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TOHOKU UNIVERSITY

Current-induced dynamics in noncollinear antiferromagnetic Mn_3Sn

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3. Center for Innovative Integrated Electronic Systems (CIES), Tohoku Univ.
4. WPI-Advanced Institute for Materials Research (WPI-AIMR), Tohoku Univ.
5. Inamori Research Institute of Science (InaRIS)

RIEC cies CSIS AIMR InaRIS

[Collaborators for this topic]

Y. Takeuchi, **J.-Y. Yoon**, **Y. Yamane**, T. Uchimura, Y. Sato, R. Itoh, B. Jinnai, **J. Han**, S. Kanai, S. DuttaGupta, H. Ohno (Tohoku Univ.), J. Ieda (JAEA)

Luqiao Liu and his team members (MIT)

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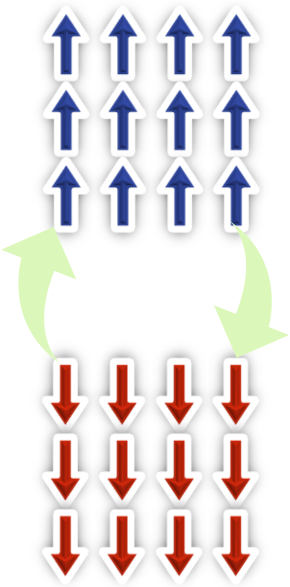
Outline

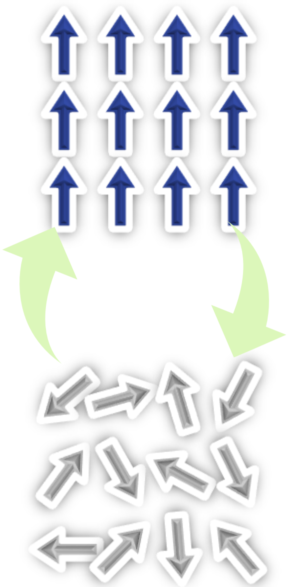
1. Introduction: Non-collinear antiferromagnet
2. Current-induced dynamics in non-collinear antiferromagnet Mn_3Sn
   - Preparation of epitaxial M-plane-oriented Mn_3Sn thin film
   - Chiral-spin rotation by spin-orbit torque
   - Handedness anomaly in current-induced switching
3. Thermal stability of single nanodot
4. Summary

Electrical control of collective spin structures

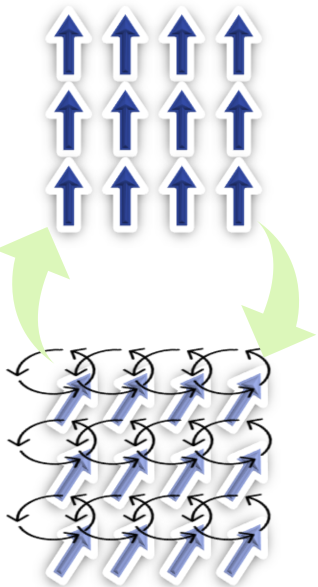
Collinear Ferromagnet



Magnetization reversal (1999)

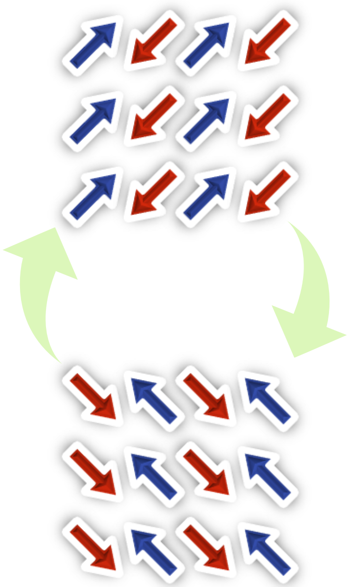


Magnetic phase transition (2000)



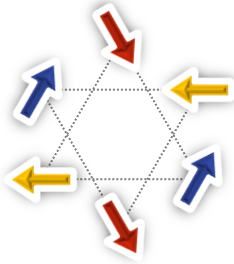
Oscillation (2003)
Resonance (2005)

Collinear Antiferromagnet



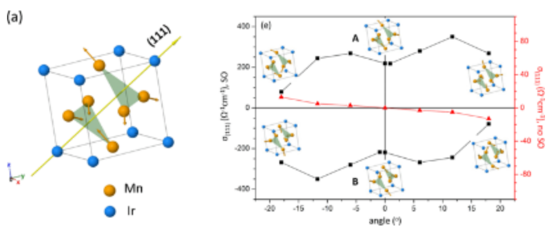
Néel-vector rotation (2016)

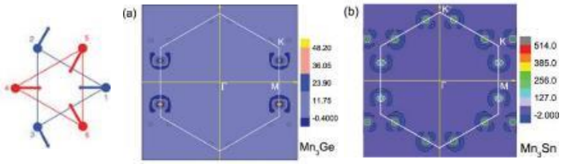
Non-collinear Antiferromagnet



Non-collinear antiferromagnets (NC-AFM)

◆ Theory



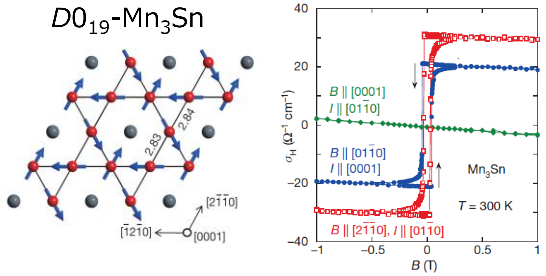


H. Chen *et al.*, PRL **112**, 017205 (2014).

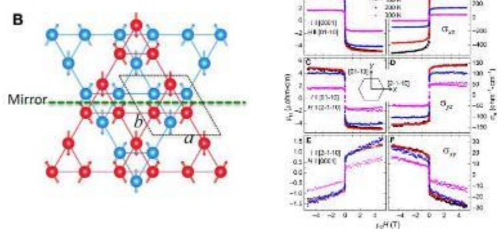
J. Kübler & C. Felser, EPL **108** 67001 (2014).

◆ Experiment (Anomalous Hall effect)

$D0_{19}$-Mn_3Sn



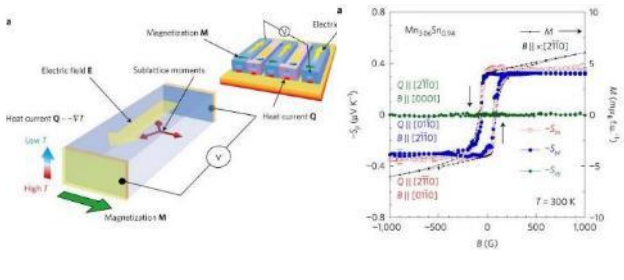
$D0_{19}$-Mn_3Ge

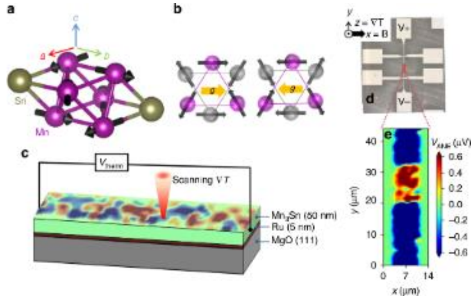


S. Nakatsuji *et al.*, Nature **527**, 212 (2015).

A. K. Nayak et al., Sci.Adv. **2**, e1501870 (2016).

◆ Experiment (Anomalous Nernst effect)

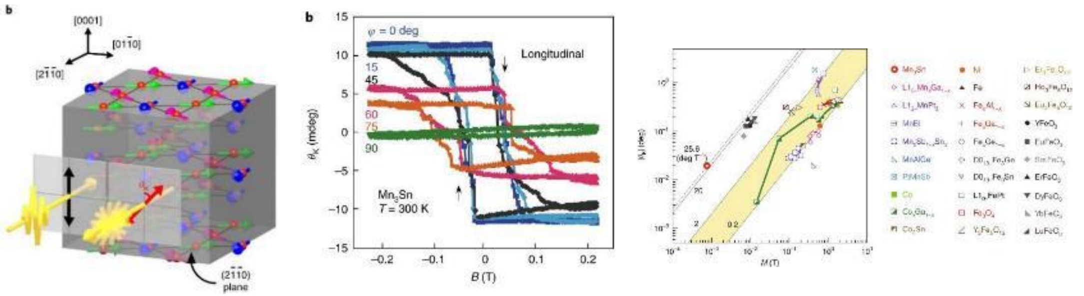




M. Ikhlas *et al.*, Nat. Phys. **13**, 1085 (2017).

H. Reichlova *et al.*, NCOMM **10**, 5459 (2019).

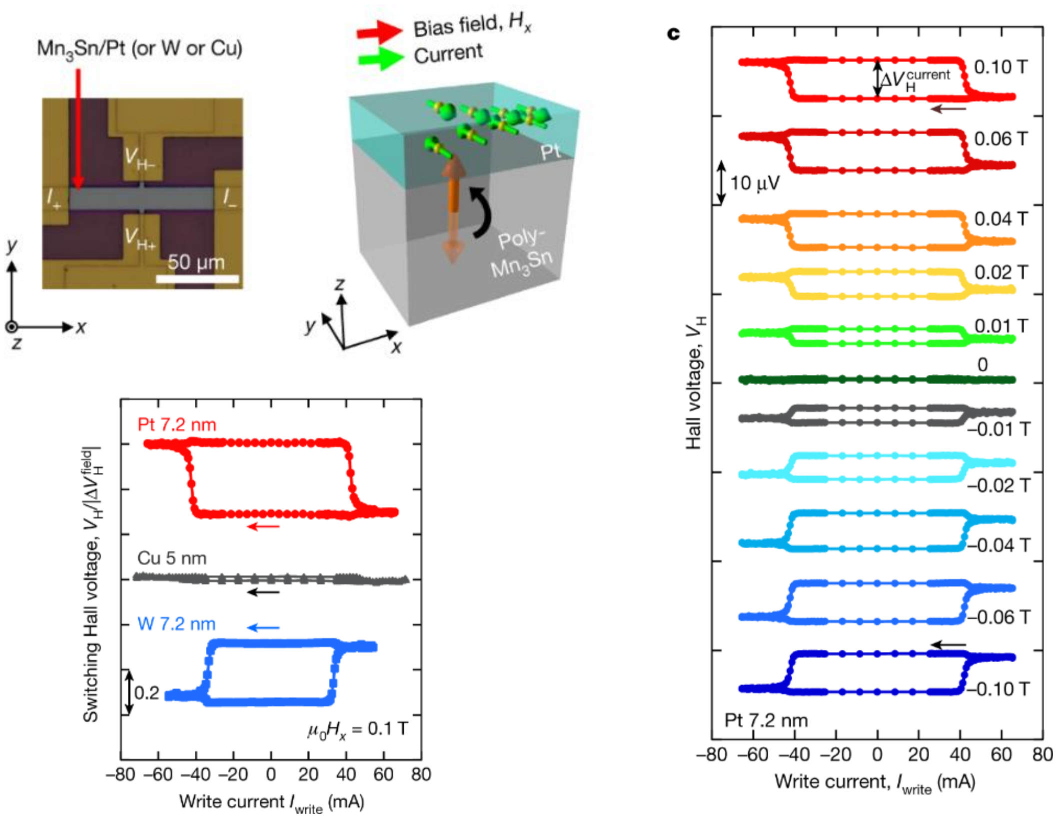
◆ Experiment (Magneto-optical Kerr effect)

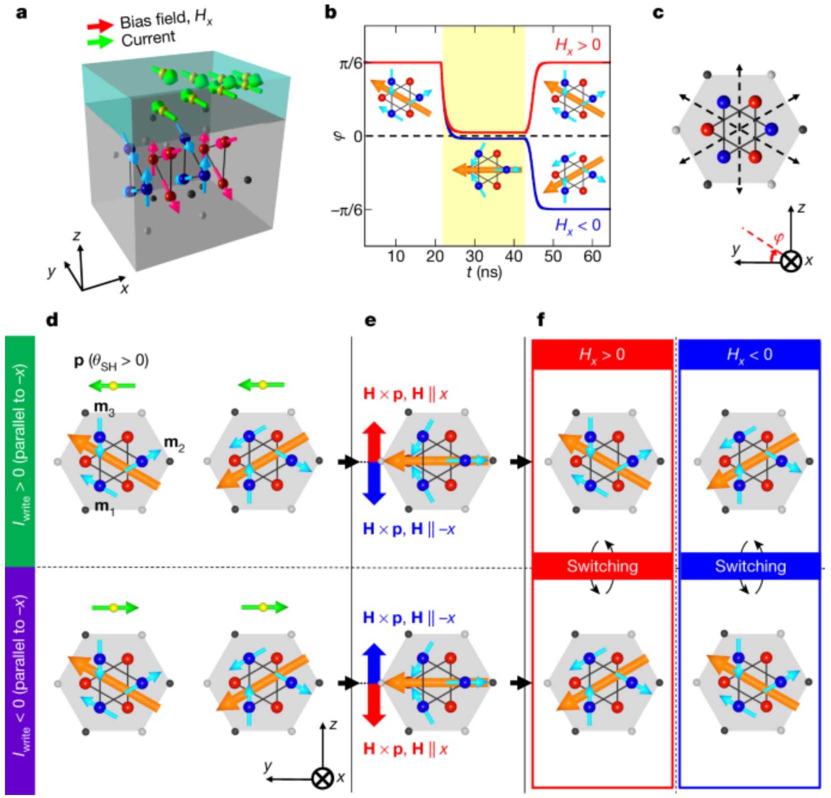


T. Higo *et al.*, Nat. Photo. **12**, 73 (2018).

Behaves like ferromagnet due to non-vanishing Berry curvature

Switching of chiral-spin structure





H. Tsai *et al.*, Nature **580**, 608 (2020); T. Higo *et al.*, Nature **607**, 474 (2022)

Same protocol as SOT-induced switching of magnetization in FMs.

- ➢ **Any unique phenomena in NC-AFM? ··· Chiral-spin rotation**
- ➢ **Is it really the same? ··· Handedness anomaly**

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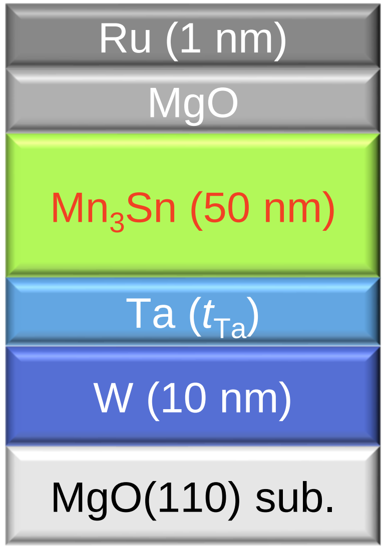
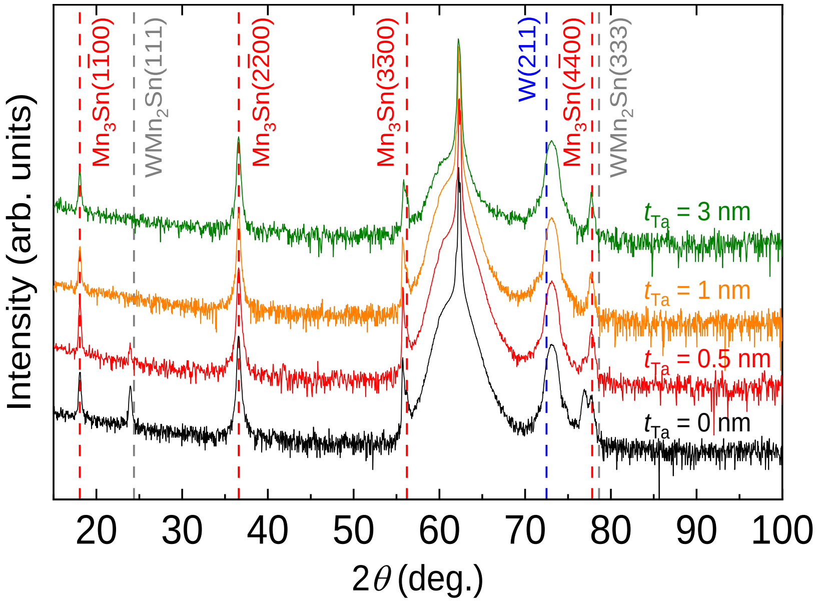
Structural characterization by XRD

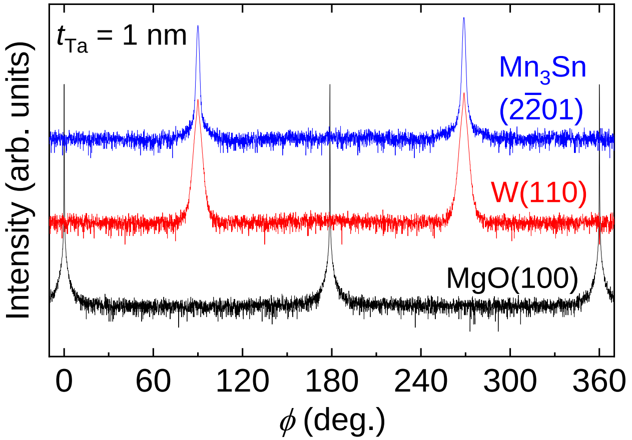
- Stack structure



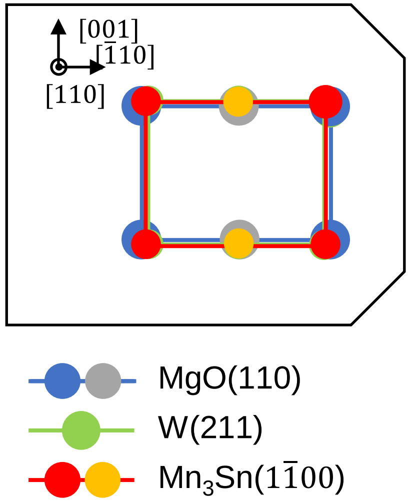
- XRD (2θ-θ scan)

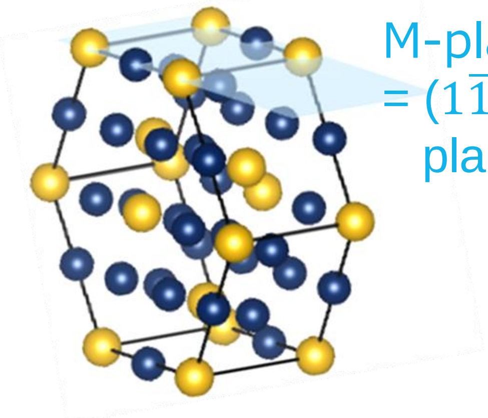


- XRD (Φ scan)



Epitaxial relationship



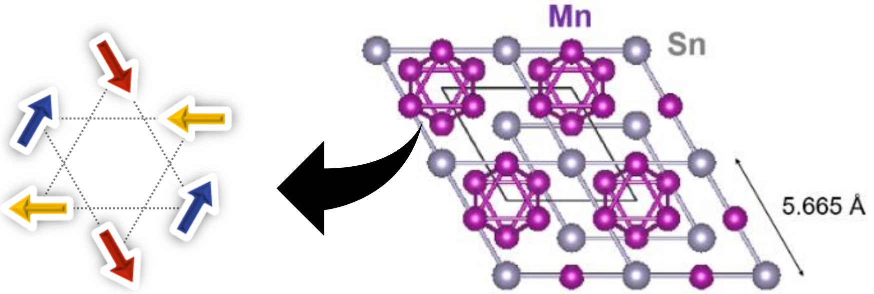


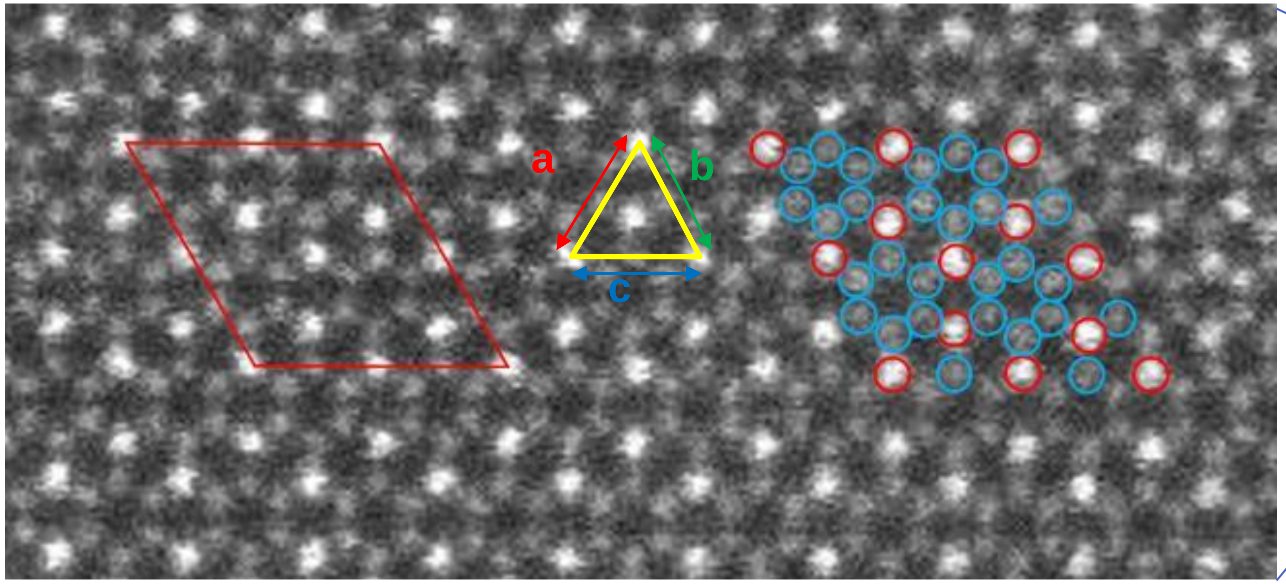
M-plane = (1$\bar{1}$00) plane

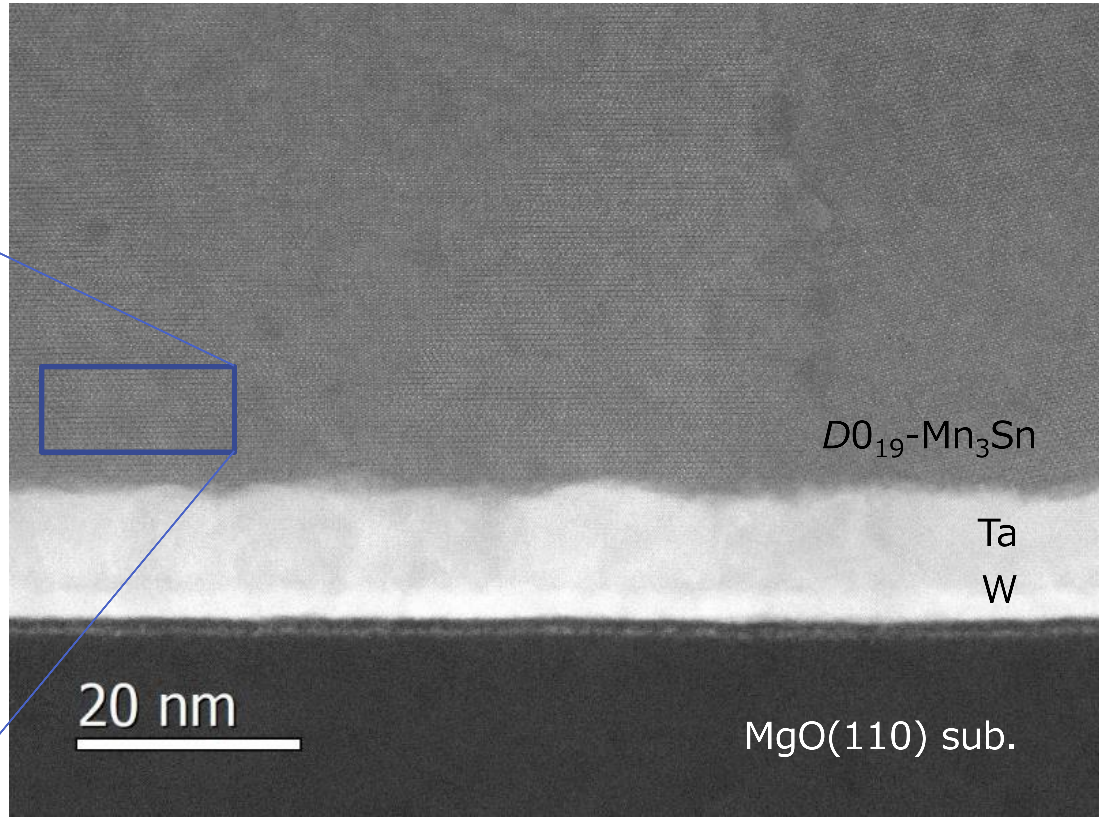
- W underlayer is suitable to form M-plane-oriented Mn_3Sn.
- Insertion of Ta prevents the formation of WMn_2Sn.
- Epitaxial relationship:
  - MgO(110)[001] ll W(211)[01$\bar{1}$] ll Mn_3Sn(1$\bar{1}$00)[0001]

J.-Y. Yoon *et al*., Appl. Phys. Express **13**, 013001 (2020).

TEM image of M-plane epitaxial stack





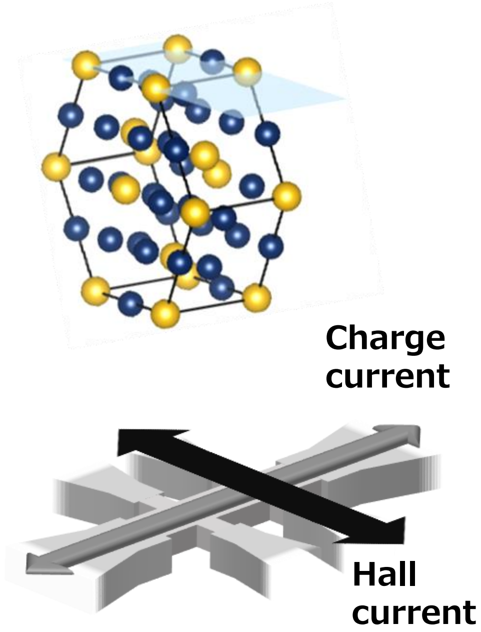


a ≈ 5.6 Å
b ≈ 5.6 Å
c ≈ 5.6 Å

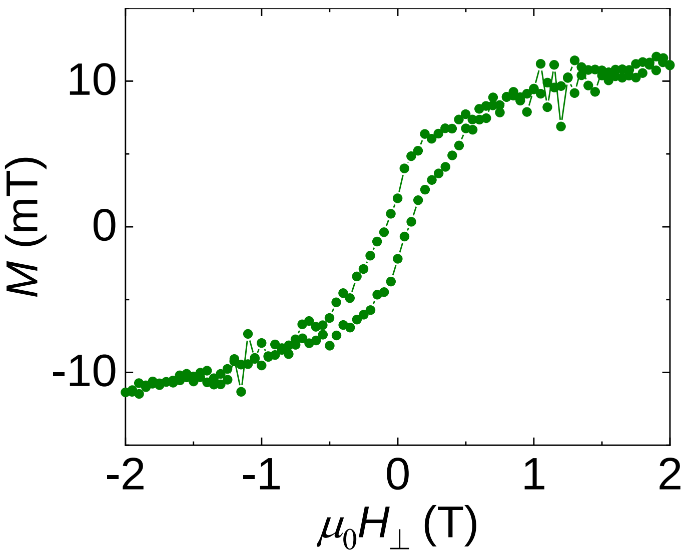
○ : Mn
○ : Sn

Y. Takeuchi *et al*., Nat. Mater. **20**, 1364 (2021)

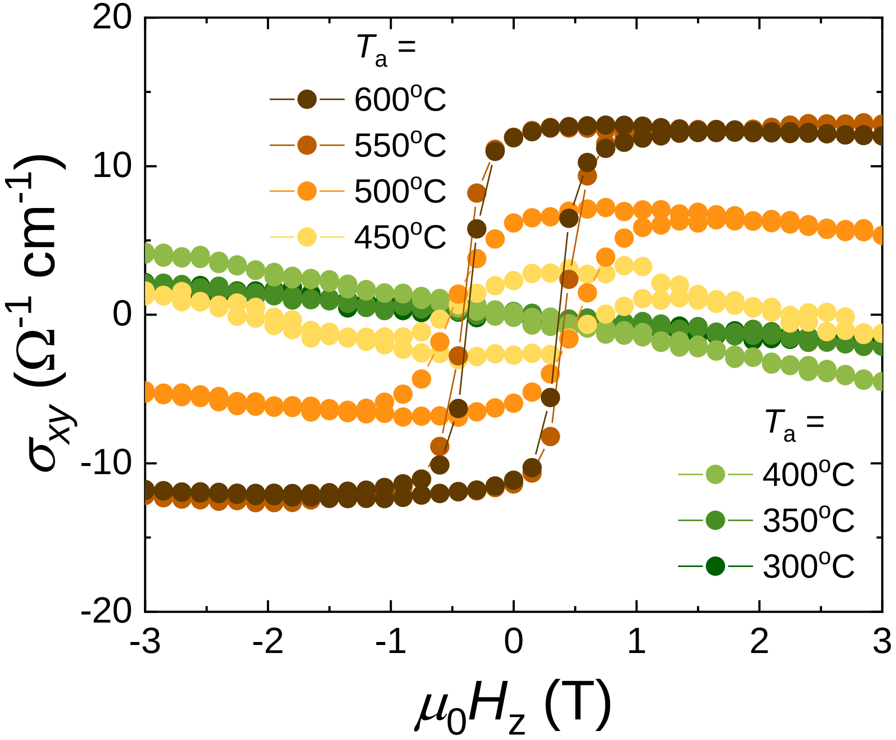
Magnetic and magneto-transport properties



- $M - H$



- $\sigma_{xy} - H_{\perp}$



- Small residual magnetization ~ 5 mT
- Large anomalous Hall conductivity ~ 13 $\Omega^{-1}cm^{-1}$ (close to the bulk value)

J.-Y. Yoon et al., Appl. Phys. Express **13**, 013001 (2020).
J.-Y. Yoon et al., AIP Adv. **11**, 065318 (2021).

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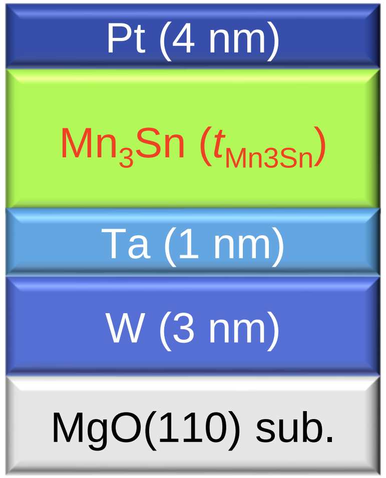
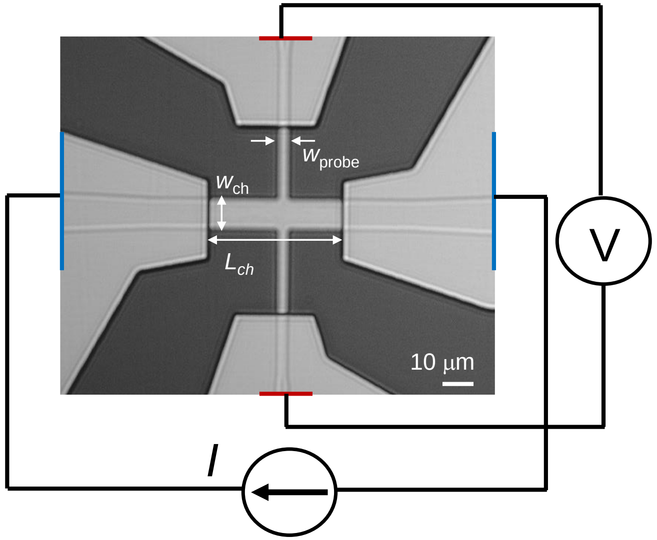
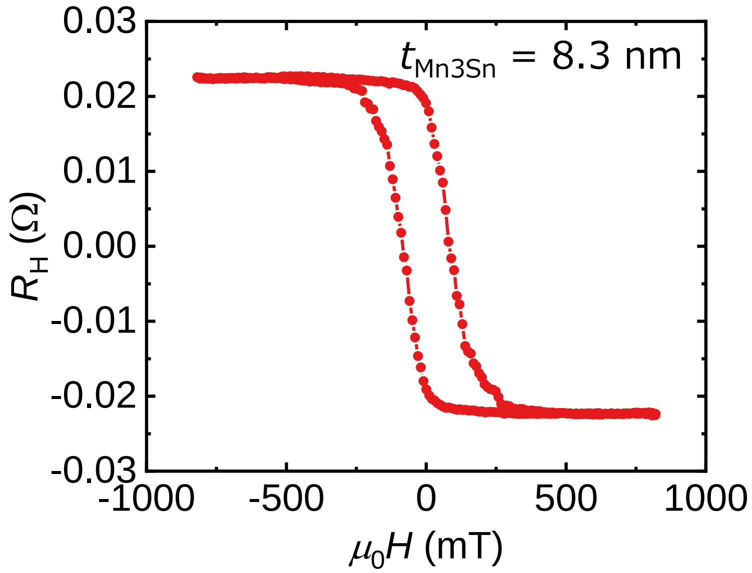
Sample structure and R_H-H loop







- t_{Mn3Sn}: 8.3 – 22.5 nm
- Sandwiched by Pt and W/Ta
  ➔ Enhanced SOT

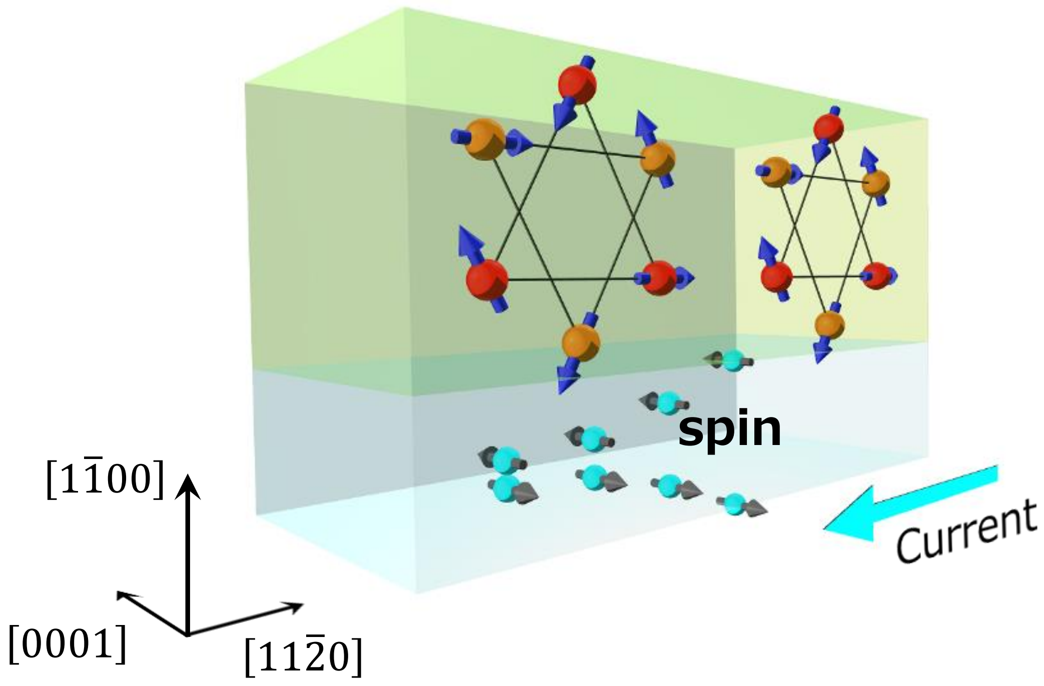
- W_{ch}: 3 – 50 μm
  (focus on 10 μm today)
- L_{ch}: 50 μm
- W_{probe}: 3 μm

- Negative R_H-H loop
  ➔ AHE due to chiral-spin structure
- Square hysteresis
  even at t_{Mn3Sn} = 8.3 nm

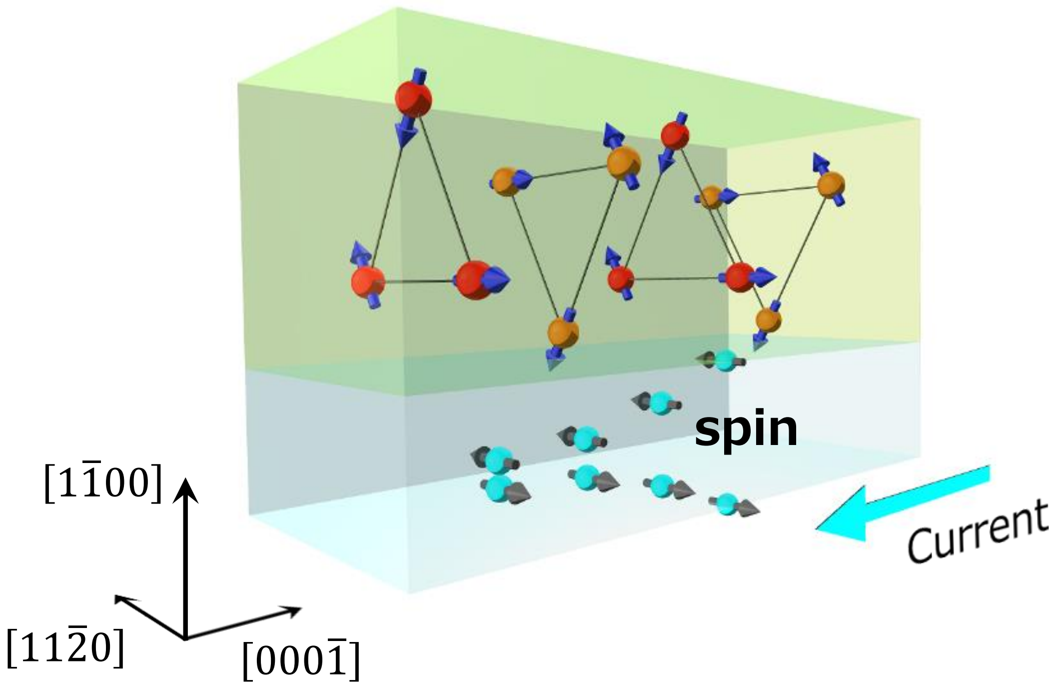
Y. Takeuchi *et al*., Nat. Mater. **20**, 1364 (2021)

Configurations

s ⊥ kagome plane

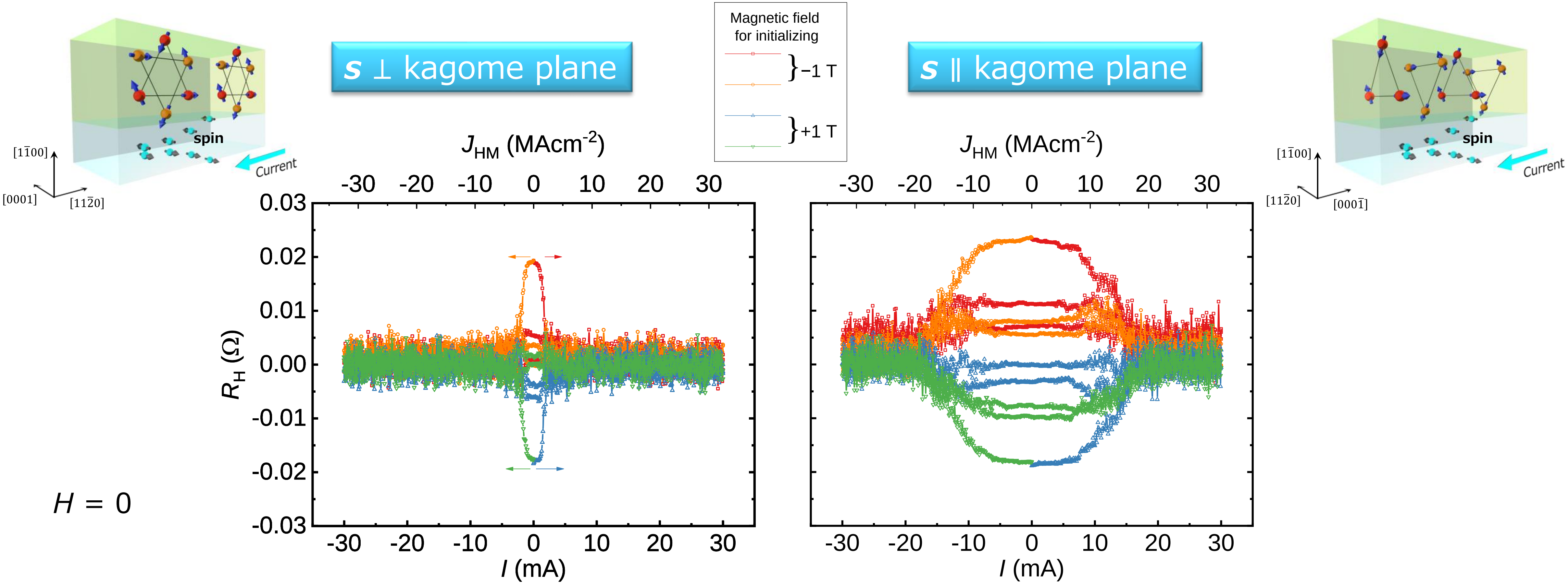


s ∥ kagome plane



Y. Takeuchi *et al*., Nat. Mater. **20**, 1364 (2021)

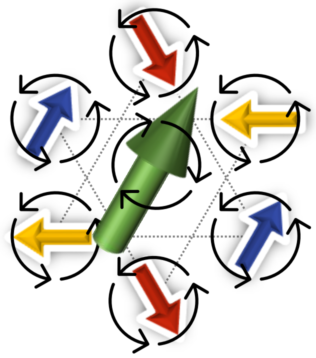
Response of Hall resistance to current

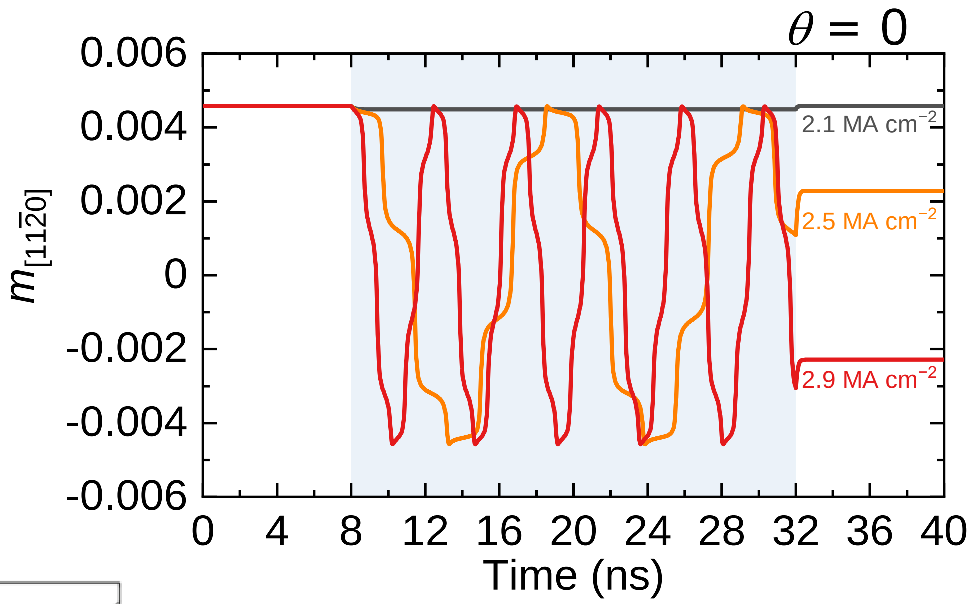


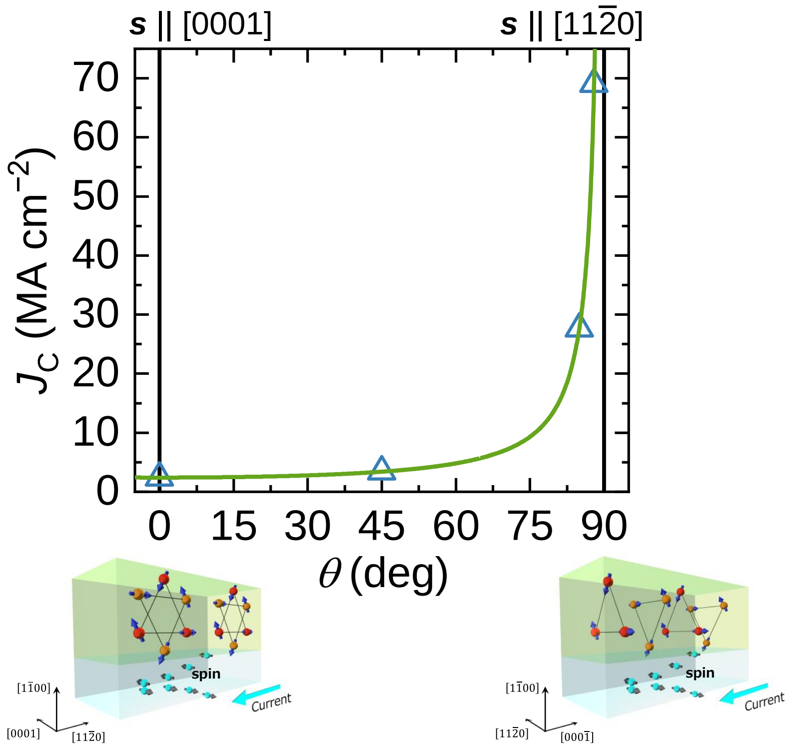
- R_H transits to intermediate level regardless of directions of initializing field and current.
- Threshold currents are largely different between the two configurations.
- Fluctuation level is largely different below and above the threshold current.

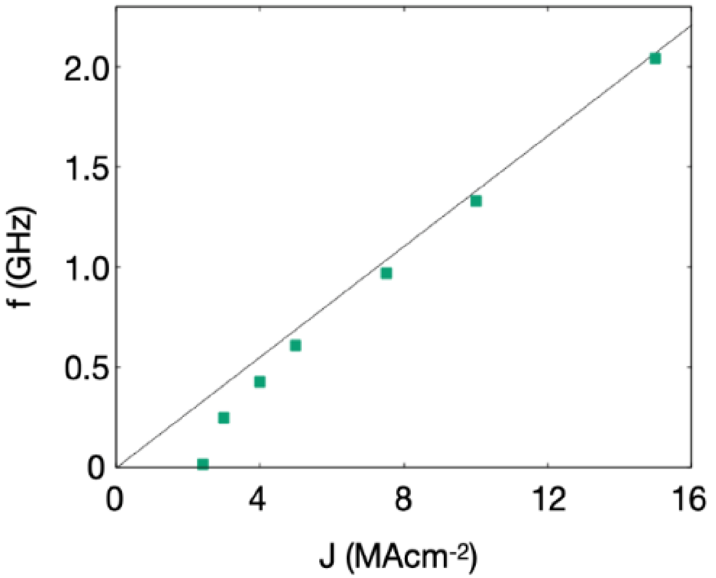
Y. Takeuchi *et al*., Nat. Mater. **20**, 1364 (2021)

Numerical calculation with LLG equation









- Chiral-spin structure coherently rotates above a threshold.
- Frequency varies with the applied current.
  - Tunable oscillator?
- Threshold current increases with θ, consistent with experiment.

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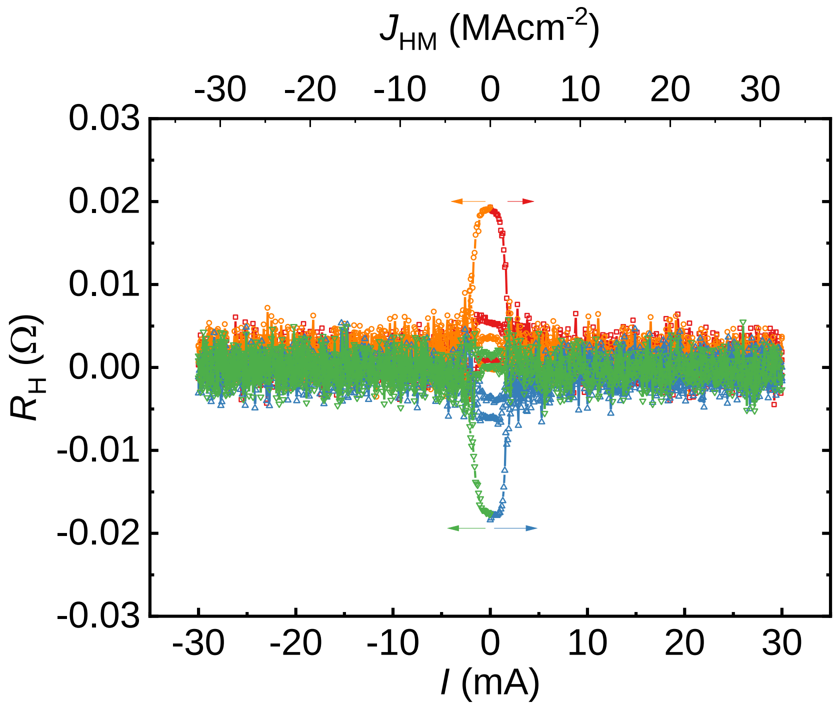
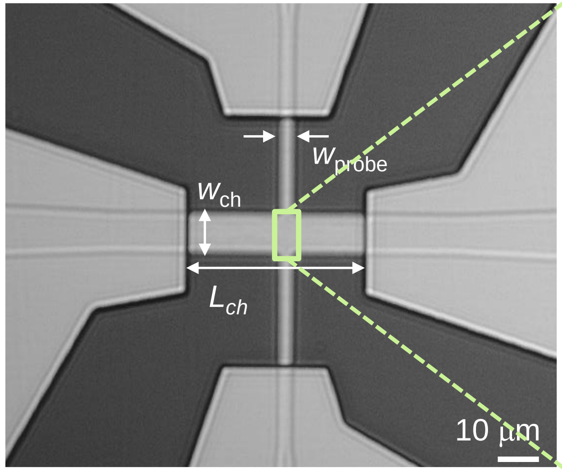
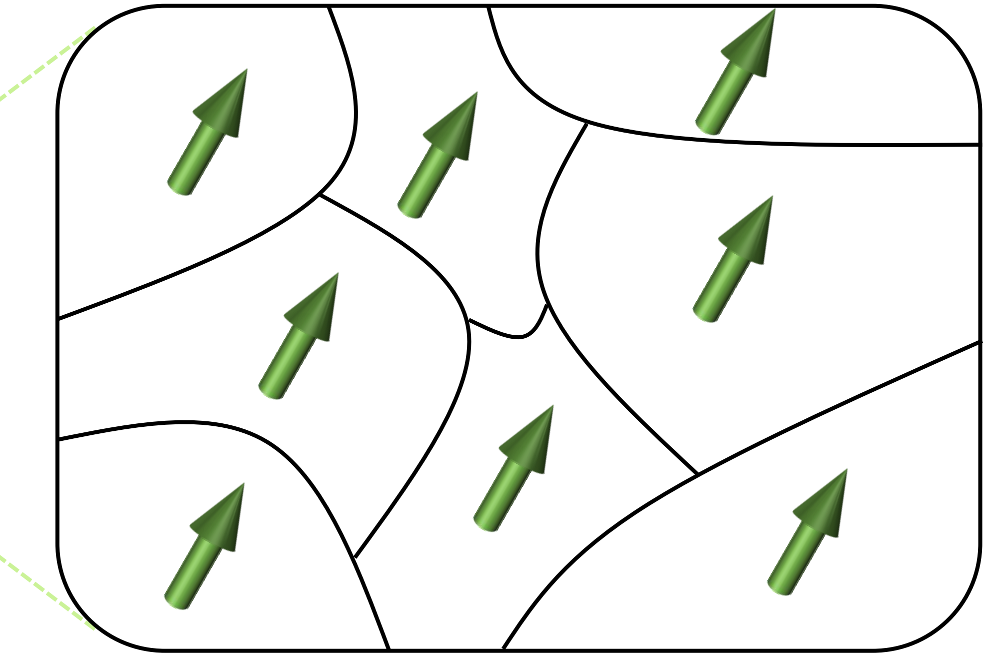
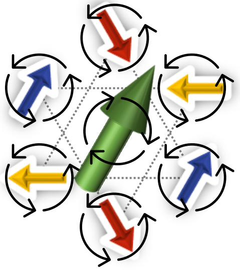
Possible scenario







1. Chiral-spin structure starts with uniform state by initializing field.
2. Hall cross (3 x 10 μm^2) should consist of multiple domains.
3. Chiral-spin structure in each domain starts rotating above I_C.
4. When I is turned off, each domain settles into one of the six stable points.
5. R_H is observed as an average of each domain.



Y. Takeuchi *et al*., Nat. Mater. **20**, 1364 (2021)

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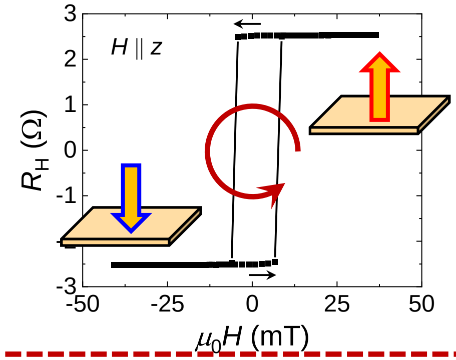
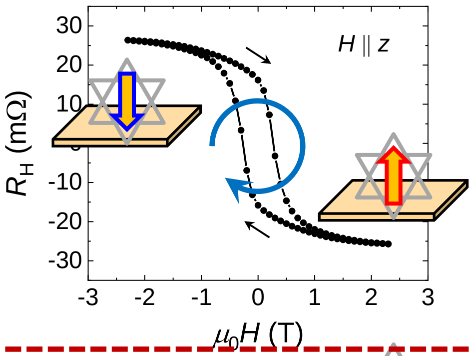
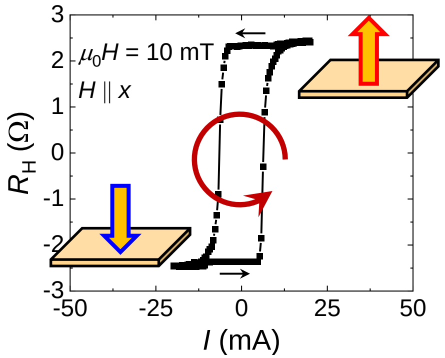
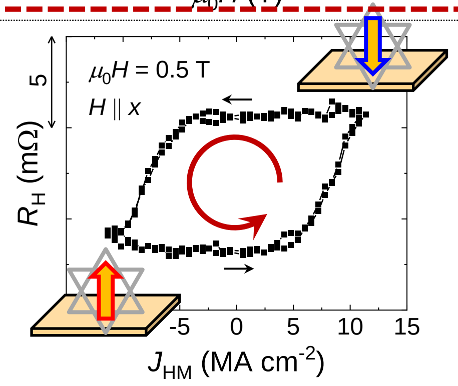
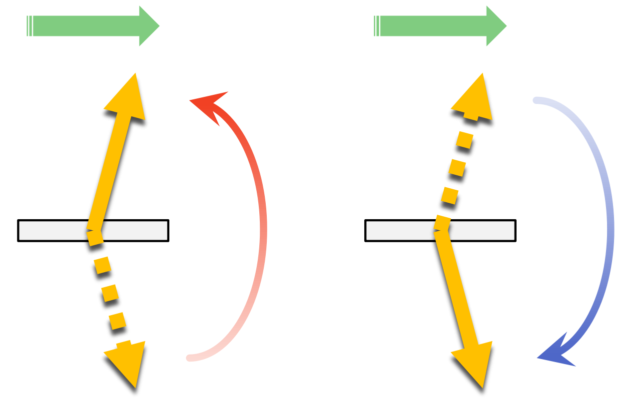
Anomaly in switching behavior in NCAFM

z, $y \otimes \rightarrow x$; $\otimes$ $\boldsymbol{\sigma}$ in Mn_3Sn or CoFeB; $\rightarrow$ ***I*, *H*$_x$**	W/CoFeB/MgO	Mn_3Sn/Pt
R-H_z loop		
R-*I* loop		
Switching polarity	Same	Opposite

SOT-induced switching

Dipole	Octupole
$+H_x \parallel +I_x$	$+H_x \parallel +I_x$



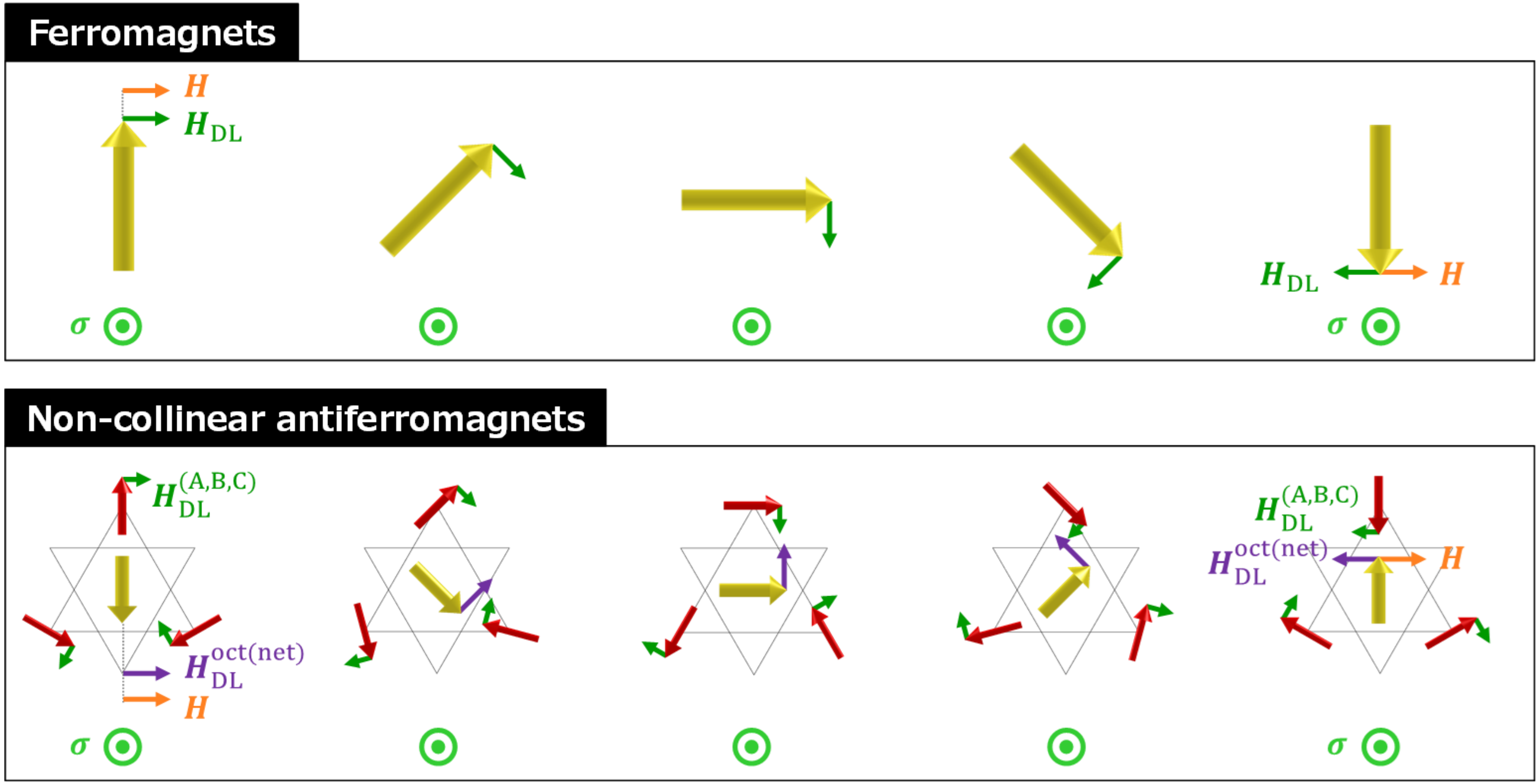
CoFeB	Mn_3Sn

Opposite rotation handedness under SOT?

We track the SOT effect by harmonic measurements **during the rotation of octupole moment**

J.-Y. Yoon et al., *Nat. Mater.* **22**, 1106–1113 (2023).

Handedness anomaly in octupole dynamics



The handedness anomaly of the octupole dynamics originates from

- the chiral nature of the non-collinear AFM
- the coordinative and assembled SOT effect on the sublattice spins

J.-Y. Yoon et al., *Nat. Mater.* **22**, 1106–1113 (2023).

Handedness anomaly in octupole dynamics

nature materials

Article

https://doi.org/10.1038/s41563-023-01620-2

Handedness anomaly in a non-collinear antiferromagnet under spin–orbit torque

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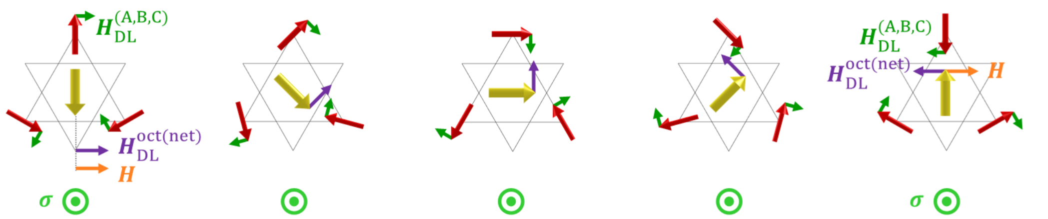
Ju-Young Yoon[1,2,3,10], Pengxiang Zhang[3,10], Chung-Tao Chou[3,4], Yutaro Takeuchi[5], Tomohiro Uchimura[1,2], Justin T. Hou[3], Jiahao Han[1], Shun Kanai[1,2,5,6,7], Hideo Ohno[1,2,5,6,8], Shunsuke Fukami[1,2,5,6,8,9] & Luqiao Liu[3]

Non-collinear antiferromagnets are an emerging family of spintronic materials because they not only possess the general advantages of antiferromagnets but also enable more advanced functionalities. Recently, in an intriguing non-collinear antiferromagnet Mn_3Sn, where the octupole moment is defined as the collective magnetic order parameter, spin–orbit torque (SOT) switching has been achieved in seemingly the same protocol as in ferromagnets. Nevertheless, it is fundamentally important to explore the unknown octupole moment dynamics and contrast it with the magnetization vector of ferromagnets. Here we report a handedness anomaly in the SOT-driven dynamics of Mn_3Sn: when spin current is injected, the octupole moment rotates in the opposite direction to the individual moments, leading to a SOT switching polarity distinct from ferromagnets. By using second-harmonic and d.c. magnetometry, we track the SOT effect onto the octupole moment during its rotation and reveal that the handedness anomaly stems from the interactions between the injected spin and the unique chiral-spin structure of Mn_3Sn. We further establish the torque balancing equation of the magnetic octupole moment and quantify the SOT efficiency. Our finding provides a guideline for understanding and implementing the electrical manipulation of non-collinear antiferromagnets, which in nature differs from the well-established collinear magnets.

Non-collinear antiferromagnets



J.-Y. Yoon et al., *Nat. Mater.* **22**, 1106–1113 (2023).

News & views

Spintronics

https://doi.org/10.1038/s41563-023-01647-5

A handy way to rotate chiral spins

Enrique del Barco & Andrew D. Kent

In a non-collinear antiferromagnet, elementary spins rotate with opposite handedness with respect to the collective octupole magnetic moment when stirred by spin currents.

The reorientation and excitation of mag[illegible] moments in magnetic materials by injecting currents is fundam[illegible] field of spintronics and its wide range of applications. C[illegible] the most relevant applications involve[illegible] dvanced semiconducto[illegible] ics has envi[illegible] rom[illegible] atomic [illegible] a specific [illegible] category, characterize[illegible] tating around a [illegible] point within a crystal lattice. A ke[illegible] ite for utilizing these materials in spintronic devices is then to u[illegible] erstand how they respond when stimulated by spin currents. Now, writing in *Nature Materials*, Luqiao Liu and colleagues[3] report that the response of chiral antiferromagnets is distinct from that of other magnetic materials in intriguing and counterintuitive ways.

The material they studied is Mn_3Sn, in which the spins of Mn atoms form a non-collinear chiral structure, with the three Mn spins orienting themselves along different axes. To grasp the essence of the findings, envision yourself on the terrace of a fancy restaurant on the French Riviera. You have just ordered an espresso to complement a delight-

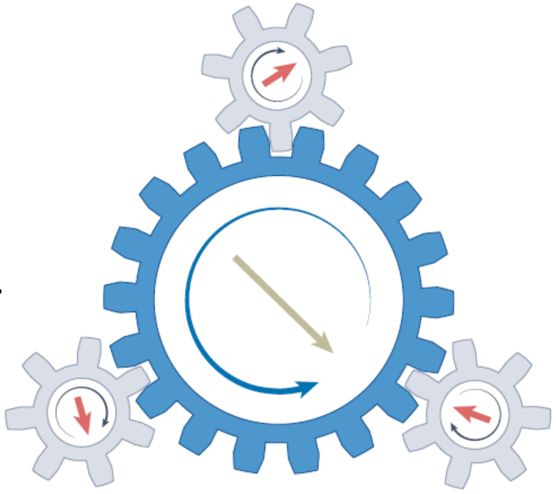


Fig. 1 | Opposite handedness of elemental and collective moments in chiral antiferromagnets. Mechanical analogy illustrating the collective octupole moment in Mn_3Sn, represented by the large blue gear, rotating with opposite handedness compared with the individual Mn spins, symbolized by the small grey gears.

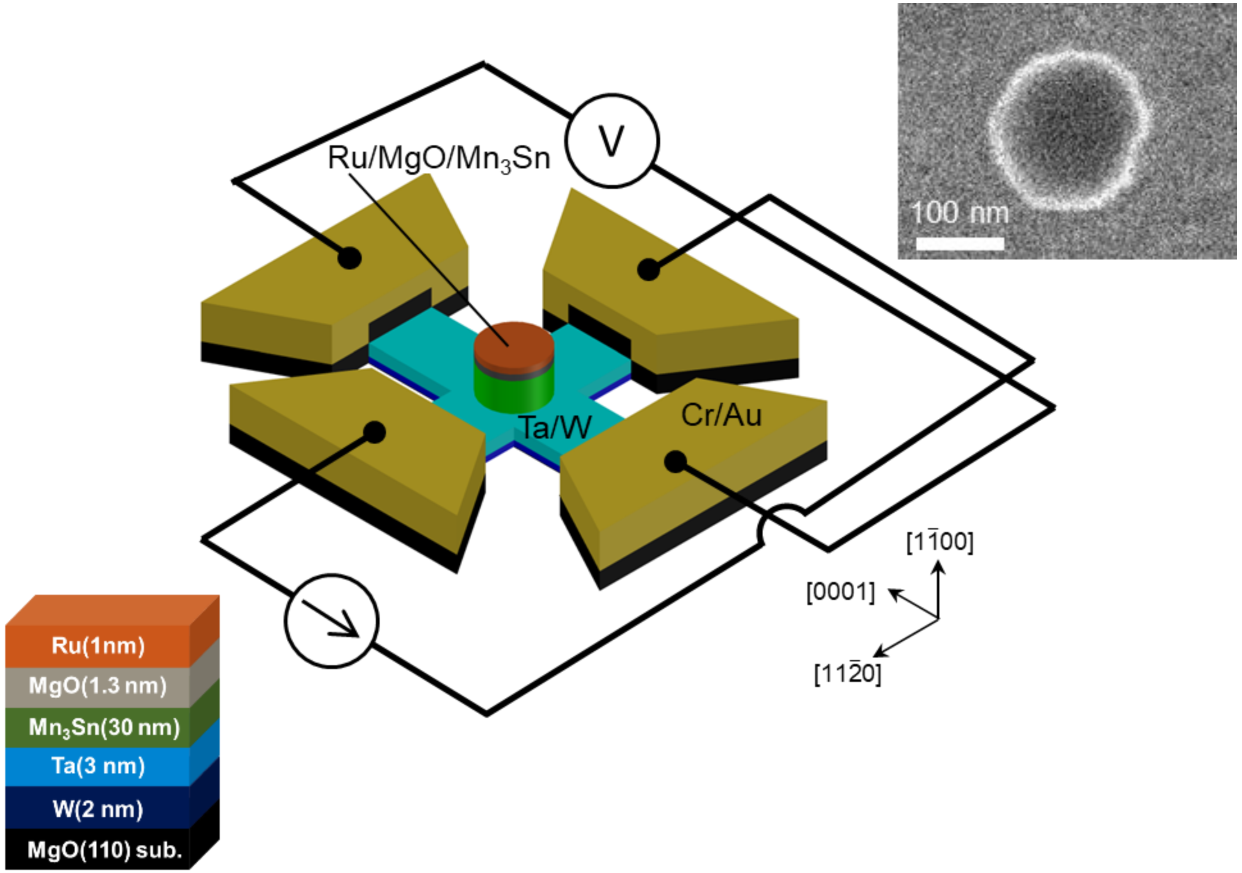
E. del Barco, A. D. Kent, *Nat. Mater.* **22**, 1051 (2023).

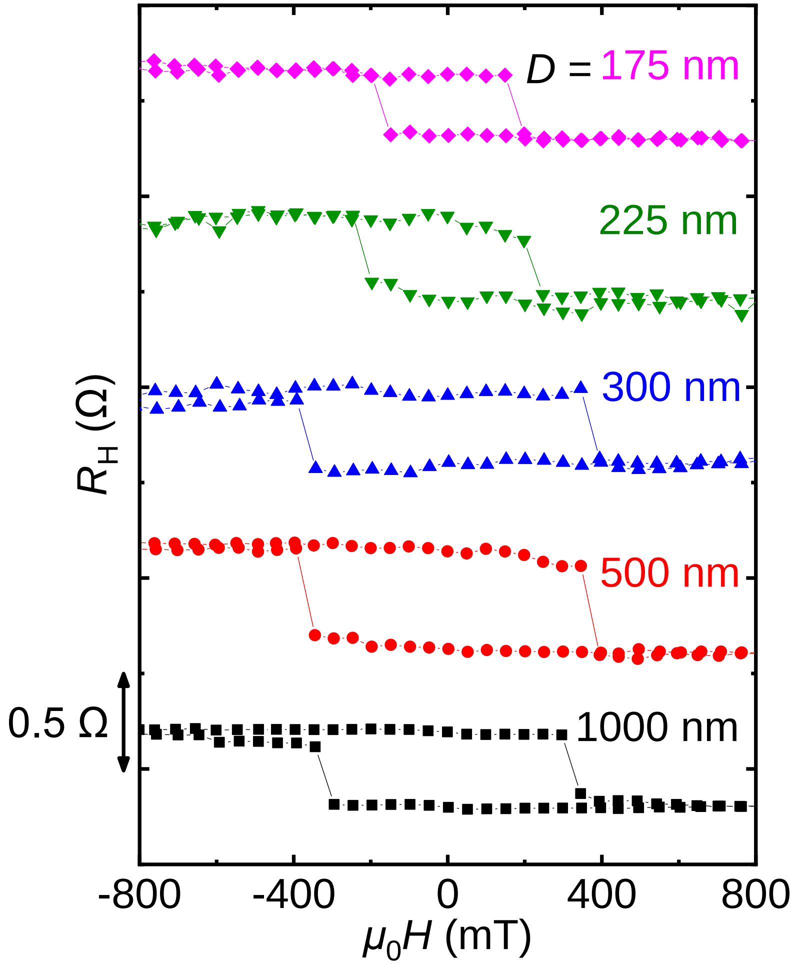
Outline

1. Introduction: Non-collinear antiferromagnet
2. Current-induced dynamics in non-collinear antiferromagnet Mn_3Sn
   – Preparation of epitaxial M-plane-oriented Mn_3Sn thin film
   – Chiral-spin rotation by spin-orbit torque
   – Handedness anomaly in current-induced switching
3. Thermal stability of single nanodot
4. Summary

Samples for thermal stability measurement

- **Setup for electrical measurement of single nanodot**

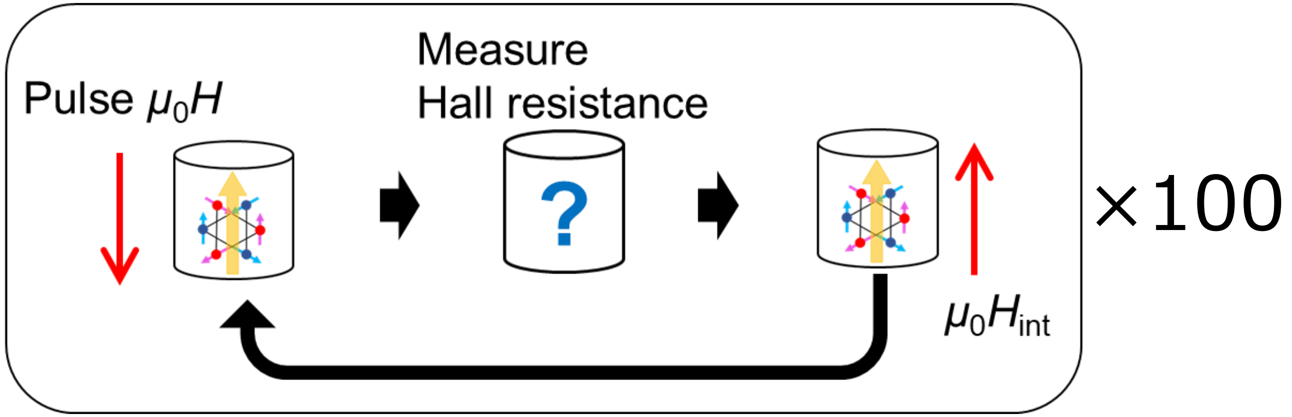




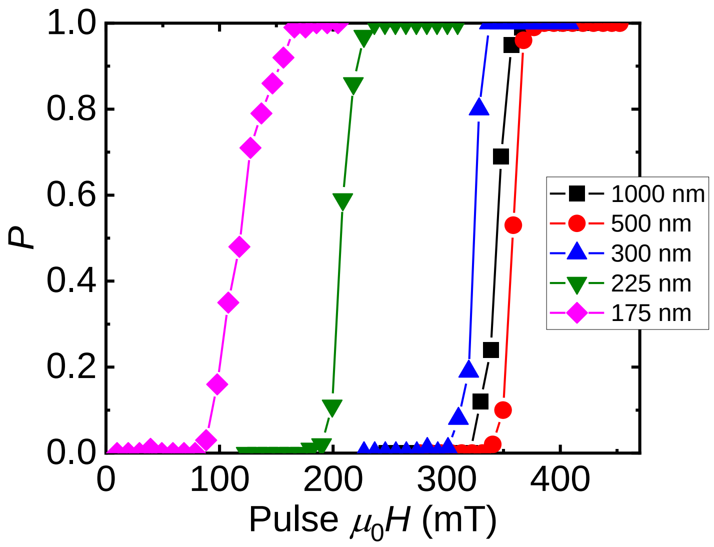
Y. Sato *et al.*, Appl. Phys. Lett. **122**, 122404 (2023)

How to quantify thermal stability factor Δ

■ Sequence of switching probability measurement



■ *P-H* curve for different dot diameter *D*



・Switching probability by Néel-Arrhenius model

$$P = 1 - \exp\left\{-\frac{\tau}{\tau_0}\exp\left(-\Delta\left(1-\frac{H}{H_K}\right)^n\right)\right\}$$

P: switching probability, τ: pulse duration, τ_0: attempt time = 1 ns,
H: external magnetic field, H_K: magnetic anisotropy field,
n: switching exponent… 2.0 for two-fold anisotropy, 1.55 for six-fold anisotropy

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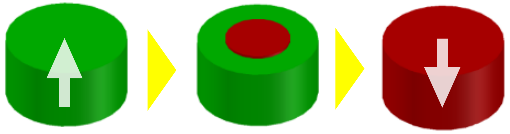
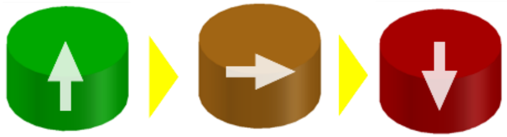
Size dependence of thermal stability factor Δ

Nucleation mode

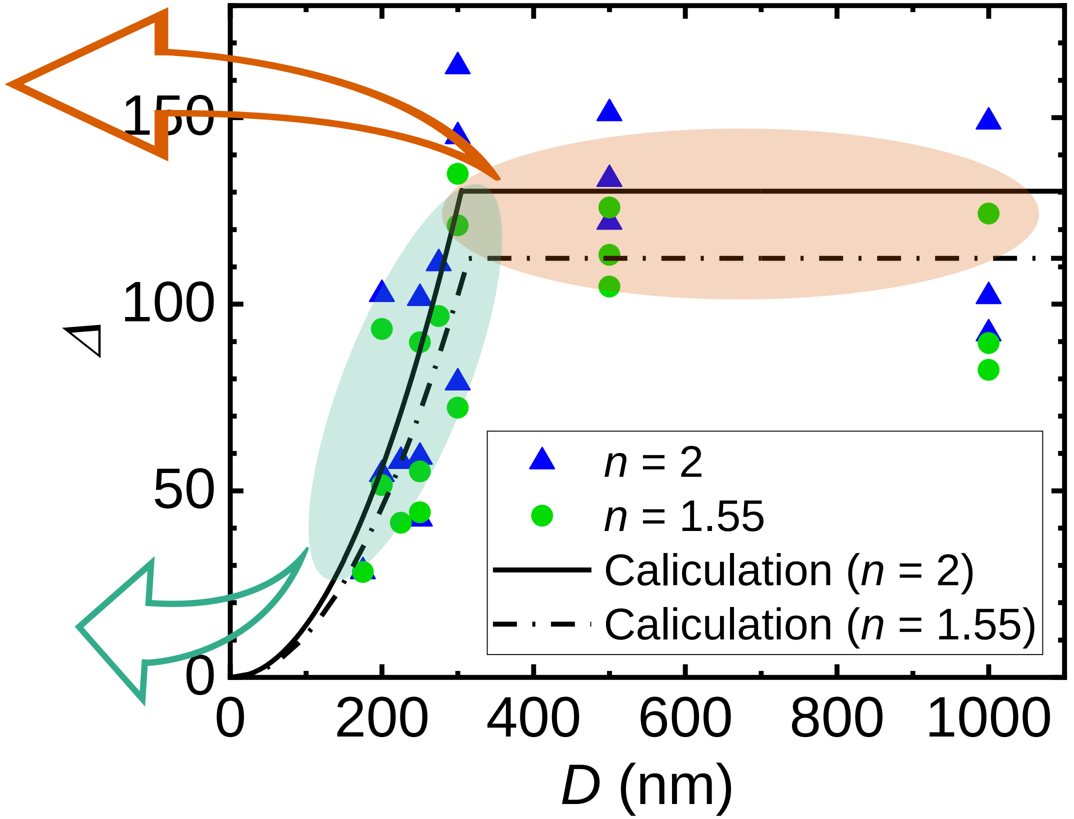


$$\Delta = \frac{\pi^3 t A_s}{4 k_B T}$$

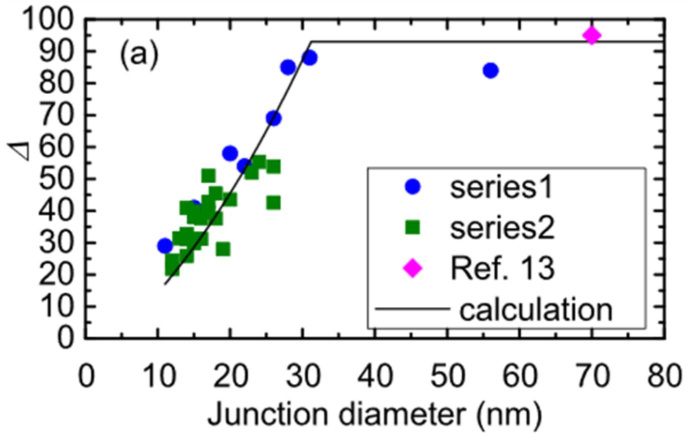
Single domain mode



$$\Delta = \frac{K_{eff} V}{k_B T}$$



CoFeB/MgO MTJ



H. Sato *et al.*, APL **105**, 062403 (2014)

- Two regimes: Size dependent (D < 300 nm), Size independent (D > 300 nm) ⋯ explained by single-domain model and nucleation model
- Δ ~ 100-150 @ D > 300 nm, Δ < 20 @ D < 100 nm

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Summary

- **Epitaxial M-plane-oriented Mn_3Sn thin film with large AHE close to bulk value**
  - Prepared on MgO(110) substrate with W/Ta buffer layer.

J.-Y. Yoon *et al.*, Appl. Phys. Express **13**, 013001 (2020).
J.-Y. Yoon *et al.*, AIP Adv. **11**, 065318 (2021).

- **Chiral-spin rotation by spin-orbit torque**
  - Observed as a transition and fluctuation of Hall resistance at H = 0, whose threshold current depends on the Kagome-plane orientation.
  - Planar rotation with GHz frequency tunable by applied current

Y. Takeuchi *et al.*, Nature Materials **20**, 1364 (2021).

- **Handedness anomaly in current-induced switching**
  - SOT acts on sublattice moment, rotating octupole moment in the opposite direction.

J.-Y. Yoon *et al.*, Nature Materials **22**, 1106 (2023).

- **Thermal stability of Mn_3Sn nanodots**
  - Size dependence explained by single-domain/nucleation model.

Y. Sato *et al.*, Appl. Phys. Lett. **122**, 122404 (2023).

Thank you