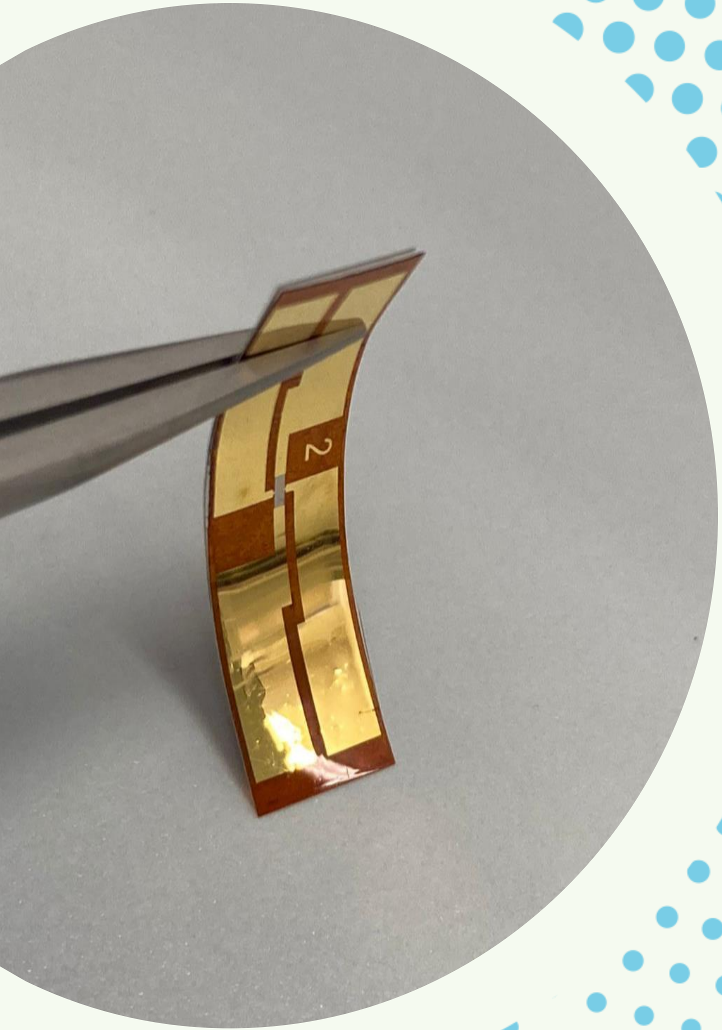


Multi-Functional Flexible Planar Hall Effect Sensors

Daniel Lahav[1], Hariharan Nhalil[1], Moty Schultz[1], Shai Amrusi[2], Asaf Grosz[2] and Lior Klein[1]

[1]Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 52900, Israel

[2]Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

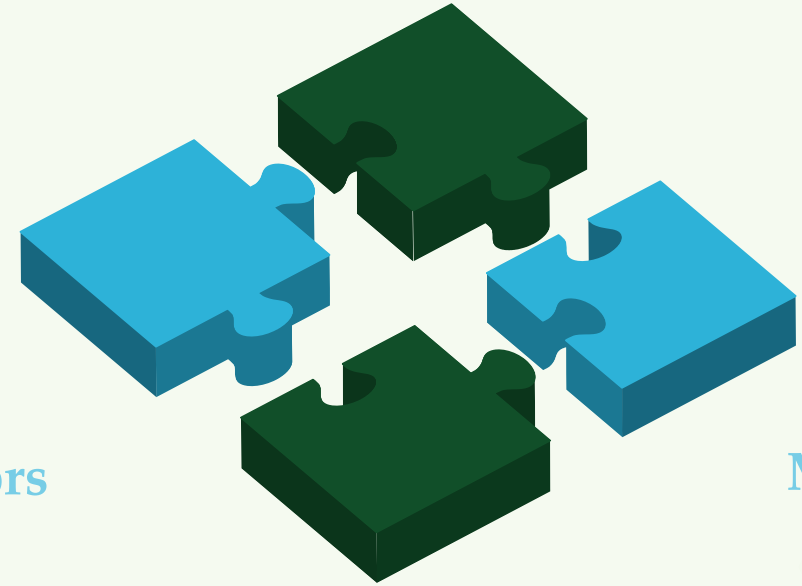
BINA Bar-Ilan Institute of Nanotechnology & Advanced Materials Bar-Ilan University

2025 Annual Conference

Overview

1 Strain Gauge

2 Magnetic Field Sensors



3 Planar Hall Effect Sensors

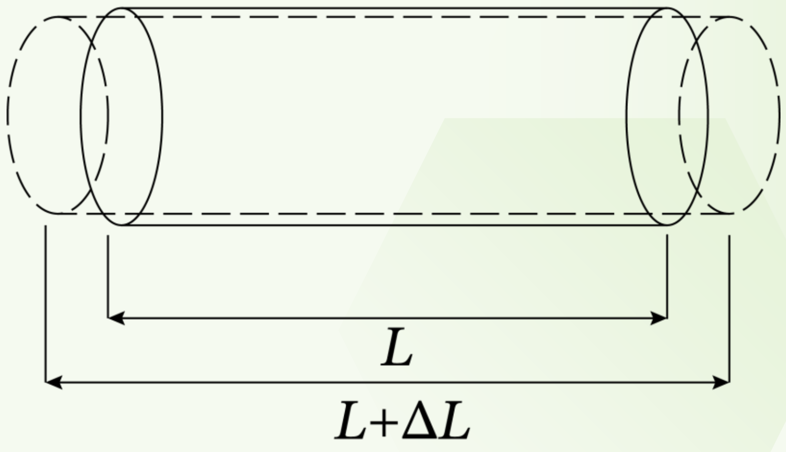
4 Multi-Functional Sensors

Strain Gauge: Introduction

Strain

- The relative <u>deformation</u> of a material when subjected to an external force.
- Quantifies how much a material stretches or compresses under applied stress.

$$\epsilon = \frac{\Delta L}{L}$$



Strain Gauge: Applications

Aerospace & Automotive Engineering

Measures strain in fuselage, aircraft wings, and jet engine to ensure structural integrity.

Manufacturing & Industrial Equipment

Monitors stress in machinery, pipelines, and pressure vessels to prevent mechanical failure.

Structural Health Monitoring

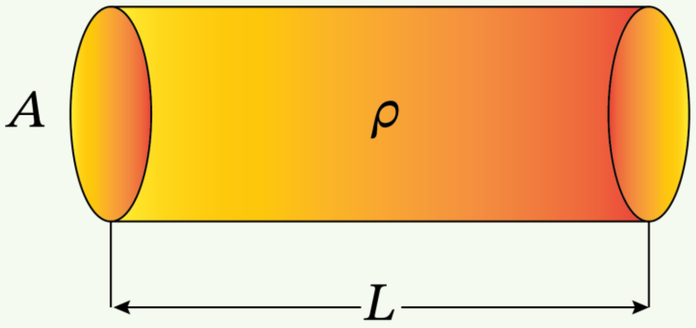
Used in bridges, dams, buildings, and tunnels to detect stress and prevent failures.

Strain Gauge:
Working Principle

Strain Gauge

- Sensor used to measure strain by converting physical changes into electrical signals.

$$R = \rho \frac{L}{A}$$

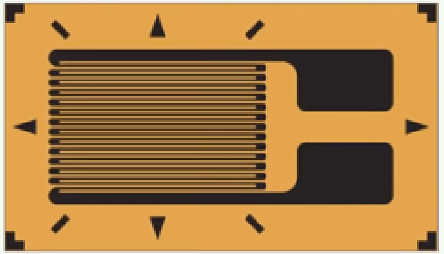


Strain Gauge: Working Principle

Strain Gauge

- Sensor used to measure strain by converting physical changes into electrical signals.

$$R = \rho \frac{L}{A}$$

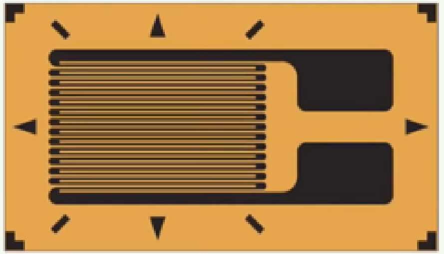


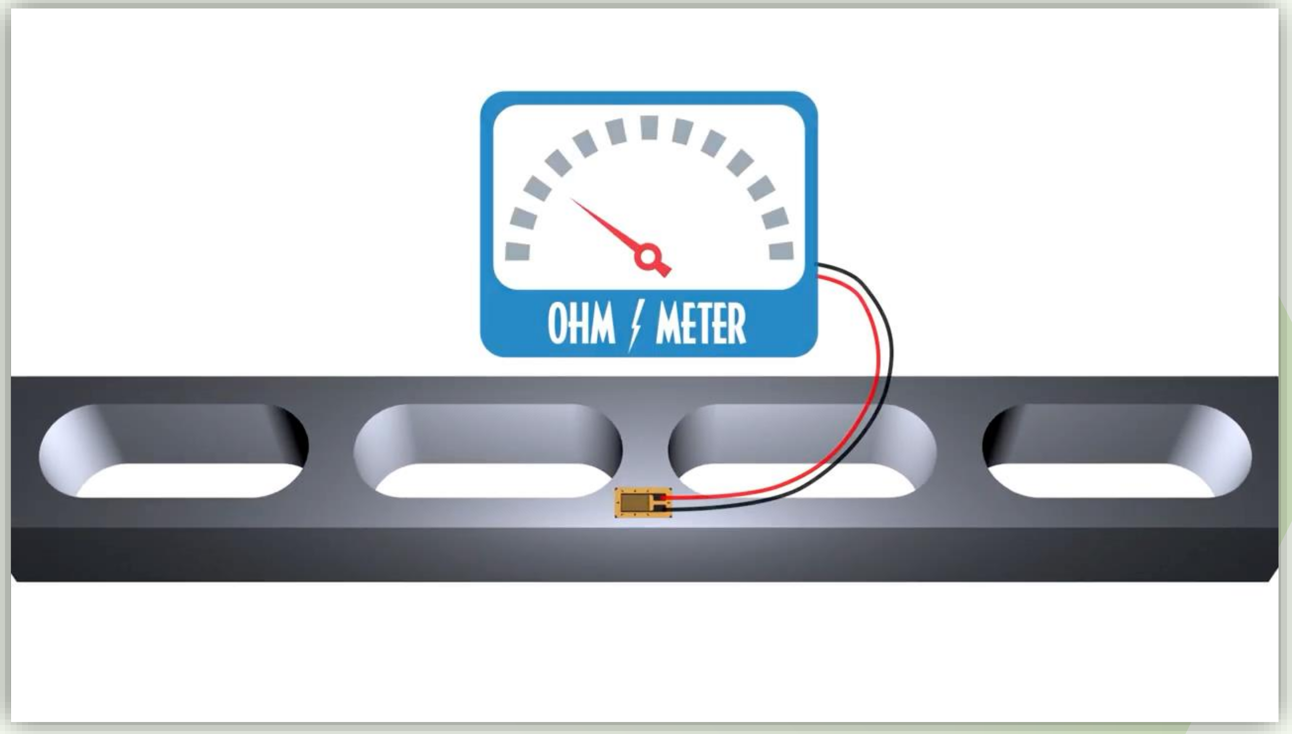
Strain Gauge:
Working Principle

Strain Gauge

- Sensor used to measure strain by converting physical changes into electrical signals.

$$R = \rho \frac{L}{A}$$





Strain Gauge: Disadvantages

Strain Gauge

- Sensor used to measure strain by converting physical changes into electrical signals.

$$R = \rho \frac{L}{A}$$

Limited Sensitivity

Small strain causes minimal resistance change, making detection difficult.

Susceptibility to Noise

Electrical interference and signal drift can reduce measurement reliability.

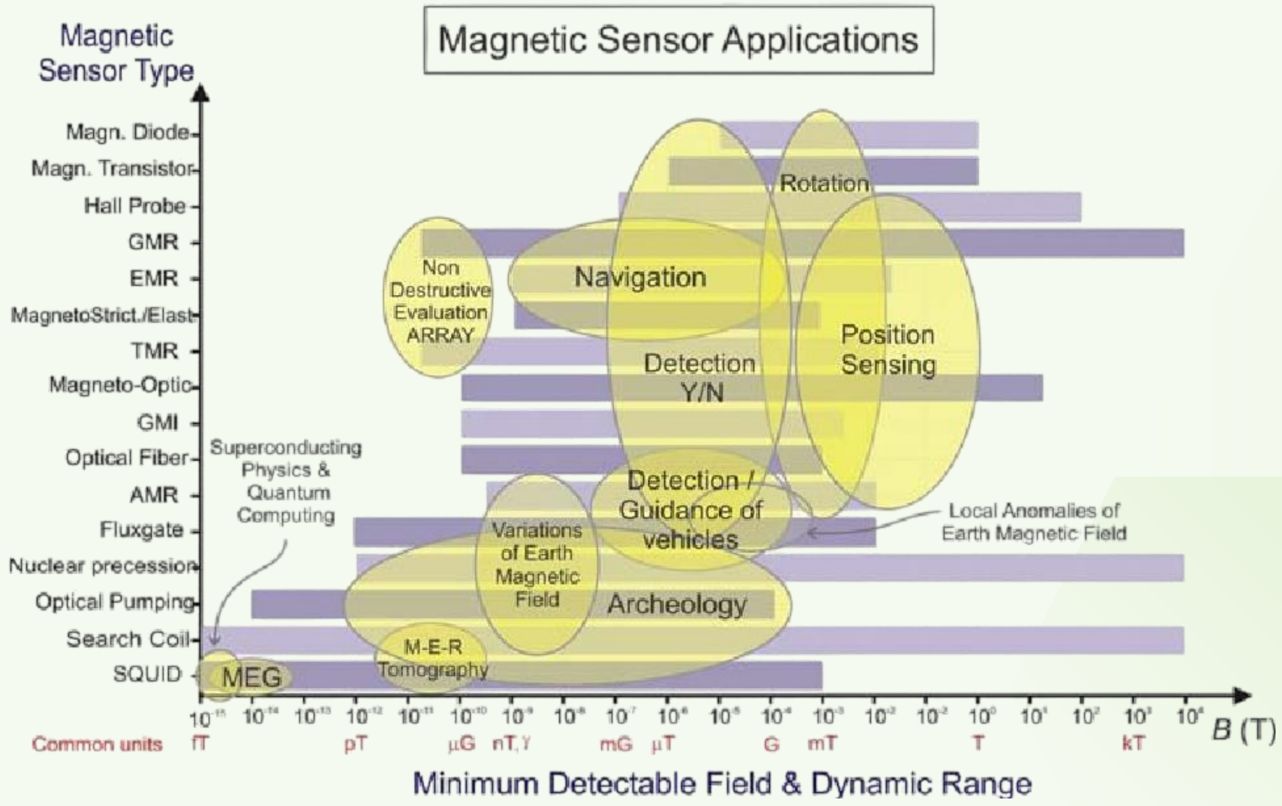
Frequent Calibration

Requires regular calibration to maintain accuracy.

Temperature Sensitivity

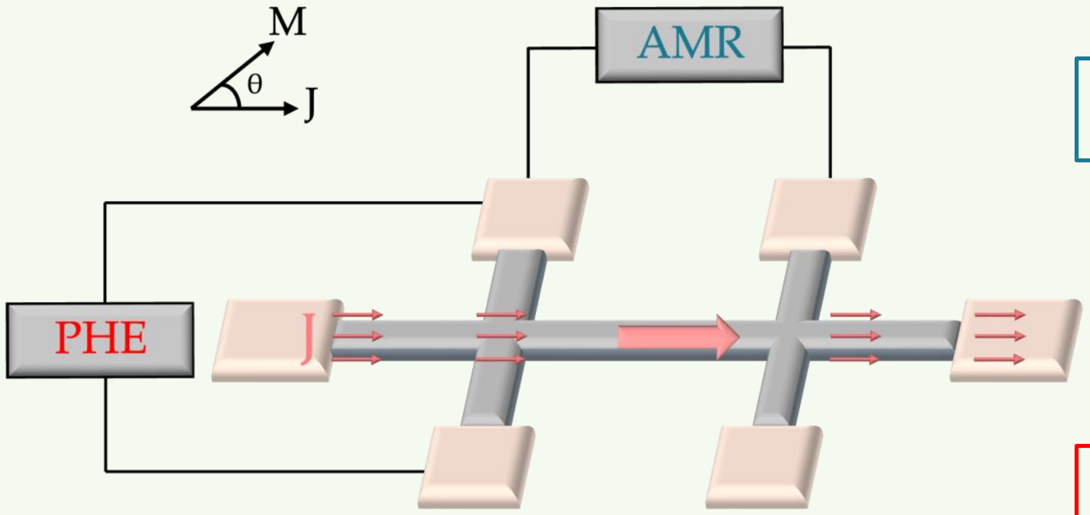
Thermal expansion can introduce errors, necessitating compensation techniques.

Magnetic Field Sensors: Types and Applications



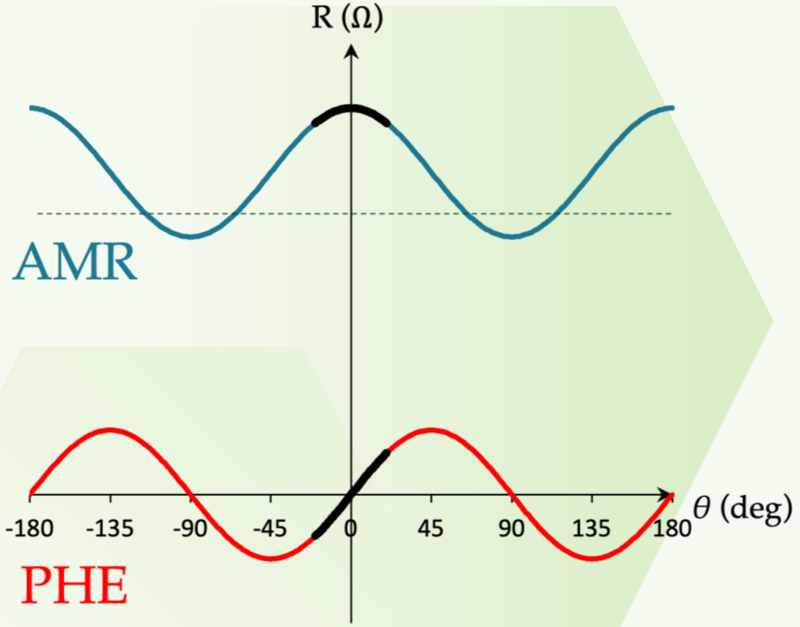
Magnetic Field Sensors:
Magnetoresistive Sensors

Anisotropic Magnetoresistance (AMR) and Planar Hall Effect (PHE)



$$\rho_{xx} = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp})\cos^2\theta$$

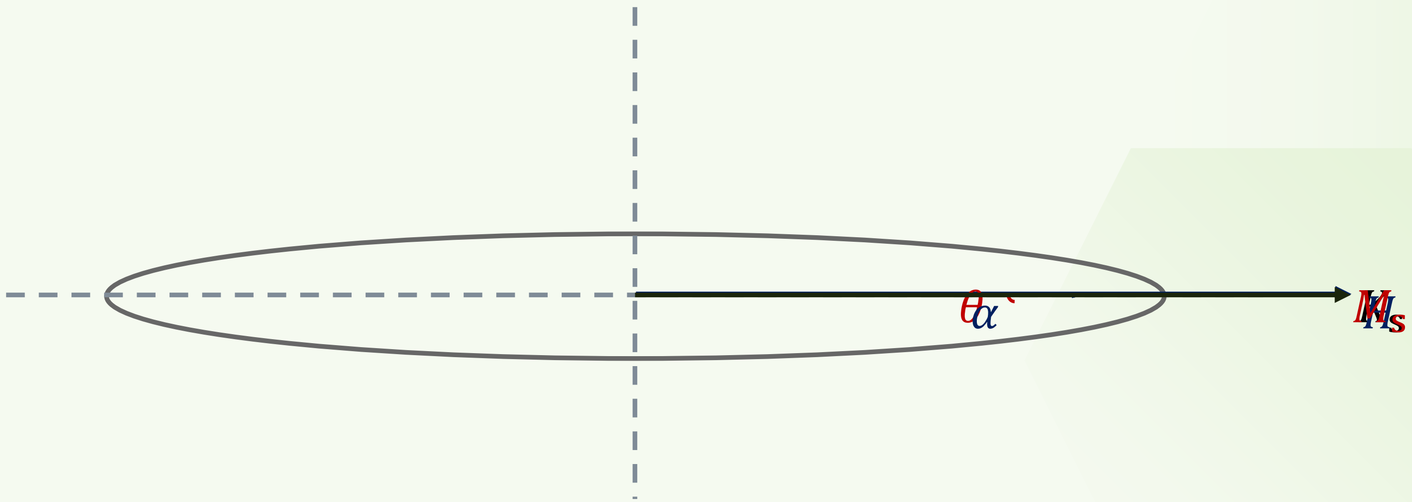
$$\rho_{xy} = 0.5 \cdot (\rho_{\parallel} - \rho_{\perp})\sin 2\theta$$



Planar Hall Effect Sensors:
Elliptical PHE Sensors

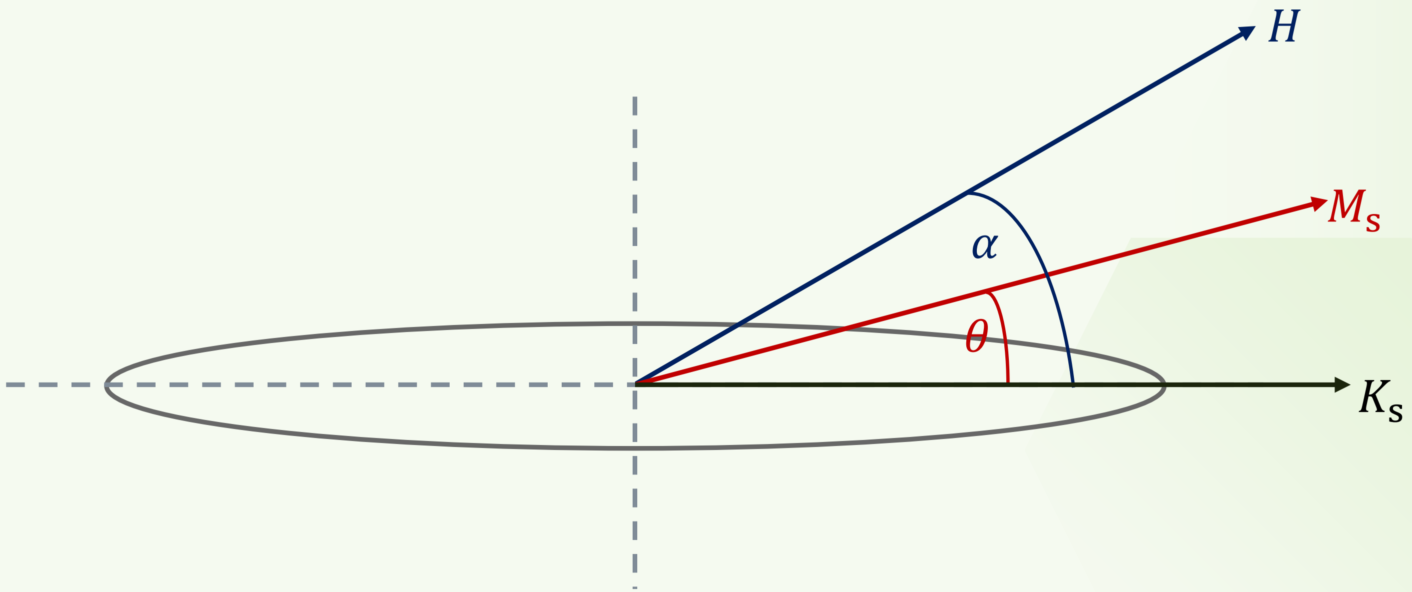
Why Elliptical?

- Stable uniform magnetization (shape anisotropy).
- Low anisotropy fields (higher signal).

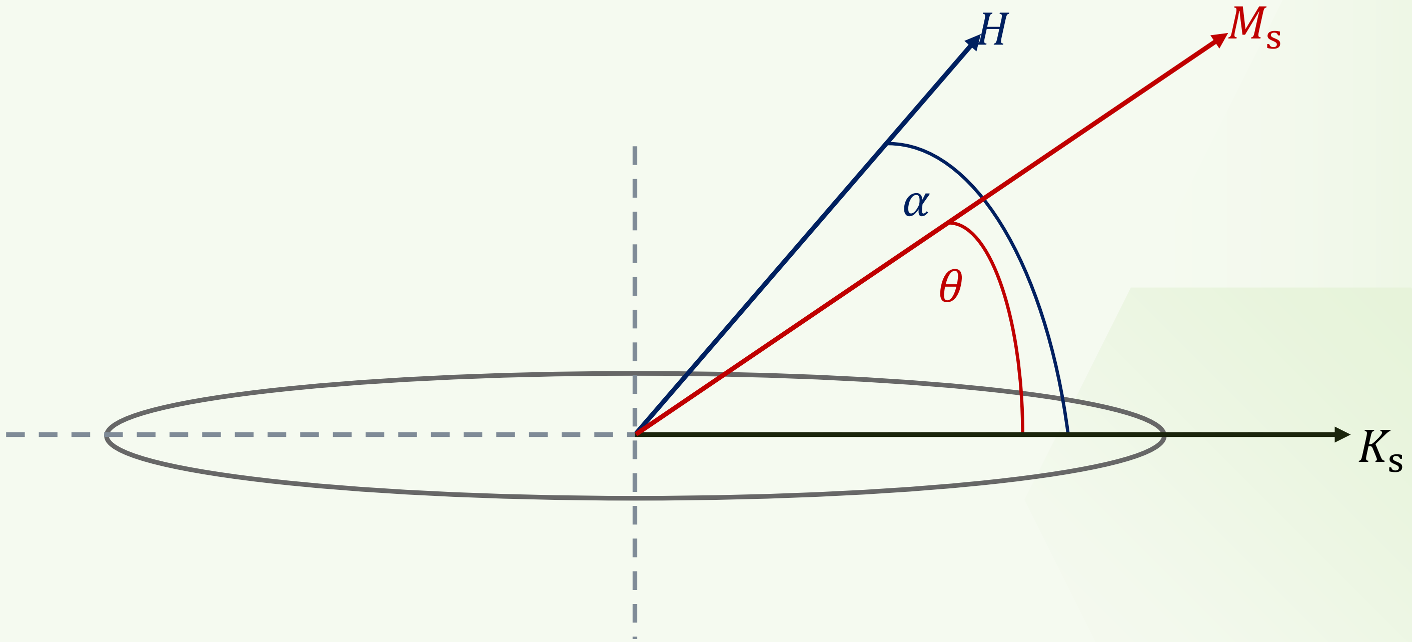


Planar Hall Effect Sensors:
Elliptical PHE Sensors

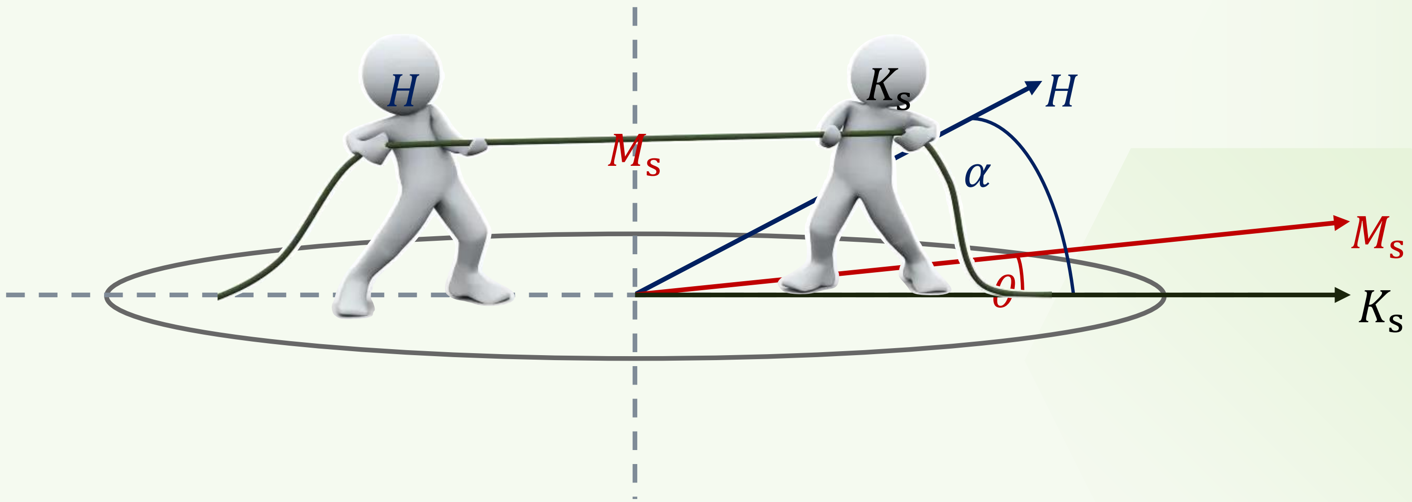
Magnetic Field Disturbance → Magnetic Response: Magnetization Reorientation → Resistance Change



Planar Hall Effect Sensors:
Elliptical PHE Sensors

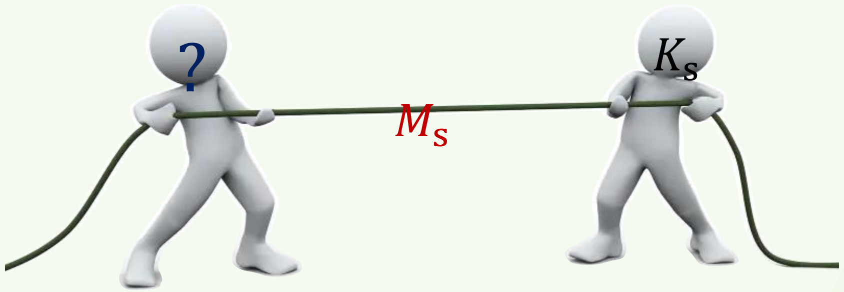


Planar Hall Effect Sensors:
Elliptical PHE Sensors



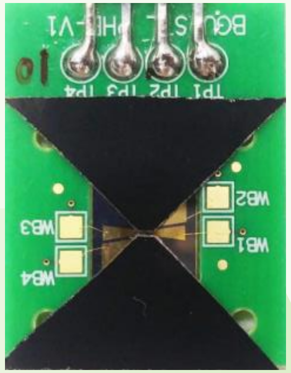
Planar Hall Effect Sensors:
Elliptical PHE Sensors

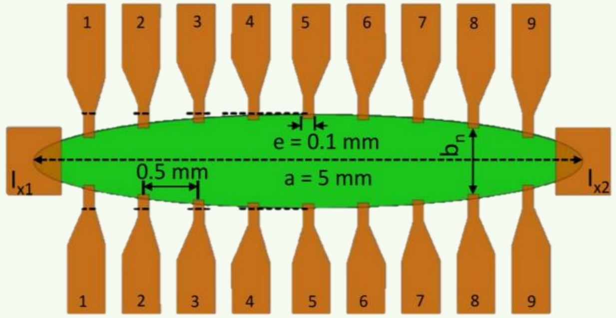
— — ? — —
Disturbance → Magnetic Response: Magnetization Reorientation → Resistance Change

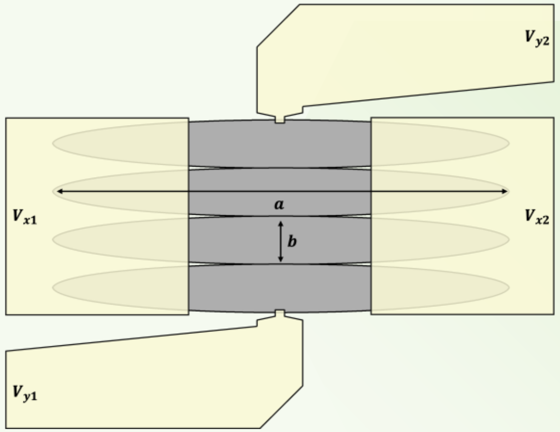


Planar Hall Effect Sensors: Configurations and Best Resolutions

- **PHE Sensor without Magnetic Flux Concentrators:** 24 pT/√Hz at 50 Hz.
- **PHE Sensor with Magnetic Flux Concentrators:** 5 pT/√Hz at 10 Hz.
- **PHE Sensor Array (4 Ellipses):** 16 pT/√Hz at 100 Hz.
- **Gradiometer Configuration:** 26 pT/mm/√Hz at 50 Hz.
- **Flexible PHE Sensor:** Better than 200 pT/√Hz at 10 Hz.







Planar Hall Effect Sensors:
Potential Areas of Applications

- **Automotive Industry:** Suitable for applications needing a dynamic range >100 Oe and nano-tesla resolution, ideal for advanced vehicle technologies.
- **Lab-on-Chip Systems:** PHE sensors outperform xMR sensors, enhancing compact, integrated lab systems.
- **Flexible Electronics:** Highly applicable in fields such as soft robotics, consumer electronics, healthcare devices, and more.
- **Strain Gauges:** Have the potential to function as ultra-sensitive strain gauges capable of detecting micro-strain variations down to a few percent.

sensors MDPI

Article

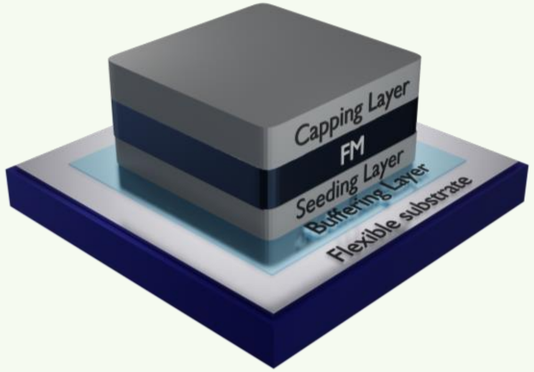
Planar Hall Effect Magnetic Sensors with Extended Field Range

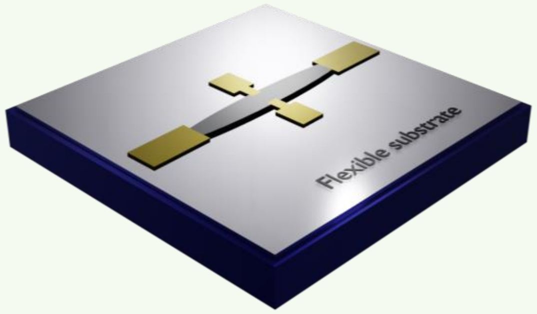
Daniel Lahav [1], Moty Schultz [1], Shai Amrusi [2], Asaf Grosz [2] and Lior Klein [1,*]

Planar Hall Effect Sensors: Flexible Elliptical PHE Sensors

Materials and Layer Stack

- **Permalloy (Py,$Ni_{80}Fe_{20}$)** – FM layer, due to its low MCA coefficient, high permeability, and low coercive field.
- **Tantalum (Ta)** – Dual purpose as a seeding layer and a capping layer.
- **Aluminum oxide (Al_2O_3)** – Buffering layer.
- **Kapton tape** – Serves as a flexible substrate.
- **SU-8 TF 6002** – For surface smoothening.

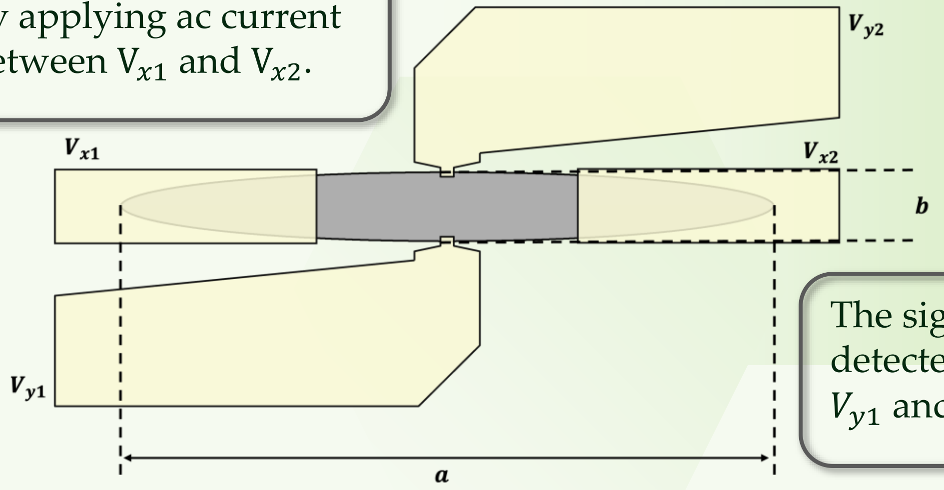




Device Design

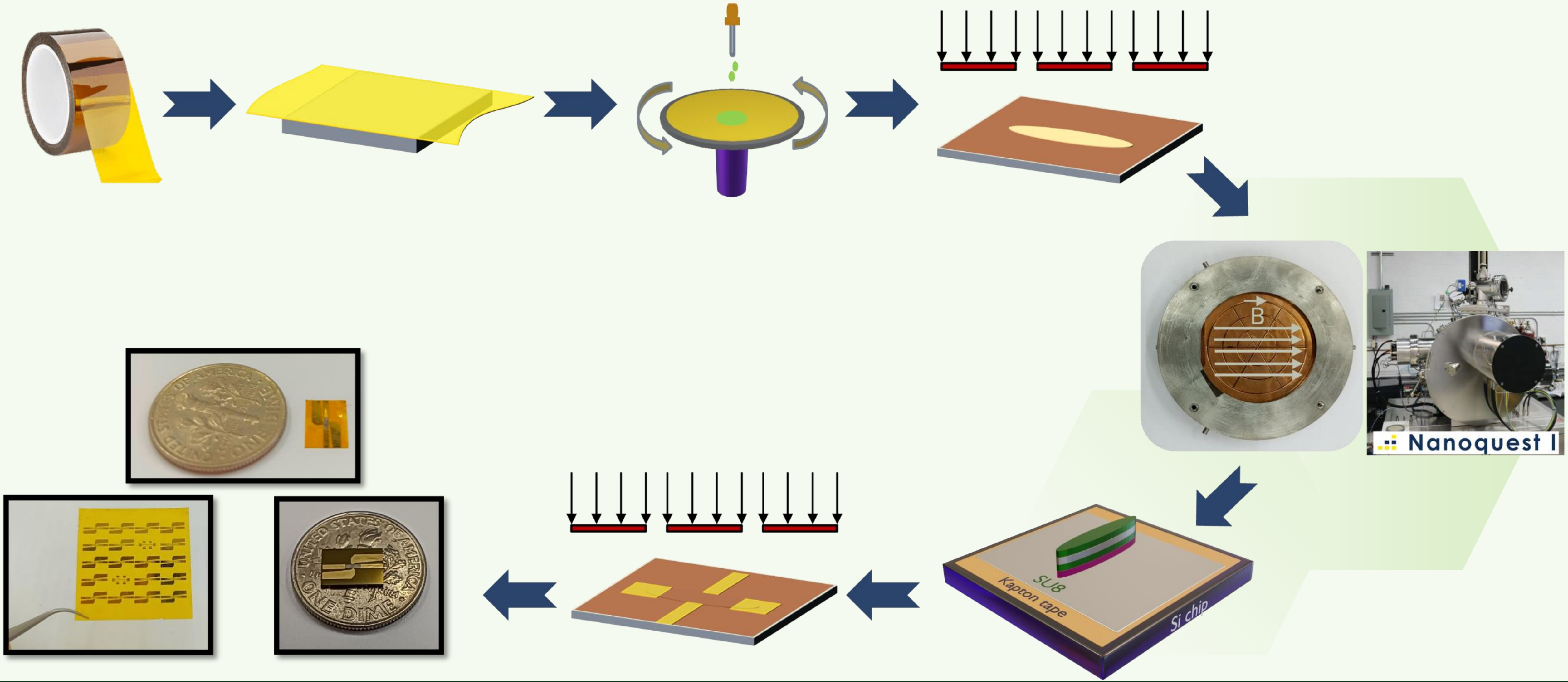
- Elliptical PHE (EPHE) sensor - aspect ratio 1:8.
  - Major axis (a) – 5 mm.
  - Minor axis (b) – 625 μm.
- Flexible substrate thickness – 125 μm.

The sensor is excited by applying ac current between V_{x1} and V_{x2}.

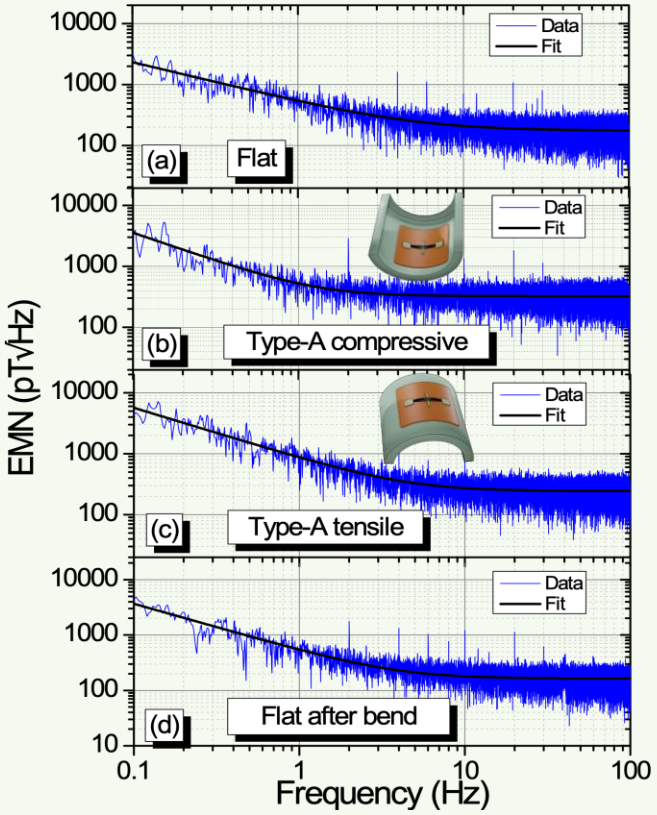


The signal is detected between V_{y1} and V_{y2}.

Planar Hall Effect Sensors: Fabrication Process

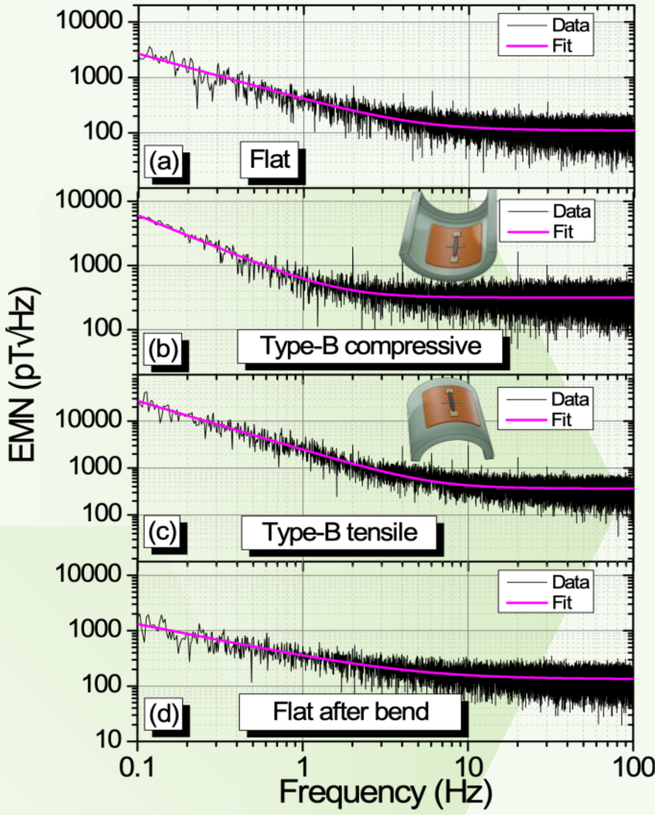


Planar Hall Effect Sensors:
Sub-200 pT Resolution

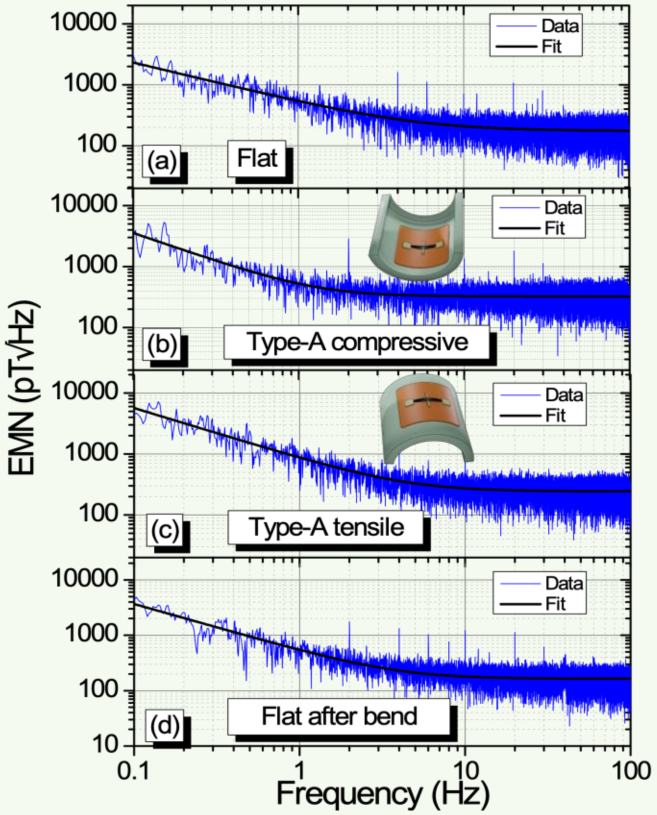


Mode	100 Hz (pT/√Hz)	10 Hz (pT/√Hz)	1 Hz (pT/√Hz)	0.1 Hz (pT/√Hz)
Flat	177	209	544	2335
Type-A compressive	244	273	876	5684
Type-A tensile	323	327	524	3557
Flat after-bent	164	179	547	3669
Flat	111	125	414	2664
Type-B compressive	317	320	628	6050
Type-B tensile	365	426	2467	26975
Flat after-bent	134	157	358	1317

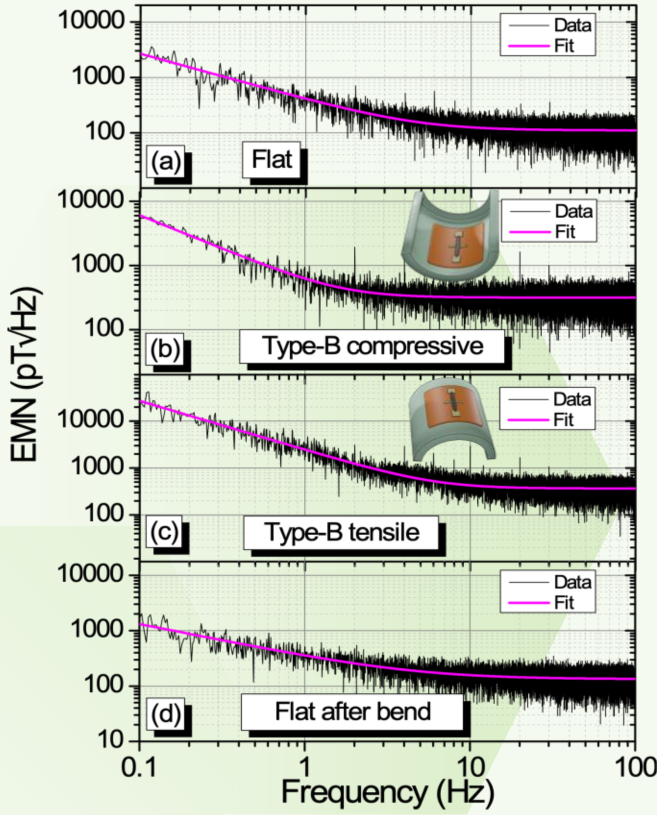
Among the best reported values for flexible magnetic sensors.



Planar Hall Effect Sensors:
Sub-200 pT Resolution



What About Strain?



Multi-Functional Flexible Planar Hall Effect Sensors: Magnetostriction and Magnetoelasticity

- Two closely linked phenomena that describe the interaction between the magnetic and mechanical properties of FM materials.
- Both effects arise from the coupling between the material's magnetic domain structure and its elastic properties.

Magnetostriction

The deformation of a material—whether expansion or contraction—induced by the application of a magnetic field.

Magnetoelasticity

The material's magnetic properties are altered when subjected to mechanical stress or strain.

Multi-Functional Flexible Planar Hall Effect Sensors:
Magnetostriction and Magnetoelasticity

- Two closely linked phenomena that describe the interaction between the magnetic and mechanical properties of FM materials.
- Both effects arise from the coupling between the material's magnetic domain structure and its elastic properties.

Magnetostriction

External Magnetic Field → Strain

Magnetoelasticity

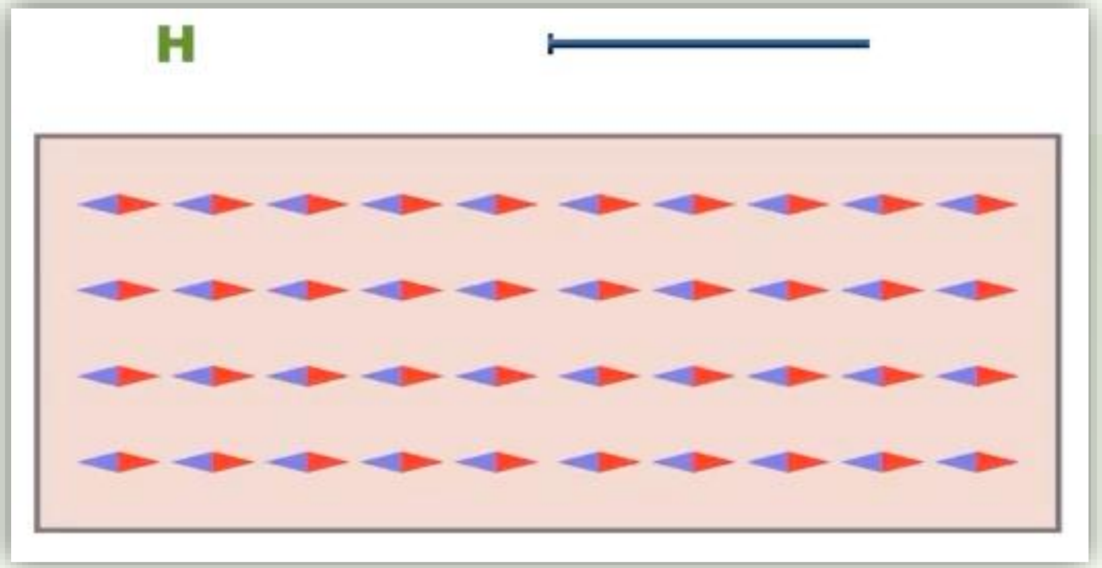
Magnetic Properties Change ← Strain

Multi-Functional Flexible Planar Hall Effect Sensors: Magnetostriction and Magnetoelasticity

- Two closely linked phenomena that describe the interaction between the magnetic and mechanical properties of FM materials.
- Both effects arise from the coupling between the material's magnetic domain structure and its elastic properties.

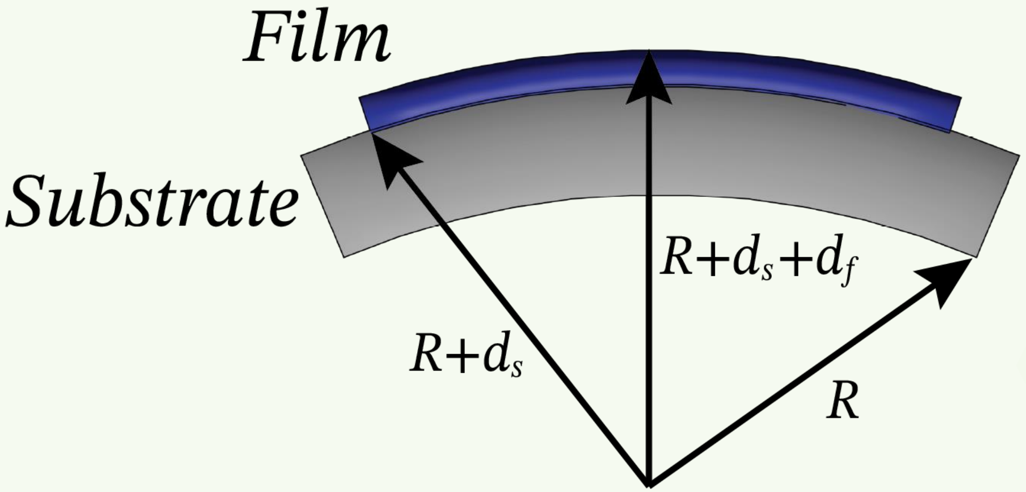
Magnetostriction

Magnetic Field Change → Strain



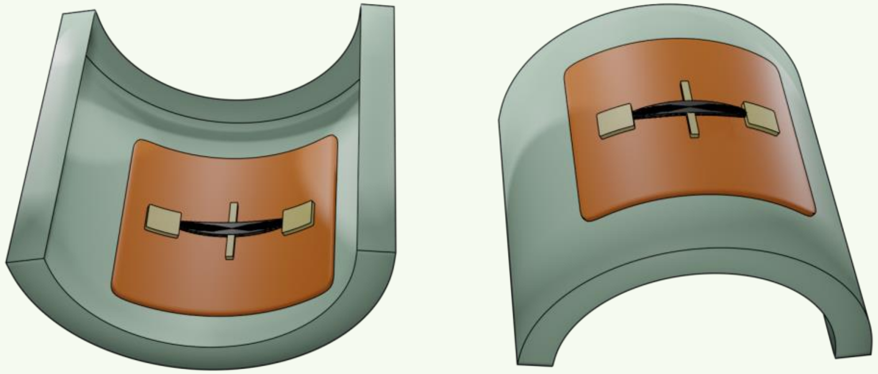
Uniaxial Bending of a Thin Film

$$\varepsilon = \frac{d_f + d_s}{2R} \Longleftrightarrow H_\sigma = \frac{3Y_f\lambda_s}{(1-\nu^2)M_s}\varepsilon$$



Multi-Functional Flexible Planar Hall Effect Sensors:
Flexible EPHE Sensors Under Bending

$\varepsilon = 0.84\%$



Mode	H_{eff} (Oe)
Flat	7.2
Type-A compressive	7.8
Type-A tensile	17.8
Flat after-bent	6.6
Flat	6.7
Type-B compressive	14.0
Type-B tensile	7.8
Flat after-bent	7.5

$H_{eff}^{(f)}$ → 7.8 (Type-A compressive)

$H_{eff}^{(i)}$ → 7.2 (Flat)

$$H_{eff}^{(i)} = H_{int}$$
$$H_{eff}^{(f)} = H_{int} + H_{\sigma}$$
$$\Longrightarrow \delta H = H_{eff}^{(f)} - H_{eff}^{(i)} = H_{\sigma}$$

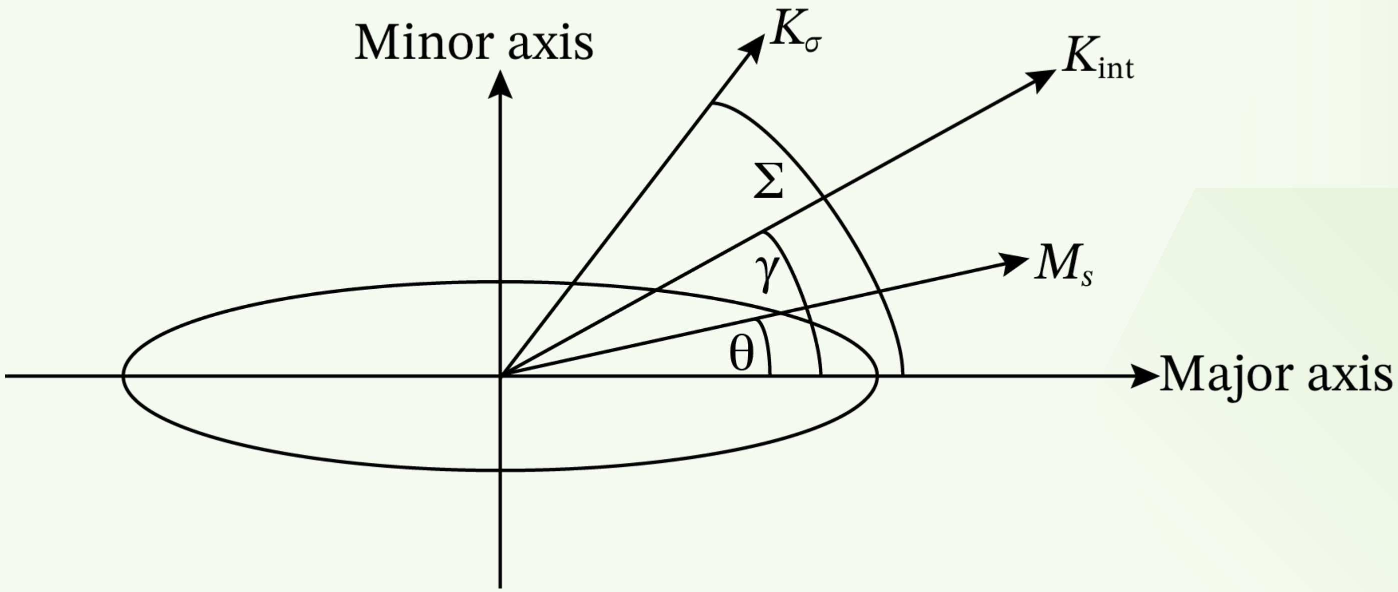
Flexible EPHE sensors can measure both magnetic fields and strains simultaneously **under the application of an external field.**

Multi-Functional Flexible Planar Hall Effect Sensors: Essential Steps for Realization

- Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?
- Is it feasible to fabricate a device that meets these requirements?
- What is the expected strain-gauge resolution for such a device?

Multi-Functional Flexible Planar Hall Effect Sensors: A Tunable Anisotropy Landscape

$$E = K_{\text{int}} \sin^2(\gamma - \theta) + K_\sigma \sin^2(\Sigma - \theta)$$



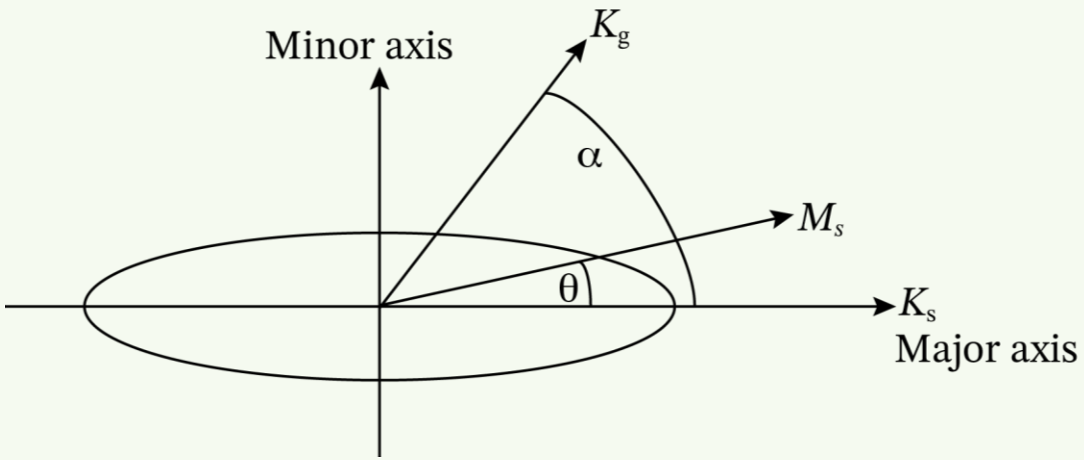
Multi-Functional Flexible Planar Hall Effect Sensors:
Essential Steps for Realization

- ☑ Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?
- ☐ Is it feasible to fabricate a device that meets these requirements?
- ☐ What is the expected strain-gauge resolution for such a device?

Multi-Functional Flexible Planar Hall Effect Sensors:
Tuning the Easy Magnetization Direction

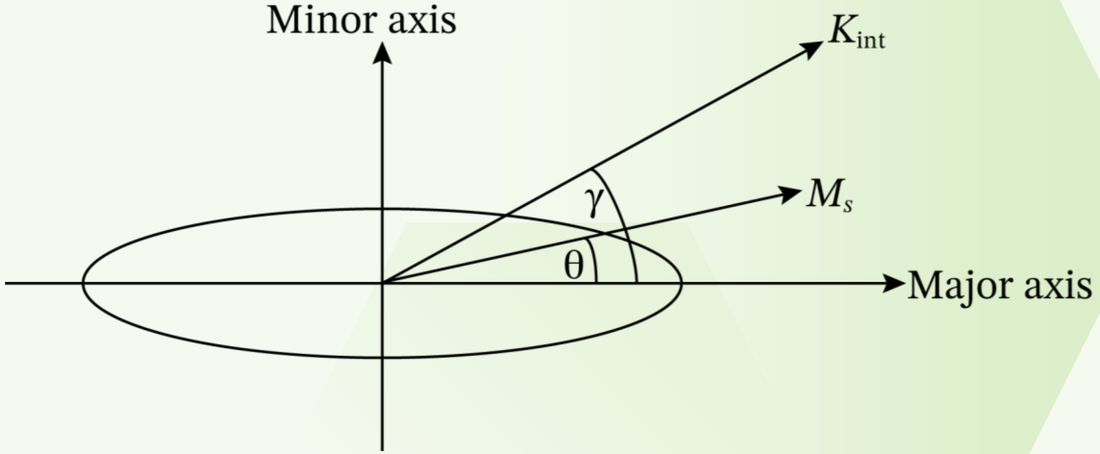
Balancing Shape and Growth Anisotropies

$$E = K_g \sin^2(\alpha - \theta) + K_s \sin^2(\beta - \theta)$$



The Resulting Equilibrium

$$E = K_{int} \sin^2(\gamma - \theta)$$



Multi-Functional Flexible Planar Hall Effect Sensors:
Essential Steps for Realization

- ☑ Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?
- ☑ Is it feasible to fabricate a device that meets these requirements?
- ☐ What is the expected strain-gauge resolution for such a device?

Multi-Functional Flexible Planar Hall Effect Sensors: Expected Strain Gauge Resolution

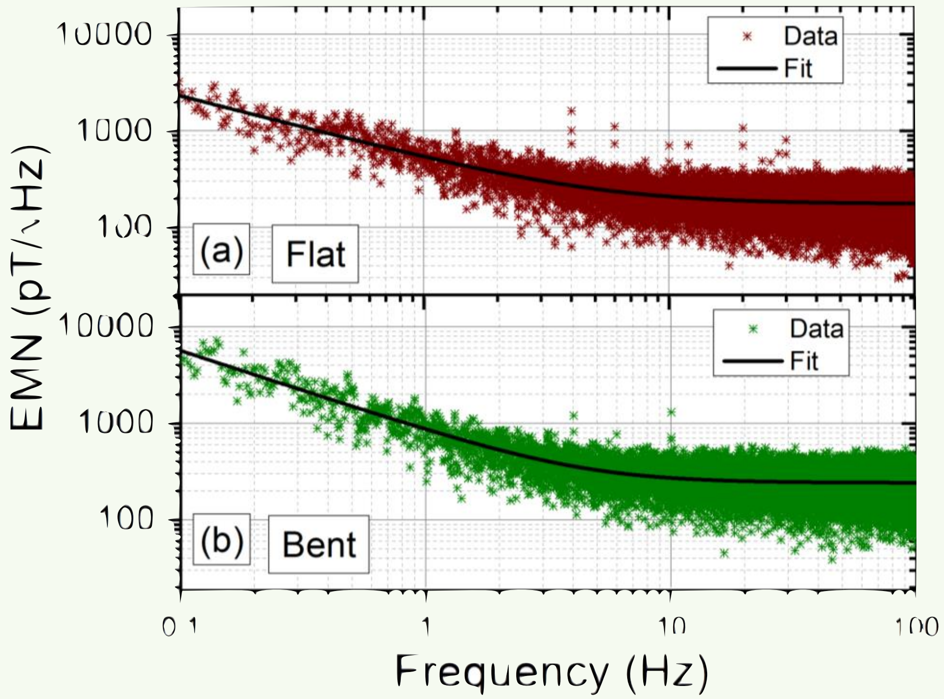
$\Delta\theta = \kappa \cdot \Delta\varepsilon$

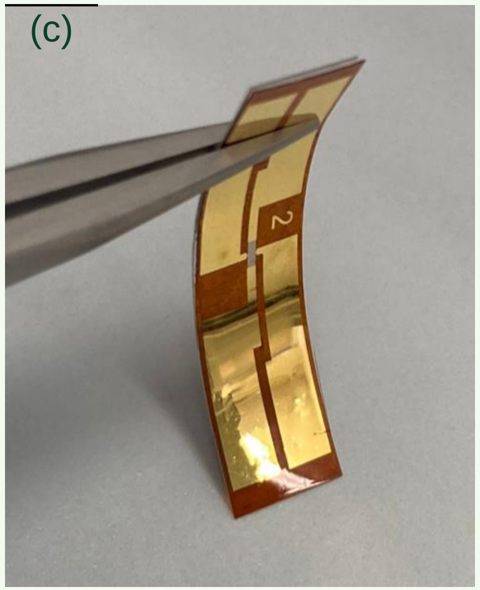
$\Delta V = \lambda \cdot \Delta\theta$

$$\Delta\varepsilon = \frac{\Delta V}{\lambda \cdot \kappa}$$

$$\varepsilon_{\min} = \frac{\Delta V_{\min}}{\lambda \cdot \kappa}$$

$$B_{\min} = \frac{\Delta V_{\min}}{S_y}$$





Minimum detectable strain

$$\varepsilon_{\min} \approx 2 \cdot 10^{-8}$$

Multi-Functional Flexible Planar Hall Effect Sensors:
Essential Steps for Realization

- ☑ Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?
- ☑ Is it feasible to fabricate a device that meets these requirements?
- ☑ What is the expected strain-gauge resolution for such a device?

Conclusions

- **Multi-Functional Capability:** Our flexible EPHE sensors go beyond magnetic field detection, demonstrating their ability to act as strain gauges capable of detecting micro-strain with exceptional sensitivity.

Thank you!