The development of GSR sensor excited by GHz pulse current

Outline

1. Background
2. Progress of the Research from 2015
   1) Discover GSR Effect
   2) Development ASIC type GSR sensor
3. Applications of GSR sensors
4. Summary

7st February, 2020

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§ 1 : Backgrond:
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

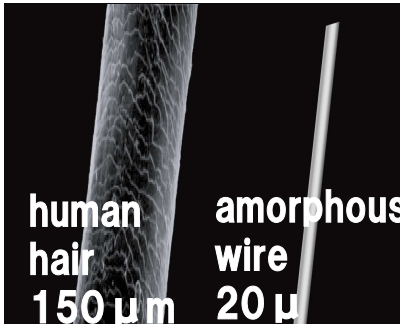
1999 Prof. Mohri Developed Coil type GMI sensor

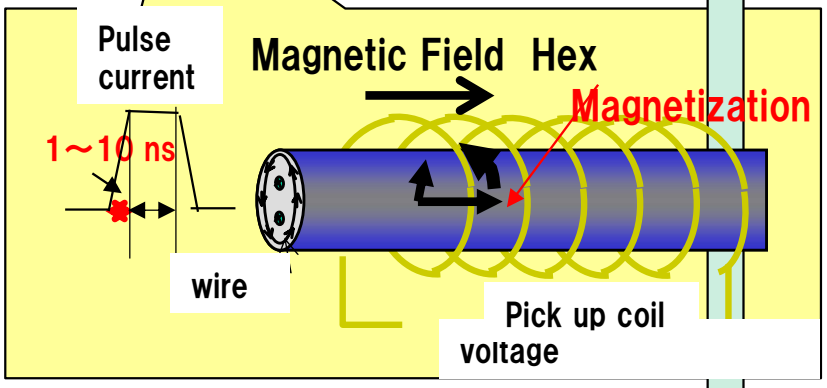
2004-10 Aichi Steel developed compass

200MHz→2GHz

2015 Honkura Developed GSR sensor

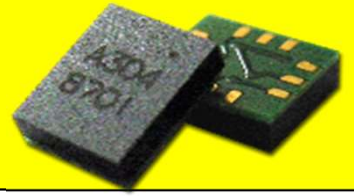
Fe-Co Amorphous wire





Prof. Zhukov produced Amorphous Wire

2004- 2010 Aichi Steel developed Electronics compass Frequency of 200MHz Size: 2㎜×2㎜×1㎜



1970 Prof.Masumoto produced Amorphous Metal

1991 Prof. Makhotkin Discovered GMI effect

1993Prof. Mohri Developed GMI sensor

高感度マイクロ磁気センサの開発の背景

検出力：コイル電圧／素子おおきさV×N
⇒1000倍改善

進化　FG センサ ⟹ MI センサ ⟹ GSR センサ

検出原理＋回路構成は　同じ

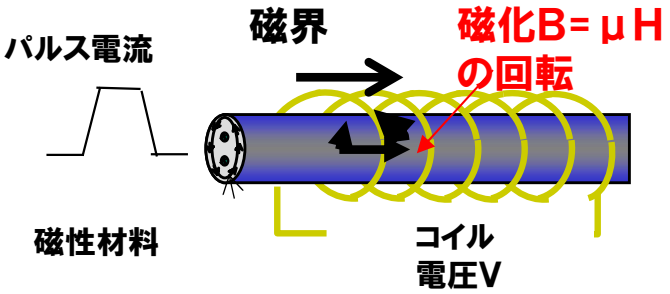
小型化実現の手段

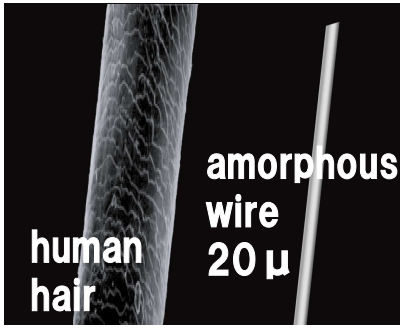
①パーマロイからアモルファス
　直径2㎜　⇒　直径10μm

②コイルの小型化
　機械巻き　⇒　薄膜コイル
　直径3mm　⇒　直径20μm

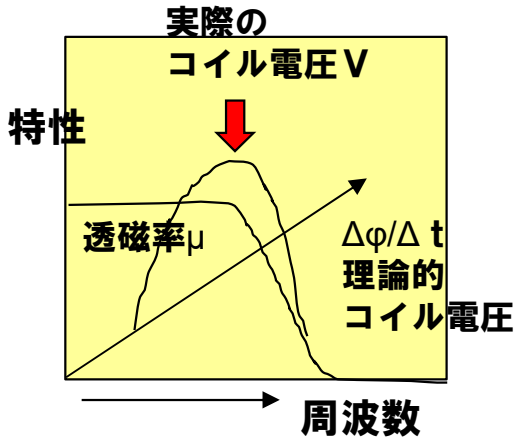
③パルス周波数の高周波化
　30KHz⇒200MHz⇒2GHz

④誘起される電磁現象の変化
　最表面の電磁現象　0.2μm





基本的な考え方



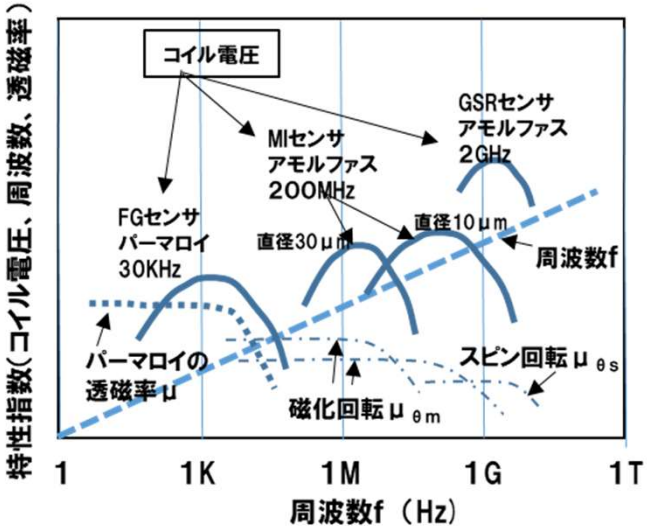
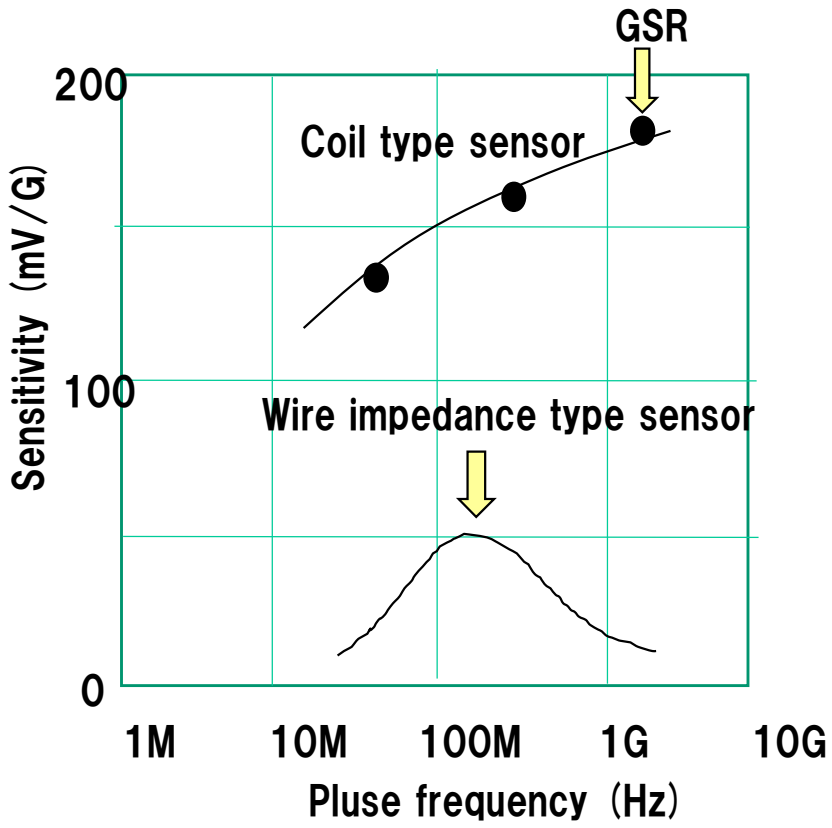


図15　各種センサのコイル電圧の周波数依存性

§2: Development of GSR senor from 2015
（1）Discover GSR effect in 2015

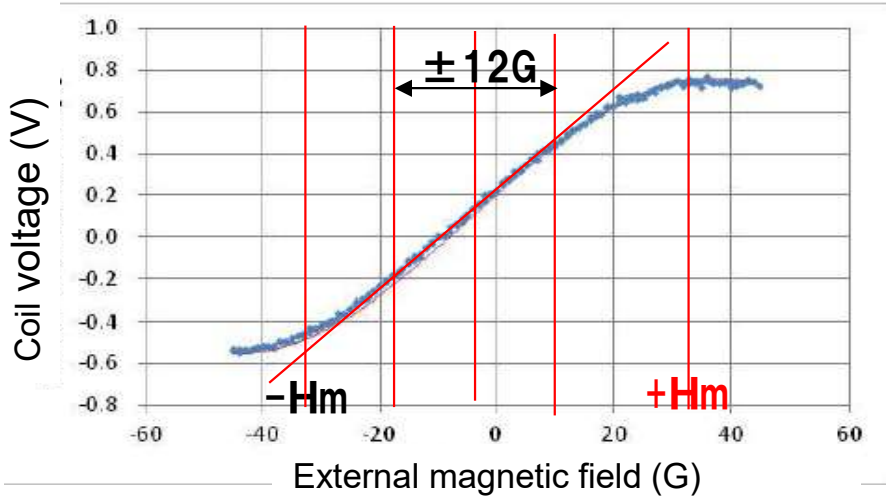
Effect of Pulse frequency on sensitivity

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

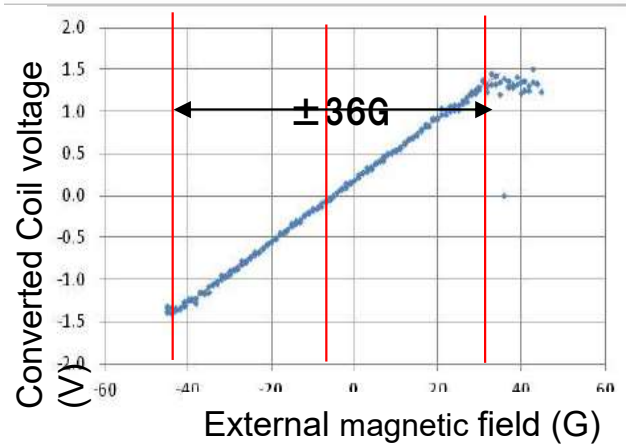


I found a sine functional relationship between the output voltage and magnetic field.

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

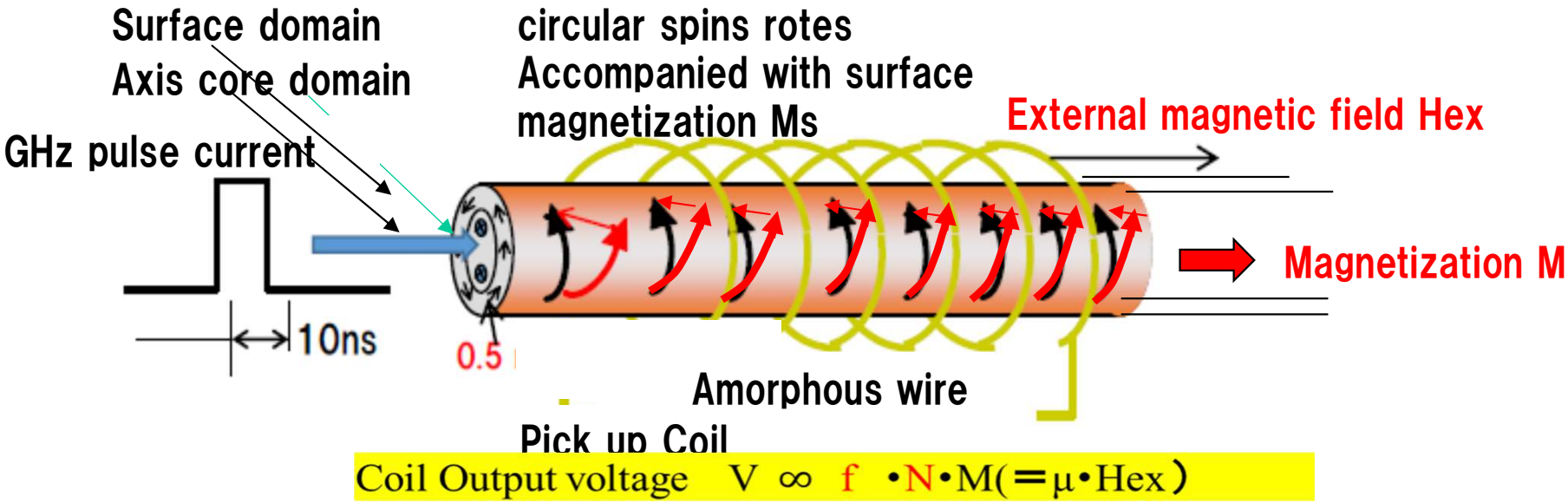


$$\arcsin(V/Vo) = \pi H/2Hm$$

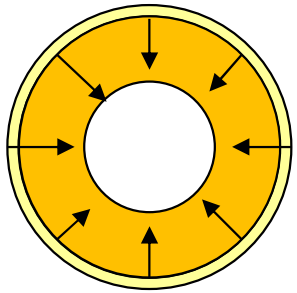


(9) Comparison on Principles of GSR effect and GMI effect

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.

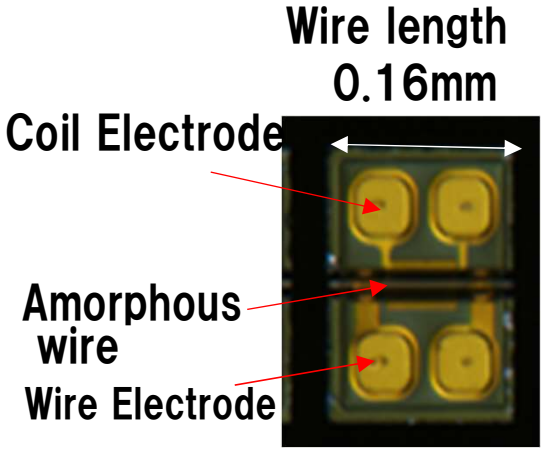


Coil type GMI effect is based on the rotation of Core Magnetization M accelerated by 90° domain wall, It means skin effect. so that, GMI effect makes a high sensitivity but accompanied with hyserisis

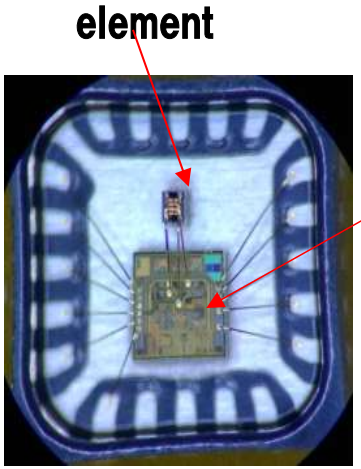


Core Magnetization M
Is rotated by 90° domain wall

(2) Detail Experiments using ASIC

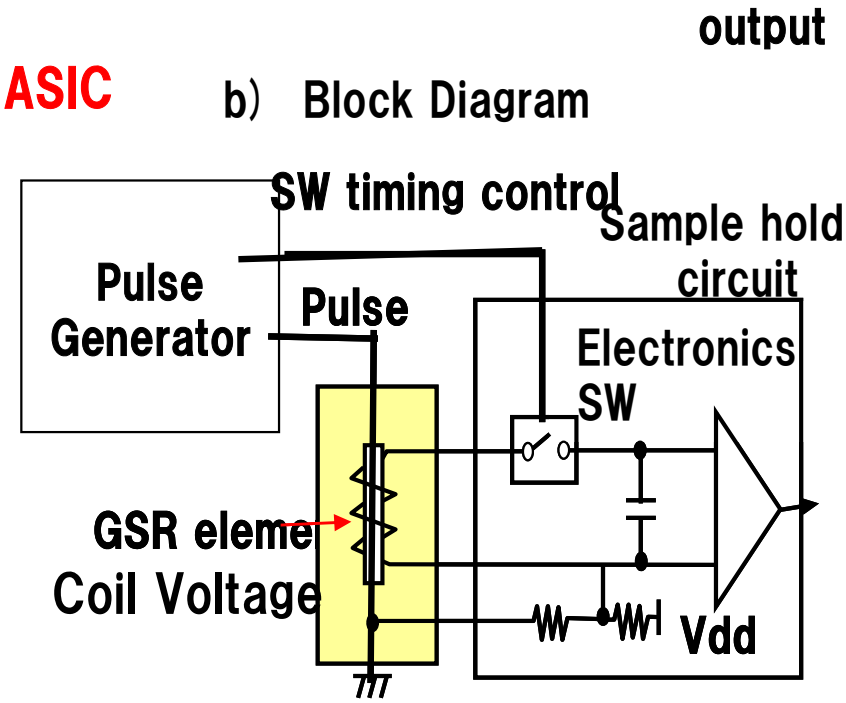


Micro coil type
of GSR element



ASIC used in the test

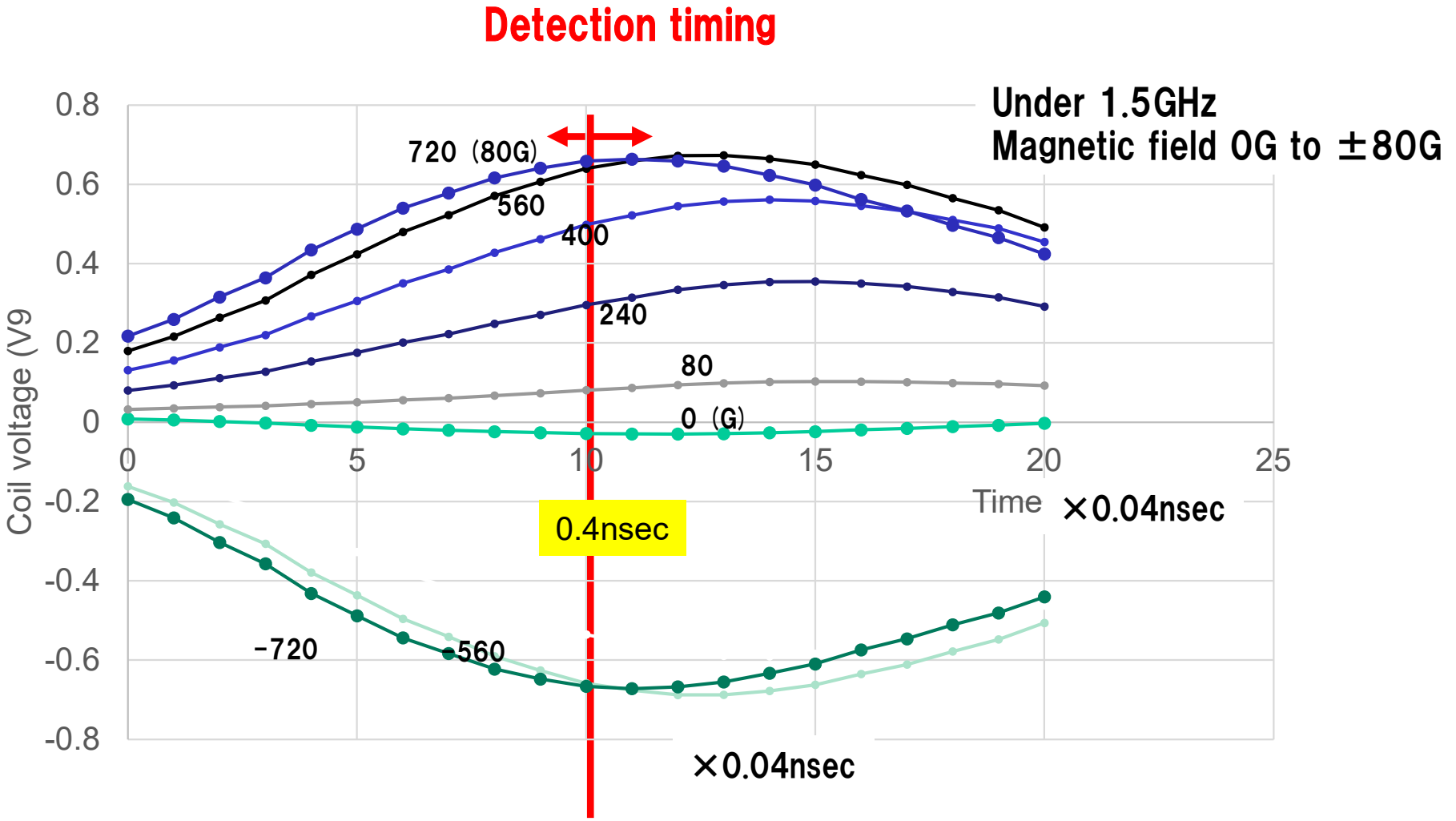
b) Block Diagram



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

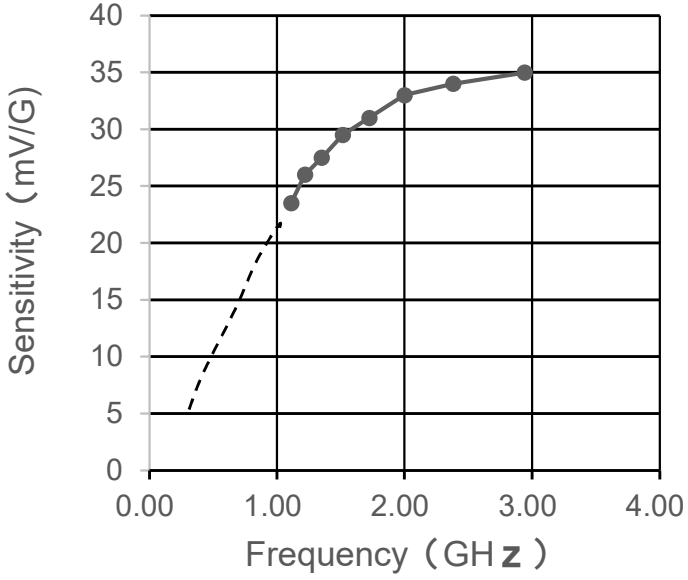
Result（1）effect of the detection timing on Coil voltage wave

- 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.

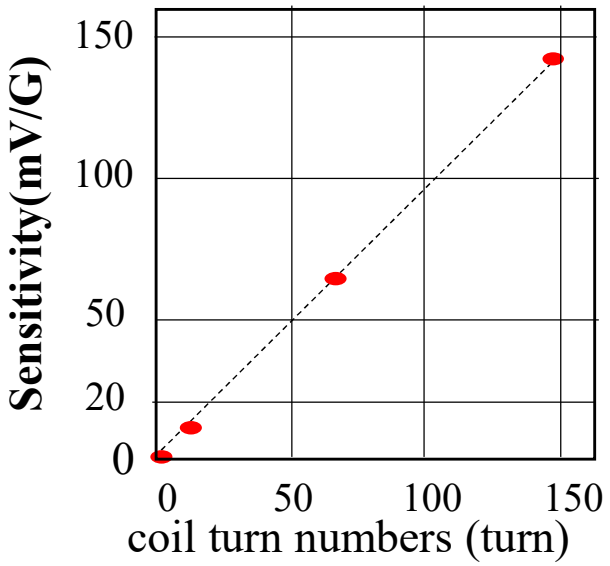


Result (2) Effect of frequency and coil turns on Sensitivity

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



a) frequency

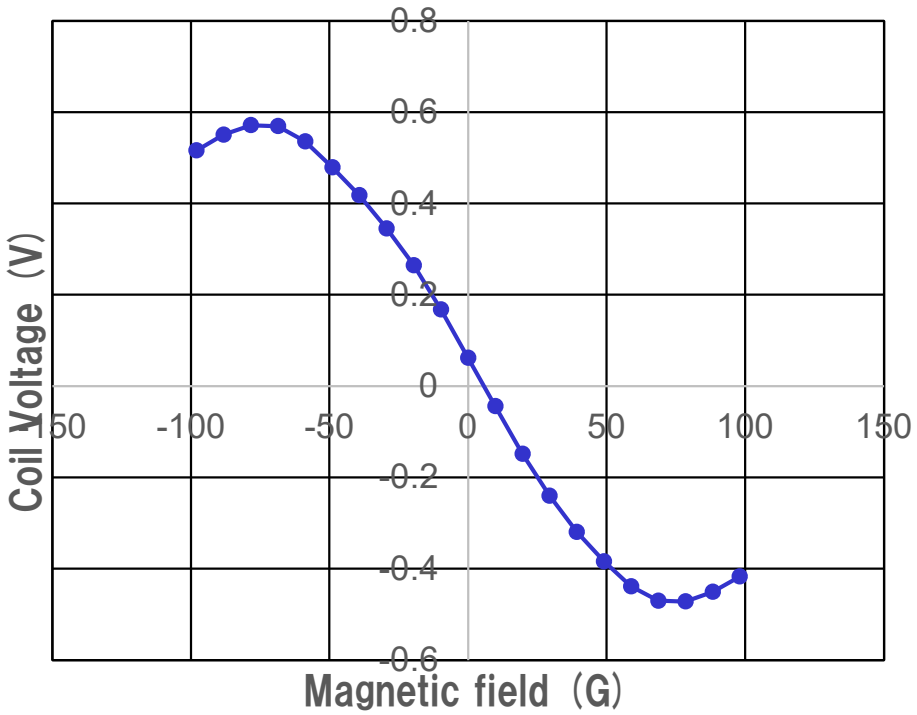


b) coil turn numbers

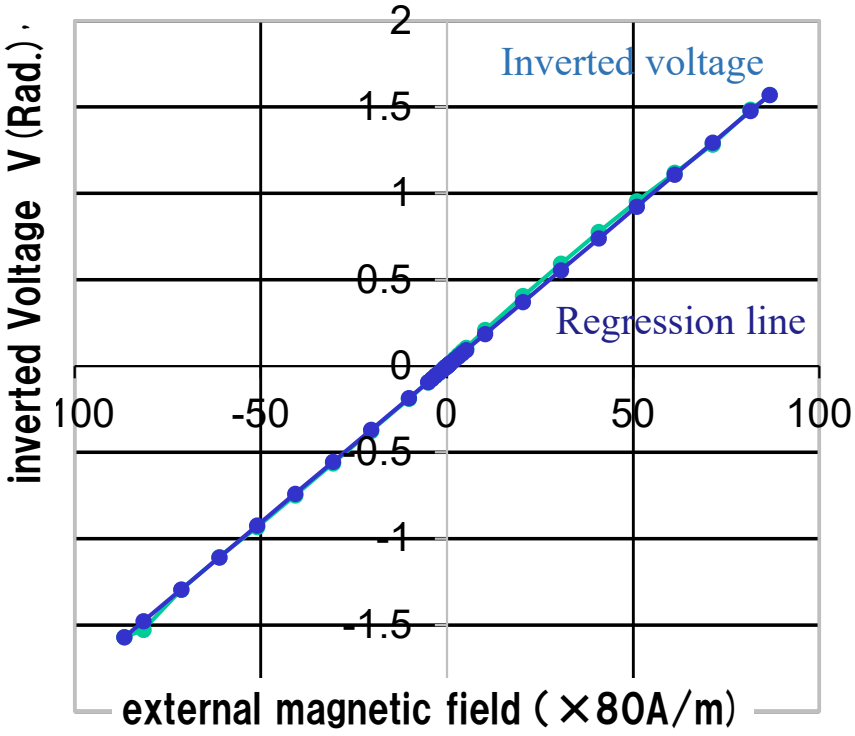
Fig. 7 Effect of frequency, coil turn numbers and wire permeability on Sensitivity

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

I also checked ASIC type sample
GSR effect makes the sine functionality between the magnetic field and the coil voltage

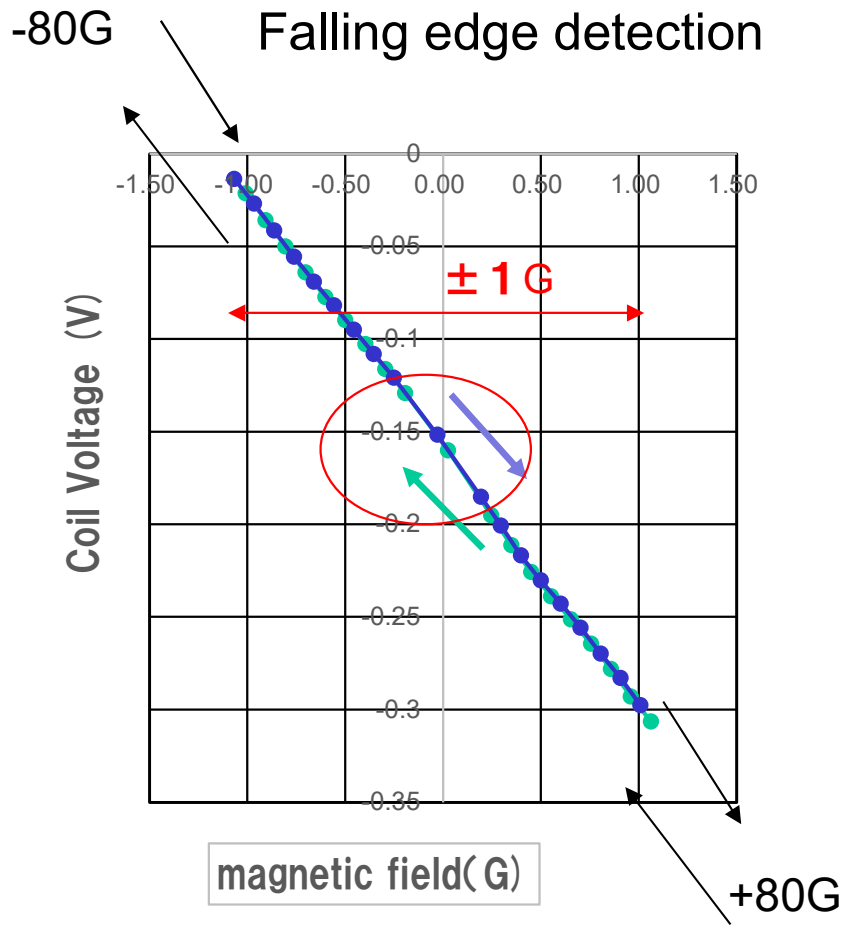


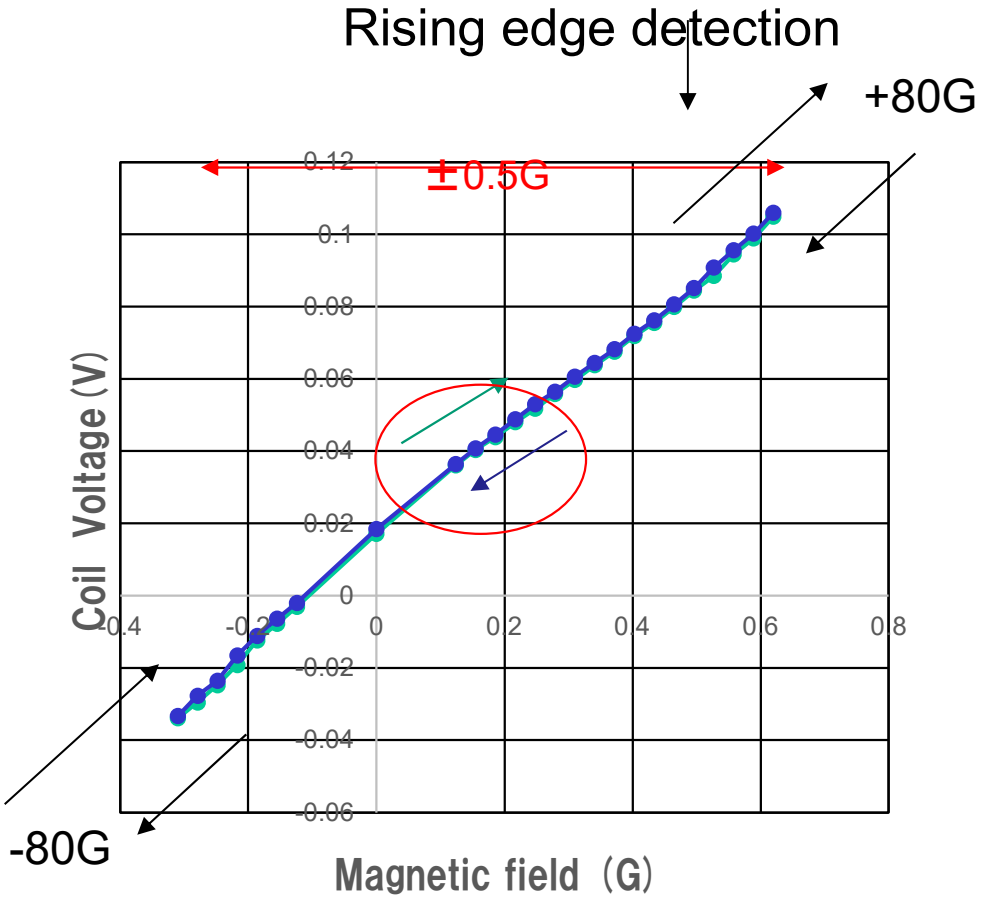
The relationship has a linearity of 0.5%FS



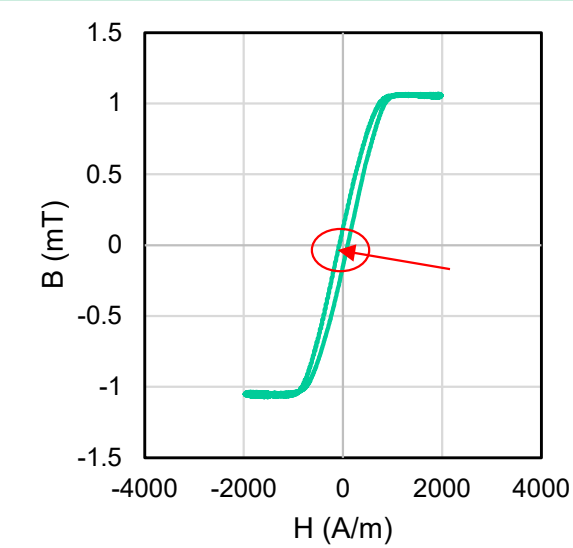
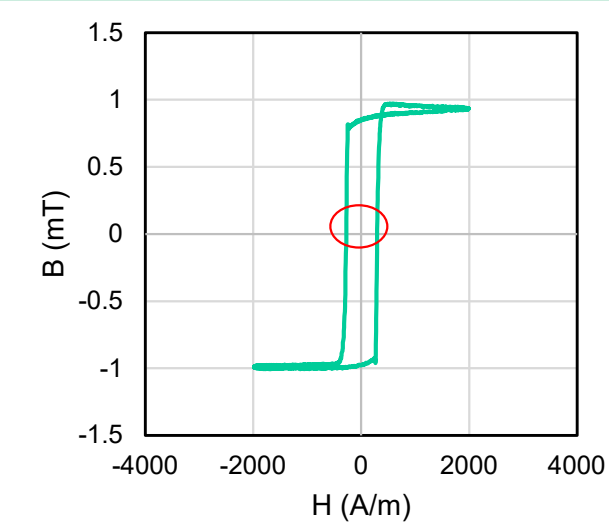
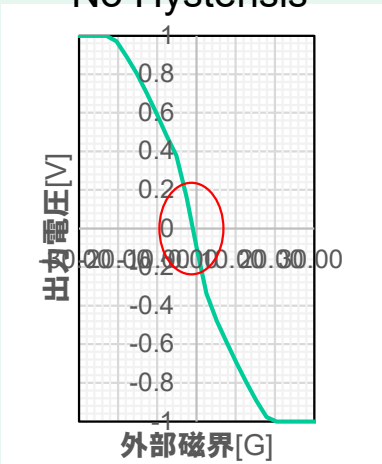
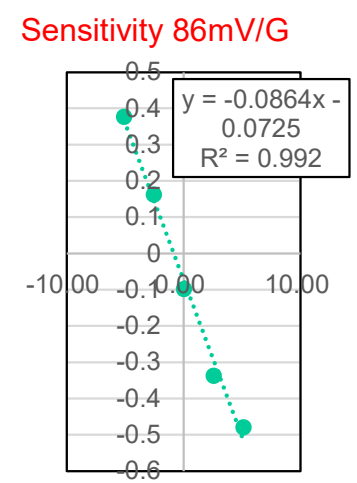
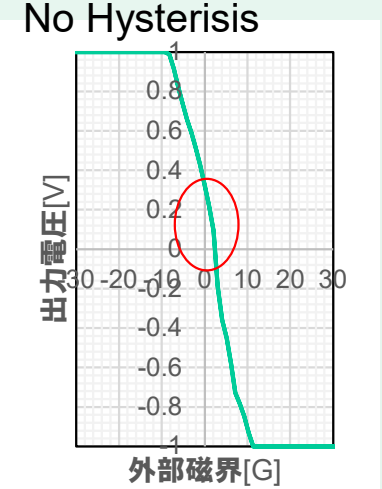
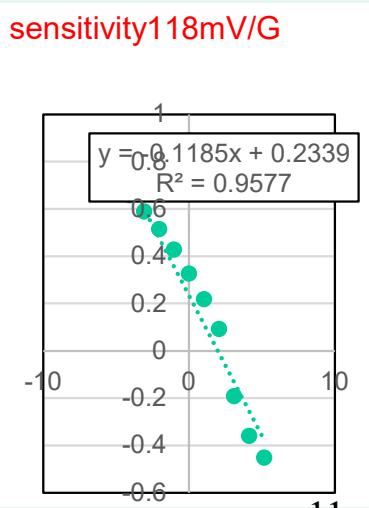
Result (4) Hysteresis of GSR sensor

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
Because coil type GMI sensor shows big hysteresis at the rising detection.
The reason is that the only spin rotation is not accompanied with domain wall movement, so that it makes no hysteresis





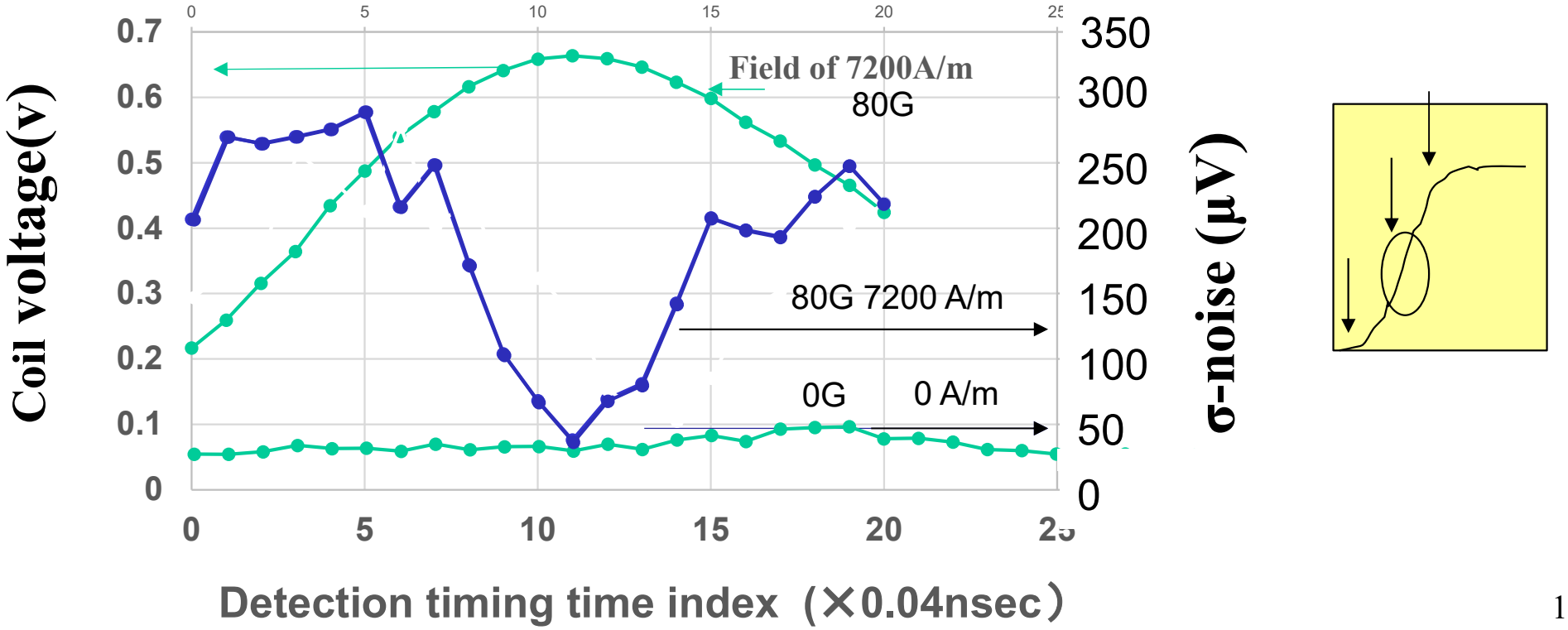
Result（6）Effect of BH curve hysteresis of the wire on the GSR output

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

Detecting at Rising edge of Pulse current

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

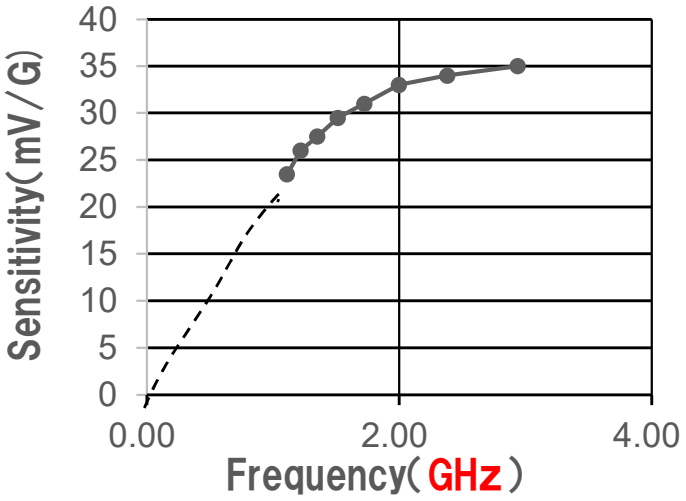
The σ—noise at 80G has minimum value at the peak coil voltage timing.



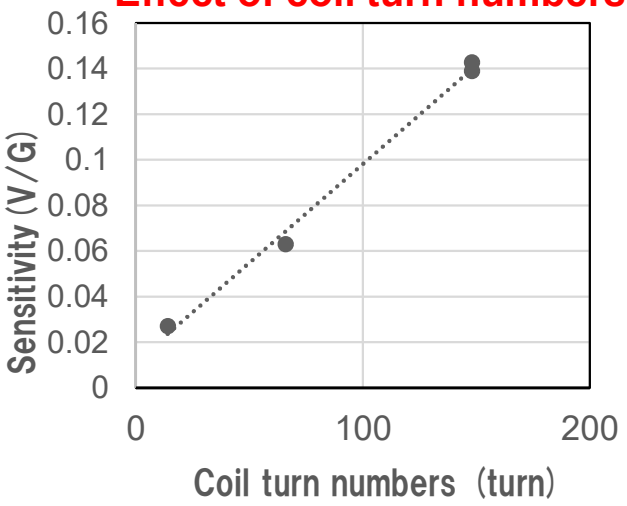
Result (7) Summing up results on GSR effect GHz-Spin-Rotaion

GSR effect gives the high sensitivity is increased by GHz frequency and coil turn numbers.
And excellent properties such as a sine functionality, the wide measuring range,
the good linearity,, low noise and no hysteresis.

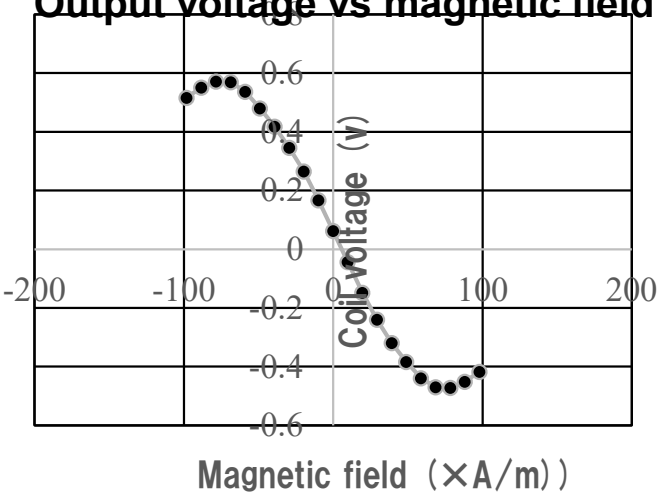
Effect of GHz frequency



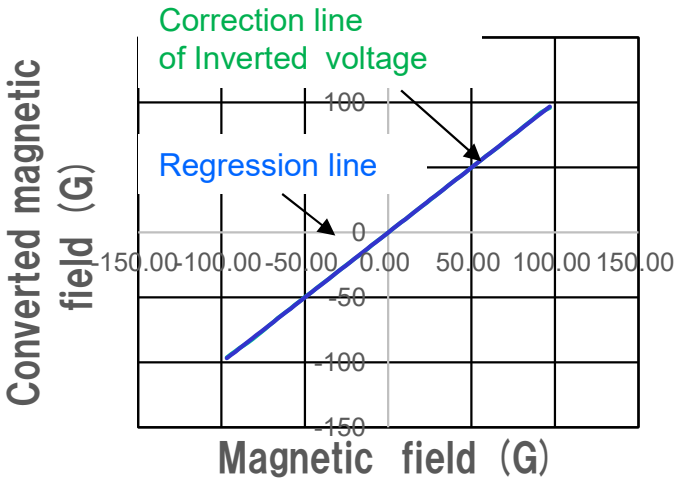
Effect of coil turn numbers



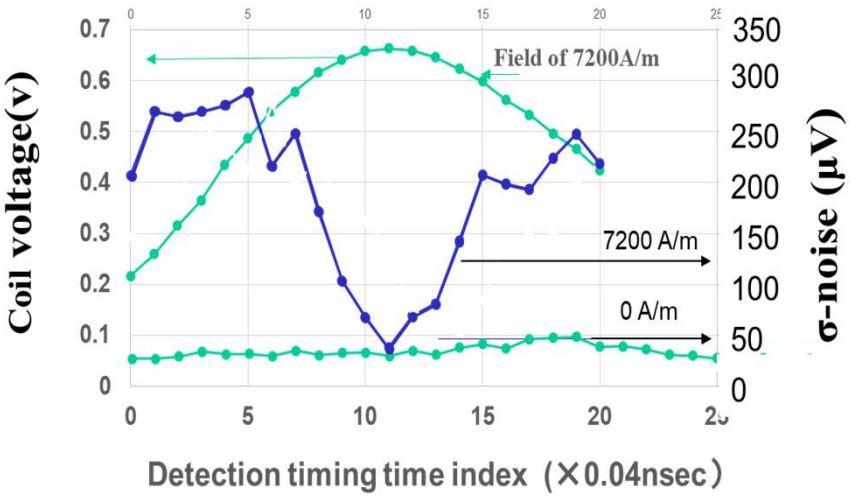
Sine functionality With Output voltage vs magnetic field



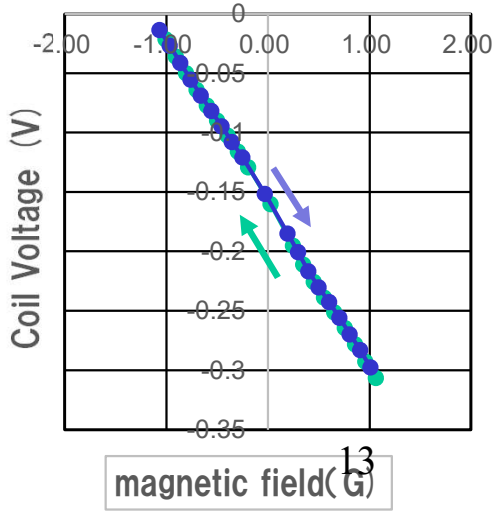
Good linearity



Low noise at peak detection timing

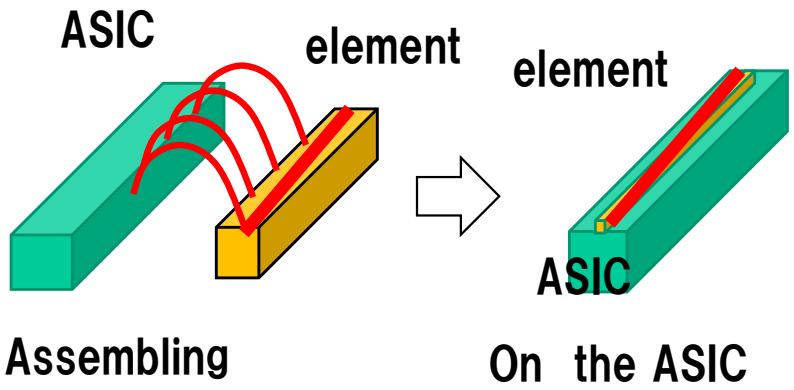


Nearly no hysteresis

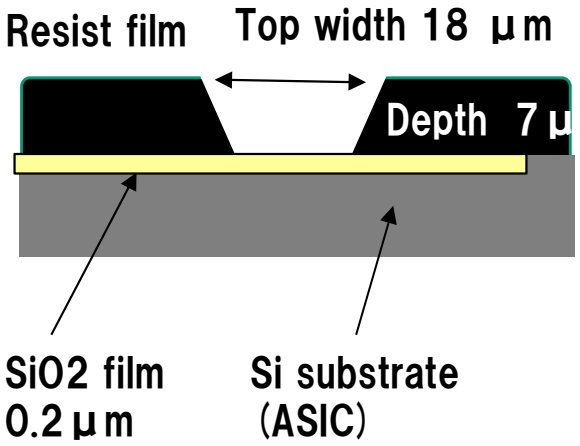


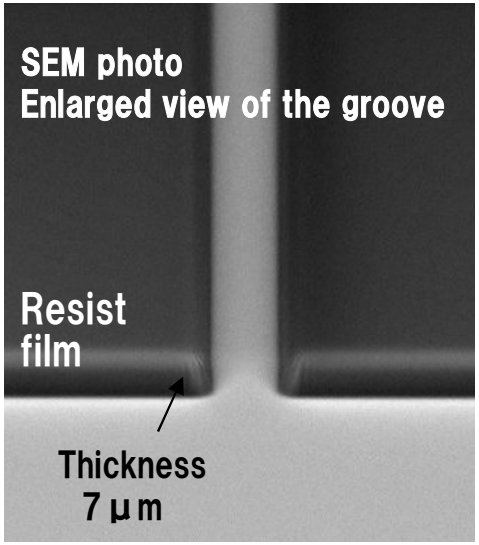
§3: Production technique to produce GSR sensor element

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



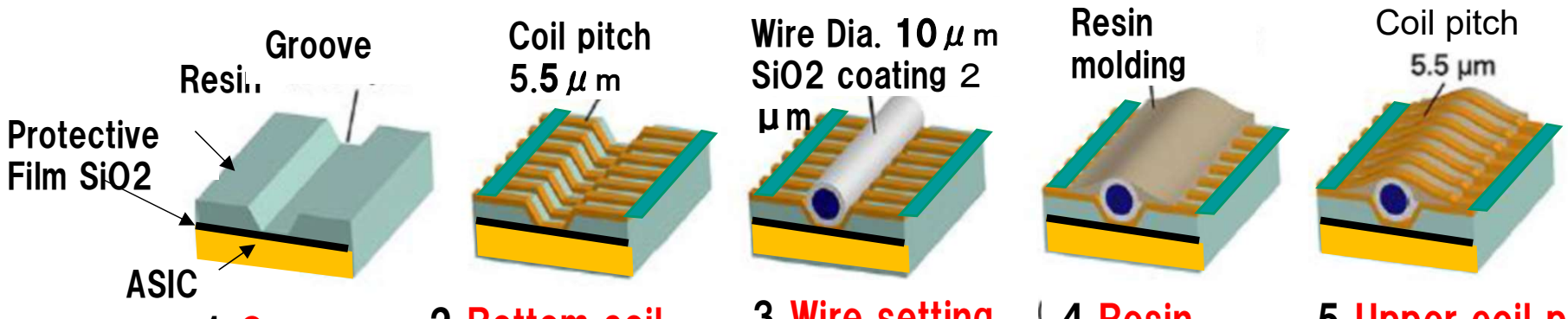
Dimensions of the groove





(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)



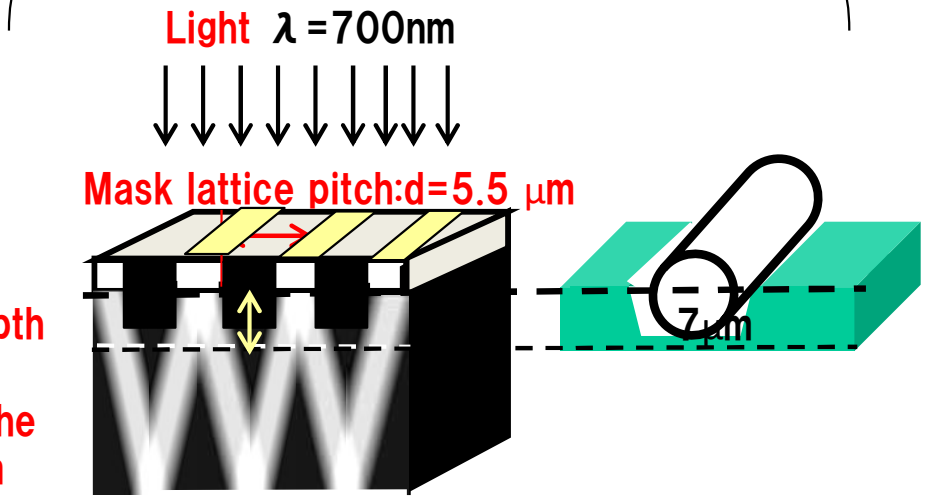
STEP: 1 Groove

2 Bottom coil pattern

3 Wire setting

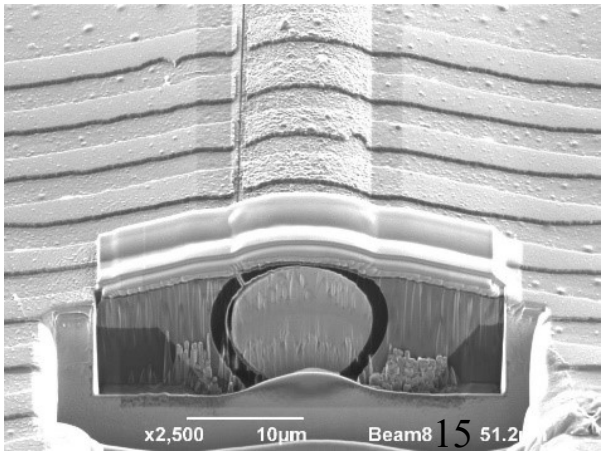
4 Resin molding

5 Upper coil pattern



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

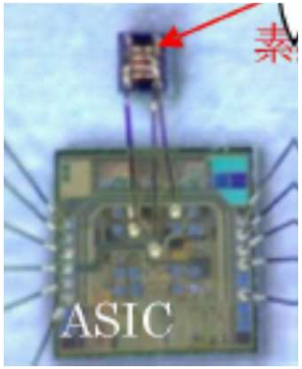
cross section of the Element



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

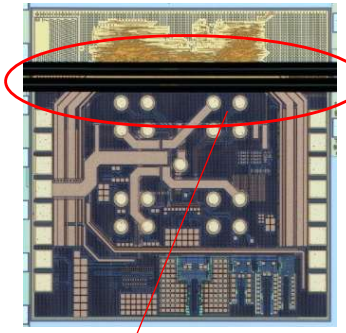
(3) The performance of on-ASIC type GSR sensor

Wire bonding type



Element
Wire length=450μm
Coil turns=66
Wire resistance=7.7Ω
Coil resistance=470Ω

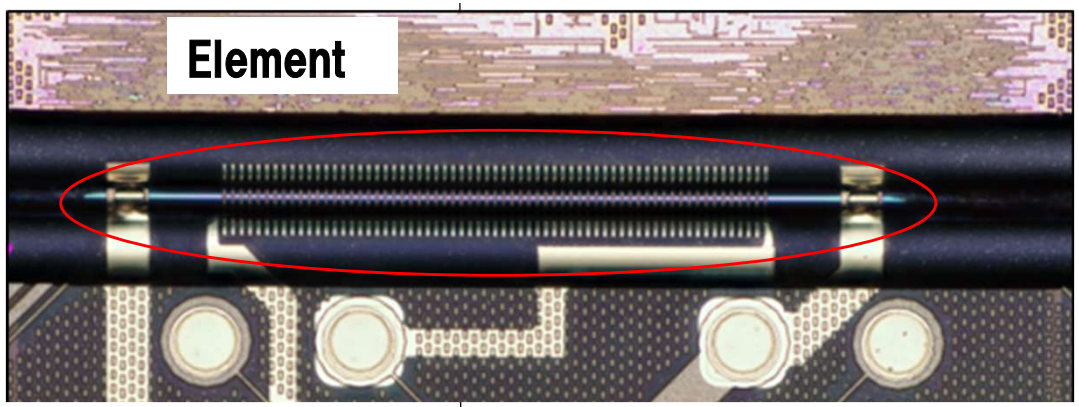
On-ASIC type



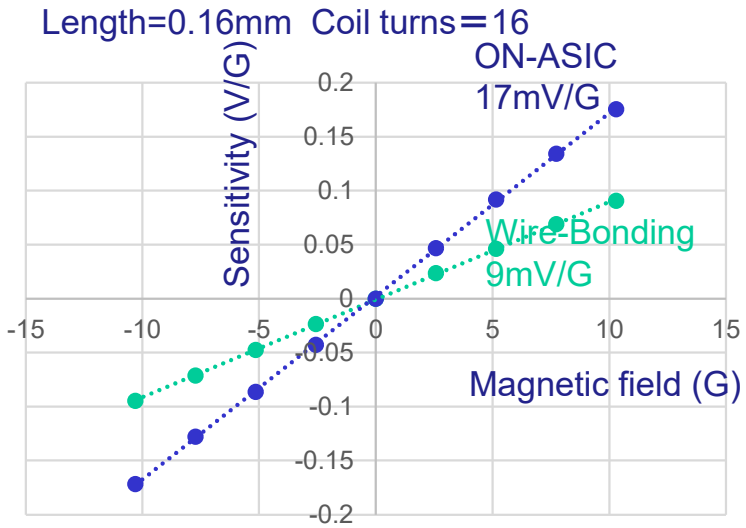
ASIC size:1.2 ×1.2×0.2mm

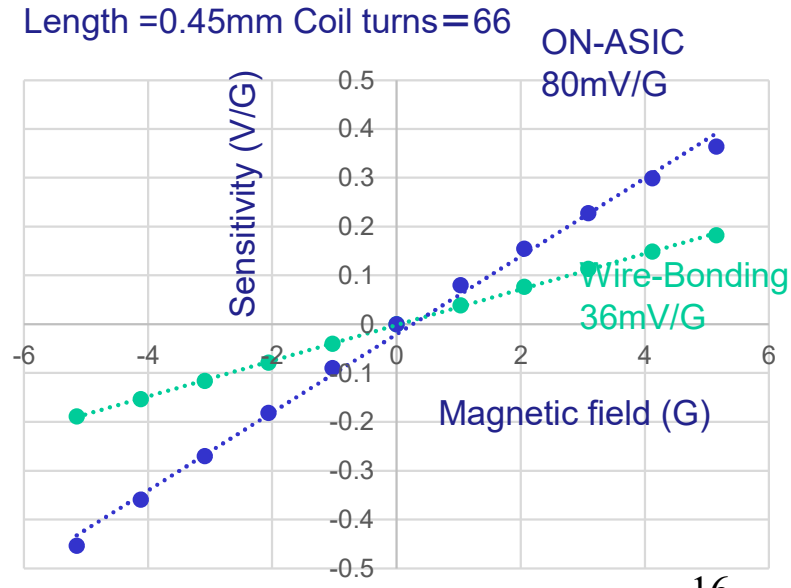
Element
Length=450μm
Coil turns=66
Thickness=20μm

Enlarged view element



output of the sensor

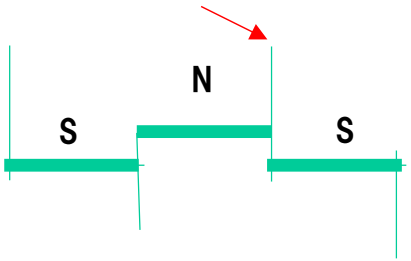


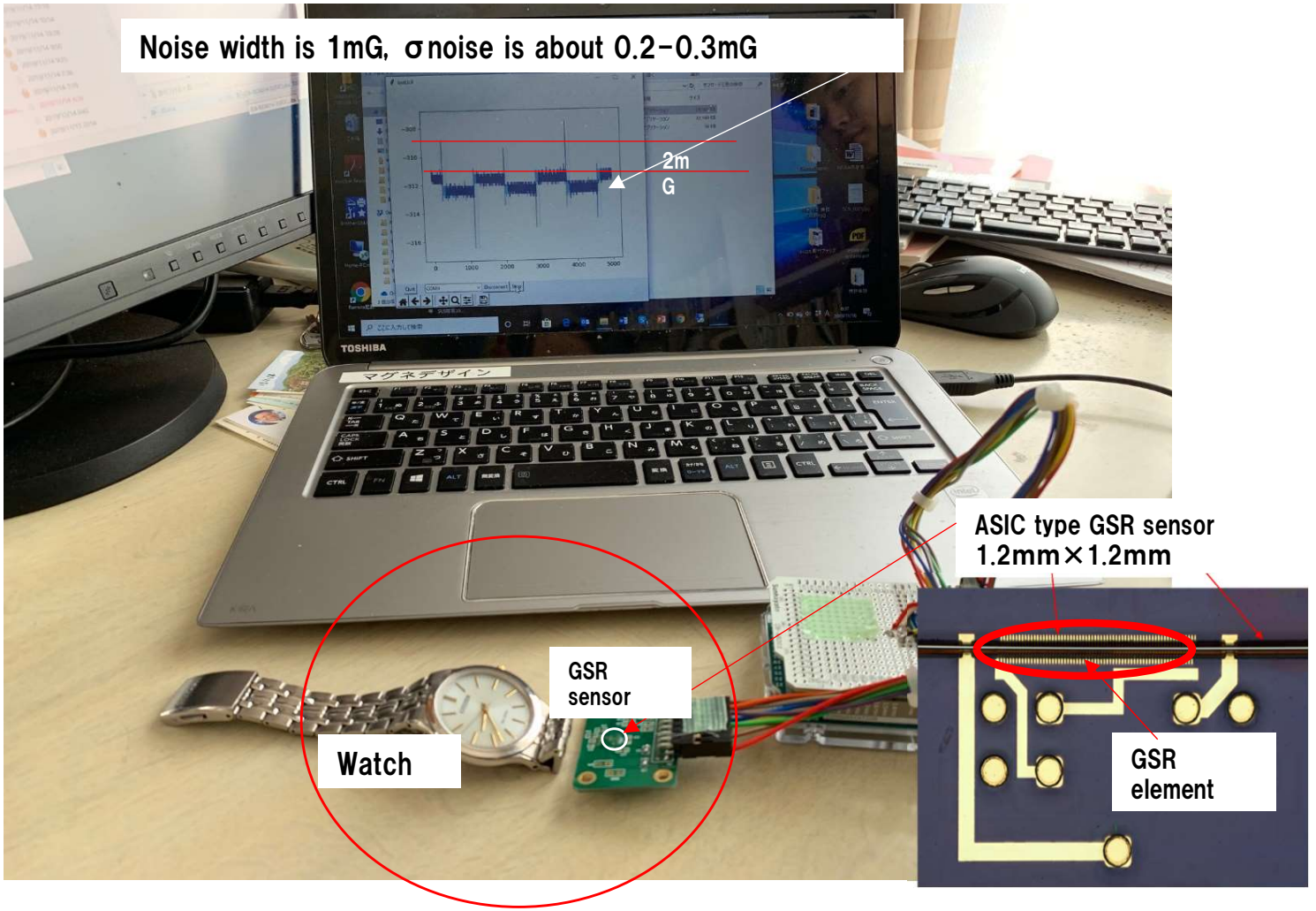


I produced on-ASIC type GSR senor with 100 times better sensitivity which measured the magnetic field caused by a watch. The field is very small @ high speed so that it is measured for the first time in the world.

The measurement is carried out
by 1000 times per 1 second
The second hand 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.

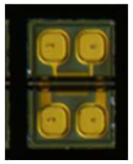
Pulse 1/1000sec



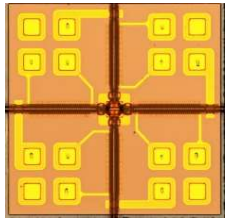


§ 4: Developments for Promising Applications

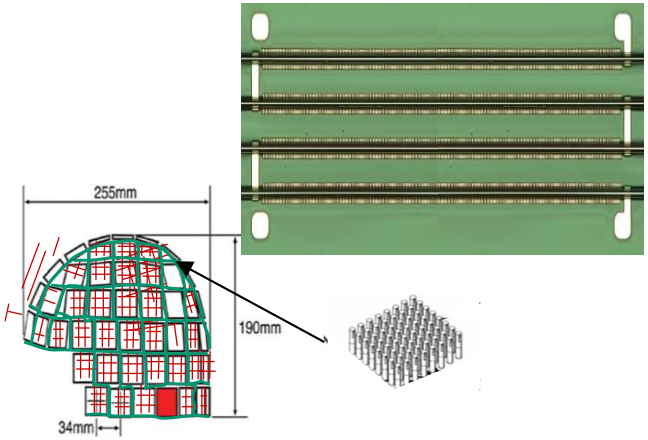
Project 1) Standard type for car use
- -wide range of 80G
- -high resolution of 3mG/LSB in 16bits
- -Analog circuit Bandwidth of 1MHz



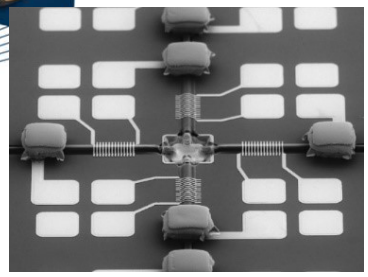
40 sensors used in one car
- Angle sensor,
- speed sensor,
- Current sensor



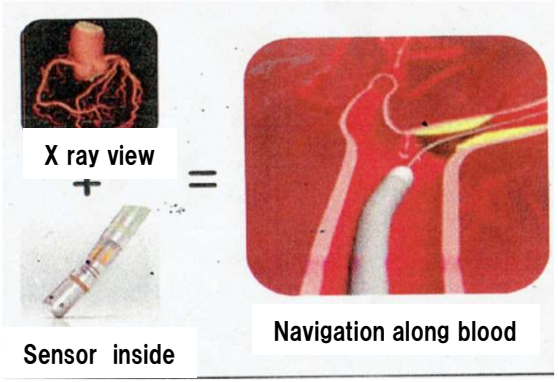
Project 3) nTmeter to detect the bio-magnetism
- -noise under 1nT
- - **Developing** for a wearable type of magnetoencephalography instead SQUID

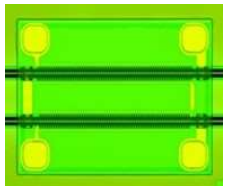


Project 2) the XYZ dimensional type for Gyro-Compass used in smart phone and wearable computer
- - 3 dimensional type GSR element
- - Low noise under 1mG and high speed mearing 1KHz



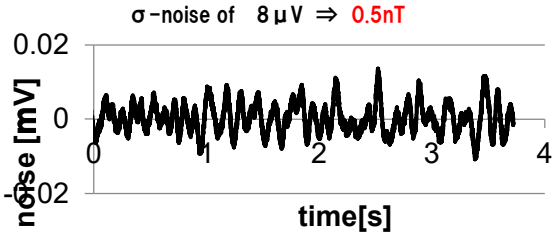
Project 4) ultra small type for catheter navigation in Body
- - size of width 0.4mm and length 1.2mm
- - keeping the performance of the standard type

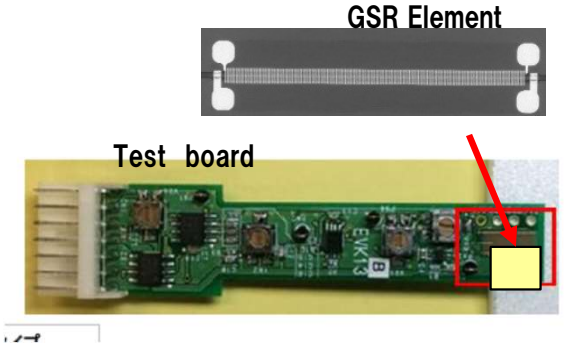




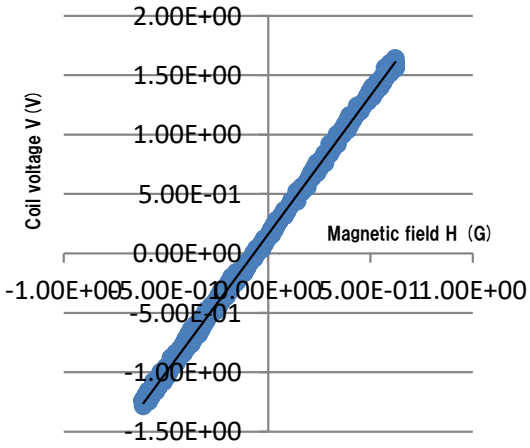
Project（3）Bio-Mag Project using 3D -nT sensor
development of nT sensor with 0.4nT

EVK with 3mm type element
・Coil turns numbers of N=528
・Sensitivity 1600mV/G, σnoise 8μV
・σノイズ 0.5nT@10Hz





Sensitivity 1600mV/G



EVK 12A type+ Element 3mm Ciol turn numbers of 538

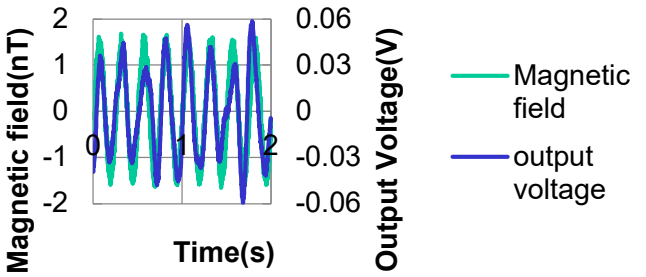
Sample	Coil Resistance	Sensitivity	Noise	Magnetic noise
1	662Ω	1.44V/G	7.08uV	0.49nT
2	672Ω	1.44V/G	8.35uV	0.58nT
3	682Ω	1.10V/G	5.35uV	0.49nT
4	678Ω	1.31V/G	4.67uV	0.36nT
Average	674Ω	1.322	6.363	**0.48ｎT**

4） nT sensor can detect 1nT magntic field

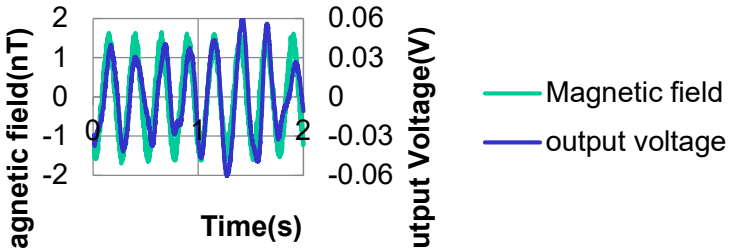
nTsensors can detect magnetic field of 1 nT easily

基板No.	測定時感度(V/G)	測定時回路ノイズ(uV)	磁気ノイズ(nT)
12A2-4	1.167	8.685	0.744
12A2-6	1.441	7.819	0.543
12A2-8	1.417	7.284	0.514
12A2-9	1.440	4.567	0.317

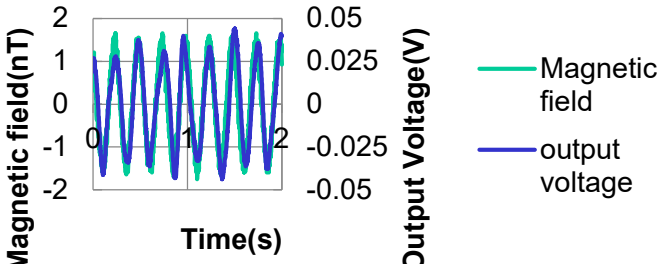
EVK12A2-8 Magnetic field of 1nT



EVK12A2-6 Magnetic field of 1nT

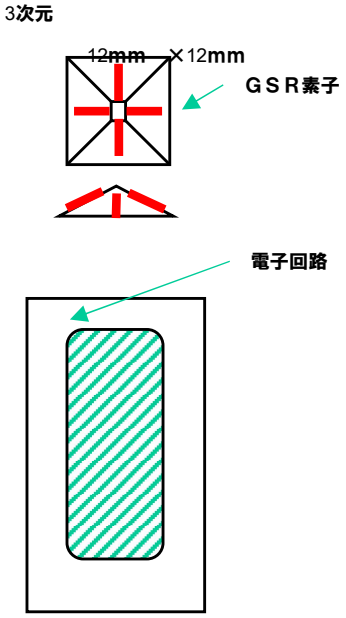


EVK12A2-9 Magnetic field of 1nT

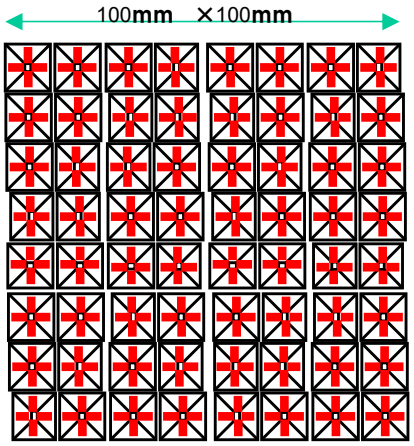


(2) Bio-Mag Project using 3D –nT sensor

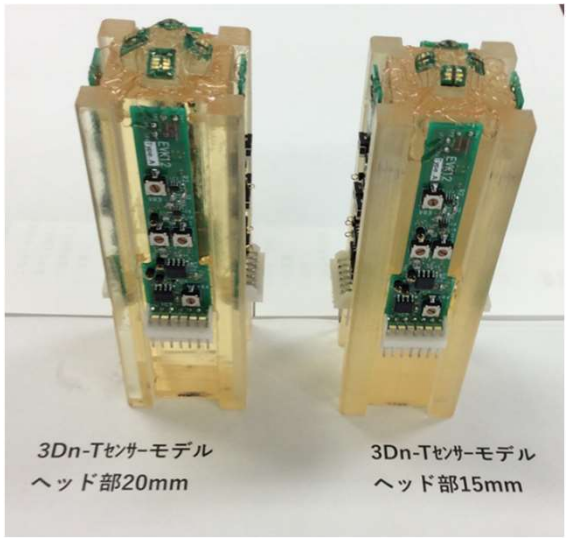
a truncated pyramid



nT sensor grid

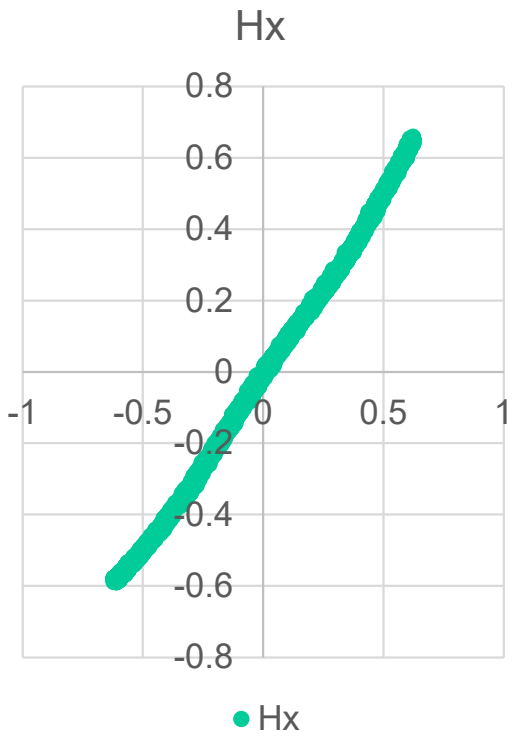


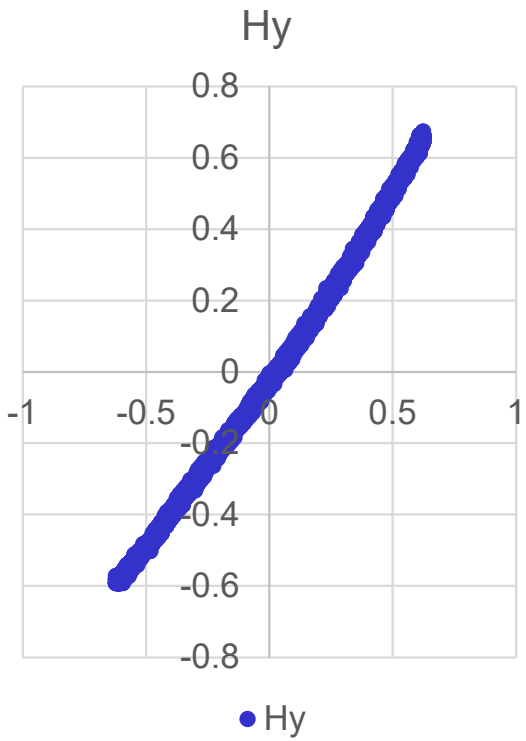
a truncated pyramid

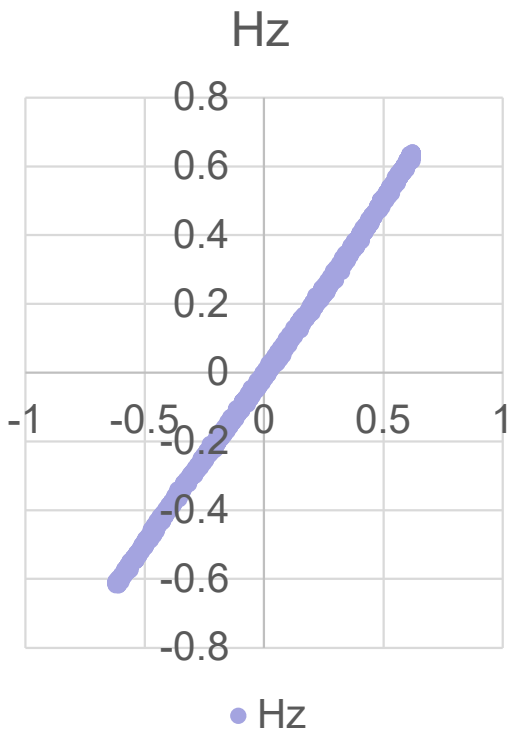


Data　Hx,Hy,Hz　**測定可能**

6） Result of the magnetic vector measured by 3 D nTsenor







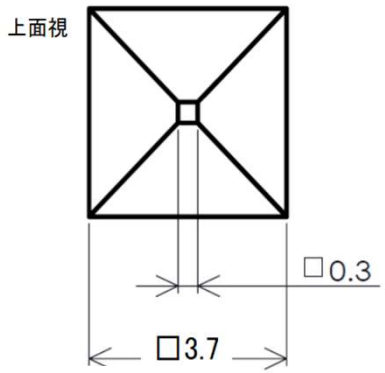
9) 3D GSR sensor head with a truncated pyramid

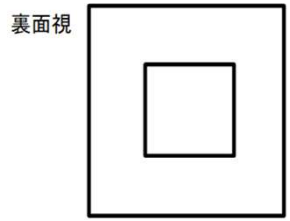
2019年11月13日
菊池

1．GSR elemnt size ：0.4mm×0.35mm×0.3mm thickness
2．**Pyramid head size** ：3.7mm×3.7mm×１．５mm height
3．ASIC size ：1.16mm×1.16mm×0.5mm height
4．Sesnor circuit board ：5mm～7mm square thickness 1mm

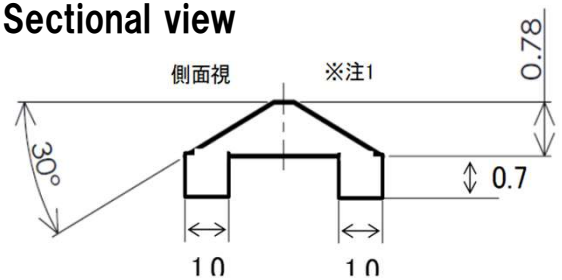
Top view

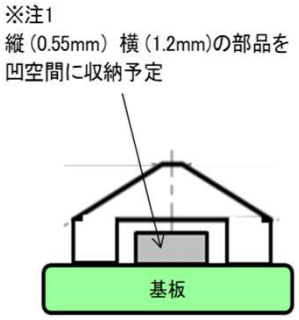
Type A: skirt type with a hole space

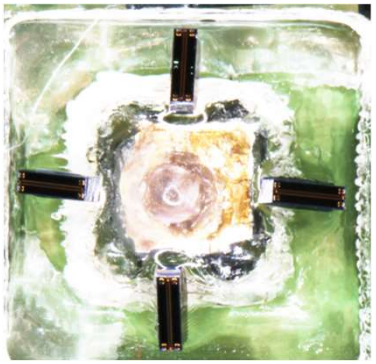




Sectional view





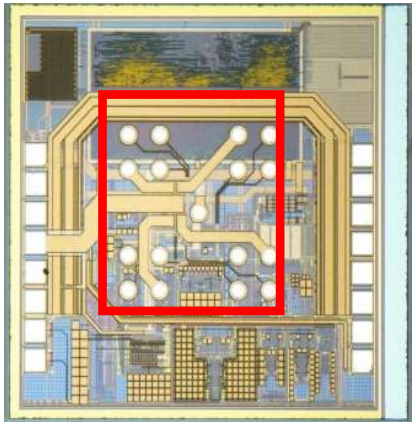


Trial sample of 3D head and 4 GSR sensors

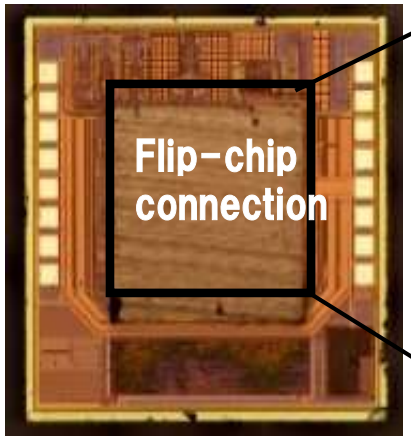
Project （2） Electronics Compass for smart phone

Prototype with 2 dimensional electronics compass

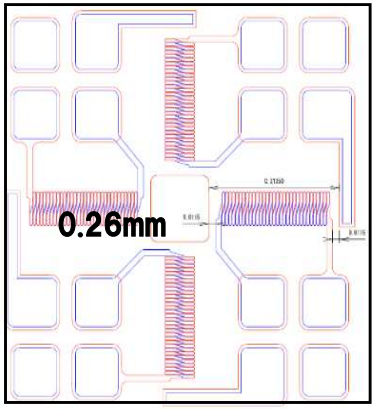
ASIC：1.2㎜×1.2㎜



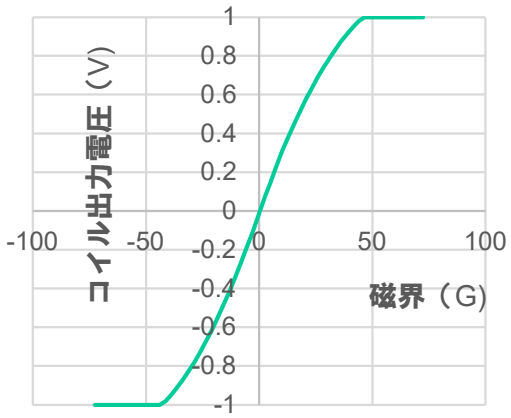
ASIC＋X-Y axis



X-Y axis element
0.6㎜×0.6㎜



Sensitivity ：40mV/G



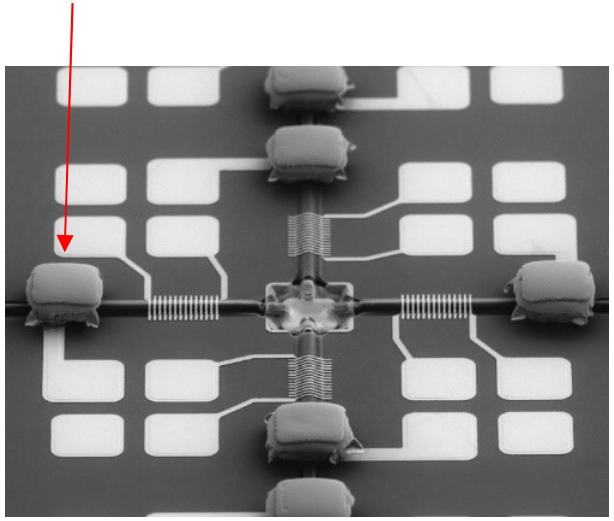
Target of <1mG

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)	30
2 element（N=63）	0.26✕0.6 （1）	80 （12）	＊60 0.75mG	0.3mG	1320 (28)	40 (3.3)	30
AMI306ー N=16	0.60✕0.35	3.3	＊70 7mG	3mG	47	12	1

Challenging to develop XYZ type GSR Element

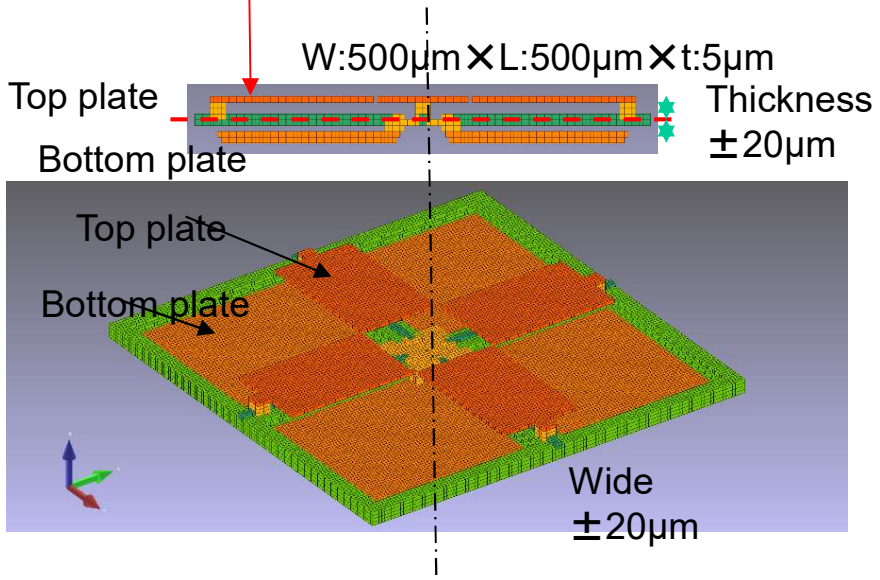
First challenge

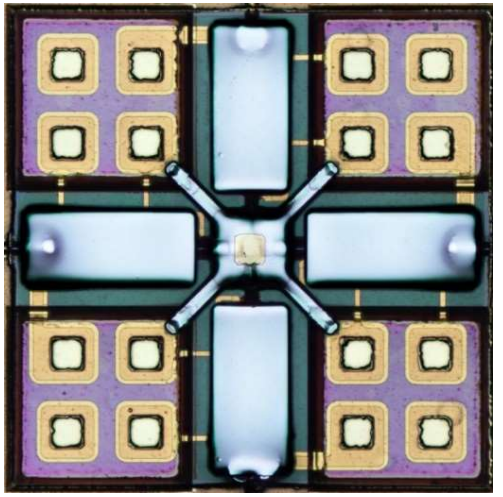
Permallloy button for
Attracting Z-axis magnetic field Hz



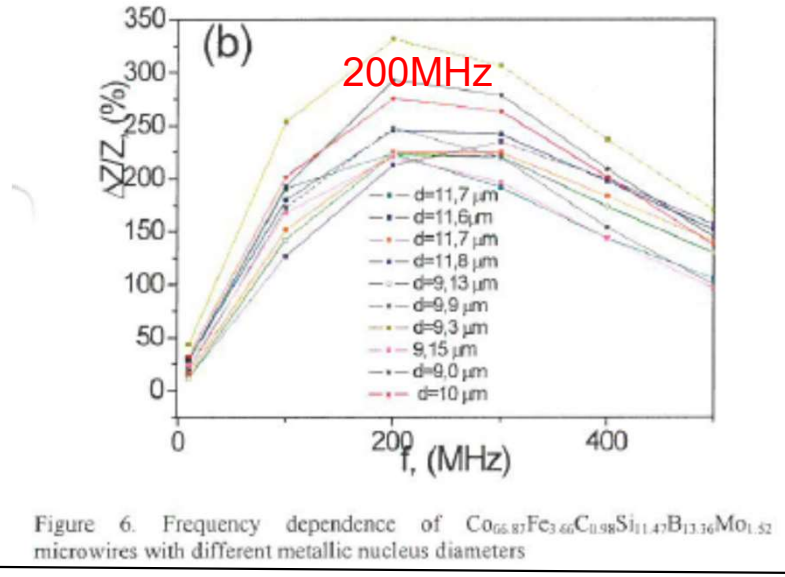
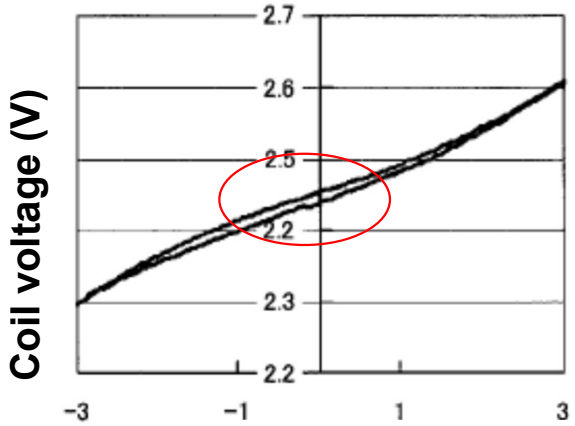
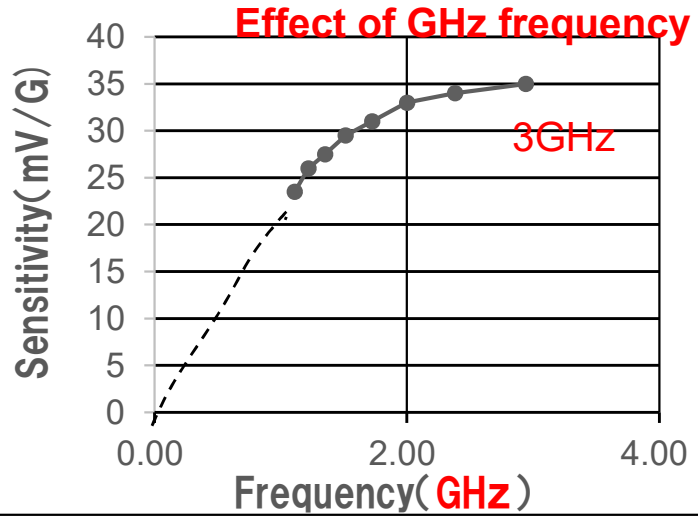
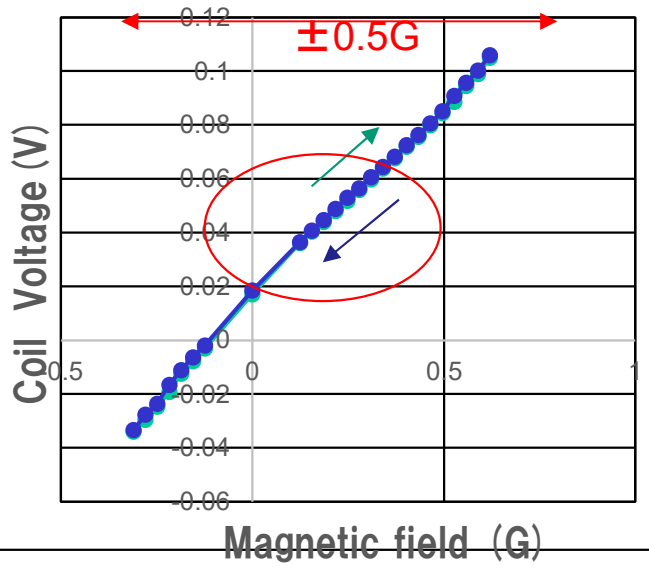
Second challenge

Permalloy plate for attracting Z-axis magnetic field Hz





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

	Effect of frequency	Hysteresis at rising edge detection
GMI	 Figure 6. Frequency dependence of $Co_{65.87}Fe_{3.66}C_{0.98}Si_{11.47}B_{13.36}Mo_{1.52}$ microwires with different metallic nucleus diameters	
GSR		

§5: まとめ

1） GSR効果を発見
- GHzパルスで励起すれば検出感度が向上（コイル電圧は増加）
- 出力特性は　正弦関数となる
- 良質な出力特性（ヒスなし、良好な直線性、低ノイズ）

2）GSR素子の製造技術を開発した。
- マイクロコイル
- ASIC表面に直接素子形成

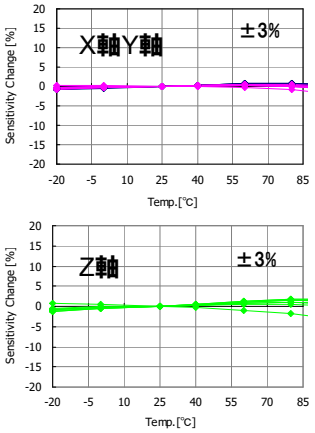
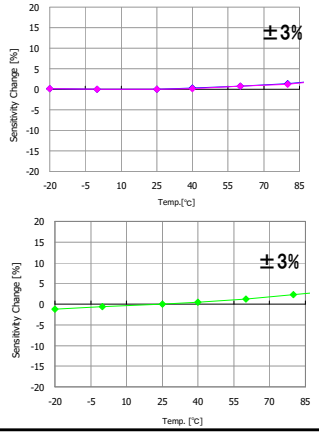
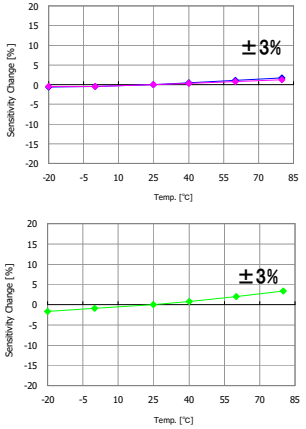
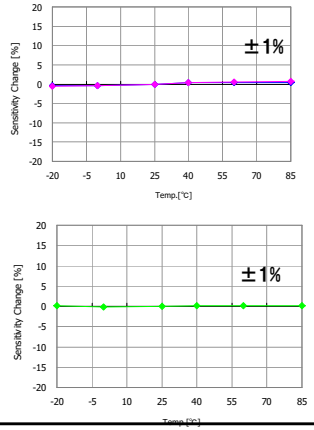
3） ASICタイプのGSRセンサを試作した


Thank you for your kind attention!

要望への回答

項目	品質レベル	コメント
分解能	1nT	
サイズ	5×5mm×3mm　以下	
絶対精度	0.1%	直線性補正　改善可能
測定レンジ	±25000nT ±100000nT	16ビット　1nT 18ビット　1nT
温度ドリフト	現行品レベル 感度：±1%/FS 原点：10nT/℃	温度補正　改善可能
方向分解能	0.01度	

参考：市販電子コンパスの温度特性

	MI Sensor	GMR Sensor	TMR Sensor	Hall Sensor
感度ドリフト				
原点ドリフト