Large Antisymmetric Interlayer Exchange Coupling

Takeshi SEKI

Institute for Materials Research, Tohoku University, Japan

EPSRC International Network for Spintronics Early Career Researchers symposium on Material Development Towards Energy Efficient Magnetic Memory
Dec. 5 – 6, 2022 @ imec, Belgium

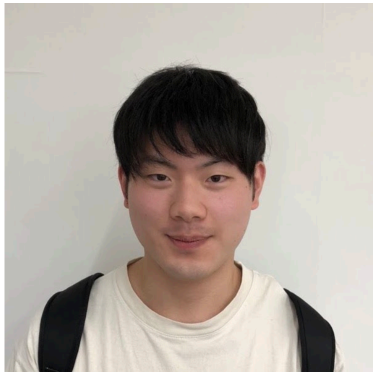
York TOHOKU KAISERSLAUTERN LEEDS Manchester spintec symposium

Symposium Spintronics 5-6 december2022

Collaborators

Hiroto Masuda
Takeshi Seki
Yong-Chang Lau*
Koki Takanashi

*CAS, China from Oct. 2021



Yuta Yamane

Rajkumar Modak
Ken-ichi Uchida

Jun'ichi Ieda

Shunsuke Fukami

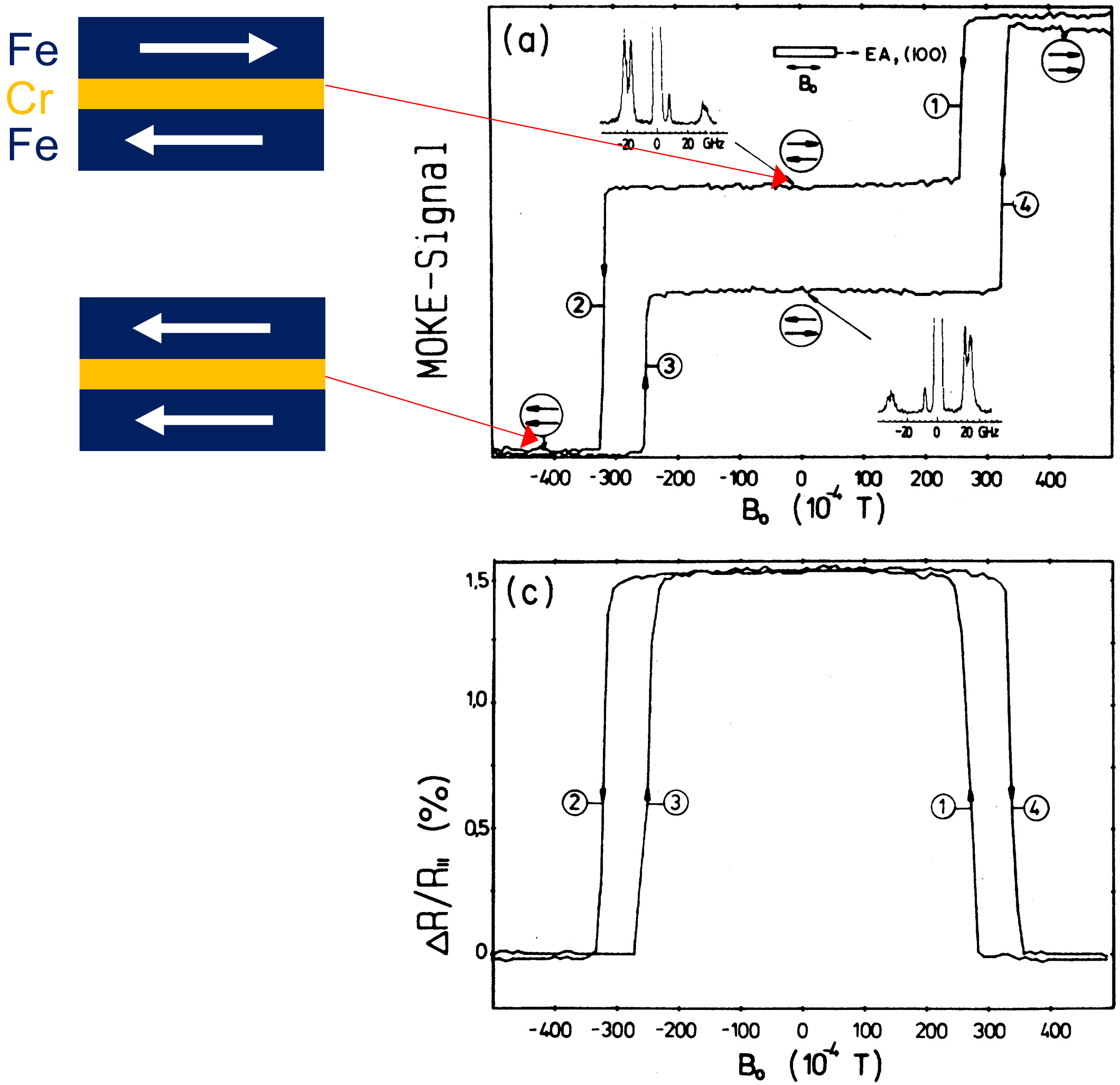
Acknowledgements
Supported by the Grant-in-Aid for Scientific Research (S) (JP18H05246)

Today’s Contents

1. “Symmetric” interlayer exchange coupling (IEC)
   - ✓ General introduction
   - ✓ Cu - Ir alloys
   - ✓ Spin-orbit torque switching

2. “Antisymmetric” interlayer exchange coupling
   - ✓ What is antisymmetric IEC?
   - ✓ Large antisymmetric IEC for wedge-shaped film
   - ✓ Perpendicular magnetization switching induced by in-plane magnetic field

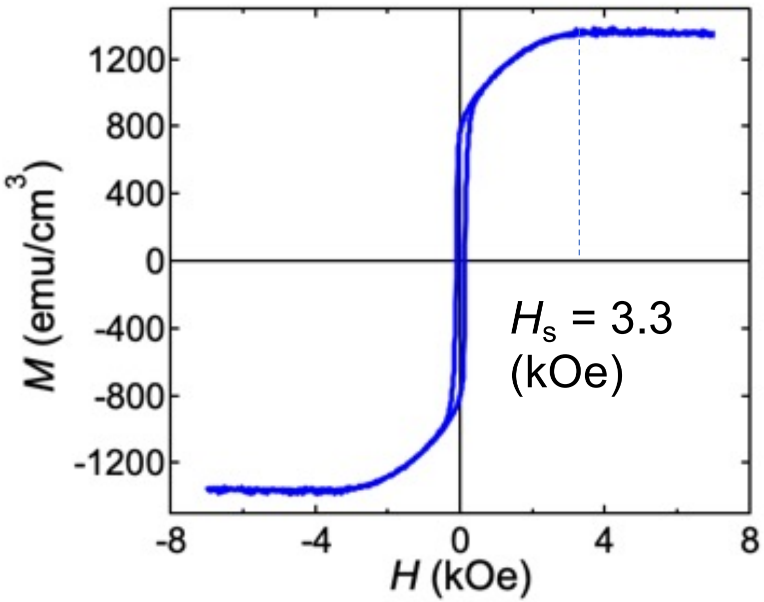
Interlayer Exchange Coupling (IEC)

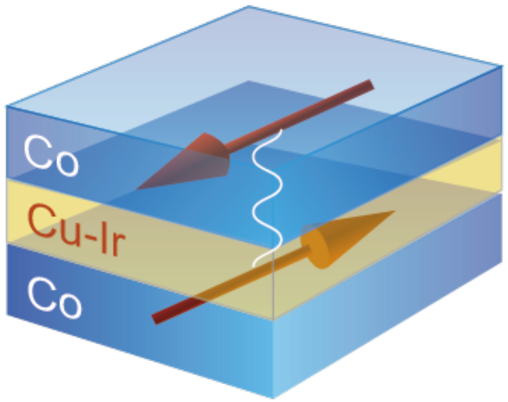


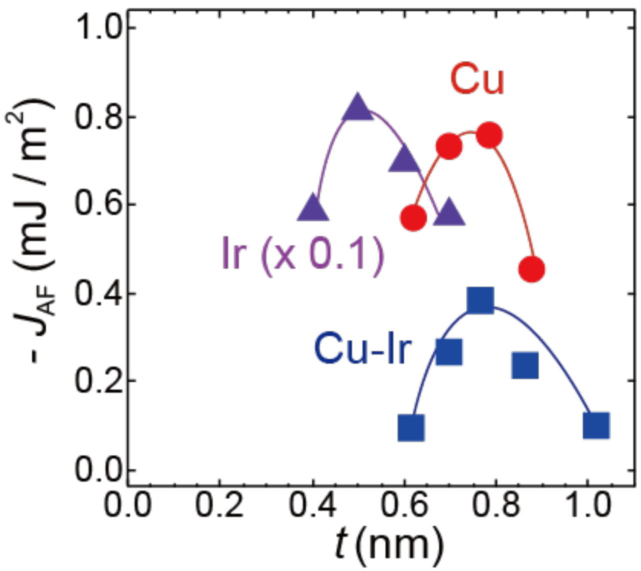
PRB, **39** (1989) 4828

Interlayer Exchange Coupling (IEC)

Co (2) / **$Cu_{95}Ir_{5}$ (0.75)** / Co (2)



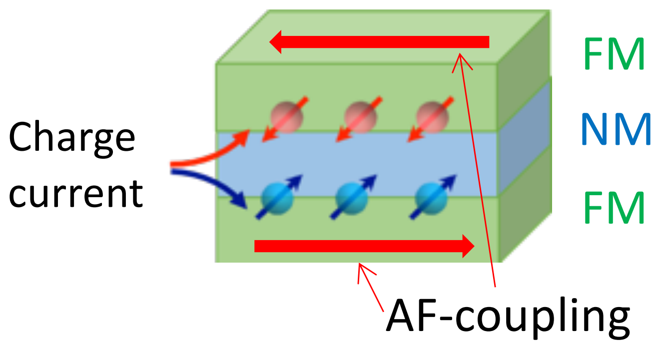




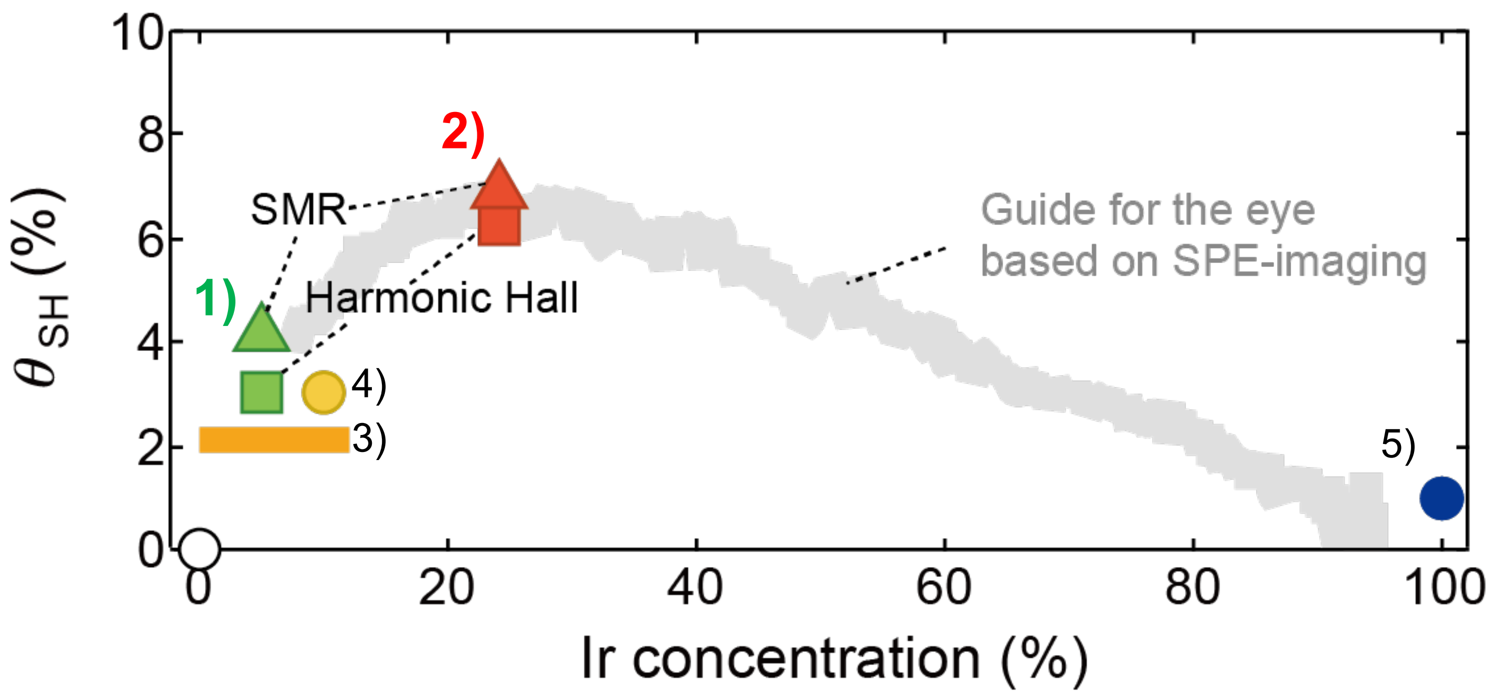
AF-coupling with the $Cu_{95}Ir_{5}$ interlayer

H. Masuda, **TS** *et al.*, *PRB* **101**, 224413 (2020).

Cu-Ir alloy as a spin Hall material



Nonmagnetic interlayer simultaneously showing AF-coupling and large SHE



3) Y. Niimi *et al.*, PRL **106**, 126601 (2011)
4) M. Yamanouchi *et al.*, APL **102** 212408 (2013)
5) Y. Ishikuro *et al.*, PRB **99**, 134421 (2019)

1) H. Masuda, **TS** *et al.*, *Phys. Rev. B* **101**, 224413 (2020).

2) H. Masuda, **TS** *et al.*, *Commun. Mater.* **1**, 75-1-8 (2020).

Today's Contents

1. "Symmetric" interlayer exchange coupling (IEC)
   - ✓ General introduction
   - ✓ Cu - Ir alloys
   - ✓ Spin-orbit torque switching

2. "Antisymmetric" interlayer exchange coupling
   - ✓ What is antisymmetric IEC?
   - ✓ Large antisymmetric IEC for wedge-shaped film
   - ✓ Perpendicular magnetization switching induced by in-plane magnetic field

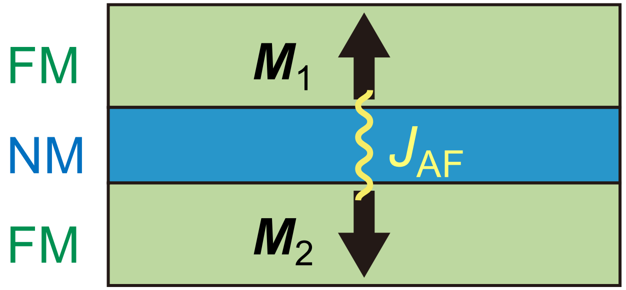
Antisymmetric interlayer exchange coupling (IEC)

Symmetric IEC

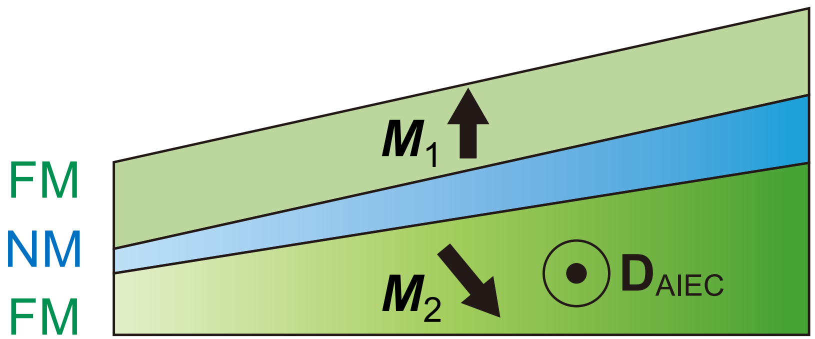
$$E_{IEC} = -J_{AF}\,(\boldsymbol{M}_1 \cdot \boldsymbol{M}_2)$$

Antiferromagnetic coupling (AFC) is induced at the specific layer thickness.

Antiferromagnetically-coupled metallic superlattice



Antisymmetric IEC



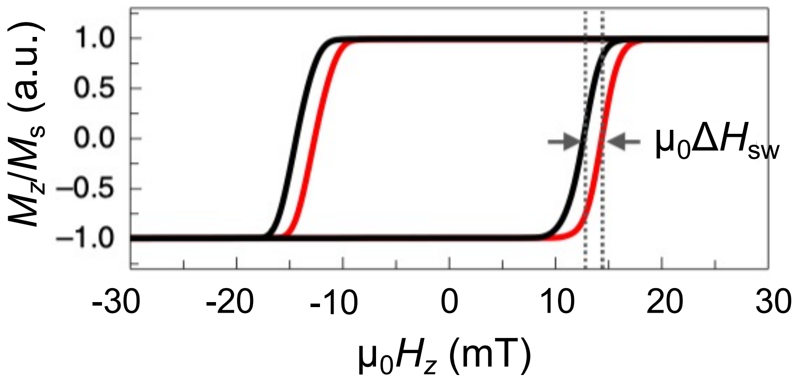
$$E_{AIEC} = -\boldsymbol{D}_{AIEC} \cdot (\boldsymbol{M}_1 \times \boldsymbol{M}_2)$$

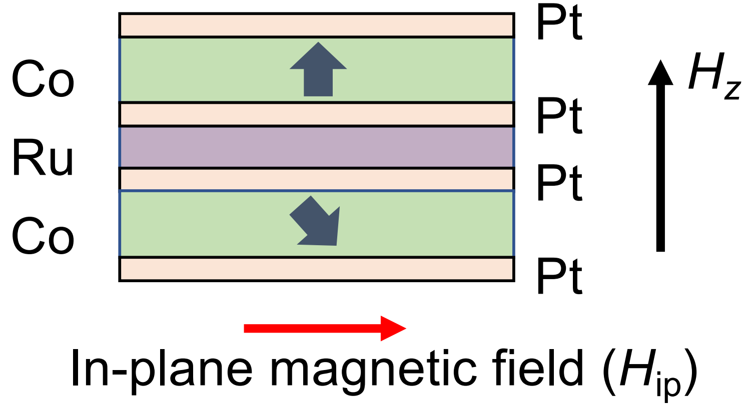
Inversion symmetry breaking in in-plane direction induces the antisymmetric IEC.

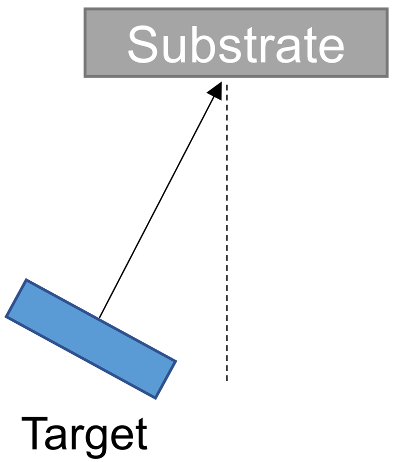
⇨ Chiral magnetic structure

Antisymmetric interlayer exchange coupling (IEC)

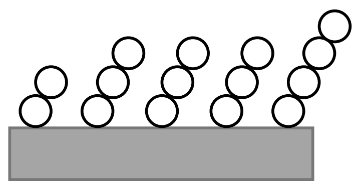
Anomalous Hall effect (AHE)
under H_z + additional H (H_{ip})
in Pt/Co/Pt/Ru/Pt/Co/Pt







- Oblique sputtering
- Thickness inhomogeneity



D.-S. Han, *et al.*, *Nat. Mater.* **18**, 703-708 (2019).

Problems

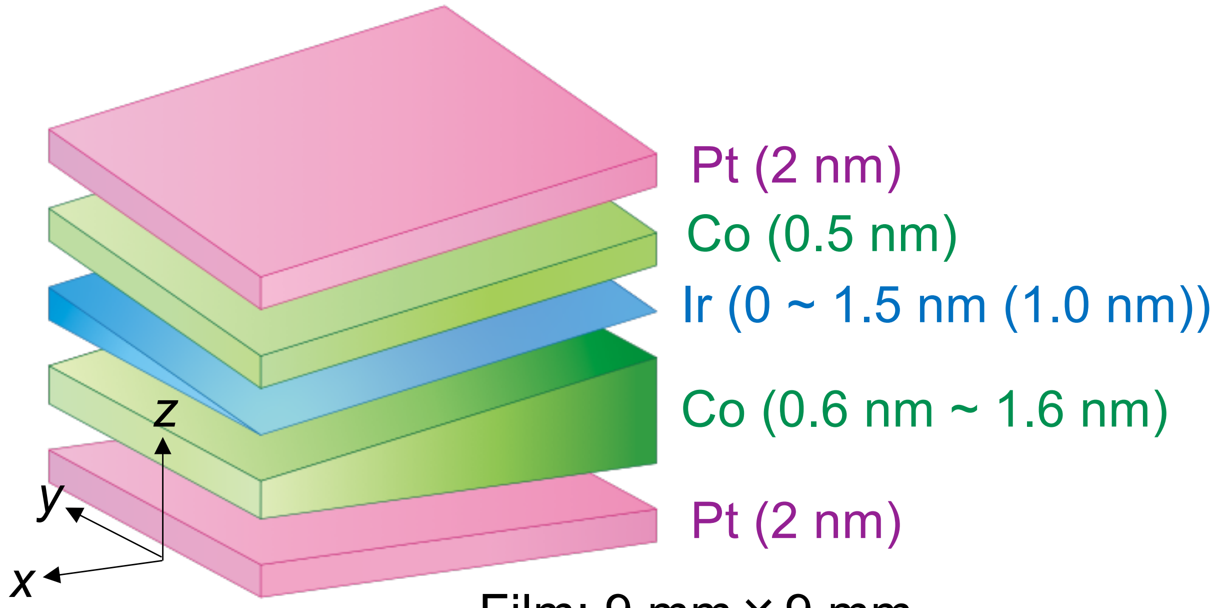
- Small $\mu_0 \Delta H_{sw}$ (0.7 mT ~ 1.7 mT)
- Mechanism of the antisymmetric IEC is still under debate and has not been understood well.

Systematic experiments are indispensable.

Purpose of this study

Elucidation of mechanism of the antisymmetric IEC
using the double and single wedge-shaped Pt/Co/Ir/Co/Pt

Double wedged (DW-) sample



Film: 9 mm × 9 mm

Thin film preparation: Magnetron sputtering at RT
Substrate: SiO_x,
Buffer and cap layer: Ta (1 nm)

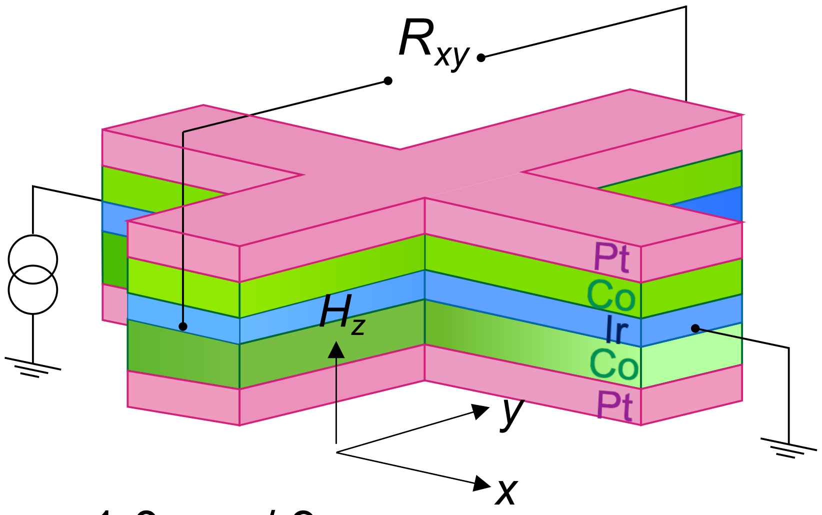
Single-wedged (SW-) sample

Ir-SW-sample:
t_{Co}: 0.8 nm
t_{Ir}: 0 ~ 1.5 nm

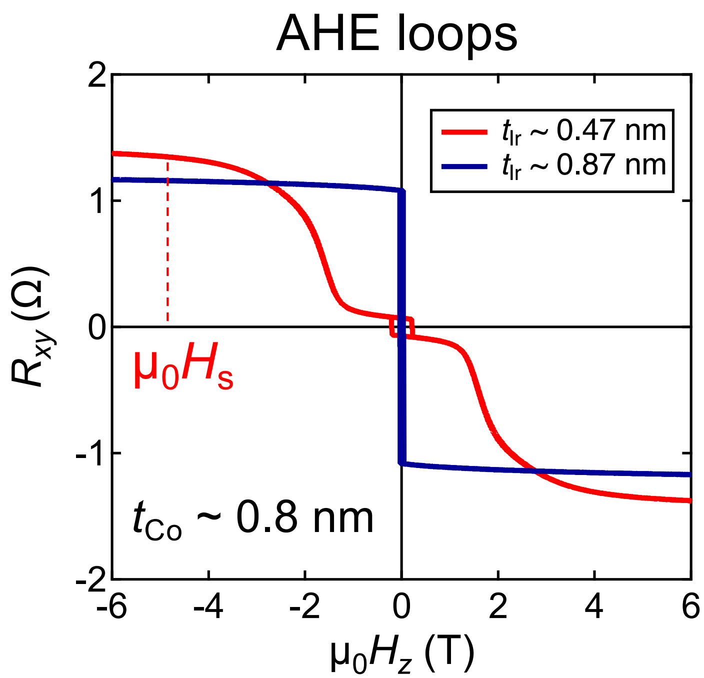
Co-SW-sample:
t_{Co}: 0.6 nm ~ 1.6 nm
t_{Ir}: 0.45 nm or 1.3 nm

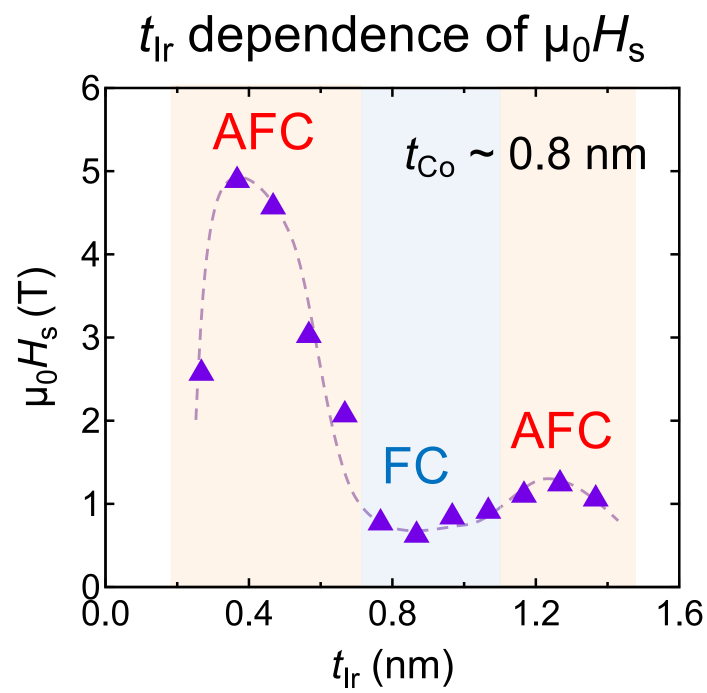
AHE in Double-wedged Pt(2)/Co (t_{Co})/Ir (t_{Ir})/Co (0.5)/Pt (2)

Without in-plane field



∇t_{Co} ~ 1.0 nm / 9 mm
∇t_{Ir} ~ 1.5 nm / 9 mm



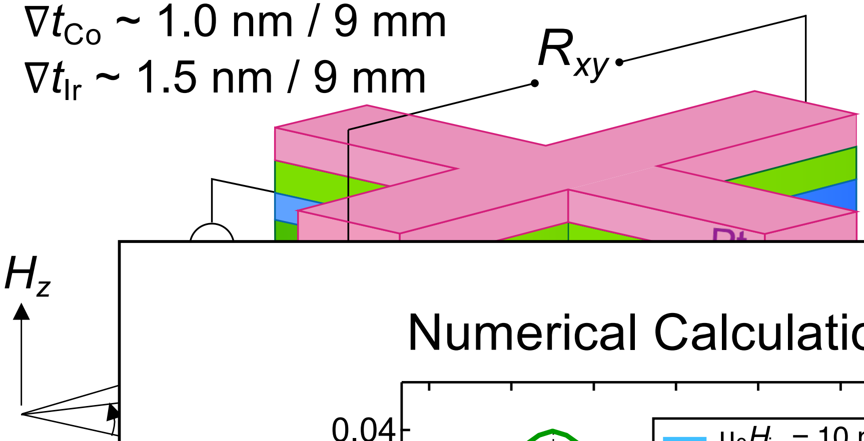


Periodic change of $\mu_0 H_s$ by
the symmetric IEC was confirmed.

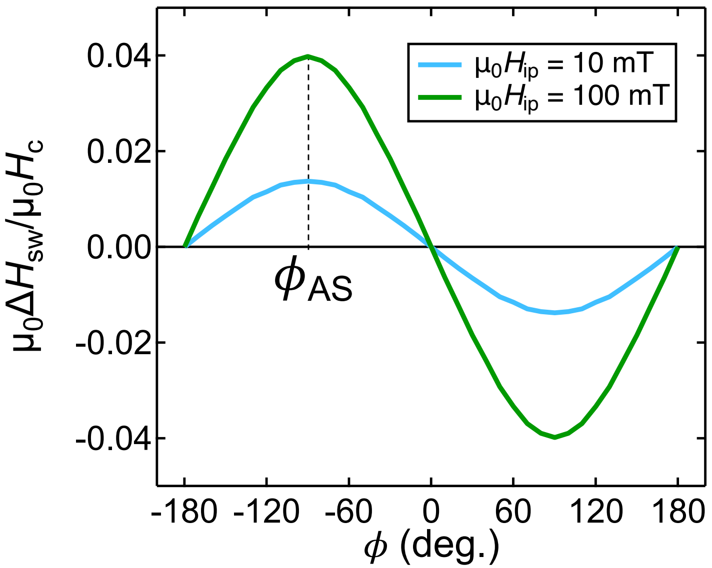
AHE in Double-wedged Pt(2)/Co (t_{Co})/Ir (t_{Ir})/Co (0.5)/Pt (2)

With in-plane field ($|\mu_0 H_{ip}|$ = 50 mT)

∇t_{Co} ~ 1.0 nm / 9 mm
∇t_{Ir} ~ 1.5 nm / 9 mm

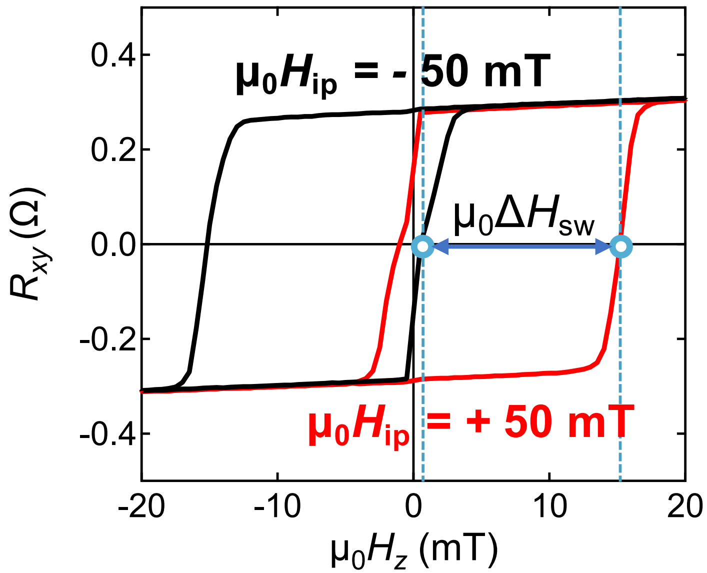


Numerical Calculation

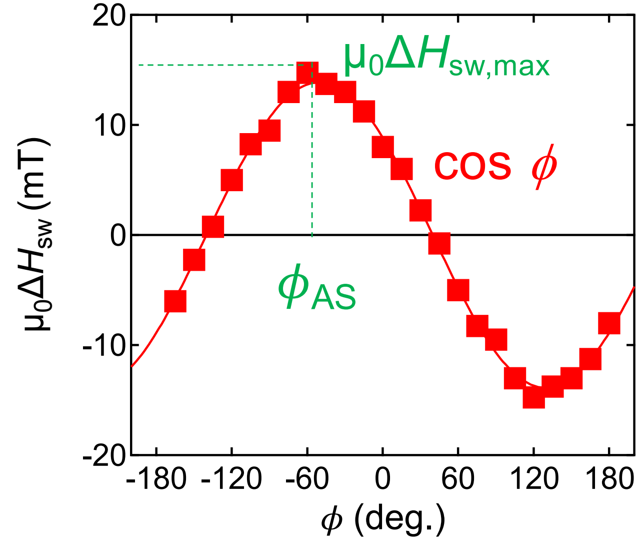


$M_s = 1.1 \times 10^6$ A/m, $K = 5.7 \times 10^5$ J/m^3
J_{AF} = 1.5 mJ/m^2,
$\mathbf{D}_{AIEC} = -0.03\, J_{AF}\, \mathbf{x}$

ϕ = - 60 deg.



ϕ dependence of $\mu_0 \Delta H_{sw}$

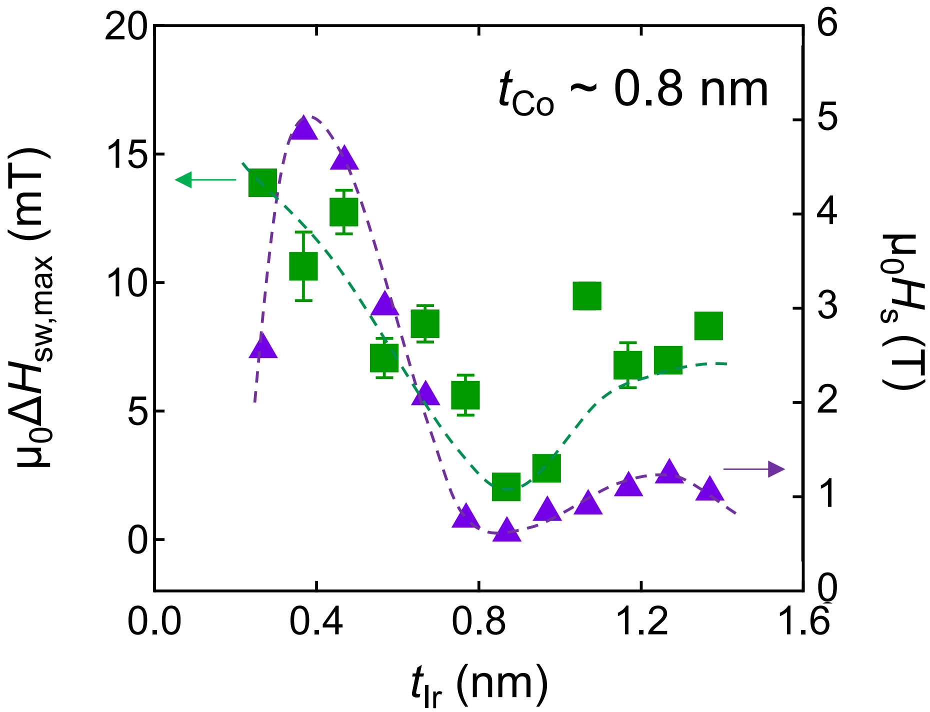


The large value of $\mu_0 \Delta H_{sw,max}$ (**~14.8 mT**) was observed.

Previous studies: $\mu_0 \Delta H_{sw,max}$ = 0.7 mT ~ 1.7 mT

AHE in Double-wedged Pt(2)/Co (t_{Co})/Ir (t_{Ir})/Co (0.5)/Pt (2)

t_{Ir} dependence of $\mu_0 \Delta H_{sw,max}$

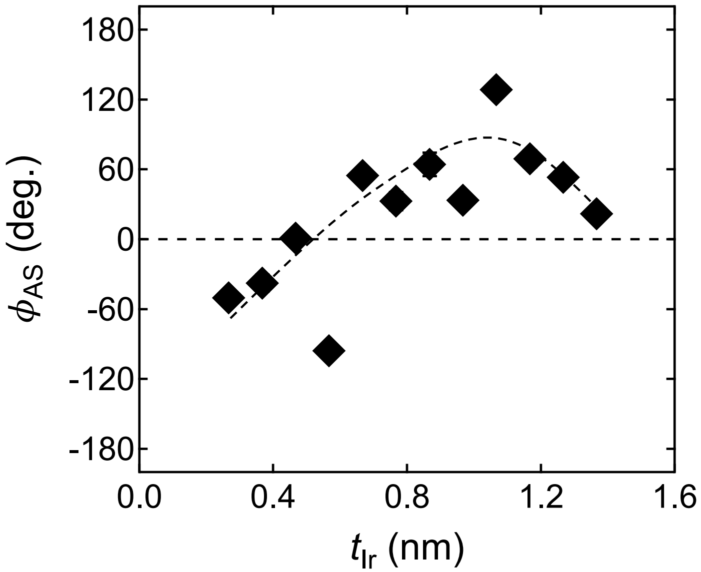


At present, the ϕ_{AS} behavior is not understood clearly.

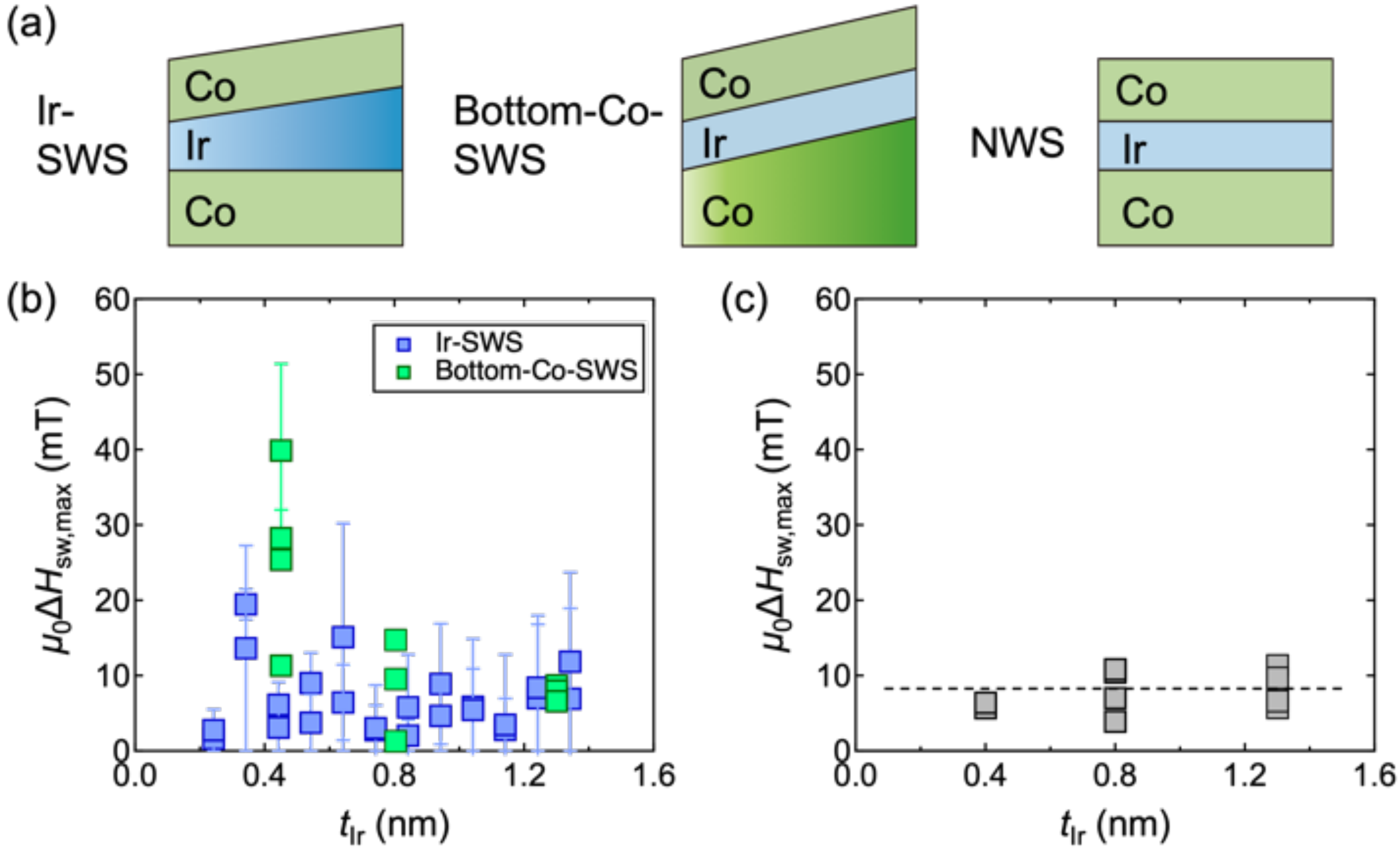
The t_{Ir} dependence of $\mu_0 \Delta H_{sw,max}$ was analogous to that of $\mu_0 H_s$.

Correlation between the antisymmetric IEC and the symmetric IEC

t_{Ir} dependence of ϕ_{AS}



Single-Wedged Sample (SWS) / Non-Wedged Samples(NWS)



- ✓ Bottom-Co-SWS shows larger $\mu_0\Delta H_{sw,max}$ compared with Ir-SWS.
- ✓ $\mu_0\Delta H_{sw,max}$ for NWS are small and hardly dependent on t_{Ir}.

Phenomenological Model

Coupled Landau-Lifshitz-Gilbert (LLG) equations for $\boldsymbol{m}_\mu$ ($\mu = 1$ and 2)

$$\partial \boldsymbol{m}_\mu / \partial t = -\gamma \boldsymbol{m}_\mu \times \boldsymbol{h}_\mu + \alpha \boldsymbol{m}_\mu \times (\partial \boldsymbol{m}_\mu / \partial t)$$

Critical field for switching

$$\left(m_0 \omega_h^y - \frac{\omega_D}{\omega_E} \omega_h^z, \quad m_0 \omega_h^z + \frac{\omega_D}{\omega_E} \omega_h^y \right) = \omega_K \left(\sin^3 \theta , \quad -\cos^3 \theta \right).$$

$$\boldsymbol{\omega}_h = \gamma \boldsymbol{h}_{\rm ext}$$

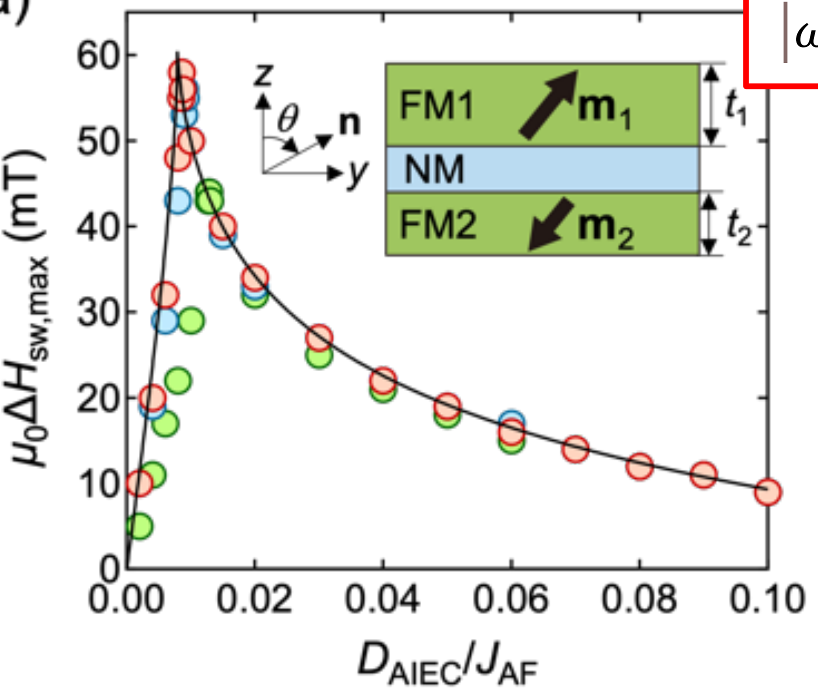
$$\boldsymbol{\omega}_{\boldsymbol{D}} = [(t_1 + t_2)/2t_1 t_2](\gamma \boldsymbol{D}_{\rm AIEC}/\mu_0 M_{\rm s}) \qquad m_0 = (t_1 - t_2)/(t_1 + t_2)$$

$$\omega_E = [(t_1 + t_2)/t_1 t_2](\gamma J_{\rm AF}/\mu_0 M_{\rm s})$$

$$\omega_K = [(t_1 + t_2)^2/2t_1 t_2](\gamma K/\mu_0 M_{\rm s})$$

$$|\omega_h^y|/\gamma = (\omega_K/\gamma)\left[m_0^{2/3} + (\omega_D/\omega_E)^{2/3}\right]^{-3/2}$$

(a)



Circles: Numerical result

$\omega_h^y/\gamma = 10$ mT,

$K = 1 \times 10^4$ J/m^3

$\mu_0 M_{\rm s} = 1$ T,

$t_1 = 0.55$ nm,

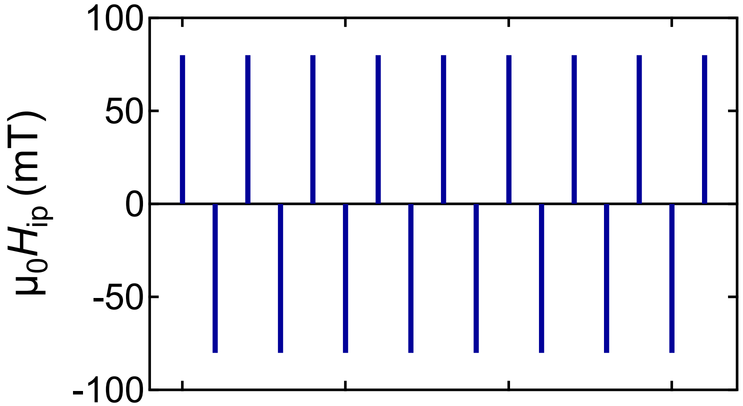
$t_2 = 0.45$ nm

$J_{\rm AF} = 1.5$, 7.5, and 15.0 mJ/m^2

Perpendicular magnetization switching induced by H_{ip}

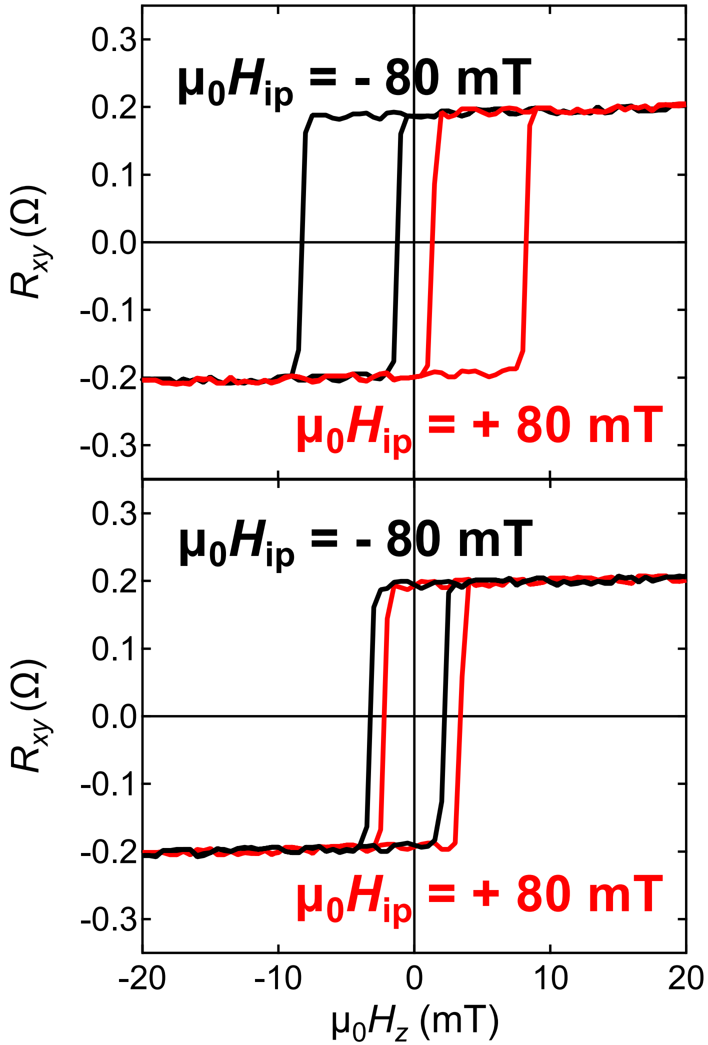
Double-wedged sample:

t gradient: ∇t_{Co} ~ 1.0 nm, ∇t_{Ir} ~ 1.0 nm per 9 mm,
Device: t_{Ir} ~ 0.32 nm, t_{Co} ~ 0.79 nm

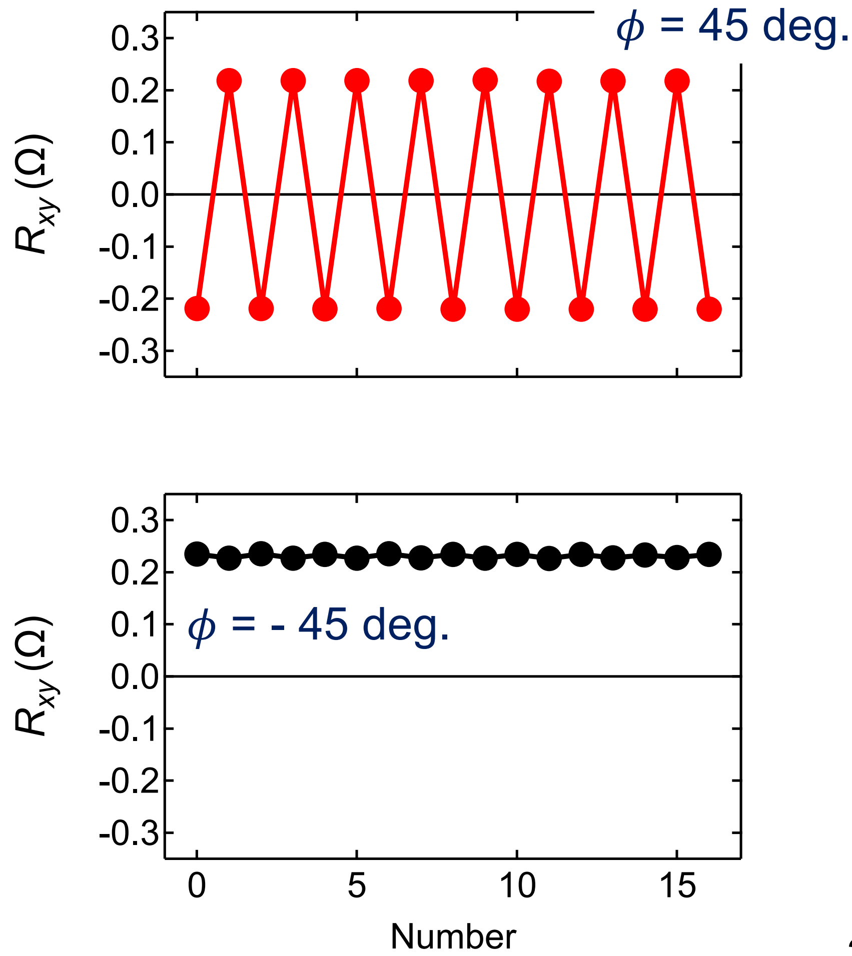


ϕ = 45 deg.

ϕ = - 45 deg



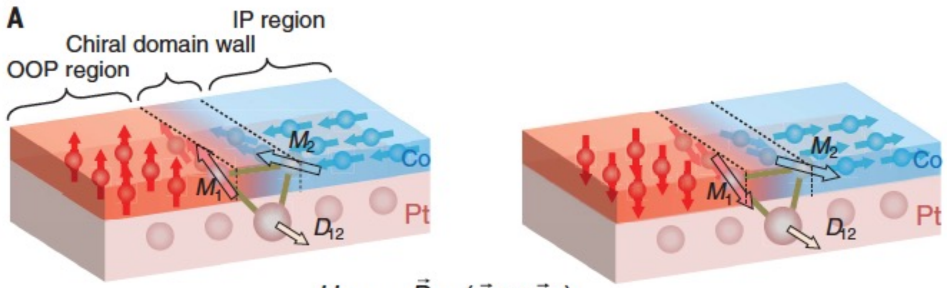
Full magnetization switching



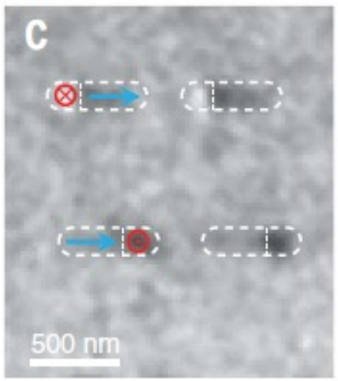
Artificial 3-D Chiral Magnetic Structure

2-D Chiral Magnetic Structure

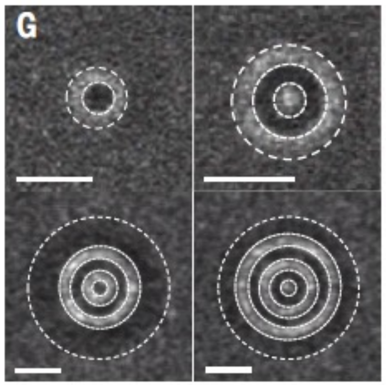
Interface DMI



$$H_{DM} = -\vec{D}_{12} \cdot (\vec{m}_1 \times \vec{m}_2)$$



OOP-IP element



Synthetic Néel skyrmions

Z. Luo *et al.*, *Science* **363**, 1435 (2019).

Large Antisymmetric IEC

Way to manipulate
the **3-D** magnetic textures

Summary

Antisymmetric interlayer exchange coupling

- Large $\mu_0 \Delta H_{sw,max}$ in AHE loops was observed for the double-wedged Pt (2)/Co (t_{Co})/Ir (t_{Ir})/Co (0.5)/Pt (2).
- The t_{Ir} dependence of $\mu_0 \Delta H_{sw,max}$ indicates the correlation between the antisymmetric IEC and the symmetric IEC.
- The bottom Co wedged layer plays an important role for the large antisymmetric IEC.
- H_{ip}-induced perpendicular magnetization switching was demonstrated using the double-wedged sample.

H. Masuda, **TS** *et al.*, *PR Appl.* **17**, 054036 (2022).

Today’s Contents

1. “Symmetric” interlayer exchange coupling (IEC)
   - ✓ General introduction
   - ✓ Cu - Ir alloys
   - ✓ Spin-orbit torque switching

2. “Antisymmetric” interlayer exchange coupling
   - ✓ What is antisymmetric IEC?
   - ✓ Large antisymmetric IEC for wedge-shaped film
   - ✓ Perpendicular magnetization switching induced by in-plane magnetic field

Open Position

Postdoctoral Researcher

Experimental study on “creation and control of electron spin wave in a semiconductor with a ferromagnetic metal” for developing “Spin-based wave parallel computing”.

Contact: takeshi.seki@tohoku.ac.jp