Amorphous Wire Micro-Magnetic Sensor for OSI Magnetic Field Mapping

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Presentation Date: 11 September 2025

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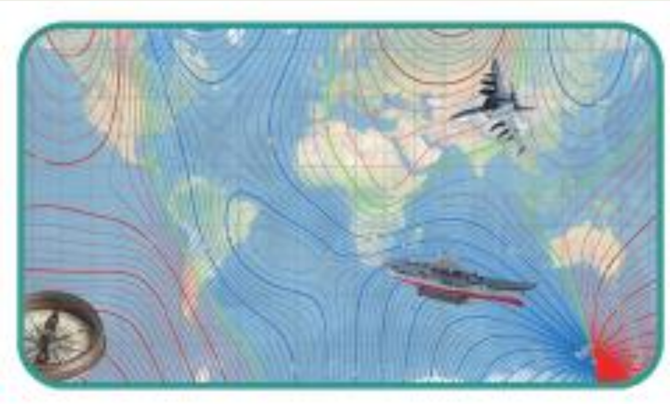
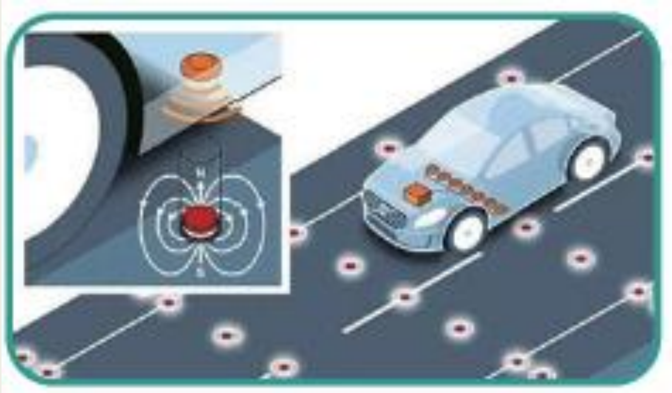
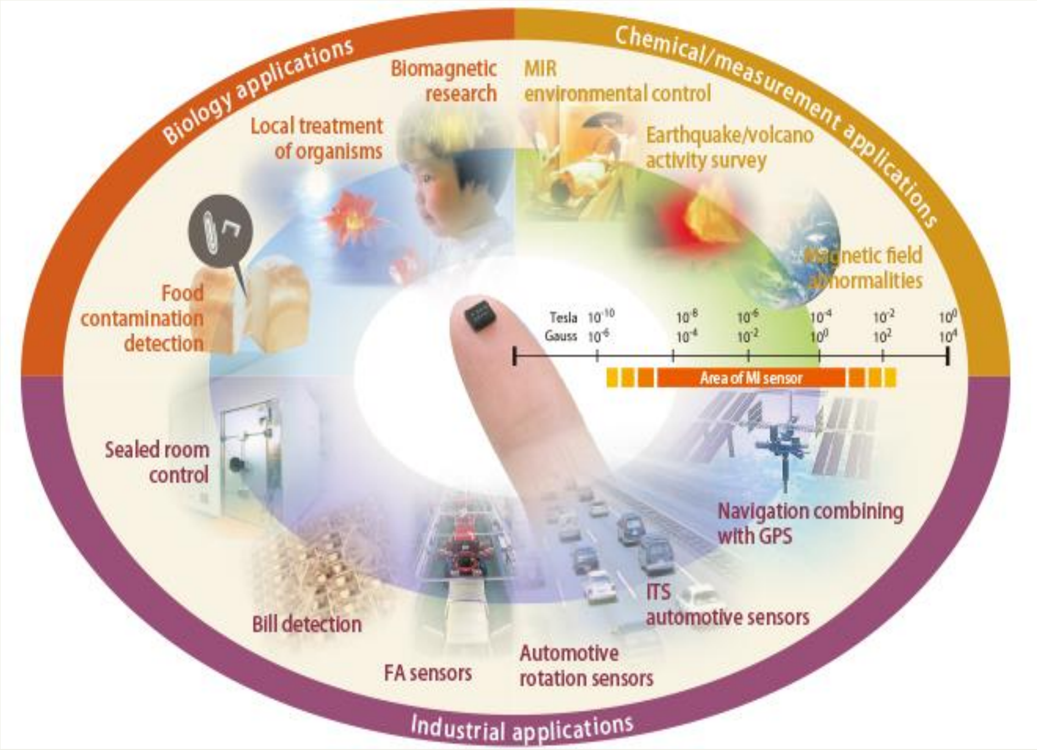
INTRODUCTION

- There are many places where weak magnetic signals need to be measured precisely, including geological exploration, environmental monitoring, biomedical, geomagnetic disturbance, industrial, earthquake warning.







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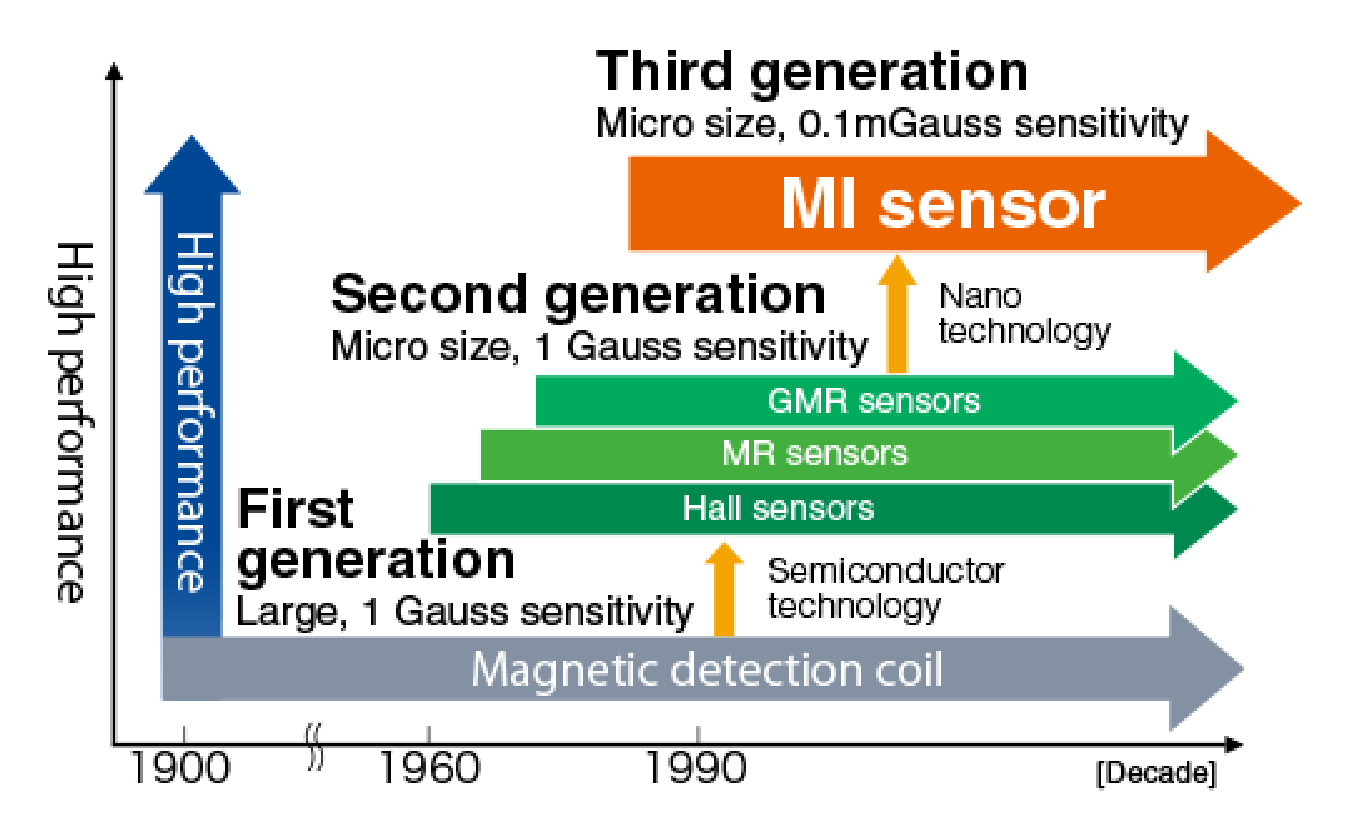
INTRODUCTION

Magnetic field mapping, as one of the continued period technologies, plays a vital role for on-site Inspection. Looking back into the recent science and technology development history, magnetic sensing have been under decades of development.

This work would propose a high-performance magnetic sensor based on the giant magneto impedance effect of special magnetic materials



HERAL

Primary authors:Mr LIU,Wangeng;Ms GUO,Xingling;Co-authors:LIU,Xinzhuang;Ms YANG,Jing;Mr LI,Peng

INTRODUCTION

Compared with current magnetic sensors such as GMR magnetic resistance sensors, flux meters and Hall sensors, Amorphous wire magnetic sensor has comprehensive technical advantages.

such as :

high response speed (up to MHz),

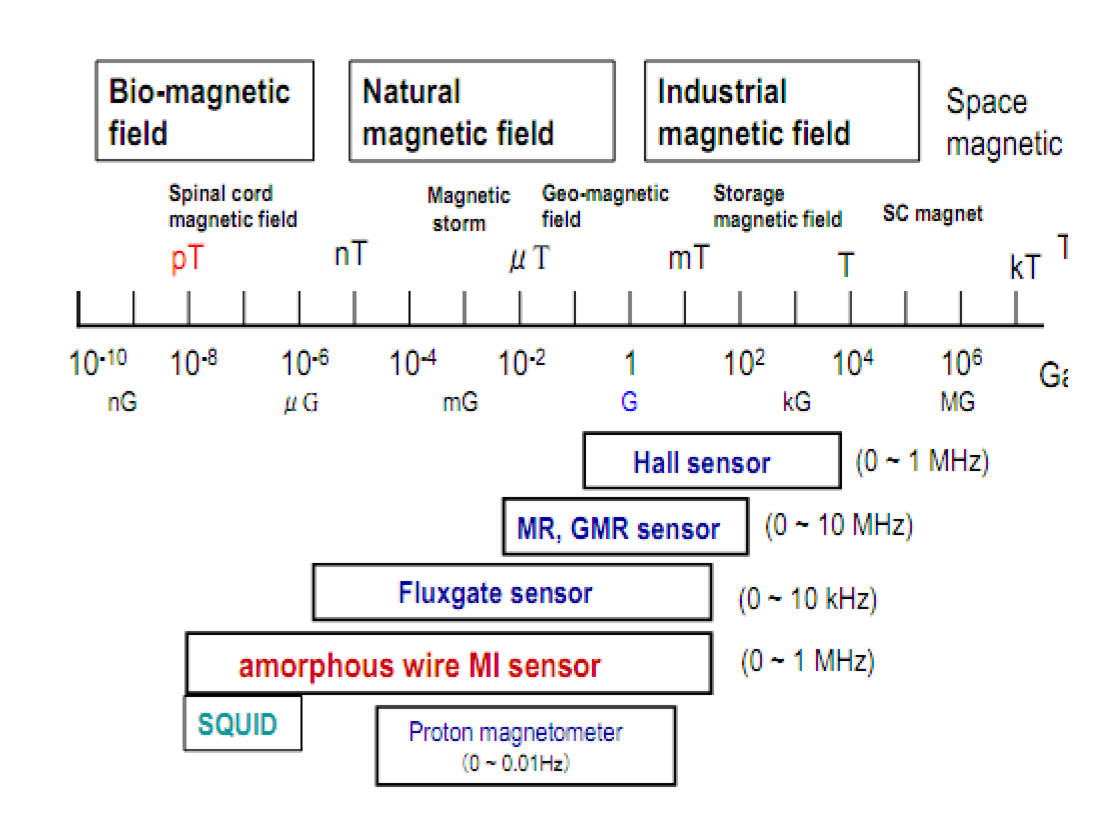
high sensitivity (>1000mv/Gs),

high resolution(up to 0.05nT),

wide measurement range (up to ±3Gs),

low power consumption (10mW),

small size (1-2mm).



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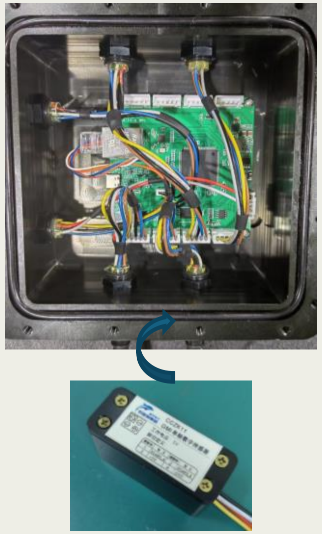
INTRODUCTION

A prototype UAV based magnetic field mapping equipment has been developed. Field experiments have been carried out to demonstrate its potential application to the OSI of CTBT.



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Amorphous Wire Micro-Magnetic Sensor for OSI Magnetic Field Mapping

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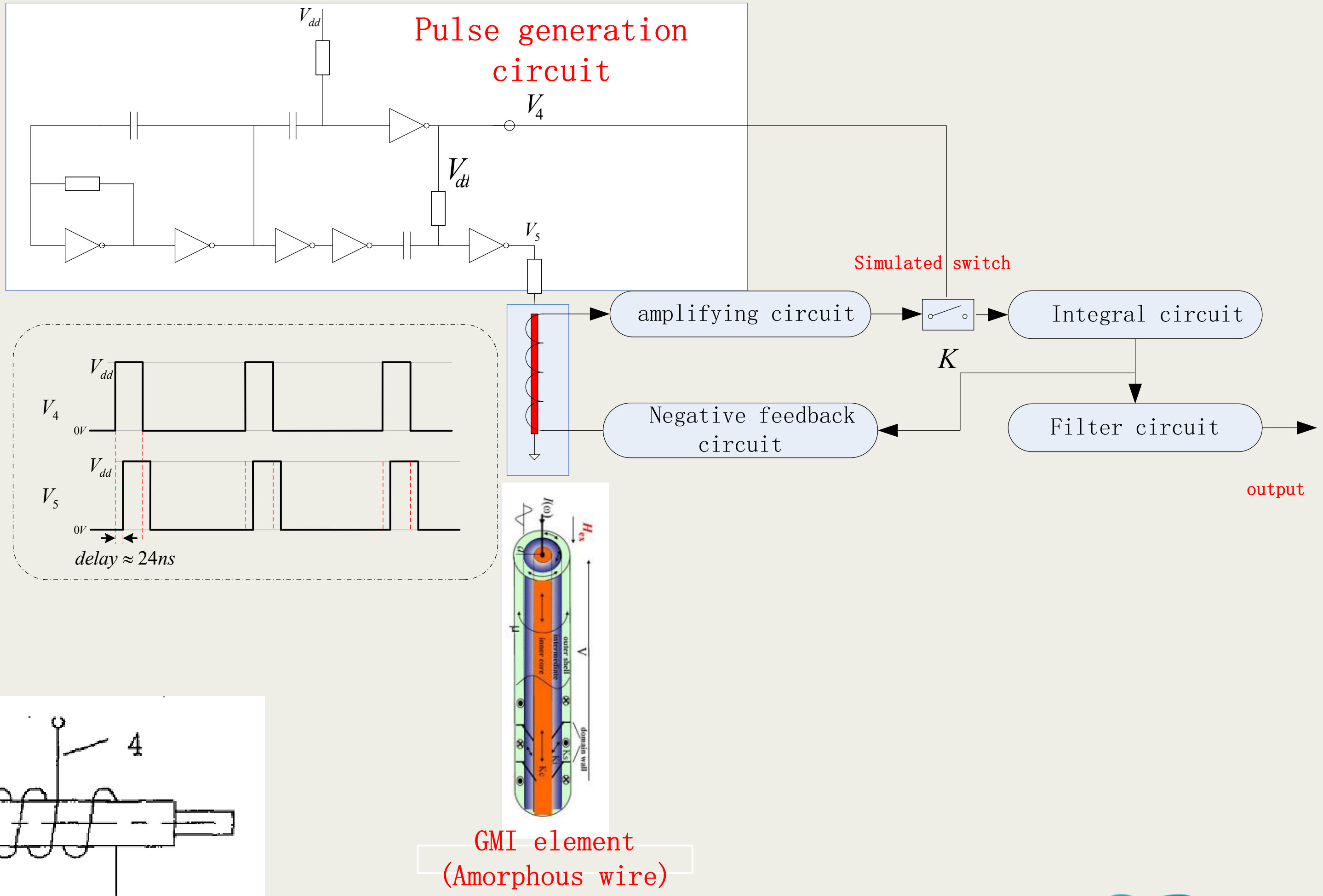
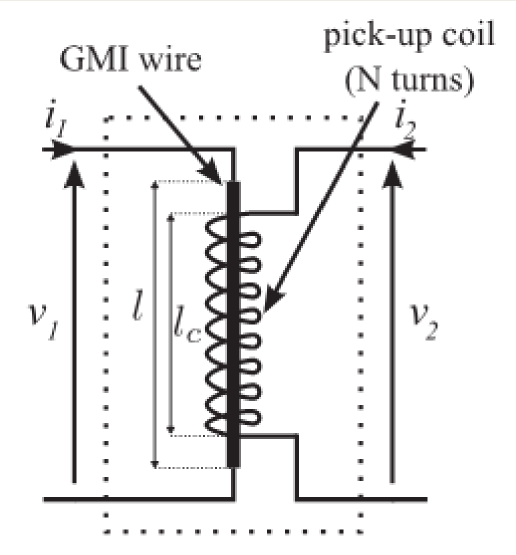
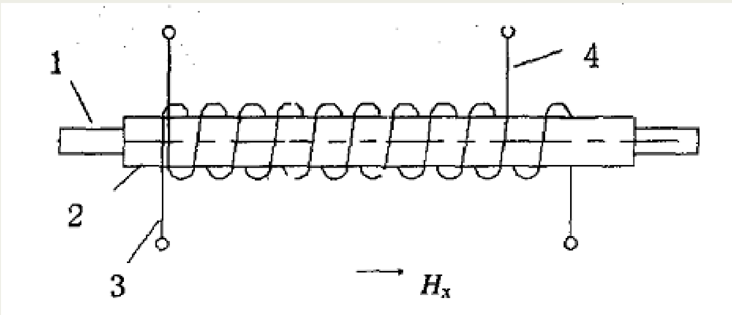
OBJECTIVES

- Design amorphous alloy wire weak magnetic sensor probe;
- Study the matched post-processed circuit;
- Develop special high precision sensor;







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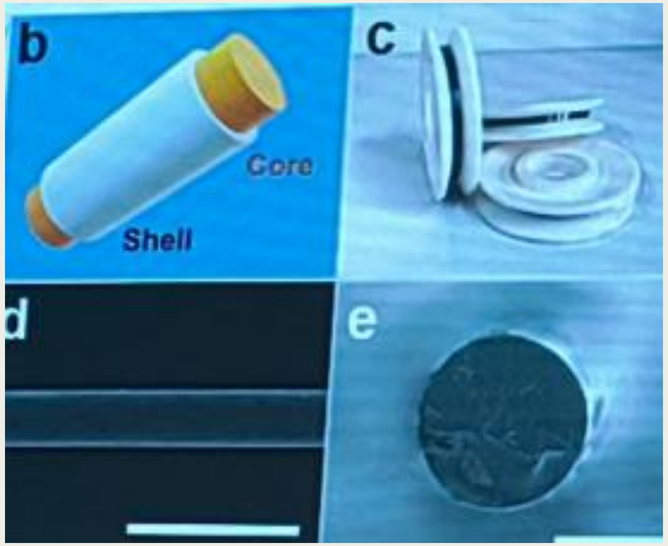
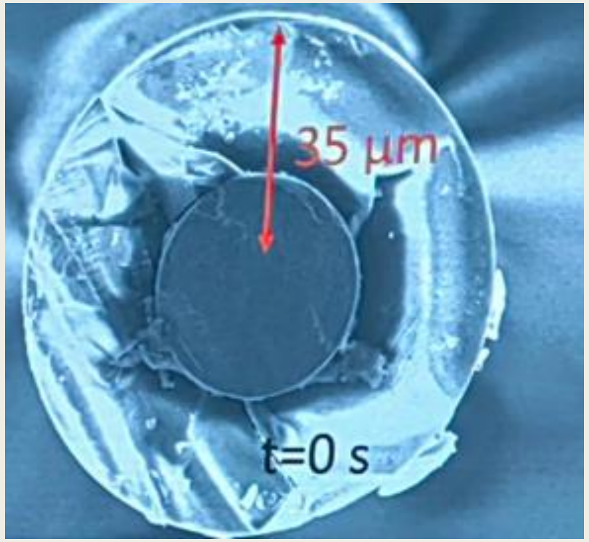
METHODS--PREPARATION OF AMORPHOUS WIRES

- The amorphous alloy wire is the key material of sensor.
- The material is a kind of Co-based CoFeSiB amorphous alloy wire.
- The special characteristics of the material is the giant magnetoimpedance effect (GMI), namely, The phenomenon that the ac impedance of magnetic materials changes significantly with the change of external magnetic field;





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METHODS--PREPARATION OF AMORPHOUS WIRES

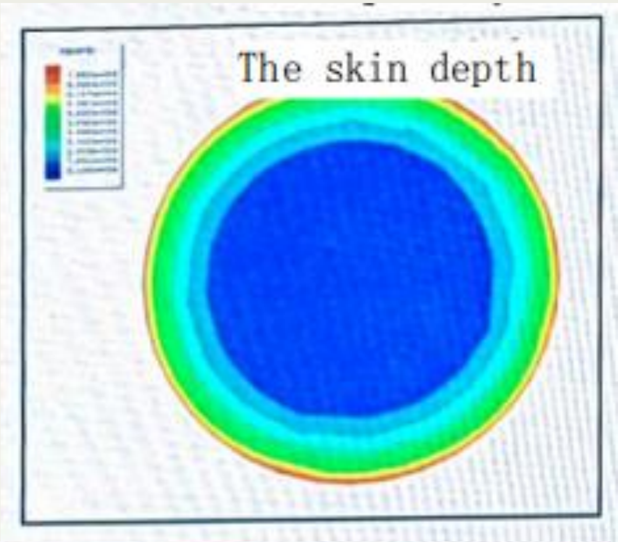
- The electromagnetic properties of amorphous wires are mainly evaluated by the following parameters:
- (1)Giant Magnetoimpedance Effect (GMI):rate of change of impedance,
- (2)Hysteresis loop parameters:Correctional force,Residual magnetism,
- (3)Anisotropic permeability

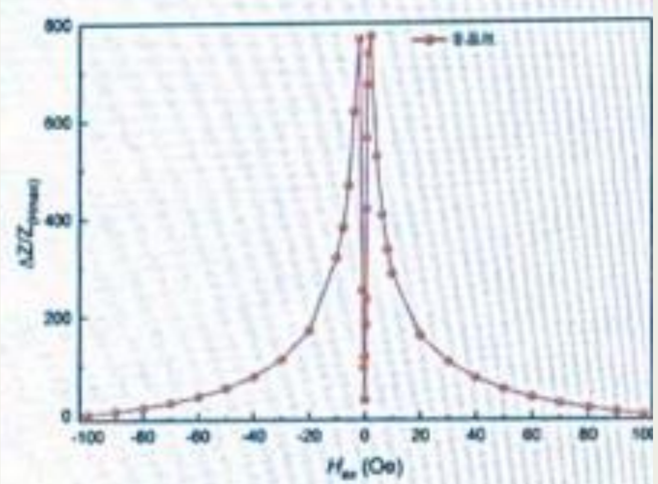
- The GMI sensor is based on the GMI effect resulting from the skin effect in amorphous wires with circular domain structure .
- Calculation of giant magnetoresistance Z:

$$Z = R_{dc} \cdot jka \coth(jka),$$

$$V(\varpi, H_{ex}) = Z[\varpi, \mu(\varpi, H_{ex})] \cdot I_{ac}$$

$$\delta_m = \frac{c}{\sqrt{4\pi^2 f \sigma \mu_\phi}},$$





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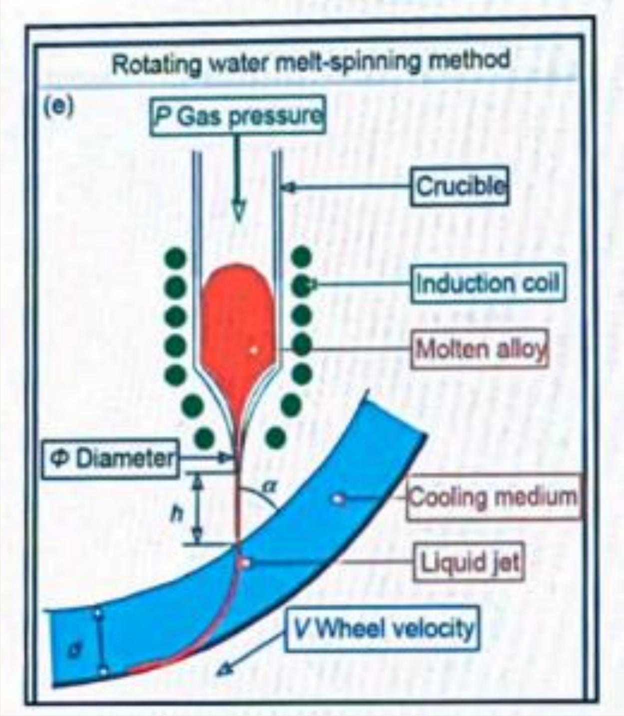
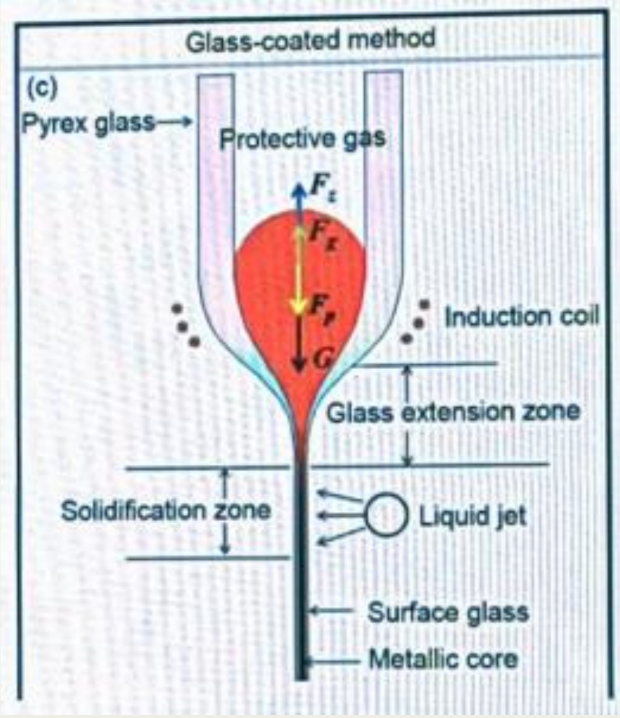
METHODS--PREPARATION OF AMORPHOUS WIRES

- The preparation of high-quality, continuous, and uniform amorphous fibers places extremely high demands on the process level of the equipment.
- (1)Preparation principle of the inner water spinning method-A
- (2)Preparation principle of the glass-coated drawing method-B



A



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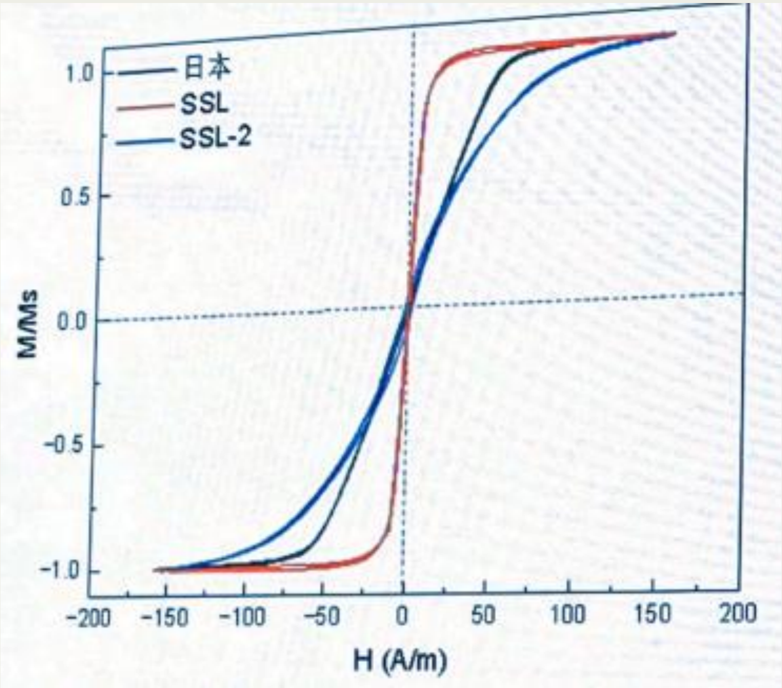

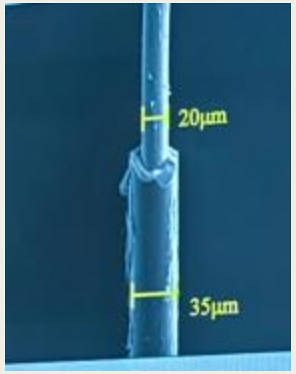

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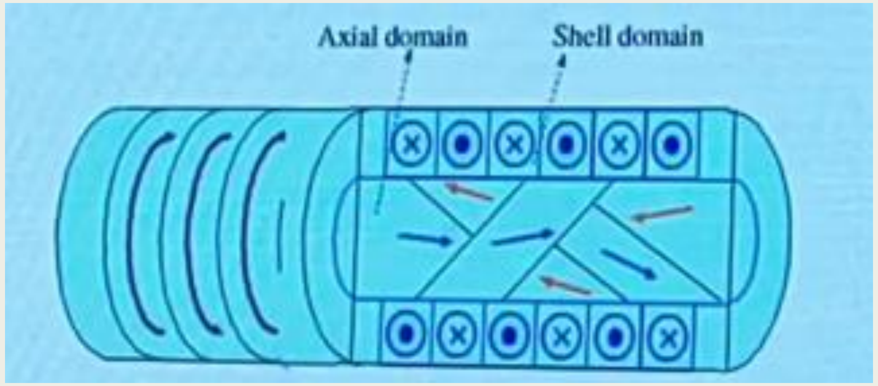
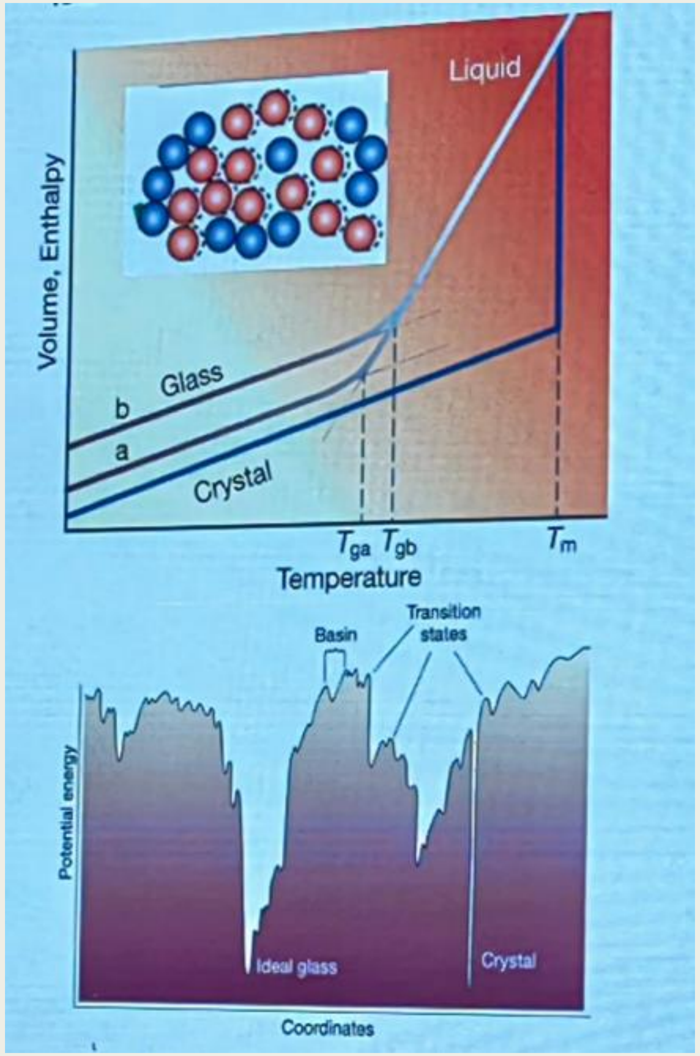
METHODS--PREPARATION OF AMORPHOUS WIRES

- Due to the amorphous characteristics of the amorphous fiber itself, the material is prone to structural relaxation or crystallization phenomenon when the temperature is high. At the same time, larger residual stress is generally introduced due to the ultra-high cooling rate during the preparation of the amorphous fiber.



Magnetic anisotropy of Co-based amorphous wires with negative magnetostrictive coefficients



Amorphous metastable characteristics

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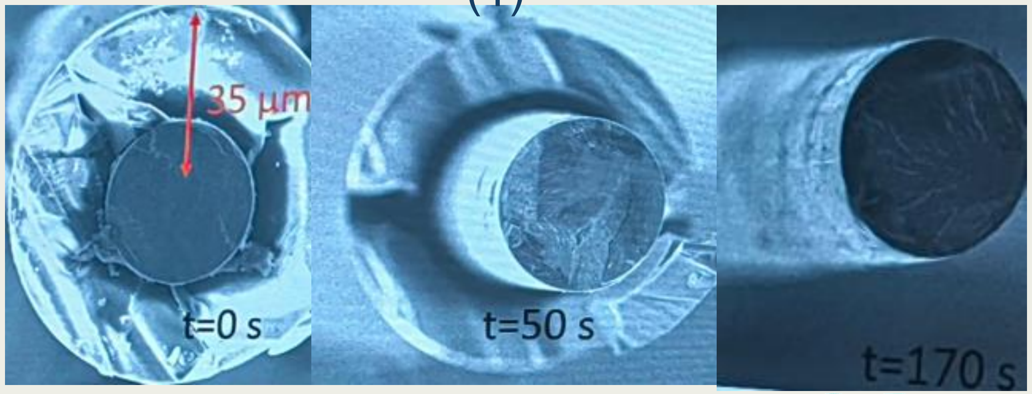
METHODS--PREPARATION OF AMORPHOUS WIRES

- We must remove the glass-coated on the amourphous wire before heat treatment to maintain long-term stability of performance during and use.
- We can choose the chemical or mechanical treatment method.
- (1)the chemical method :10-20 wt %HF+Anticorrosive (inhibiting the occurrence of overcorrosion)
- (2)the mechanical method:using the mechanical extrusion

(1)



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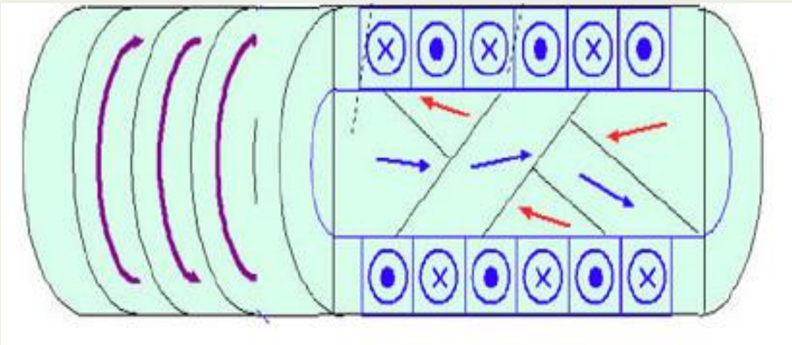
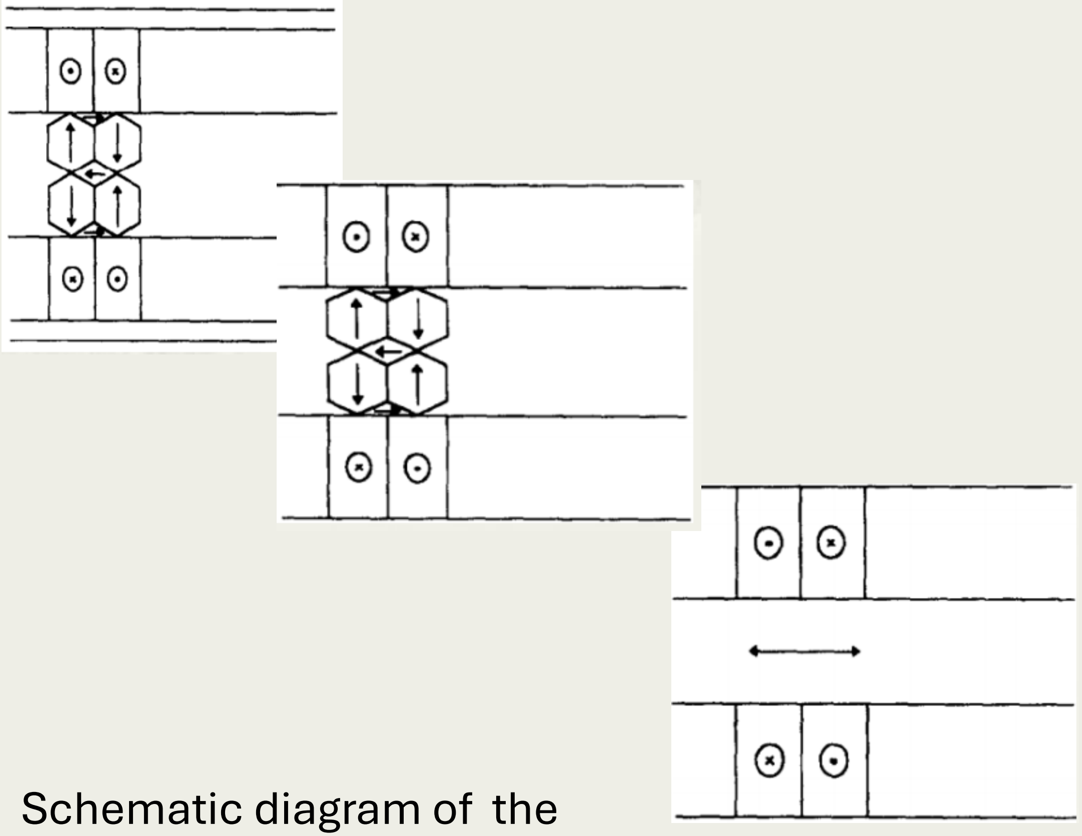
INTRODUCTION

- When the glass layer is removed, the magnetic elastic energy is less than the static magnetic and exchange energy due to the partial release of internal stress, so the internal magnetic domains transform from radial distribution to axial distribution.





Schematic diagram of the CoFeSiB magnetic domain structure before and after glass-coated removal

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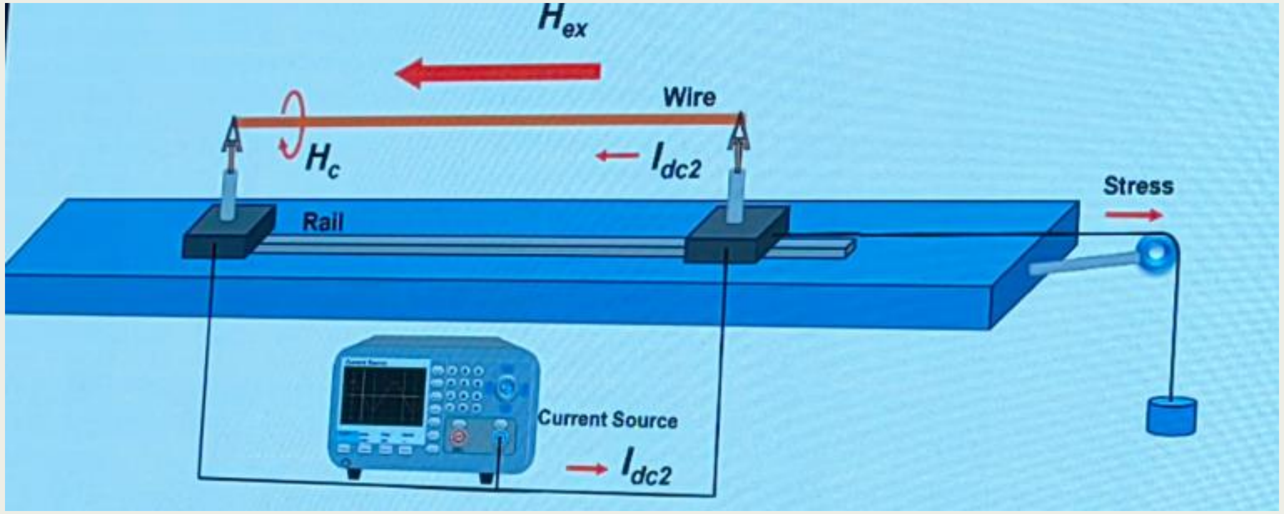
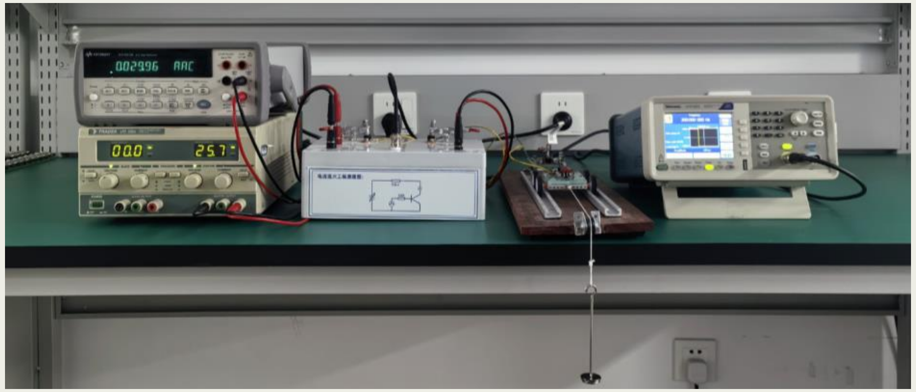
METHODS--PREPARATION OF AMORPHOUS WIRES

- The amorphous wire generally needs to be heat treated before it is used as a sensitive material.
- The purpose of heat treatment is to form a part of the nanocrystalline phase in the amous phase of the material, so as to obtain an excellent soft magnetic composite structure of amorphous/nanocrystalline.
- We can choose one of heat treatments:
- (1)Isothermal annealing;
- (2)Direct current annealing;
- (3)Joule annealing;
- (4)Stress annealing;
- (5)Electromagnetic annealing.





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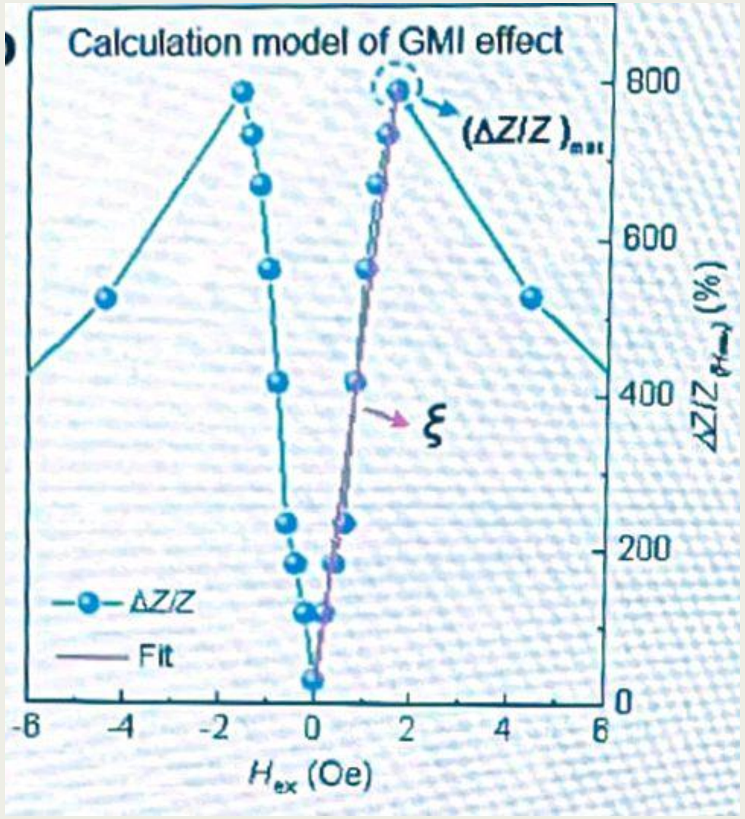
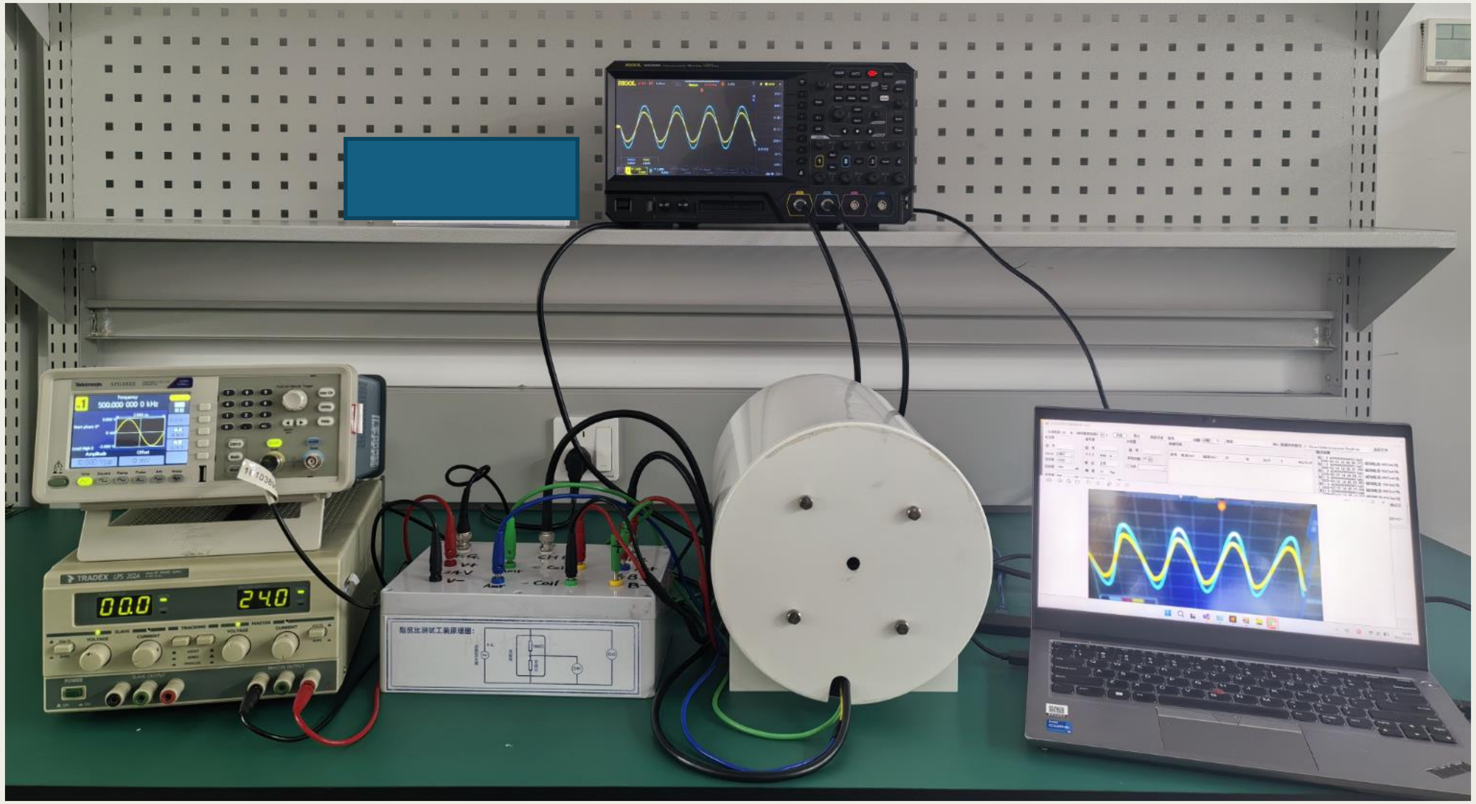
METHODS-- ANALYSIS OF THE PERFORMANCE OF THE AMORPHOUS WIRES

- Impedance ratio test of amorphous wire





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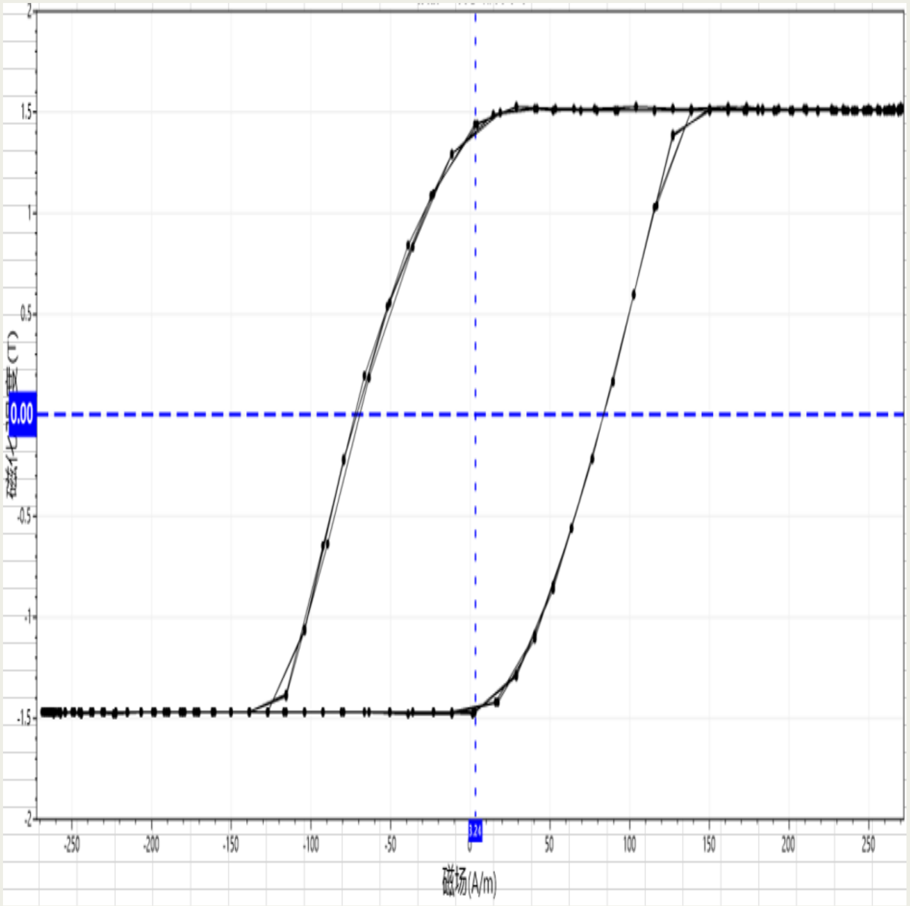
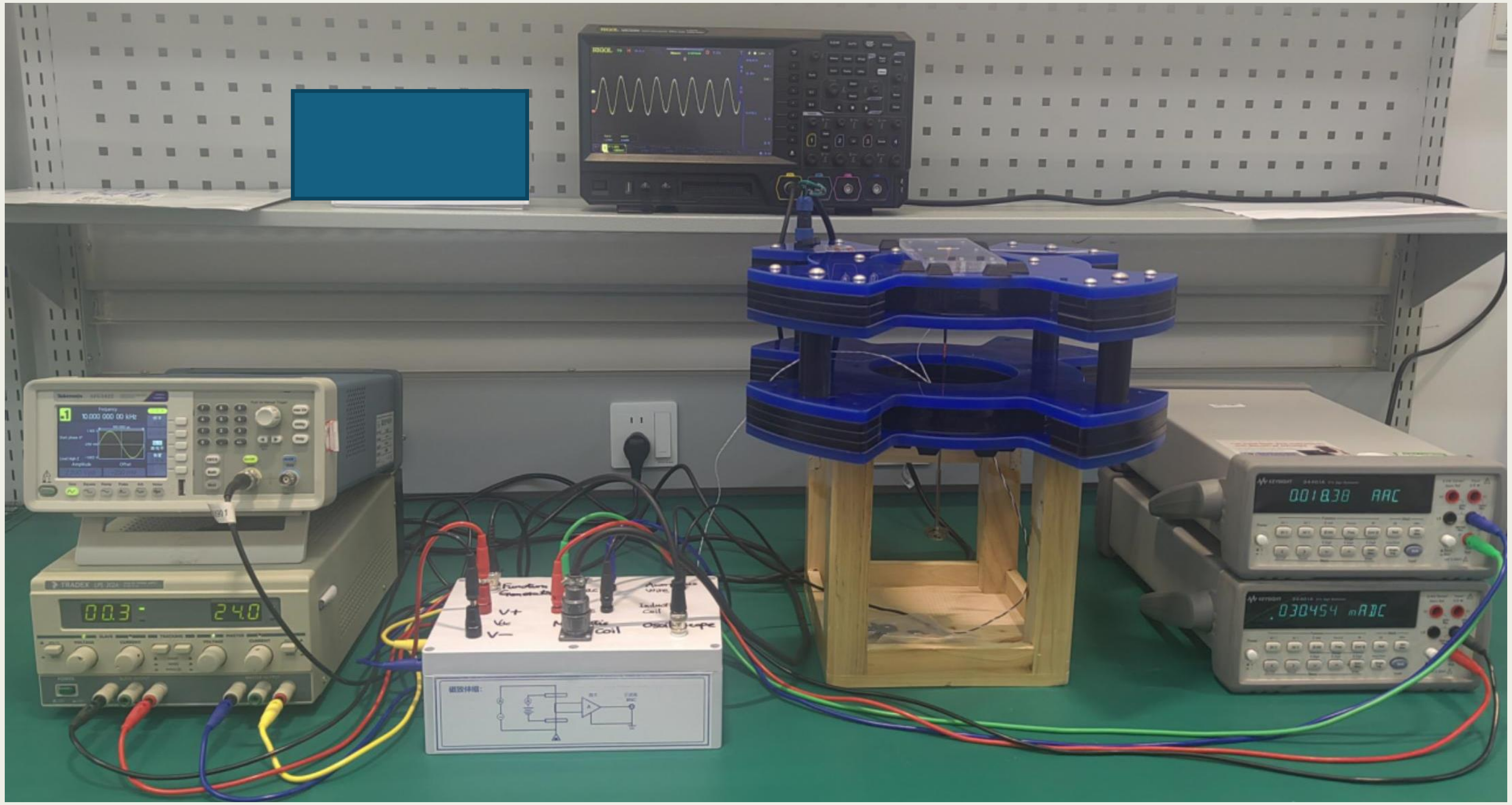
METHODS-- ANALYSIS OF THE PERFORMANCE OF THE AMORPHOUS WIRES

Hysteresis loop test and axial hysteresis loop test



METHODS-- ANALYSIS OF THE PERFORMANCE OF THE AMORPHOUS WIRES

Magnetostrictive coefficient test



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METHODS-- THE PRODUCTION OF THE AMORPHOUS WIRE PROBE

The amorphous wire probe is one of the key factor for the micro-magnetic sensor to achieve the designed performance.

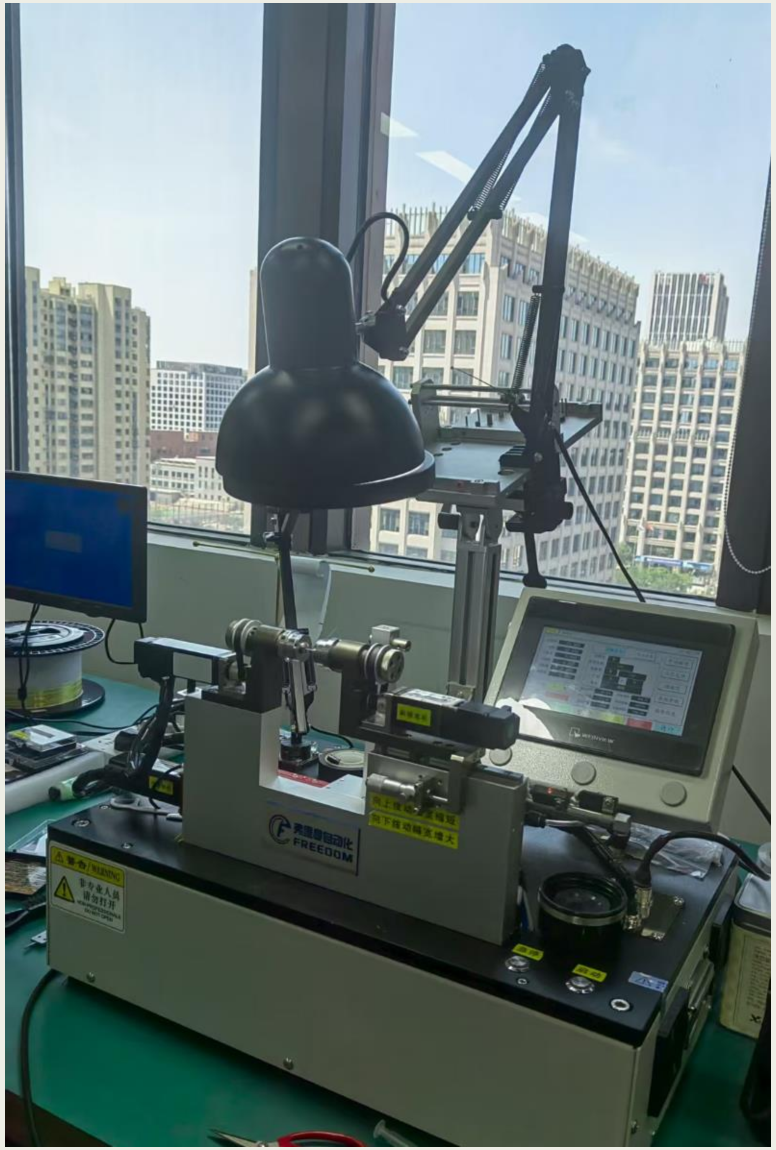
The basic components of the amorphous wire probe are:

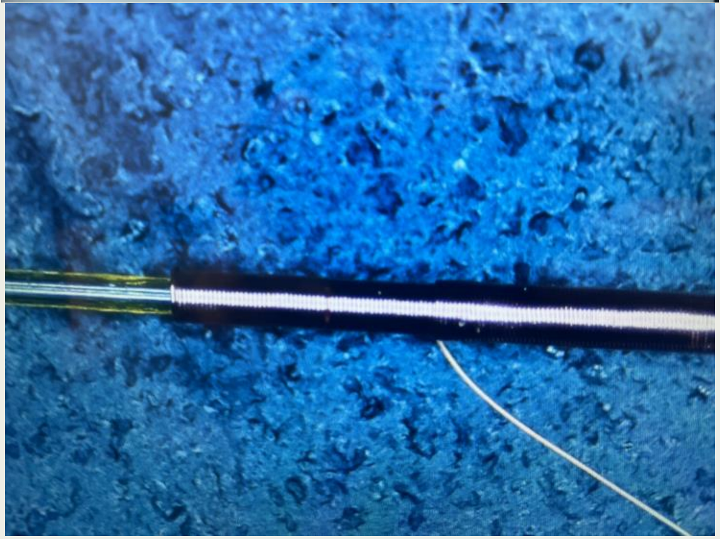
(1)amorphous wire

(2)induction coil

(3)bias coil

Considering the stress effect of the coil winding on the amorphous wire, a glass tube or a non-metallic support tube is used as a support body for the coil winding, and the amorphous wire passes through the glass tube or the non-metallic support tube.





METHODS-- THE PRODUCTION OF THE AMORPHOUS WIRE PROBE

- The following aspects determine the performance of the amorphous wire probe:
- 1) Co-based amorphous alloy is used, which has high material sensitivity due to its axial anisotropy.
- 2) The driving mode of the probe: applying a driving magnetic field in the easy magnetization direction of the material can produce a significant change in magnetic resistance, using a transverse driving 0 non-diagonal mode, that is, passing a current through the amorphous wire and taking the induced voltage on the wound coil.
- 3) The diameter and length of the amorphous wire.
- 4) The diameter and the number of turns of the induction coil and the bias coil.

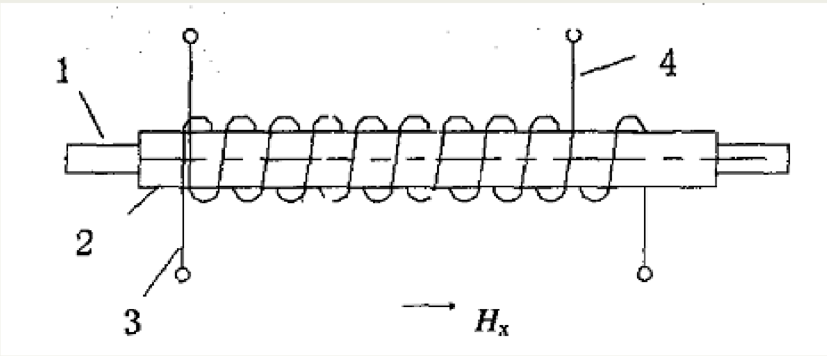
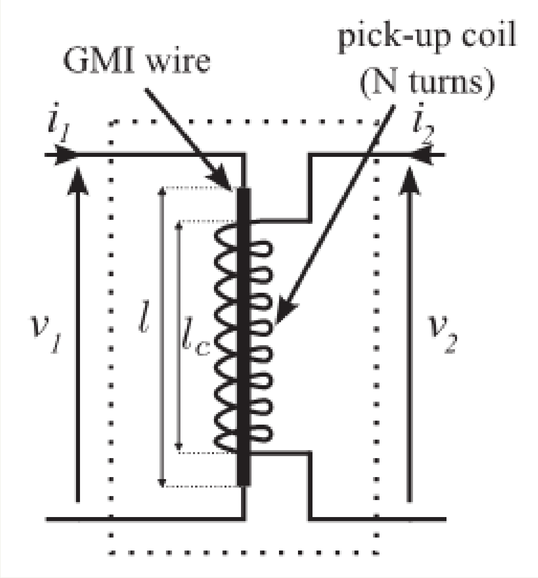


Fig. Amorphous wire probe
(1-amorphous wire; 2-supporting tube; 3-induction coil; 4bias coil)



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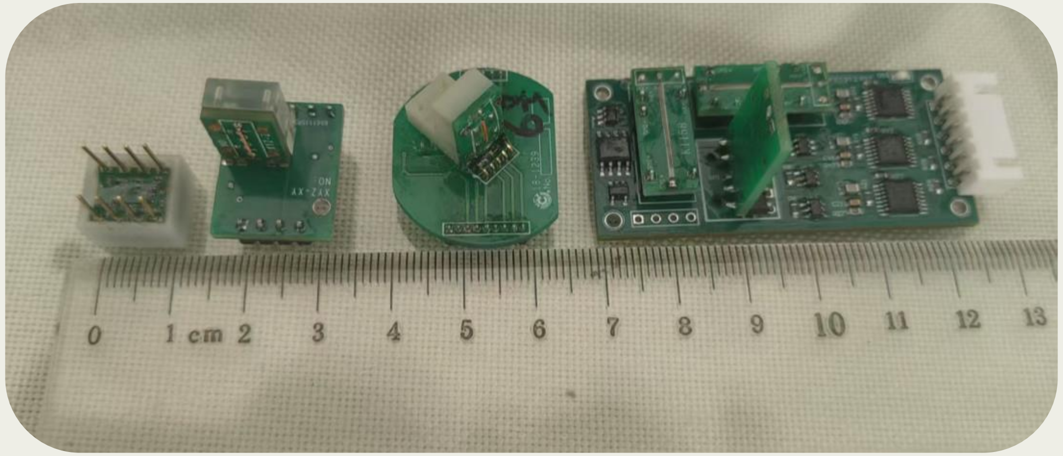
METHODS-- THE PRODUCTION OF THE AMORPHOUS WIRE PROBE

- Amorphous wire probe:
- Amorphous wire probe with 25um diameter of Co-based amorphous wire and 20um diameter of enameled wire is designed with different lengths (1mm, 2mm, 5mm, 10mm) and different turns of coil (800 turns ,1000 turns, 1300 turns).



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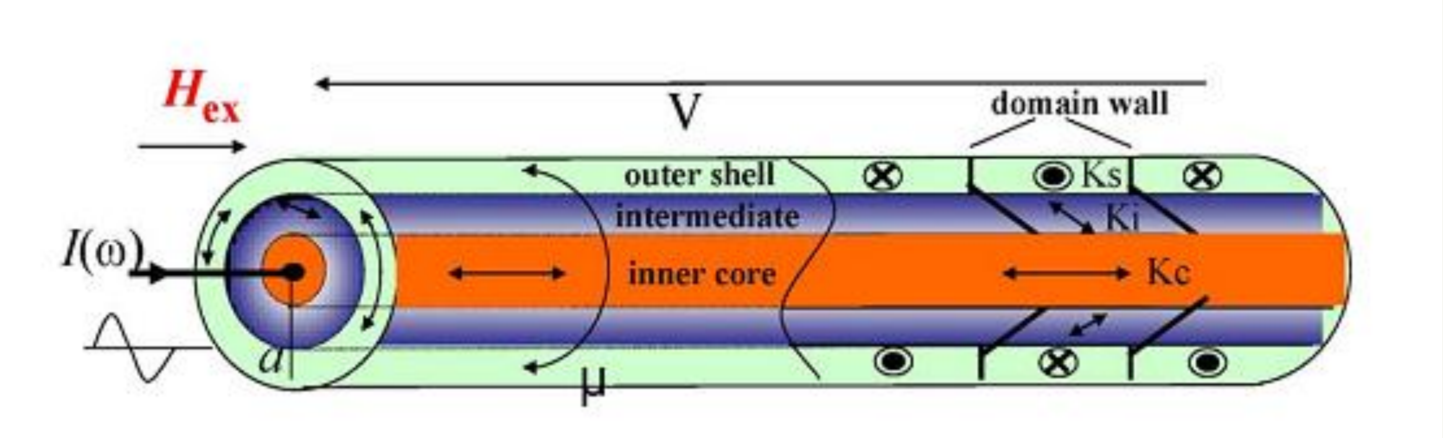
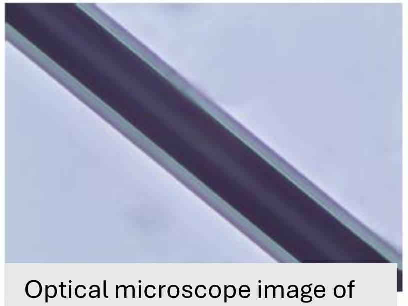
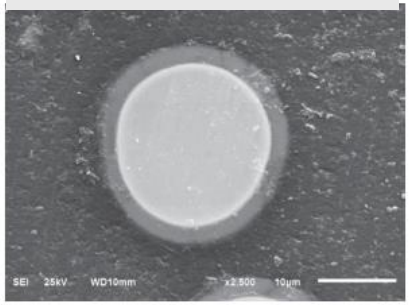
METHODS--(Working Principle of Amorphous Wire Weak Magnetic Sensor)

- Under the action of high frequency exciting current, when there is a weak magnetic field or a slight change of magnetic field outside, the anisotropic magnetic domains inside the amorphous wire are deflected, and the direction of the magnetic domains is unified to the easy magnetization direction-axis, and the impedance of the amorphous wire changes.





Optical microscope image of amorphous wire



Glass-coated amorphous fiber (CoSIB, inner diameter of amorphous fiber 23um, outer diameter 25um, of glass layer 1um)

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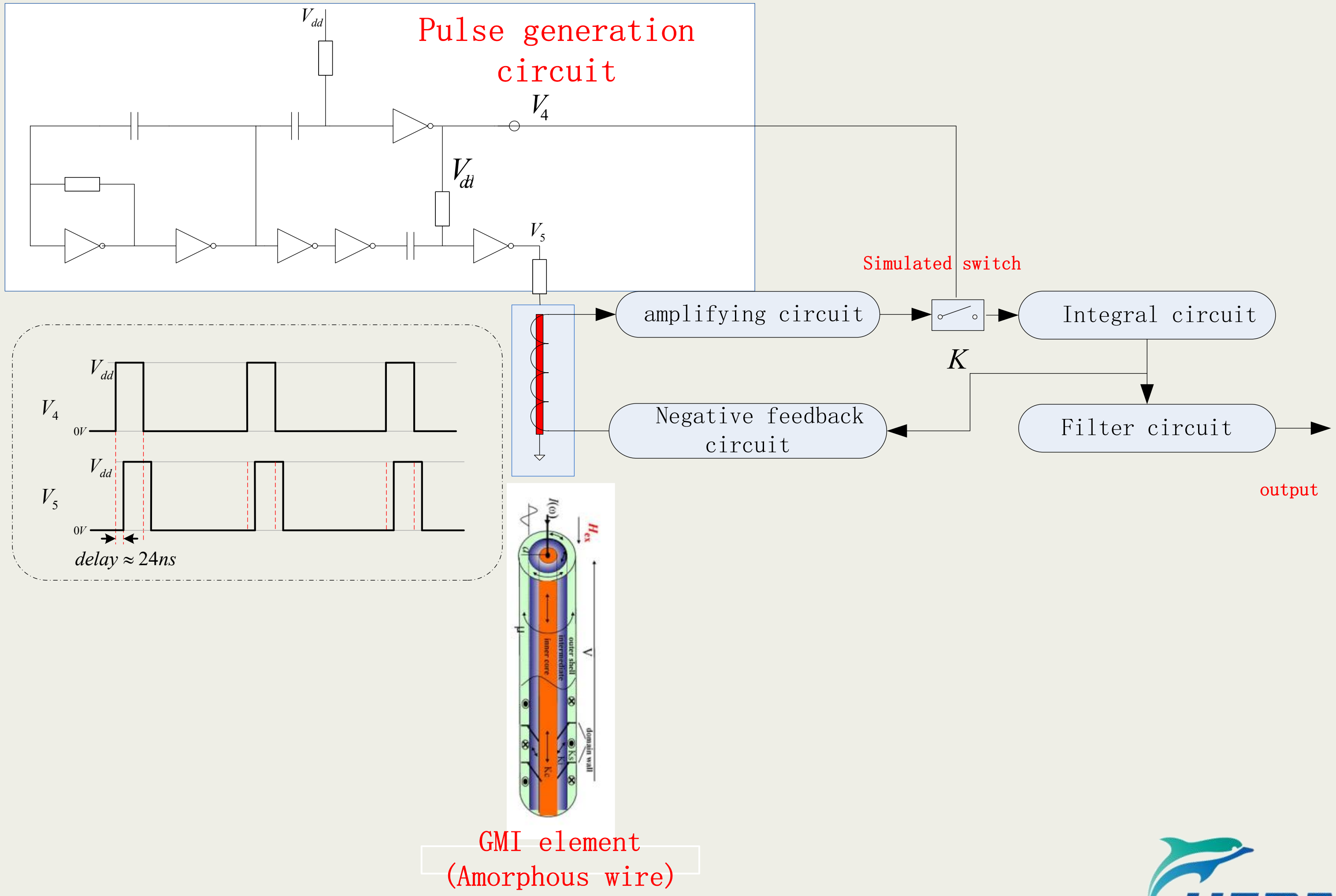
METHODS---Amorphous Wire Weak Magnetic Sensor Circuit Design

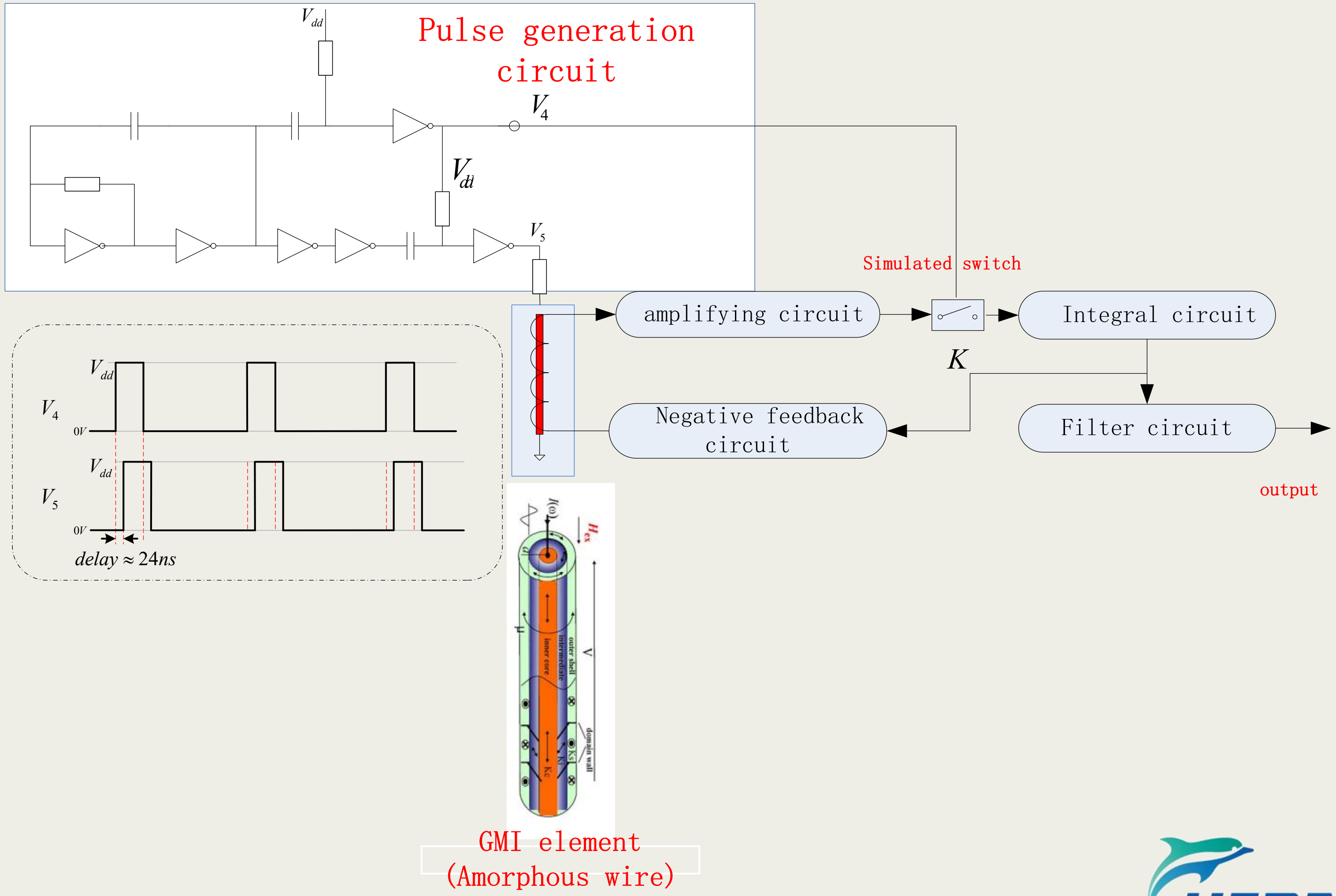
Based on the working principle of the amorphous wire magnetic sensor, a high-frequency signal is needed to excite the amorphous wire.

The excitation of sharp narrow pulse is used, which has strong harmonic signals, and the amorphous wire is more sensitive to the frequency response of high-order harmonics, which can improve the sensitivity of the sensor.



METHODS---Amorphous Wire Weak Magnetic Sensor Circuit Design

- The coil collects the signal of the changing amorphous wire
- The signal is amplified by using an amplifying circuit
- The signal is integrated by using an integrating;
- A feedback circuit is used to generate a reverse magnetic field to achieve magnetic equilibrium with the external magnetic field;
- The stable voltage signal after magnetic equilibrium is filtered by a lowpass filter, and the output result is obtained



Results--Amorphous wire weak magnetic sensor index

Parameter	Symbol	Condition	Minimum	Typical value	Maximum	Unit
Measurement range	FS	VCC = 5 V	-	±100	±300	uT
Sensitivity	Sen	-100 ~ 100 uT	20	22	25	mV/uT
Non-linearity	δL	±100 uT	0.005	0.01	0.05	%
Frequency response		H=100uT	DC	1K	1M	Hz
Hysteresis	δH	±100 uT	0.005	0.01	0.02	%
Repeatability	δR	±100 uT	0.005	0.01	0.02	%
Magnetic noise density	BN	H = 0, 1Hz	6	10	20	pT/√ Hz@1Hz
Magnetic field noise peak-to-peak	BNPP	0.1 ~ 10Hz	0.01	0.05	0.1	nTpp
Single/dual supply voltage	VCC	-	±5.5 3.3	±6 5	±12 9	V
Vcc static operating current (analog output/digital output)	IQ+	H = 0	-	10/50	-	mA
Dimensions	-	-	-	40.8x16.3x21.5	-	mmxmmxmm
Weight (analog output/digital output)	-	不含线及接头	-	11/17	-	g

Results--Comparison of the performance of various magnetic sensors

Magnet sensor type	Probe size (mm)	Resolution	Response speed	Consumption (mA)	working range	Sensitivity (mv/V/Oe)	Working temperature range
HALL	1x1 (mm)	4000nT	1MHz	5-20	±1000Oe	0.05	-40^{0}C-125^{0}C
AMR	1x1 (mm)	10 nT	1MHz	1-10	±100Oe	1	-40^{0}C-125^{0}C
GMR	2x2 (mm)	3nT	1MHz	1-10	±20Oe	3	-40^{0}C-125^{0}C
fluxgate	10~20mm	0.1 nT	5KHz	100	±3Oe	1000	-40^{0}C-125^{0}C
TMR	0.5x0.5 (mm)	1nT	1MHz	0.001-0.01	±20Oe	100	-40^{0}C-125^{0}C
GMI	**1~2mm**	**0.01nT**	**1MHz**	**1-10**	**±30Oe**	**1000**	-40^{0}C-125^{0}C

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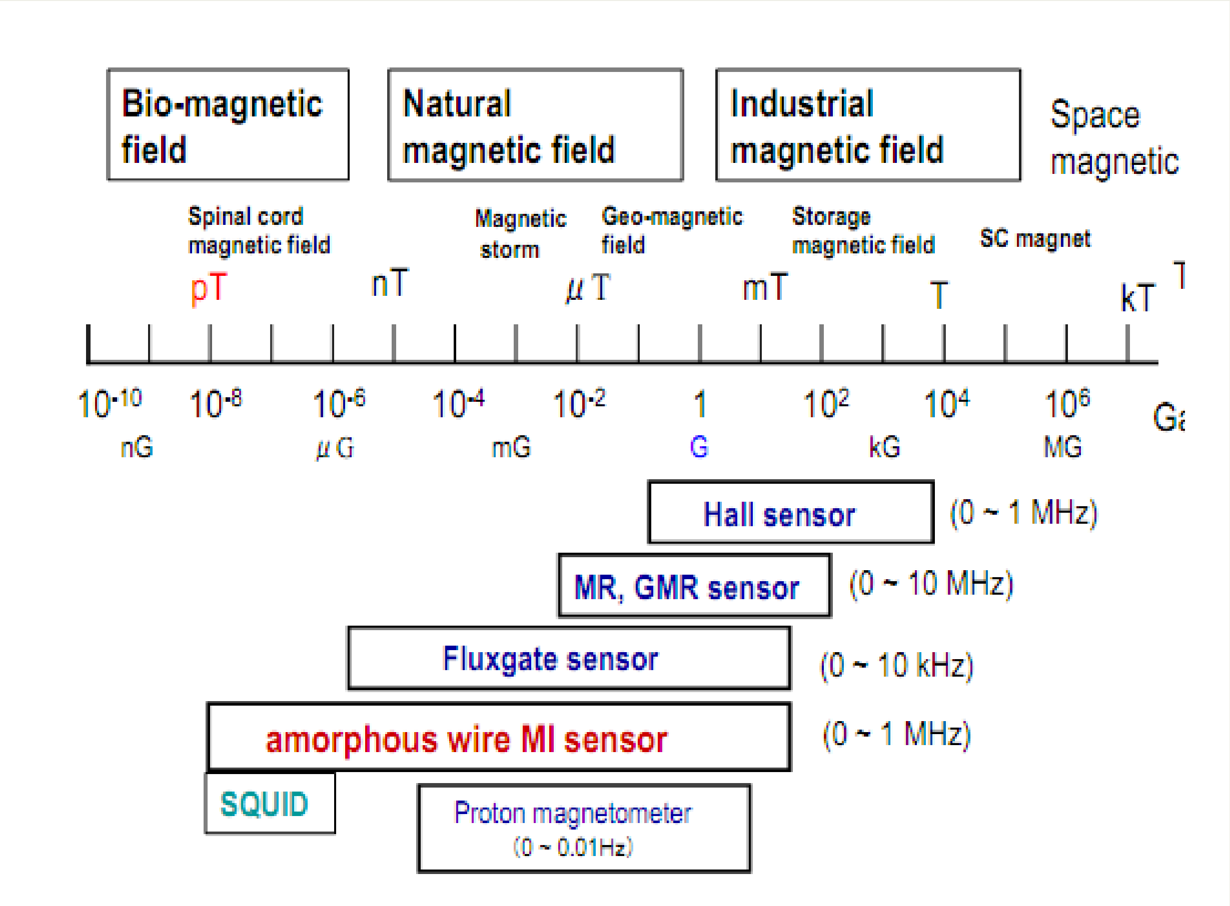
Results--Comparison of the performance of various magnetic sensors



It has the comprehensive advantages of high response speed, high sensitivity, low power consumption, miniaturization, wide working temperature range and range.

Results--Comparison of the performance of various magnetic sensors

Weak magnetic sensor	advantages	disadvantages	working principle
TMR magnetic sensor	Ultra-low power consumption	Large hysteresis, low sensitivity	Use the tunnel magnetoresistance effect of magnetic multilayer film materials to sense the magnetic field
Magnetoresistive magnetic sensor -- amorphous wire weak magnetic sensor	With comprehensive advantages of high response speed, high sensitivity, low power consumption, miniization, wide working temperature range and range	Range:-100000 to 100000nT Minimum sensitivitty: at least 0.01nT Operating temperature range:-40^{0}C To +85^{0}C	Giant magnetoimpedance effect
MAGa-1.1 Magnetometer		Range:20000 to 100000nT Minimum sensitivitty: at least 0.1nT Heading error:0.2nT or lower Operating temperature range:-35^{0}C To +50^{0}C	

Results--Handheld magnetic detection system

For target buried at a depth of 2-5m : (diameter 155 mm, length 810 mm) the total induced magnetic moment is：

M=3.14*0.155*0.155/4*0.81*73.6=1.124A.m^2

Magnetic induction strength at about 2m：

$$B=\frac{\mu_0 M\sqrt{3\cos^2\theta+1}}{4\pi r^3}=\frac{4\pi\times10^{-7}\times1.124\times\sqrt{3\cos^2 90+1}}{4\pi\times2^3}=28nT$$

Magnetic induction strength at about 5m：

$$B=\frac{\mu_0 M\sqrt{3\cos^2\theta+1}}{4\pi r^3}=\frac{4\pi\times10^{-7}\times1.124\times\sqrt{3\cos^2 90+1}}{4\pi\times5^3}=1.7nT$$

UAV-based target magnetic exploration system

UAV

Data acquisition module

GMI sensor

Bracket

Software processing system

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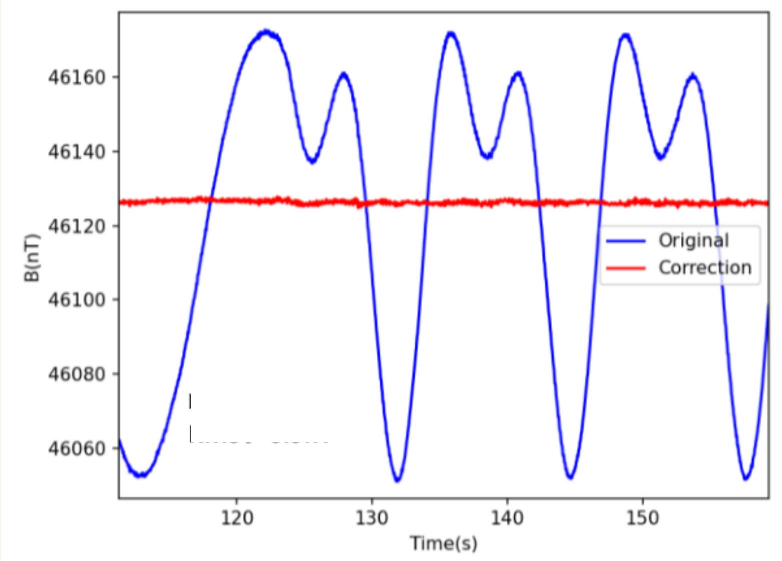
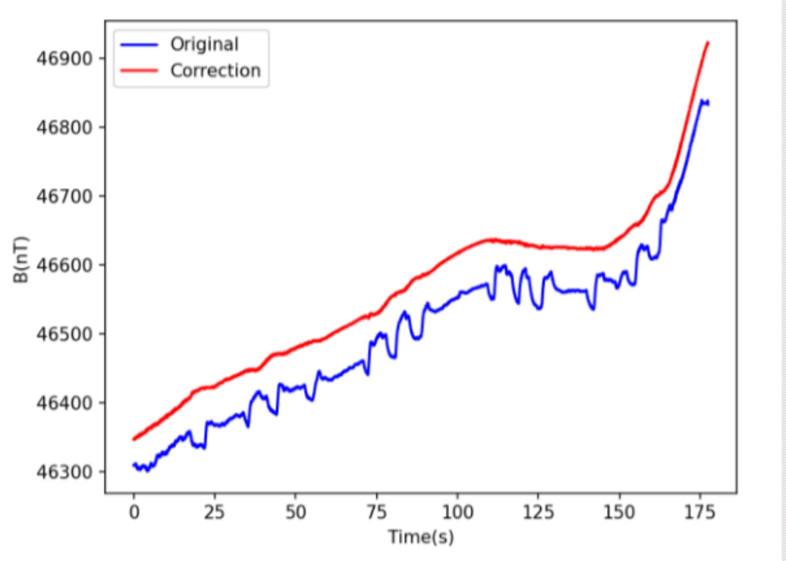
Results-- System magnetic field compensation algorithm

Total field synthesis result



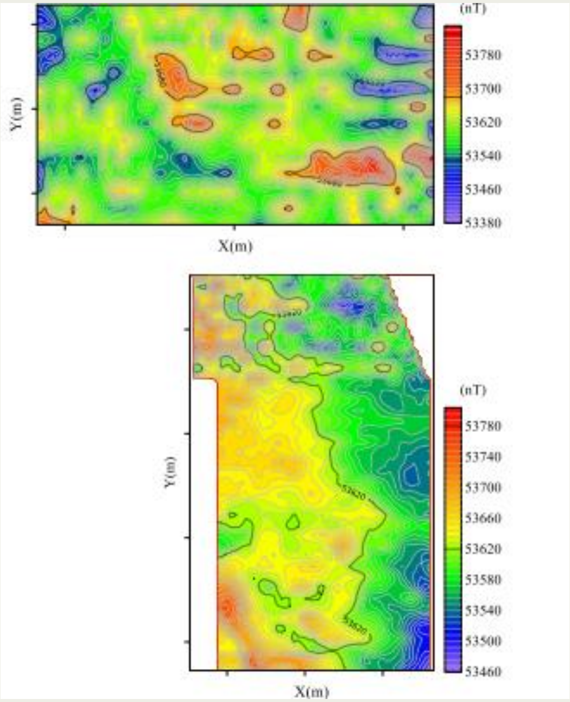
Measurement line compensation results



Three-axis synthetic total field+Magnetically compensated:RMS=0.9nT
The overall measurement accuracy of the entire area is approximately:4.1nT

HERAL

Results--UAV-based target magnetic exploration system detection results



Aeromagnetic map of a certain area- red fo suspected iron ore

Using UAV-based target magnetic exploration system based on the GMI magnetic sensor array, the ferromagnetic ore area can be detected

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Conclusion

- Magnetic field mapping, as one of the Continued Period Technologies, plays a vital role for On-Site Inspection. Looking back into the recent science and technology development history, magnetic sensing have been Under decades of development.
- This work would propose a high-performance magnetic sensor based on the giant magnetoimpedance effect of special magnetic materials . Compared with current magnetic sensors such as GMR magnetic resistance sensors, flux meters and Hall sensors, armorphous wire magnetic sensor has comprehensive technical advantages .