Multi-Functional Flexible Planar Hall Effect Sensors

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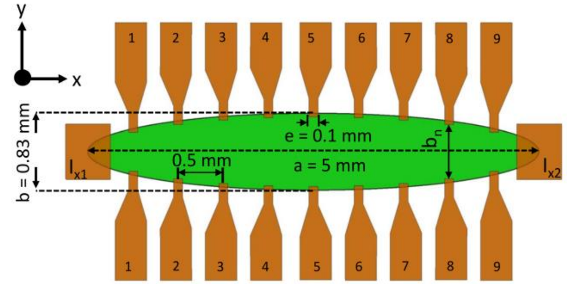
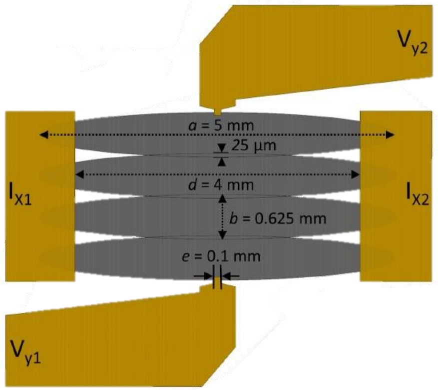
Planar Hall Effect Sensors

Configurations and Best Magnetic 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

<u>Potential Areas of Applications:</u>

- **Automotive Industry**: Ideal for applications requiring a dynamic range exceeding 100 Oe, with expected resolutions in the nano-tesla range, making it suitable for advanced vehicle technologies.
- **Lab-on-Chip Systems**: Published studies highlight the superior performance of PHE sensors compared to previously utilized xMR sensors, offering enhanced capabilities for 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.

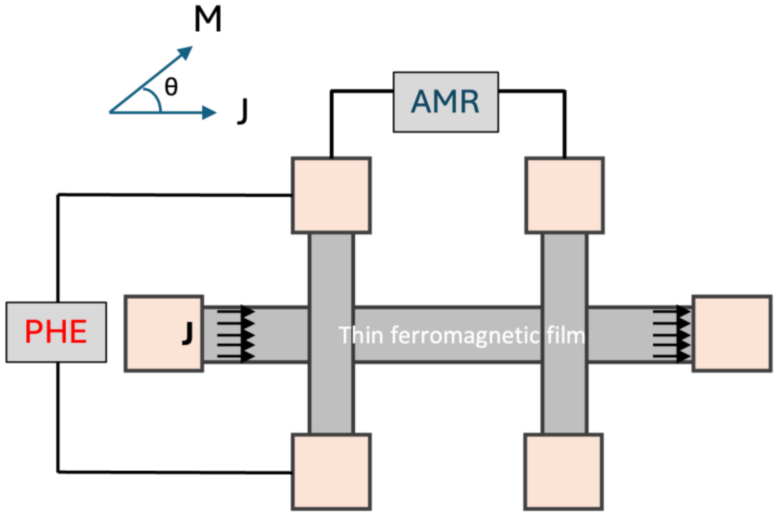

sensors MDPI

Article

Planar Hall Effect Magnetic Sensors with Extended Field Range

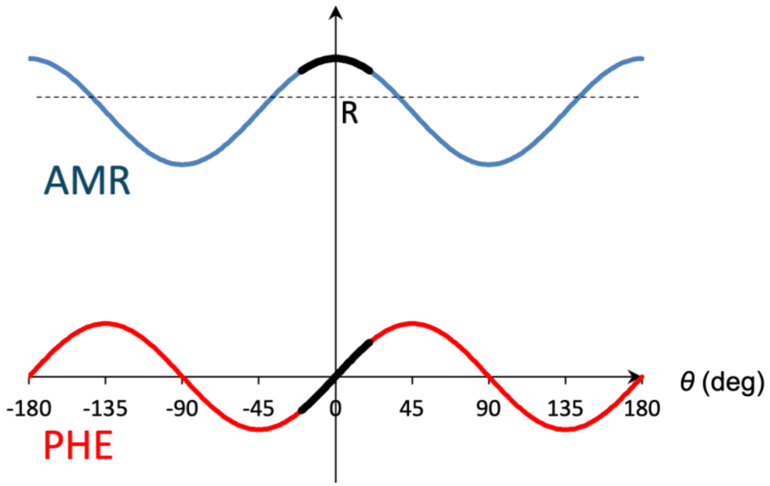
Daniel Lahav [1], Moty Schultz [1], Shai Amrusi [2], Asaf Grosz [2] and Lior Klein [1,*]

AMR and PHE



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

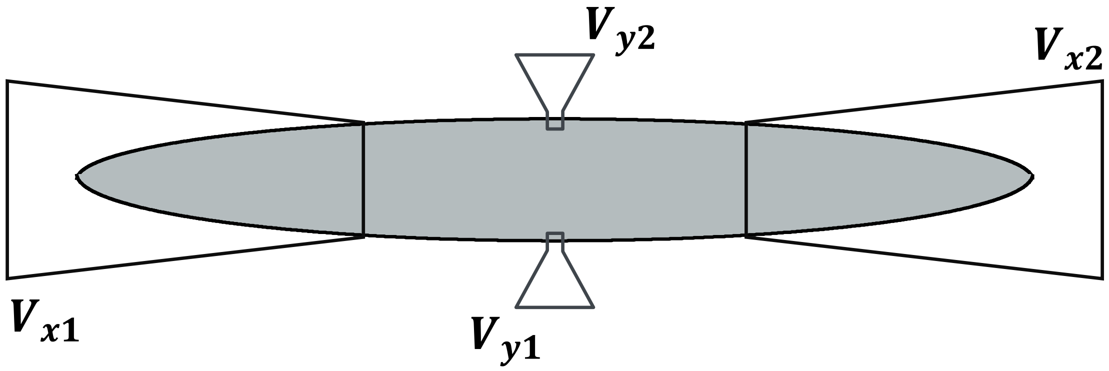
$$\rho_{xy} = 0.5 \cdot (\rho_{\parallel} - \rho_{\perp}) \sin 2\theta$$



Elliptical PHE Sensors

<u>Why Elliptical?</u>

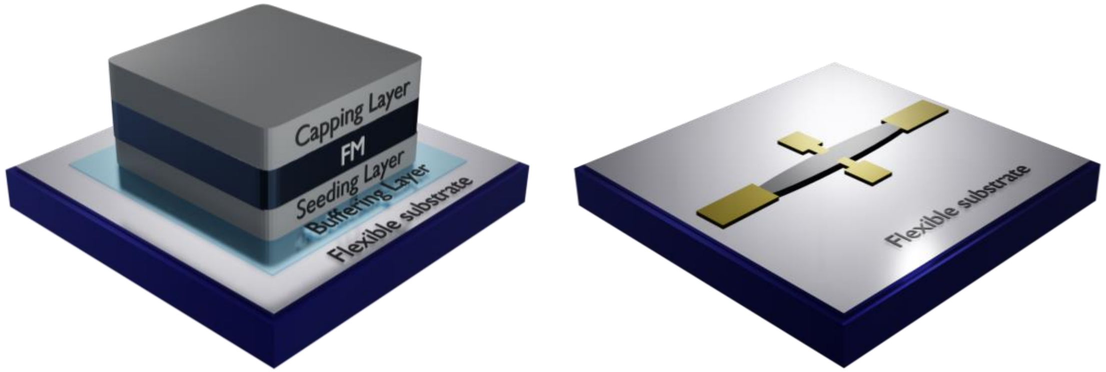
- Stable uniform magnetization (shape anisotropy).
- Low anisotropy fields (higher signal).



Flexible EPHE Sensors

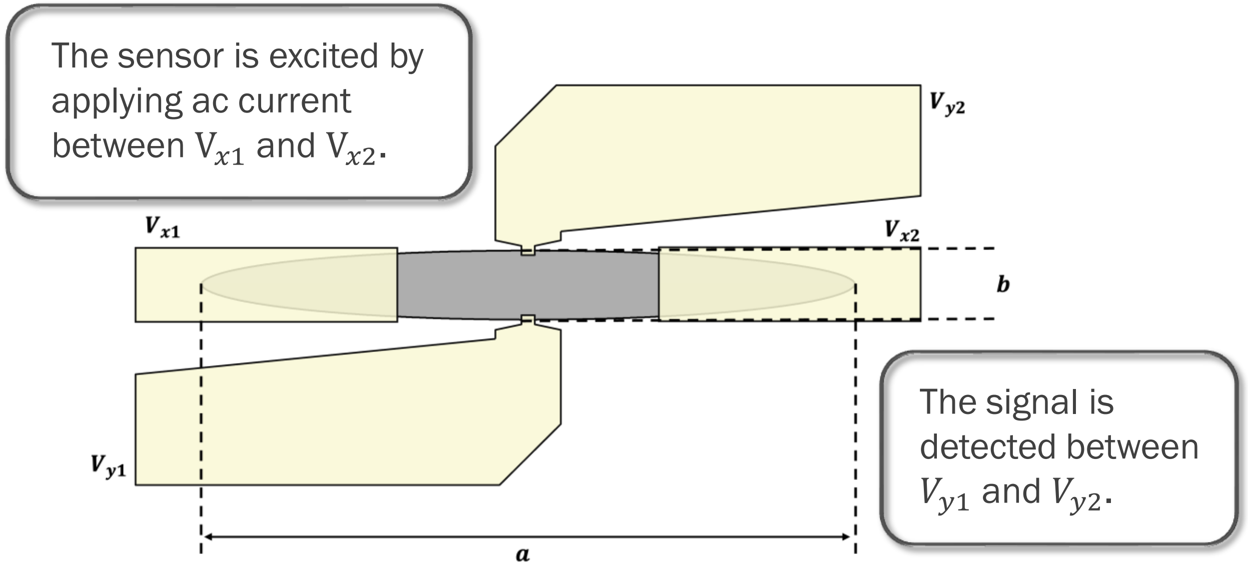
Materials and Layer Stack

- **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.

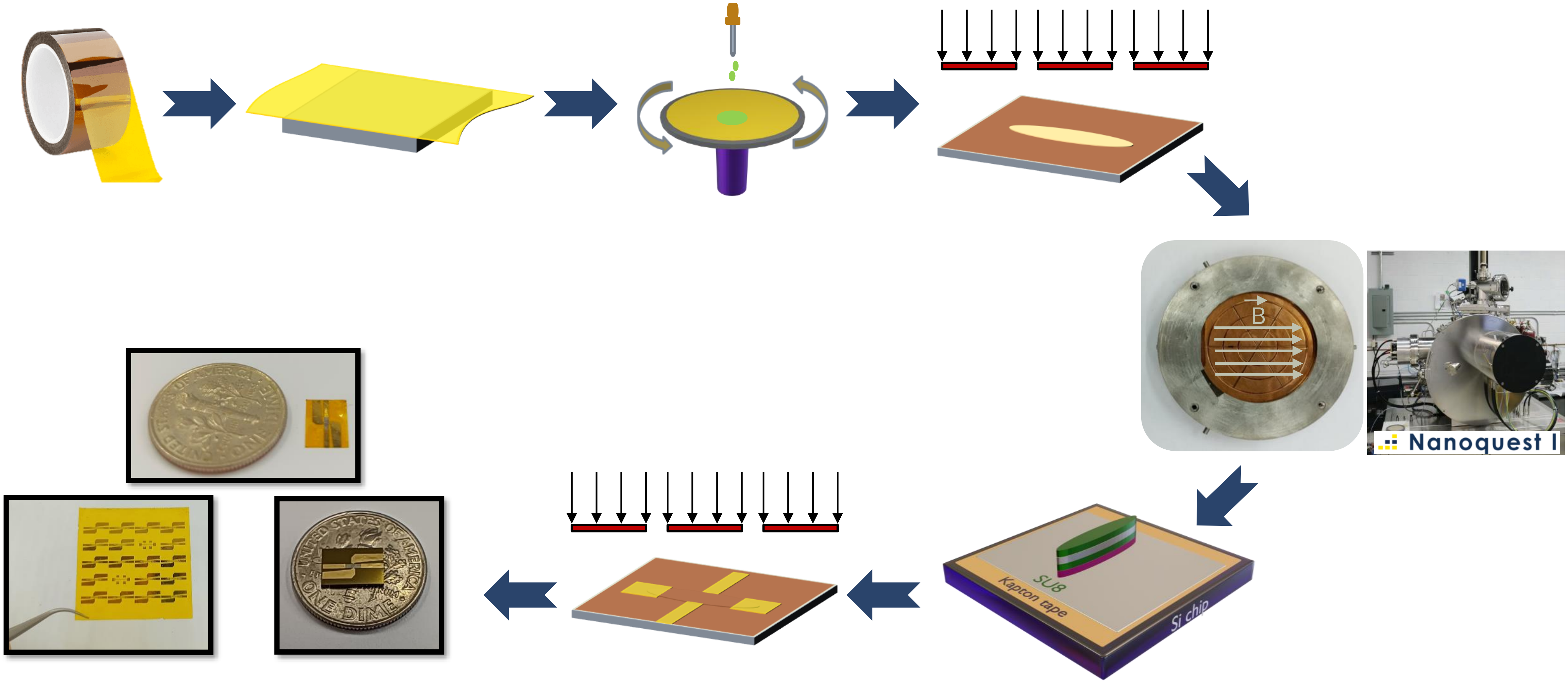


Device Design

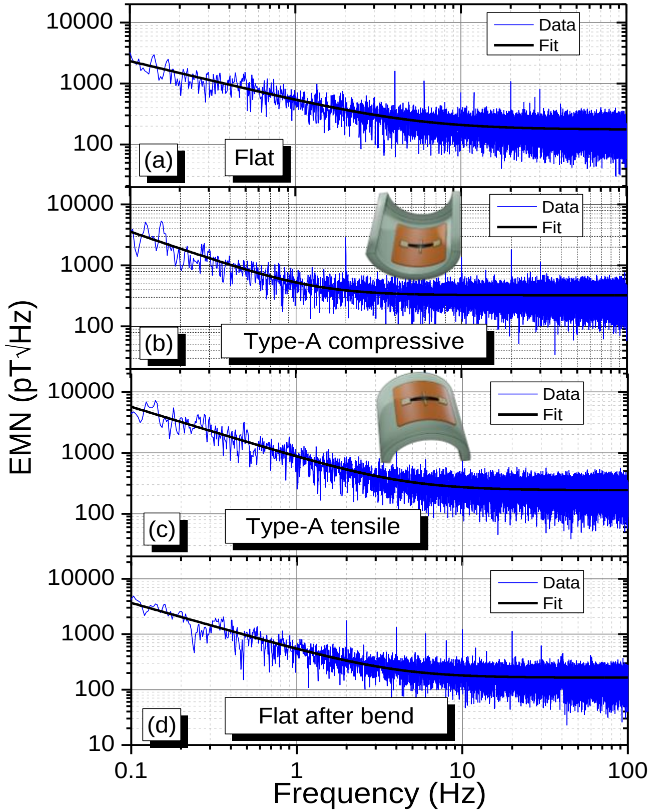
- Elliptical PHE sensor - aspect ratio 1:8.
  - Major axis (a) – $5\ mm$.
  - Minor axis (b) – $625\mu m$.
- Flexible substrate thickness – $125\ \mu m$.



Fabrication Process

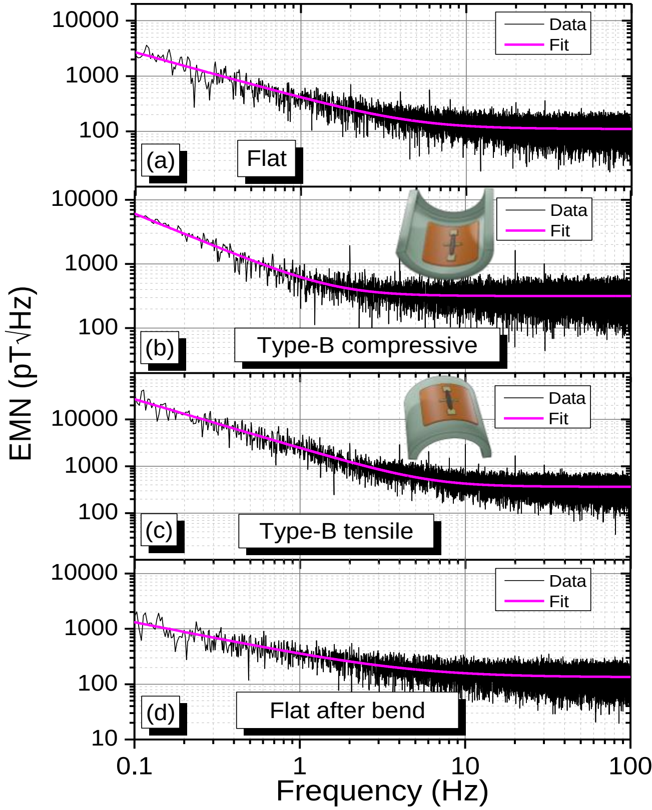


Sub-200 pT Resolution of Flexible EPHE Sensors



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

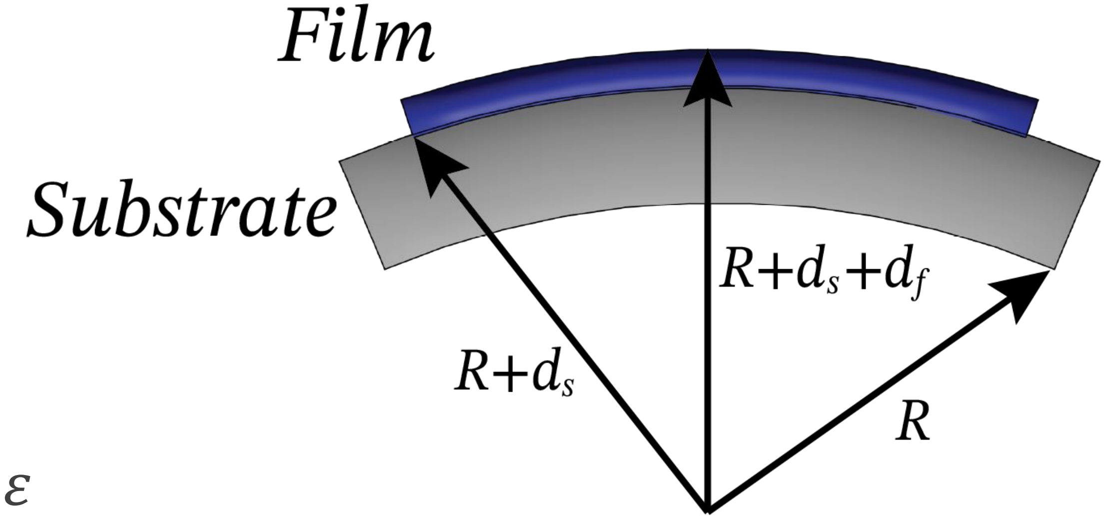
Among the best reported values for flexible magnetic sensors.



Flexible EPHE Sensors Under Bending Conditions

Strain Anisotropy

$$\varepsilon = \frac{d_f + d_s}{2R}$$



Strain anisotropy constant:

$$K_\sigma = \frac{3}{2}\frac{Y_f \lambda_s}{1-\nu^2}\varepsilon$$

Strain anisotropy field:

$$H_\sigma = \frac{2K_\sigma}{M_s} = \frac{3Y_f \lambda_s}{(1-\nu^2)M_s}\varepsilon$$

Flexible EPHE Sensors Under Bending Conditions

The Effect of Bending on the Effective Anisotropy Field

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

$H_{\text{eff}}^{(\text{f})}$ → 7.8

$H_{\text{eff}}^{(\text{i})}$ → 7.2

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

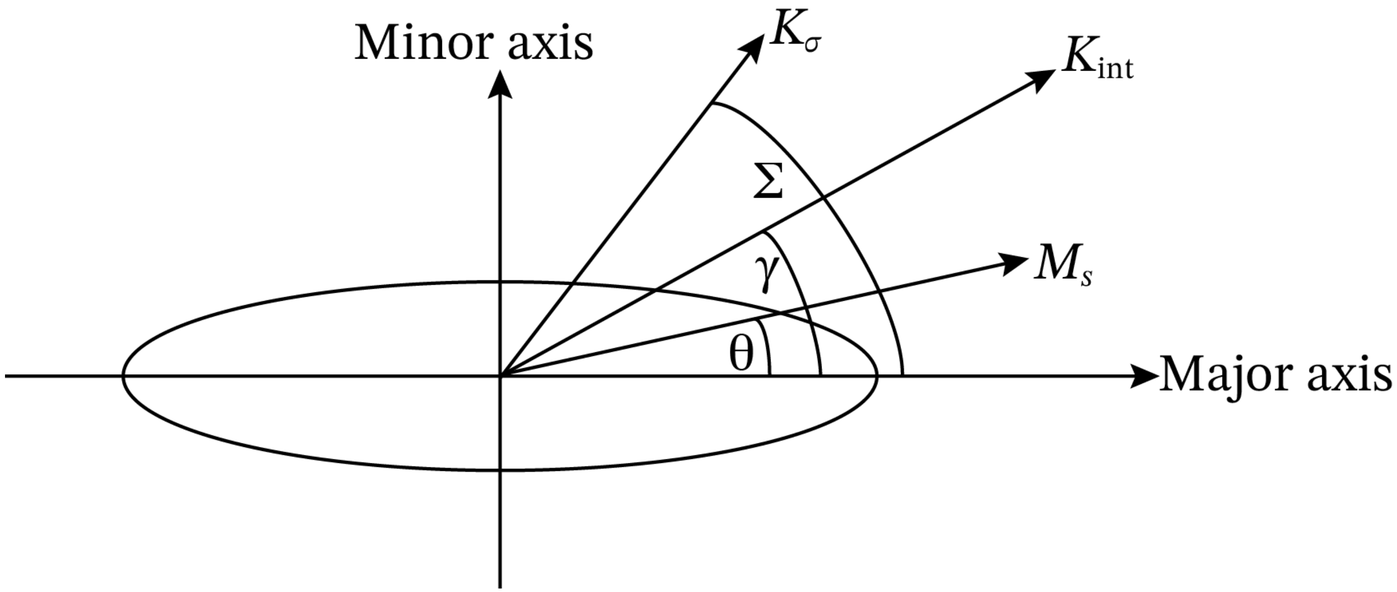
Flexible EPHE sensors can measure both magnetic fields and strains simultaneously **under the application of an external field.**

Multi-Functional Flexible EPHE Sensor

- Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?

Introducing a Tunable Anisotropy Landscape

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



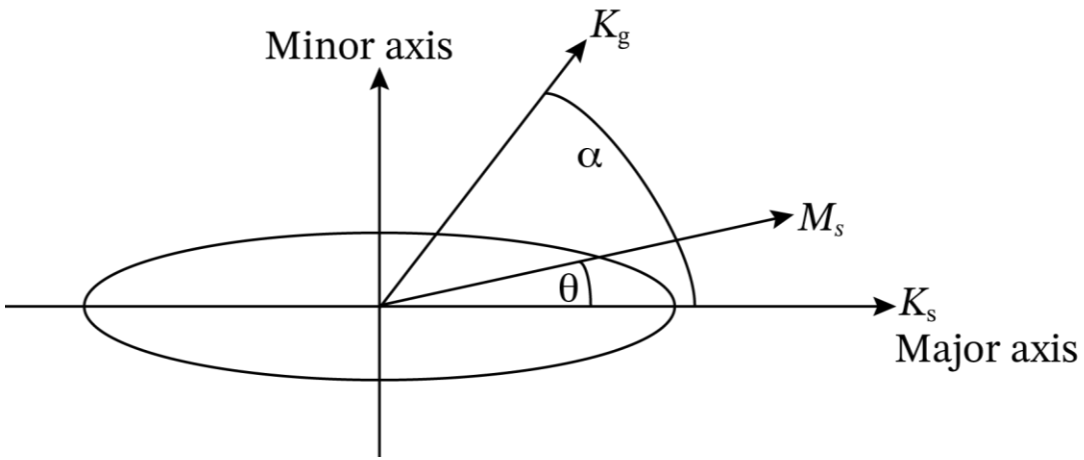
Multi-Functional Flexible EPHE Sensor

- ☑ 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?

Tuning the Easy Magnetization Direction

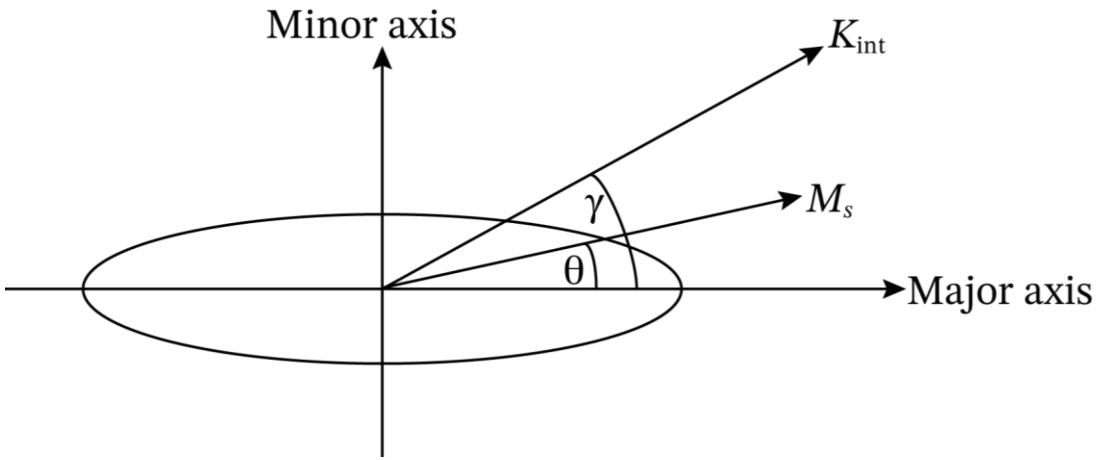
Balancing Shape and Growth Anisotropies

$$E = K_{\mathrm{g}} \sin^2(\alpha - \theta) + K_{\mathrm{s}} \sin^2(\beta - \theta)$$



The Resulting Equilibrium

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



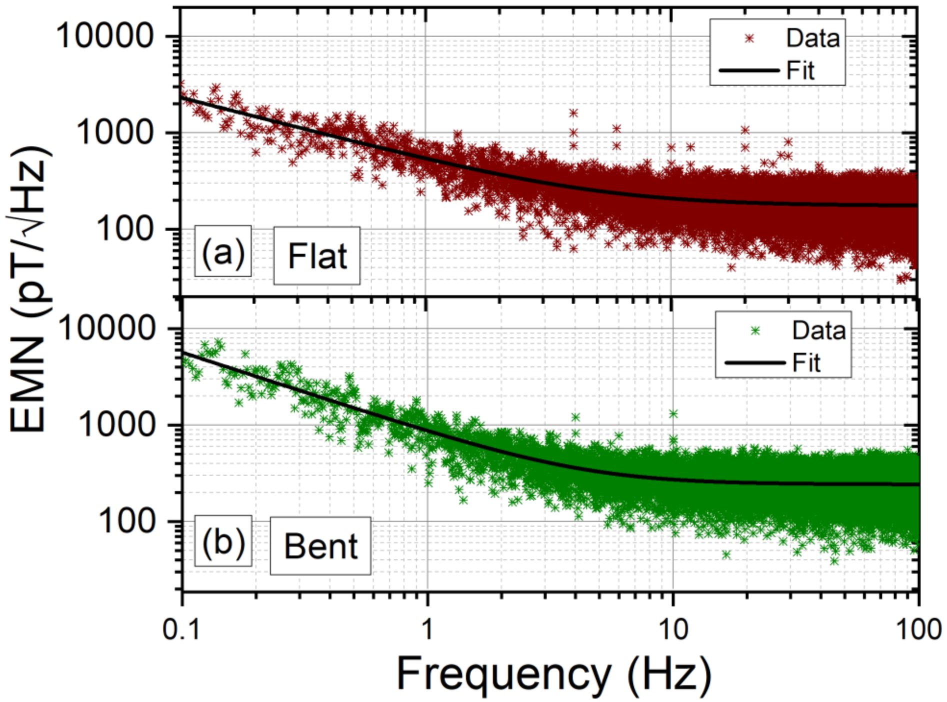
Multi-Functional Flexible EPHE Sensor

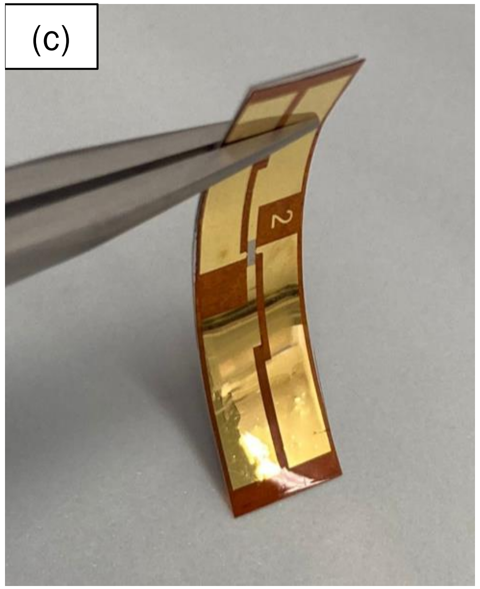
- ☑ Can minute strain be measured with a flexible EPHE sensor without the reliance on an external magnetic field?
- ☑ Is it feasible to fabricate a device that meets these requirements?
- ☐ What is the expected strain-gauge resolution for such a device?

Expected Strain Gauge Resolution

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

$$\Delta\varepsilon = \frac{\Delta V}{\lambda \cdot \kappa} \quad \varepsilon_{\min} = \frac{\Delta V_{\min}}{\lambda \cdot \kappa} \quad B_{\min} = \frac{\Delta V_{\min}}{S_y}$$





Minimum detectable strain

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

Multi-Functional Flexible EPHE Sensor

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- ☑ Is it feasible to fabricate a device that meets these requirements?
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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!

Sensitivity and Noise

Sensitivity

$$S_y = \frac{V_y}{\mathrm{H_y}} = \mathrm{I}_x \frac{\Delta\rho}{\mathrm{t}} \frac{1}{H_{\mathrm{eff}}}$$

Bias current

Resistivity anisotropy
($\Delta\rho = \rho_{\parallel} - \rho_{\perp}$)

Sensor thickness

Effective anisotropy

Equivalent magnetic noise (EMN)

$$\mathrm{EMN}(f) = \frac{e_{\Sigma}(f)}{S_y} = \frac{\sqrt{e_{1/f}^2 + e_T^2 + e_{amp}^2}}{\mathrm{I}_x \frac{\Delta\rho}{\mathrm{t}} \frac{1}{H_{\mathrm{eff}}}}$$

1/f noise

Thermal noise

Amplifier noise

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Strain anisotropy field:

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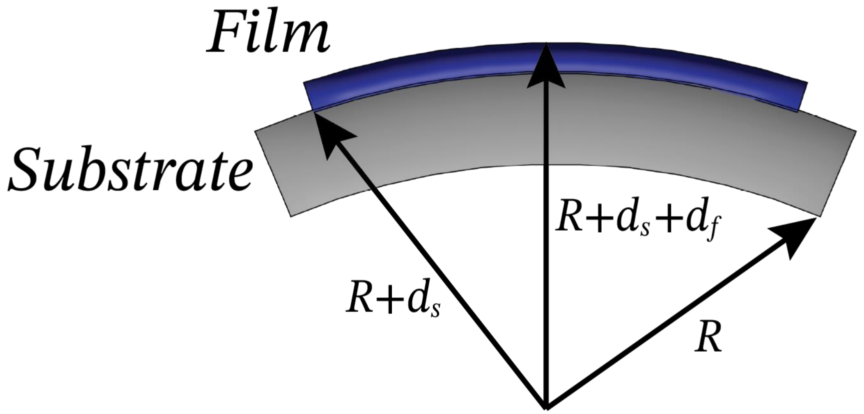


Anisotropy Landscape

The effective anisotropy (H_{eff}) represents the combined influence of the sensor's intrinsic properties and external effects.

- The intrinsic anisotropy (H_{int}) define the sensor's fundamental and stable anisotropic properties, which remain fixed after fabrication.
  - Shape anisotropy (H_{s}).
  - Growth-induced anisotropy (H_{g}).
- External effects - dynamically modify the anisotropy landscape during the sensor's operation.
  - Strain-Induced Anisotropy (H_σ).

$$E = K_{\text{s}} \sin^2 \vartheta + K_{\text{g}} \sin^2 \phi + K_\sigma \sin^2 \Sigma$$

$$\Downarrow$$

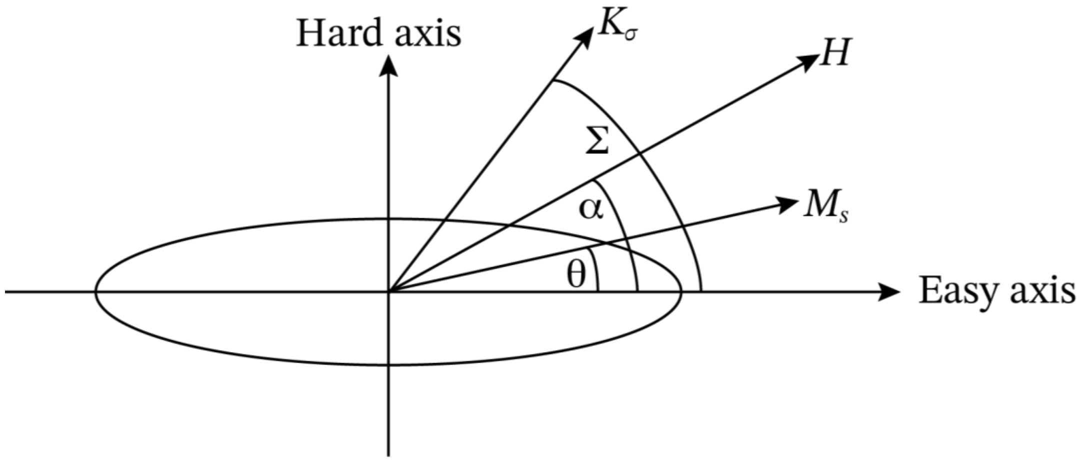
$$E = K_{\text{int}} \sin^2 \gamma + K_\sigma \sin^2 \Sigma$$

Flexible EPHE Sensors Under Bending Conditions

Modified Stoner-Wohlfarth model

- SW Model - A theoretical model describing the behavior of single domain particles under an external magnetic field.
- Modified SW Model - Incorporates both intrinsic MA and strain-induced anisotropy.

$$E = K_{\text{int}} \sin^2 \theta + K_\sigma \sin^2(\Sigma - \theta) - M_s H \cos(\alpha - \theta)$$



The effect of bending on the effective anisotropy field

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$H_{\text{eff}}^{(f)}$ $H_{\text{eff}}^{(i)}$

$$H_{\text{eff}}^{(i)} = H_{\text{int}}$$
$$H_{\text{eff}}^{(f)} = H_{\text{int}} + H_\sigma$$
$$\Longrightarrow \delta H = H_{\text{eff}}^{(f)} - H_{\text{eff}}^{(i)} = H_\sigma = \frac{3Y_f \lambda_s}{(1-\nu^2)M_s}\varepsilon$$

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

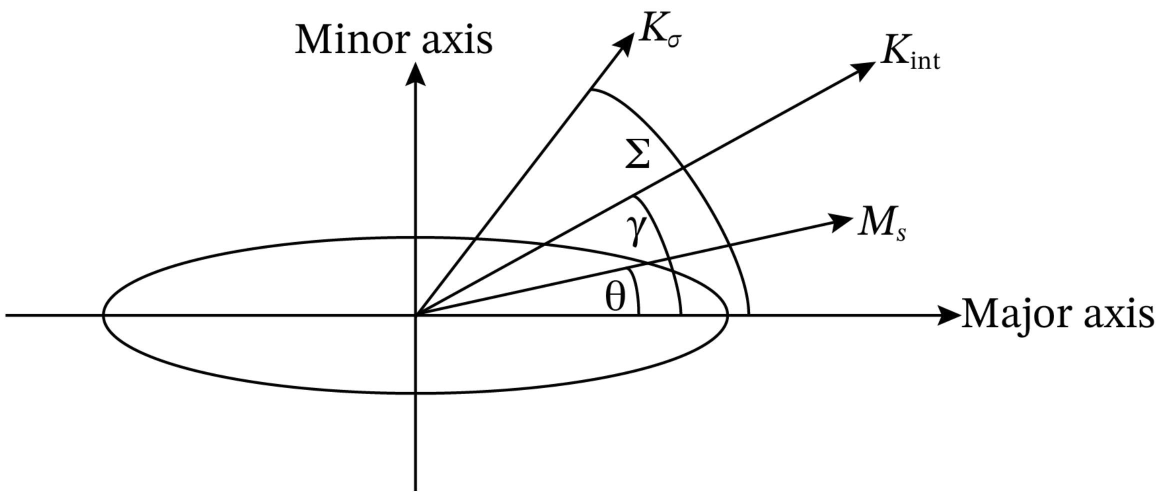
Introducing a Tunable Anisotropy Landscape

Energy Landscape and PHE signal:

- The total energy of the system is given by:

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

- Strain is applied solely along the principal axes ($\Sigma_1 = 0°$ and $\Sigma_2 = 90°$) to **maximize its impact on the anisotropy** landscape and ensure a **predictable**, **simplified** response.



Optimal angle for maximizing the PHE signal

- The PHE signal is proportional to $\sin 2\theta$, and the change in the signal due to strain is:

$$\Delta V_{\text{PHE}} \propto \left|\sin 2\theta_{\min,1} - \sin 2\theta_{\min,2}\right|$$

- To maximize ΔV_{PHE}, γ must be chosen such that the perturbation results in the largest relative shift between $\theta_{\min,1}$ and $\theta_{\min,2}$.

Through analysis, $\gamma = 22.5°$ is found to be the optimal angle for the intrinsic anisotropy.