TMS2020 , 24 February 2020
Symposium Advanced Magnetic Materials for Energy and Power Conversion Applications

The Development of on-ASIC type GSR sensor excited by GHz pulse current

Outline

1. Background
2. Research on GSR effect
3. How to produce GSR element
4. Development of on-ASIC type GSR sensor
5. Summary

24st February, 2020

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§１:Backgrond:
（１） Development History of amorphous wire type magnetic sensor

80 85 90 95 00 05 10 15 20

Study of Amorphous Wire	Develop of GMI Sensor	Production of E-compass Based on GMI sensor	More sensitive More micro

Using Amorphous wire, coil type Magnetic sensors have been developed

1982 Prof.Onaka produced **Amorphous Wire**

1987 TDK developed **FG sensor**

100KHz→20MHz

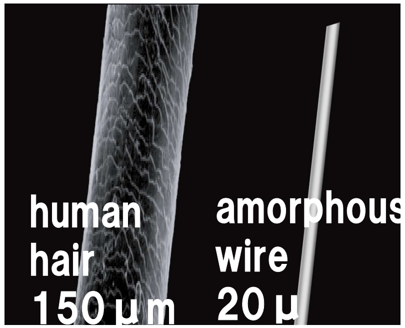
1999 Prof. Mohri Developed **Coil type GMI sensor**

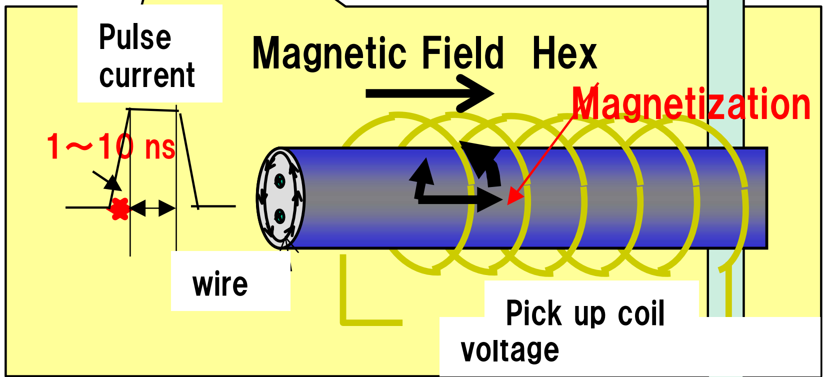
2004-10 Aichi Steel developed **compass**

200MHz→2GHz

2015 Honkura Developed **GSR sensor**

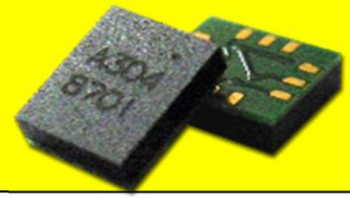
Fe-Co Amorphous wire





Prof. Zhukov produced **Amorphous Wire**

2004- 2010
Aichi Steel developed
Electronics compass
Frequency of 2OOMHz
Size: 2㎜×2㎜×1㎜



1970 Prof.Masumoto produced **Amorphous Metal**

1991 Prof. Makhotkin Discovered **GMI effect**

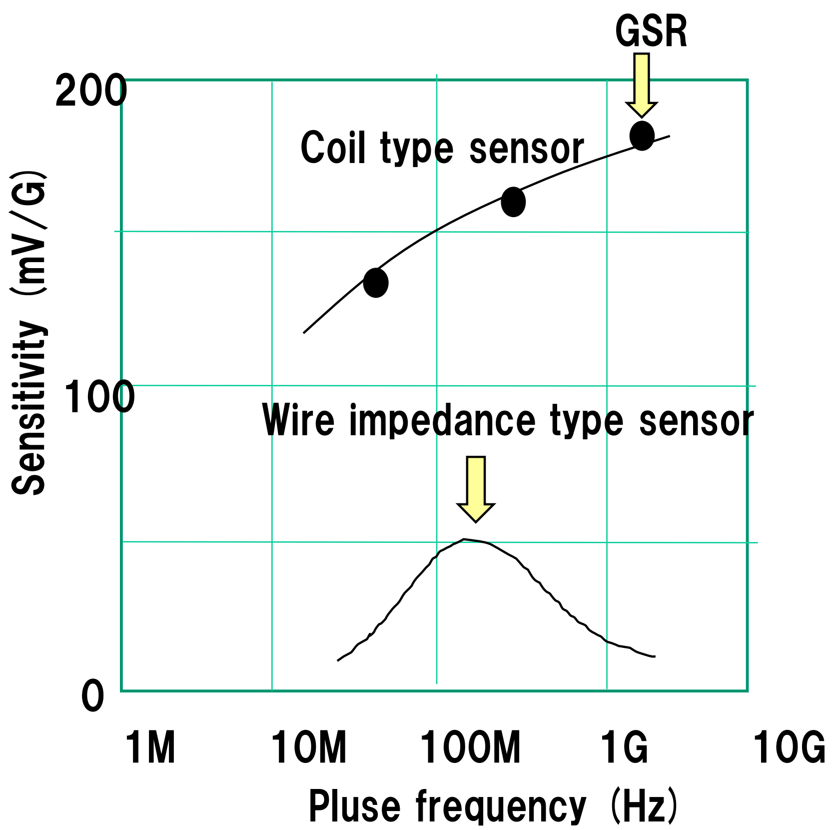
1993Prof. Mohri Developed GMI sensor

§2: Research on GSR effect

(1) Discover GSR effect in 2015

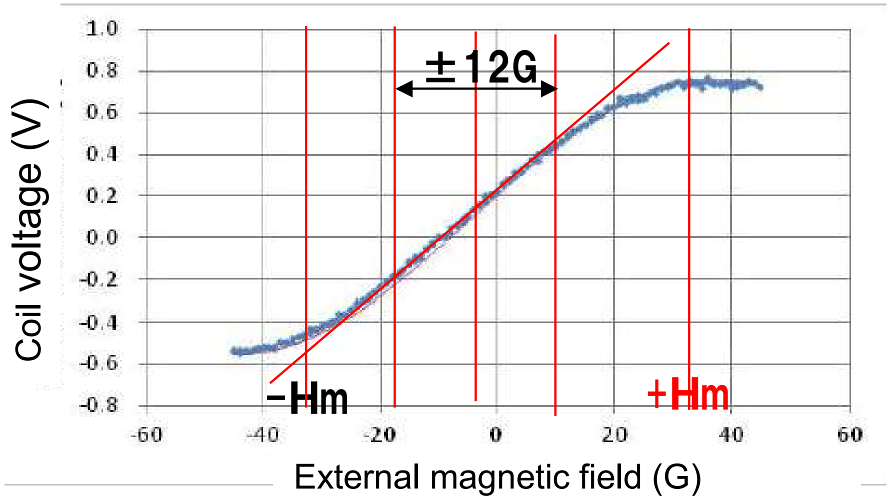
Effect of Pulse frequency on sensitivity

I observed the sensitivity increases with increase of the pulse frequency up to 2GHz .

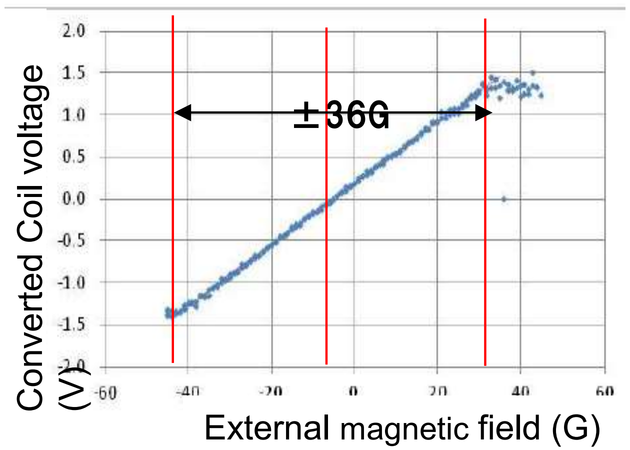


I found a sine functional relationship between the output voltage and magnetic field.

$V=V_0 \sin(\pi H/2Hm)$

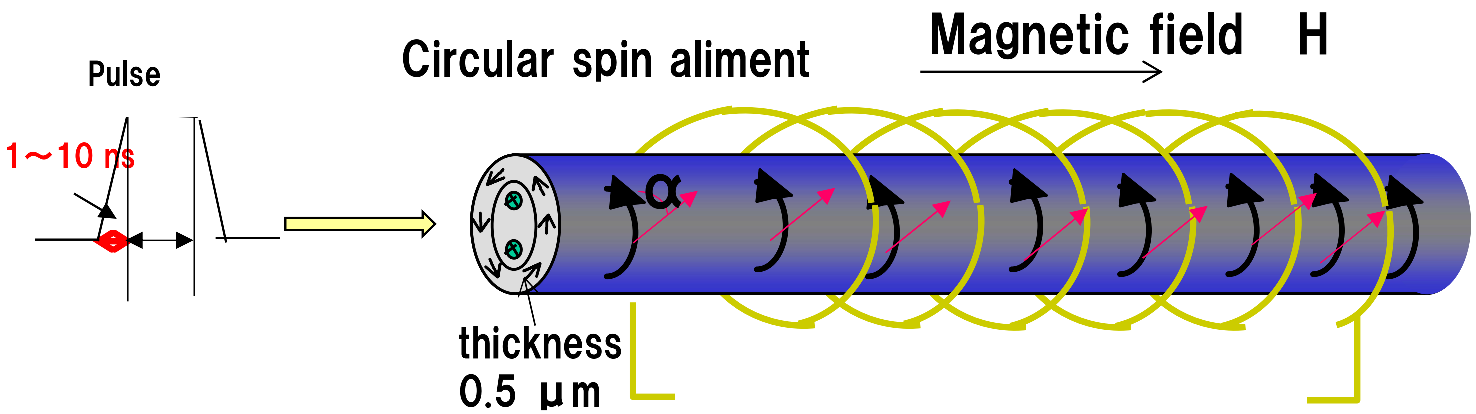


$\arcsin(V/Vo) = \pi H/2Hm$



(2) my hypothesis

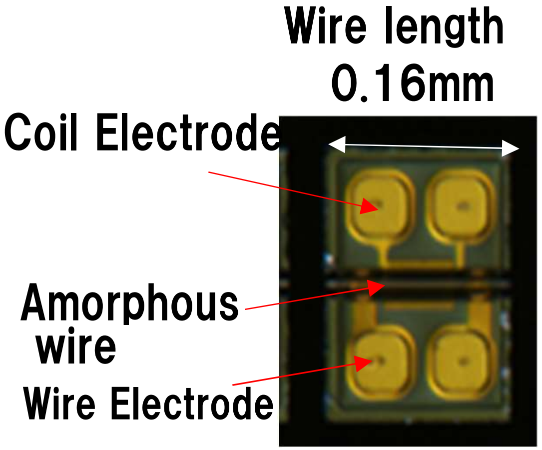
The wire has a surface domains with circular spins. When external magnetic field is applied to the wire along axis direction, spins tilt toward the axis direction. GHz pulse current passes through the wire to make strong circular magnetic field and makes spin rotation with GHz angular velocity. The pickup coil detects themagnetization change to make the coil voltage. It is noted spins can rotate, but the magnetic walls do not move because of strong skin effect induced by GHz current pulse.



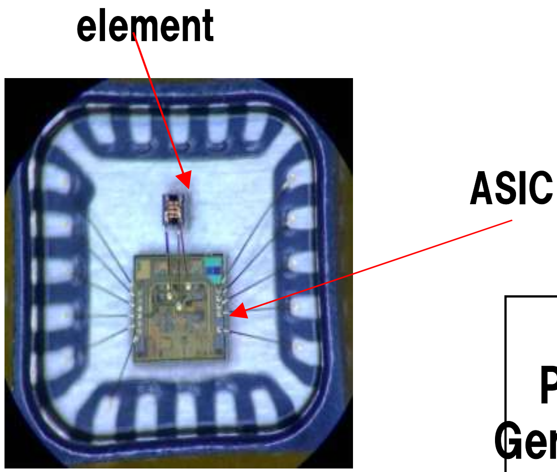
If only spin rotates in the surface magnetic domain,
the coil voltage will be increased proportional to root frequency.
If spins rotes form tilt angle θ ro zero, the change of magnetization is proportional to sinθ、and the changing speed is proportional to cosθ、so that, coil voltage is proportional to sinθ by cosθ、that is, sin 2 θ.
The hypnosis only spins rotate, can explain new result,
So we proposed to name these result as the Ghz-Spin Rotaion effect, that is, GSR effect.

(3) Experiments

a) Test sample

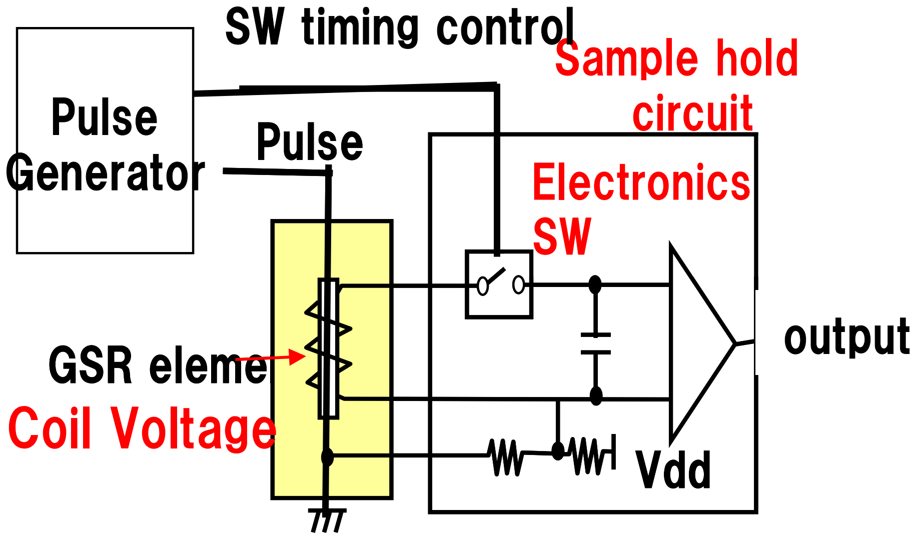


Micro coil type of GSR element



ASIC used in the test

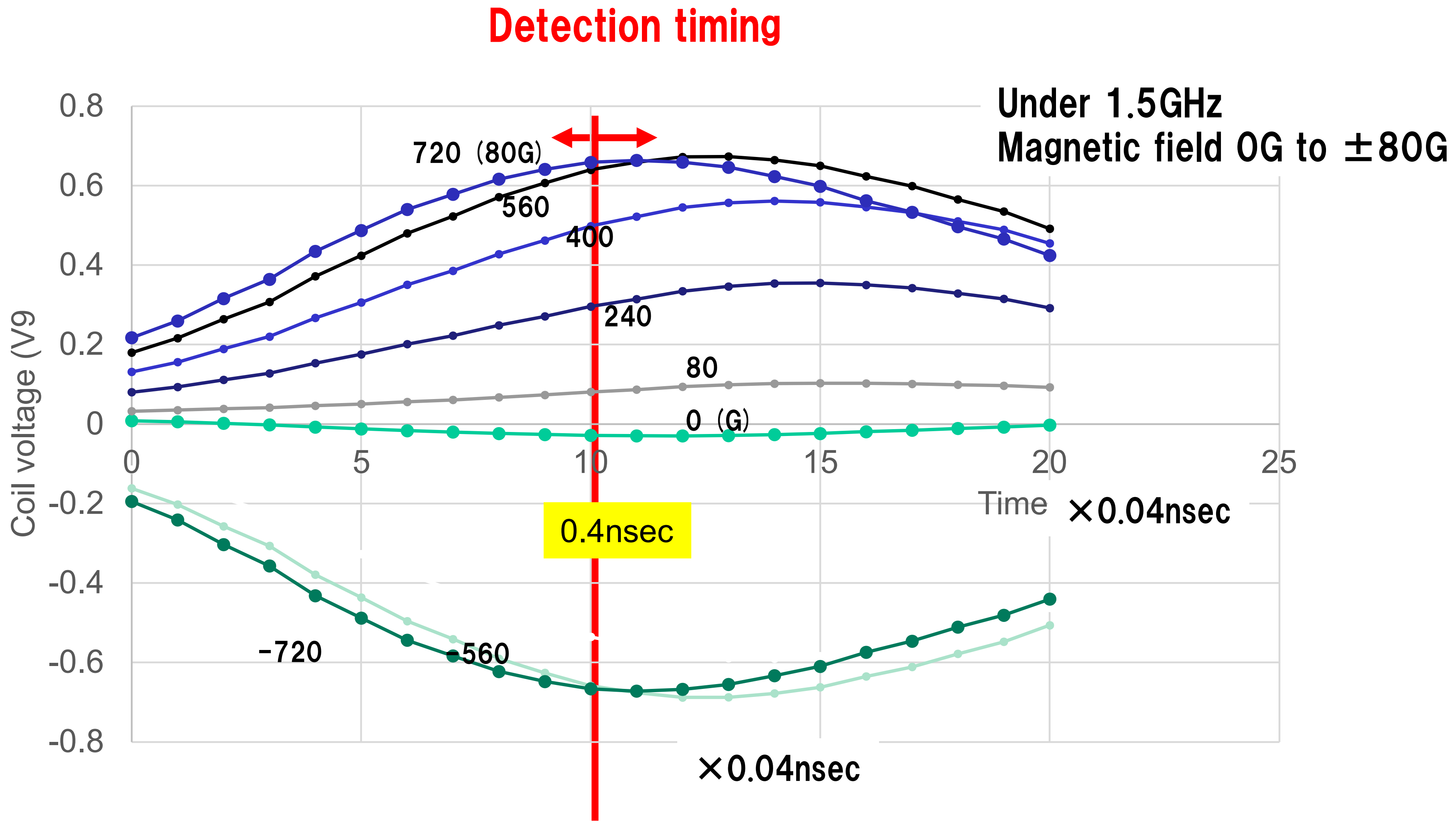
b) Block Diagram



- This block diagram is for GSR sensor circuit of ASIC.
- The coil voltage is detected <u>by sample hold circuit</u> operated by <u>the electronic switch.</u>

(4) Result（1） effect of the detection timing on Coil voltage wave

- Coil voltages are observed at the change of the detection timing under a frequency of 1.5GHz and applied magnetic field changed from 0 G to ±80G.
- It takes a maximum voltage at the detection timing of 0.4 nsec
- We decided to use the detection timing to take a maximum voltage.



Result (2) Effect of frequency and coil turns on Sensitivity

The Sensitivity increases with increase of pulse frequency and shows saturation up to 3GHz
The sensitivity also increases proportional to coil turn numbers from16 to 148.c

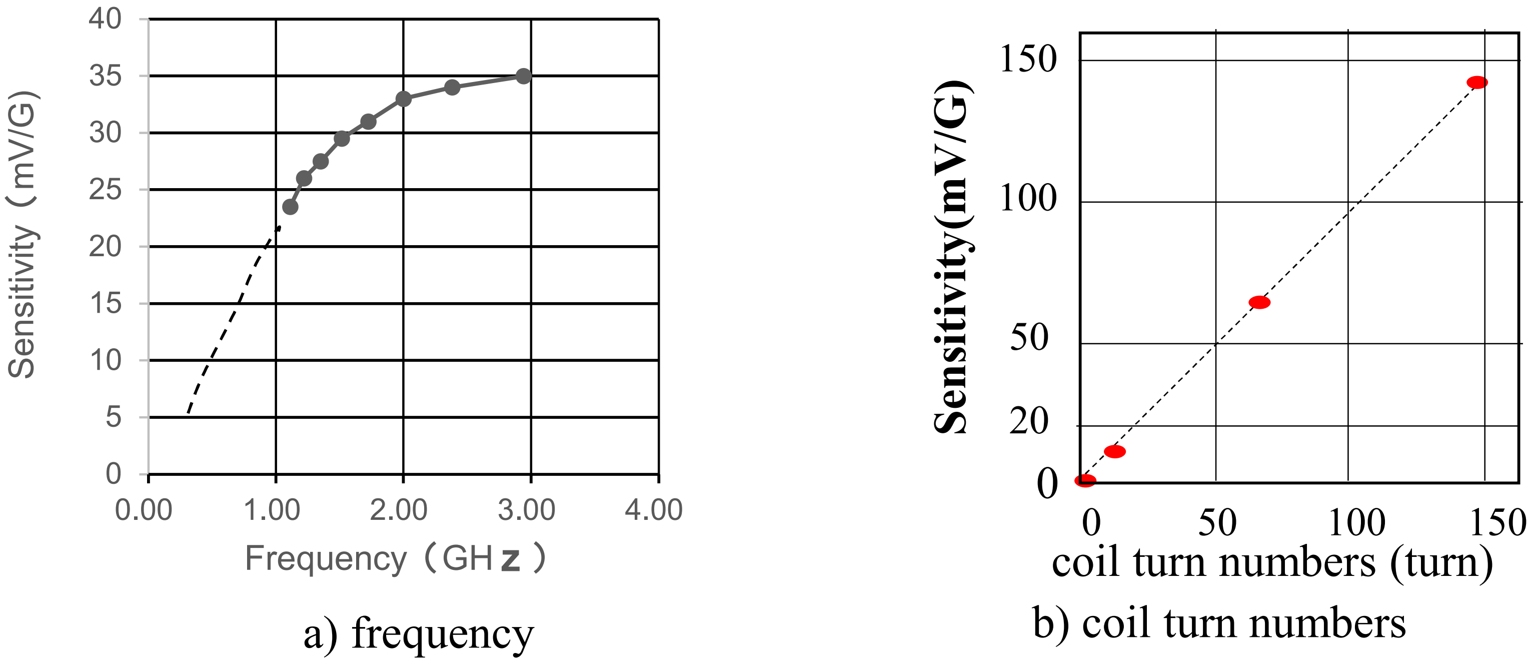


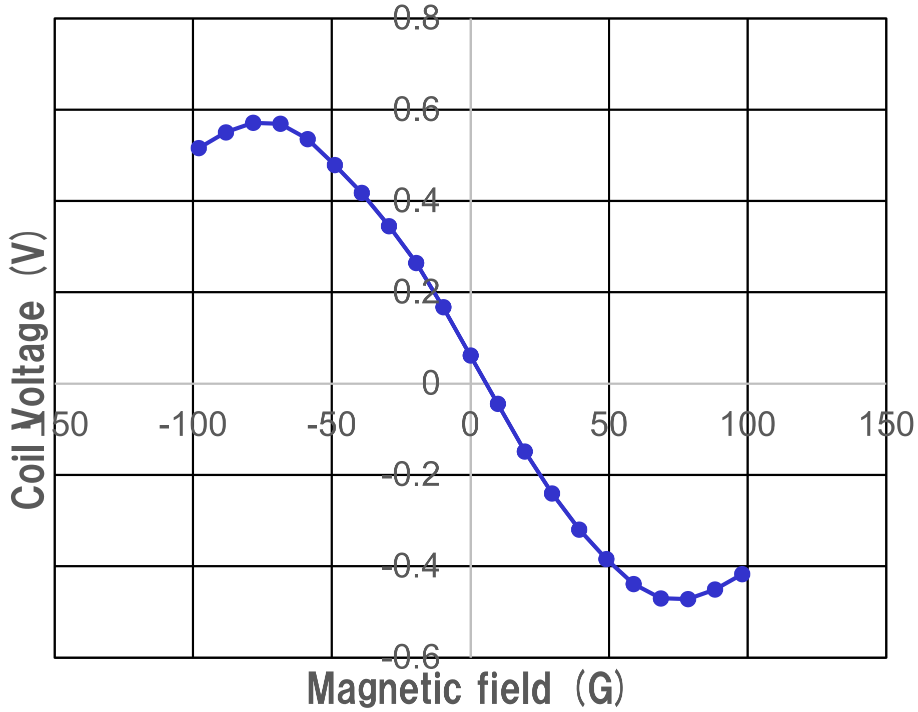
Fig. 7 Effect of frequency, coil turn numbers and wire permeability on Sensitivity

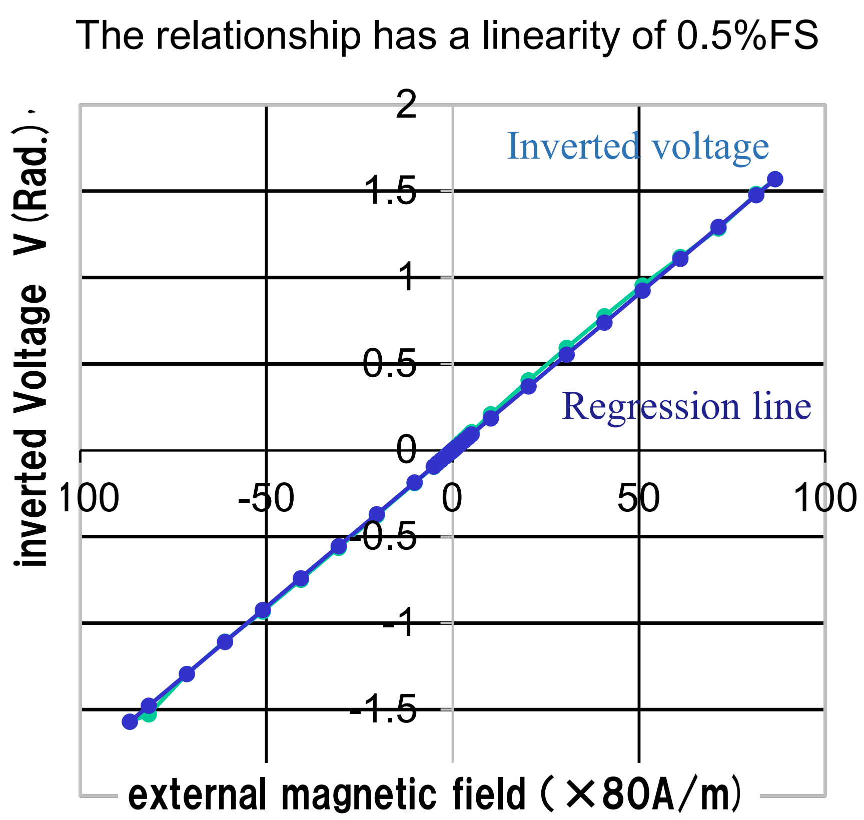
Result(3) the relationship between the magnetic field and the coil voltage

I also checked ASIC type sample

GSR effect makes the sine functionality <u>between the magnetic field and the coil voltage</u>

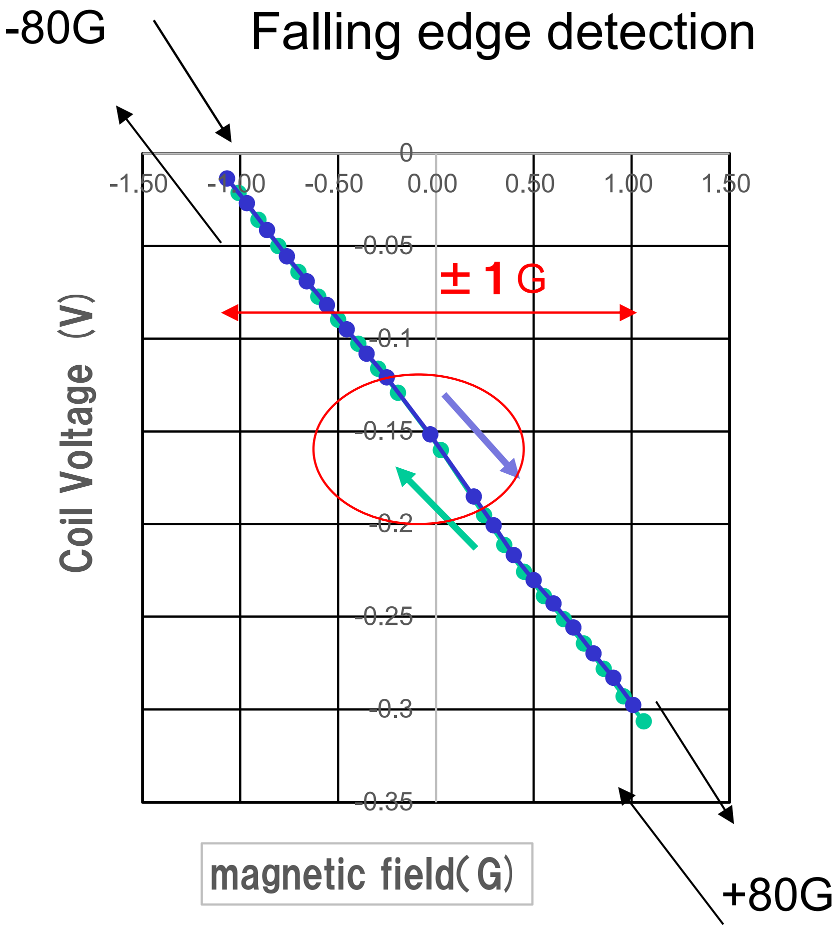
•<u>Arcsine inverted voltage </u>shows good linearity of only 0.5% FS.

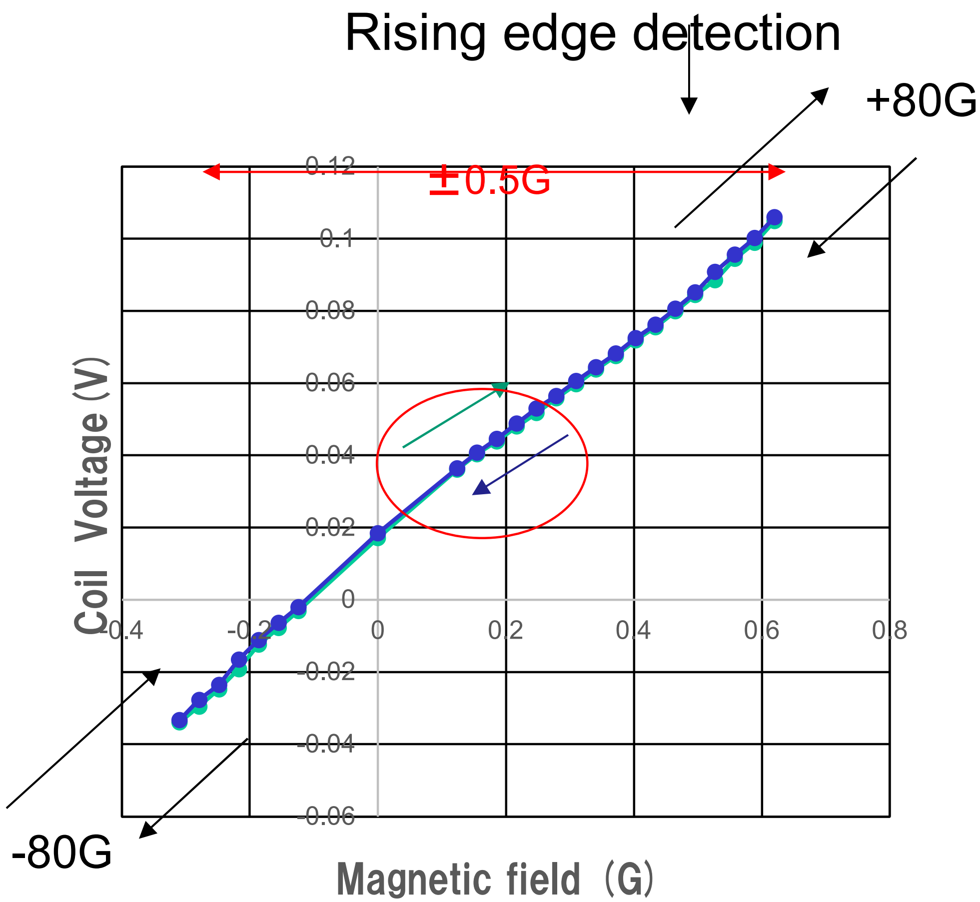




Result (4) Hysteresis of GSR sensor

The hysteresis is measured by changing magnetic field from -80G to +80G round trip.
The falling edge detection and rising edge detection show nearly zero hysteresis.
It is a surprising result



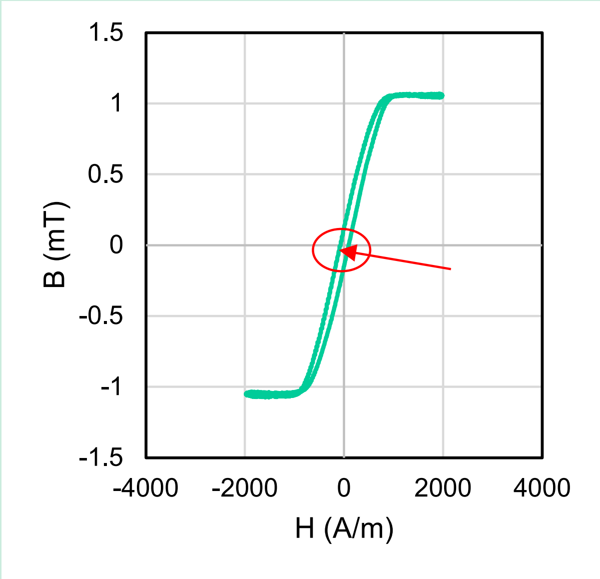


Result (5) Effect of BH curve hysteresis of the wire on the GSR output

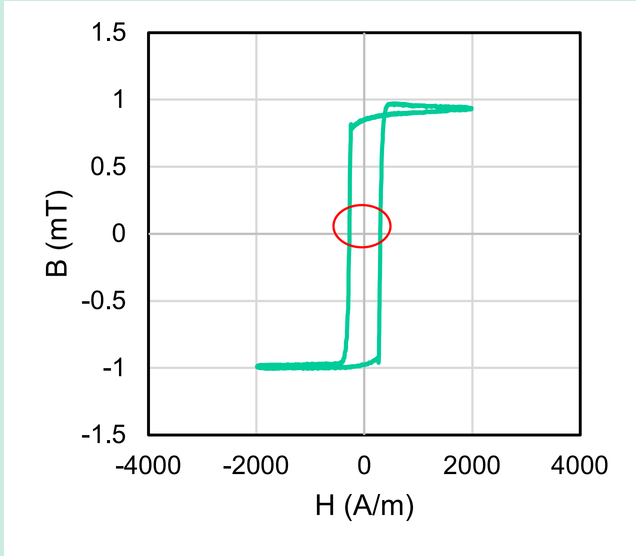
Ni	As cast	Tension Annealing at 400℃ under 20Kg/mm2

B-H

As cast



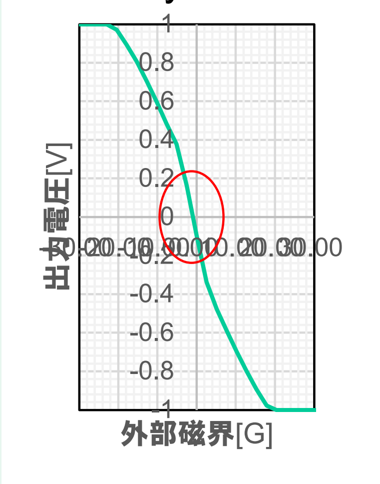
Tension Annealing at 400℃ under 20Kg/mm2



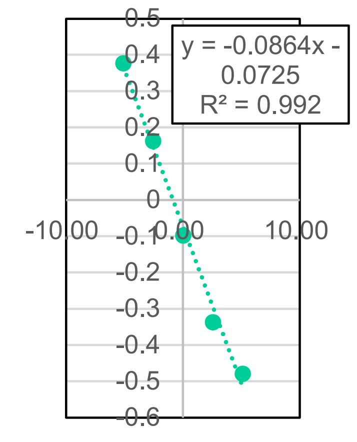
GSR

As cast

No Hysterisis

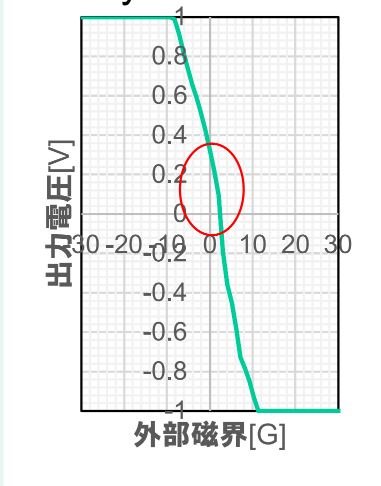


Sensitivity 86mV/G

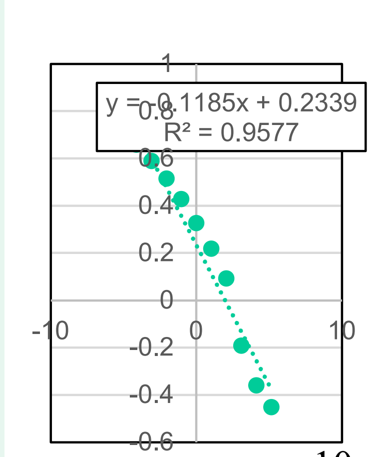


Tension Annealing at 400℃ under 20Kg/mm2

No Hysterisis



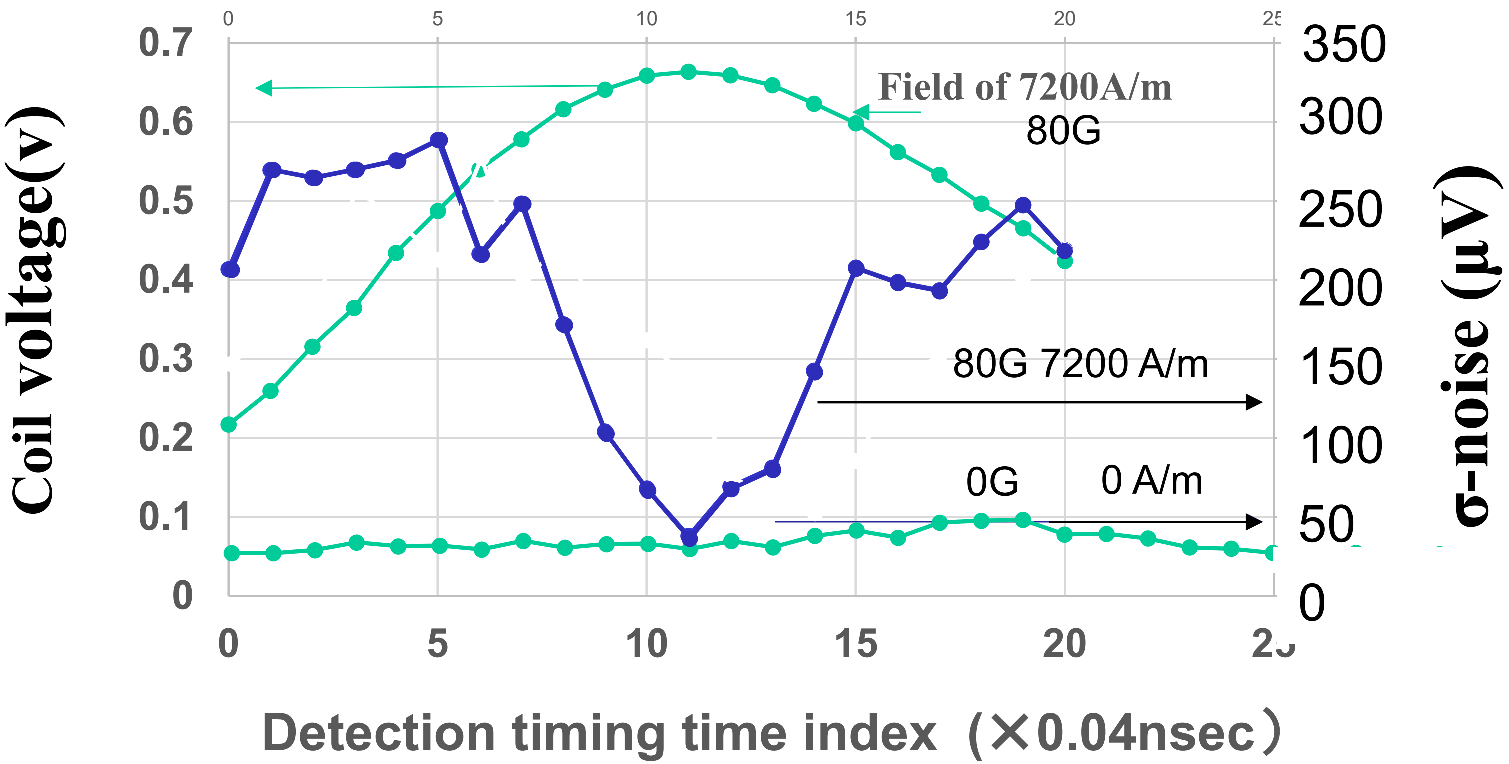
sensitivity118mV/G

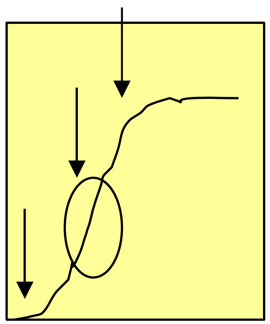


Detecting at Rising edge of Pulse current

Result (6) Effect of detection timing on σ-noise

<u>At 0 G</u>, the σ-noise is not dependent on the detection timing.
<u>At 80 G, the σ-noise takes the minimum value around the peak coil voltage timing.</u>
<u>The early timing and ending timing have big noises.</u>
The reason might be that at peak coil voltage timing, the pulse frequency takes designated frequency of 1.5 GHz and arises only spin rotation not accompanied with the domain walls
On the contrary, At early or ending timing, the pulse edges become round and decrease frequency, so that the domain walls move and make big noise.

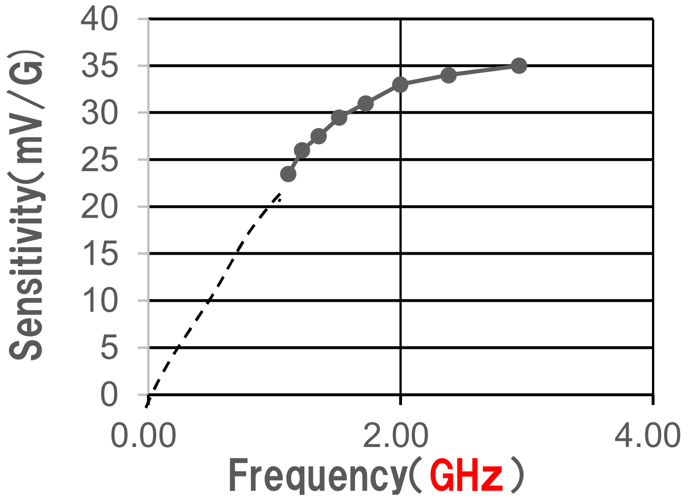




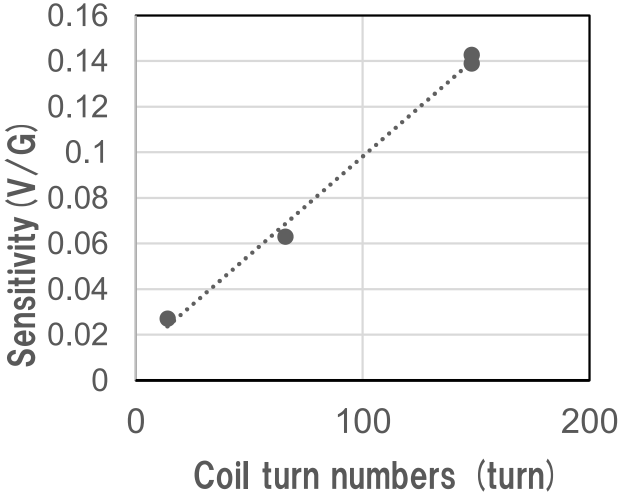
Result (7) Summing up results on GSR effect

GSR effect gives the good performance on high sensitivity ,a sine functionality, the wide measuring range, the good linearity,, low noise and no hysteresis.

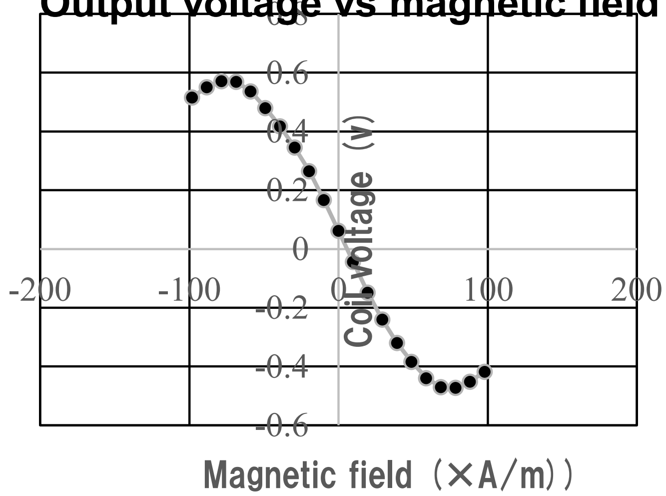
Effect of GHz frequency



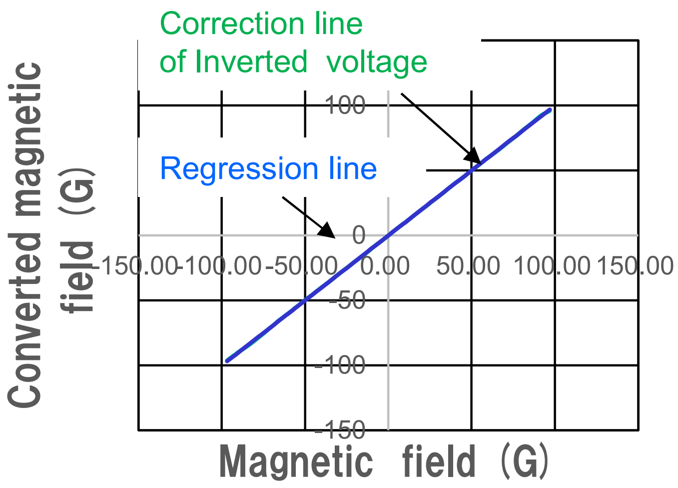
Effect of coil turn numbers



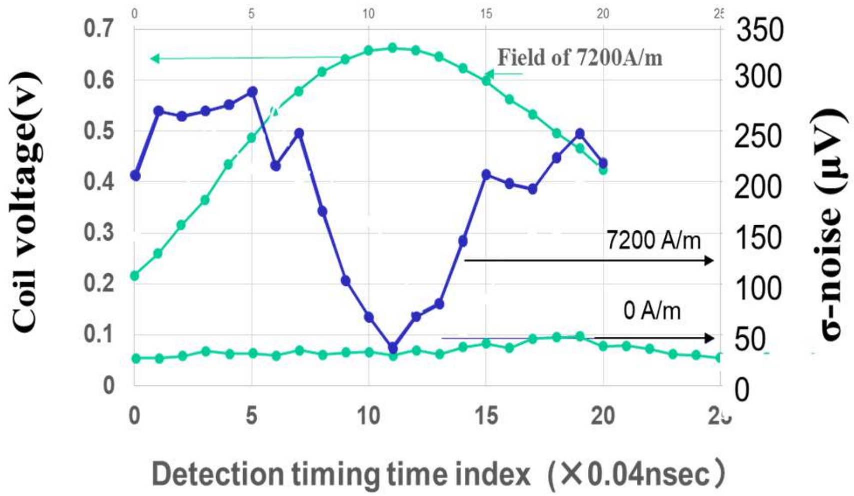
Sine functionality With Output voltage vs magnetic field



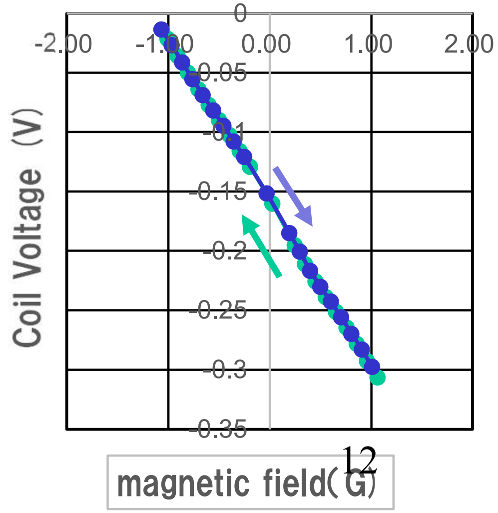
Good linearity



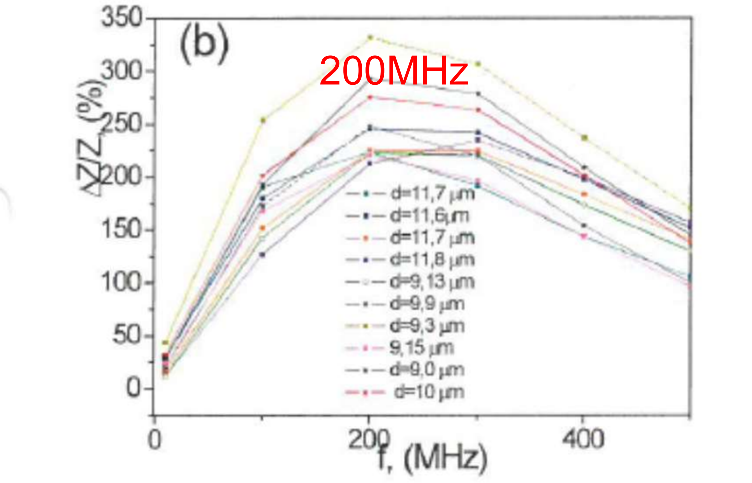
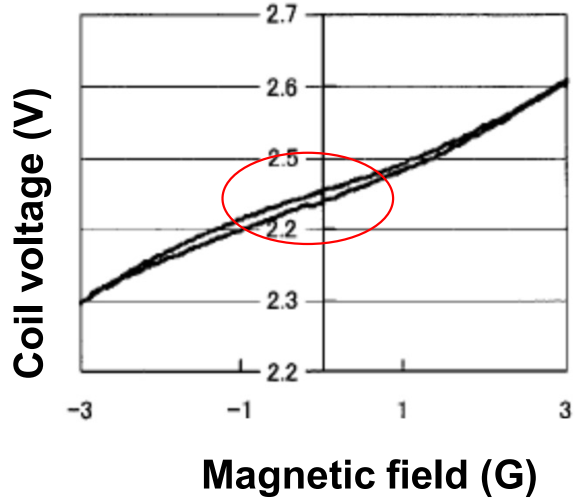
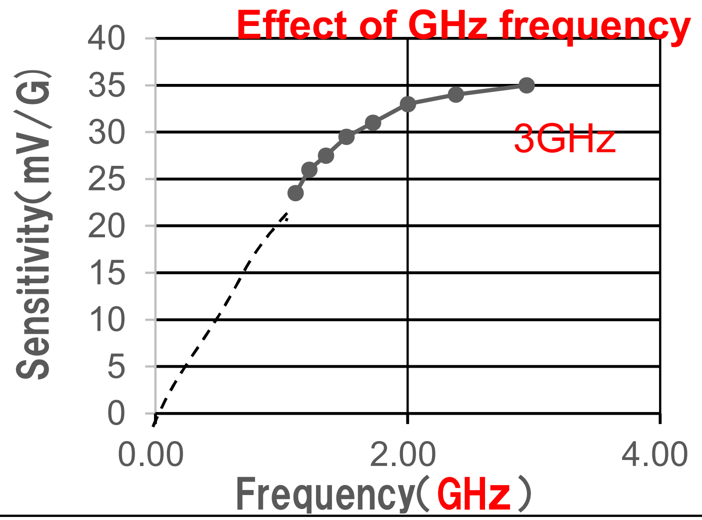
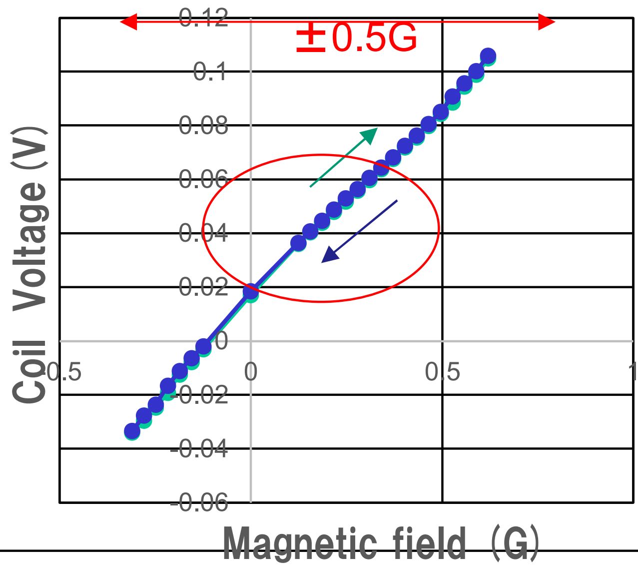
Low noise at peak detection timing



Nearly no hysteresis

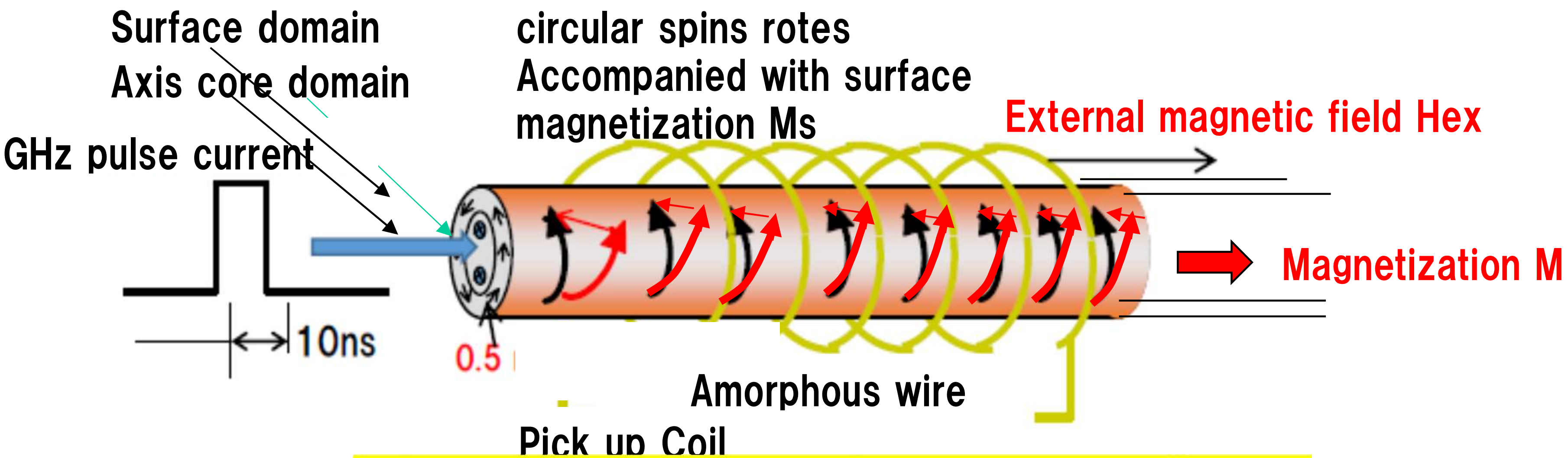


(5) Discussions on comparison between GMI effect and GSR effect

	Effect of frequency	Hysteresis at rising edge detection
GMI	 Figure 6. Frequency dependence of $Co_{66.87}Fe_{3.66}C_{0.98}Si_{11.47}B_{13.36}Mo_{1.52}$ microwires with different metallic nucleus diameters	
GSR		

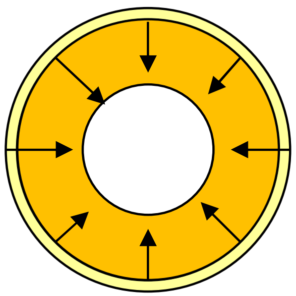
(6) Comparison on Mechanism of GSR effect and GMI effect

GSR effect is based on only spin rotation existing in the surface domain without 90 degree domain wall movement. So that, GSR makes a sine functionality and no hysteresis.



Coil Output voltage V ∞ f •N•M(=μ•Hex)

Coil type GMI effect is based on the rotation of Core Magnetization M accelerated by 90° domain wall, It means skin effect. so that, GMI effect makes a high sensitivity but accompanied with hyserisis

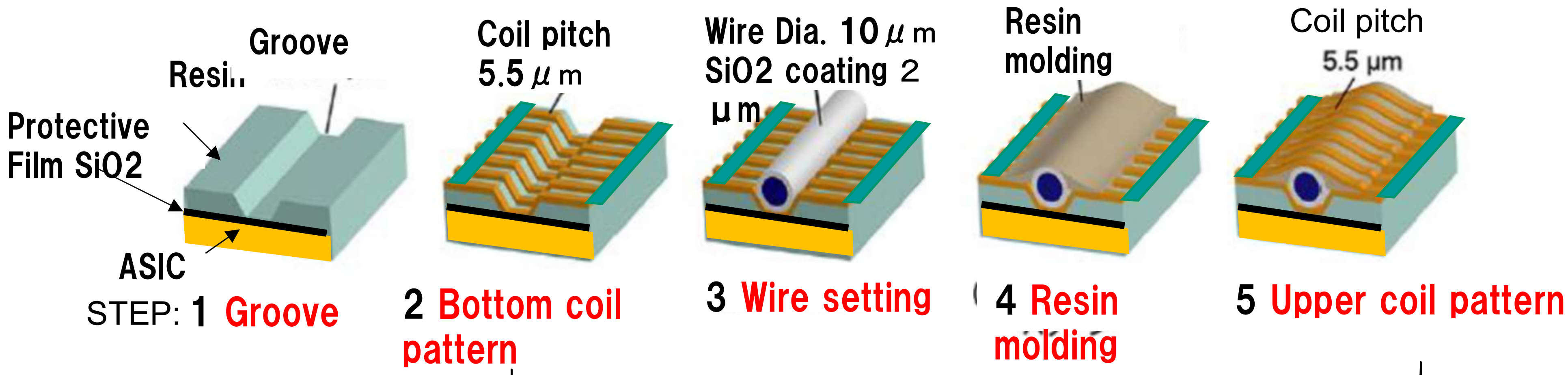


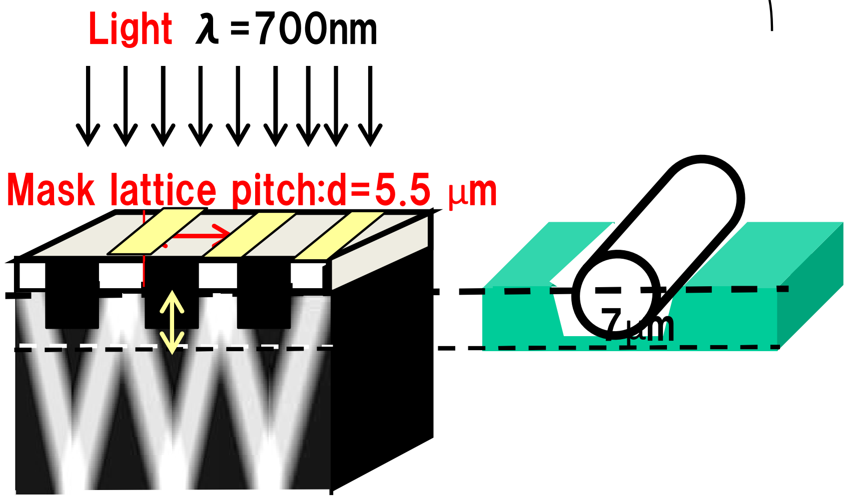
Core Magnetization M
Is rotated by 90° domain wall

§3: Production technique to produce GSR sensor element

(1) Base process to produce a micro coil using 3 dimensional photolithography

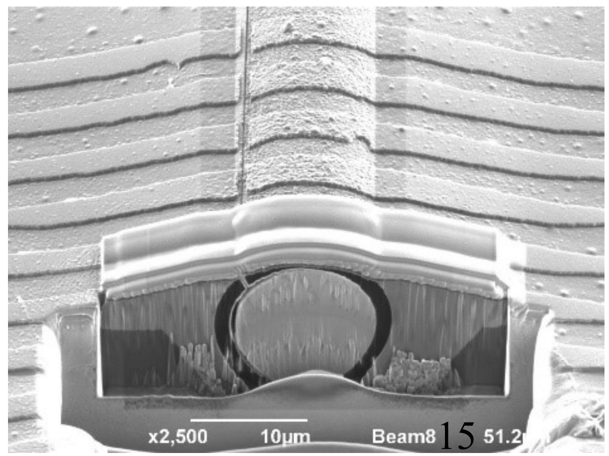
Coil pitch of 5.5 μm and Inner diameter of 16 μm (wire diameter of 10 μm)





Diffraction depth
$z = d^2/4\lambda$
⇒ depth of the groove : 7 μm

cross section of the Element

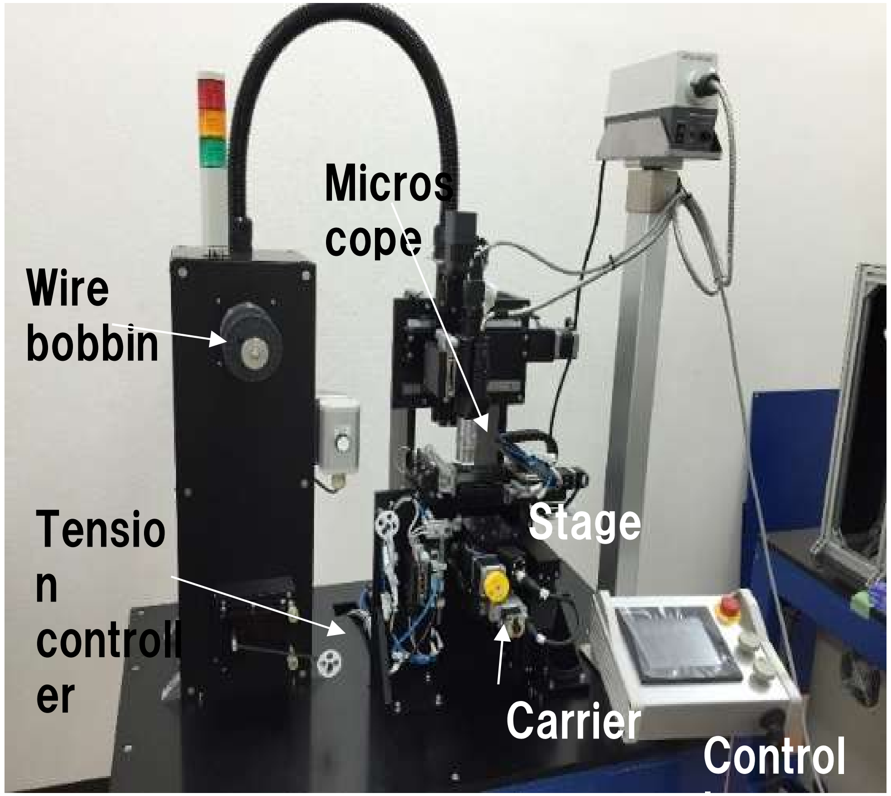


When the light passing through the mask lattice, the grooves makes the light diffraction and it limits the groove depth of 7 μm.

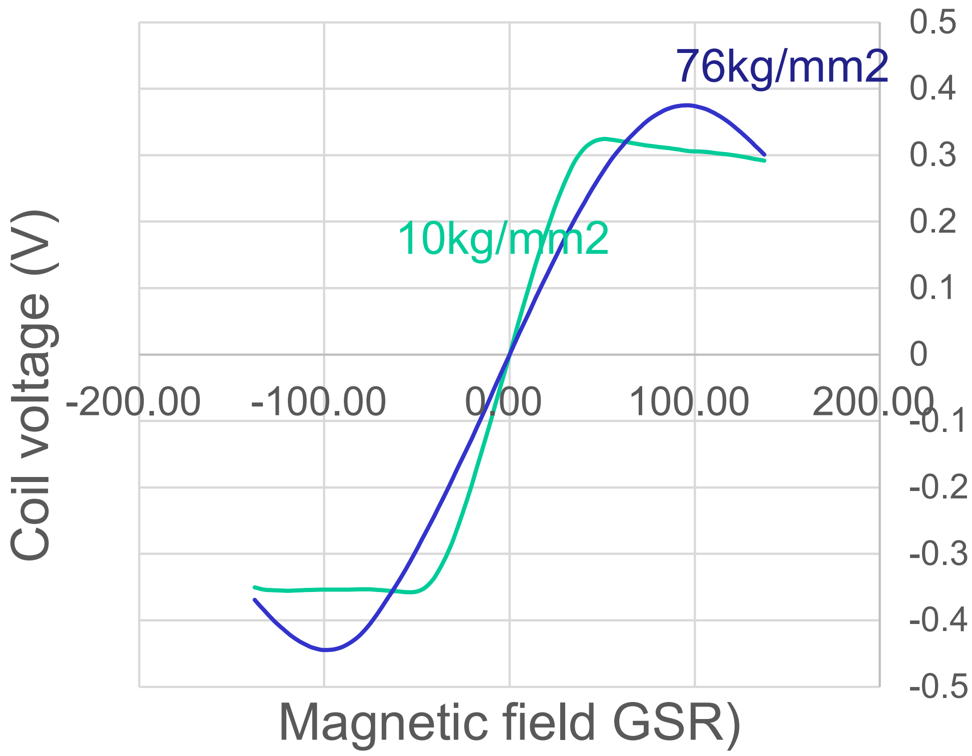
(2) The amorphous wire aliment machine

can set the wire with accuracy of ±1 μm and high tension of under 100kg/mm2

Aliment accuracy of <±1 μm
Tension 10 ~ 100kg/mm2



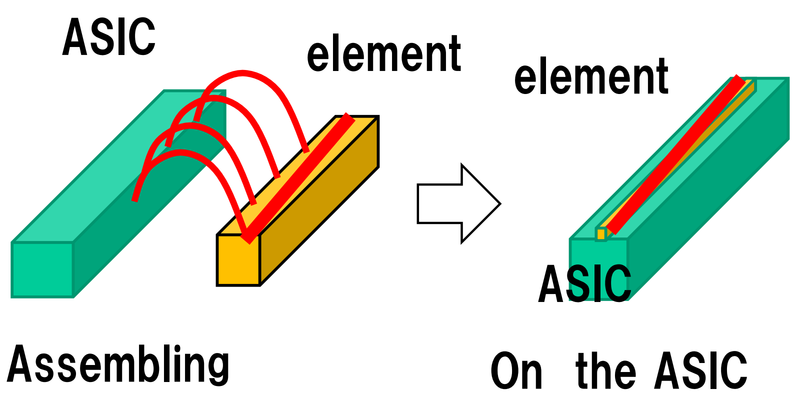
Effect of High tension of 76 kg/mm2



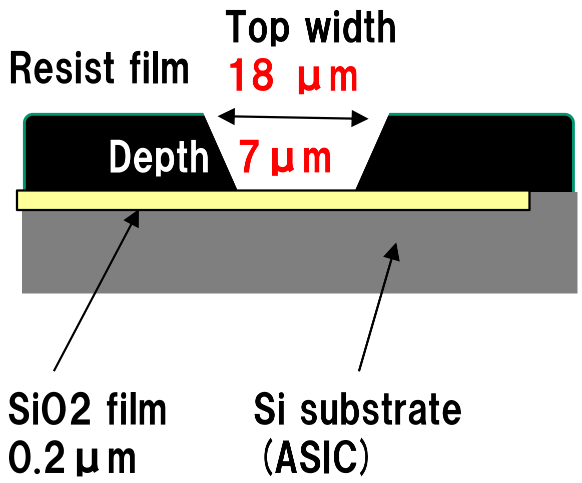
High tension improve makes a sine functionality.

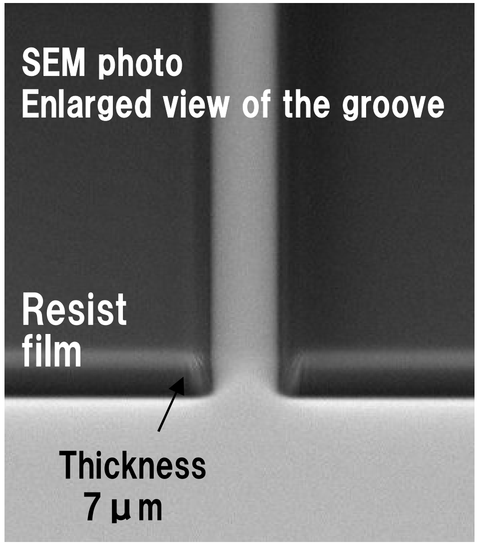
(3) Production technique to produce GSR element directly on the ASIC

Wire bonding technique is changed to direct on ASIC connection



Dimensions of the groove

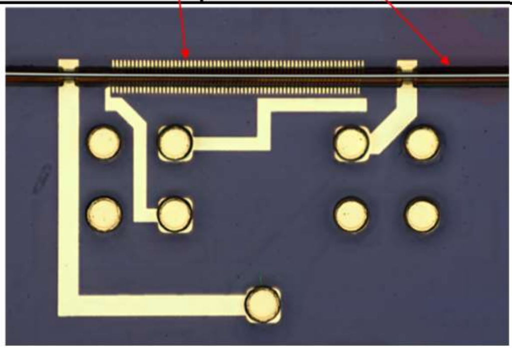




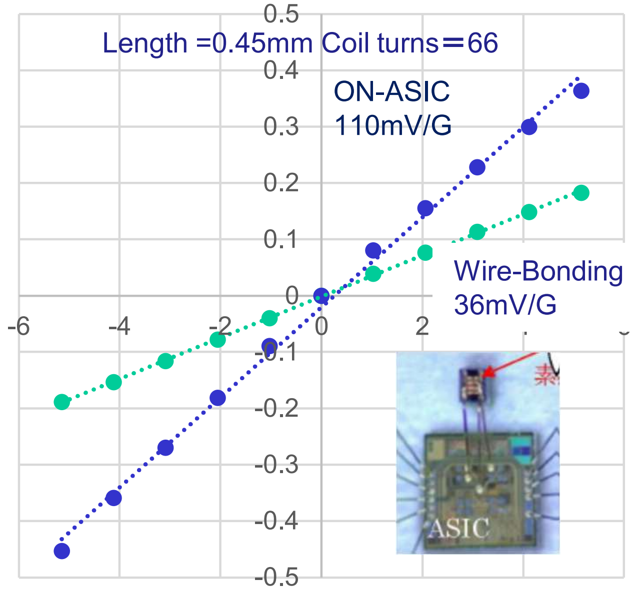
§4: Development of On–ASIC type GSR sensor

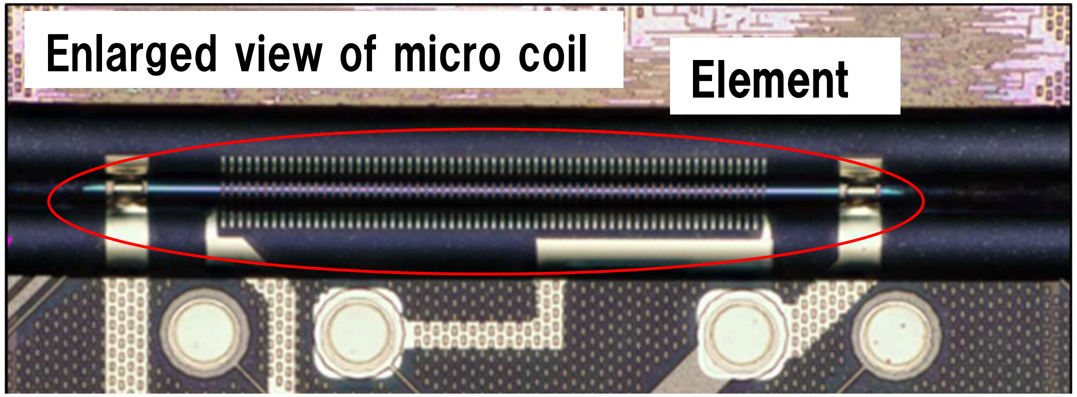
(1) High sensitive type : σ noise of 0.4mG @1KHz

Types L: length(mm) W: wire number N:coil turn numbers	Sensor Size	Sensitivity	σNoise @1KHz	σNoise @10Hz	Measuring range	Total performance
	mm×mm	mV/G	mG	mG	Oe	index
GSR sensor L0.45*W0.16 N=66	1.2×1.2×0.2 1.5smaller	110mV/G	**0.2mG** 35 times better	**0.0 2mG** 35 times better	**12Oe** (1)	50 Times better
MI sensor L0.60*W0.40 N=16	2.0×2.0×0.6	10mV/G	7mG	0.7mG	12G	1



ASIC size: 1.2 ×1.2×0.2mm
Element: L=0.45mm



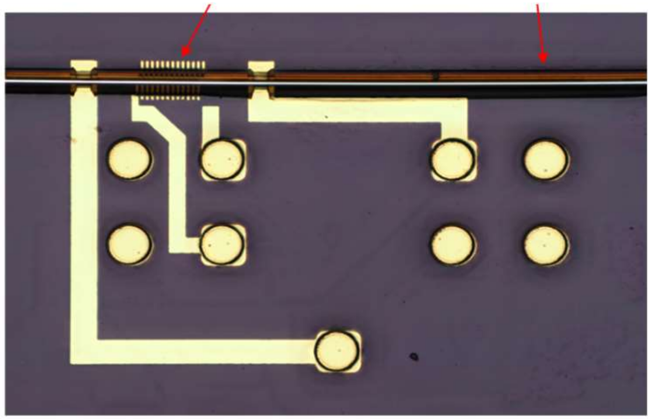


(2) Wide Range type : ±80G Coil length of 0.12mm for automotive use

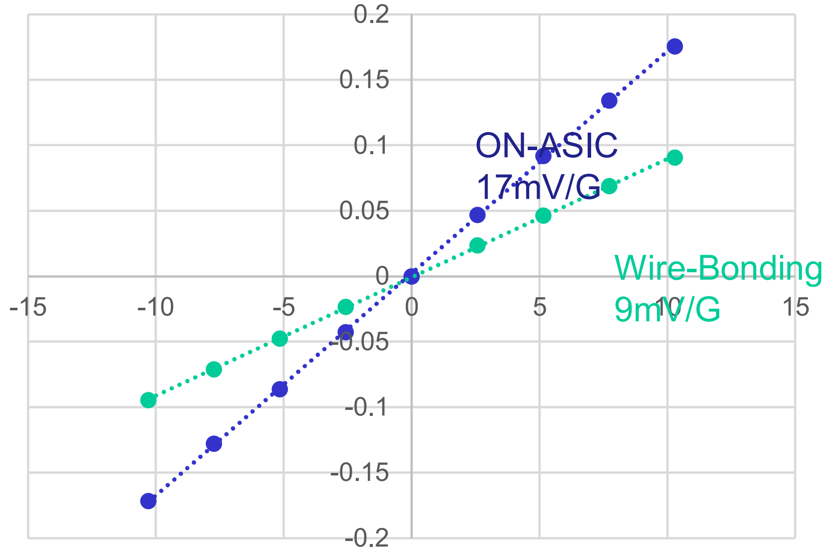
Types L: length(mm) W: wire number N:coil turn numbers	element Size	Sensitivity	σNoise @1KHz	Measuring range	resolution	Totalperformance
	mm✕mm	mV/G	mG	G	bit	index
GSR sensor N=14	0.2✕0.18 (3)	17 (5)	2mG (3)	80G (6.5)	16 (16)	55
MI sensor N=16	0.6✕0.4	3	7mG	12G	12	1

This ASIC analog circuit is operated by 500KHz. We can estimate 40mG @100KHz

ASIC size:1.2 ×1.2×0.2mm
Element: L=0.12mm
N= 14

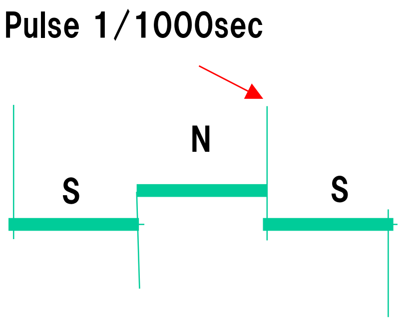


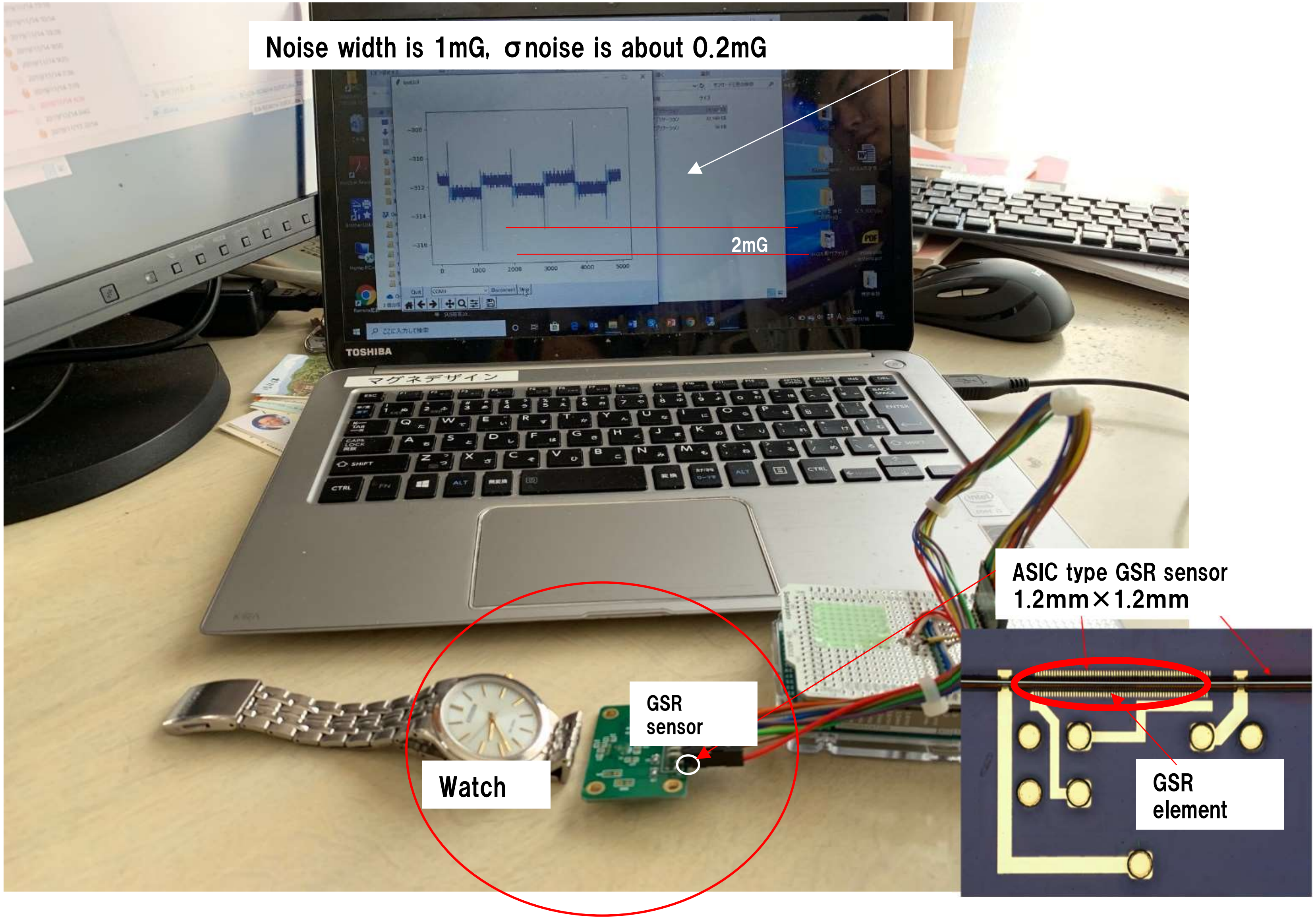
Length=0.16mm Coil turns＝16



(3) on-ASIC type GSR senor can detect the small magnetic field caused by a watch.

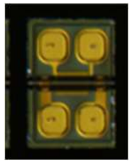
The second hand of a watch is operated by a step motor. When an Inside magnet rotates from N-pole to S-pole by one second. So that, the magnetic field changes from **N** to, **S** and from S to **N**.
At the switching time, a sharp pulse field occur.



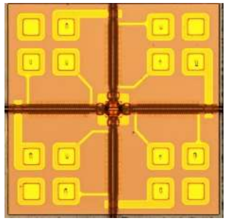


§ 5: Expected Promising Applications

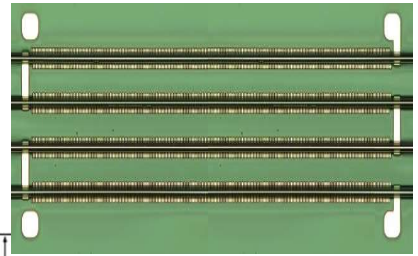
Project 1) Standard type for car use
-wide range of 80G
-high resolution of 3mG/LSB in 16bits
-Analog circuit Bandwidth of 1MHz

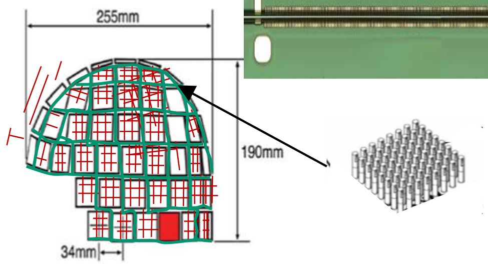


40 sensors used in one car
- Angle sensor,
- speed sensor,
- Current sensor

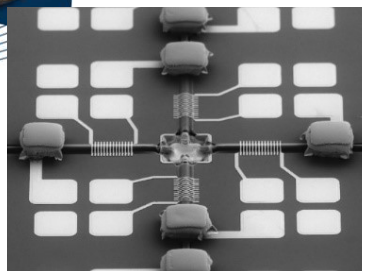


Project 3) nTmeter to detect the bio-magnetism
-noise under 1nT
– **Developing** for a wearable type of magnetoencephalography instead SQUID

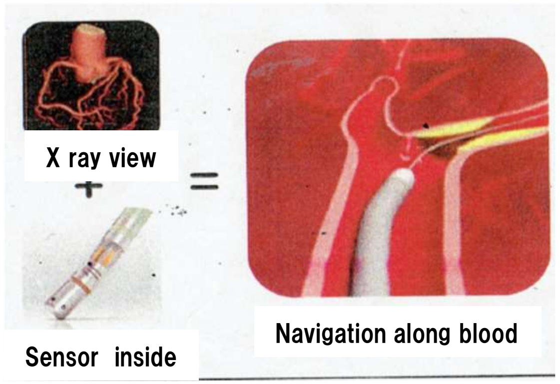


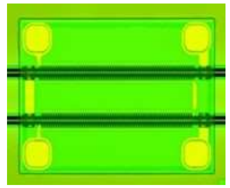


Project 2) the XYZ dimensional type for Gyro-Compass used in smart phone and wearable computer
– 3 dimensional type GSR element
– Low noise under 1mG and high speed mearing 1KHz



Project 4) ultra small type for catheter navigation in Body
– size of width 0.4mm and length 1.2mm
– keeping the performance of the standard type





§5: Summary

1) I made observation on the basic performance of GSR effect

- Sensitivity increases with GHz frequency
- high S/N ratio , good linearity, no hysteresis and low noise.

2) I developed Production technology to produce GSR element

- to produce the micro GSR element.
- to produce GSR elements on the ASIC surface

3) I produced prototypes of on-ASIC type GSR sensor

(1) high sensitivity type with σnoise of 0.4mG @1KHz

(2) Wide measuring type with ±80G and σnoise of 4mG@1KHz

4) GSR sensor will be promising for
(1) Automotive applications (2) Compass use (3) Navigation system for body inside (4) Medical device using bio-magnetism


Thank you for your kind attention!