

Chapter 8

Antiferromagnetic spintronics

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量子材料科学中心

2017年12月8日

Review of last class

1. Topology

2. Quantum anomalous Hall effect

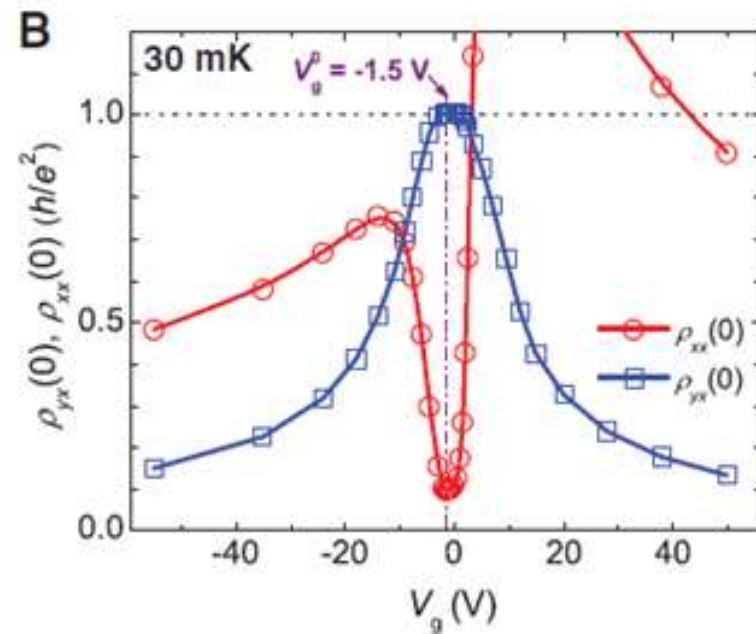
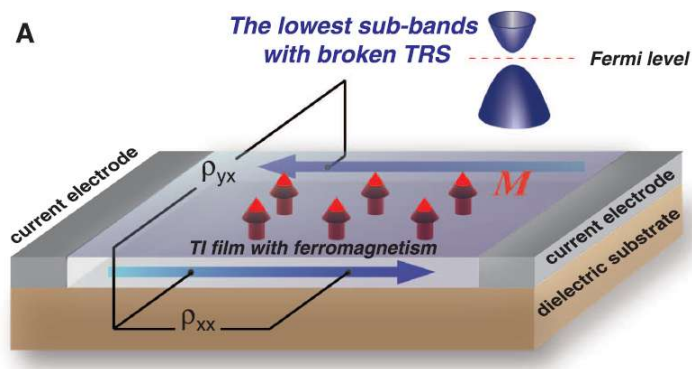
3. Skyrmions

4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**
- **Spin Seebeck effect**

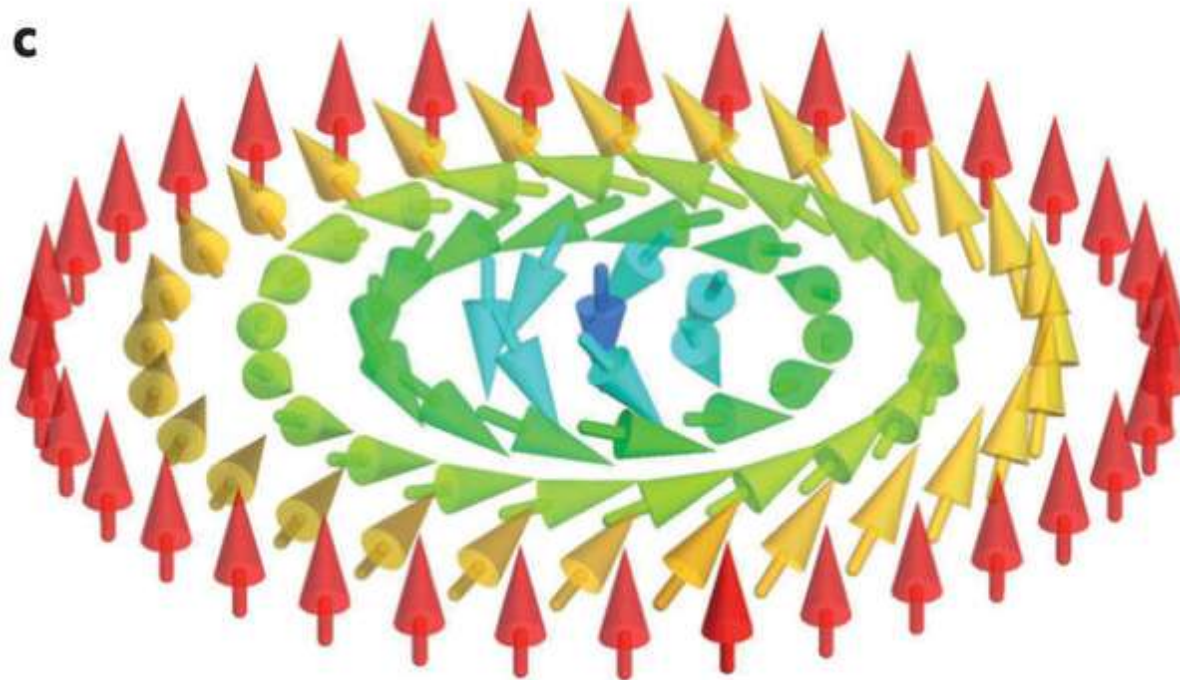
Review of last class

2. Quantum anomalous Hall effect



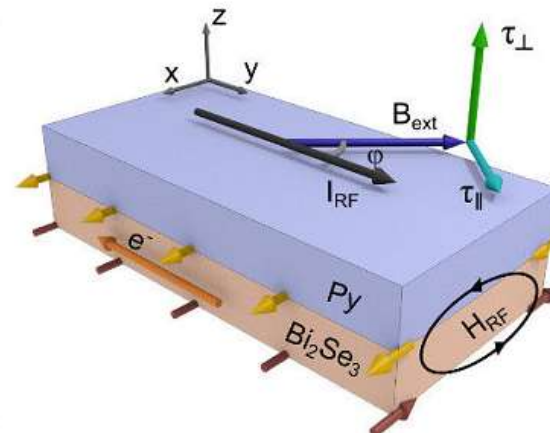
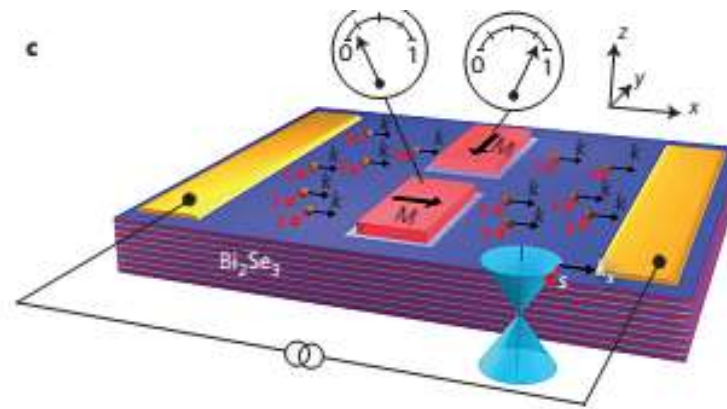
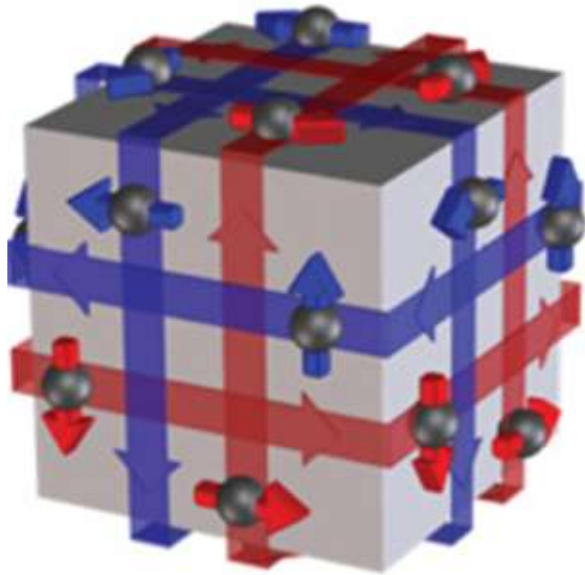
Review of last class

3. Skyrmions



Review of last class

4. Spin-momentum locking of 3D TI



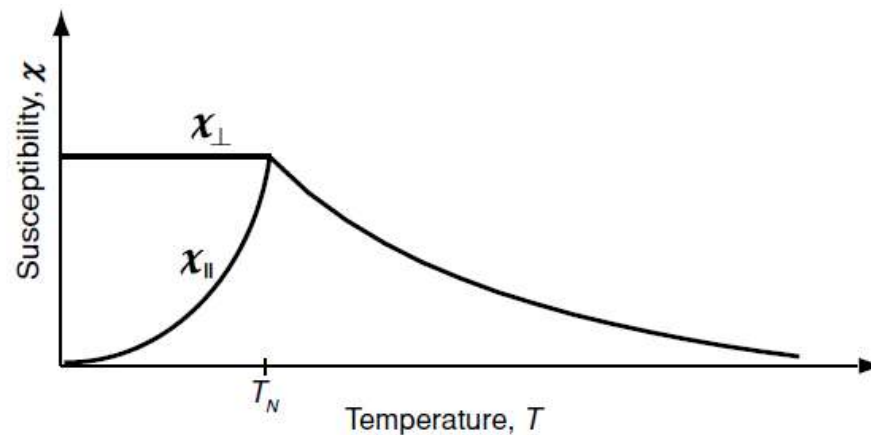
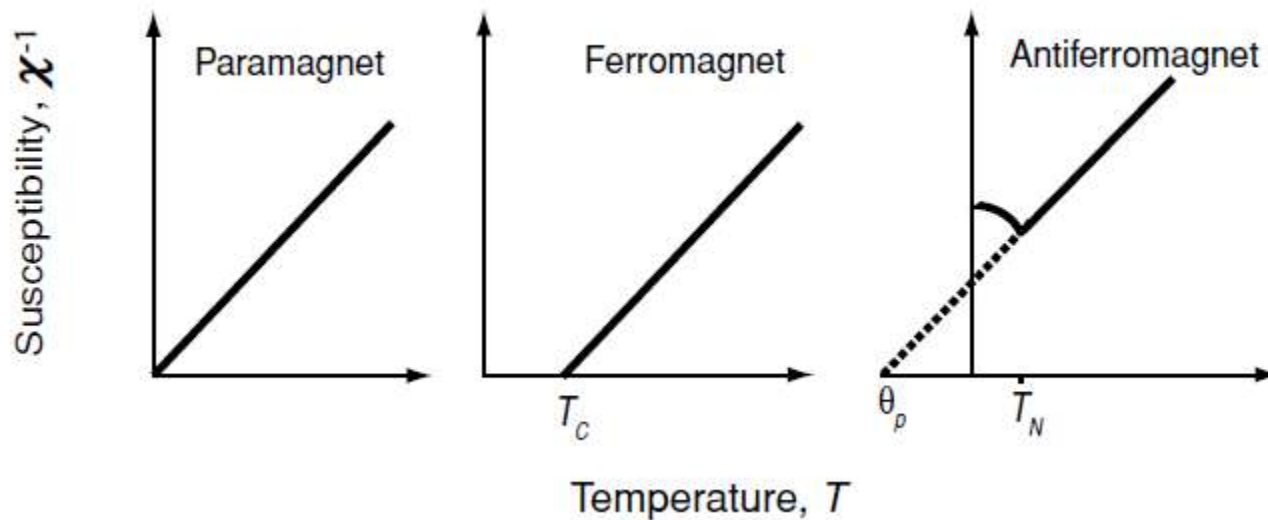
Outline

- 1. Antiferromagnetism and Exchange bias**
- 2. Spin Seebeck effect in AFM**
- 3. AMR of AFM**
- 4. Switching of AFM**
- 5. Anomalous Hall effect in AFM**
- 6. Spin orbit torque in AFM**

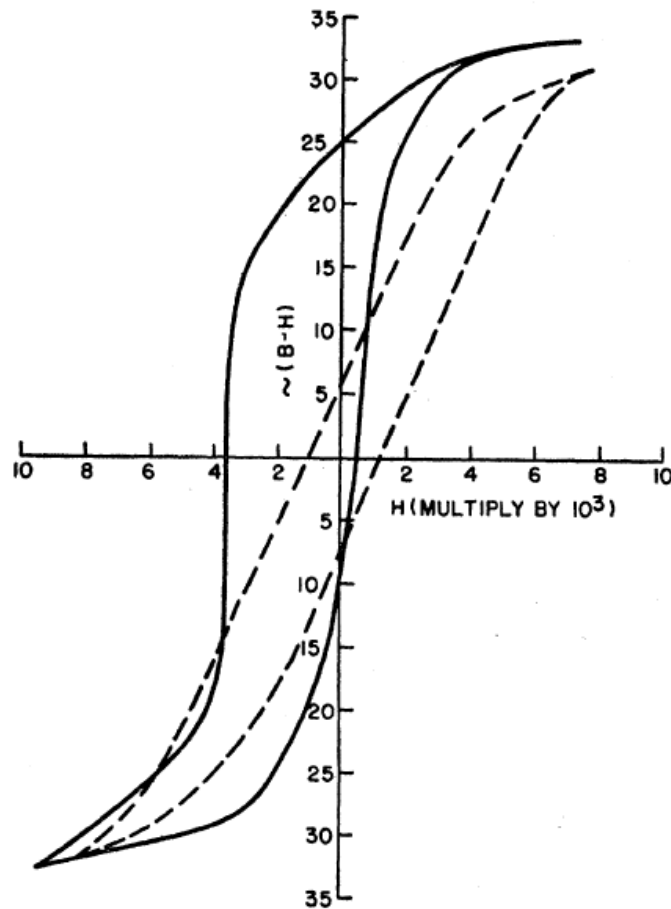
Outline

1. Antiferromagnetism and Exchange bias

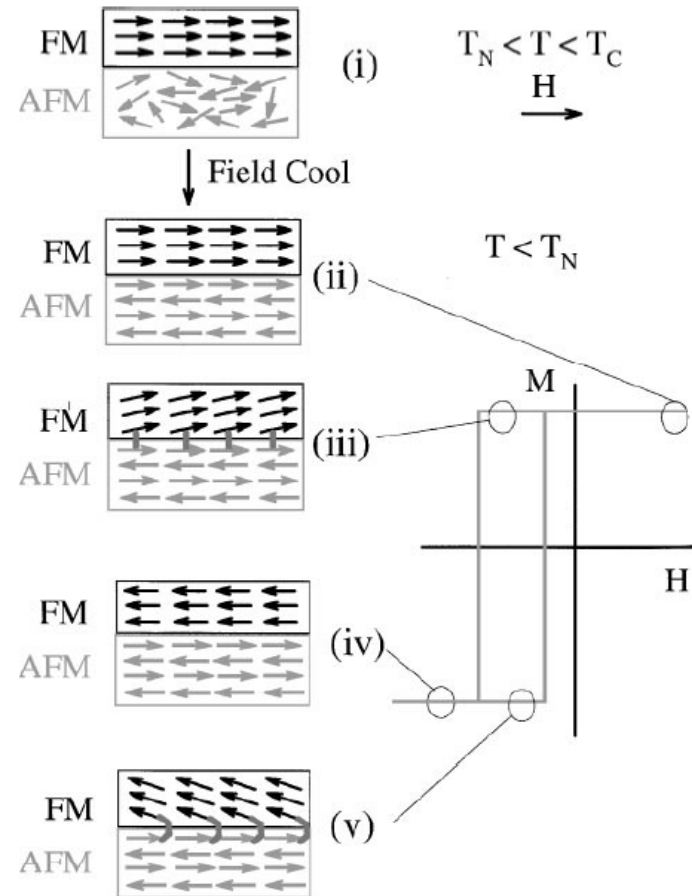
Antiferromagnetism and Exchange bias



Antiferromagnetism and Exchange bias

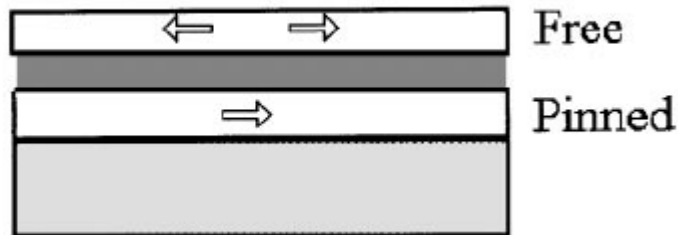


W. H. Meiklejohn and C. P. Bean
Physical Review **102**, 1413 (1956).

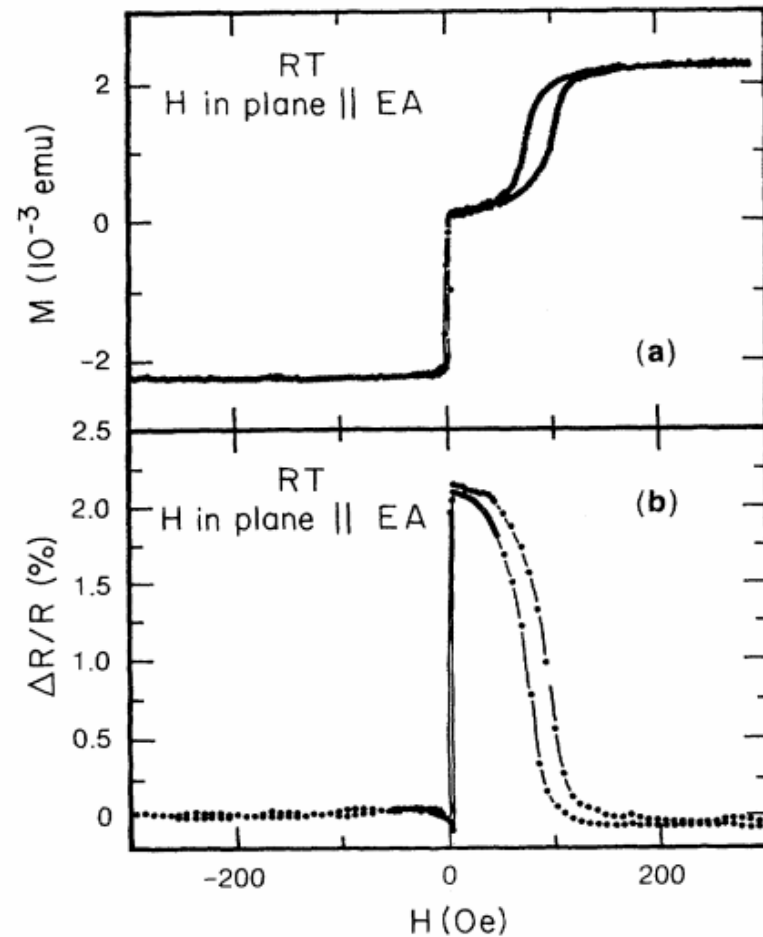


J. Nogue and I. K. Schuller JMMM
192, 203 (1999).

Antiferromagnetism and Exchange bias



NiFe(15nm)/Cu(2.6nm)/
NiFe(15nm)/FeMn(10nm)



B. Dieny et al PRB, **43** 1297 (1991).

Antiferromagnetism and Exchange bias

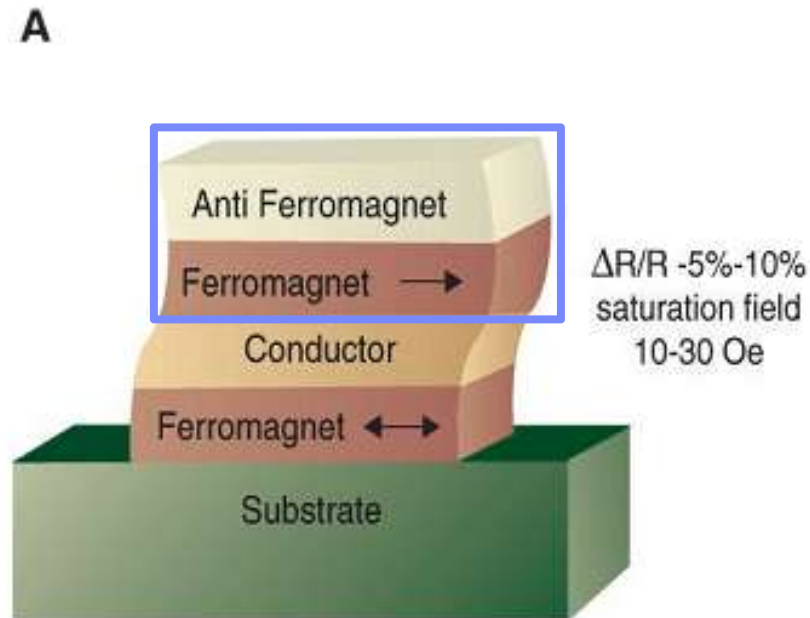


Fig. 1. Spin-dependent transport structures. (A) S

Yang & Parkin, Nature Nanotech (2014)

Antiferromagnetism and Exchange bias

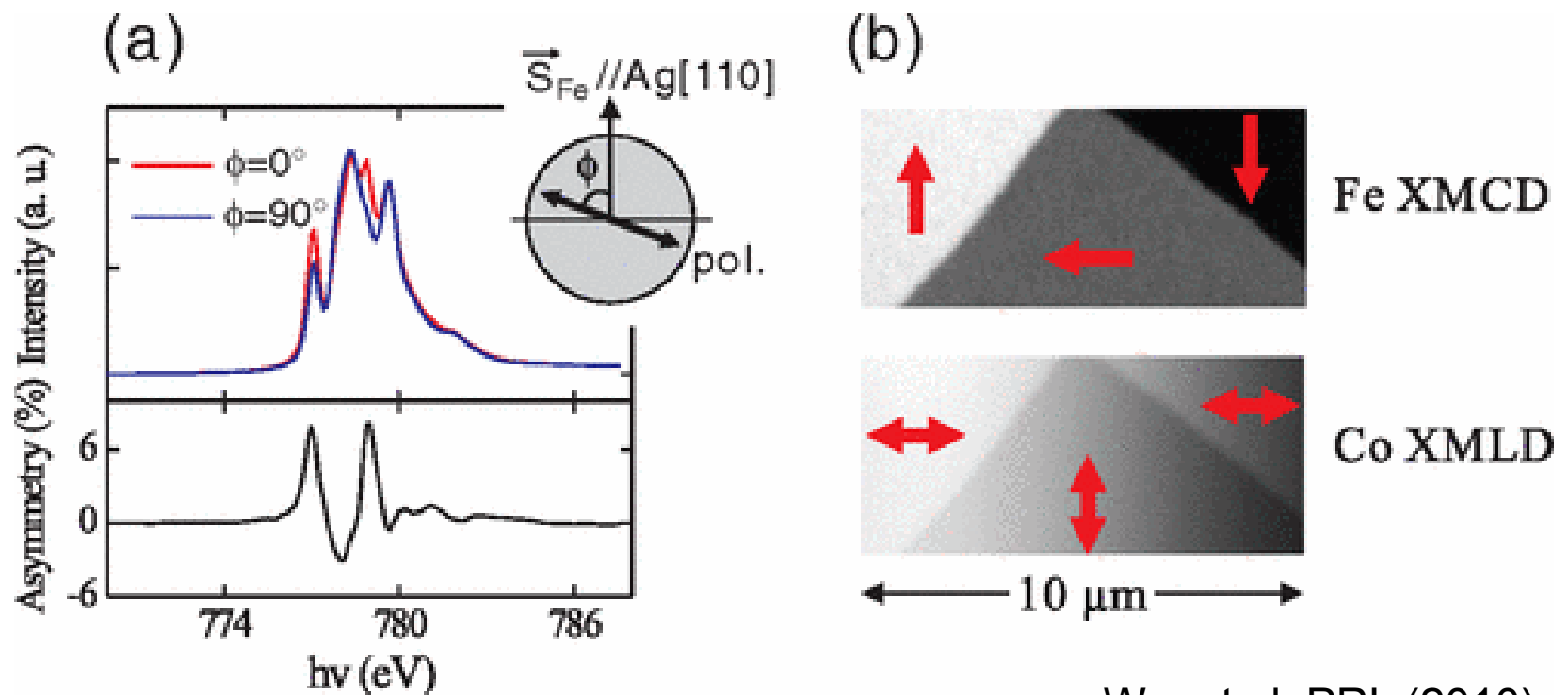
Table 6.1. Some common antiferromagnets

	Structure	T_N (K)	θ_p (K)	$\mu_0 M_\alpha$ (T)
Cr	sdw	311		0.20
Mn	Complex	96	~ -2000	0.20
NiO	Néel	524	-1310	0.54
$\alpha\text{Fe}_2\text{O}_3$	Canted	958	-2000	0.92
MnF ₂	Néel	67	-80	0.78
FeMn	Néel	510		0.53
IrMn ₃	Néel	690		0.50

sdw – spin density wave; Néel – two collinear sublattices.

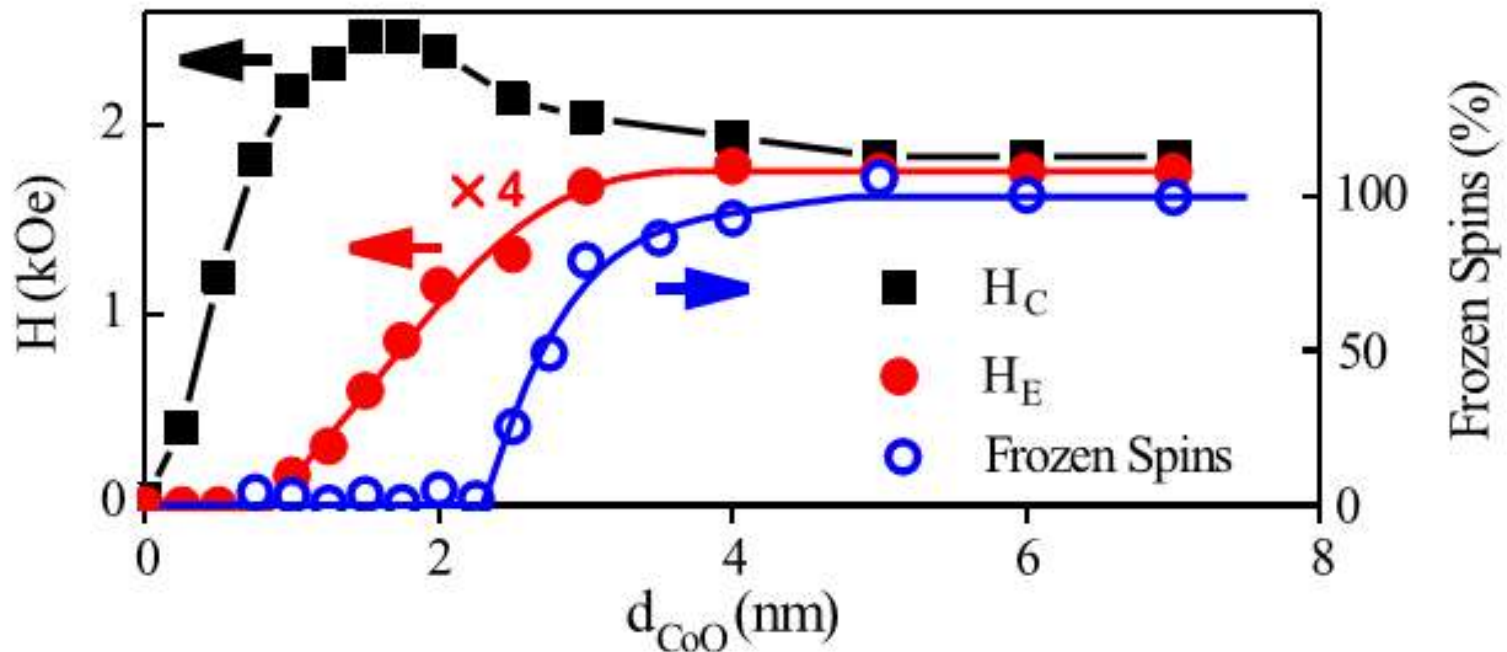
Exchange bias

Antiferromagnetic CoO spins are 90° coupled to Fe spins.



Wu, et al, PRL (2010)

Exchange bias

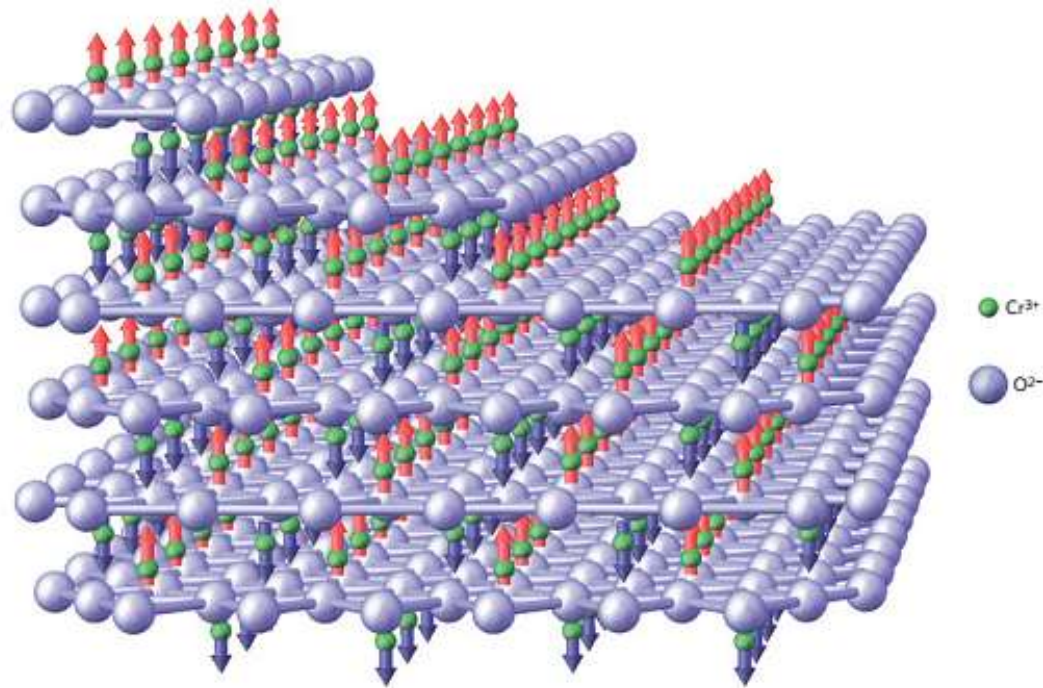


Only 5 % of the Frozen spins are needed for exchange bias.

Exchange bias

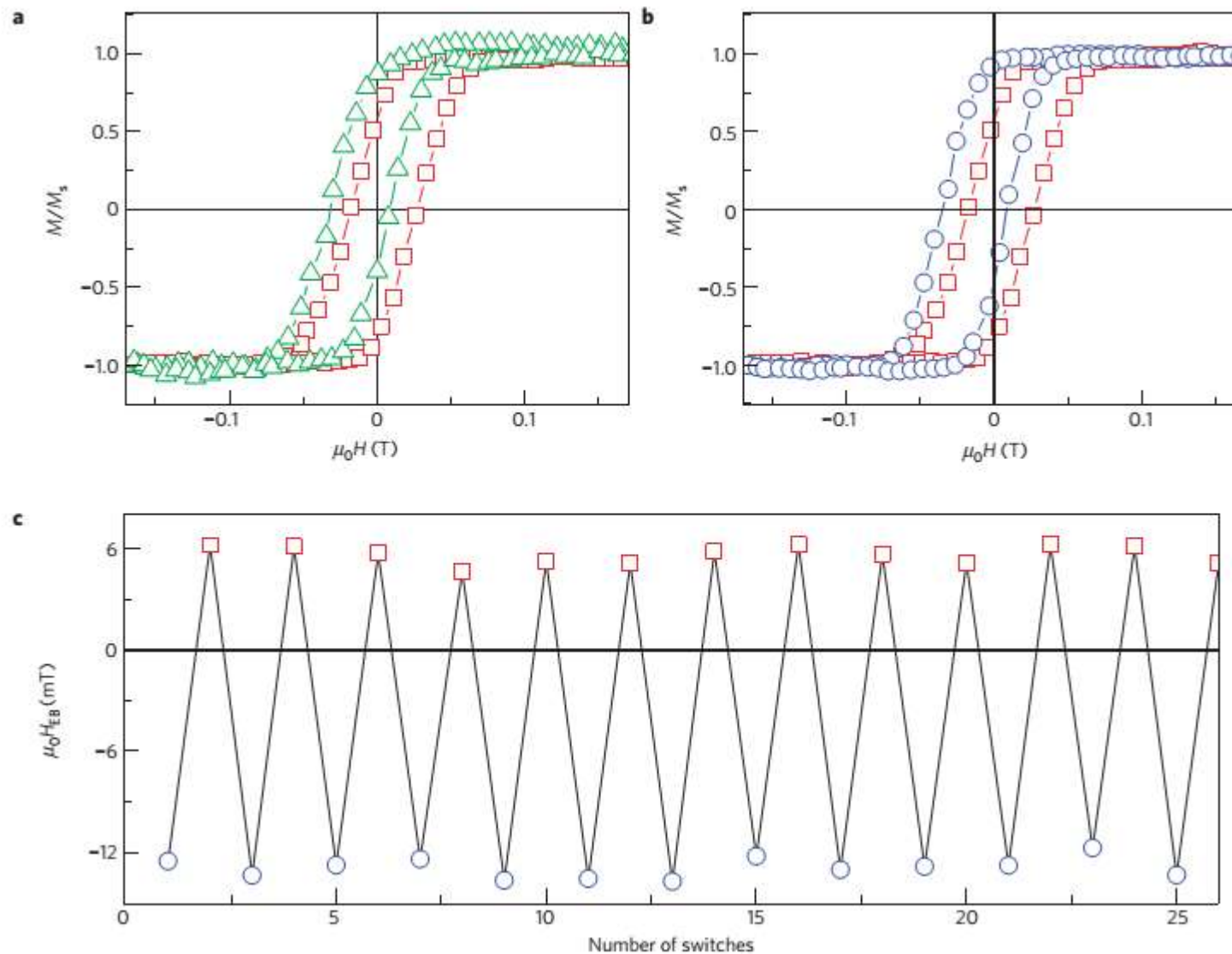
Collinear exchange coupling

Cr₂O₃

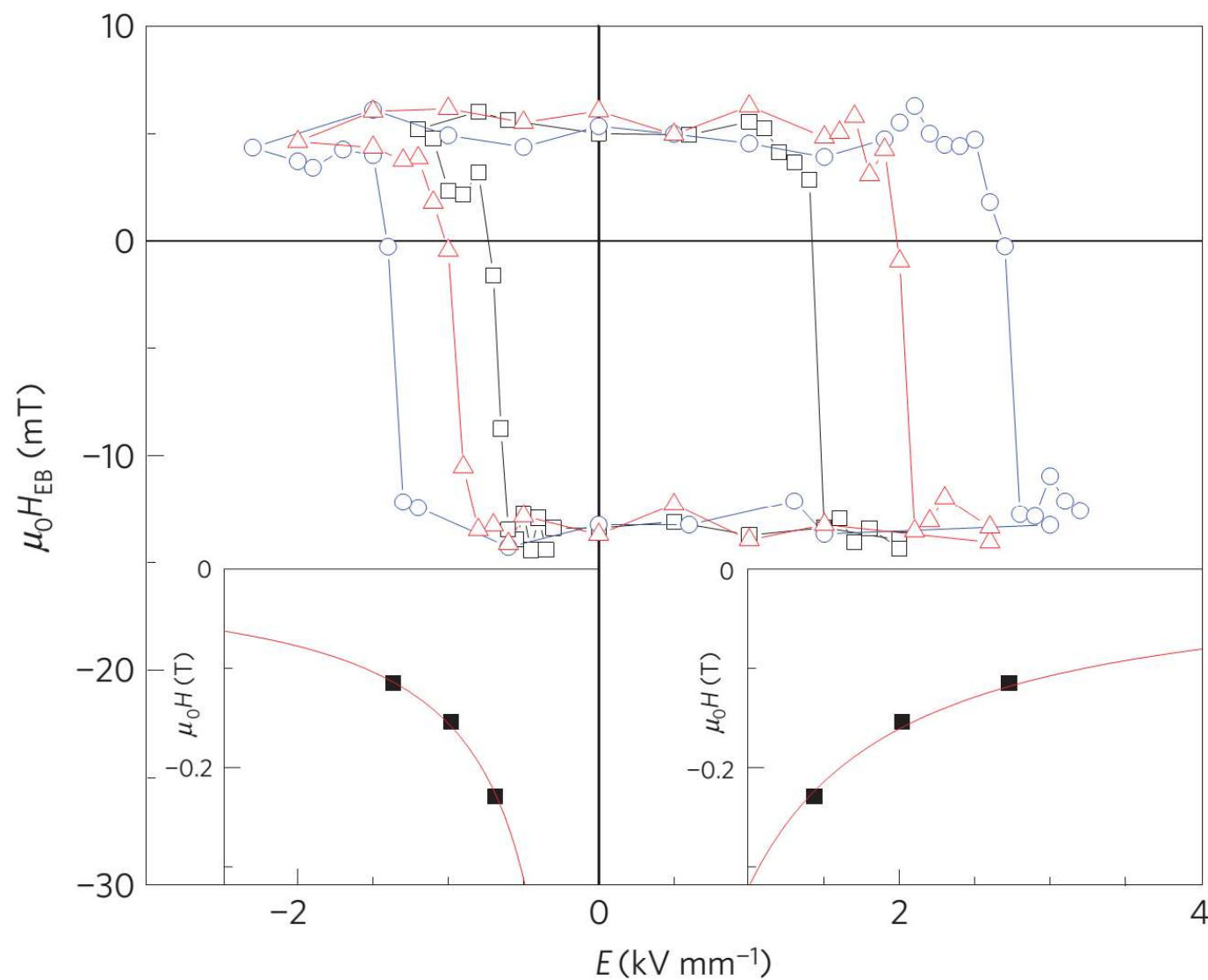


He, et al, Nature Materials (2010)

Electric field to tune Exchange bias

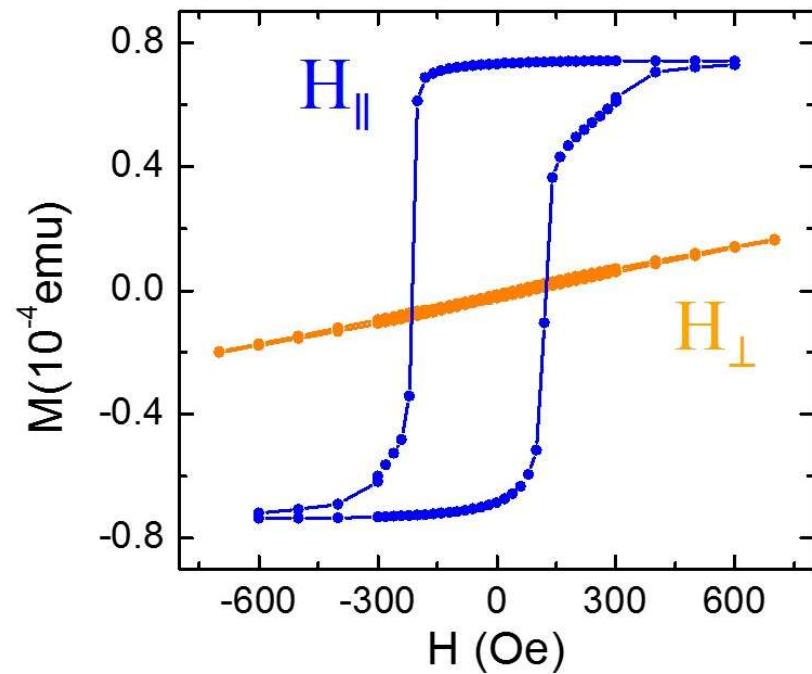
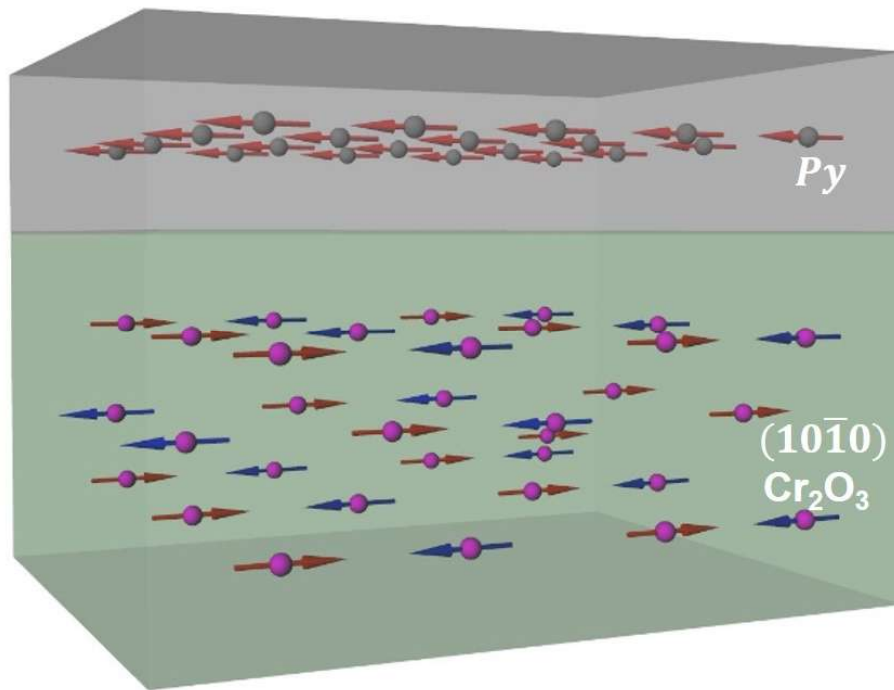


Electric field to tune Exchange bias



Exchange bias

Collinear exchange coupling

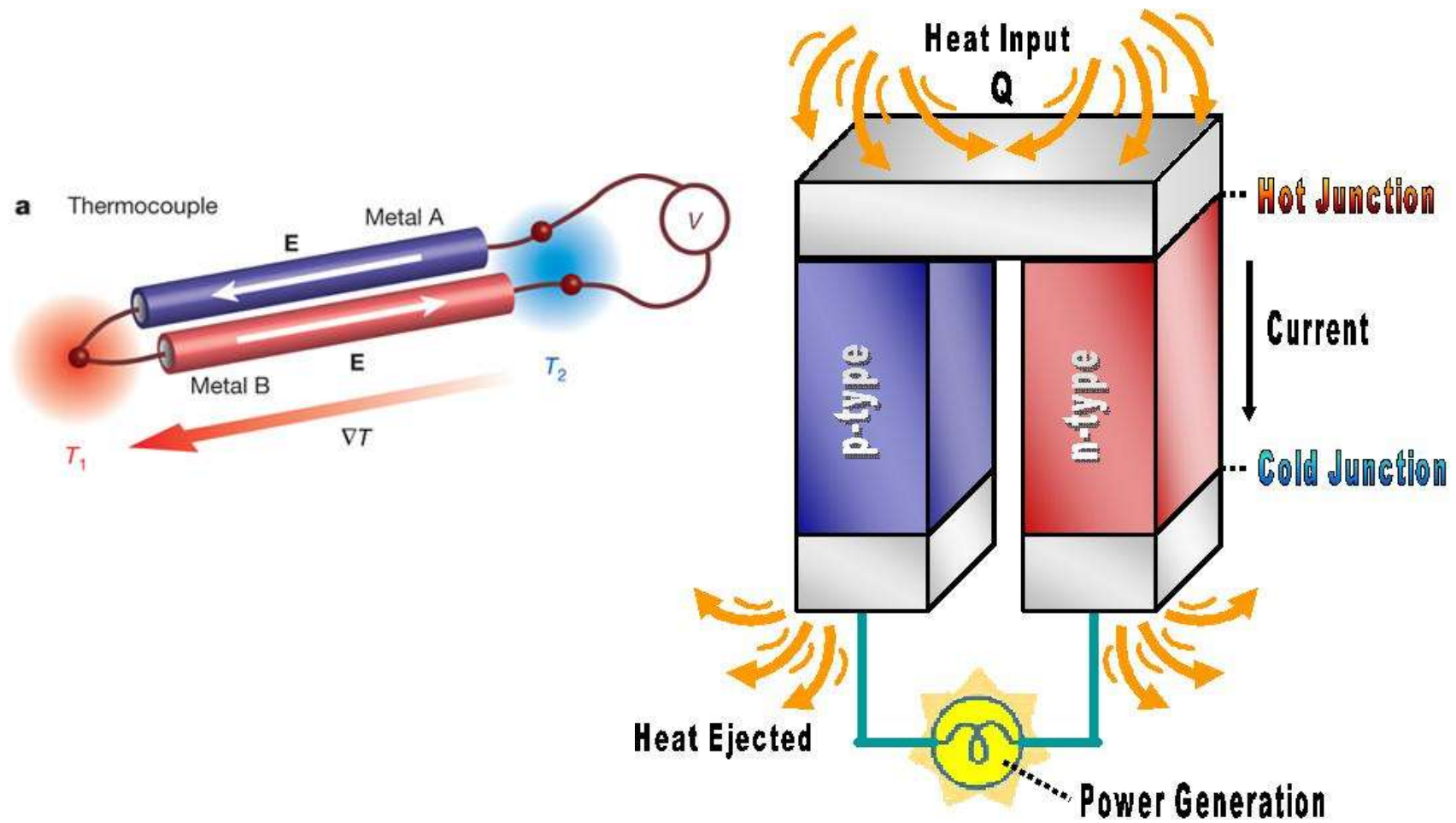


Yuan, et al, Scientific Reports (2016)

Outline

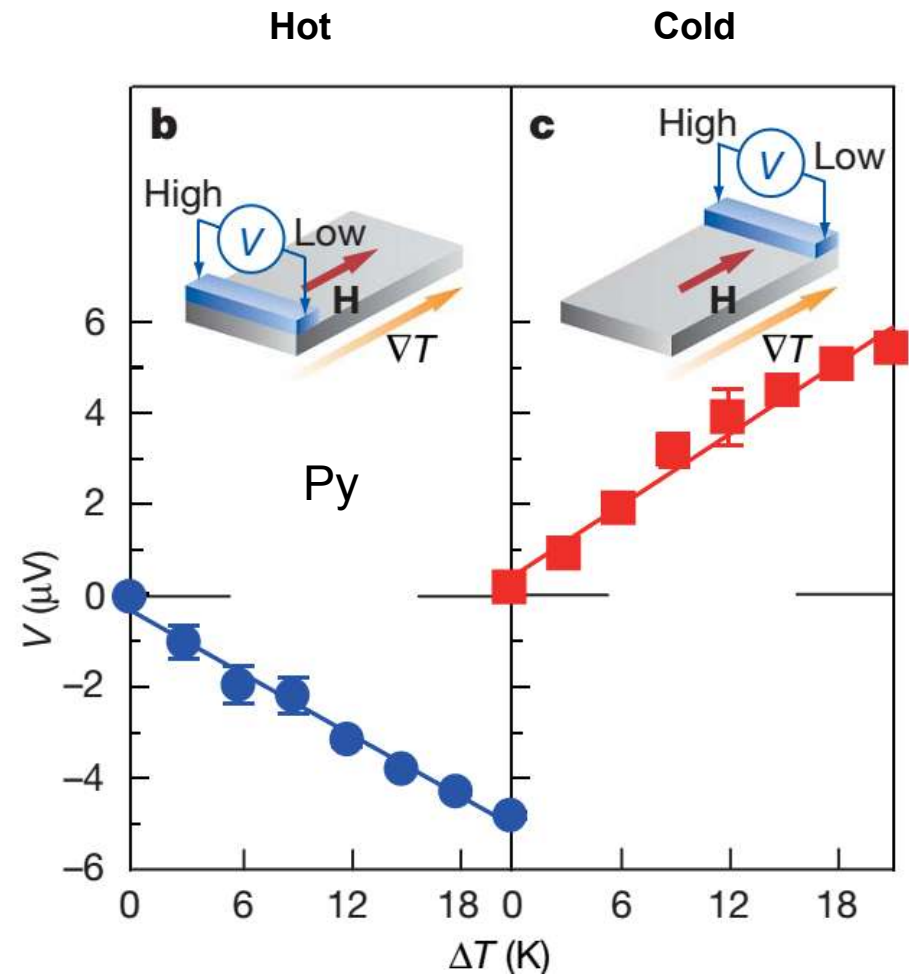
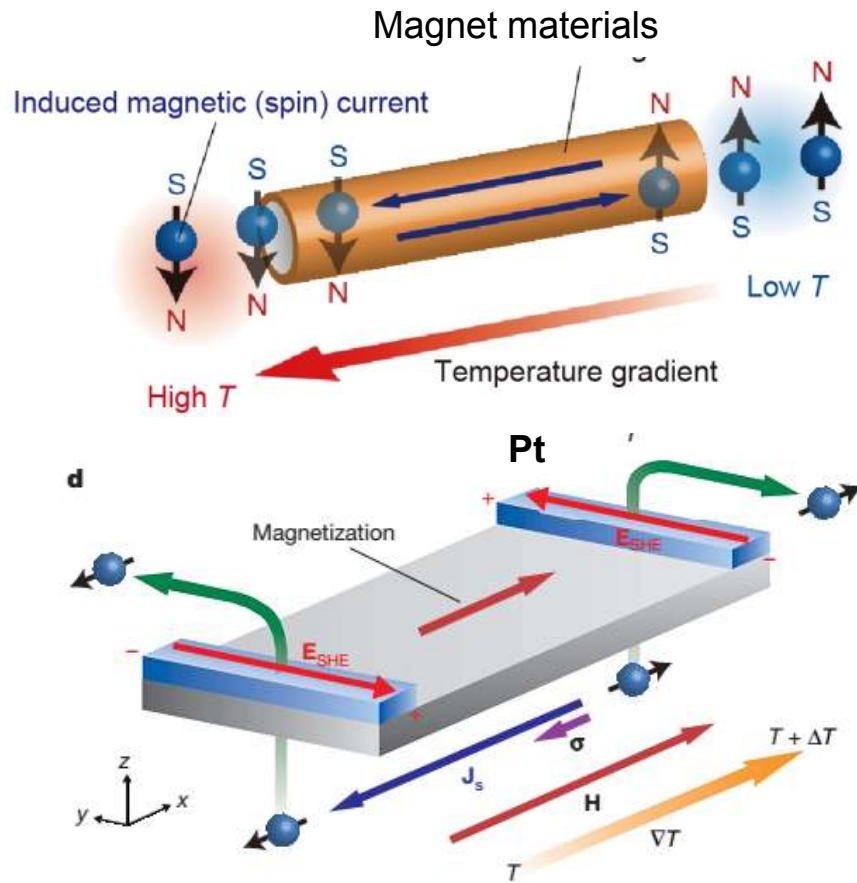
2. Spin Seebeck effect in AFM

Seebeck effect



Spin Seebeck effect

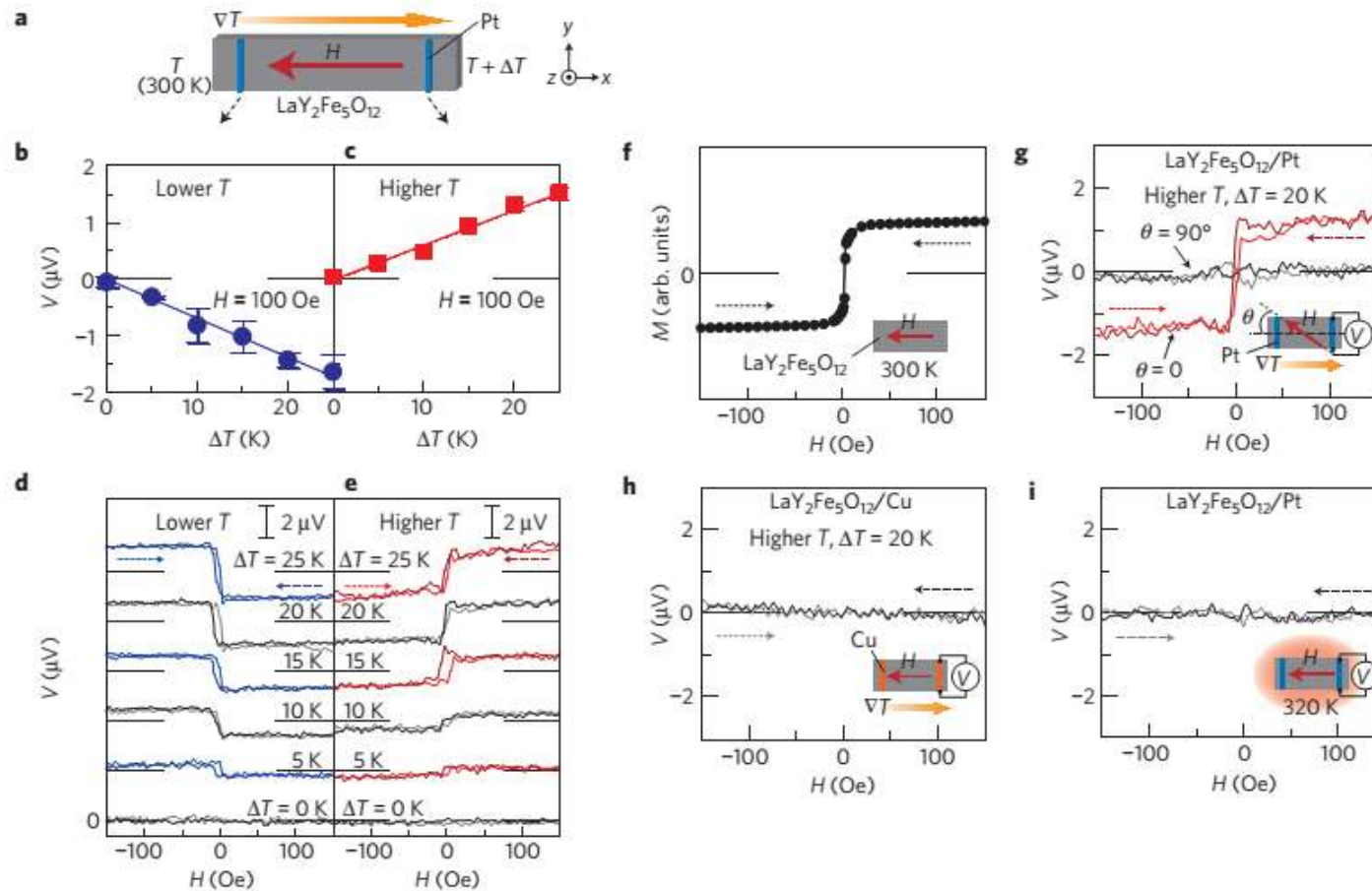
Spin Seebeck effect in FM metal



Uchida, et al. Nature (2008)

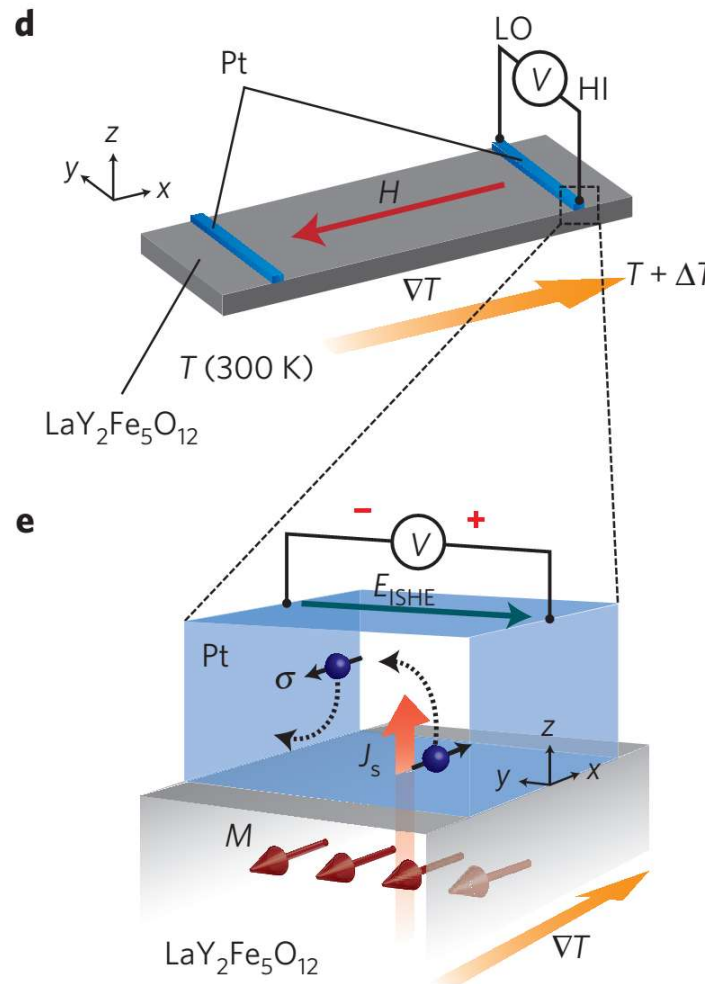
Spin Seebeck effect

Spin Seebeck effect in FM insulator



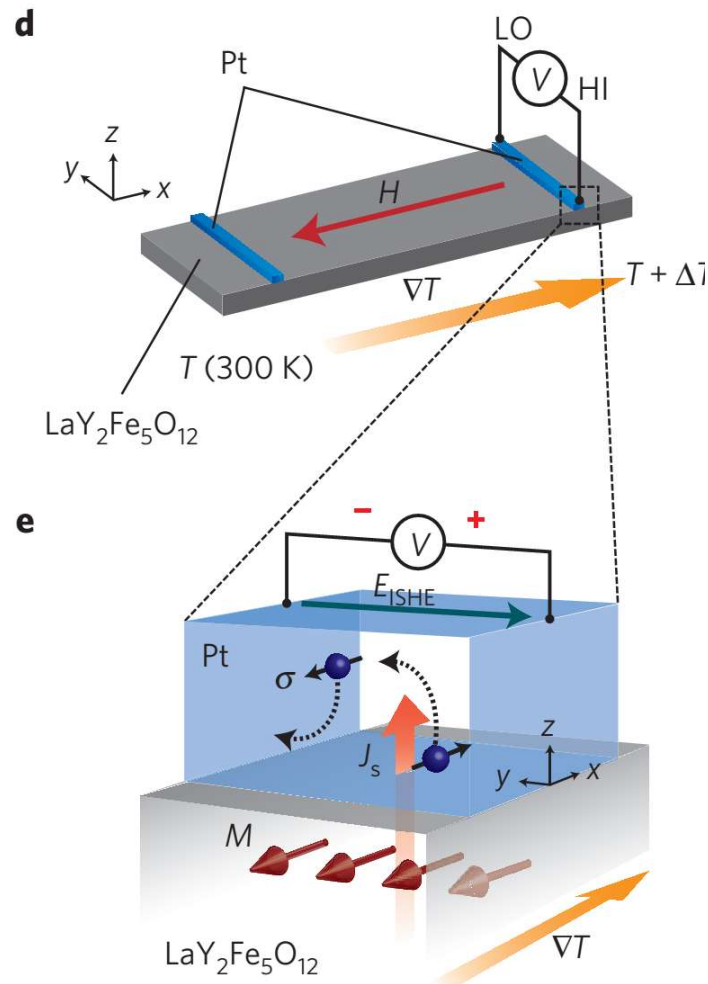
Uchida, et al. Nature Mater. (2010)

Spin Seebeck effect



Question:
How about **AFM**
insulator?

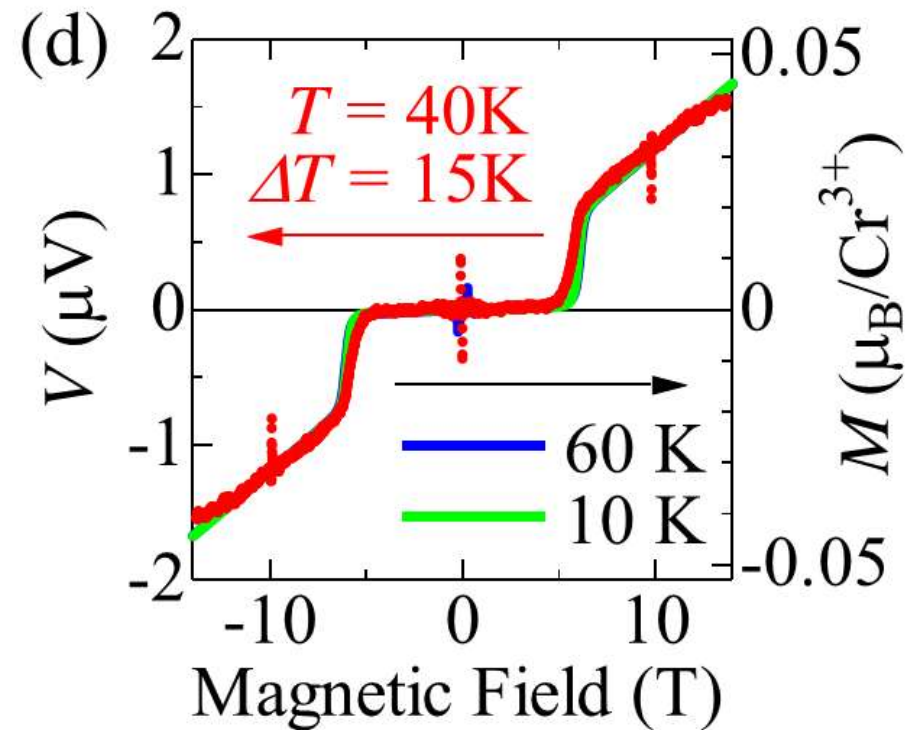
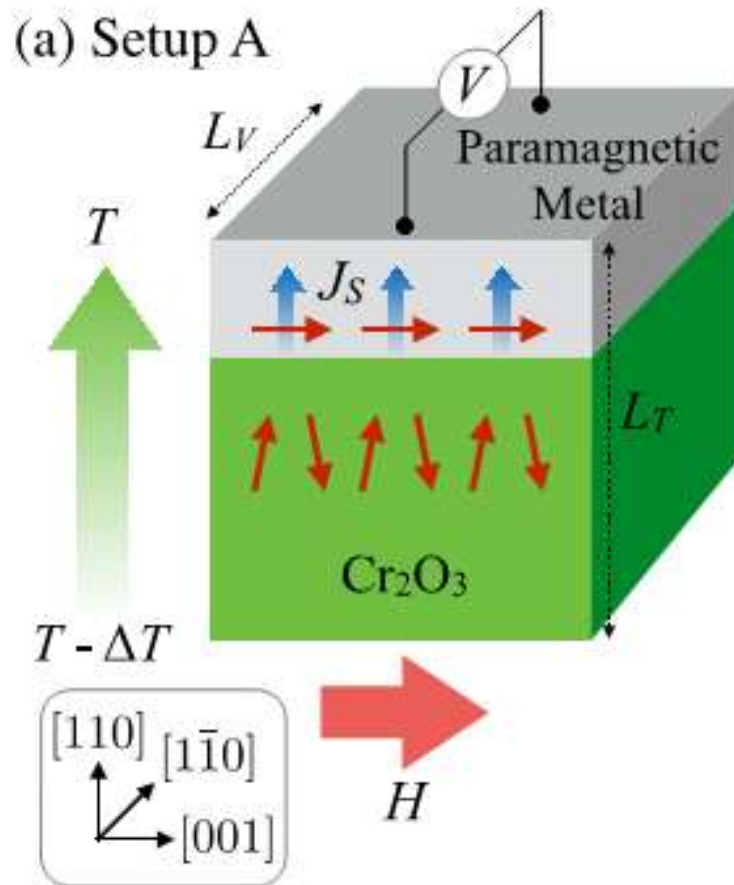
Spin Seebeck effect



Question:
How about **AFM**
insulator?

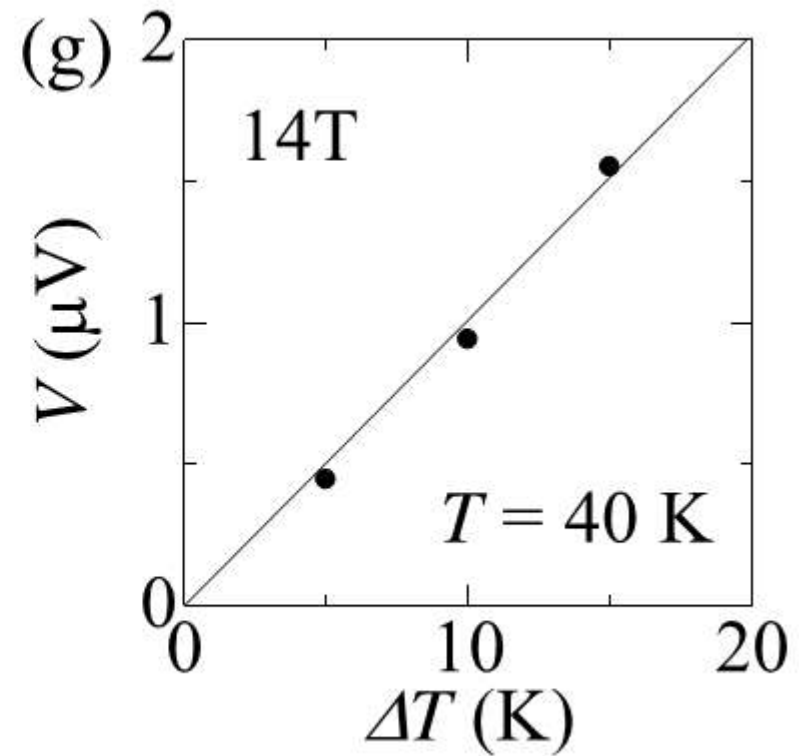
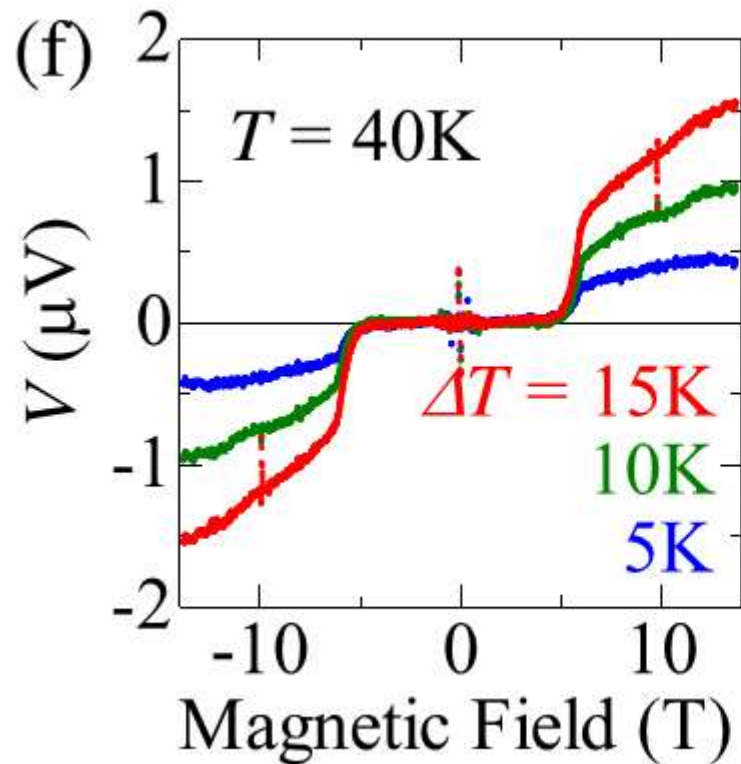
YES!

Spin Seebeck effect in AFM



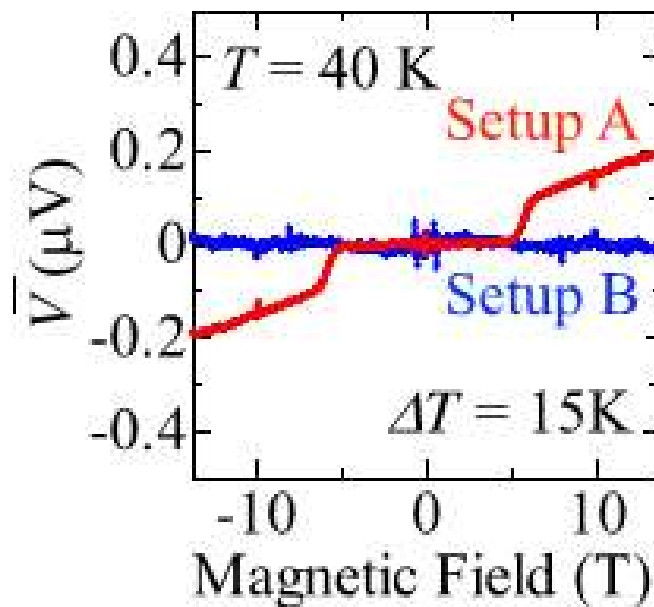
Seki et al, PRL (2015).

Spin Seebeck effect in AFM

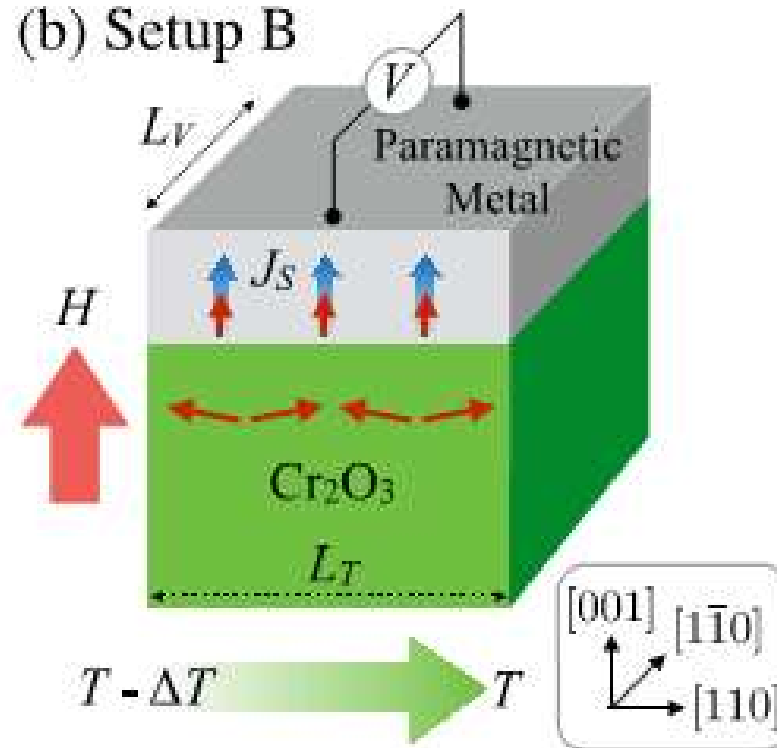


Spin Seebeck effect in AFM

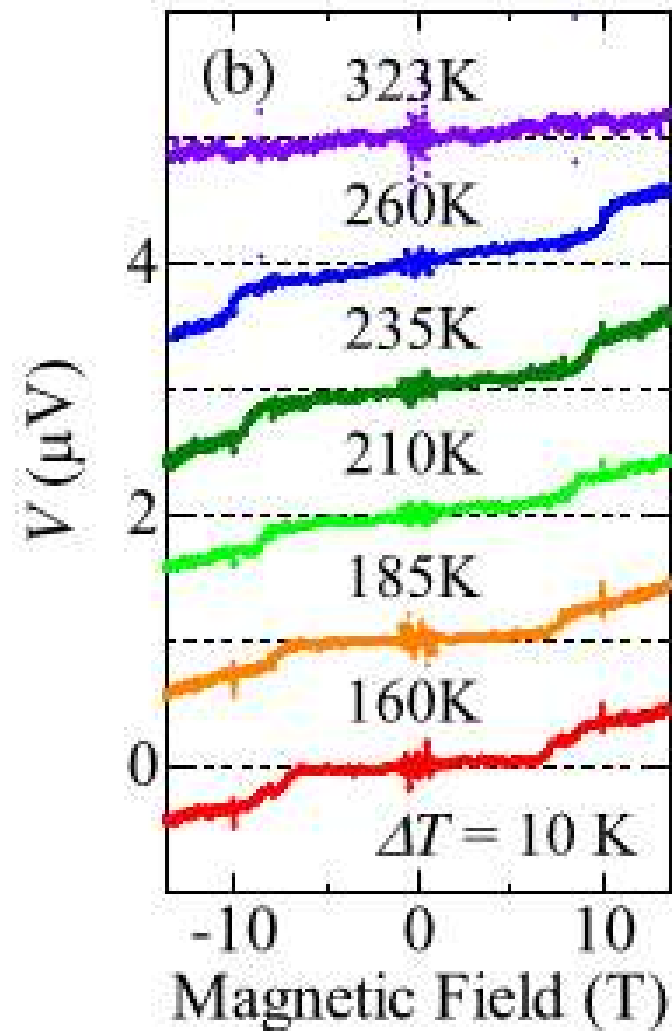
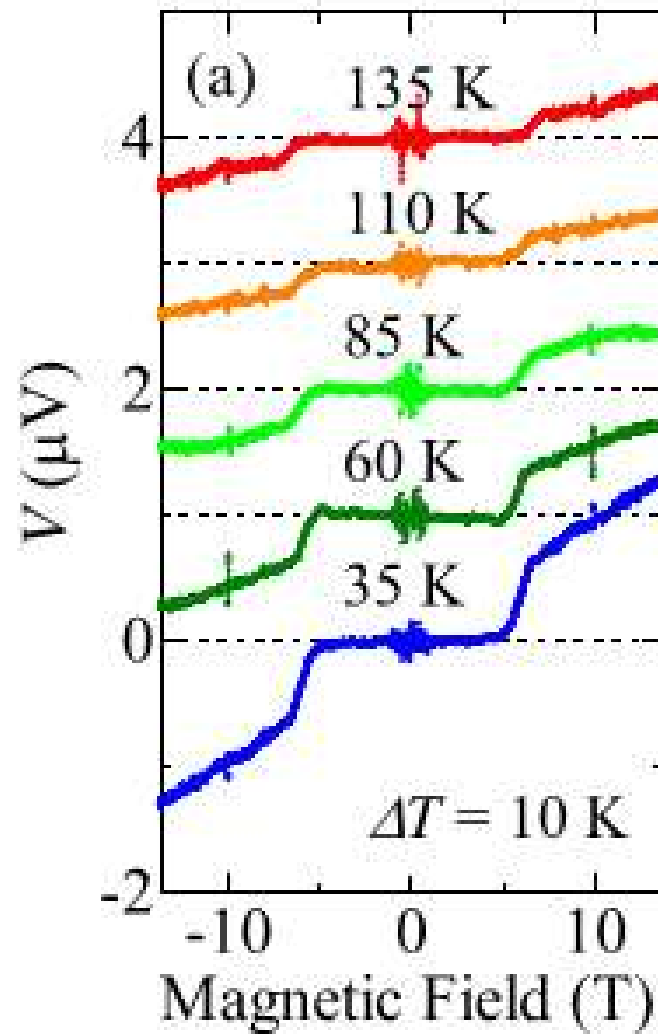
(a) $\text{Cr}_2\text{O}_3/\text{Pt}$ $H \parallel [001]$



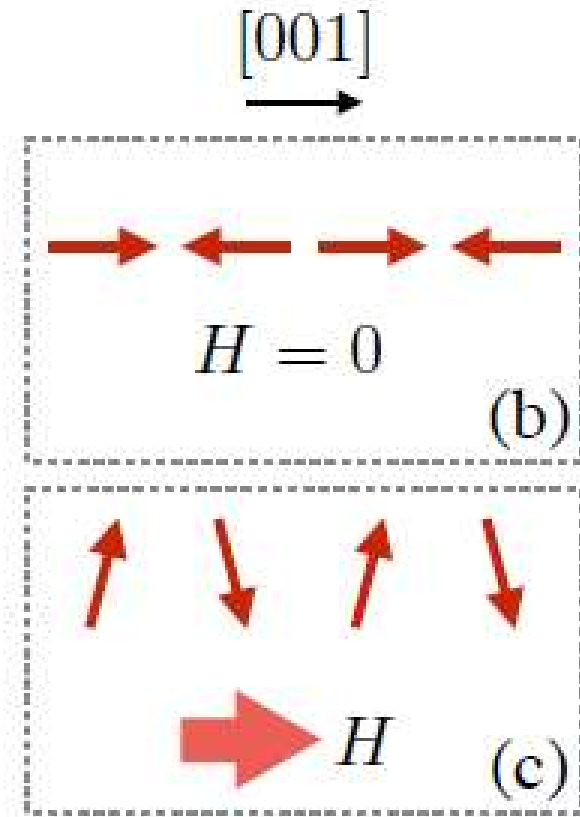
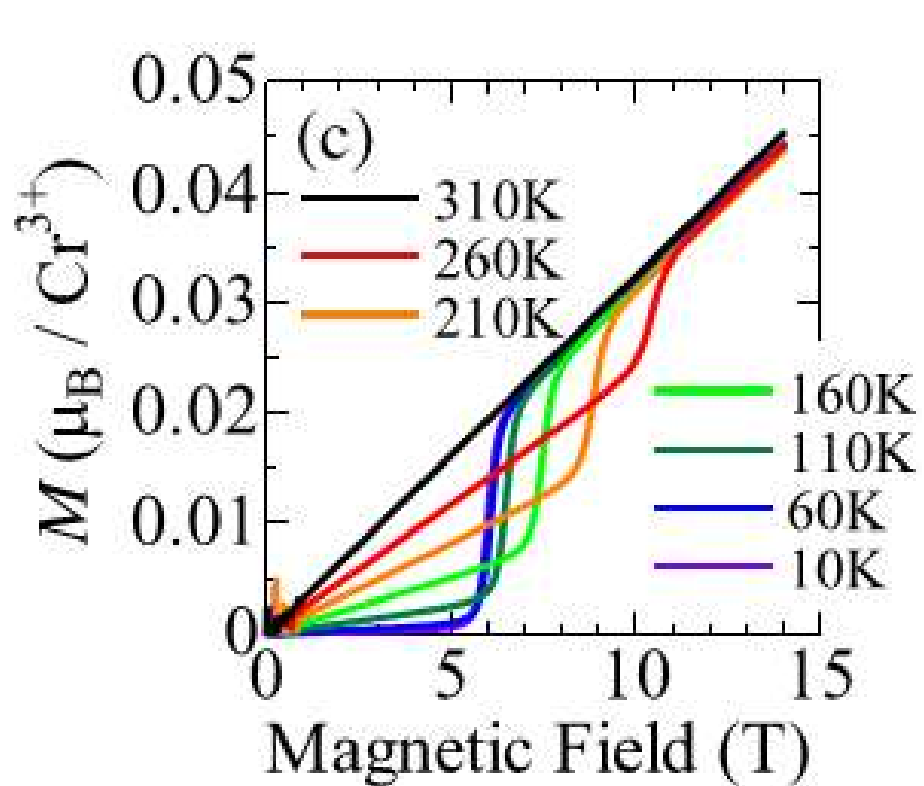
(b) Setup B



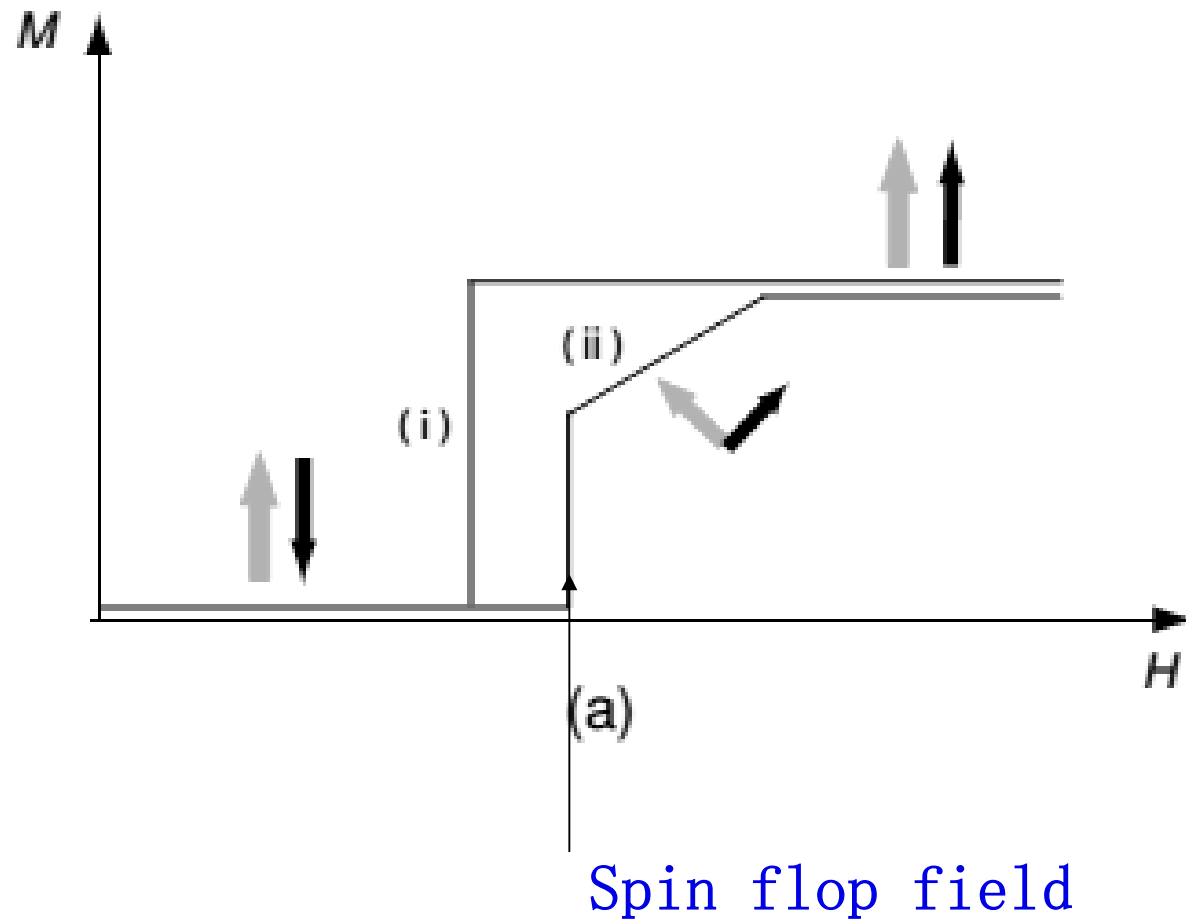
Spin Seebeck effect in AFM



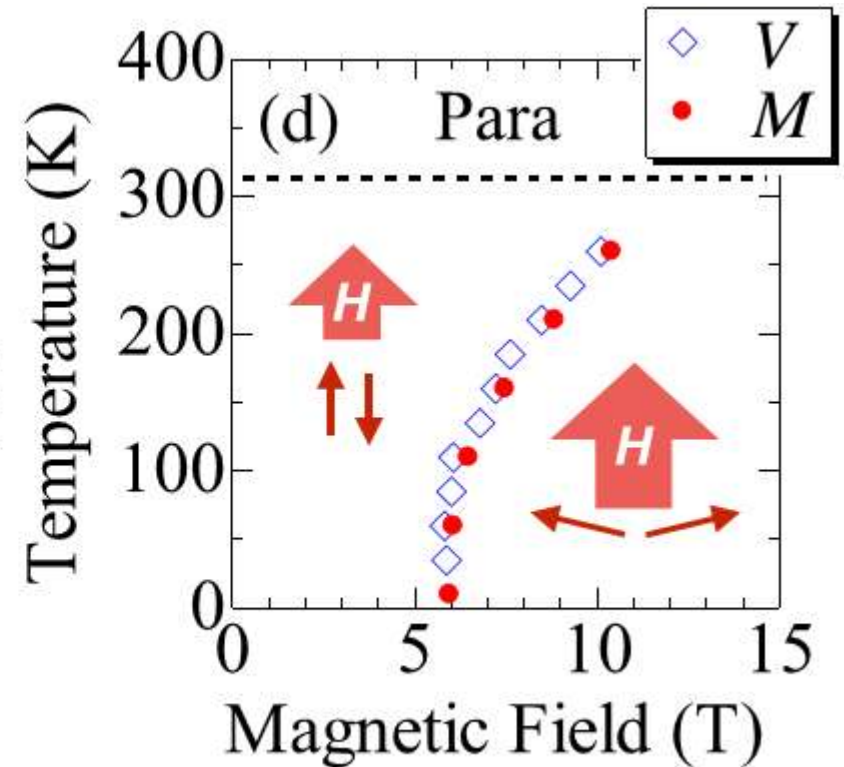
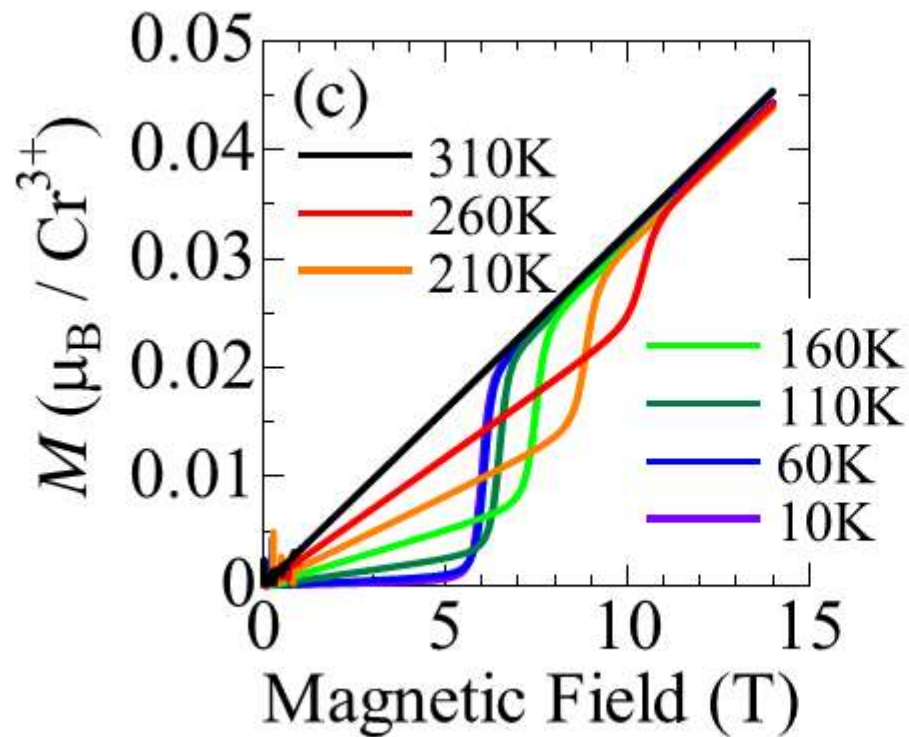
Spin Seebeck effect in AFM



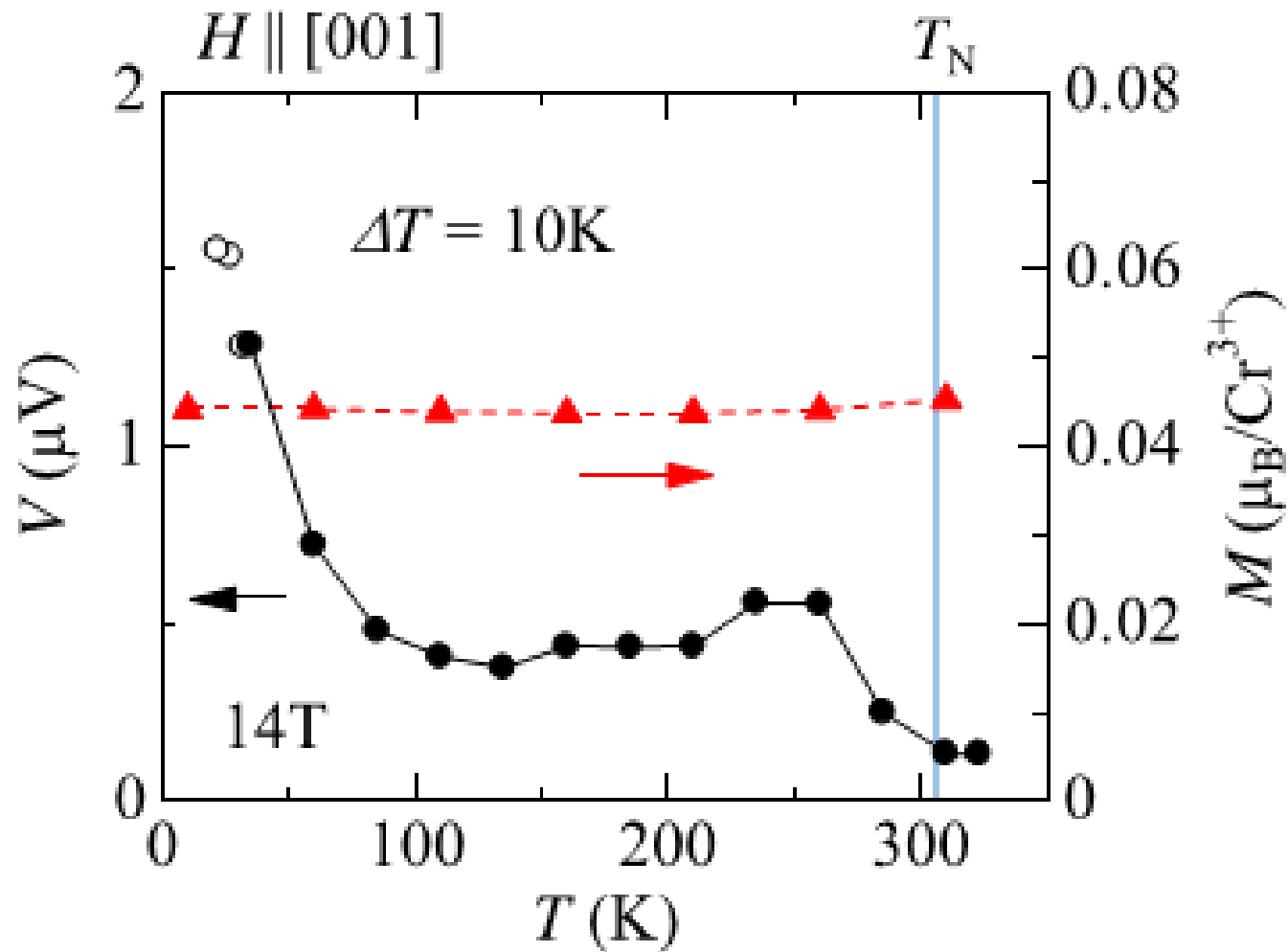
Spin Seebeck effect in AFM



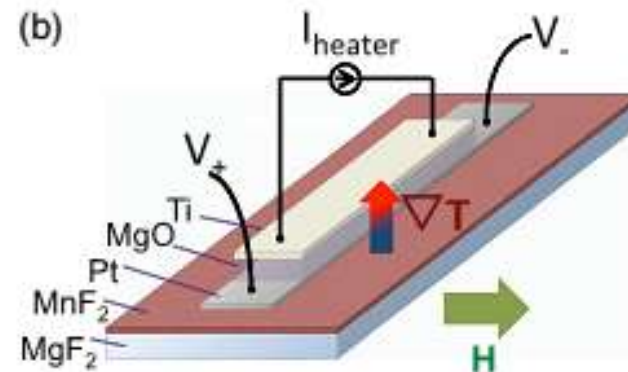
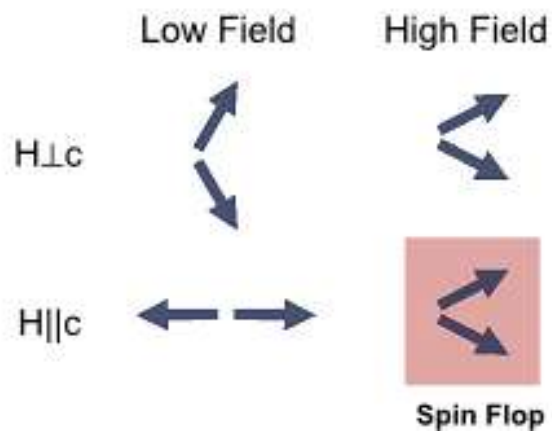
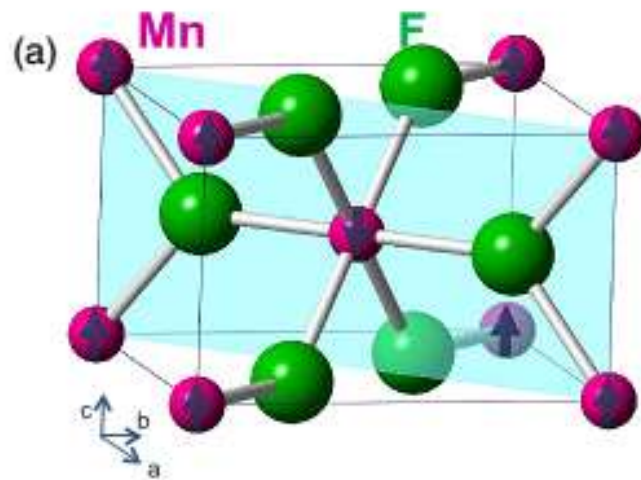
Spin Seebeck effect in AFM



Spin Seebeck effect in AFM

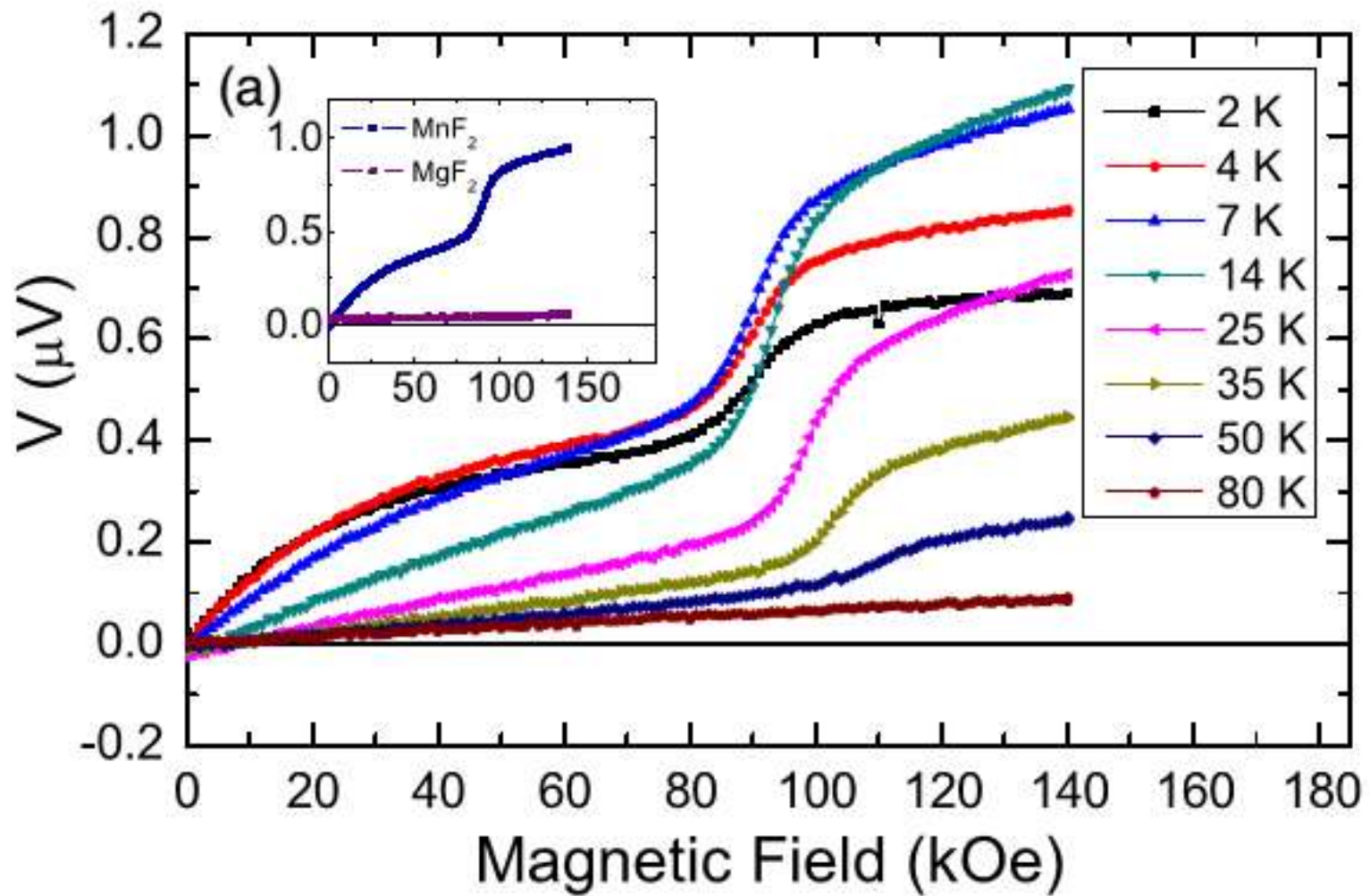


Spin Seebeck effect in AFM

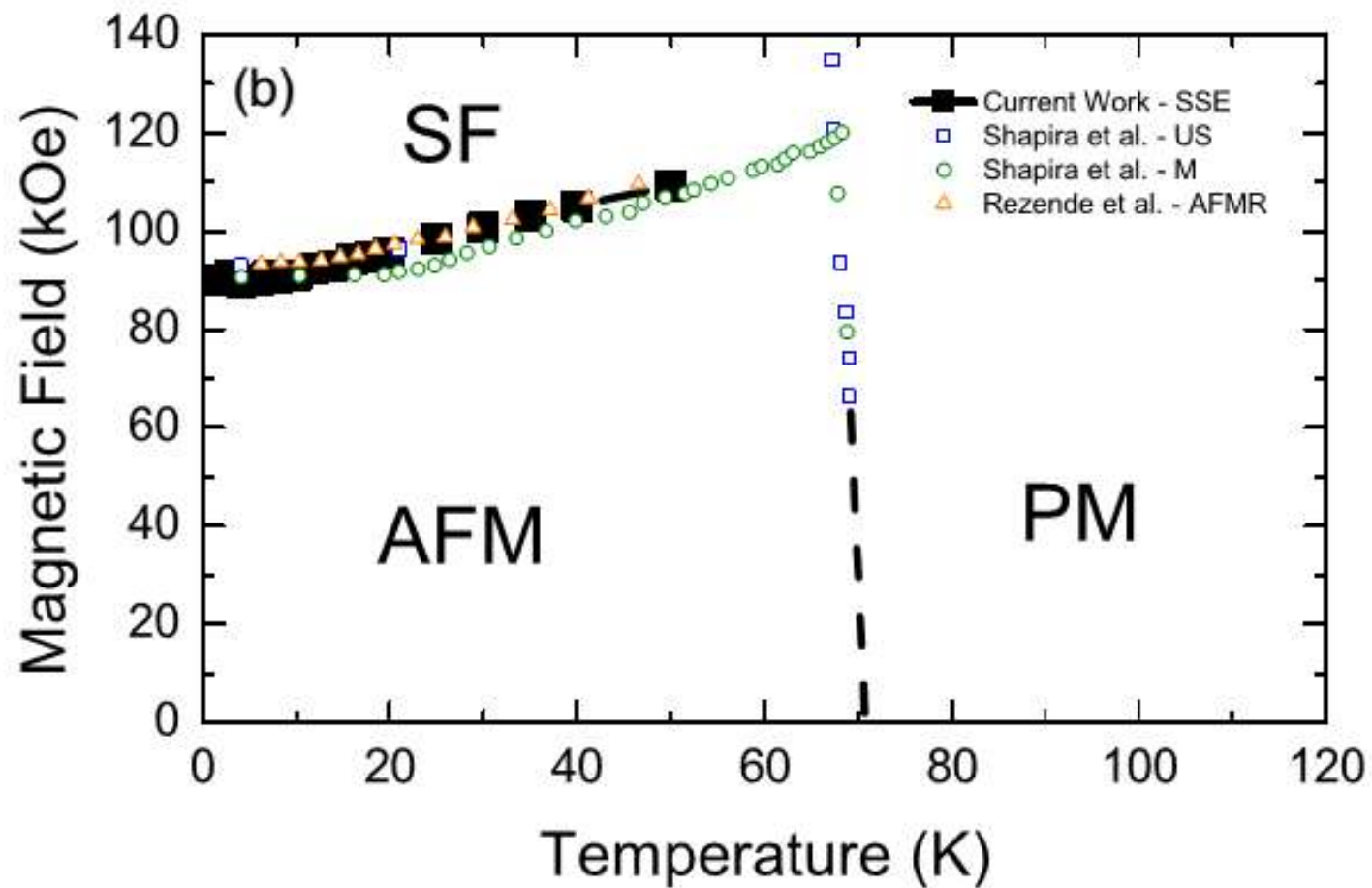


Wu, et al, PRL (2016)

Spin Seebeck effect in AFM



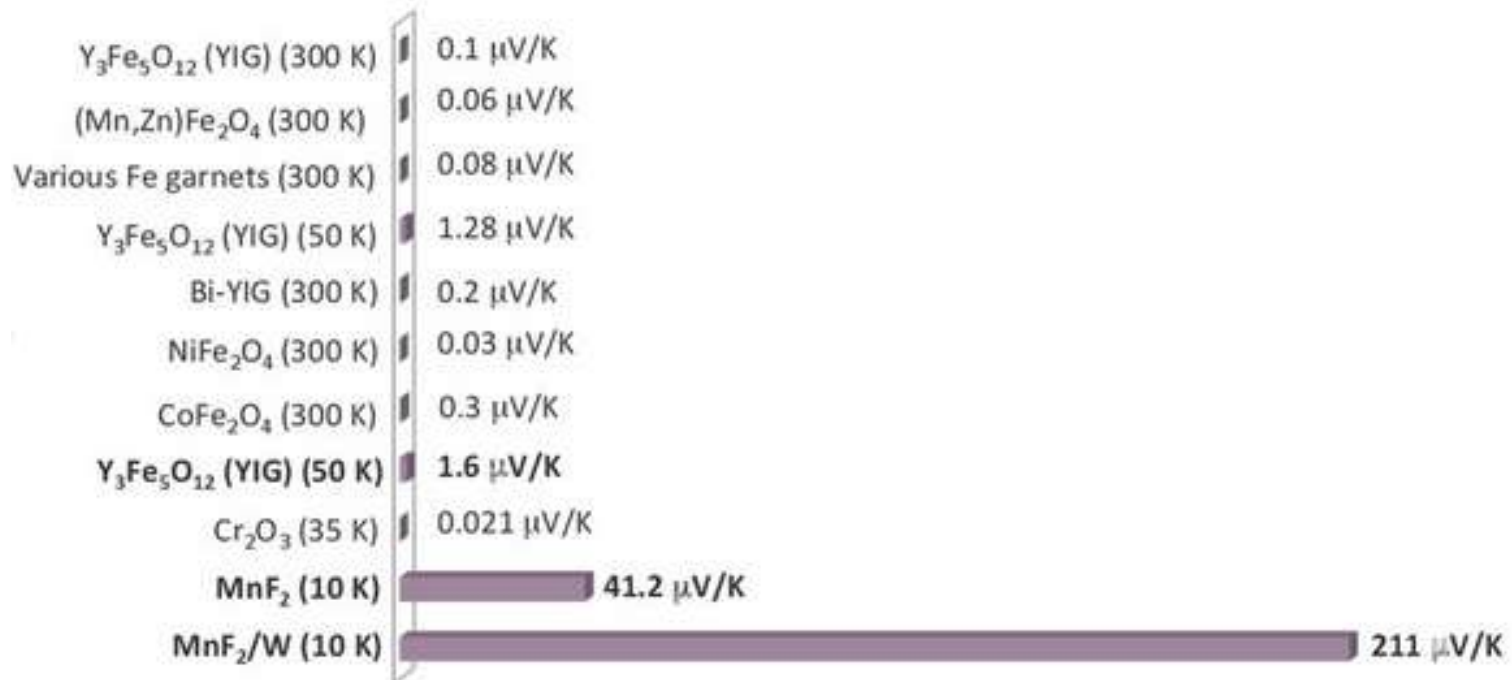
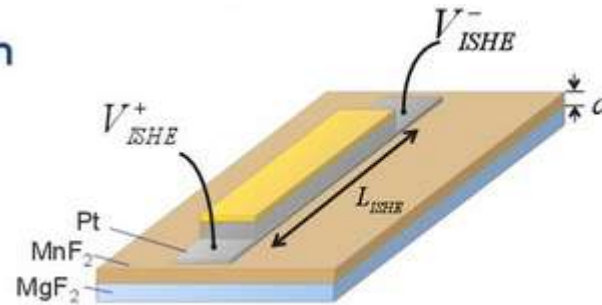
Spin Seebeck effect in AFM



Spin Seebeck effect in AFM

Magnitude comparison

$$S = \frac{E_{ISHE}}{\nabla T} = \frac{V_{ISHE} / L_{ISHE}}{\Delta T / d}$$



1.6 μV/K → 211 μV/K

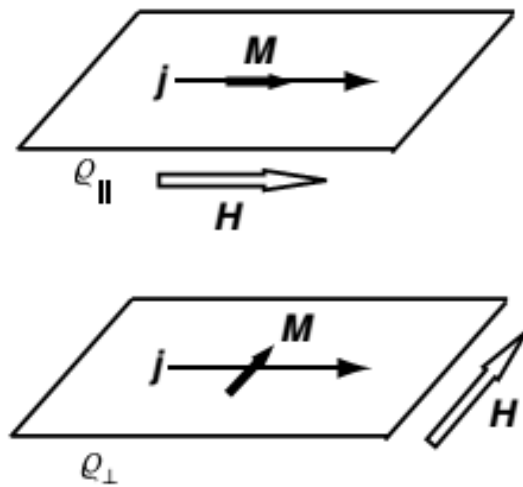
Outline

3. AMR of AFM

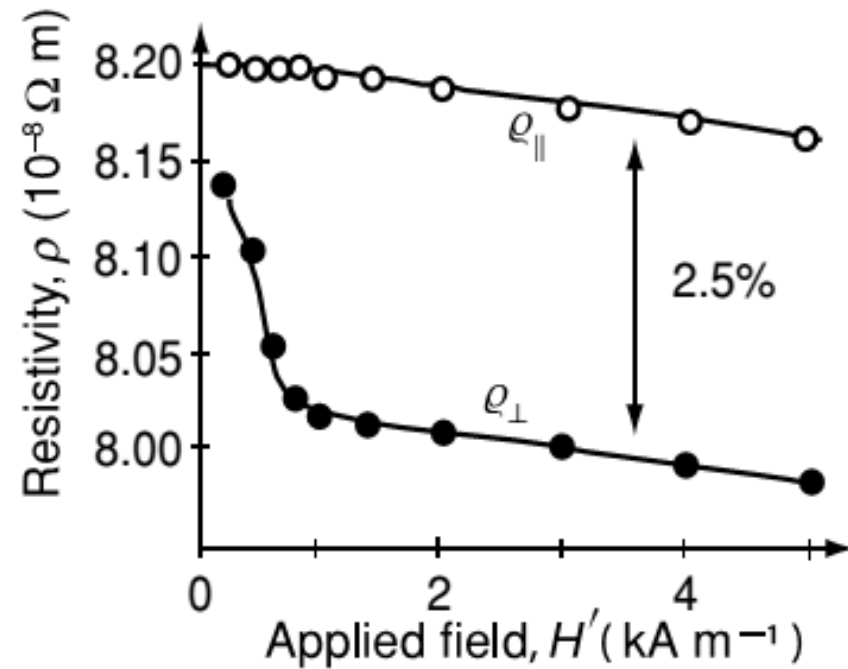
AMR in FM

AMR of a Nickel

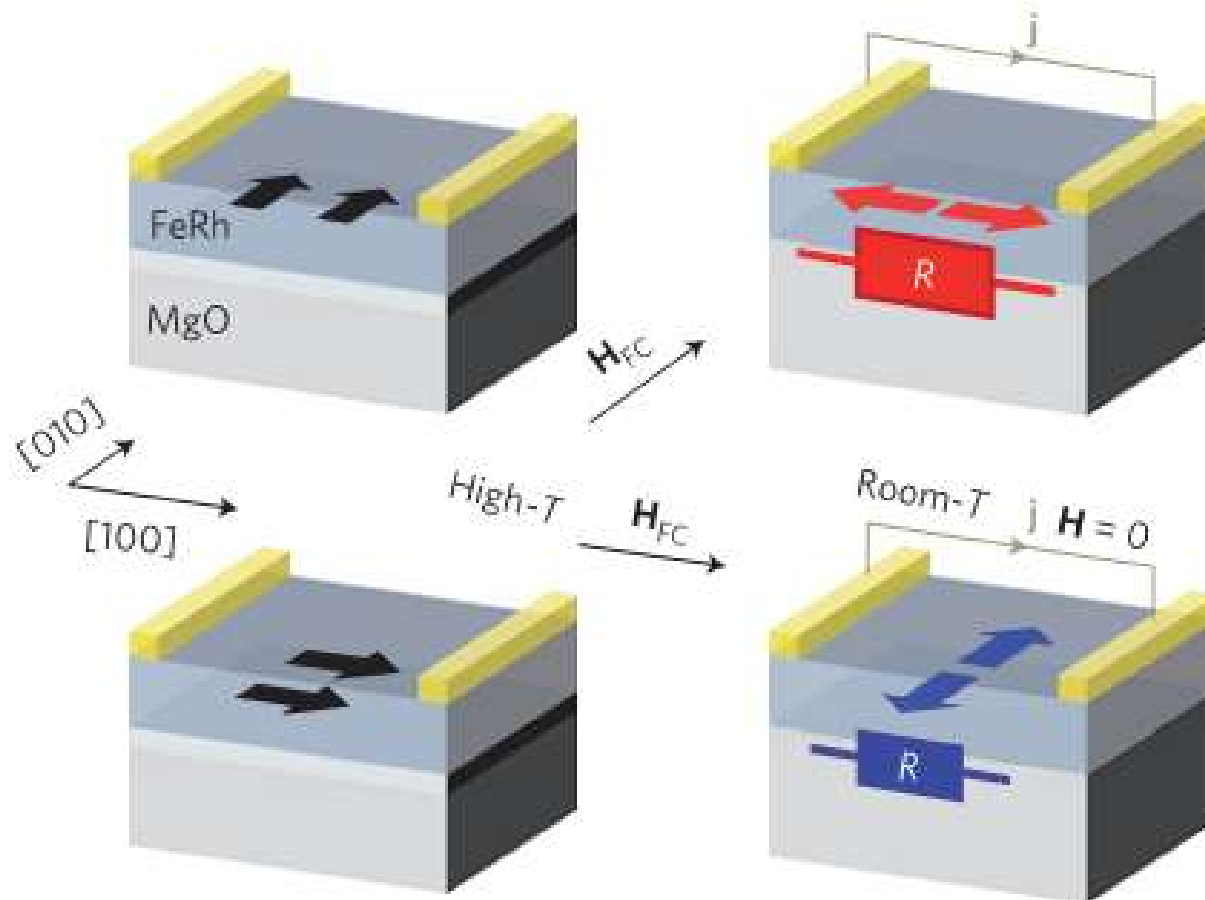
Discovered by William Thompson (1857)



Measurement of AMR for a thin film.

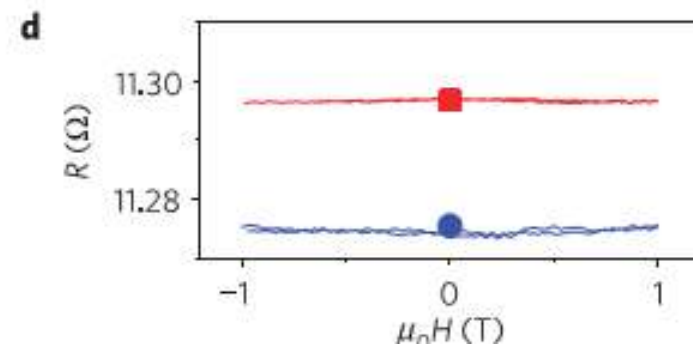
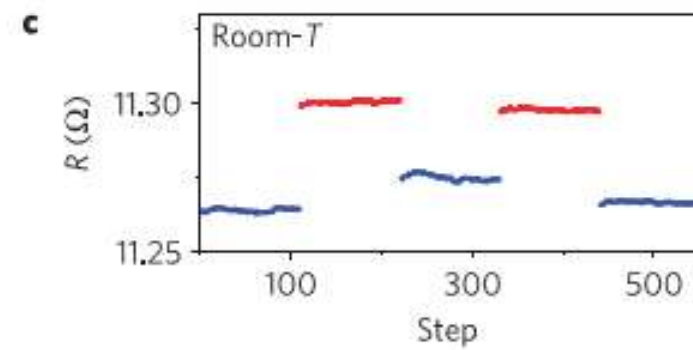
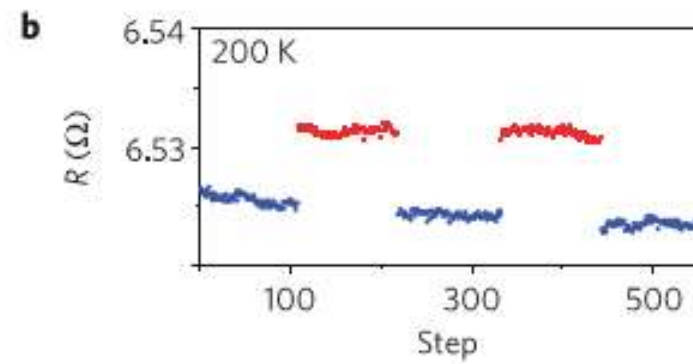
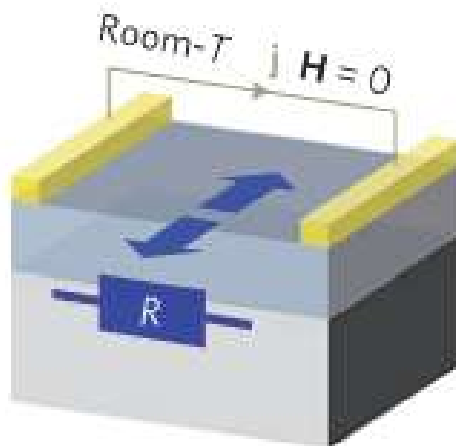
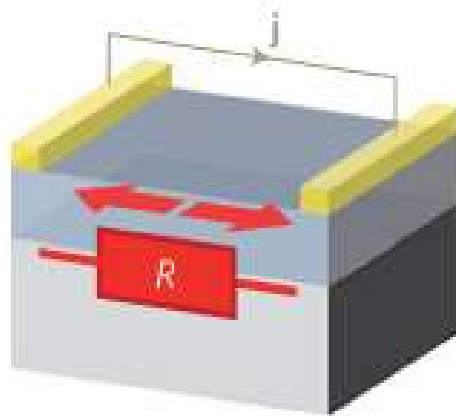


AMR in AFM



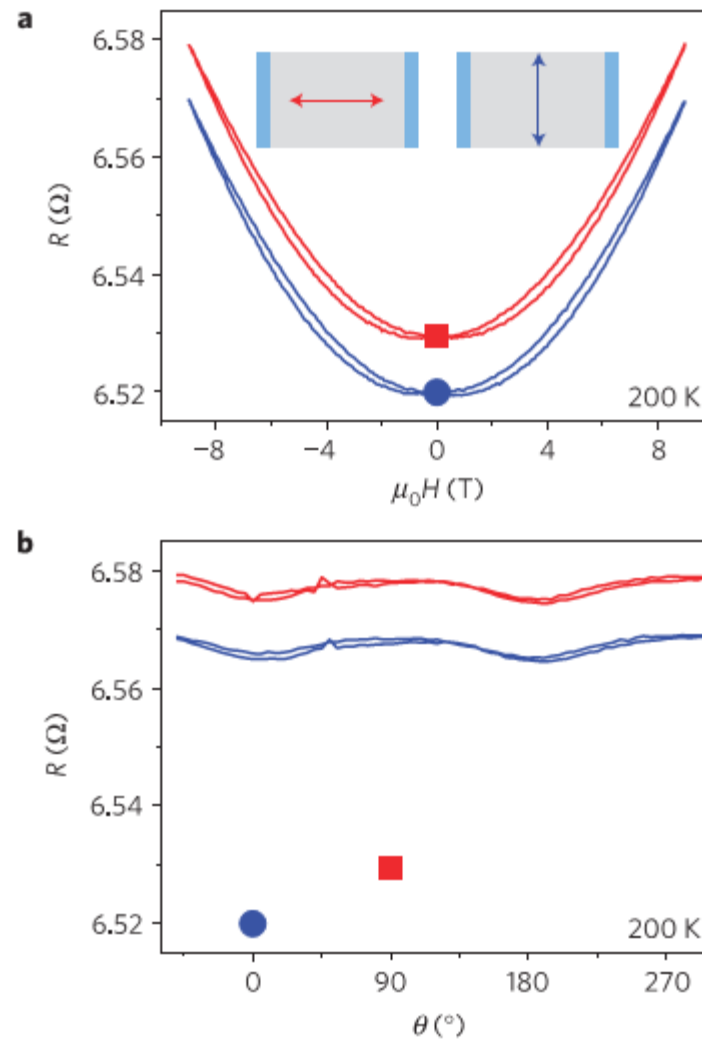
Marti, et al, Nature Materials (2014)

AMR in AFM



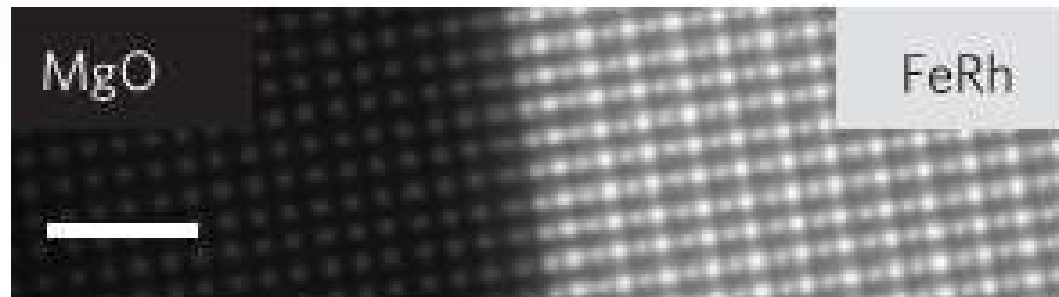
AMR in AFM

Advantage: Signal robust in magnetic field

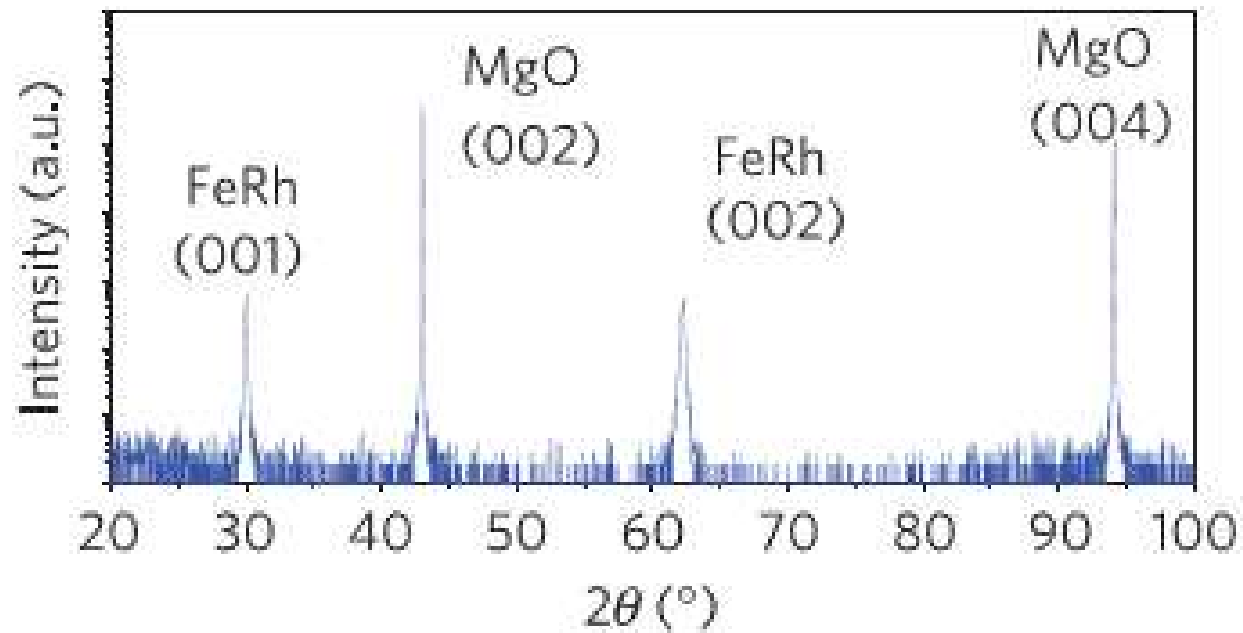


AMR in AFM

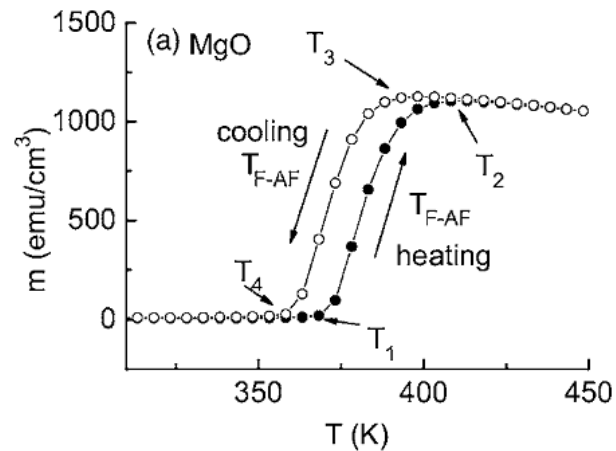
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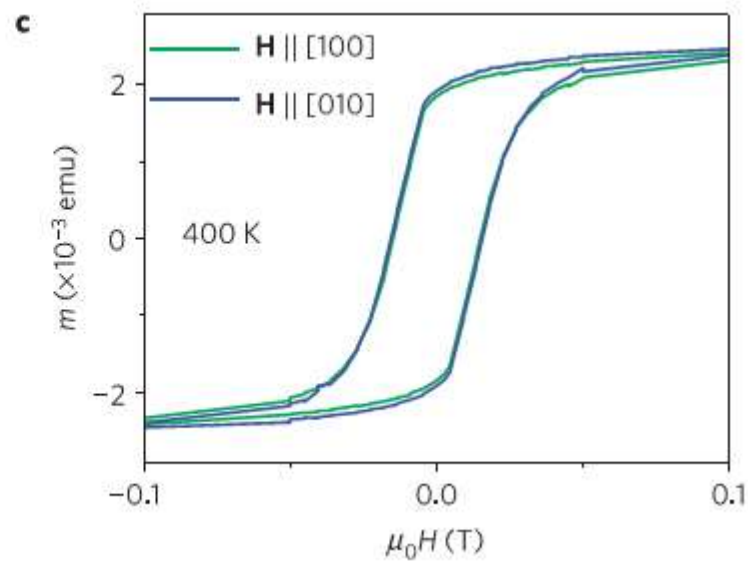
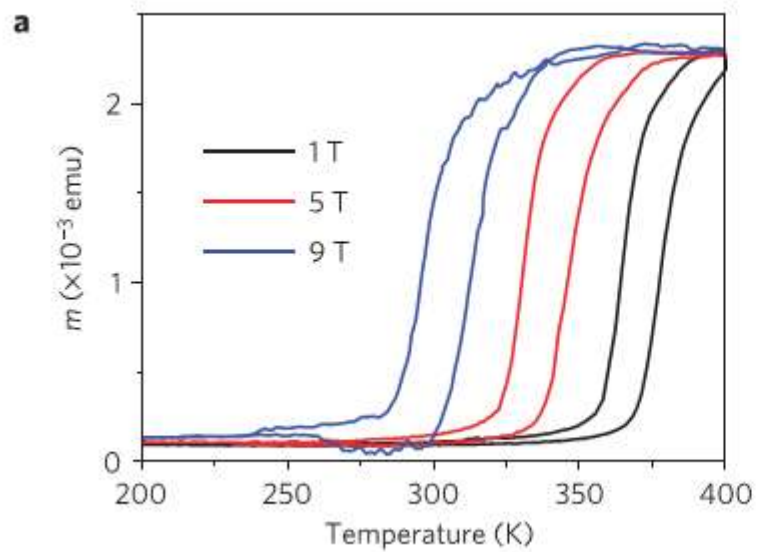
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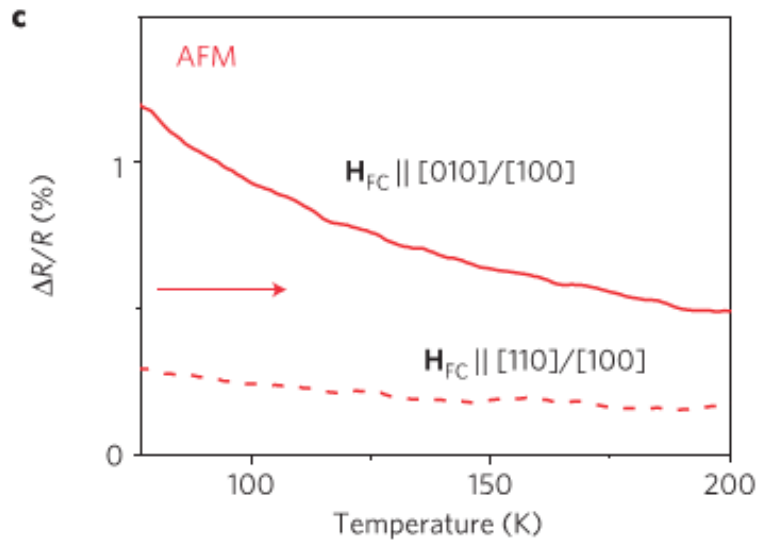
AMR in AFM



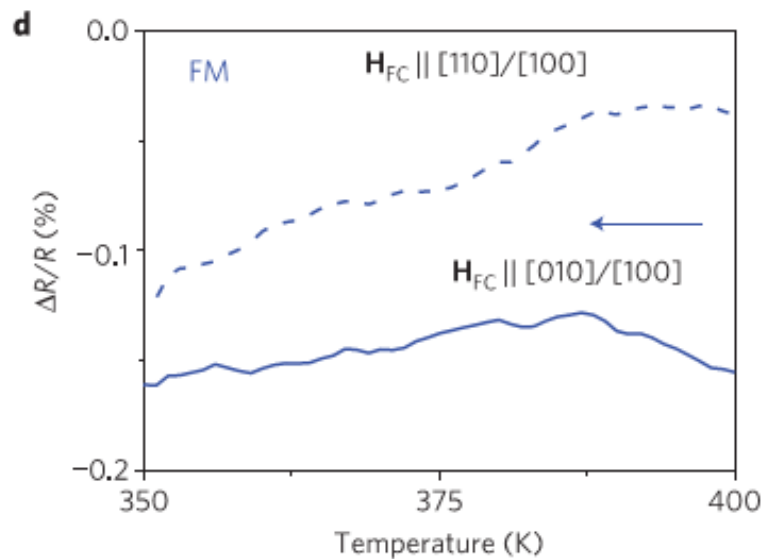
Maat, et al, PRB (2006)



AMR in AFM



Larger AMR in the AFM state



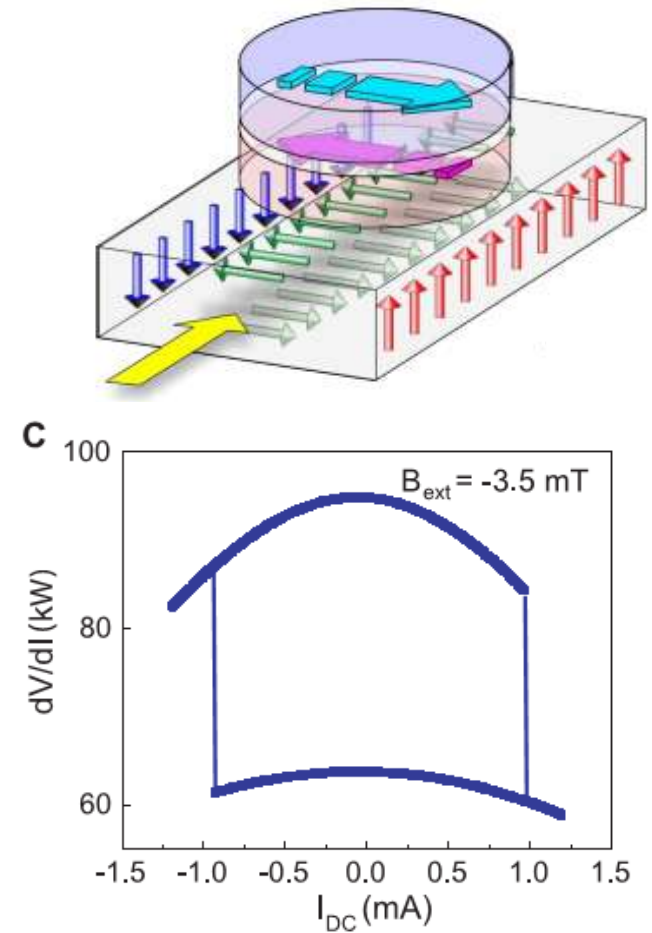
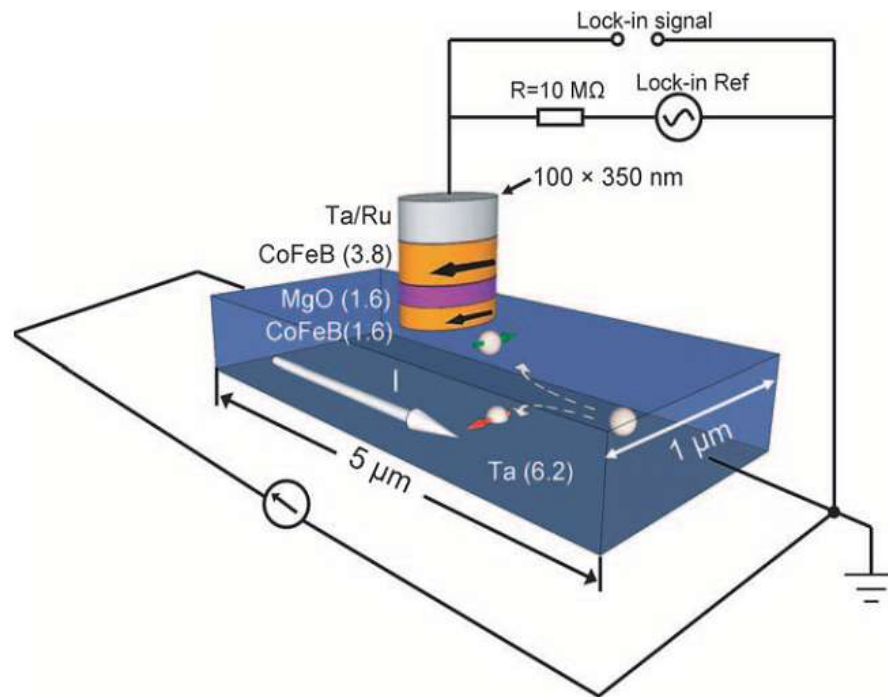
Smaller AMR in the FM state

休息10分钟

Outline

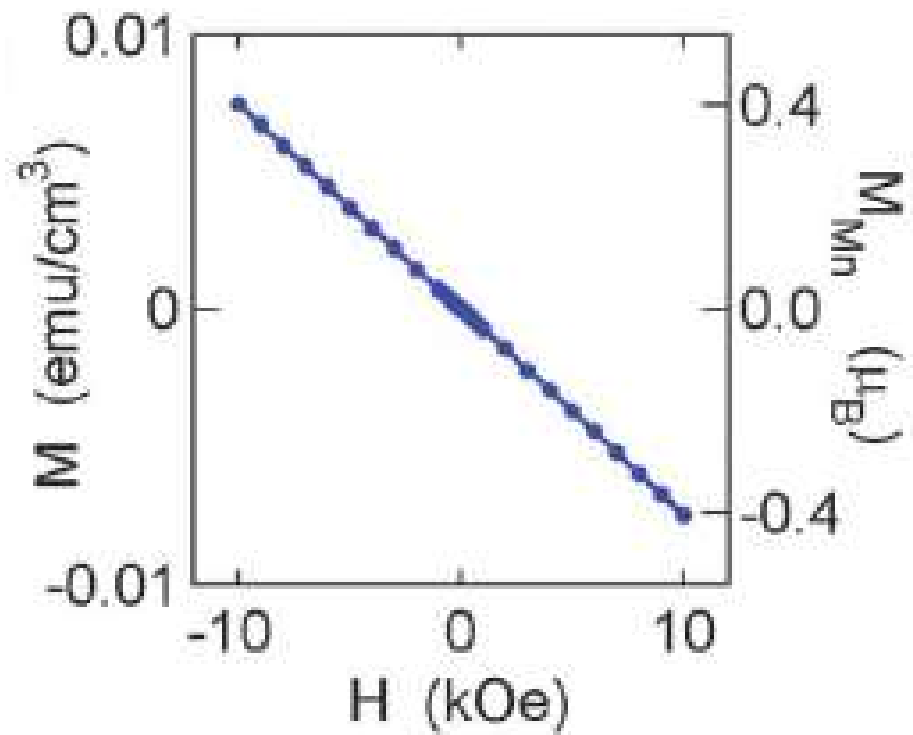
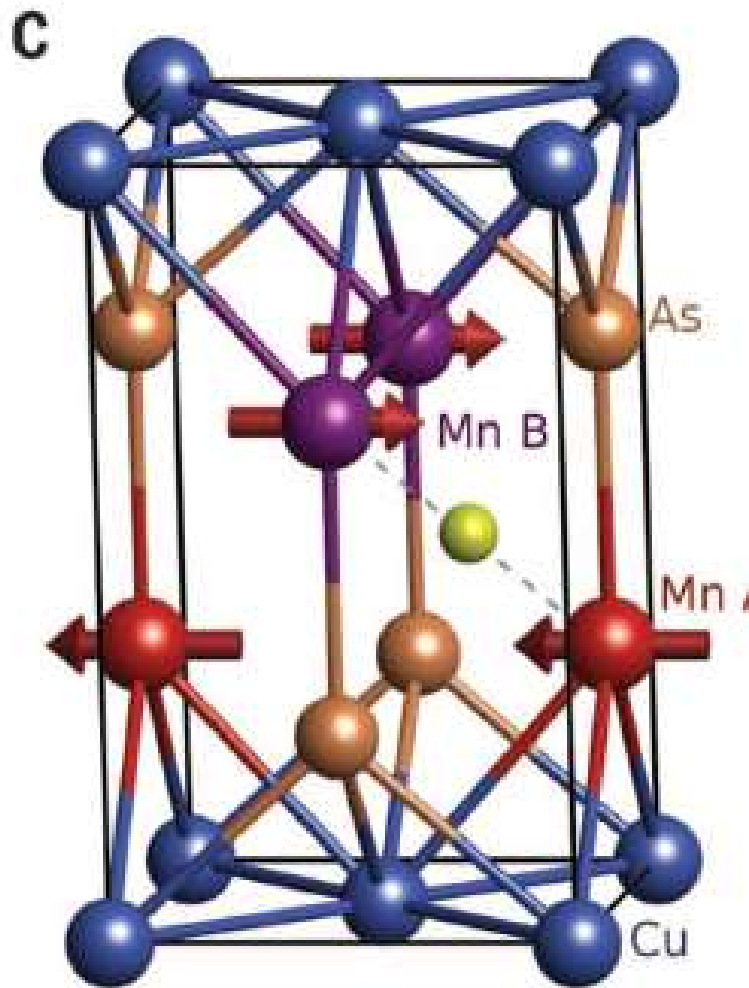
4. Switching of AFM

Switching of FM by spin torque



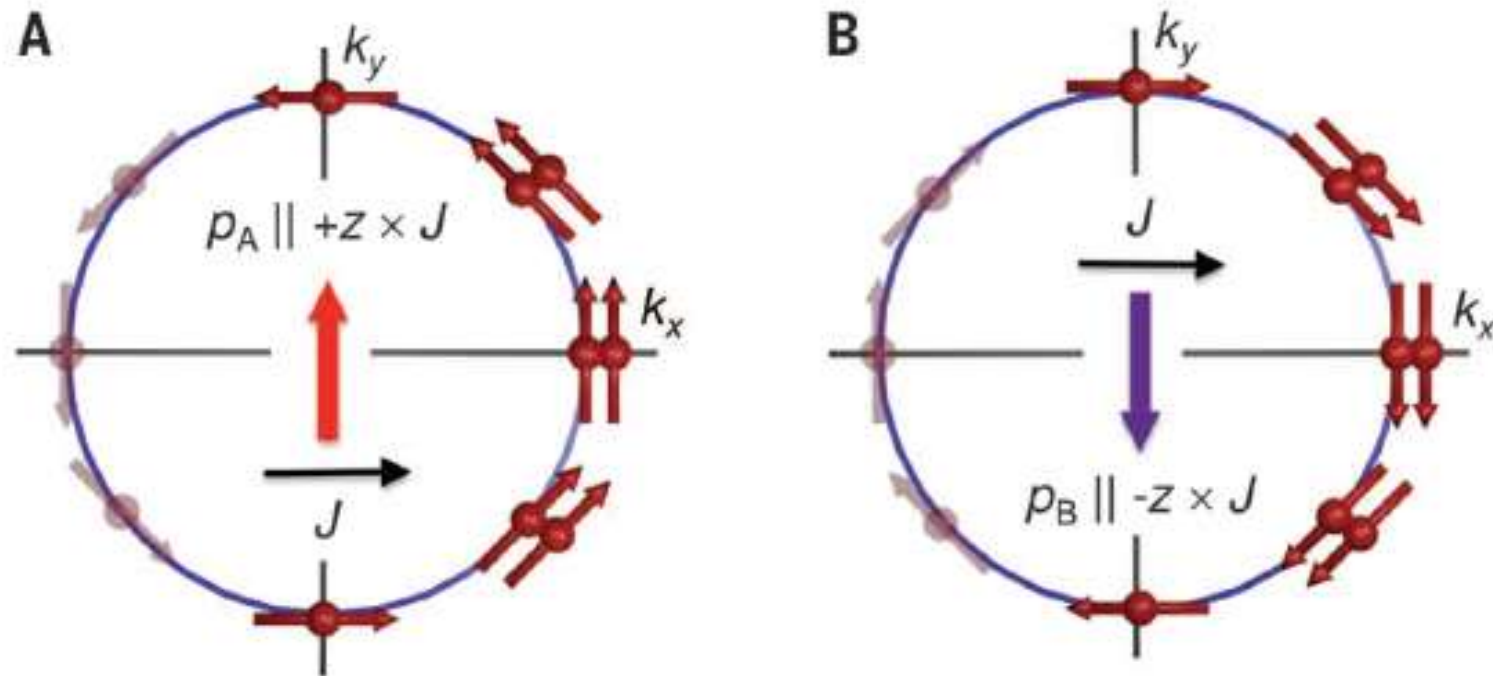
Liu, et al., Science (2012)

Switching of AFM



Wadley et al, science **351**, 587(2016)

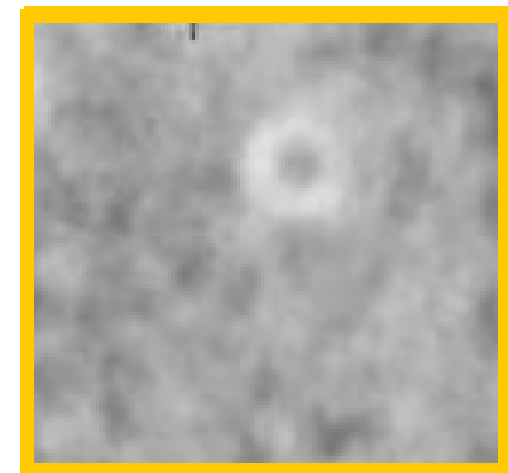
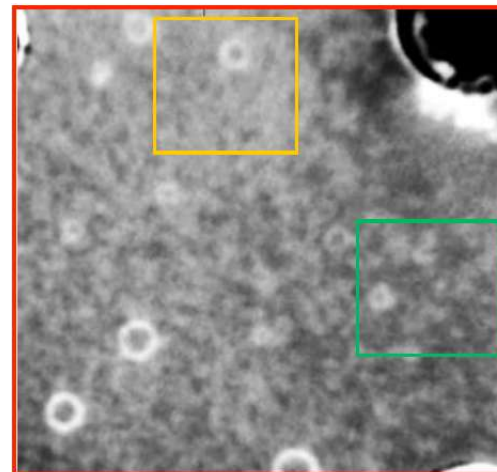
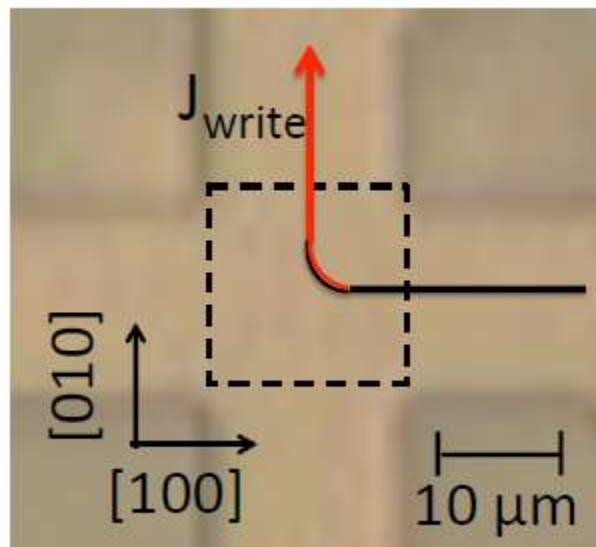
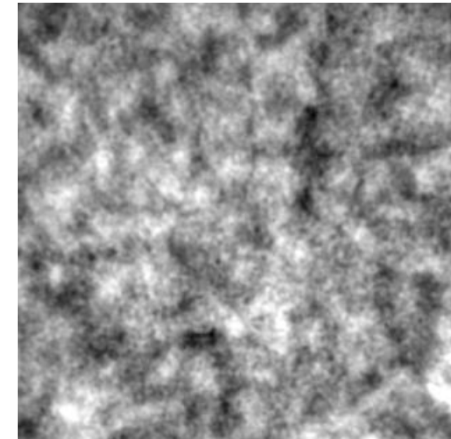
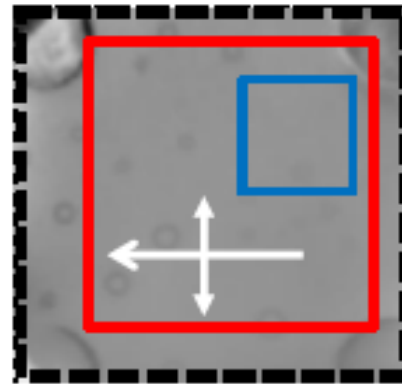
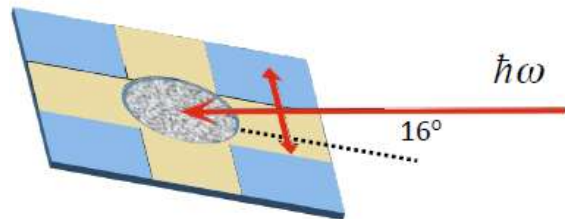
Switching of AFM



Inverse spin-galvanic effect

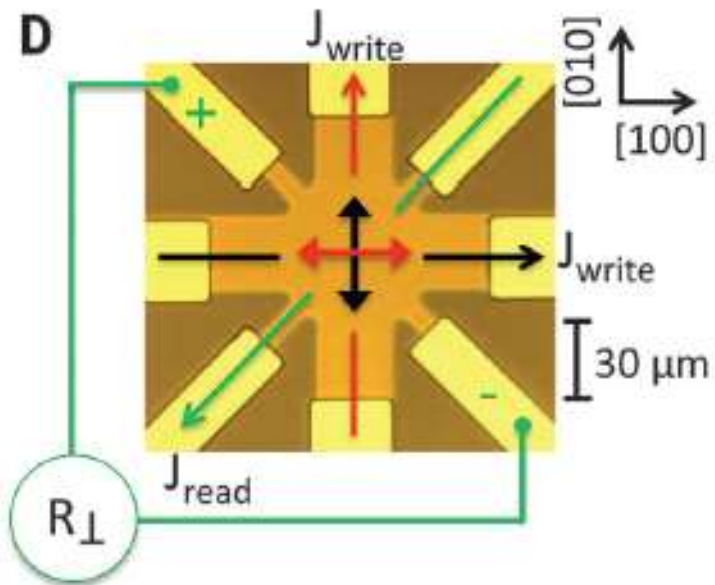
Switching of AFM

Before writing pulses

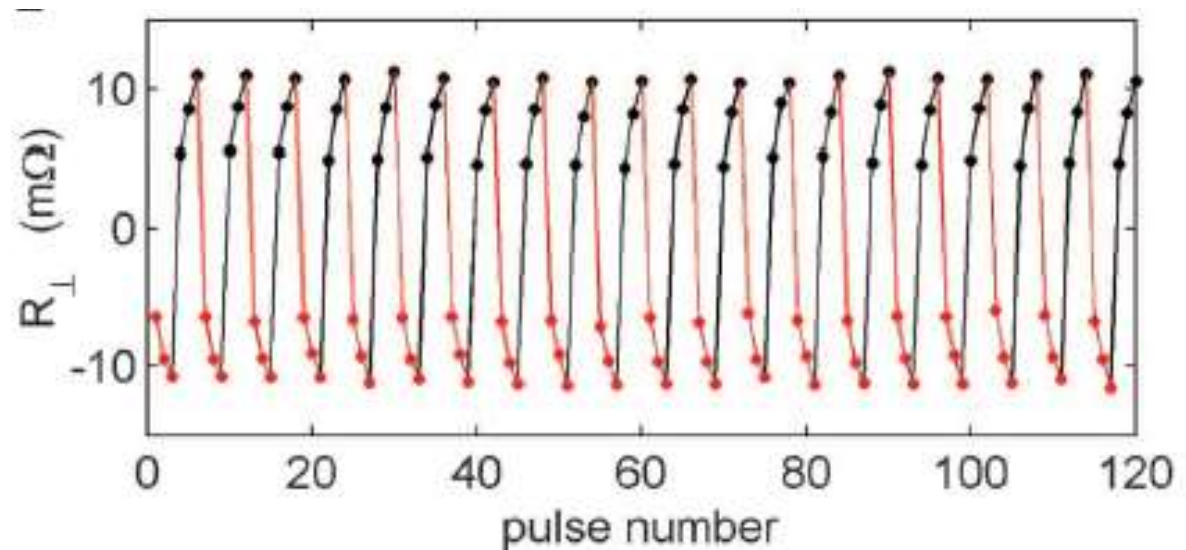


After writing pulses

Switching of AFM

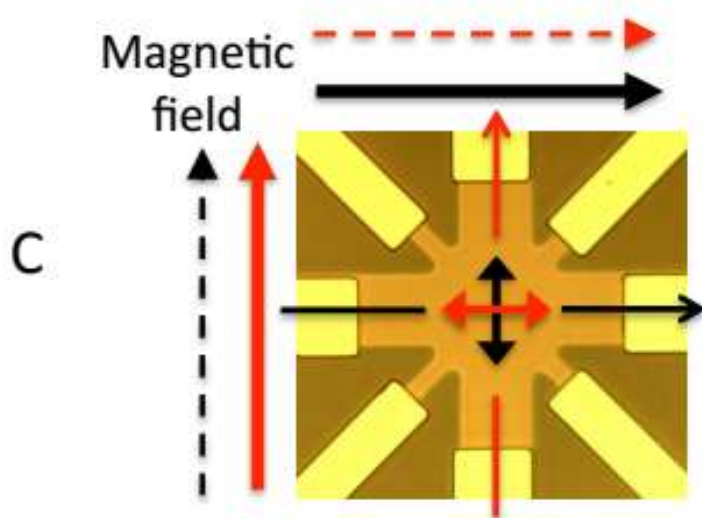


Writing current: during time=50ms,
amplitude= $4 \cdot 10^{-6} \text{Acm}^{-2}$.

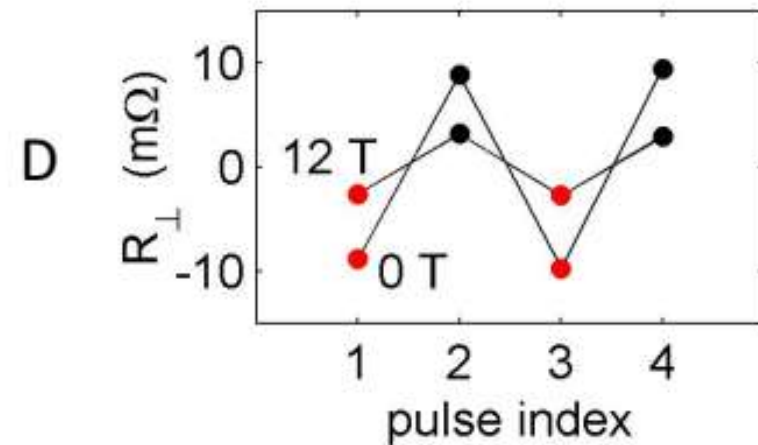


Switching of AFM

Advantage: Signal robust in magnetic field



B (T)



Outline

5. Anomalous Hall effect in AFM

AHE in AFM

PRL 112, 017205 (2014)

PHYSICAL REVIEW LETTERS

week ending
10 JANUARY 2014

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

Hua Chen, Qian Niu, and A. H. MacDonald

Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA

(Received 3 October 2013; published 10 January 2014)

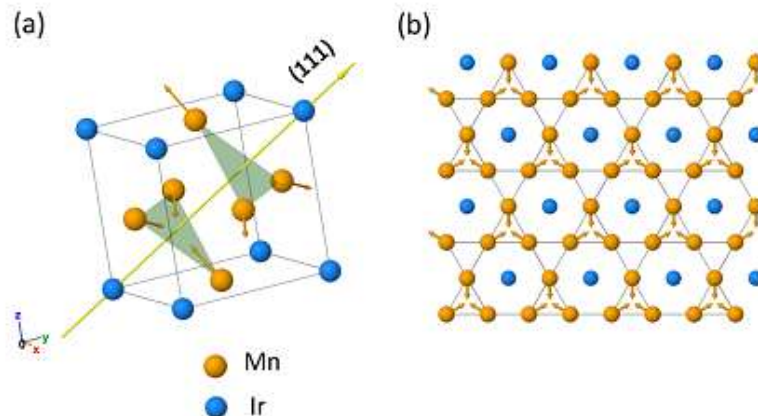


FIG. 1 (color online). Structure of Mn₃Ir. (a) Unit cell of Mn₃Ir with triangular antiferromagnetic order. (b) An individual (111) plane of Mn₃Ir. The Mn atoms form a kagome lattice.

- Large spin orbit coupling of Ir transfer to Mn.
- Non-collinear antiferromagnetism

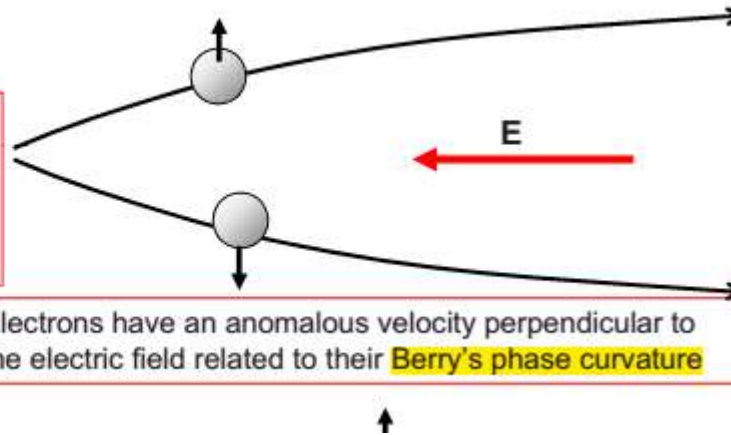
AHE in AFM

a) Intrinsic deflection

Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

$$\frac{d\langle \vec{r} \rangle}{dt} = \frac{\partial E}{\hbar \partial \vec{k}} + \frac{e}{\hbar} \vec{E} \times \vec{b}_n$$

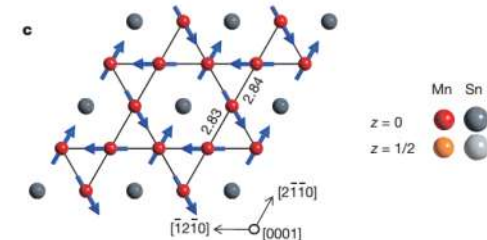
Electrons have an anomalous velocity perpendicular to the electric field related to their **Berry's phase curvature**



$$\sigma_{lm} = \frac{e^2}{\hbar} \int \frac{d\mathbf{k}}{(2\pi)^3} \Omega_p(\mathbf{k}) f(\mathbf{k}),$$

$$\Omega_n(\vec{k}) = i \langle \nabla_{\vec{k}} u_{nk} | \times | \nabla_{\vec{k}} u_{nk} \rangle$$

Non-collinear antiferromagnetic structure



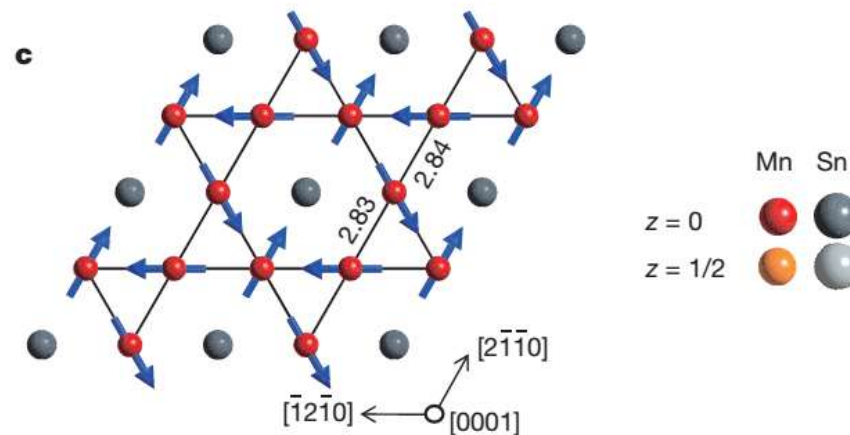
AHE in AFM

LETTER

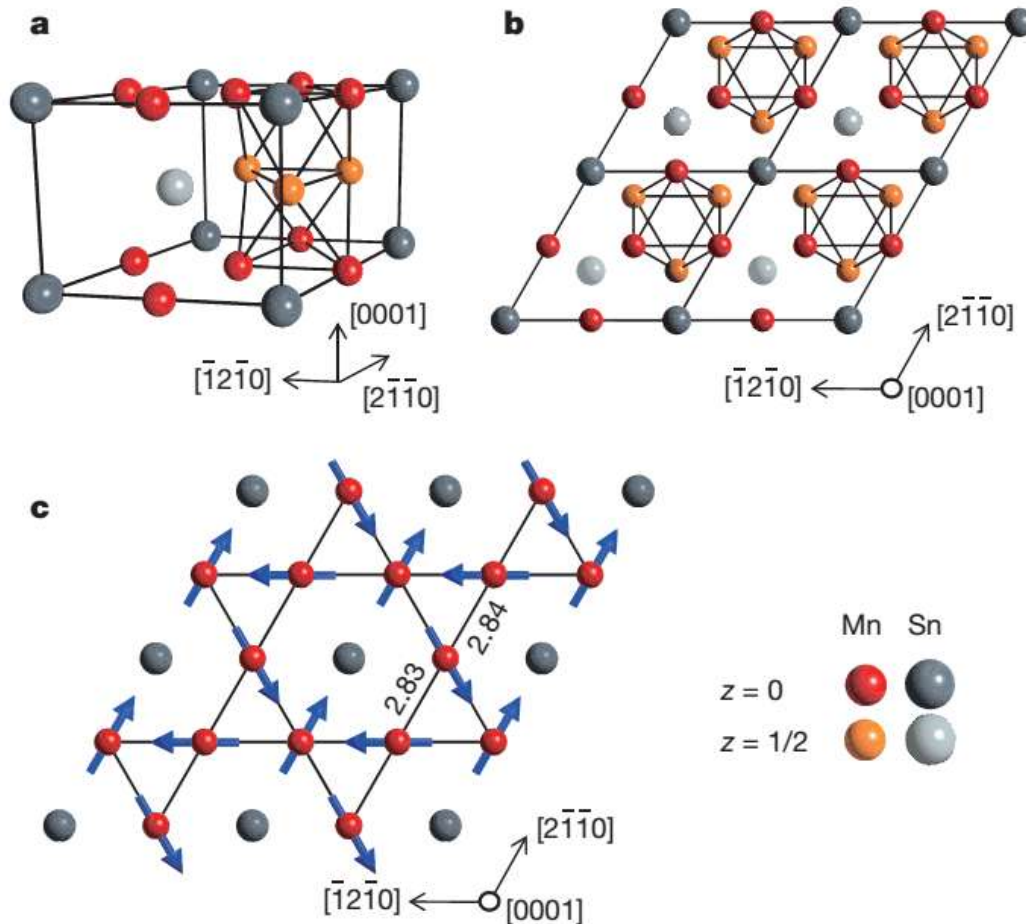
doi:10.1038/nature15723

Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature

Satoru Nakatsuji^{1,2}, Naoki Kiyohara¹ & Tomoya Higo¹



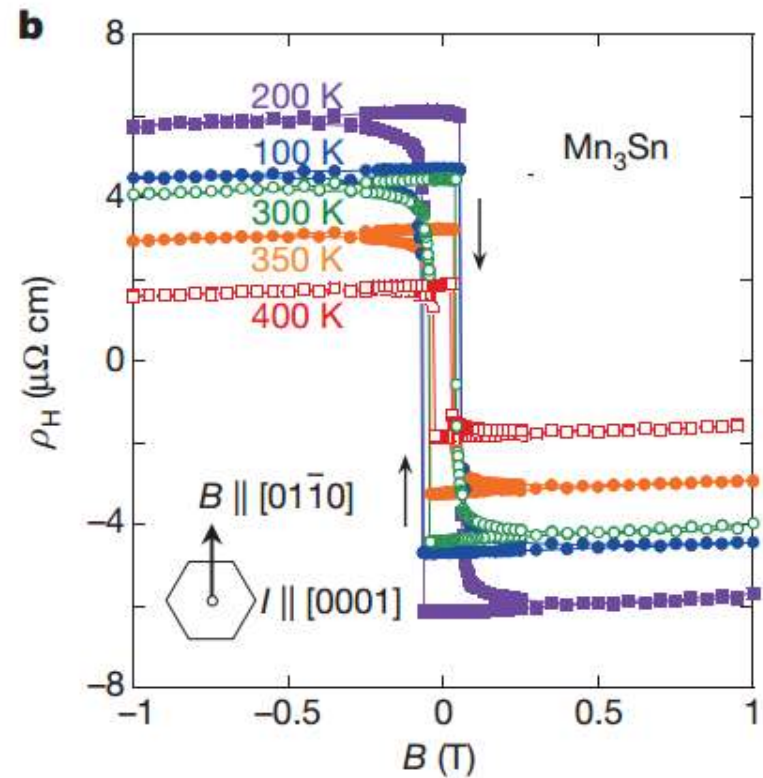
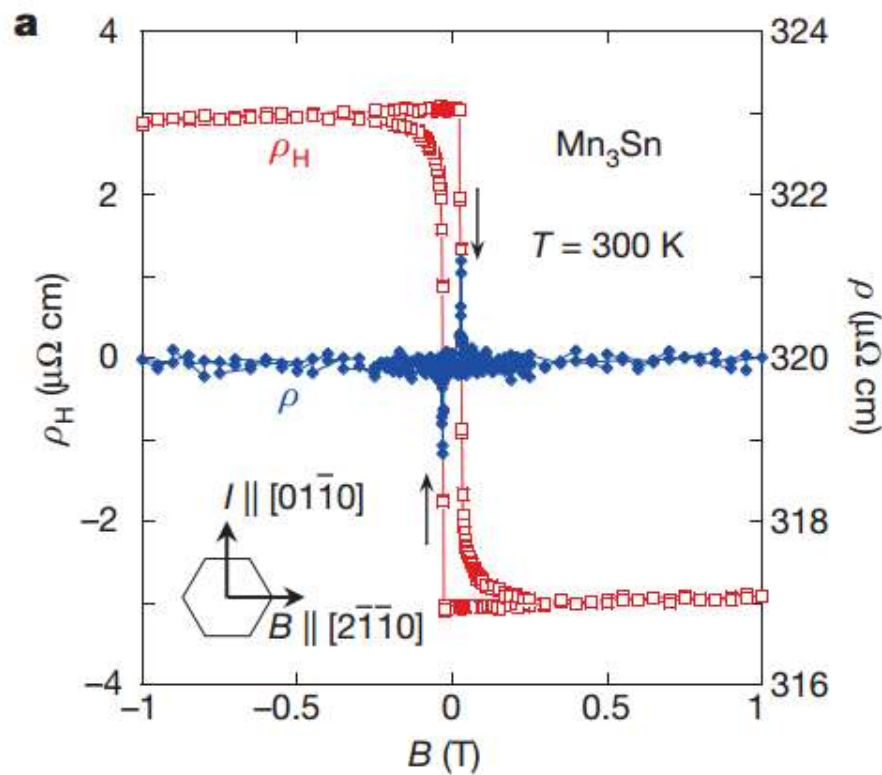
AHE in AFM



Mn_3Sn is a hexagonal antiferromagnet (AFM) that exhibits noncollinear ordering of Mn magnetic moments at the Néel temperature of $T_N \approx 420$ K

The canting of the other two spins towards the local easy-axis is considered to be the origin of the weak ferromagnetic moment.

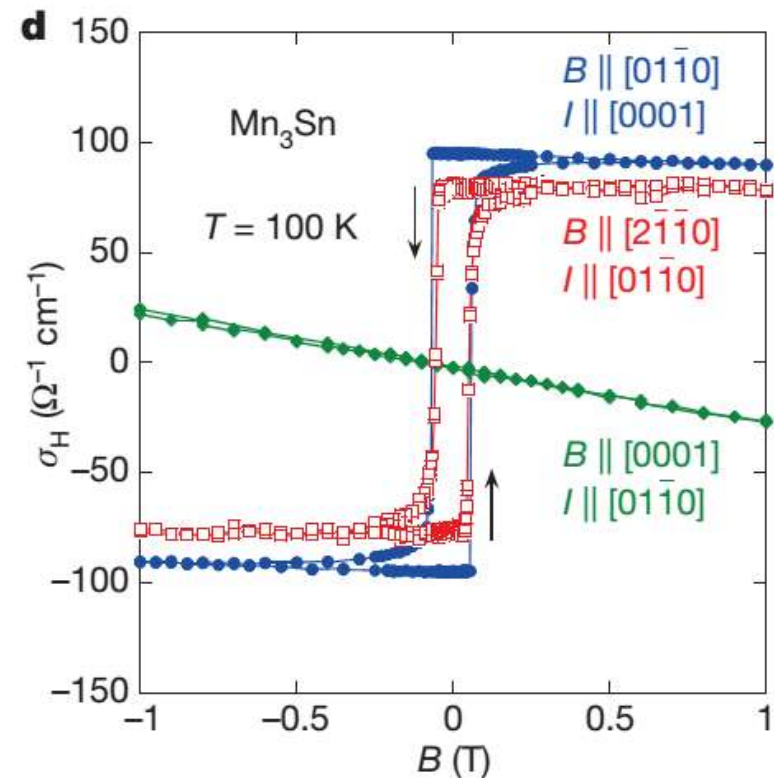
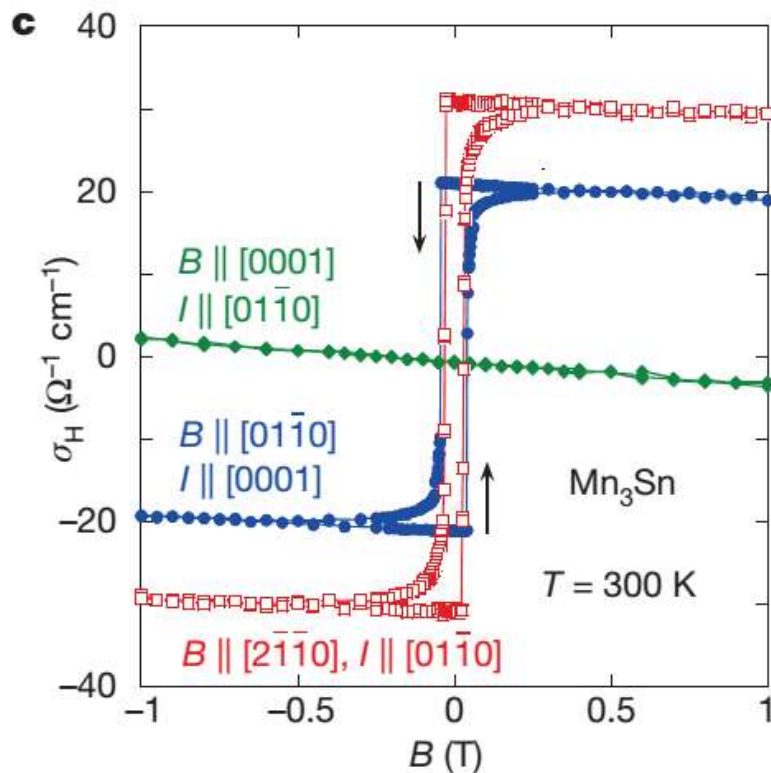
AHE in AFM



$$|\Delta\rho_H| \approx 6 \mu\Omega \text{ cm}$$

a small field of ~ 300 Oe

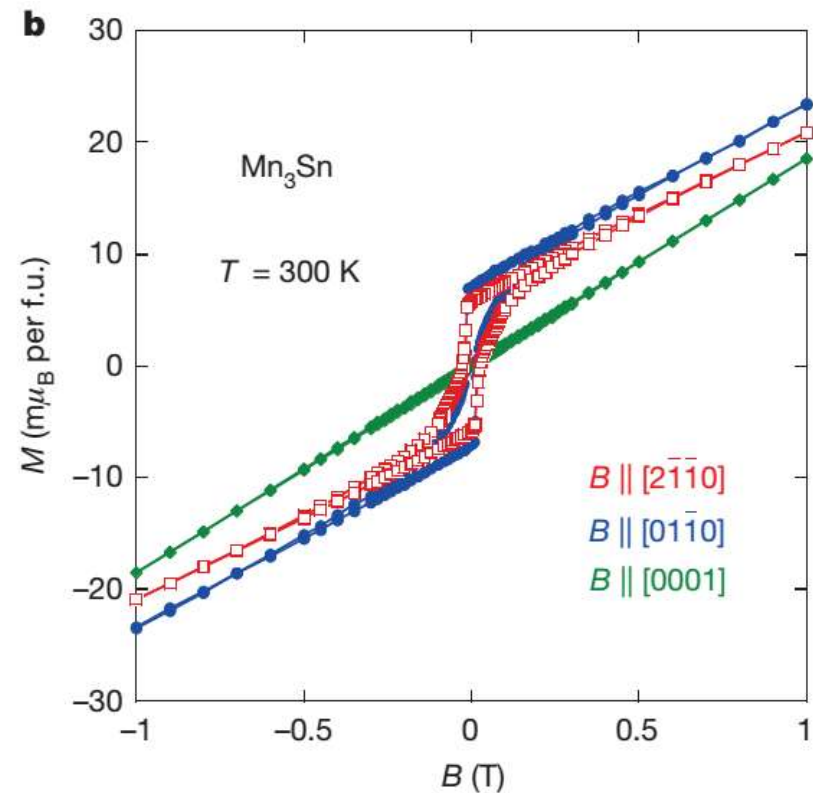
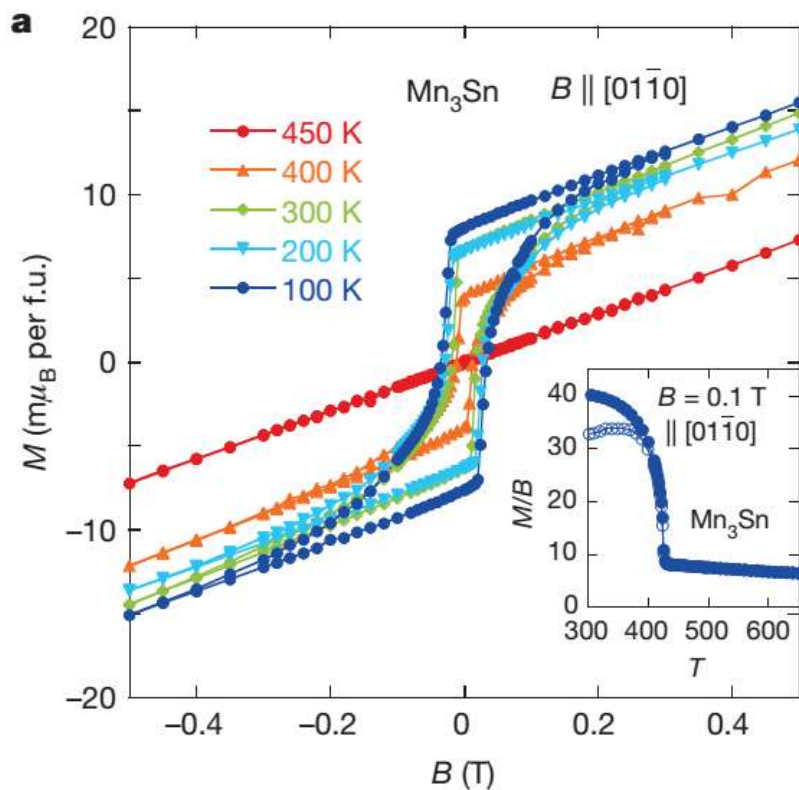
AHE in AFM



$$\sigma_H = -\rho_H / \rho^2$$

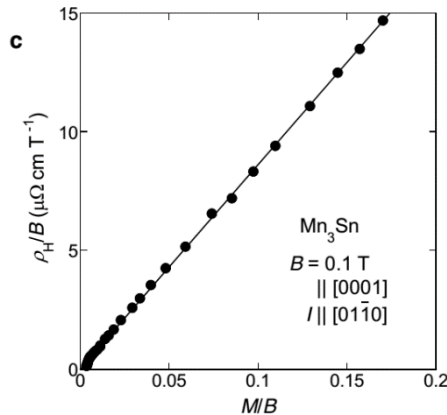
**Hysteresis for $H \parallel [01-11]$ and $H \parallel [2-1-10]$
Linear for $H \parallel [0001]$**

AHE in AFM



The similar anisotropic and hysteretic behaviours found in both $\rho_H(B)$ and $M(B)$ indicate that the existence of the small and soft ferromagnetic component allows us to switch the sign of the Hall effect.

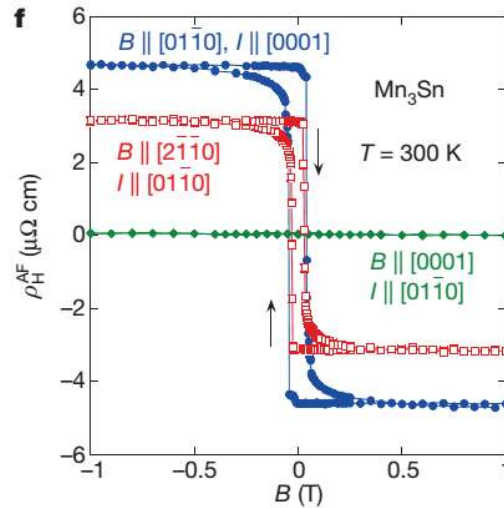
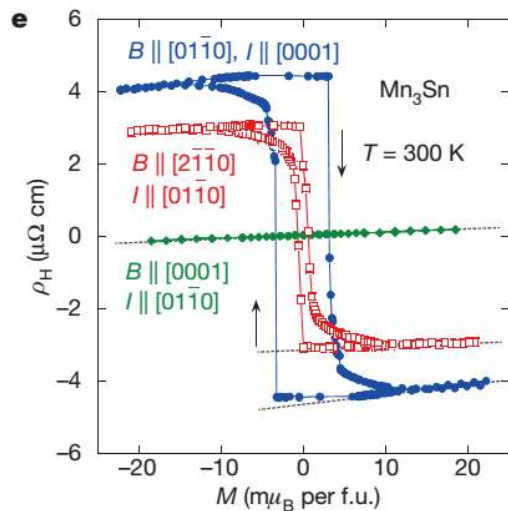
AHE in AFM



$$\rho_H = R_0 B + R_s \mu_0 M$$

R_0 and R_s are the ordinary and anomalous Hall coefficients, and μ_0 is the permeability.

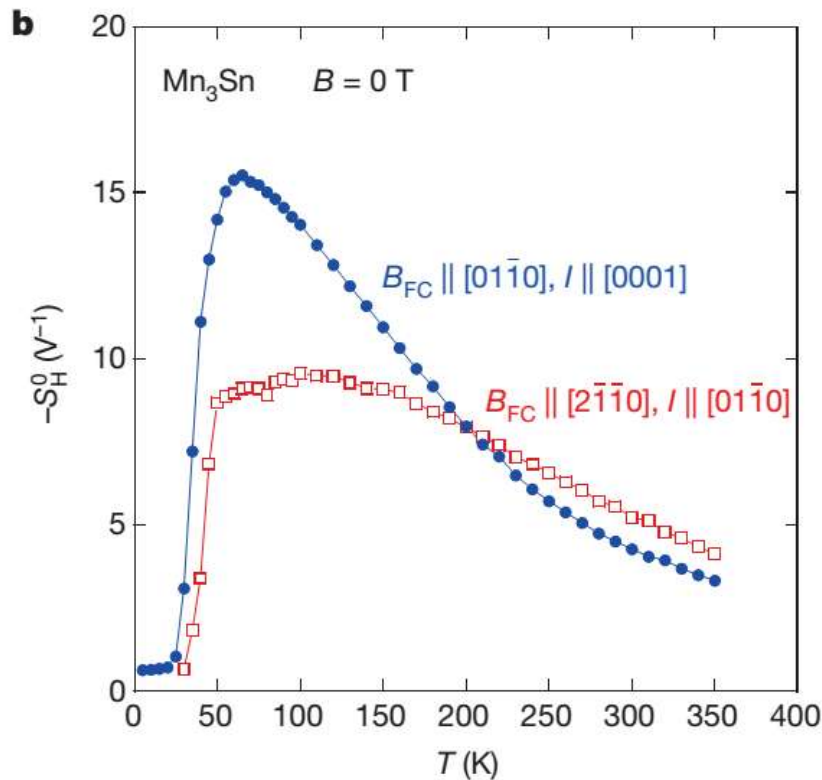
$R_0 = 3.0 \times 10^{-4} \text{ cm}^3 \text{ C}^{-1}$ indicates that $R_0 B$ is negligibly small



$$\rho_H = R_0 B + R_s \mu_0 M + \rho_H^{\text{AF}}$$

the large AHE ρ_H^{AF} , must have a distinct origin driven by the antiferromagnetic order.

AHE in AFM



$$S_H = \mu_0 R_s / \rho^2$$

$$\sigma_H = -\rho_H / \rho^2$$

$$\rho_H = R_0 B + R_s \mu_0 M$$

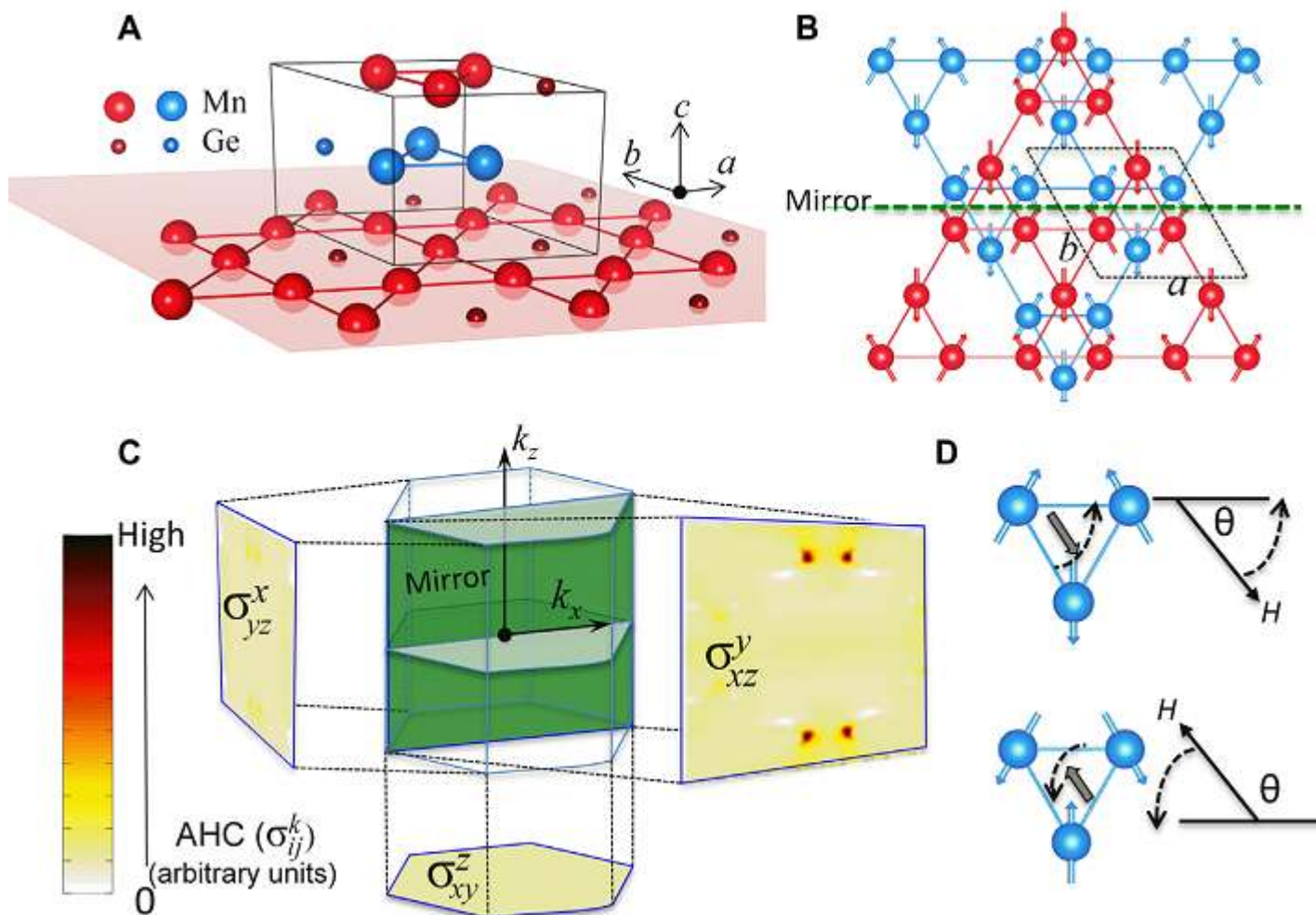
$$S_H^0 = -\sigma_H(B=0) / M(B=0)$$

S_H^0

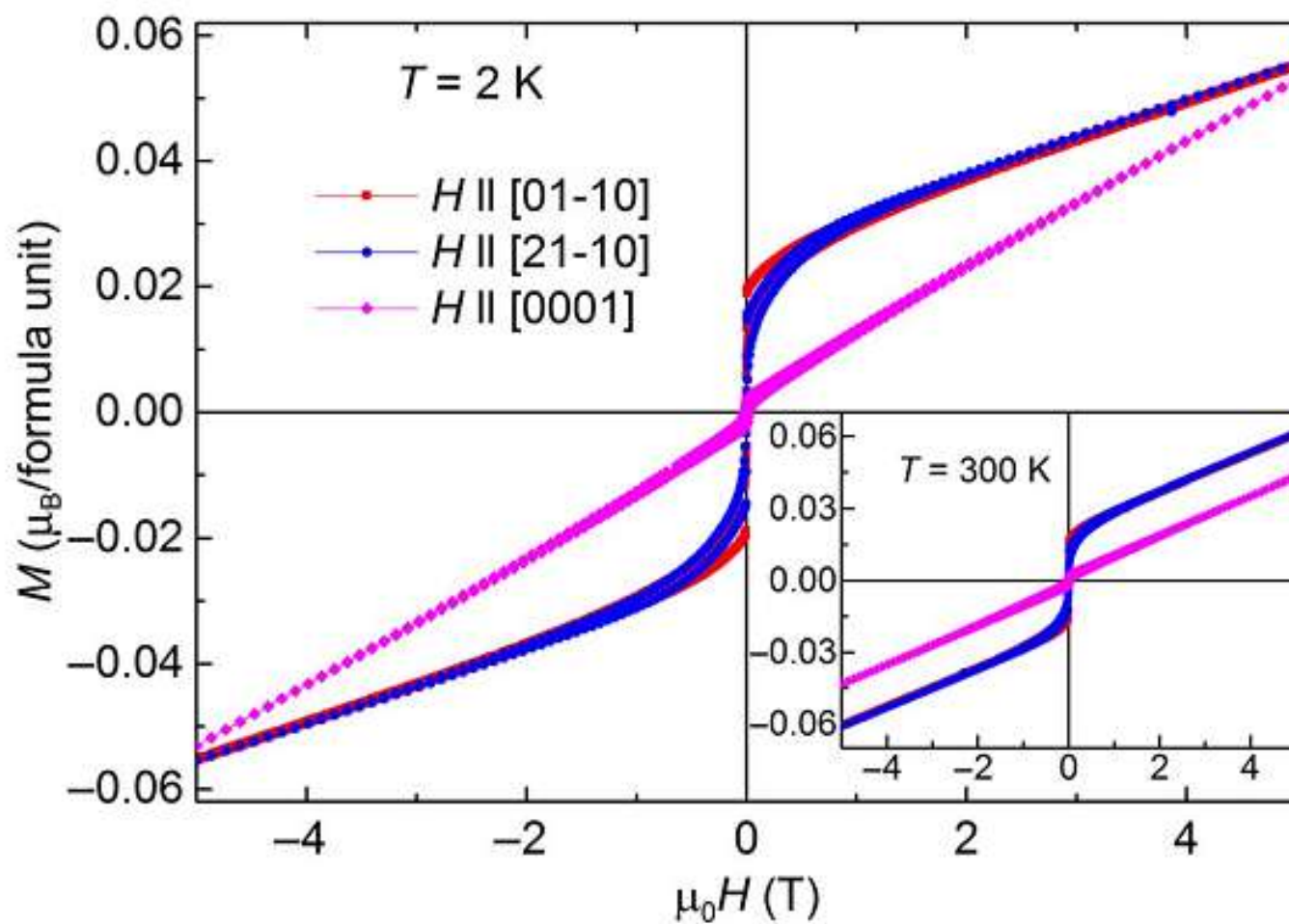
In a magnetic conductor with relatively high resistivity, the AHE is dominated by S_H .

14 V⁻¹ (Mn₃Sn) at 100 K >> 0.01–0.1 V⁻¹(like Fe, Ni, Co...)

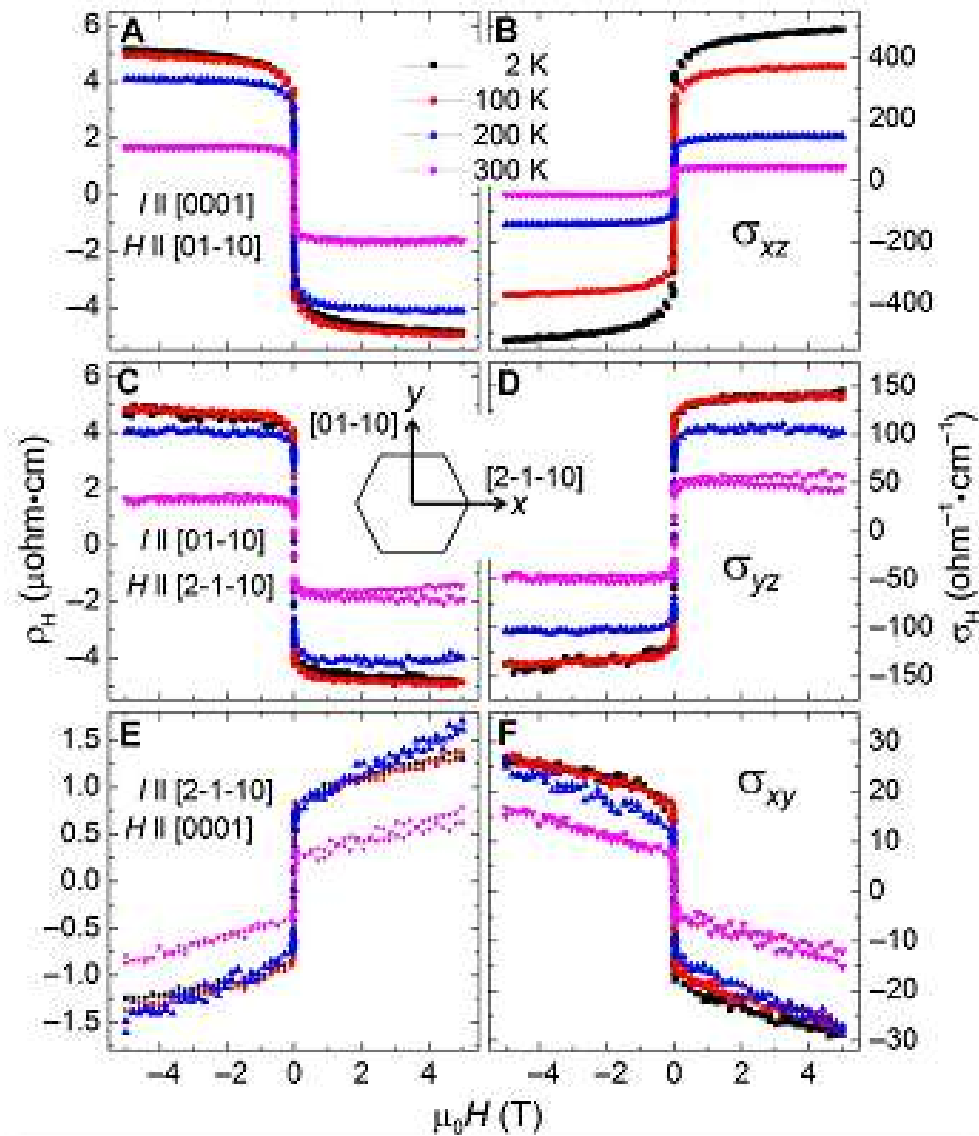
AHE in AFM Mn_3Ge



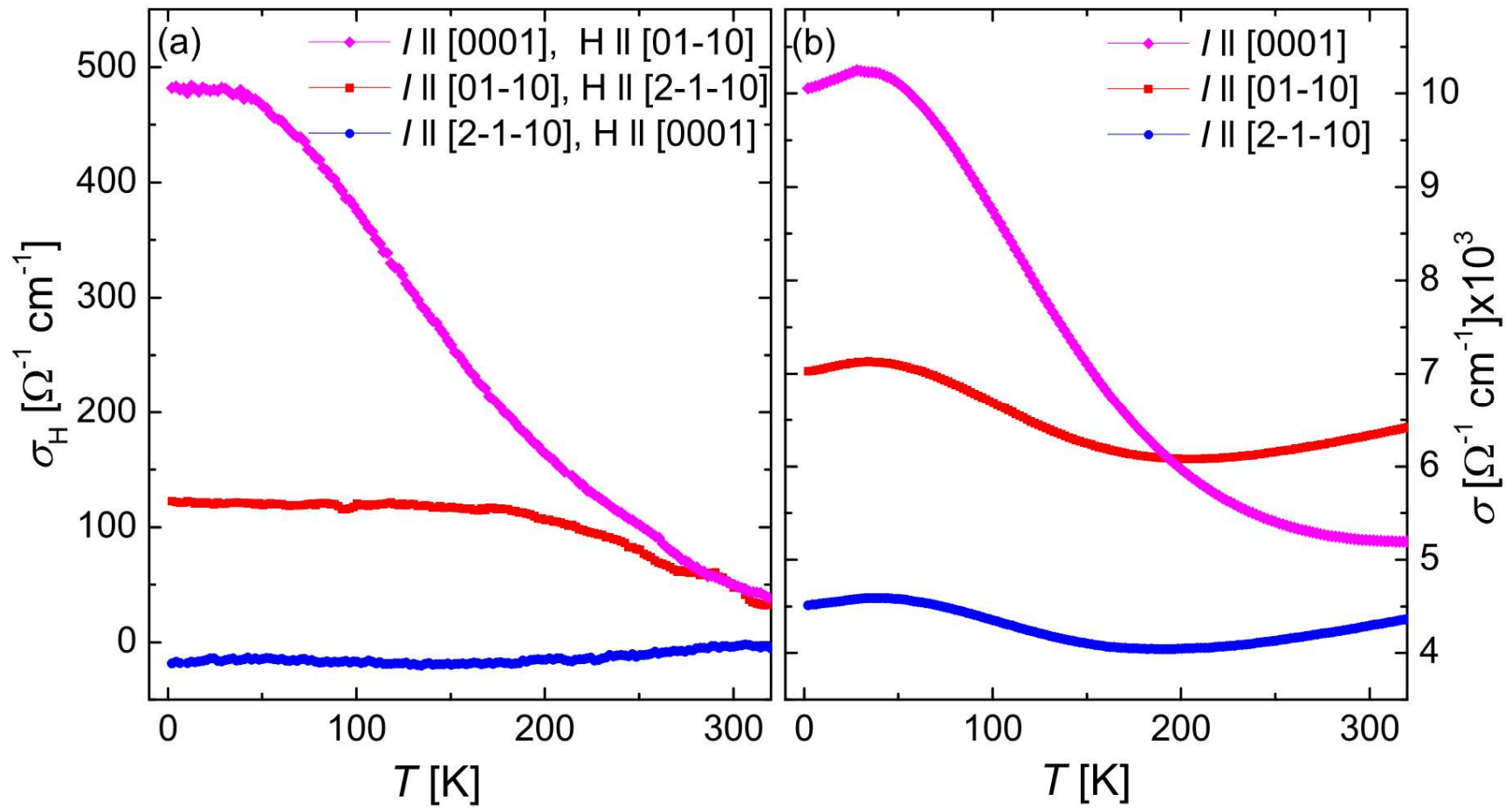
AHE in AFM Mn_3Ge



AHE in AFM MnGe₃



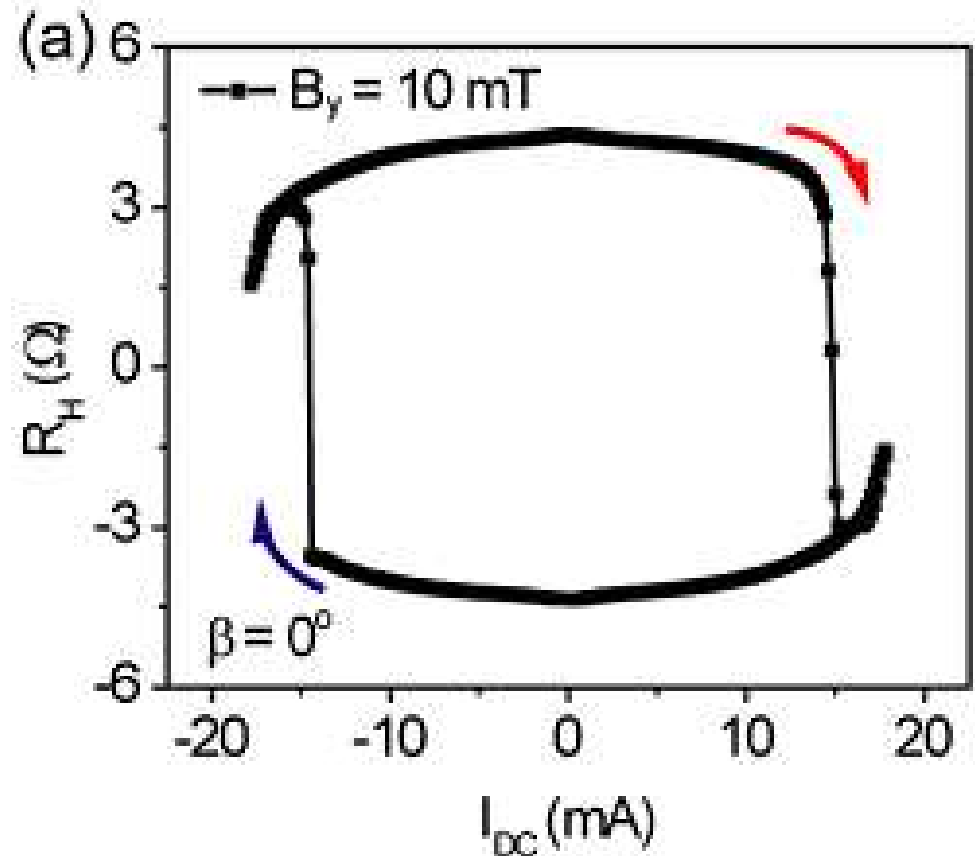
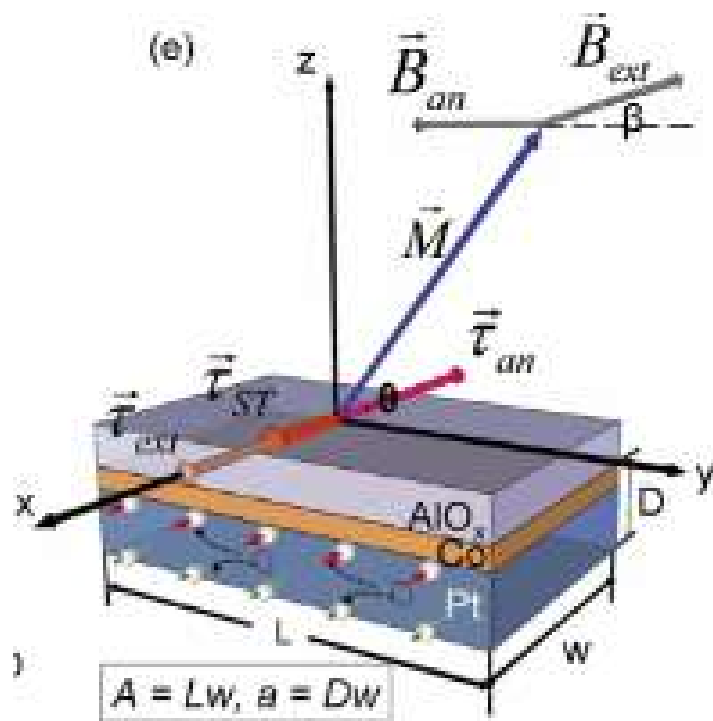
AHE in AFM Mn₃Ge



6. Spin orbit torque in AFM

Spin orbit torque in AFM

Spin Hall orbit torque to FM



Liu et al., PRL 109, 096602 (2012)

Spin orbit torque in AFM

PRL 113, 196602 (2014)

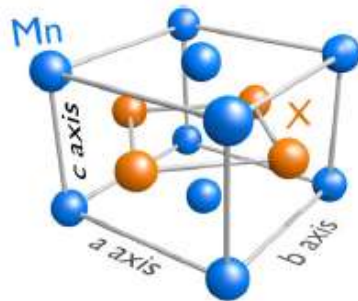
PHYSICAL REVIEW LETTERS

week ending
7 NOVEMBER 2014

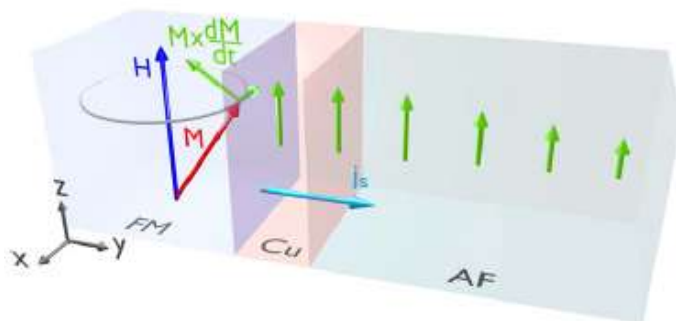
Spin Hall Effects in Metallic Antiferromagnets

Wei Zhang, Matthias B. Jungfleisch, Wanjun Jiang, John E. Pearson, and Axel Hoffmann
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

Frank Freimuth and Yuriy Mokrousov
Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany
(Received 12 August 2014; published 4 November 2014)

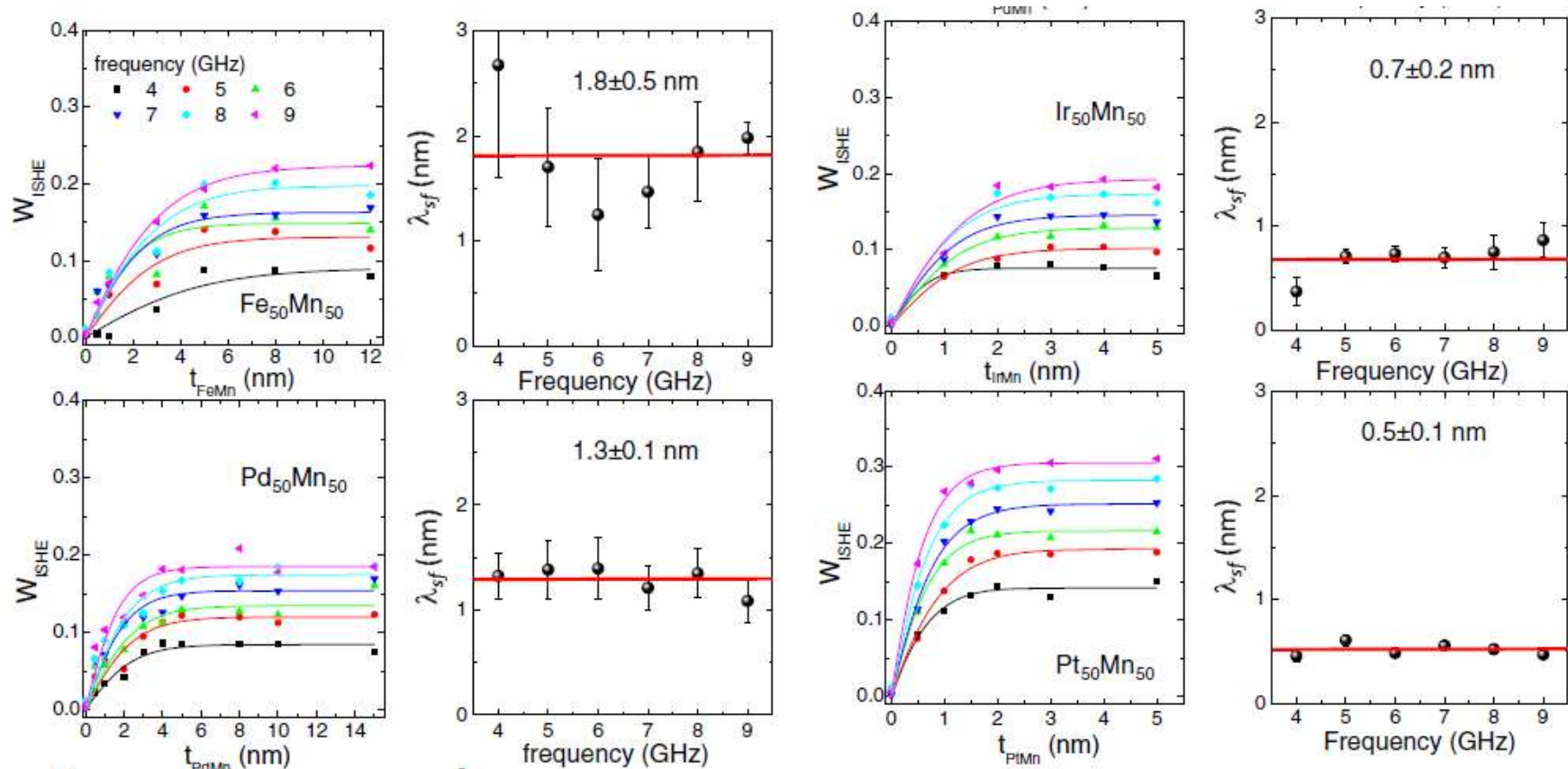


Crystal structure of CuAu- I -type Afs



Schematic of spin pumping and spin Hall effect

Spin orbit torque in AFM



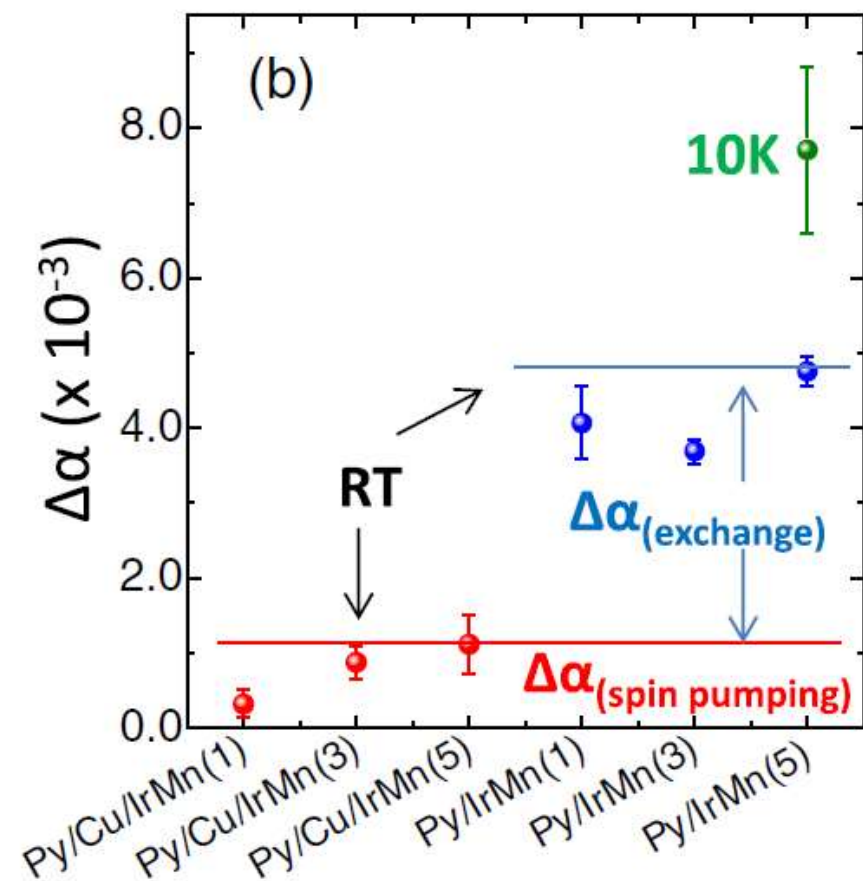
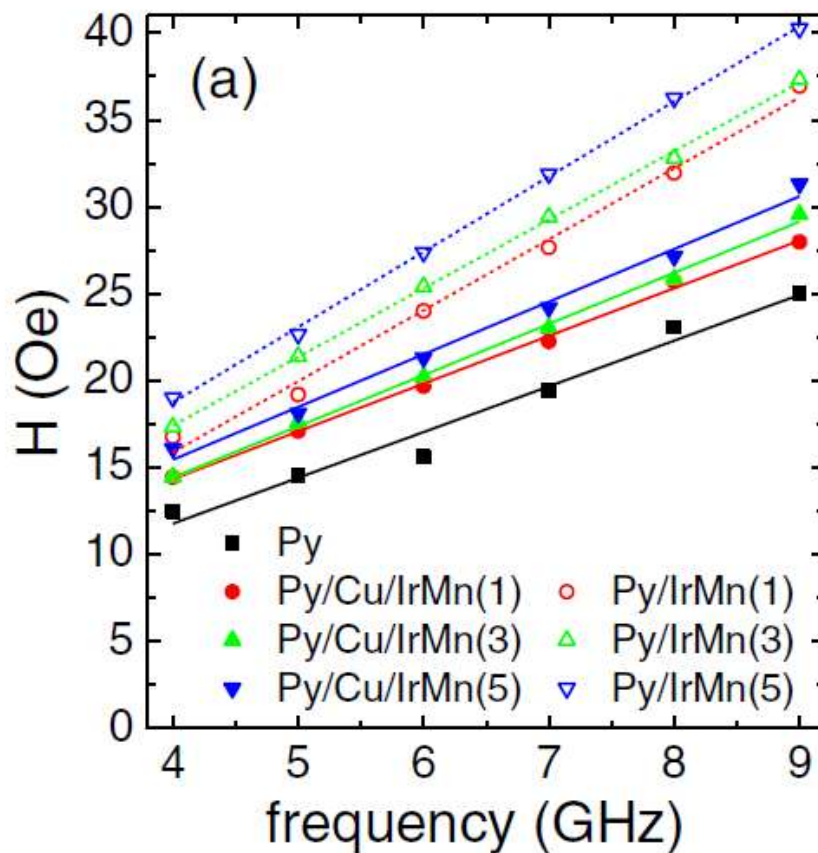
Thickness dependence shows
spin diffusion length to be short
~1nm

Fe₅₀Mn₅₀
Pd₅₀Mn₅₀

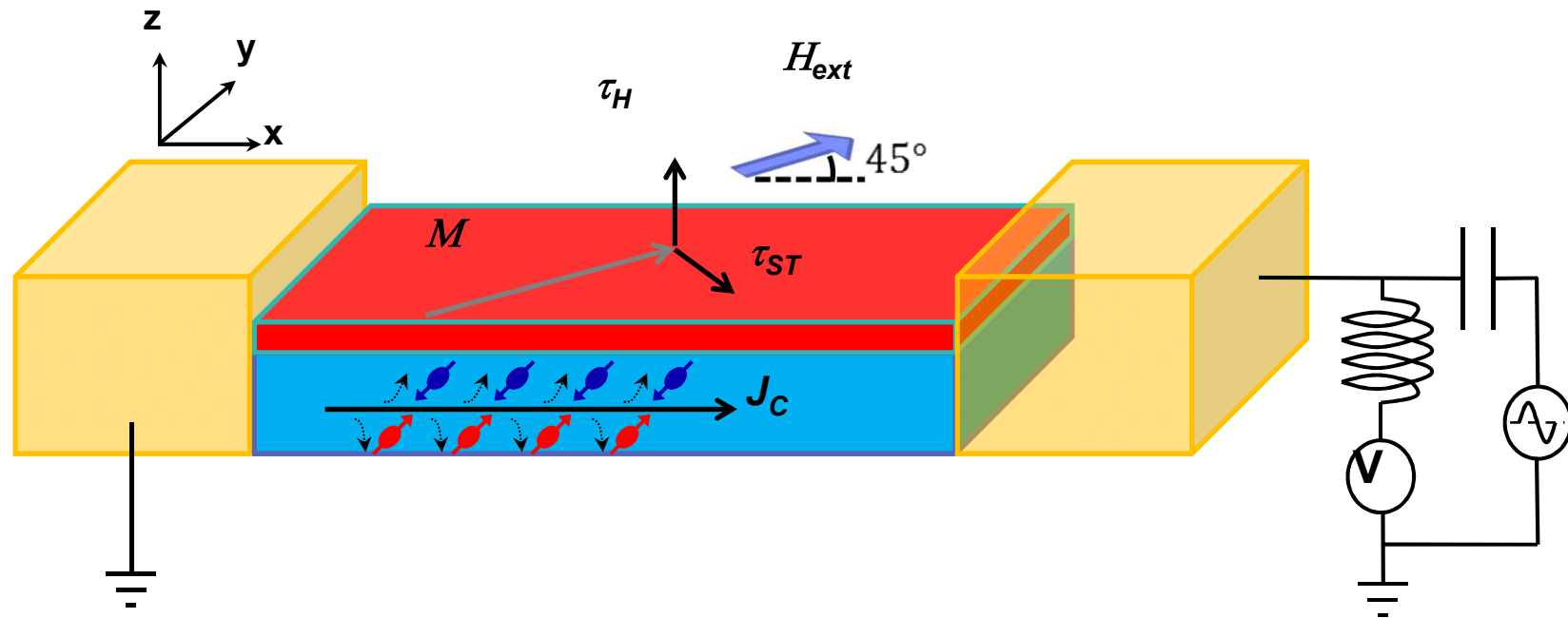
Ir₅₀Mn₅₀
Pt₅₀Mn₅₀

Spin orbit torque in AFM

Comparison between with and without a Cu spacer,
Showing an additional damping enhancement due to exchange
coupling at FM/AF interface



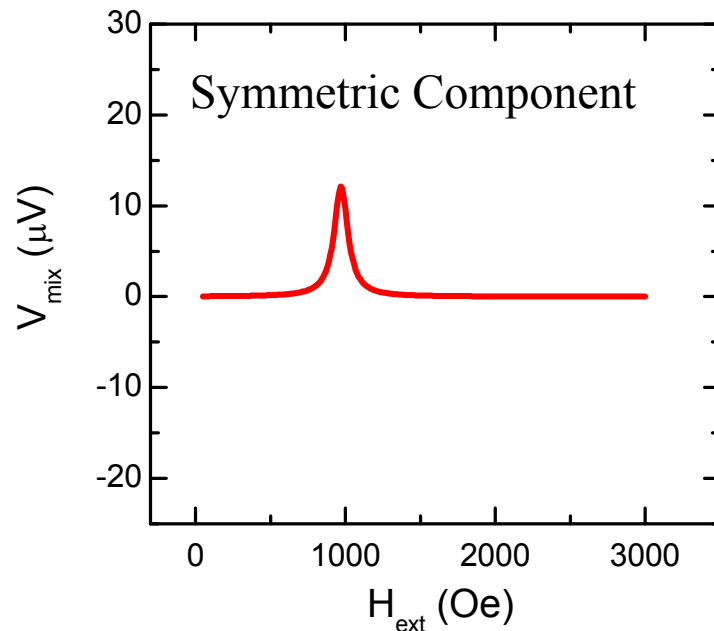
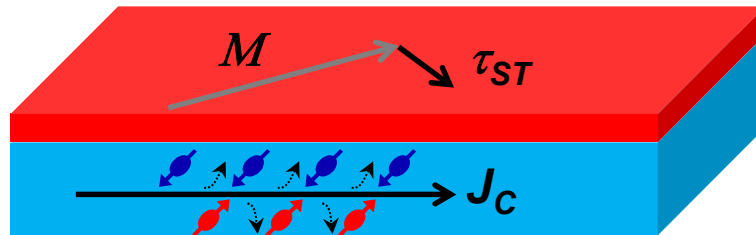
Spin orbit torque FMR



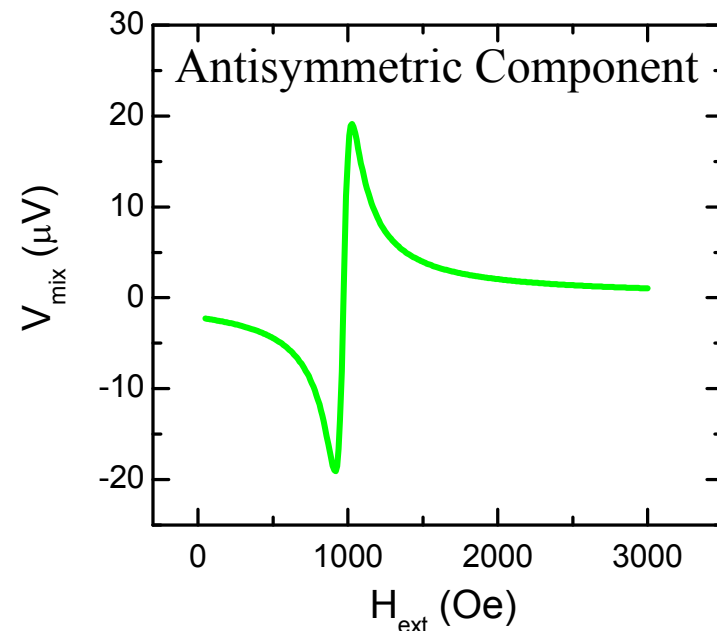
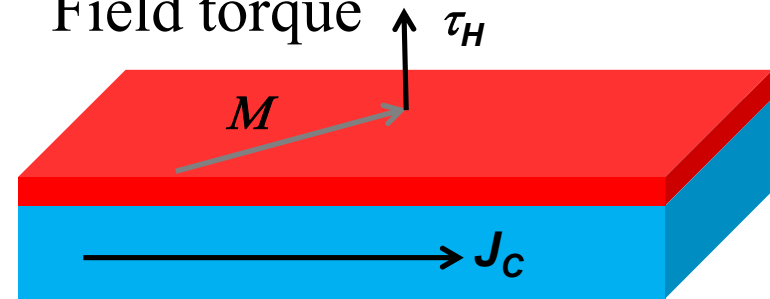
Liu et al., PRL 106, 036601 (2011)

Spin orbit torque FMR

Spin Hall torque



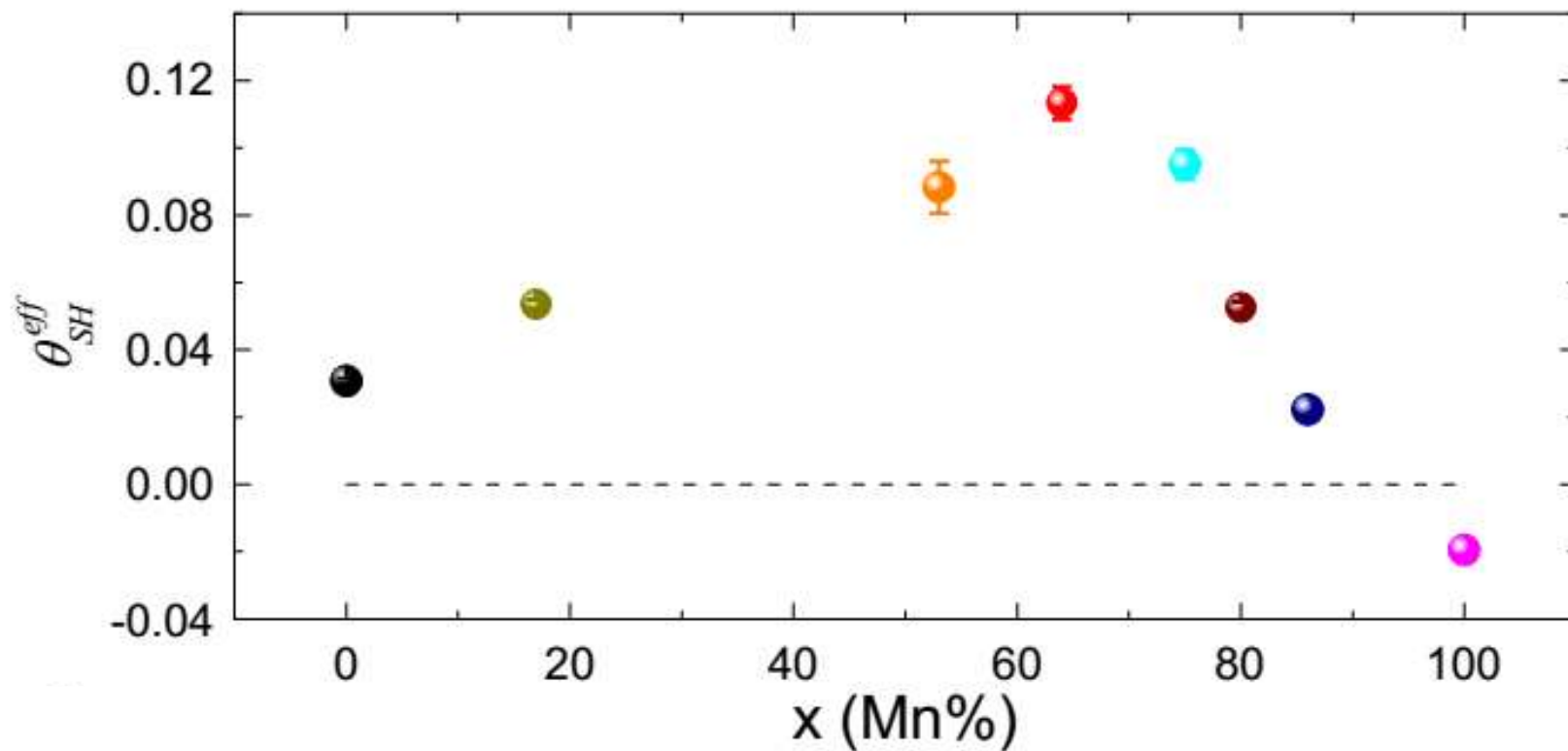
Field torque



$$SHA = \frac{S}{A} \frac{e\mu_0 M_s t d}{\hbar} [1 + (4\pi M_{eff}/H_{ext})]^{1/2}$$

Spin orbit torque in AFM

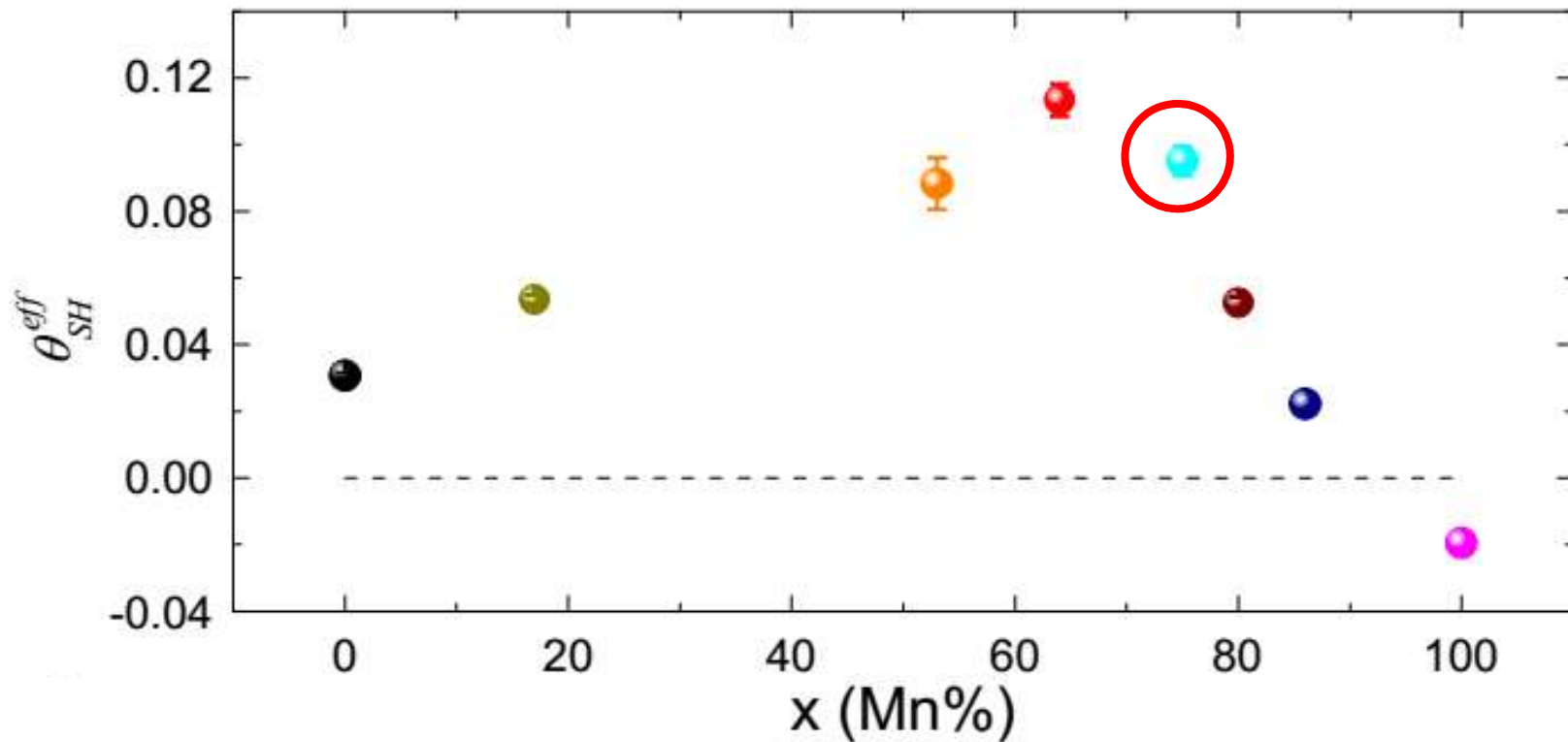
$\text{Ir}_{1-x}\text{Mn}_x$



- Large effective SHA observed in IrMn- IrMn3

Spin orbit torque in AFM

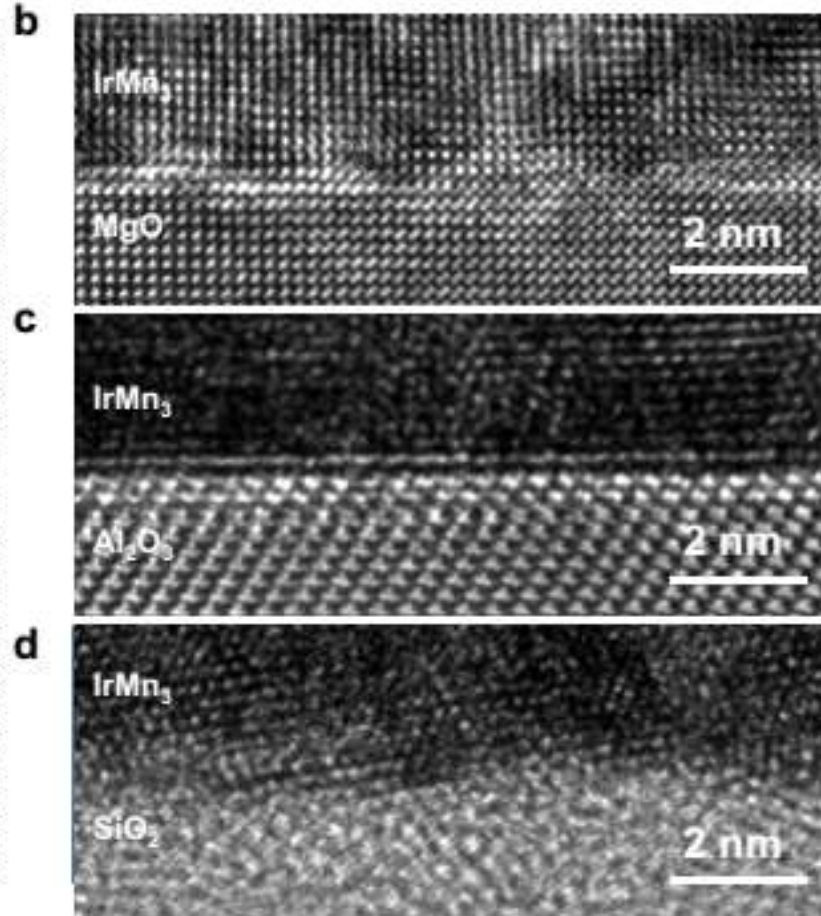
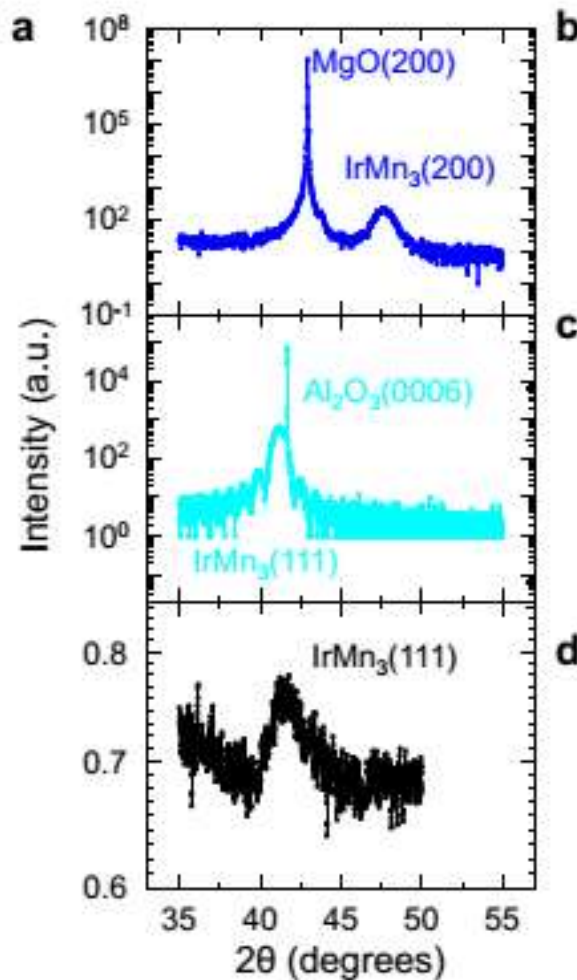
$\text{Ir}_{1-x}\text{Mn}_x$



Related work on $\text{Ir}_{20}\text{Mn}_{80}$ and IrMn have also been reported by other groups.
 IrMn : Zhang, et al. PRL (2014).
 $\text{Ir}_{20}\text{Mn}_{80}$: Mendes, et al. PRB (2014).

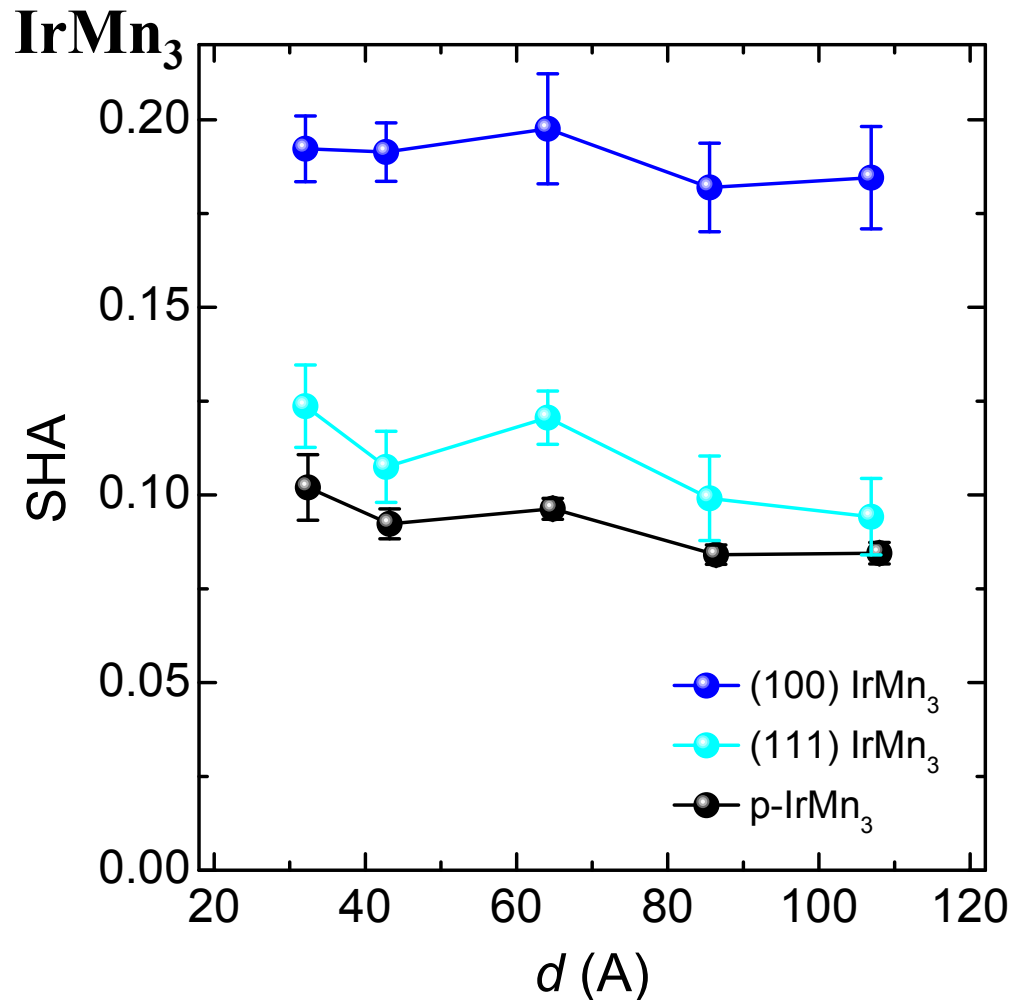
Spin orbit torque in AFM

IrMn₃



- (100) on MgO
- (111) on Al₂O₃
- Grown by magnetron sputtering

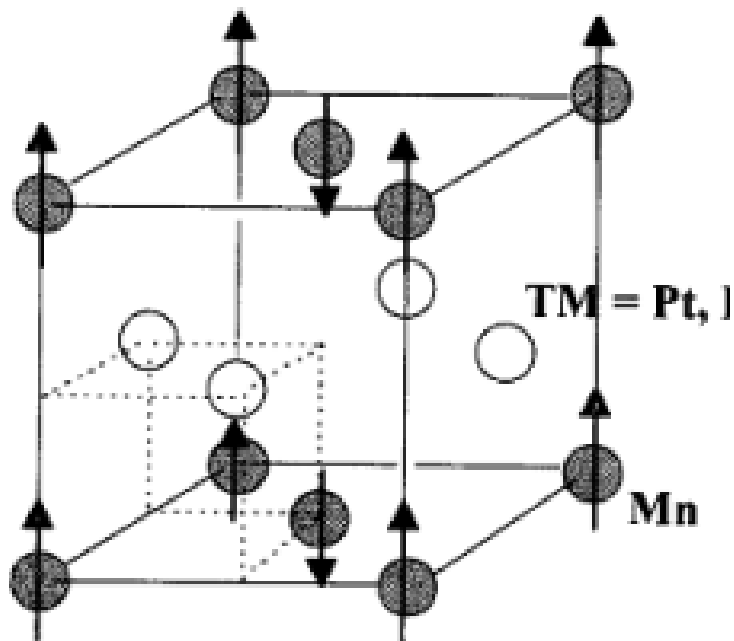
Spin orbit torque in AFM



- The effective SHA is the largest for (100) IrMn₃
- (111) and polycrystalline IrMn₃ show similar SHA.

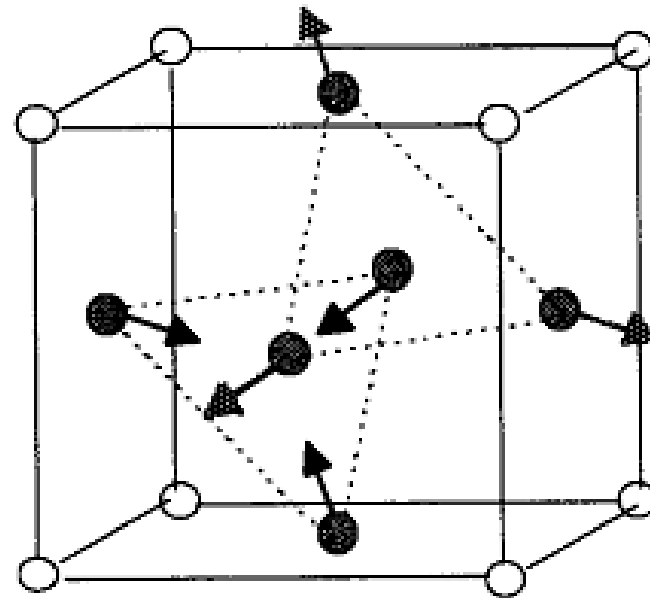
Spin orbit torque in AFM

IrMn



➤ Collinear AFM

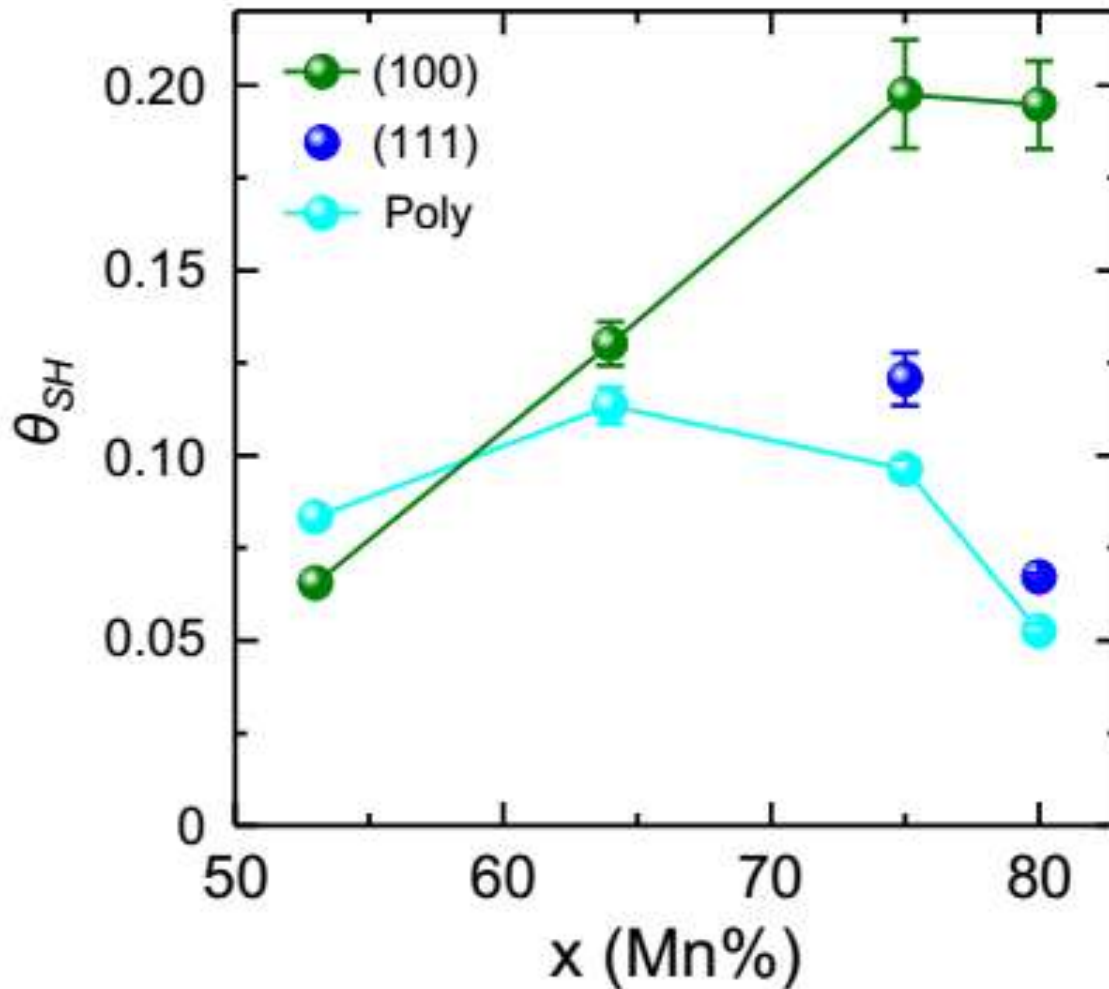
IrMn₃



➤ Non-Collinear AFM

Non-collinear AFM spin structure

Spin orbit torque in AFM

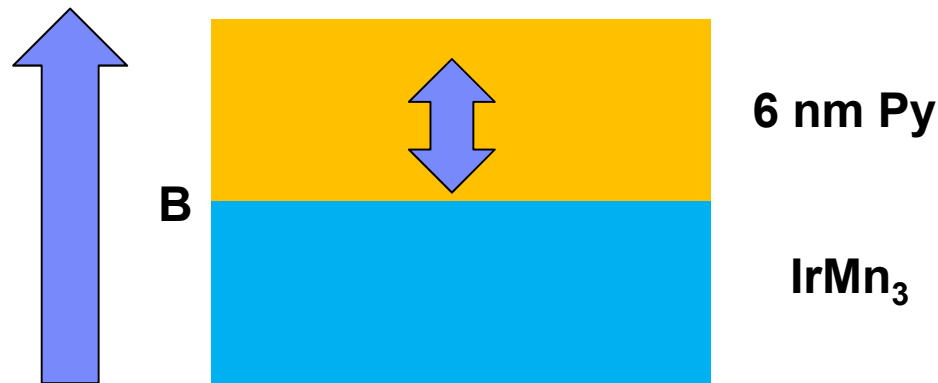


➤ Little facet dependence in **collinear** AFM

➤ Strong Facet dependence in **non-collinear** AFM

Spin orbit torque in AFM

Annealing IrMn_3 in perpendicular magnetic field

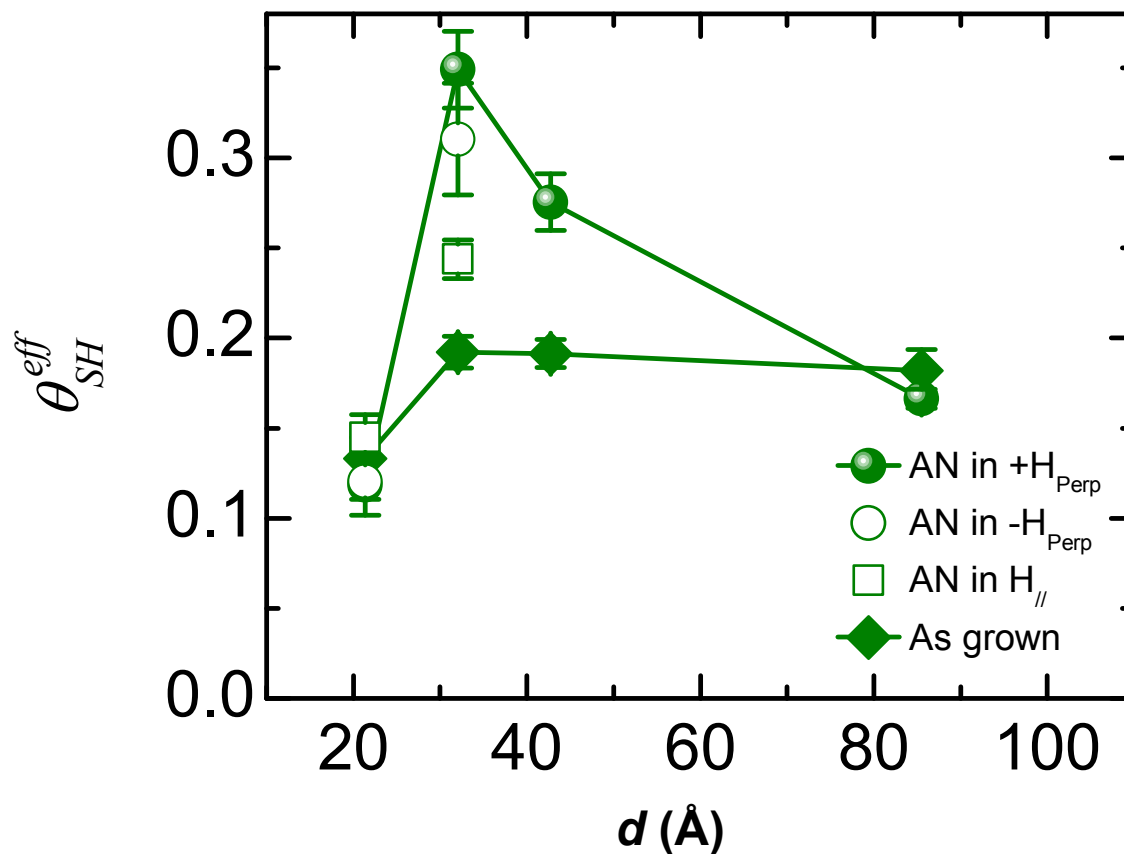


Effect:

Tune the AFM domains configurations on the IrMn_3 surface.

Spin orbit torque in AFM

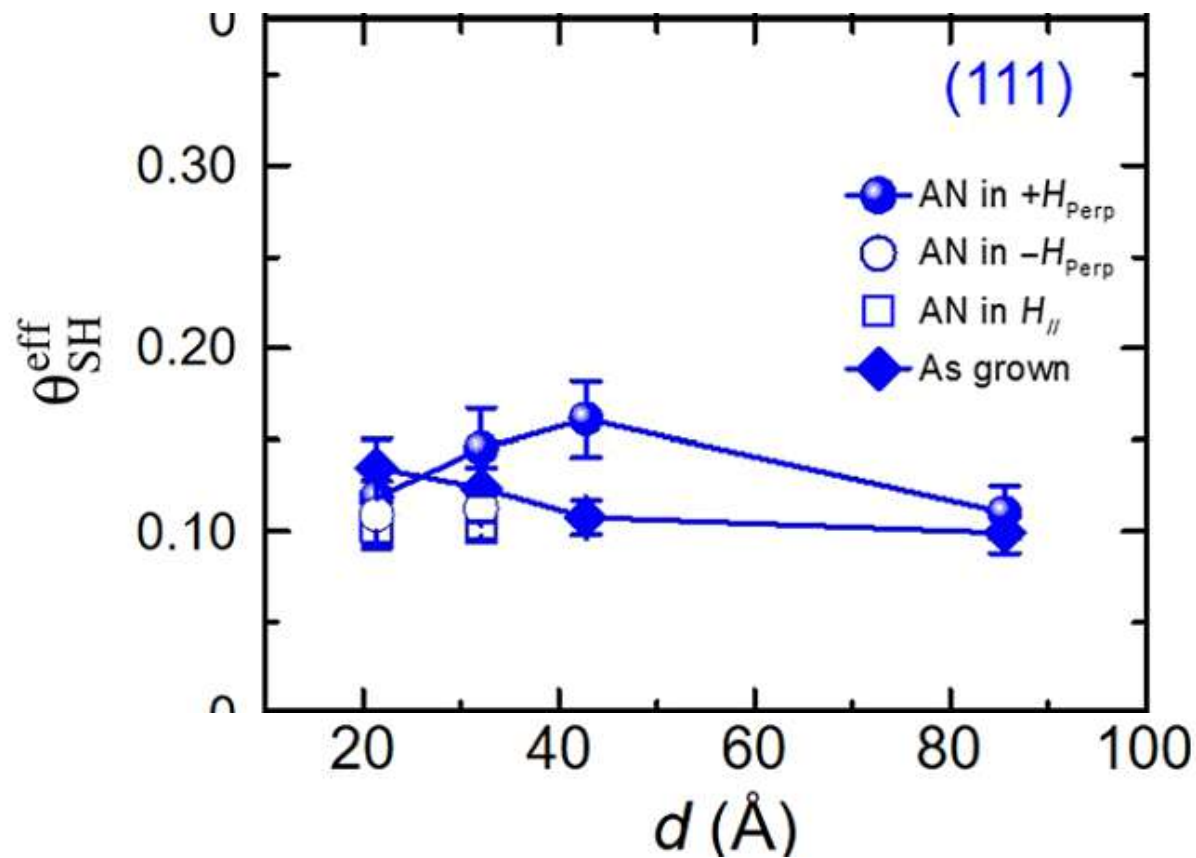
(100) IrMn₃



- The SHA increases from 0.20 up to 0.35 for 3 nm (100) IrMn₃
- For 2 nm and 8 nm, the enhancement effect is small

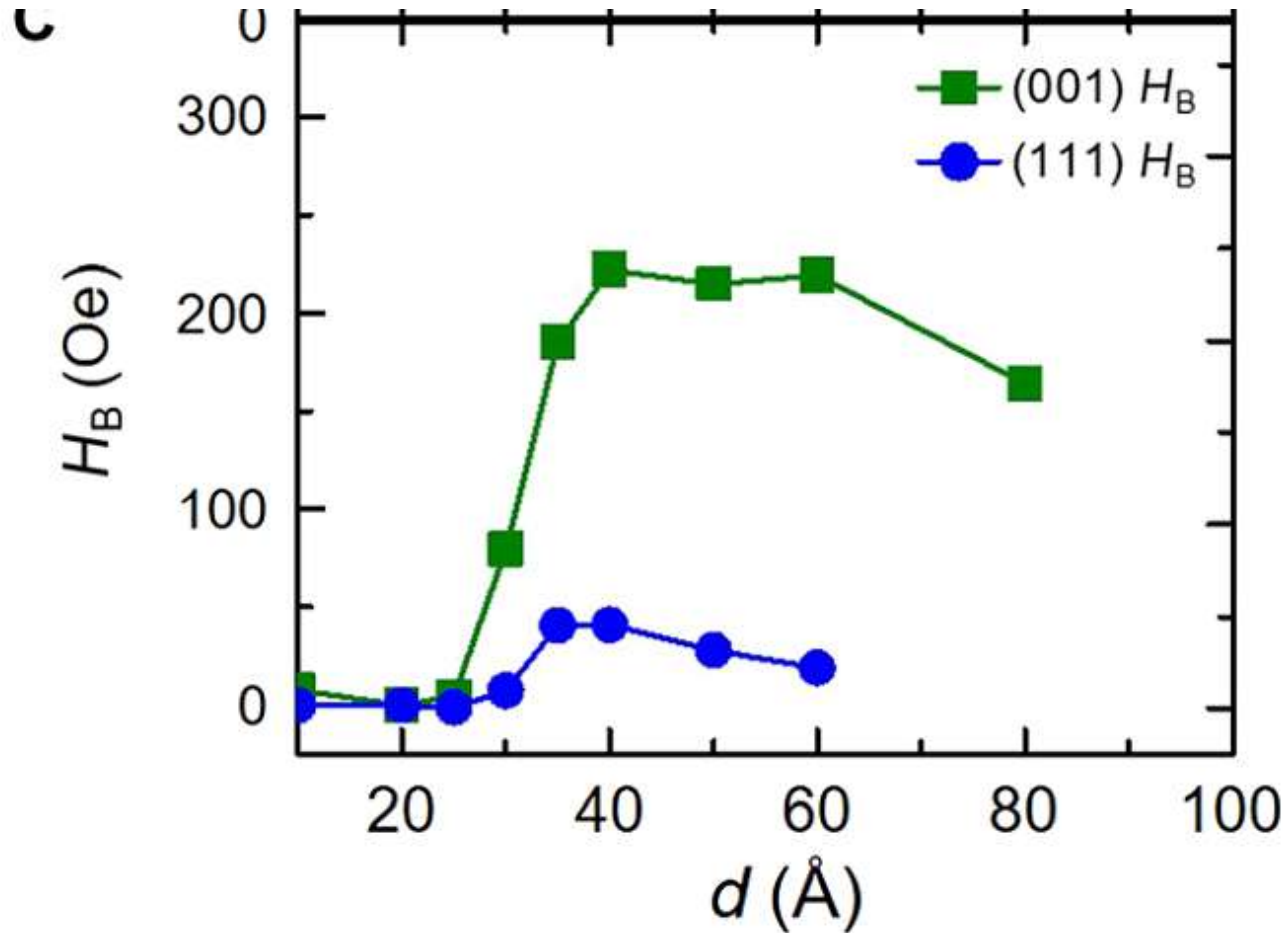
Spin orbit torque in AFM

(111) IrMn₃

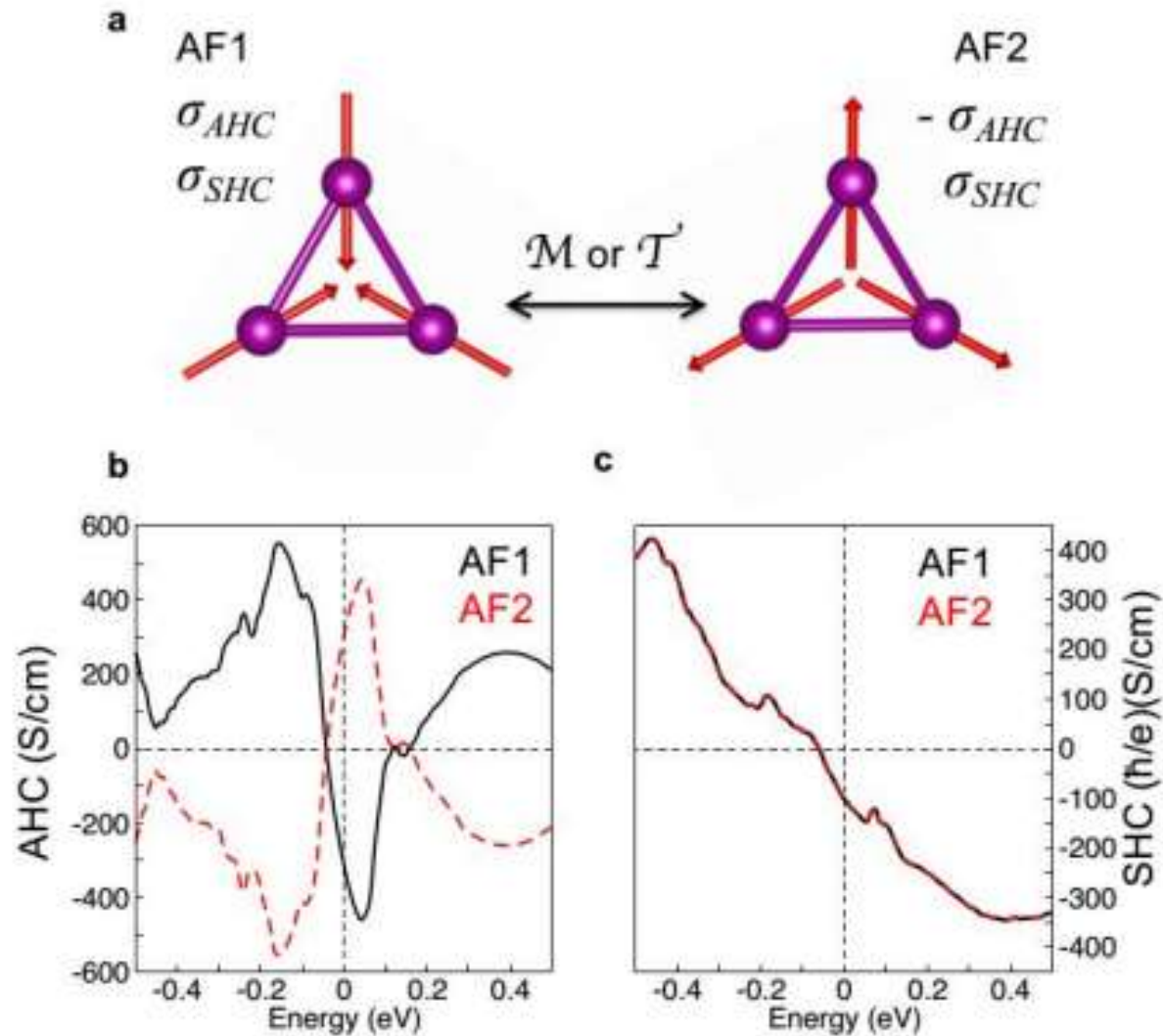


➤ Very small effect on (111) IrMn₃

Spin orbit torque in AFM

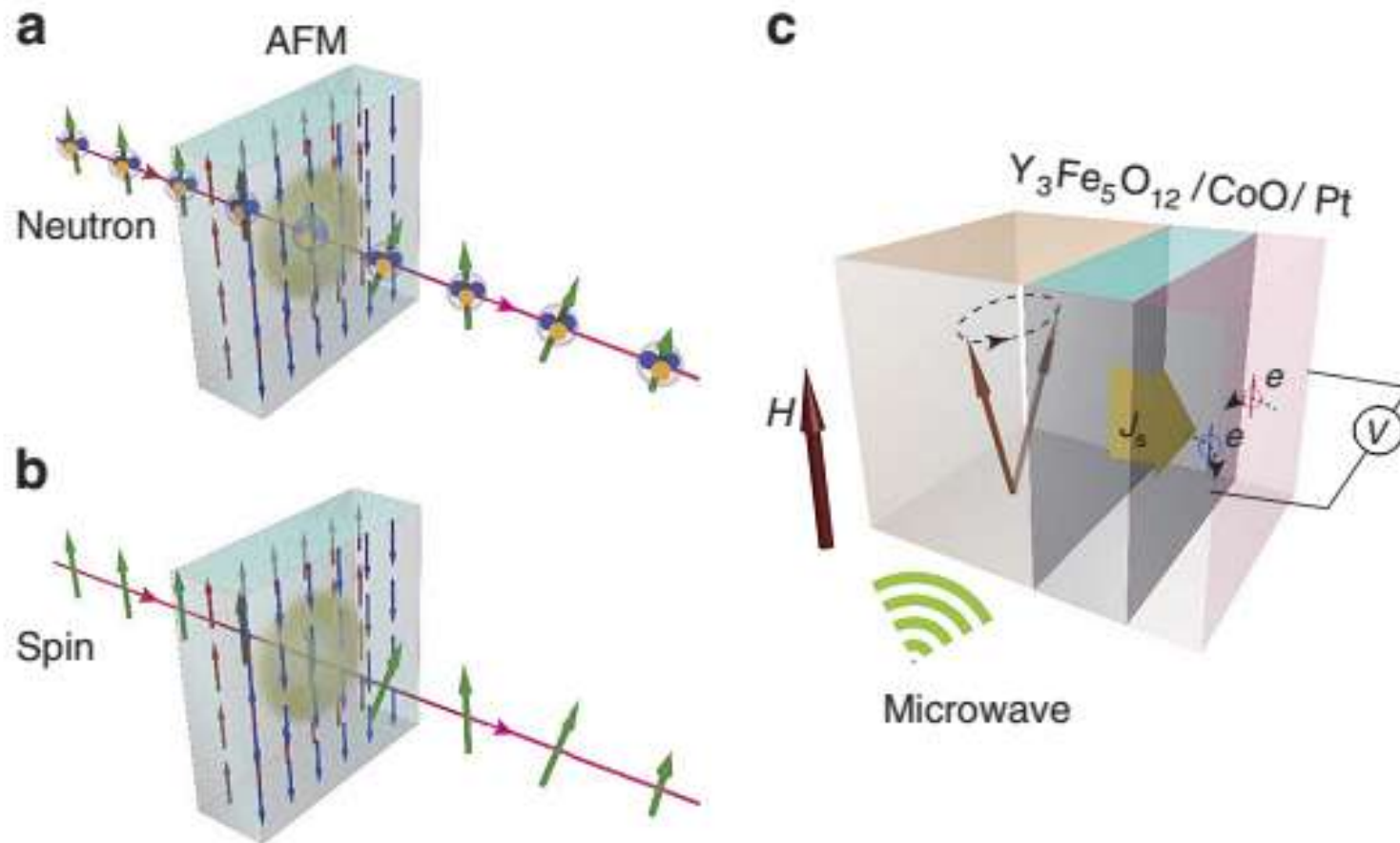


Spin orbit torque in AFM



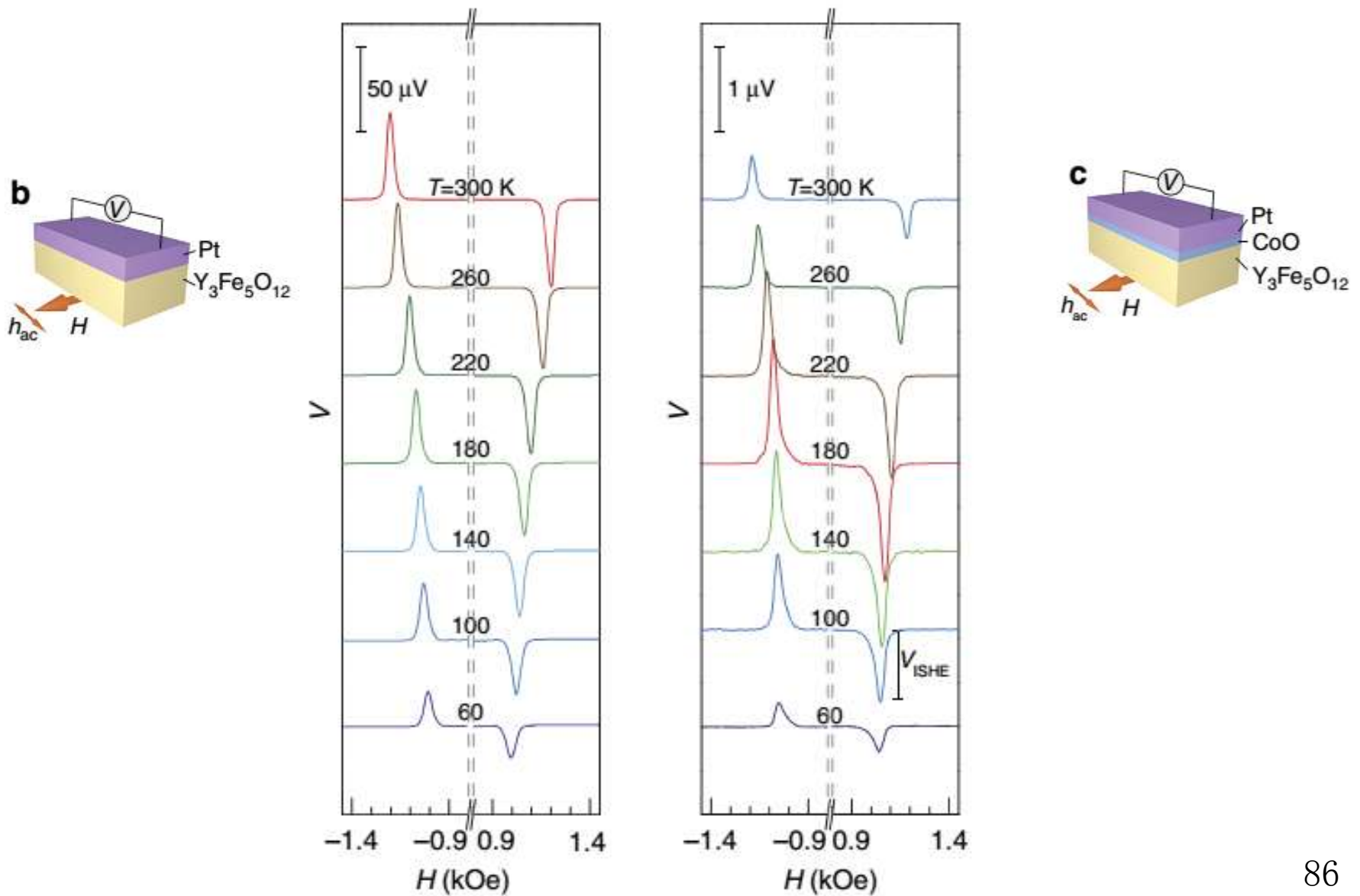
Zhang, Han, et al, Science Advances (2016)

Spin orbit torque through AFM

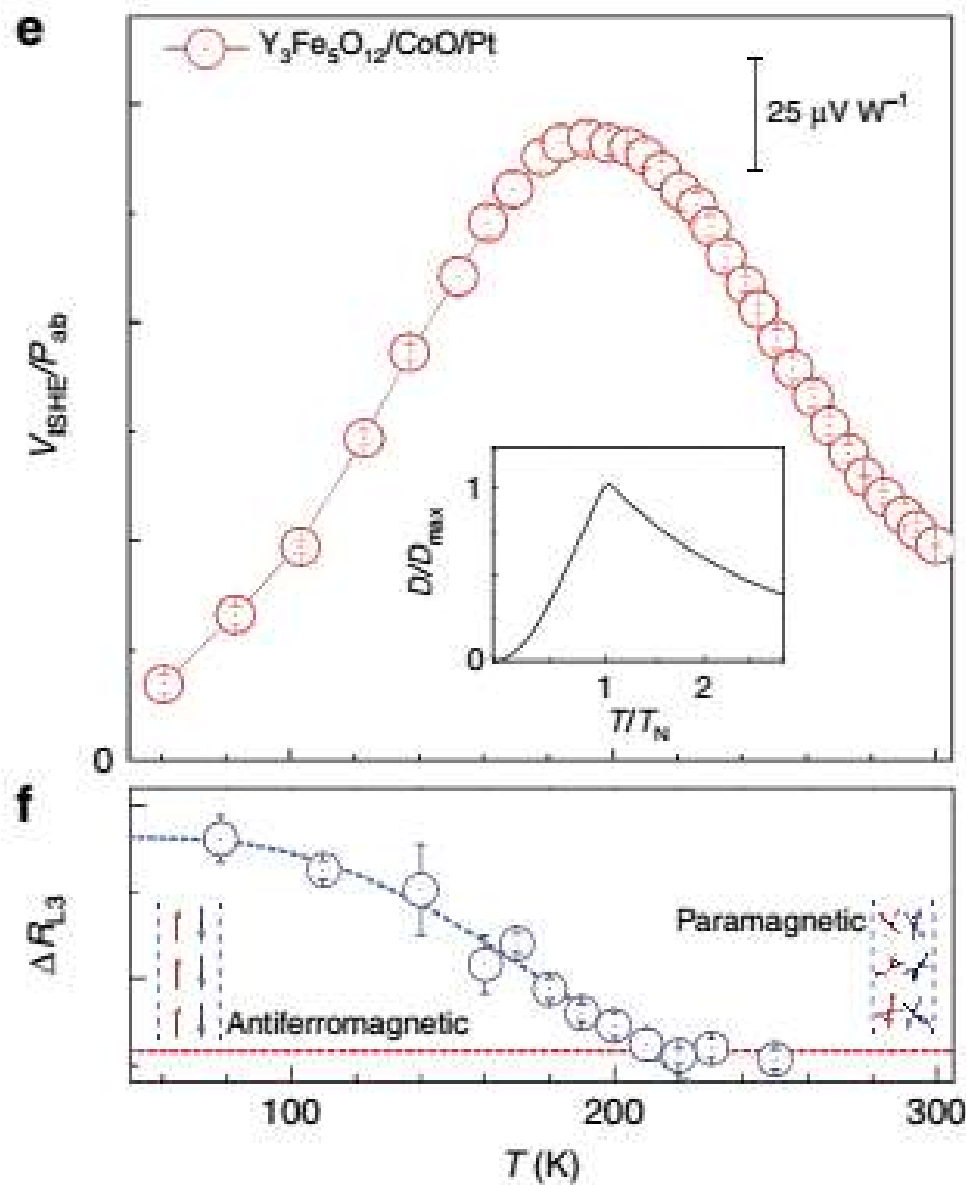


Qiu, et al, Nat. Commun. 7, 12670 (2016)

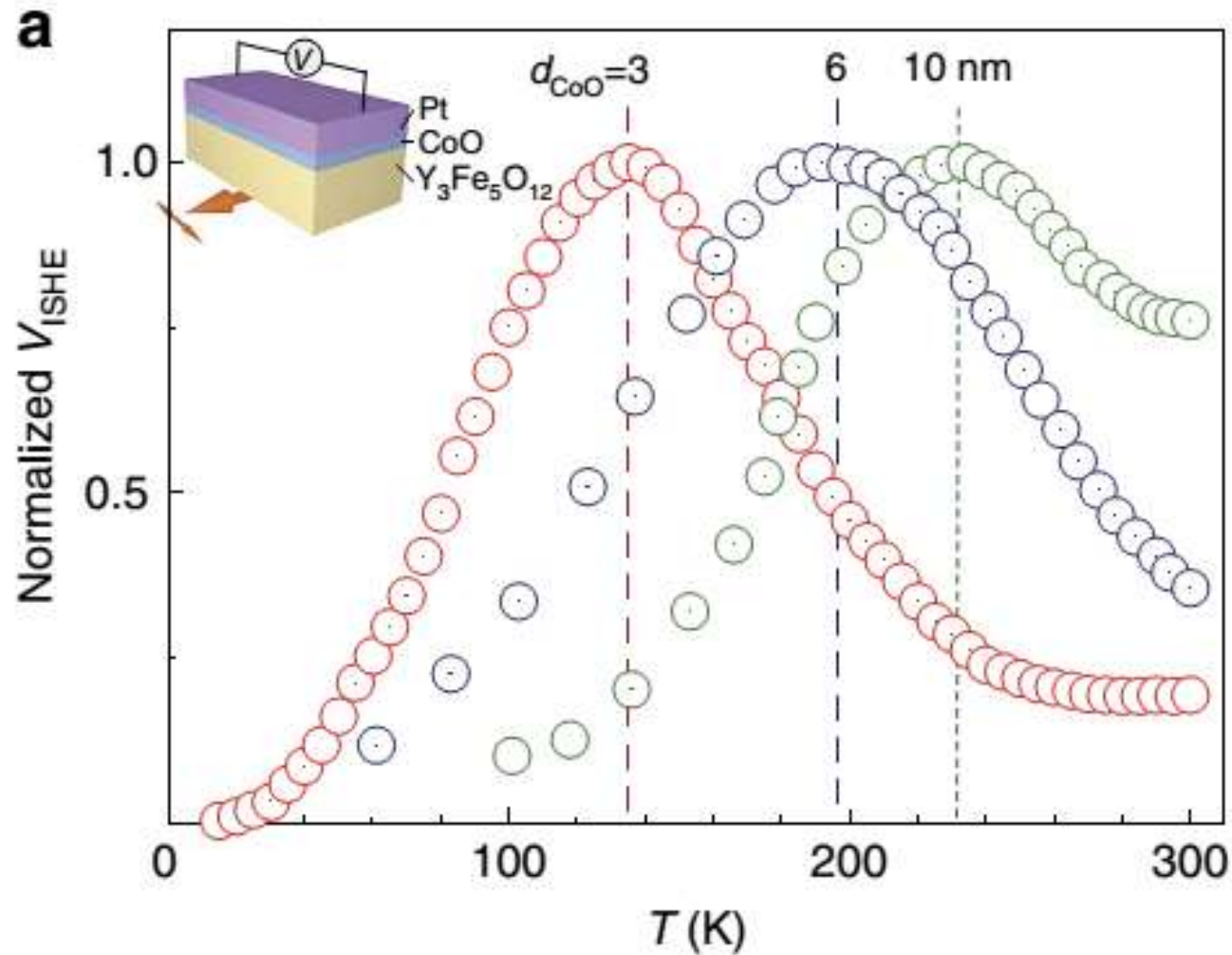
Spin orbit torque through AFM



Spin orbit torque through AFM



Spin orbit torque through AFM

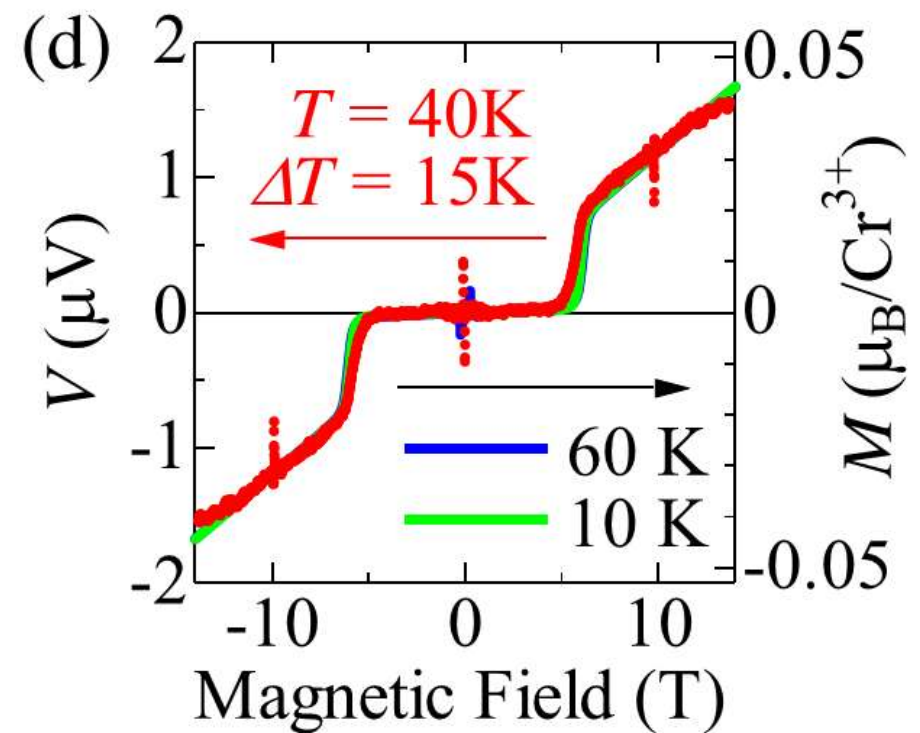
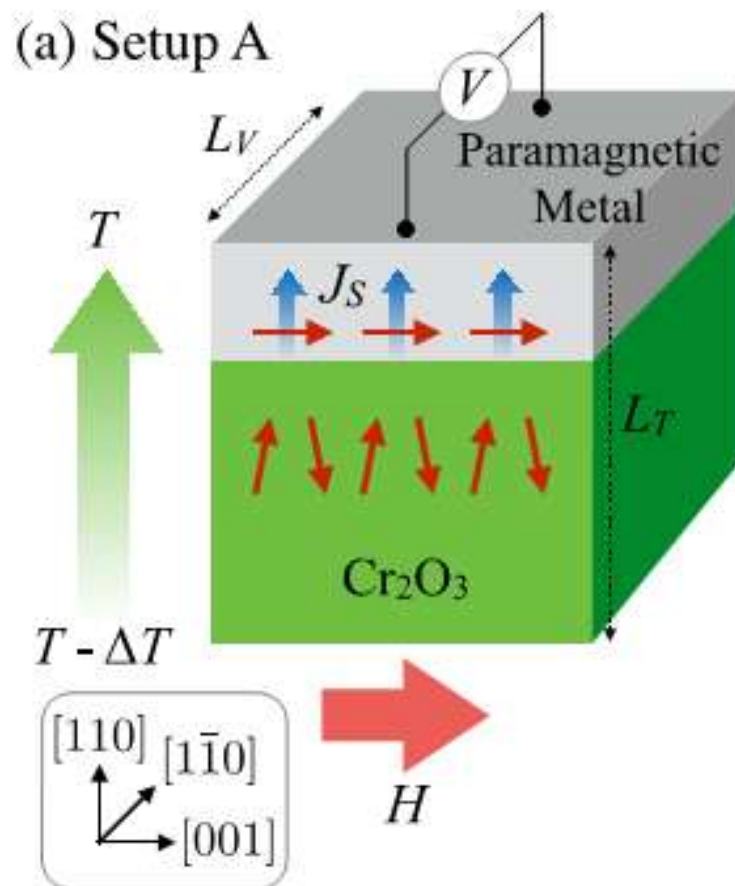


Summary

- 1. Antiferromagnetism and Exchange bias**
- 2. Spin Seebeck effect in AFM**
- 3. AMR of AFM**
- 4. Switching of AFM**
- 5. Anomalous Hall effect in AFM**
- 6. Spin orbit torque in AFM**

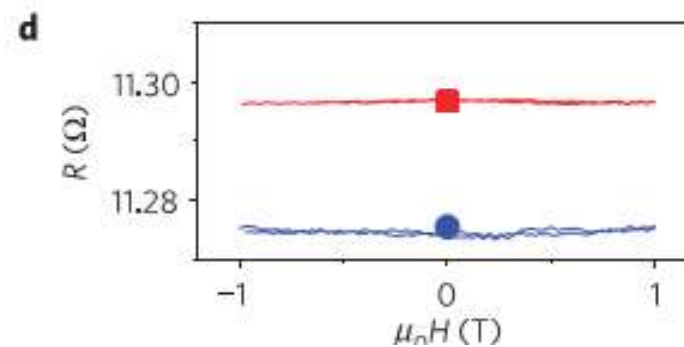
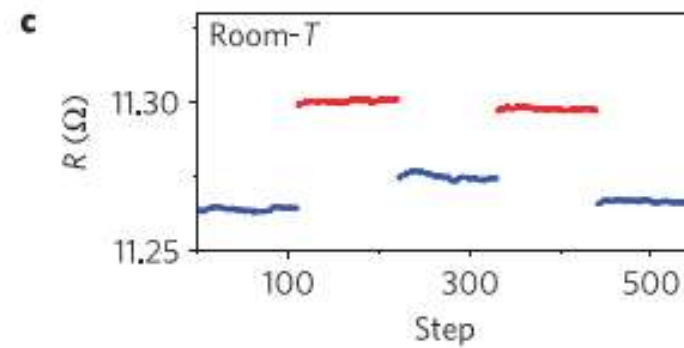
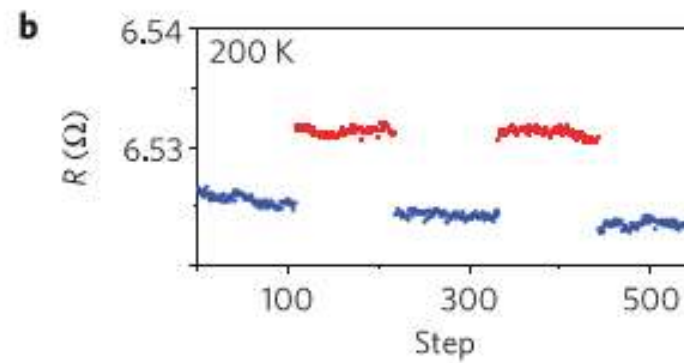
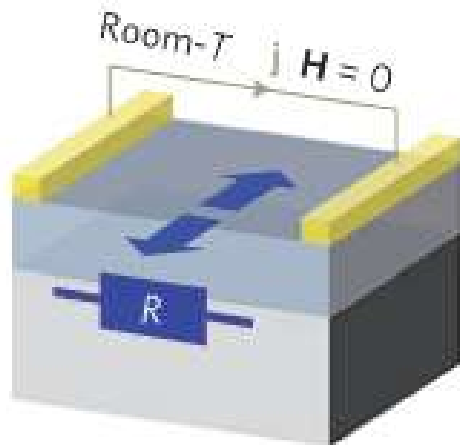
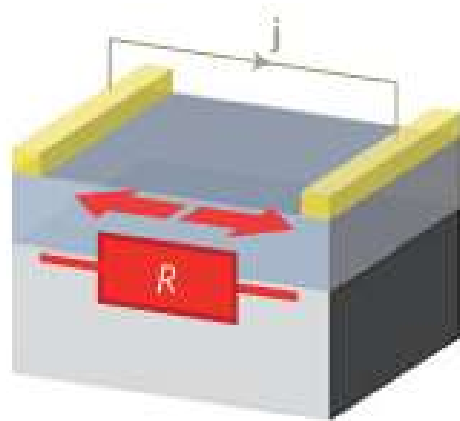
Summary

2. Spin Seebeck effect in AFM



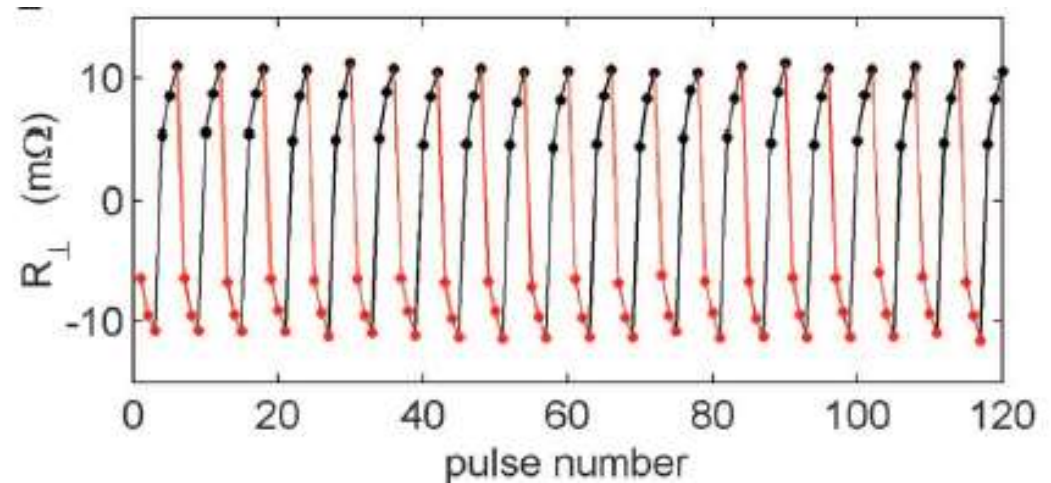
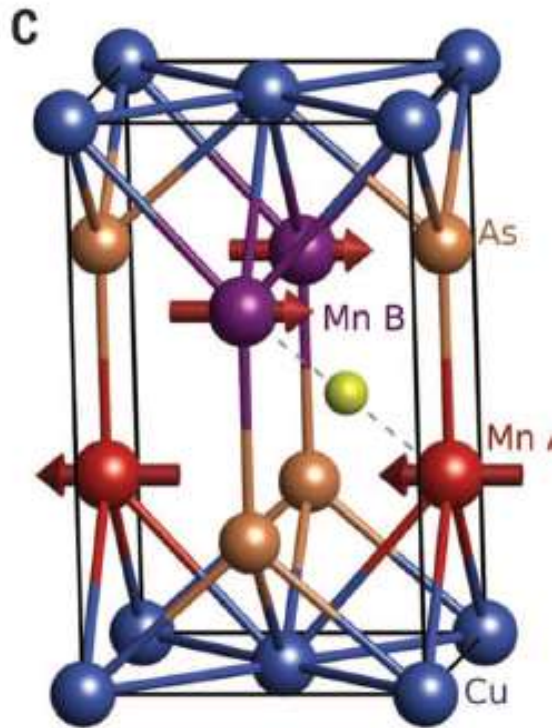
Summary

3. AMR in AFM



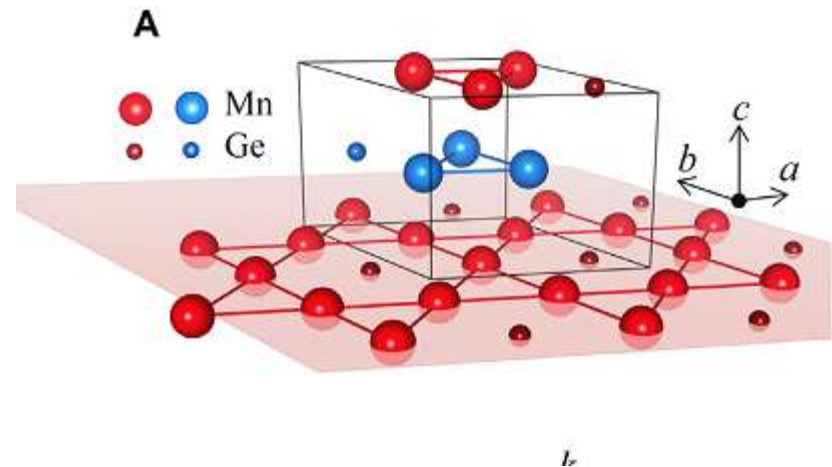
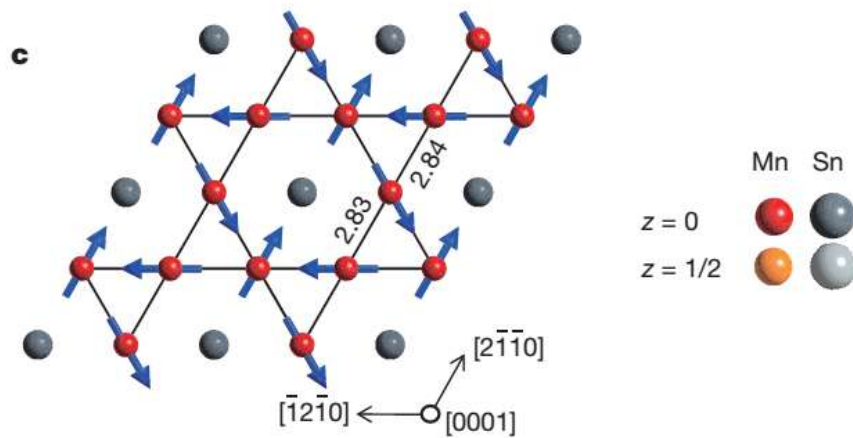
Summary

4. Switching of AFM



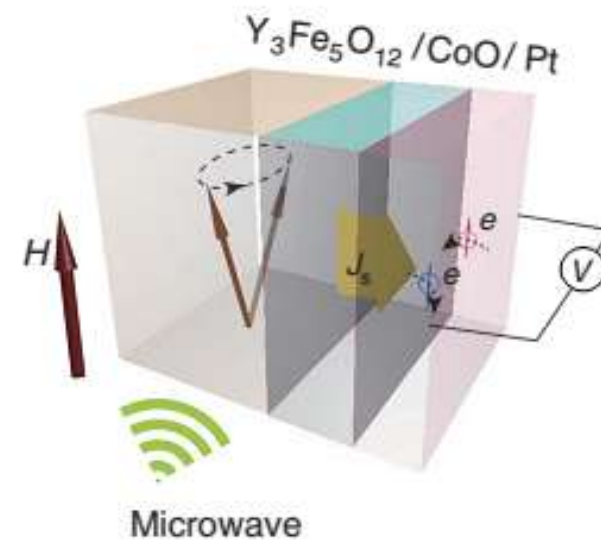
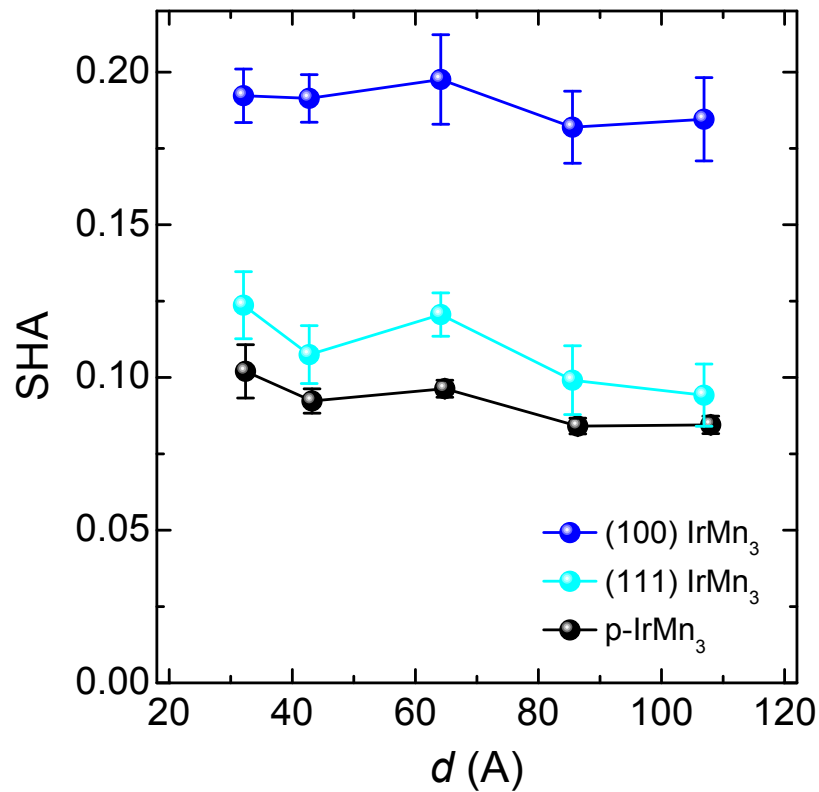
Summary

5. Anomalous Hall effect in AFM



Summary

6. Spin orbit torque in AFM



下一节课: Dec. 15th, 22th

Student Presentations

~ 15 mins/ Per person

12 mins talk + 3 mins questions

课件下载：

<http://www.phy.pku.edu.cn/~LabSpin/teaching.html>

下一节课: Dec. 15th, 22th

Date	Names
Dec. 15 th	江鹏；彭泽龙；李鑫；蔡冉冉；陈光毅；江丙炎
Dec. 22 th	刘星辰；吕超；闫姣婕；闫青；杨宁选；张志斌
Dec. 29 th	交期末考试（电子版和纸版都可以）

谢谢！