Multi-Functional Flexible Planar Hall Effect Sensors

Department of Physics
Faculty of Exact Sciences
Bar-Ilan University

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

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

1 Introduction

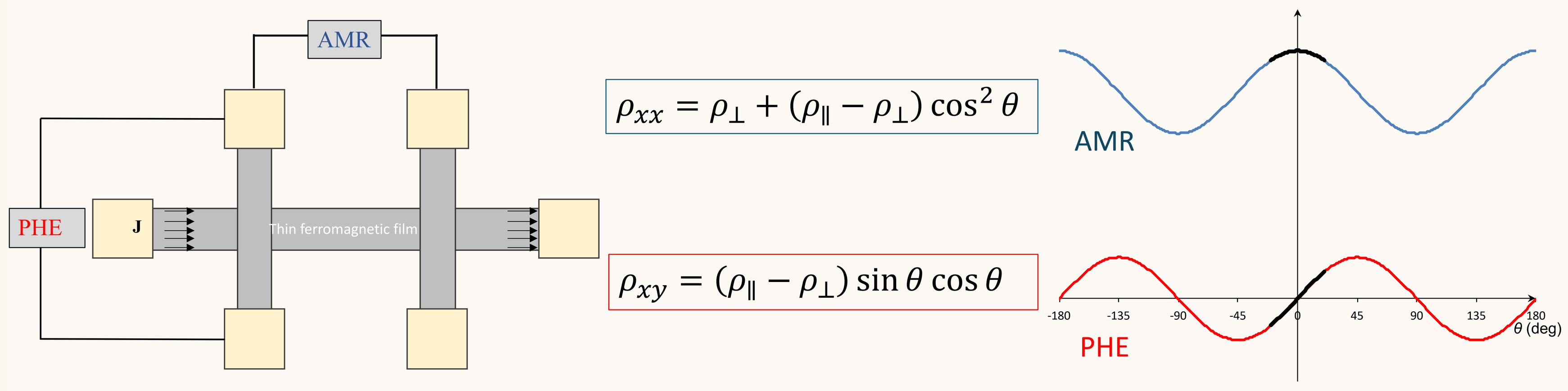
Magnetic sensors play a vital role in applications such as navigation, medical diagnostics, industrial automation, and consumer electronics. Among various magnetoresistive technologies, planar Hall effect (PHE) sensors are particularly notable for their ultra-low equivalent magnetic noise (EMN), simplicity, and cost-effectiveness.

Recent advancements in PHE sensors focus on enhancing their performance and versatility. While rigid elliptical PHE sensors have achieved exceptional EMN values, flexible versions demonstrate comparable performance in both flat and bent states, making them superior to other flexible magnetic sensors. Building on these developments, we explore the potential of flexible elliptical PHE sensors as multi-functional devices capable of measuring not only magnetic fields but also minute strains, broadening their applicability in diverse fields.

2 Fundamentals and Theory

Magnetoresistance

Ferromagnetic materials exhibit a phenomenon called anisotropic magnetoresistance (AMR), in which their resistance changes depending on the orientation of their magnetization (**M**) relative to the direction of an applied electric current density (***J***). This phenomenon gives rise to a transverse voltage as a function of the angle θ between **M** and **J**. This effect is called PHE as the magnetization, the electric current, and the transverse electric field are in the same plane.



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

$$\rho_{xy} = (\rho_\parallel - \rho_\perp)\sin\theta\cos\theta$$

Planar Hall Effect Sensors

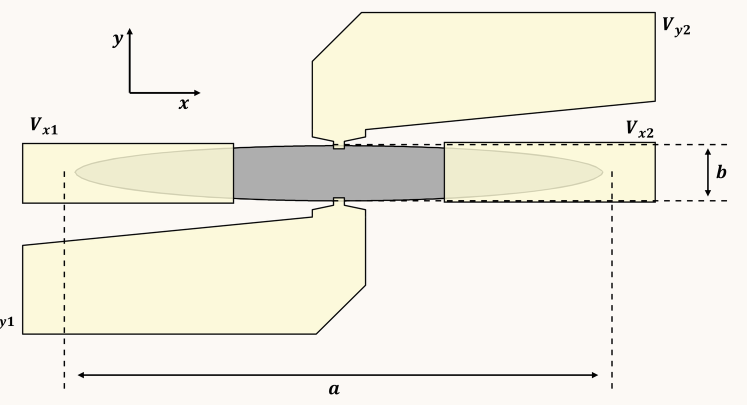
PHE sensors detect magnetic fields by measuring the transverse voltage, which depends on the angle between magnetization and current. Uniform magnetization with reversible behavior, ensured by aligning magnetic anisotropy parallel to the current, is essential for optimal performance.

Elliptical Planar Hall Effect Sensors

The elliptical shape of PHE sensors induces uniaxial 'shape anisotropy' along the long axis, referred to as the easy axis (EA). For a flat ellipsoid with thickness *t*, major axis *a*, and minor axis *b*, the anisotropy field (H_s) is:

$$H_s \sim 4\pi M_s \frac{t}{b} \sim 10807\frac{t}{b}$$

A schematic of the sensor showing the major (*a*) and minor (*b*) axes of the ellipse and the gold contact pads (yellow).



The sensor is excited with an ac current between V_{x1} and V_{x2}, and the signal is measured at V_{y1} and V_{y2}.

Mechanics of Bendings

Strain-Induced Anisotropy

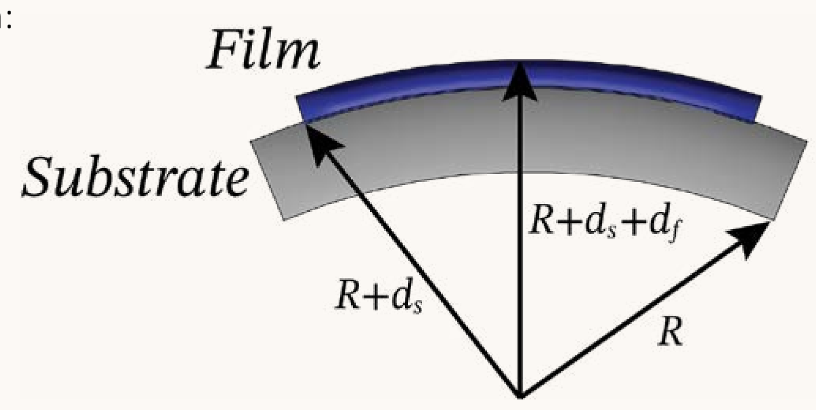
Strain-induced anisotropy arises in ferromagnetic materials when mechanical stress alters the magnetic energy landscape, shifting the magnetic easy axis and modifying the magnetic anisotropy (MA) energy.

The strain induced in the film:

$$\varepsilon = \left(\frac{d_f + d_s}{2R}\right)$$

The stress in the film:

$$\sigma = \frac{\varepsilon Y}{1-\nu^2}$$



Strain anisotropy constant:

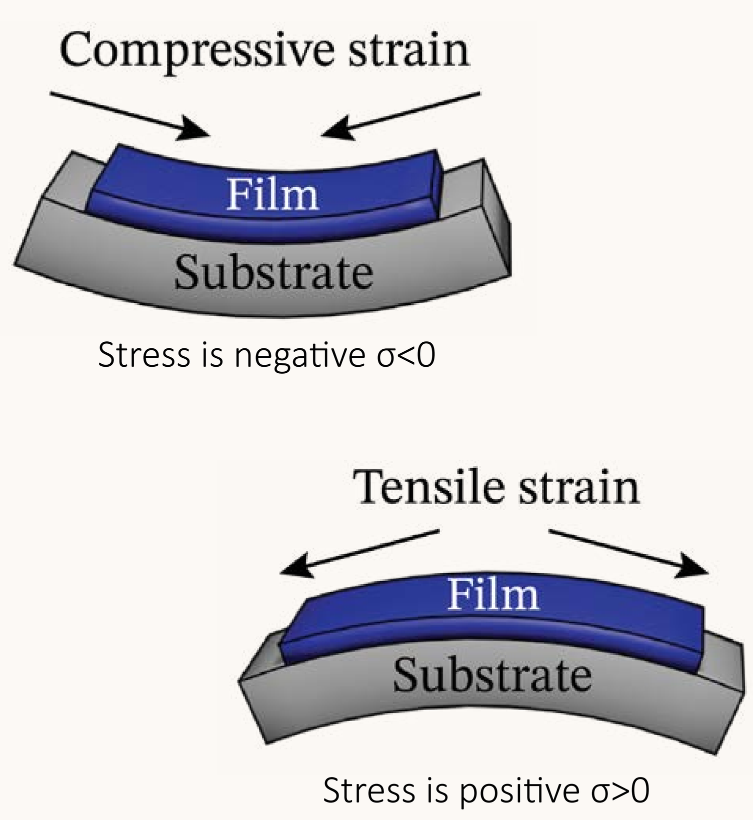
$$K_\sigma = \frac{3}{2}\frac{Y_f\lambda_s}{1-\nu^2}\varepsilon$$

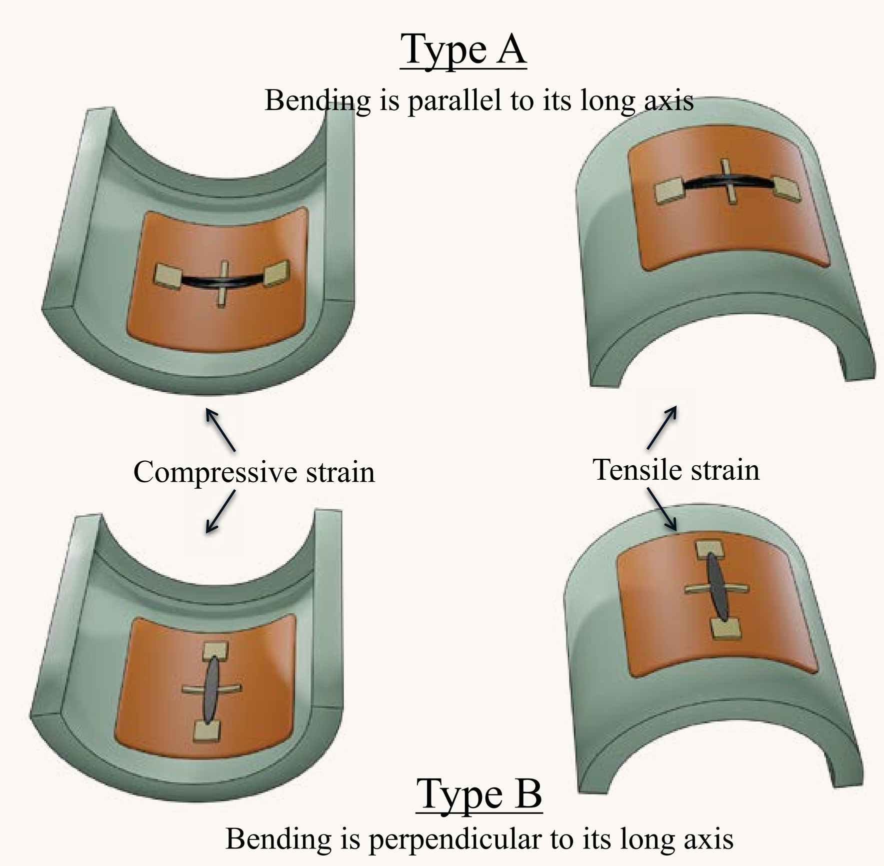
Strain anisotropy field:

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

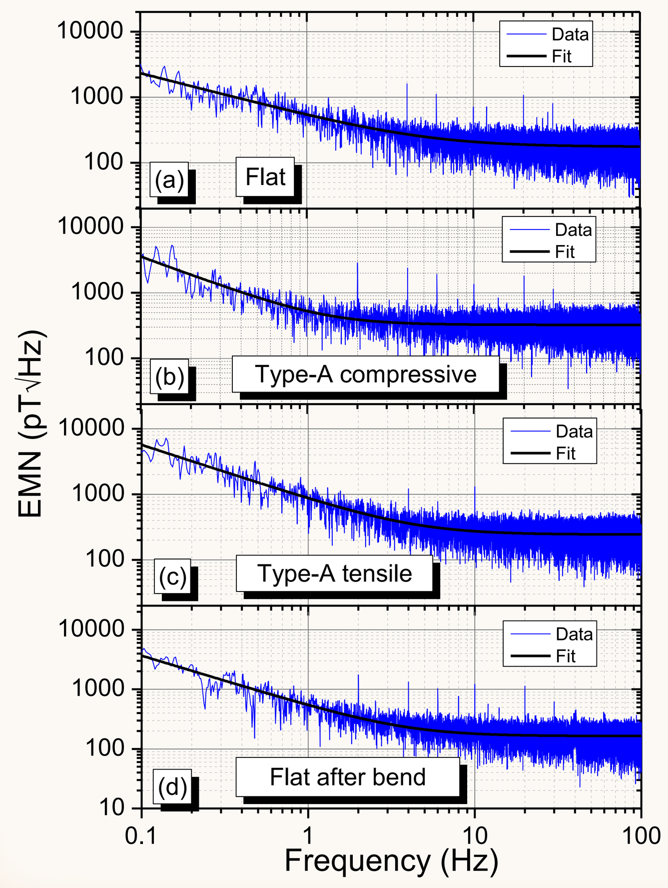
Bending Configurations

Bending inward (compressive) or outward (tensile) induces strain in flexible sensors, with Type-A bending applying strain parallel to the EA and Type-B bending applying strain perpendicular to it, each affecting the magnetic anisotropy and response differently.





3 Sub-200 pT Resolution Sensors



The figure illustrates the EMN across different bending modes, with an excitation current of 40 mApp, close to the sensor's maximum limit before heating impacts EMN performance.

The data, fitted over the frequency range of 0.1 Hz to 100 Hz using the reveals impressively low EMN values—under 200 pT/√Hz in the flat state and below 400 pT/√Hz in the bent state—outperforming many reported flexible and rigid magnetic sensors.

Mode	100 Hz ($pT/\sqrt{Hz}$)	10 Hz ($pT/\sqrt{Hz}$)	1 Hz ($pT/\sqrt{Hz}$)
Flat	177	209	544
Type-A compressive	244	273	876
Type-A tensile	323	327	524
Flat after-bent	164	179	547
Flat	111	125	414
Type-B compressive	317	320	628
Type-B tensile	365	426	2467
Flat after-bent	134	157	358

The accompanying table summarizes typical EMN values for 40 mApp at 0.1, 1, 10, and 100 Hz, with an error margin below 2%. These results highlight the sensor's exceptional performance and stability under various conditions.

4 Multi-Functional PHE Sensors

- Can minute strain be measured with a flexible EPHE sensor without relying 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?

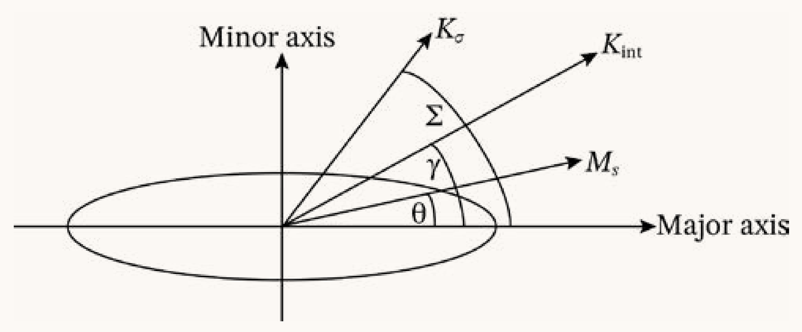
Introducing a Tunable Anisotropy Landscape

Energy Landscape

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 along principal axes (Σ_1=0°, Σ_2=90°) to maximize impact on anisotropy and ensure a predictable response.



Optimal Angle for PHE Signal

The PHE signal is proportional to sin²θ, and the change in the signal due to strain is:

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

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, γ=22.5° is found to be the optimal angle for the intrinsic anisotropy.

Tuning the Easy Magnetization Direction

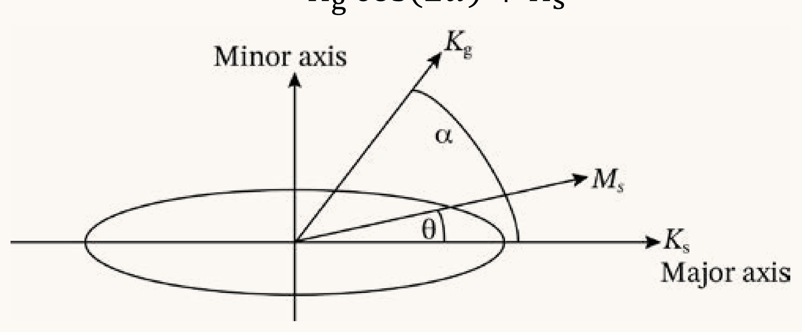
Balancing Anisotropy Contributions

The combined anisotropy energy takes the form:

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

The intrinsic anisotropy direction (γ) is determined by minimizing the total energy and is expressed as:

$$\tan(2\gamma) = \frac{K_g\sin(2\alpha)}{K_g\cos(2\alpha) + K_s}$$



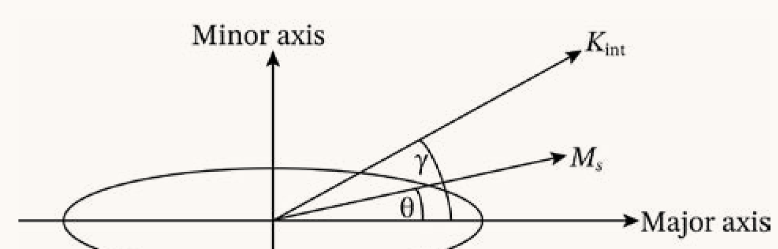
The Resulting Equilibrium

The intrinsic anisotropy energy follows the expression:

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

where:

$$K_{\text{int}} = \sqrt{K_s^2 + K_g^2 + 2K_gK_s\cos(2\alpha)}$$



Expected Strain Gauge Resolution

The multi-functional flexible EPHE sensor demonstrates an outstanding minimum detectable strain of around ε_{min} ≈2·10⁻⁸, highlighting its remarkable sensitivity for precision measurements.

The expected strain gauge resolution, representing the minimum detectable strain (ε_{min}), is determined through the following steps:

1. Minimization of the Energy: The energy minimization process determines the angular change Δθ. Where:
$$\Delta\theta = \theta_{\text{min}}^{(f)} - \theta_{\text{min}}^{(i)}$$
2. Calculation of Δε: Using the known relationships between the strain (ε) and angular changes, the coupling coefficient (κ) is calculated using:
$$\Delta\theta = \kappa \cdot \Delta\varepsilon$$
3. Determination of λ: The sensitivity constant λ is derived, which quantifies the change in the PHE signal with respect to magnetization rotation.
$$\lambda = \frac{\partial V_{\text{PHE}}}{\partial\theta}$$
4. Extraction of ΔV_{min} min: The smallest detectable change in the PHE voltage (ΔV_{min}) is determined from experimental data previously published in our work.
5. Resolution Calculation: The expected minimum detectable strain is calculated using
$$\Delta\varepsilon = \frac{\Delta V}{\lambda\cdot\kappa} \Longrightarrow \varepsilon_{\text{min}} = \frac{\Delta V_{\text{min}}}{\lambda\cdot\kappa}$$