulse current takes the designated frequency of 1.5 GHz around peak position but becomes low at the

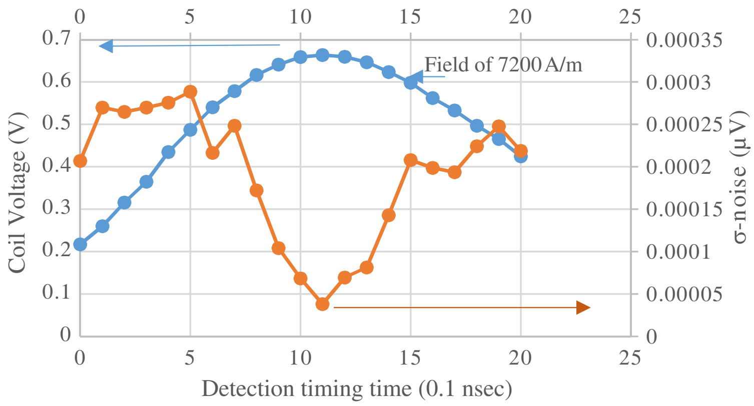


Figure 12: Detection timing vs σ-noise.

initial and ending time of pulse current. The reason to take high noise beside the peak timing is probably that the High frequency generates spin rotation accompanied with low noise and the Low frequency induces the domain wall movement to make big noise proportional to magnetic field strength.

Figure 13 shows effects of tension treatment [12] at room temperature on hysteresis, sin functionality and noise. When tension takes 1 cN, not good results occurs in spite of GSR sensor. One is hysteresis occurs under rising detection of GSR sensor. Second is the relationship is not characterized by sin function in spite of falling detection. Third is noise increases compared to that of tension of 7 cN. The reason is supposed that the tension supports GSR effect by increasing surface circular magnetic domain and by pushing 90 degree magnetic wall into inner position of the wire not to suffer GSR effect.

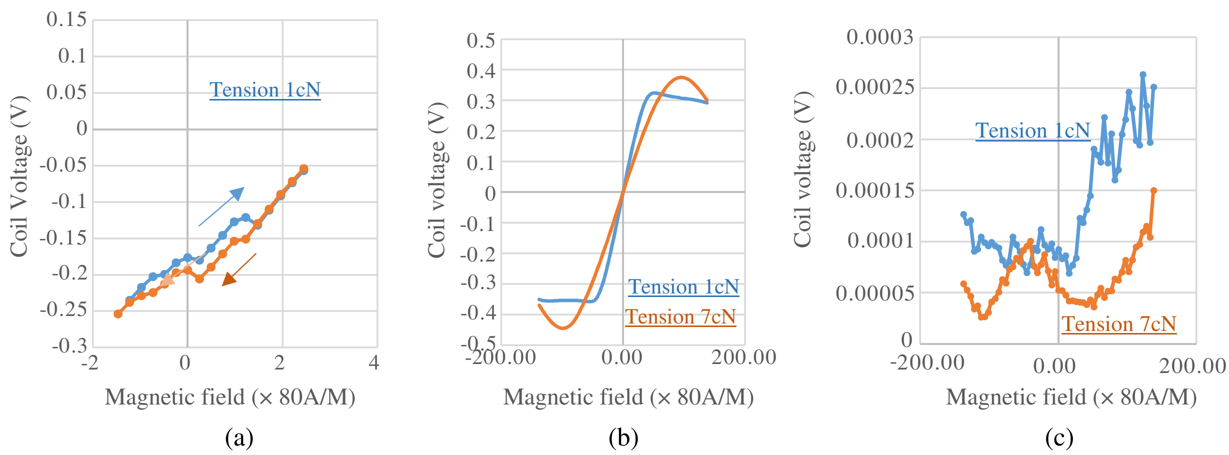


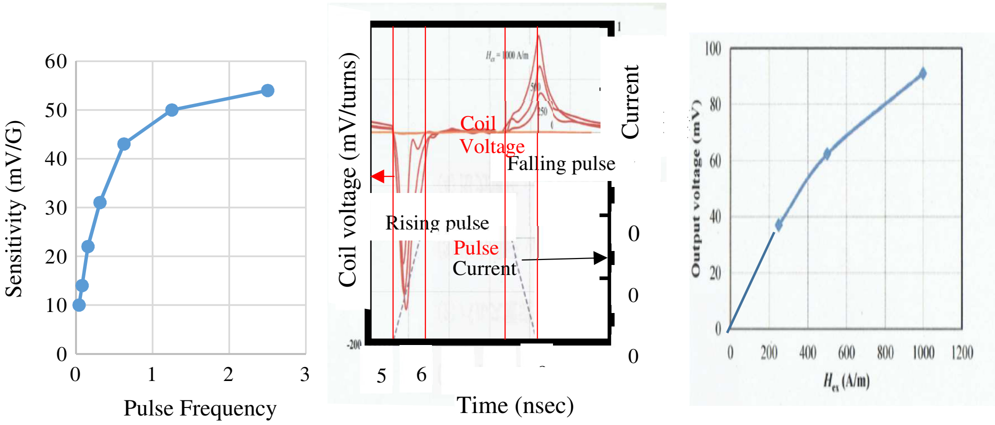
Figure 13: Effects of tension treatment on coil voltage ($L = 0.16$ mm, $N = 14$ turns). (a) Hysteresis under Rising. (b) Sin function under falling. (c) σ Noise vs magnetic field Under falling.

3.4. The Mechanism of GSR Effect

Dr. Y. Uehara [13] studied the mechanism of GSR effect using LLG equation computer analysis under spin vortex model of amorphous wire with the diameter of 10 μm and reported the results in Fig. 14. As for the frequency dependence, the sensitivity increases with increase of pulse frequency up to 3 GHz. The rising coil voltage has about 50% larger than the falling coil voltage. The relationship between magnetic field and coil voltage shows sin function. These results are similar to our experimental results. These results suggest that GSR effect will be based on spin rotation without movement of magnetic walls.

4. DEVELOPMENT OF ASIC TYPE GSR SENSOR

We developed four prototypes of GSR sensors with the length of 0.16 mm, 0.26 mm and 0.45 respectively as shown in Table 1. Type 0.16 mm has wide measuring range of 6400 A/m. It is suitable



(a) (b) (c)

Figure 14: Results calculated by LLG equation. (a) Sensitivity dependent on frequency. (b) Rising vs falling. (c) Magnetic field vs coil voltage.

for applications in automotive use to detect strong magnetic field generated by magnets used in sensor system. Type 0.26 mm has good balance performance of high ODR and low noise and is expected to be used for electronic compass with magnetic gyro functionality. Type 0.45 mm has high sensitivity and it will be applied for magnetic positioning system.

Table 1: Performance of various ASIC type GSR sensors.

Types L: length(mm) W: wire number N:coil turn numbers	Length×width =Element size	Sensitivity	σNoise @5KHz	S/N ratio	Measuring range	Total performance index	Typical Applications futures
	mm×mm	mV/G	∗μV mG		A/m	index	
GSR sensor L0.45*W1*N64	0.45×0.3 (1.2)	63 (20)	∗60 1mG	1050 (22)	2400 (2.5)	66	Positioning High sensitivity
GSR sensor L0.26*W1*N36	0.26×0.3 (2)	40 (12)	∗60 1.5mG	660 (14)	3200 (3.3)	92	Gyro Compass Balance of ODR +noise
GSR sensor L0.16*W1*N14	0.16×0.24 (3)	10 (3)	∗60 6mG	167 (3.5)	6400 (7)	74	Automotive Wide range
GSR sensor L0.16*W2*N28	0.16×0.3 (3)	13 (4)	∗60 3mG	325 (6.9)	6400 (7)	145	Automotive Wide range
MI sensor L0.6*W1*N16	0.60×0.3	3.3	∗70 7mG	47	960	1	compass

Total performance index = S/N ratio × measuring range × element size. ( ) means How large better than MI sensor.

The performance of GSR sensor developed are shown in Table 1 comparing commercial type of GMI sensor. Exact comparison is difficult because the sensor performance consists of sensitivity, noise, S/N ratio, measuring range, ODR speed, element size, consumption current, cost and so on. More over a lot of parameters have trade-off relationship. We attempt to compare both sensors using "Total performance index = S/N ratio × measuring range × element size" assuming similar conditions on consumption current and ODR speed. The comparison suggests that GSR sensor has 60 to 150 times better performance than GMI sensor.

Coil type GMI sensor detects the rotation of wire direction magnetism induced by movement of 90 degree magnetic wall excited by MHz pulse current. The wall movement gives to GMI output the good sensitivity but at the same time makes many dis advantages of big noise, nonlinearity, and hysteresis. On the contrary GSR sensor detects spin rotation with high speed excited by GHz pulse current not accompanied with magnetic wall movements to make good magnetic properties on sensitivity, noise, linearity, and hysteresis.

5. CONCLUSION

We found GSR effect based on the GHz speed rotation of spins existing in surface circular magnetic domain. The effect makes new futures that coil voltage increases with pulse frequency to make big sensitivity and its relationship with magnetic field and coil voltage has the sin function to extend the range of linearity as well as it gives non hysteresis and low noise. These futures are explained by spin rotation not accompanied with magnetic wall movements. We produced various ASIC type GSR sensor and made clear to have the advanced 100 better performance than that of commercial GMI sensor. GSR sensor will contribute to develop a lot of new applications.

ACKNOWLEDGMENT

This work was financial supported by the subsidized projects of METI, NEDO and Aichi prefecture of Japan and carried out under the technological support of Prof. Iwata, Prof. Kato in Nagoya university and Prof. Sasaki in Toyota university of Technology. We wish to acknowledge these supports and their cooperation.

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