The development of GSR sensor excited by GHz pulse current

Outline

1. My previous report in 7th IMWM
2. Progress of the Research of GSR Effect
3. Production technique for GSR element
4. GSR sensors for Promising Applications
5. Summary

21st August, 2019

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President of [1]Magnedesign incorporation in Japan

§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

Amorphous wire Magnetic sensor with pickup coil driven by pulse current

1982 Prof.Masumoto produced Amorphous Wire In Japan

1987 TDK FG sensor Operated by Pulse current

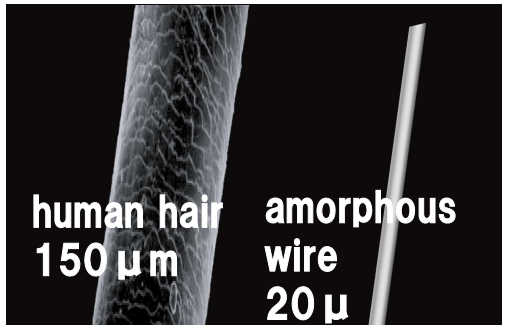
KHz→MHz

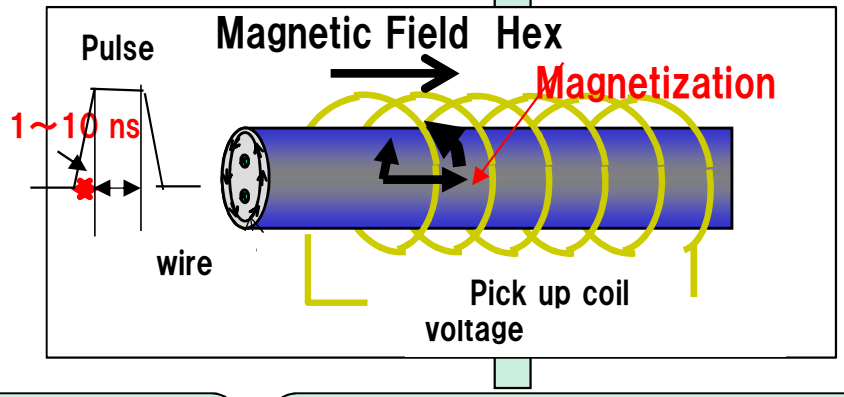
1999 Prof. Mohri Developed Coil type GMI sensor

MHz→GHz

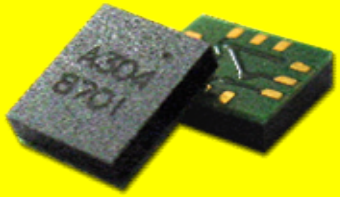
2015 Honkura Developed GSR sensor

Fe-Co base Amorphous wire





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

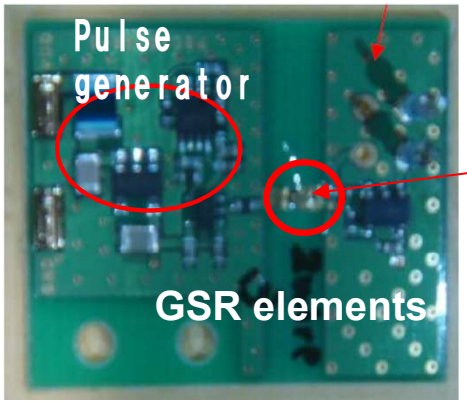


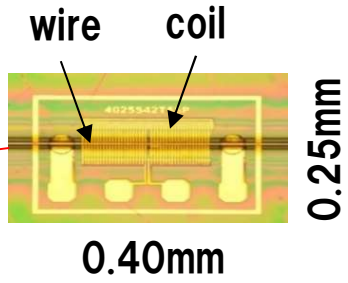
1991 Prof. Makhotkin Discovered GMI effect

1993 Prof. Mohri Developed GMI sensor

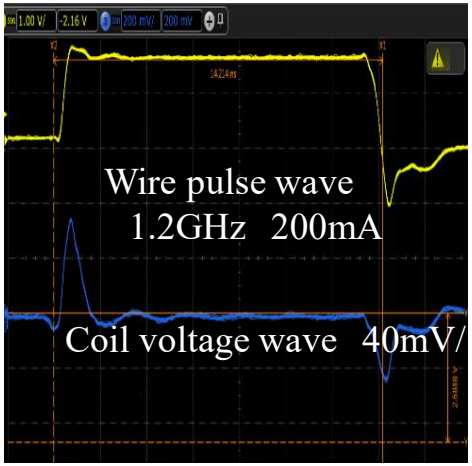
（２）My previous report in 7th IWMW(2015 Spain)

EVK board with GMI elements
And Pulse generater

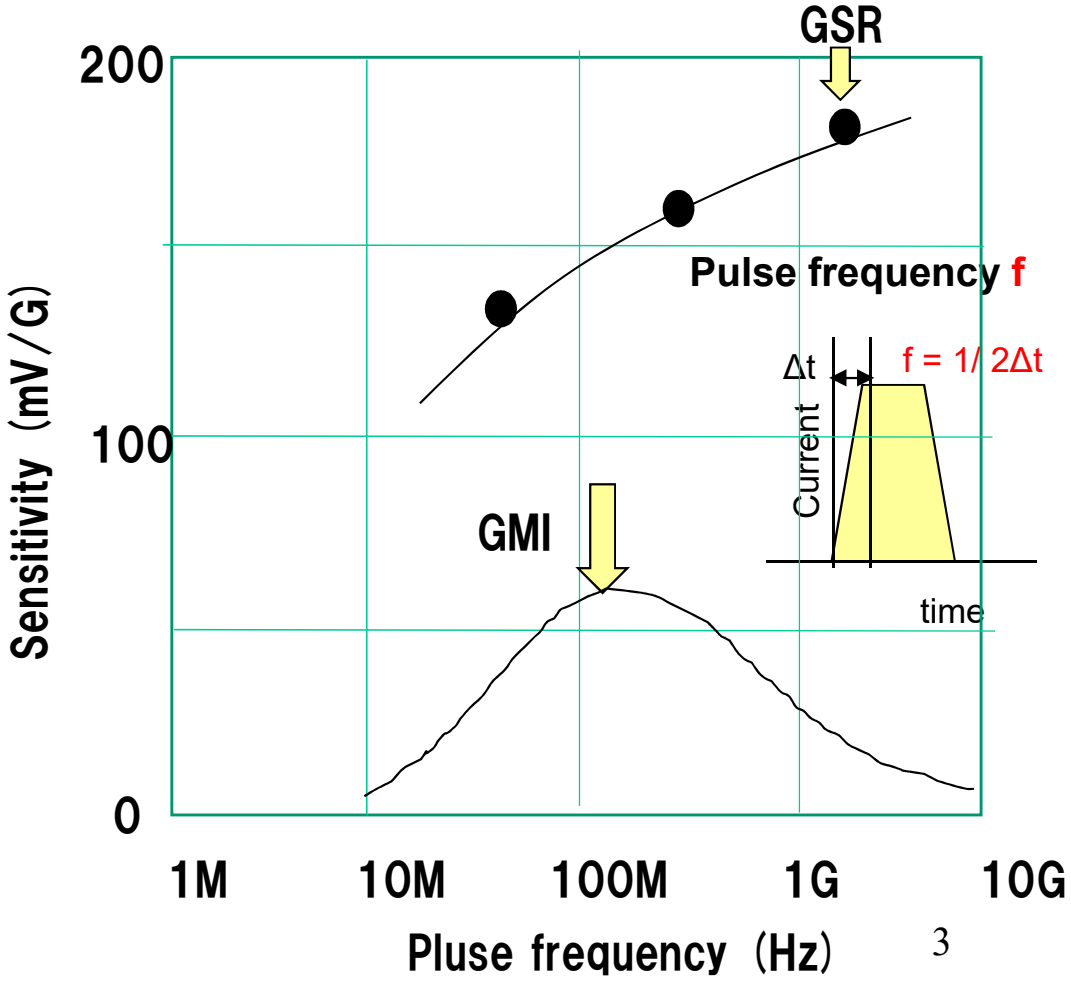




Pulse current wave
and coil voltage wave



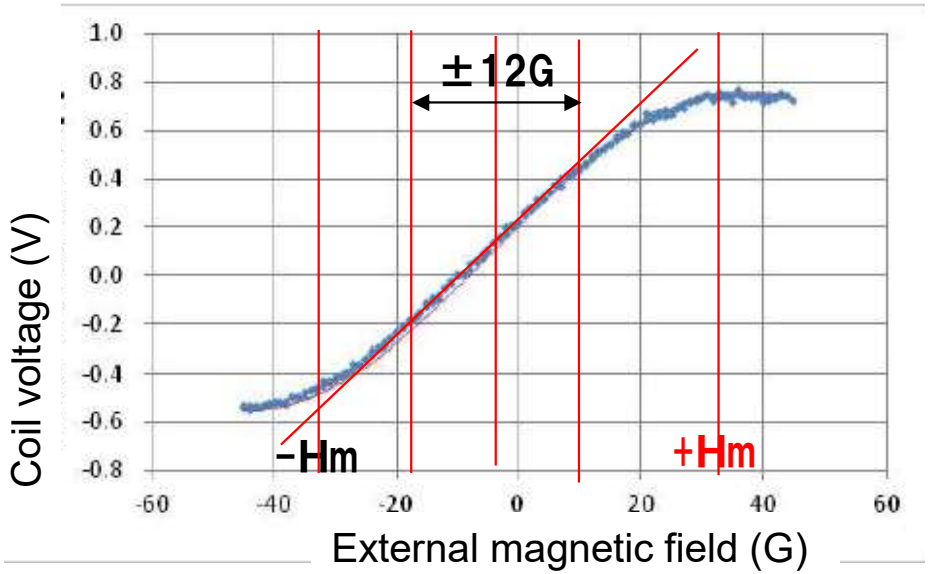
Effect of Pulse frequency on sensitivity



3-6 new relationship on the output voltage against magnetic field

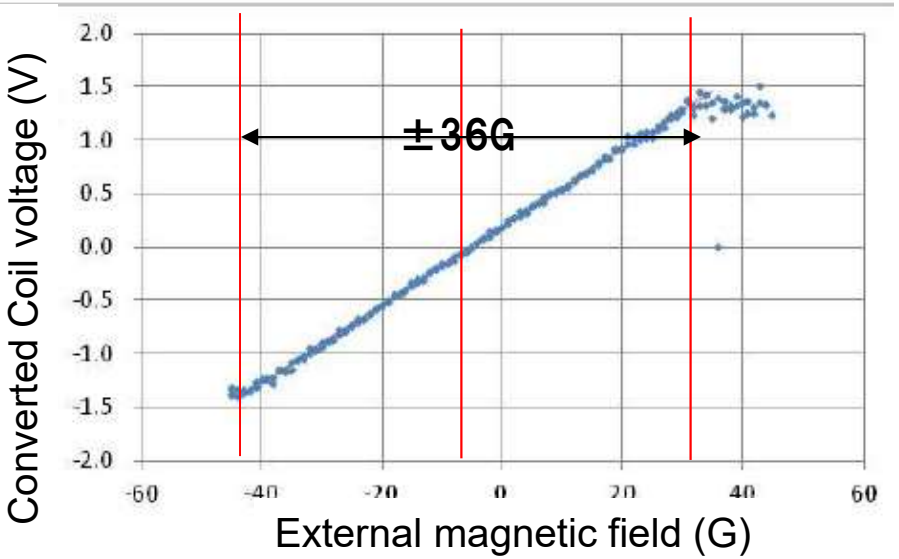
Using the equation , the measuring range can be extended from ±12G to ±36G.

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



converted to

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

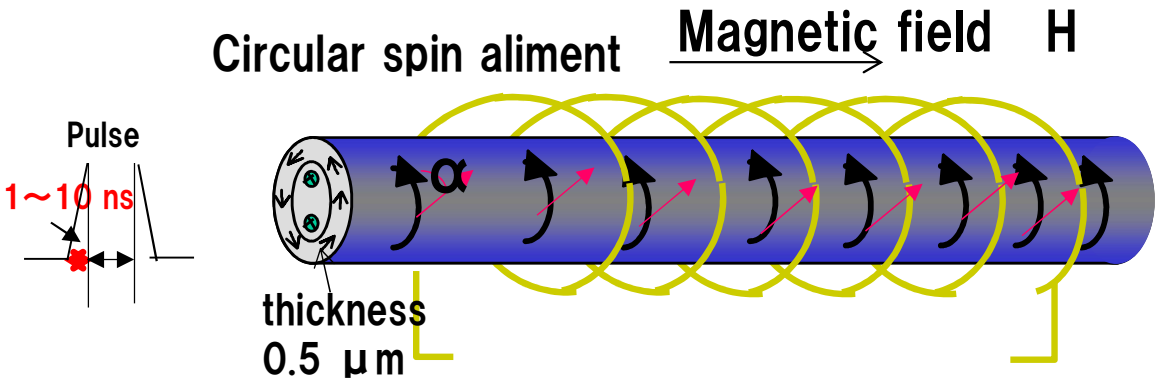


my hypothesis : Why is there $V=V_0\sin(\pi H/2Hm)$ between with V and H ?

If spin rotation with angel of θ on the surface is detected by the micro coil,
Theoretical Eq. :$V=Vo\cdot\sin(2\theta)$ here $\tan\theta = Hin/K\theta$ (Hk)
Hin: effective magnetic field
Kθ :the intrinsic circular anisotropy magnetic field of the amorphous wire related to Hk .

Experimental Eq. :$V=Vo\cdot\sin(2\phi)$ $\phi = \pi H/4Hm$, Hm =Hk

Using two equation, θ = ϕ is proofed.



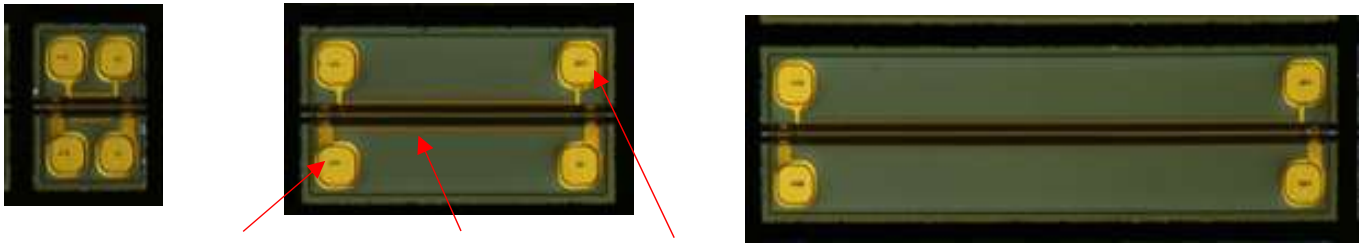
The wire has a surface domains with circular spins. When external magnetic field is applied to the wire along axis direction, spins tilt toward the axis direction.
GHz pulse current passes through the wire to make strong circular magnetic field and makes spin rotation with GHz angular velocity.
The pickup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

§1: Progress on GSR senor from 2015

(1) Various elements used in the present experiments

Length	0.16mm	0.45mm	0.96mm
Coil turn numbers	N=16	N=66	N=148

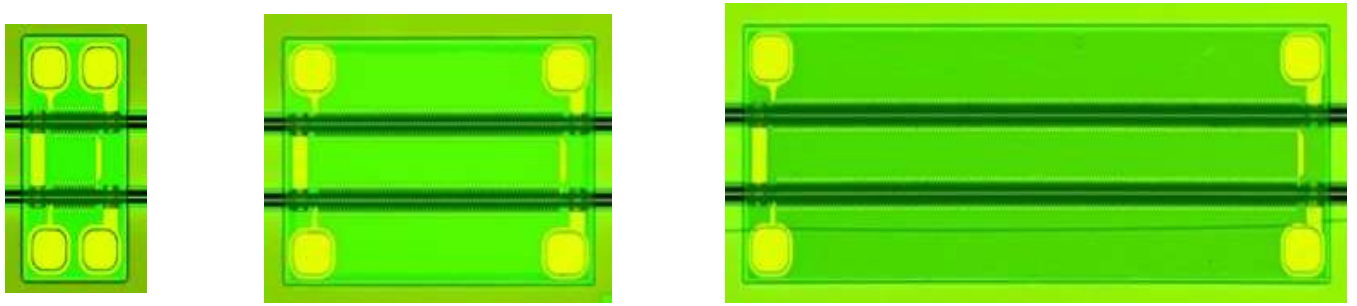
a) One wire types



W=0.22

b) Two wire types

N=32 N=132 N=296

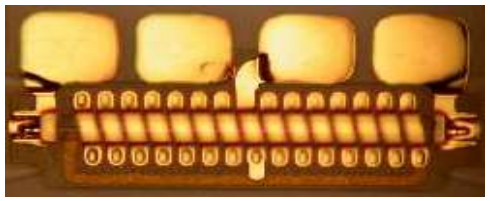


W=0.28

Commercial type

Metal plating process
Coil pitch of 30 μm

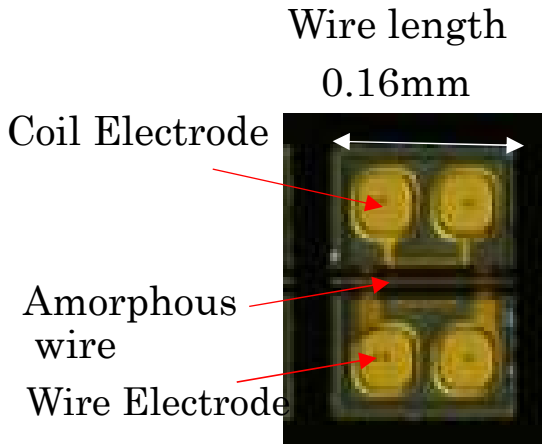
N=16



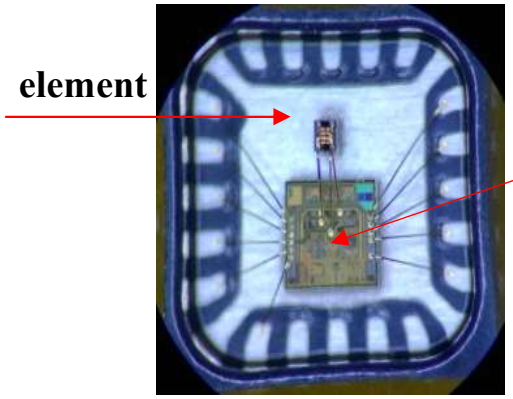
0.30 mm

0.60 mm

(2) Experiments

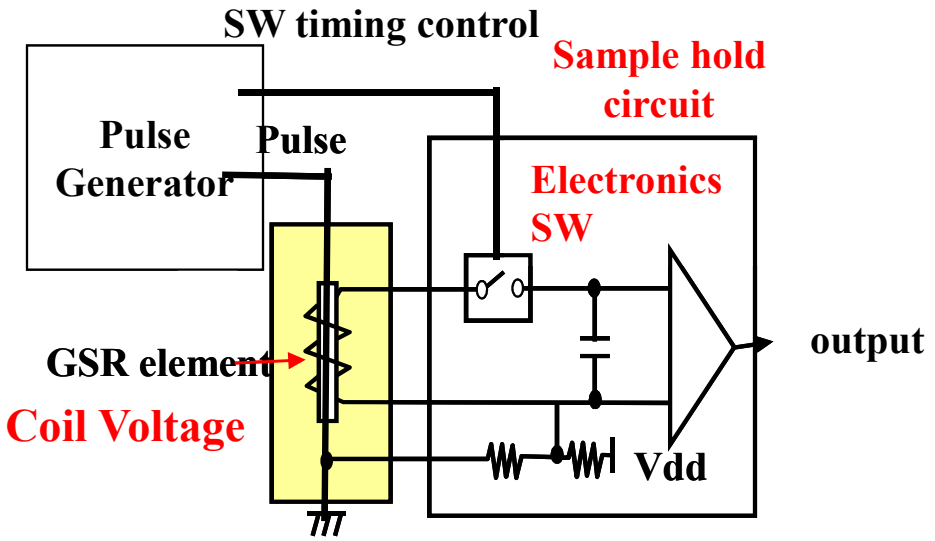


a) Micro coil type of GSR element



C)ASIC used in the test

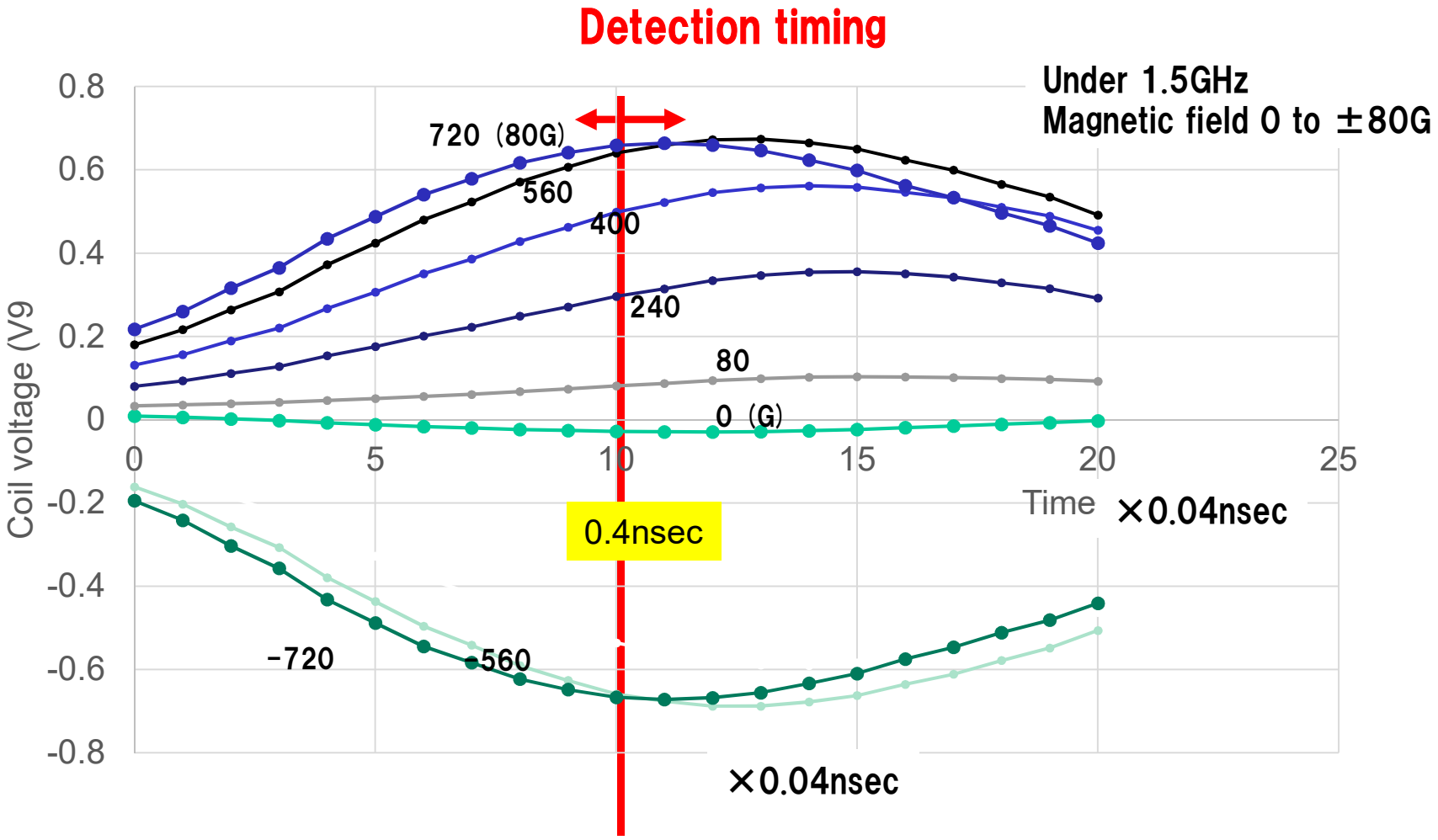
b) Block Diagram



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

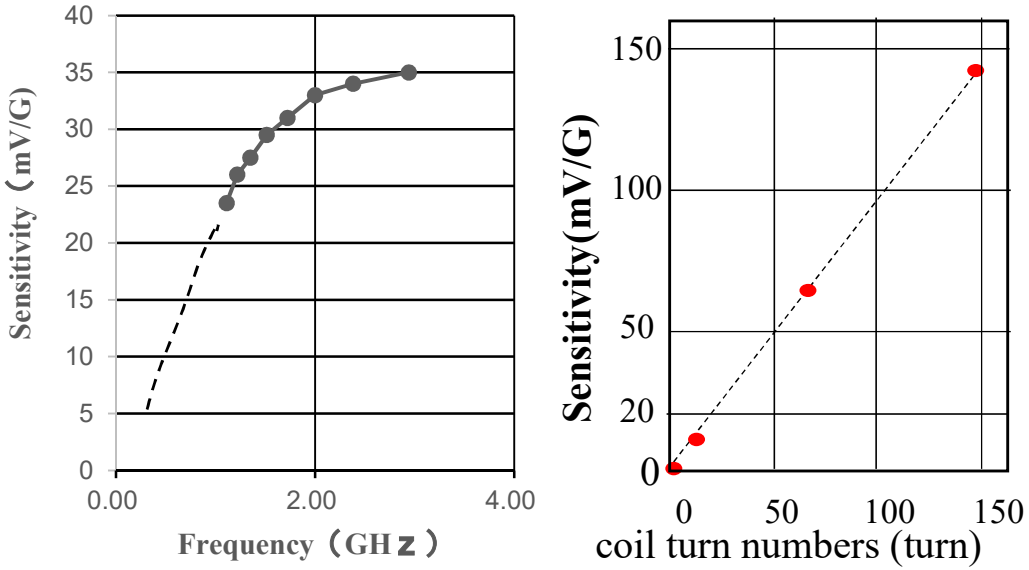
Result（1）effect of the detection timing on Coil voltage wave vs magnetic filed

- A coil voltage of GSR sensor is observed under a frequency of 1.5GHz and applied magnetic field of 0 G to ±80G.
- It takes a maximum voltage at the detection timing of 0.4 nsec and then decreases.



Result (2) Effect of frequency, coil turns of the wire on Sensitivity

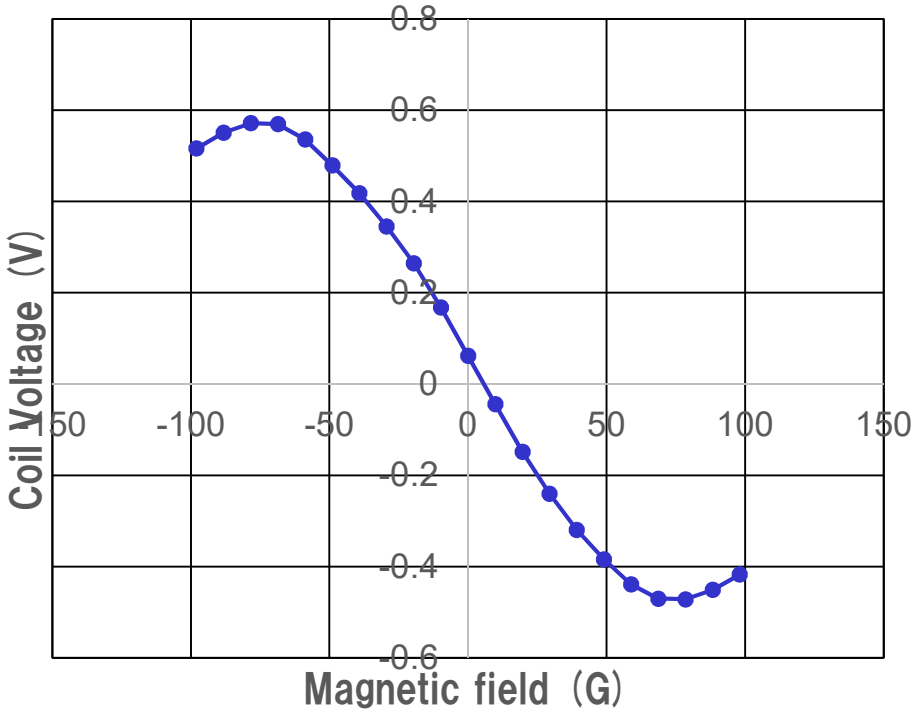
The Sensitivity increases with increase of pulse frequency and shows saturation over 3GHz
And with increase of coil turn numbers proportionally and with increase of the effective permeability of the wire.
These experimental results accord to
the theoretical equation as $\text{Coil Output voltage} \quad V \propto f^{1/2} \cdot N \cdot M(=\mu \cdot Hex)$



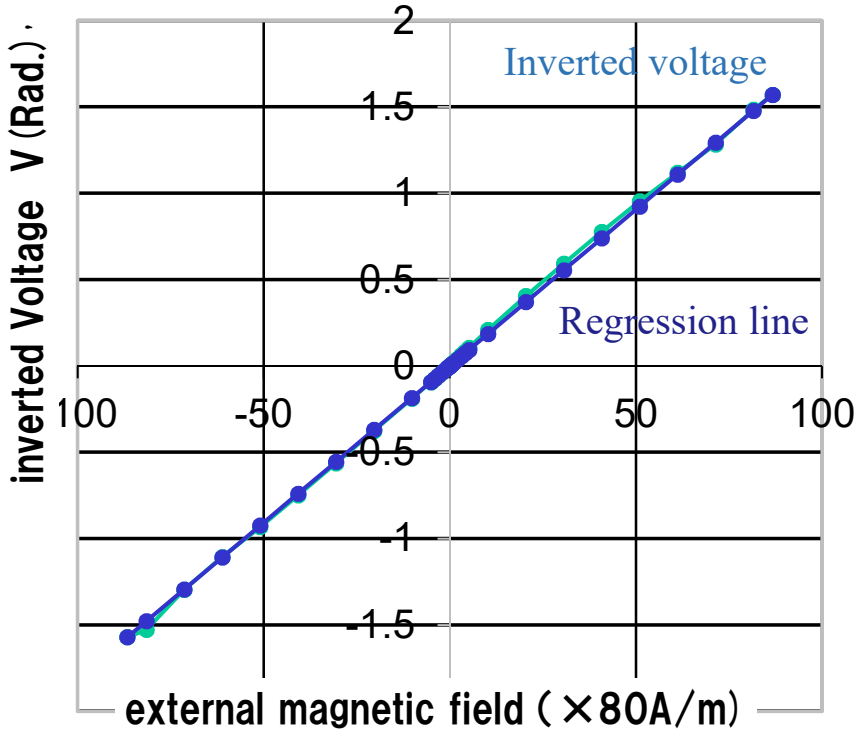
a) frequency b) coil turn numbers

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

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

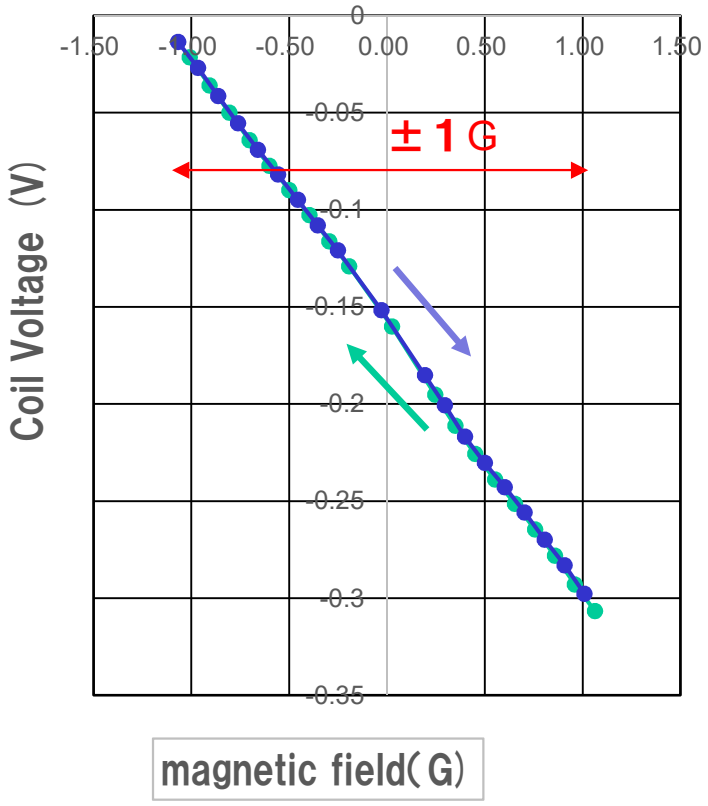


Inverted voltage has a linearity of 0.5%FS

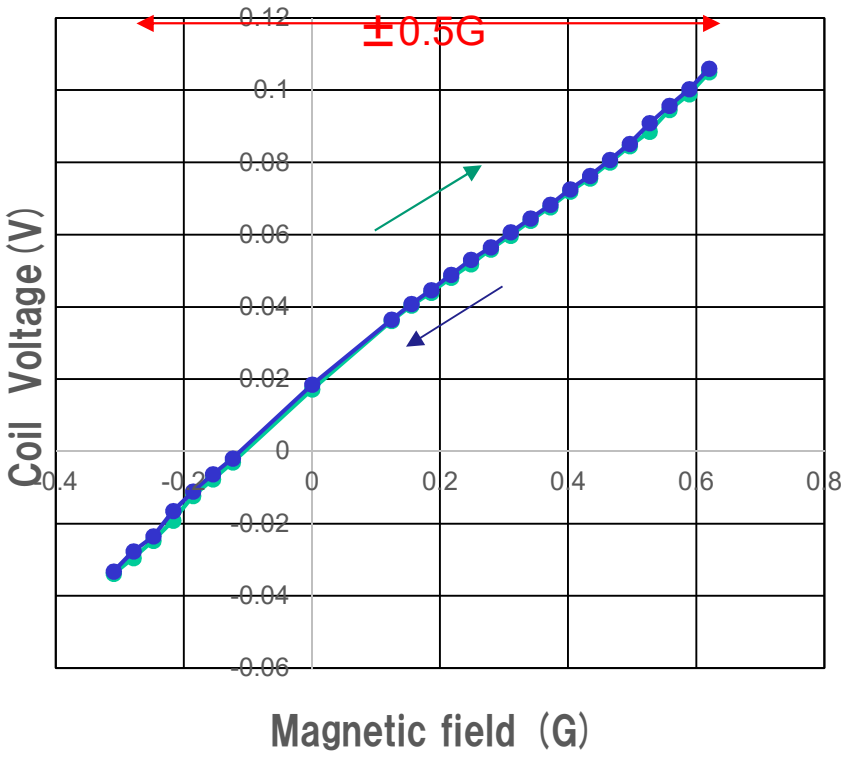


Result (4) Hysteresis of GSR sensor

Falling edge

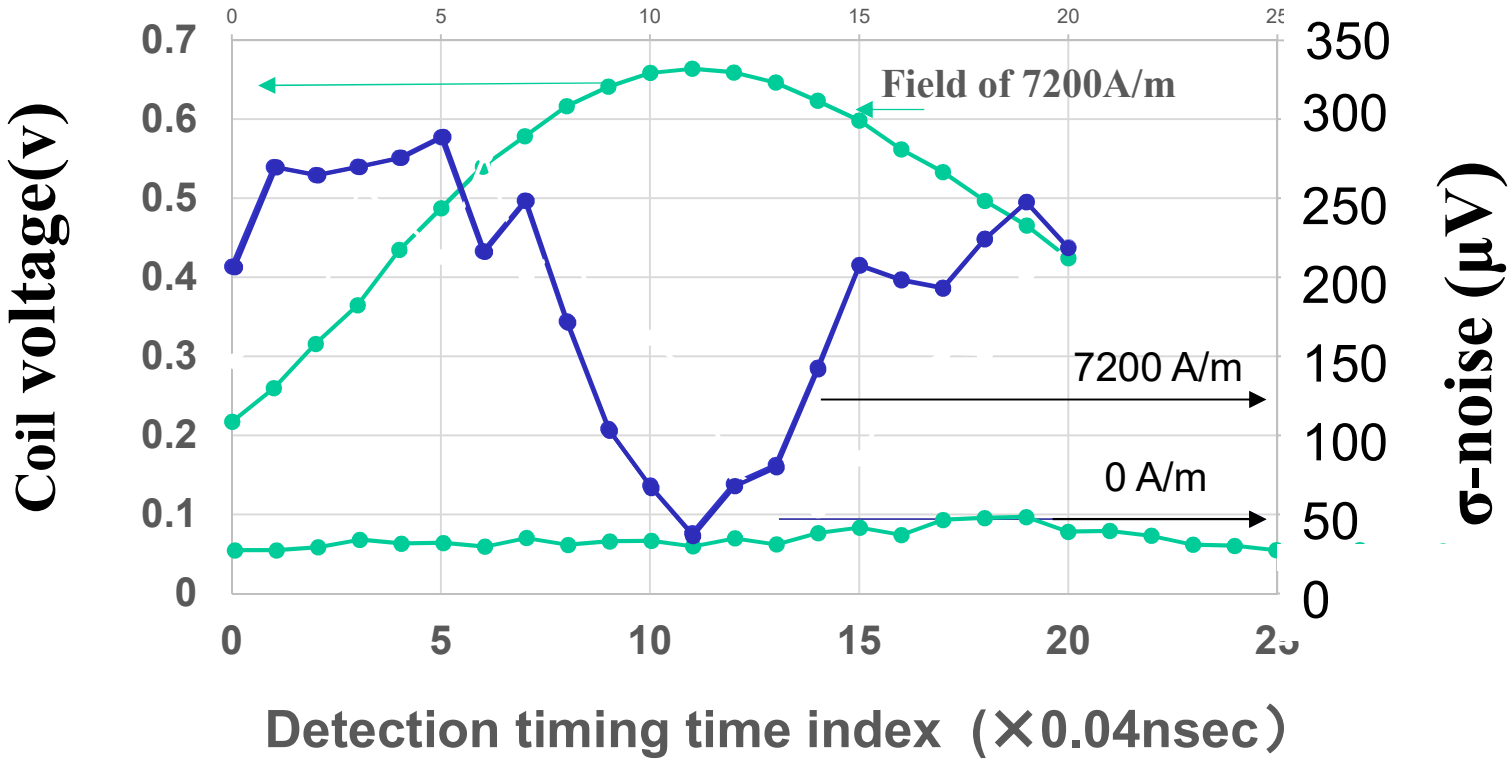


Rising edge



Result (5) Effect of detection timing on σ-noise

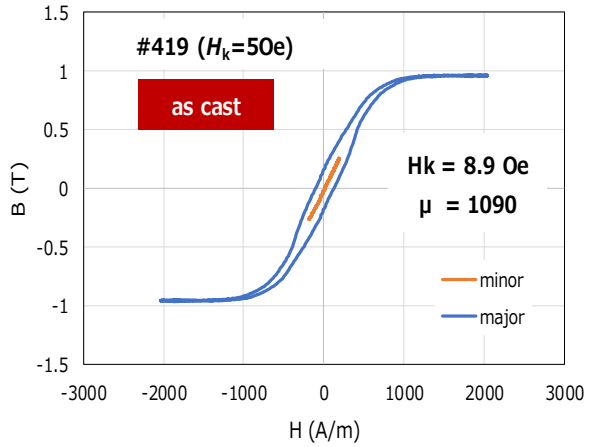
The σ—noise has minimum value around peak coil voltage.



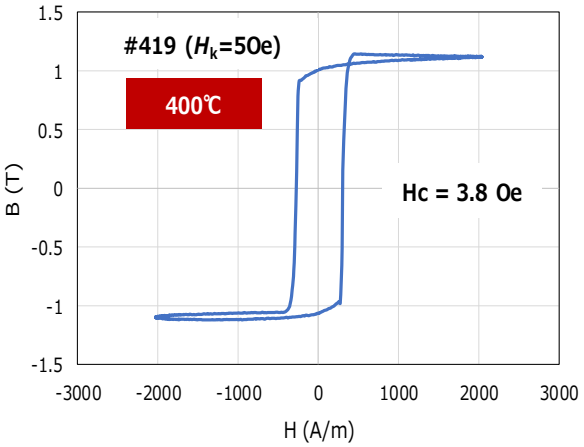
Result (6) Improving wire property by Effect of TA-temperature

Tension : 20Kg/mm2

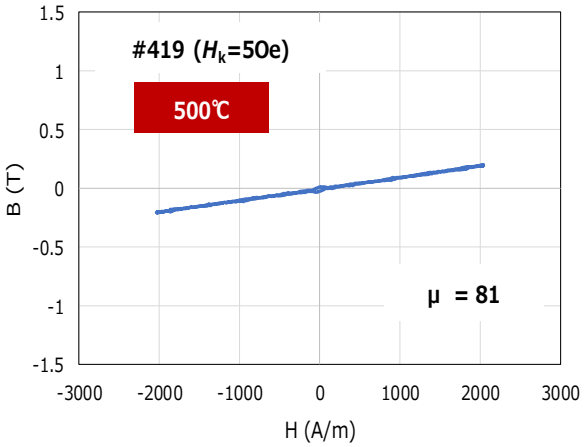
Amorphous



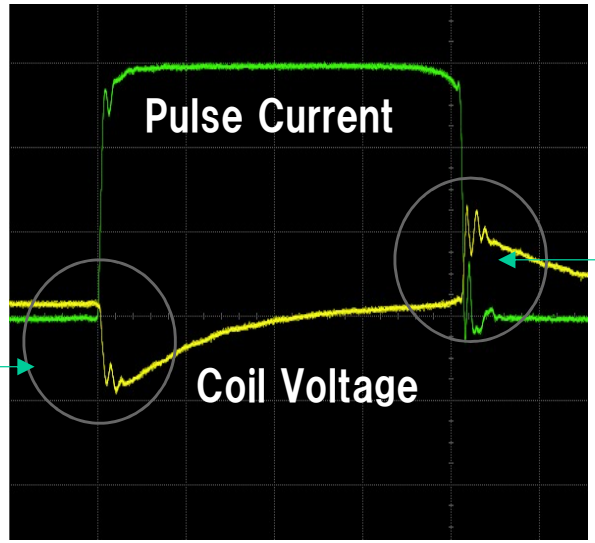
Amorphous



Crystallization



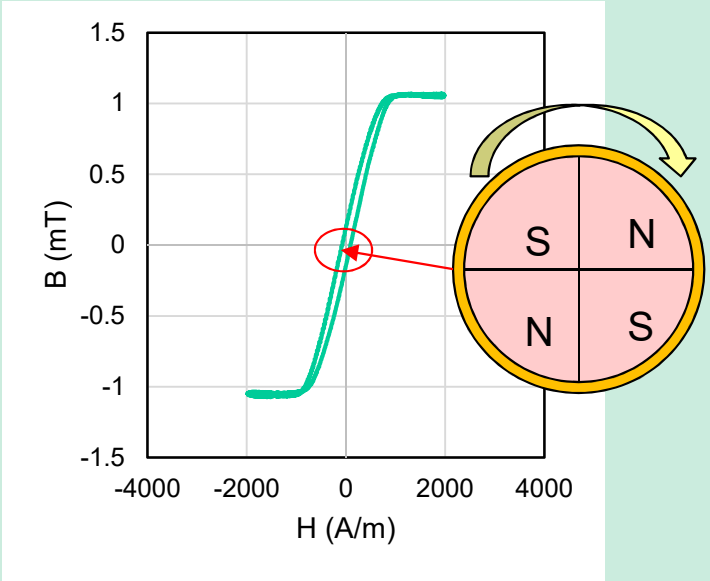
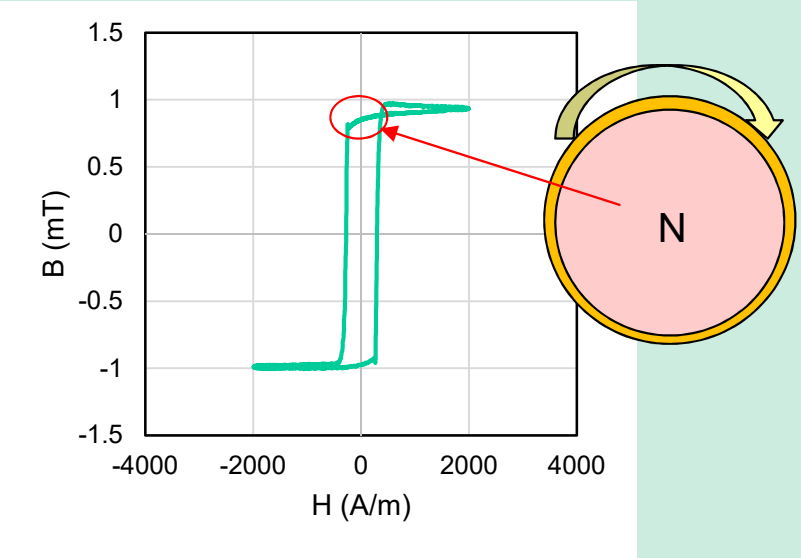
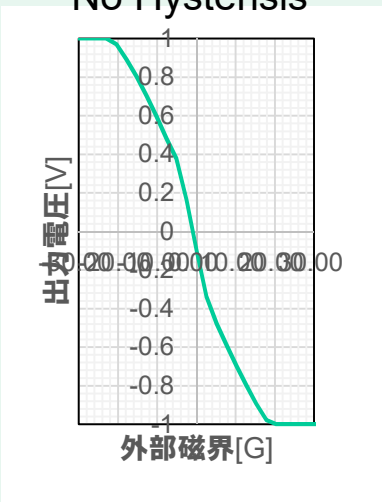
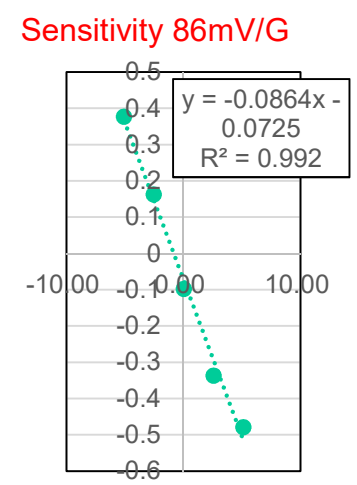
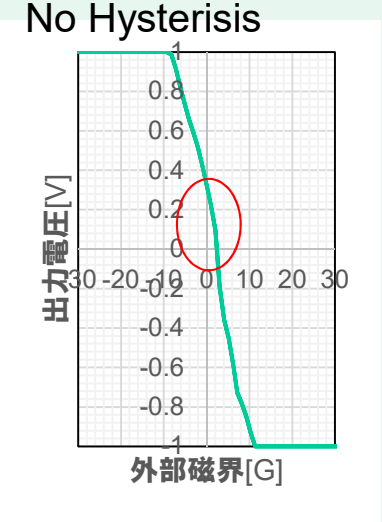
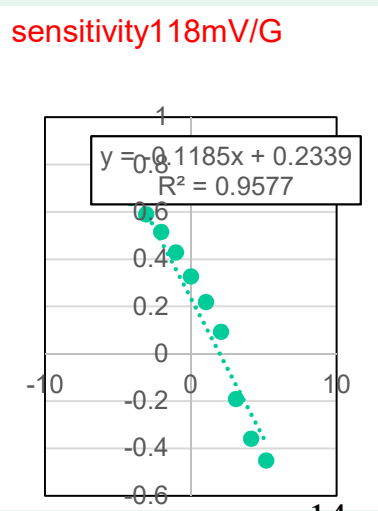
Amorphouse



Rising edge detection

Falling edge detection

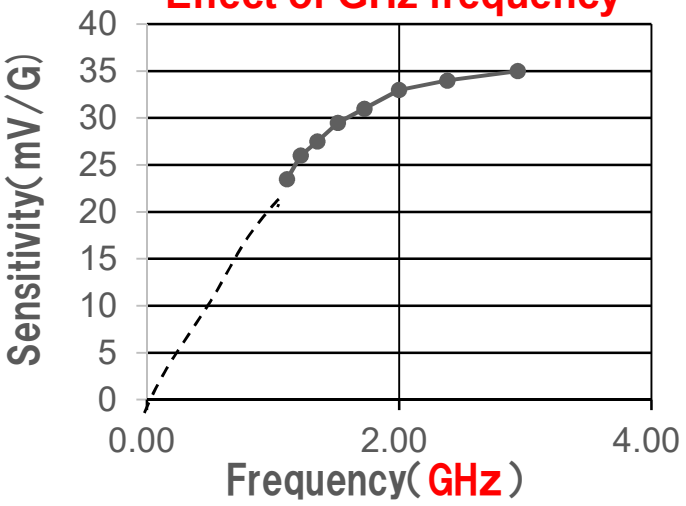
Detecting at Rising edge of Pulse current

Ni	As cast	Tension Annealing at 400℃ under 20Kg/mm2
B-H		
GSR	No Hysterisis  Sensitivity 86mV/G 	No Hysterisis  sensitivity118mV/G 

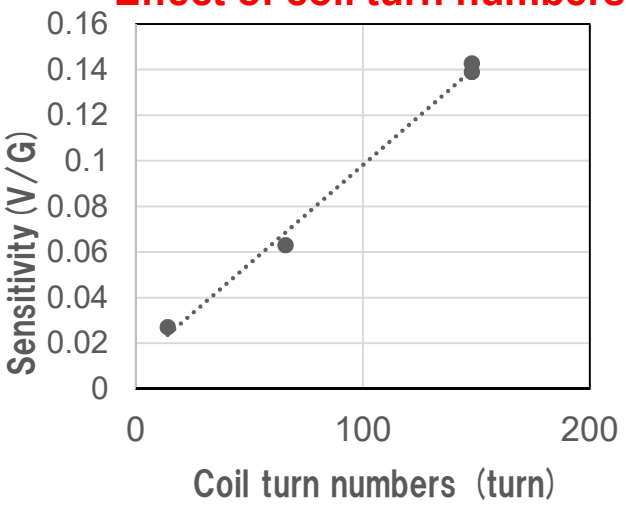
Result（7）Summing up results on GSR effect GHz-Spin-Rotaion

The high sensitivity is increased by GHz frequency and coil turn numbers.
GSR effect has a sine functionality to make the wide measuring range and the good linearity
And no hysteresis and low noise.

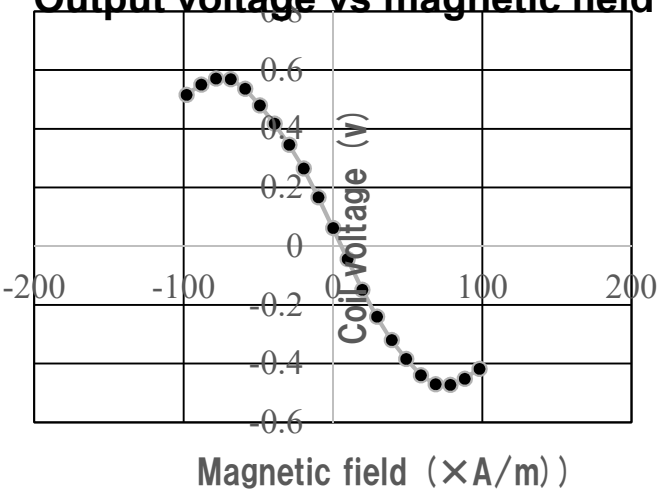
Effect of GHz frequency



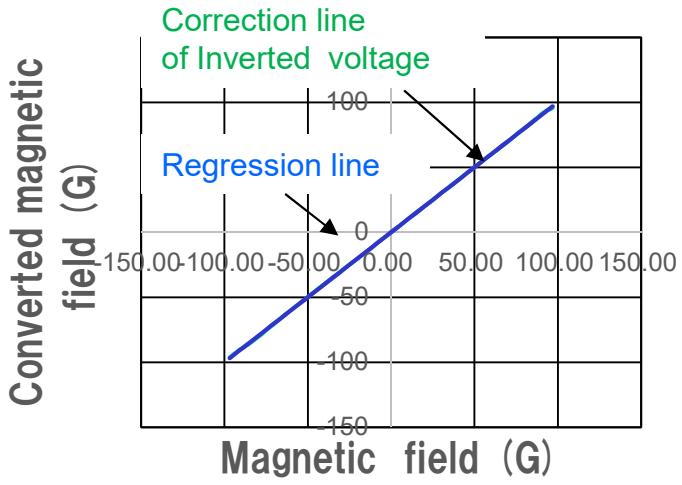
Effect of coil turn numbers



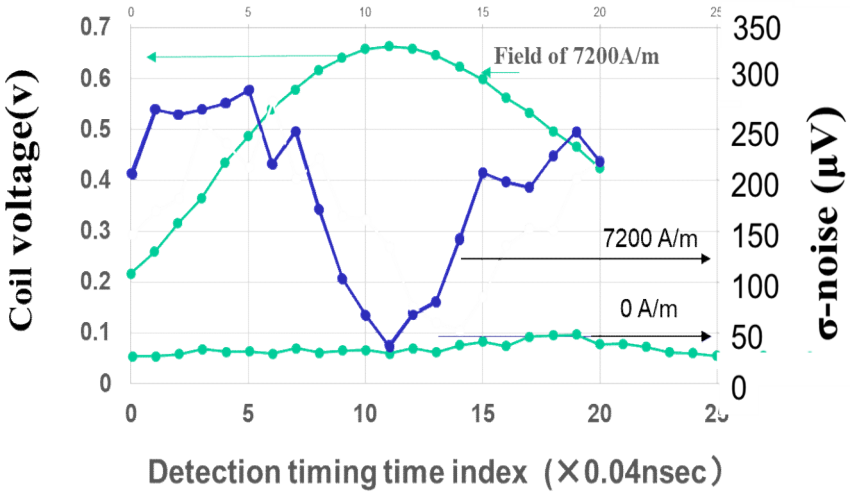
Sine functionality With Output voltage vs magnetic field



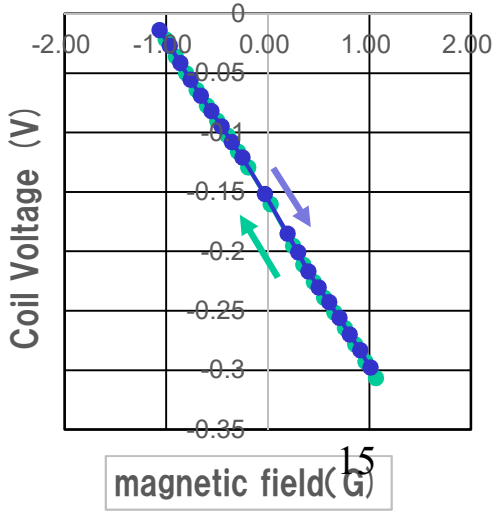
Good linearity



Low noise at peak detection timing



Nearly no hysteresis



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

1) Diffrence on the frequency dependency of the sensitivity

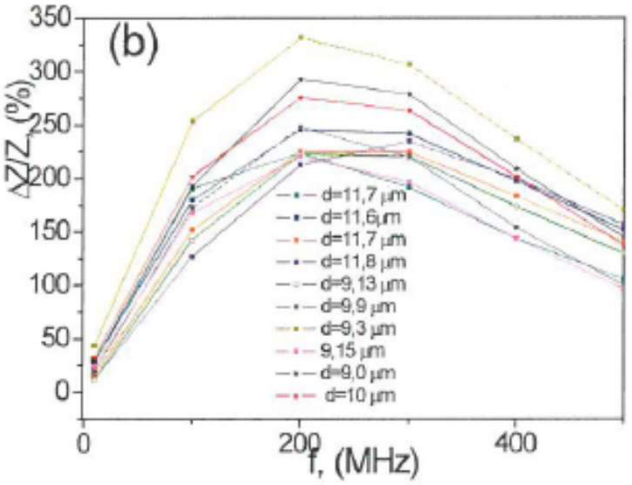
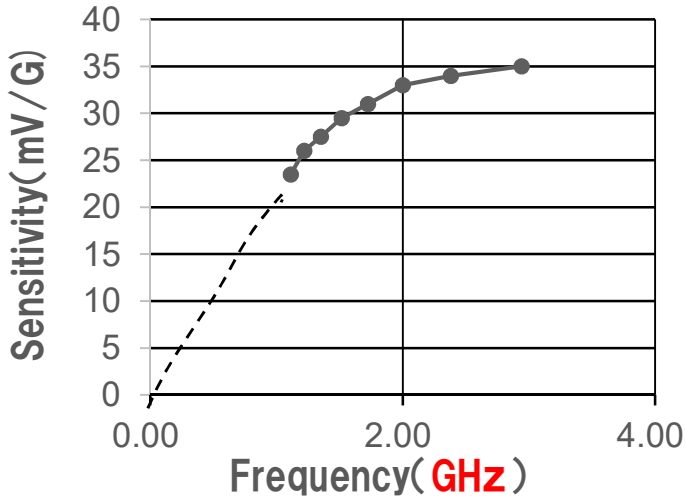


Figure 6. Frequency dependence of $Co_{66.87}Fe_{3.66}C_{0.98}Si_{11.47}B_{13.36}Mo_{1.52}$ microwires with different metallic nucleus diameters

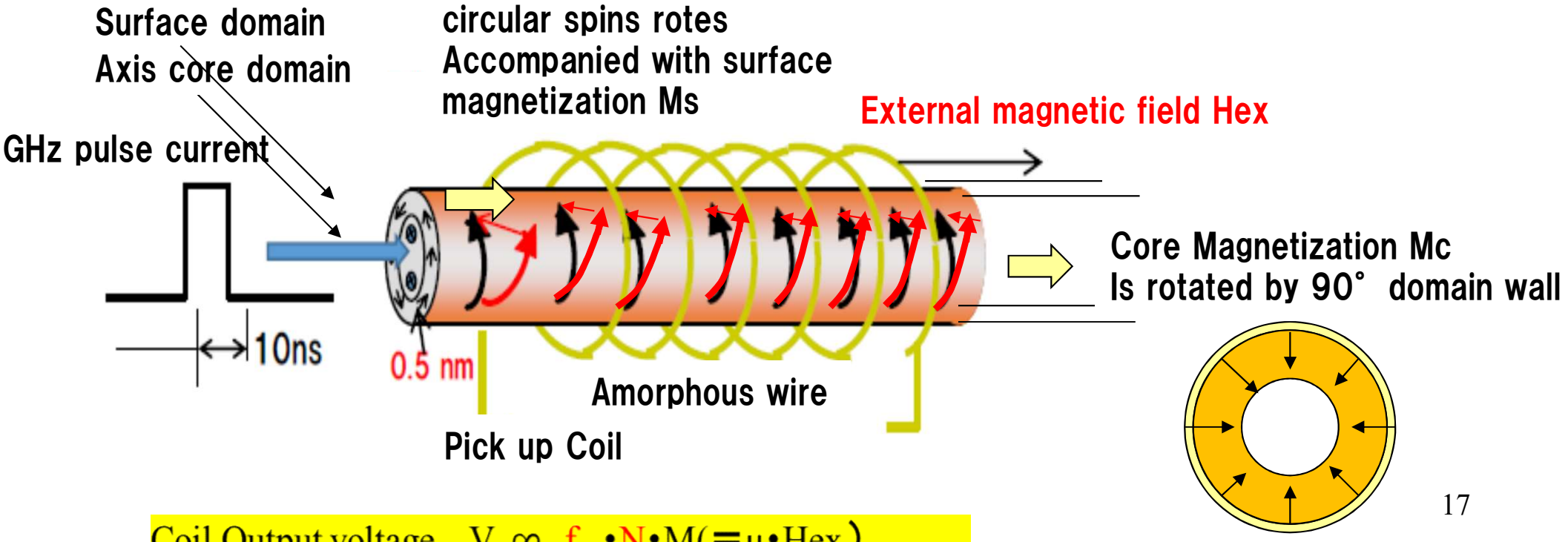
Effect of GHz frequency



(9) Discussion on Principles of GSR effect and GMI effect

GMI effect is based on the movement of 90 degree domains going to the inner side to produce the rotation of core magnetization Mc and shows the maximum impedance change at 200MHz because iddy current surpress the domain movement.

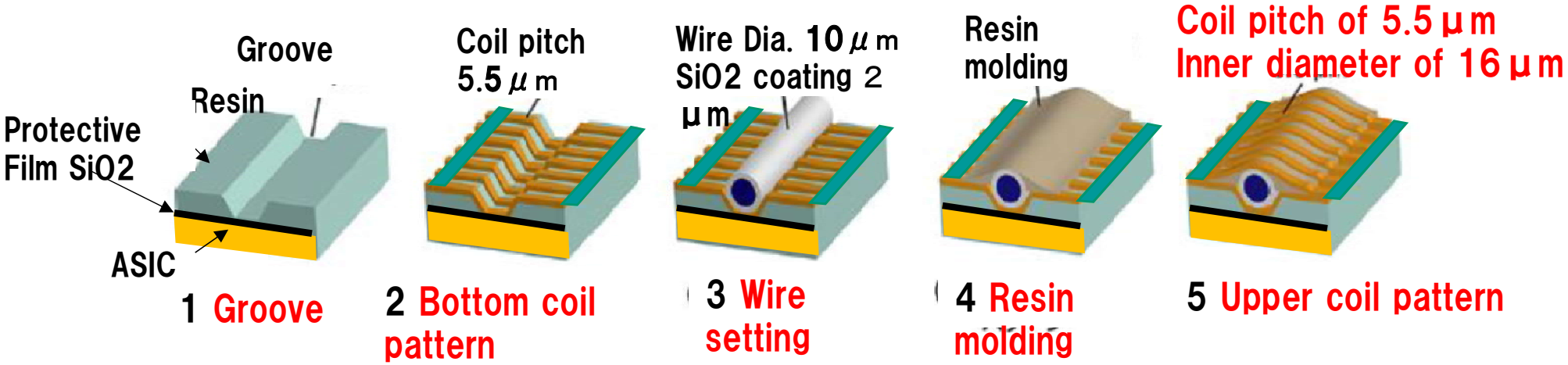
GSR effect is based on the spin ration existed in the circular domains with GHz angular velocity and shows the maximum coil voltage at 3GHz because spin can rotates easily.

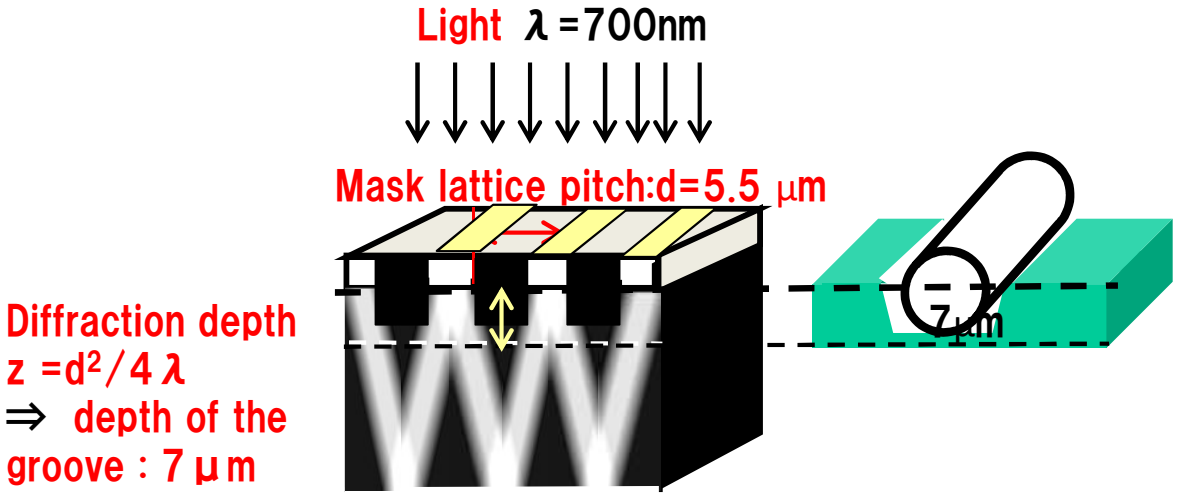


Coil Output voltage $V \propto f \cdot N \cdot M(=\mu \cdot Hex)$

§3: Production technique to produce GSR sensor element

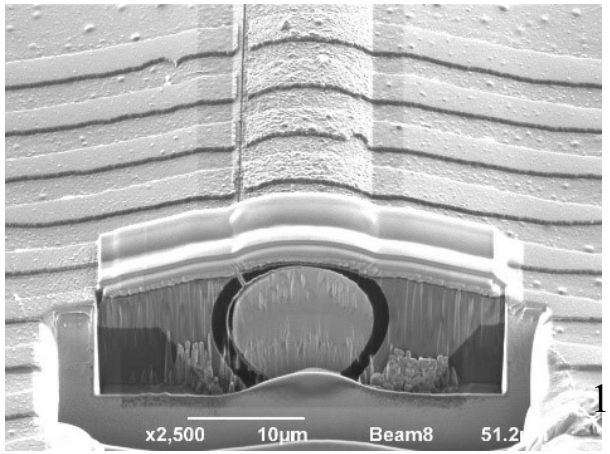
(1) Base process to produce a micro coil using 3 dimensional phtolithograpy



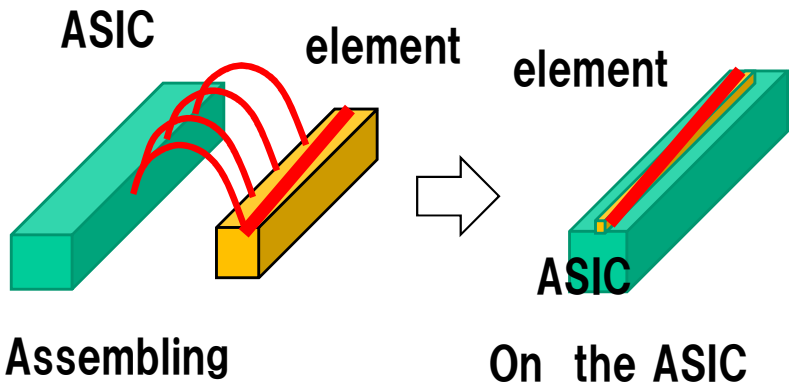


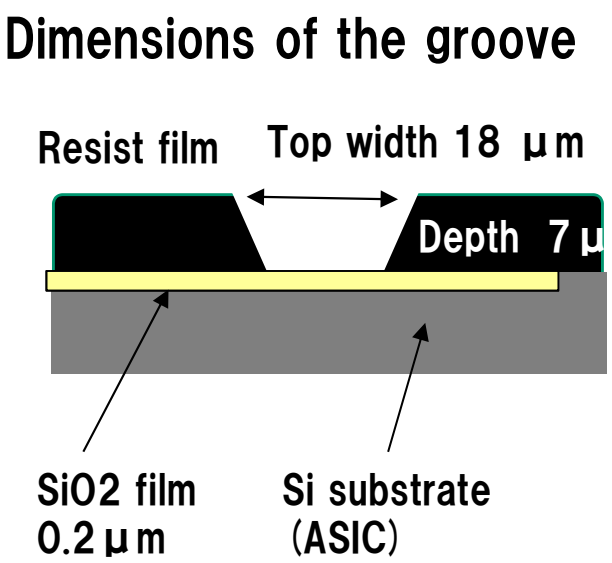
light pass through the mask splits

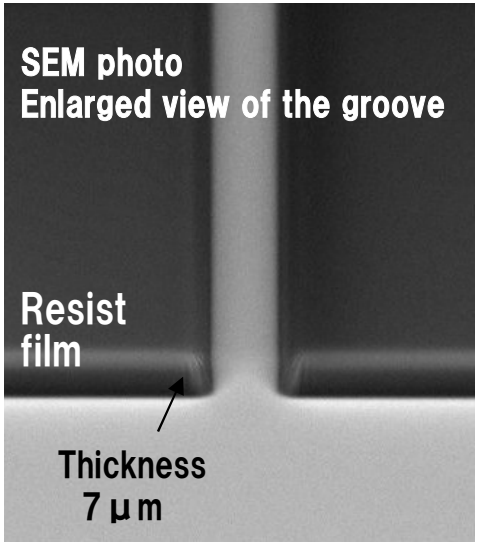
cross section of the Element



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

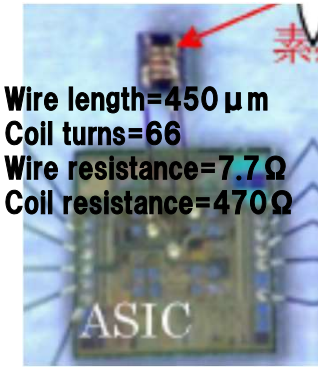






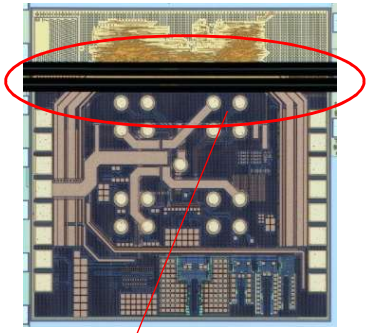
(3) The performance of on-ASIC type GSR sensor

Wire bonding type



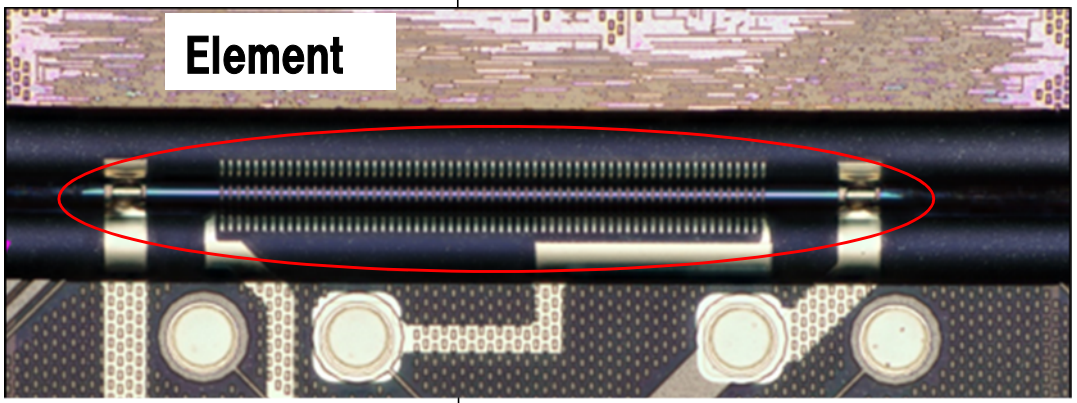
Enlarged view element

On-ASIC type



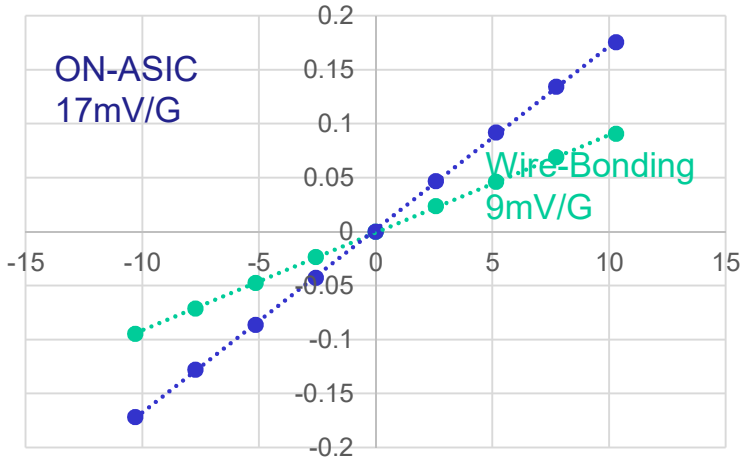
ASIC size: 1.2 ×1.2×0.2mm

Length=450μm
Coil turns=66
Thickness
=20μm

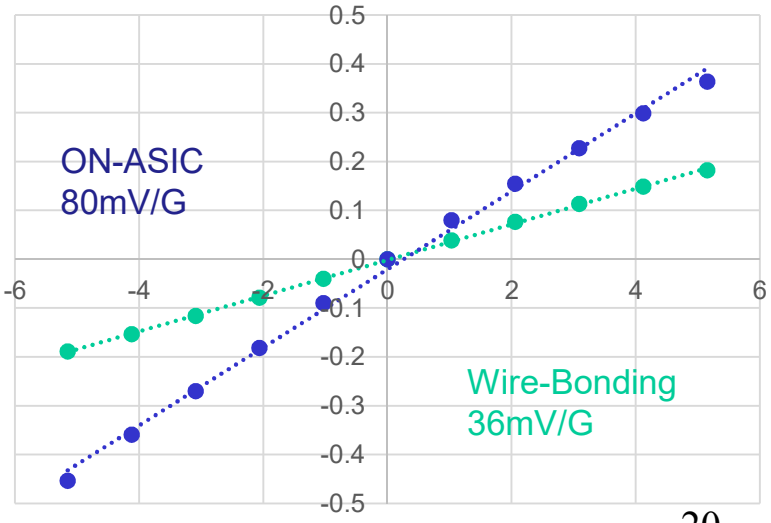


Output of the sensor

Coil turns=16

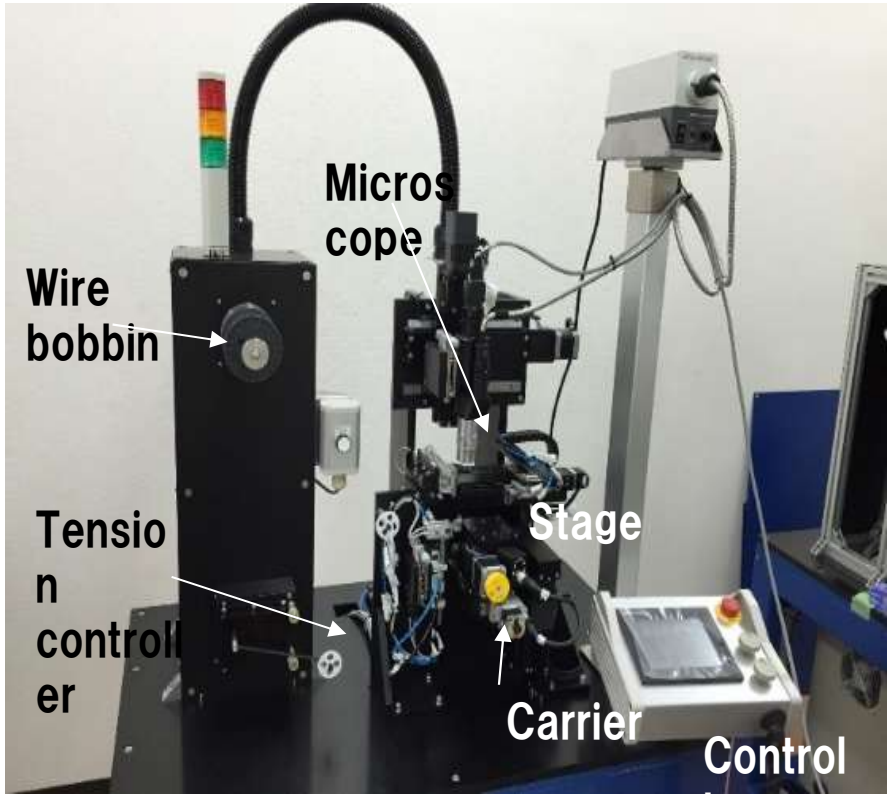


Coil turns=66

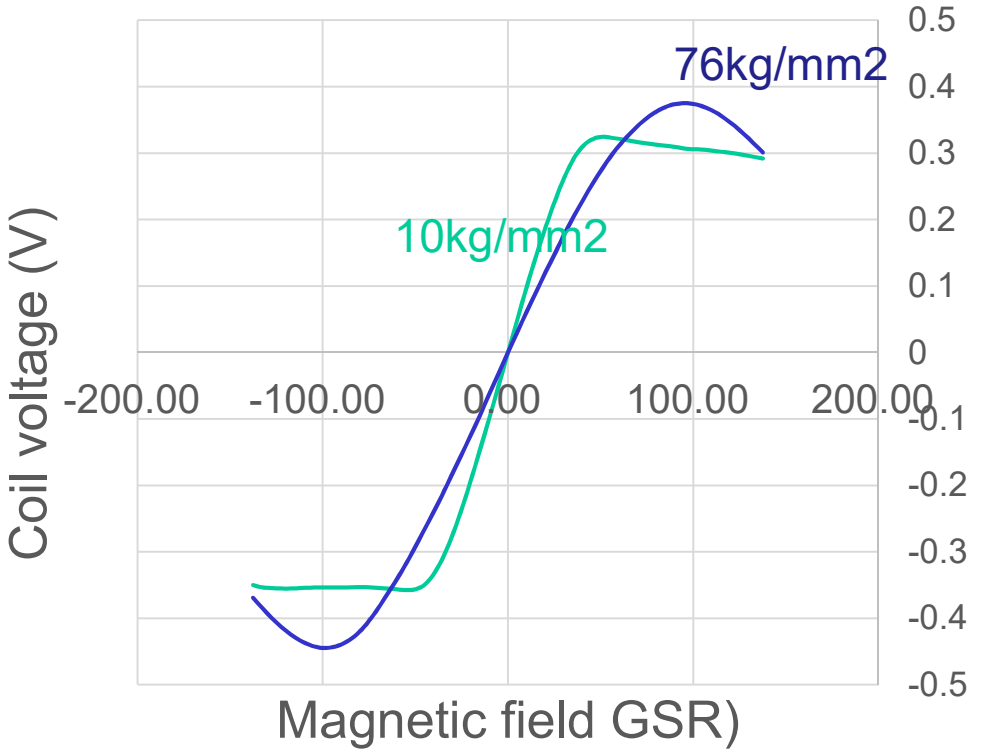


(4) The amorphous wire aliment machine
with high aliment accuracy of ±1μm and high tension of 76kg/mm2

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



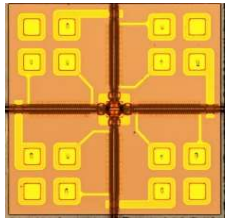
Effect of High tension of 76 kg/mm2



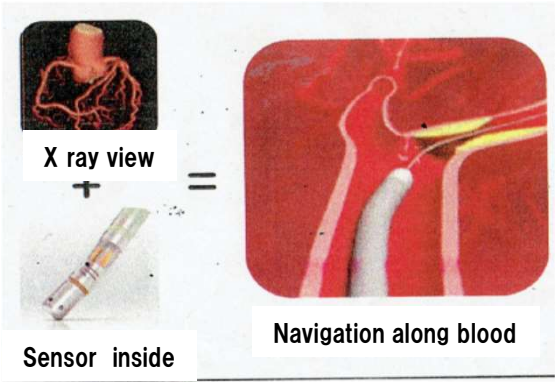
§ 4: Developments for Promising Applications

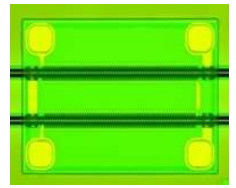
Project 1) Standard type for car use
- -wide range of 80G
- -high resolution of 3mG/LSB in 16bits
- -Analog circuit Bandwidth of 1MHz

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

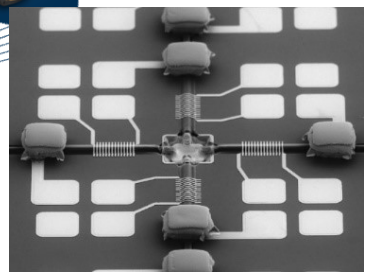


Project 2) ultra small type for catheter navigation in Body
- - size of width 0.4mm and length 1.2mm
- - keeping the performance of the standard type

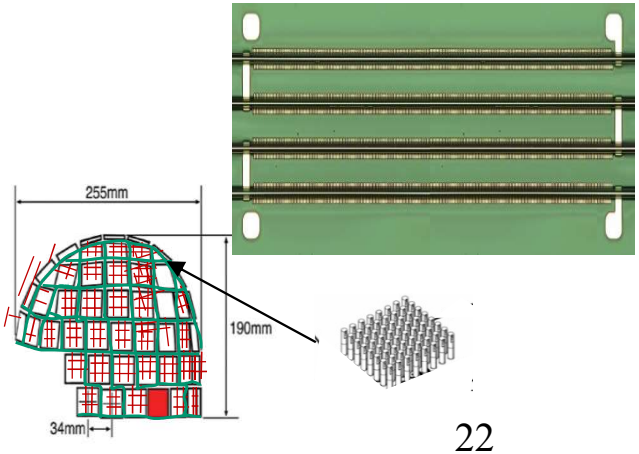




Project 3) the XYZ dimensional type for Gyro-Compass used in wearable computer
- - 3 dimensional type GSR element
- - Low noise under 1mG and high speed mearing 1KHz



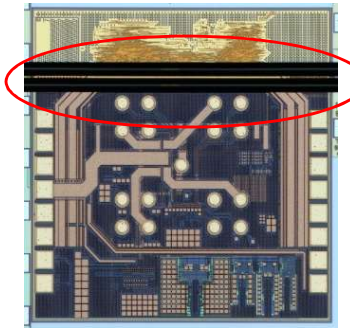
Project 4) pT meter to detect the bio-magnetism
- -noise under 1nT
- - **Developing** for a wearable type of magnetoencephalography instead SQUID



Project (1) Automobile use GSR sensors

Types L: length(mm) W: wire number N:coil turn numbers	element Size	Sensitivity	σNoise @1KHz	Measuring range	Total performance
	mm×mm	mV/G	mG	A/m	index
GSR sensor L0.16*W0.2 N=16	0.16×0.18 (8)	17	3mG (2)	50G (4)	64
MI sensor L0.6*W0.4 N=16	0.6×0.4	3	7mG	12G	1

ASIC size:1.2 ×1.2×0.2mm
Element:



Element

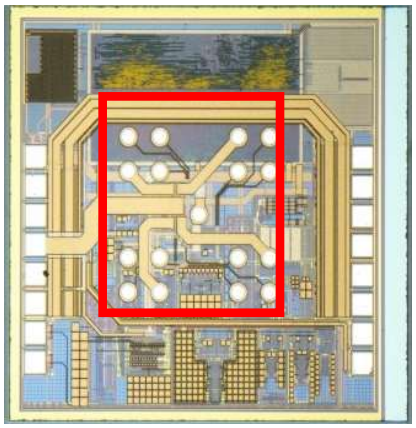
Thickness =20μm

Analog Circuit bandwidth : 500KHz
⇒1MHz possible
ODR is 5KHz
Power consumption is 0.4mA
ADC has 16 bits
σ-noise:3 times higher

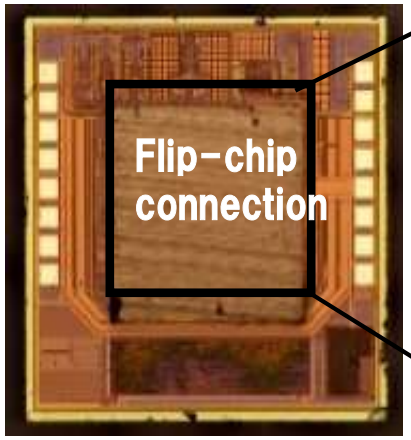
Project （2） Electronics Compass for smart phone

Prototype with 2 dimensional

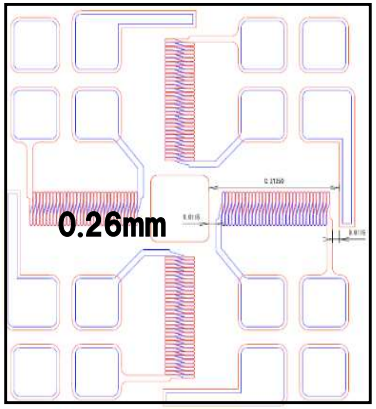
ASIC：1.2㎜×1.2mm



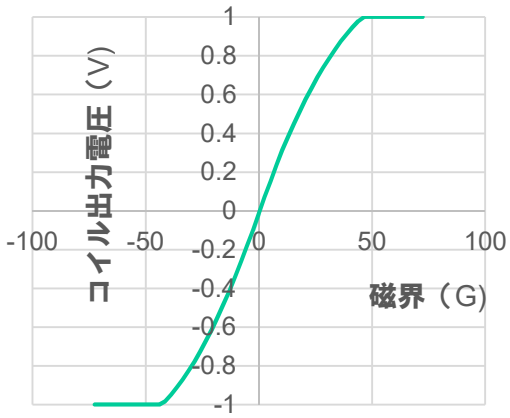
ASIC＋X-Y axis



X-Y axis element 0.6㎜×0.6mm



Sensitivity ：40mV/G



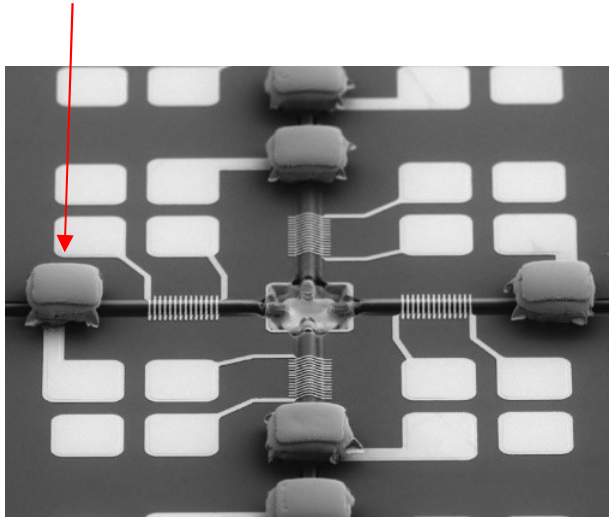
Target of <1mG

Types N:coil turn numbers	Length✕width =Element size	Sensitivity	σNoise @1KHz	σNoise @200Hz	S/N ratio	Measuring range	Total performance
	mm✕mm	mV/G	＊μV　mG			G	index
1 element（N=31）	0.26✕0.3　（2）	40　（12）	＊60　1.5mG	0.7mG	660　(14)	40　(3.3)	92
2 element（N=63）	0.26✕0.6　（1）	80　（12）	＊60　0.75mG	0.3mG	1320　(28)	40　(3.3)	92
AMI306ー1素子16回	0.60✕0.35	3.3	＊70　7mG	2mG	47	12	1

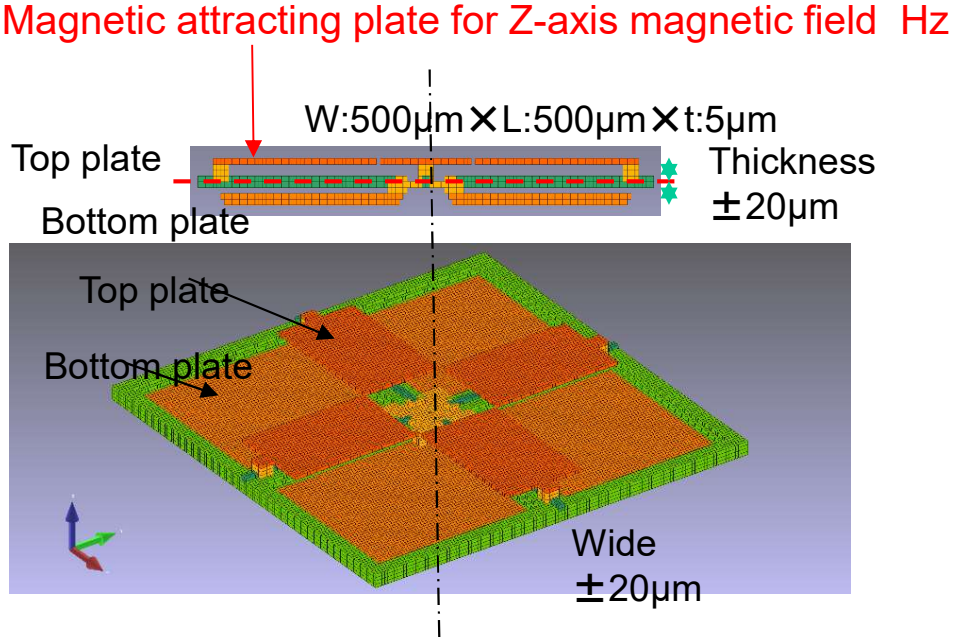
Challenging to develop XYZ type GSR Element

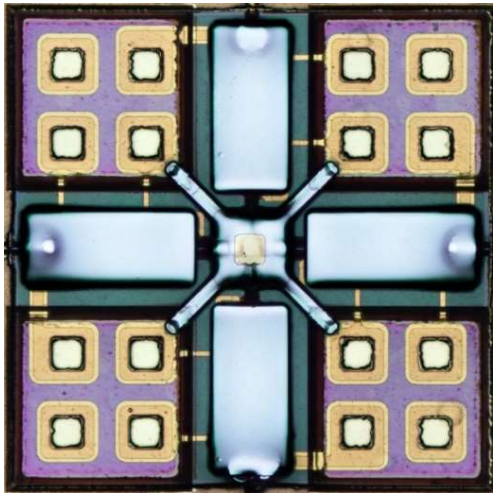
First challenge

Magnetic attractive button for Z-axis magnetic field Hz



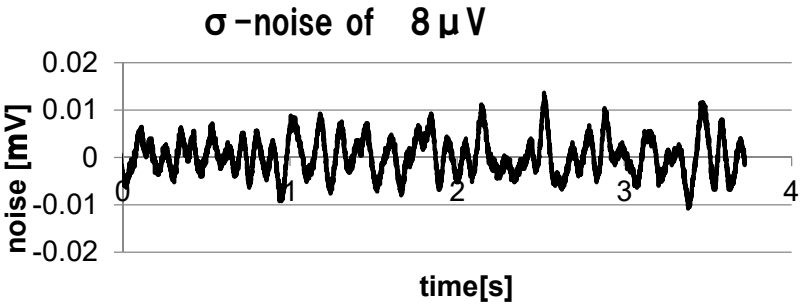
Second challenge



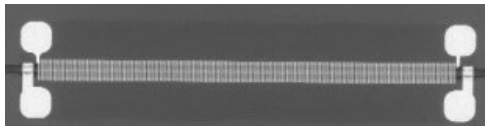


Project (3)　nT sensor to detect bio-magneism

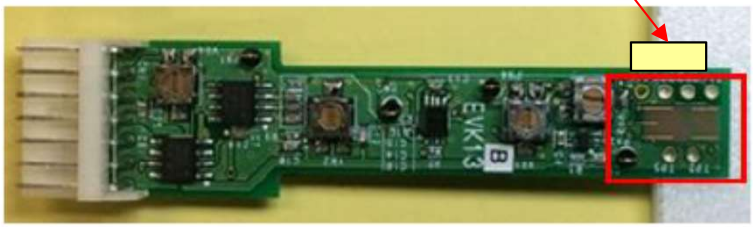
EVK with 3mm type element
- Coil turns numbers of N=528
- Sensitivity 1600mV/G, σnoise 8μV
- σノイズ 0.5nT



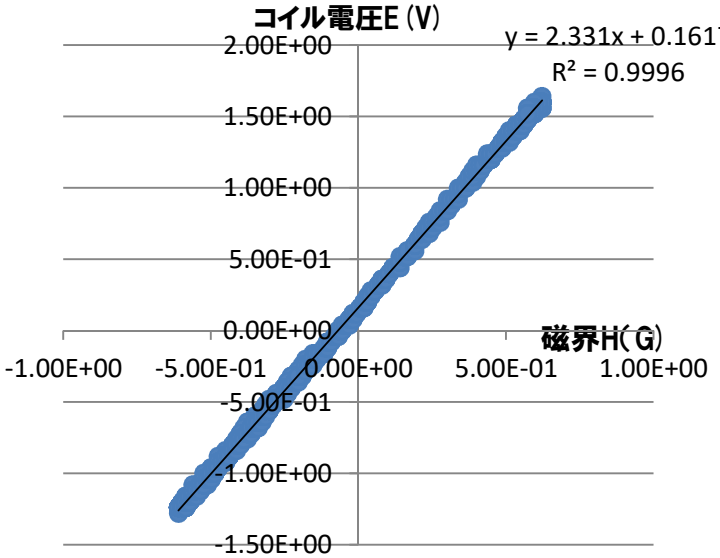
Element



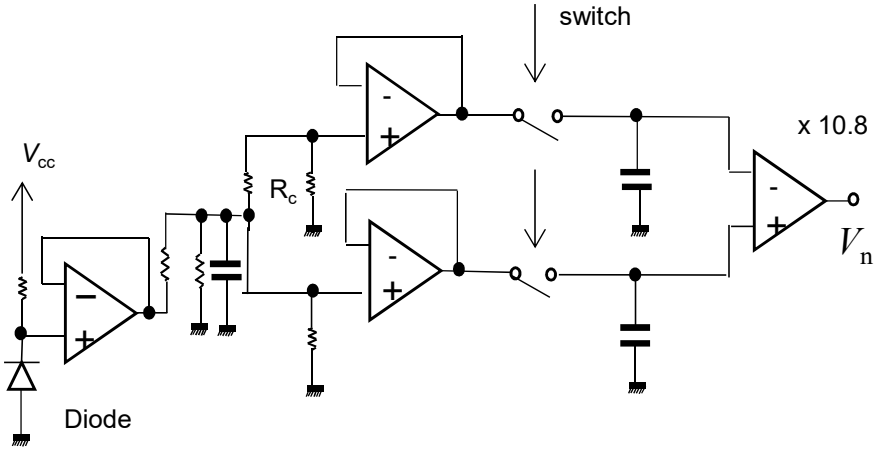
EVK board



Sensitivity 1600mV/G



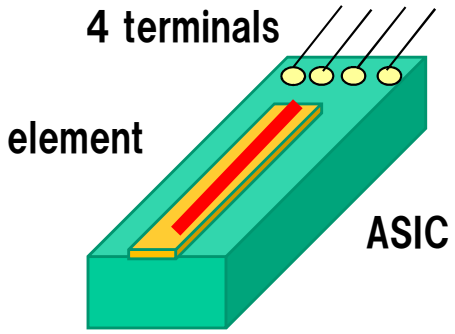
Circuit block



Project (4) Chathter use GSR sensors for in-Body Navigation

Types L: length(mm) W: wire number N:coil turn numbers	Sensor Size	Sensitivity	σNoise @1KHz	σNoise @1KHz	Total performance
	mm×mm	mV/G	∗μV	mG	index
GSR sensor L0.45*W0.16 N=66	0.4×1.2×0.2 10 times smaller	80mV/G	∗60μV	0.7mG 10 times better	100 Times better
GMI sensor L0.40*W0.16 N=16	2.0×2.0×0.6	10mV/G	∗70μV	7mG	1

We are developing a Small size ASIC with W: 0.4 ×L:1.2×t:0.2mm



§ 5: Summary

1) I found basic performance of GSR effect
   - high sensitivity increased by GHz frequency and coil turn numbers
   - high S/N ratio with good linearity, no hysteresis and low noise.
2) I developed Production technology to produce GSR eleemnt
   - to produce the micro GSR element.
   - to produce GSR elements on the ASIC surface
3) GSR sensor will be promising for various applicaitions

(1) Automotive use

(2) Compass use

(3) nT sensor to detect bio-magnetism

(4) catherter use for in body Navigation system


Thank you for your kind attention!