

Chapter 3

Magnetoresistance

韩伟

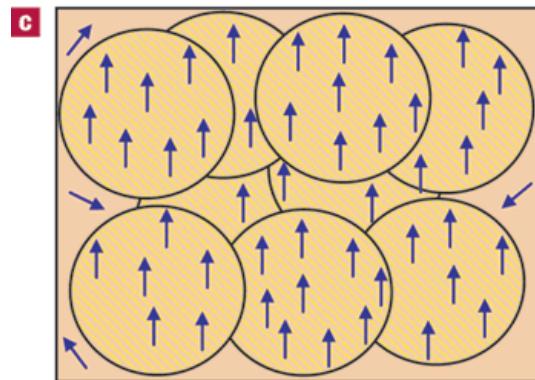
量子材料科学中心

2018年10月19日

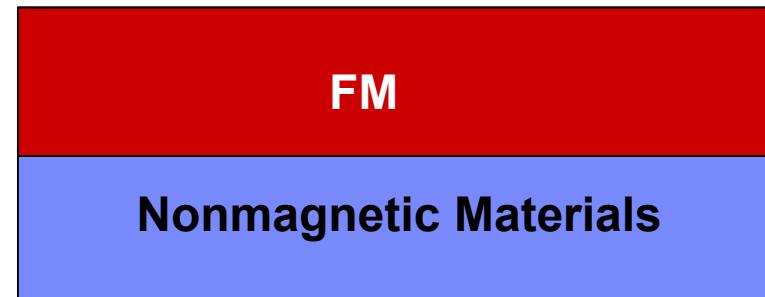
Review of last class

How to induce magnetic moment

Doping



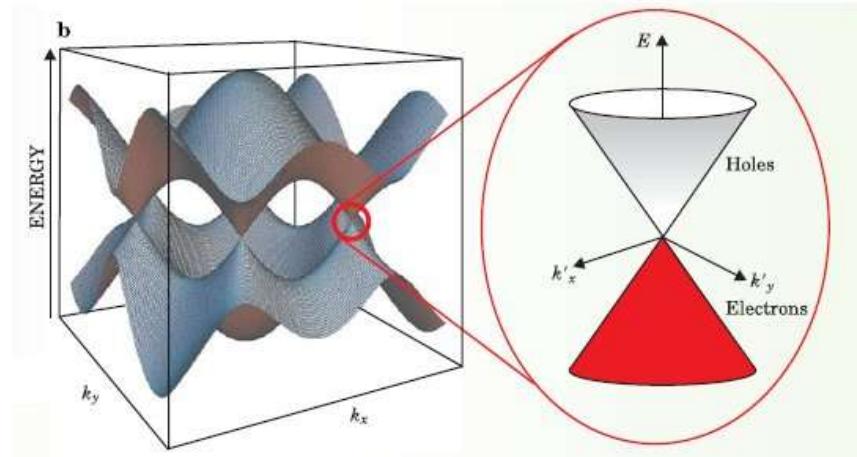
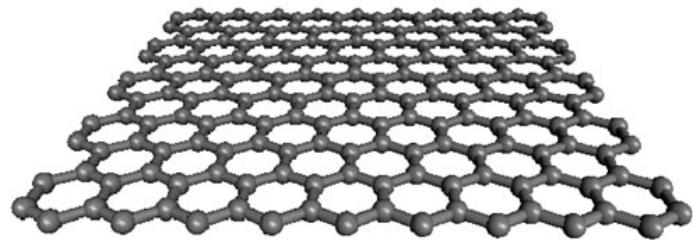
Proximity effect



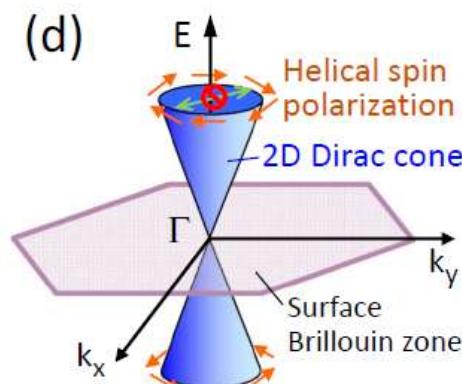
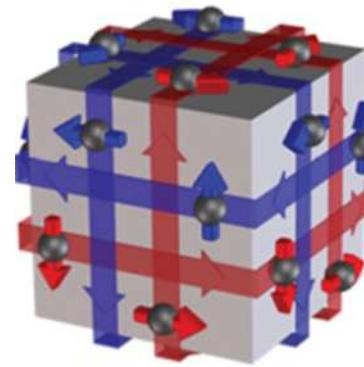
Review of last class

Induce M in two Quantum Materials

Graphene

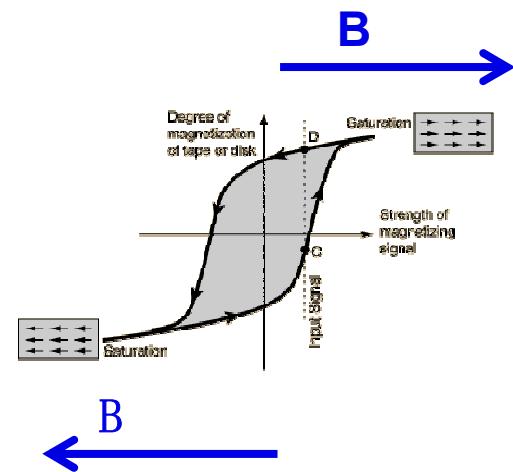


Topological Insulator



Review of last class

Magnetic field



Without B
???

Control

Electric field

Spin torque

Ultrafast Laser

Interface Strain

Outline

1. Magnetoresistance and ordinary MR

2. Anisotropic MR

3. Tunneling AMR

4. Colossal MR

5. Giant MR

6. Tunneling MR

7. Spin Hall MR

8. Nonlocal MR

9. Hanle MR

Outline

1. Magnetoresistance

Magnetoresistance

Ordinary
magnetoresistance (OMR)

Anisotropic
magnetoresistace (AMR)

Tunneling AMR
(TAMR)

Colossal magnetoresistance
(CMR)

Giant magnetoresistance
(GMR)

Tunneling
magnetoresistance (TMR)

Spin Hall
magnetoresistance (SMR)

Nonlocal MR

Hanle magnetoresistance

Ordinary MR

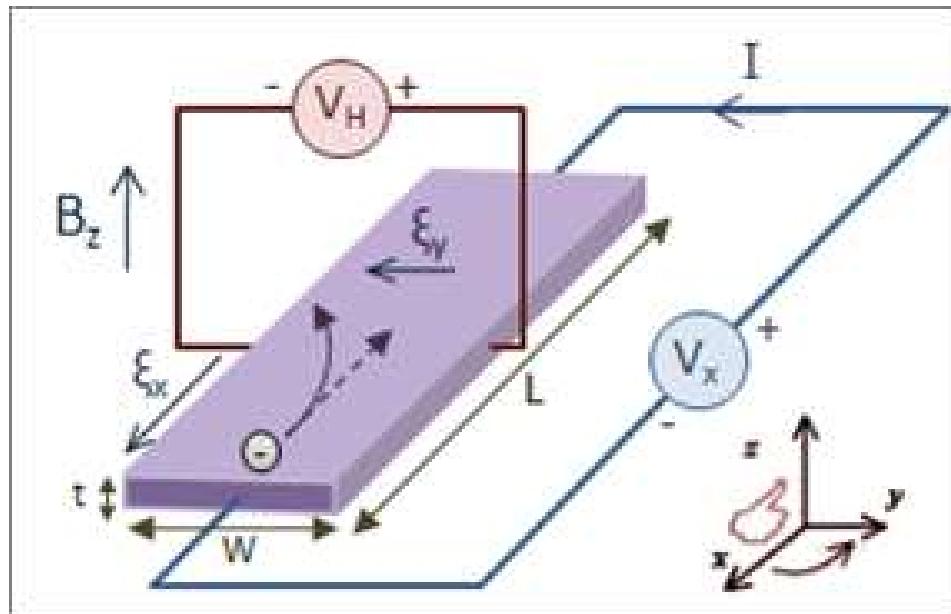
A resistor in magnetic field



The resistance change in a magnetic field

Ordinary MR

Ordinary MR in a semiconductor—Lorentz force



$$v = \mu(E + v \times B)$$

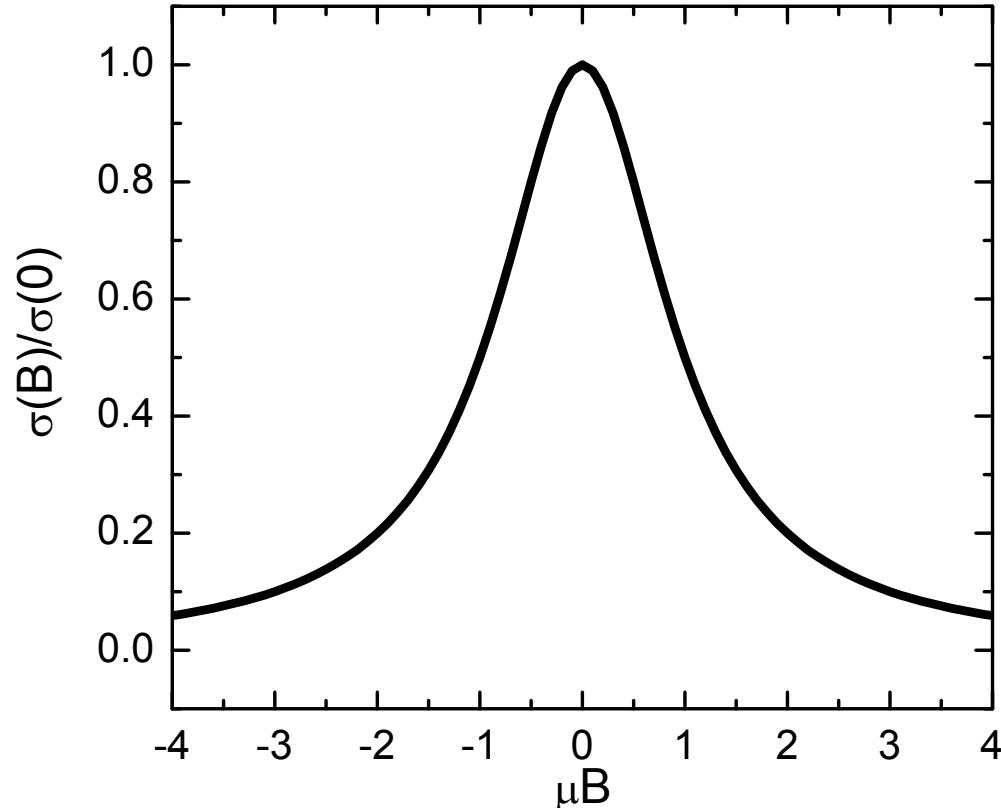
$$v = \frac{\mu Ex}{(1 + (\mu B)^2)}$$

$$\mu_{eff} = \frac{\mu(0T)}{(1 + (\mu B)^2)}$$

$$\sigma = ne\mu = \frac{\sigma(0T)}{(1 + (\mu B)^2)}$$

Ordinary MR

$$\sigma = ne\mu = \frac{\sigma(0T)}{(1 + (\mu B)^2)}$$



Ordinary MR

Two carriers MR

First type

$$\sigma_{1xx} = \frac{en_1\mu_1}{(1 + (\mu_1 B)^2)}$$

$$\sigma_{1xy} = \frac{eBn_1\mu_1^2}{(1 + (\mu_1 B)^2)}$$

Second type

$$\sigma_{2xx} = \frac{en_2\mu_2}{(1 + (\mu_2 B)^2)}$$

$$\sigma_{2xy} = \frac{eBn_2\mu_2^2}{(1 + (\mu_2 B)^2)}$$

Ordinary MR

Two carriers MR

$$\sigma = \sigma_1 + \sigma_2$$

$$\rho = \sigma^{-1}$$

$$\rho = \begin{bmatrix} \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} & \frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} \\ \frac{-\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} & \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \end{bmatrix}$$

Ordinary MR

Two carriers MR

$$e\rho_{xx} = \frac{\frac{n_1\mu_1}{1+B^2\mu_1^2} + \frac{n_2\mu_2}{1+B^2\mu_2^2}}{\left(\frac{n_1\mu_1}{1+B^2\mu_1^2} + \frac{n_2\mu_2}{1+B^2\mu_2^2}\right)^2 + B^2\left(\frac{n_1\mu_1^2}{1+B^2\mu_1^2} + \frac{n_2\mu_2^2}{1+B^2\mu_2^2}\right)^2}$$

$$e\rho_{xy} = B \frac{\frac{n_1\mu_1^2}{1+B^2\mu_1^2} + \frac{n_2\mu_2^2}{1+B^2\mu_2^2}}{\left(\frac{n_1\mu_1}{1+B^2\mu_1^2} + \frac{n_2\mu_2}{1+B^2\mu_2^2}\right)^2 + B^2\left(\frac{n_1\mu_1^2}{1+B^2\mu_1^2} + \frac{n_2\mu_2^2}{1+B^2\mu_2^2}\right)^2}$$

Ordinary MR

Two carriers MR

$$e\rho_{xx} = \frac{\frac{n_1\mu_1}{1+B^2\mu_1^2} + \frac{n_2\mu_2}{1+B^2\mu_2^2}}{\left(\frac{n_1\mu_1}{1+B^2\mu_1^2} + \frac{n_2\mu_2}{1+B^2\mu_2^2}\right)^2 + B^2\left(\frac{n_1\mu_1^2}{1+B^2\mu_1^2} + \frac{n_2\mu_2^2}{1+B^2\mu_2^2}\right)^2}$$

$$B > 1/\mu_1; B > 1/\mu_1$$

$$e\rho_{xx} = \frac{\left(\frac{n_1}{\mu_1} + \frac{n_2}{\mu_2}\right)}{(n_1 + n_2)^2 + \frac{1}{B^2}\left(\frac{n_1}{\mu_1} + \frac{n_2}{\mu_2}\right)^2} \sim \frac{n_1\mu_2 + n_2\mu_1}{(n_1 + n_2)\mu_1\mu_2}$$

Ordinary MR

Two carriers MR

$$B = 0 \quad e\rho_{xx}(0) = \frac{1}{(n_1\mu_1 + n_2\mu_2)}$$

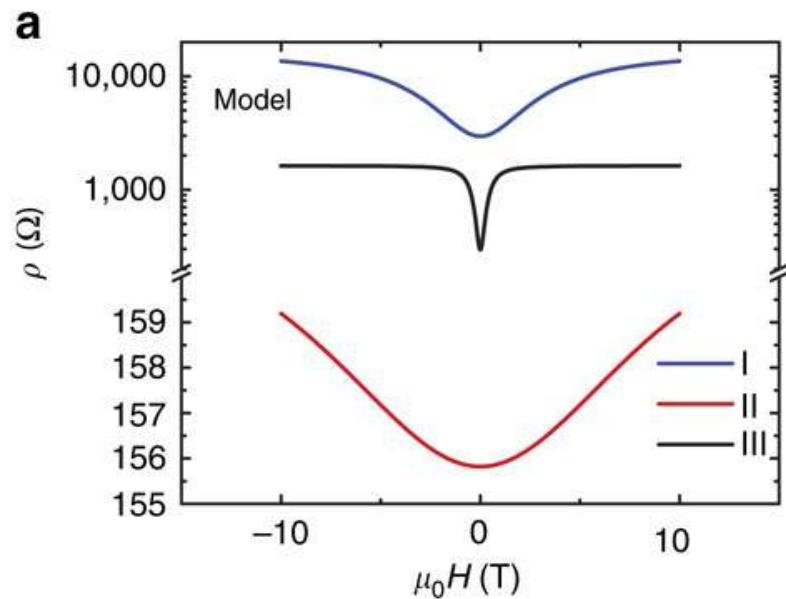
$$MR = \frac{\rho_{xx} - \rho_0}{\rho_0} = \frac{\frac{n_1\mu_2 + n_2\mu_1}{(n_1 + n_2)\mu_1\mu_2} - \frac{1}{(n_1\mu_1 + n_2\mu_2)}}{\frac{1}{(n_1\mu_1 + n_2\mu_2)}}$$

$$\mu_1 \gg \mu_2; \quad n_2\mu_1 \gg n_1\mu_2$$

$$MR = \frac{n_1 n_2}{(n_1 + n_2)^2} \frac{\mu_1}{\mu_2}$$

Ordinary MR

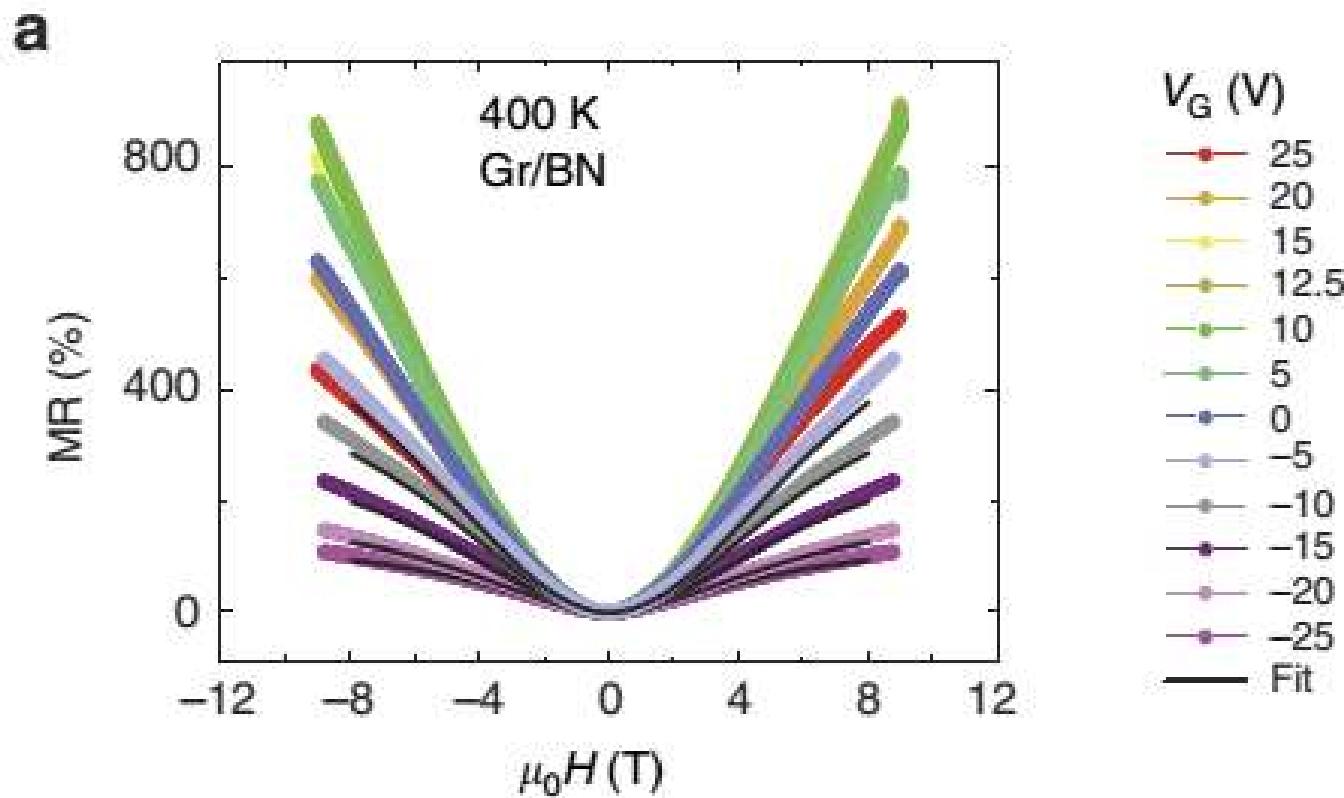
Large MR in Graphene with two carriers



	n_1 (cm^{-2})	μ_1 (cm^2/Vs)	n_2 (cm^{-2})	μ_2 (cm^2/Vs)
I	10^{11}	20,000	1.1×10^{11}	1,000
II	8×10^{12}	5000	1.1×10^{11}	1,000
III	10^{11}	200,000	1.1×10^{11}	10,000

Ordinary MR

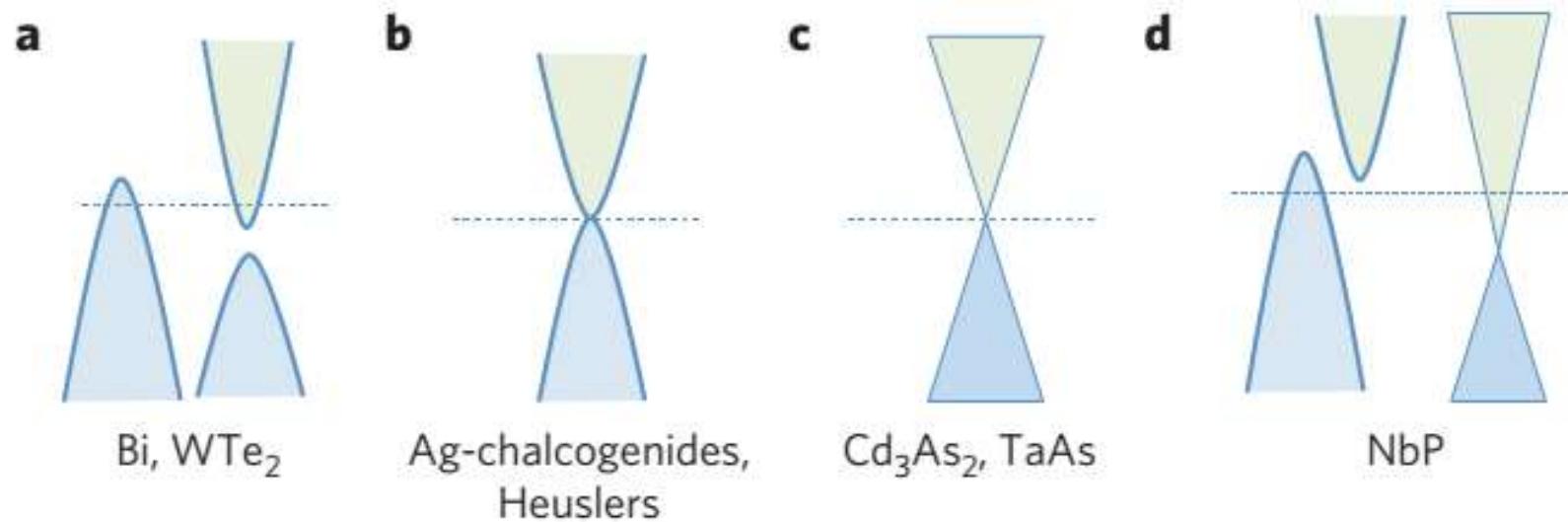
Large MR in Graphene with two carriers



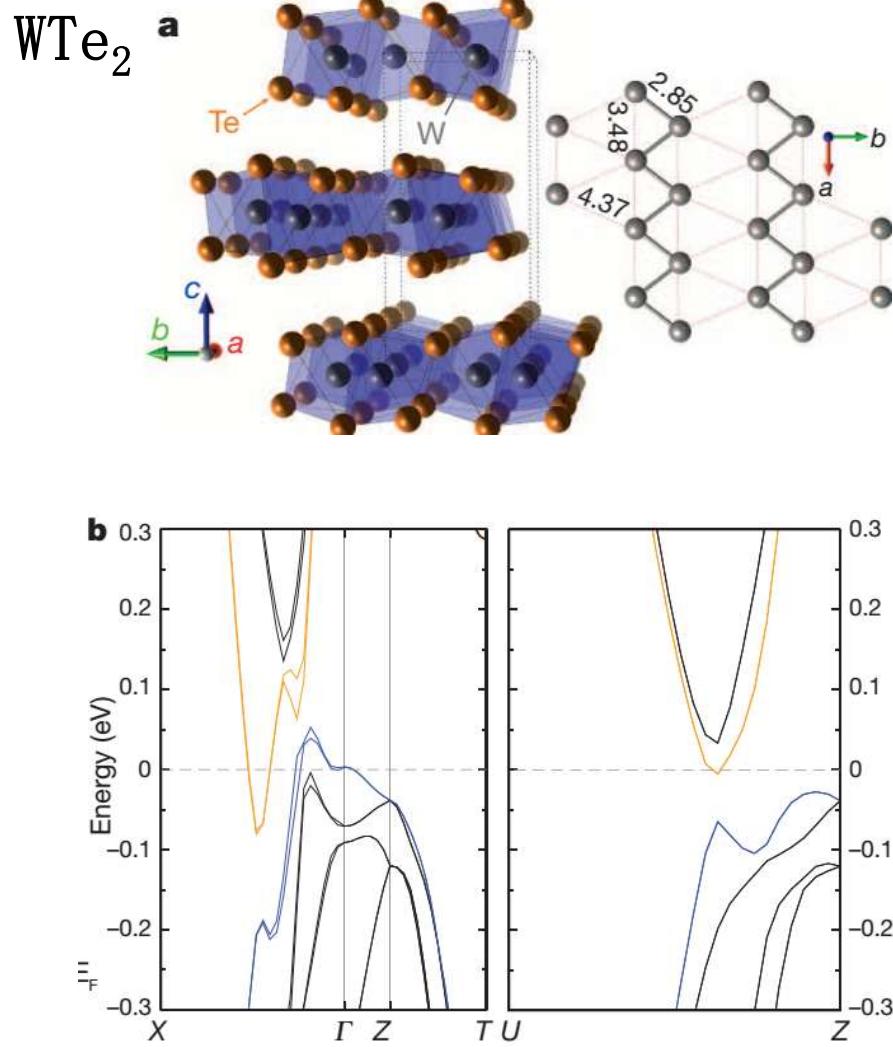
Gopinadhan, et al, Nature Commun. (2015)

Ordinary MR

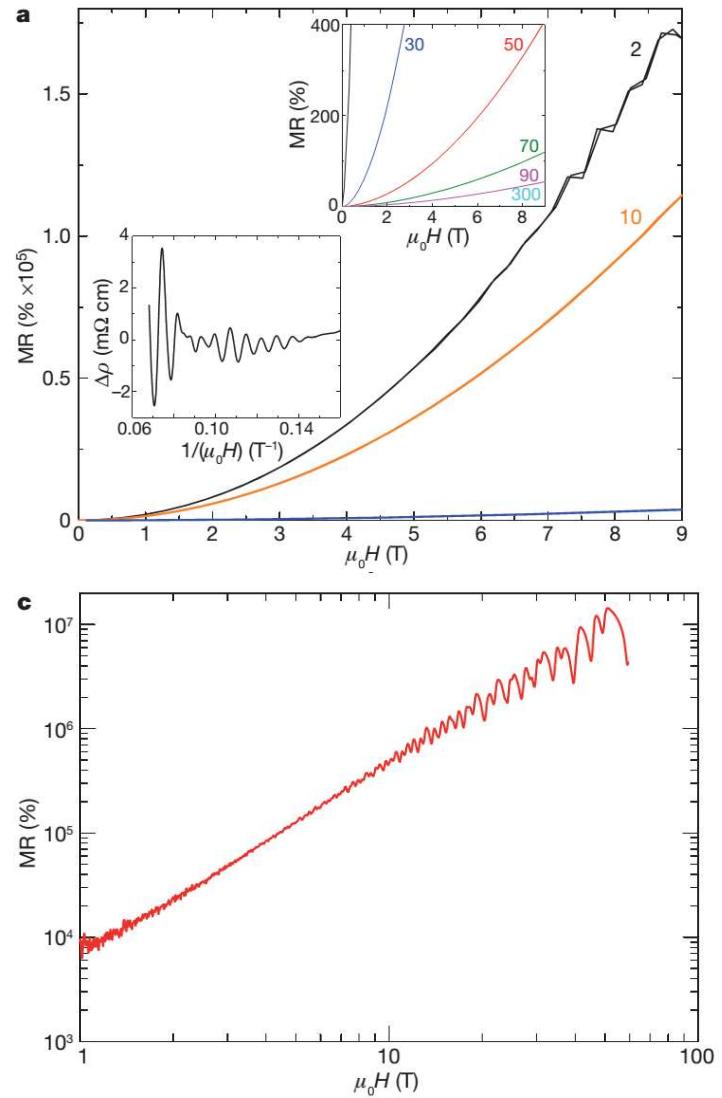
Large ordinary MR in semimetal



Ordinary MR

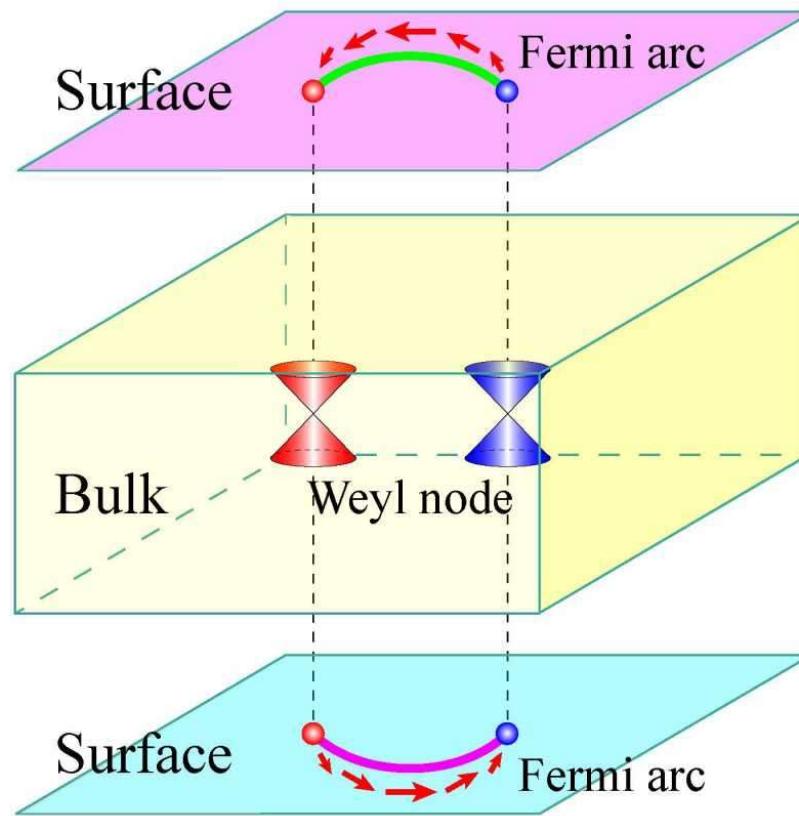


Ali, et al, Nature (2014)



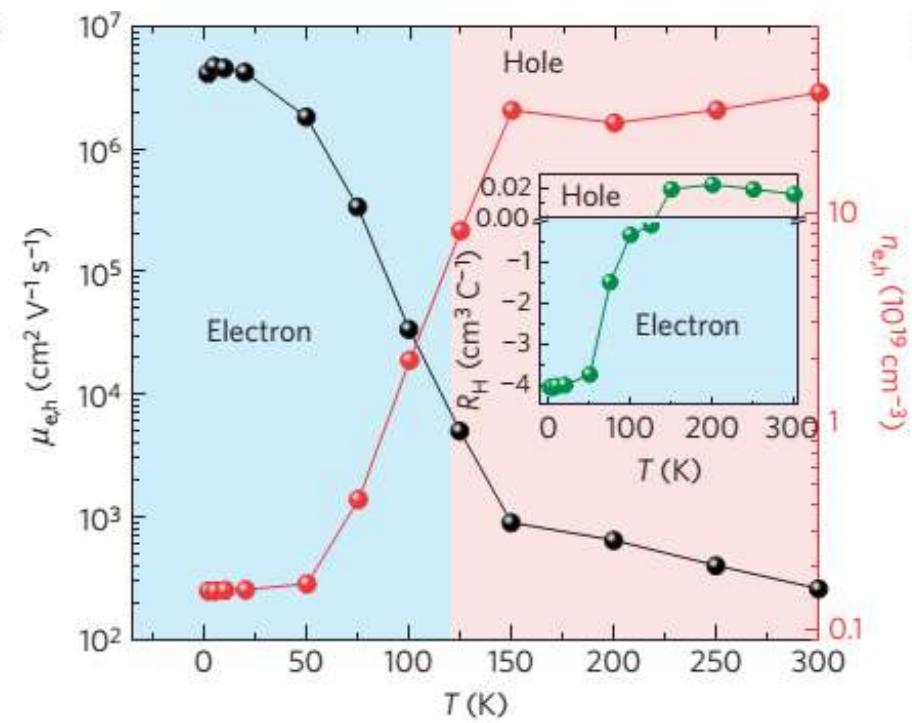
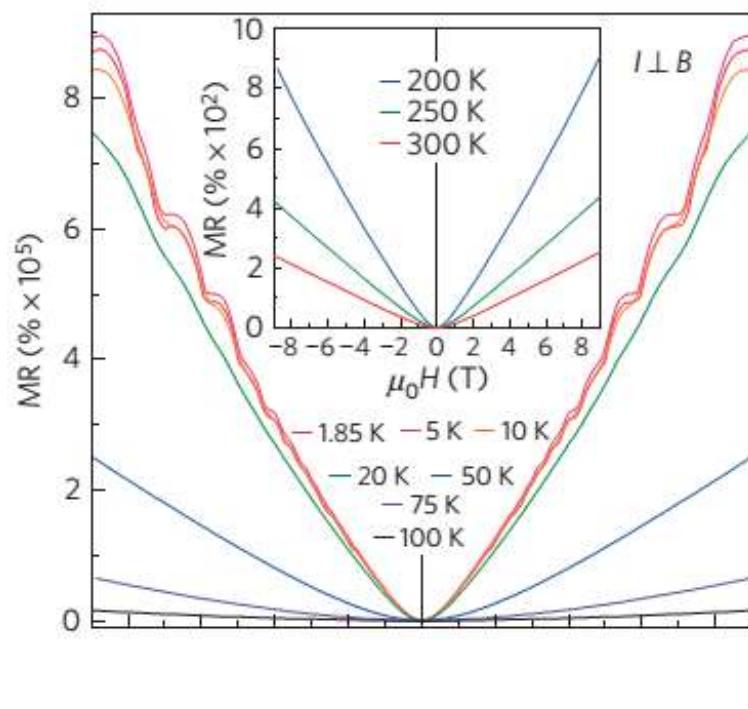
Ordinary MR

Large ordinary MR in Weyl semimetal



Ordinary MR

Large ordinary MR in Weyl semimetal: NbP



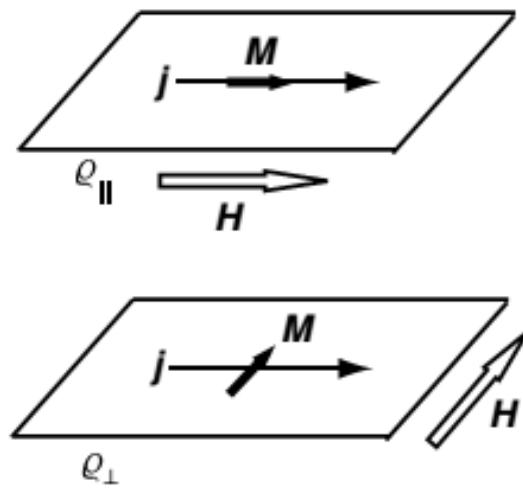
Outline

2. Anisotropic MR

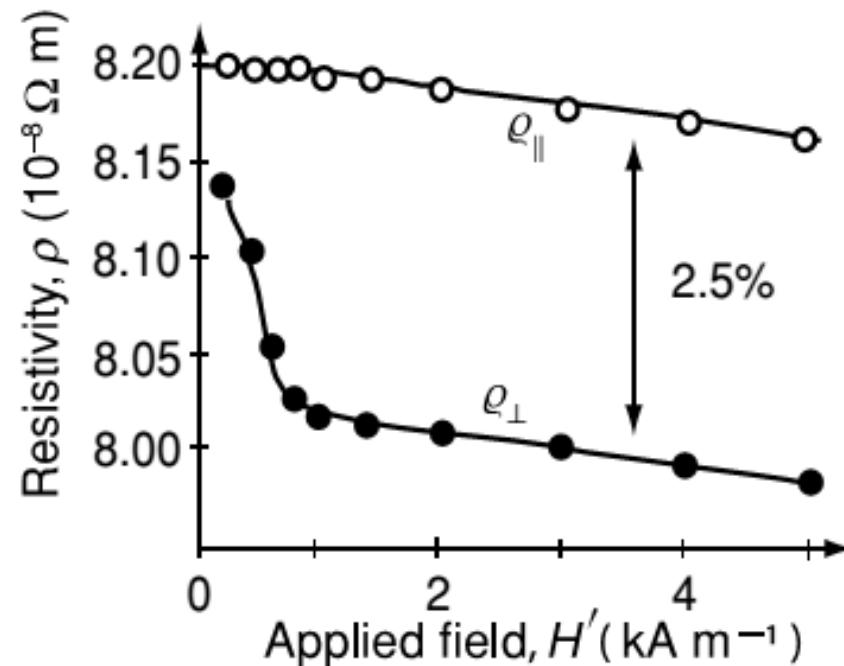
Discovery of AMR

AMR of a Nickel

Discovered by William Thompson (1857)



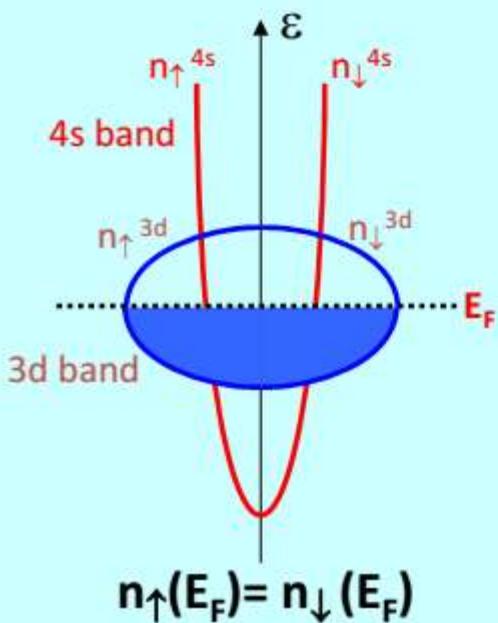
Measurement of AMR for a thin film.



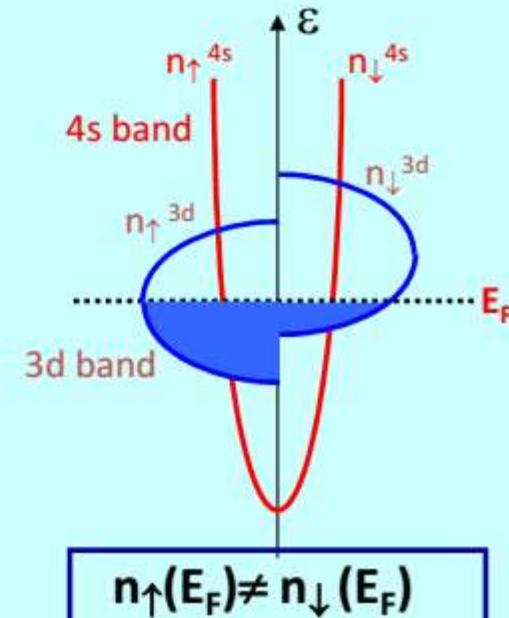
Mechanism

NM vs FM

Non magnetic Cu

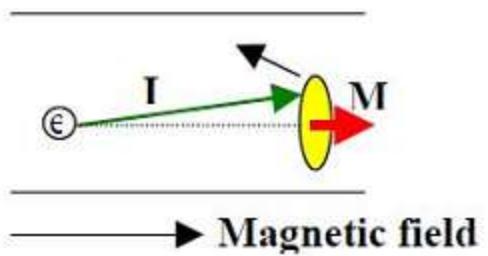


Magnetic Fe



Mechanism

Why AMR?

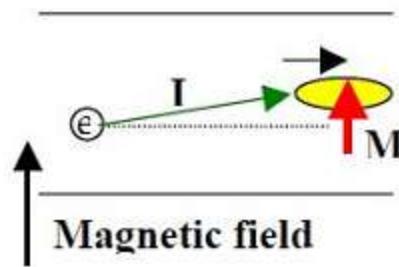


I parallel to M

↓
Electronic orbits perpendicular
to current

↓
Increased cross section for scattering

↓
High resistance



I perpendicular to M

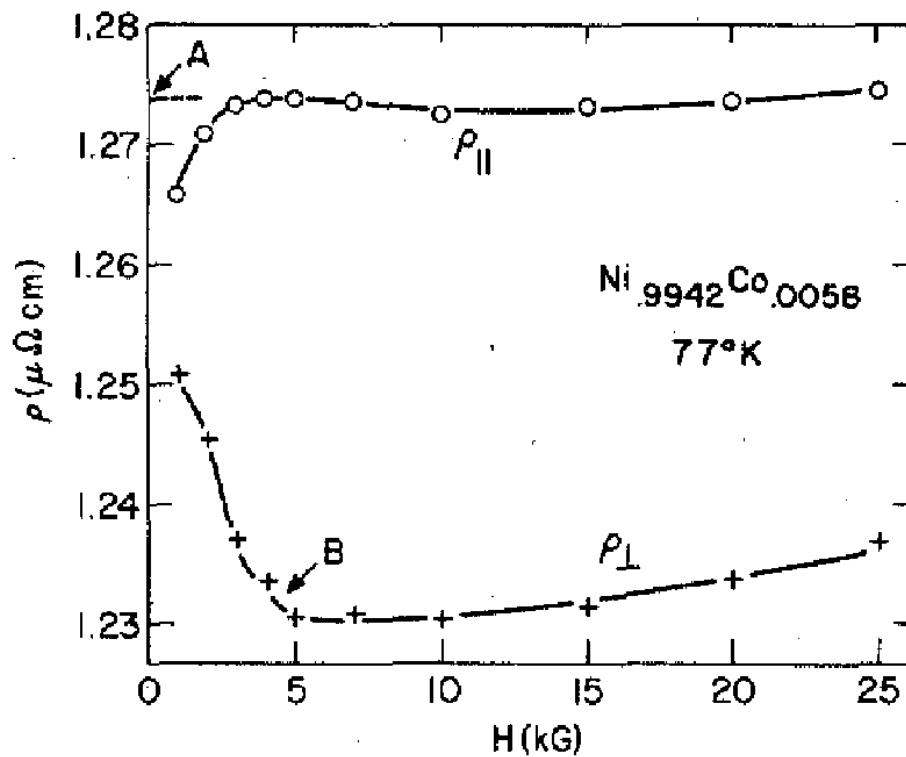
↓
Electronic orbits parallel
to current

↓
Reduced cross section for scattering

↓
Low resistance

AMR of 3d FM

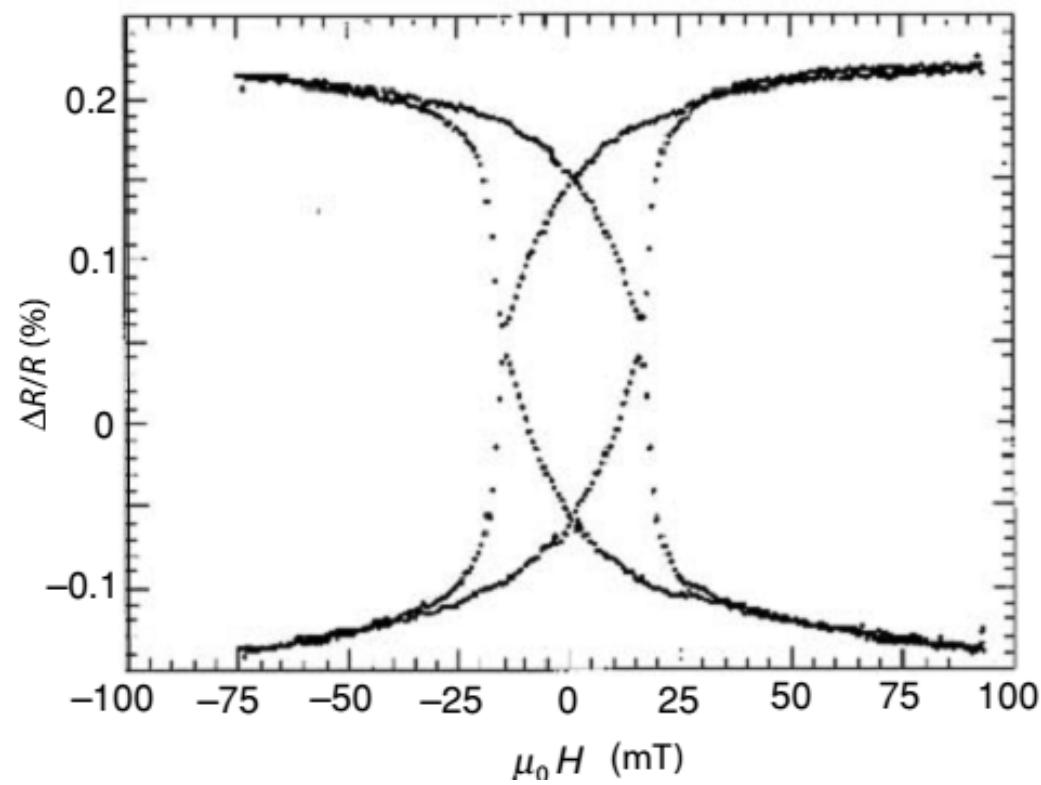
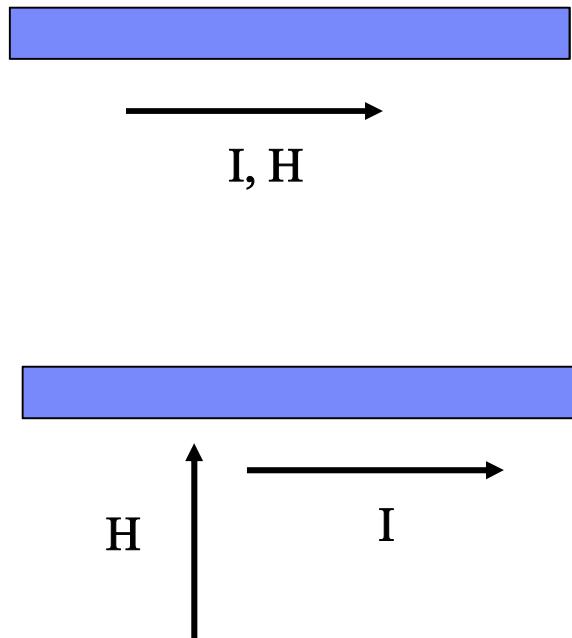
NiCo



Viret, et al, PRB (1996)

AMR of 3d FM

Py: Large AMR



Viret, et al, PRB (1996)

AMR of 3d FM alloy

Py: Large AMR

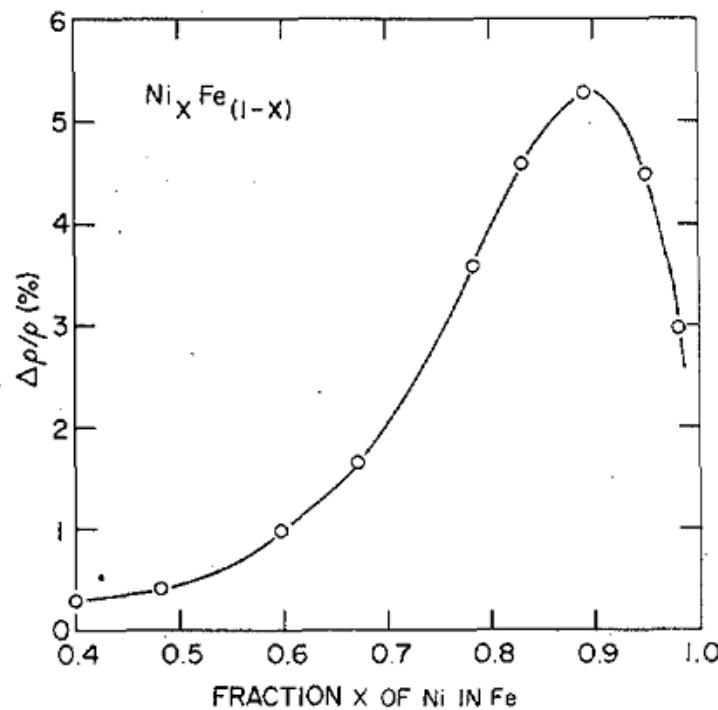
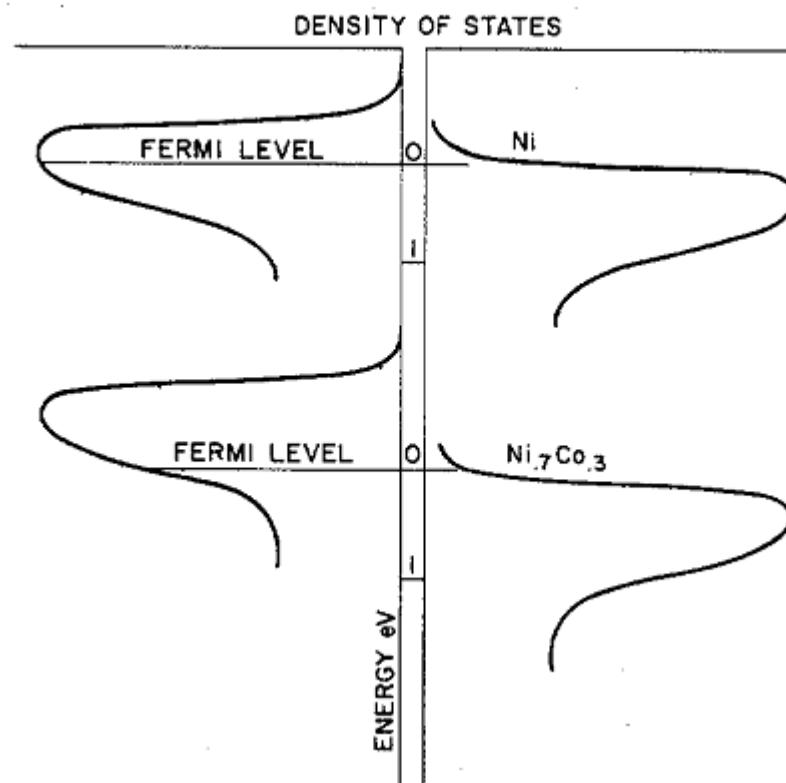
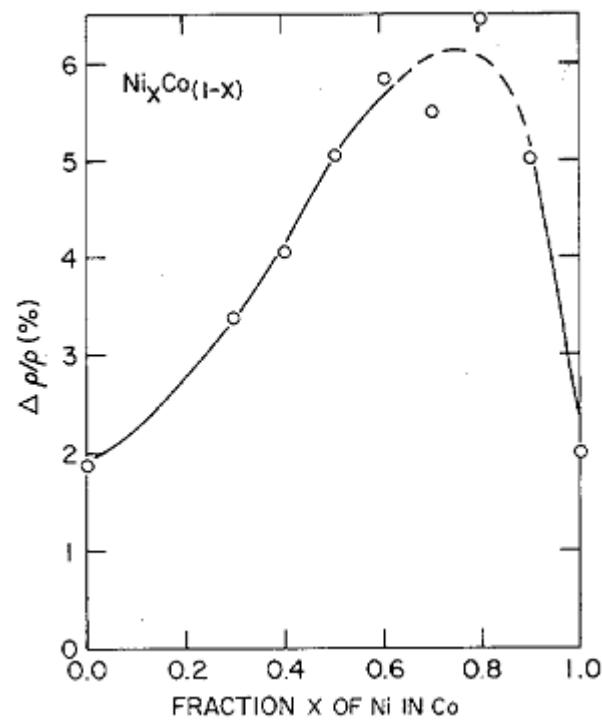


Fig. 2. Anisotropic magnetoresistivity ratio in percent for $\text{Ni}_x\text{Fe}_{(1-x)}$ alloys at room temperature (Bozorth [7]).

McGuire & Potter, et al, IEEE Magnetics (1975)

AMR of 3d FM alloy

Alloy

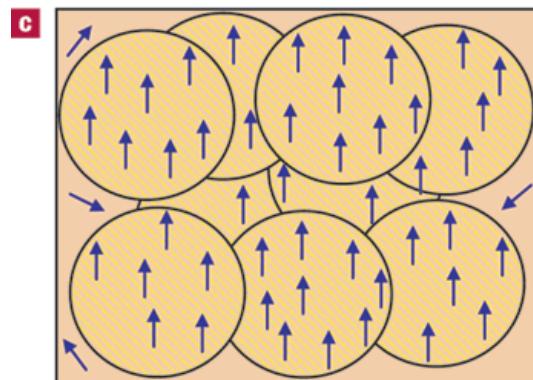


McGuire & Potter, et al, IEEE Magnetics (1975)

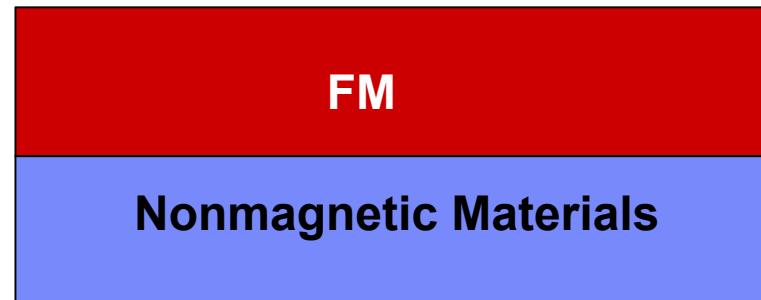
AMR to test FM

AMR to test FM

Doping

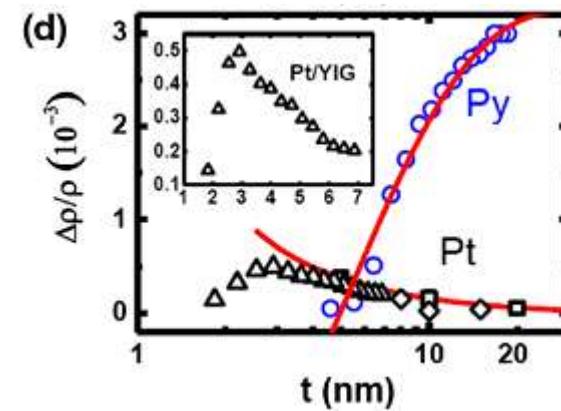
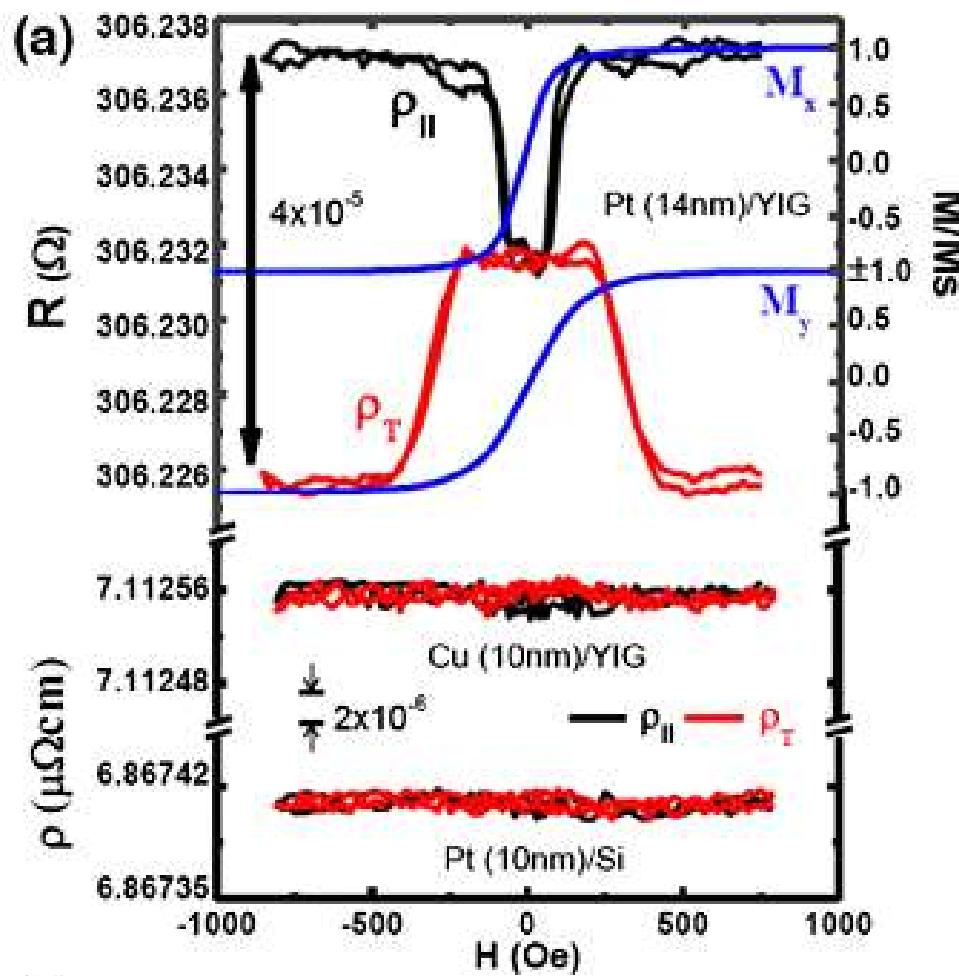


Proximity effect



AMR to test FM

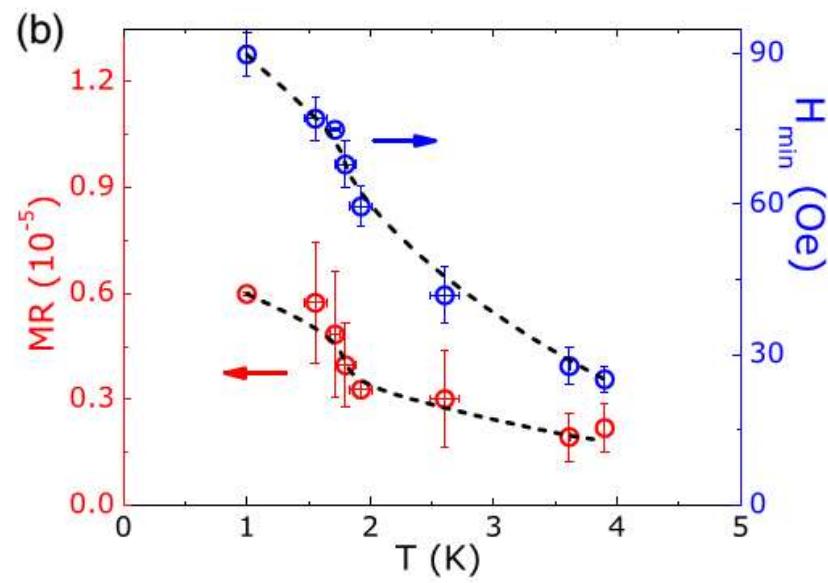
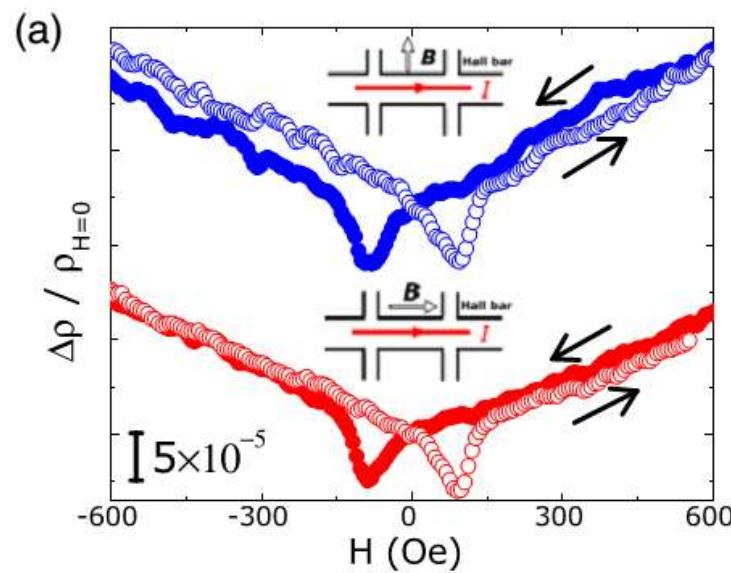
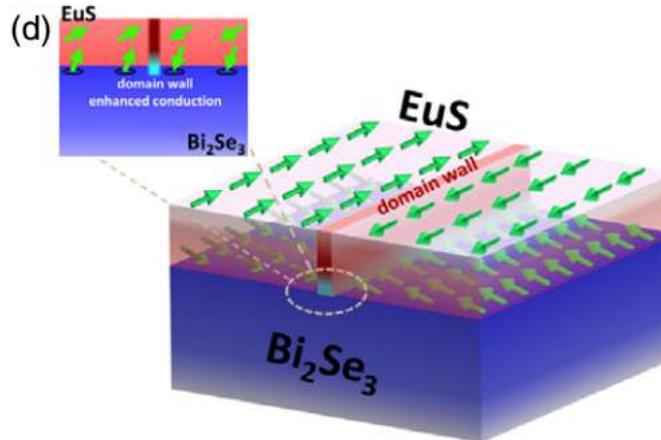
Example 1: Pt



Huang, et al, PRL (2012)

Pt and Bi₂Se₃

Example 2: Bi₂Se₃

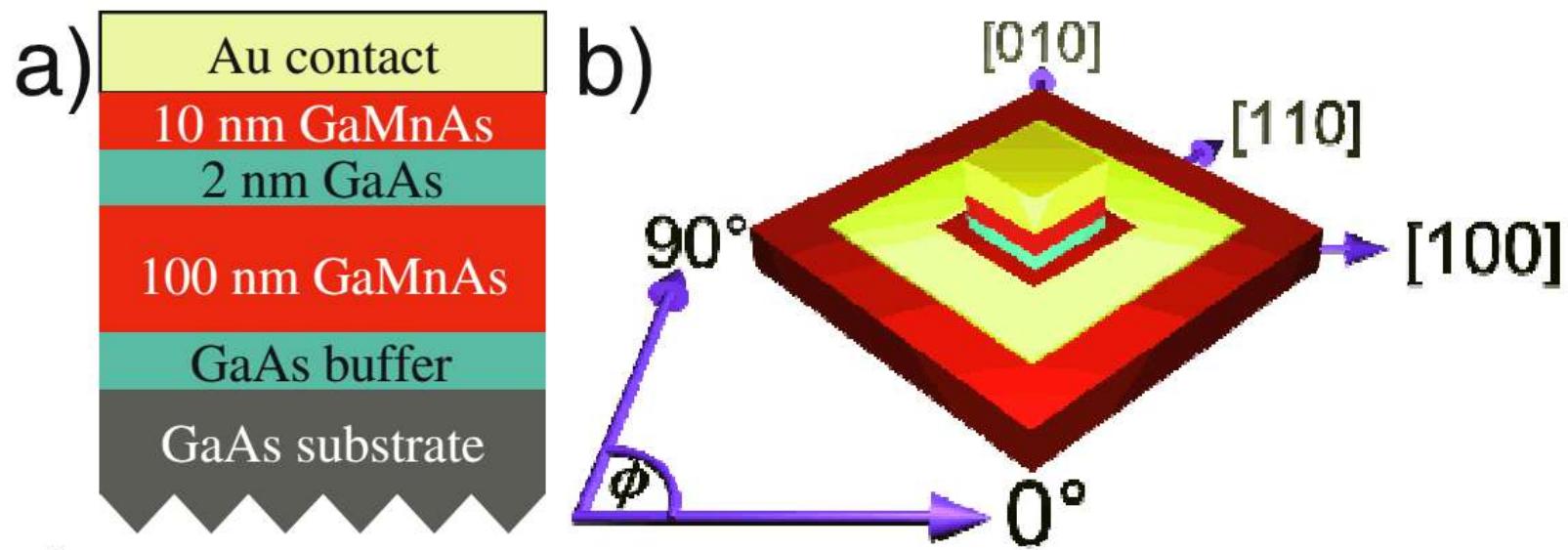


Wei, et al, PRL (2013)

Outline

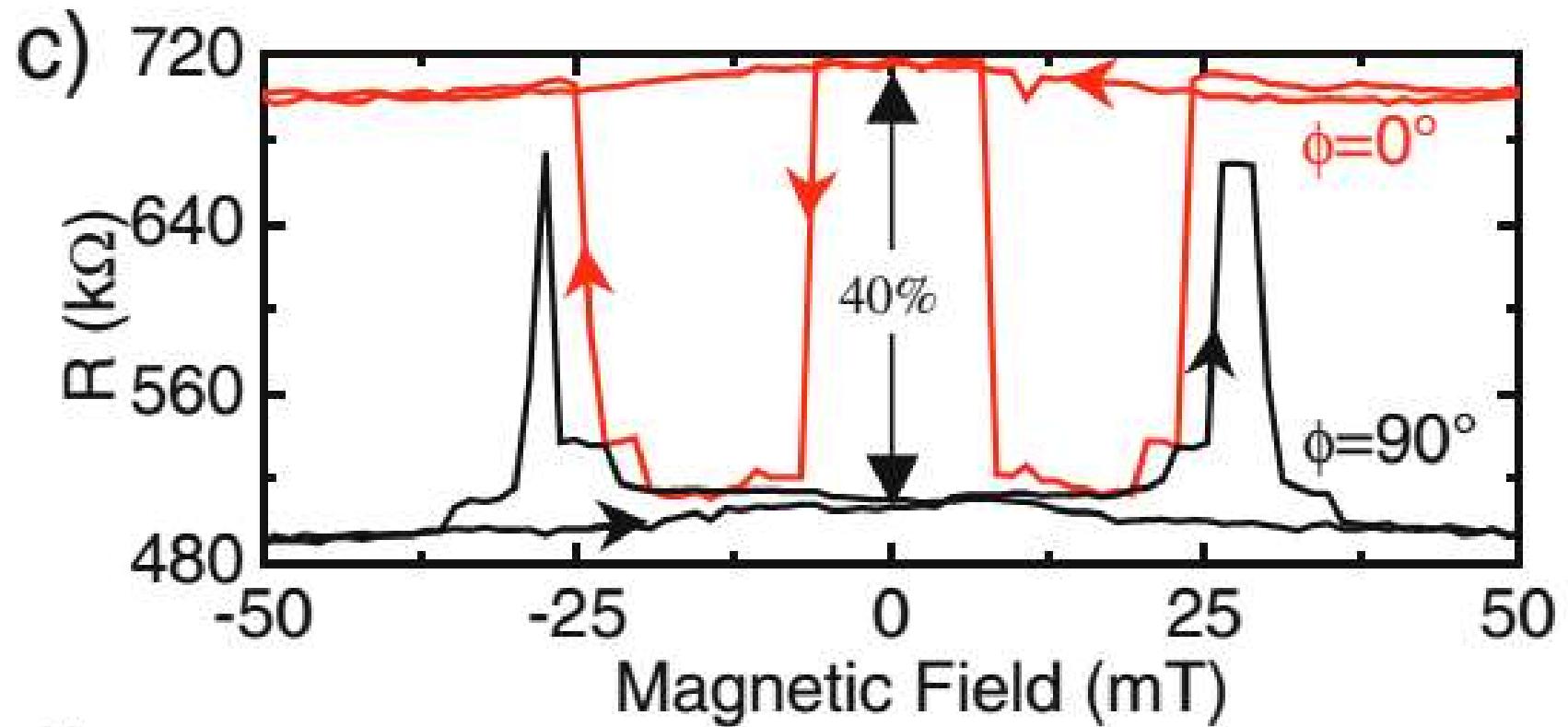
3. Tunneling AMR

Tunneling AMR



Ruster, et al, PRL (2005)

Tunneling AMR



Ruster, et al, PRL (2005)

Tunneling AMR

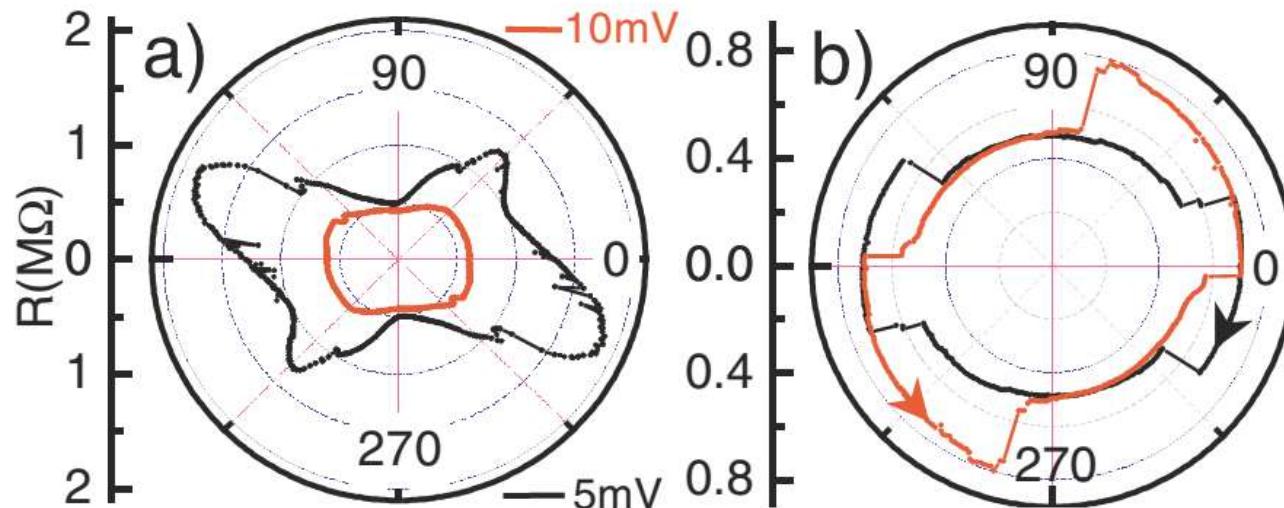
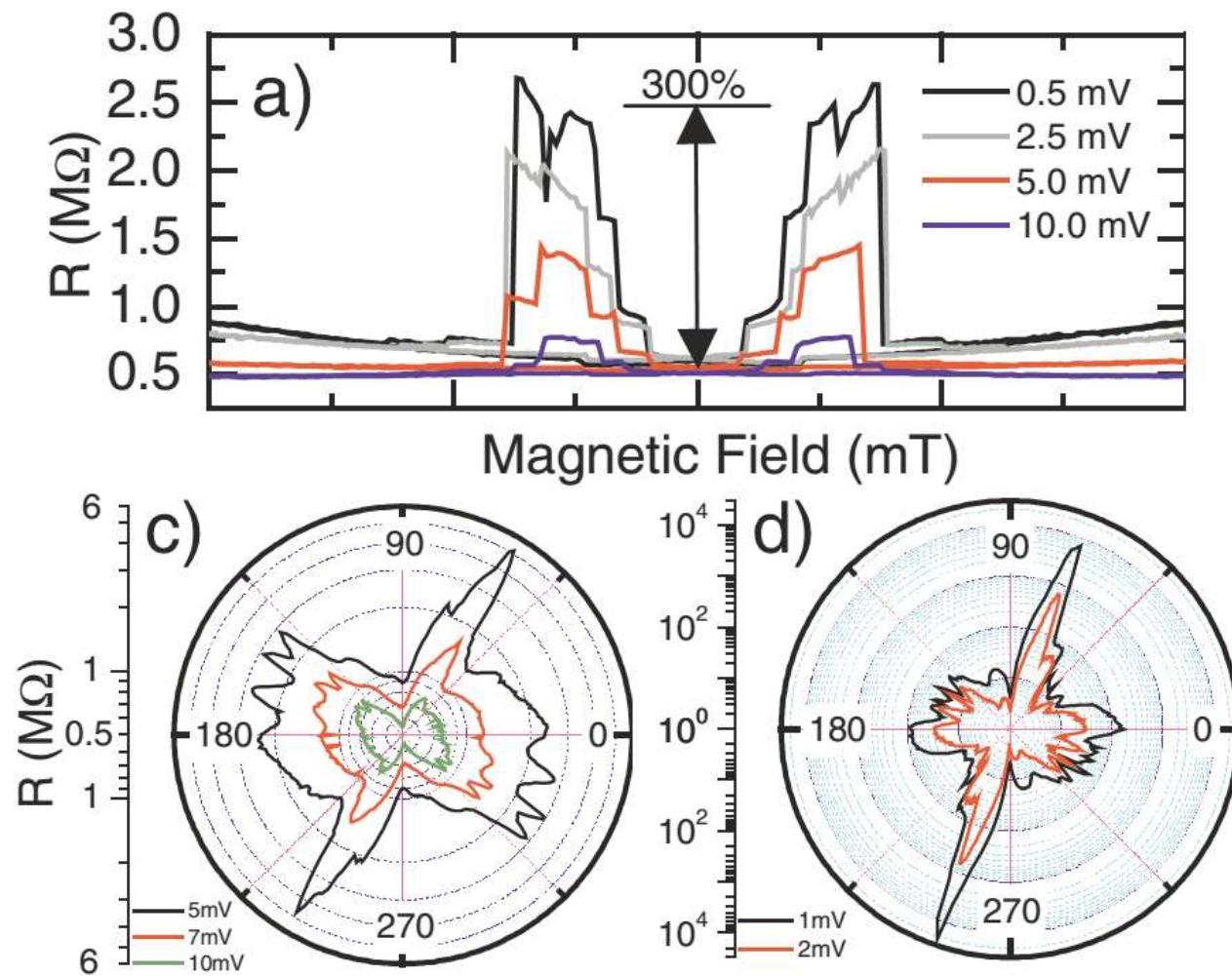


FIG. 2 (color online). ϕ scans at 4.2 K (a) in a saturation magnetic field $|\mathbf{H}| = 300$ mT, and (b) $V_B = 5$ mV at $|\mathbf{H}| = 25$ mT, just sufficient to switch M between easy axes.

Ruster, et al, PRL (2005)

Tunneling AMR



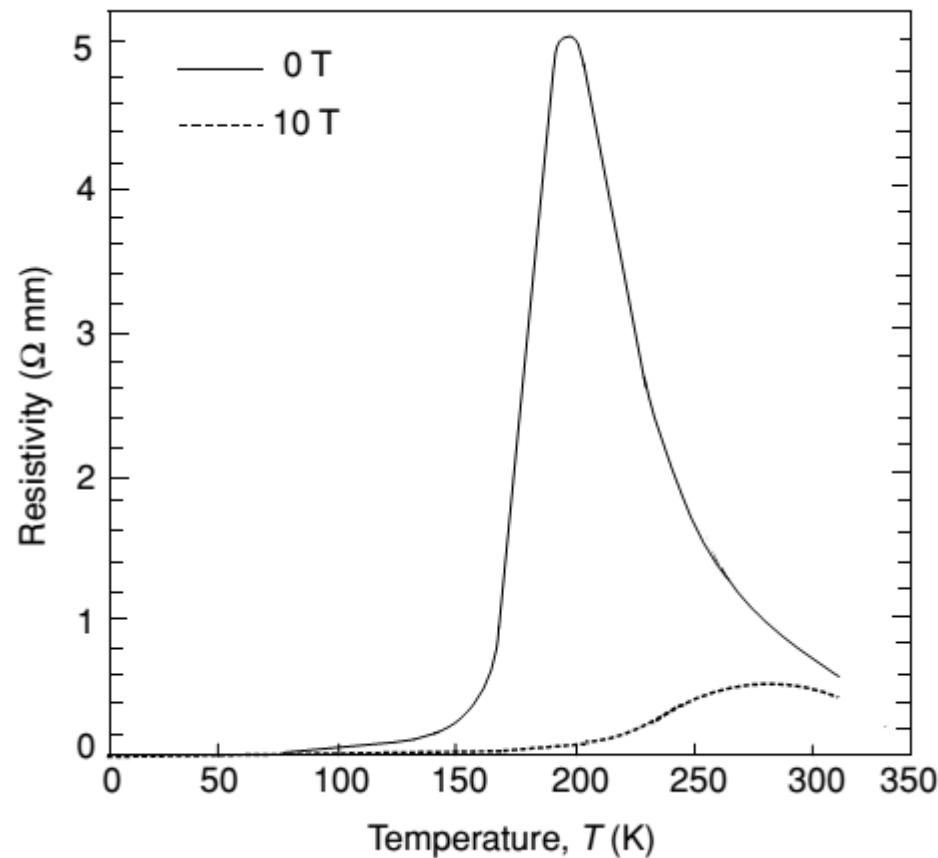
Ruster, et al, PRL (2005)

Outline

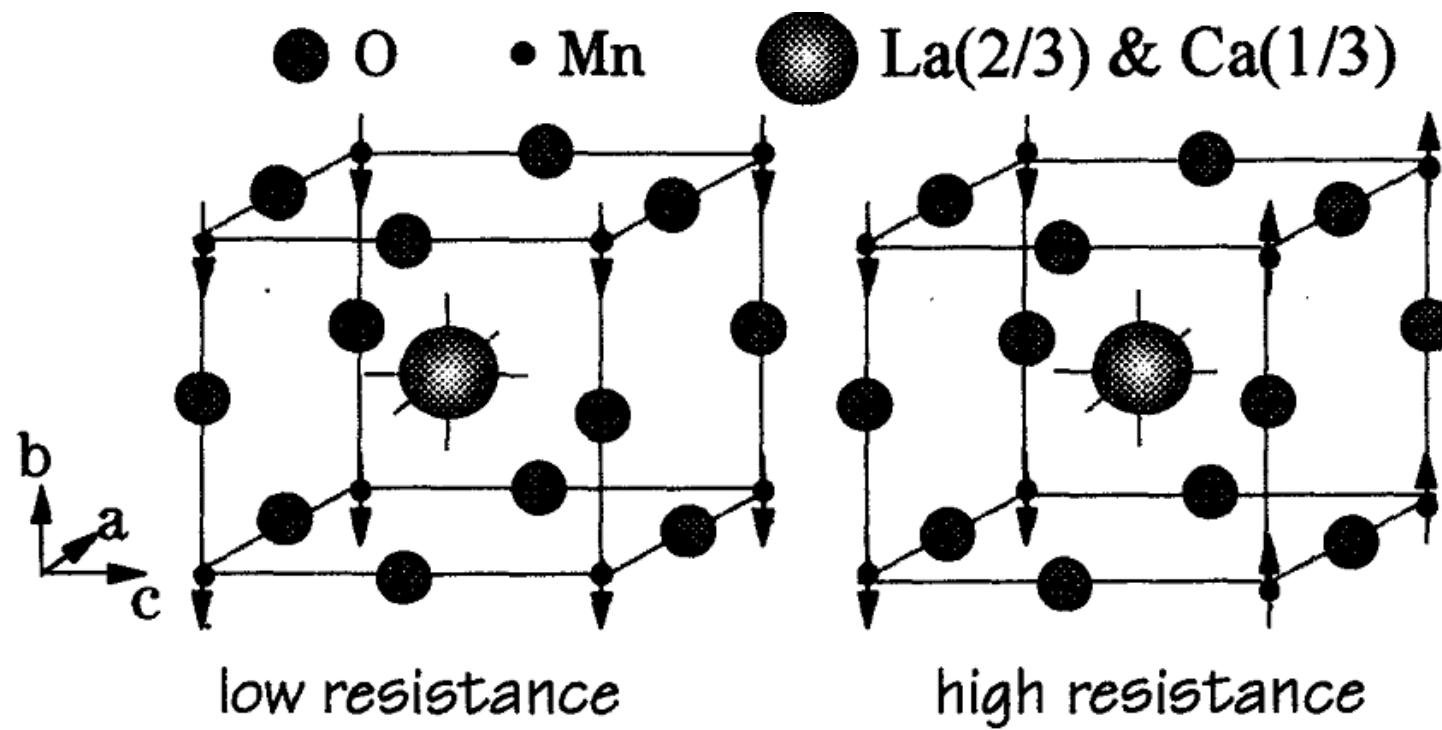
4. Colossal MR

Colossal MR

CMR in LaCaMnO₃

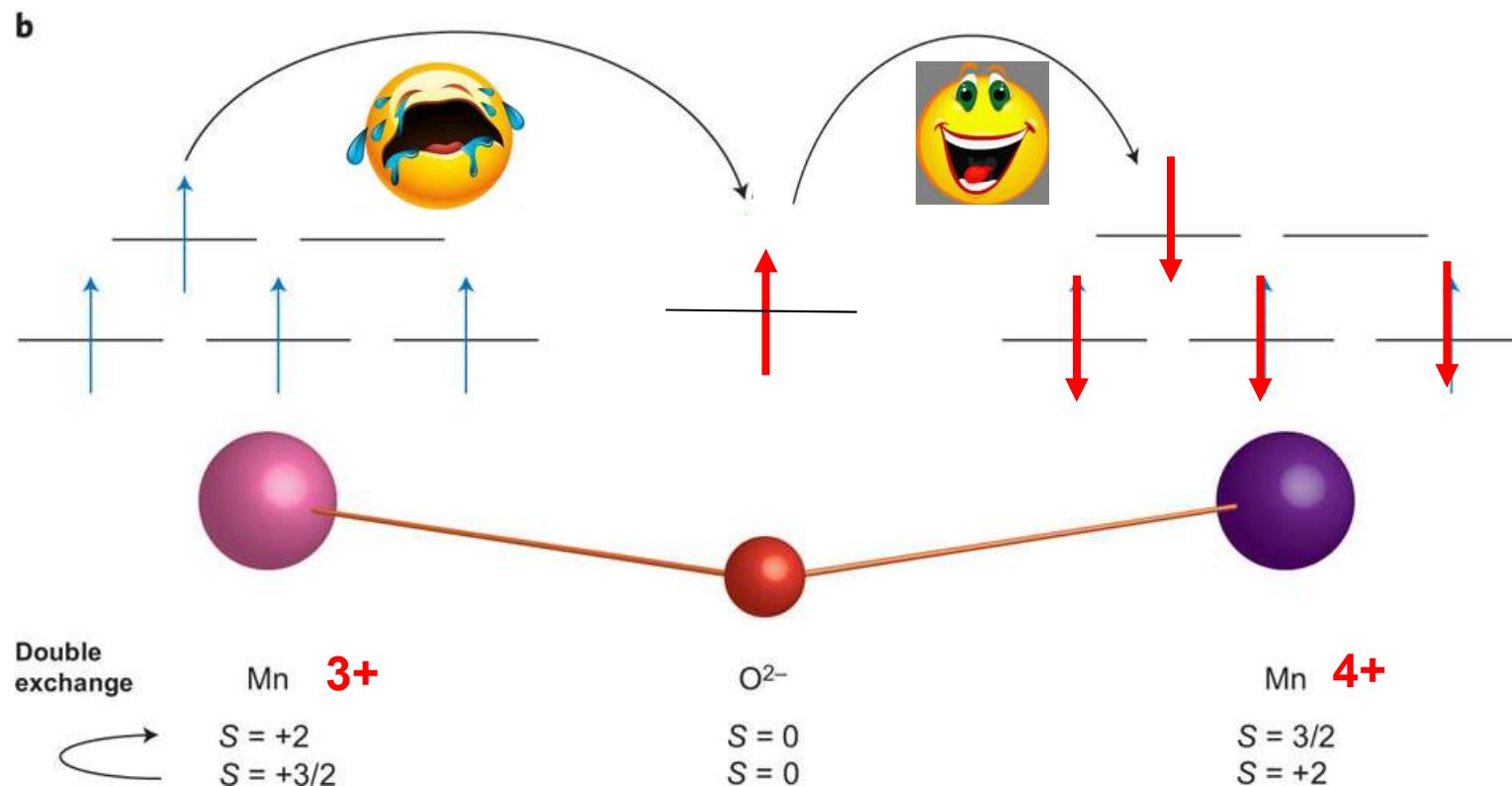


Colossal MR



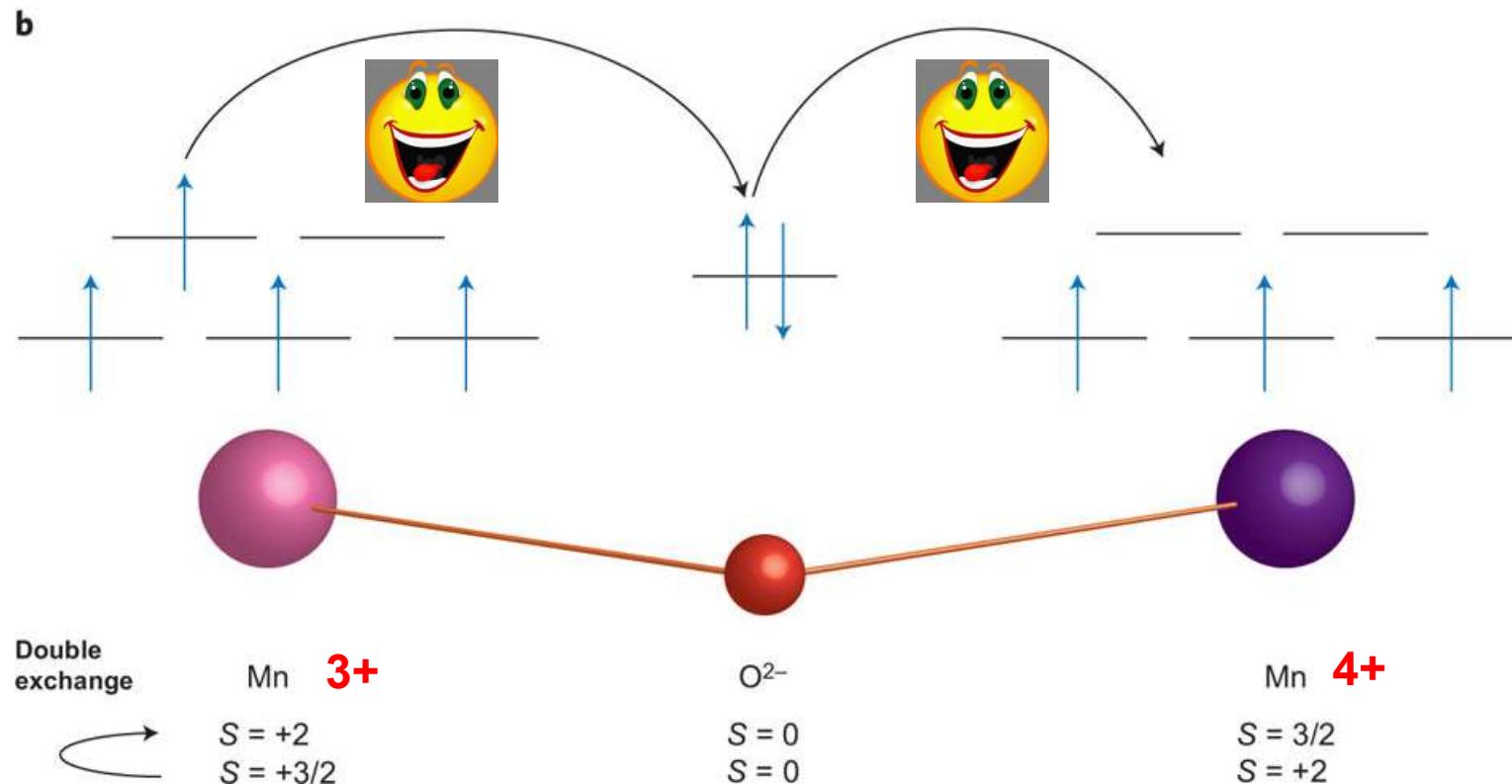
Colossal MR

Small B \rightarrow high R



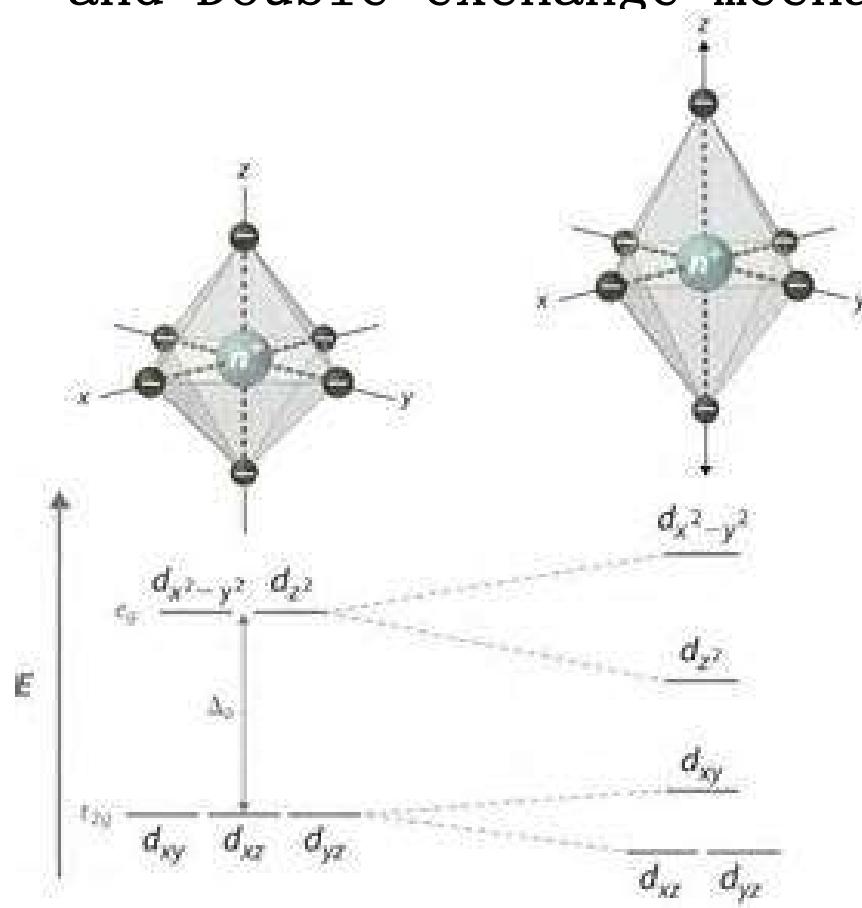
Colossal MR

Large B → Low R



Colossal MR

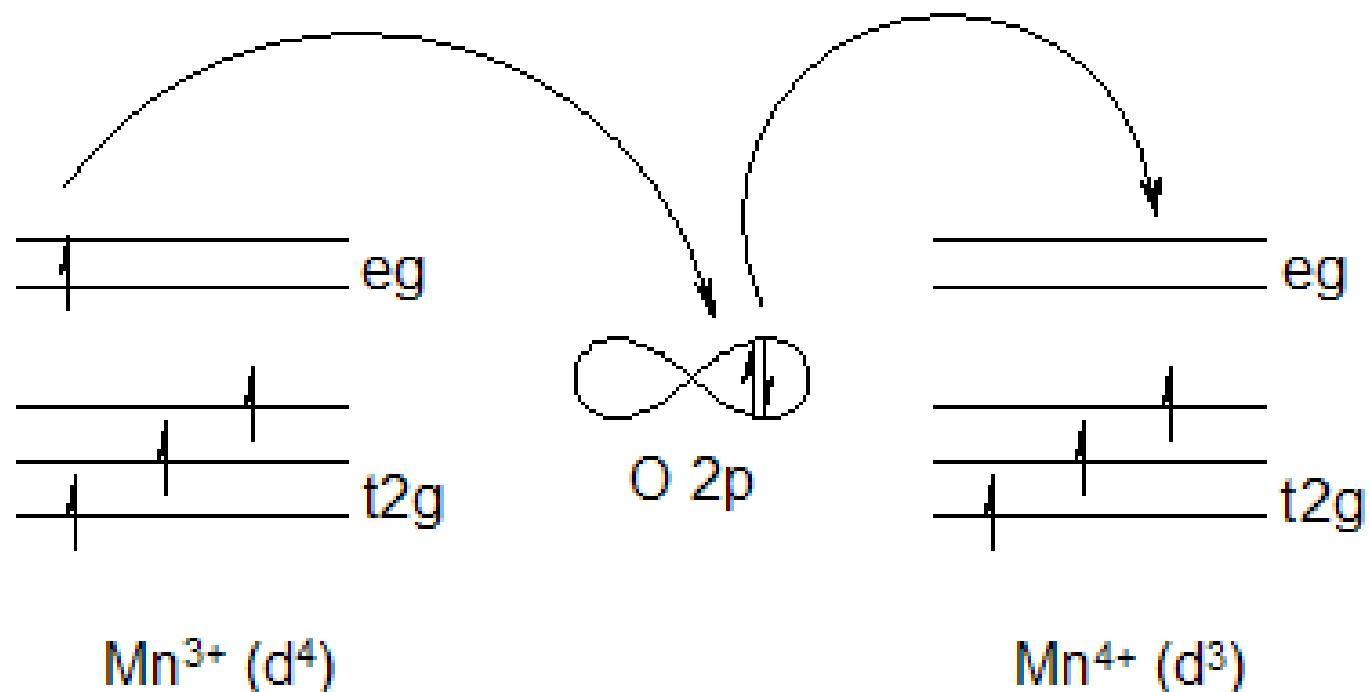
Why? → John Teller distortion
and Double-exchange mechanism



Source: wikipedia.org 43

Colossal MR

Why? → John Teller distortion
and Double-exchange mechanism



Summary

1. Magnetoresistance and ordinary MR

2. Anisotropic MR

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7. Spin Hall MR

8. Nonlocal MR

9. Hanle MR

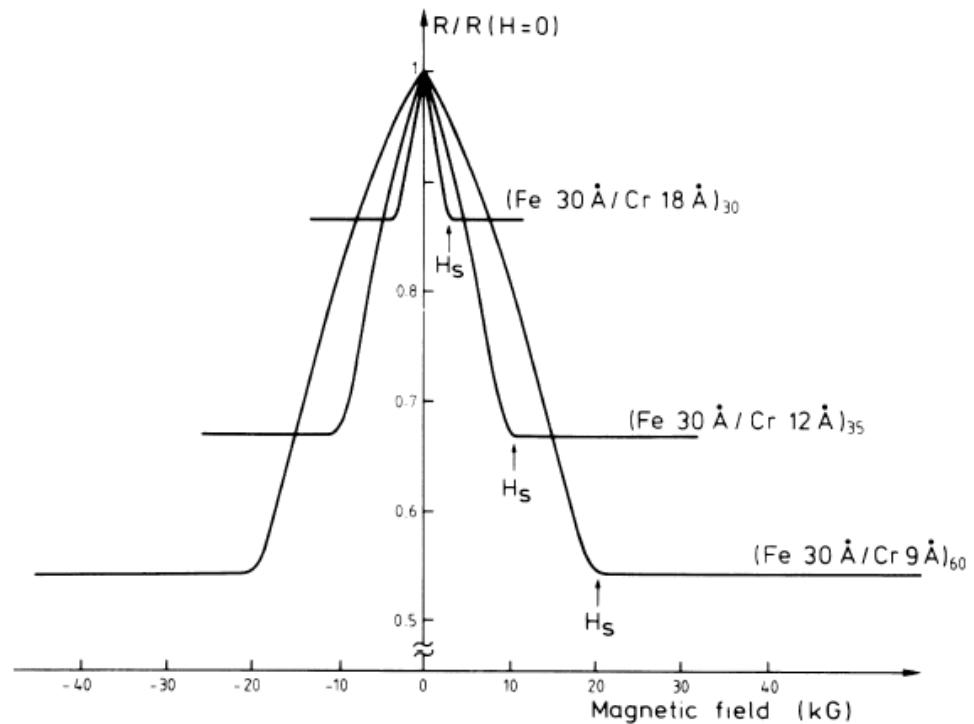
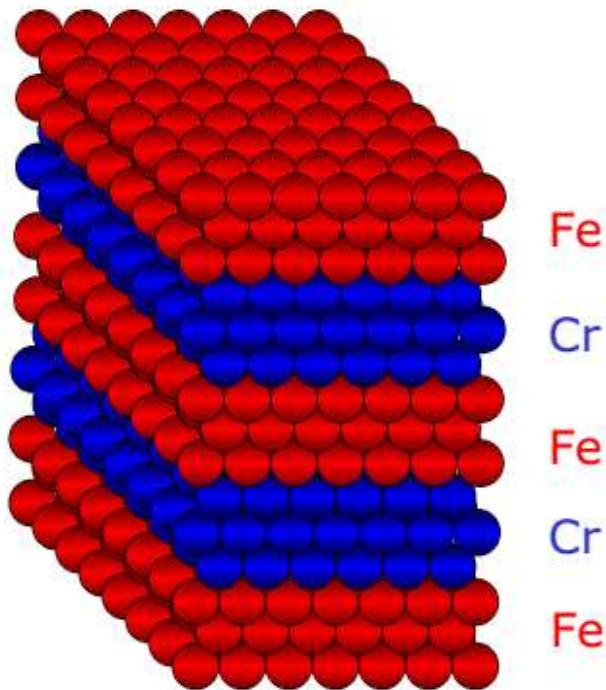
休息10分钟

Outline

5. Giant MR

GMR

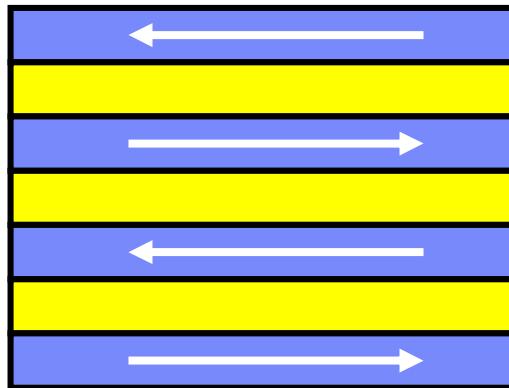
Observation of GMR



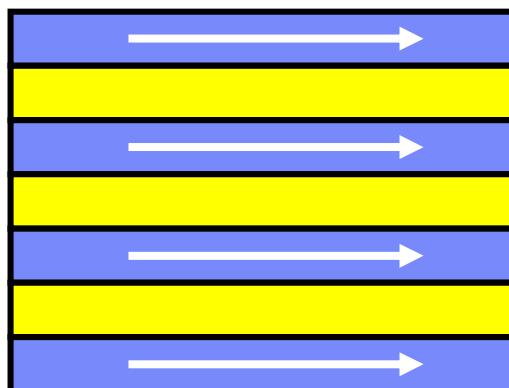
Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

GMR

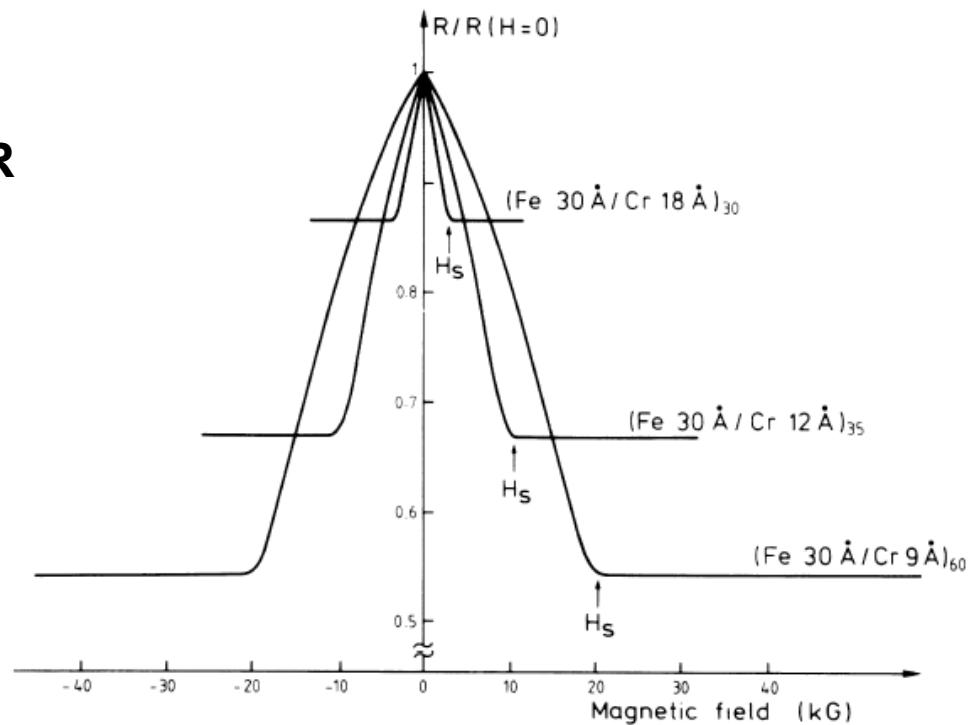
GMR--mechanism



High R



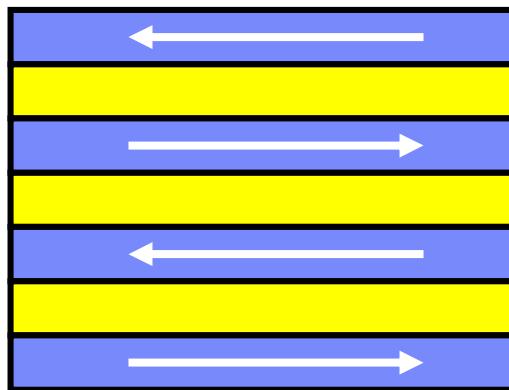
Low R



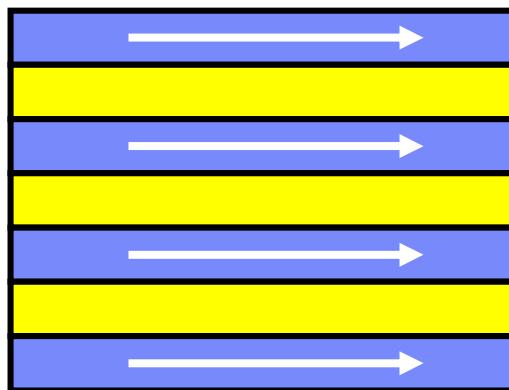
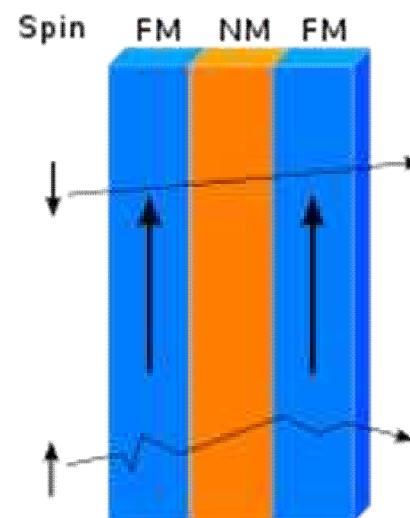
Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

GMR

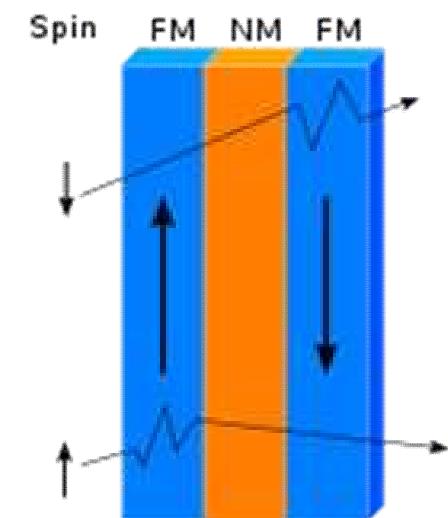
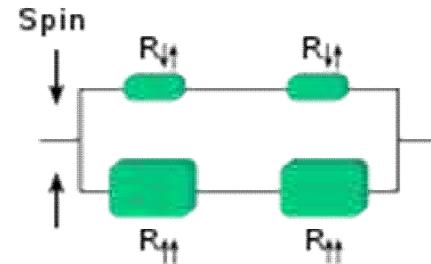
Julie Model



High R



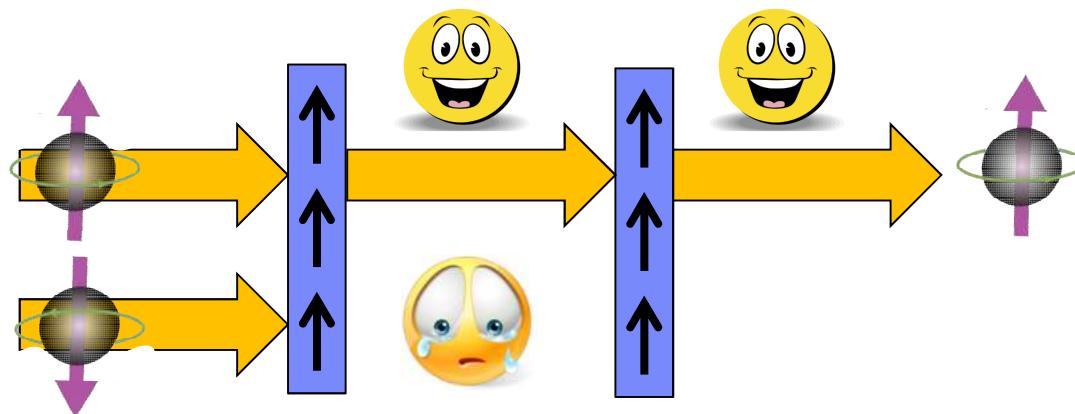
Low R



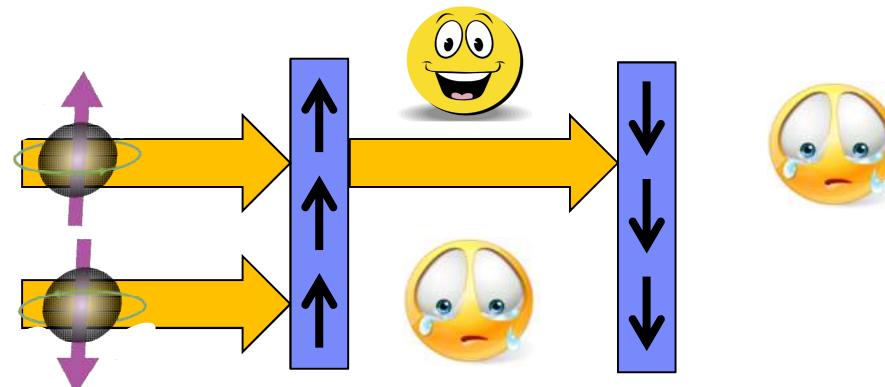
GMR

Julie Model

Parallel

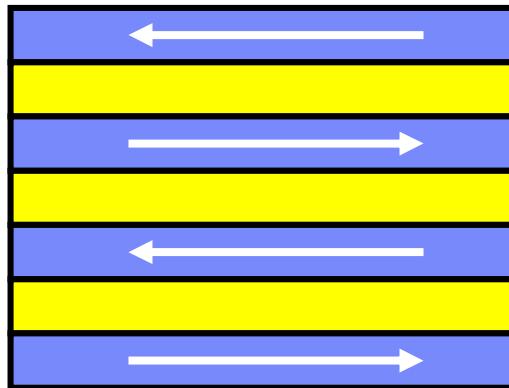


Anti-Parallel



GMR

GMR--mechanism

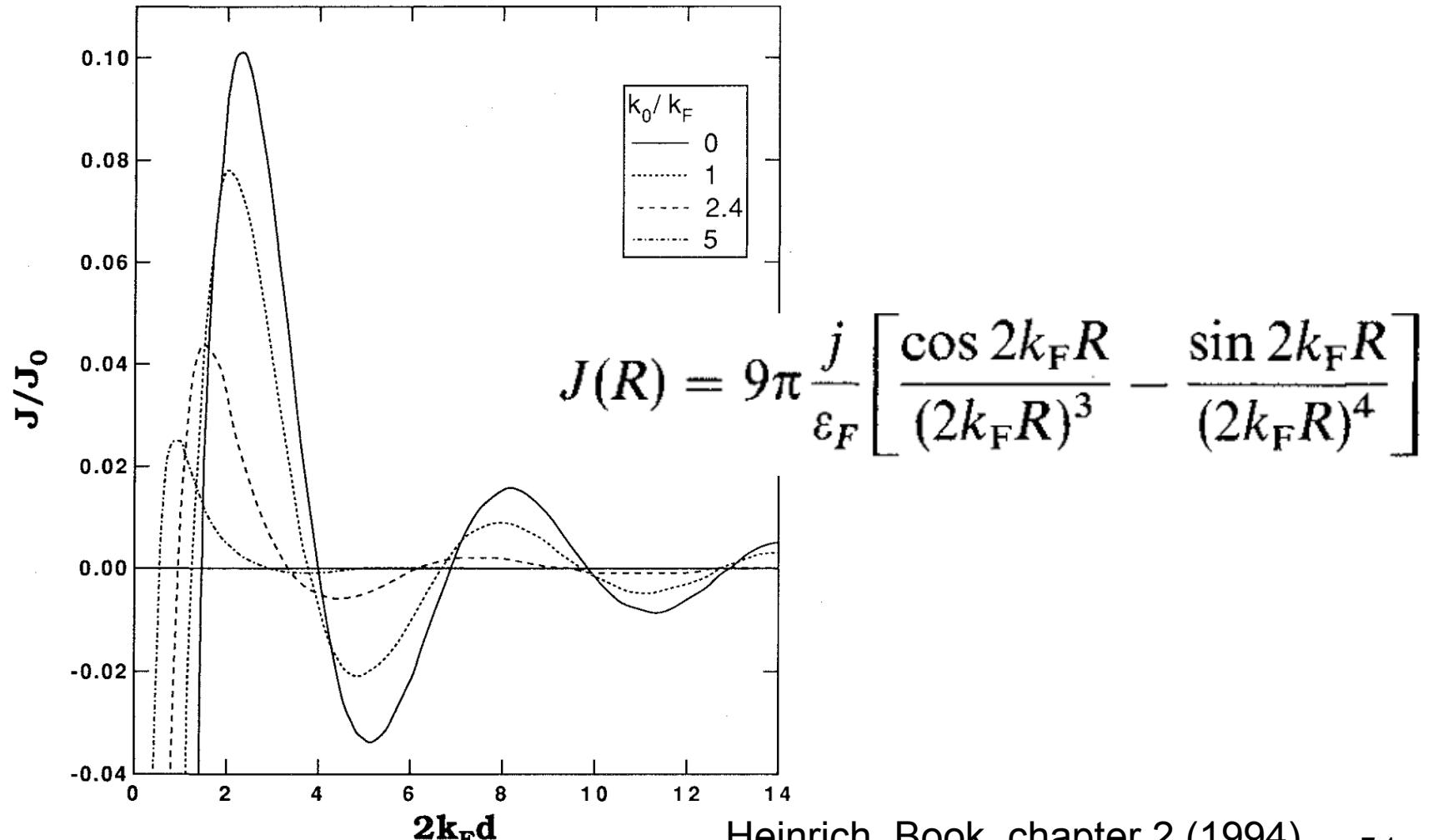


Why this is favored at low magnetic field?

Antiferromagnetic exchange interaction

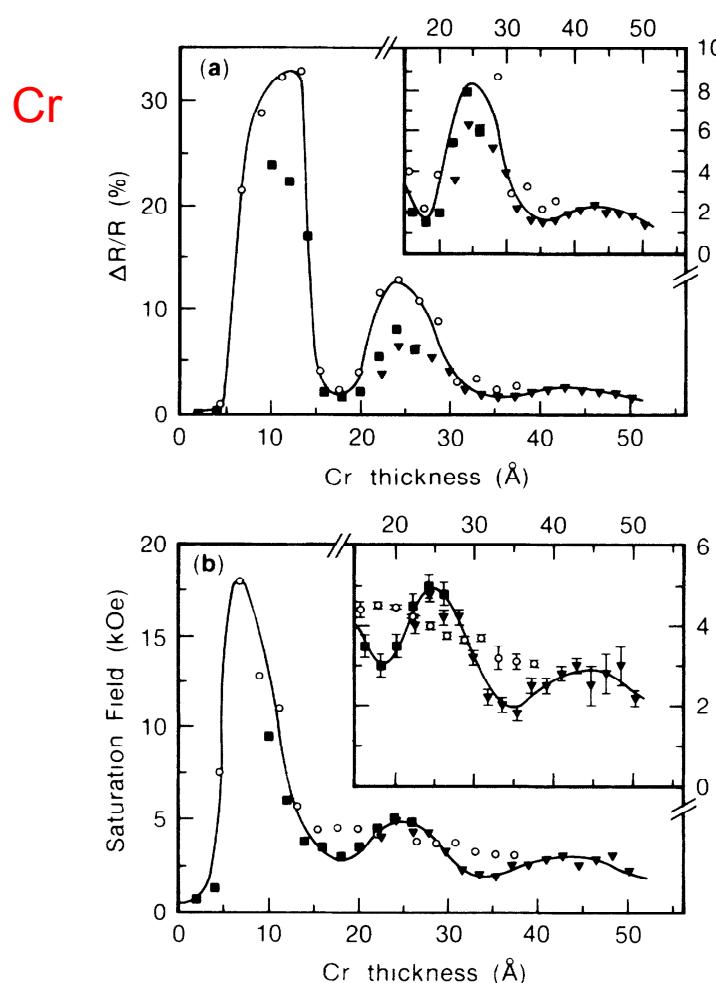
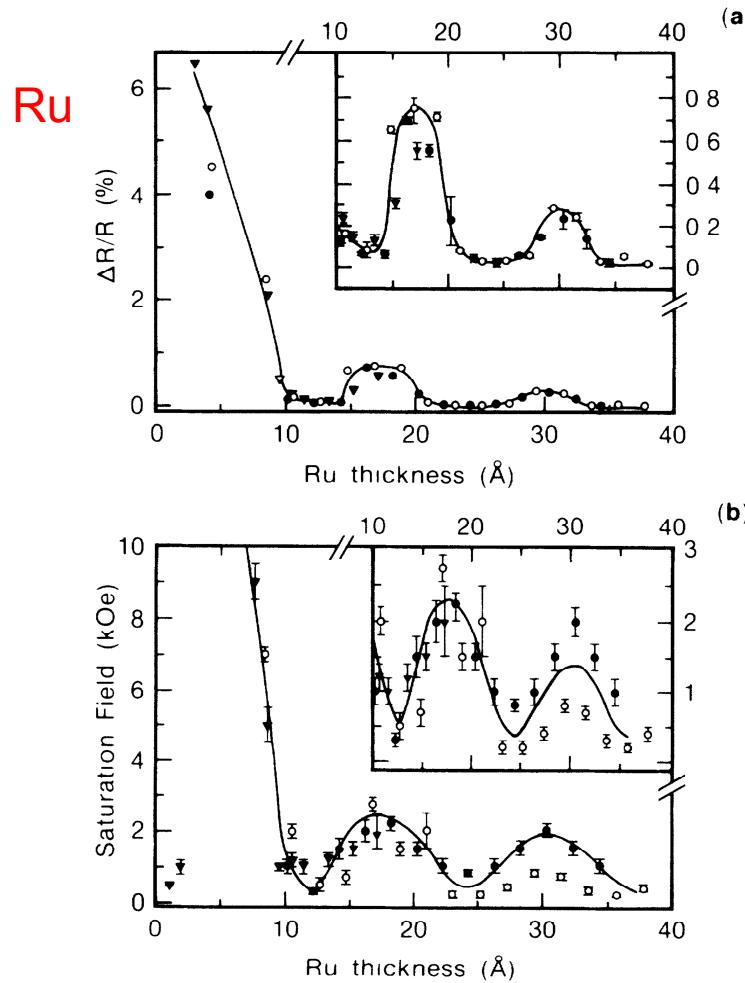
GMR

GMR—RKKY coupling



GMR

GMR—RKKY coupling



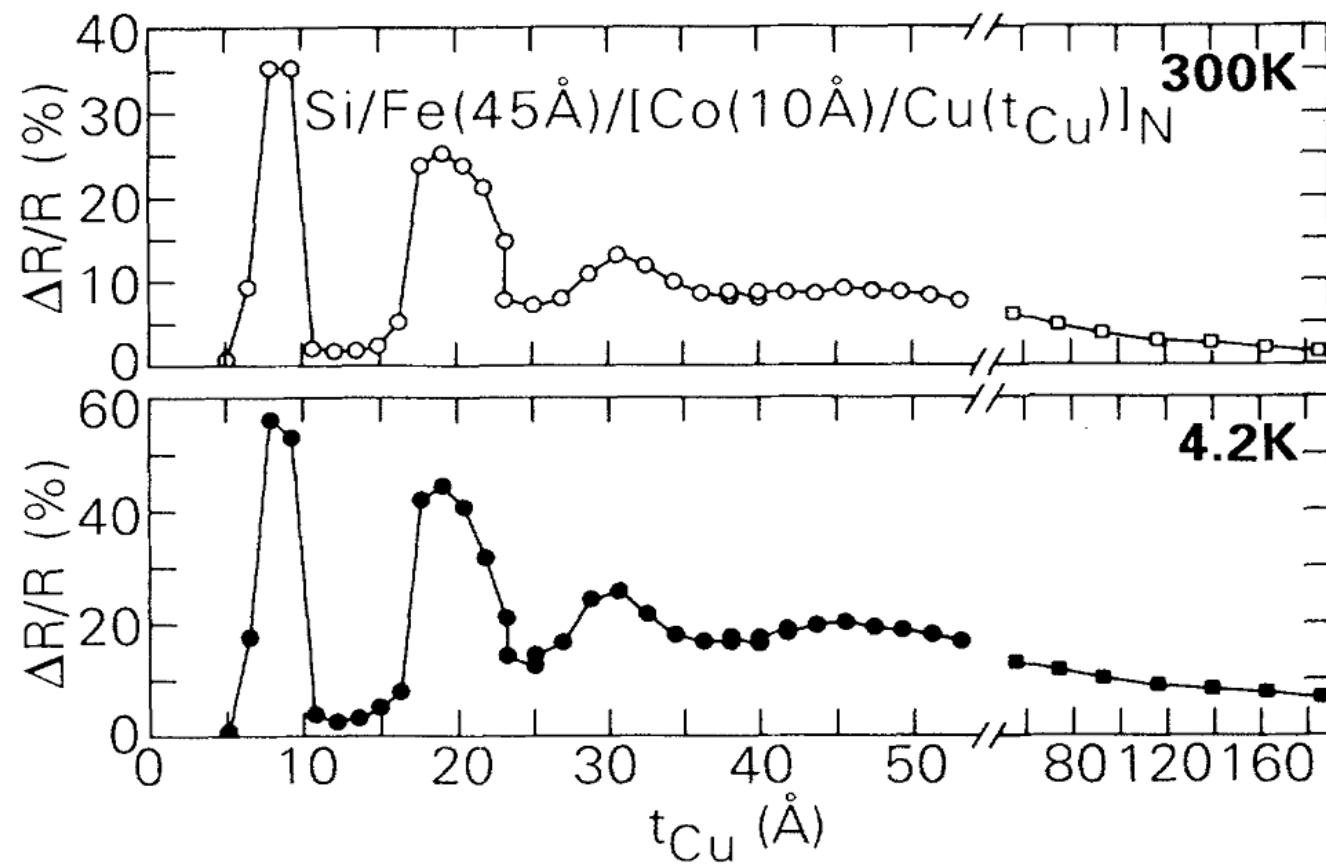
Parkin, et al, PRL (1990)

55

GMR

GMR—RKKY coupling

Cu



Outline

6. Tunneling MR

Tunneling MR

Al_2O_3 barrier for tunneling

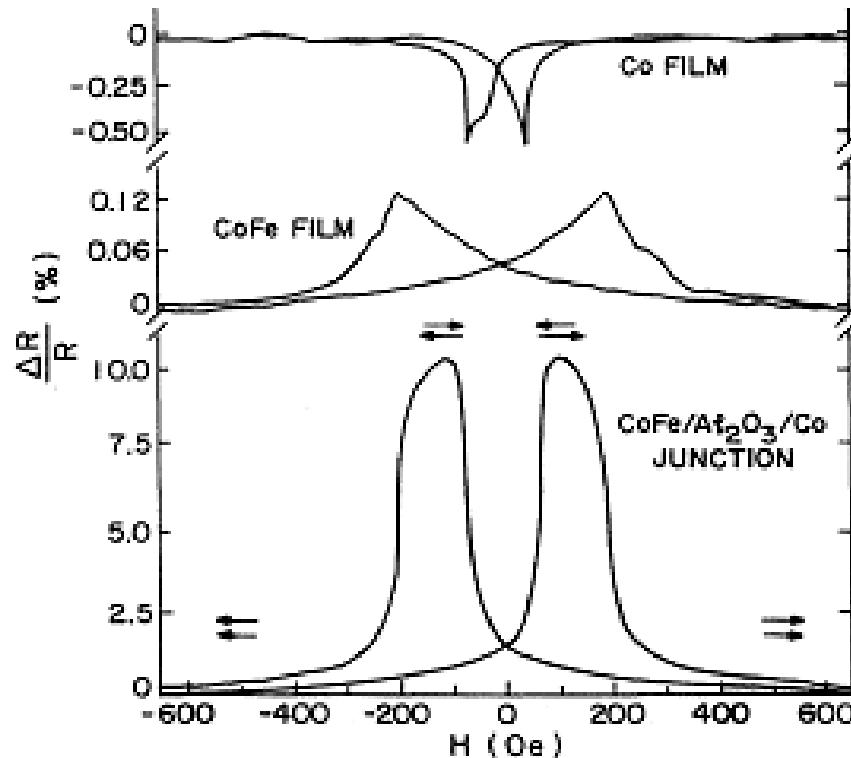
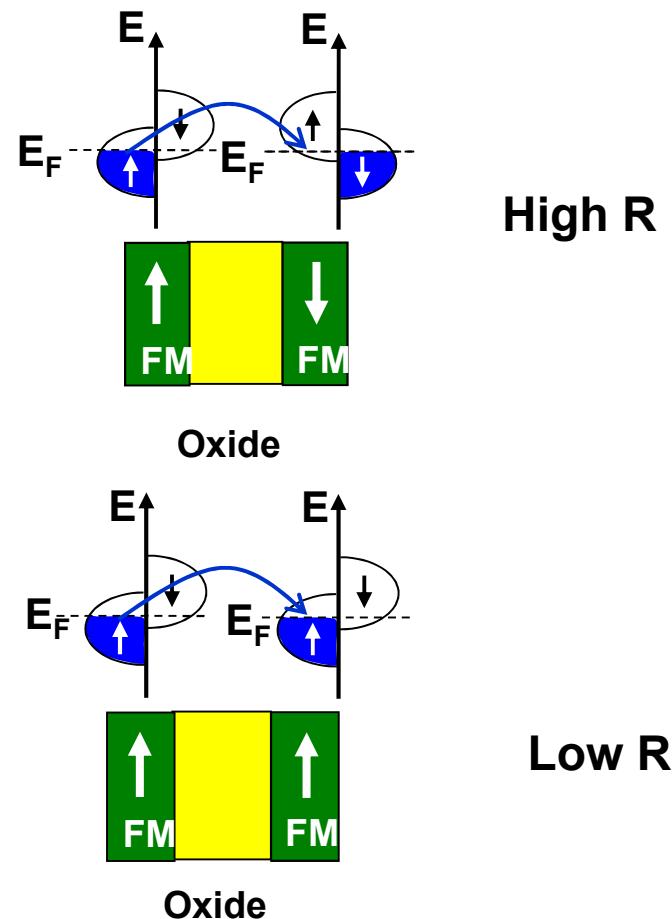
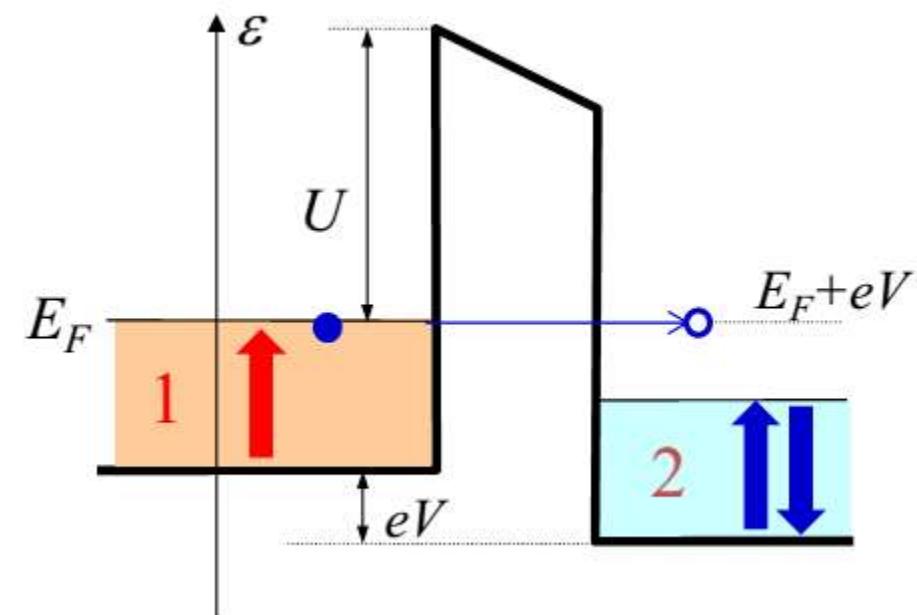
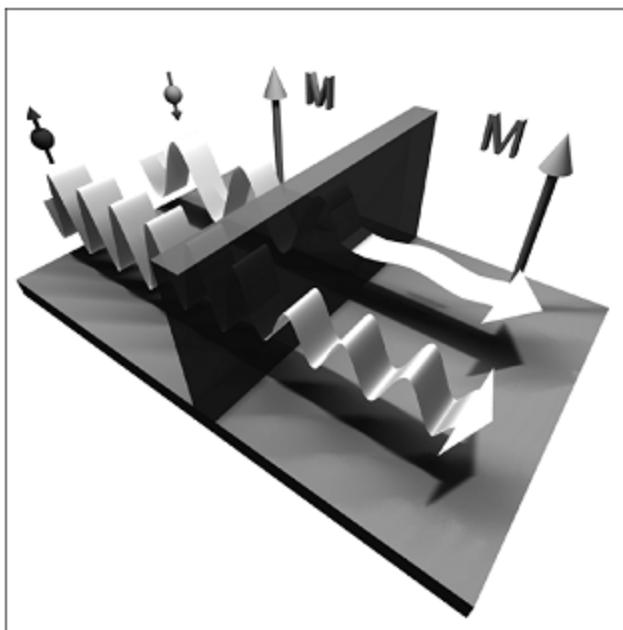


FIG. 2. Resistance of $\text{CoFe}/\text{Al}_2\text{O}_3/\text{Co}$ junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).



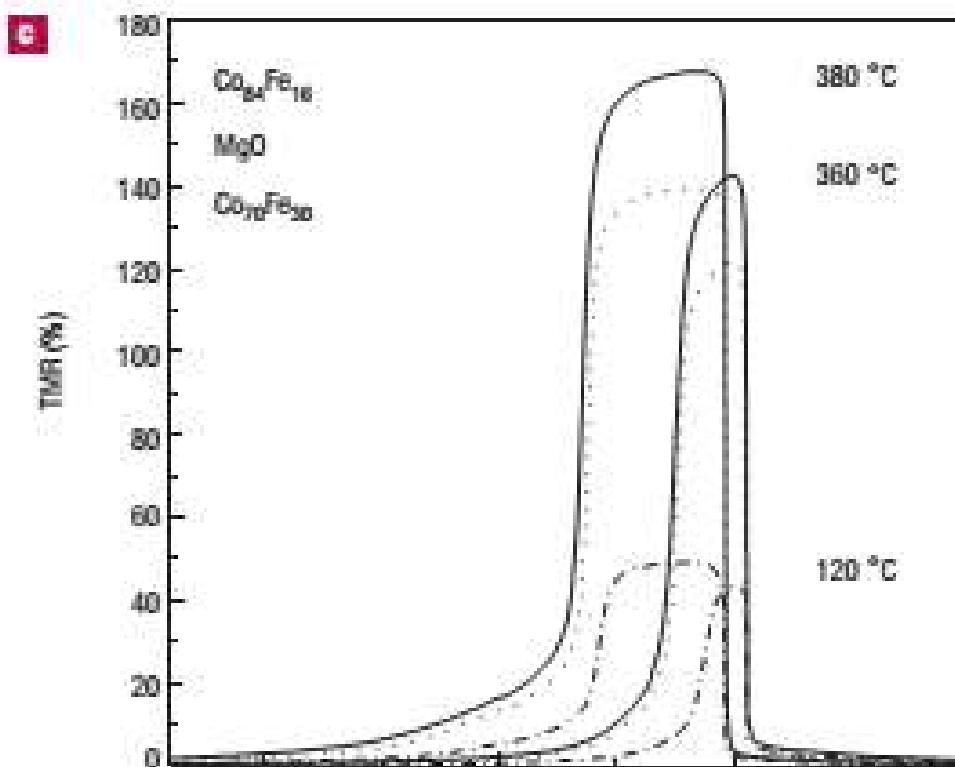
JS Moodera, et al, PRL (1995)

Tunneling MR



Tunneling MR

MgO barrier for tunneling: MR >100%



Epitaxial MgO

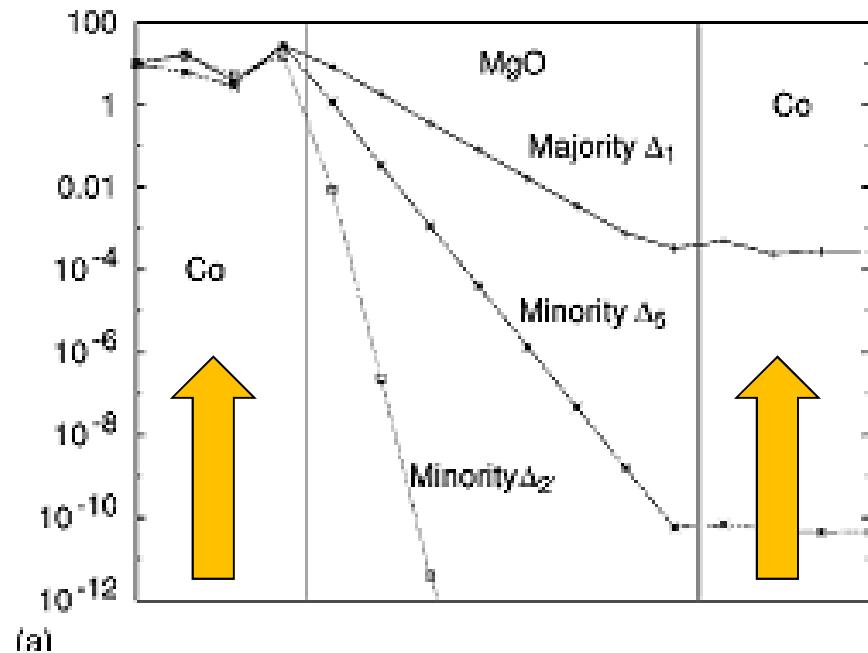


Parkin, et al, Nature Mater (2004)
Yuasa, et al, Nature Mater (2004)

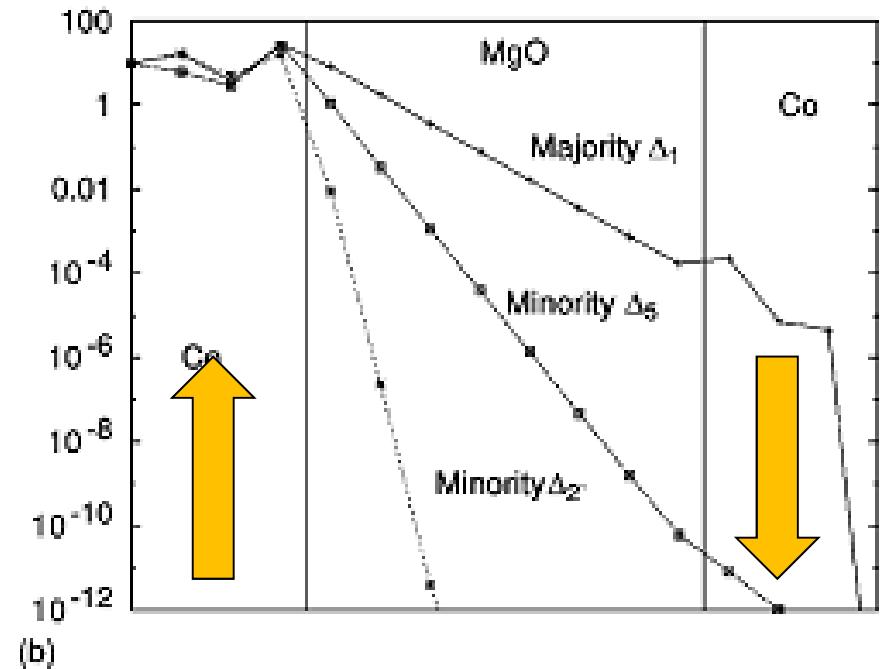
Tunneling MR

MgO barrier for tunneling: MR >100%

Parallel



Anti-Parallel

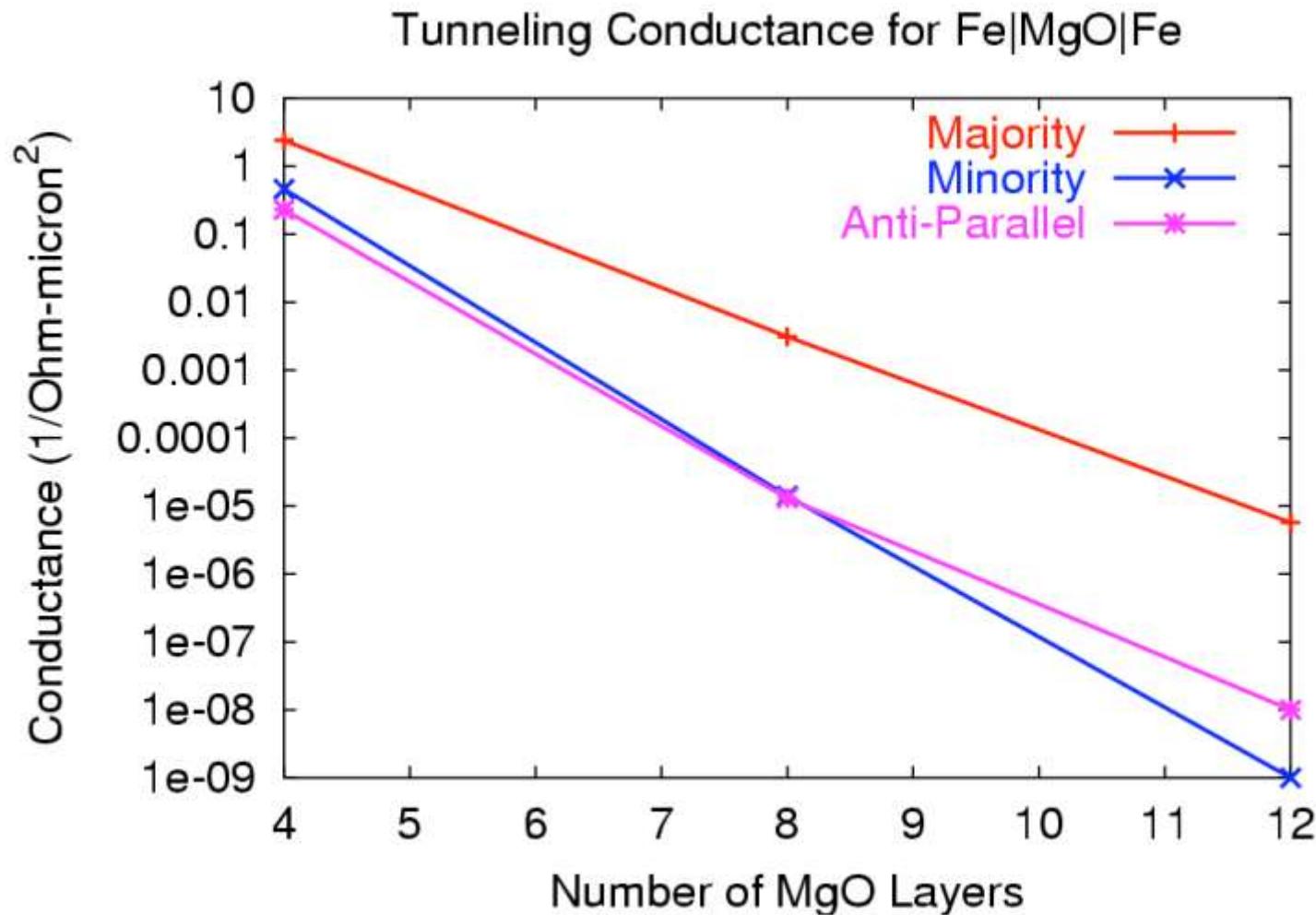


Δ_1 , symmetry, slow decaying
Tunneling of Co majority spin (SP)

Zhang & Butler, et al, PRB (2004)

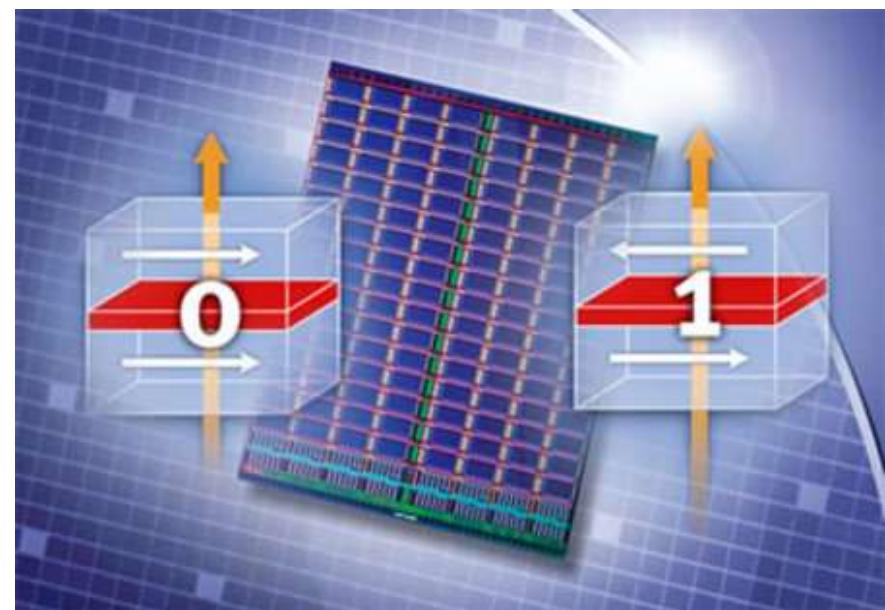
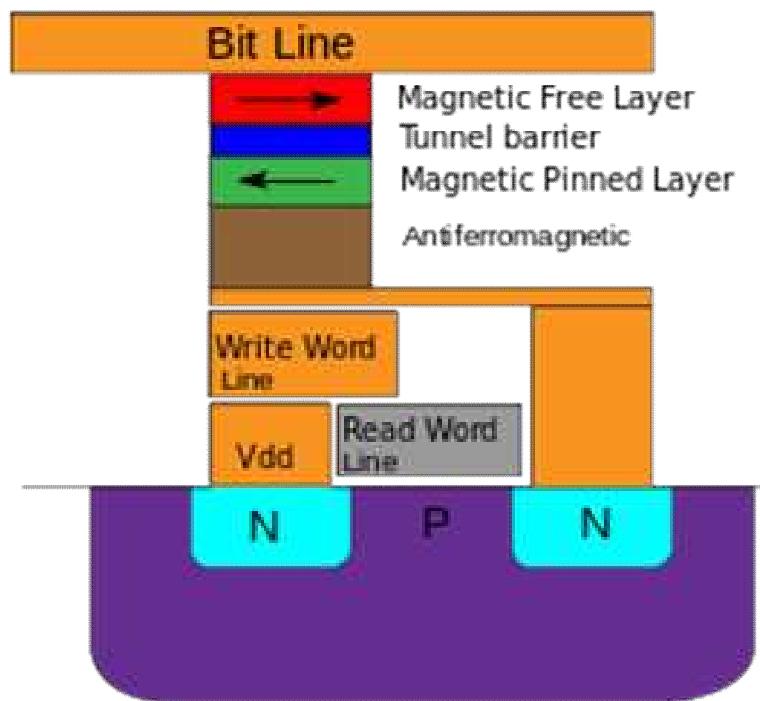
Tunneling MR

MgO barrier for tunneling: MR >100%



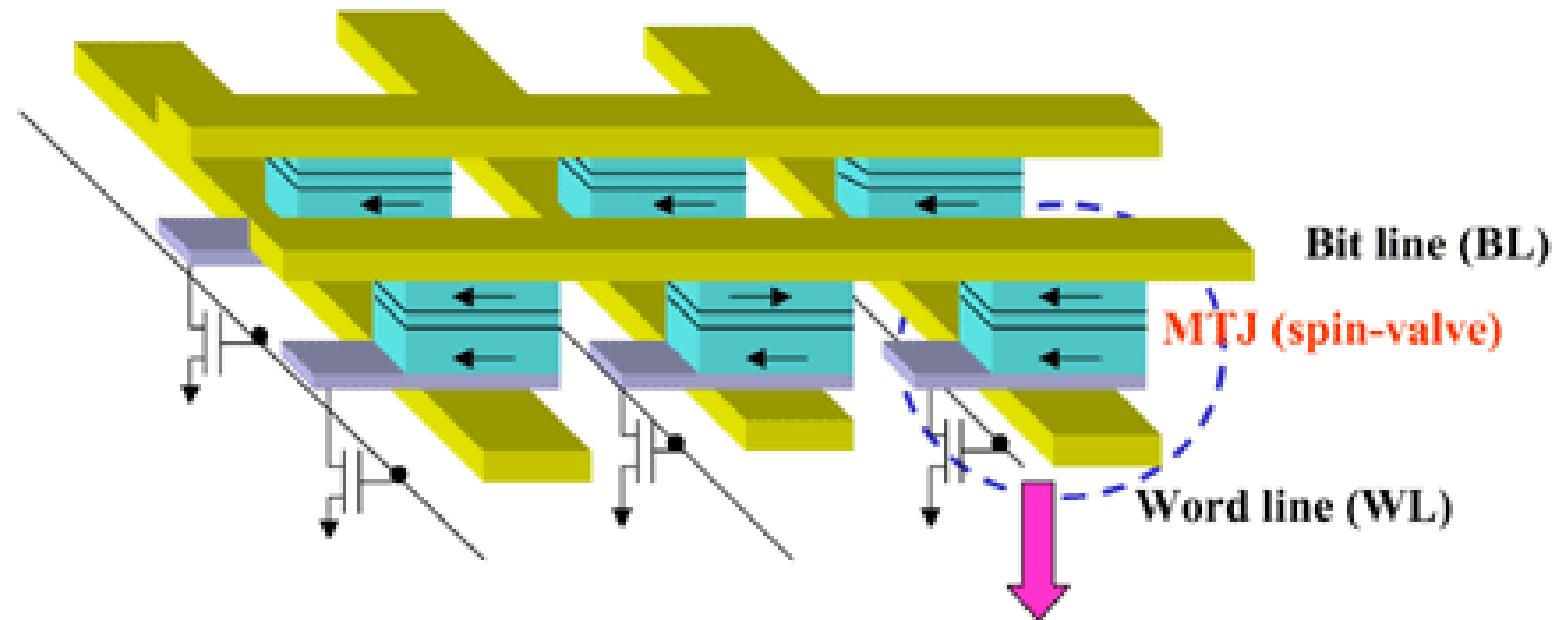
TMR for MRAM

MRAM

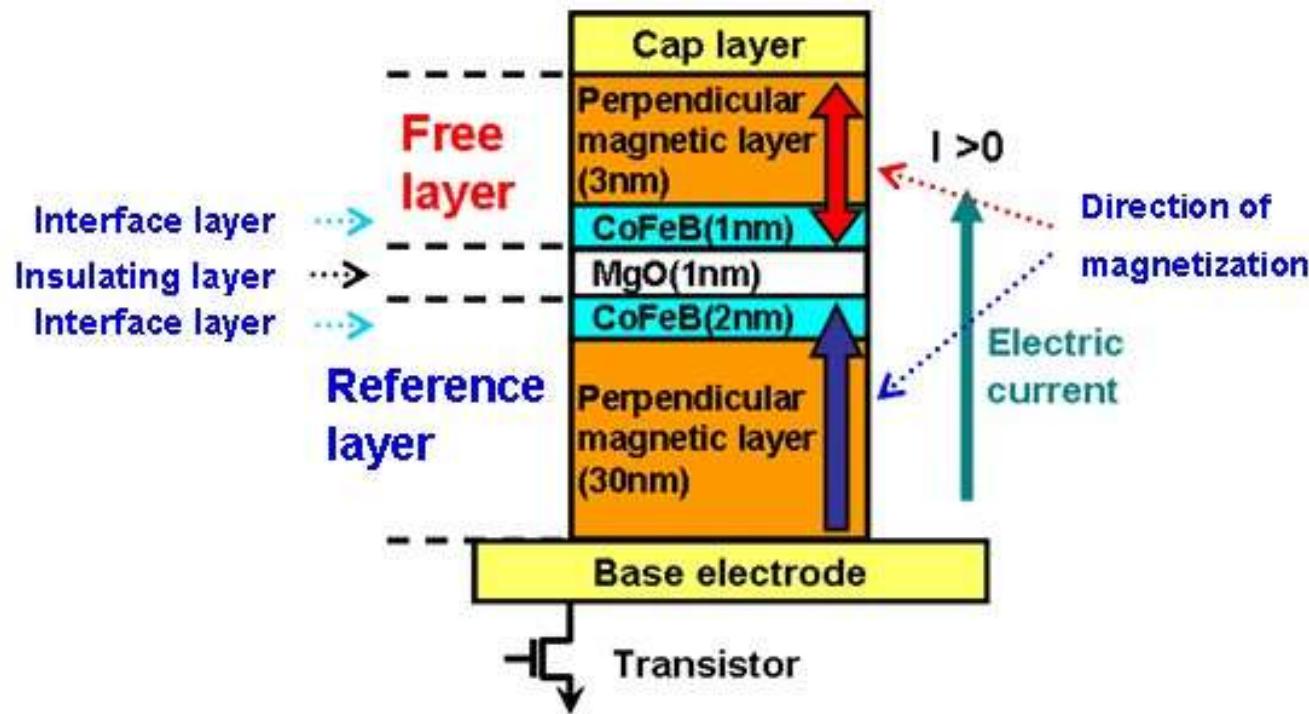


TMR for MRAM

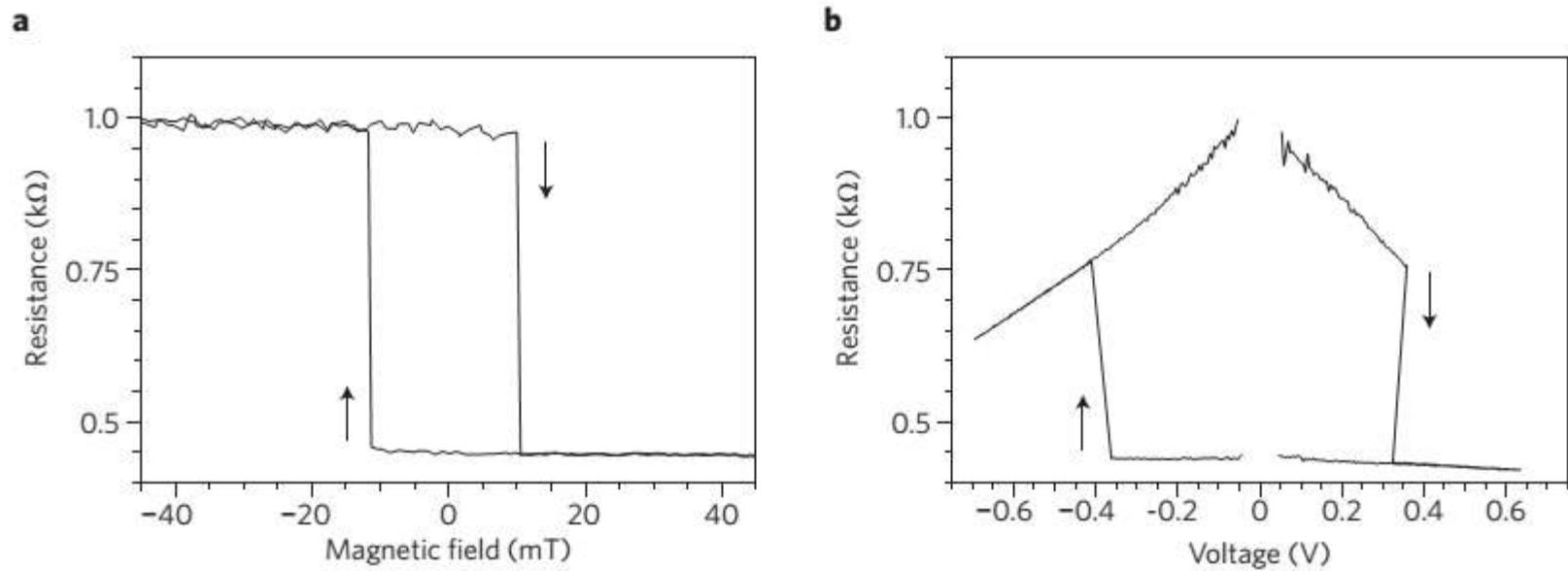
MRAM



STT-MRAM



STT-MRAM



Kent & Worledge, Nature Nano (2015)

STT-MRAM

Table 1 | Comparison of key features of existing and emerging memories.

	SRAM	eDRAM	DRAM	eFlash (NOR)	Flash (NAND)	FeRAM	PCM	STT-MRAM	RRAM
Endurance (cycles)	Unlimited	Unlimited	Unlimited	10^5	10^5	10^{14}	10^9	Unlimited	10^9
Read/write access time (ns)	<1	1-2	30	10/ 10^3	100/ 10^6	30	10/100	2-30	1-100
Density	Low (six transistors)	Medium	Medium	Medium	High (multiple bits per cell)	Low (limited scalability)	High (multiple bits per cell)	Medium	High (multiple bits per cell)
Write power	Medium	Medium	Medium	High	High	Medium	Medium	Medium	Medium
Standby power	High	Medium	Medium	Low	Low	Low	Low	Low	Low
Other	Volatile	Volatile. Refresh power and time needed	Volatile. Refresh power and time needed	High voltage required	High voltage required	Destructive readout	Operating $T < 125^\circ\text{C}$	Low read signal	Complex mechanism

Significant disadvantages are marked in bold. Estimates for emerging memories are based on expectations for functioning chips, not demonstrations of individual bits. See text for abbreviations.

Kent & Worledge, Nature Nano (2015)

Electric-field-assisted

ARTICLES

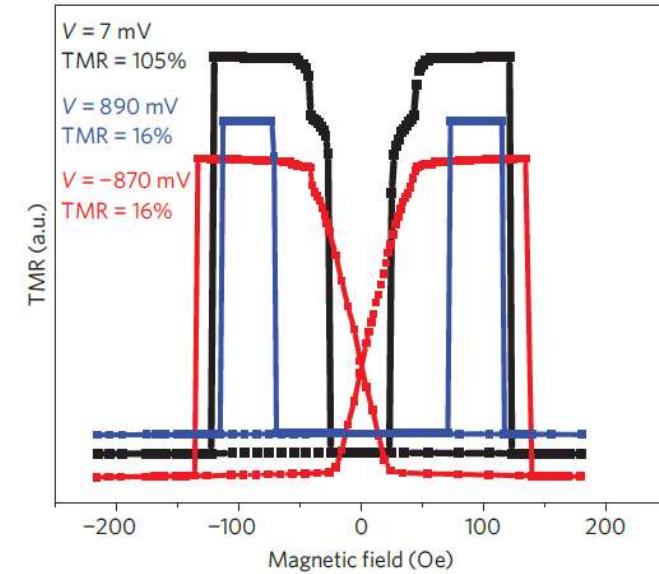
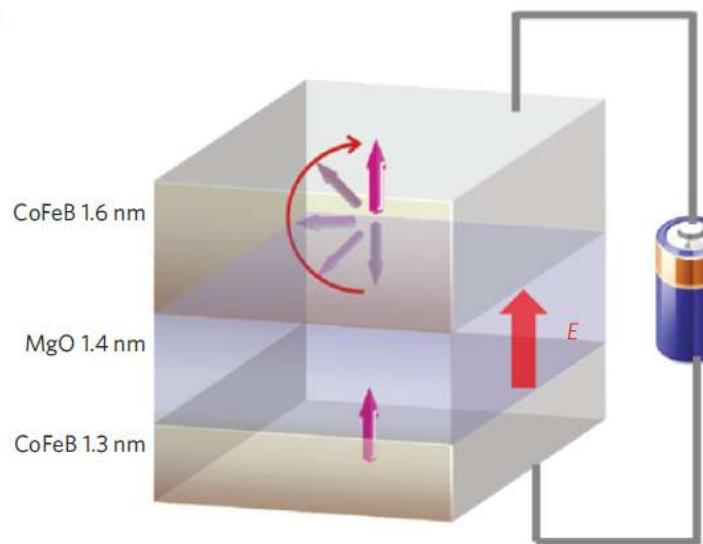
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI:10.1038/NMAT3171

nature
materials

Electric-field-assisted switching in magnetic tunnel junctions

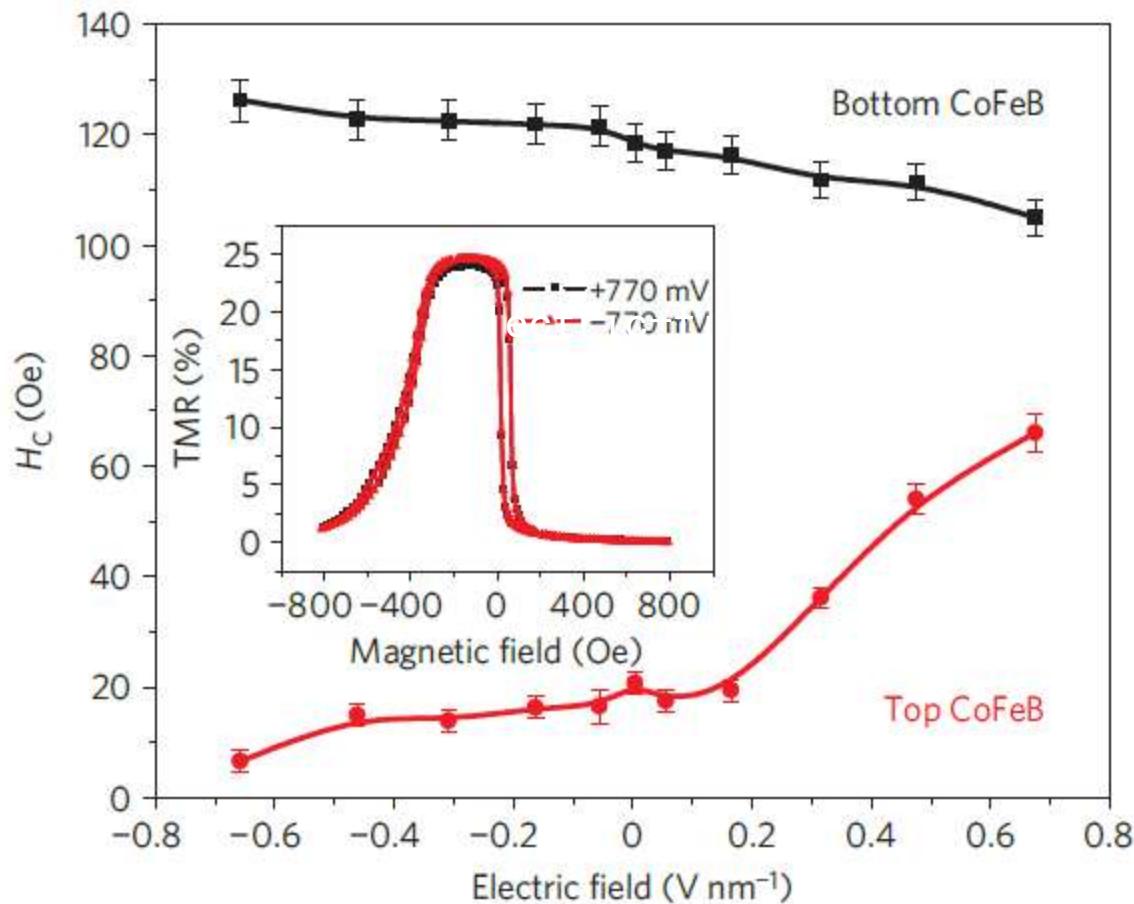
Wei-Gang Wang*, Mingen Li, Stephen Hageman and C. L. Chien*

a



Electric-field-assisted

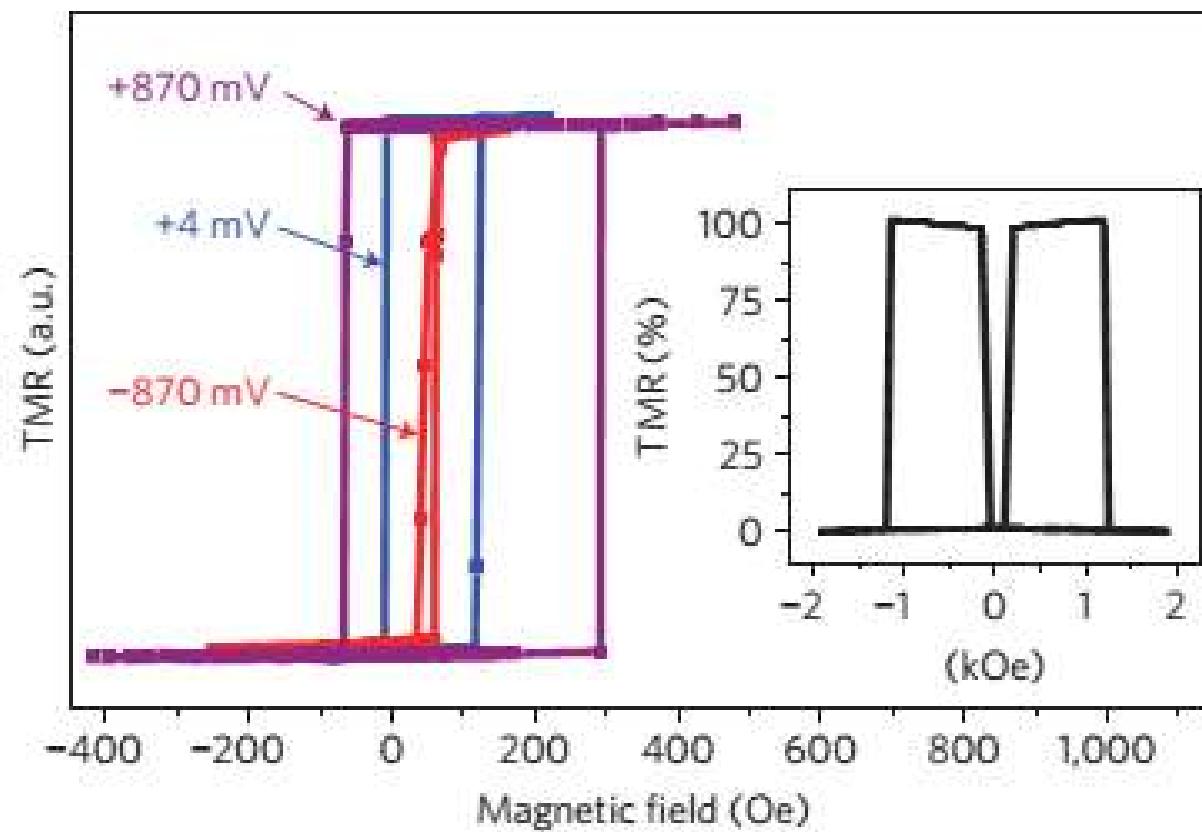
Electric-field H_c



Electric-field-assisted

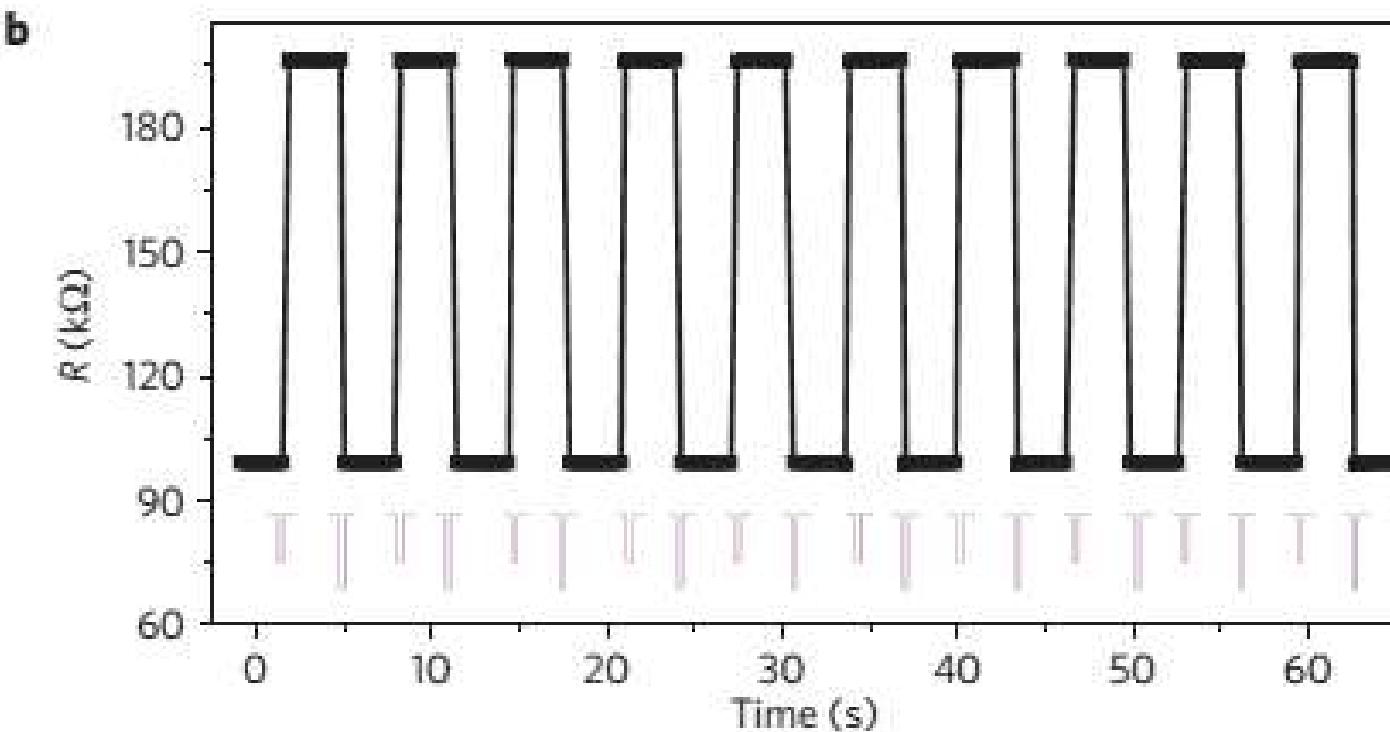
Electric-field switching

a



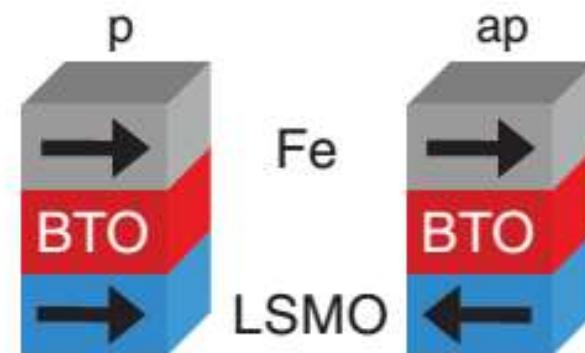
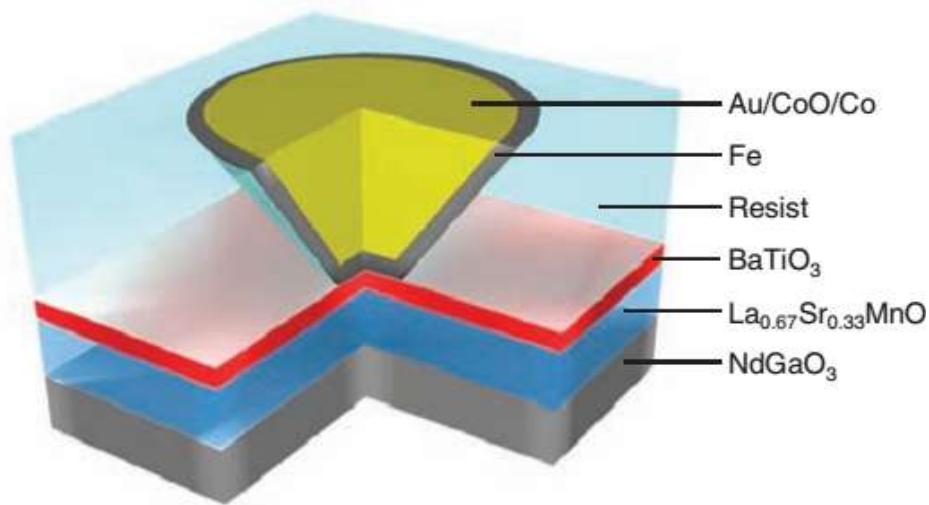
Electric-field-assisted

Electric-field switching



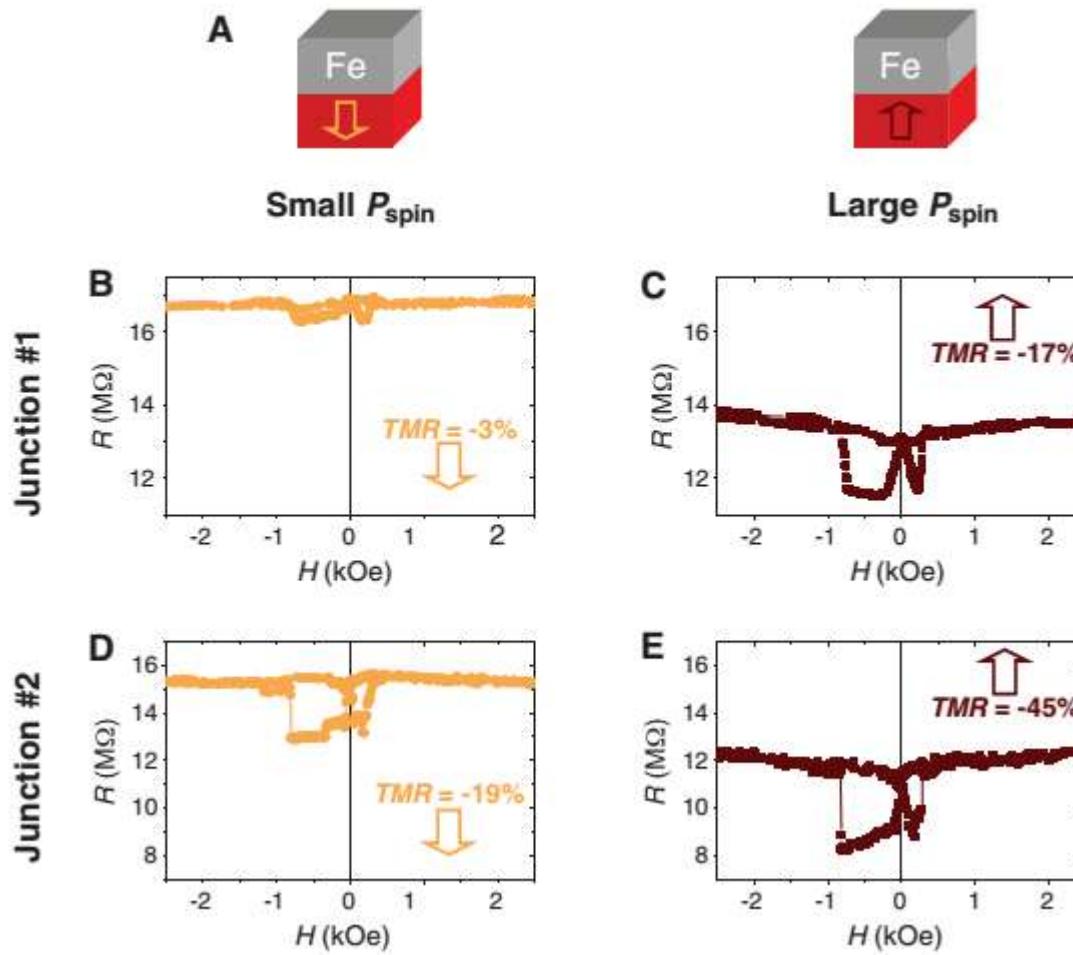
TMR by Multiferroics

A



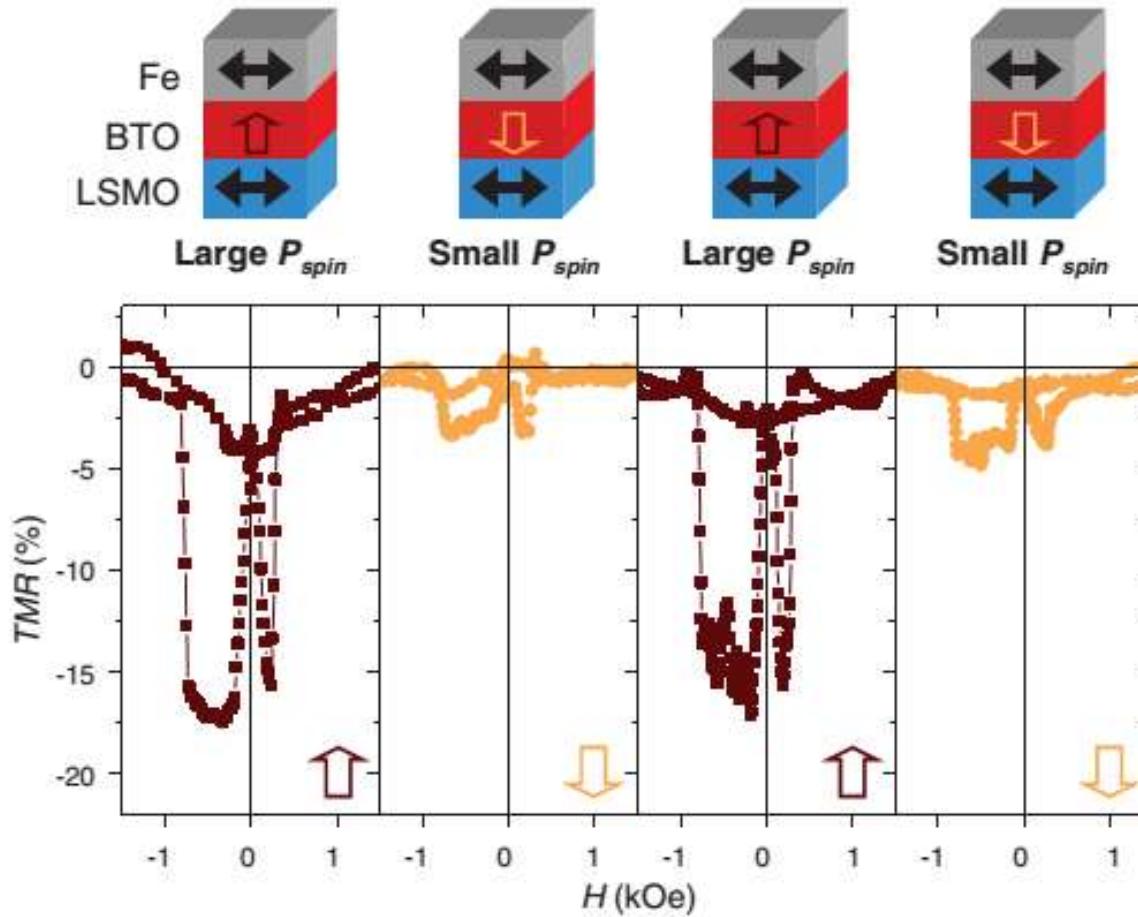
Garcia, et al, Science (2010)

TMR by Multiferroics



Garcia, et al, Science (2010)

TMR by Multiferroics



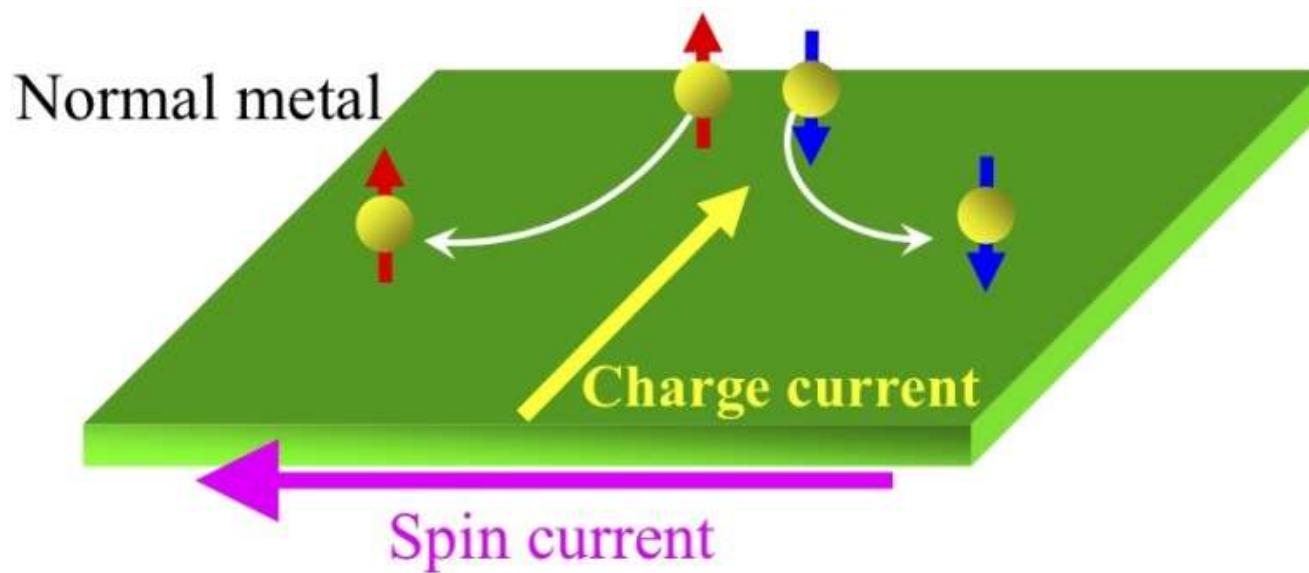
Garcia, et al, Science (2010)

Outline

7. Spin Hall MR

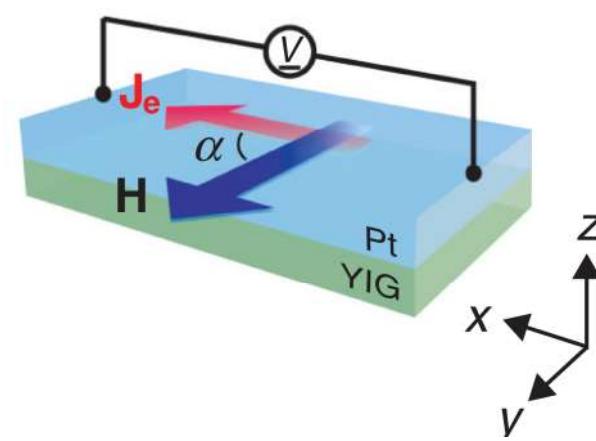
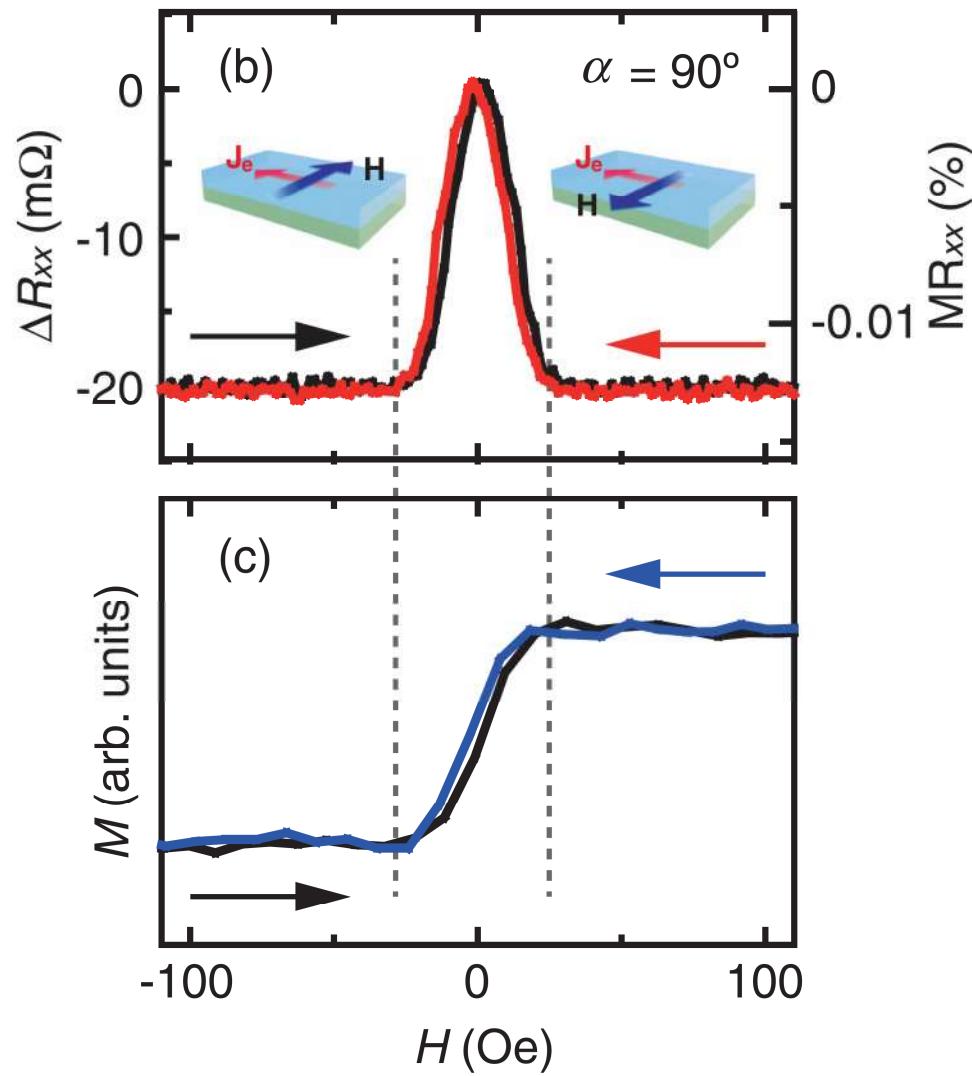
SMR

Spin Hall effect



D'yakonov, M. I. & Perel', J. Exp. Theor. Phys. Lett. 13, 467-469, (1971).
Hirsch, J. E. Phys. Rev. Lett. 83, 1834-1837, (1999).
Zhang, S. Phys. Rev. Lett. 85, 393-396, (2000).

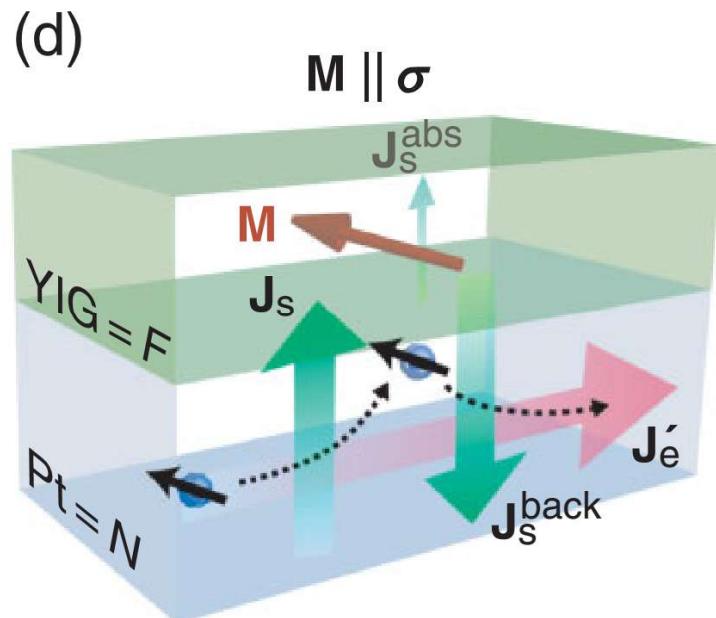
SMR



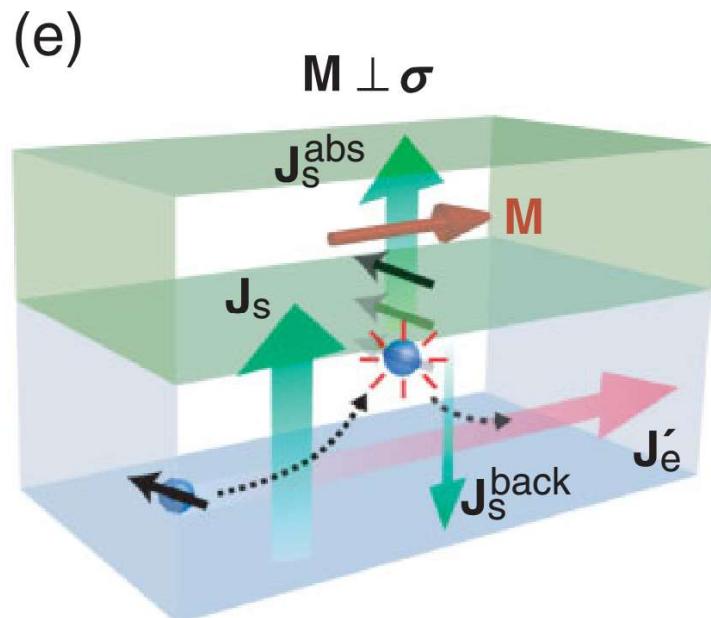
Nakayama, et al, PRL (2013)

SMR

SMR mechanism: Interfacial spin scattering



$$N_{\text{Spin in}} = N_{\text{spin out}}$$

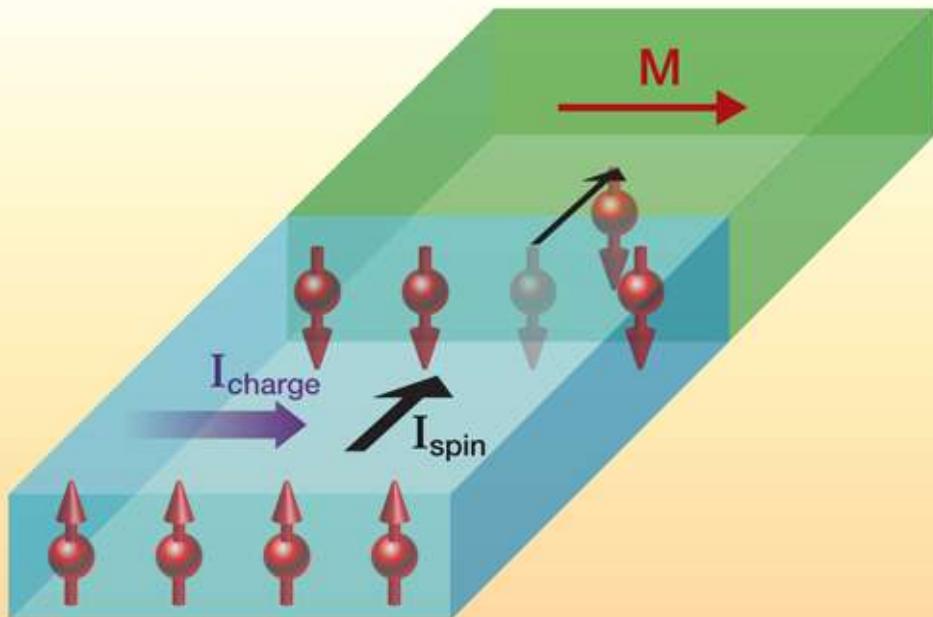


$$N_{\text{Spin in}} > N_{\text{spin out}}$$

SMR

SMR mechanism: Interfacial spin scattering

High R



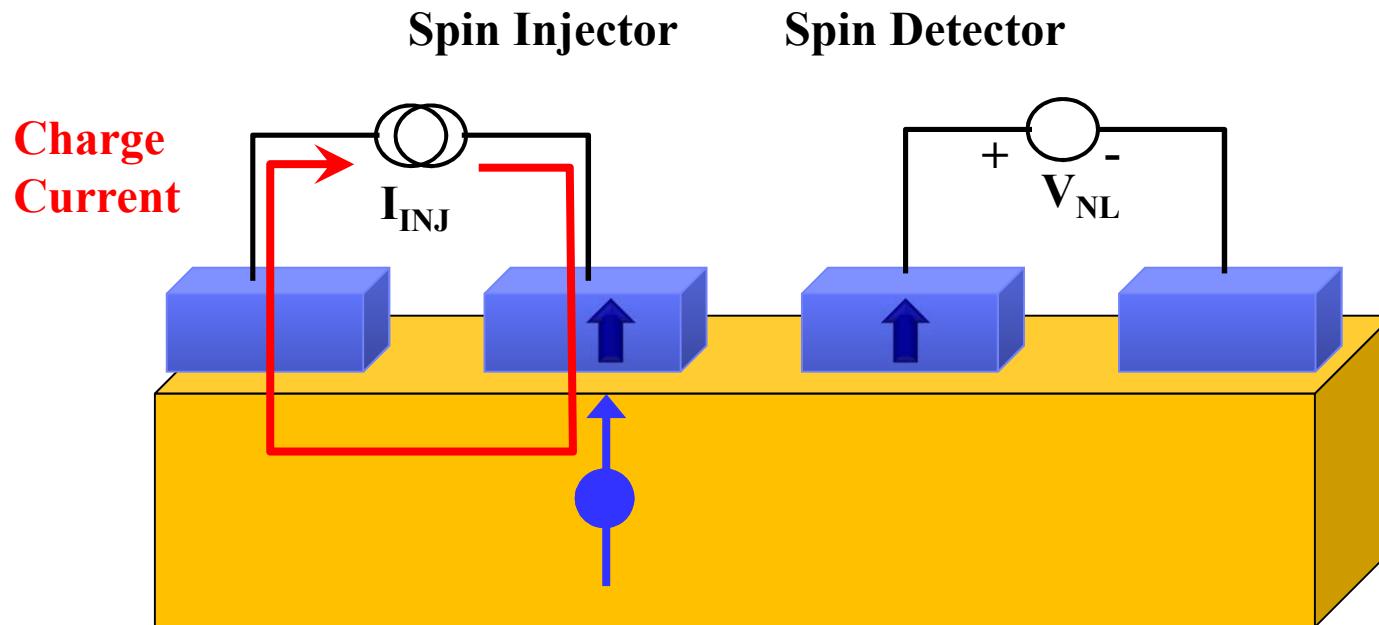
$$\tau_{ST} = \frac{\hbar}{2} \hat{m} \times (\hat{\sigma} \times \hat{m})$$

Spin polarized electrons pass the interface and apply a torque on the M , then relaxed in FM insulator

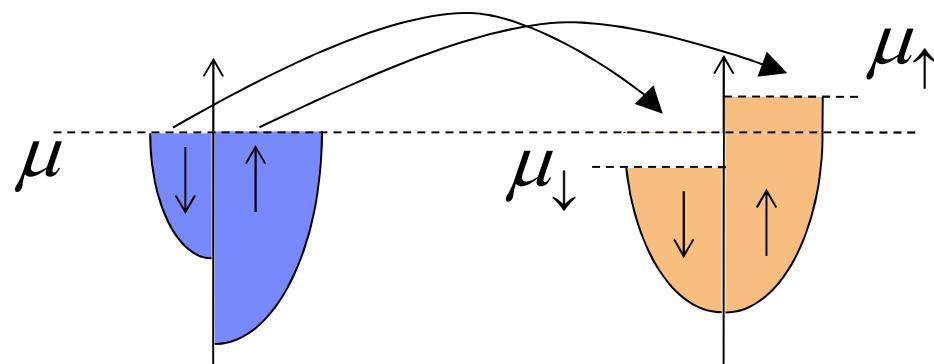
Outline

7. Nonlocal MR

Nonlocal Spin valve

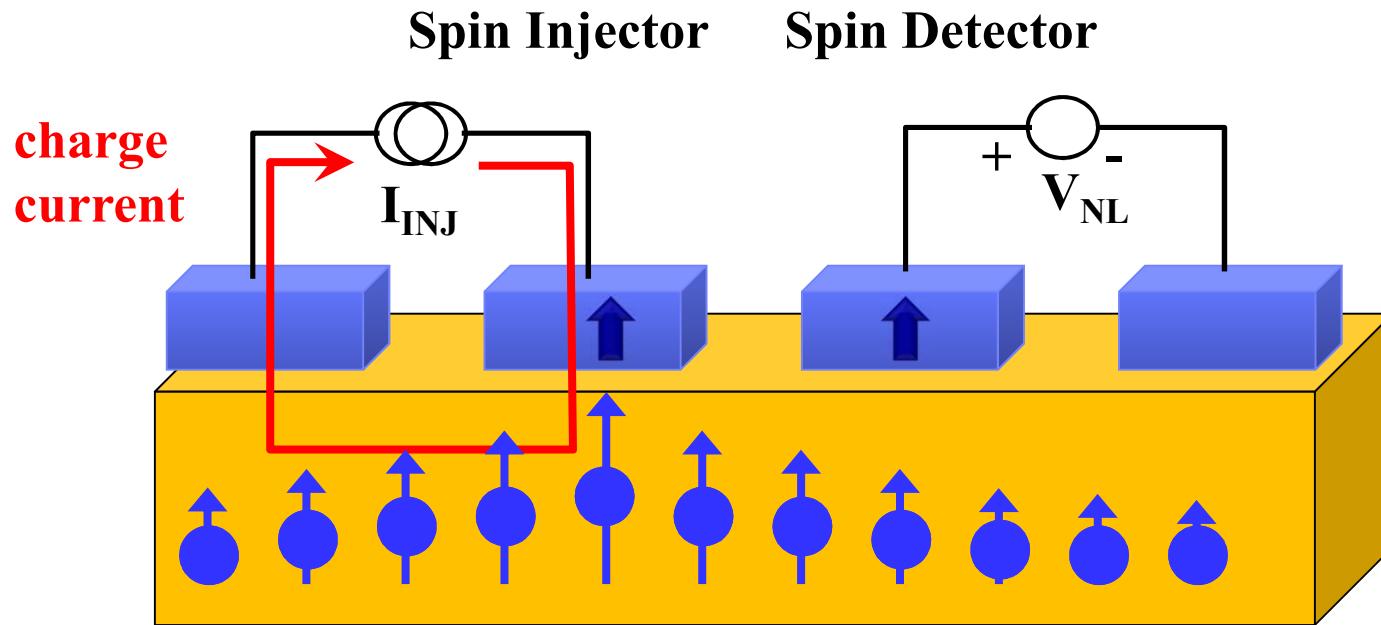


Chemical
Potential
(Fermi level)

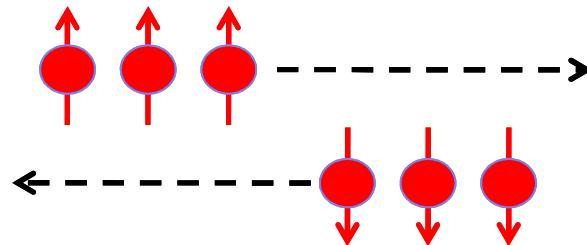


Johnson and Silsbee, PRL (1985)

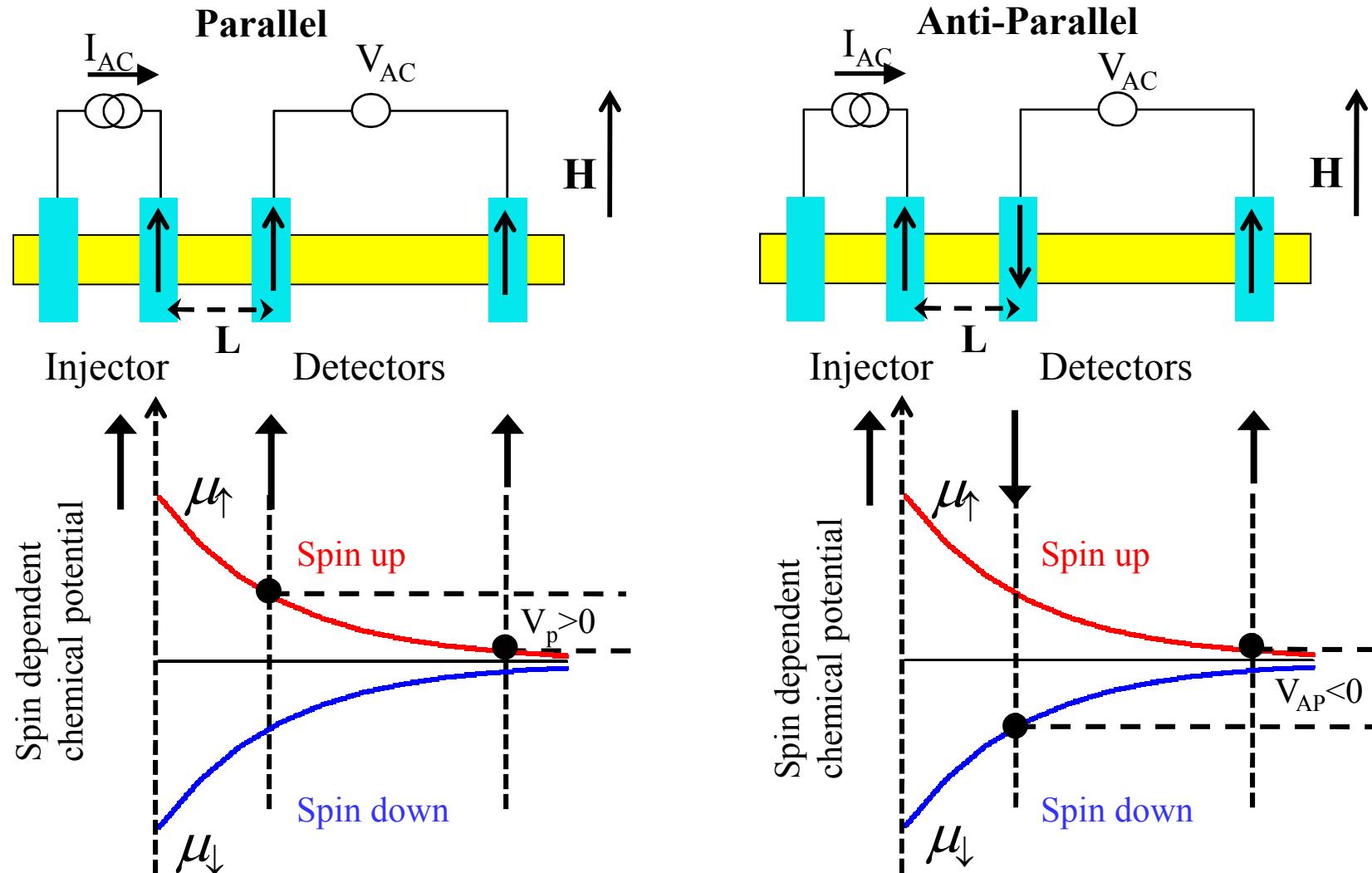
Nonlocal Spin valve



Pure spin current: Flow of spin without net flow of charge

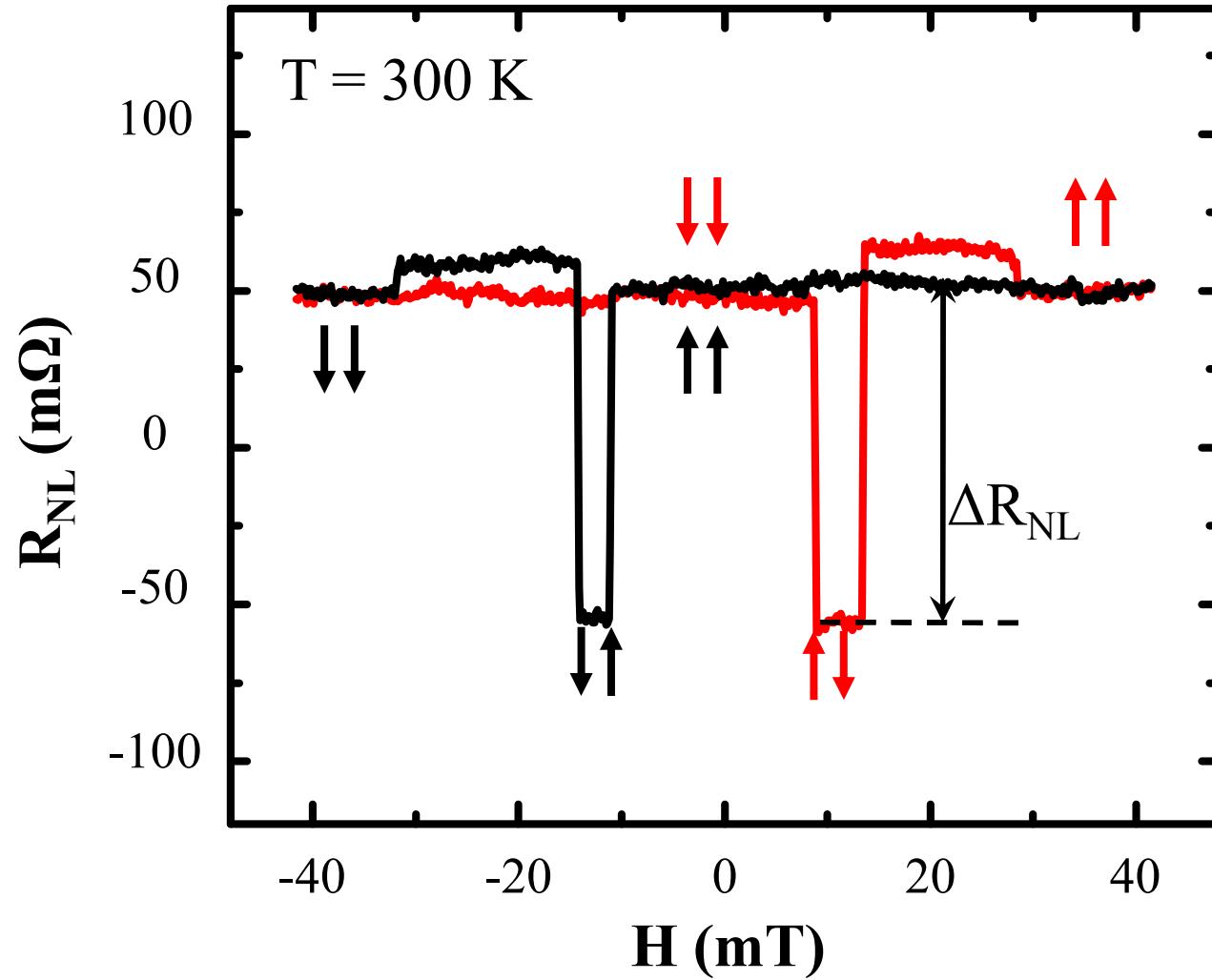


Nonlocal Spin valve

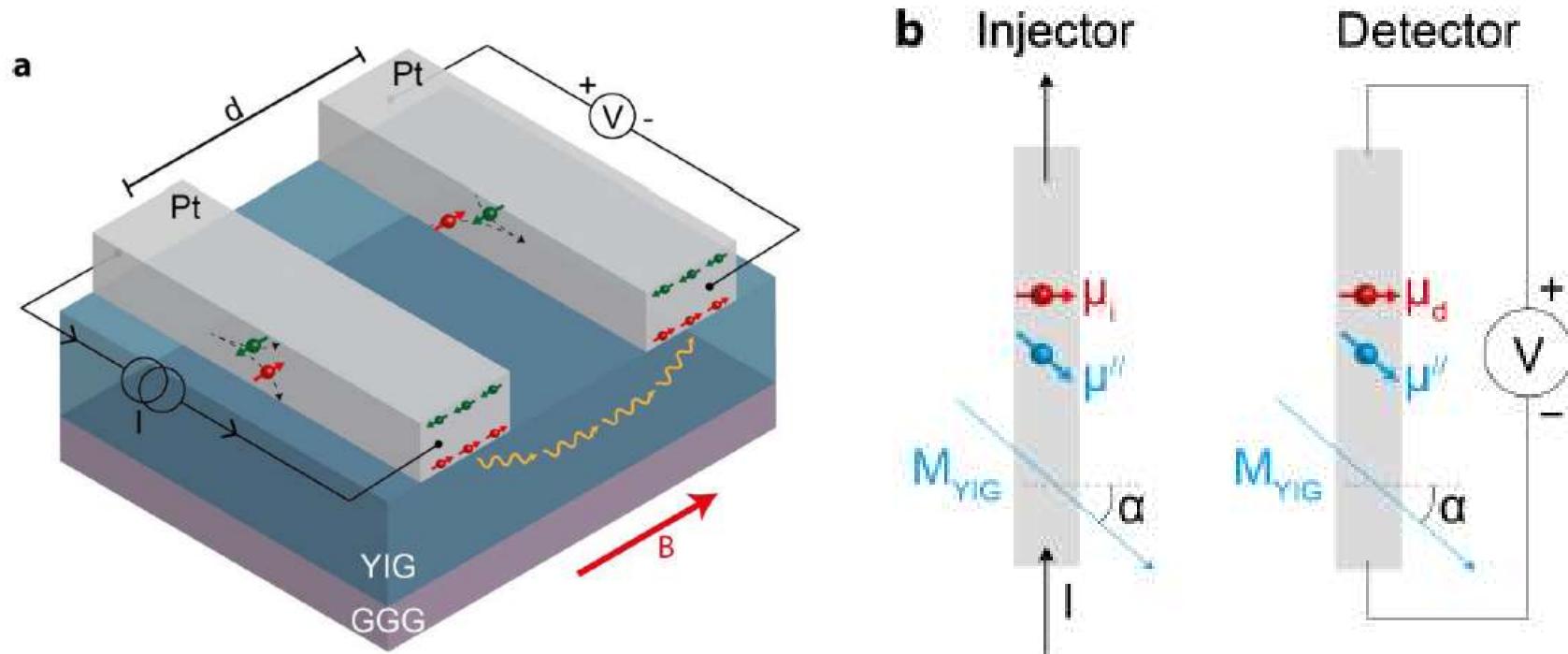


$$\text{Nonlocal MR} = (V_p - V_{AP})/I_{INJ}$$

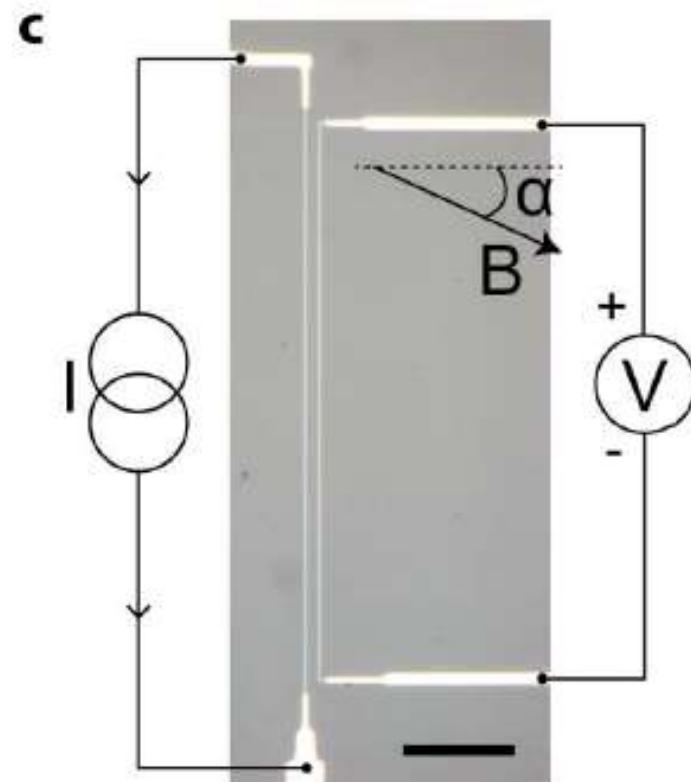
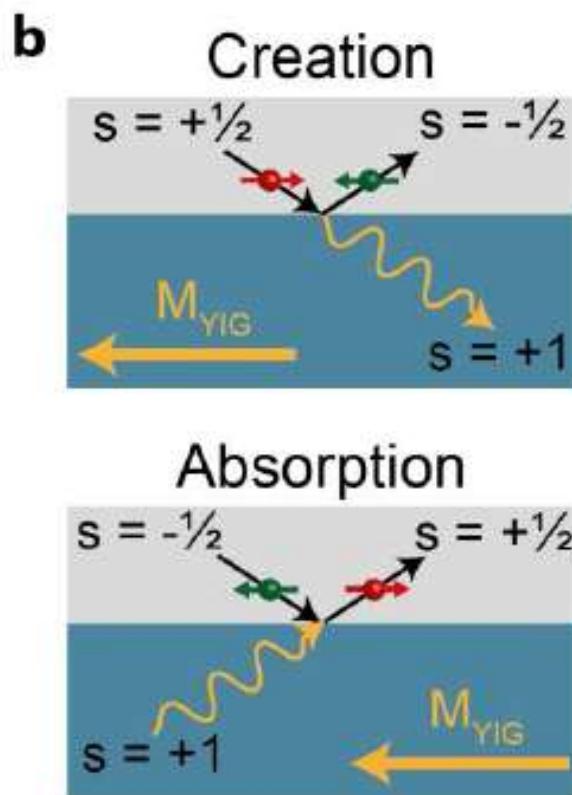
Nonlocal Spin valve



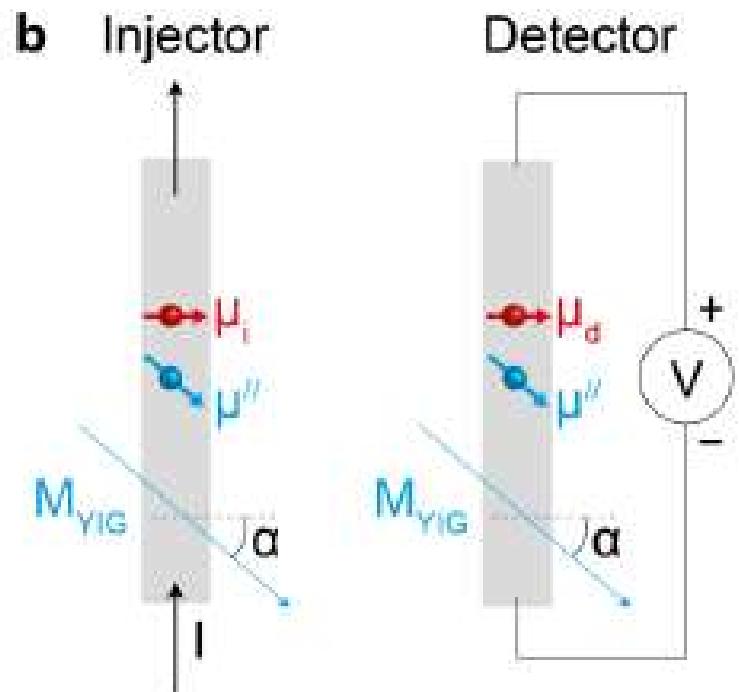
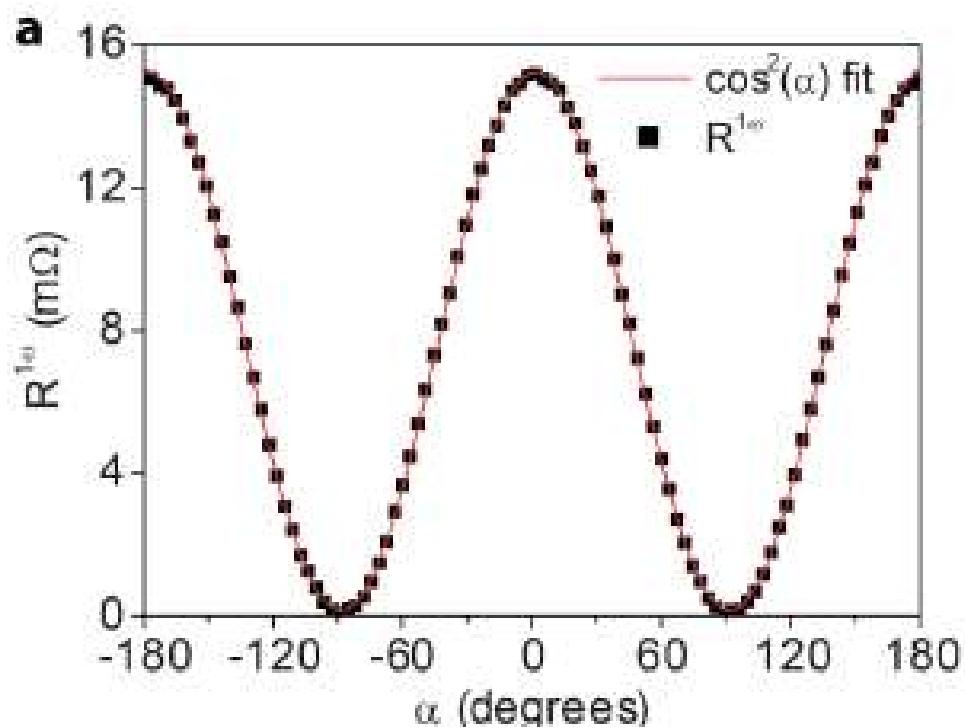
Magnon transport



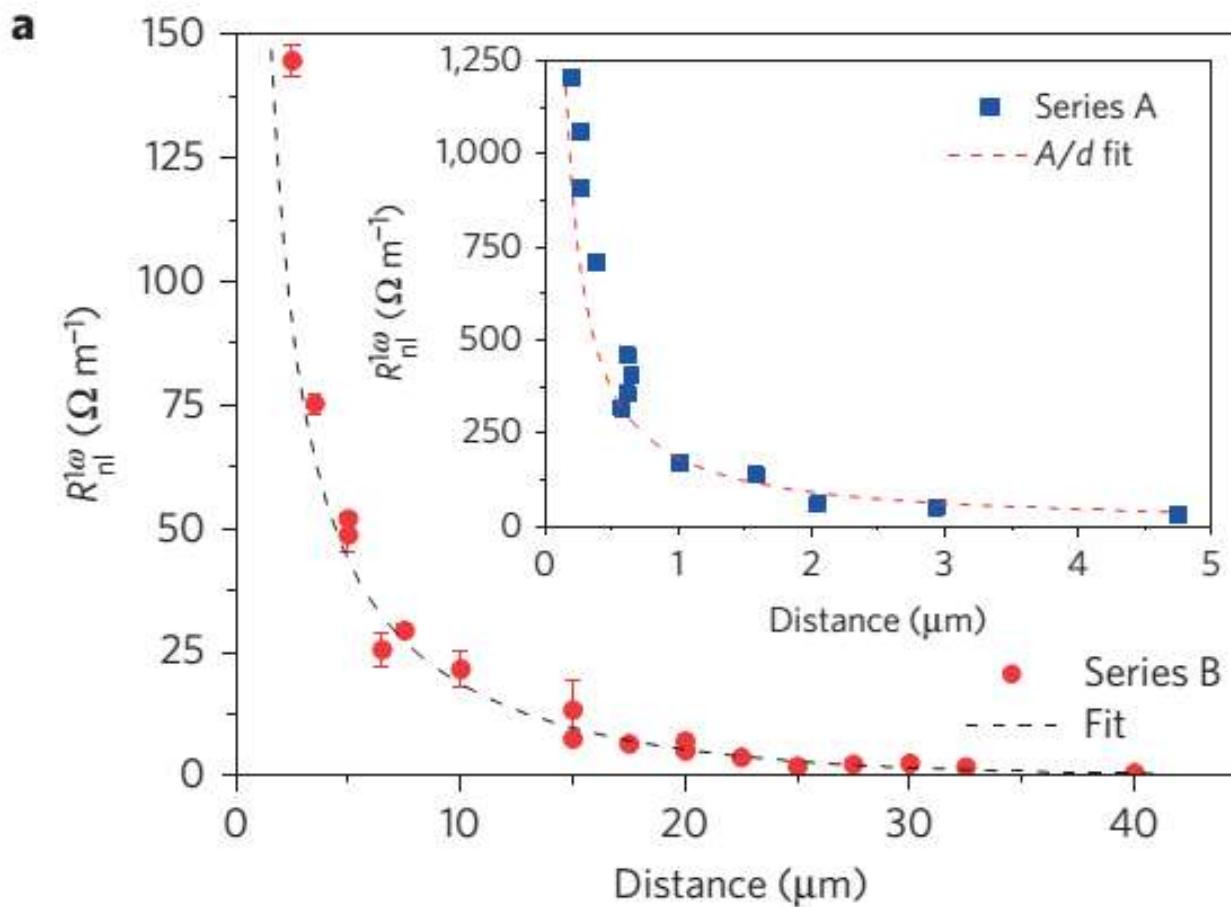
Magnon transport



Magnon transport



Magnon transport

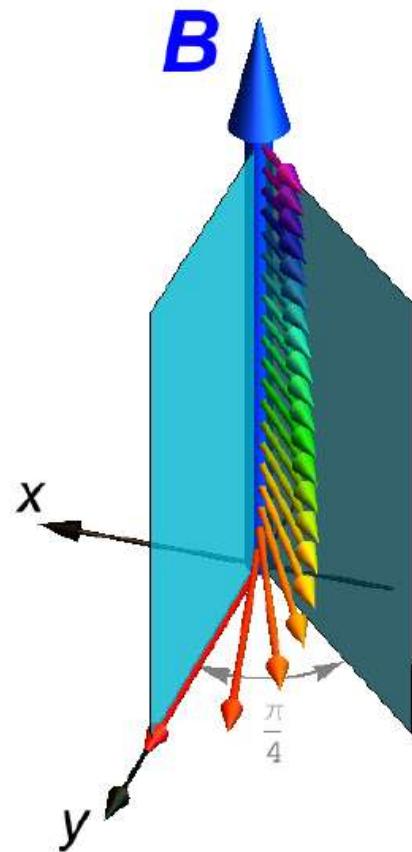


Outline

8. Handle MR

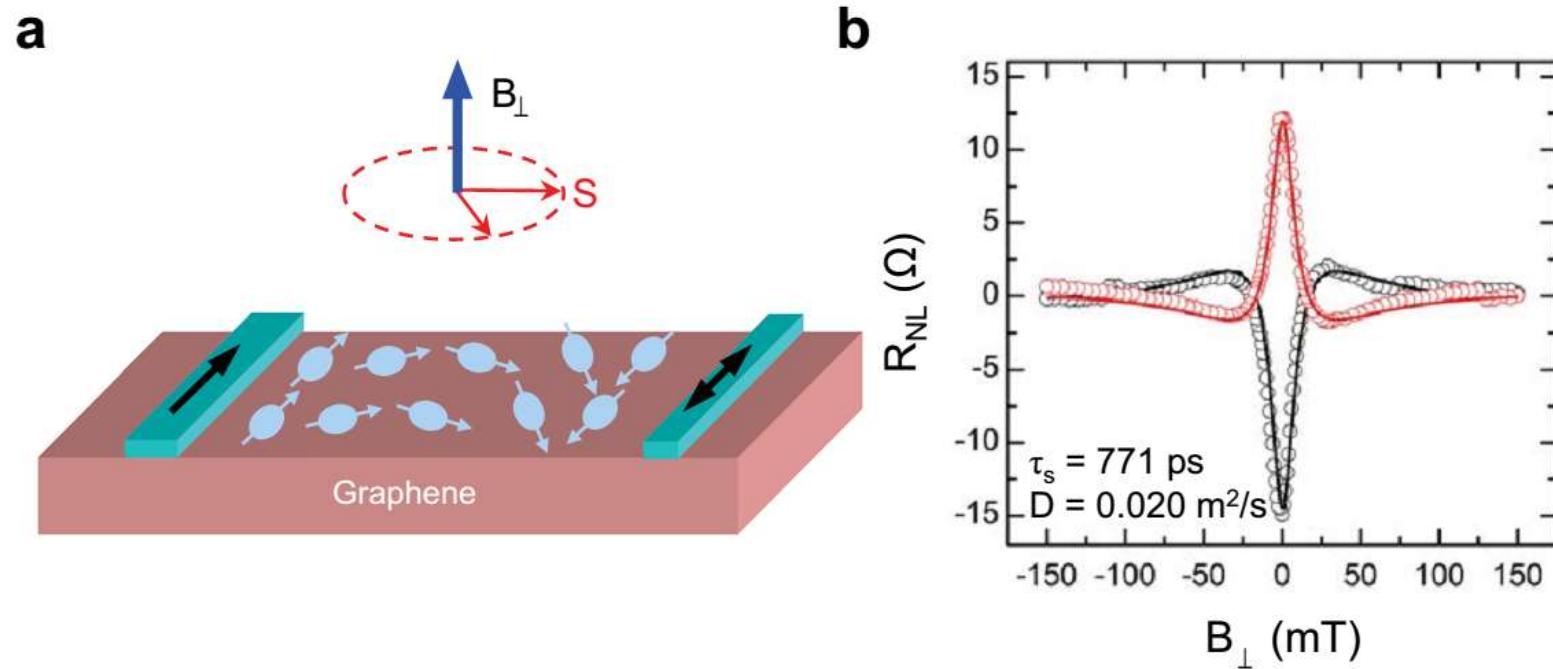
Hanle MR

a)

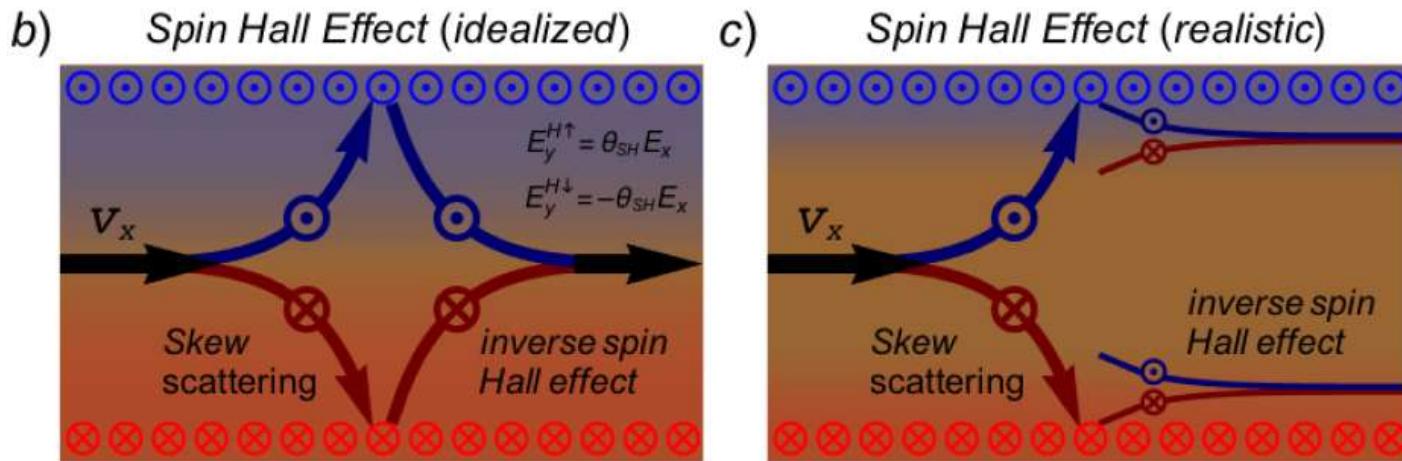


$$\vec{\tau} = -g\mu_B \vec{s} \times \vec{B}$$

Hanle MR



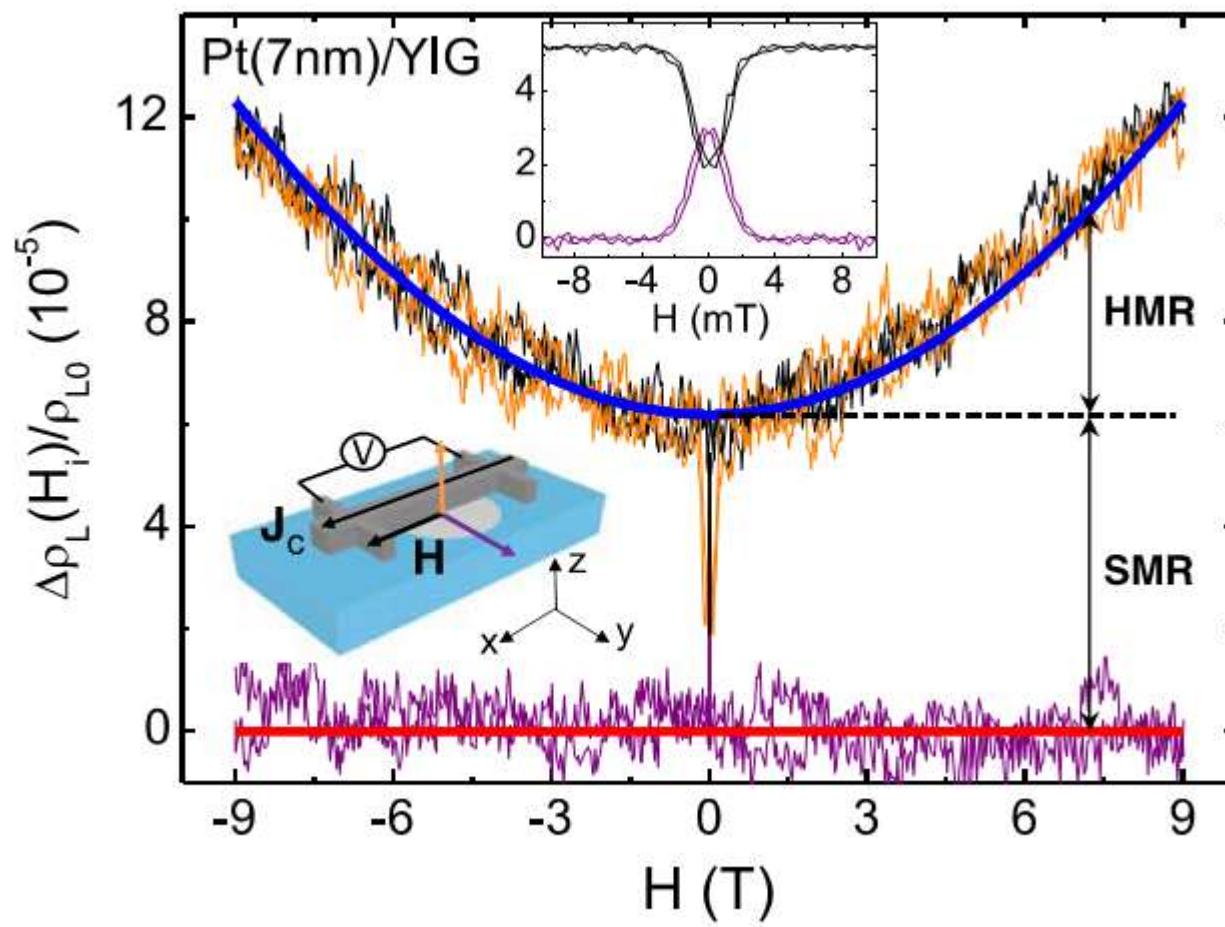
Hanle MR



- Hanle effect on the spin accumulation

Vélez,, et al, PRL (2016)

Hanle MR



- Resistance change
 $H \perp S$
- No resistance change
 $H // S$

Vélez,, et al, PRL (2016)

Summary

1. Magnetoresistance and ordinary MR

2. Anisotropic MR

3. Tunneling AMR

4. Colossal MR

5. Giant MR

6. Tunneling MR

7. Spin Hall MR

8. Nonlocal MR

9. Hanle MR

下一节课: Oct. 26th

Chapter 4: Spin Valves

课件下载 :

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