Chapter 8

Antiferromagnetic spintronics

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量子材料科学中心

2015年12月6日

Review of last class

1. Topology

2. Quantum anomalous Hall effect

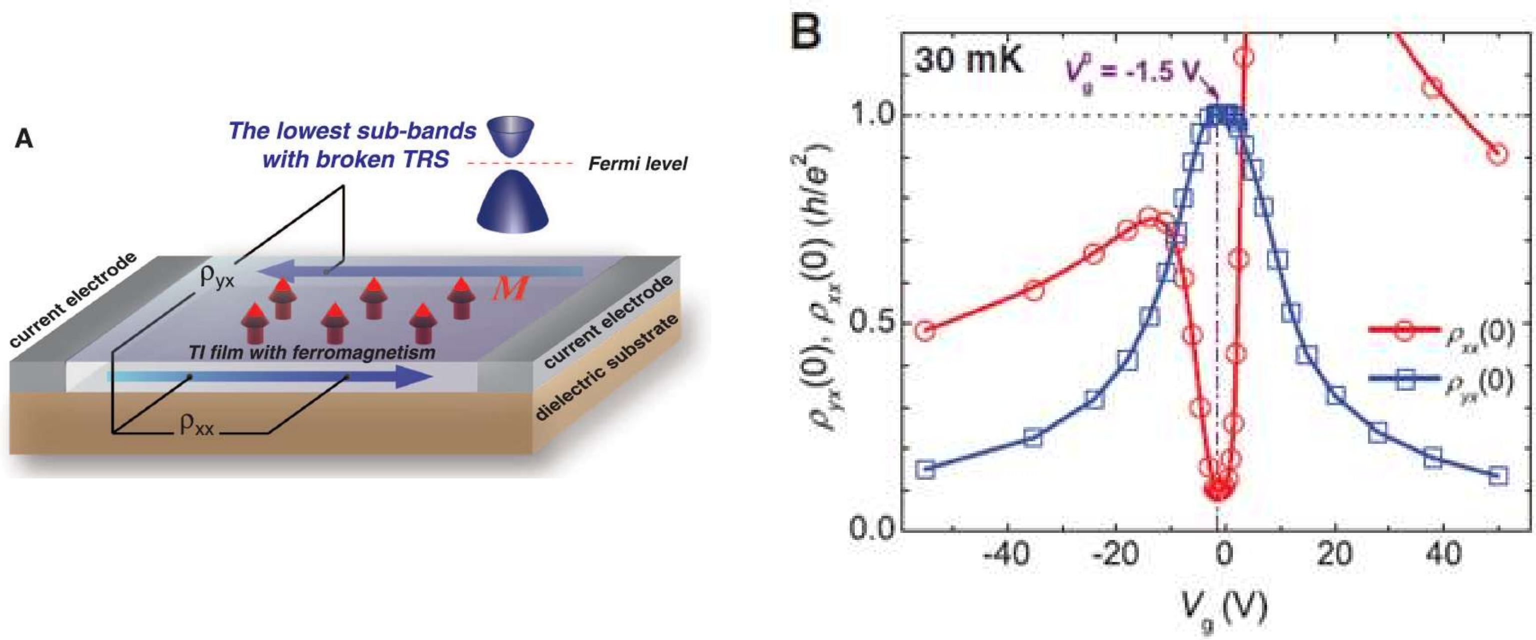
3. Skyrmions

4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**

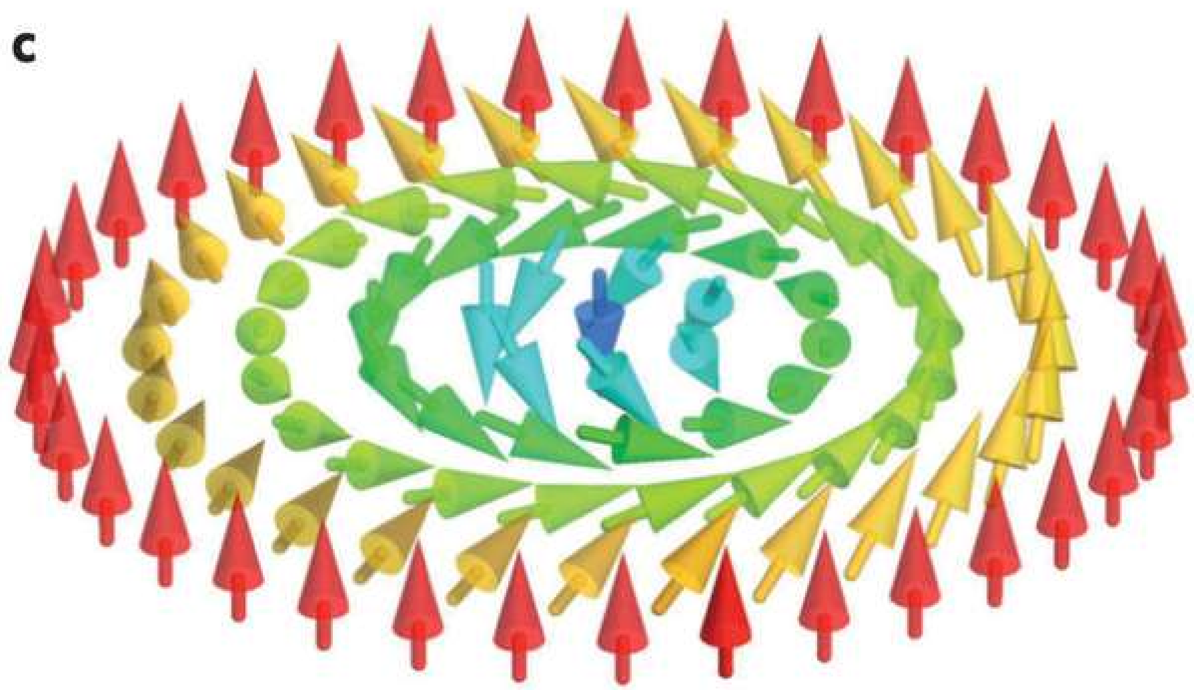
Review of last class

2. Quantum anomalous Hall effect



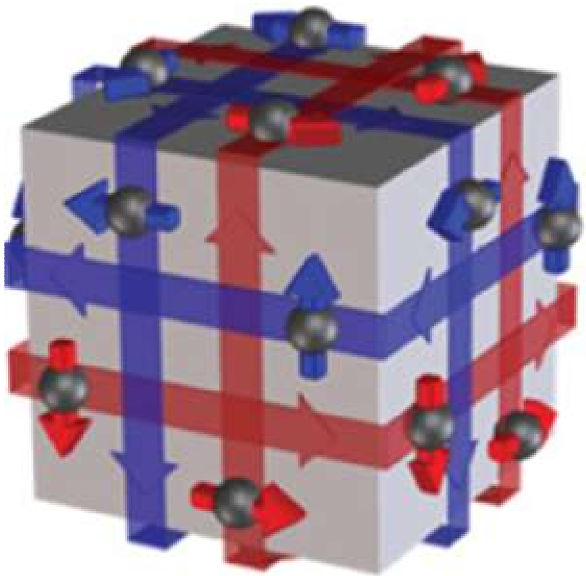
Review of last class

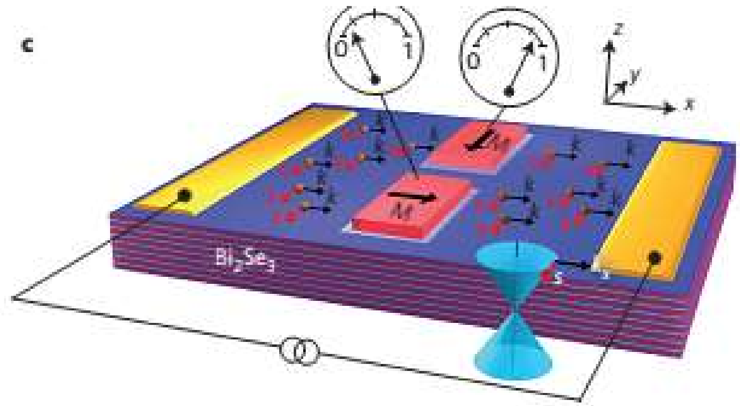
3. Skyrmions

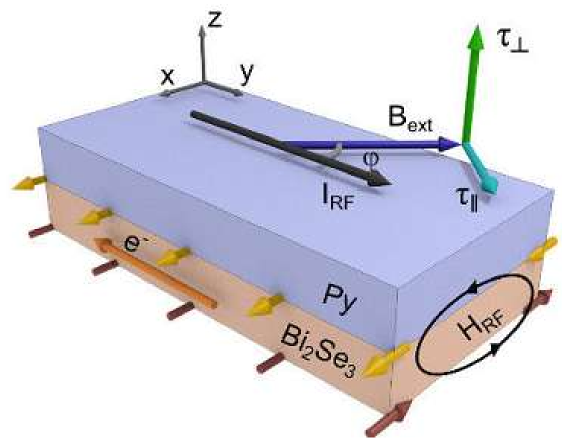


Review of last class

4. Spin-momentum locking of 3D TI



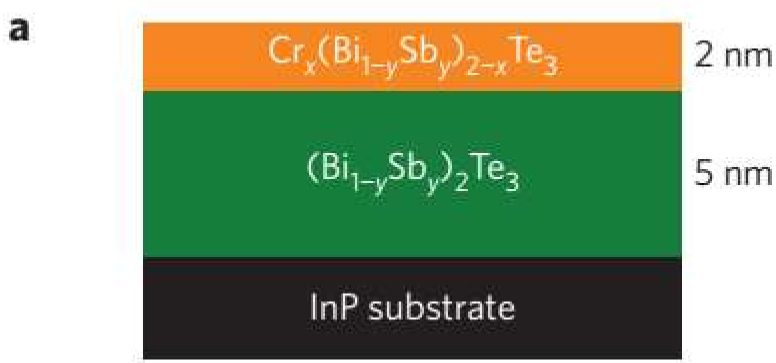


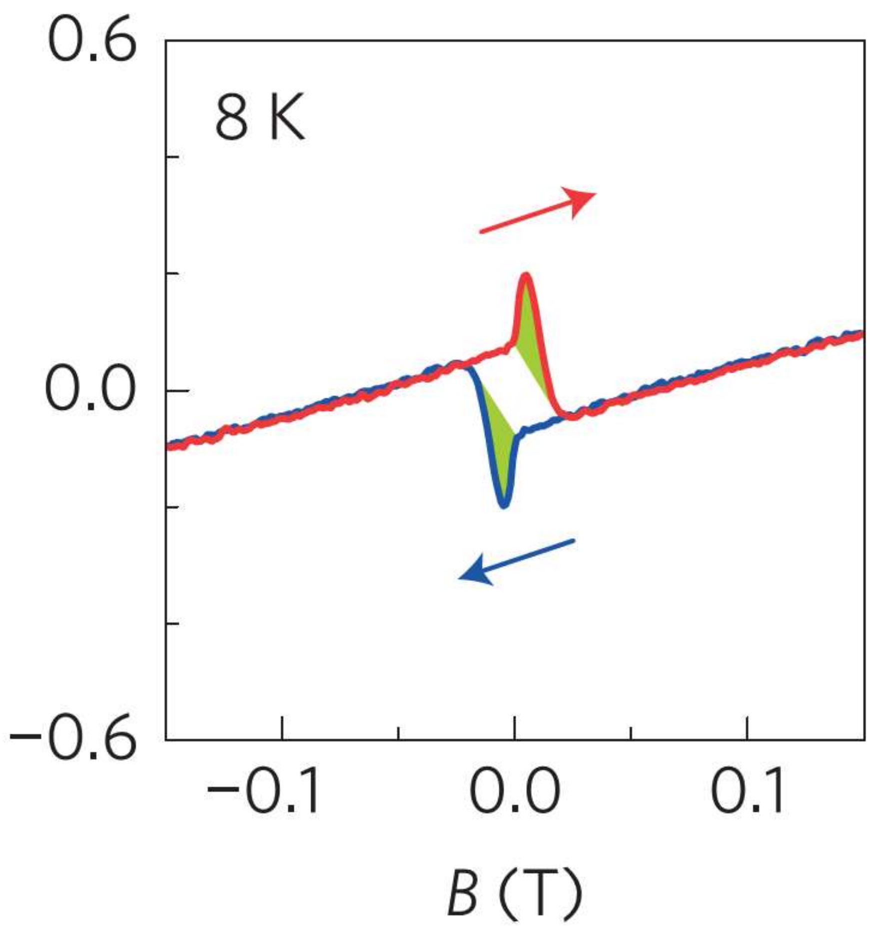


Question?

How about topology in K-space meets topology in Real-space?

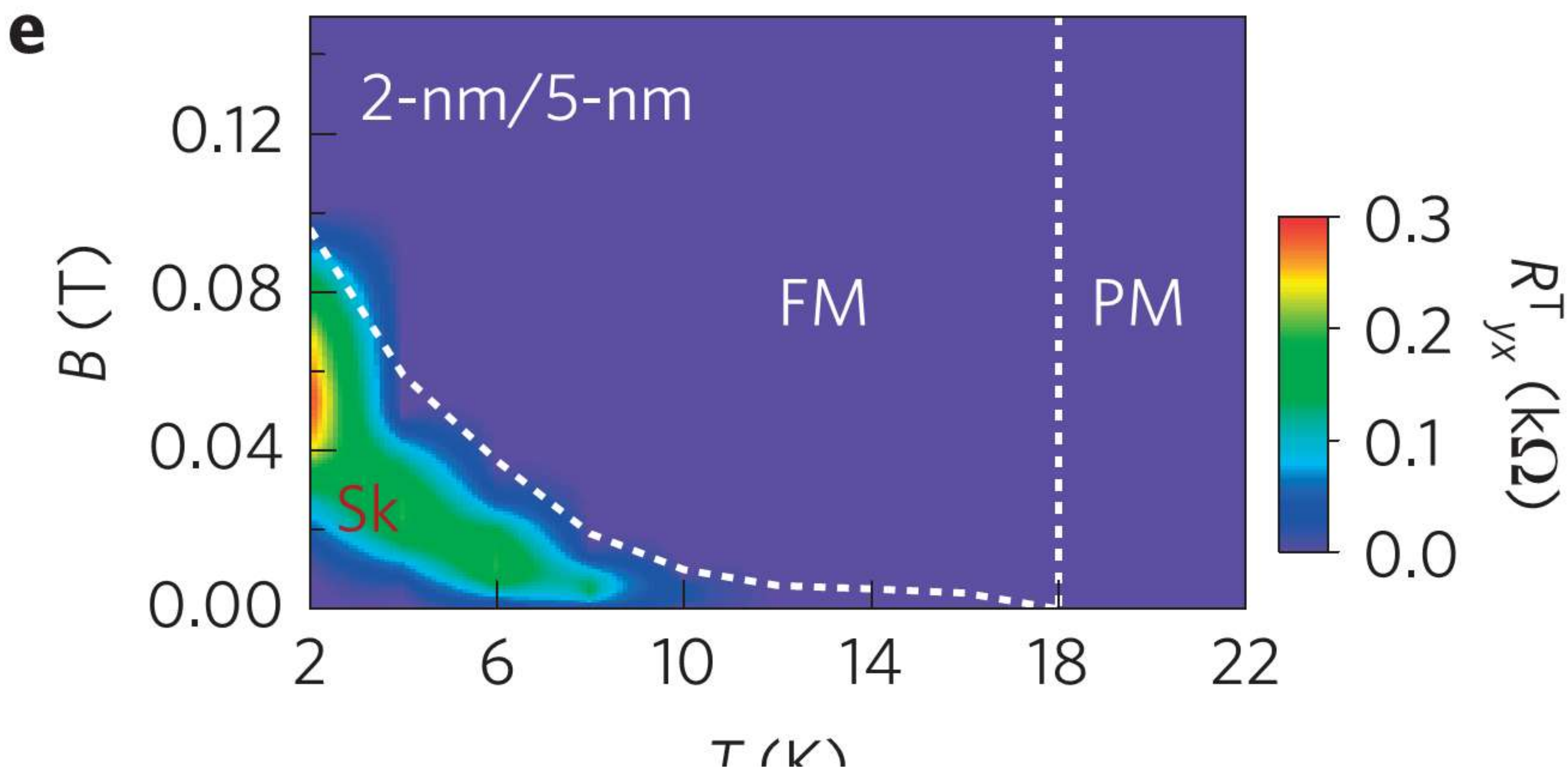
Question?





Yasuda, et al, Nature Physics (2016)

Question?



Yasuda, et al, Nature Physics (2016)

Outline

1. **Antiferromagnetism and Exchange bias**

2. **Spin Seebeck effect in AFM**

3. **AMR of AFM**

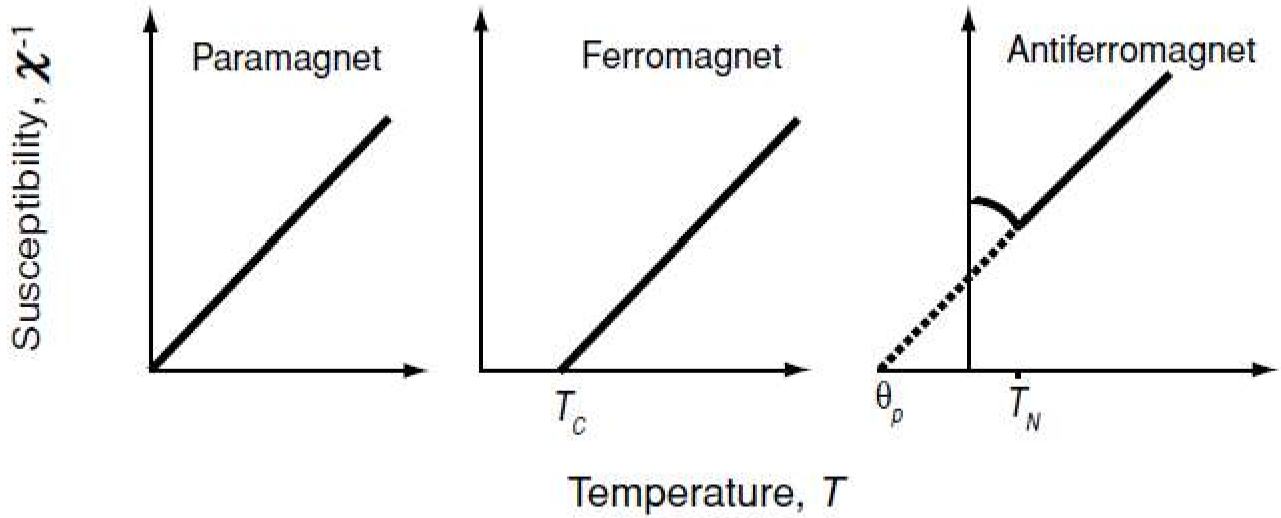
4. **Switching of AFM**

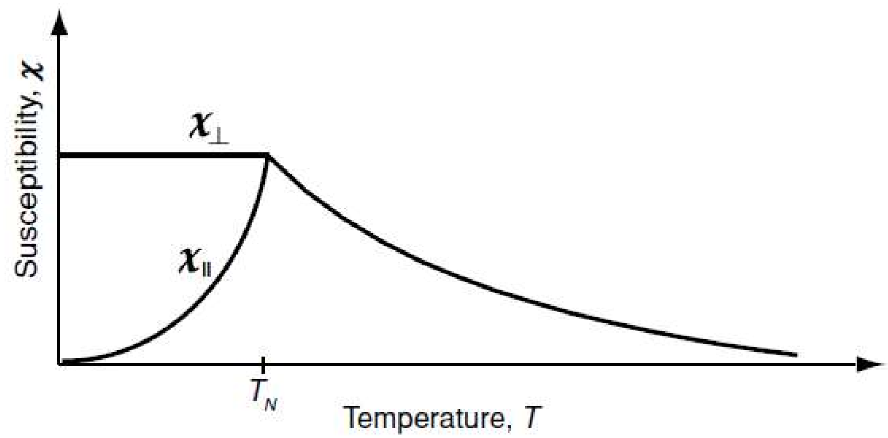
5. **Anomalous Hall effect in AFM**

6. **Spin orbit torque in AFM**

1. Antiferromagnetism and Exchange bias

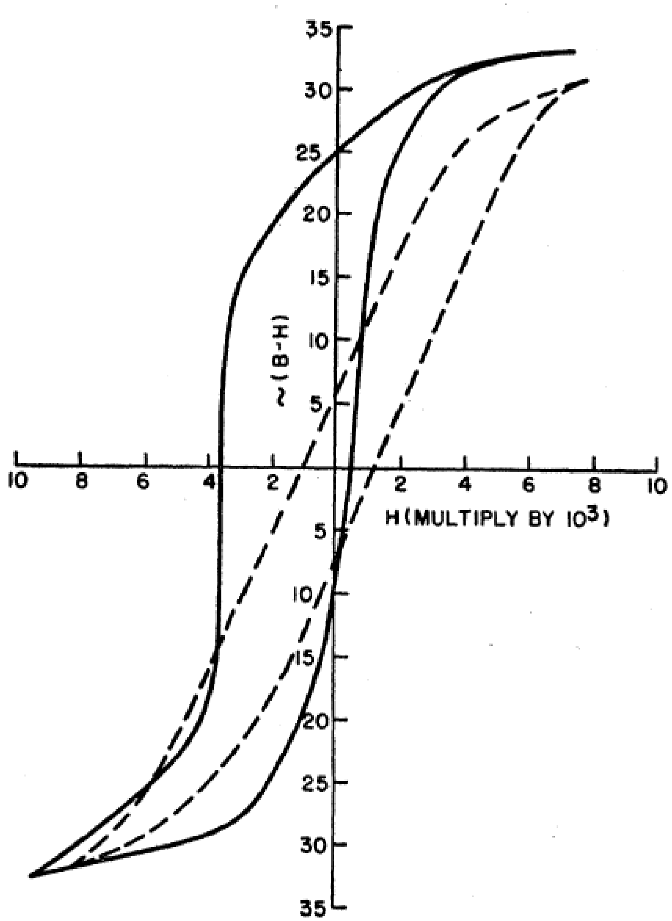
Antiferromagnetism and Exchange bias



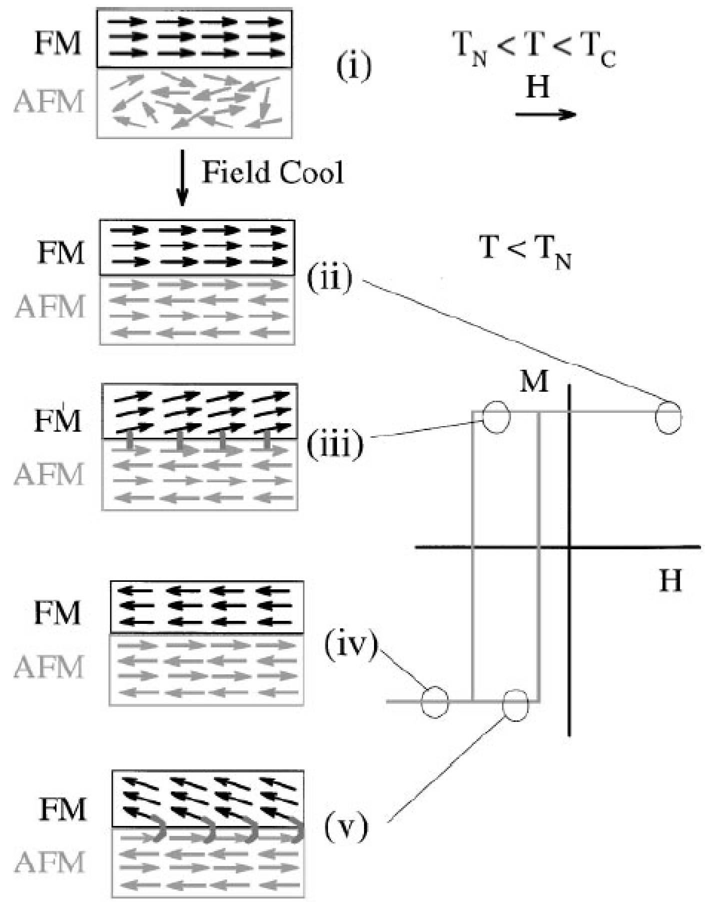


Coey, Book Magnetism and Magnetic Materials (2009)

Antiferromagnetism and Exchange bias

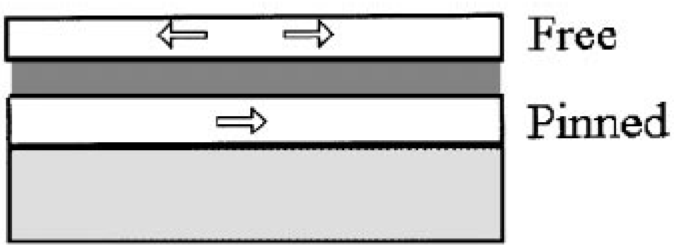


W. H. Meiklejohn and C. P. Bean
Physical Review **102**, 1413 (1956).

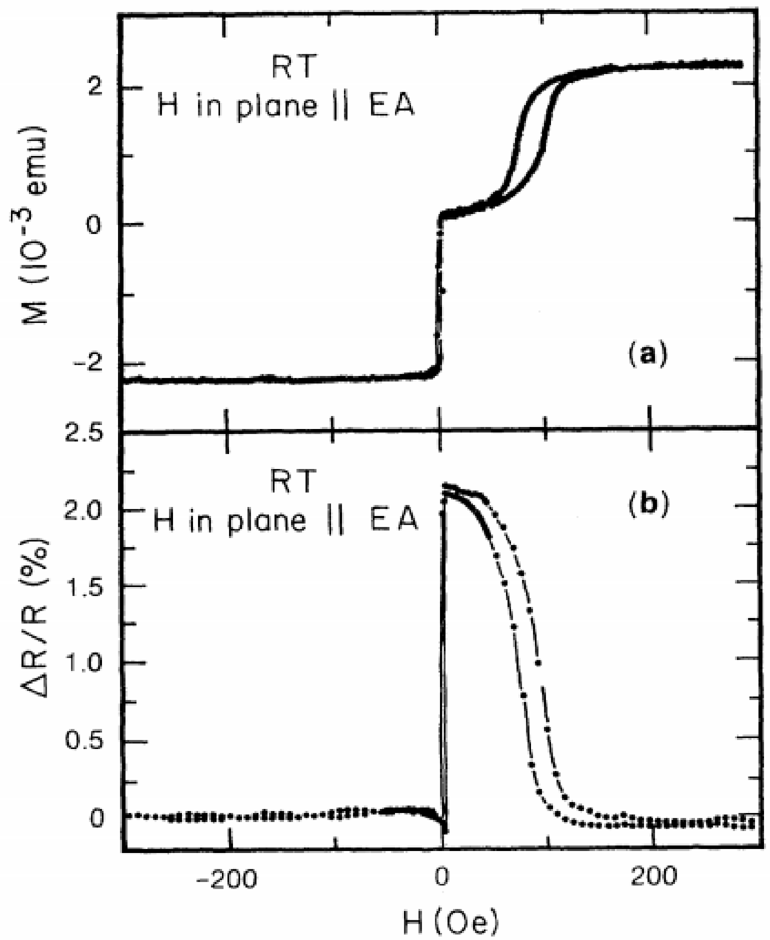


J. Nogue and I. K. Schuller JMMM
192, 203 (1999).

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

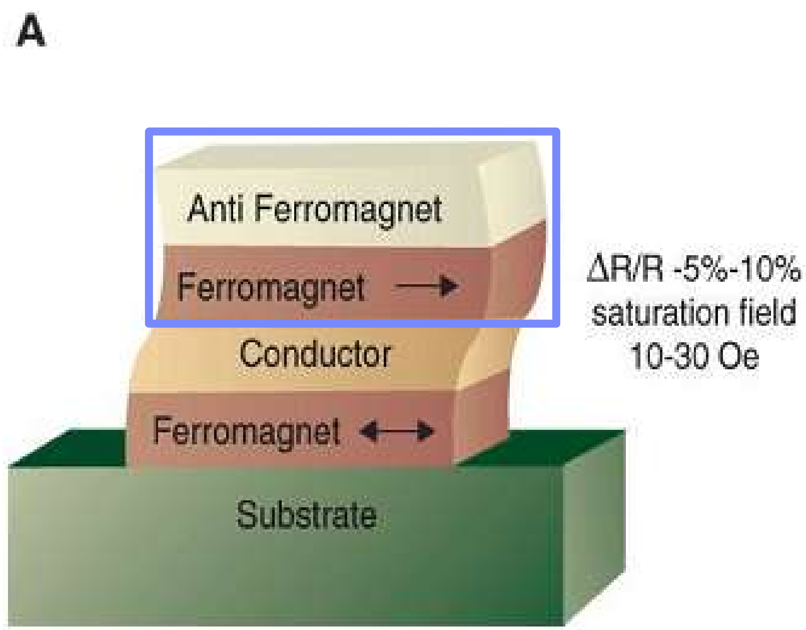


Fig. 1. Spin-dependent transport structures. (A) S

Yang & Parkin, Nature Nanotech (2014)

Antiferromagnetism and Exchange bias

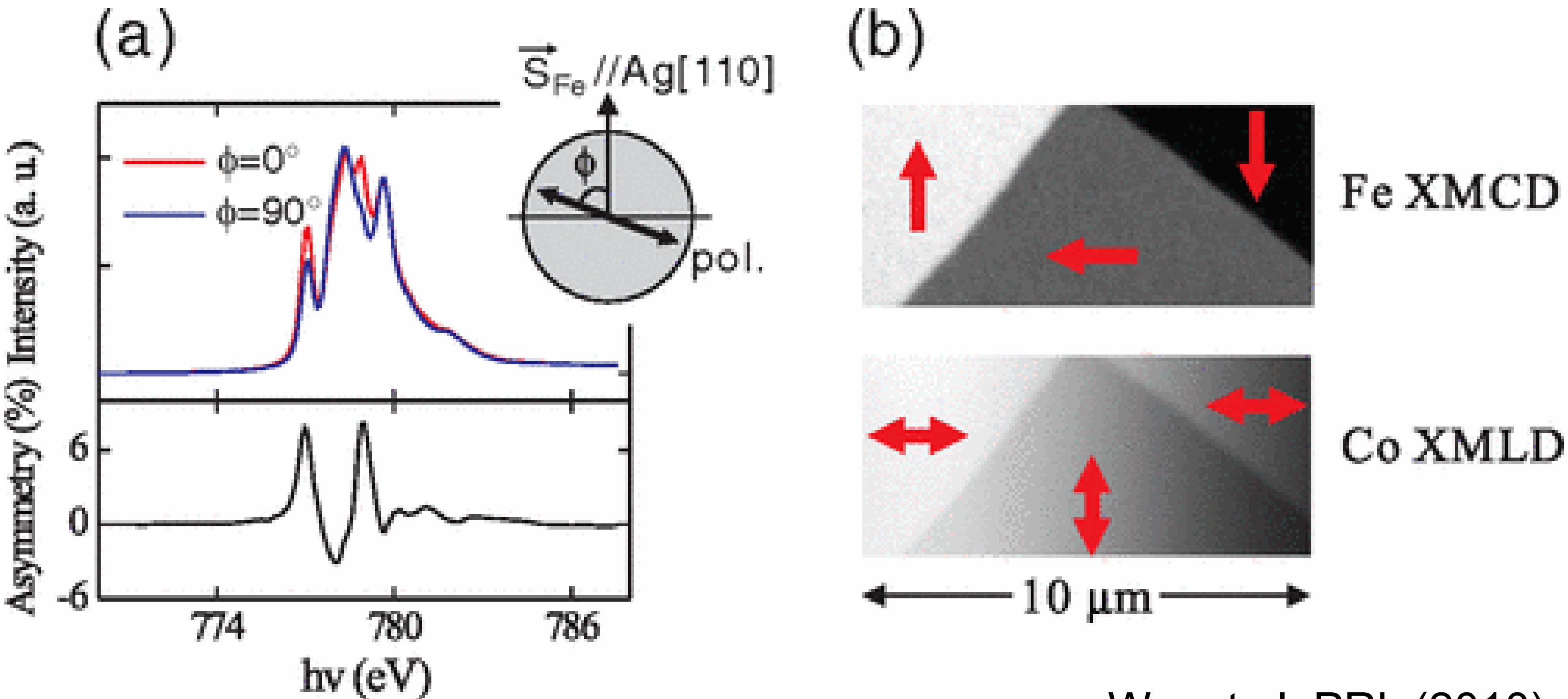
Table 6.1. Some common antiferromagnets

	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
αFe_2O_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.

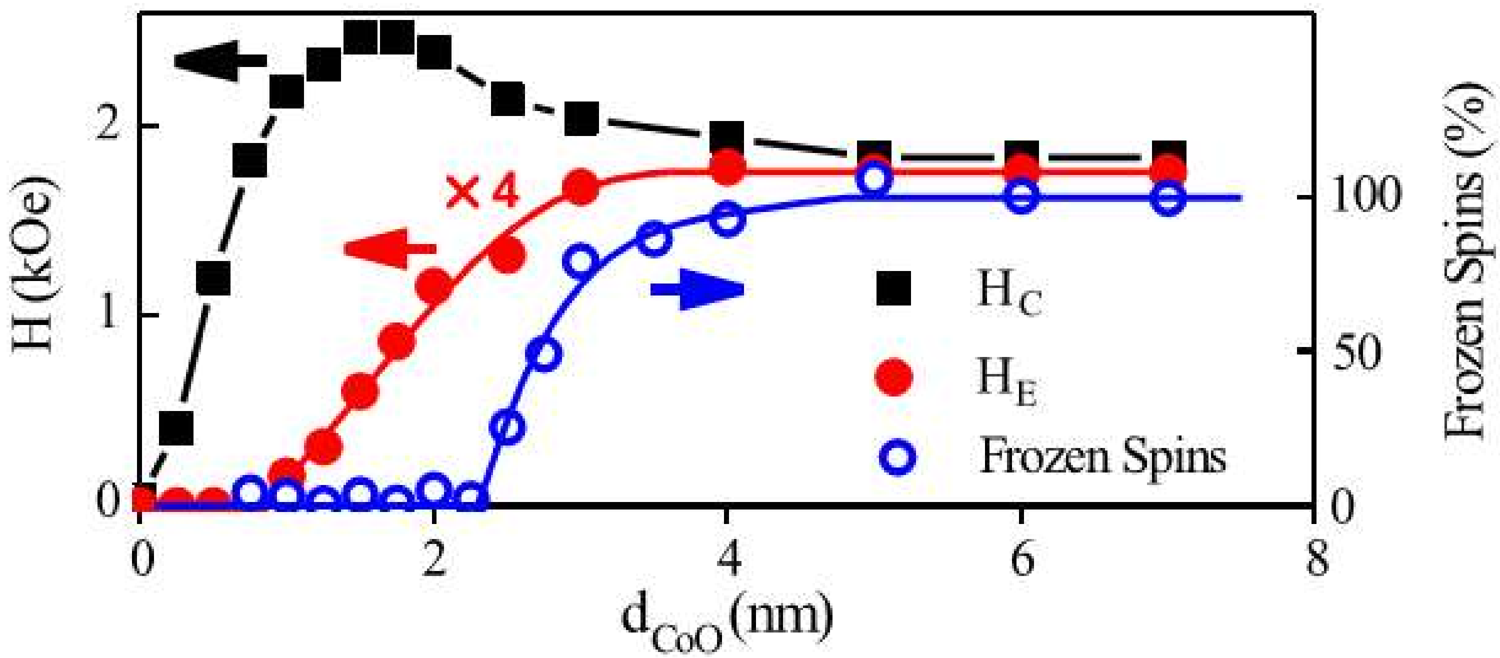
Exchange bias

Antiferromagnetic CoO spins are 90^{o} coupled to Fe spins.



Wu, et al, PRL (2010)

Exchange bias

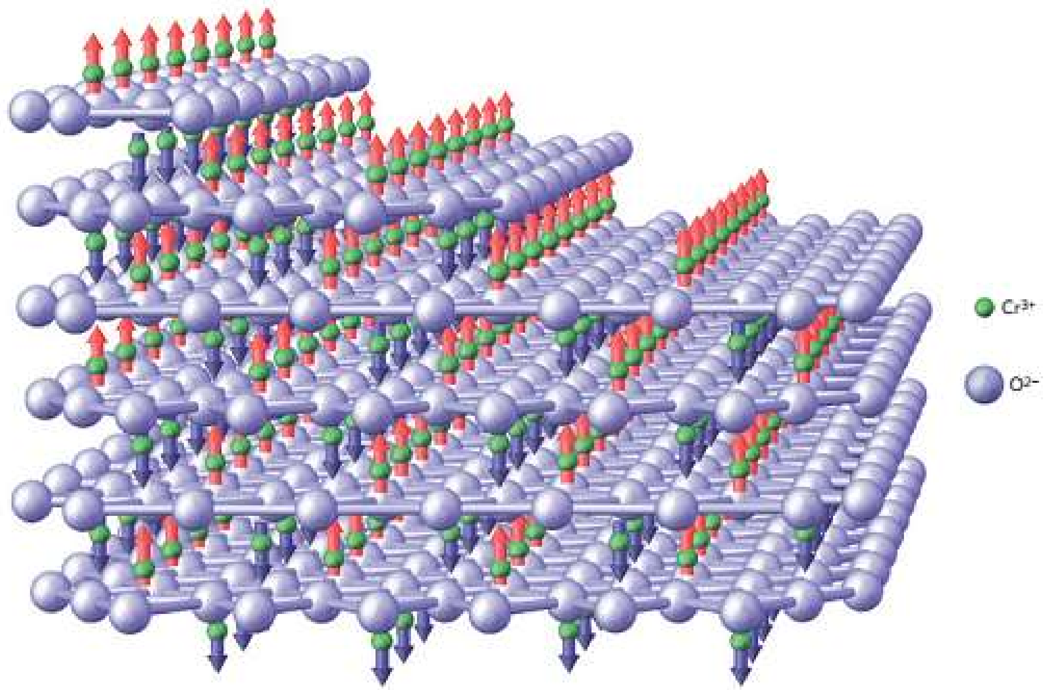


Only 5 % of the Frozen spins are needed for exchange bias.

Exchange bias

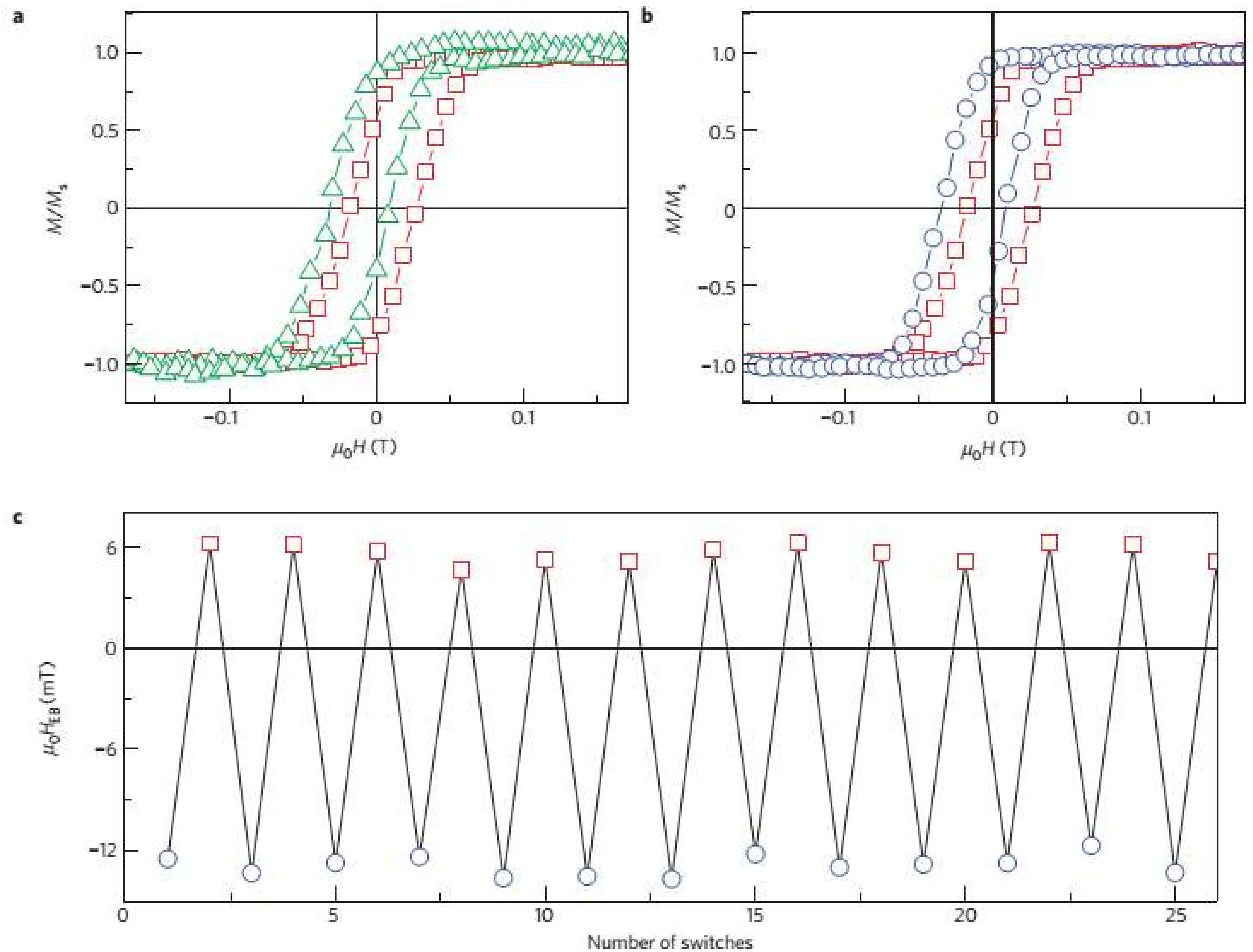
Collinear exchange coupling

Cr2O3

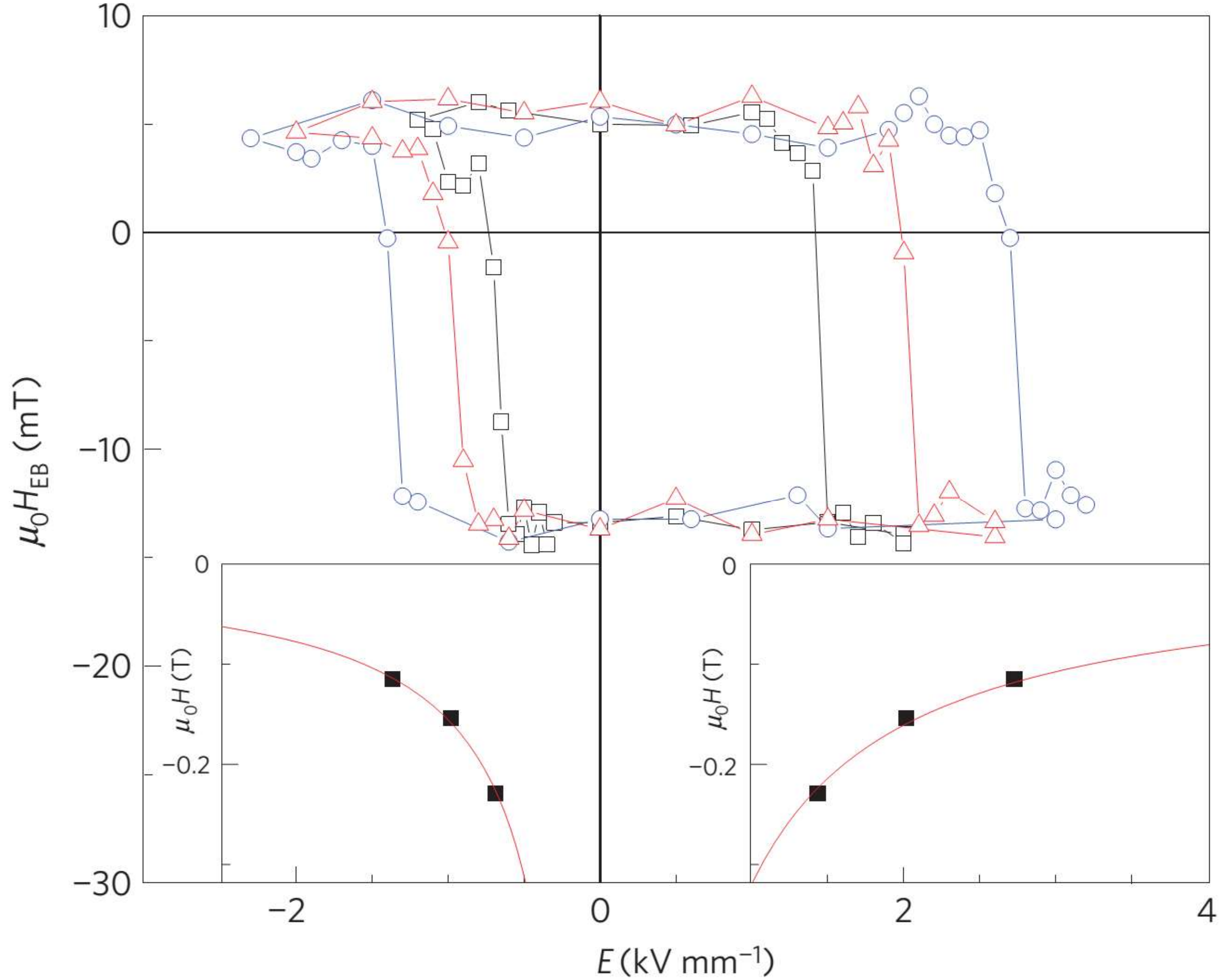


He, et al, Nature Materials (2010)

Electric field to tune Exchange bias

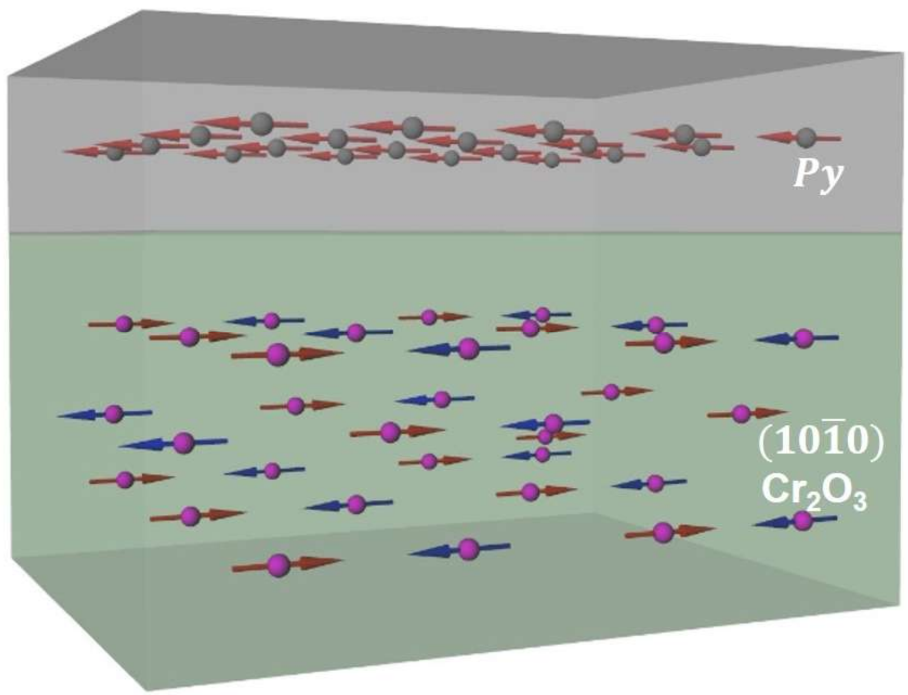


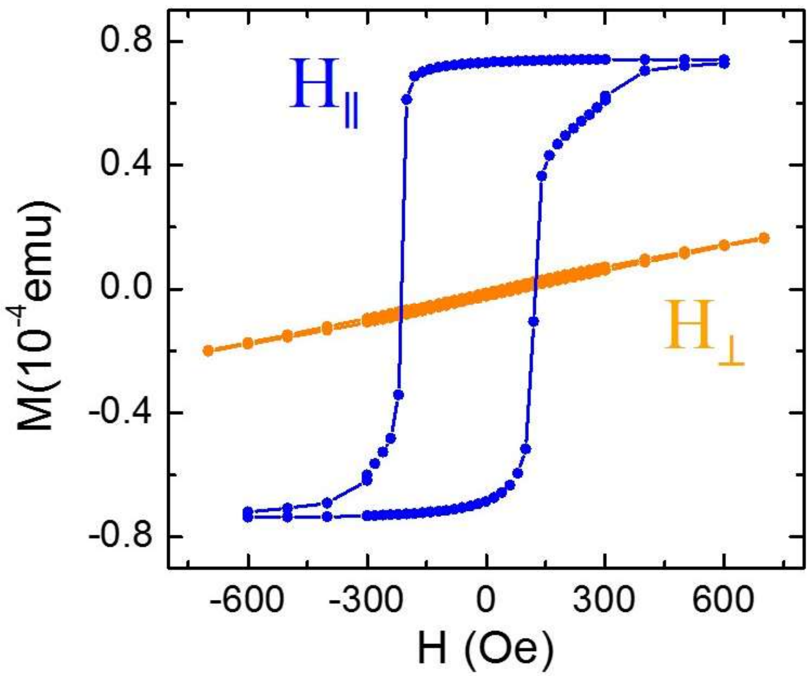
Electric field to tune Exchange bias



Exchange bias

Collinear exchange coupling



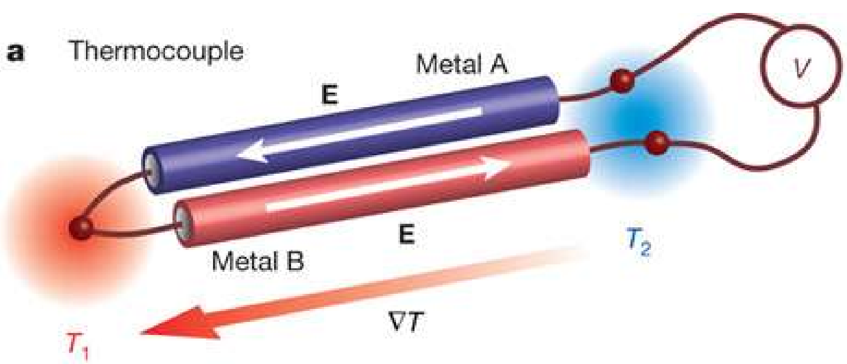


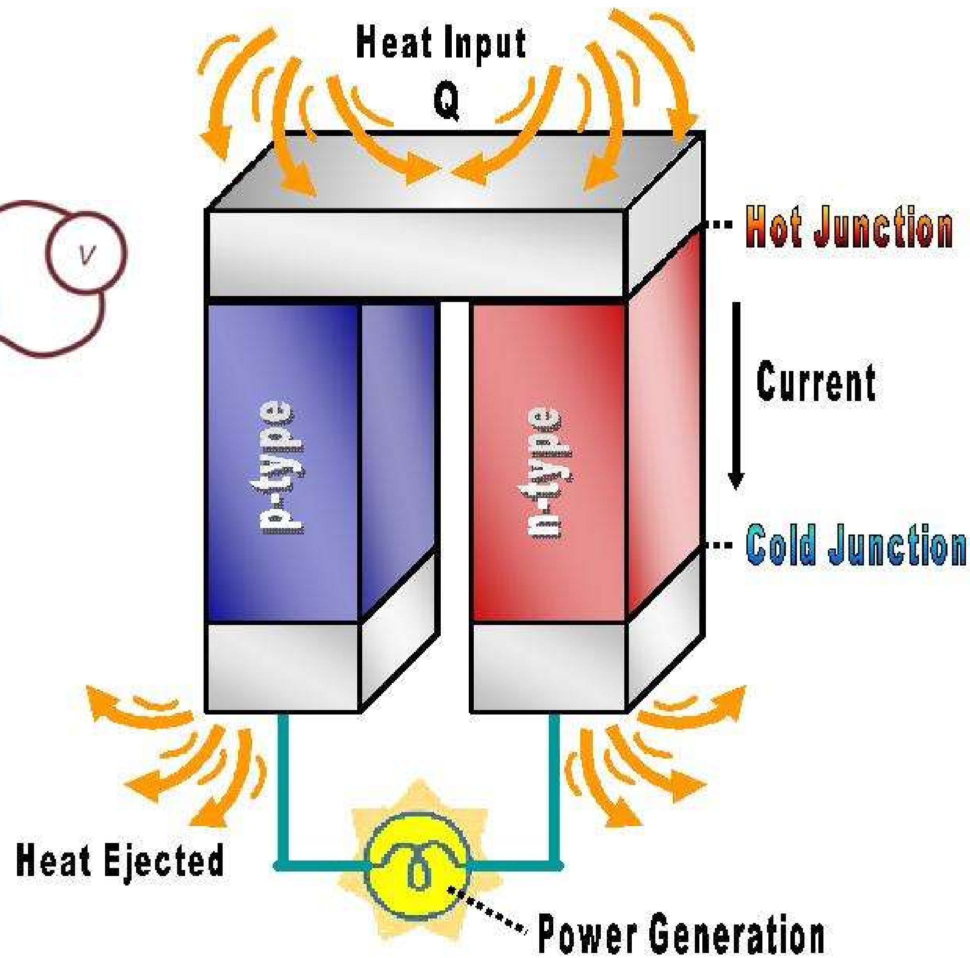
Yuan, et al, Scientific Reports (2016)

Outline

2. Spin Seebeck effect in AFM

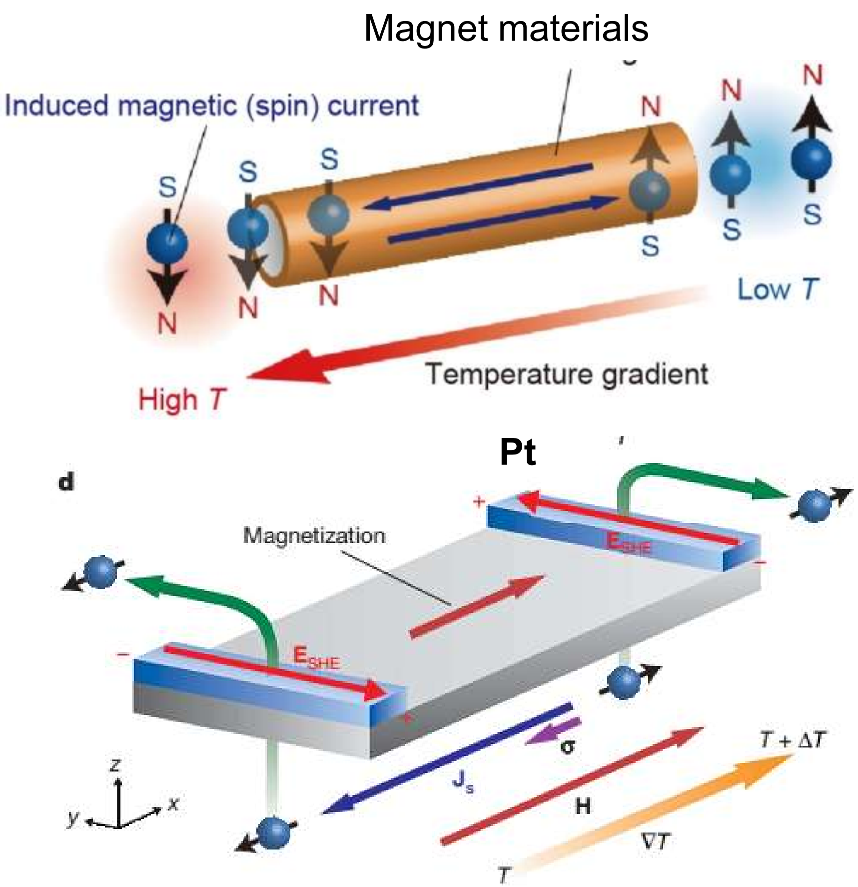
Seebeck effect

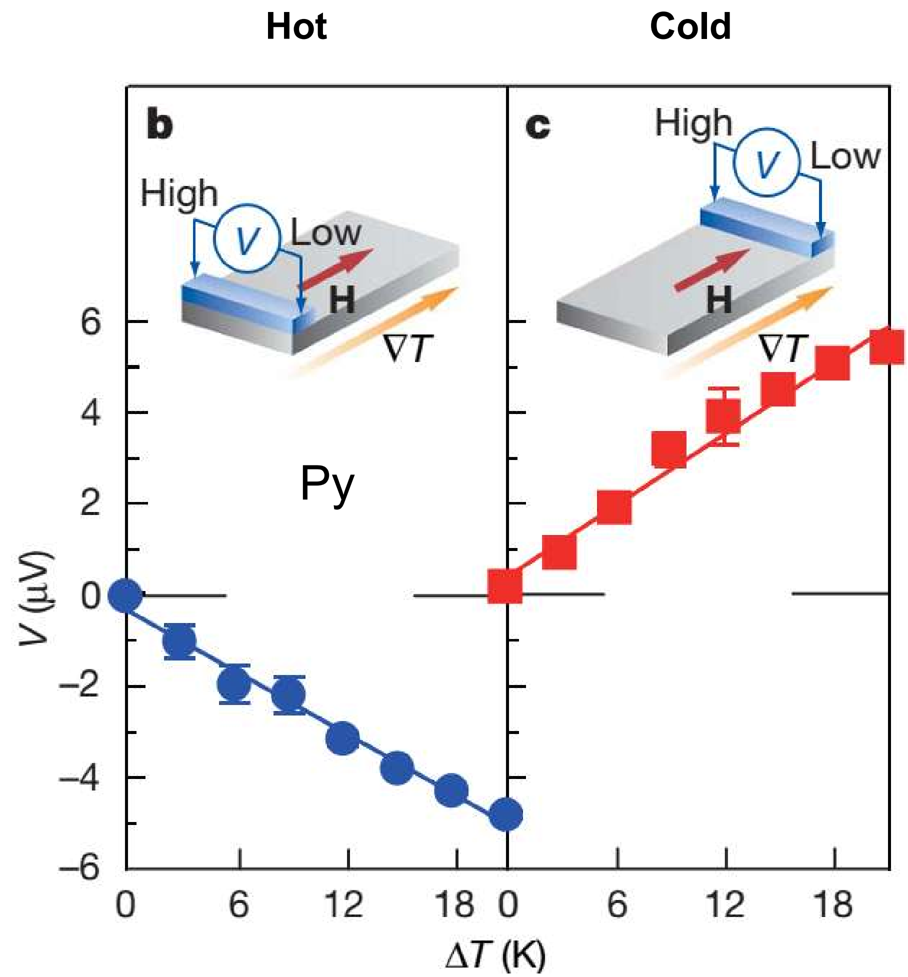




Spin Seebeck effect

Spin Seebeck effect in FM metal

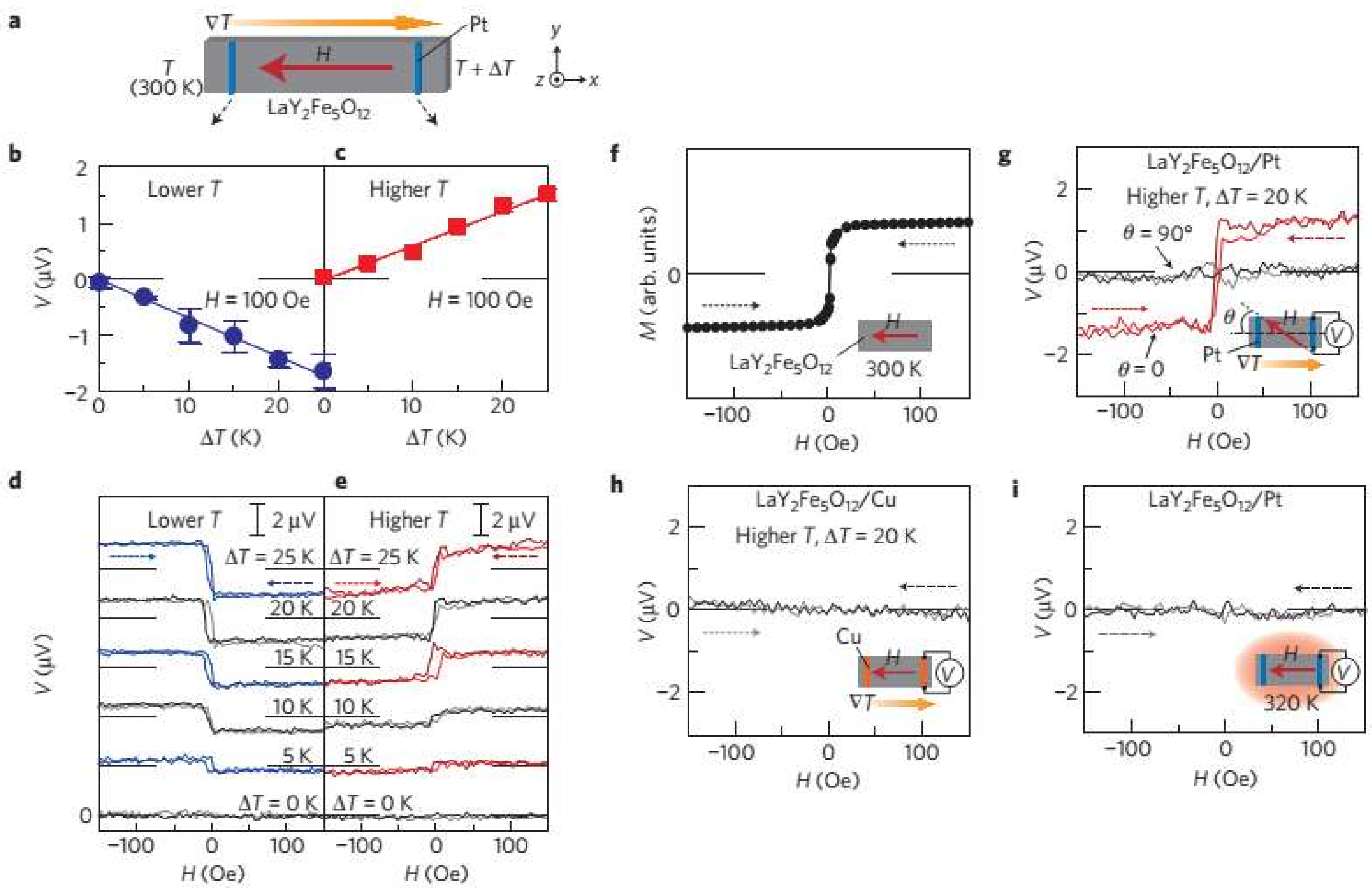




Uchida, et al. Nature (2008)

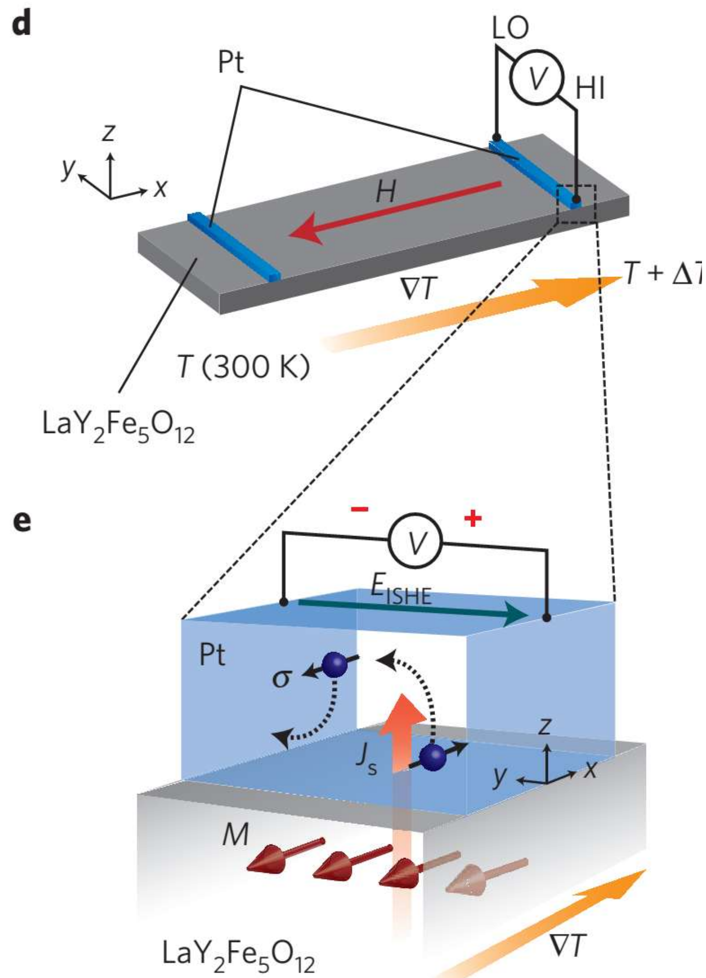
Spin Seebeck effect

Spin Seebeck effect in FM insulator



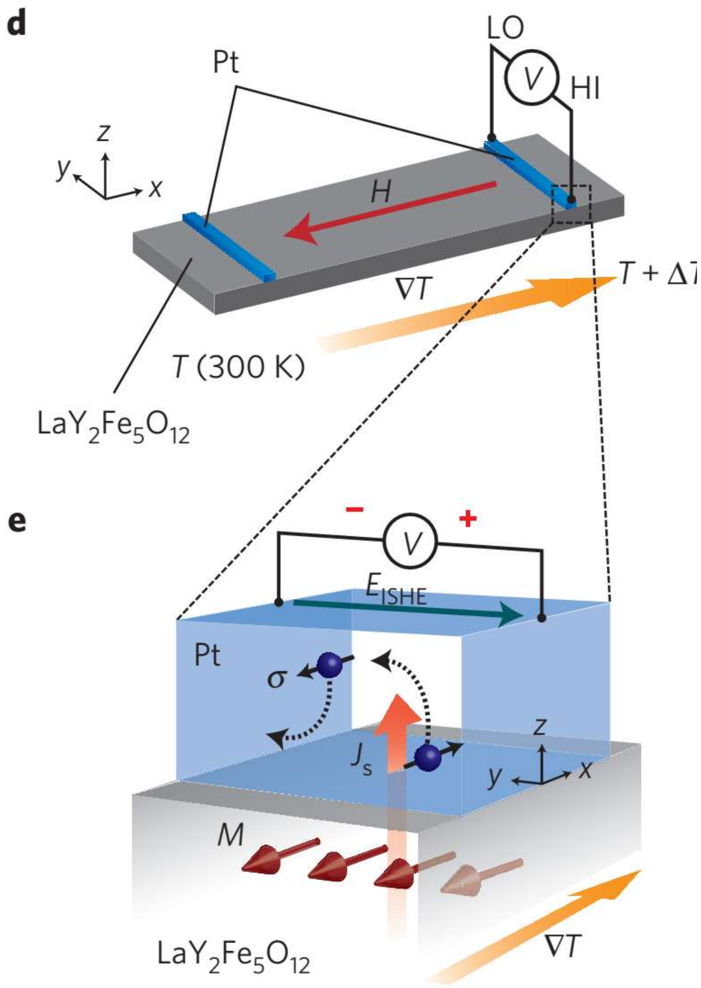
Uchida, et al. Nature Mater. (2010)

Spin Seebeck effect



Question:
How about AFM insulator?

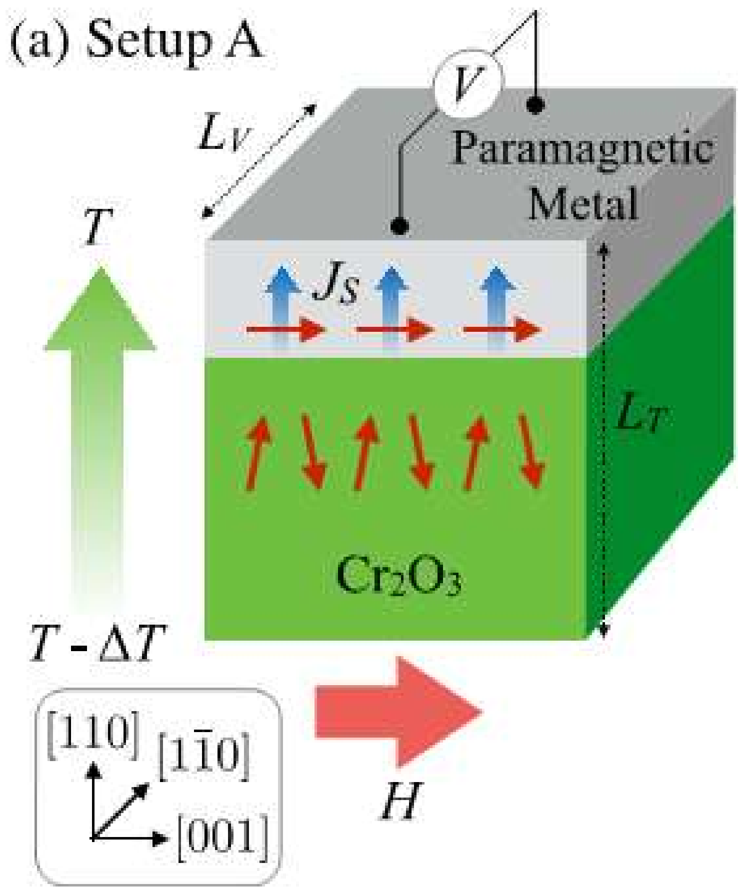
Spin Seebeck effect

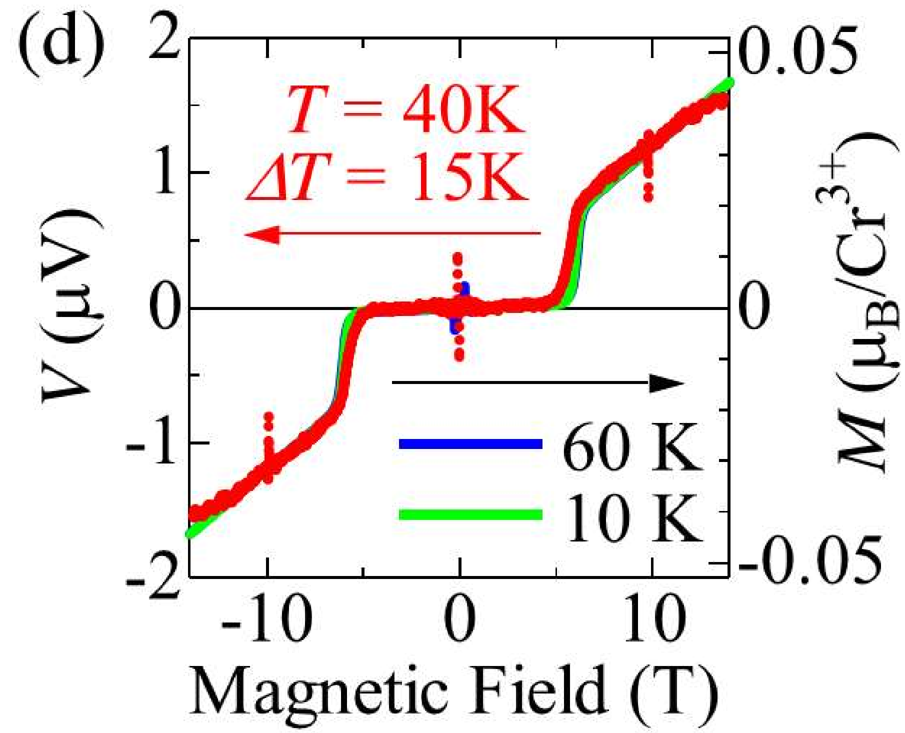


Question:
How about AFM insulator?

YES!

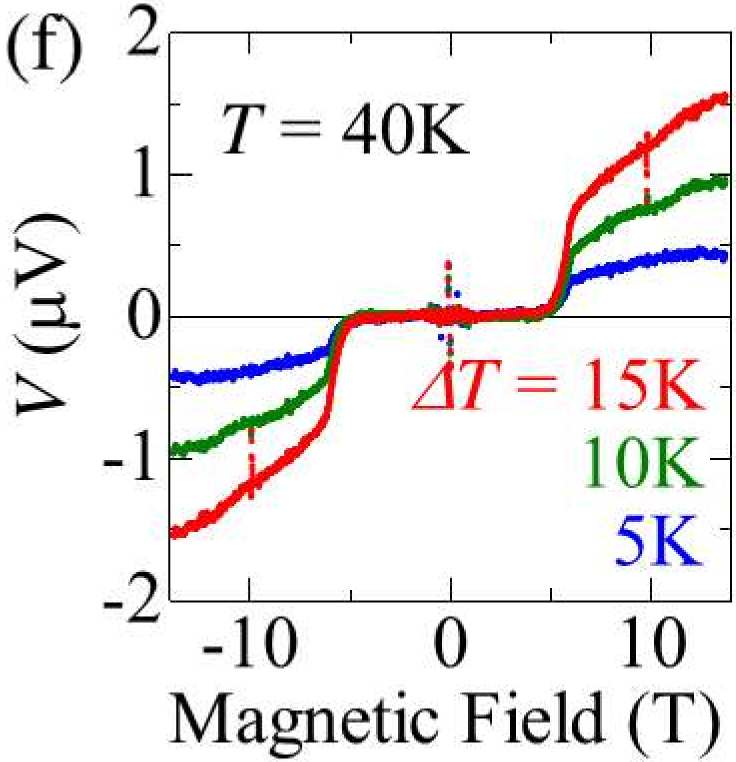
Spin Seebeck effect in AFM

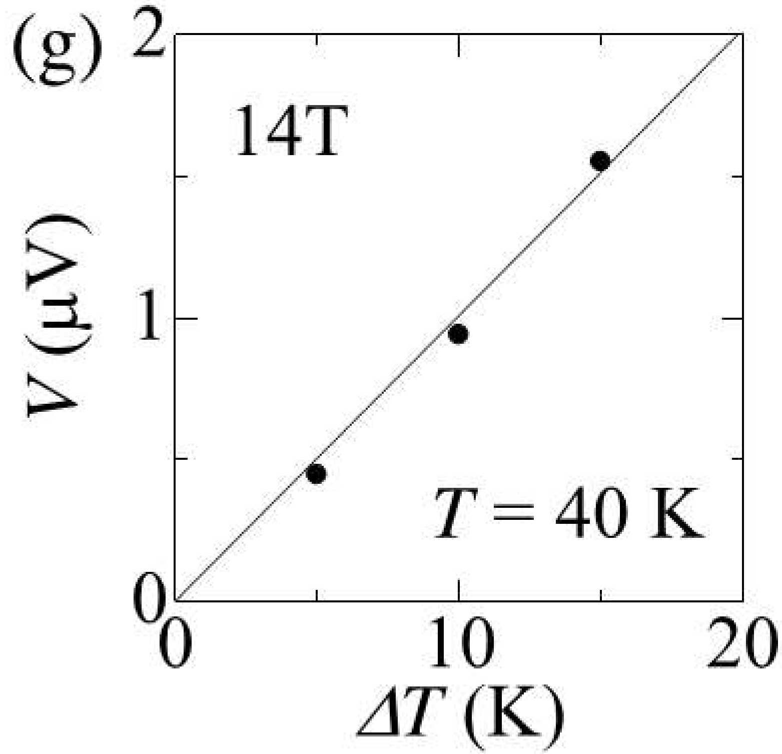




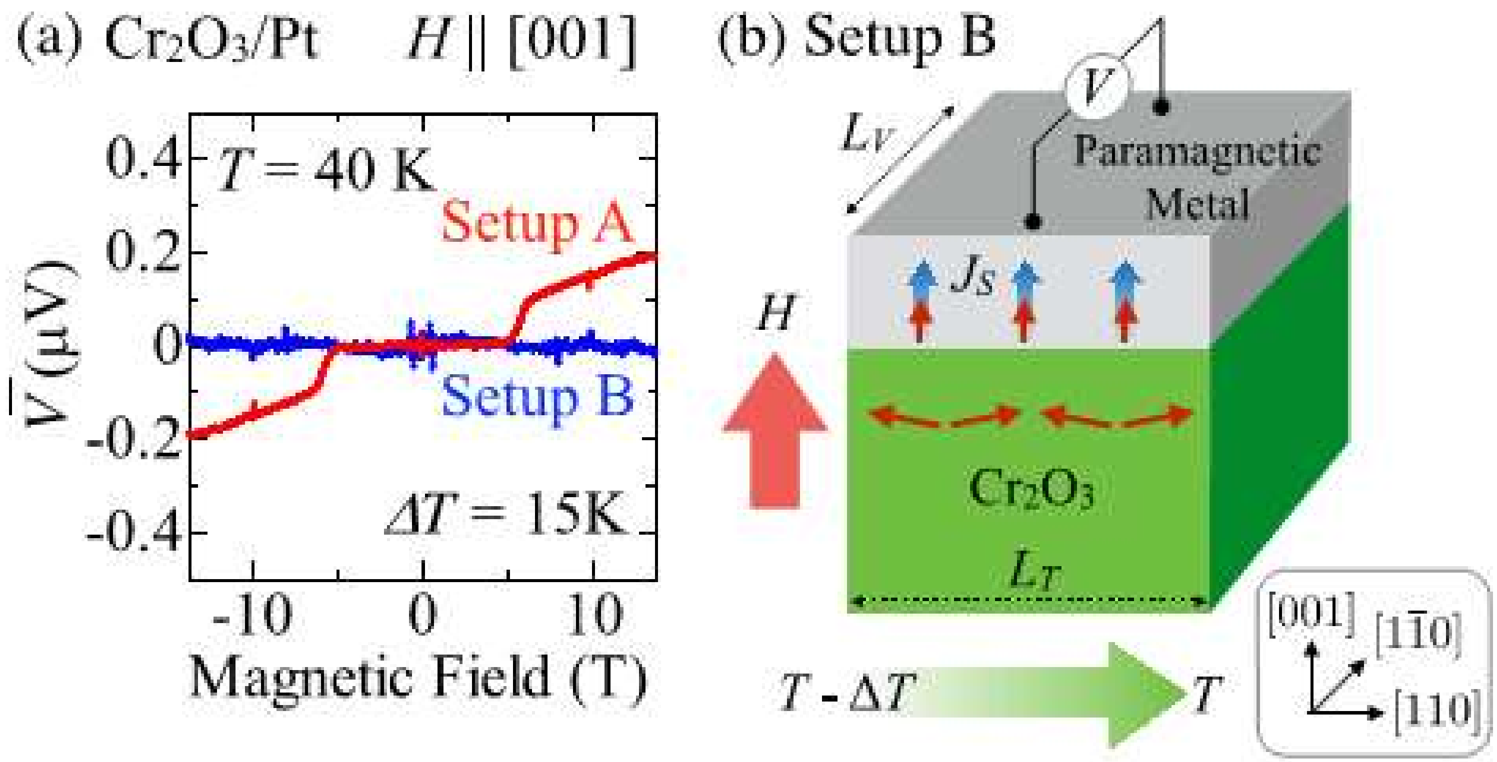
Seki et al, PRL (2015).

Spin Seebeck effect in AFM

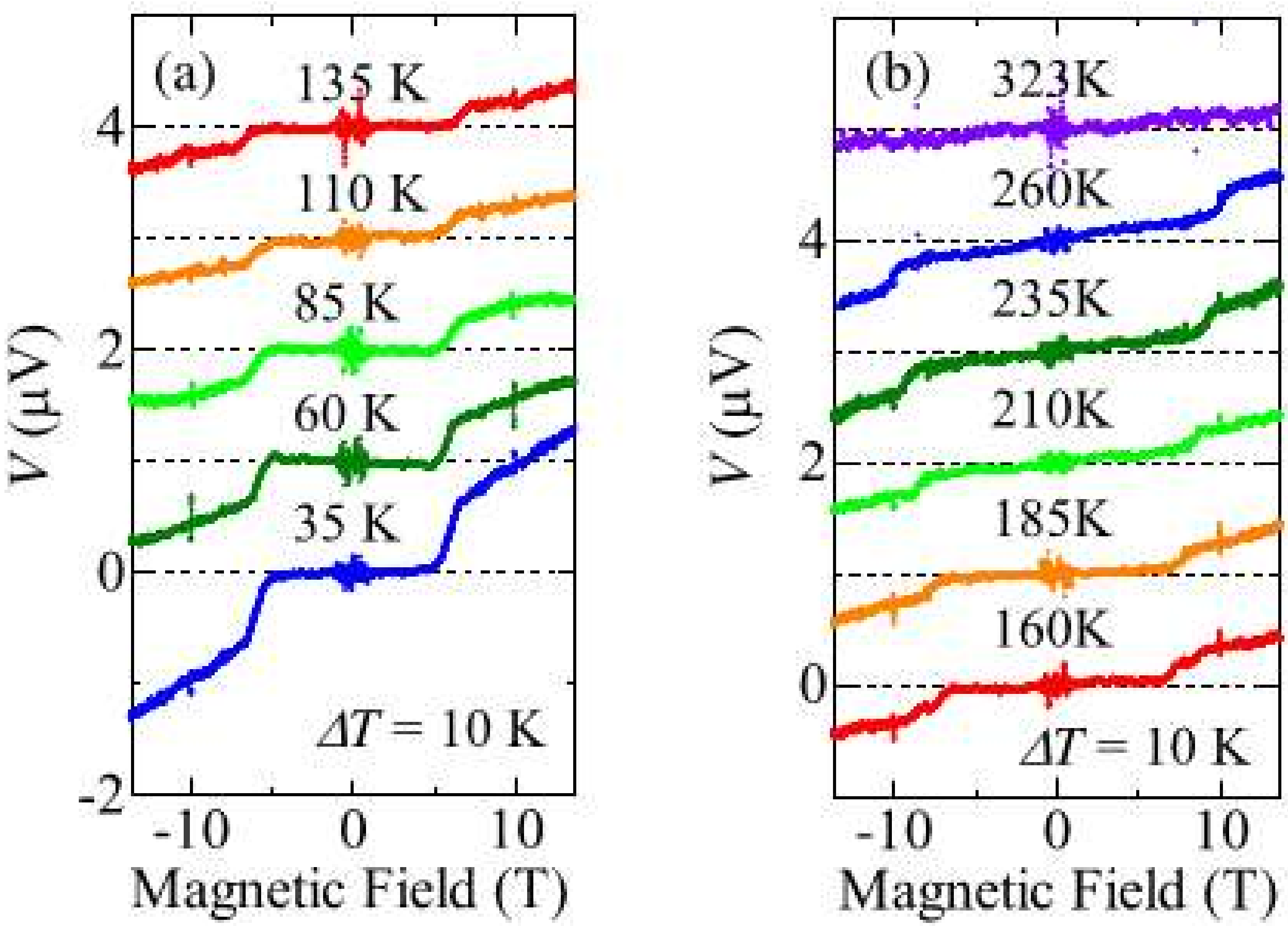




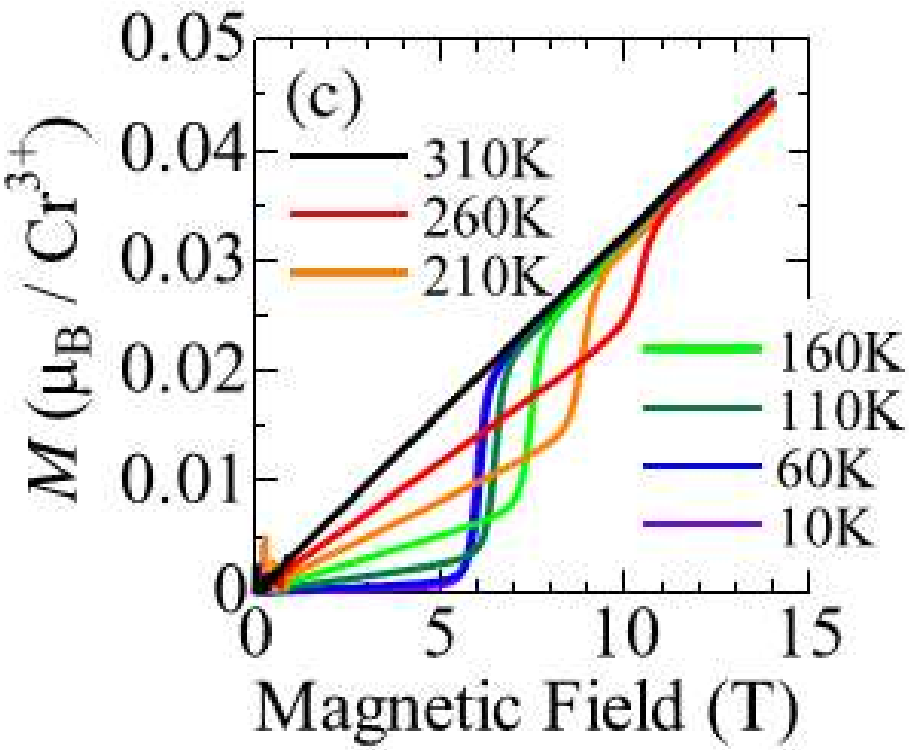
Spin Seebeck effect in AFM

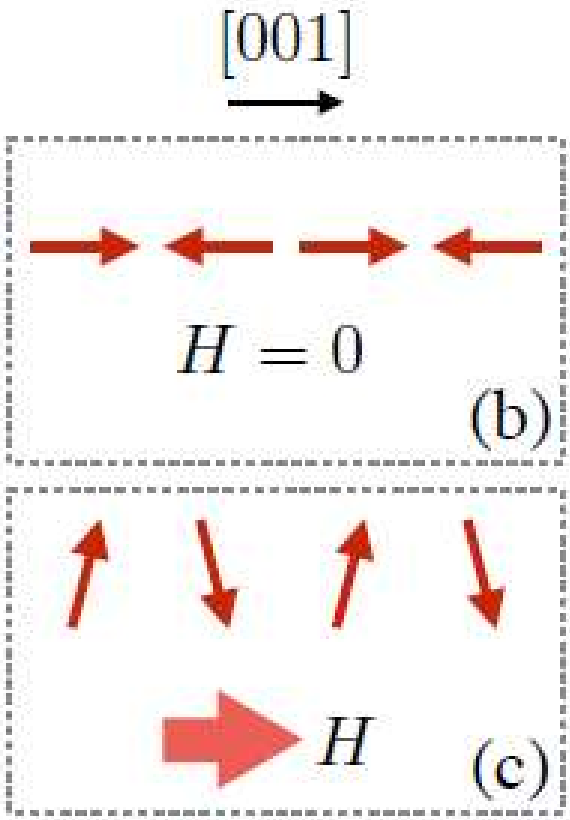


Spin Seebeck effect in AFM

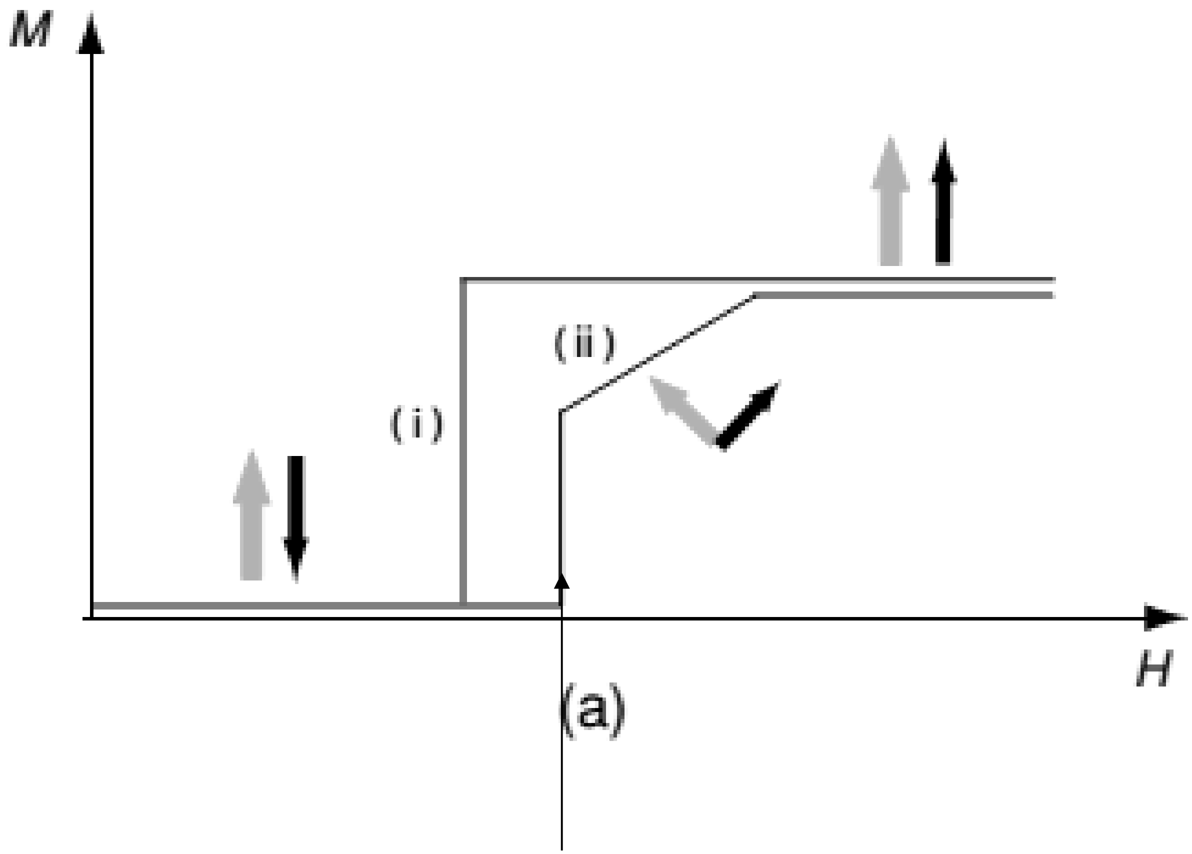


Spin Seebeck effect in AFM



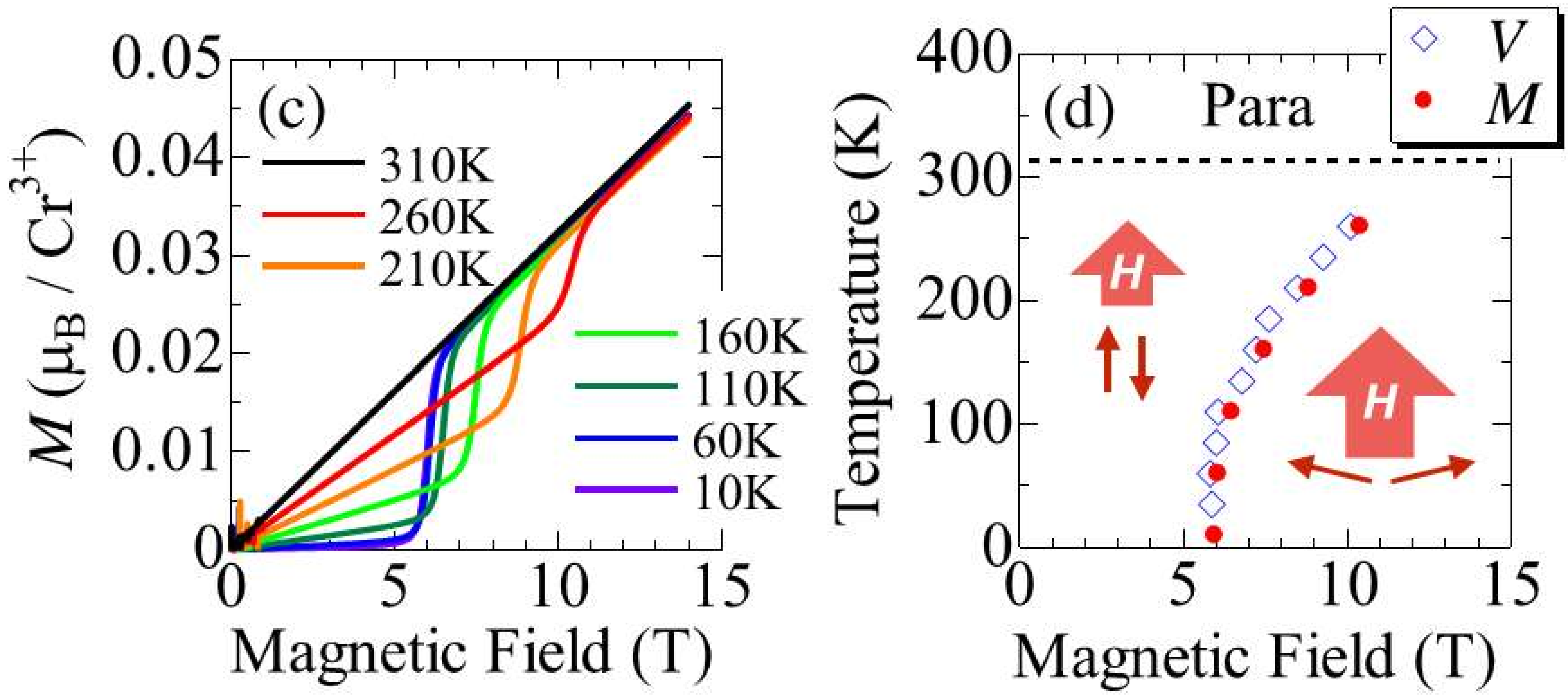


Spin Seebeck effect in AFM

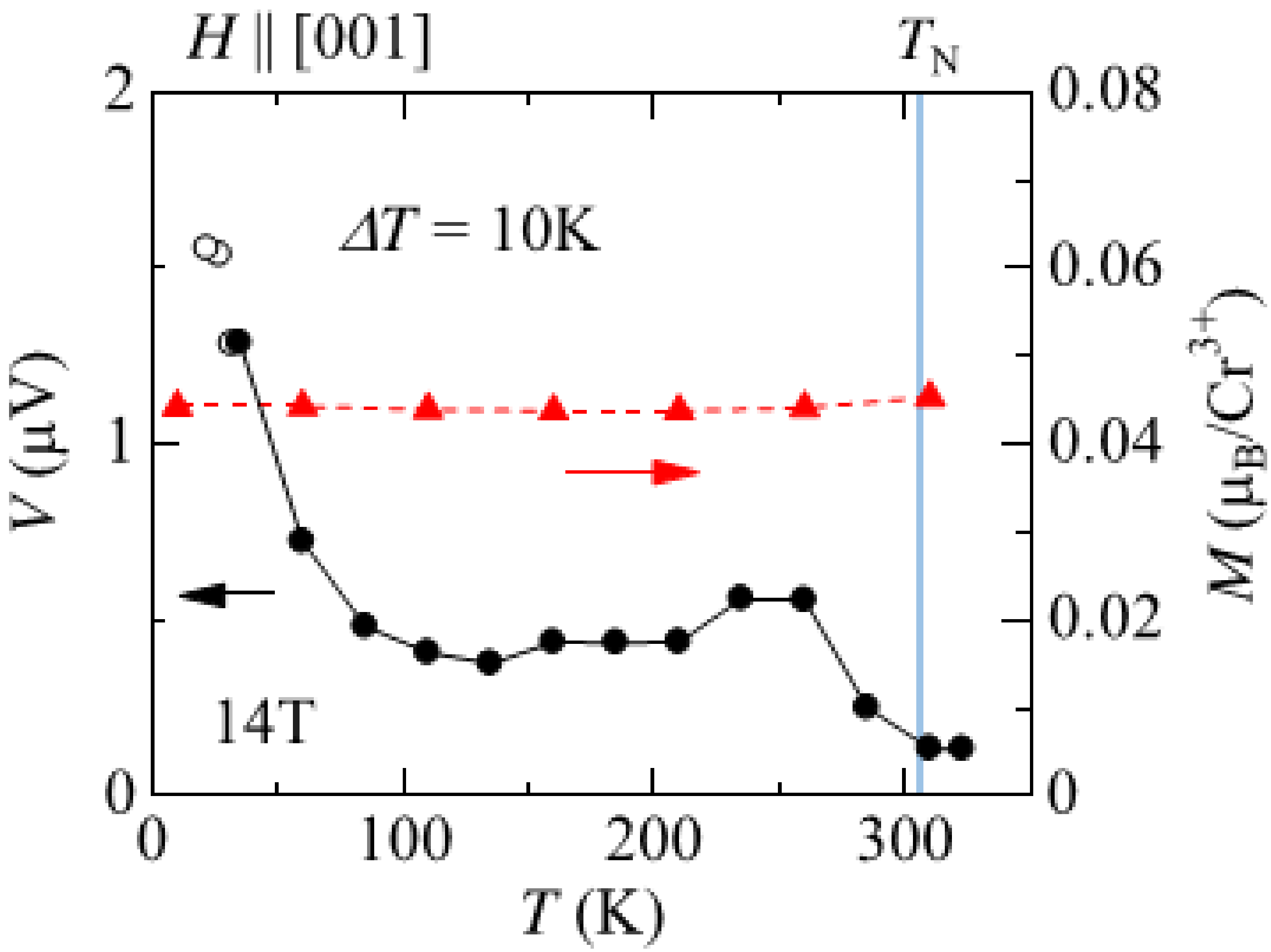


Spin flop field

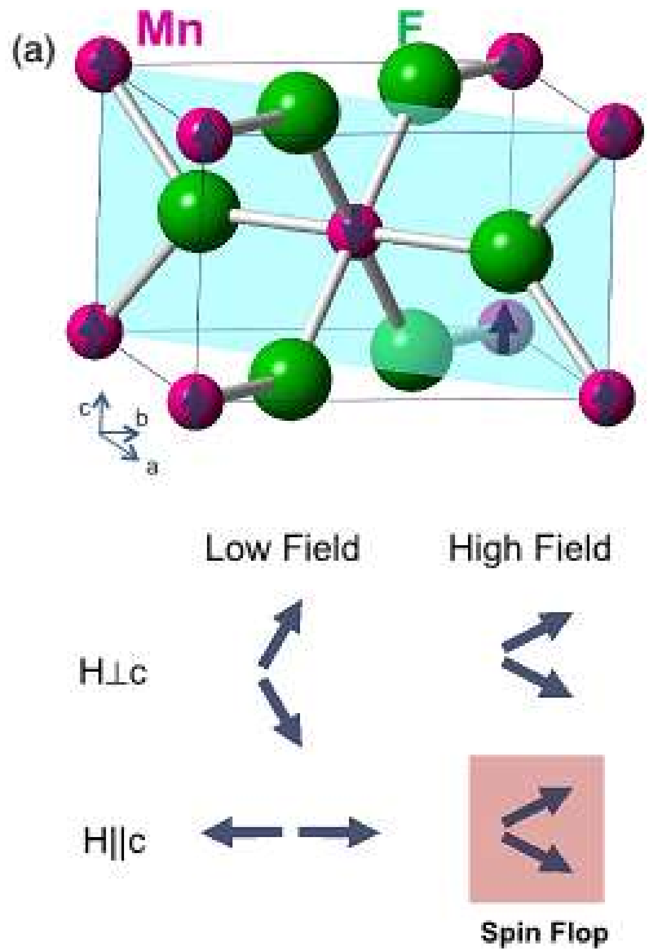
Spin Seebeck effect in AFM

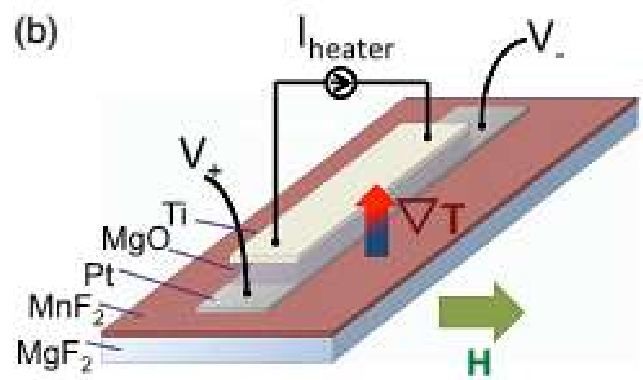


Spin Seebeck effect in AFM



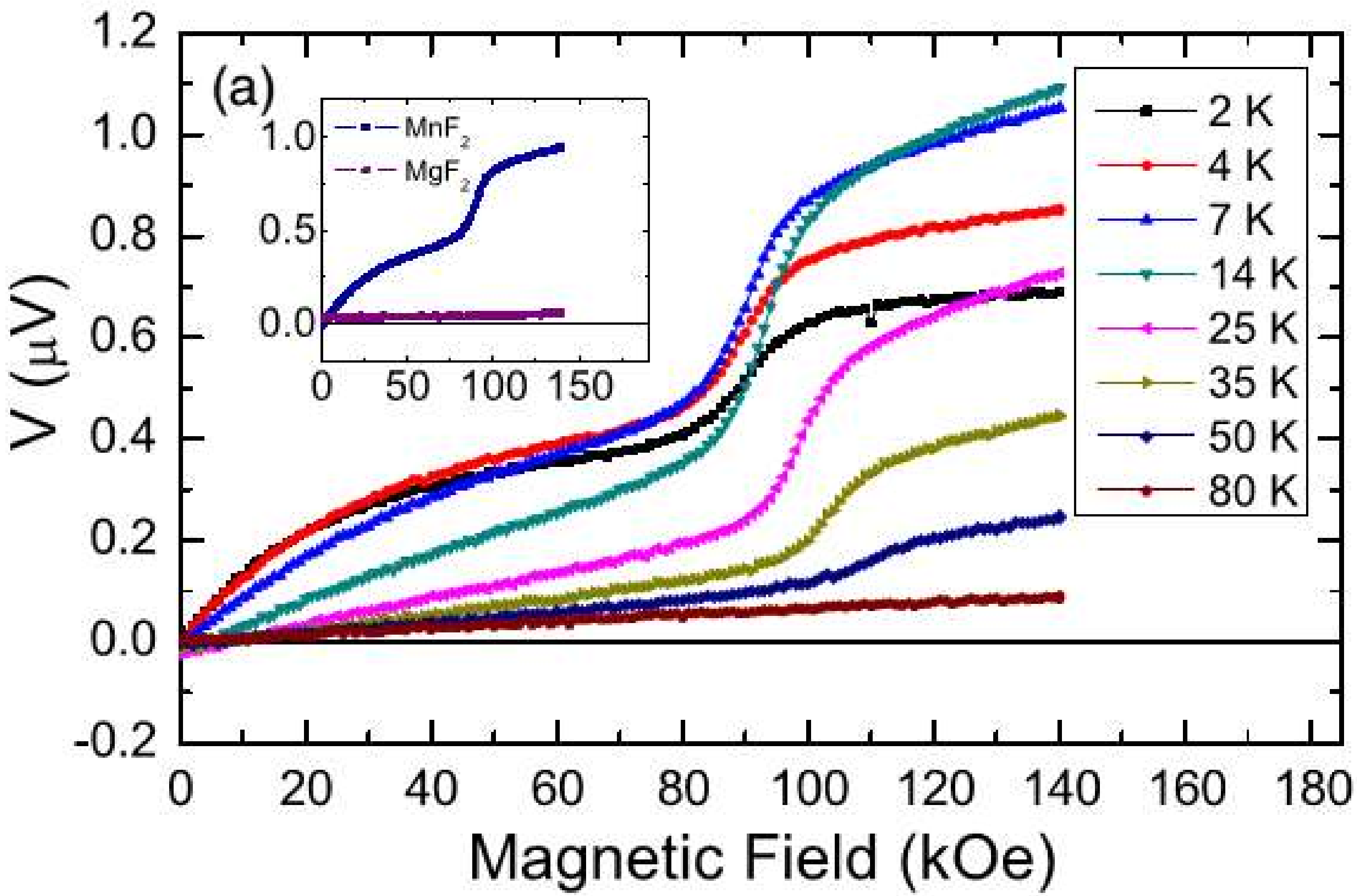
Spin Seebeck effect in AFM



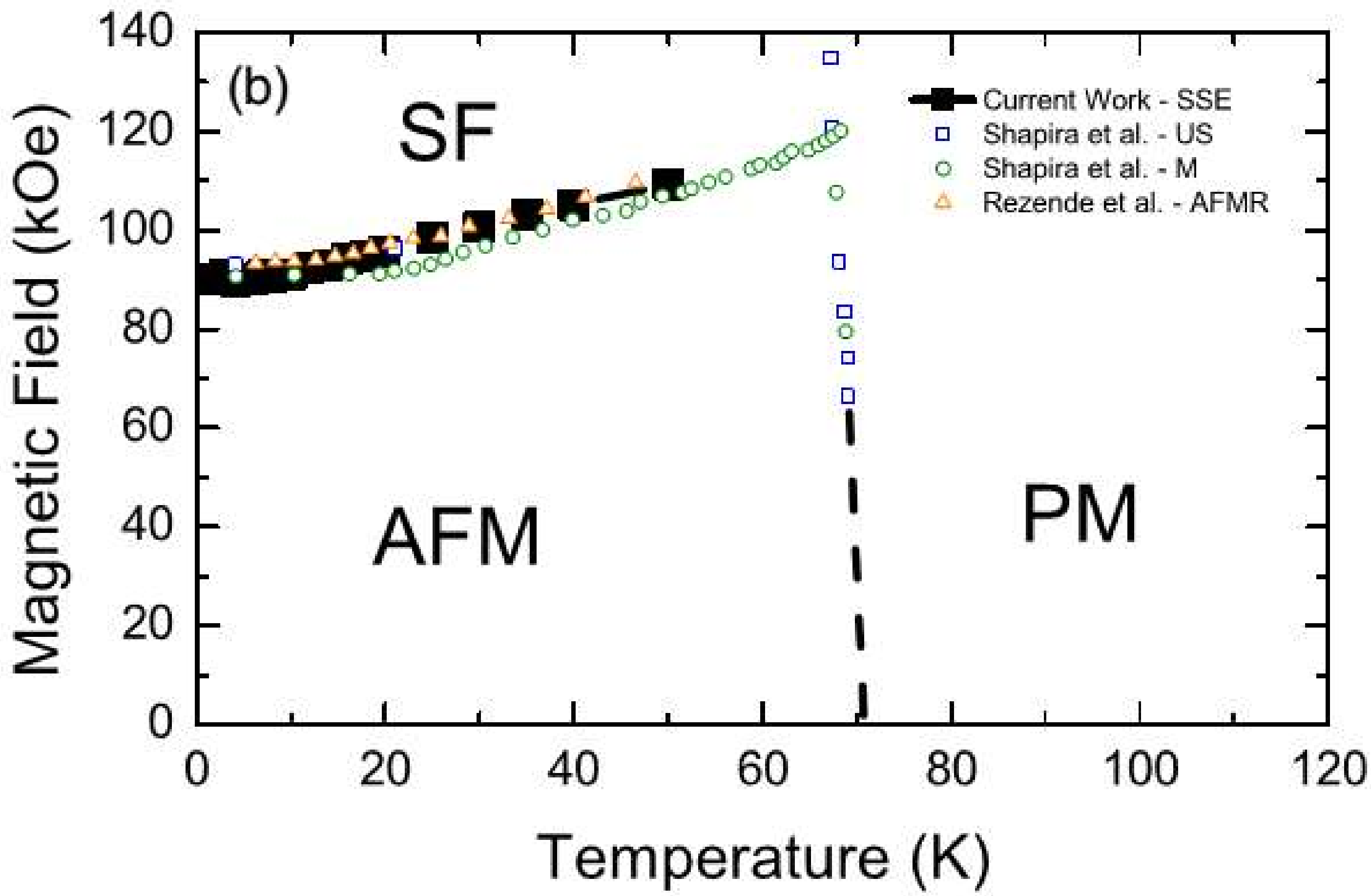


Wu, et al, PRL (2016)

Spin Seebeck effect in AFM



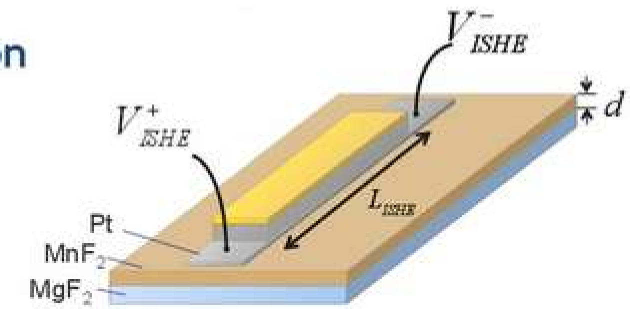
Spin Seebeck effect in AFM

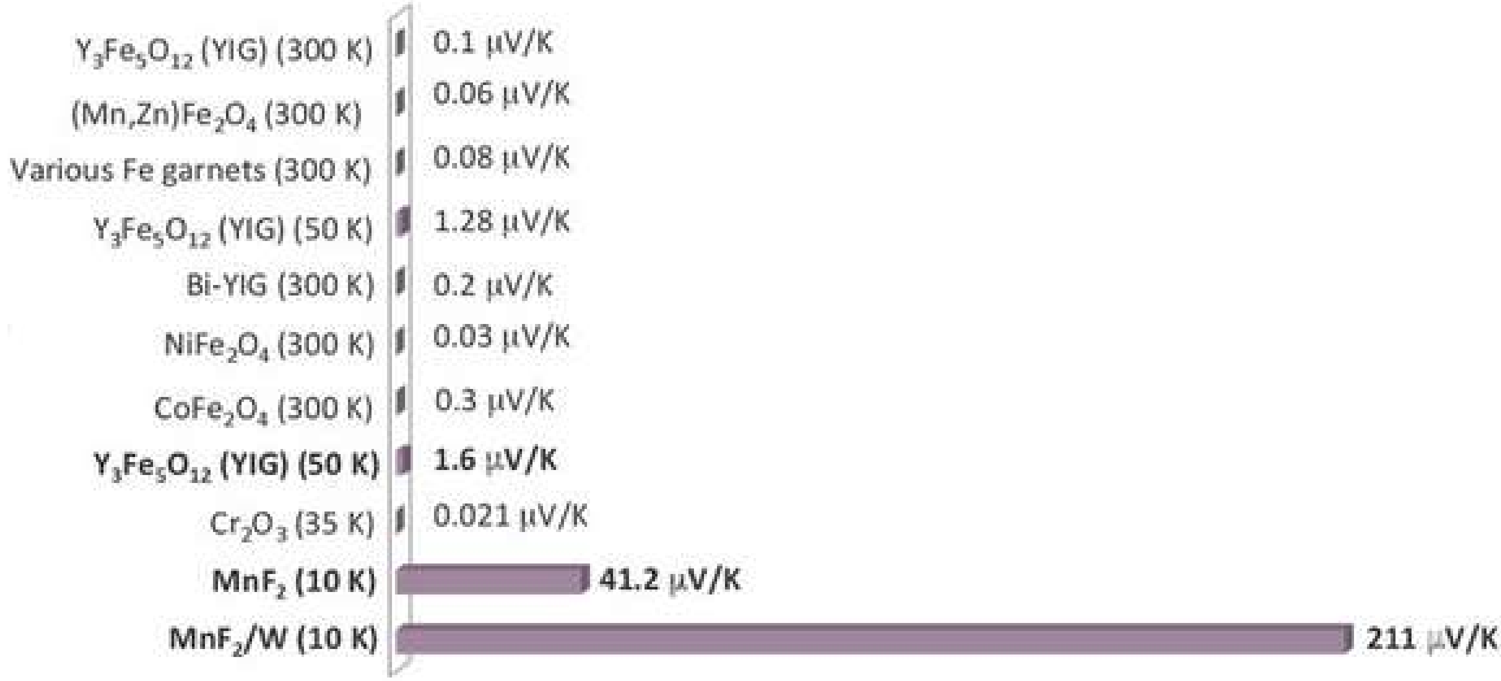


Spin Seebeck effect in AFM

Magnitude comparison

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





1.6 μV/K ⟶ 211 μV/K

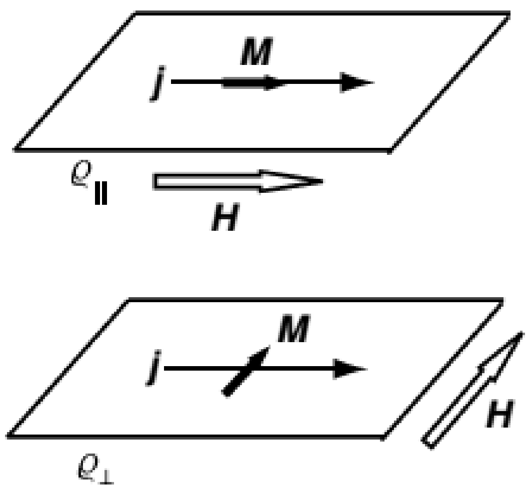
Outline

3. AMR of AFM

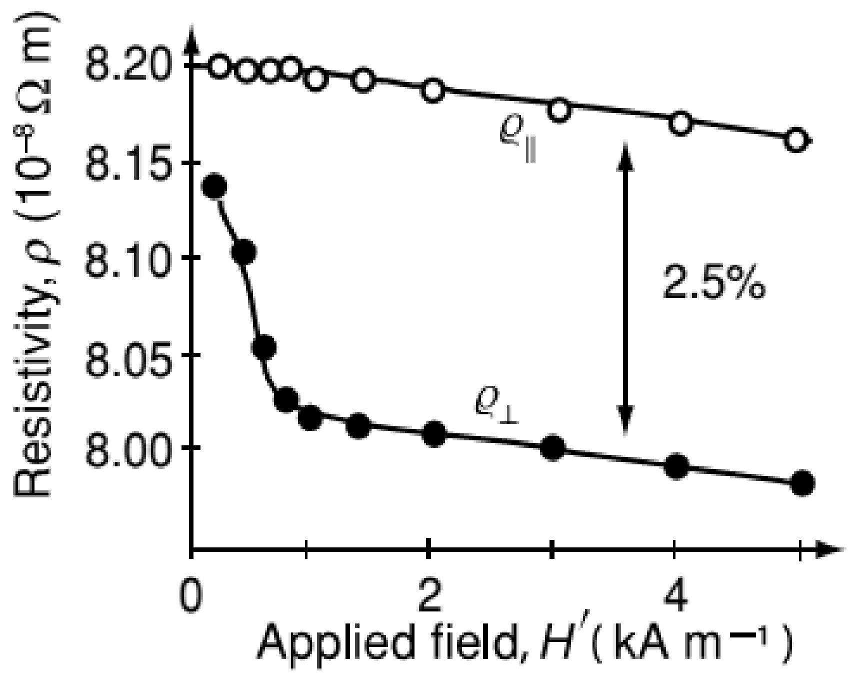
AMR in FM

AMR of a Nickel

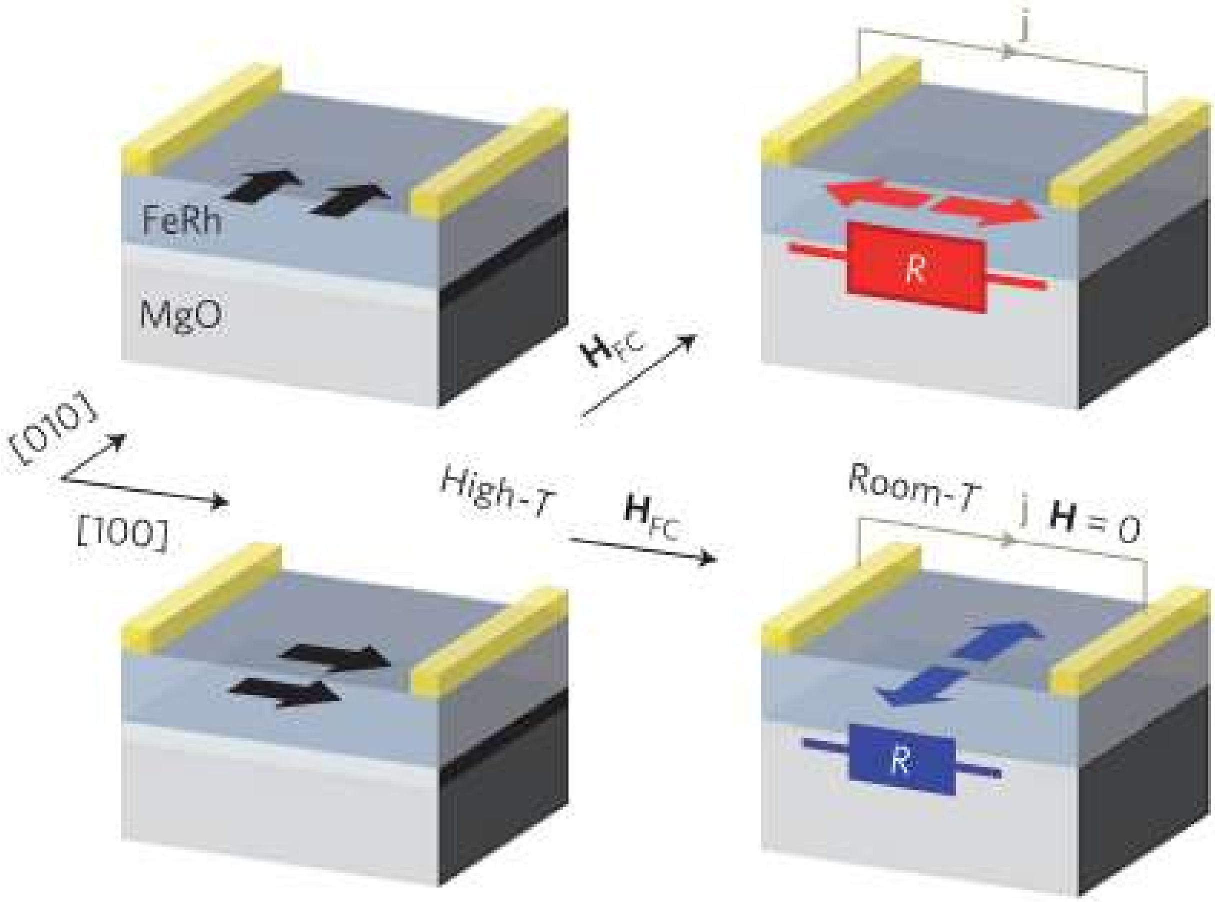
Discovered by William Thompson (1857)



Measurement of AMR for a thin film.

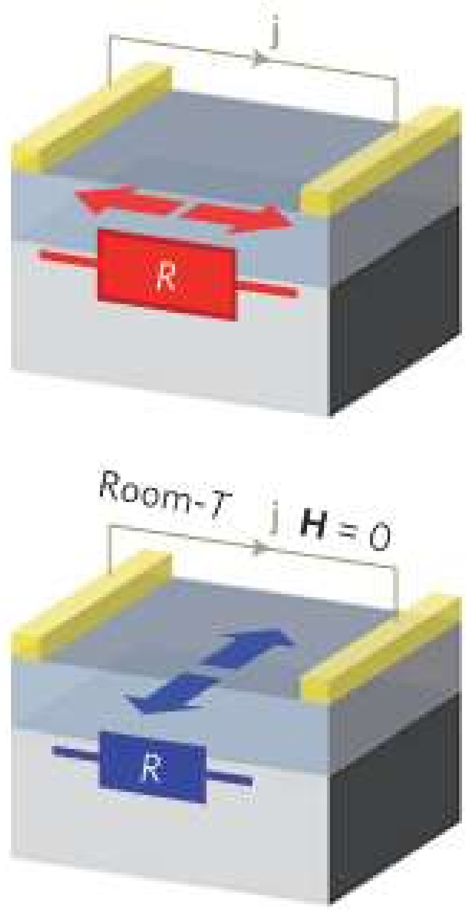


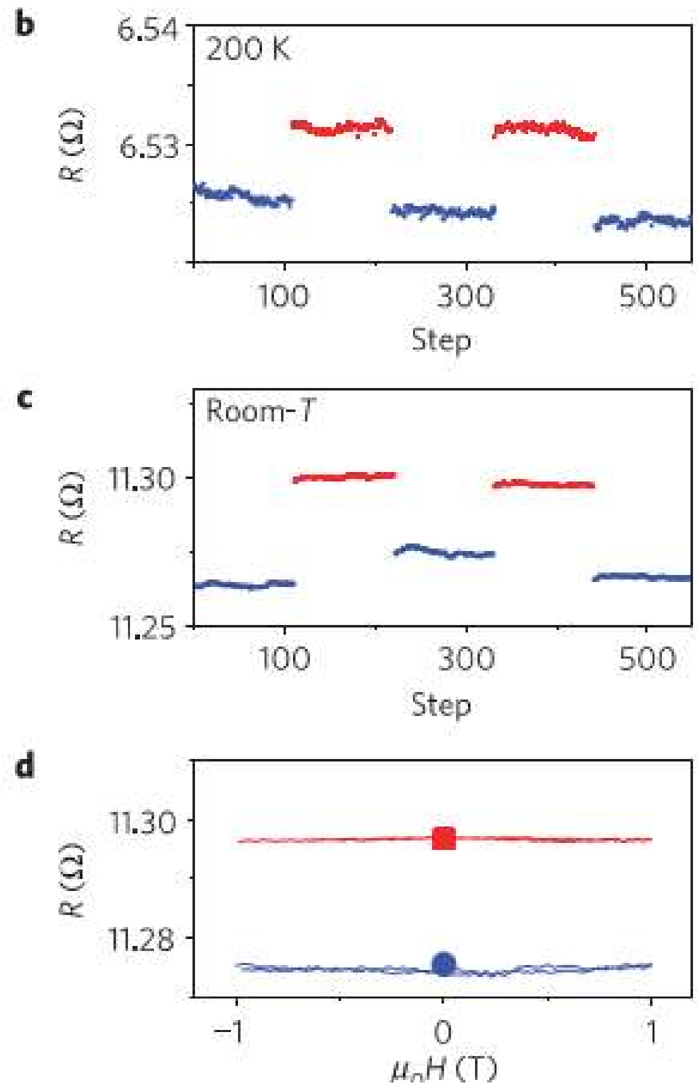
AMR in AFM



Marti, et al, Nature Materials (2014)

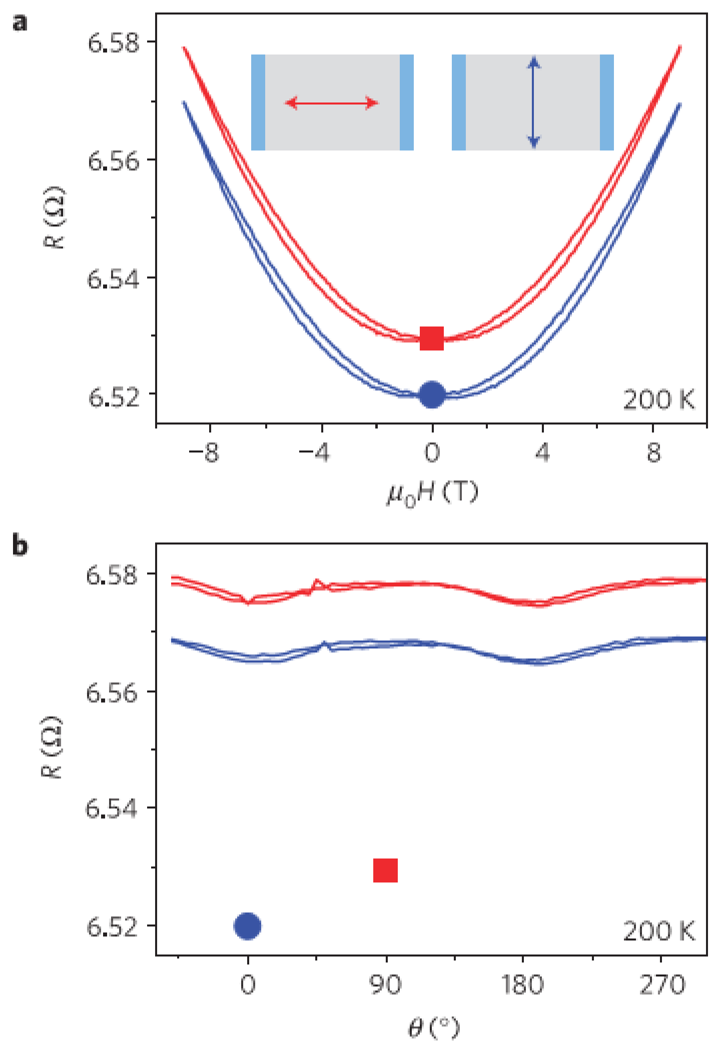
AMR in AFM


j
R
Room-T
j
H = 0
R

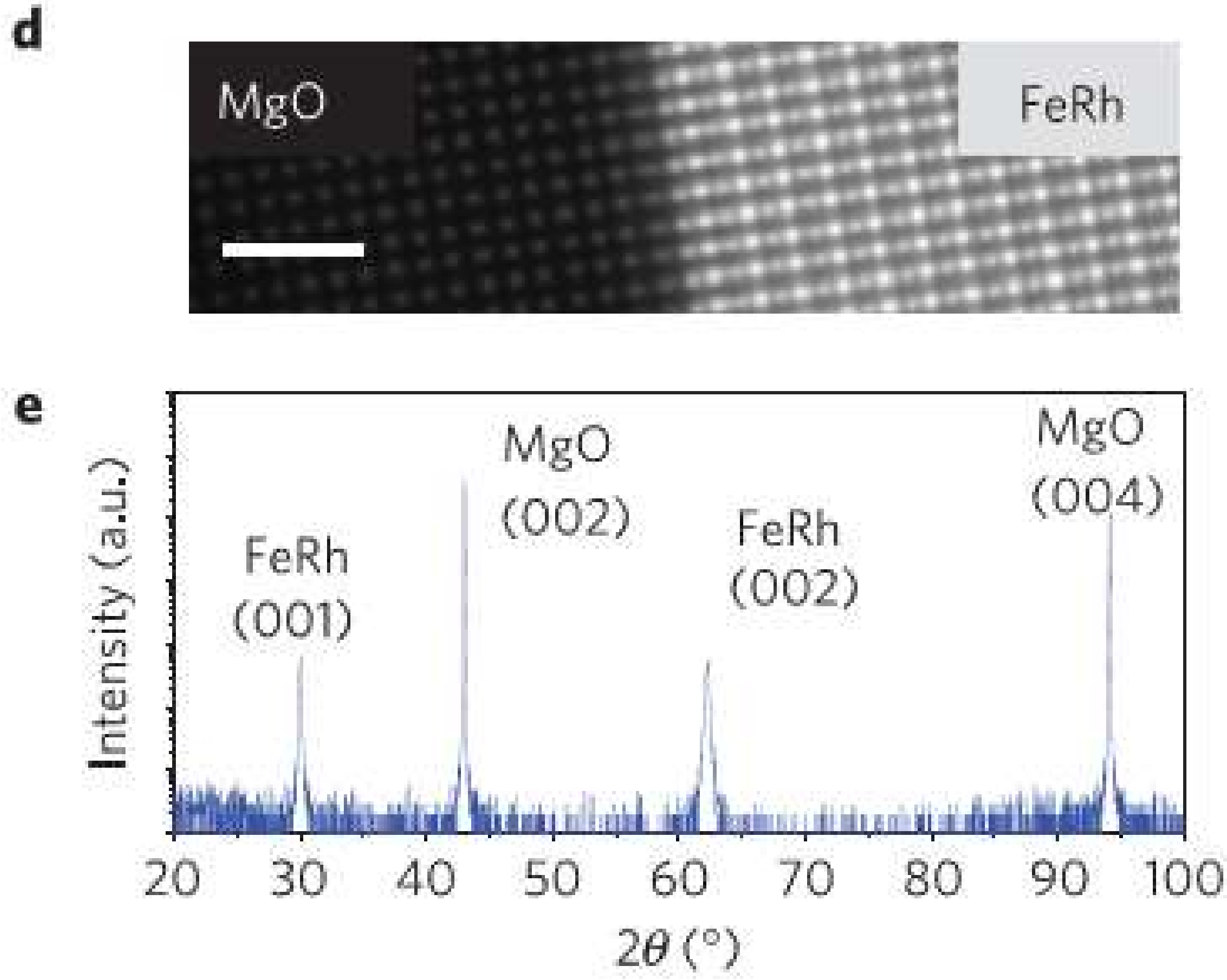

b
6.54
6.53
R (Ω)
200 K
100
300
500
Step
c
Room-T
11.30
11.25
R (Ω)
100
300
500
Step
d
11.30
11.28
R (Ω)
−1
0
1
μ0H (T)

AMR in AFM

Advantage: Signal robust in magnetic field

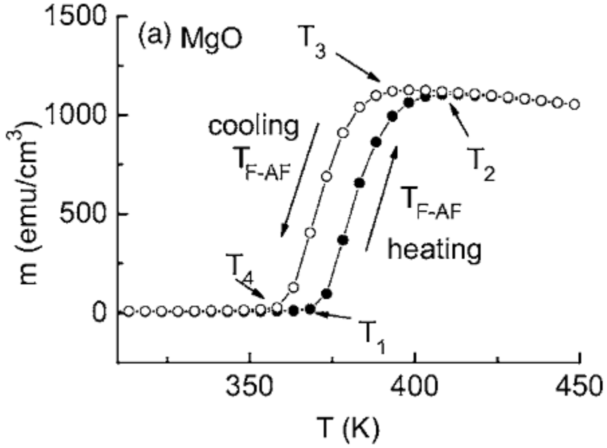


AMR in AFM

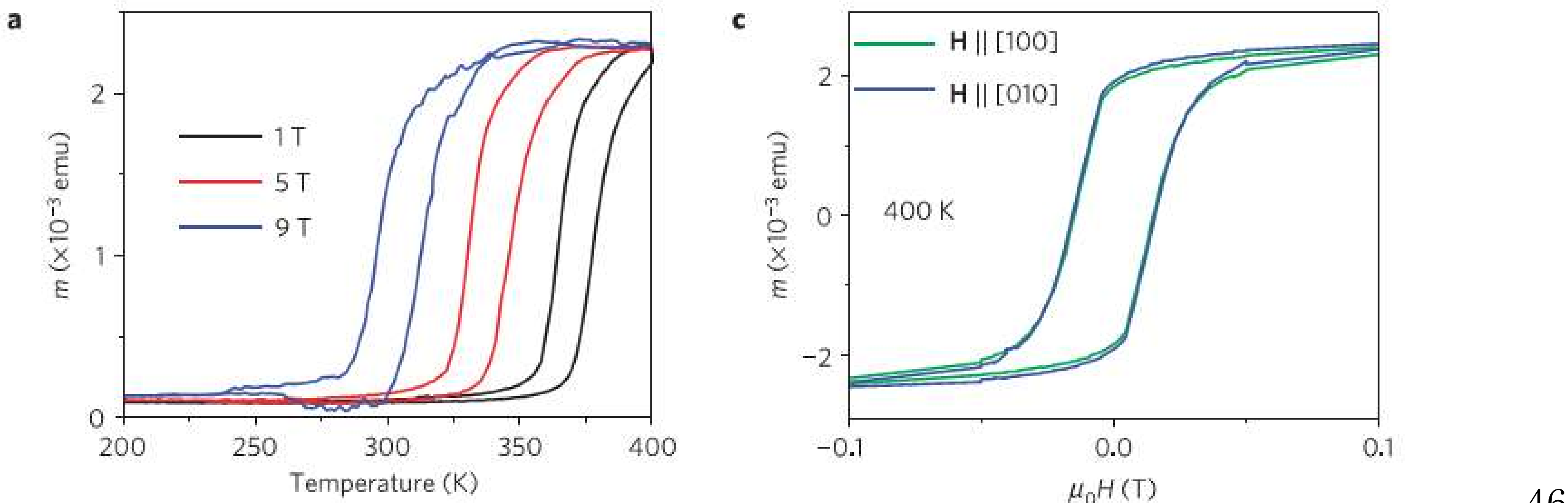


d
MgO
FeRh
e
Intensity (a.u.)
FeRh (001)
MgO (002)
FeRh (002)
MgO (004)
20 30 40 50 60 70 80 90 100
2θ (°)

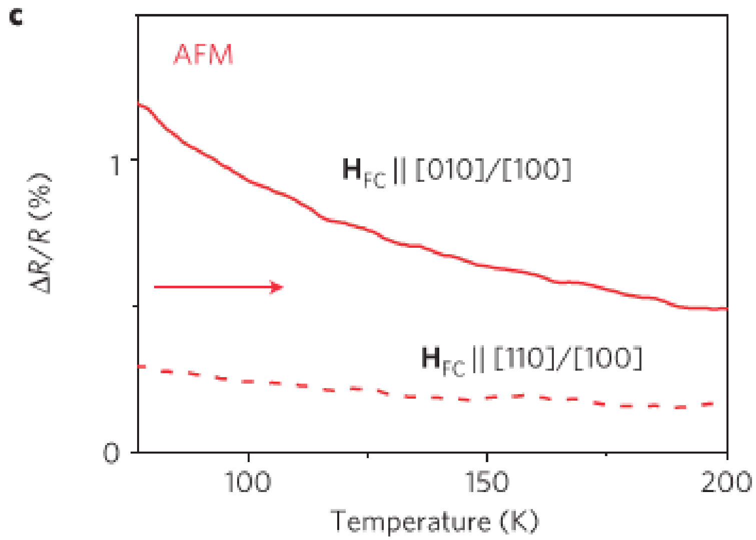
AMR in AFM



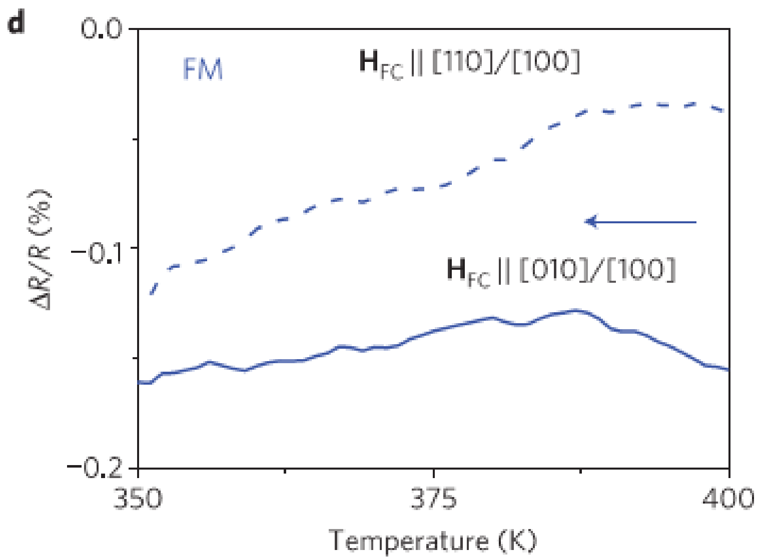
Maat, et al, PRB (2006)



AMR in AFM



Larger AMR in the AFM state

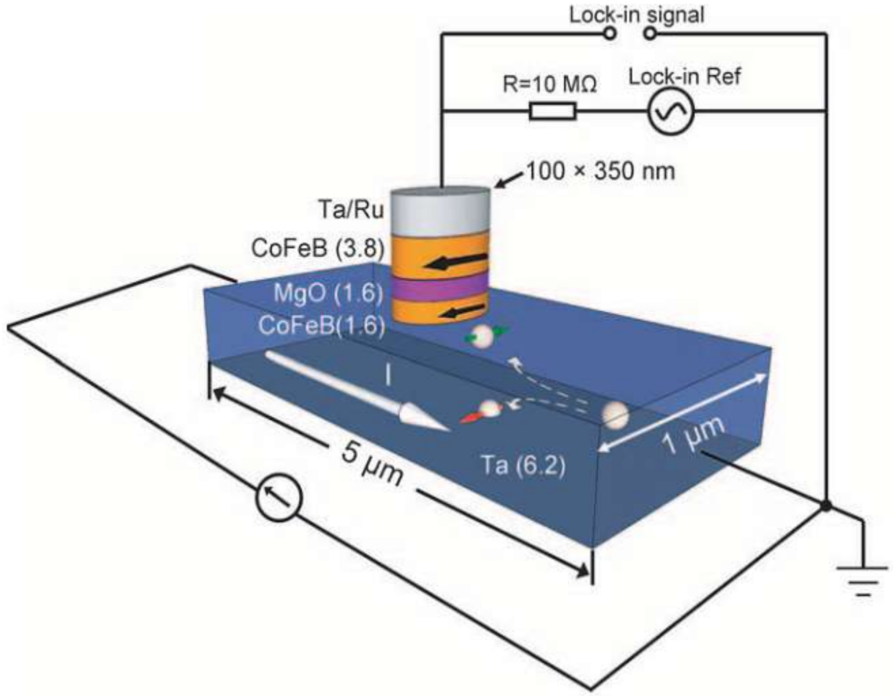


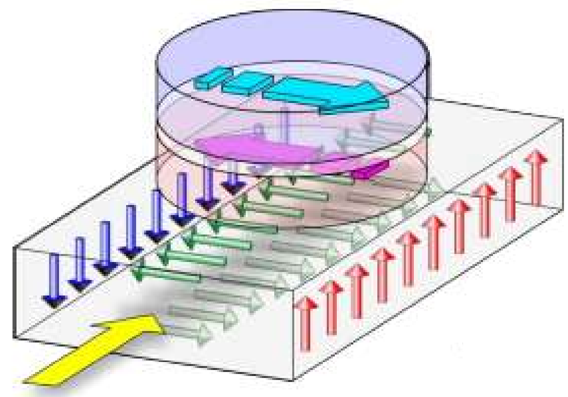
Smaller AMR in the FM state

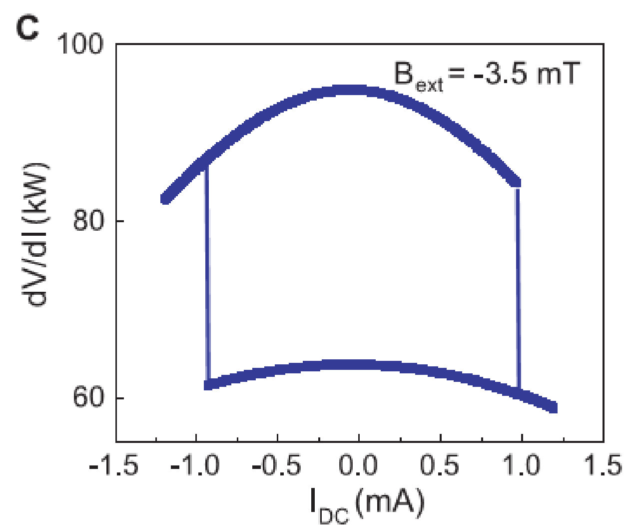
休息10分钟

4. Switching of AFM

Switching of FM by spin torque

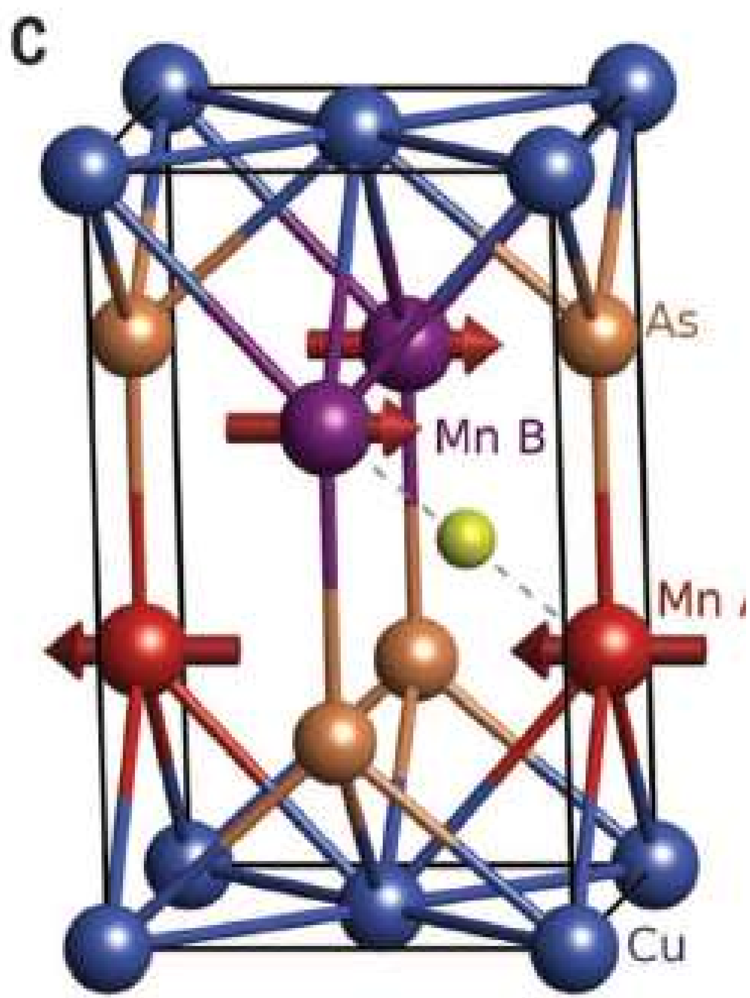


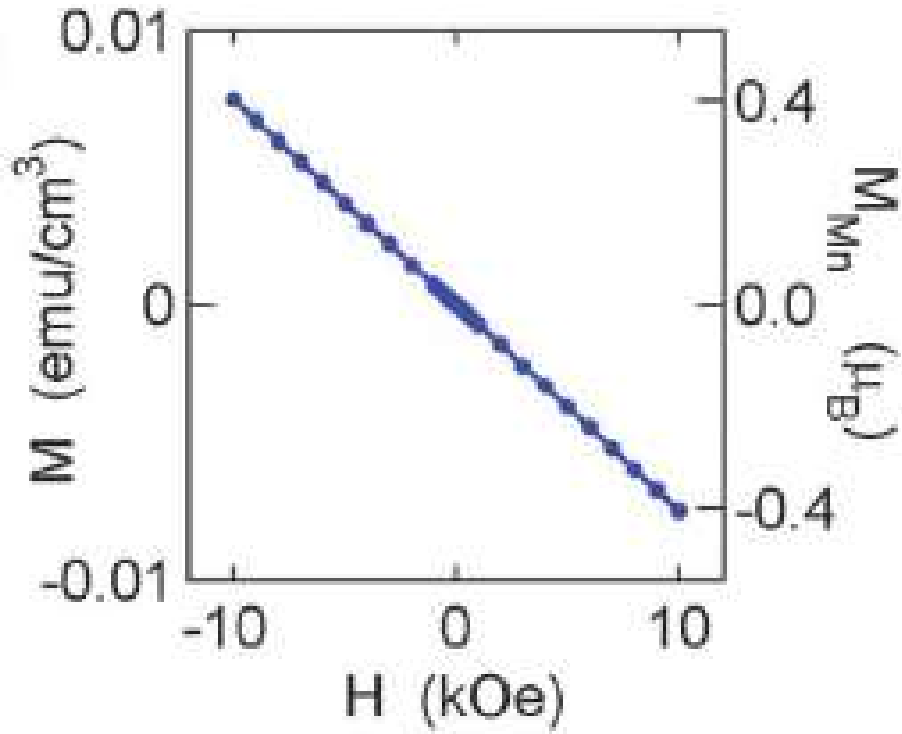




Liu, et al., Science (2012)

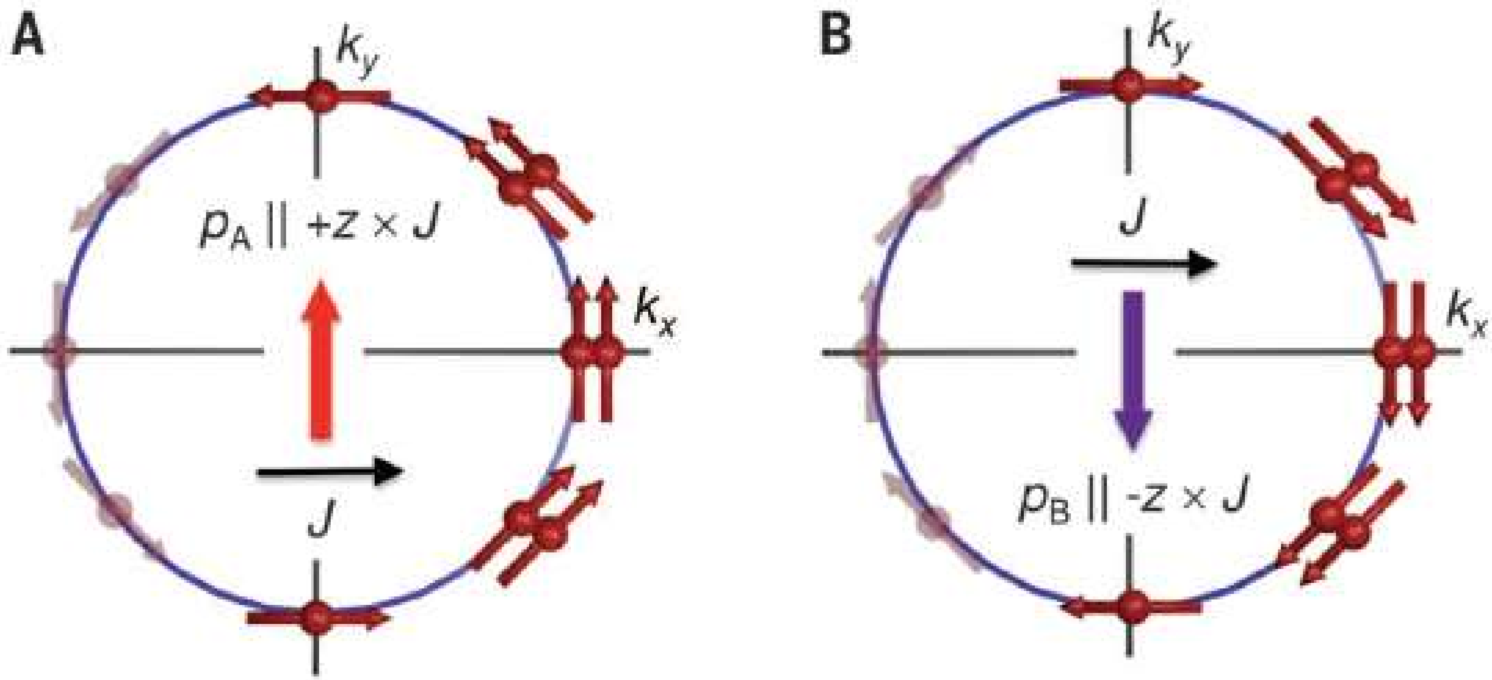
Switching of AFM





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

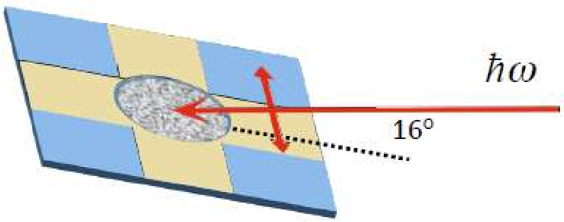
Switching of AFM

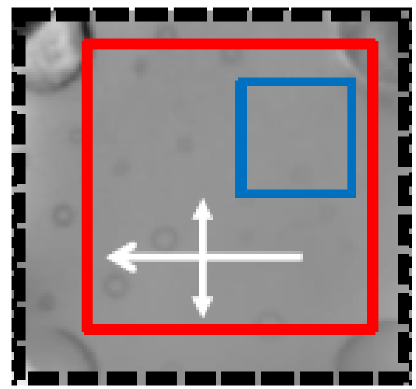


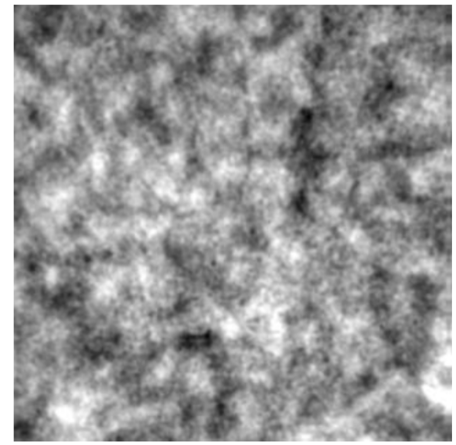
Inverse spin-galvanic effect

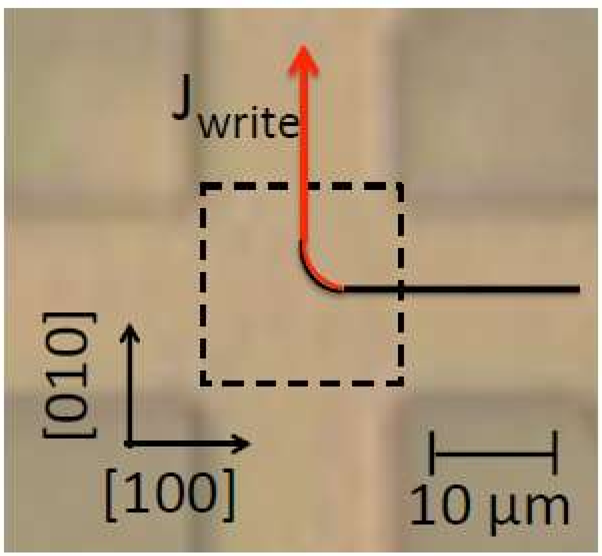
Switching of AFM

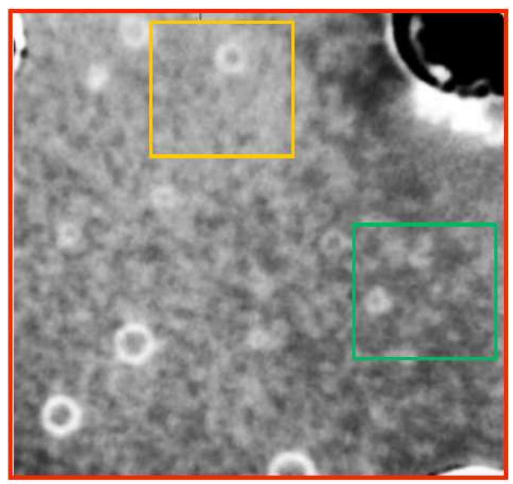
Before writing pulses

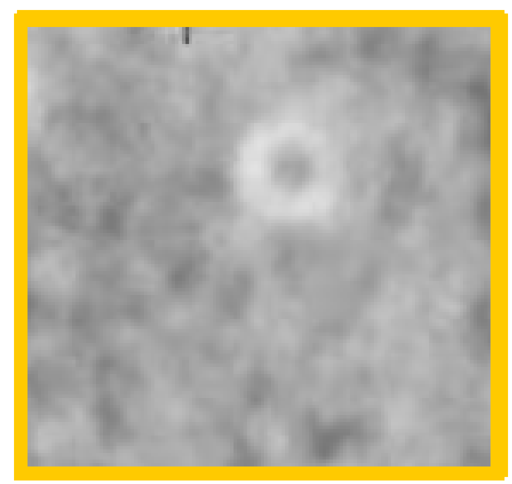






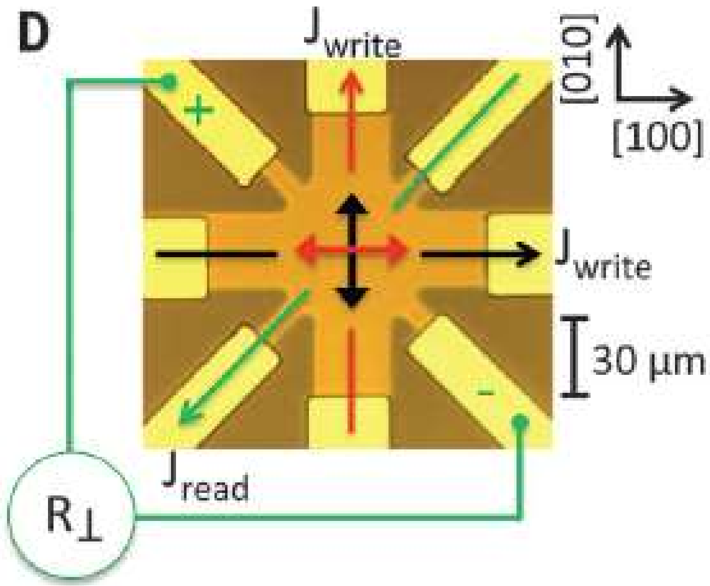




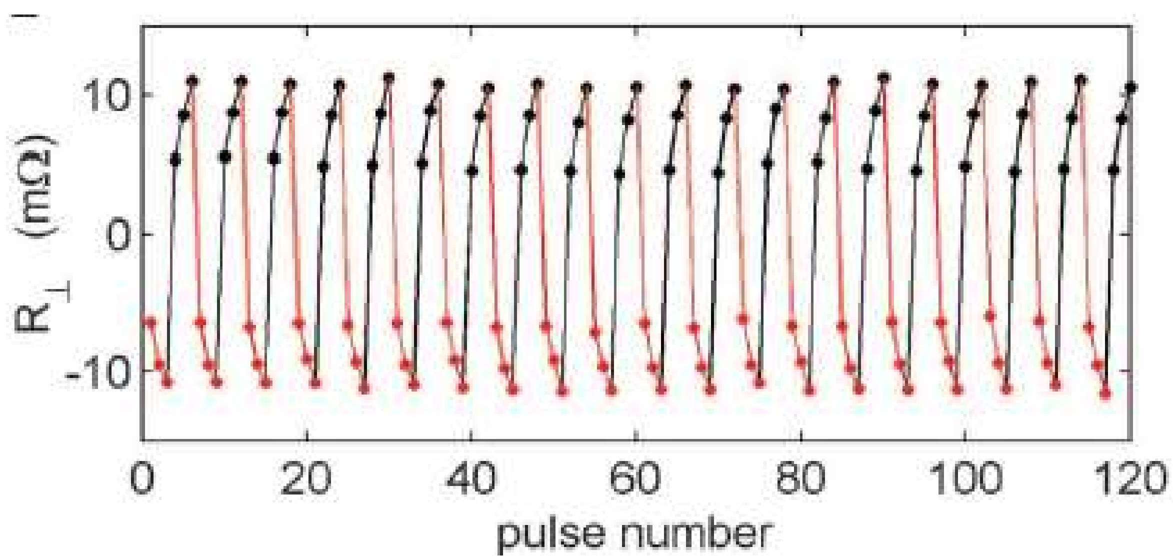


After writing pulses

Switching of AFM

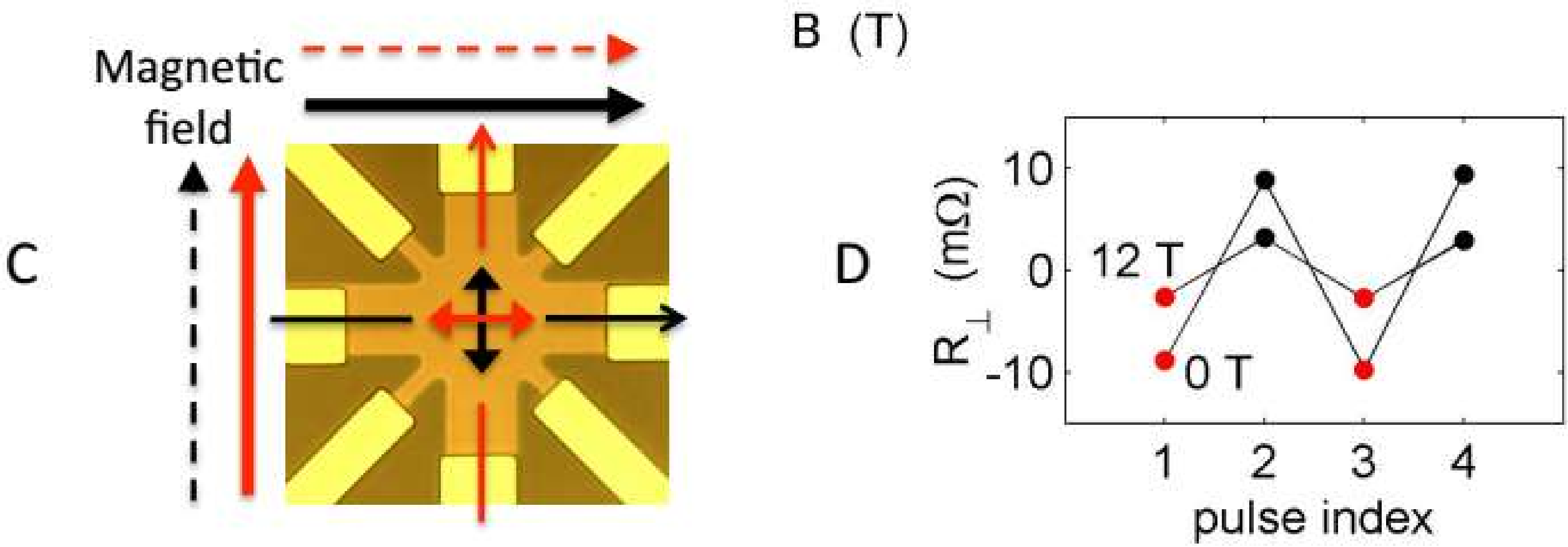


Writing current: during time=50ms, amplitude=$4*10^{-6}$Acm^{-2}.



Switching of AFM

Advantage: Signal robust in magnetic field



Outline

5. Anomalous Hall effect in AFM

AHE in FM

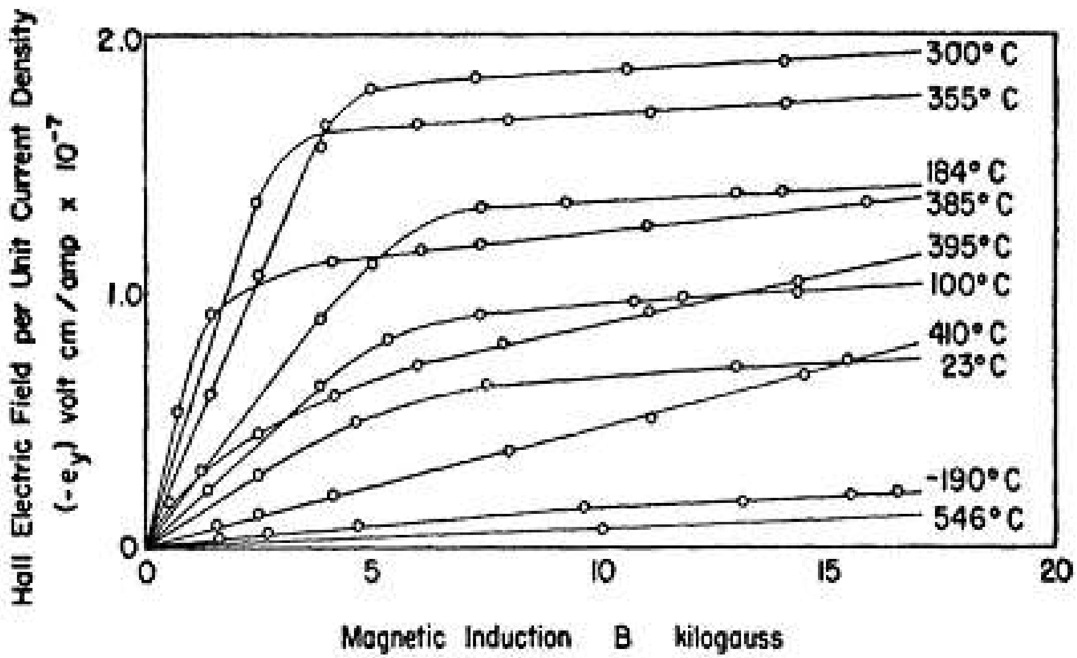


FIG. 1. The Hall effect in Ni (data from Smith, 1910). From Pugh and Rostoker, 1953.

and Lippert (1932) established that an empirical relation between ρ_{xy}, H_z, and M_z,

$$\rho_{xy} = R_0 H_z + R_s M_z, \qquad (1.1)$$

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
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(Received 3 October 2013; published 10 January 2014)

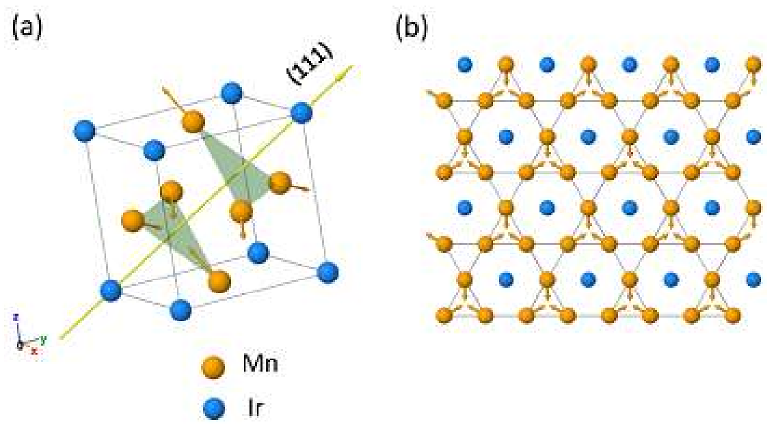


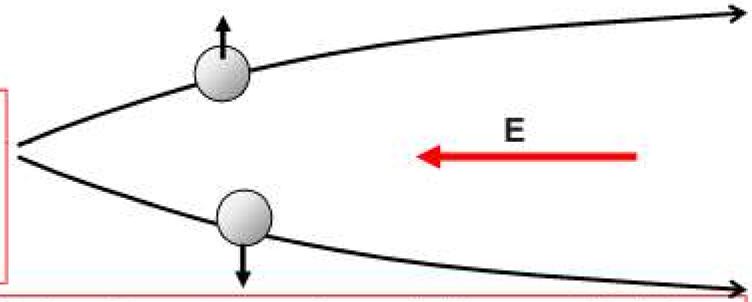
FIG. 1 (color online). Structure of Mn_3Ir. (a) Unit cell of Mn_3Ir with triangular antiferromagnetic order. (b) An individual (111) plane of Mn_3Ir. The Mn atoms form a kagome lattice.

- **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.

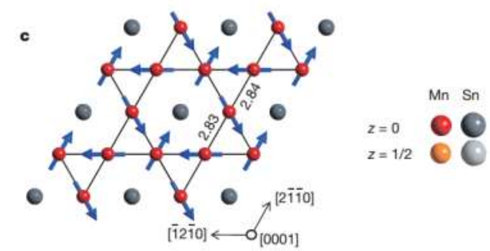


$$\frac{d\langle\vec{r}\rangle}{dt} = \frac{\partial E}{\hbar\partial\vec{k}} + \frac{e}{\hbar}E\times b_n$$

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

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

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



Non-collinear antiferromagnetic structure

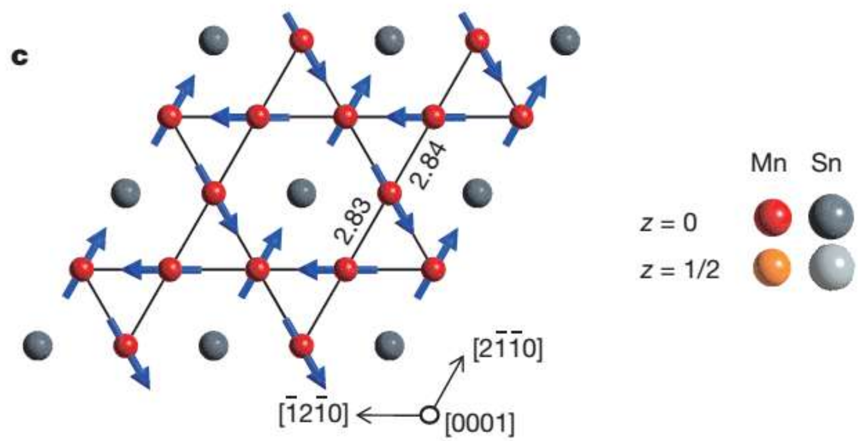
AHE in AFM

LETTER

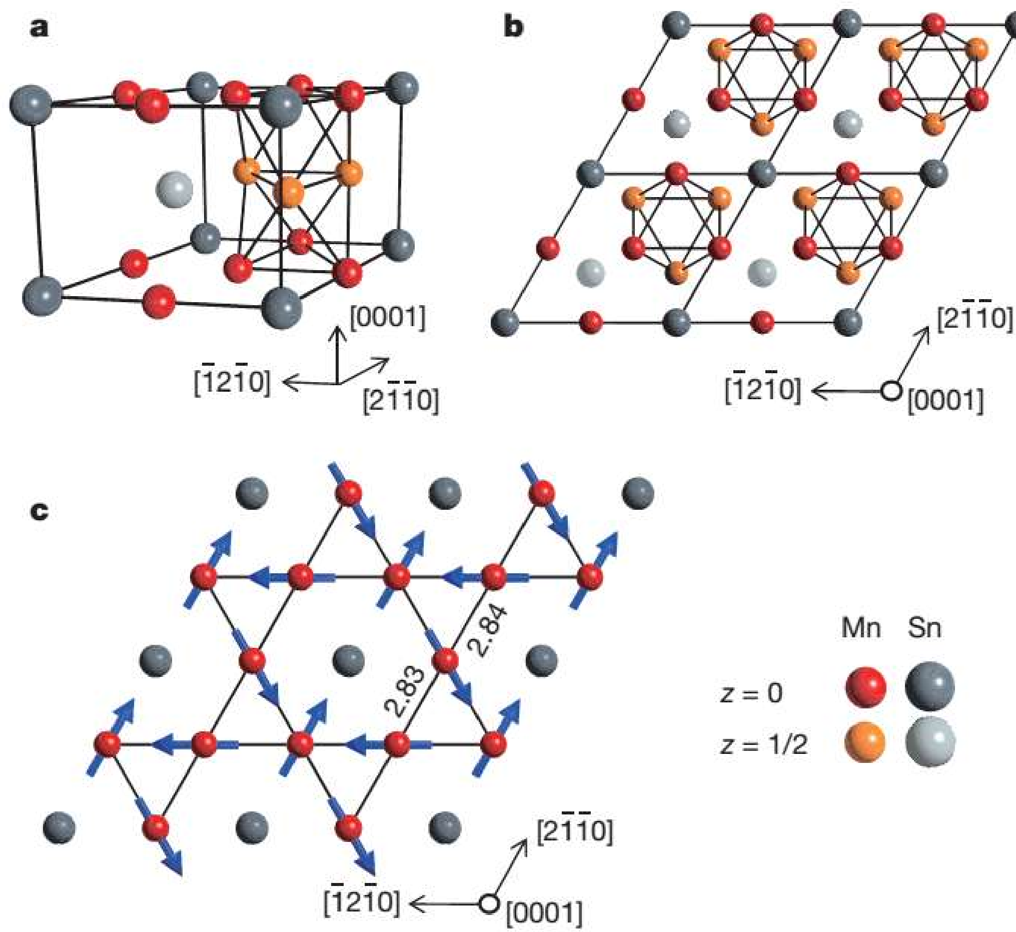
doi:10.1038/nature15723

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

Satoru Nakatsuji[1,2], Naoki Kiyohara[1] & Tomoya Higo[1]



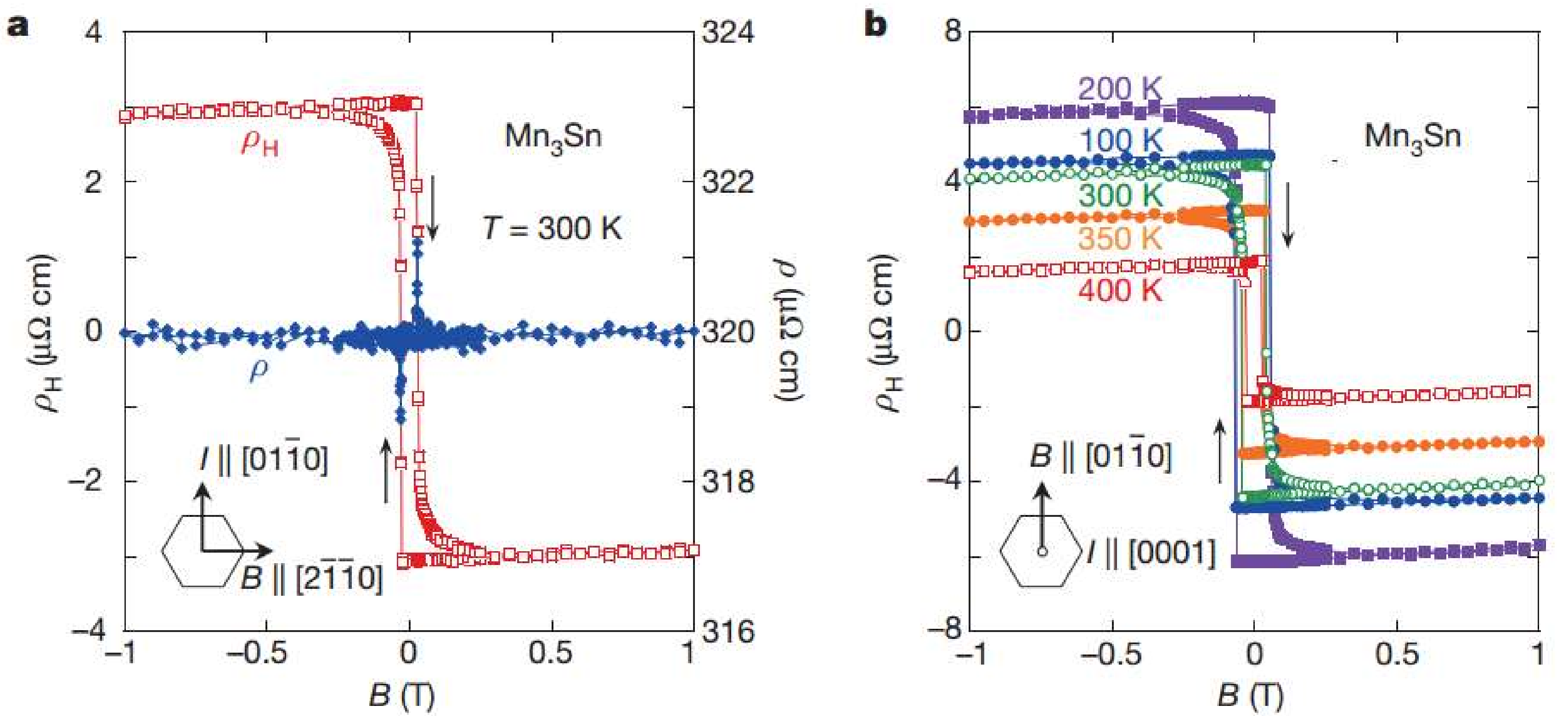
AHE in AFM



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.

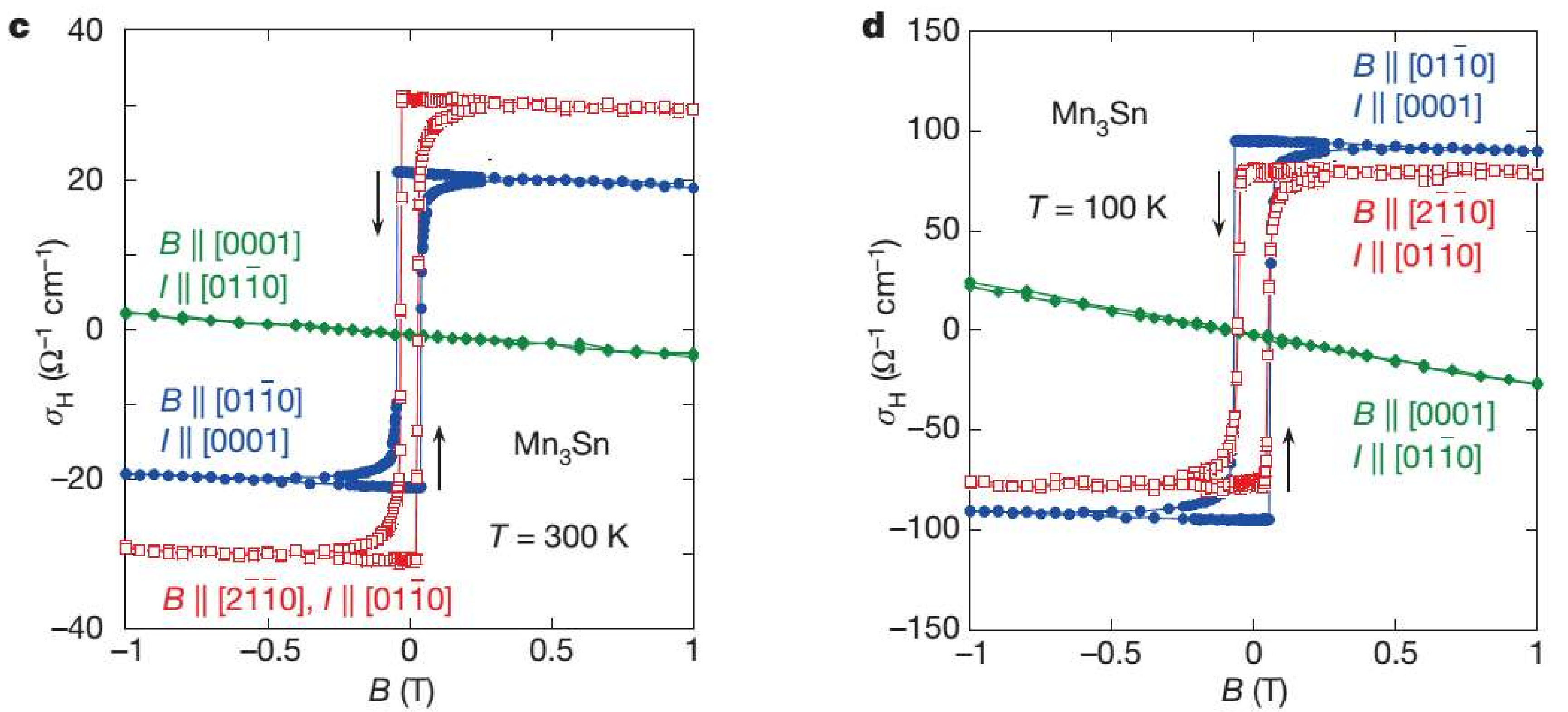
AHE in AFM



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

a small field of ~300 Oe

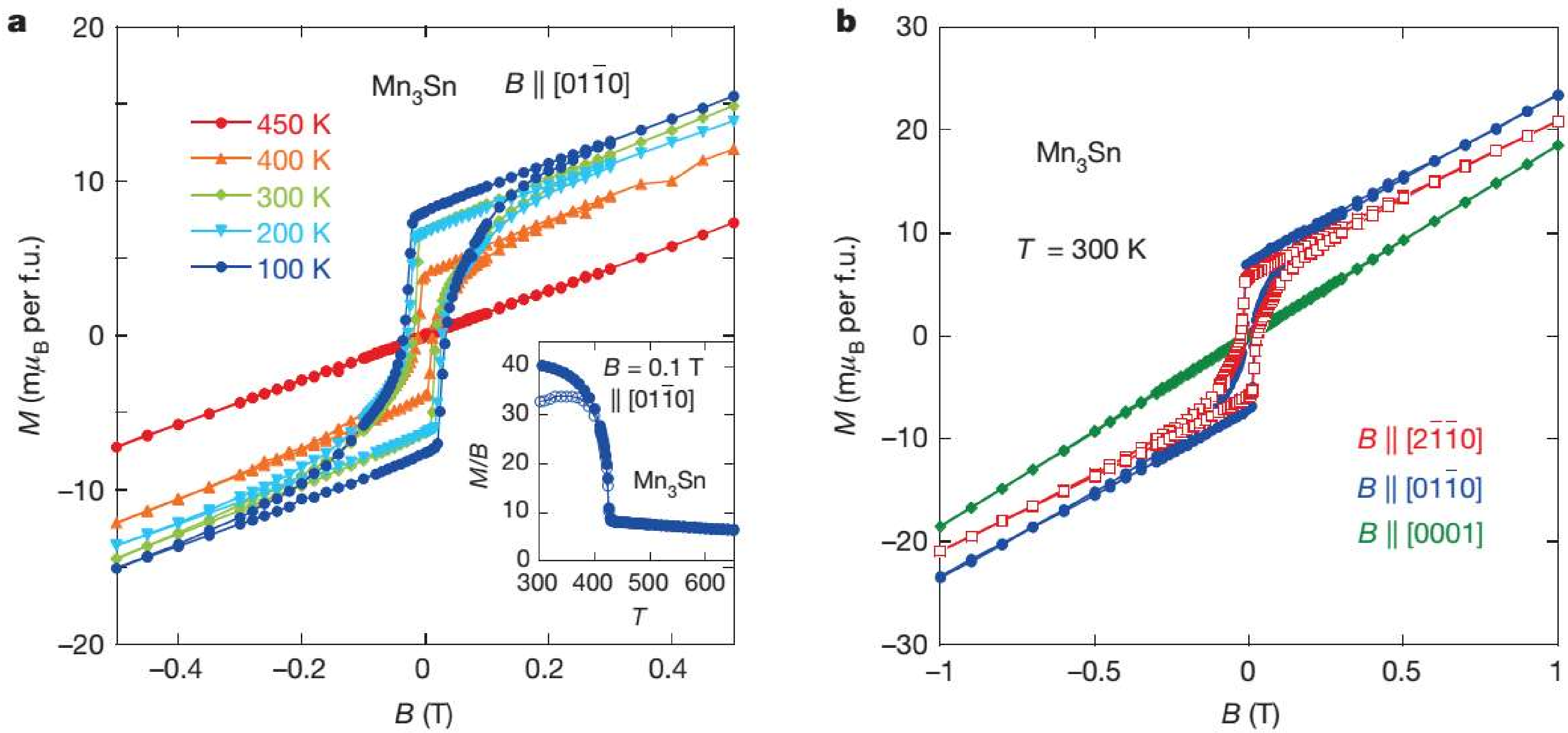
AHE in AFM



$\sigma_{\mathrm{H}} = -\rho_{\mathrm{H}}/\rho^2$

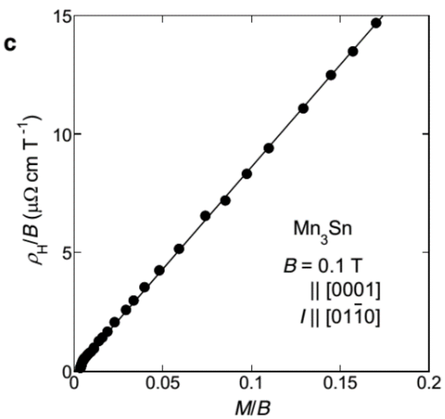
Hysteresis for *H* || [01-11] and *H* || [2-1-10]
Linear for *H* || [0001]

AHE in AFM



The similar anisotropic and hysteretic behaviours found in both ρ_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.

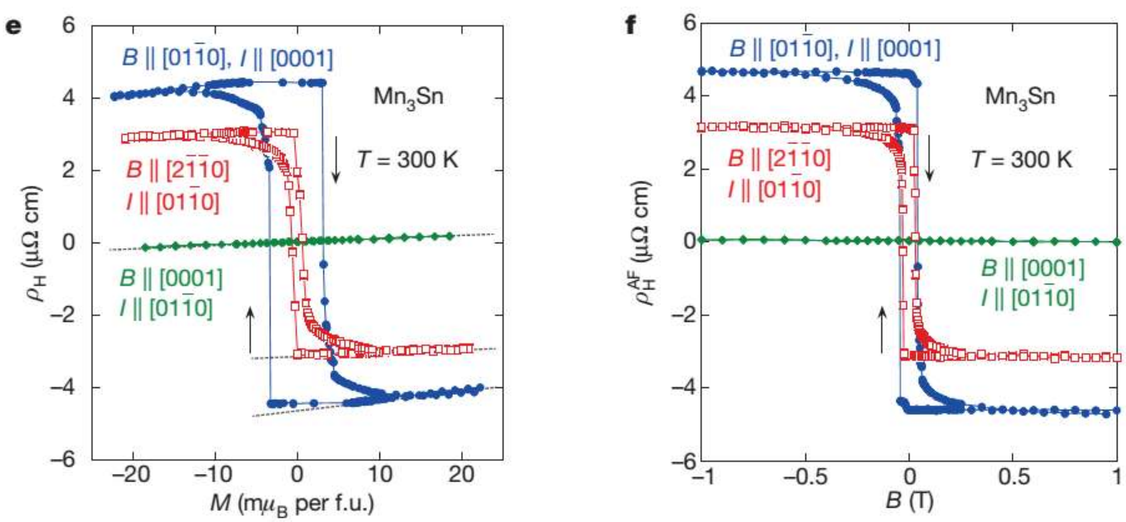
AHE in AFM



$$\rho_{\mathrm{H}} = R_0 B + R_{\mathrm{s}} \mu_0 M$$

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

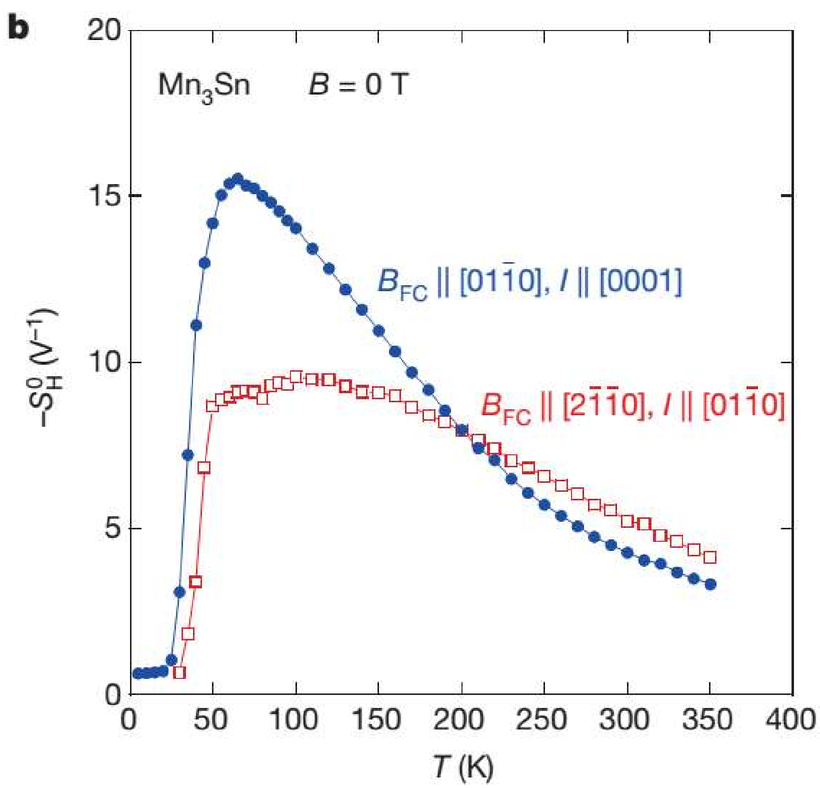
R_0= 3.0×10^{-4} cm^3 C^{-1} indicates that R_0B is negligibly small



$$\rho_{\mathrm{H}} = R_0 B + R_{\mathrm{s}} \mu_0 M + \rho_{\mathrm{H}}^{\mathrm{AF}}$$

the large AHE $\rho_{\mathrm{H}}^{\mathrm{AF}}$, must have a distinct origin driven by the antiferromagnetic order.

AHE in AFM



S_H^0

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

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

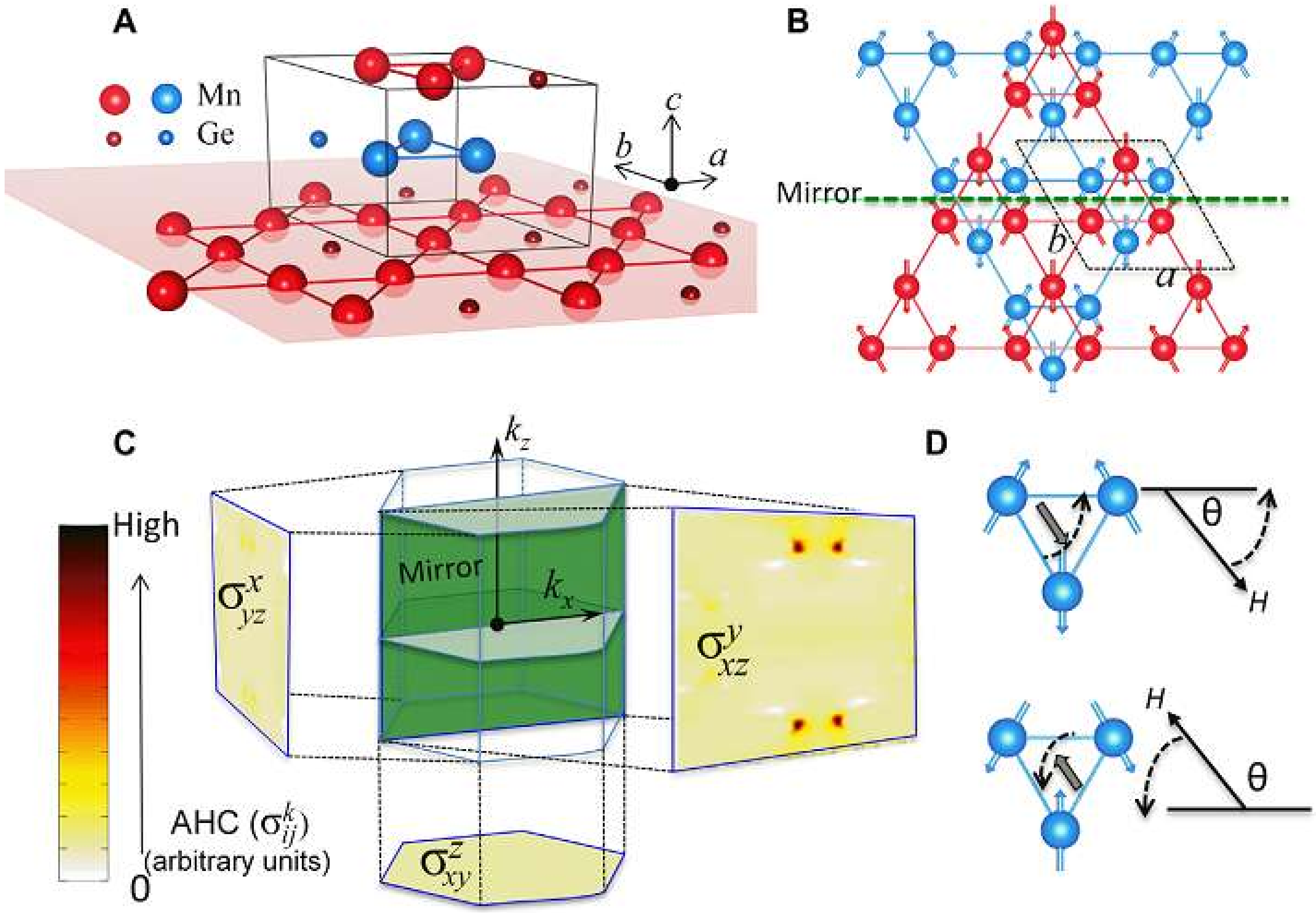
$\rho_H = R_0 B + R_s \mu_0 M$

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

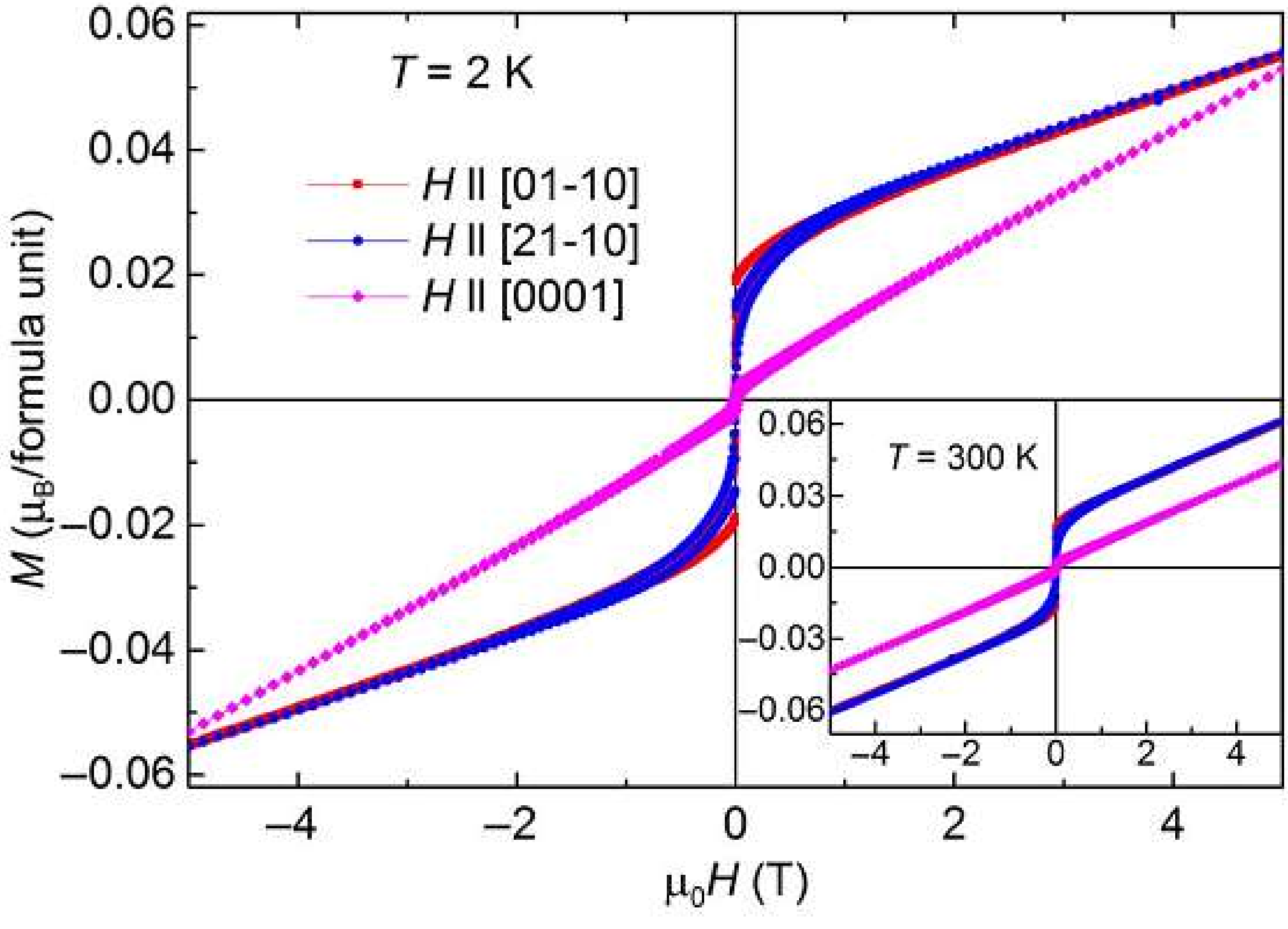
In a magnetic conductor with relatively high resistivity, the AHE is dominated by S_H.

14 V^{-1} (Mn_3Sn) at 100 K >> 0.01–0.1 V^{-1}(like Fe, Ni, Co...)

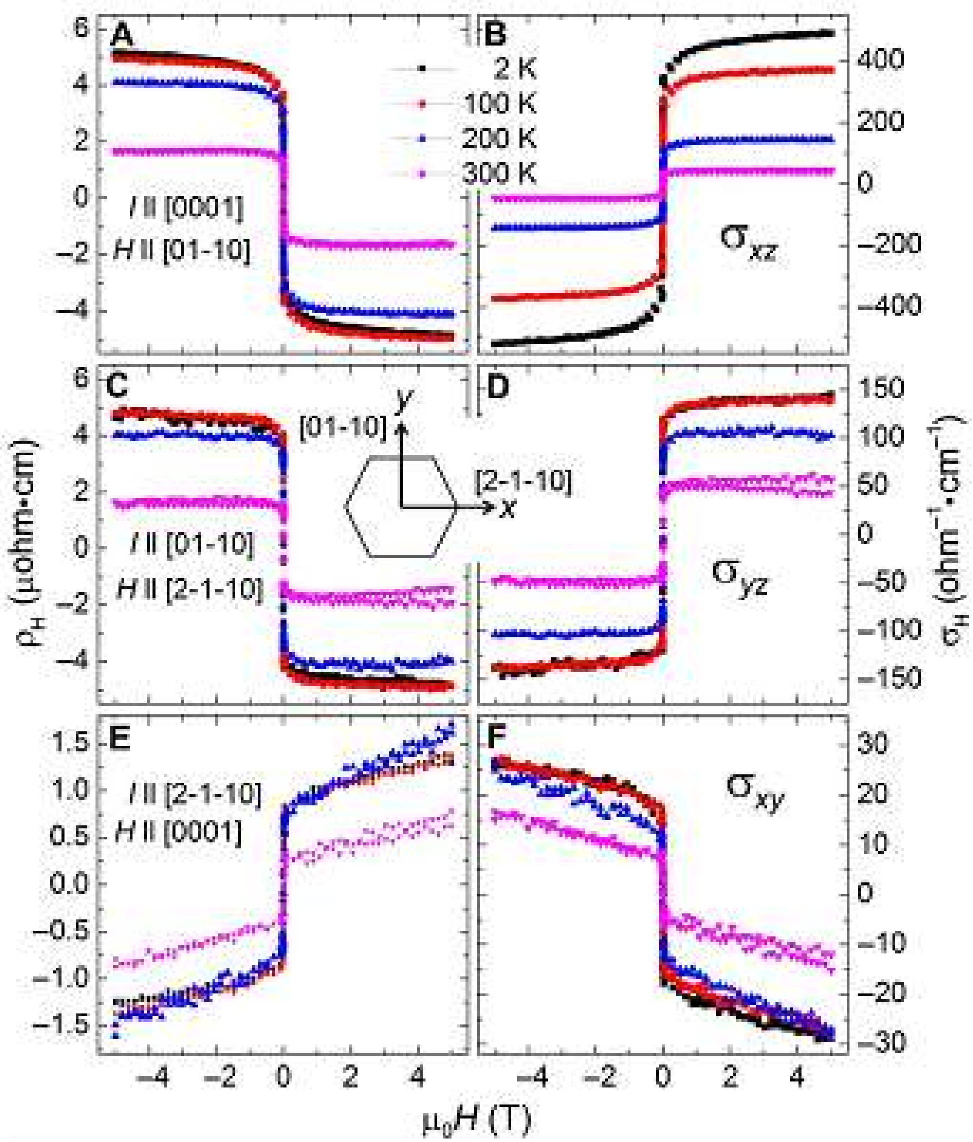
AHE in AFM $MnGe_3$



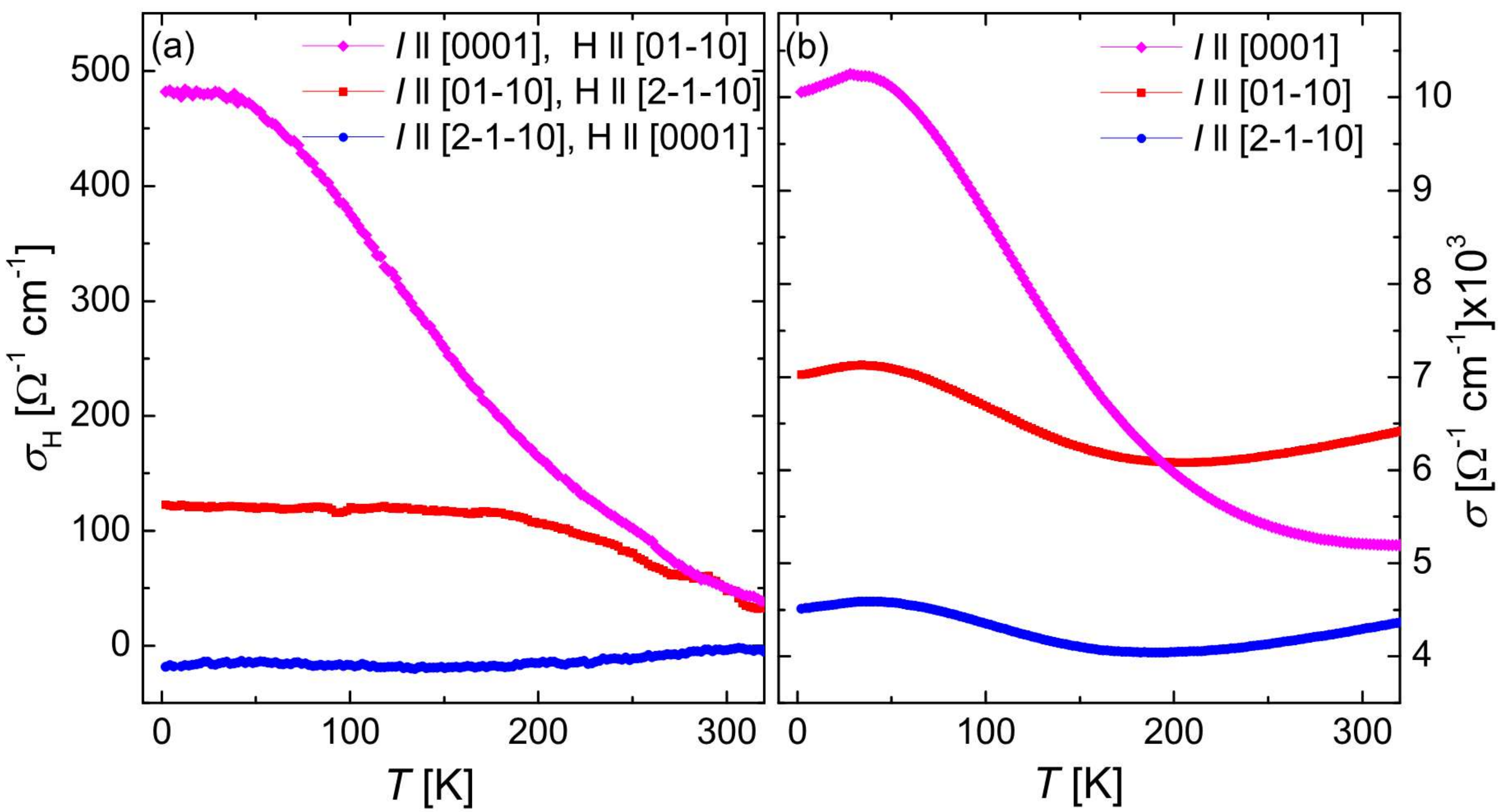
AHE in AFM $MnGe_3$



AHE in AFM $MnGe_3$



AHE in AFM $MnGe_3$

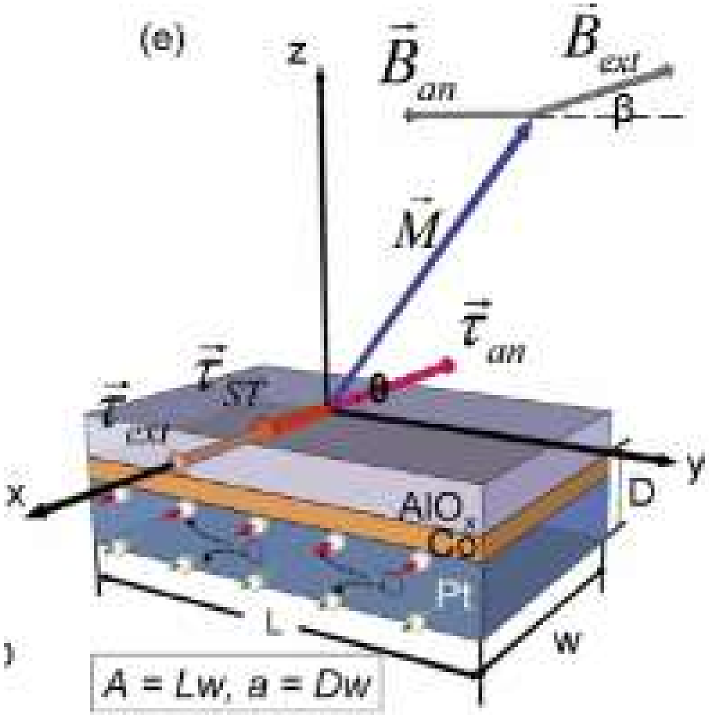


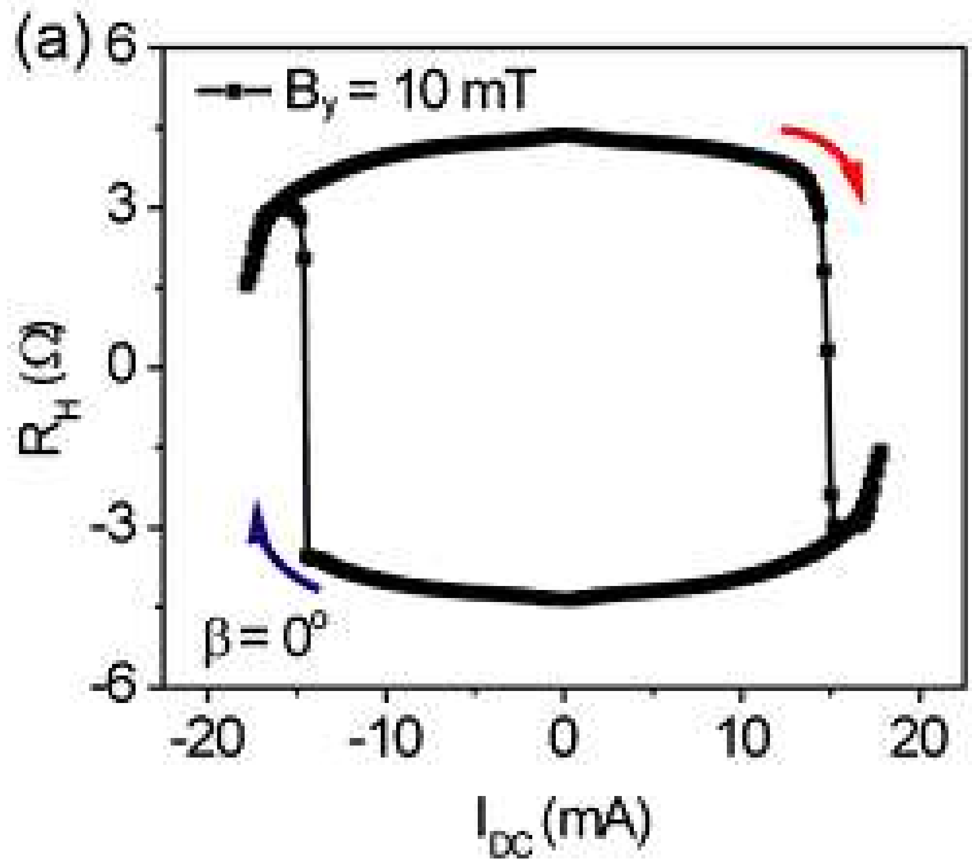
Outline

6. Spin orbit torque in AFM

Spin orbit torque in AFM

Spin Hall orbit torque to FM





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

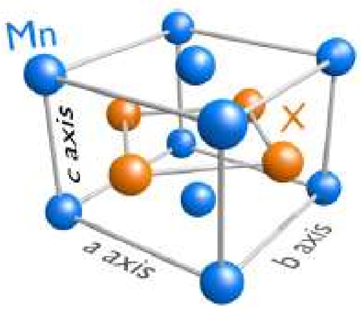
Spin orbit torque in AFM

PRL 113, 196602 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

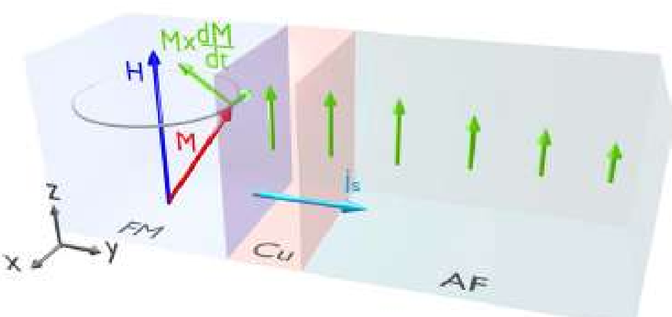
Spin Hall Effects in Metallic Antiferromagnets

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)

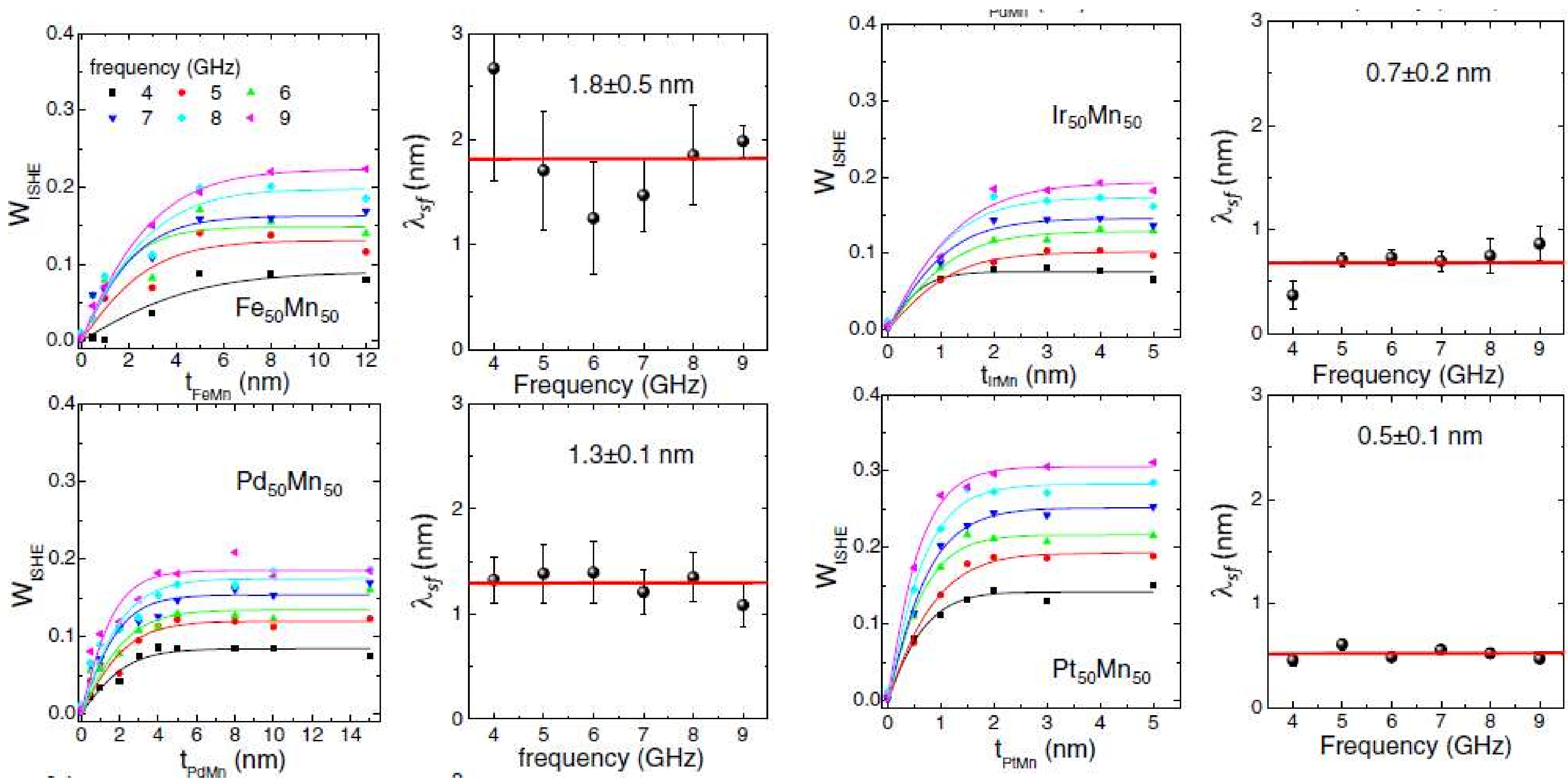


Crystal structure of CuAu-Ⅰ-type Afs



Schematic of spin pumping and spin Hall effect

Spin orbit torque in AFM



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

$Fe_{50}Mn_{50}$
$Pd_{50}Mn_{50}$

$Ir_{50}Mn_{50}$
$Pt_{50}Mn_{50}$

Spin orbit torque in AFM

Spin Hall angle

0.008 $\pm$ 0.002 for FeMn

0.015 $\pm$ 0.005 for PdMn

0.022 $\pm$ 0.005 for IrMn

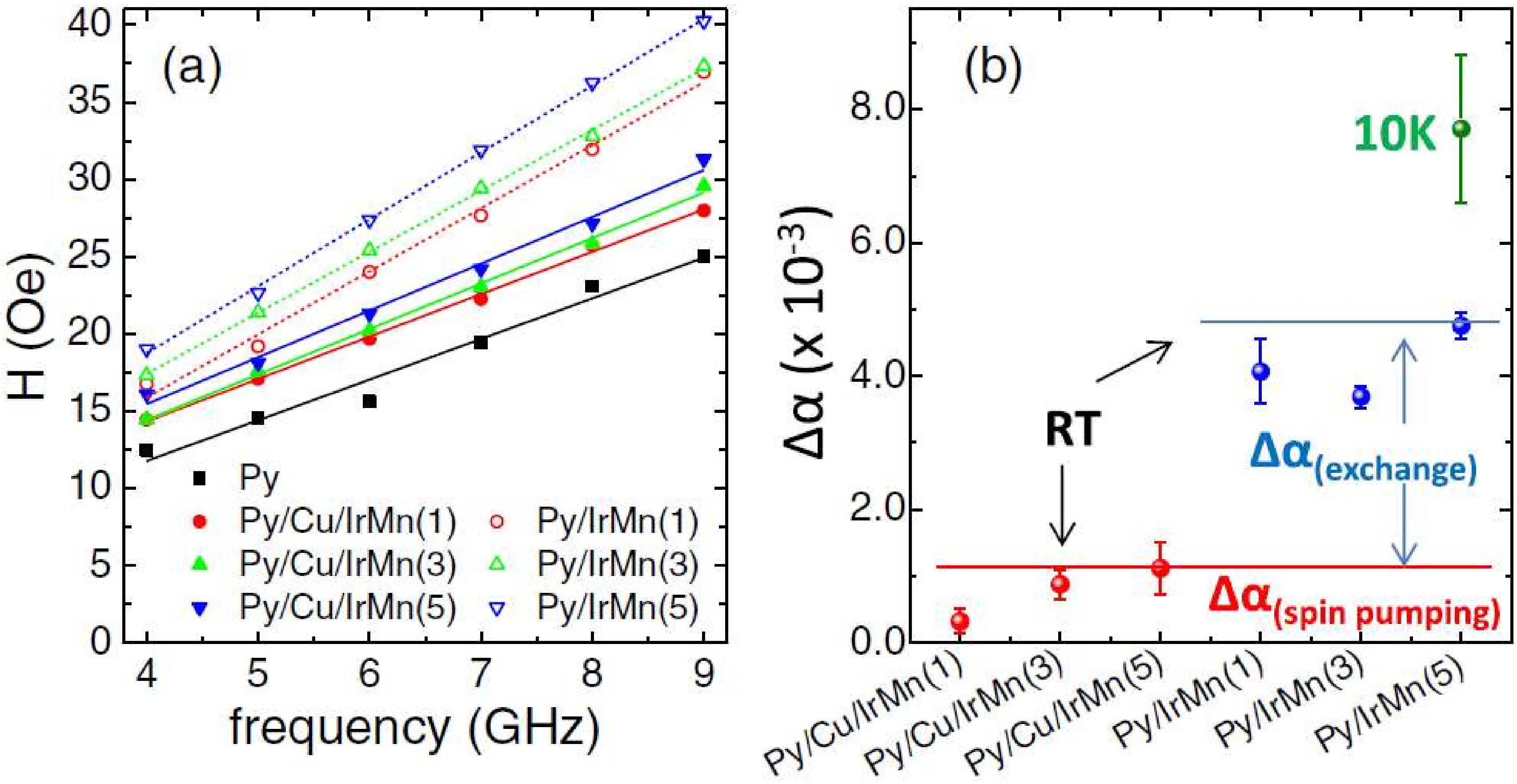
0.060 $\pm$ 0.010 for PtMn Large value, comparable to Pt

		σ^x_{yz}	σ^x_{zy}	σ^y_{zx}	σ^y_{xz}	σ^z_{xy}	σ^z_{yx}	$\bar{\sigma}$	σ_{av}	σ_{exp}
PtMn	c axis	303.9	−219.9	219.9	−303.9	60.3	−60.3	194.7	125.2	182.9
	a axis	30.4	−10.5	52.3	−260.9	92.5	−96.5	90.5		
IrMn	c axis	372.8	−59.7	59.7	−372.8	40.9	−40.9	157.8	41.6	40.8
	a axis	−21.3	−94.6	126.3	−351.6	−325.1	325.1	−16.5		
PdMn	c axis	69.5	−17.0	17.0	−69.5	17.8	−17.8	34.8	3.9	33.6
	a axis	0.0	3.5	7.4	−66.8	−70.8	69.8	−11.6		
FeMn	c axis	51.9	48.4	−47.6	50.9	−100.3	96.5	−48.6	−59.0	23.9
	a axis	−82.6	85.9	−47.8	47.5	−121.6	0.0	−64.2		

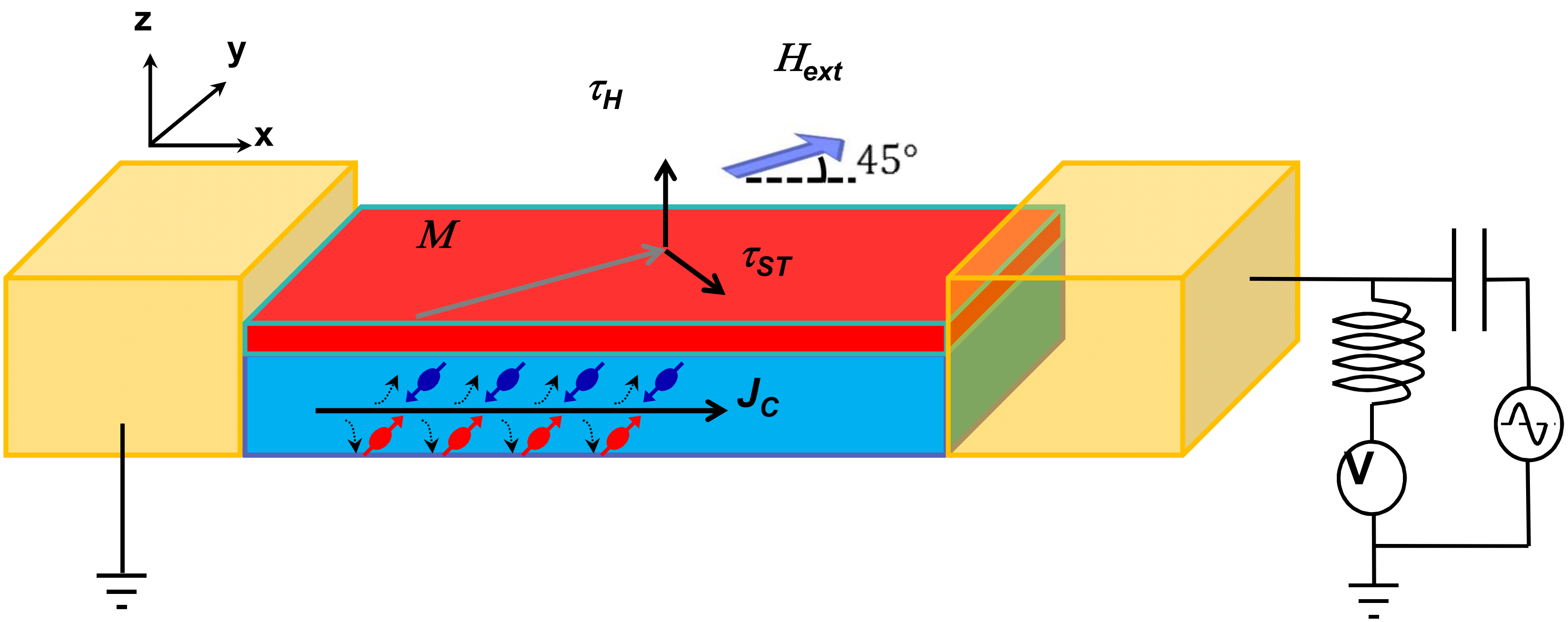
Spin orbit torque in AFM

Comparison between with and without a Cu spacer,

Showing an additional damping enhancement due to exchange coupling at FM/AF interface



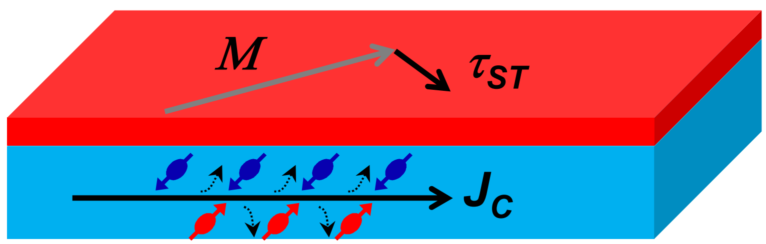
Spin orbit torque FMR



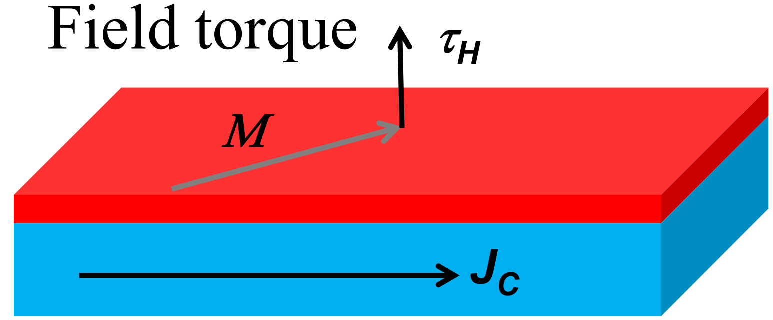
Liu et al., PRL 106, 036601 (2011)

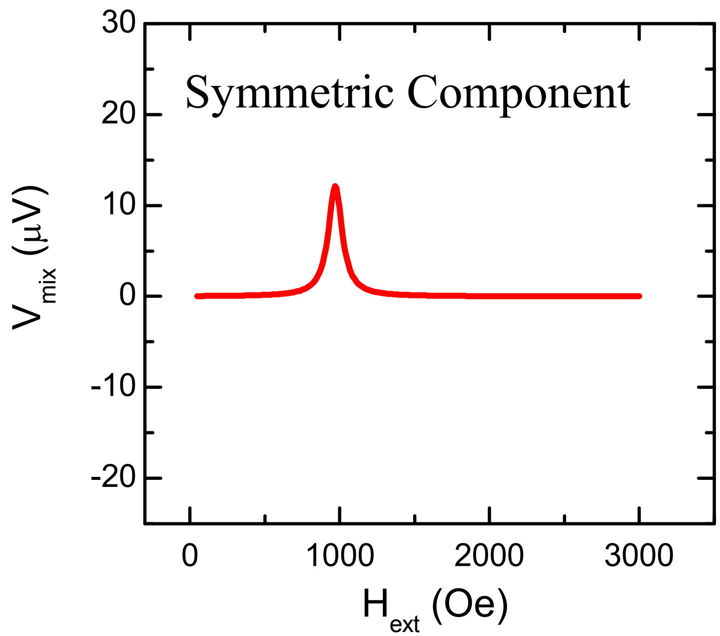
Spin orbit torque FMR

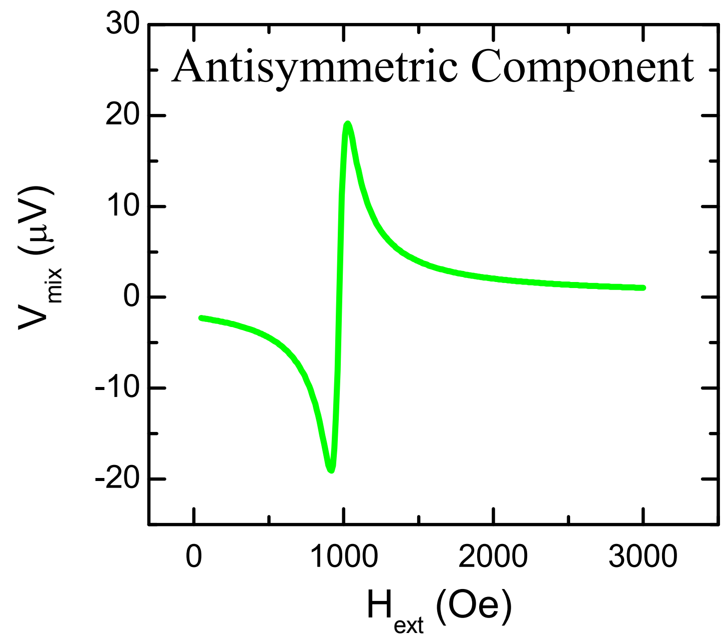
Spin Hall torque



Field torque



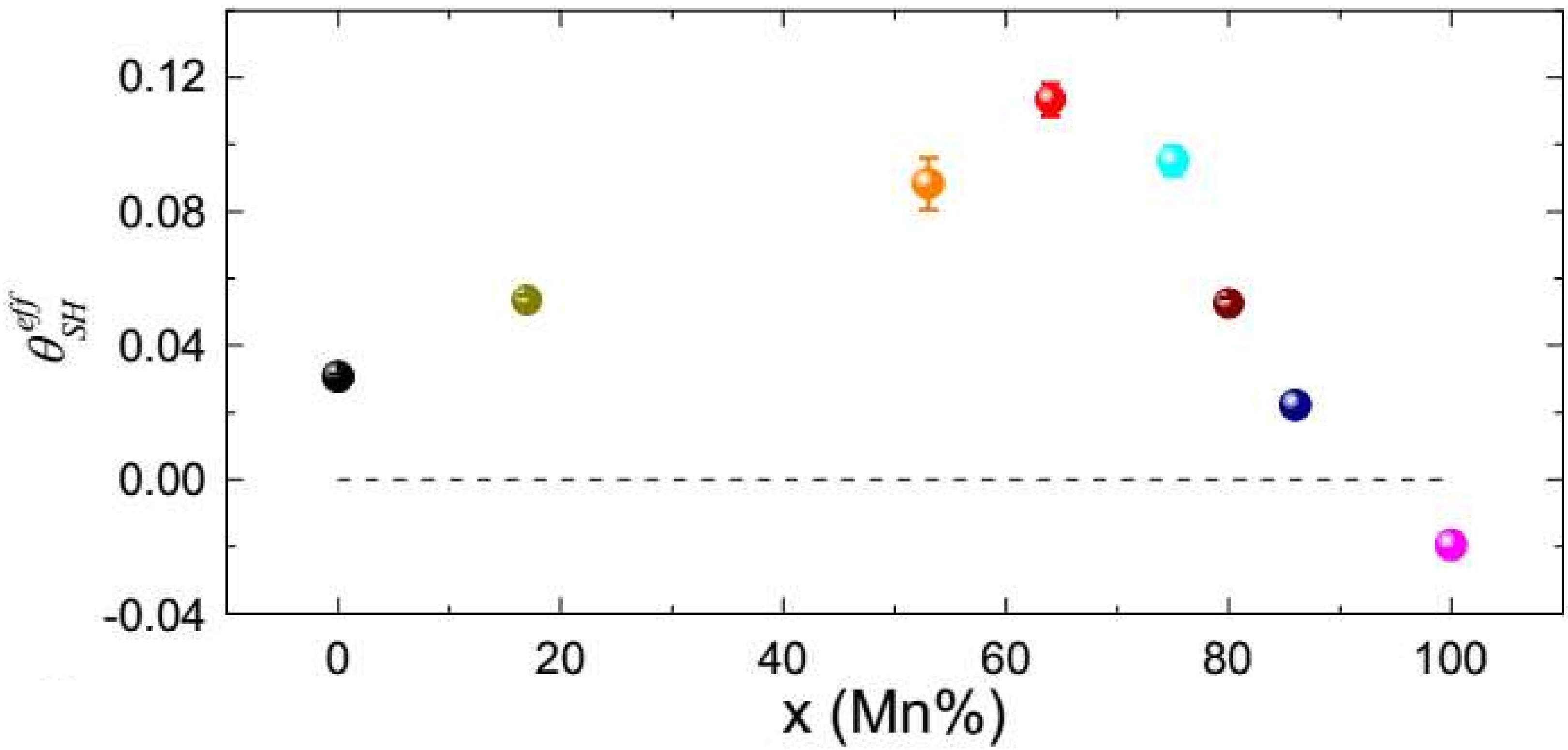




$$SHA = \frac{S}{A}\frac{e\mu_0 M_s t d}{\hbar}\left[1 + (4\pi M_{eff}/H_{ext})\right]^{1/2}$$

Spin orbit torque in AFM

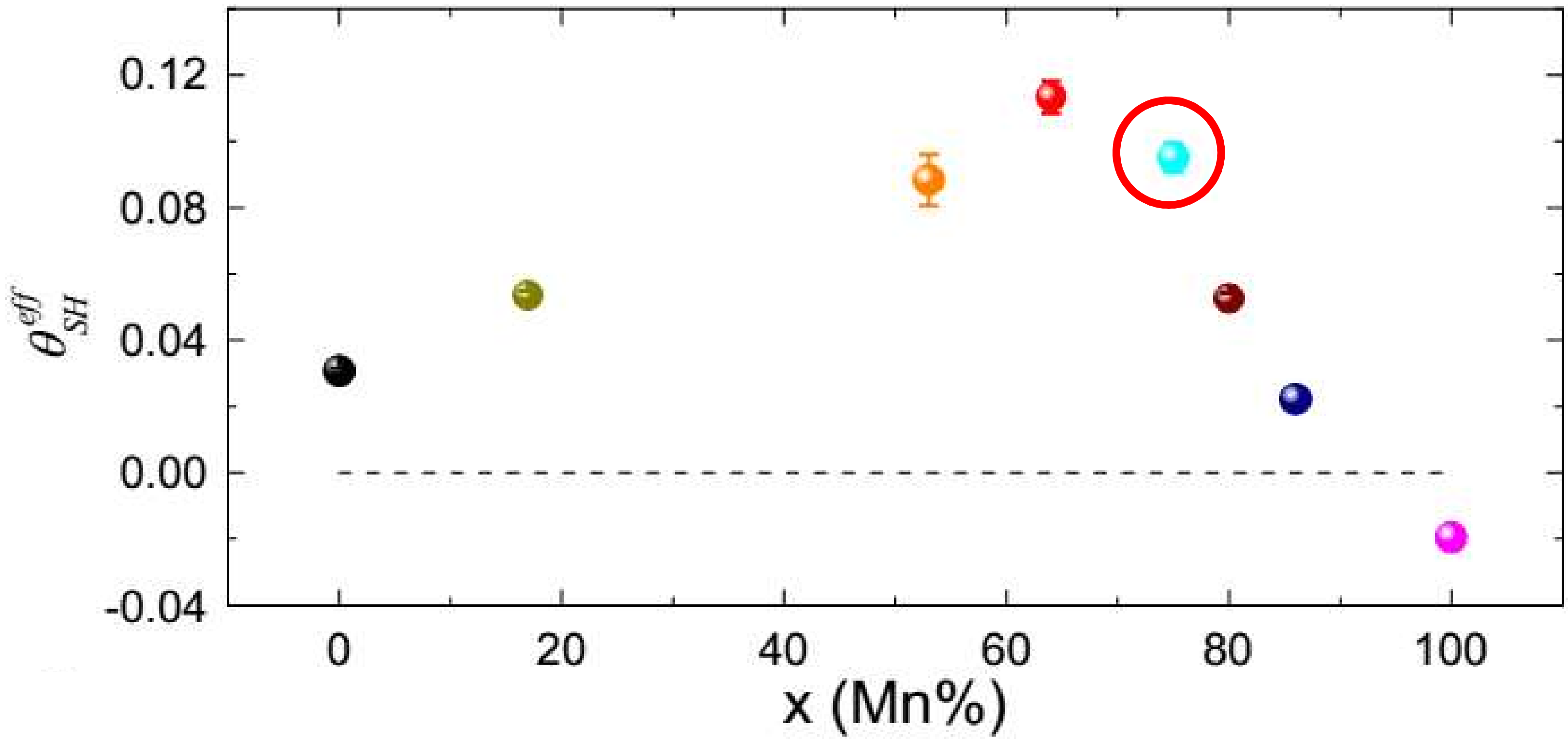
$Ir_{1-x}Mn_x$



➢ **Large effective SHA observed in IrMn- IrMn3**

Spin orbit torque in AFM

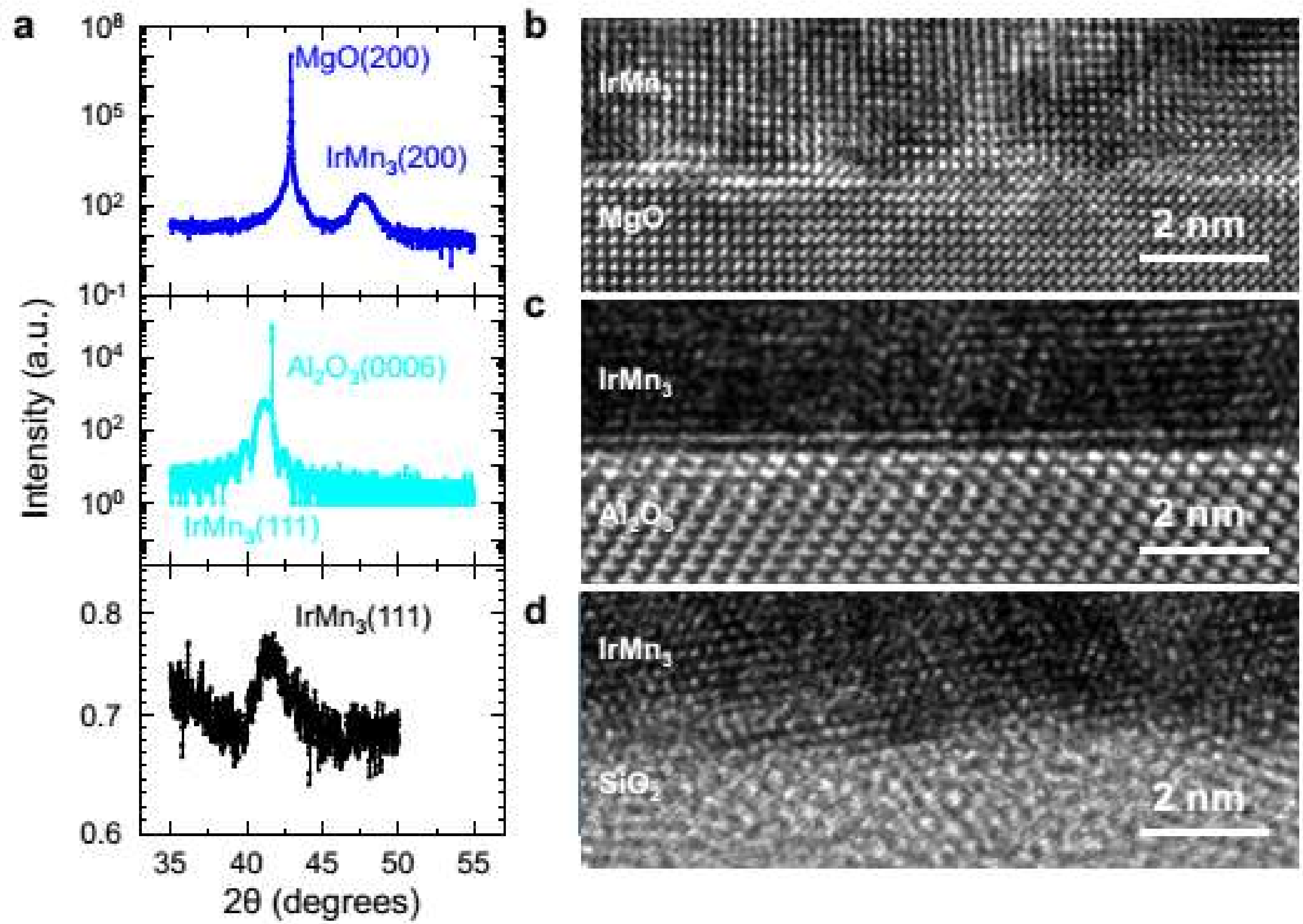
$Ir_{1-x}Mn_x$



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

Spin orbit torque in AFM

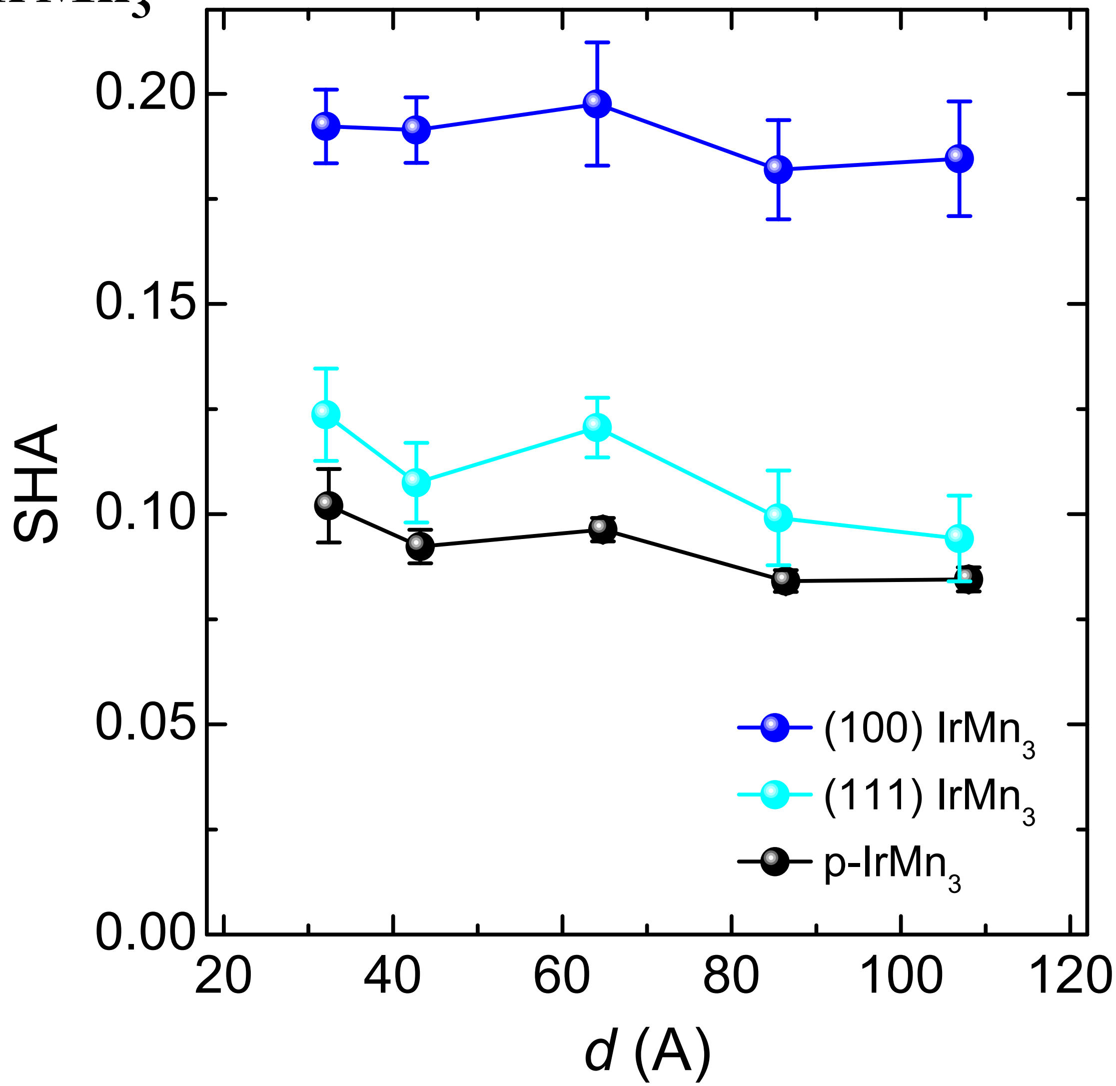
$IrMn_3$



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

Spin orbit torque in AFM

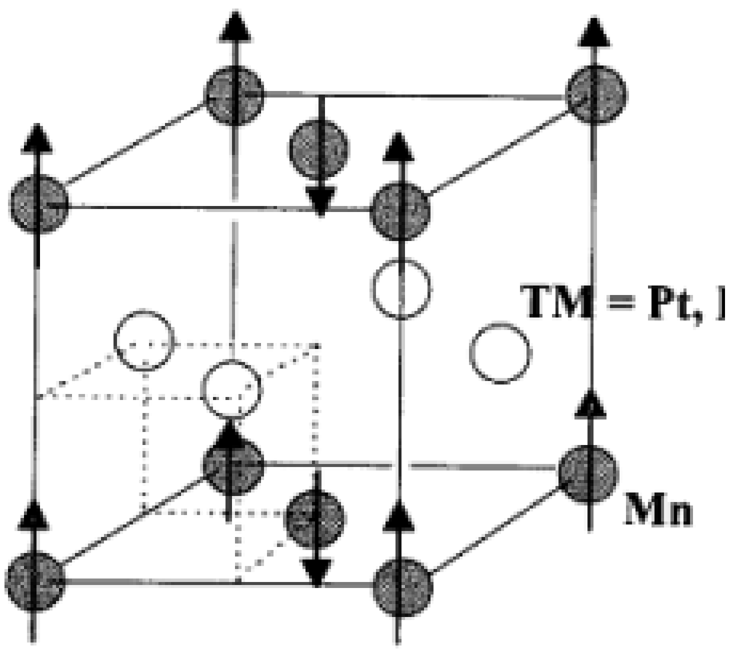
$IrMn_3$

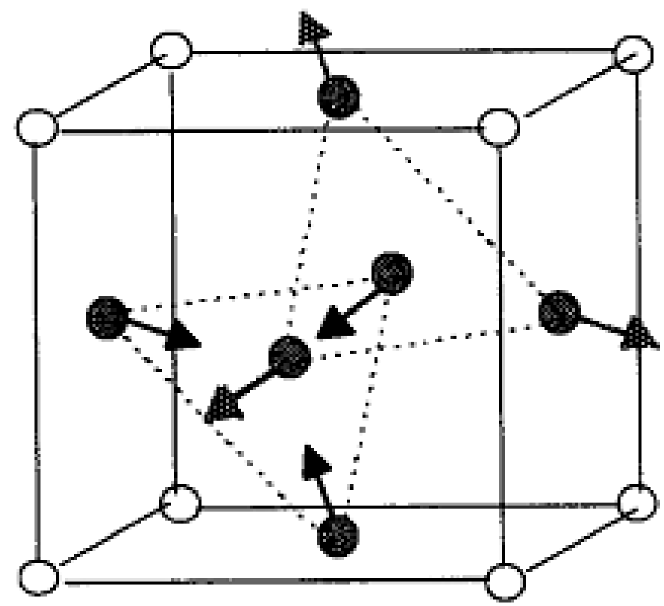


- **The effective SHA is the largest for (100) $IrMn_3$**
- **(111) and polycrystalline IrMn3 show similar SHA.**

Spin orbit torque in AFM

IrMn | **$IrMn_3$**

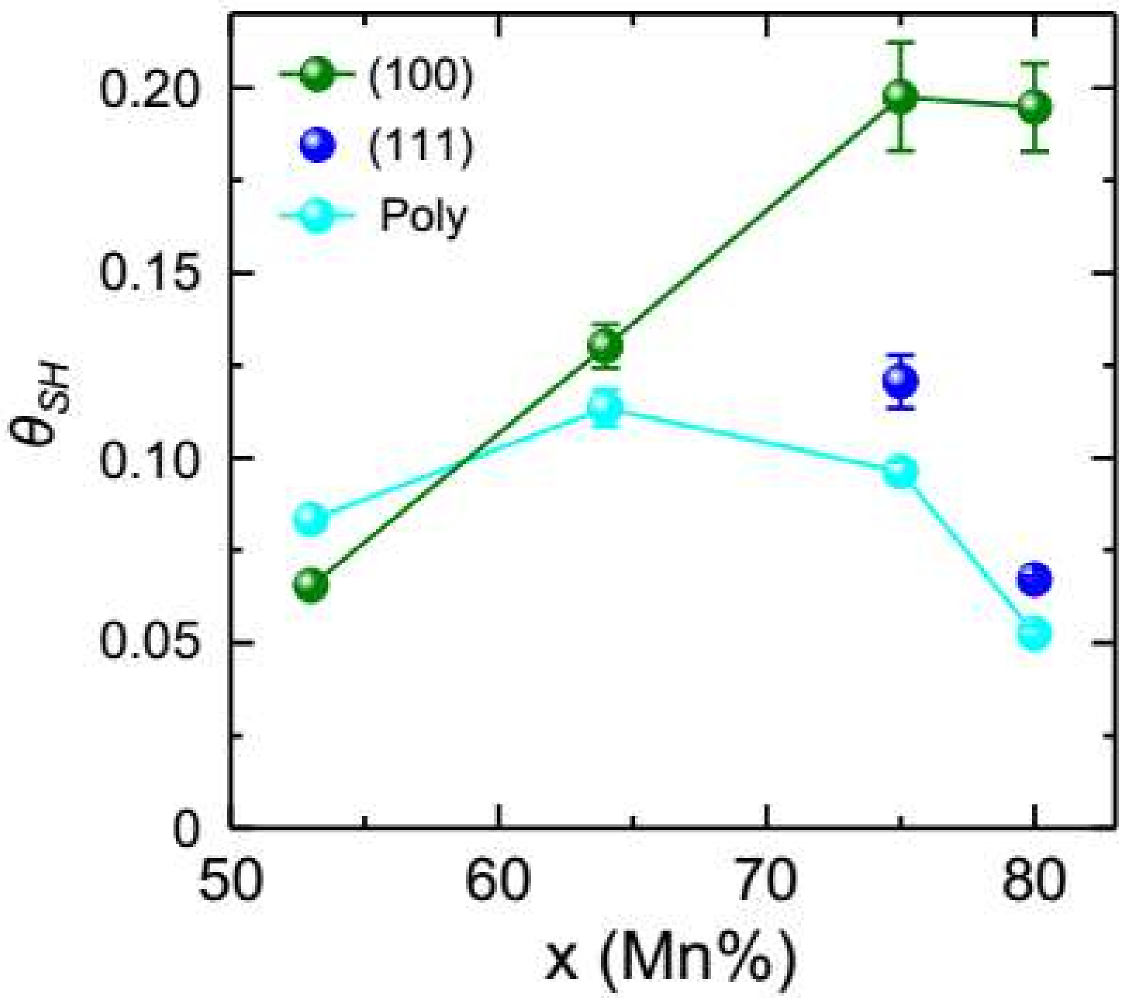




- **Collinear AFM**
- **Non-Collinear AFM**

Non-collinear AFM spin structure

Spin orbit torque in AFM

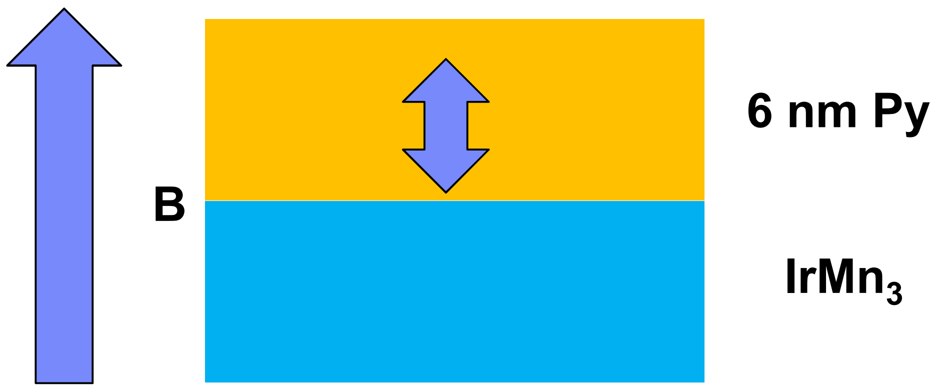


- ➢ **Little facet dependence in collinear AFM**

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

Spin orbit torque in AFM

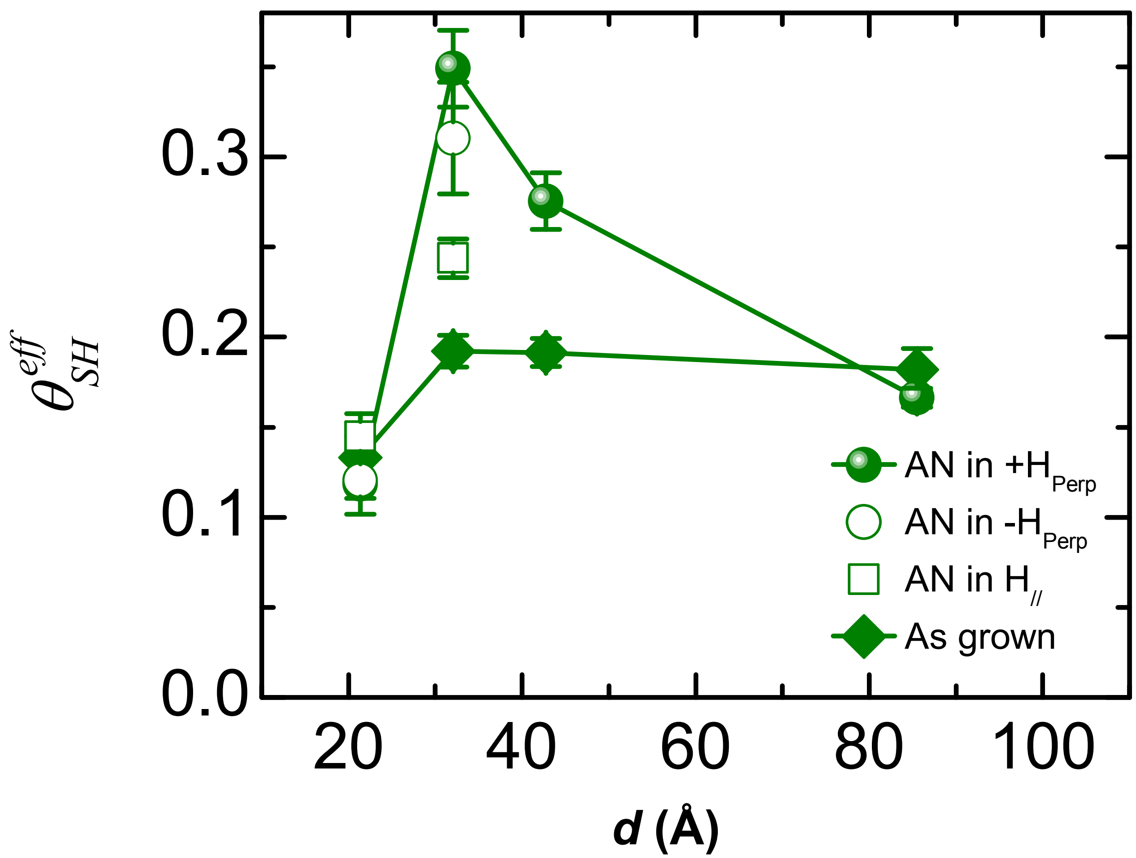
Annealing $IrMn_3$ in perpendicular magnetic field



Effect:
Tune the AFM domains configurations on the $IrMn_3$ surface.

Spin orbit torque in AFM

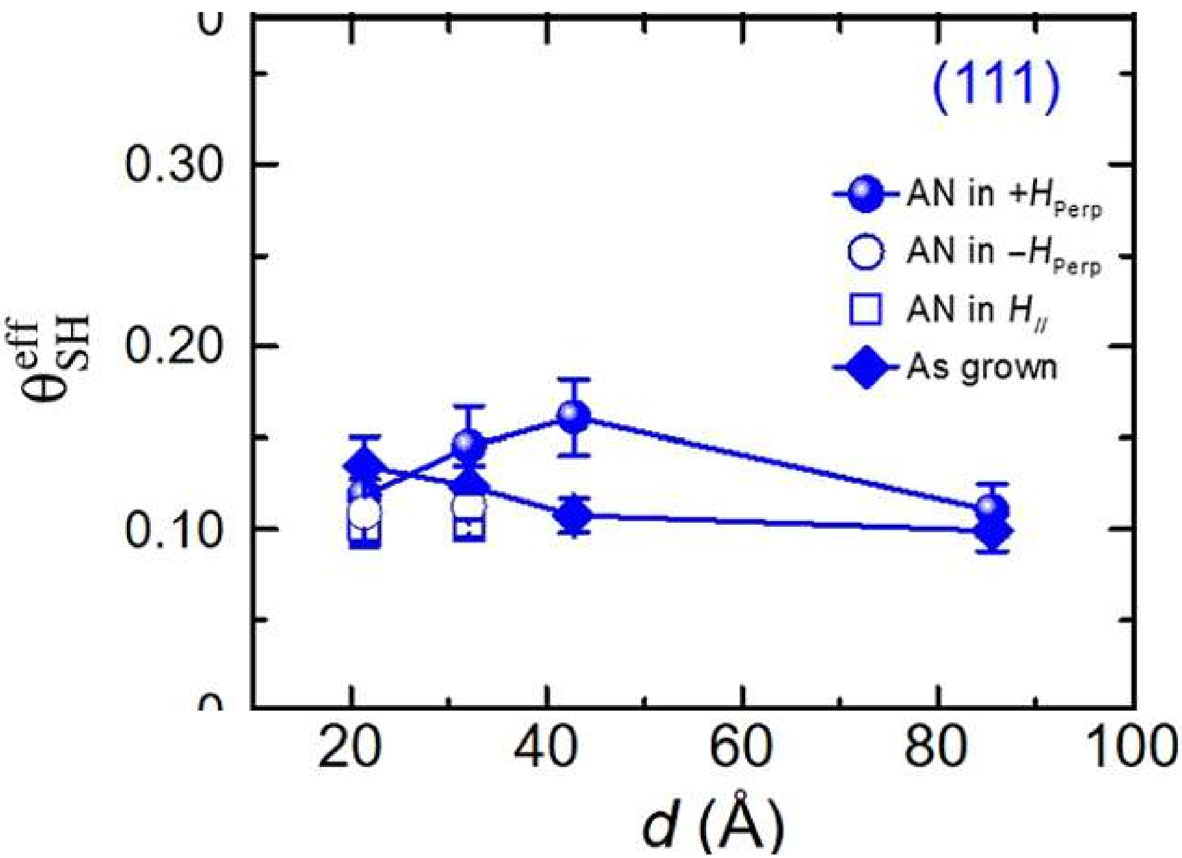
(100) $IrMn_3$



- **The SHA increases from 0.20 up to 0.35 for 3 nm (100) $IrMn_3$**
- **For 2 nm and 8 nm, the enhancement effect is small**

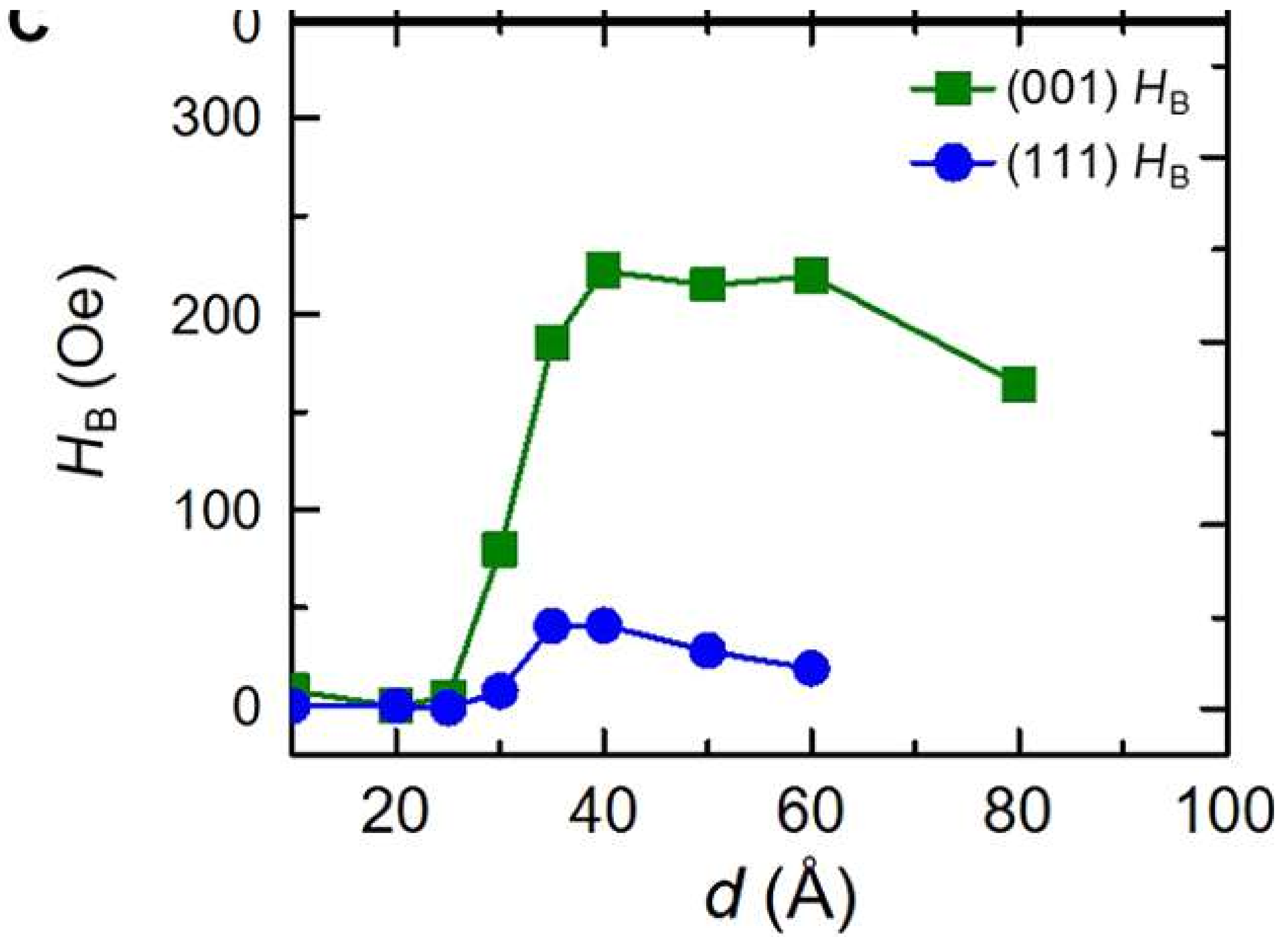
Spin orbit torque in AFM

(111) $IrMn_3$

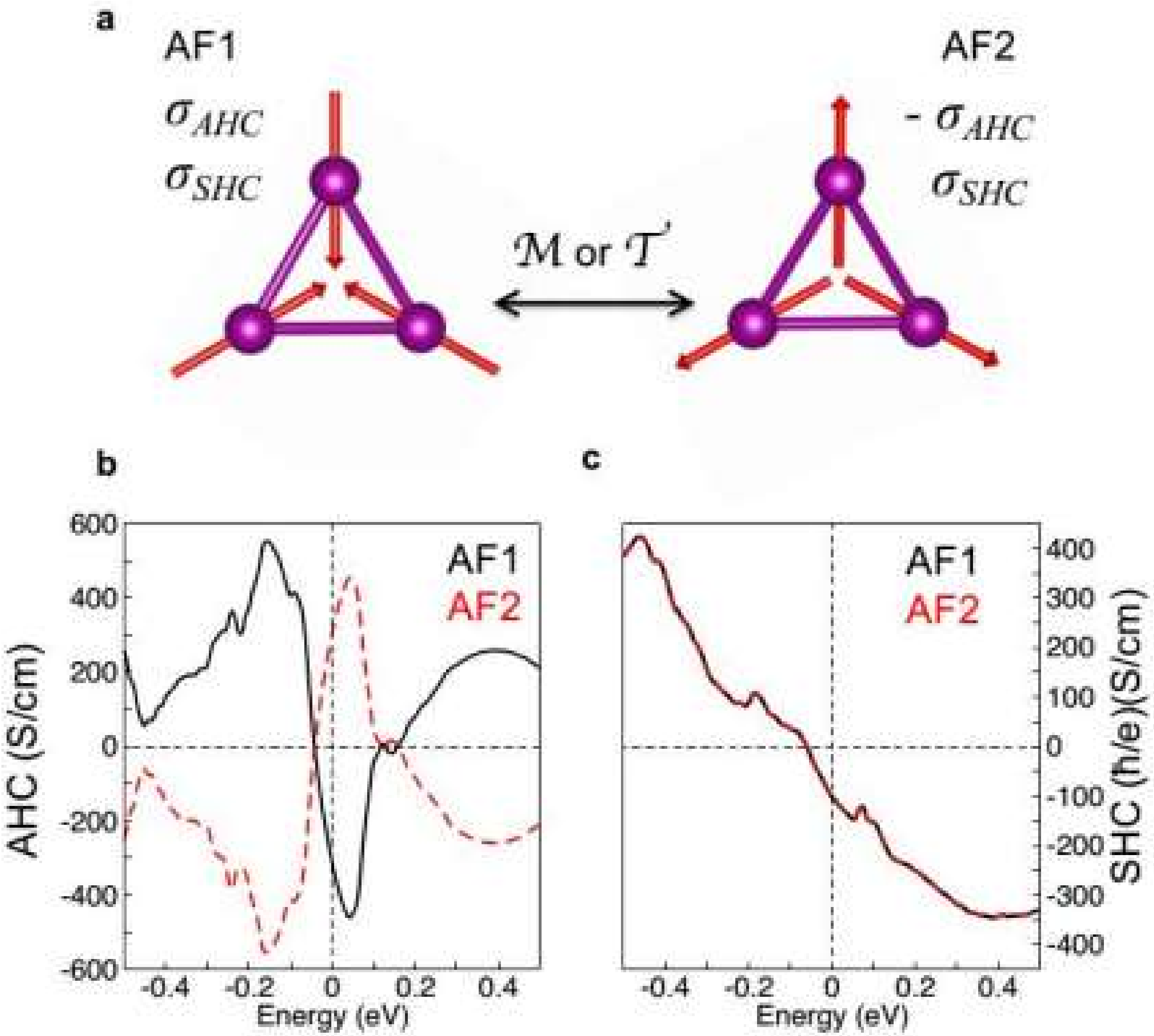


- **Very small effect on (111) $IrMn_3$**

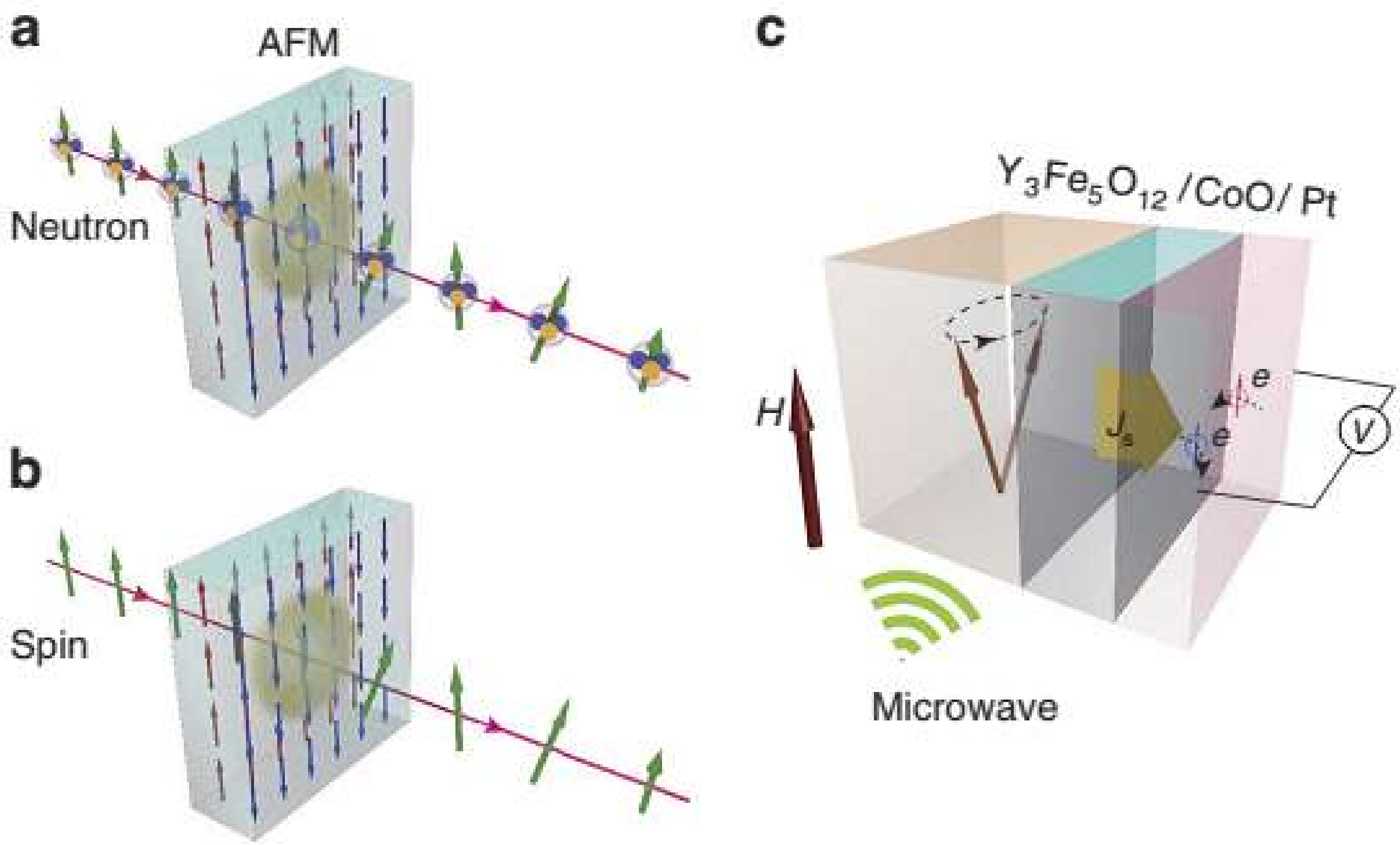
Spin orbit torque in AFM



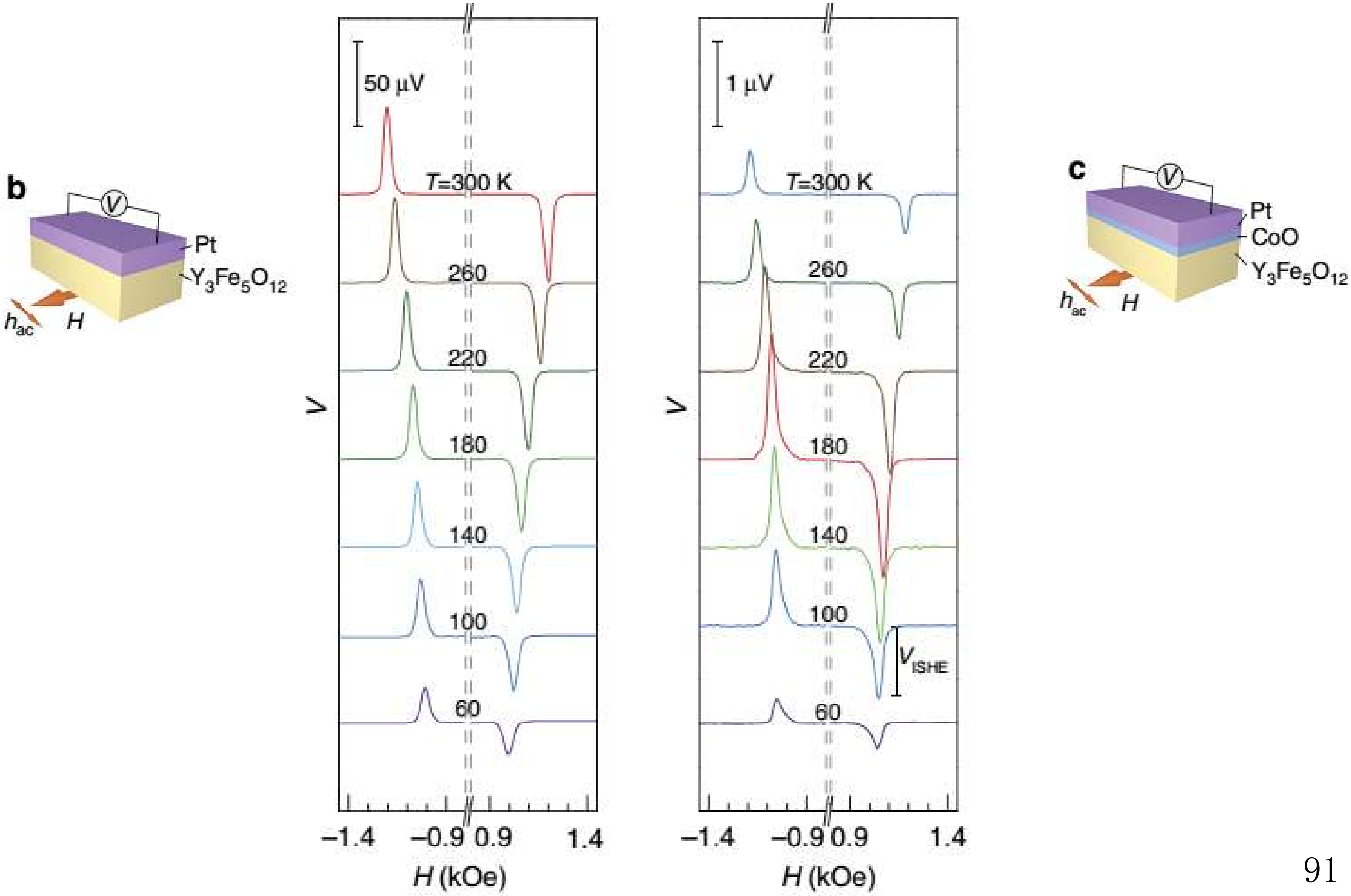
Spin orbit torque in AFM



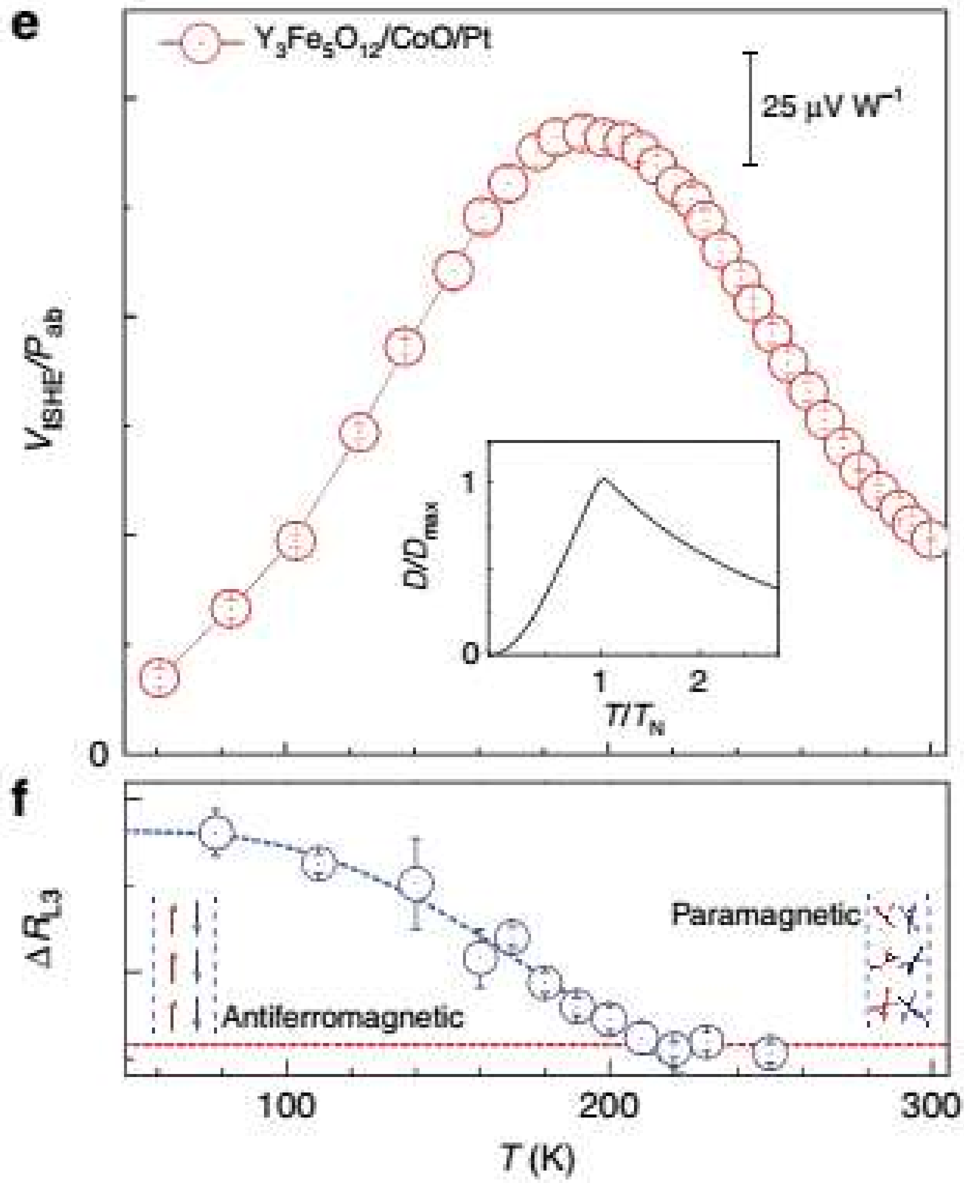
Spin orbit torque through AFM



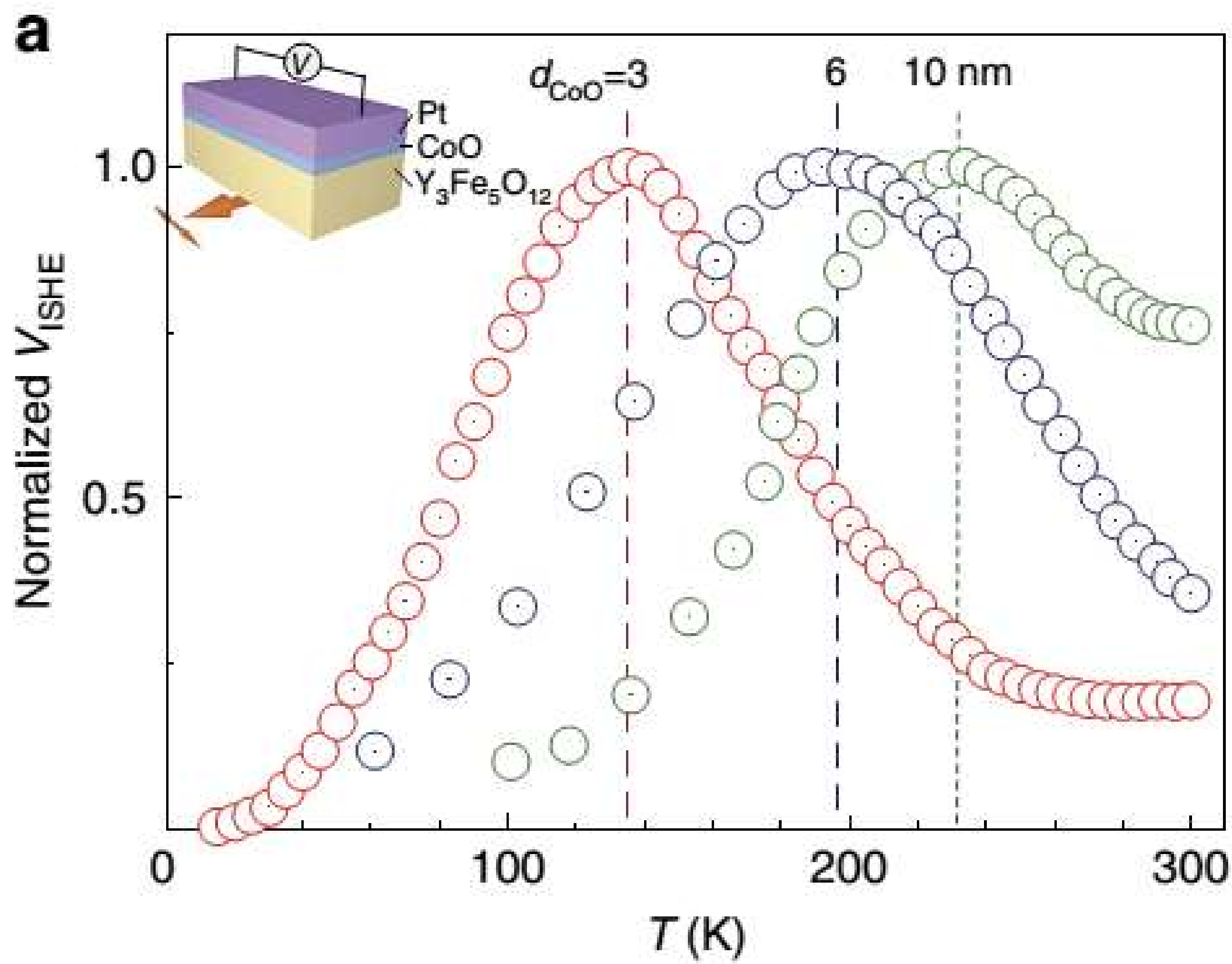
Spin orbit torque through AFM



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

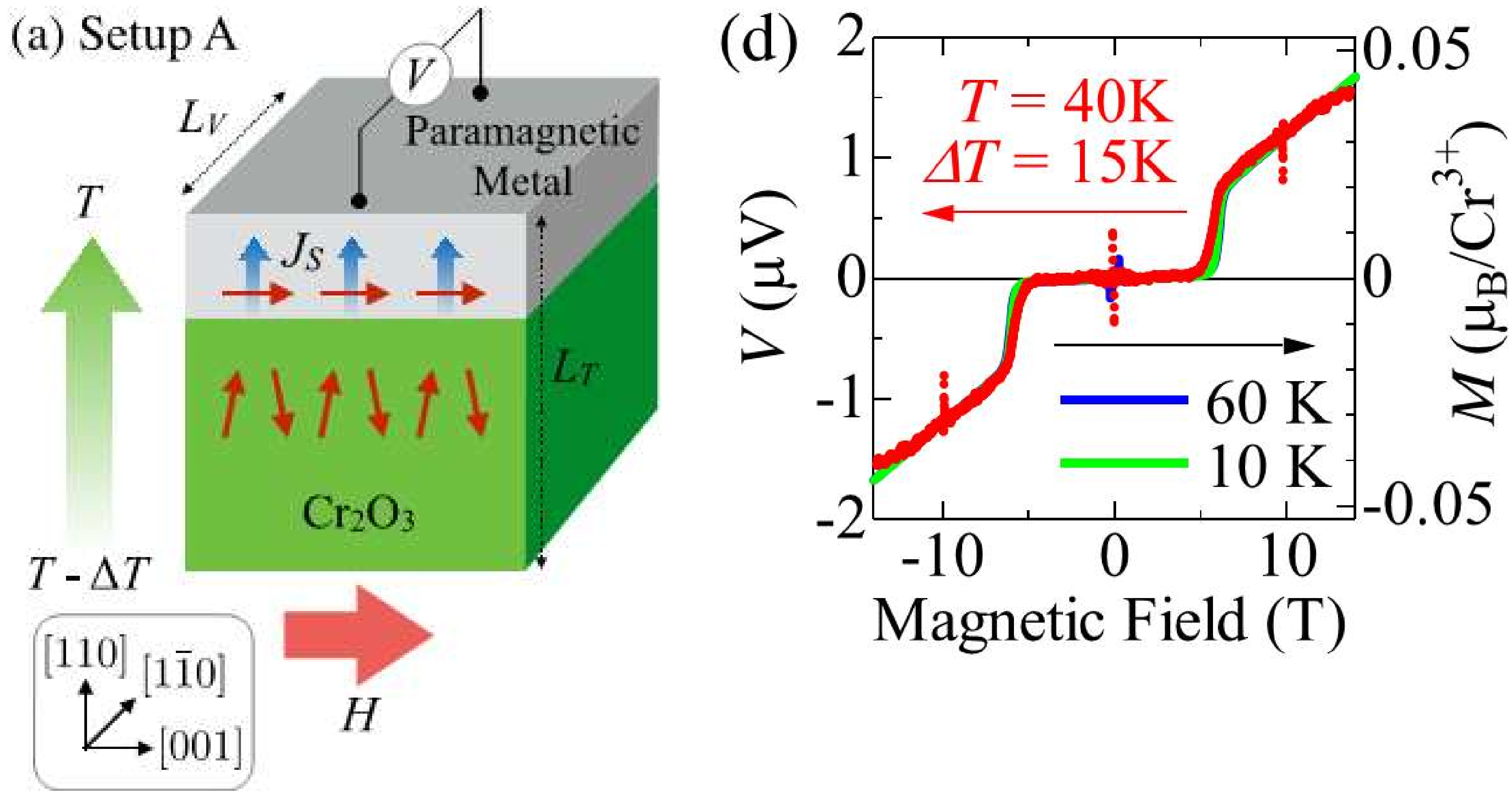
4. Switching of AFM

5. Anomalous Hall effect in AFM

6. Spin orbit torque in AFM

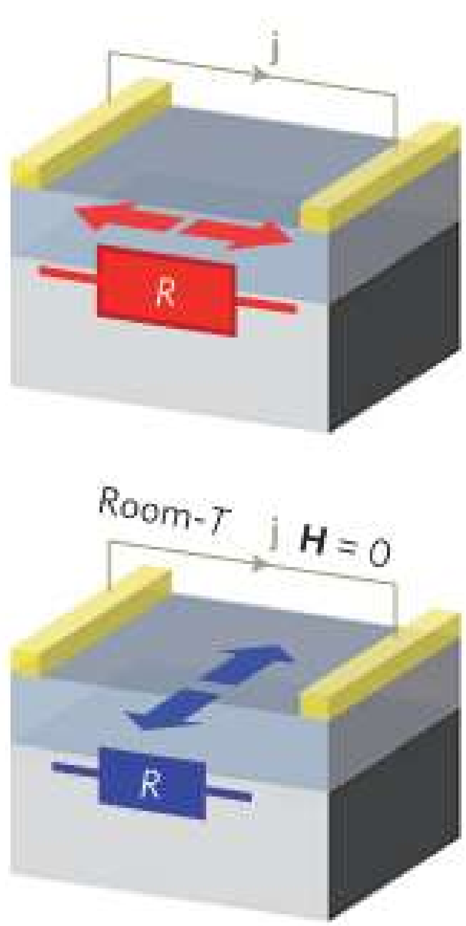
Summary

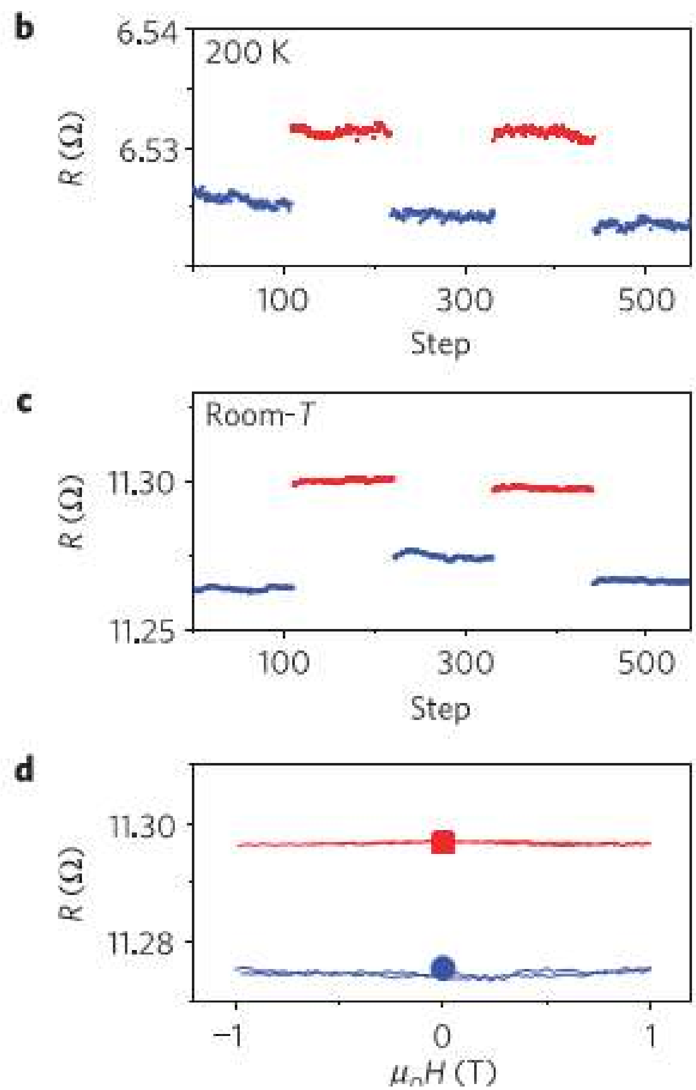
2. Spin Seebeck effect in AFM



Summary

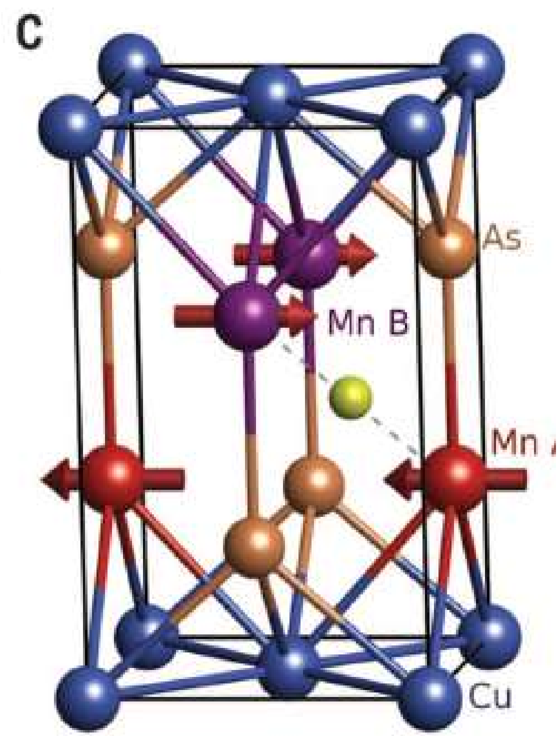
3. AMR in AFM

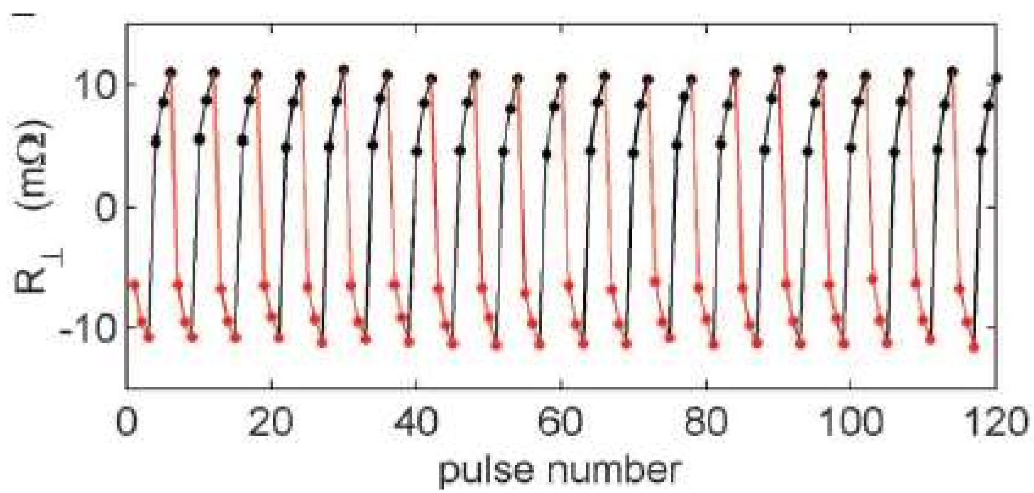




Summary

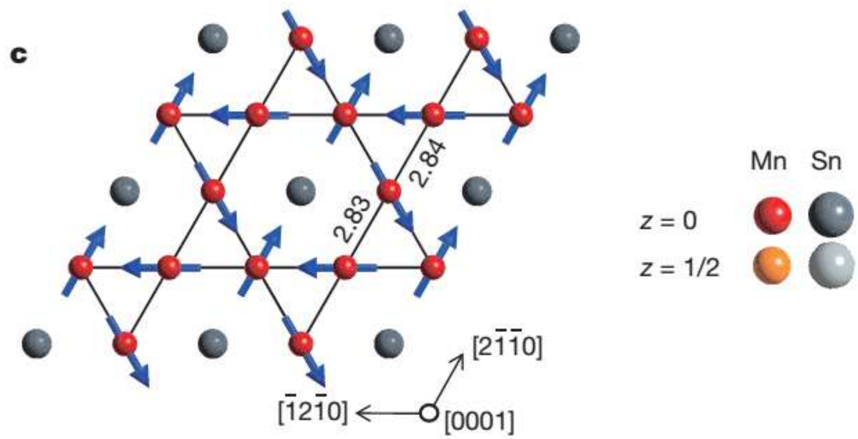
4. Switching of AFM

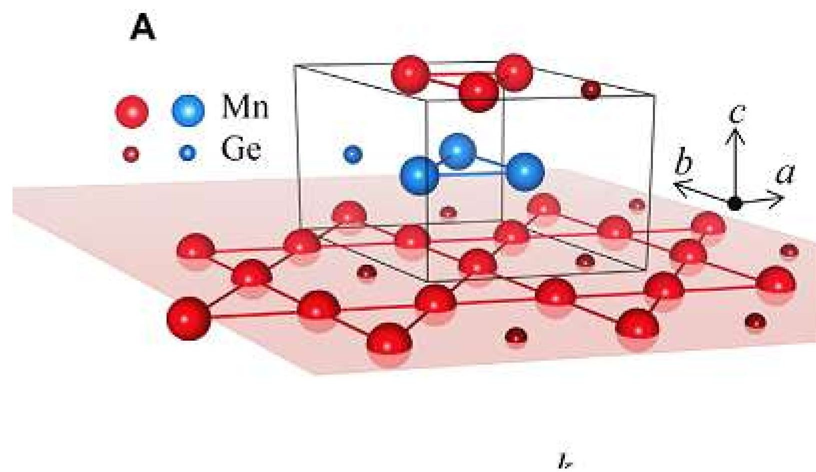




Summary

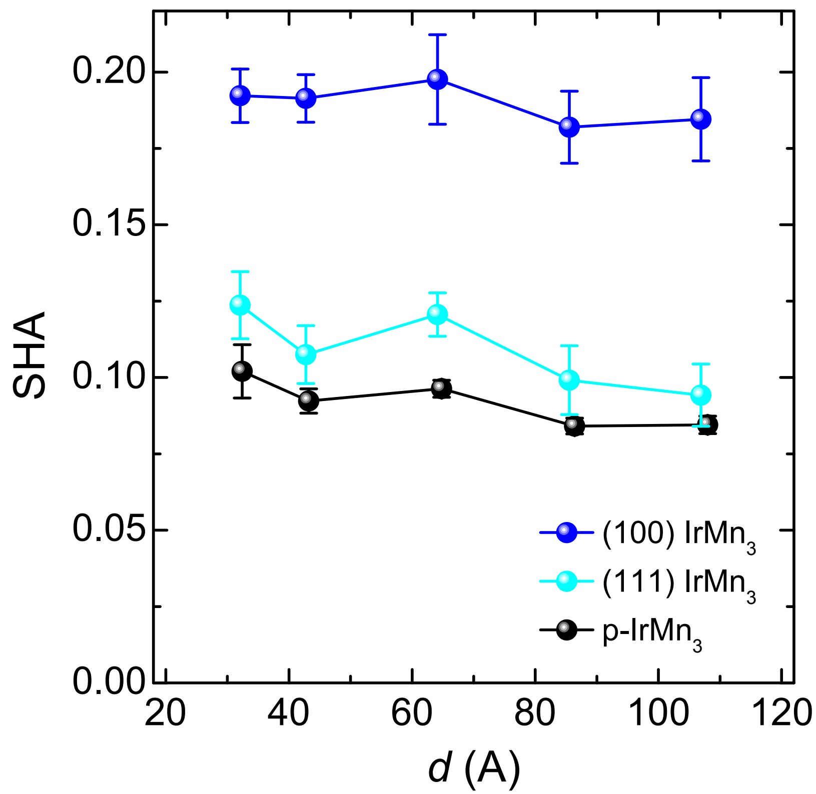
5. Anomalous Hall effect in AFM

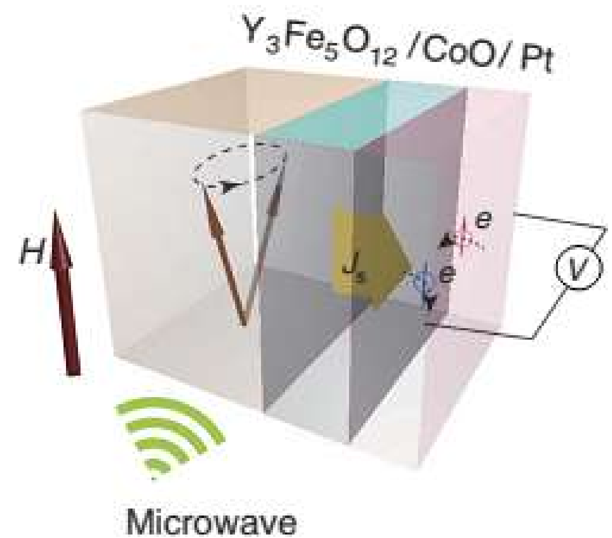




Summary

6. Spin orbit torque in AFM





下一节课: Dec. 13th, 20th, 27th

Student Presentations

20 mins/ Per person

15 mins talk + 5 mins questions

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

下一节课: Dec. 13th, 20th, 27th

Date	Names
Dec. 13^{th}	陈阳阳; 邢文宇; 刘林; 刘雅卉; 刘彦昭
Dec. 20^{th}	马扬; 孙健; 唐维; 谢志坚; 薛海鹏
Dec. 27^{th}	姚云焱; 张晓玥; 李金培；张雅文

谢谢！