

The DMI mitre gear

The measurement that would not comply

Lior Klein

CQP seminar, 29 September 2026



Funded by
the European Union

*MultiSpin.AI has received funding from the
European Union under grant agreement 101130046*



MULTISPIN.AI
AI Co-Processor Research Project

Most measurements confirm what we already know.

Once in a while, the data will not comply with the expected fit

An artifact

something in the setup, the sample or the analysis

or

Physics we did not know

a real effect that was waiting to be noticed

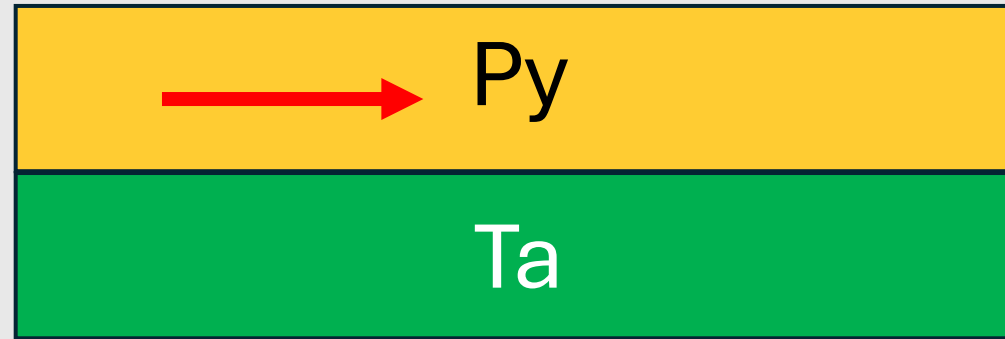
This talk is one such case, told in the order it actually happened.

The system that we study

HM/FM bi-layers
with in-plane
magnetic anisotropy

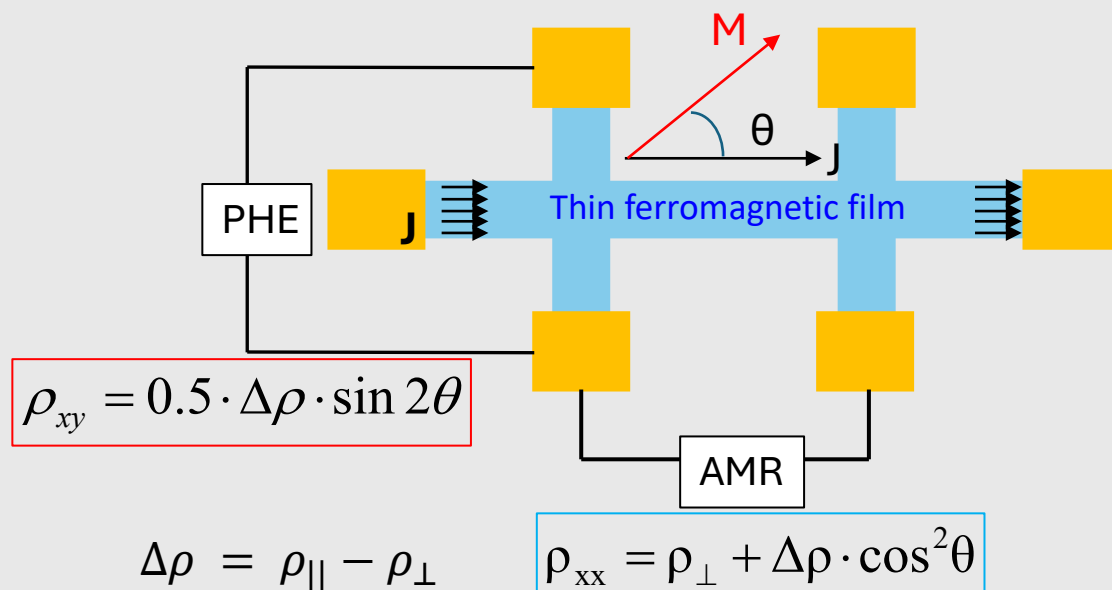
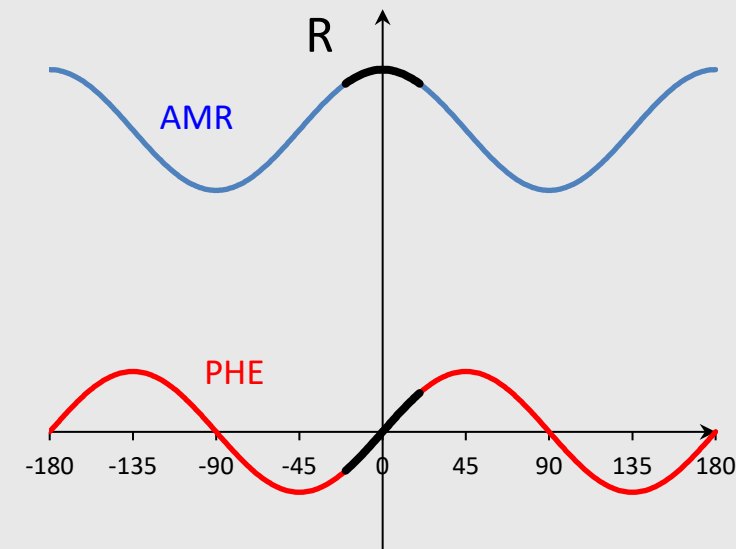
FM

HM



Planar Hall effect measurements

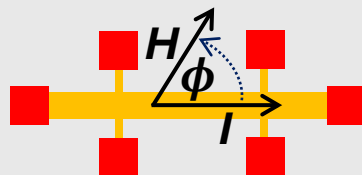
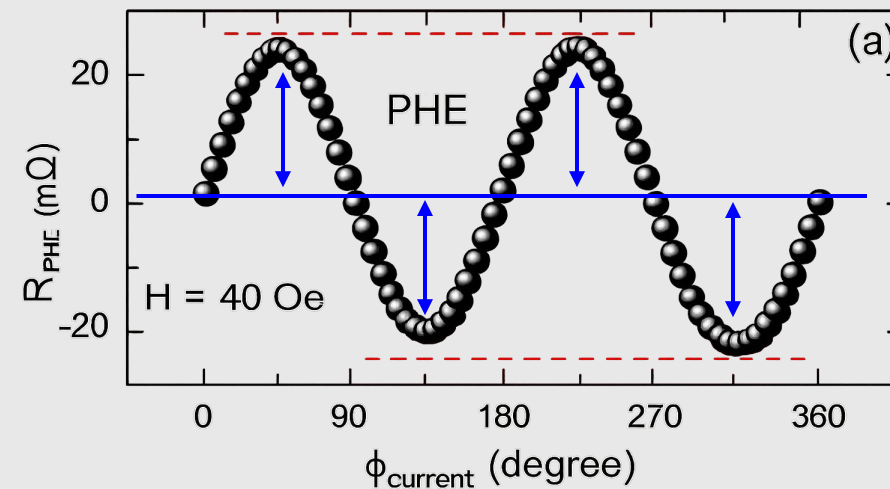
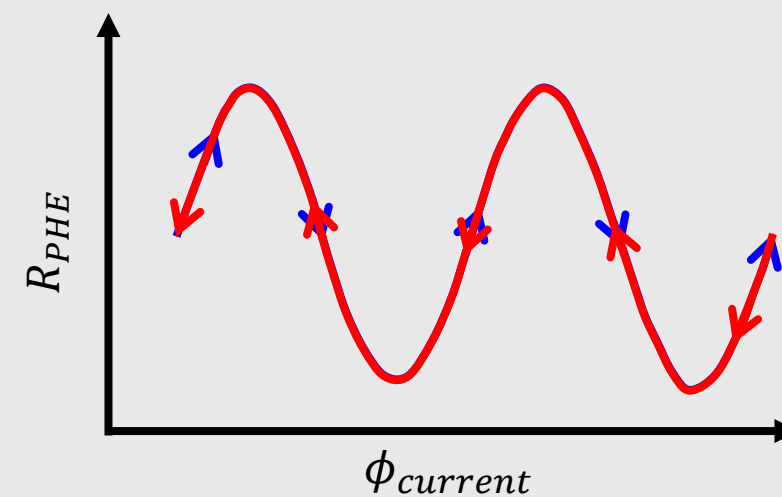
The planar Hall effect



The first clue: four peaks that should be equal

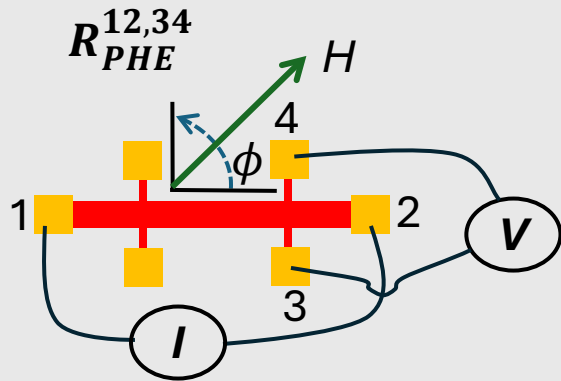
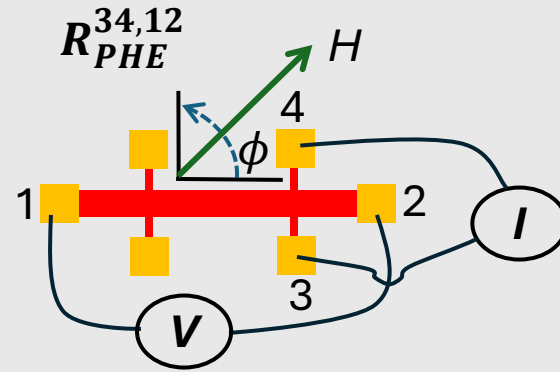
Si/SiO₂(100 nm)/Al₂O₃(20 nm)/Ta(5 nm)/Py(2 nm)/Ti(3 nm)

$$R_{PHE} = R_0 \sin 2\phi$$



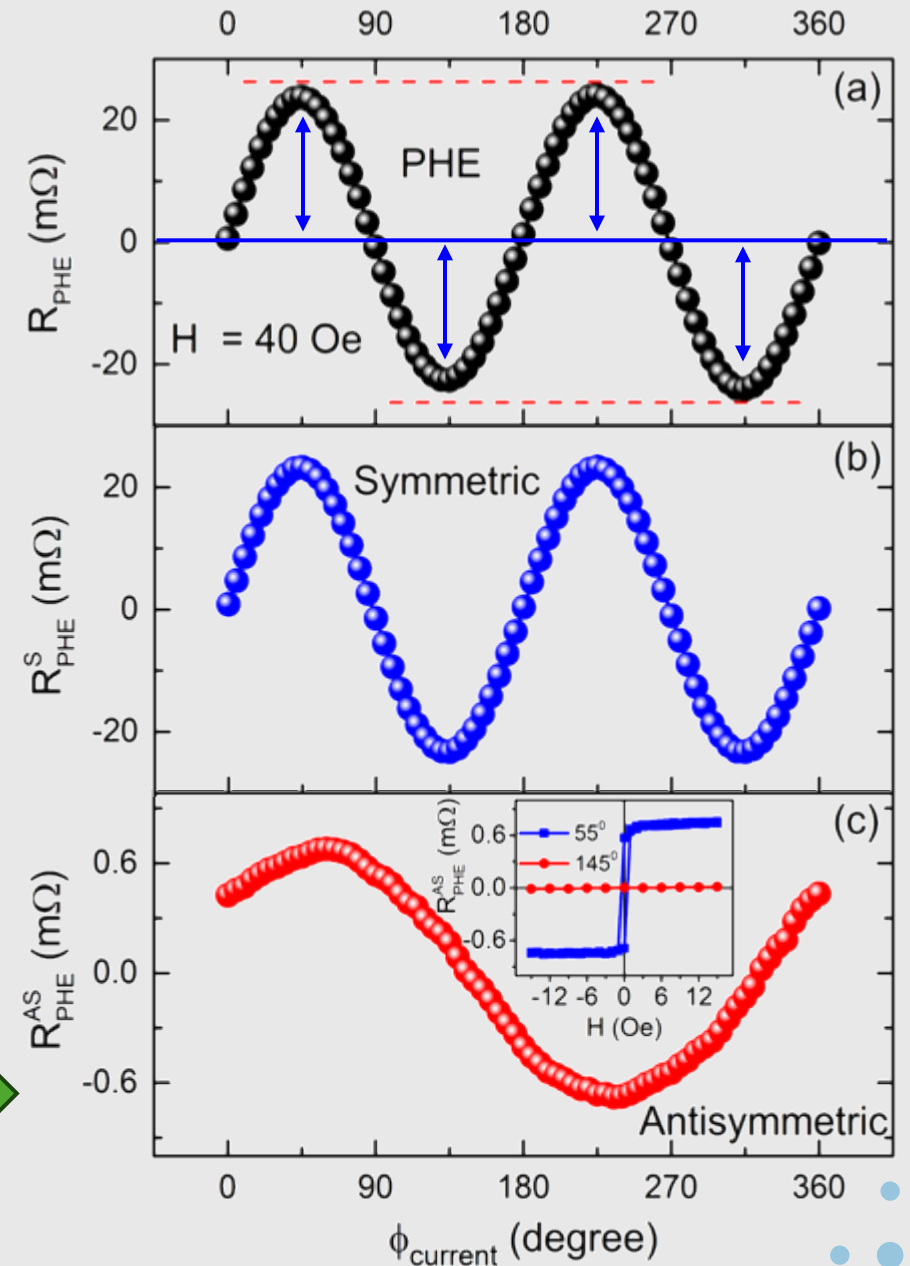
Naming it: the antisymmetric planar Hall effect

Reciprocity theorem $\Rightarrow R_{PHE}^{12,34}(+H) = R_{PHE}^{34,12}(-H)$



SPHE $\Rightarrow R_{PHE}^S = \frac{(R_{PHE}^{12,34} + R_{PHE}^{34,12})}{2} = R_0^S \sin 2\phi$

APHE $\Rightarrow R_{PHE}^{AS} = \frac{(R_{PHE}^{12,34} - R_{PHE}^{34,12})}{2} = R_0^{AS} \cos(\phi - \phi_0^{AS})$



The suspect board

Every source that could produce an antisymmetric signal makes a prediction. Each one gets its own experiment.

Suspects

1. Joule heating – temperature gradients

A signal related to Joule heating should scale with the amplitude of the current.

2. Spin-orbit torque from the Ta spin current

Should depend on the angle between the current and the magnetization, and scale with the current amplitude.

3. A field that is not exactly in plane

A perpendicular component of the field due to misalignment gives an ordinary or anomalous Hall signal that scales with the field amplitude.

Additional questions

Bulk effect or interface effect?

The same on every part of the wafer?

Does the seed layer matter?

Does annealing matter?

Two ways a current could induce it: heating and spin currents

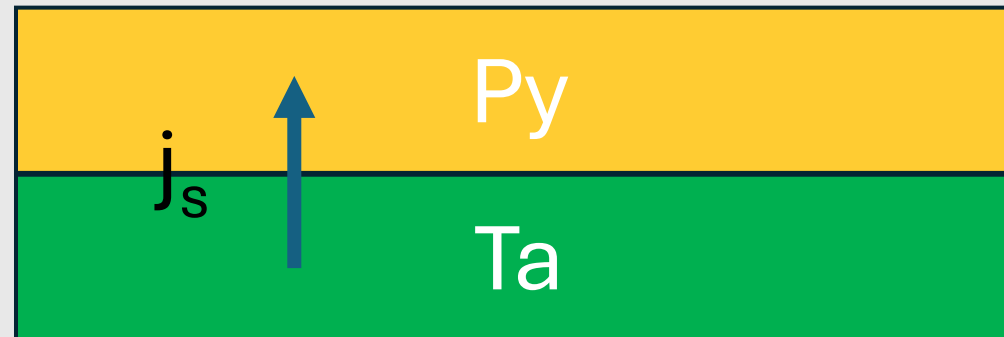
Spin-orbit Torques?

Anomalous Nernst effect

Spin currents

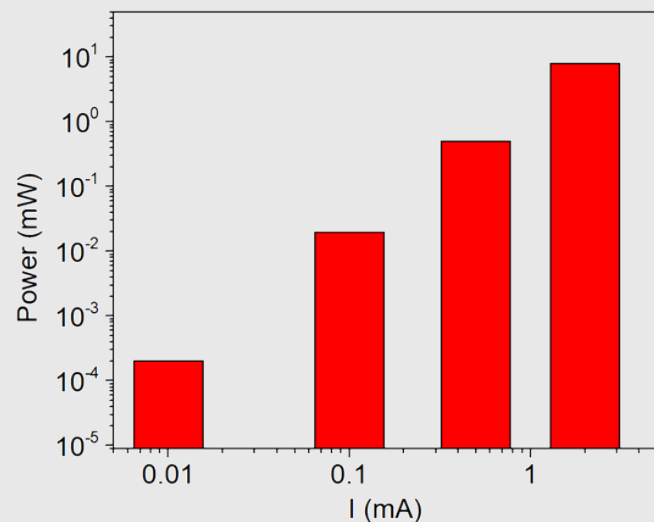
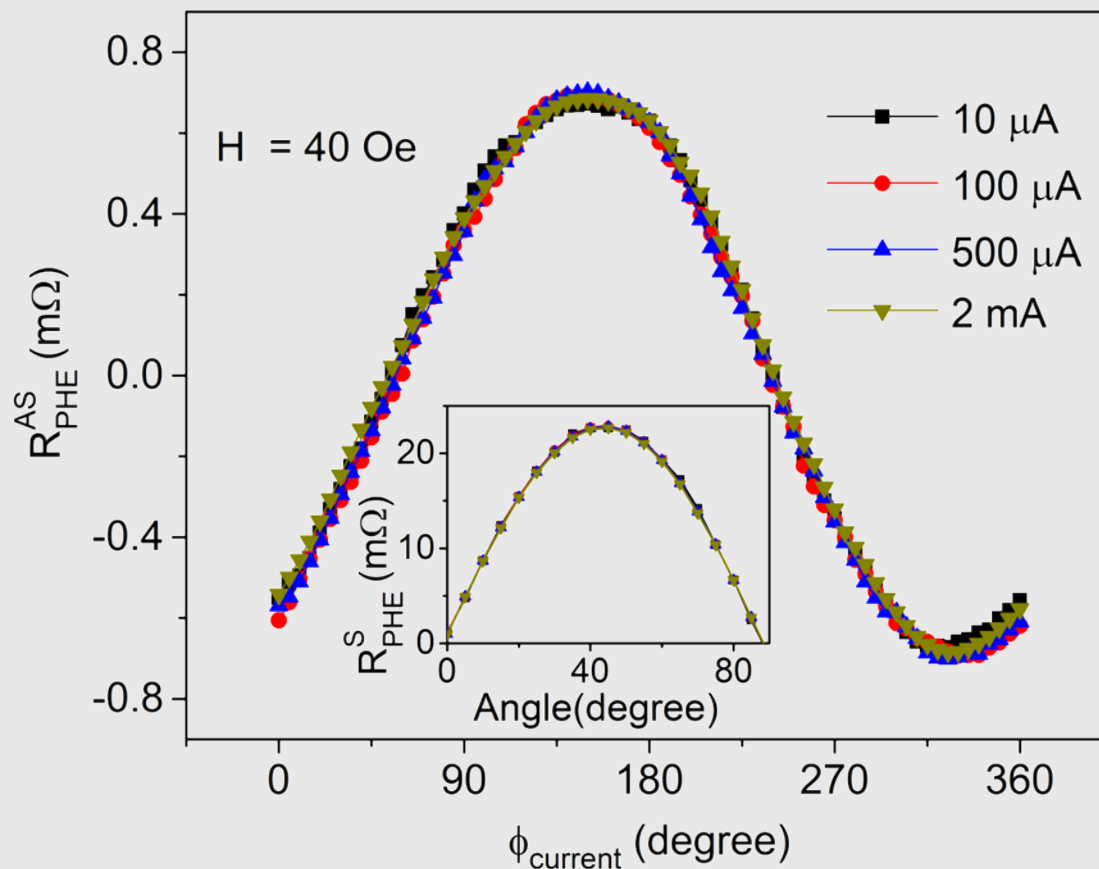
Temperature gradients

j_c



$$\vec{E} = \vec{\nabla}T \times \vec{m}$$

Suspect 1: current amplitude from 10 μ A to 2 mA



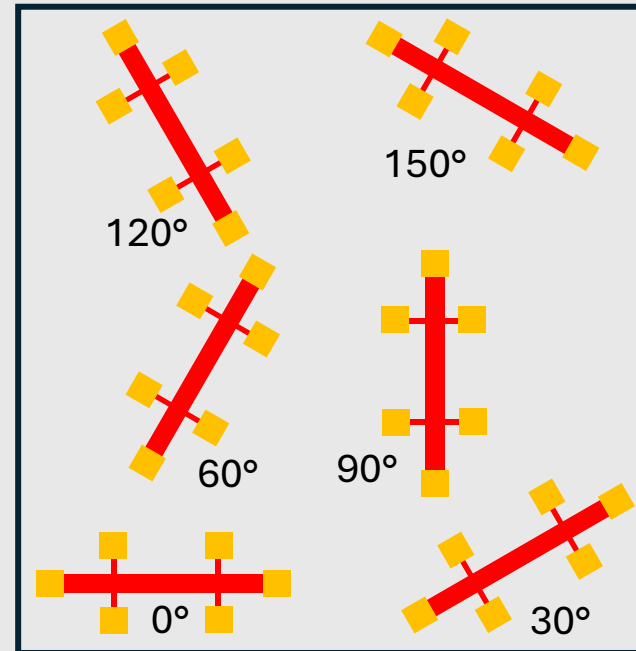
APHE does not depend on current amplitude

Excludes temperature gradients and spin currents

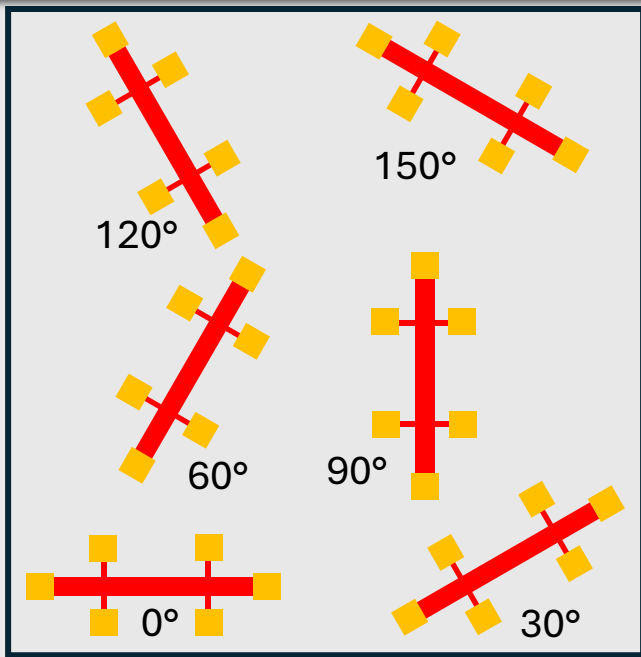
The suspect board:

Current magnitude - CLEARED

What about current direction?



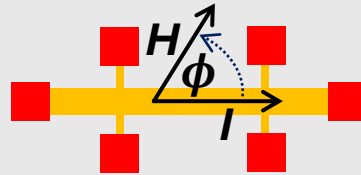
Suspect 2: does it care about the current direction?



$\alpha_{wafer} = 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ \text{ and } 150^\circ$

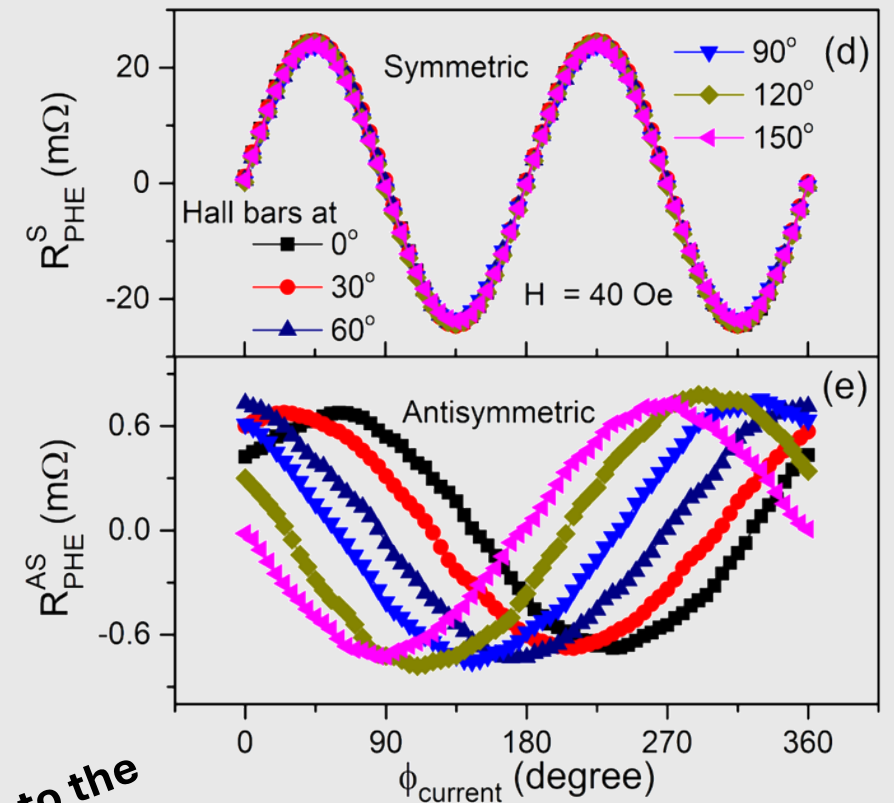
$$\phi_{wafer} = \phi_{current} + \alpha_{wafer}$$

$$R_{PHE}^{AS} = R_0^{AS} \cos(\phi_{wafer} - \phi_0^{AS})$$

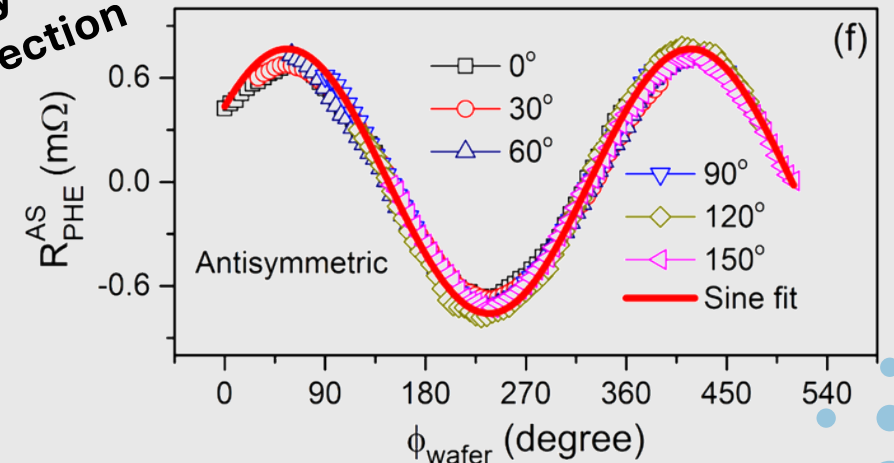


SPHE

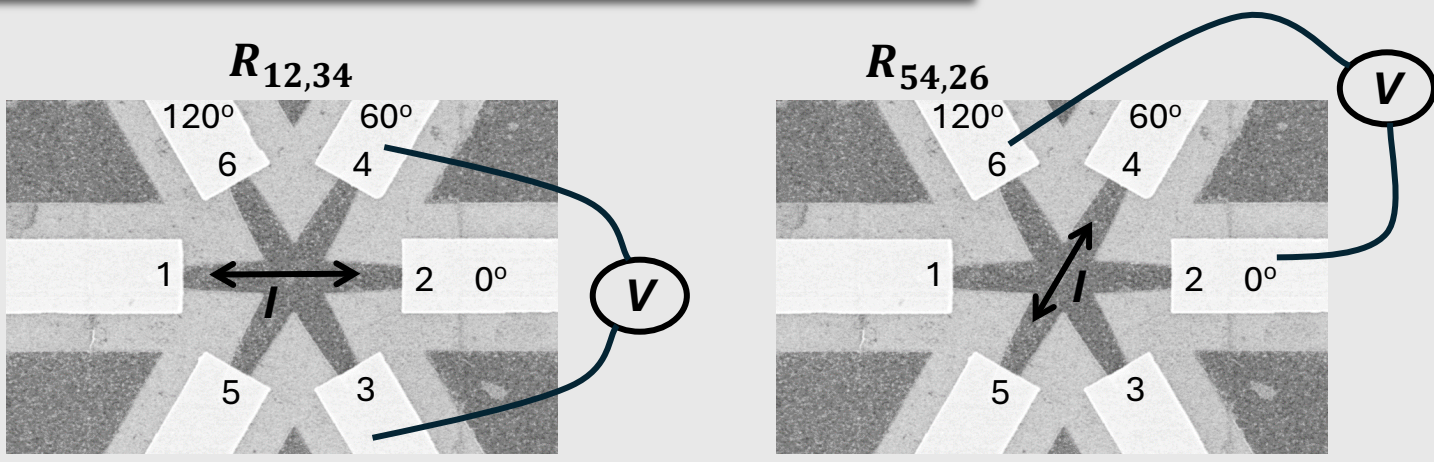
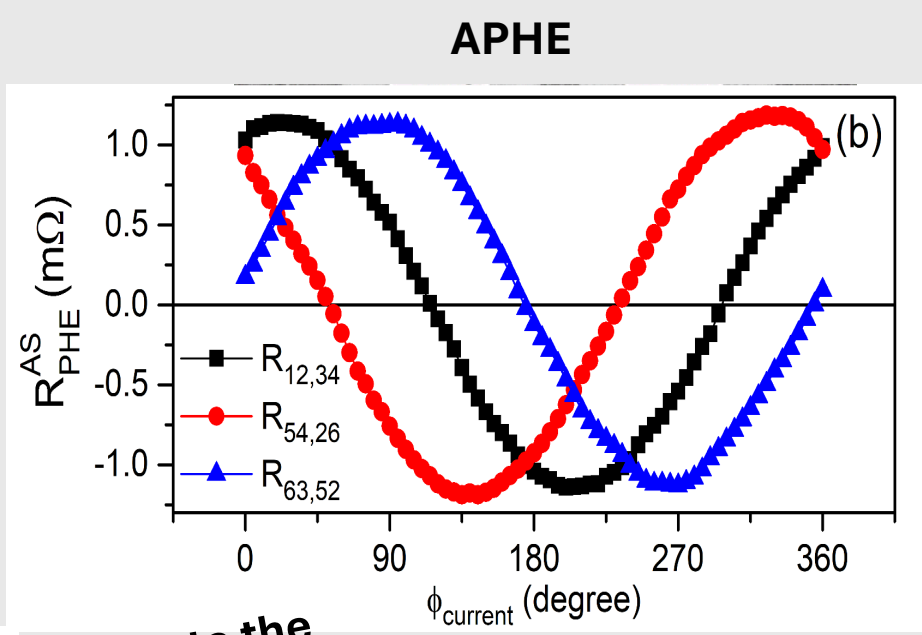
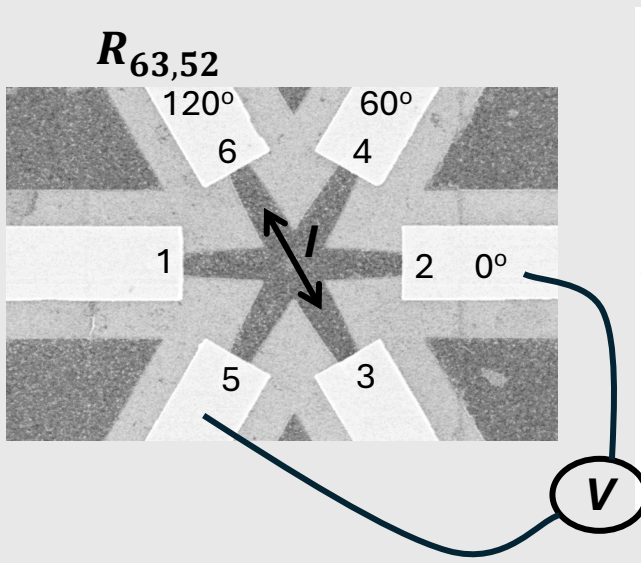
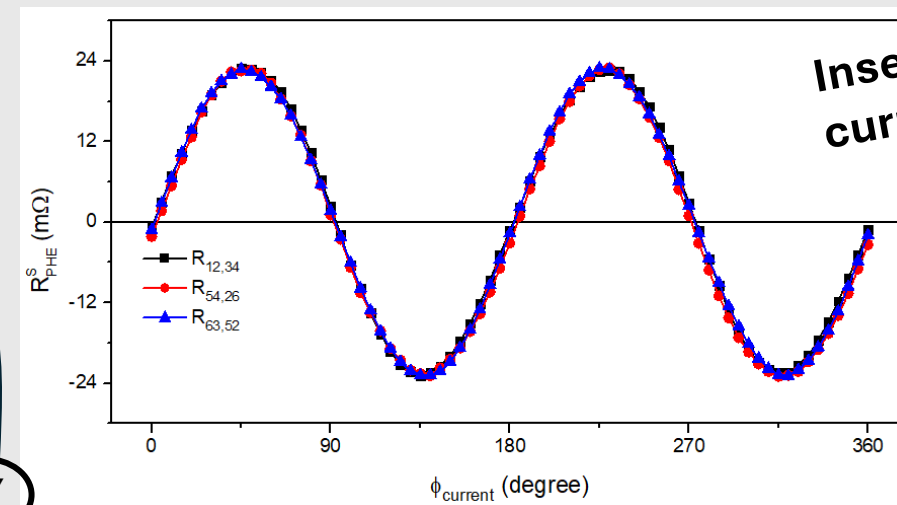
APHE



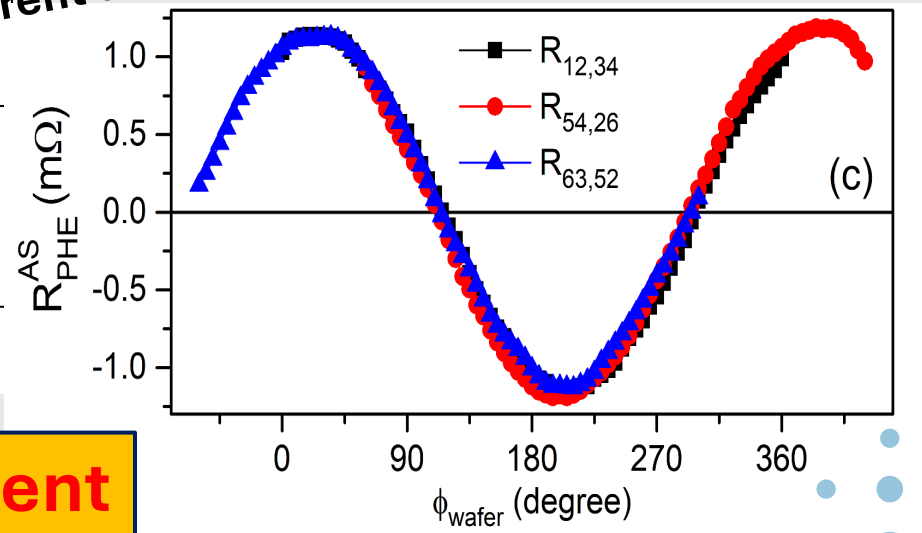
Insensitivity to the current direction



Suspect 2, test 2: three crossing ellipses



Insensitivity to the current direction



APHE is SOT independent

The suspect board: two down

Every source that could produce an antisymmetric signal makes a prediction. Each one gets its own experiment.

Suspects

~~1. Joule heating – temperature gradients~~

CLEARED

~~A signal related to Joule heating should scale with the amplitude of the current.~~

~~2. Spin-orbit torque from the Ta spin current~~

CLEARED

~~Should depend on the angle between the current and the magnetization, and scale with the current amplitude.~~

3. A field that is not exactly in plane

A perpendicular component of the field due to misalignment gives an ordinary or anomalous Hall signal that scales with the field amplitude.

Additional questions

Bulk effect or interface effect?

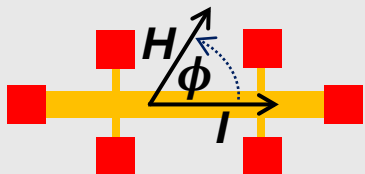
The same on every part of the wafer?

Does the seed layer matter?

Does annealing matter?

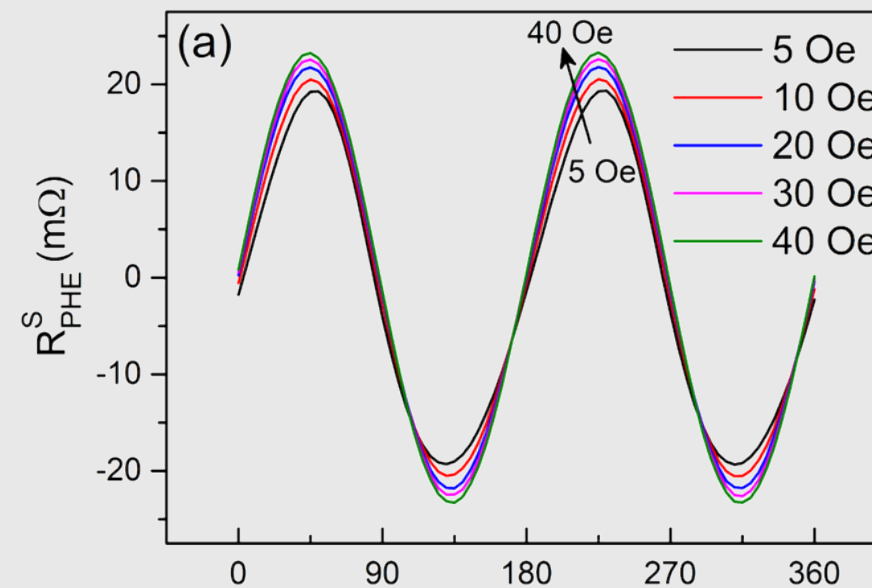
Suspect 3: is the field really in plane?

- Magnetization asymptotically saturates as the field increases
- APHE amplitude remains unchanged

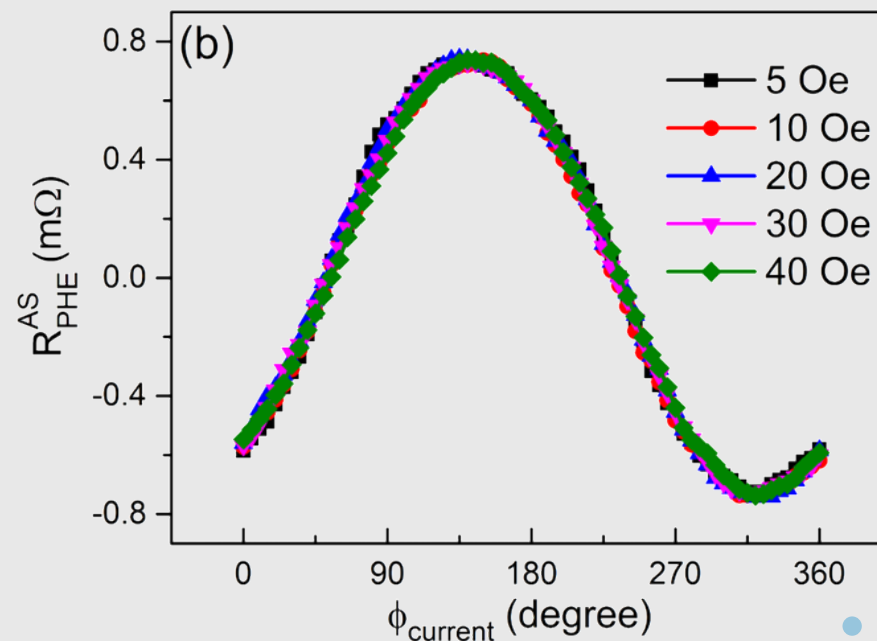


APHE does not depend directly on the magnetic field

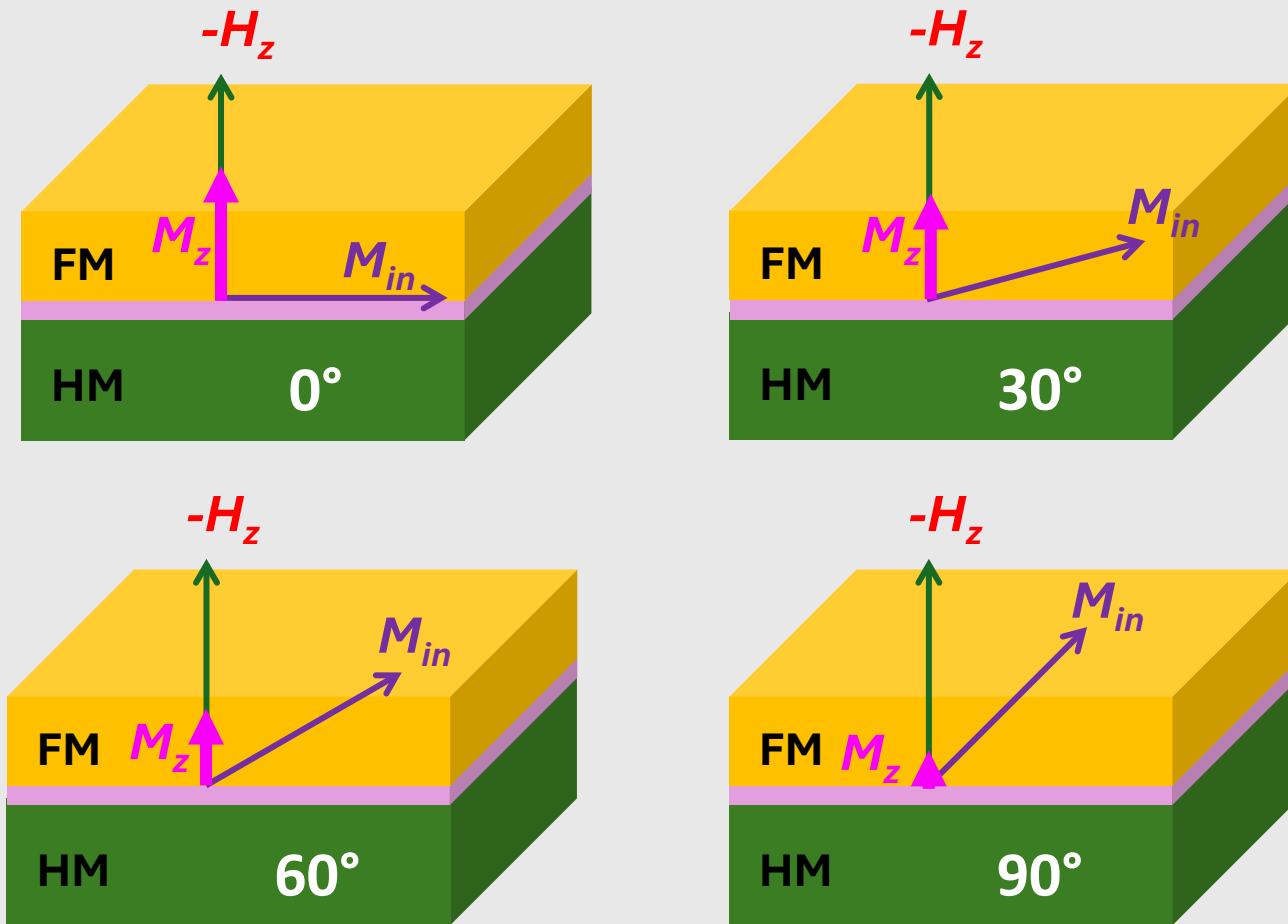
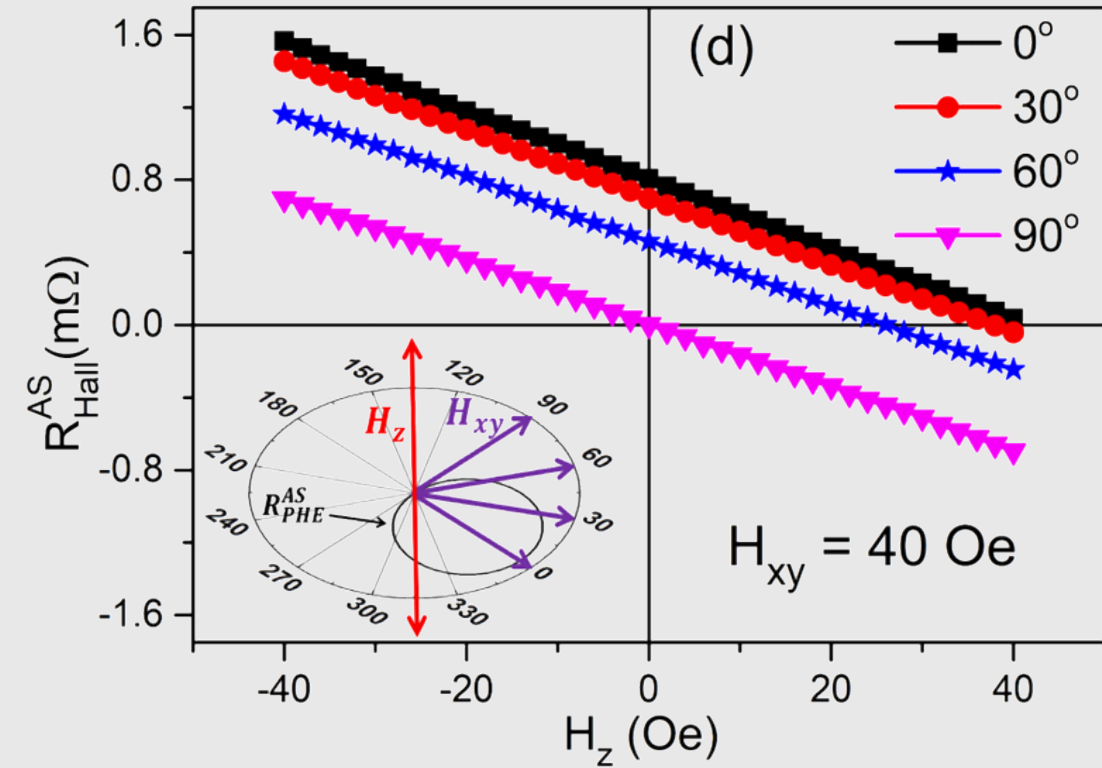
SPHE



APHE



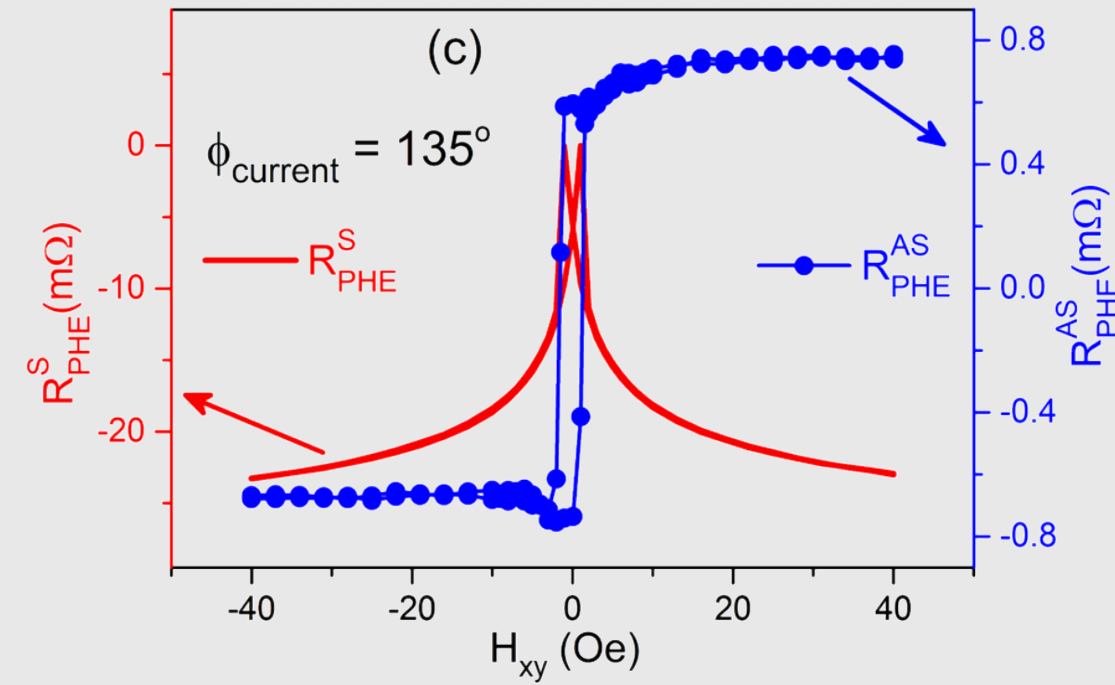
Adding a real perpendicular field: the APHE simply adds to it



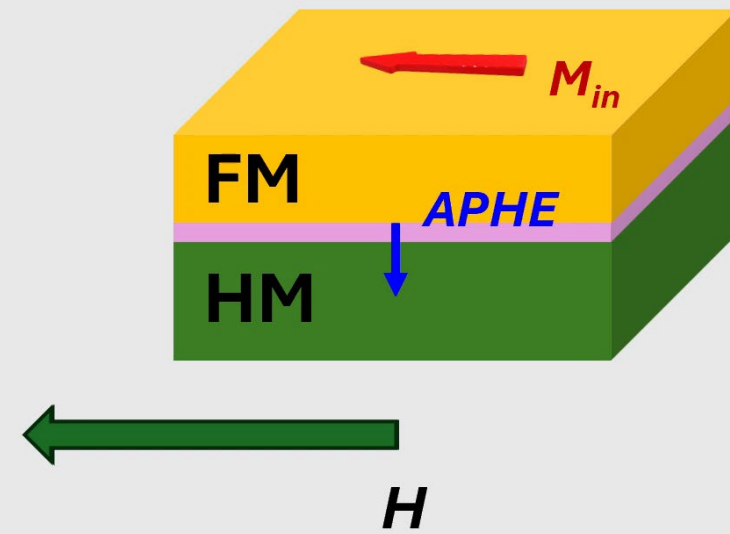
APHE is directly linked to the direction of the in-plane magnetization

It is not the field – it is the magnetization

- **APHE** shows a hysteresis loop following the in-plane magnetization



APHE is directly linked to the direction of the in-plane magnetization



The suspect board: no suspected source left

Every source that could produce an antisymmetric signal makes a prediction. Each one gets its own experiment.

Suspects

~~1. Joule heating – temperature gradients~~

CLEARED

~~A signal related to Joule heating should scale with the amplitude of the current.~~

~~2. Spin-orbit torque from the Ta spin current~~

CLEARED

~~Should depend on the angle between the current and the magnetization, and scale with the current amplitude.~~

~~3. A field that is not exactly in plane~~

CLEARED

~~A perpendicular component of the field due to misalignment gives an ordinary or anomalous Hall signal that scales with the field amplitude.~~

Additional questions

Bulk effect or interface effect?

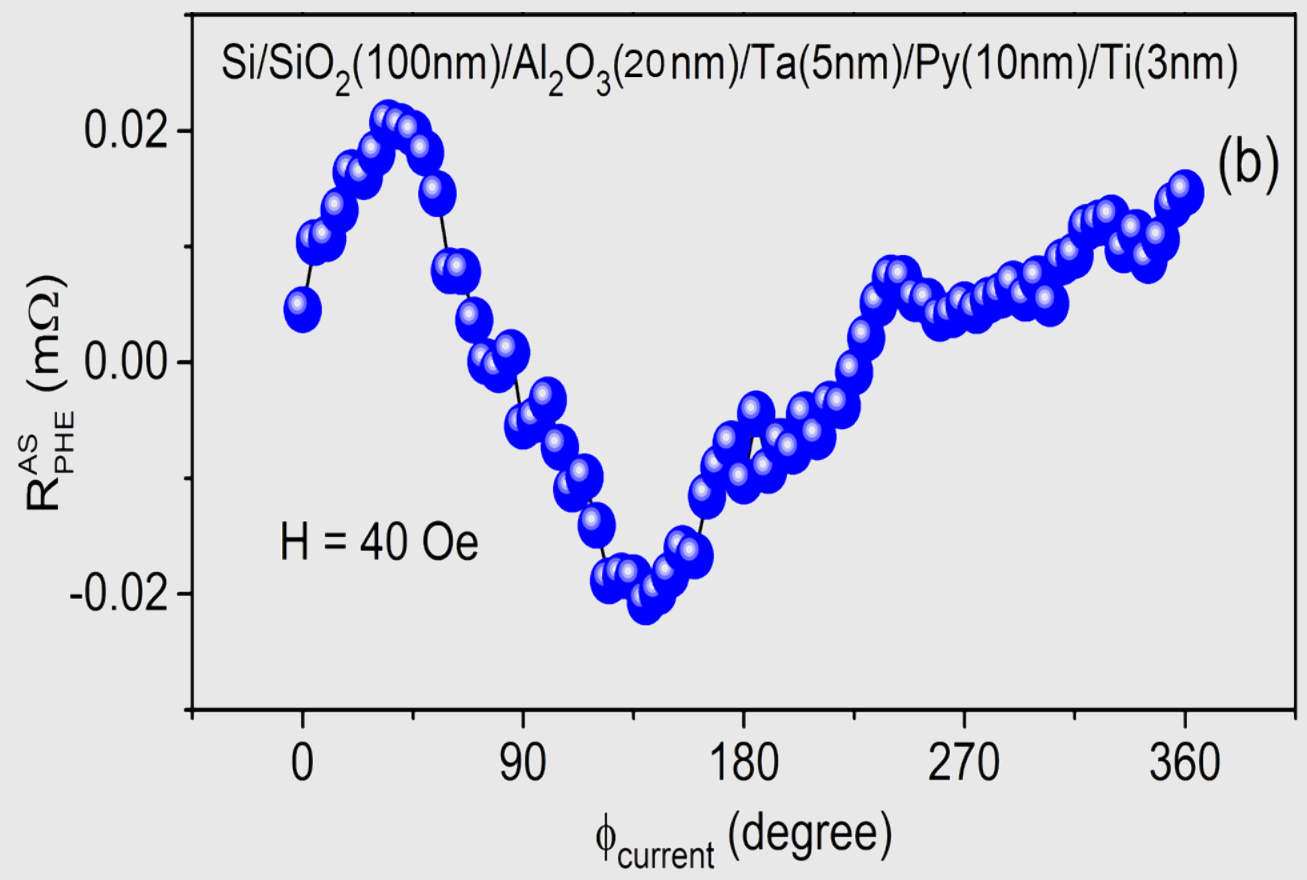
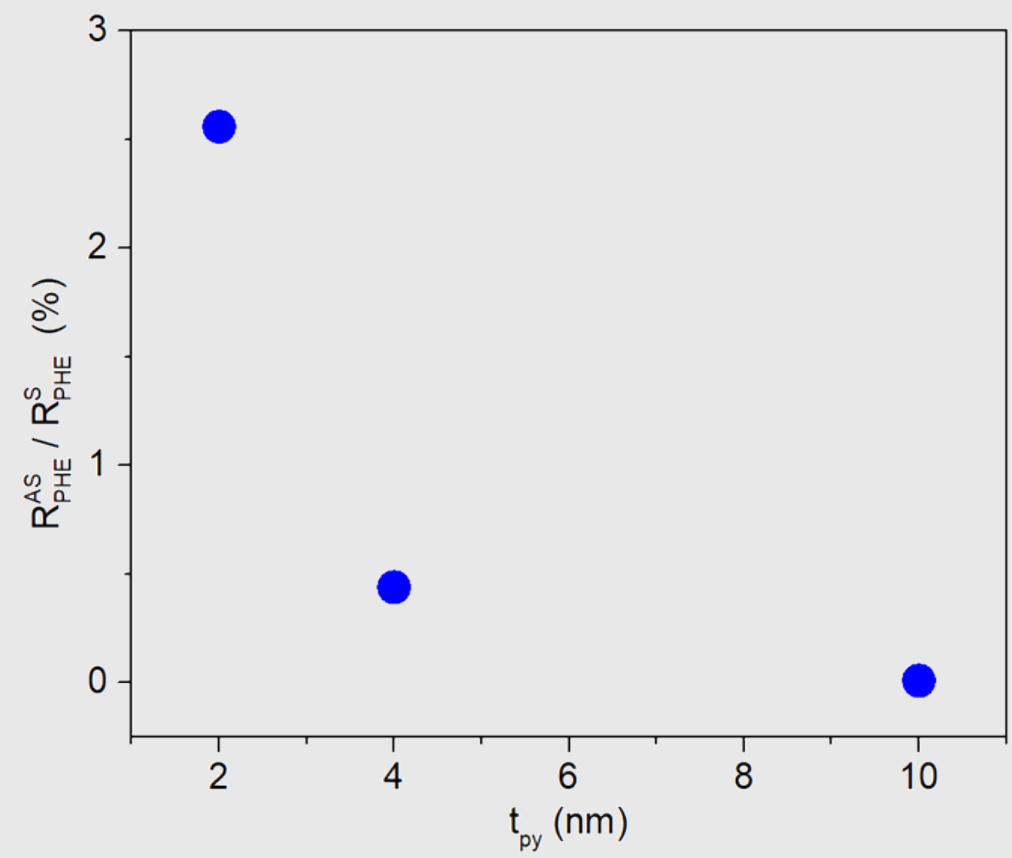
The same on every part of the wafer?

Does the seed layer matter?

Does annealing matter?

No suspected source left standing. The signal is real, and it belongs to the sample.

Bulk or interface? The thickness test



APHE is an interface effect

An antisymmetric planar Hall signal in Ta/Py

Independent of current direction and amplitude

Independent of the in-plane field amplitude

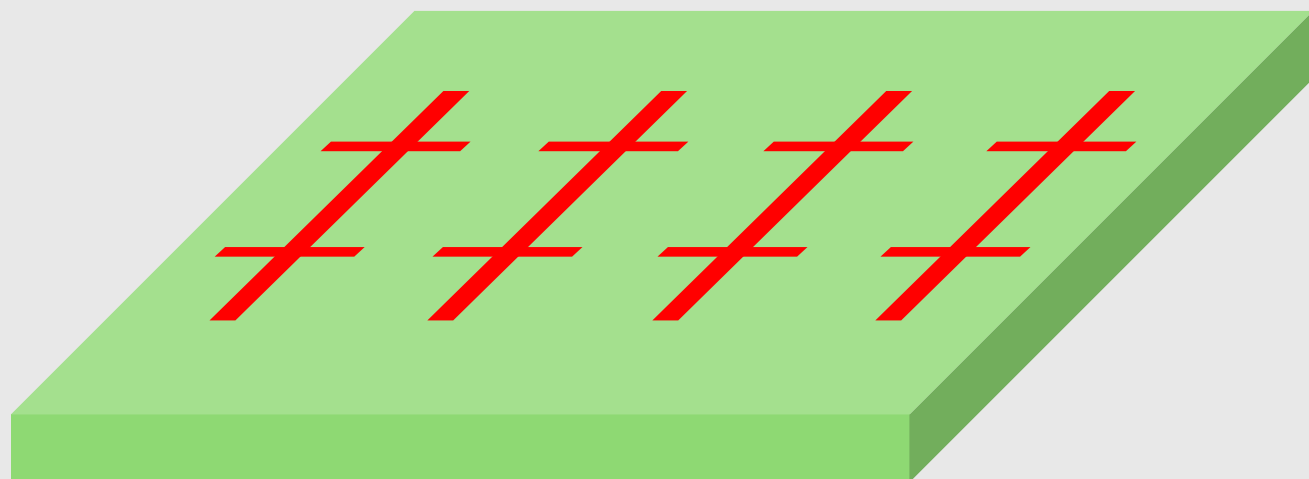
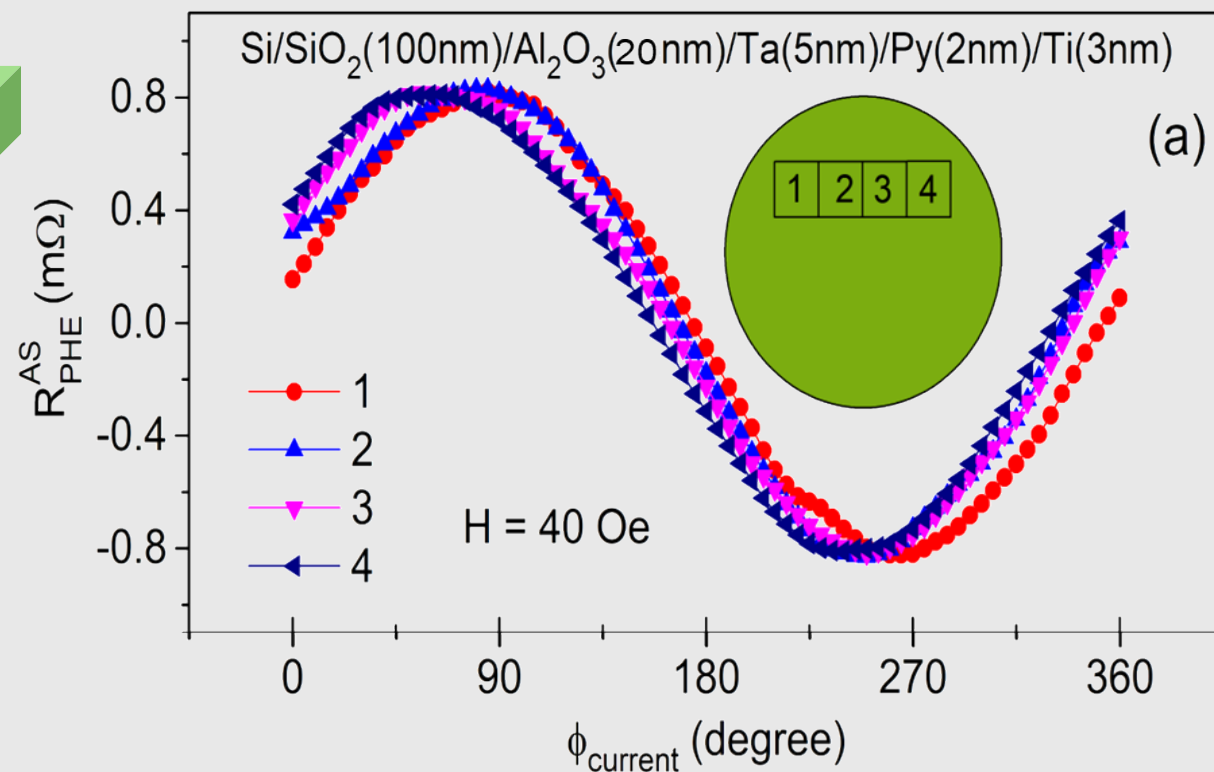
Correlated with the direction of the in-plane magnetization

Locked to an axis fixed in the wafer

Gone by 10 nm of Py: an interface effect

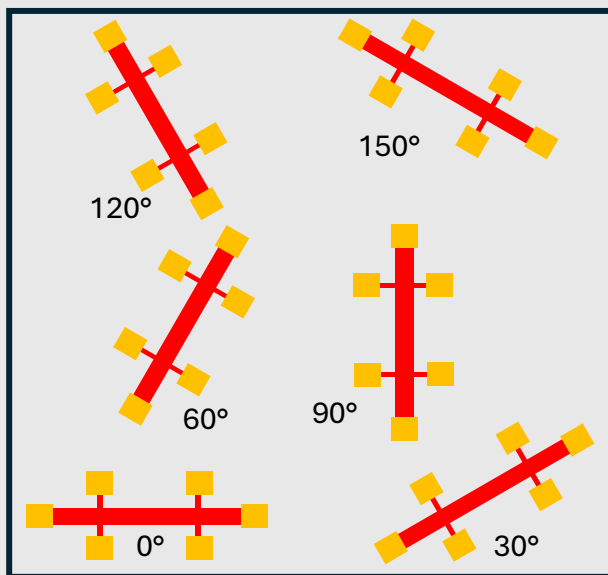
Everything fits a small perpendicular magnetization at the interface, locked to the in-plane magnetization and read out as an anomalous Hall effect

The wafer clue: it depends on where the sample came from

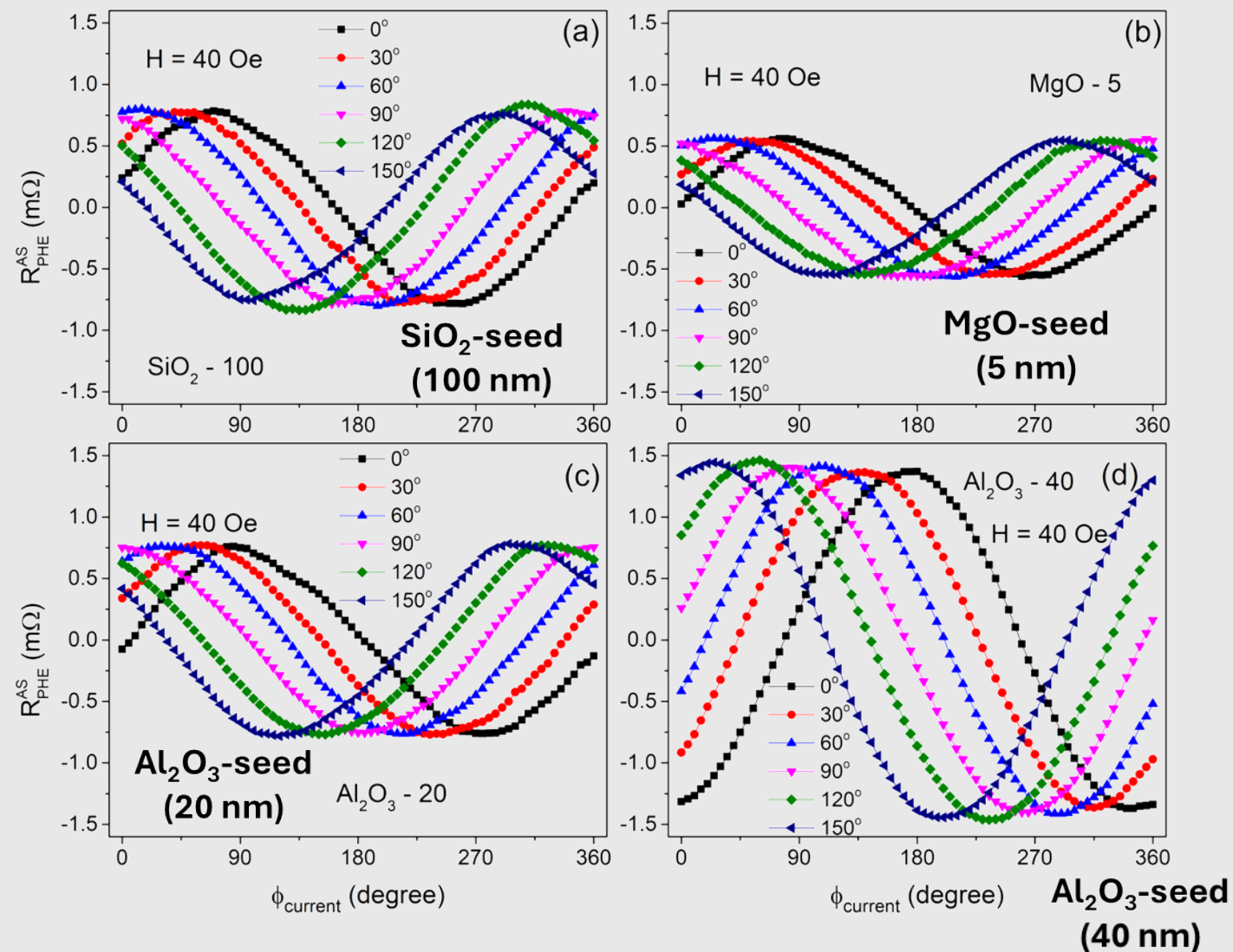


Is strain involved?

The wafer clue: seed layers

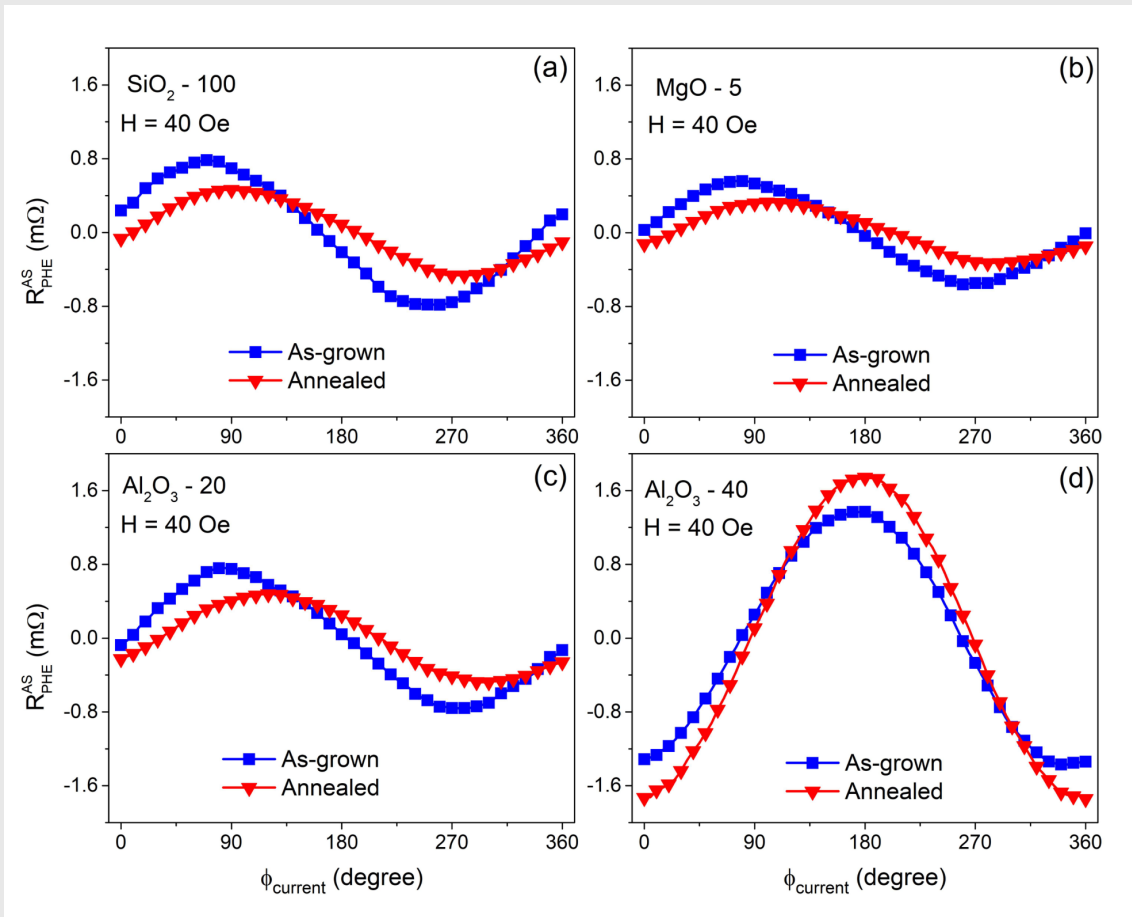


The magnitude of the APHE changes with the seed layer



Si/SiO₂(100 nm)/Seed/Ta(5 nm)/Py(2 nm)/MgO(3 nm)/Ta(2 nm)

Seed layers and annealing: what we know so far



Horizontal Hall bars on four seed layers, as grown (blue) and after annealing at 200 °C for 1 h (red)

What we did

Same Ta(5 nm)/Py(2 nm) stack grown on four seed layers: SiO₂, MgO(5 nm), Al₂O₃(20 nm) and Al₂O₃(40 nm). Then every wafer was annealed at 200 °C for 1 h and measured again.

What we see

The magnitude of the APHE varies with the seed layer, from 0.6 to 1.4 mΩ. Annealing changes both the magnitude and the direction of the effect, and not in the same way on every wafer.

What we can say at this point

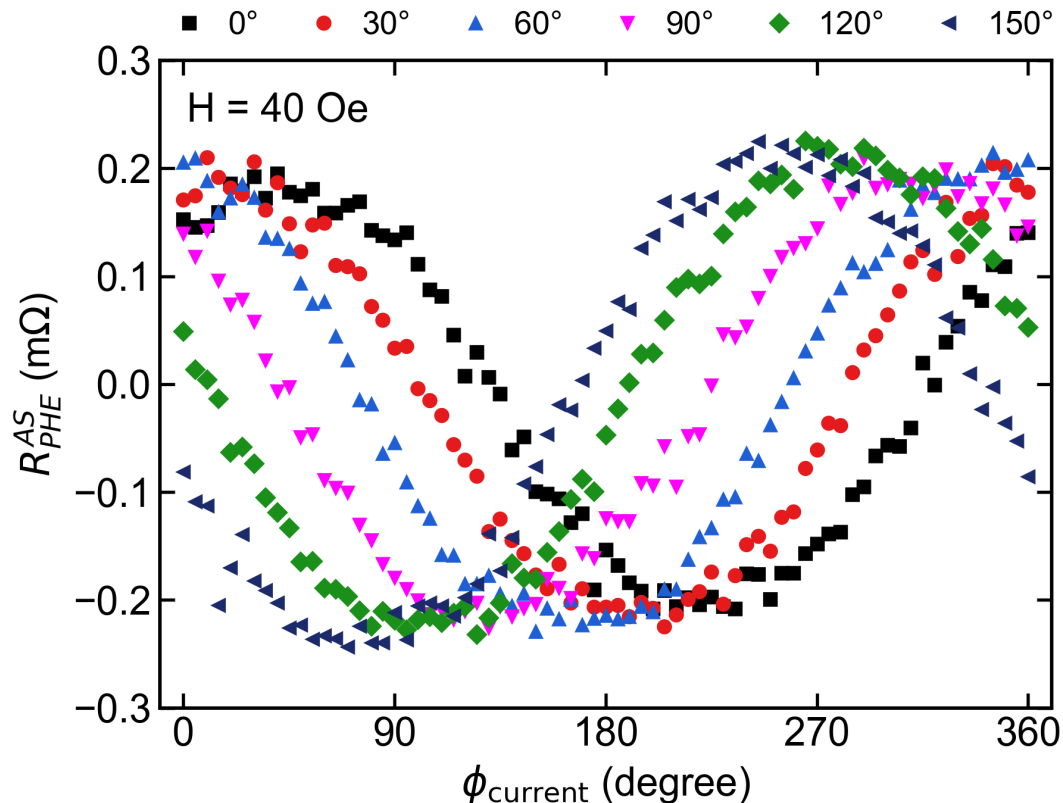
We are still looking for a consistent picture. What the data support so far: strain, or strain gradients, at the interface are relevant.

A lever on the effect, not yet a mechanism

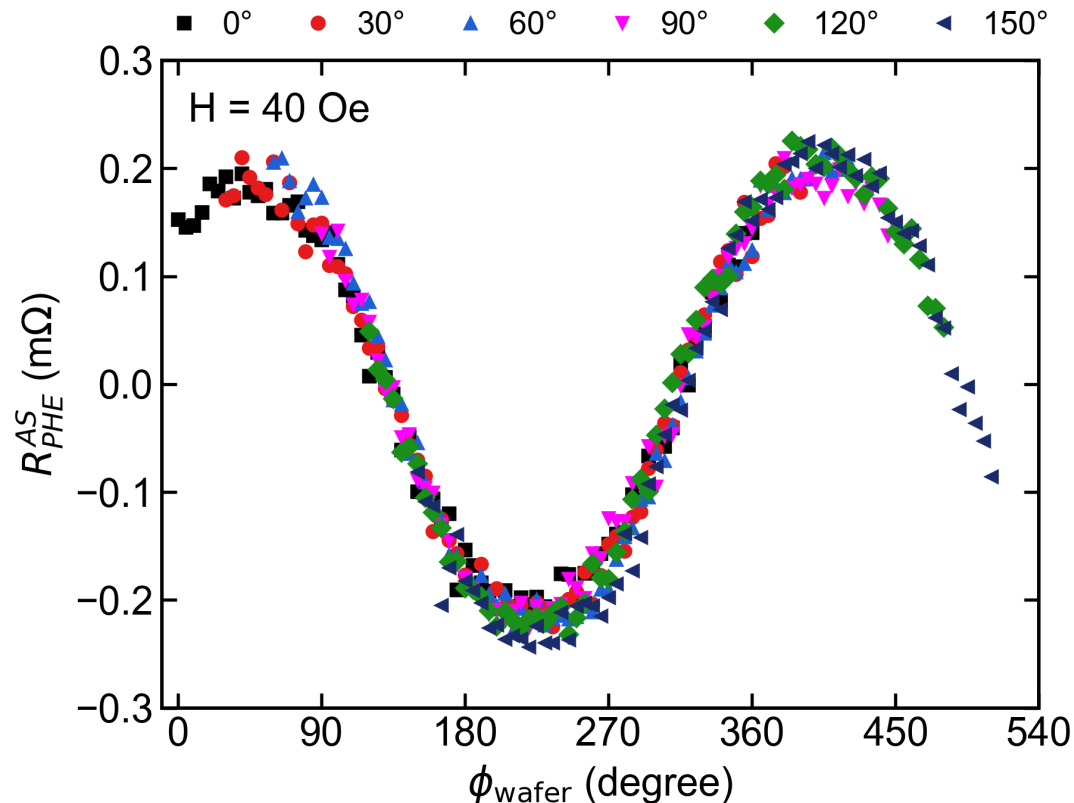
Not only Ta/Py: the same clue in Ta/CoFeB

SiO₂(100 nm)/Al₂O₃(10 nm)/Ta(5 nm)/CoFeB(2 nm)/Ru(3 nm), six Hall bars at 0 to 150 degree on the wafer

Versus the field angle relative to the current



The same data versus the angle relative to a fixed direction in the wafer



Ta/Py is not alone. The antisymmetric signal exists in a second ferromagnet, and again it follows the magnetization relative to a fixed axis in the wafer. Seen in two systems, it is probably present in many others.

Wanted: a mechanism with all of these properties

Couples an in-plane magnetization to a perpendicular component

and turns the perpendicular component as the in-plane one rotates, with a fixed axis in the film

Lives at the ferromagnet / heavy-metal interface

gone by 10 nm of Py, and not specific to Py: Ta/CoFeB shows it too

Belongs to the sample, not to the measurement

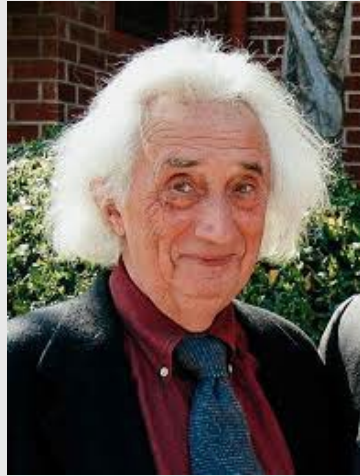
independent of the current and of the field amplitude: an equilibrium property

Responds to growth and annealing

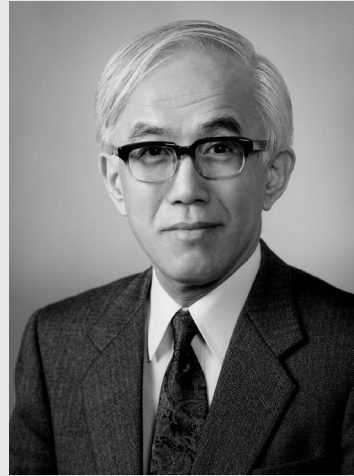
seed layer, position on the wafer and annealing all move it: consistent with strain or strain gradients at the interface

Which interaction favours spins at right angles to each other?

The suspect with a motive: the Dzyaloshinskii-Moriya interaction



Igor Dzyaloshinskii



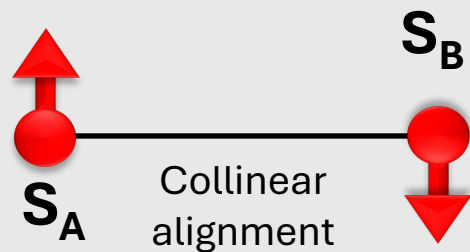
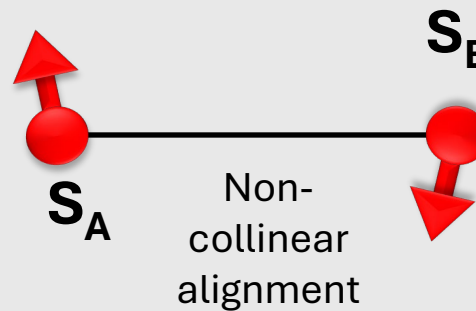
Toru Moriya

antisymmetric exchange

$$H_{DM} = \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$

Explaining weak ferromagnetism

Weak Ferromagnets/Antiferromagnets:
 $\alpha\text{-Fe}_2\text{O}_3$, MnCO_3 and CoCO_3
I. Dzyaloshinskii, J. Phys. Chem. Solids (1958)



Only in crystals that lack inversion symmetry

PHYSICAL REVIEW B

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1 JULY 1991-II

Crossover and multicriticality due to the Dzyaloshinsky-Moriya interaction

Lior Klein and Amnon Aharony

*School of Physics and Astronomy, Beverly and Raymond Sackler Faculty of Exact Sciences,
Tel Aviv University, 69978 Tel Aviv, Israel*

(Received 19 November 1990)

We show that the addition of a Dzyaloshinsky-Moriya interaction to a Heisenberg ferromagnet introduces only one crossover exponent, which is the same as for the usual uniaxial anisotropy. This result is in contrast to a previous report by Liu.

The Dzyaloshinsky-Moriya^{1,2} (DM) interaction is an anisotropic antisymmetric exchange interaction which results from a spin-orbit coupling. Its general form, for a pair of spins $\mathbf{S}_i$ and $\mathbf{S}_j$ at sites i and j , is

$$\mathcal{H}_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j), \quad (1)$$

where $\mathbf{D}_{ij} = -\mathbf{D}_{ji}$. This interaction is found in many different systems. It is responsible for weak ferromagnetism in some mainly antiferromagnetic compounds³ such as $\alpha\text{-Fe}_2\text{O}_3$, MnCO_3 , and CoCO_3 . Recently,⁴ it was also observed as being the cause of weak ferromagnetism in La_2CuO_4 . As is well known, this compound becomes a high-temperature superconductor upon doping with Sr or

was also mentioned in two letters by Calvo¹¹ and by Perk and Capel,¹² who showed that the Hamiltonian with the DM interaction can be transformed by a rotation into a Hamiltonian with a uniaxial anisotropy. Nevertheless, these authors did not observe the consequences of this mapping on the crossover, and Calvo argued¹¹ that Liu's result is consistent with the mapping.

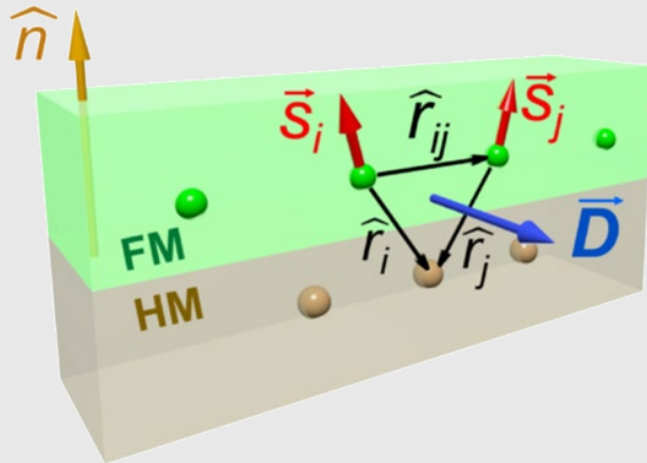
The Hamiltonian consists of three parts:

$$H = H_1 + H_2 + H_3, \quad (2)$$

where H_1 indicates the Heisenberg ferromagnet part, H_2 is the usual uniaxial anisotropy,¹³ and H_3 is the DM interaction:

DMI at a heavy-metal / ferromagnet interface

HM/FM bi-layers with
perpendicular
magnetic anisotropy



Origin

- Combination of **strong spin-orbit coupling** in HM and **broken inversion symmetry** at HM/FM interface: an **antisymmetric exchange** that favors a fixed rotation sense of spins

Features

- Stabilizes **chiral Néel domain walls** (preferred over Bloch)
- **Locks chirality** (left- vs right-handed set by sign of D)

Hellman et al., Rev. Mod. Phys. 89, 025006 (2017)

Kuepferling et. al., Rev. Mod. Phys. 95, 015003 (2023)

Göbel et. al., Phys. Rep. 895, 1–28 (2021)

How DMI would do it

$$H_{DM} = \vec{D} \cdot (\vec{S}_1 \times \vec{S}_2)$$

Dzyaloshinskii–Moriya Hamiltonian

- $\vec{D}$  DM vector
- $\vec{S}_1$  Bulk in-plane Py spin
- $\vec{S}_2$  Interfacial spin

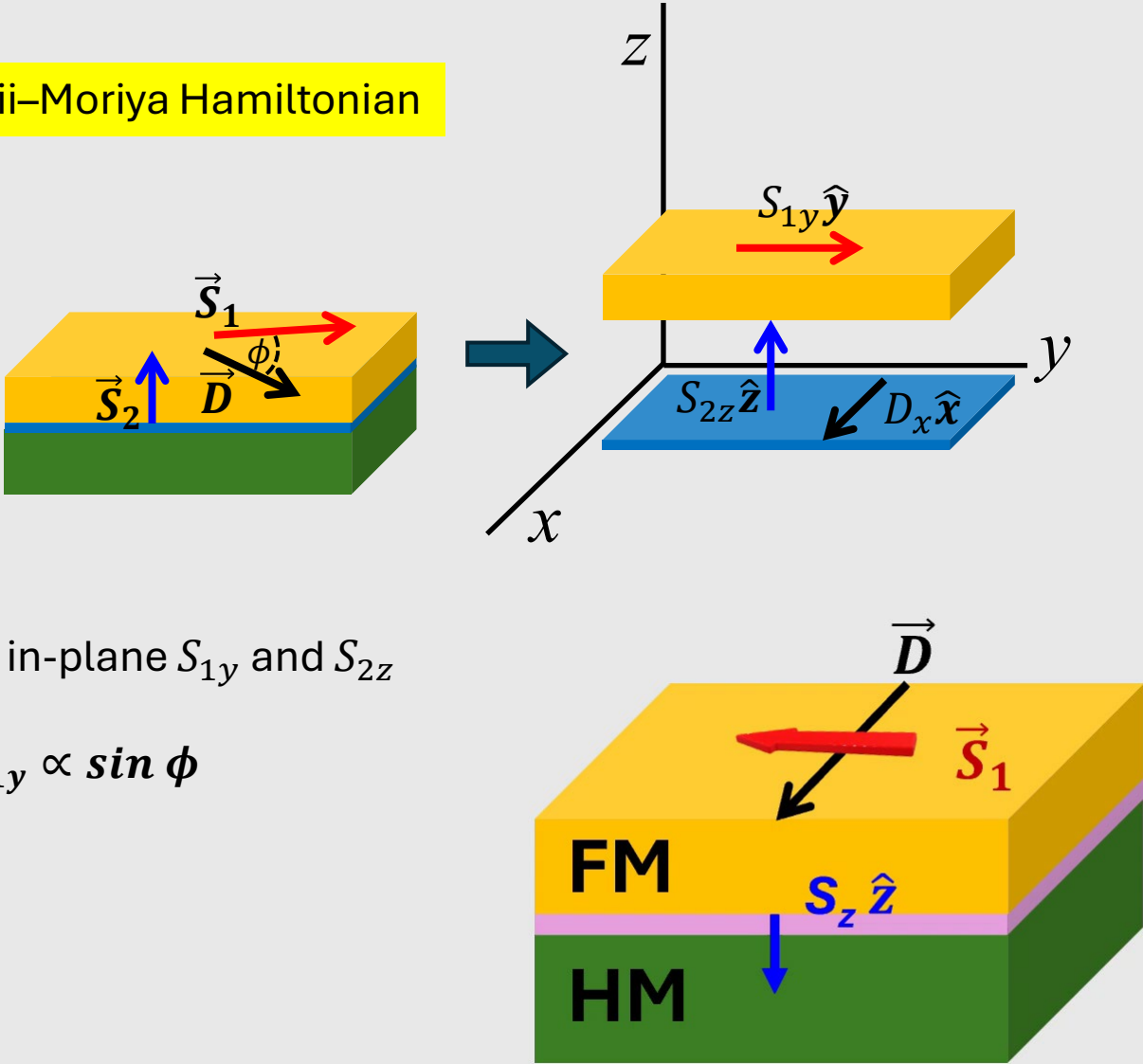
$$\vec{D} = D_x \hat{x}; \vec{S}_1 = S_{1x} \hat{x} + S_{1y} \hat{y}$$

$$H_{DM} = D_x S_{1y} S_{2z}$$

 Selectively couples the in-plane S_{1y} and S_{2z}

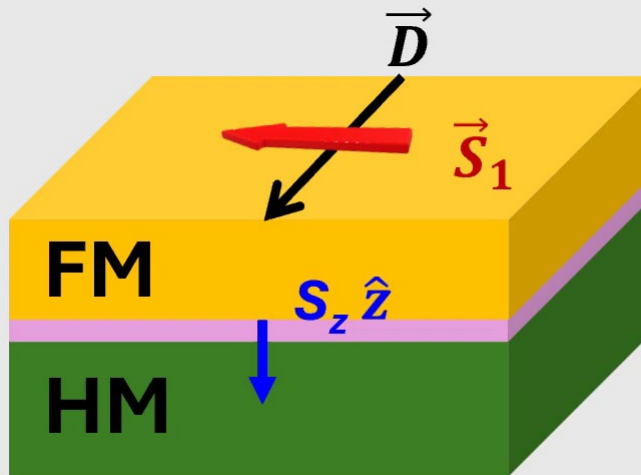
Effective field (B_{DM}) acts on $\vec{S}_2$ along $\hat{z}$ as
 
 $S_{1y} \propto \sin \phi$

Consistent with observations

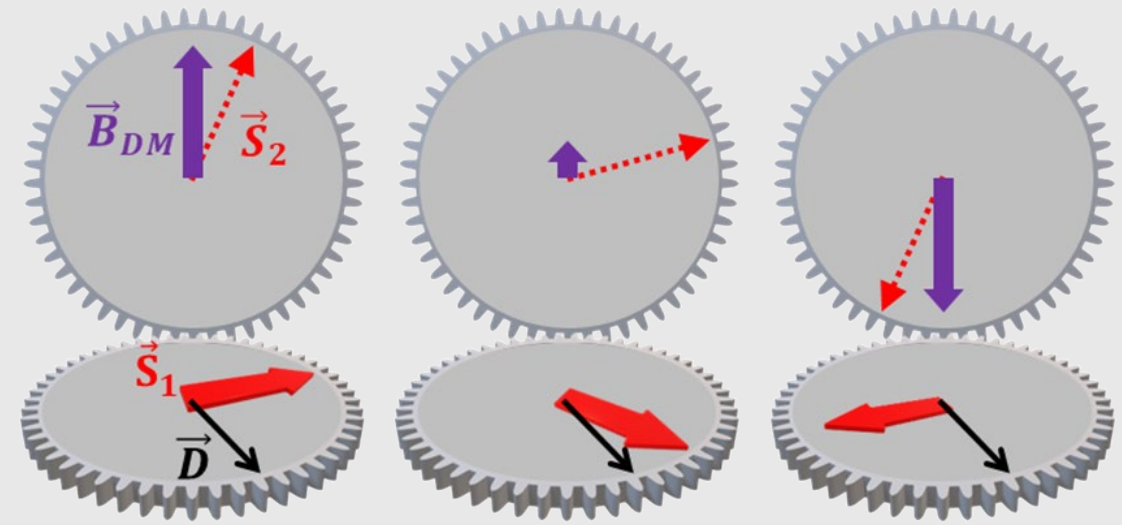
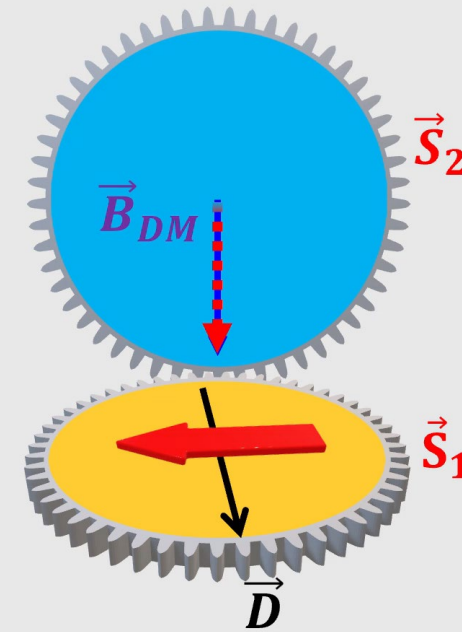


The DMI Mitre Gear

- **DMI Mitre Gear:** Rotation of the in-plane magnetization drives an orthogonal interfacial response with 1:1 gear ratio.



Our observation



DMI Mitre gear

Our suspect: interfacial DMI

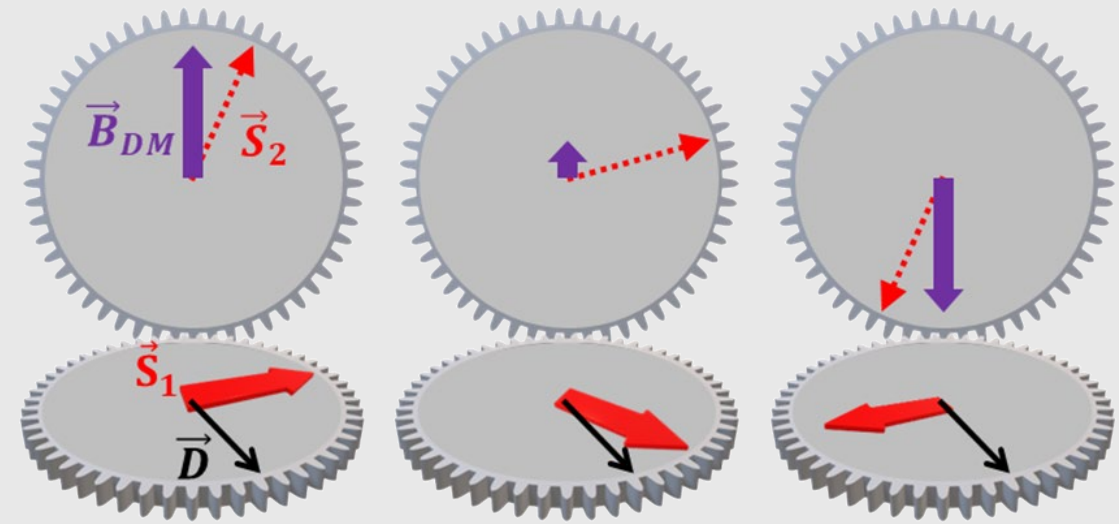
One ingredient accounts for the angular dependence, the interface origin, the response to growth and annealing and the current independence.

What is mostly missing

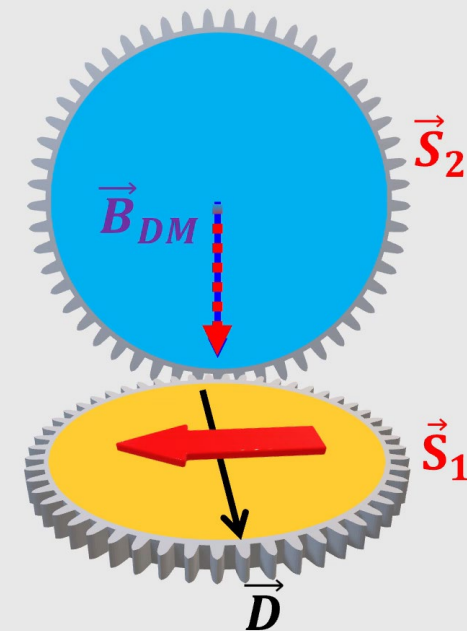
- A direct observation of the perpendicular magnetization
- A clear demonstration that spin-orbit coupling matters
- A way to control the effect

Where do we go from here?

- **Fundamental:** the generality of the phenomenon
- **Applications:** practical spintronic devices



May offer another route for achieving the goals of MultiSpin.AI

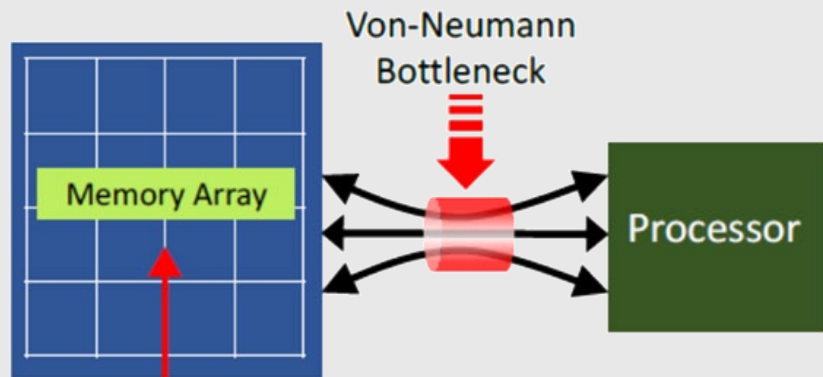


DMI Mitre gear

The end of Moore's law

Moore's Law: The number of transistors in a dense integrated circuit doubles about every two years

Von Neumann bottleneck

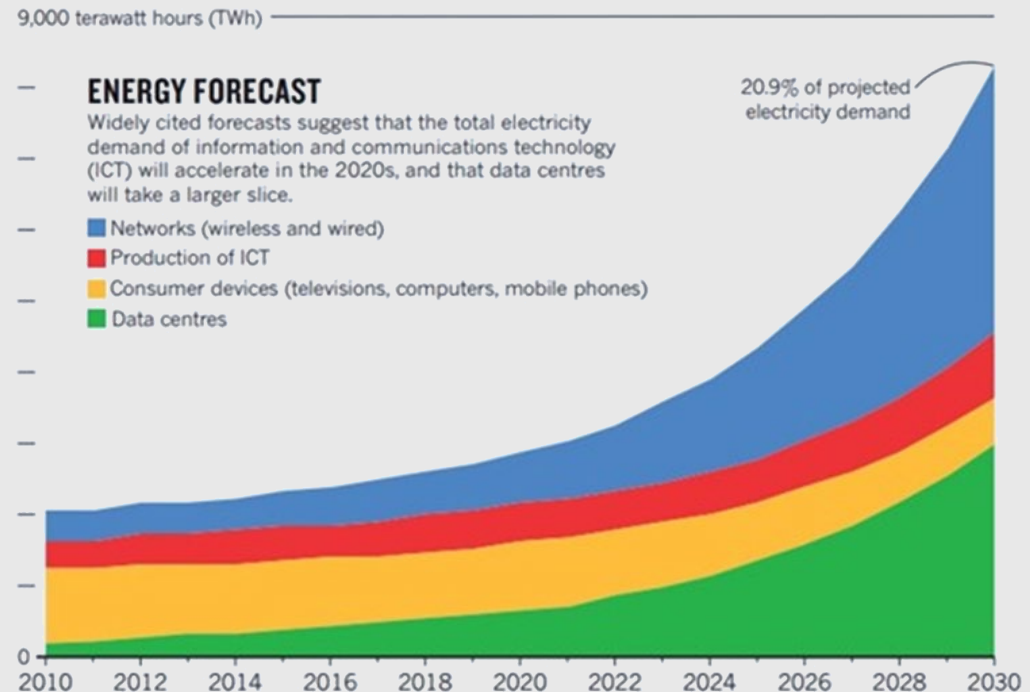


CPU execution time - a few nanoseconds or less
memory access times - tens to hundreds of nanoseconds

The end of the Dennard scaling law

Dennard scaling law: as transistors get smaller, their power density stays constant, so that the power use stays in proportion with area. Since around 2005–2007 Dennard scaling appears to have broken down

The hunger for power



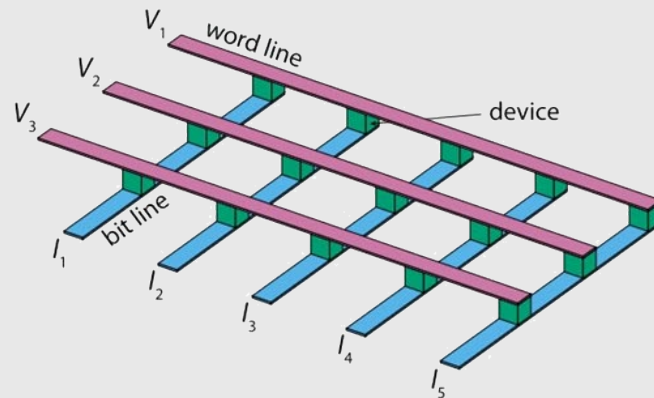
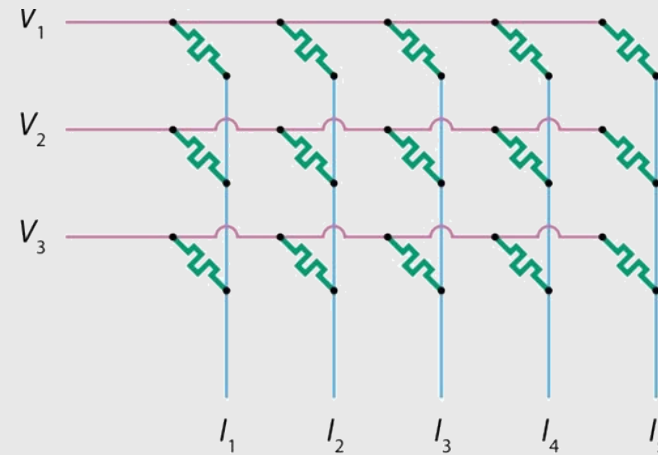
The crossbar –analogue multiplication and accumulation (MAC)

Analogue execution of the **linear** operations

In memory processing:
fast and energy efficient

removes major computation barriers
particularly for AI at the edge

$$I_i = \sum_j G_{ij} V_j$$



Ohm's law for crosspoint multiplication
Kirchhoff's law for summation

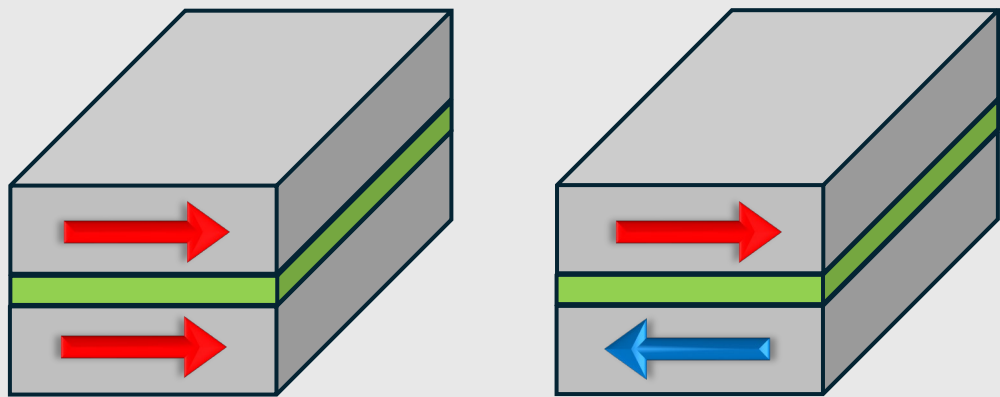
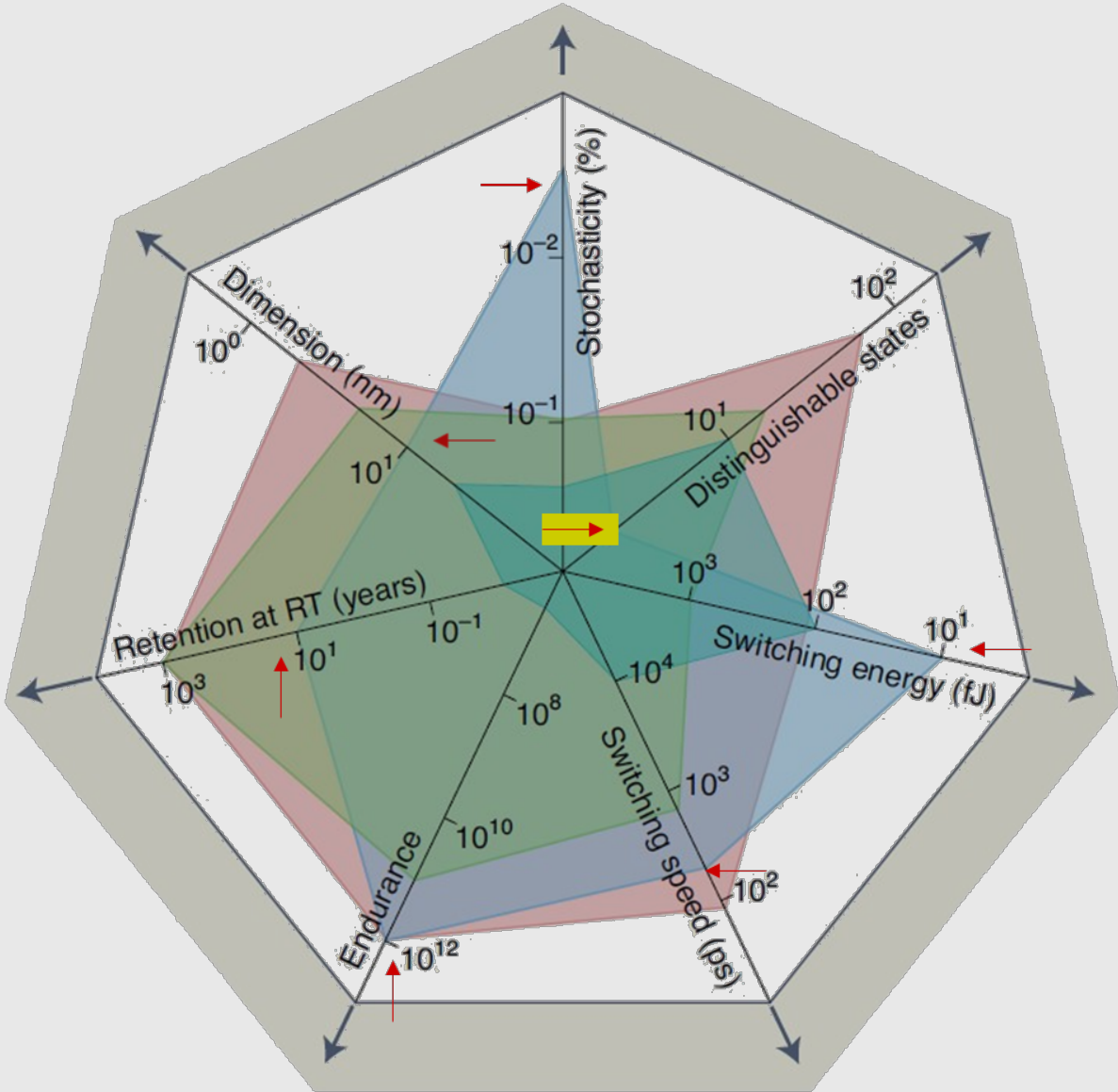
Advantages in speed and energy efficiency

The crossbar – material options

The weak spot of the magnetoresistance option

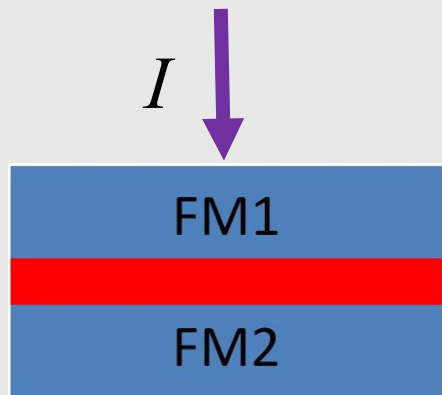
Distinguishable States

Spintronic configurations

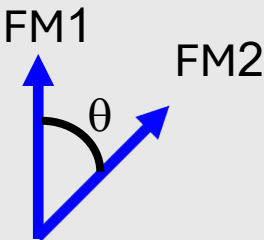


Resistive switching material:

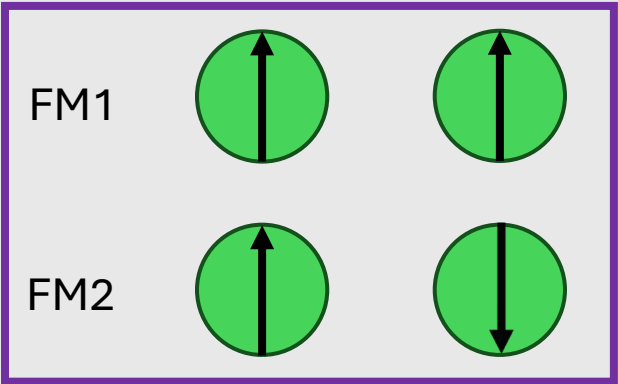
- Redox
- Magnetoresistive
- Phase change
- Ferroelectric



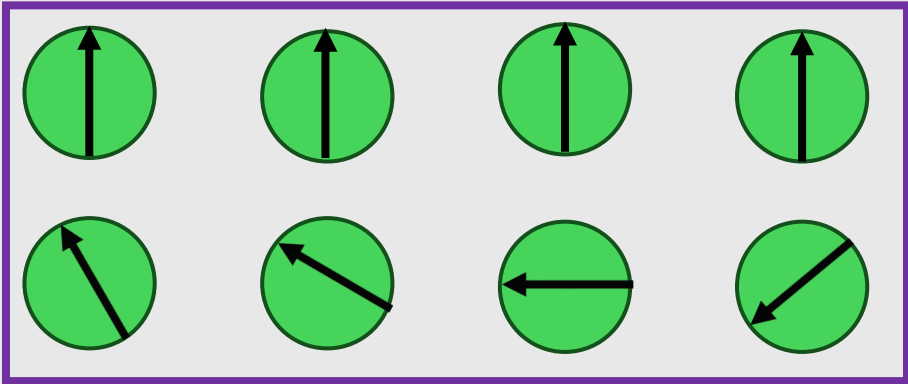
$$R_{junction} = R_{av} - \frac{1}{2} \Delta R \cos \vartheta$$



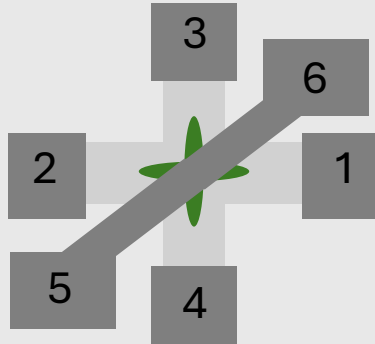
NOW



Our approach



Characterization of M²TJ

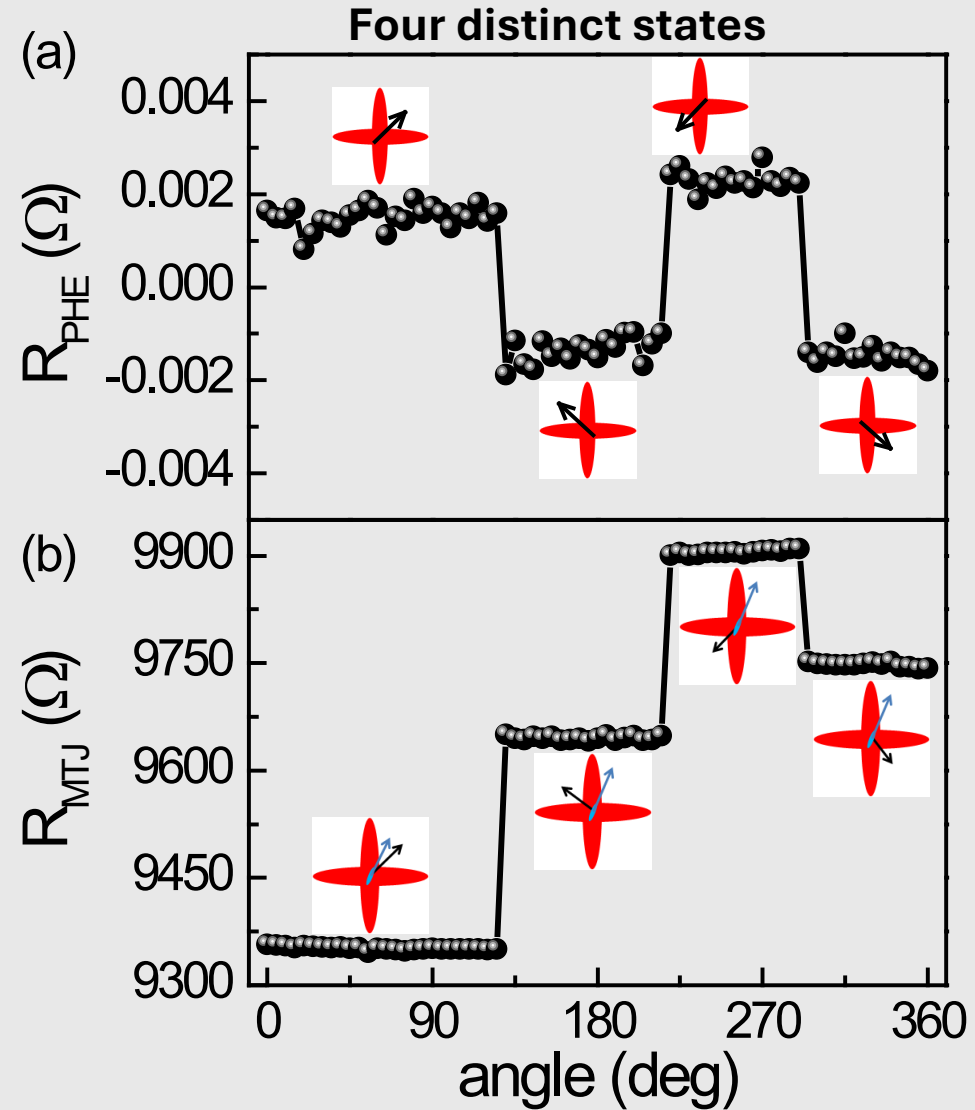


PHE: $I+, I- : V+, V- = 1, 2 : 3, 4$

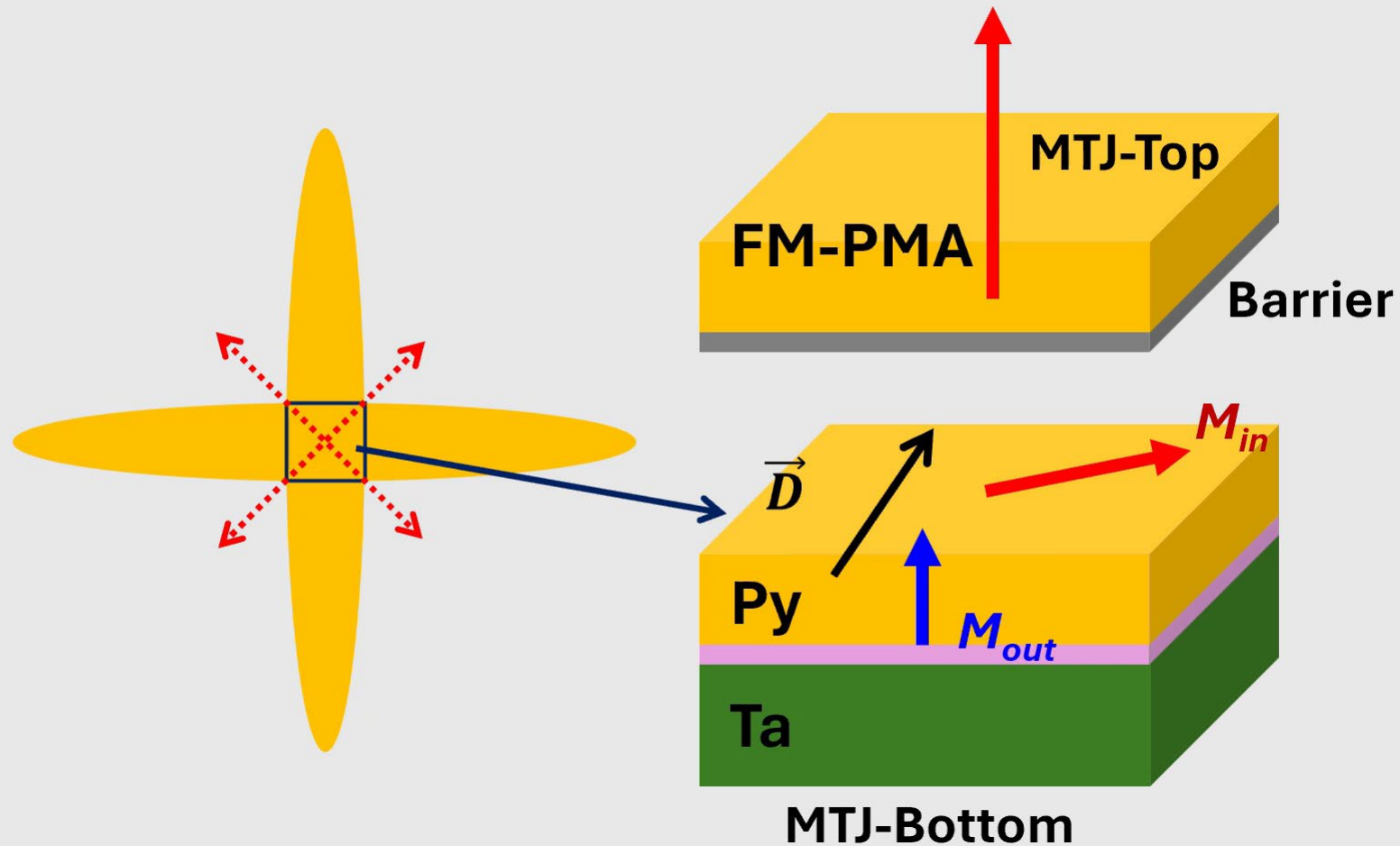
MTJ: $I+, I- : V+, V- = 6, 1 : 5, 2$

$$R_{\text{MTJ}}(\beta) = R_{\text{AV}} - a \cos(\beta - \beta_0)$$

$$R_{\text{PHE}}(\beta) = b_0 + b \sin(2\beta)$$

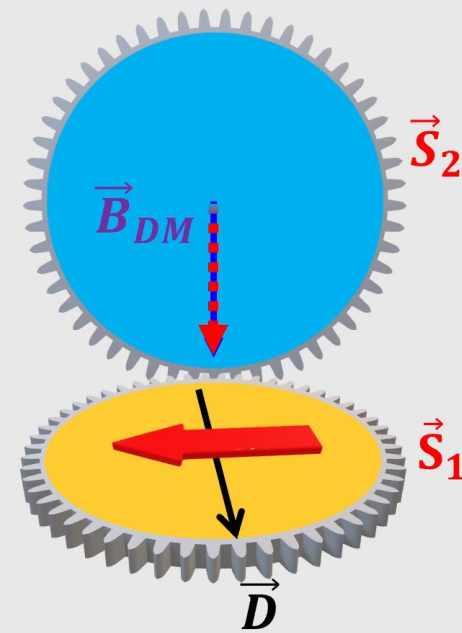


Why it matters: a perpendicular readout of an in-plane bit



One of the device routes explored in MultiSpin.AI (EIC Pathfinder)

- APHE in Ta/Py and Ta/CoFeB bilayers: probably a general phenomenon
- Interfacial perpendicular magnetization, most likely driven by DMI
- Manipulation of perpendicular magnetization by rotating in-plane magnetization
- Amplitude and phase depend on the seed layer and on annealing: consistent with a role of strain, no coherent picture yet
- A pathway to novel spintronic devices that exploit chirality controlled, multistate memory functionality



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A. Ghosh, A. Zaig, D. B. C. Gonçalves, S. Cardoso and L. Klein, Appl. Phys. Lett. 128, 221601 (2026)

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