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Motivation

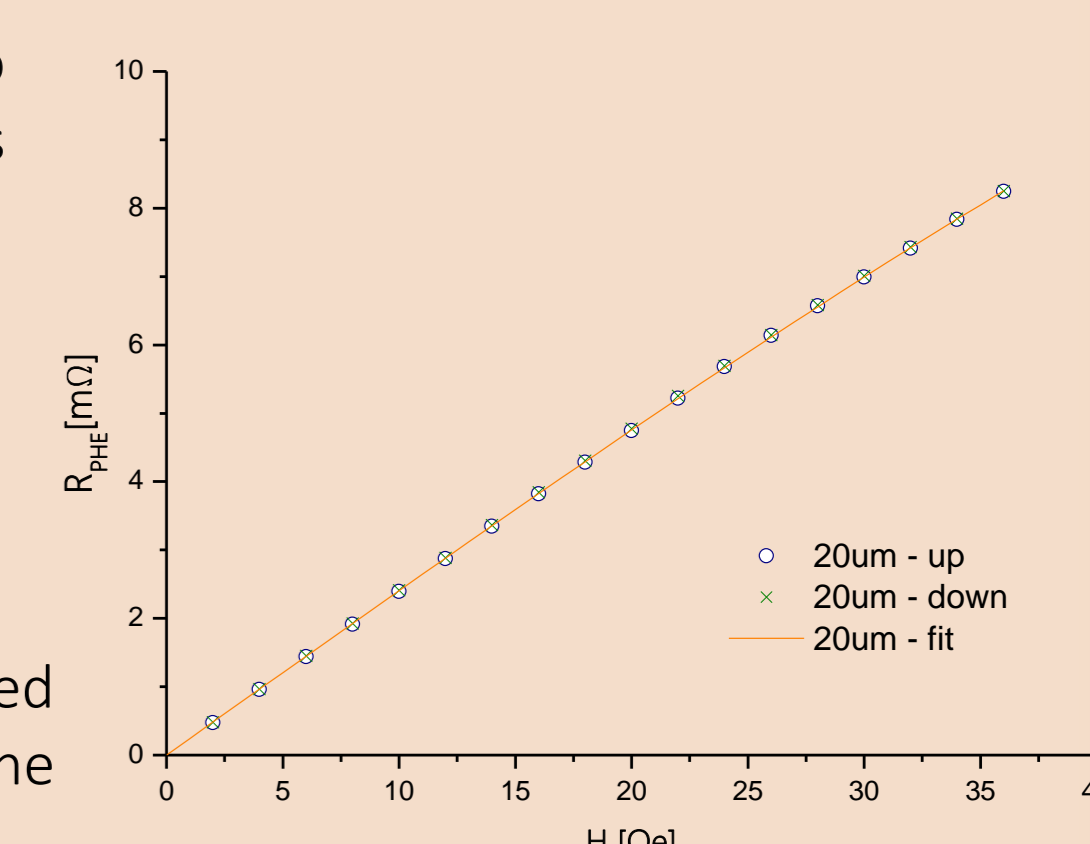
- Magnetic field sensing plays a pivotal role in numerous technological applications, including automotive, biomedical diagnostics and more.
- Among the magnetic sensors, planar Hall effect (PHE) sensors offer advantages such as superior performance compared to other sensors, simpler fabrication, high resolution, and low temperature dependence.
- However, the operational magnetic field range of high resolution PHE sensors is typically on the order of hundreds of micro Tesla, which is a limiting factor for important applications.

A need for range

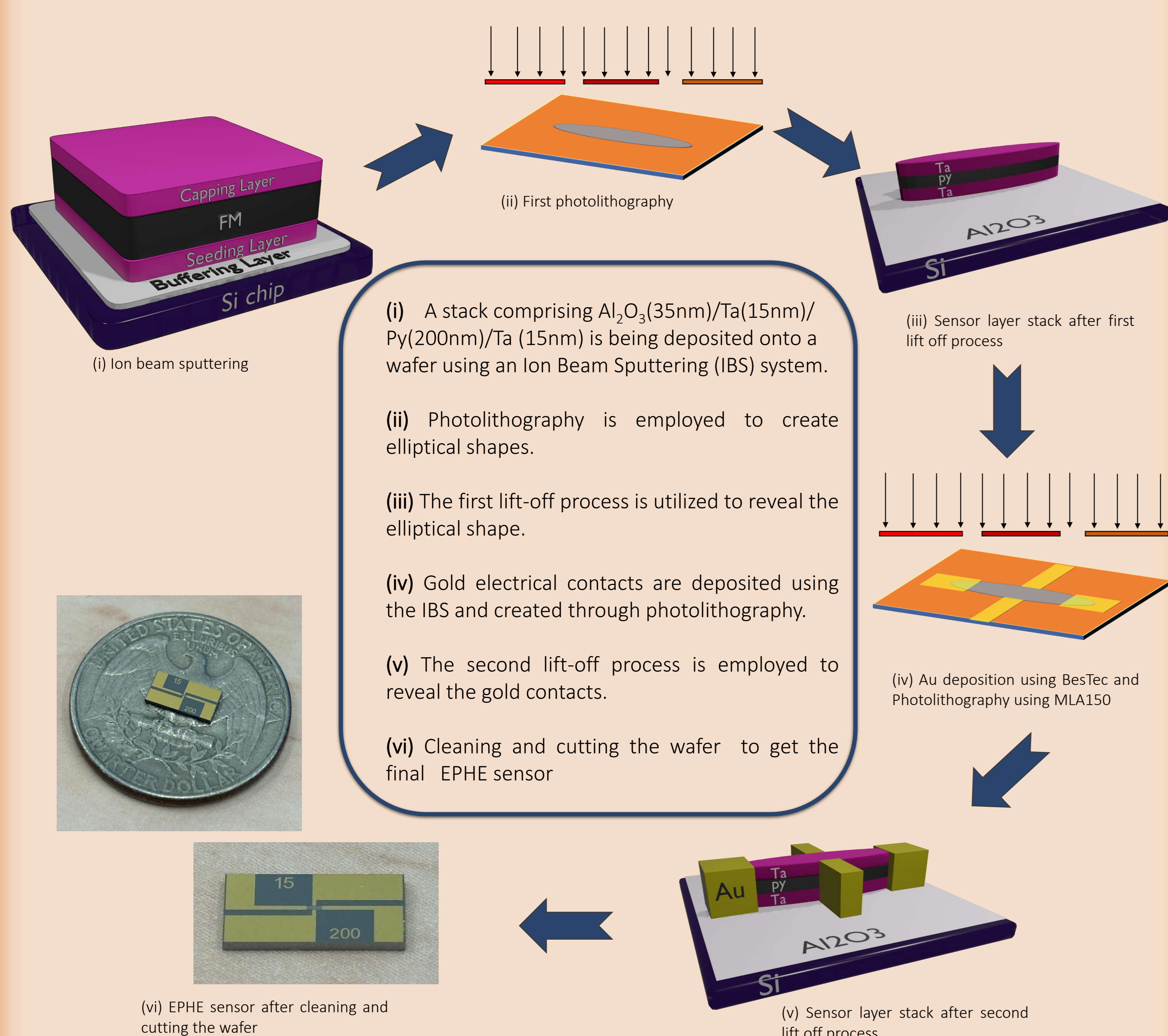
To address the growing need for sensitive magnetic sensors capable of accurately measuring a wide range of magnetic field strengths in various industrial, scientific, and consumer applications, it is important to extend the field range of PHE sensors and study the effect of such extension on their resolution.

PHE sensor with extended range

- By decreasing the short axis from 200 microns to 20 microns, the magnetic anisotropy field increases from ~12 Oe to ~120 Oe.
- The resolution values of EPHE sensors with extended field range are better than the resolutions reported for widely used sensors with the same field range.
- We successfully fabricated sensors with an extended field range that maintains its linearity even under the influence of large magnetic fields.



Fabrication Process



Results

As depicted in the table, by reducing the dimension of the hard axis, b (while maintaining a constant aspect ratio of $a:b$), from 200 microns to 20 microns while keeping the current density constant, the following achievements were observed:

- An expansion in the field range by a factor of 10.
- Sensitivity approximately 100 times lower.

b [μm]	I [mA]	H_{eff} [Oe]	Sensitivity [V/T]	ΔR_{PHE} [m Ω]	R_x [Ω]	R_y [Ω]
20	3	124.8	8.72	29	8.9	35.6
50	7.5	43.5	57.1	26	7	20.7
100	15	23.8	197	25	5.6	14.4
200	30	13.5	735	26	5.1	9.8

Typical values of H_{eff} , S_y , ΔR_{PHE} , R_x , and R_y for EPHE sensors with varying hard axis lengths, while maintaining uniform current density.

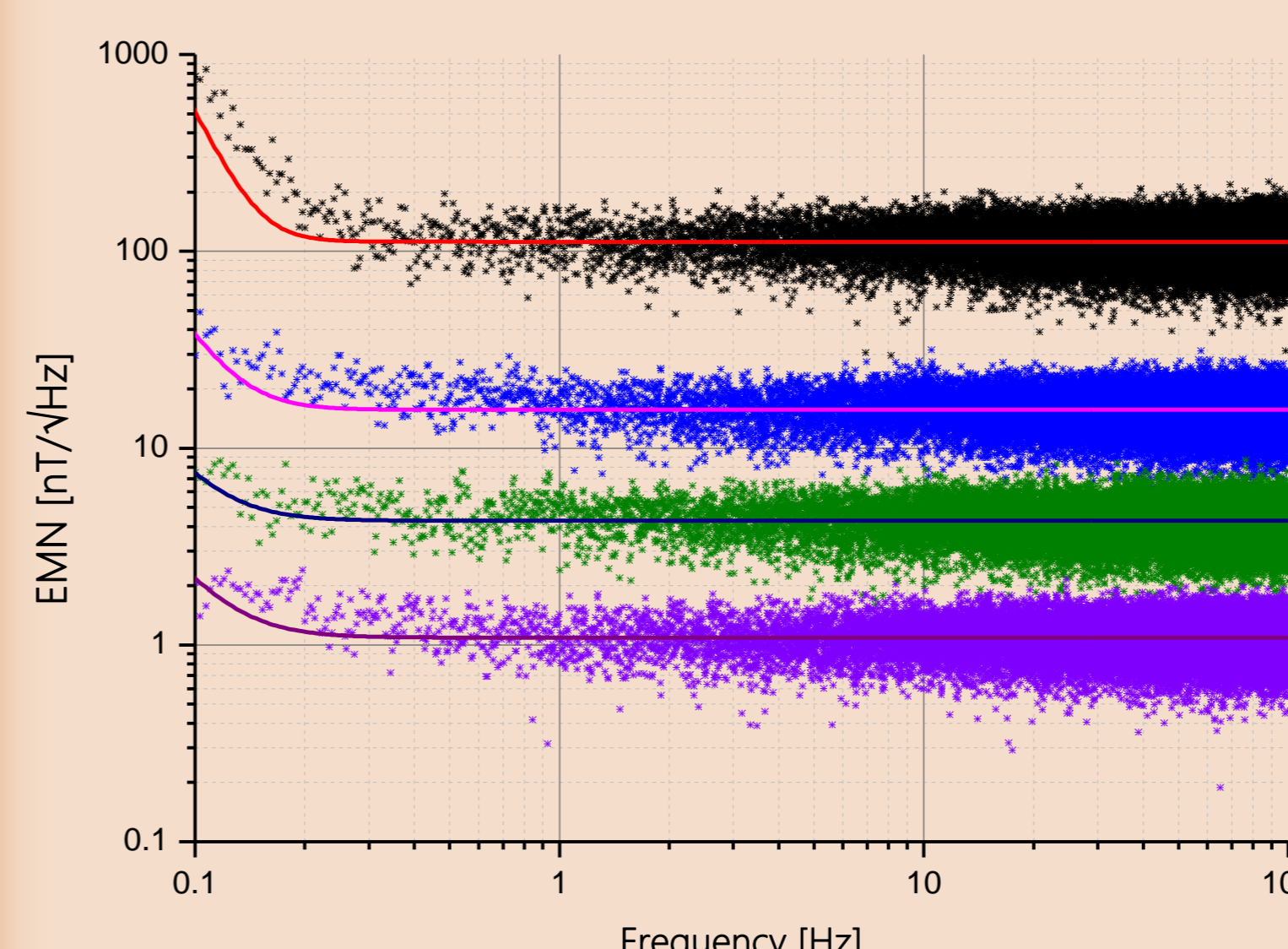


Figure 1. Equivalent magnetic noise (EMN) of the PHE sensors versus frequency for different hard axis (b) values, with the same current density.

Figure 2 showcases the EMN variation for sensors with hard axes of 20 and 50 microns, utilizing excitation currents of 6 and 15 mA, respectively. At 1 Hz, the 20-micron sensor achieved an EMN of $80 \text{ nT}/\sqrt{\text{Hz}}$ at 1Hz.

Notably, the EMN of a sensor with a hard axis length of 20 microns surpasses the resolution reported for regular Hall effect sensors, which are widely used in industrial applications.

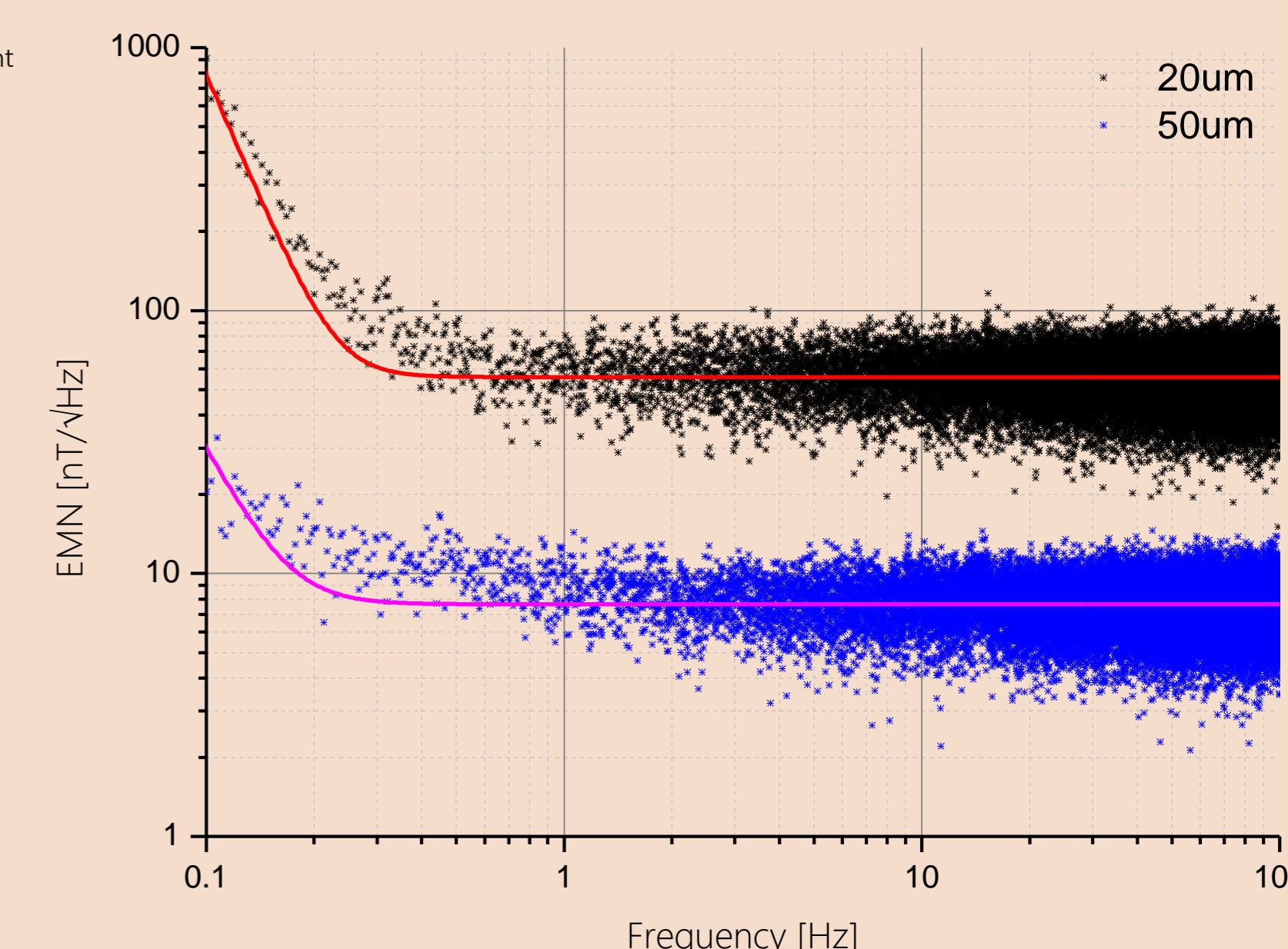
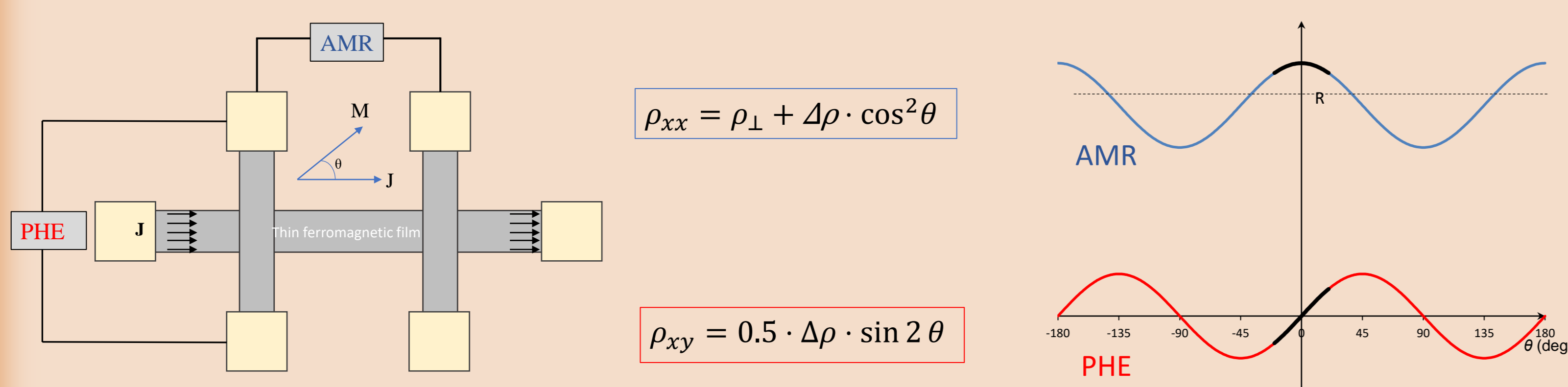


Figure 2. Equivalent magnetic noise (EMN) of PHE sensors with hard axes at 20 and 50 microns across varying frequencies, employing maximum excitation current.

Theoretical Background and Design

Planar Hall effect (PHE)

Ferromagnetic materials exhibit a phenomenon called anisotropic magnetoresistance (AMR), in which their resistance changes depending on the orientation of their magnetization \vec{M} relative to the direction of an applied electric current density \vec{J} . The AMR yields a transverse Hall like voltage, if \vec{J} is neither parallel nor perpendicular to \vec{M} . This effect is called the planar Hall effect (PHE) as the magnetization, the electric current, and the transverse electric field are in the same plane.



Sensitivity

The sensitivity (S_y) of a PHE sensor is defined as the ratio between the PHE voltage V_y and the applied magnetic field \vec{H} when the applied field is perpendicular to the easy axis.

$$S_y = \frac{V_y}{H} = I_x \frac{\Delta\rho}{t} \frac{1}{H_s + H_g} = I_x \frac{\Delta\rho}{t} \frac{1}{H_{eff}}$$

Excitation current Sensor thickness Shape anisotropy Growth anisotropy

Equivalent magnetic noise (EMN)

The total noise, e_{Σ} , has three main components: $1/f$ noise, thermal noise, and preamplifier noise.

$$e_{\Sigma} = \sqrt{e_{1/f}^2 + e_T^2 + e_{amp}^2}$$

The sensor EMN (sometimes referred to as resolution) is defined as

$$EMN = \frac{e_{\Sigma}}{S_y} = \frac{\sqrt{e_{1/f}^2 + e_T^2 + e_{amp}^2}}{I_x \frac{\Delta\rho}{t} \frac{1}{H_s + H_g}}$$

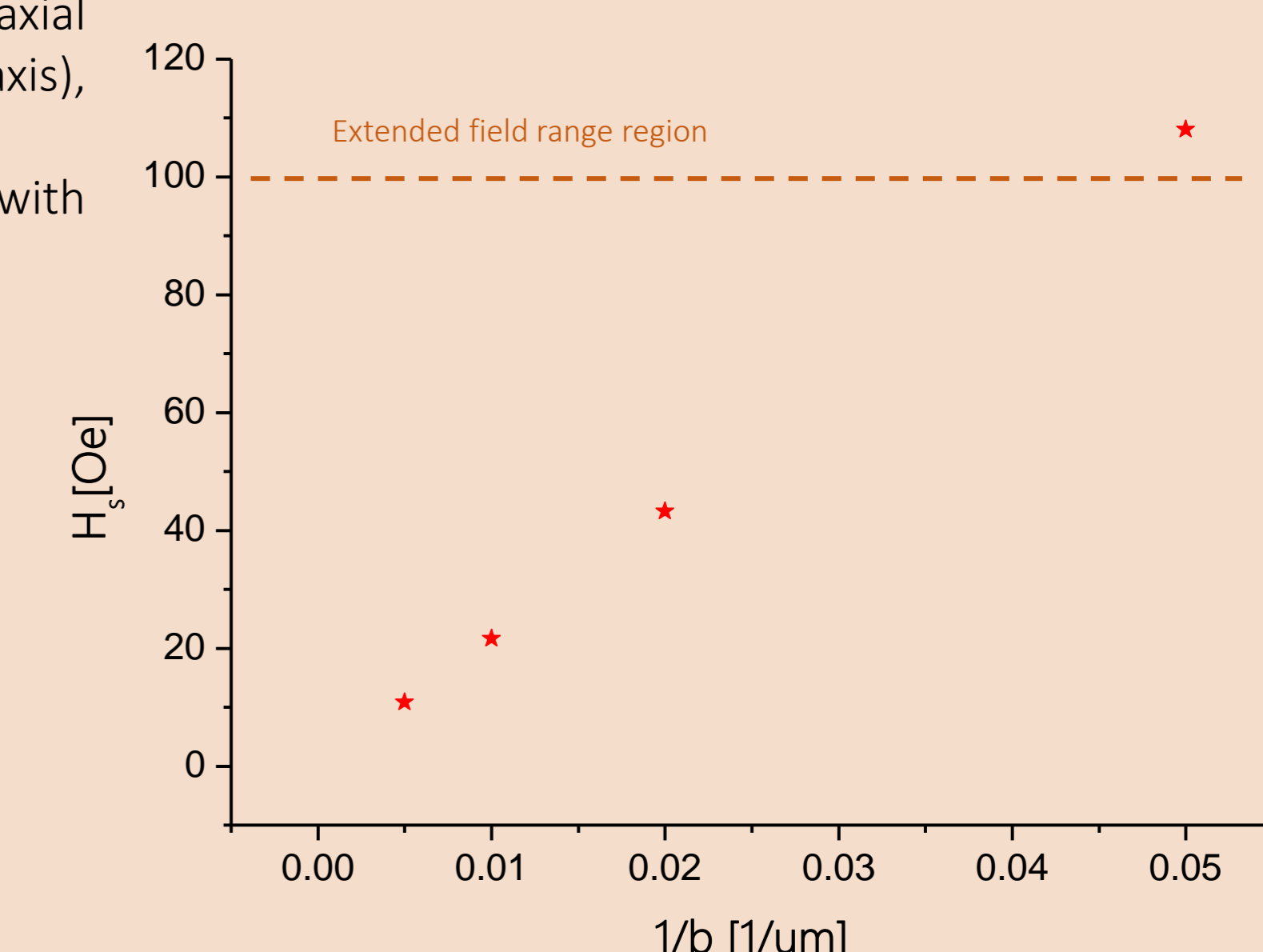
A Novel EPHE sensor with extended field range

The shape of the elliptical PHE sensors induces a uniaxial magnetic anisotropy parallel to the long axis (the easy axis), known as "shape anisotropy". For an elongated and relatively flat ellipsoid (thickness t) with principle axes a and b ($a \gg b \gg t$) will be:

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

Utilizing this relation, we computed theoretical values of the shape anisotropy field for a sensor featuring a thickness of 200 nm across various hard axis lengths.

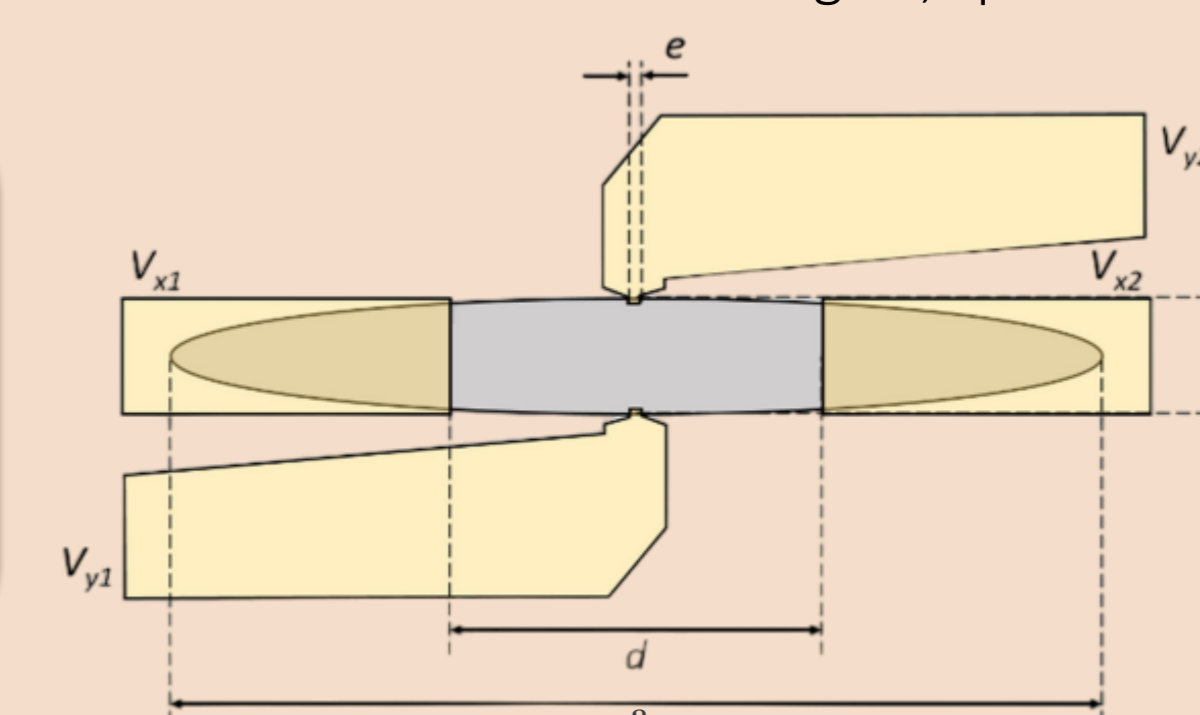
A sensor with a hard axis length of 20 microns surpasses 100 Oe, qualifying it as an extended field range sensor.



Design

Consequently, EPHE sensor with thickness of 200 nm and diverse hard axis lengths, specifically 200, 100, 50, and 20 microns.

A schematic diagram of the sensor with the ellipse's major and minor axes (denoted as a and b , respectively), with aspect ratio 1:8, and the placement of the gold electrical contact pads (highlighted in yellow).



The sensor is excited by applying an ac current between I_{x1} and I_{x2} . The signal is measured between V_{y1} and V_{y2} .