Chapter 3

Magnetoresistance

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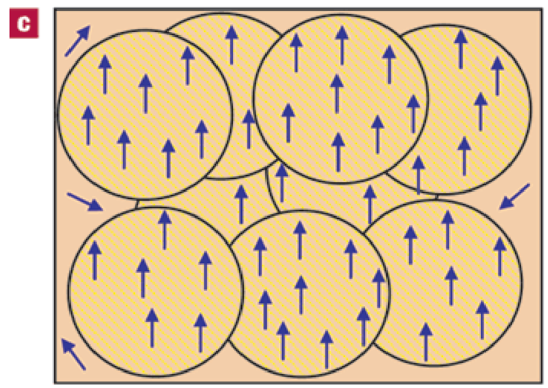
量子材料科学中心

2015年10月11日

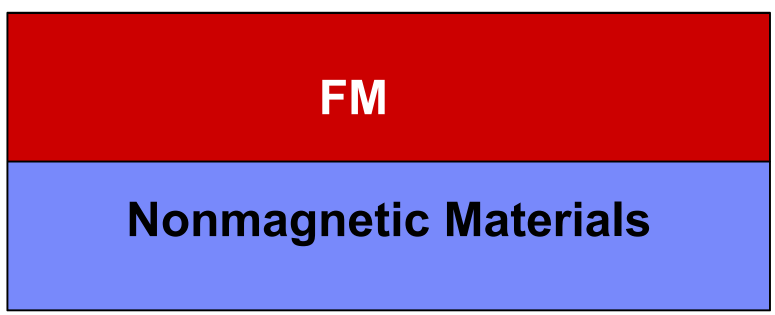
Review of last class

How to induce magnetic moment

Doping



Proximity effect

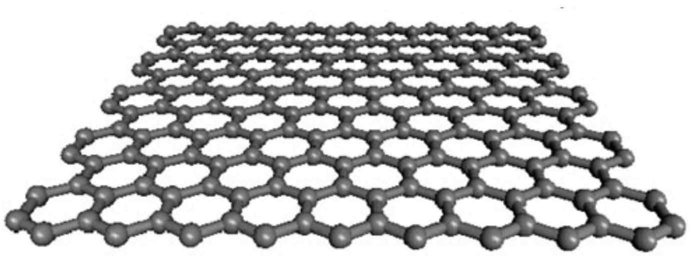


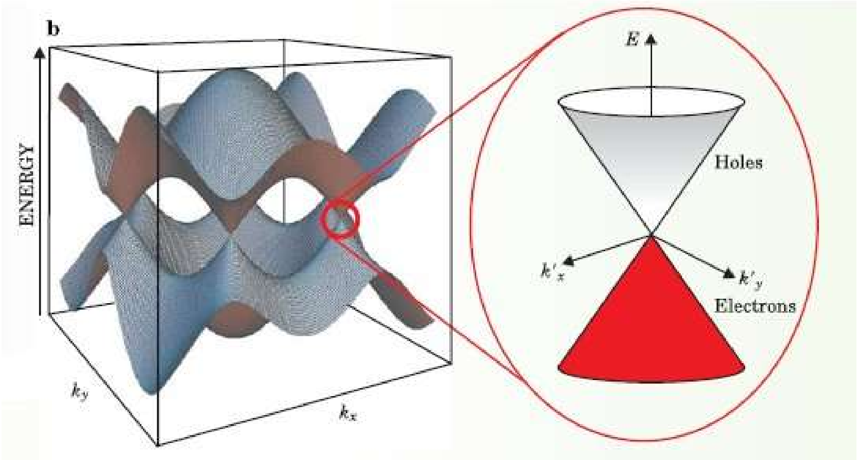
Interface hybridization

Review of last class

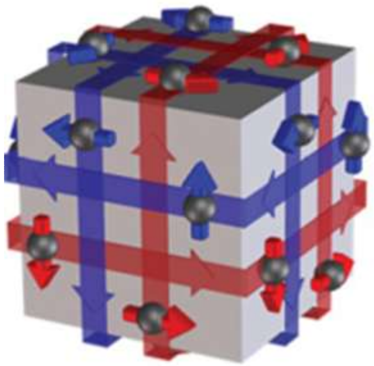
Induce M in two Quantum Materials

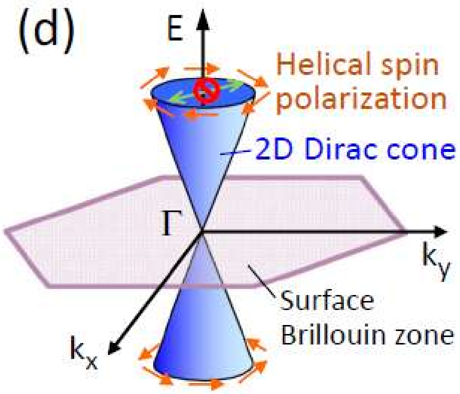
Graphene





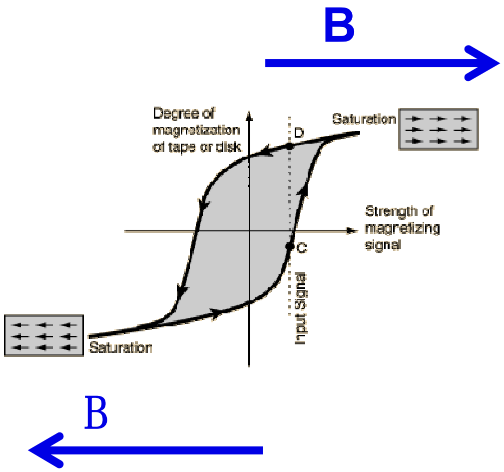
Topological Insulator





Review of last class

Magnetic field



Without B
???

Control

Electric field

Ultrafast Laser

Spin torque

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)	**Hanle magnetoresistance**

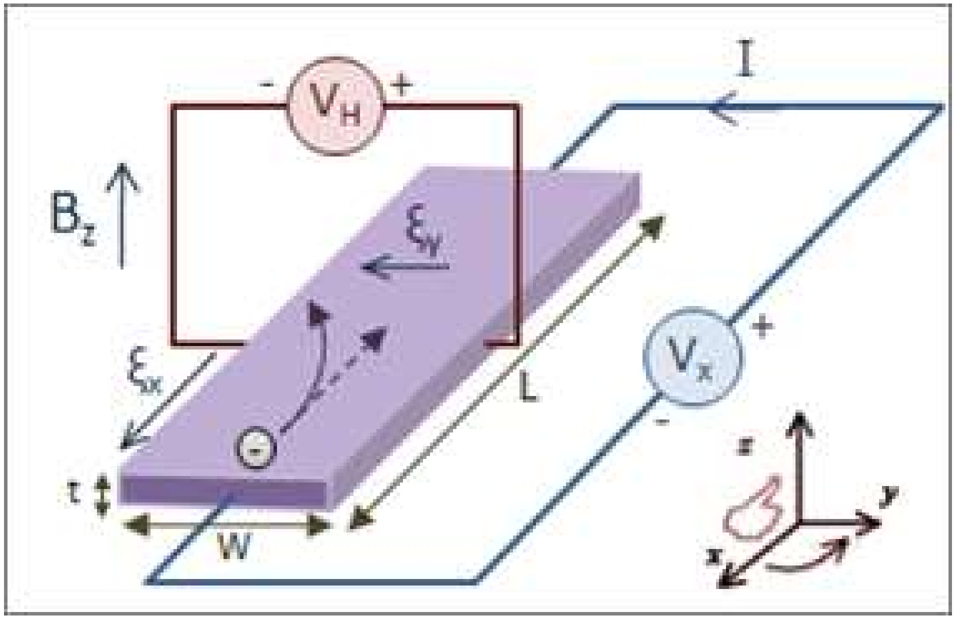
Ordinary MR

A resistor in magnetic field

The resistance change in a magnetic field

Ordinary MR

Ordinary MR in a semiconductor—Lorentz force



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

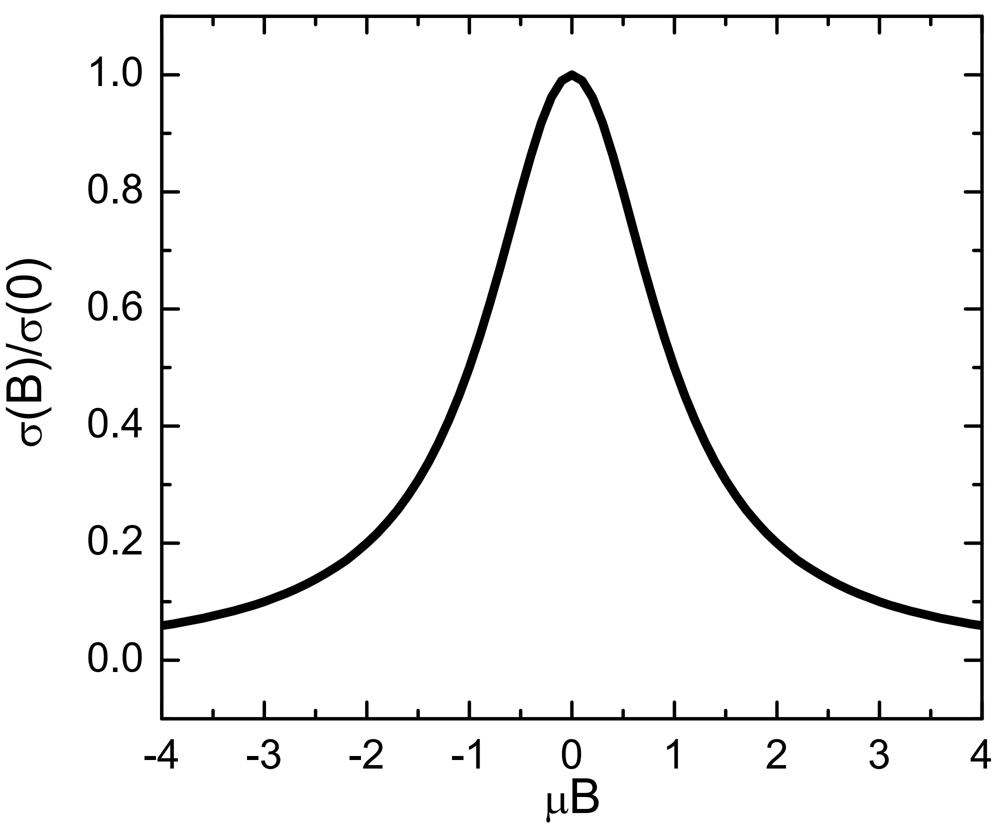
$$v = \frac{\mu E x}{(1 + (\mu B)^2)}$$

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

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

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

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

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

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

Ordinary MR

Two carriers MR

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

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

Ordinary MR

Two carriers MR

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

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

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

Ordinary MR

Two carriers MR

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

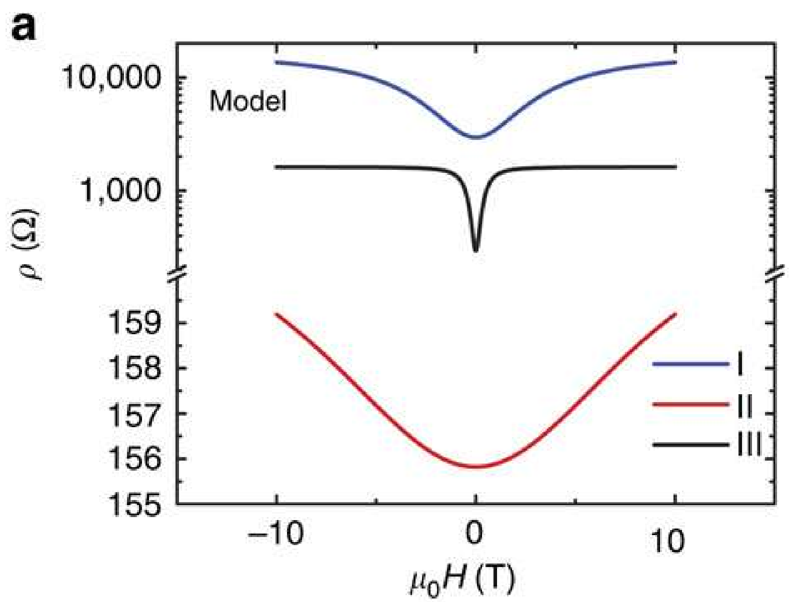
$$MR = \frac{\rho_{xx} - \rho_0}{\rho_0} = \frac{\dfrac{n_1\mu_2 + n_2\mu_1}{(n_1 + n_2)\mu_1\mu_2} - \dfrac{1}{(n_1\mu_1 + n_2\mu_2)}}{\dfrac{1}{(n_1\mu_1 + n_2\mu_2)}}$$

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

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

Ordinary MR

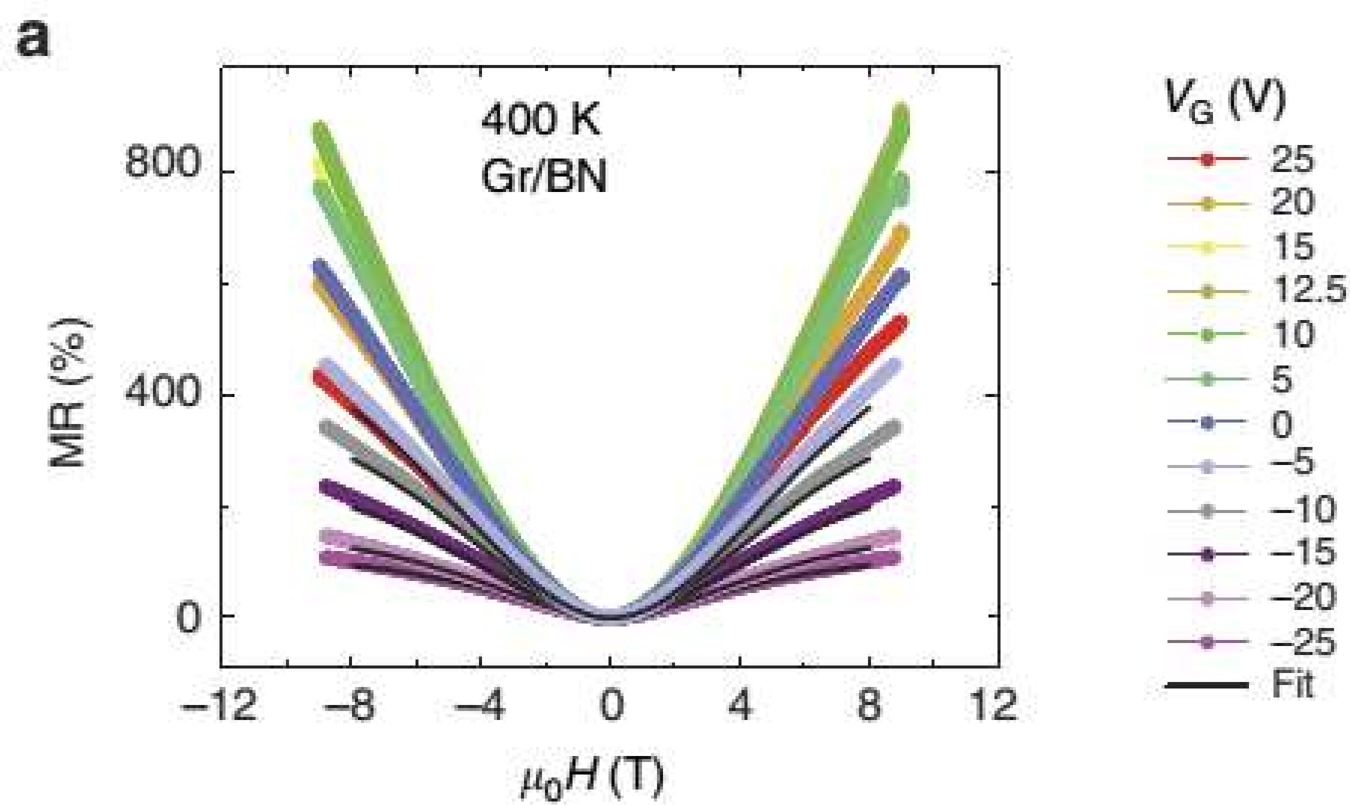
Large MR in Graphene with two carriers



	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

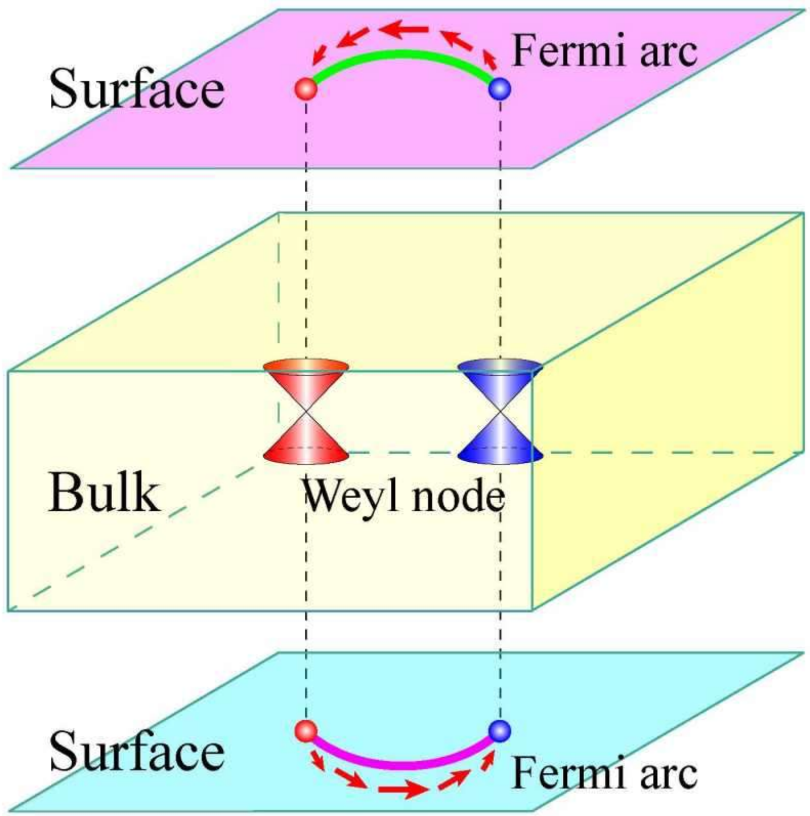
Large MR in Graphene with two carriers



Gopinadhan, et al, Nature Commun. (2015)

Ordinary MR

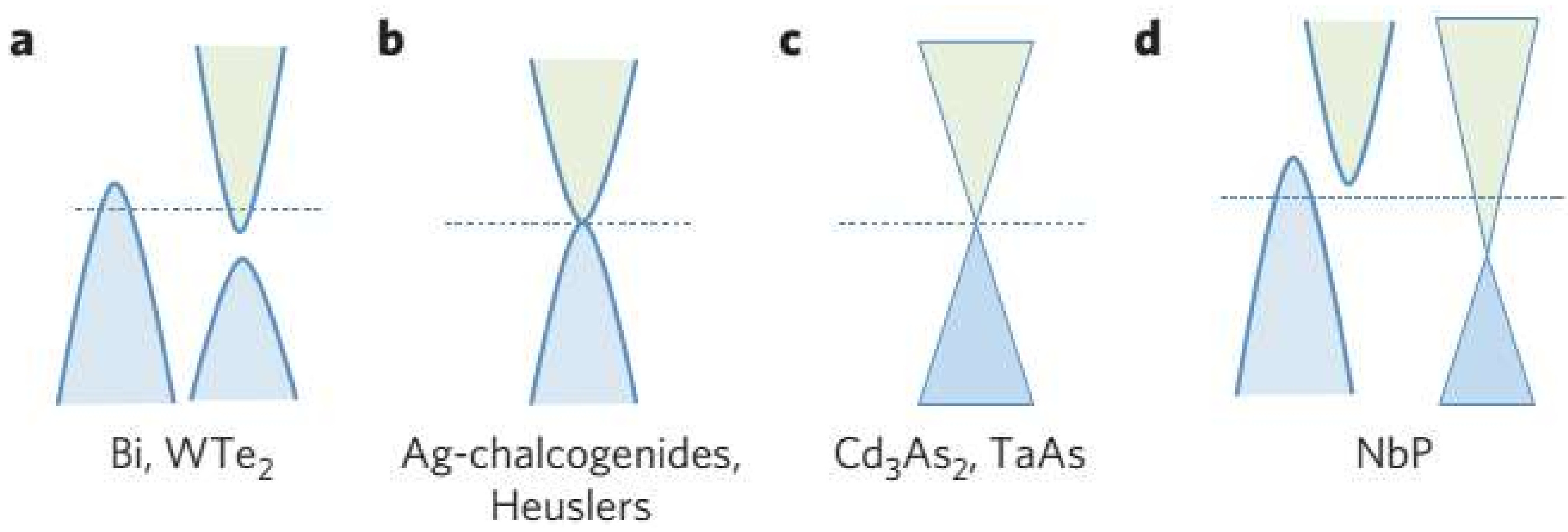
Large ordinary MR in Weyl semimetal



wikipedia

Ordinary MR

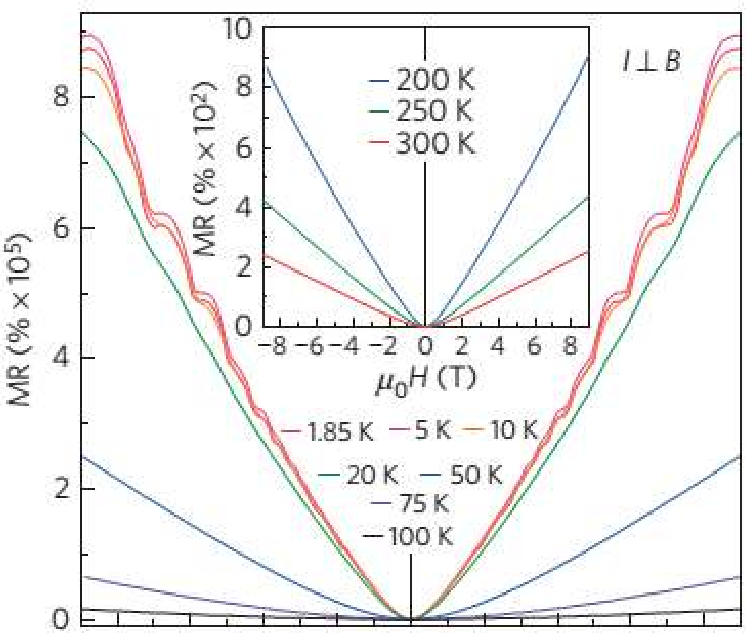
Large ordinary MR in Weyl semimetal: NbP

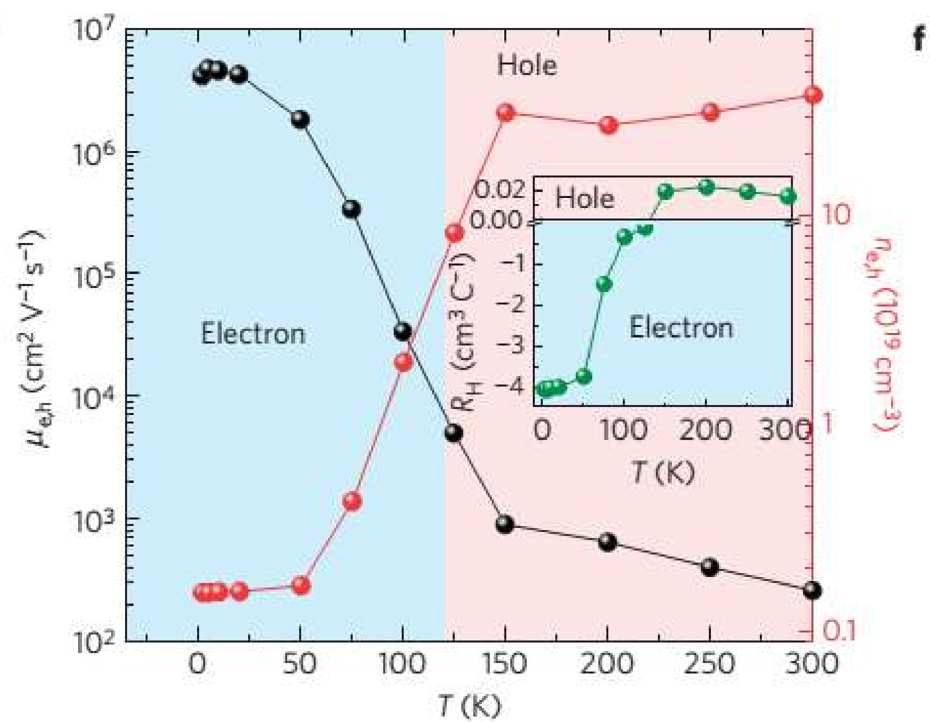


Shekhar, et al, Nature Physics (2015)

Ordinary MR

Large ordinary MR in Weyl semimetal: NbP





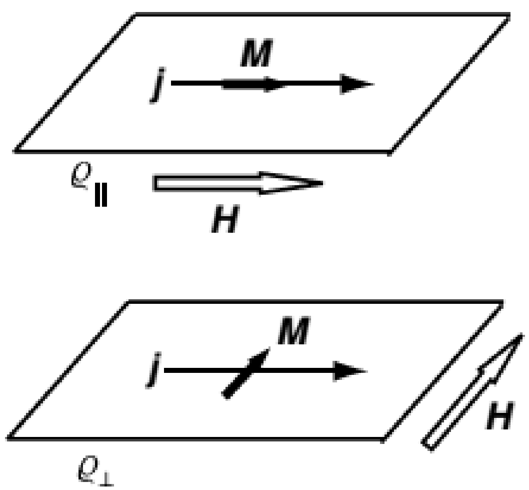
Shekhar, et al, Nature Physics (2015)

2. Anisotropic MR

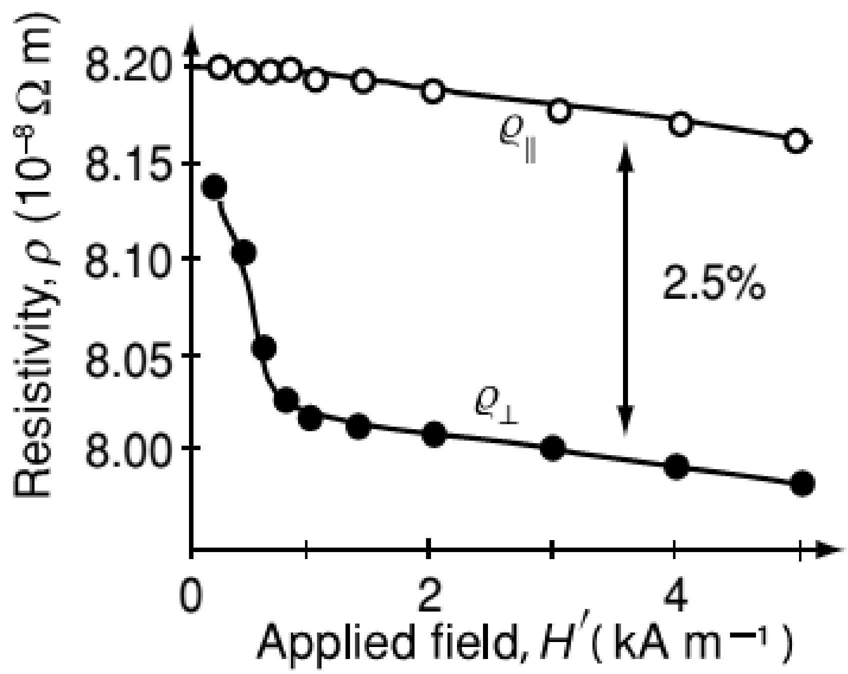
Discovery of AMR

AMR of a Nickel

Discovered by William Thompson (1857)

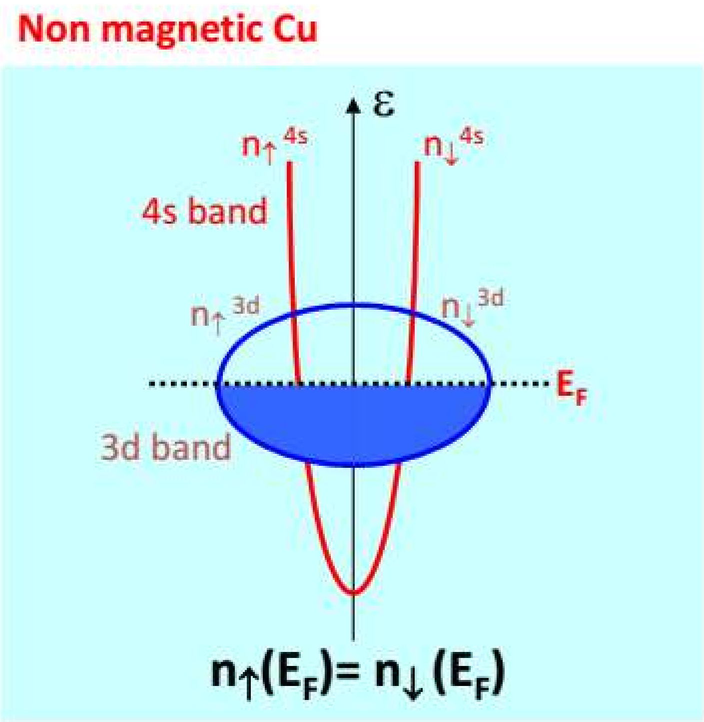


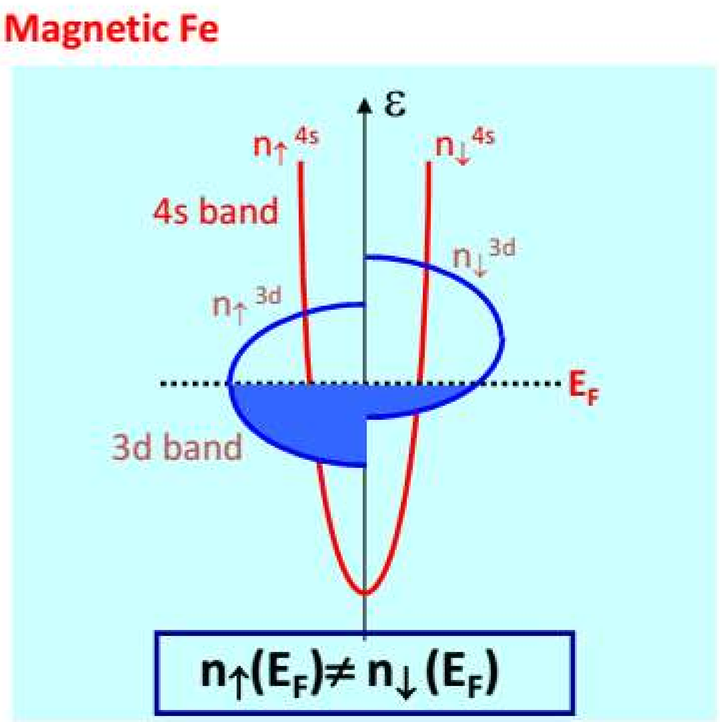
Measurement of AMR for a thin film.



Mechanism

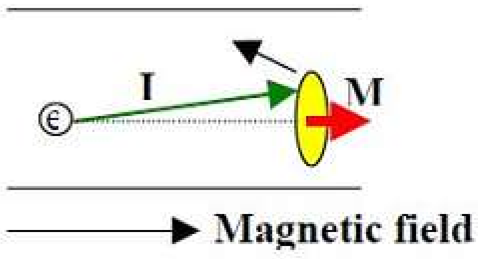
NM vs FM

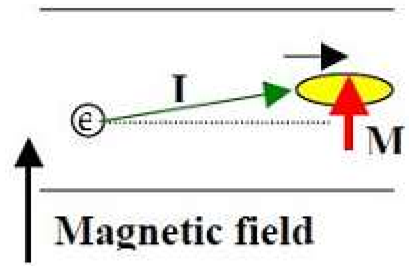




Mechanism

Why AMR?





I parallel to M

Electronic orbits perpendicular to current

Increased cross section for scatetring

High resistance

I perpendicular to M

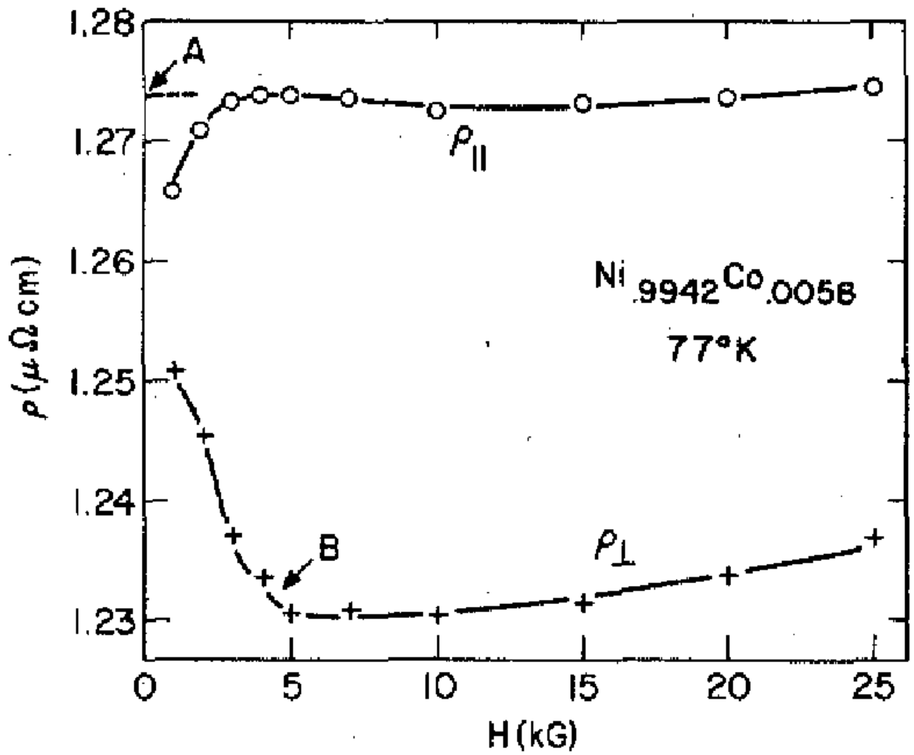
Electronic orbits parallel to current

Reduced cross section for scatetring

Low resistance

AMR of 3d FM

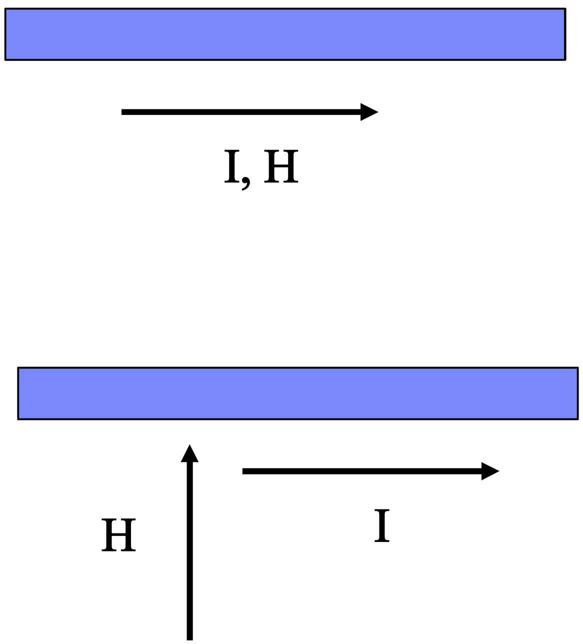
NiCo

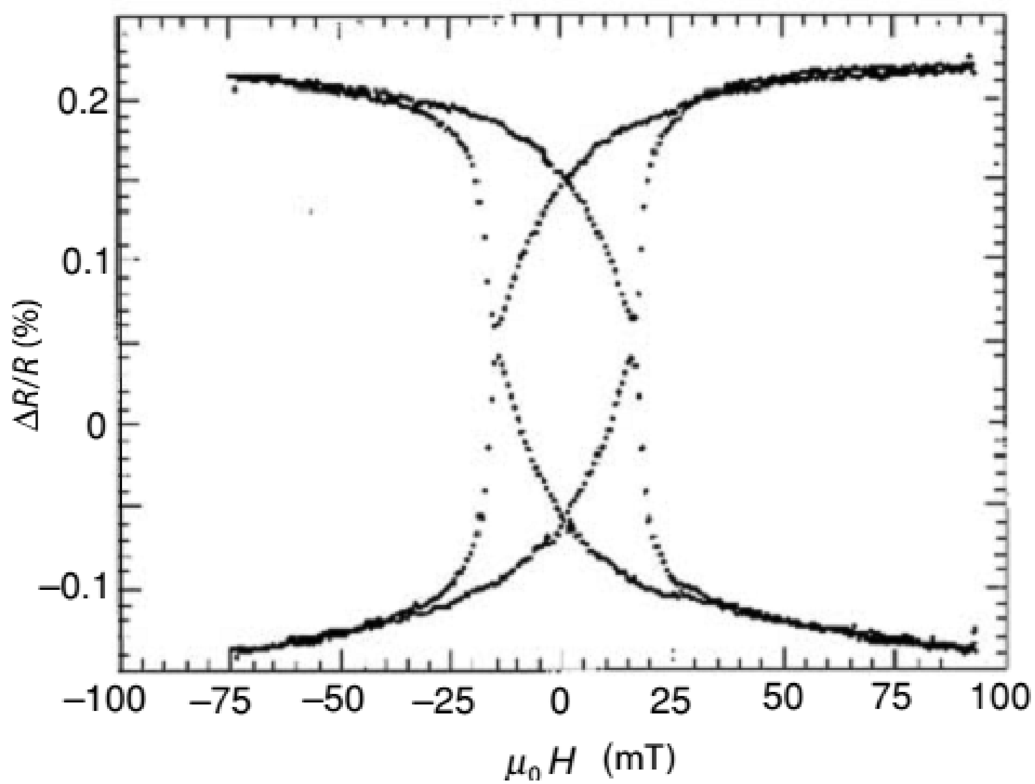


Viret, et al, PRB (1996)

AMR of 3d FM

Py: Large AMR





Viret, et al, PRB (1996)

AMR of 3d FM alloy

Py: Large AMR

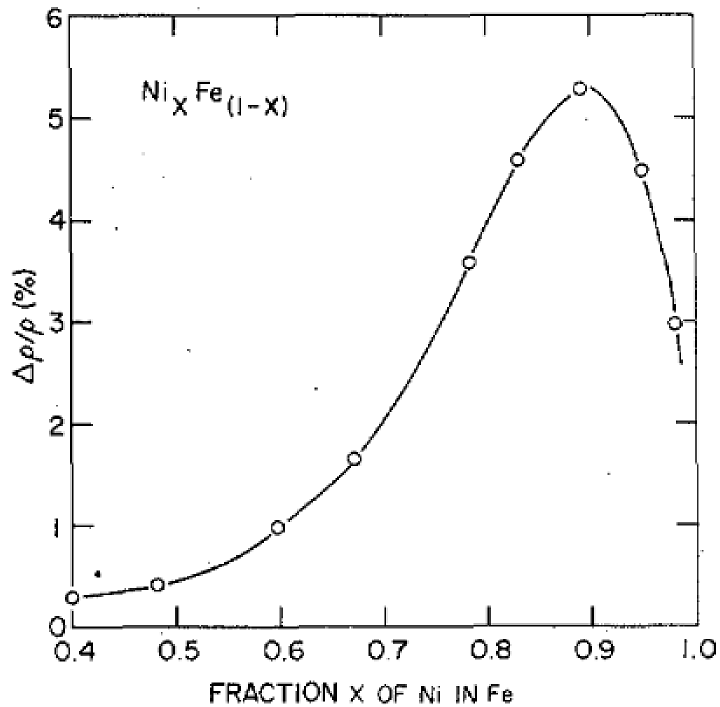
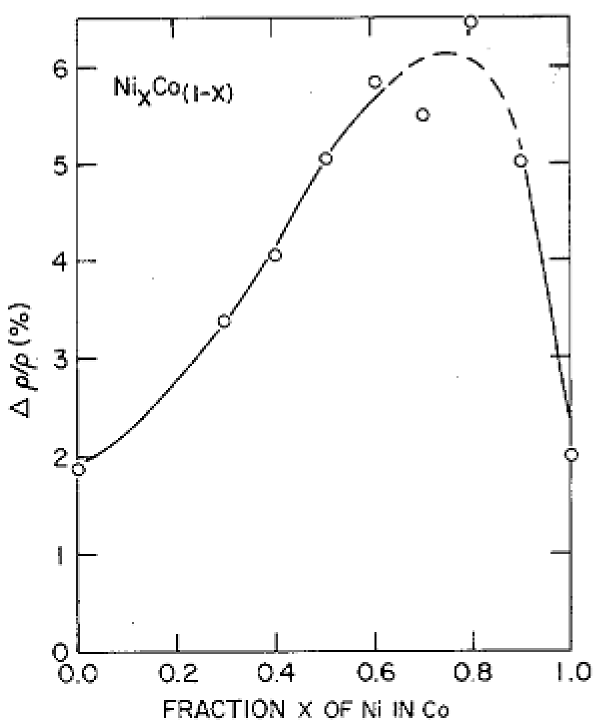


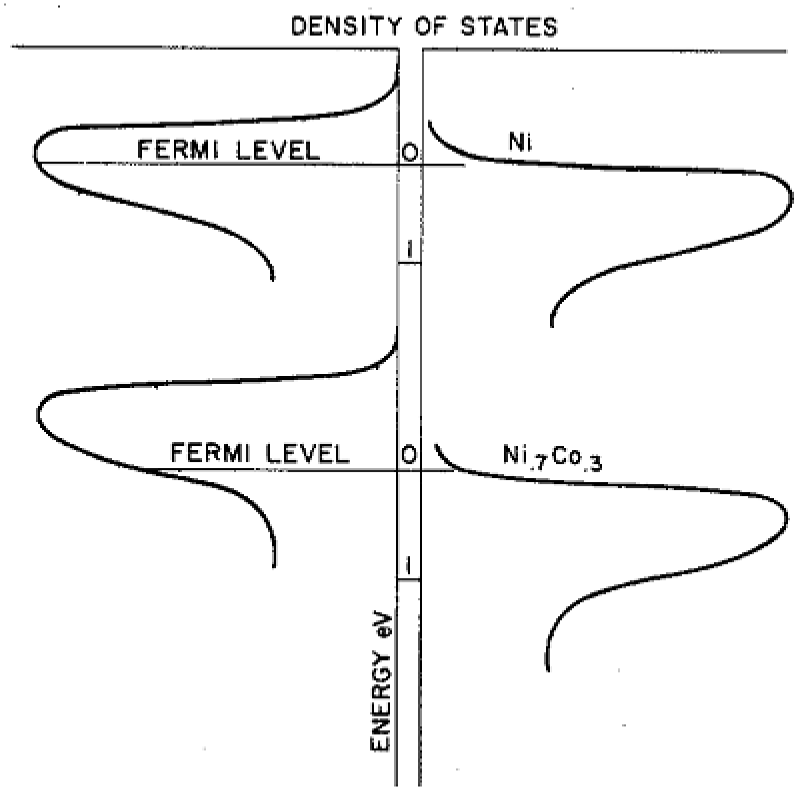
Fig. 2. Anisotropic magnetoresistivity ratio in percent for $Ni_xFe_{(1-x)}$ alloys at room temperature (Bozorth [7]).

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

AMR of 3d FM alloy

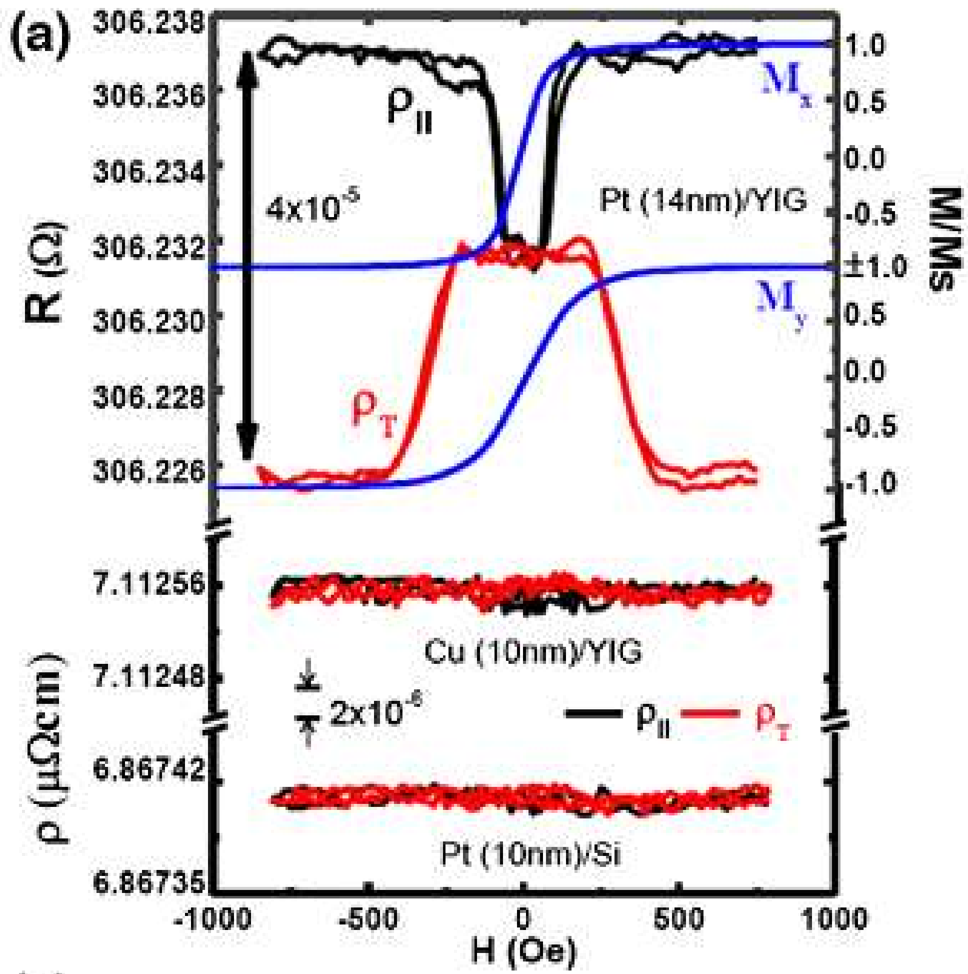
Alloy

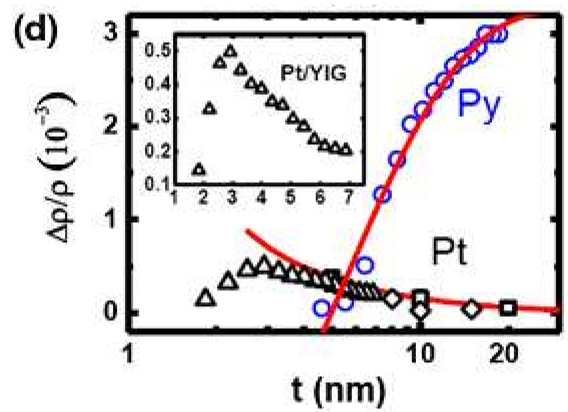




McGuire & Potter, et al, IEEE Magnetics (1975)

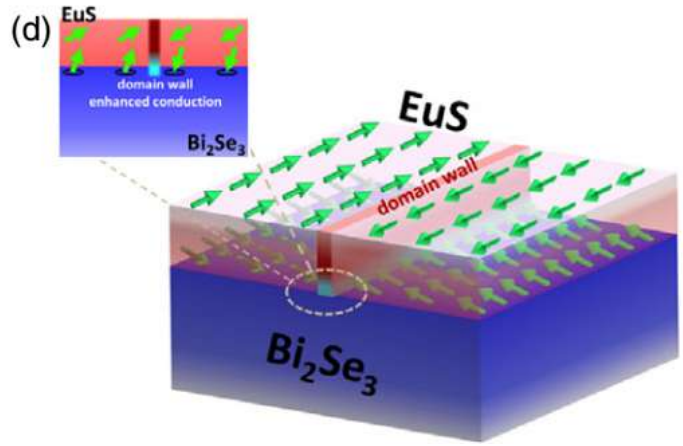
Pt and Bi2Se3

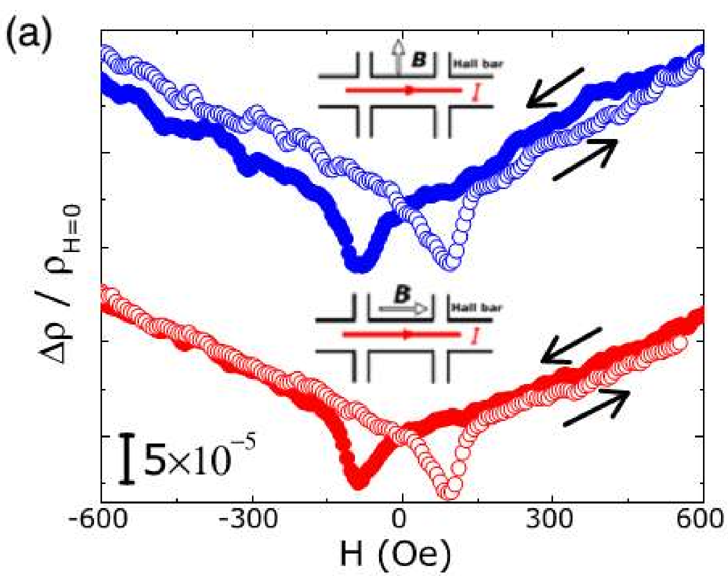


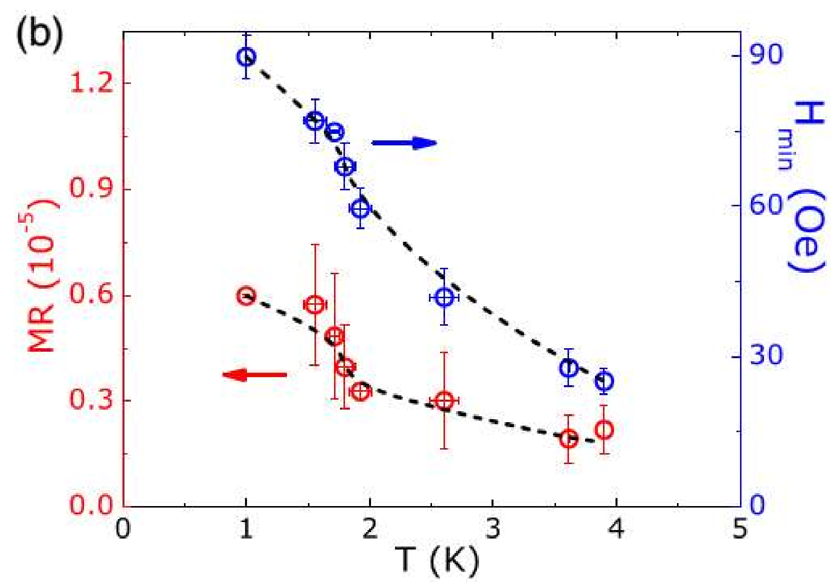


Huang, et al, PRL (2012)

Pt and Bi2Se3



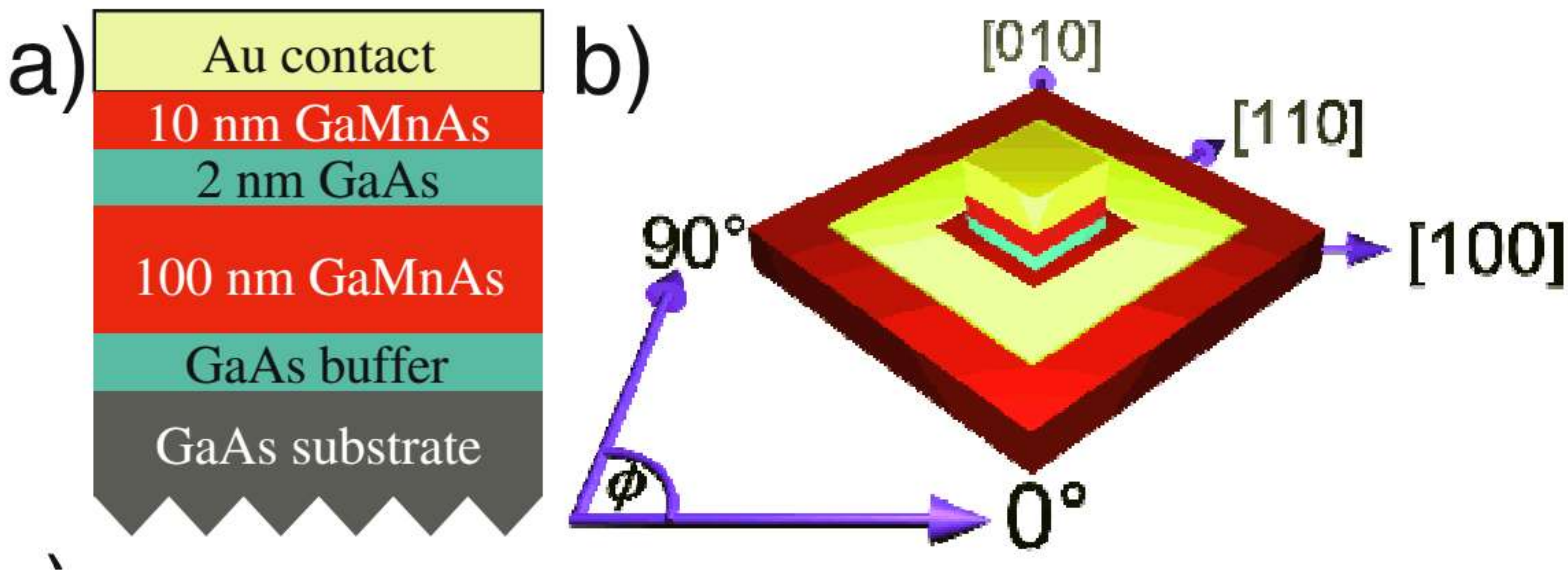




Wei, et al, PRL (2013)

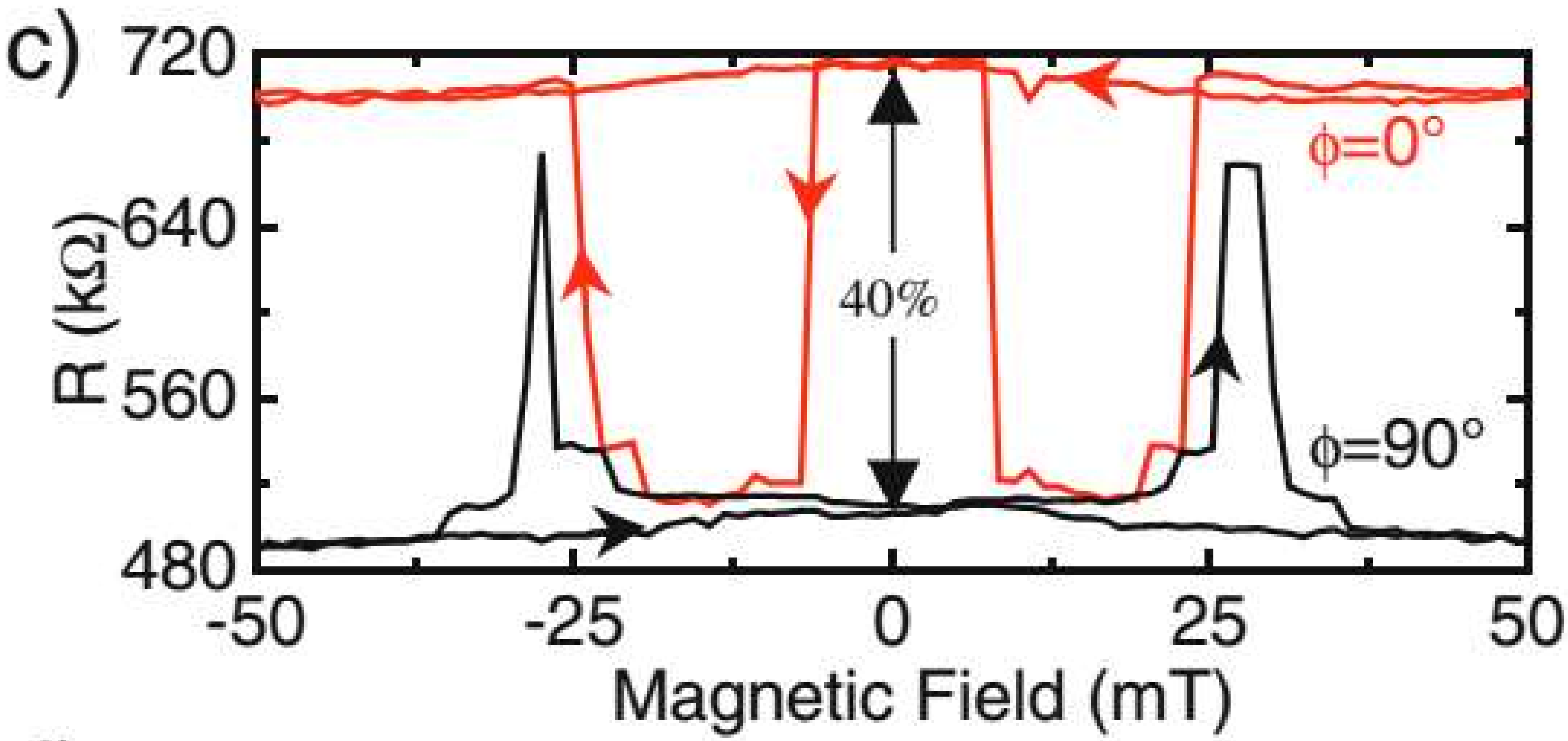
3. Tunneling AMR

Tunneling AMR



Ruster, et al, PRL (2005)

Tunneling AMR



Ruster, et al, PRL (2005)

Tunneling AMR

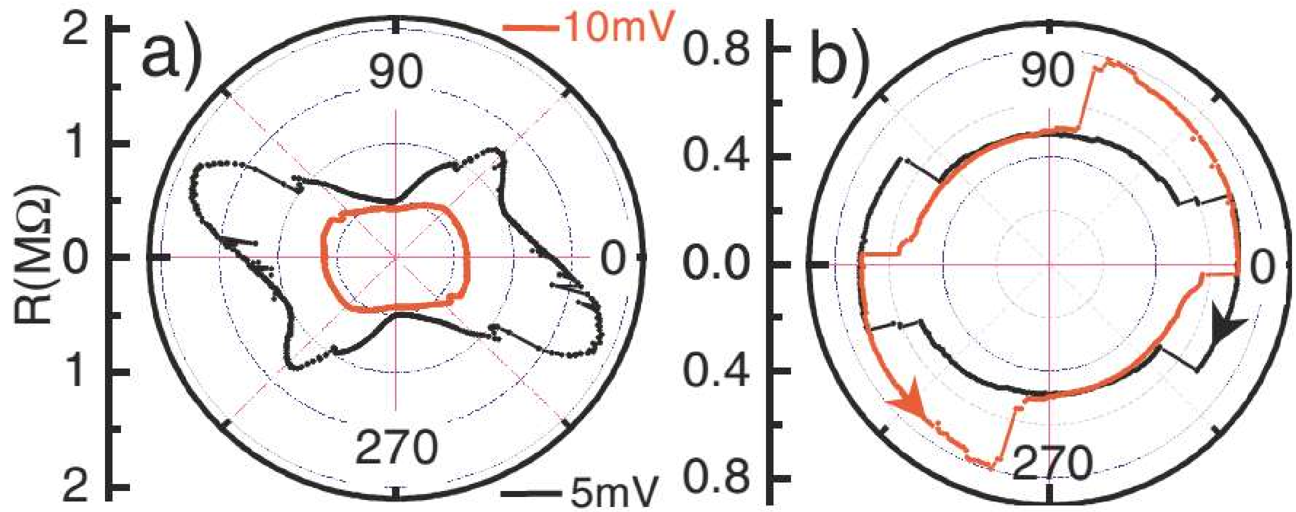
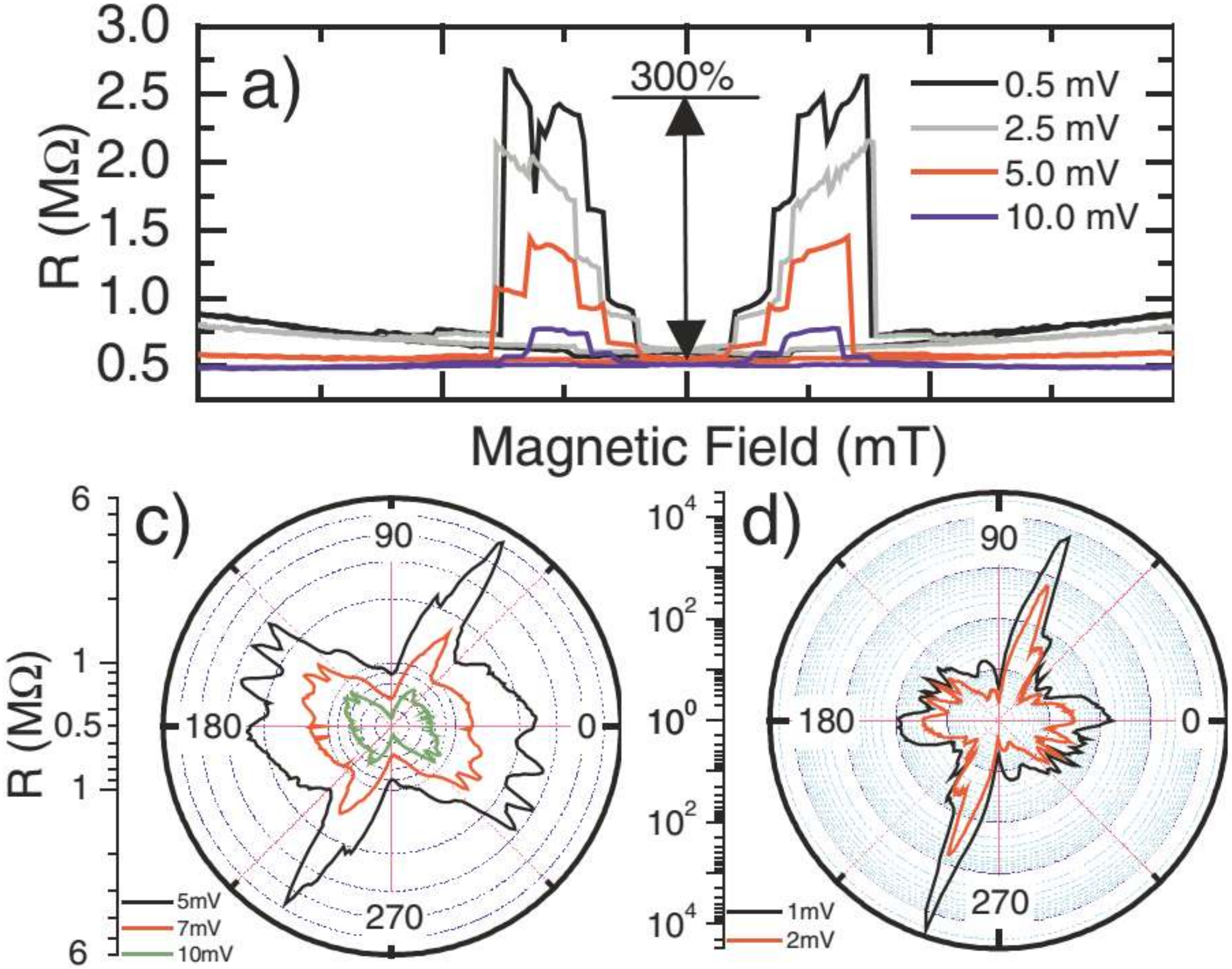


FIG. 2 (color online). ϕ scans at 4.2 K (a) in a saturation magnetic field $|\mathbf{H}| = 300$ mT, and (b) $V_B = 5$ mV at $|\mathbf{H}| = 25$ mT, just sufficient to switch M between easy axes.

Ruster, et al, PRL (2005)

Tunneling AMR



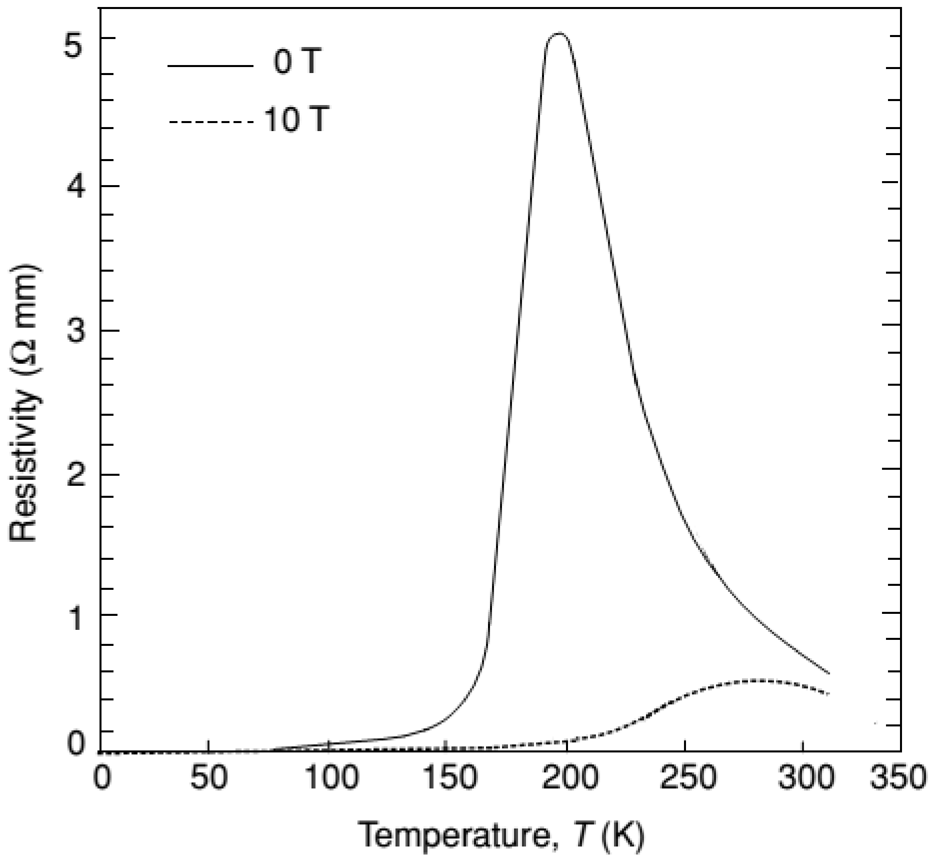
Ruster, et al, PRL (2005)

Outline

4. Colossal MR

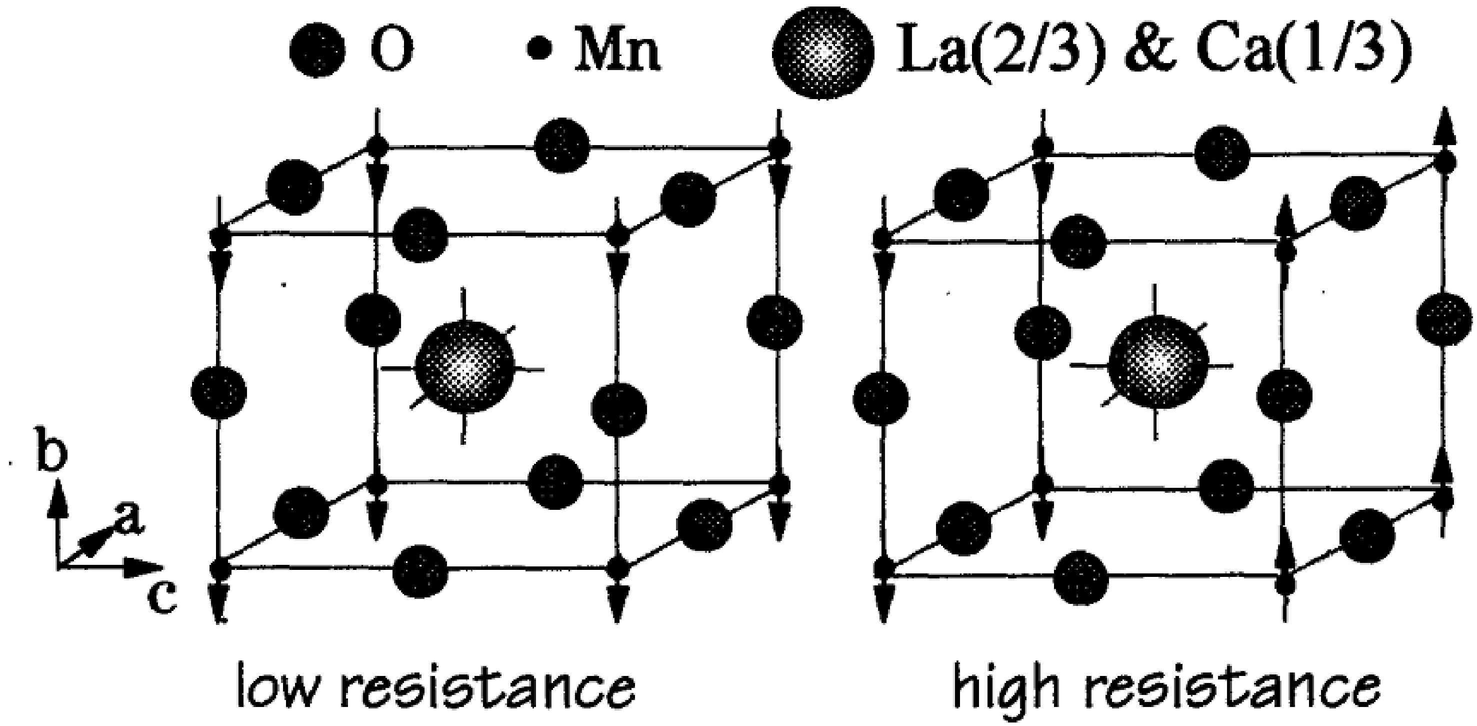
Colossal MR

CMR in $LaCaMnO_3$



Tokura & Tomioka, JMMM (1999)

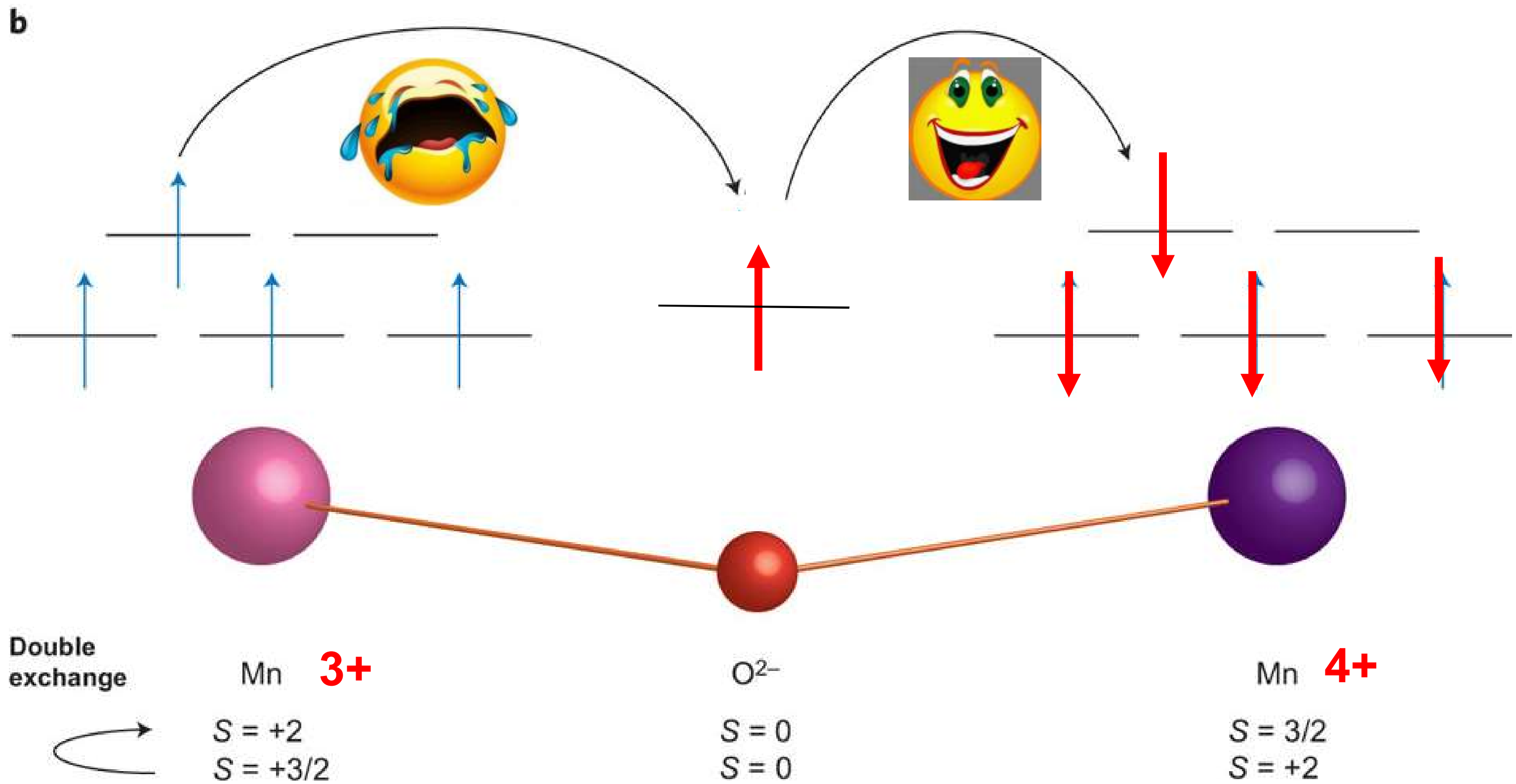
Colossal MR



Tokura & Tomioka, JMMM (1999)

Colossal MR

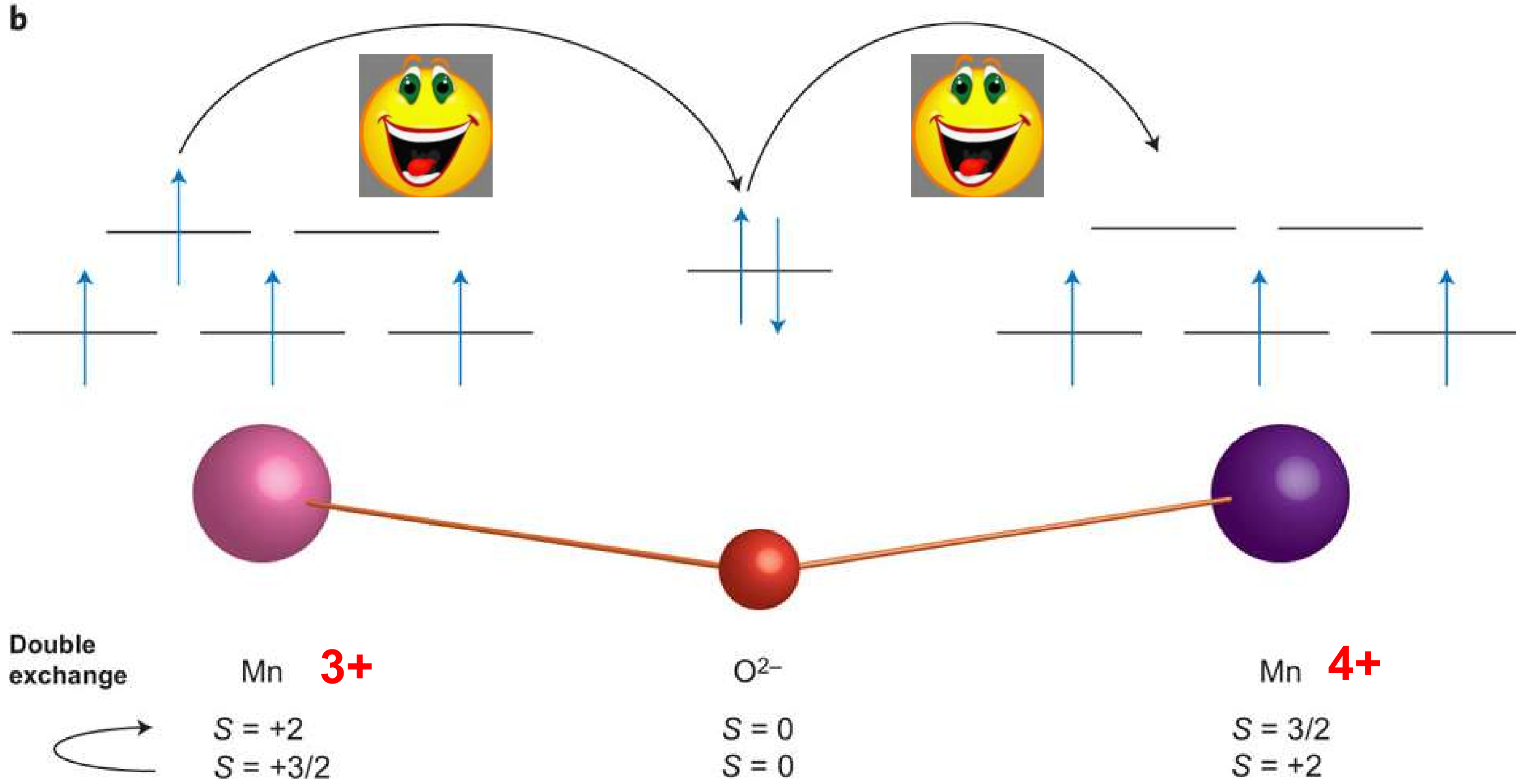
Small B → high R



Tokura & Tomioka, JMMM (1999)

Colossal MR

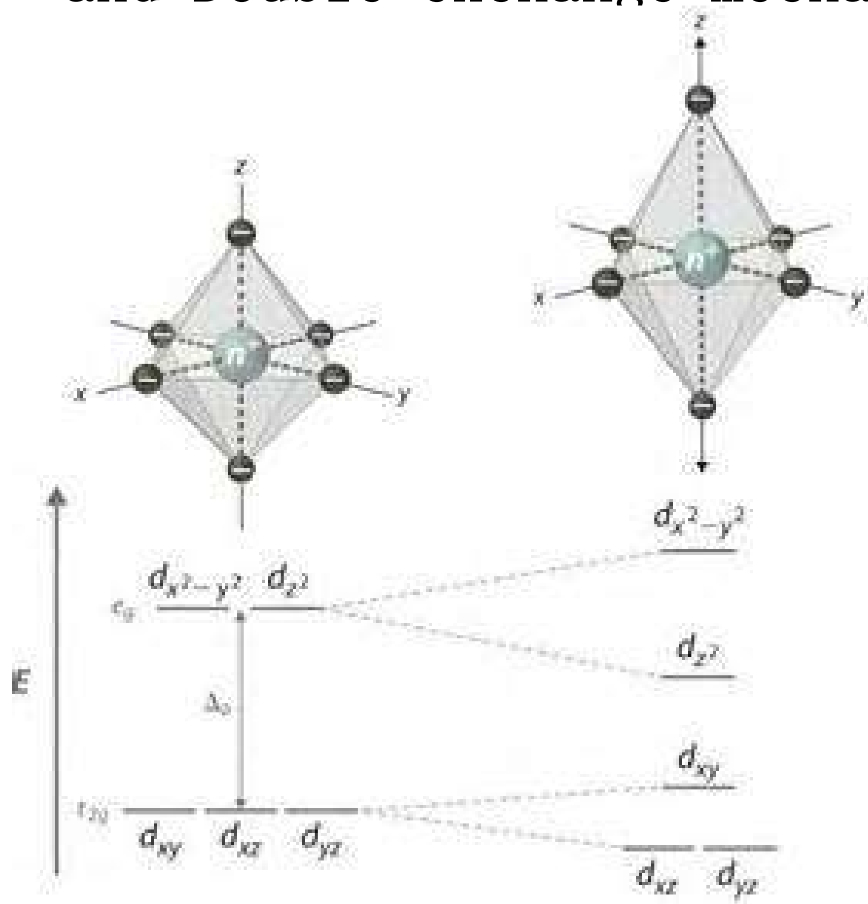
Large B→ Low R



Tokura & Tomioka, JMMM (1999)

Colossal MR

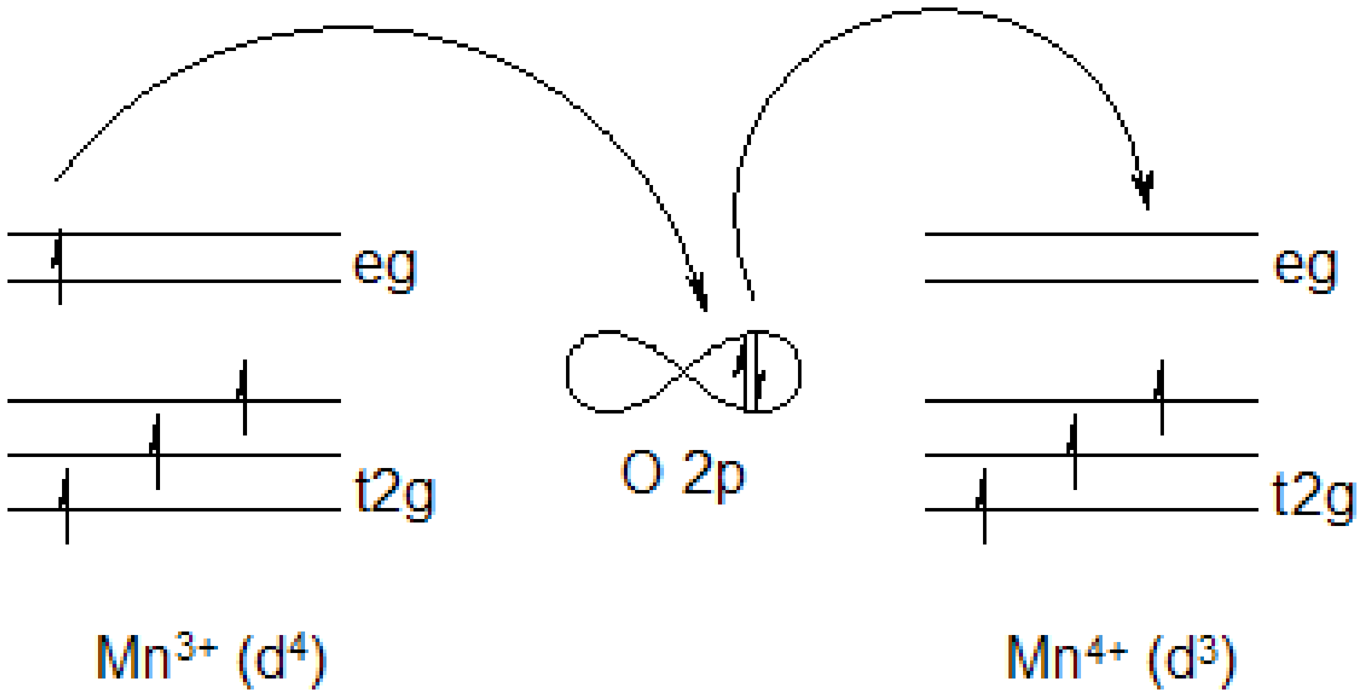
Why? -→ John Teller distortion and Double-exchange mechanism



Source: wikipedia.org

Colossal MR

Why? → John Teller distortion
and Double-exchange mechanism



Source: wikipedia.org

Summary

1. Magnetoresistance and ordinary MR

2. Anisotropic MR

3. Tunneling AMR

4. Colossal MR

5. Giant MR

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7. Spin Hall MR

8. Nonlocal MR

9. Hanle MR

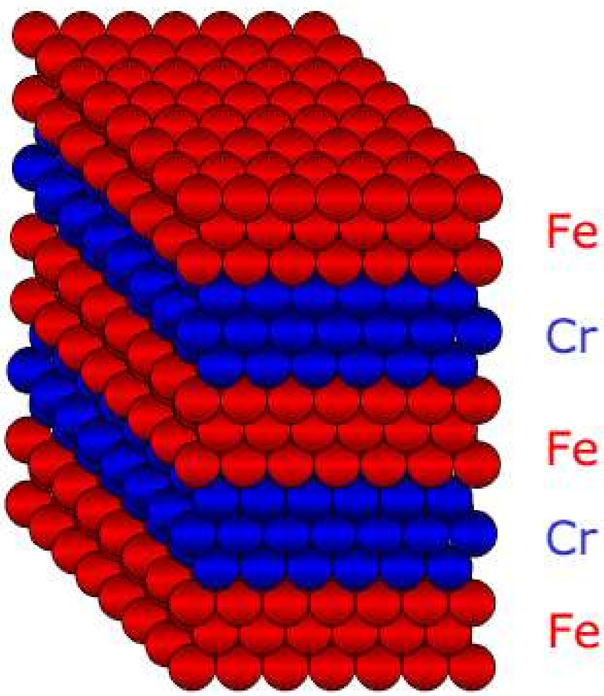
休息10分钟

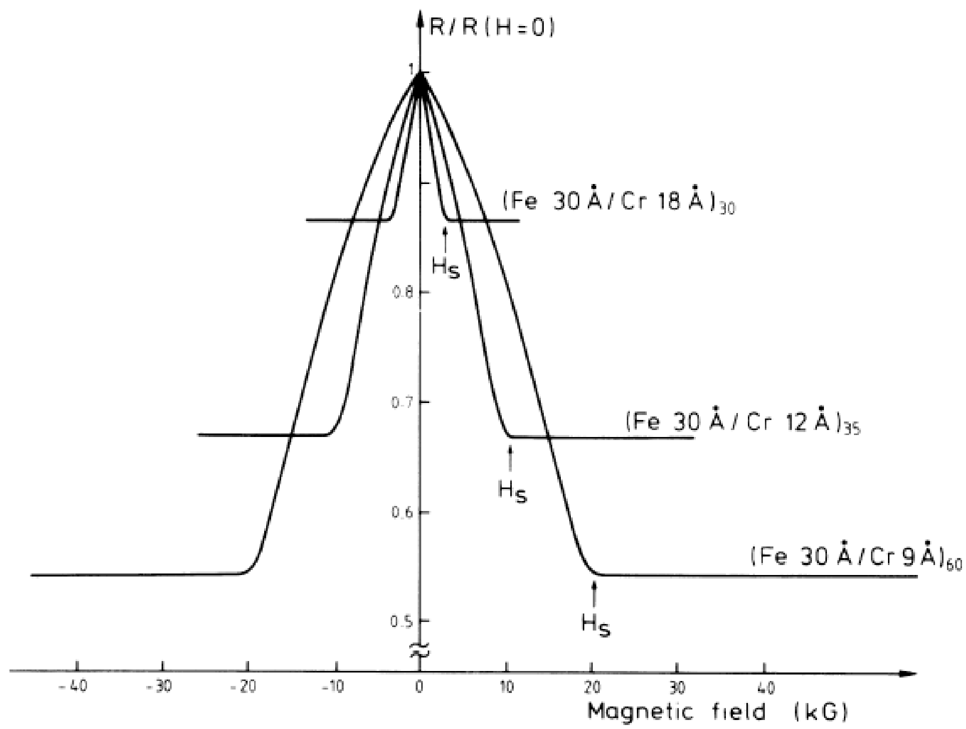
Outline

5. Giant MR

GMR

Observation of GMR

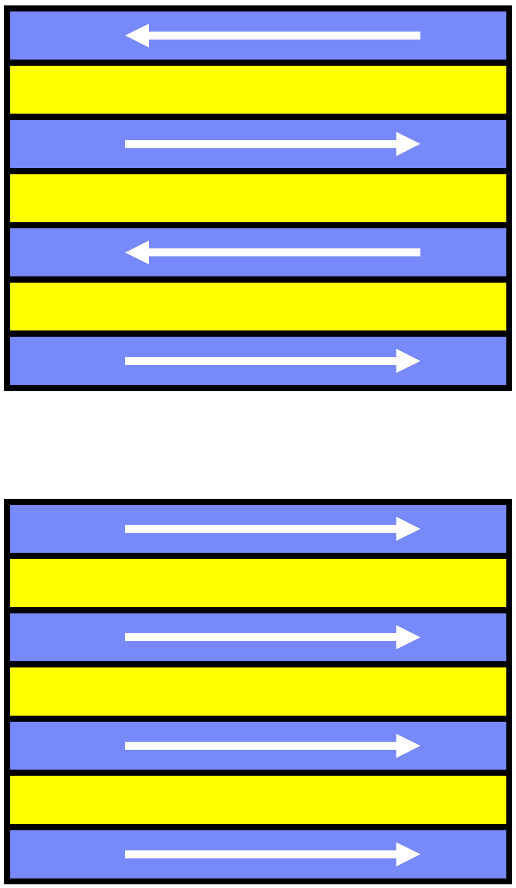




Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

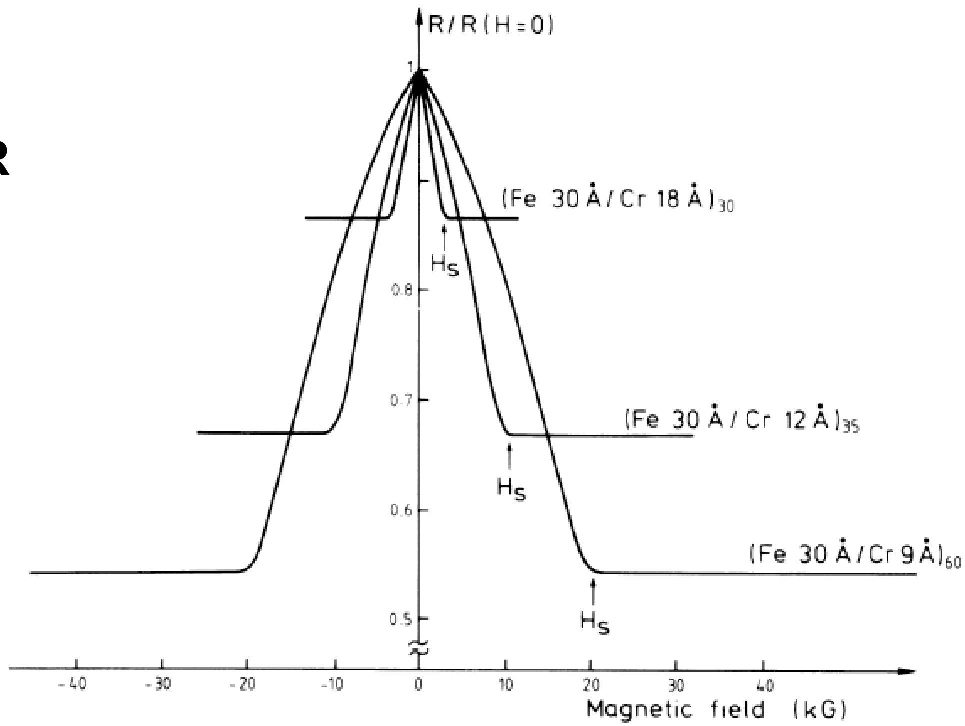
GMR

GMR--mechanism



High R

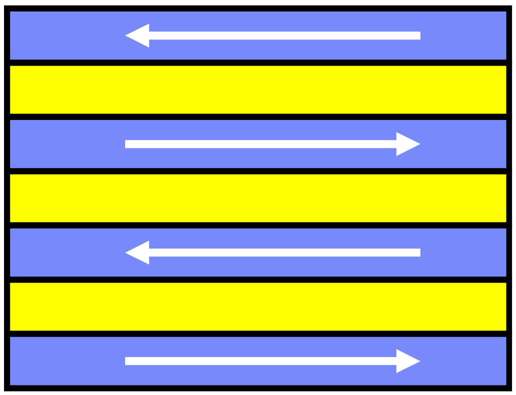
Low R



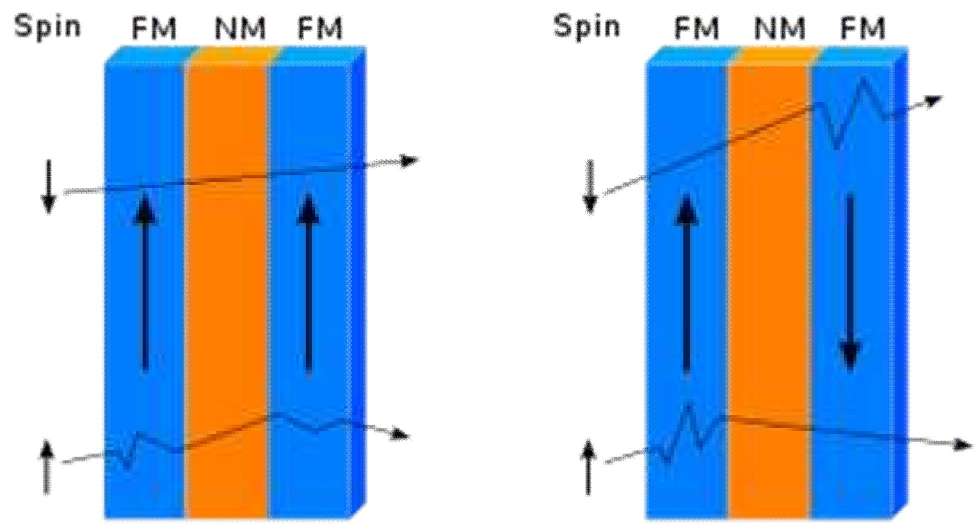
Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

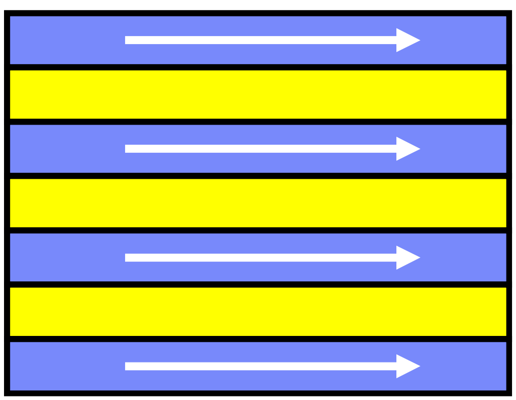
GMR

Julie Model

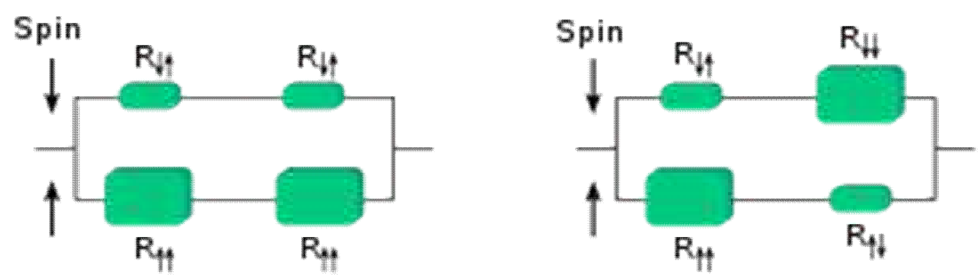


High R



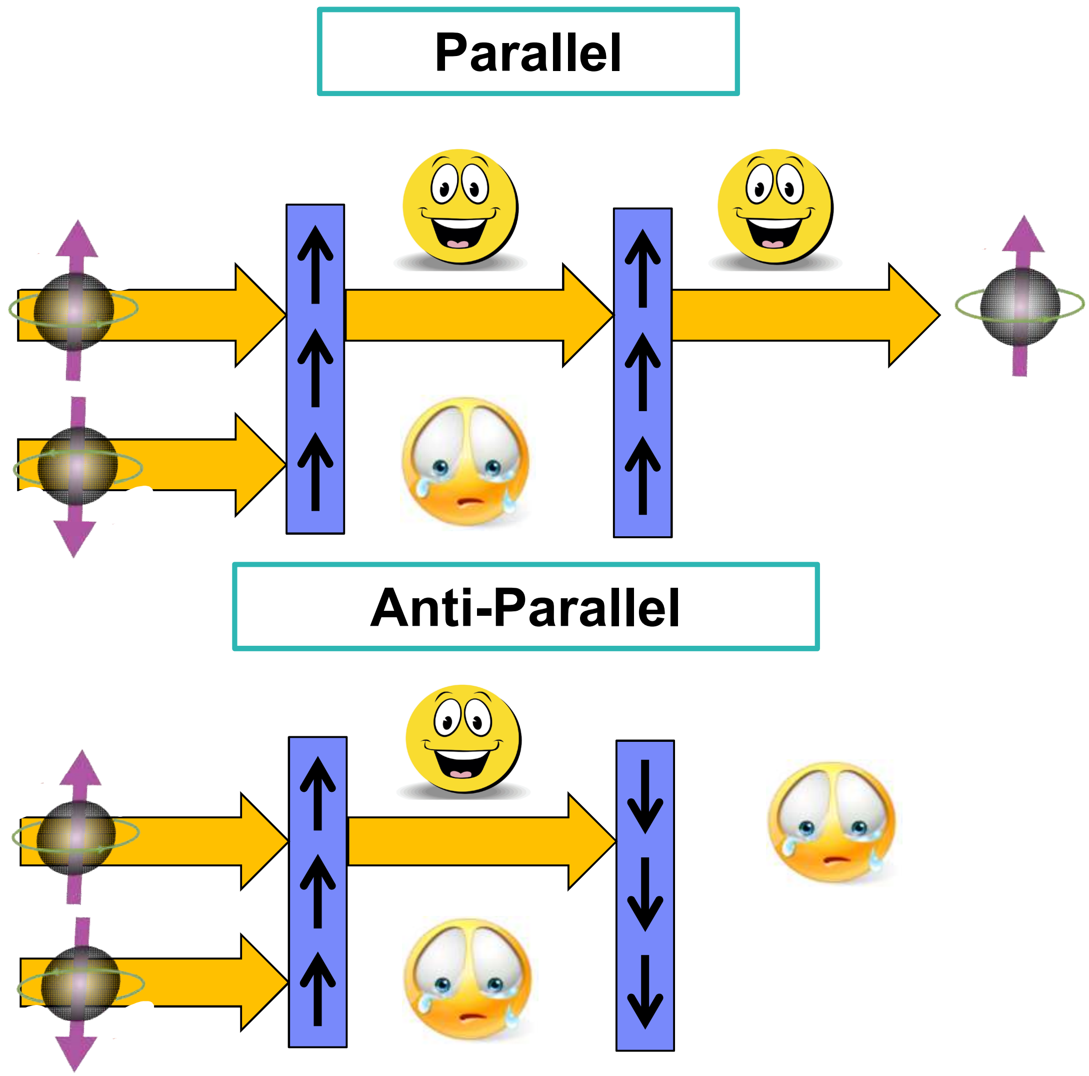


Low R



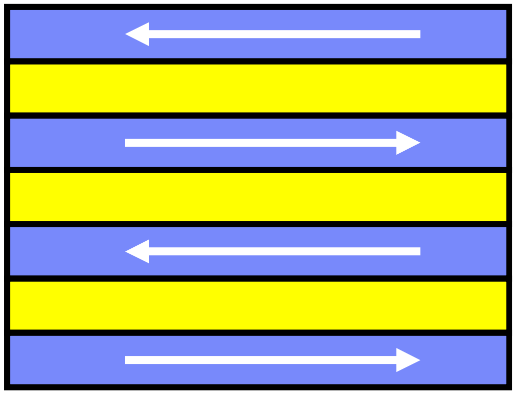
GMR

Julie Model



GMR

GMR--mechanism

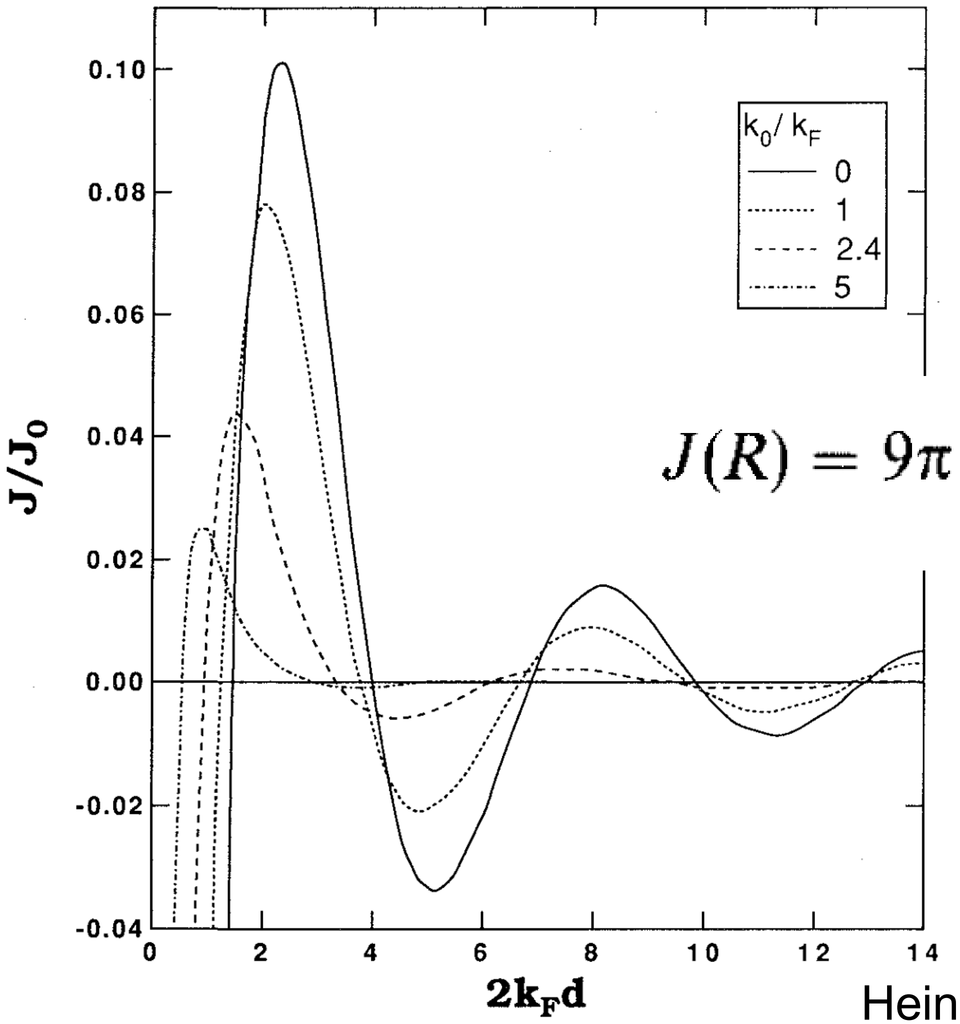


Why this is favored at low magnetic field?

Antiferromagnetic exchange interaction

GMR

GMR—RKKY coupling



$$J(R) = 9\pi \frac{j}{\varepsilon_F}\left[\frac{\cos 2k_F R}{(2k_F R)^3} - \frac{\sin 2k_F R}{(2k_F R)^4}\right]$$

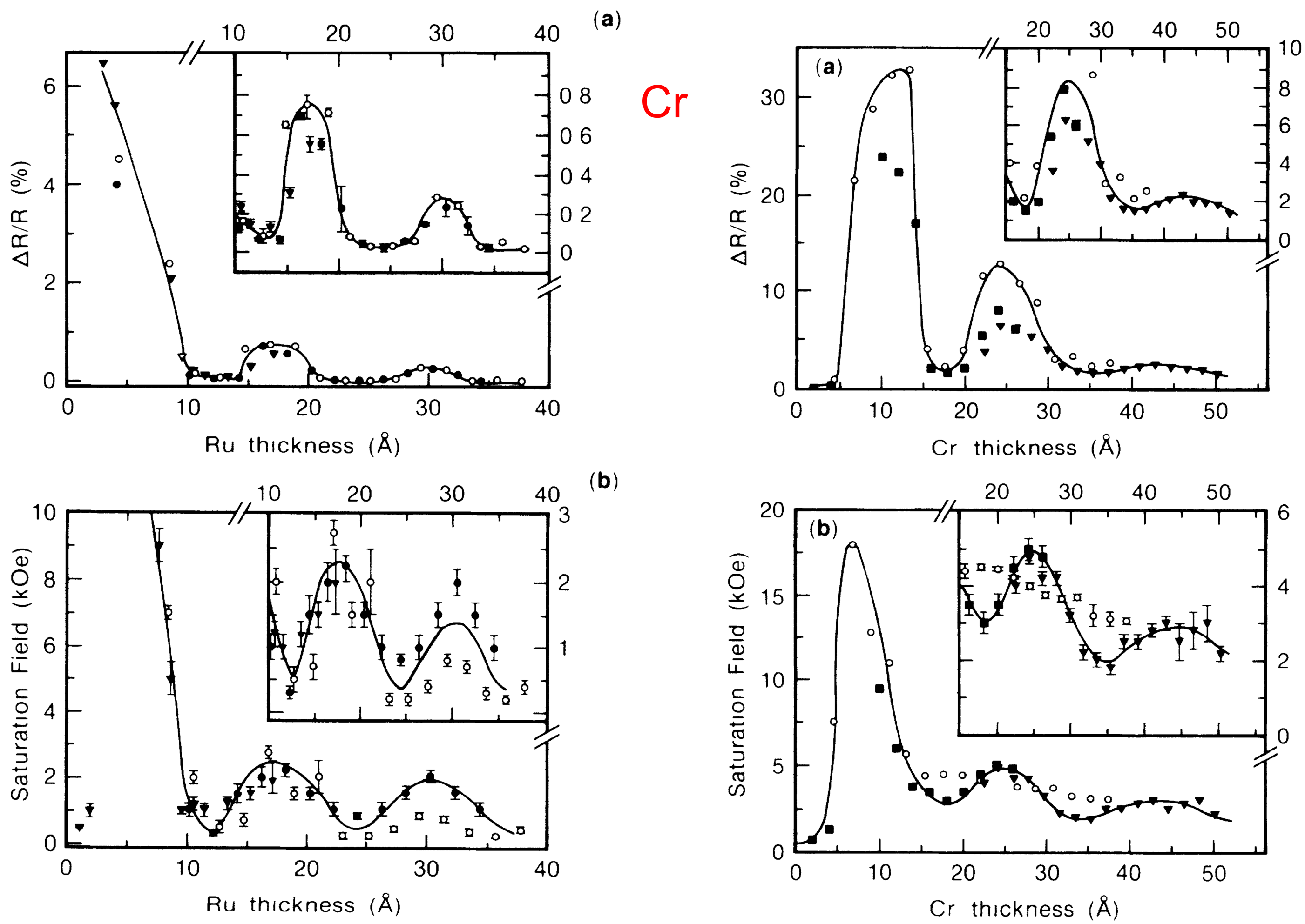
Heinrich, Book, chapter 2 (1994)

GMR

GMR—RKKY coupling

Ru

Cr

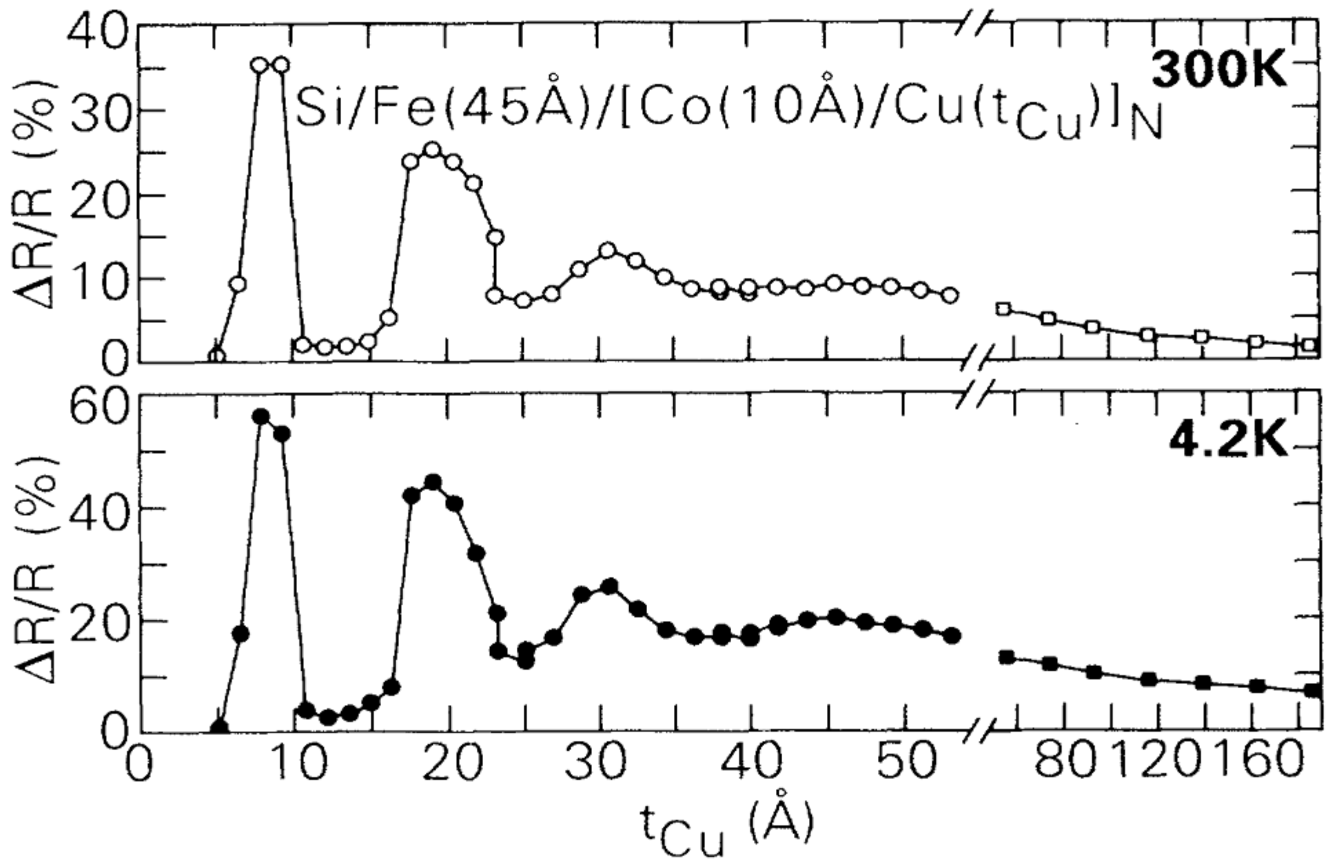


Parkin, et al, PRL (1990)

GMR

GMR—RKKY coupling

Cu



Parkin, et al, PRL (1991)

6. Tunneling MR

Tunneling MR

Al_2O_3 barrier for tunneling

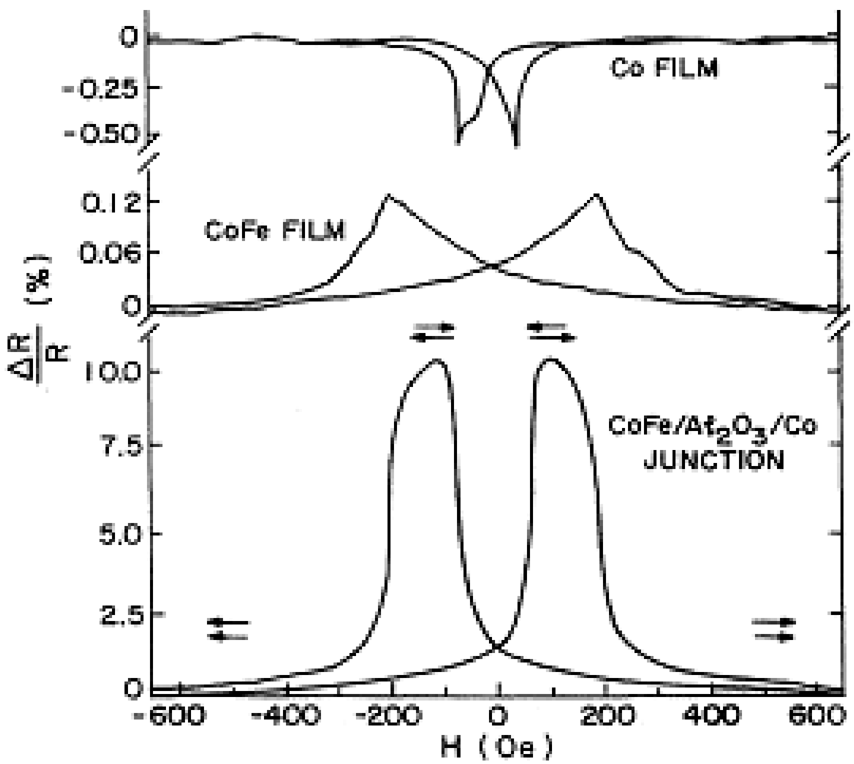
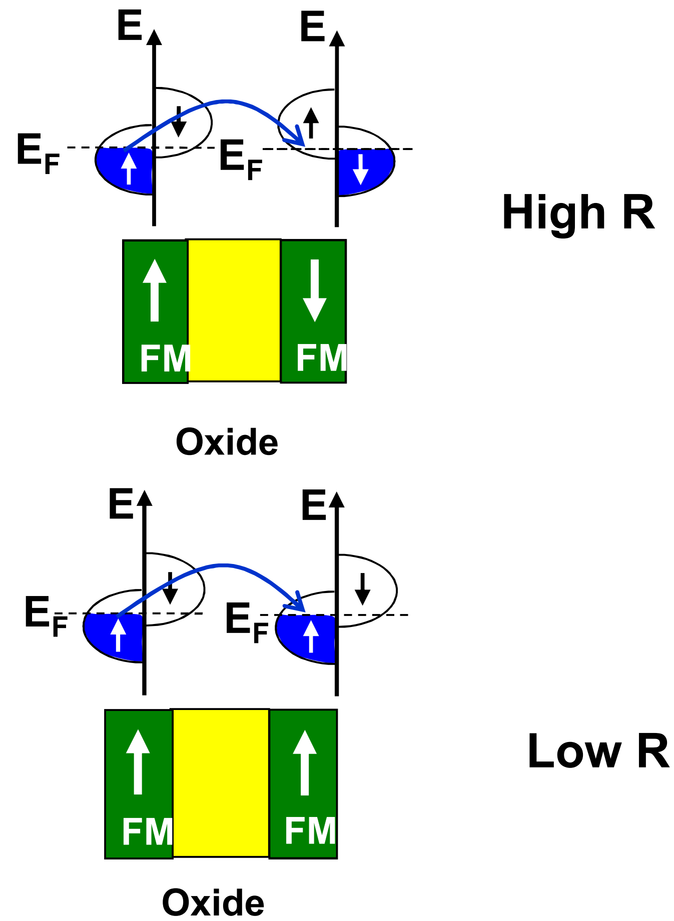
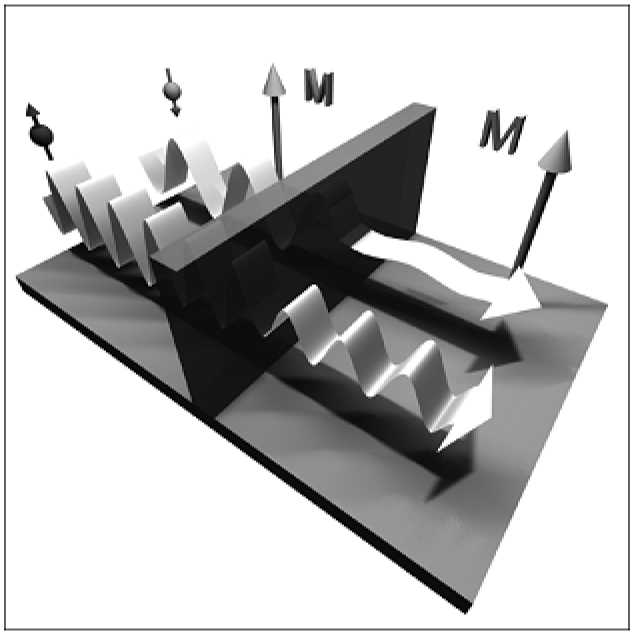


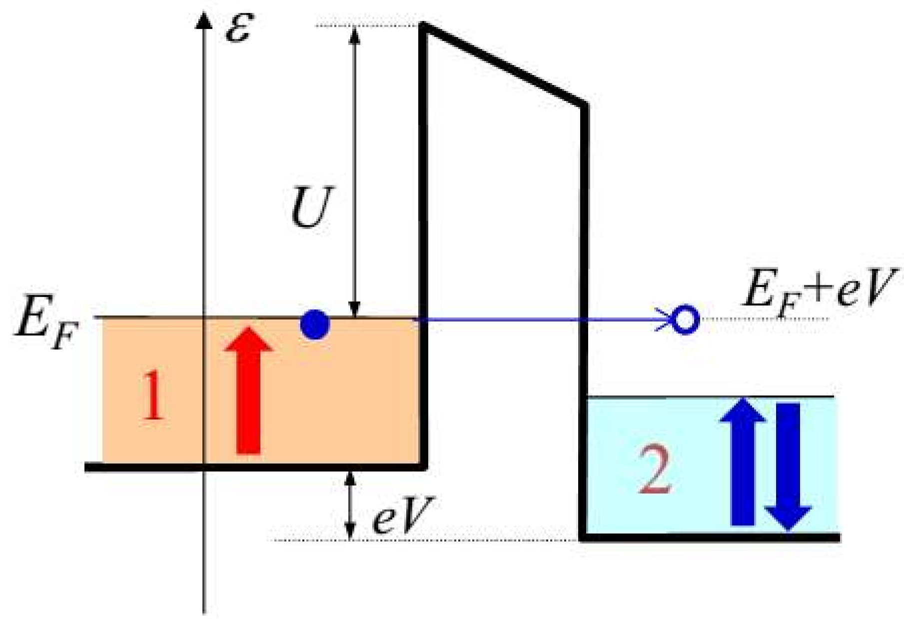
FIG. 2. Resistance of CoFe/Al_2O_3/Co junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).



JS Moodera, et al, PRL (1995)

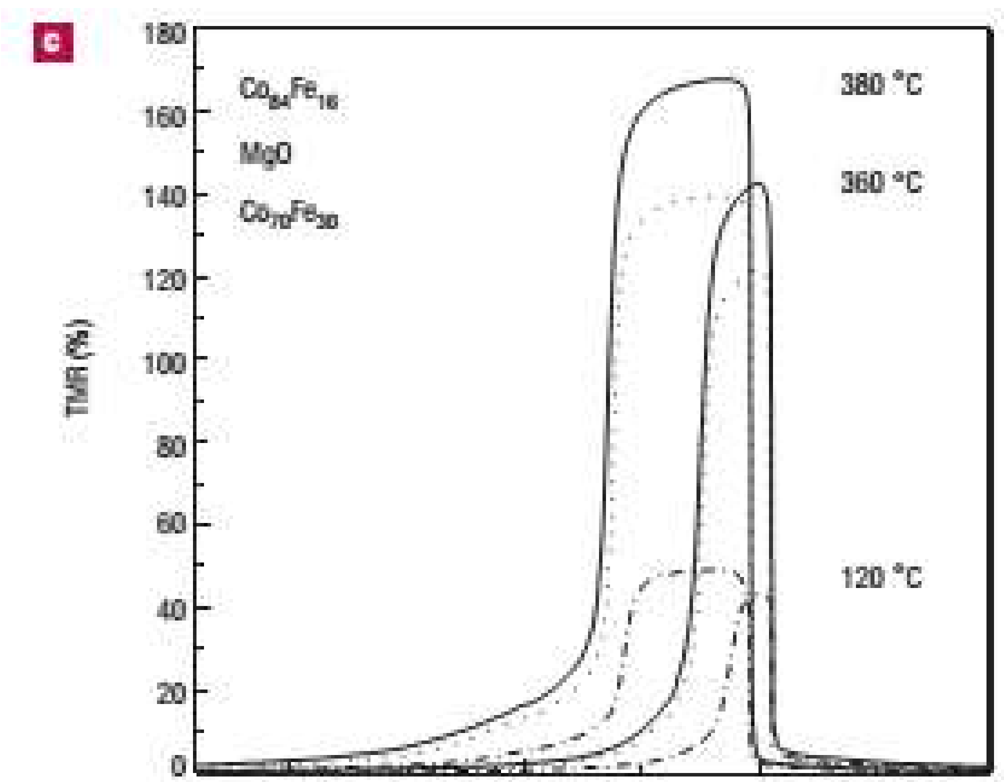
Tunneling MR



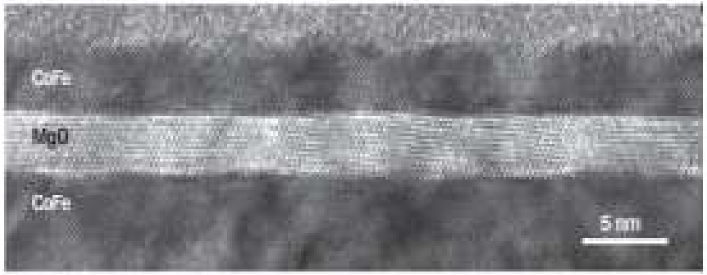


Tunneling MR

MgO barrier for tunneling: MR >100%



Epitaxial MgO

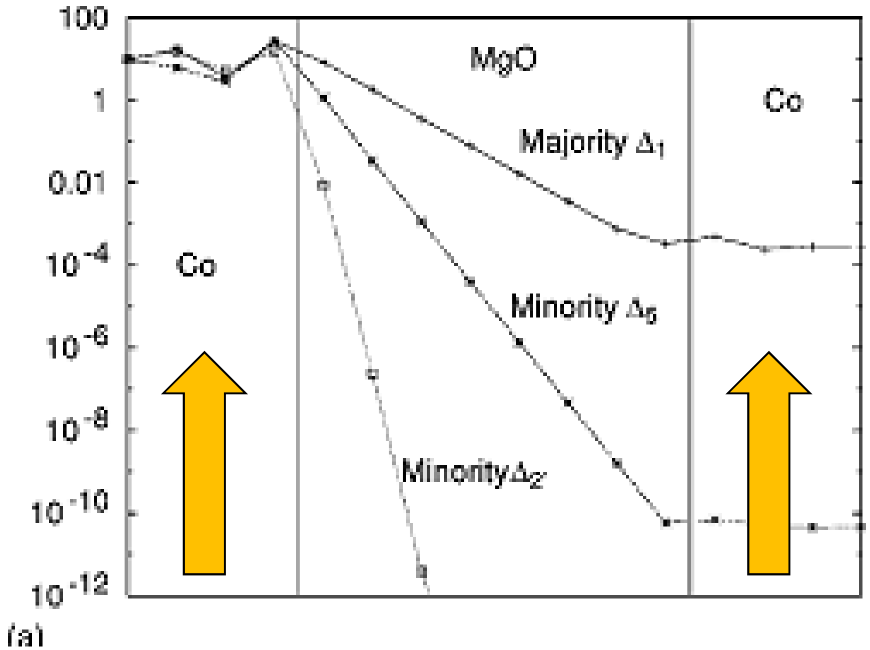


Parkin, et al, Nature Mater (2004)
Yuasa, et al, Nature Mater (2004)

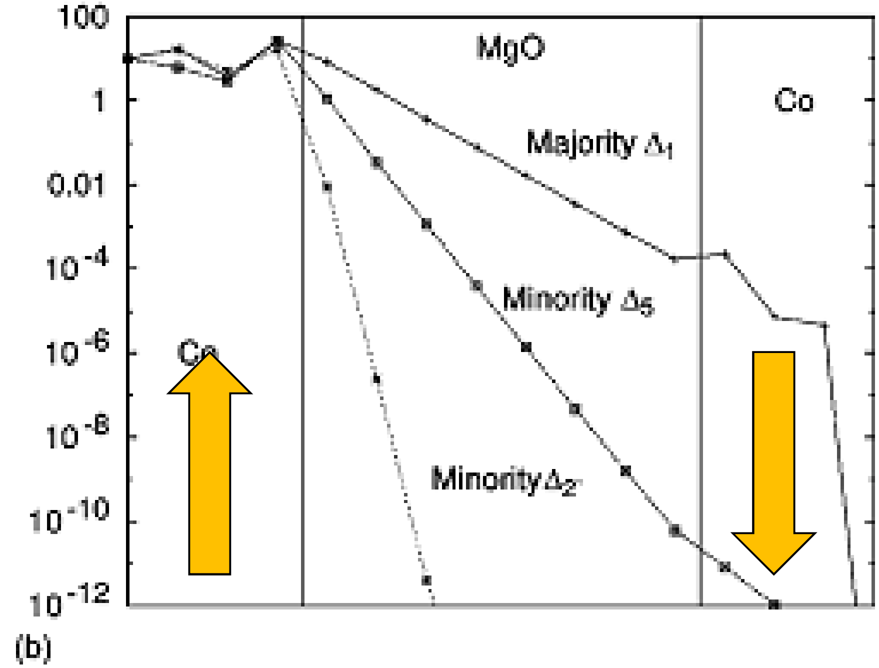
Tunneling MR

MgO barrier for tunneling: MR >100%

Parallel



Anti-Parallel

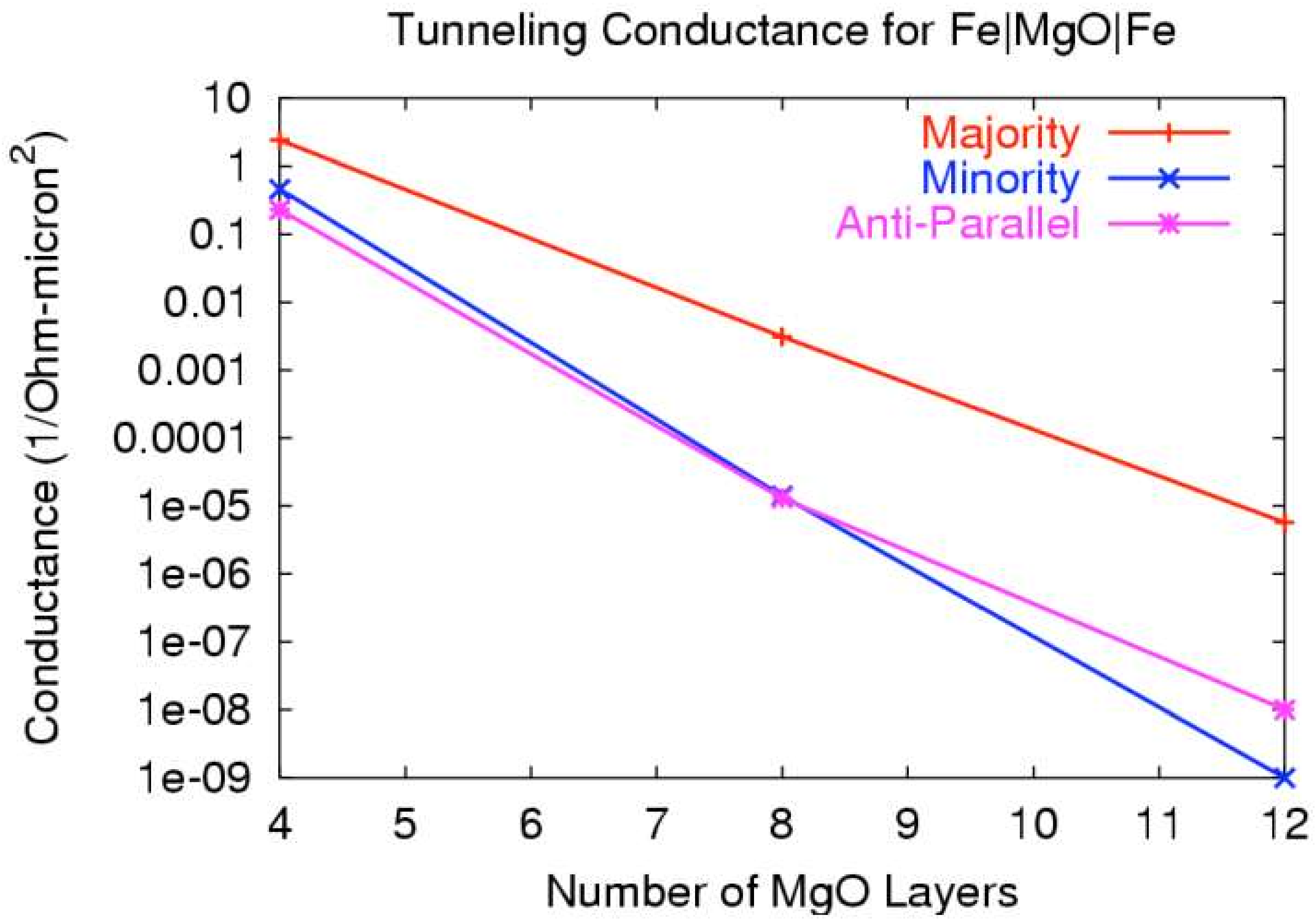


Δ_1, symmetry, slow decaying
Tunneling of Co majority spin (SP)

Zhang & Butler, et al, PRB (2004)

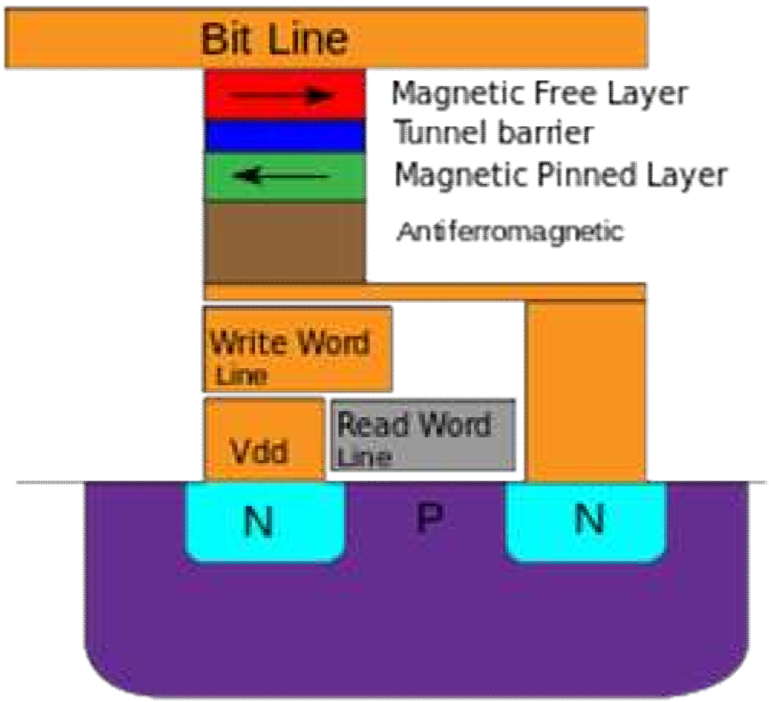
Tunneling MR

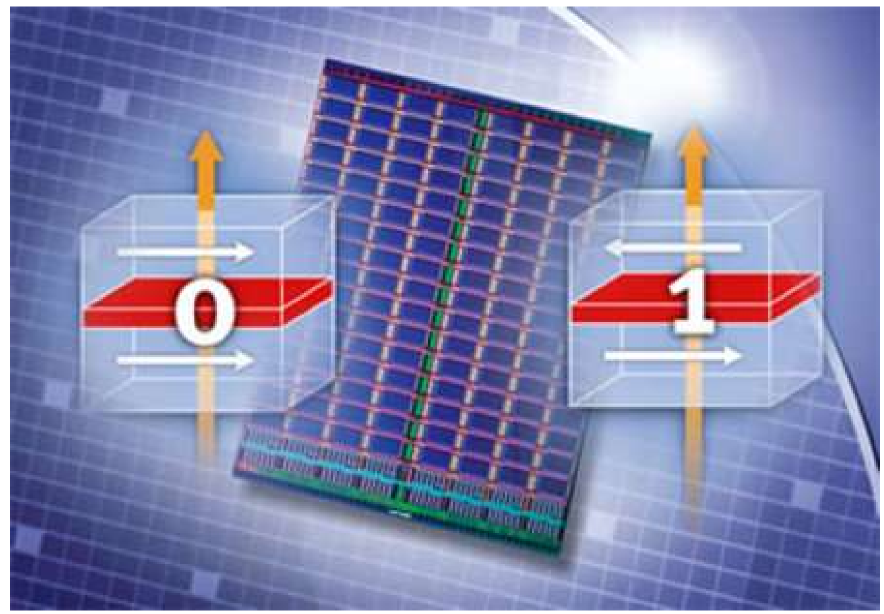
MgO barrier for tunneling: MR >100%



TMR for MRAM

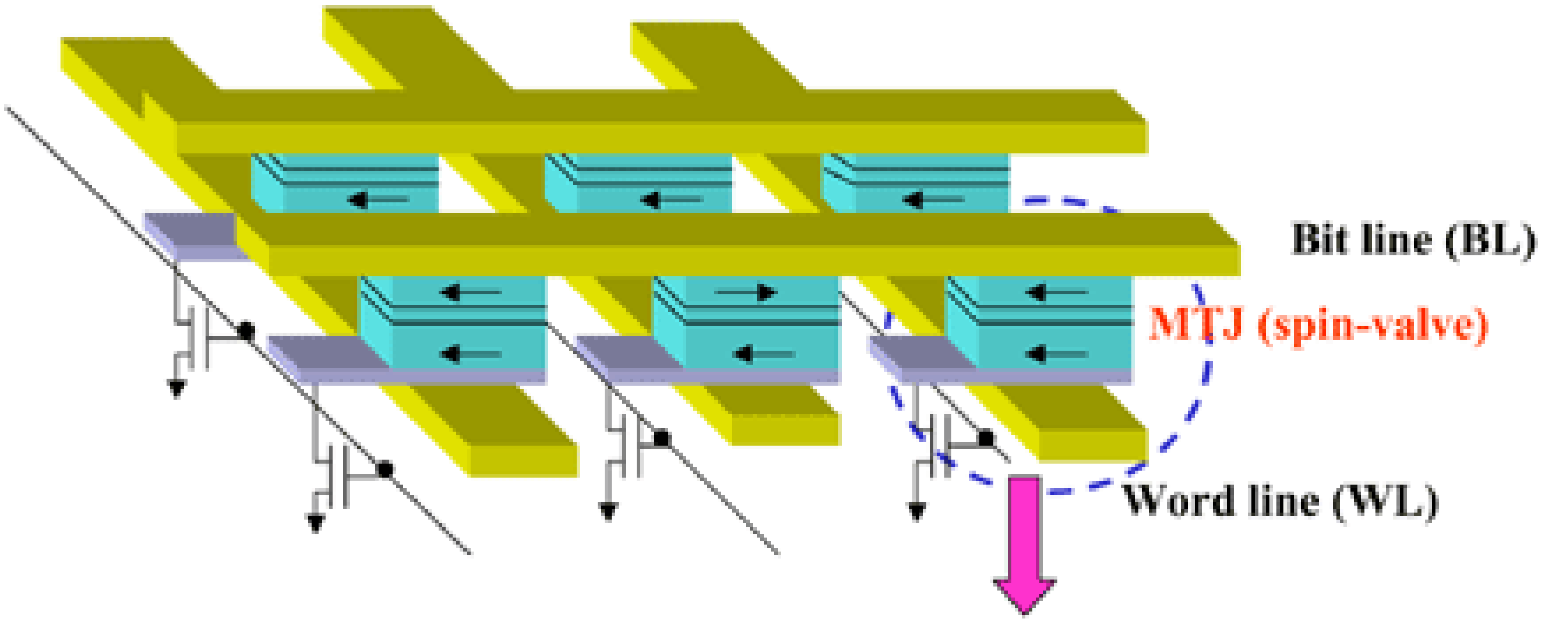
MRAM



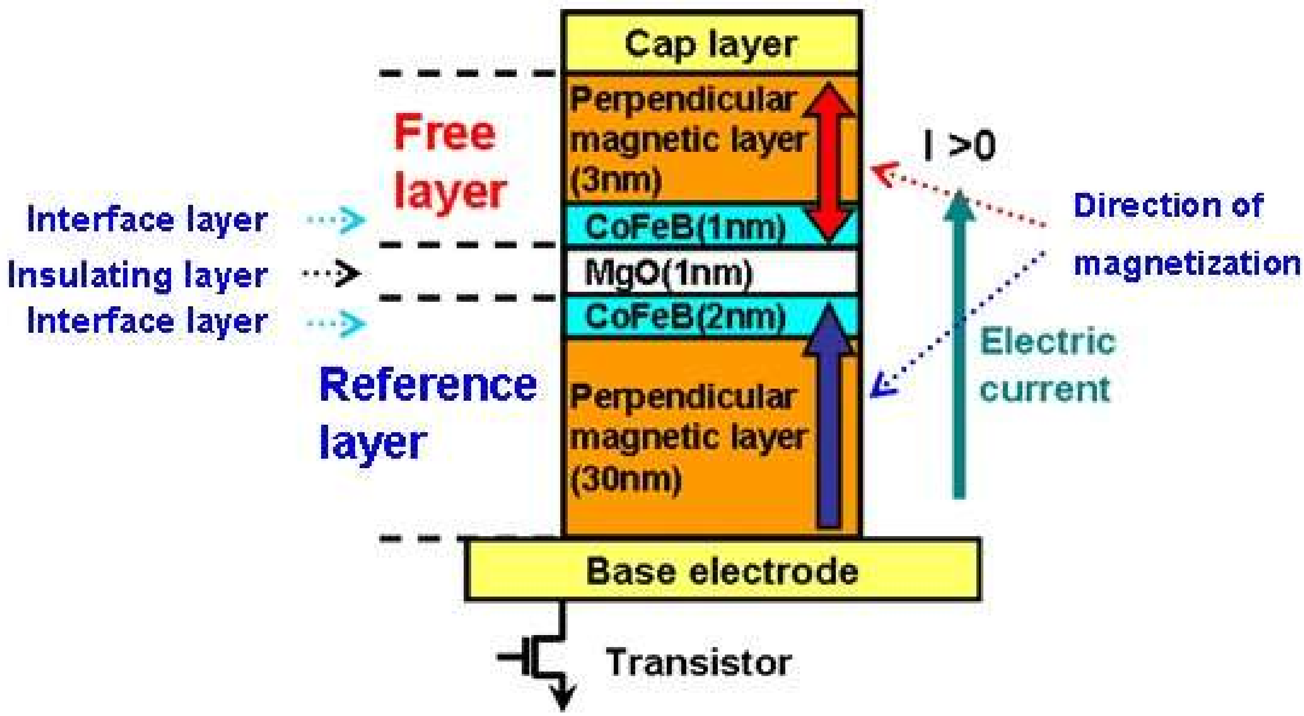


TMR for MRAM

MRAM

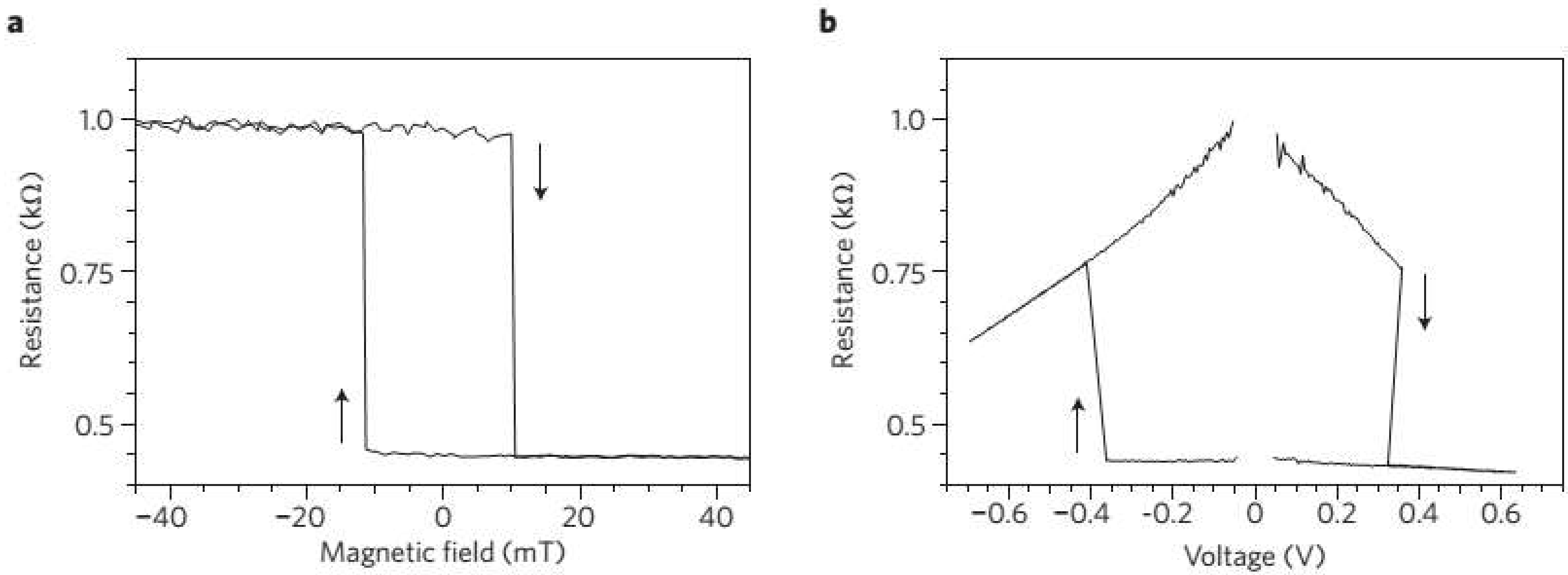


STT-MRAM



Cap layer
Free layer
Perpendicular magnetic layer (3nm)
CoFeB(1nm)
MgO(1nm)
CoFeB(2nm)
Reference layer
Perpendicular magnetic layer (30nm)
Interface layer
Insulating layer
Interface layer
I >0
Direction of magnetization
Electric current
Base electrode
Transistor

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 °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)

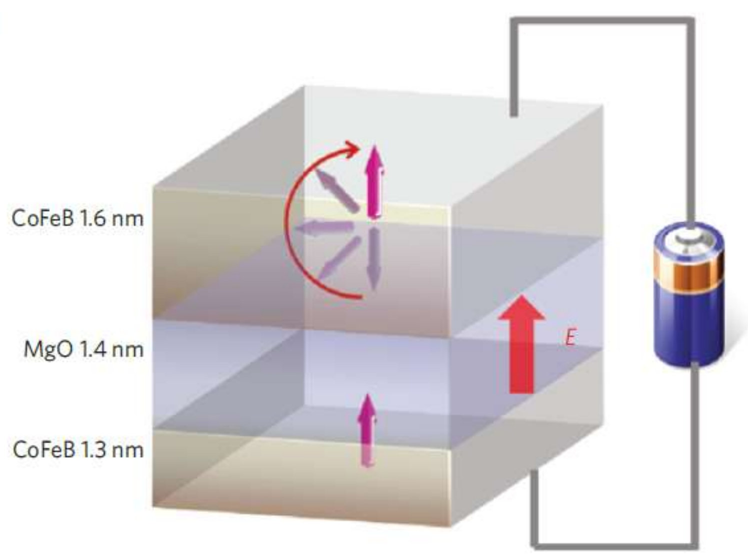
Electric-field-assisted

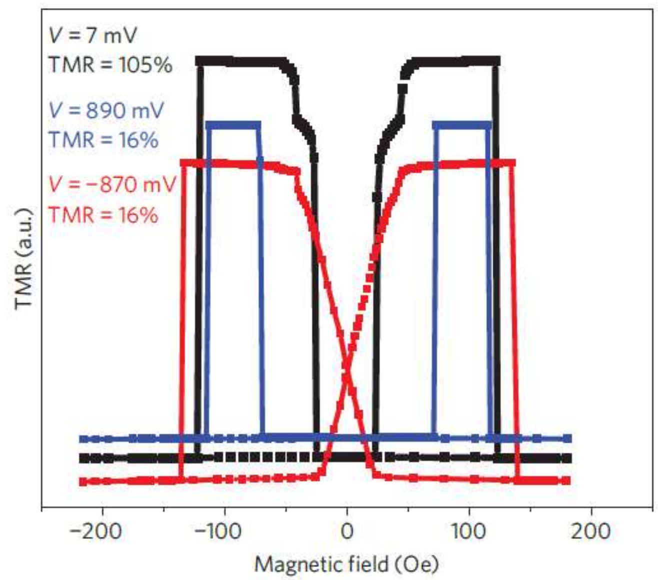
ARTICLES
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI:10.1038/NMAT3171
nature materials

Electric-field-assisted switching in magnetic tunnel junctions

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

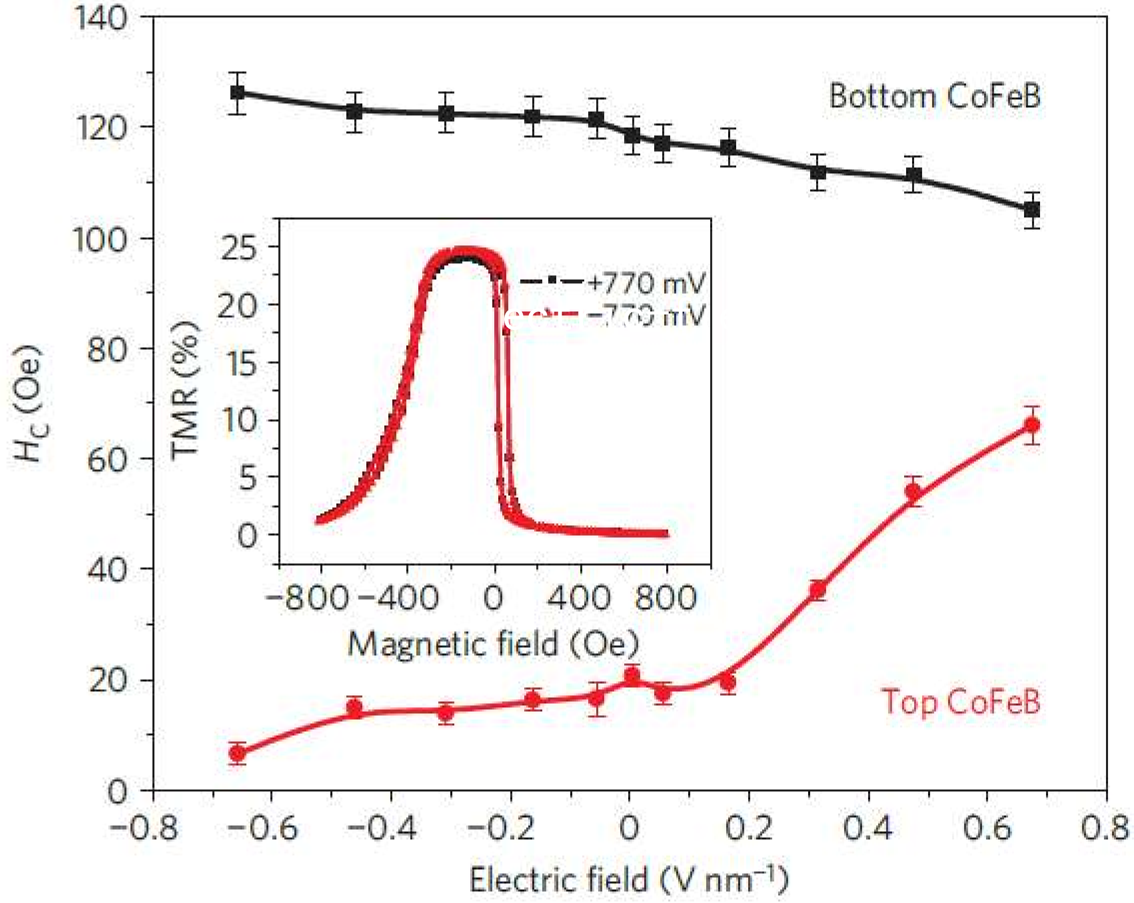
a





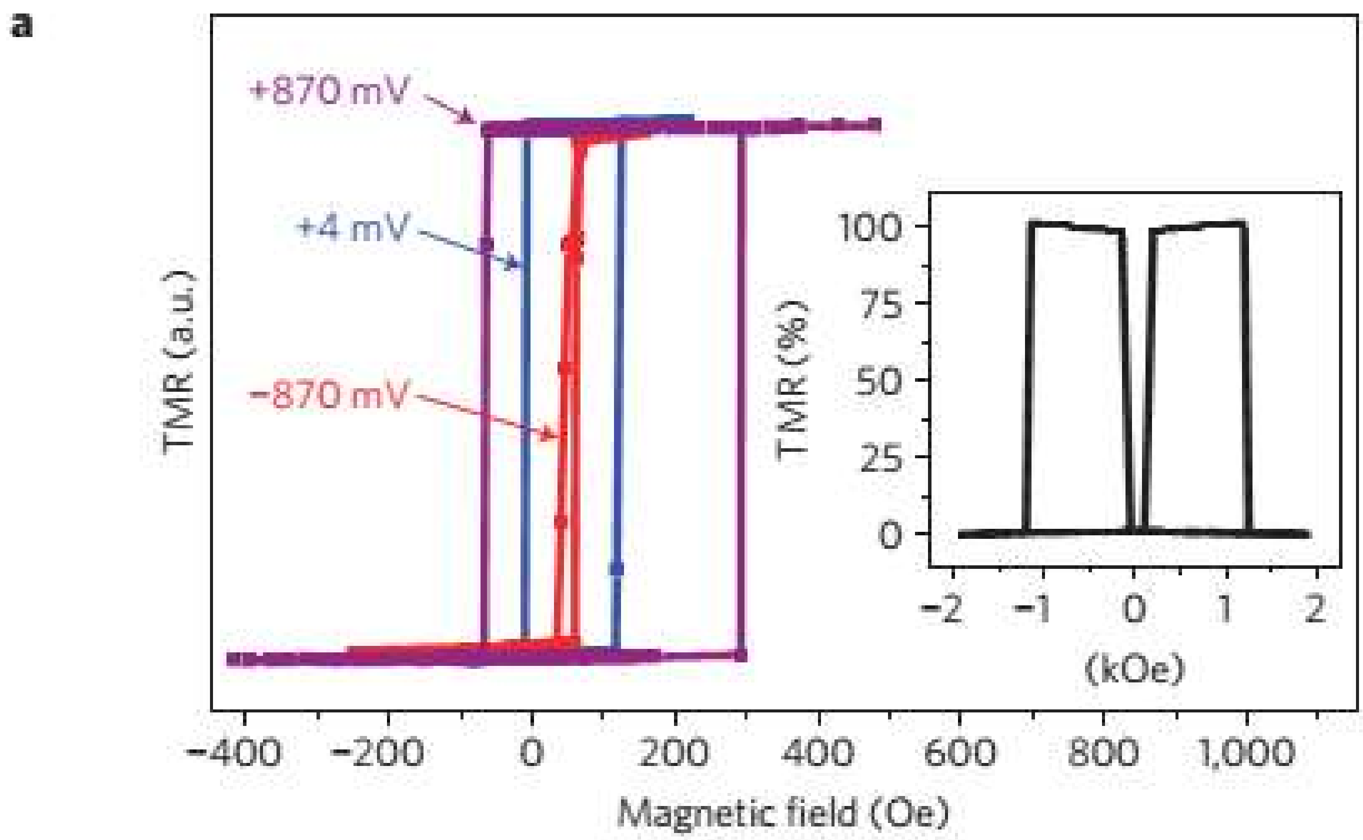
Electric-field-assisted

Electric-field H_C



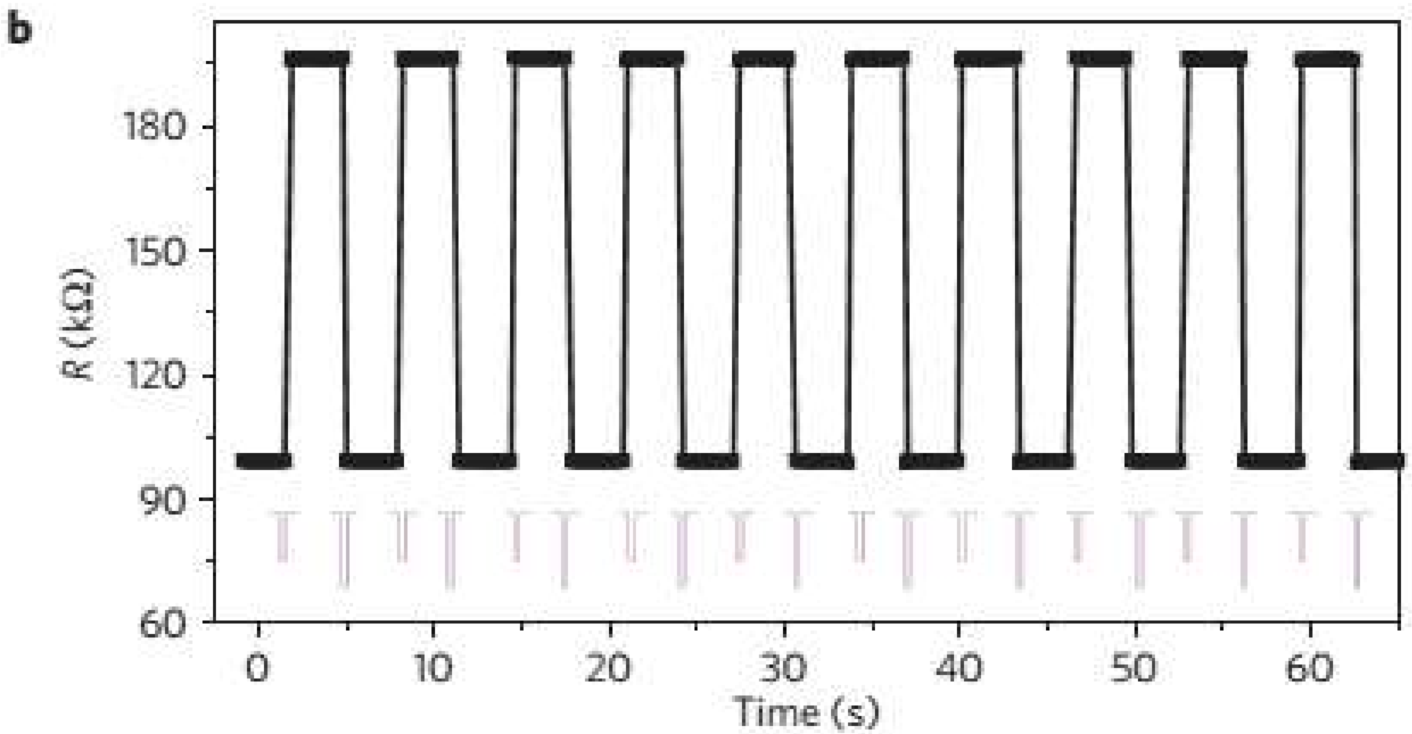
Electric-field-assisted

Electric-field switching

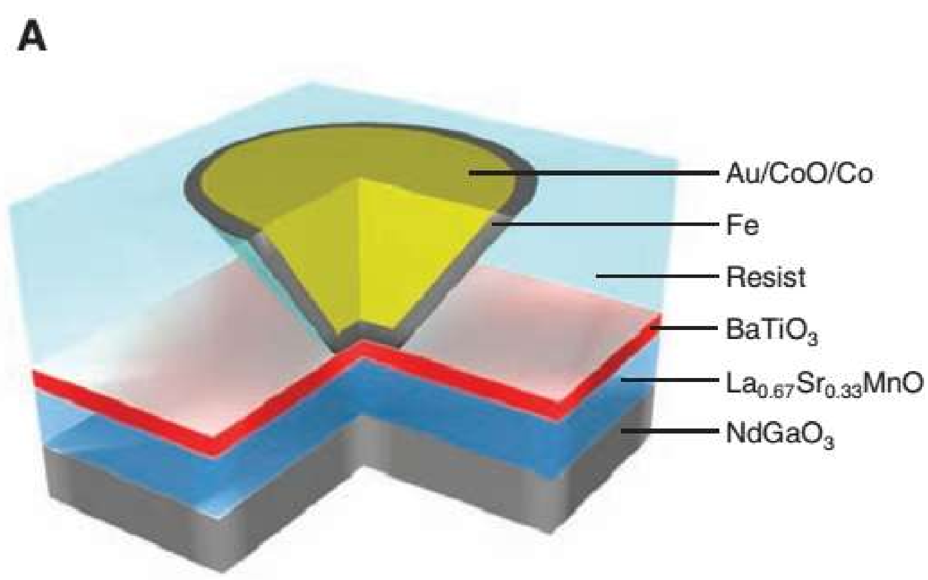


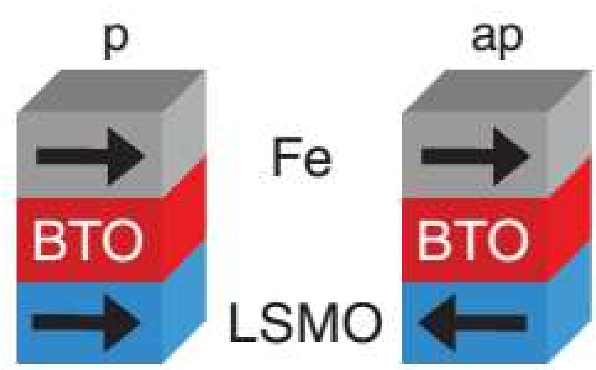
Electric-field-assisted

Electric-field switching



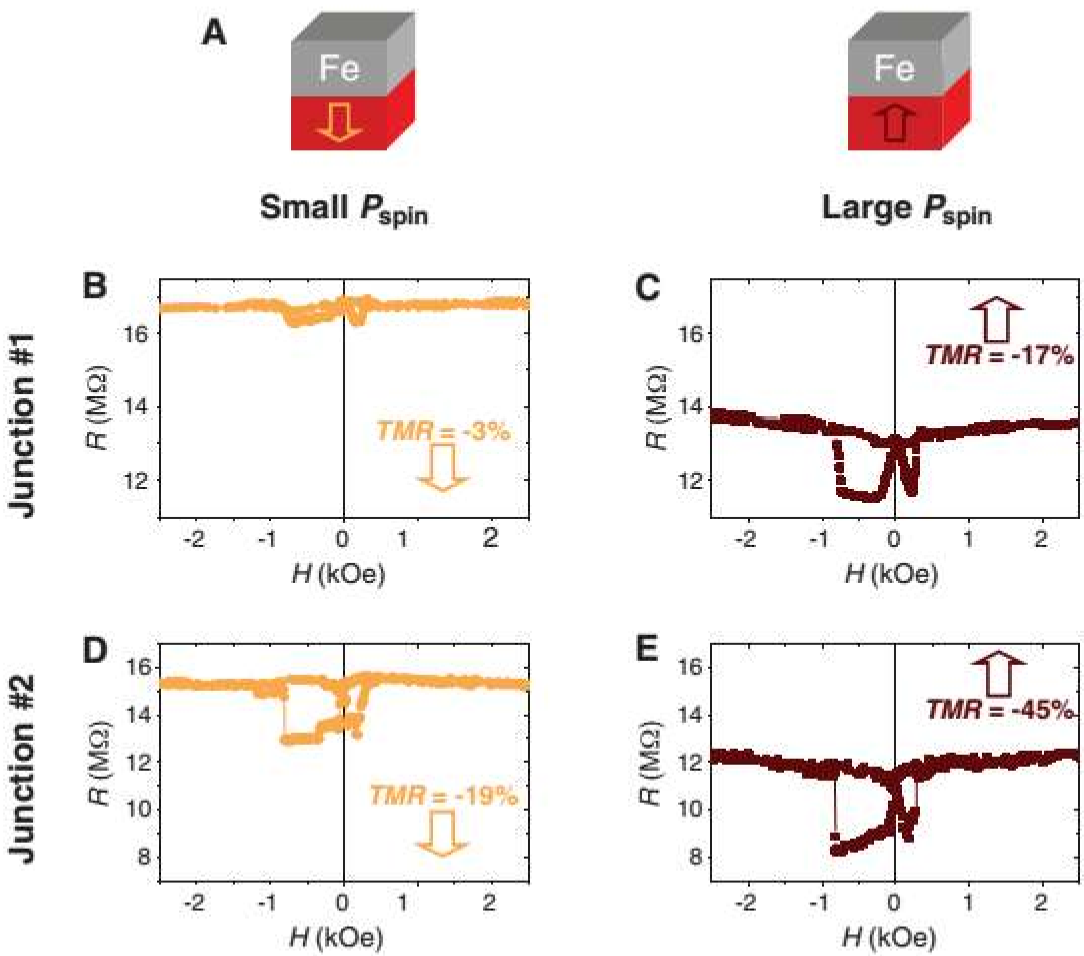
TMR by Multiferroics





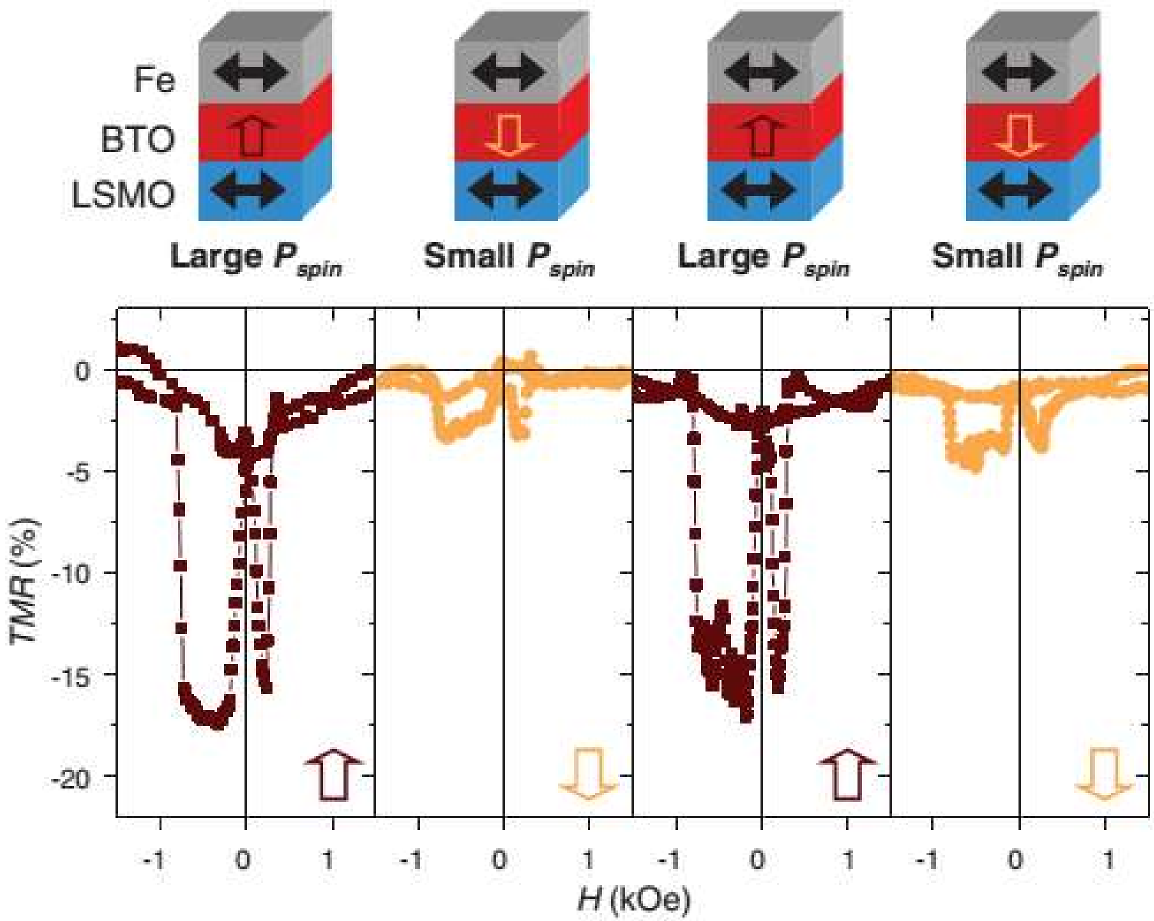
Garcia, et al, Science (2010)

TMR by Multiferroics



Garcia, et al, Science (2010)

TMR by Multiferroics

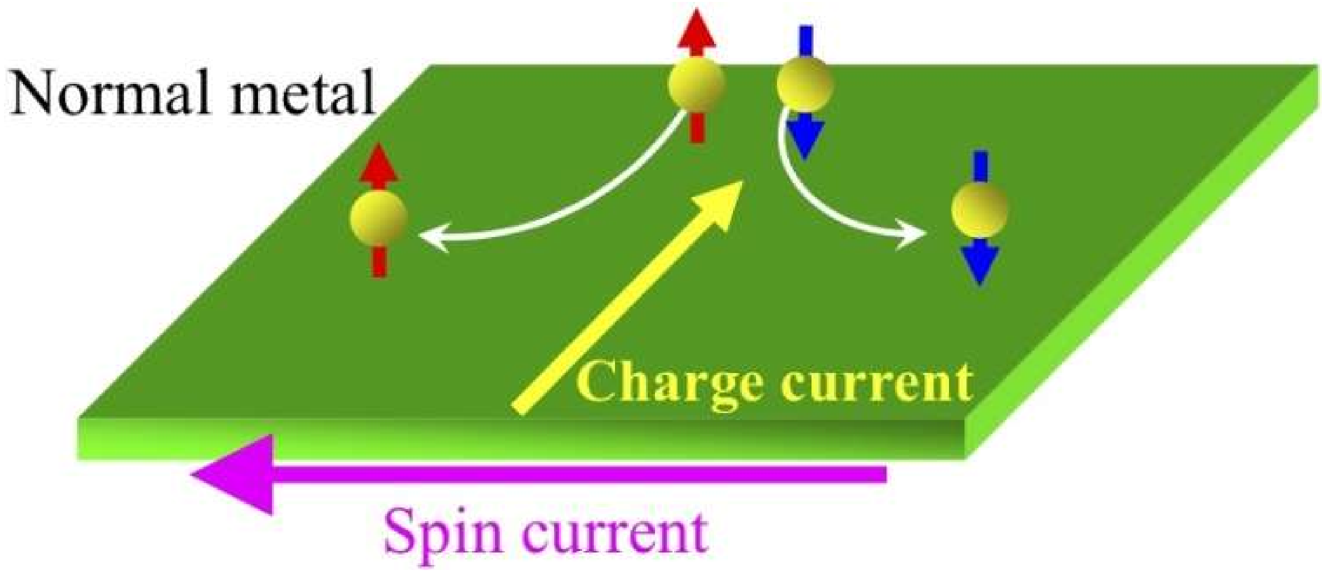


Garcia, et al, Science (2010)

7. Spin Hall MR

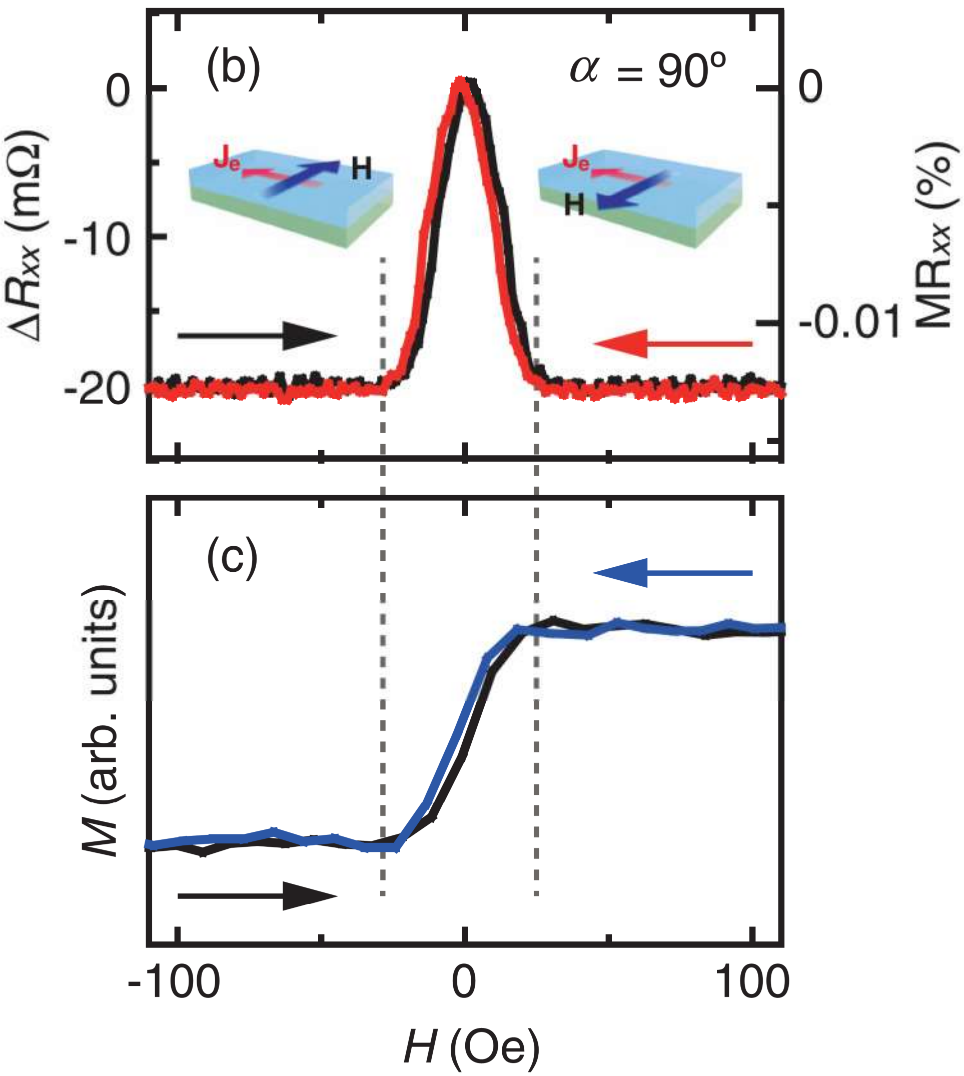
SMR

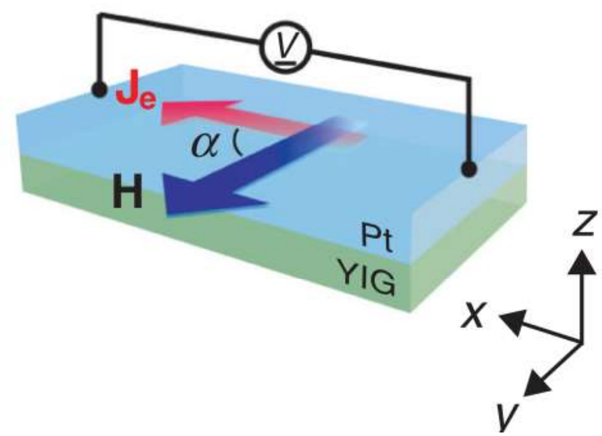
Spin Hall effect



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

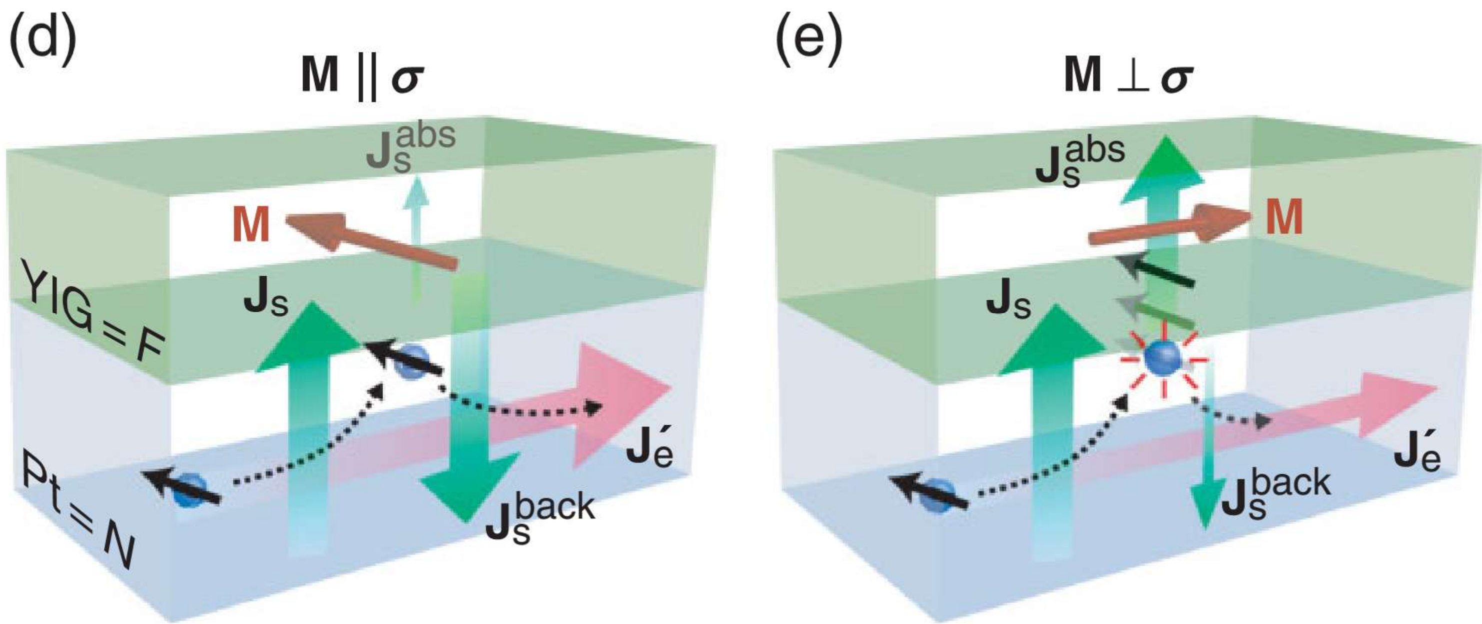




Nakayama, et al, PRL (2013)

SMR

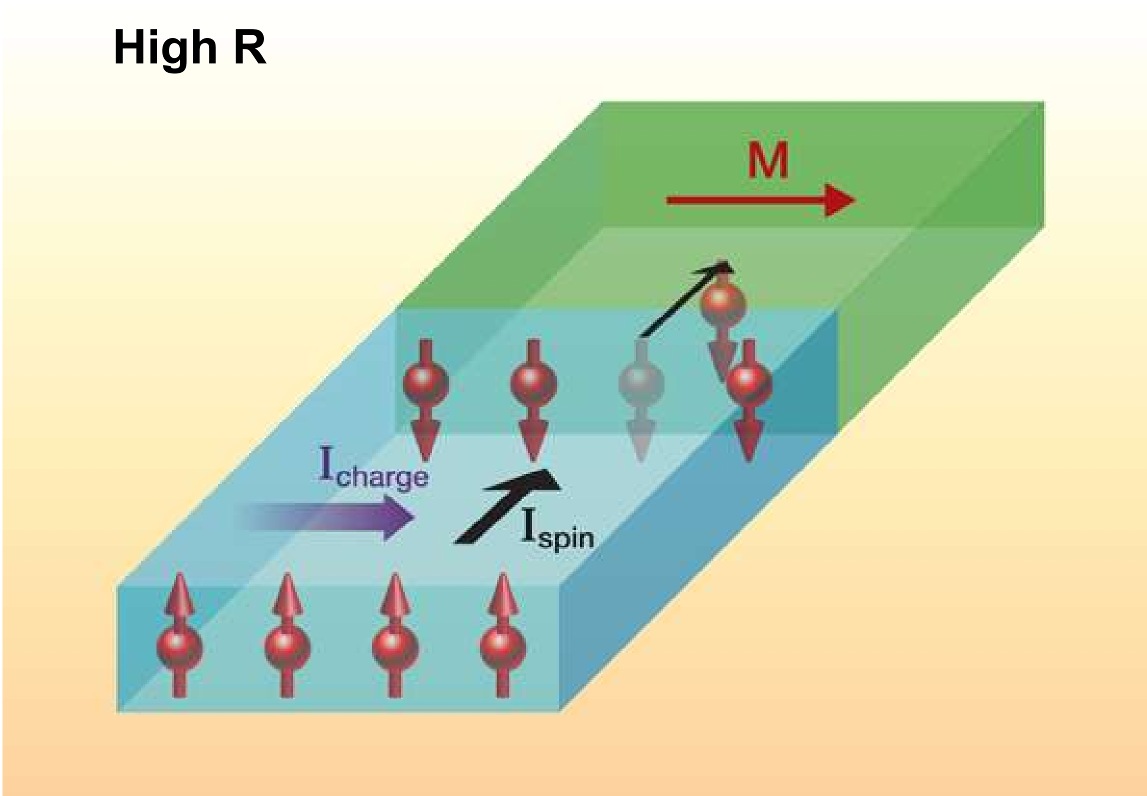
SMR mechanism: Interfacial spin scattering



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

SMR

SMR mechanism: Interfacial spin scattering

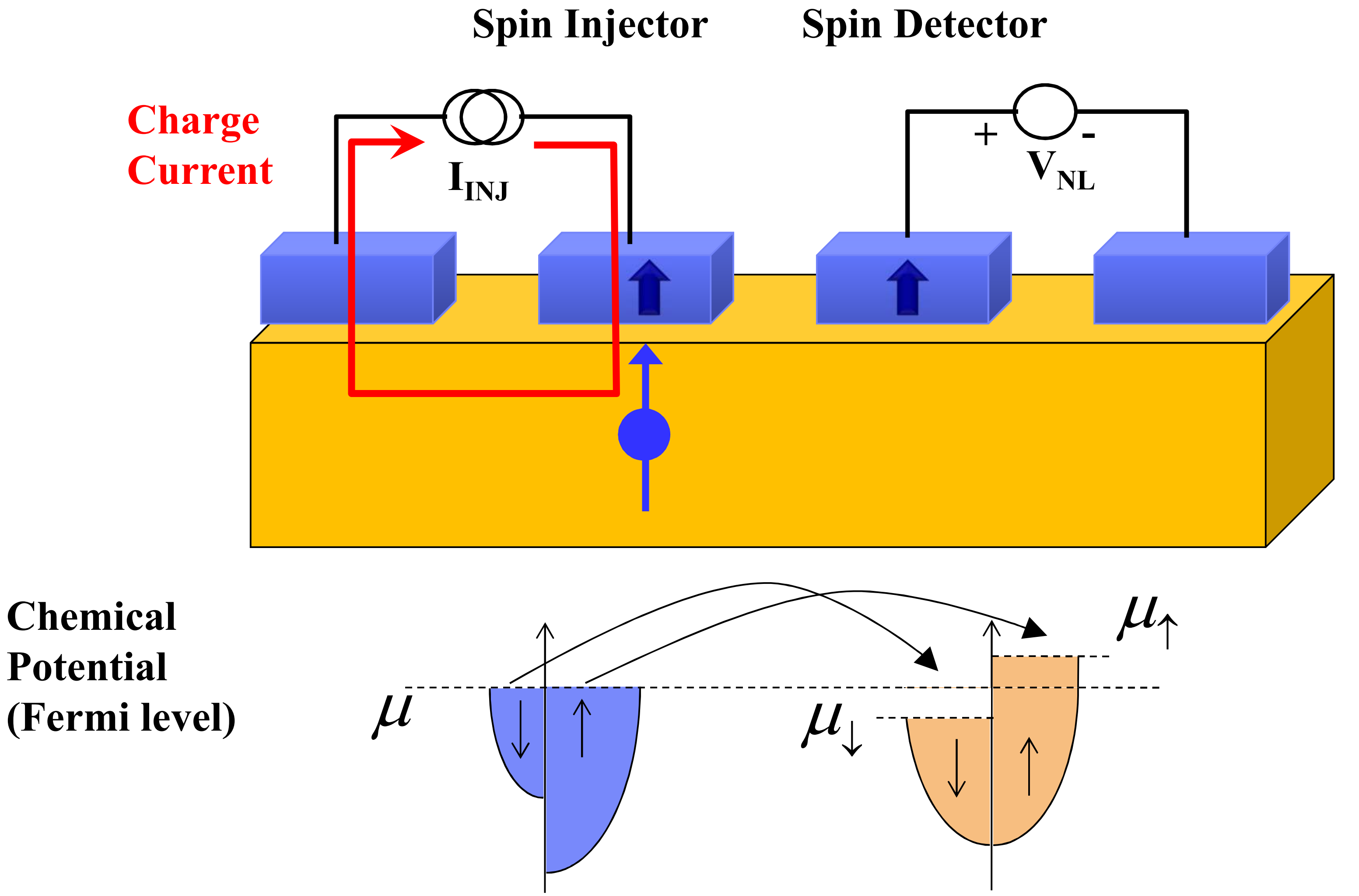


$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$

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

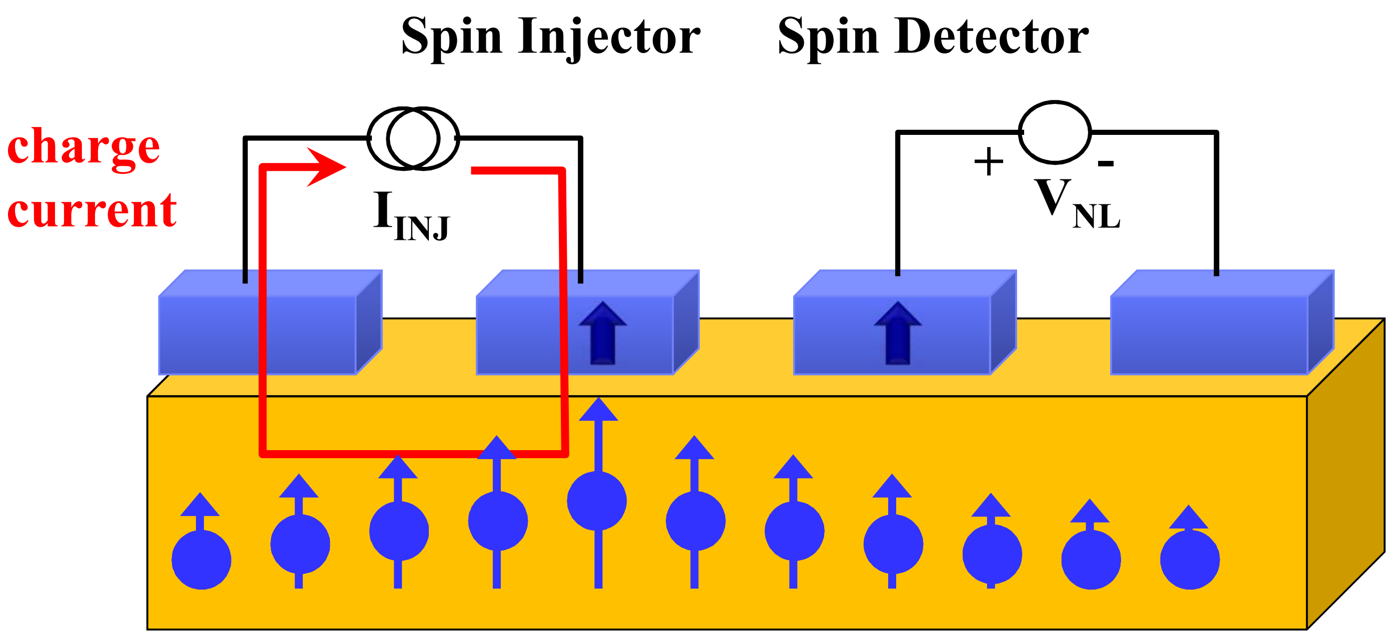
7. Nonlocal MR

Nonlocal Spin valve

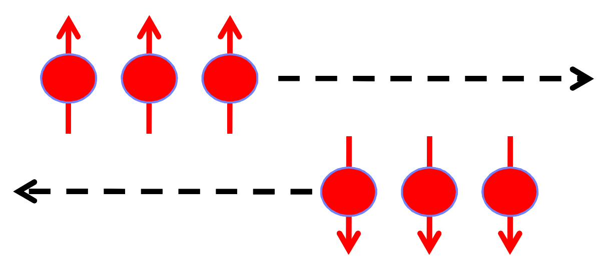


Johnson and Silsbee, PRL (1985)

Nonlocal Spin valve

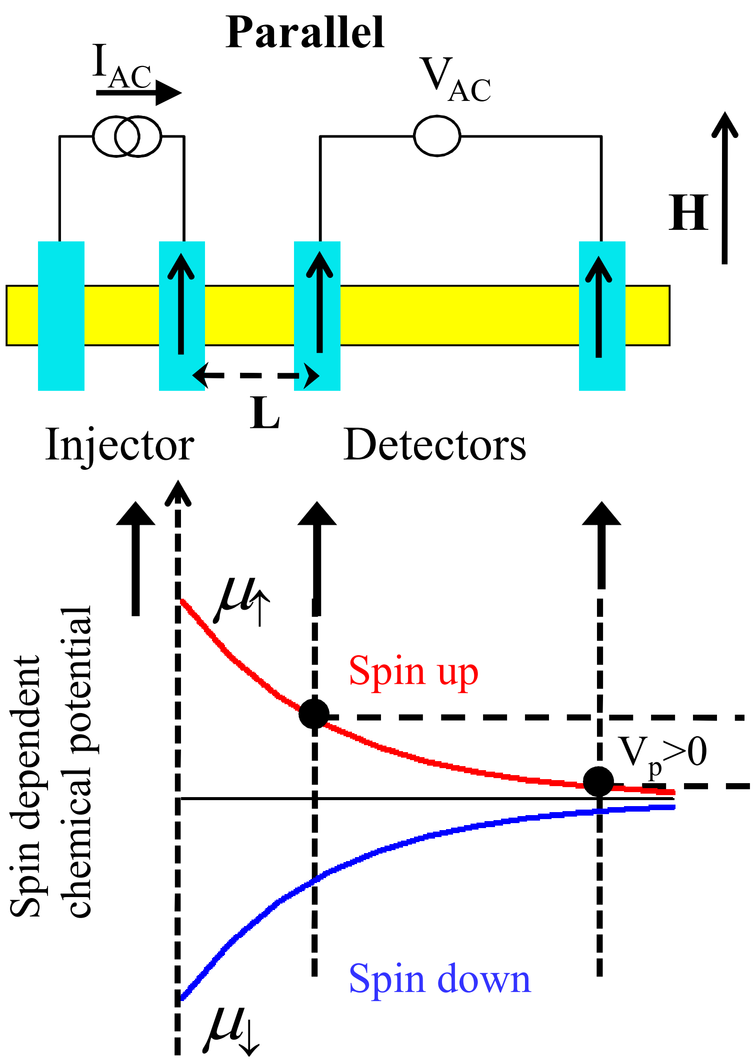


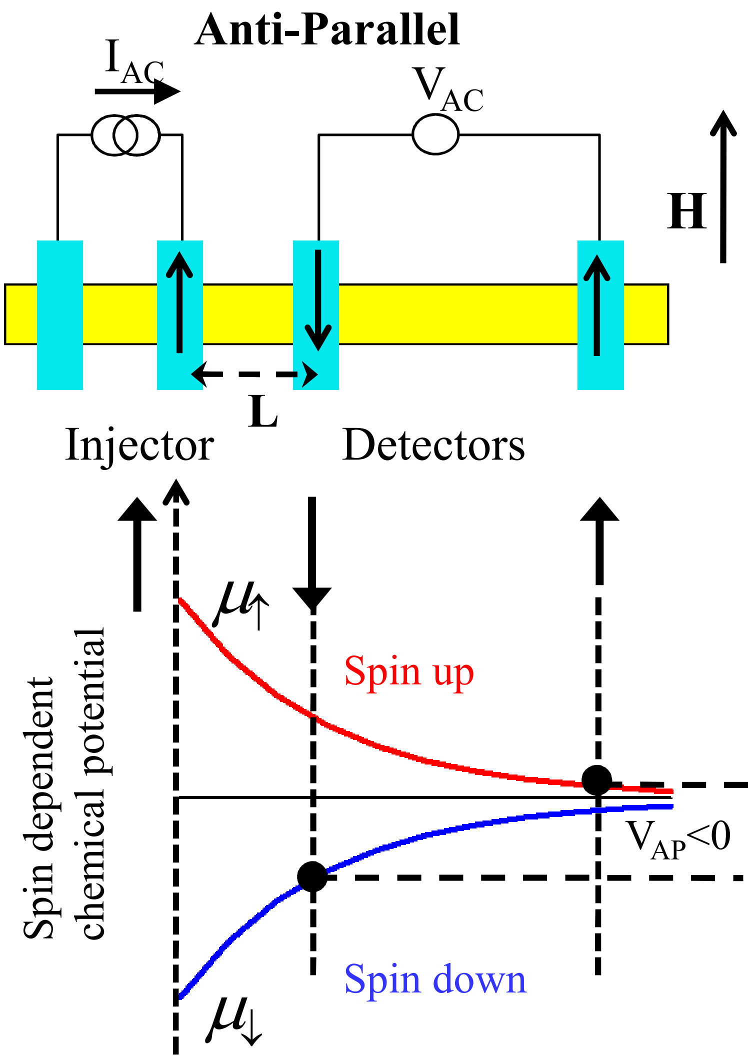
Pure spin current: Flow of spin without net flow of charge



Johnson and Silsbee, PRL (1985)

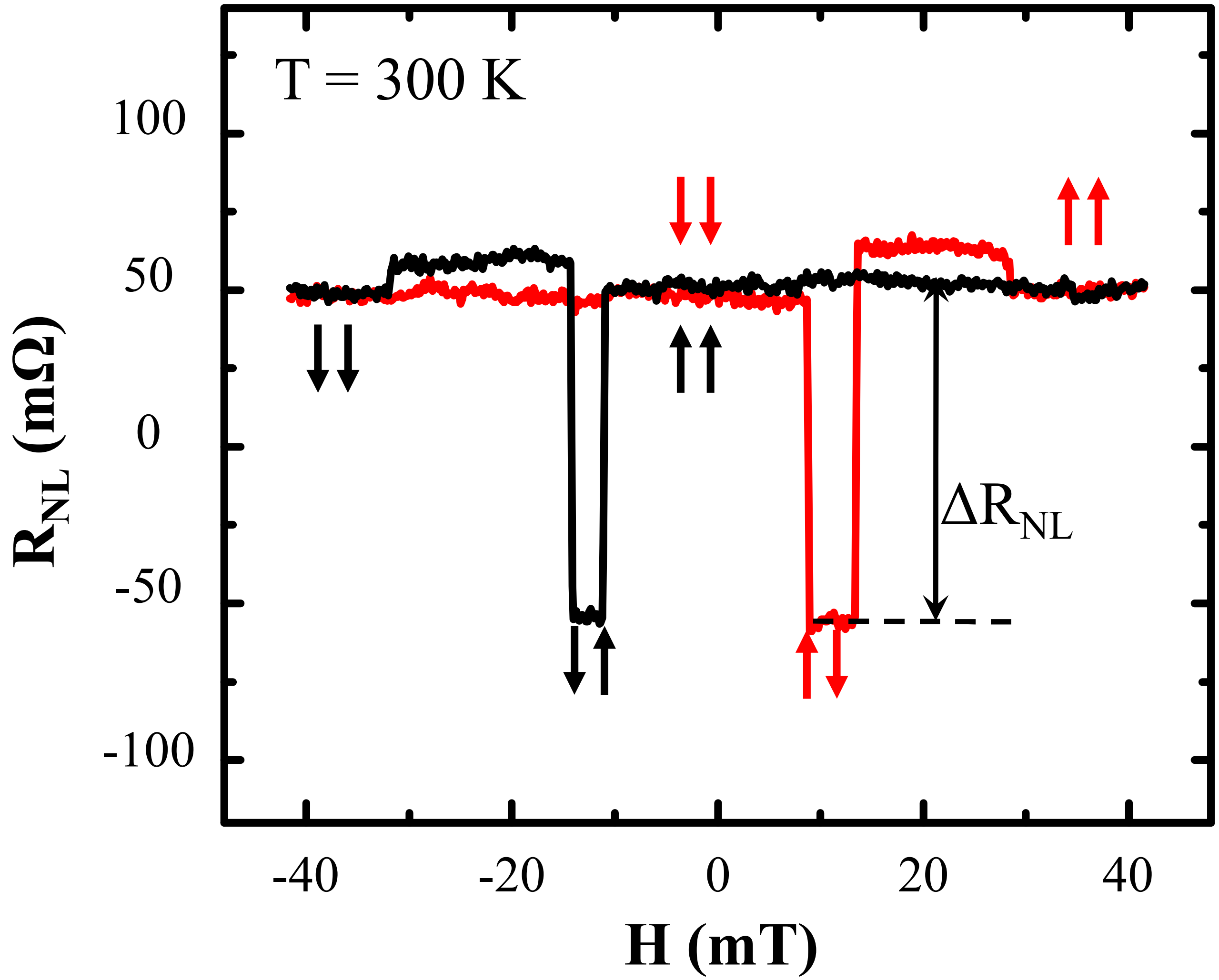
Nonlocal Spin valve





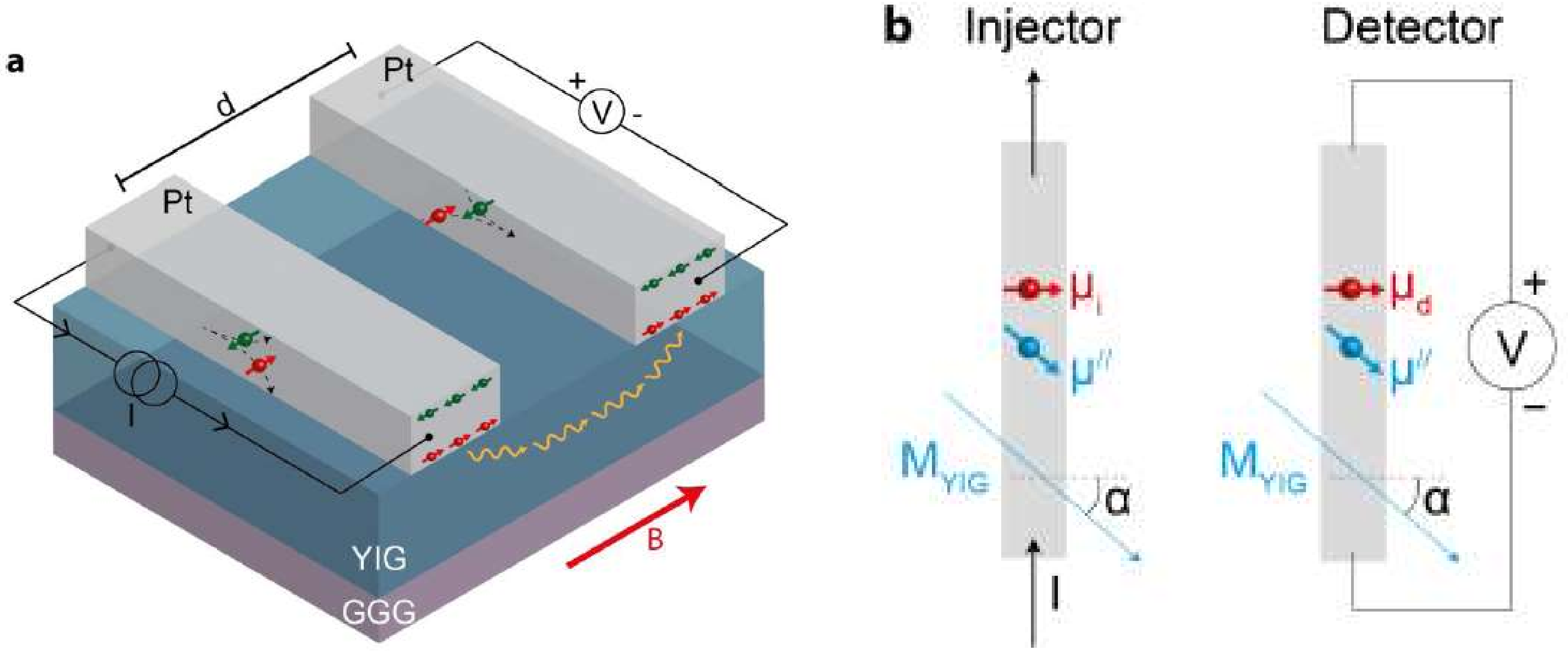
Nonlocal MR = $(V_P - V_{AP})/I_{INJ}$

Nonlocal Spin valve



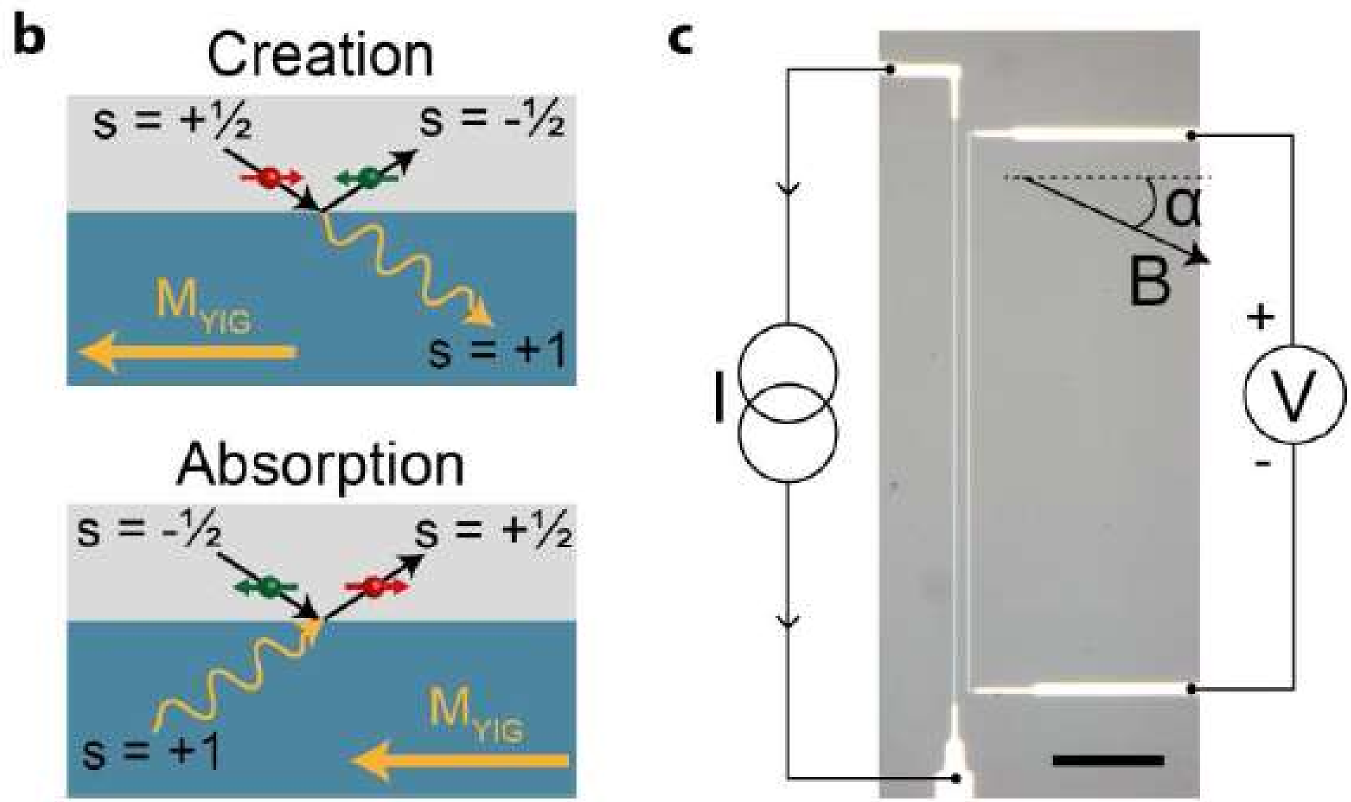
Han, et al, APL (2009)

Magnon transport

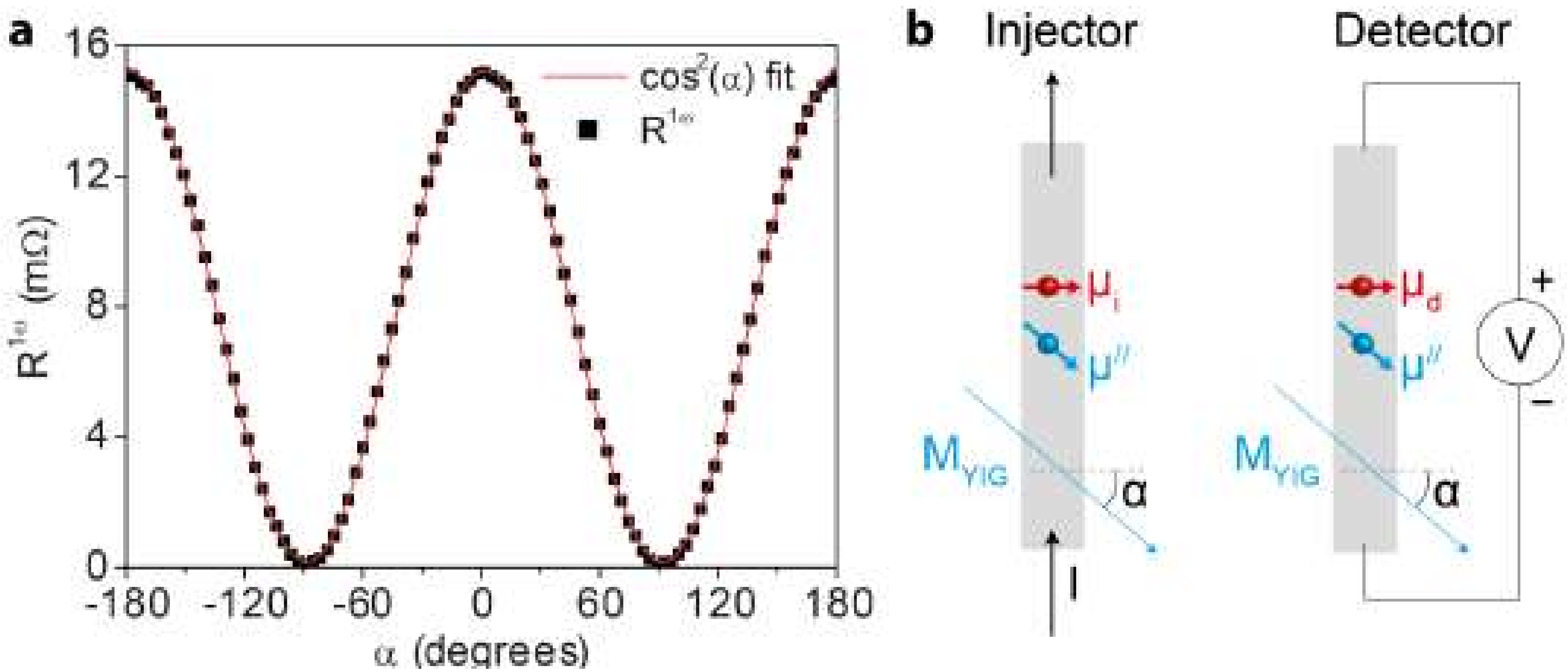


Cornelisssen, et al, Nature Physics (2015)

Magnon transport

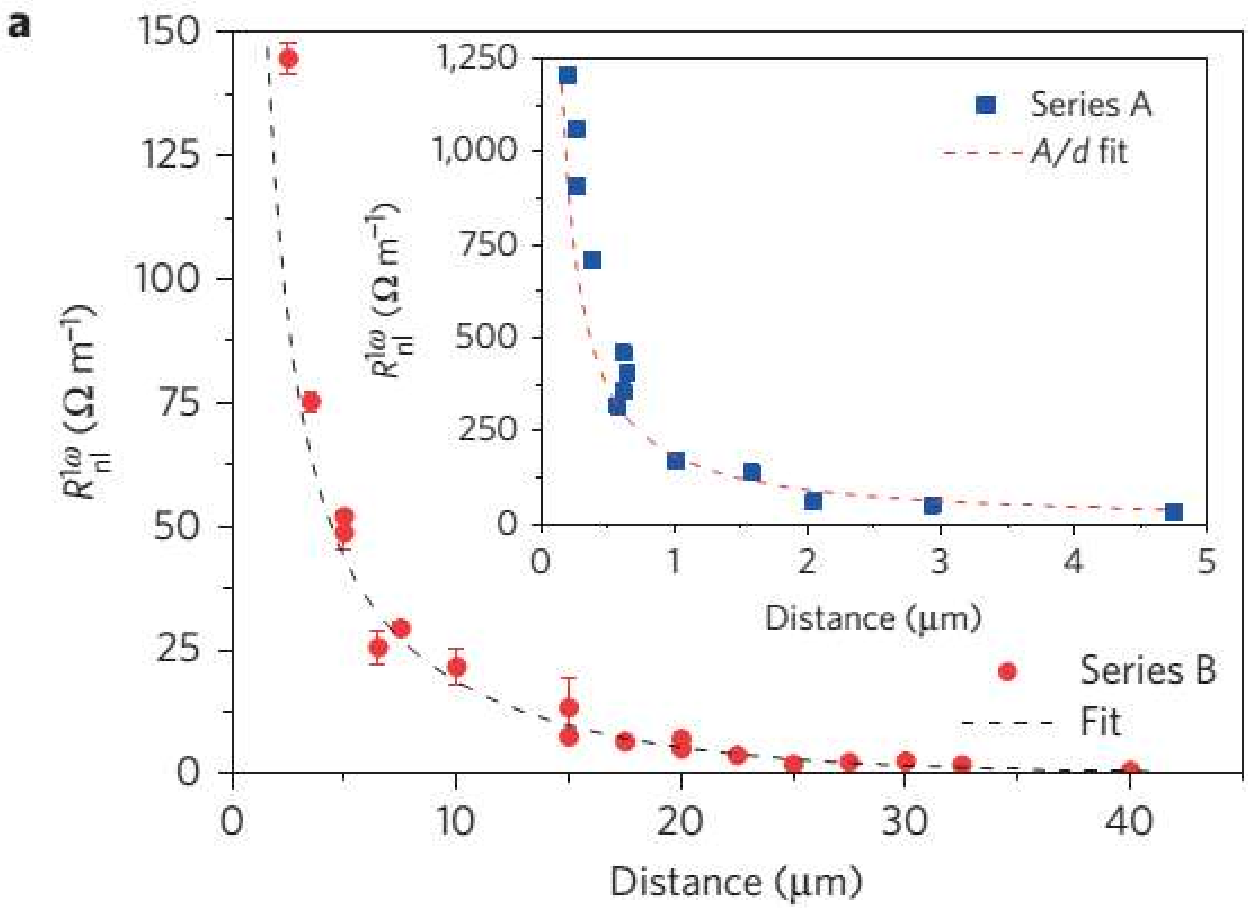


Magnon transport



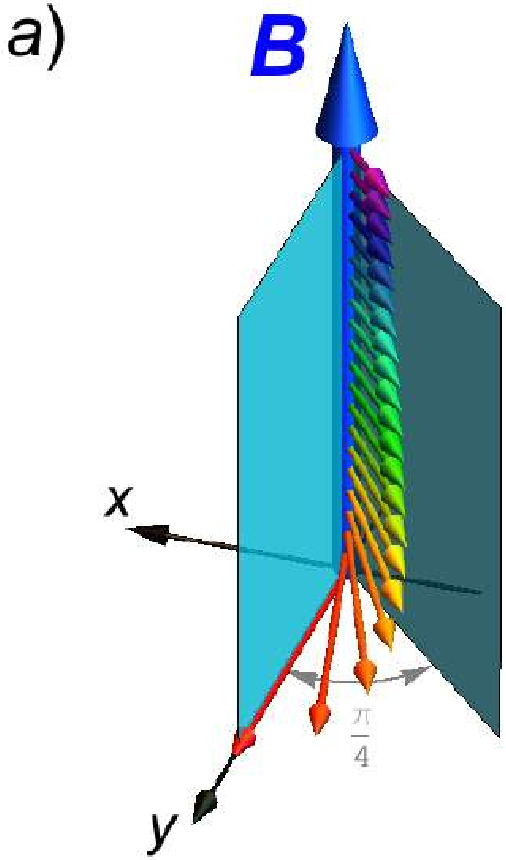
Cornelissen, et al, Nature Physics (2015)

Magnon transport



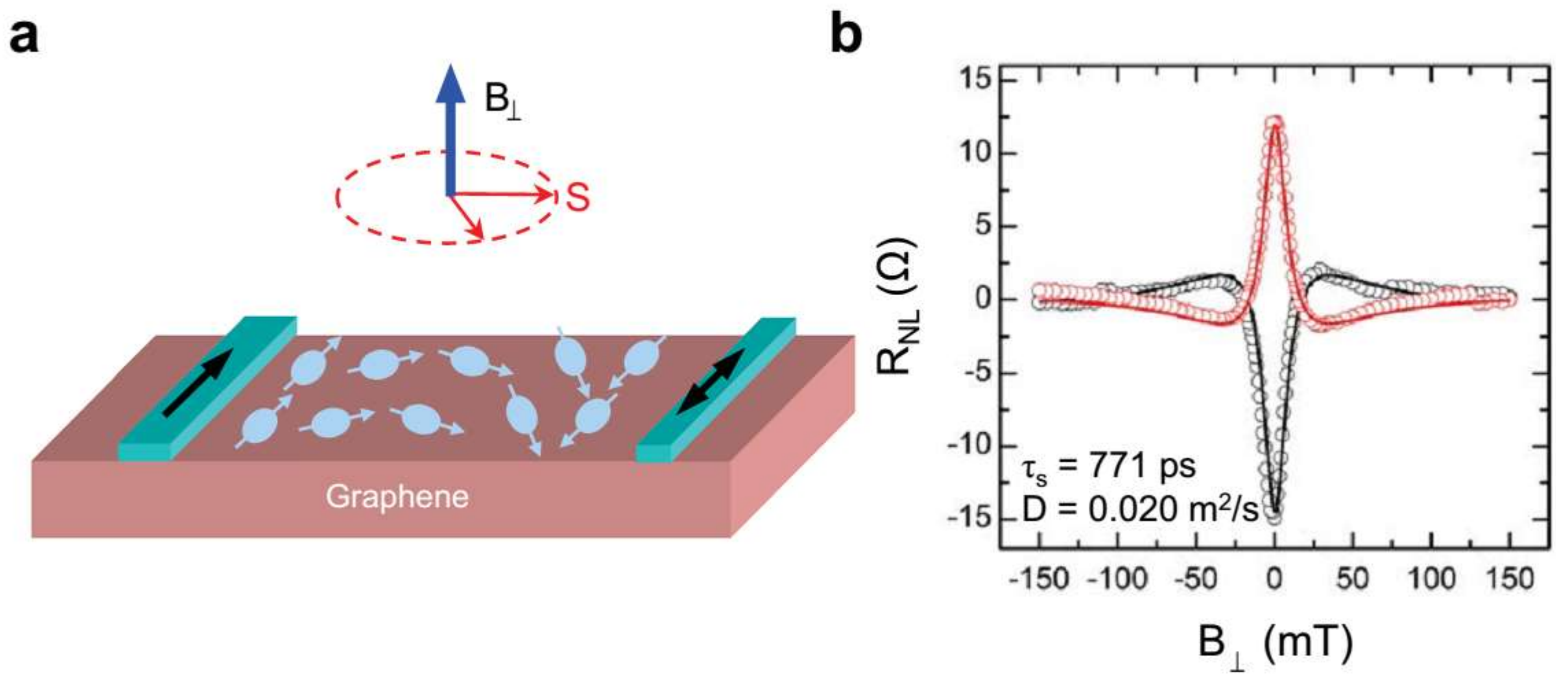
8. Hanle MR

Hanle MR



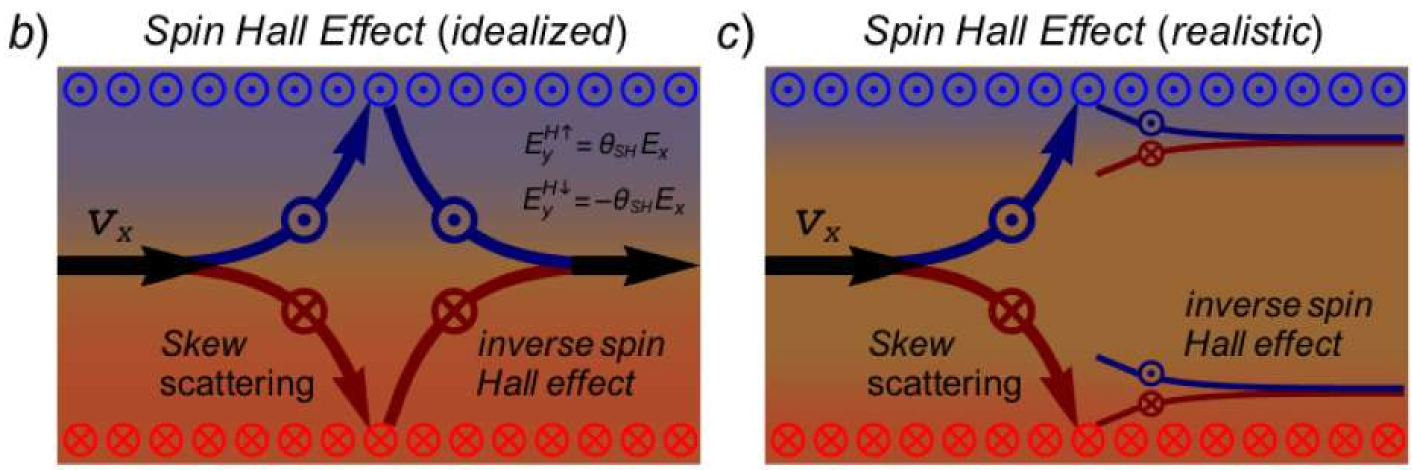
$$\vec{\tau} = -g\mu_B \vec{s} \times \vec{B}$$

Hanle MR



Han, et al, Nature Nanotech (2014)

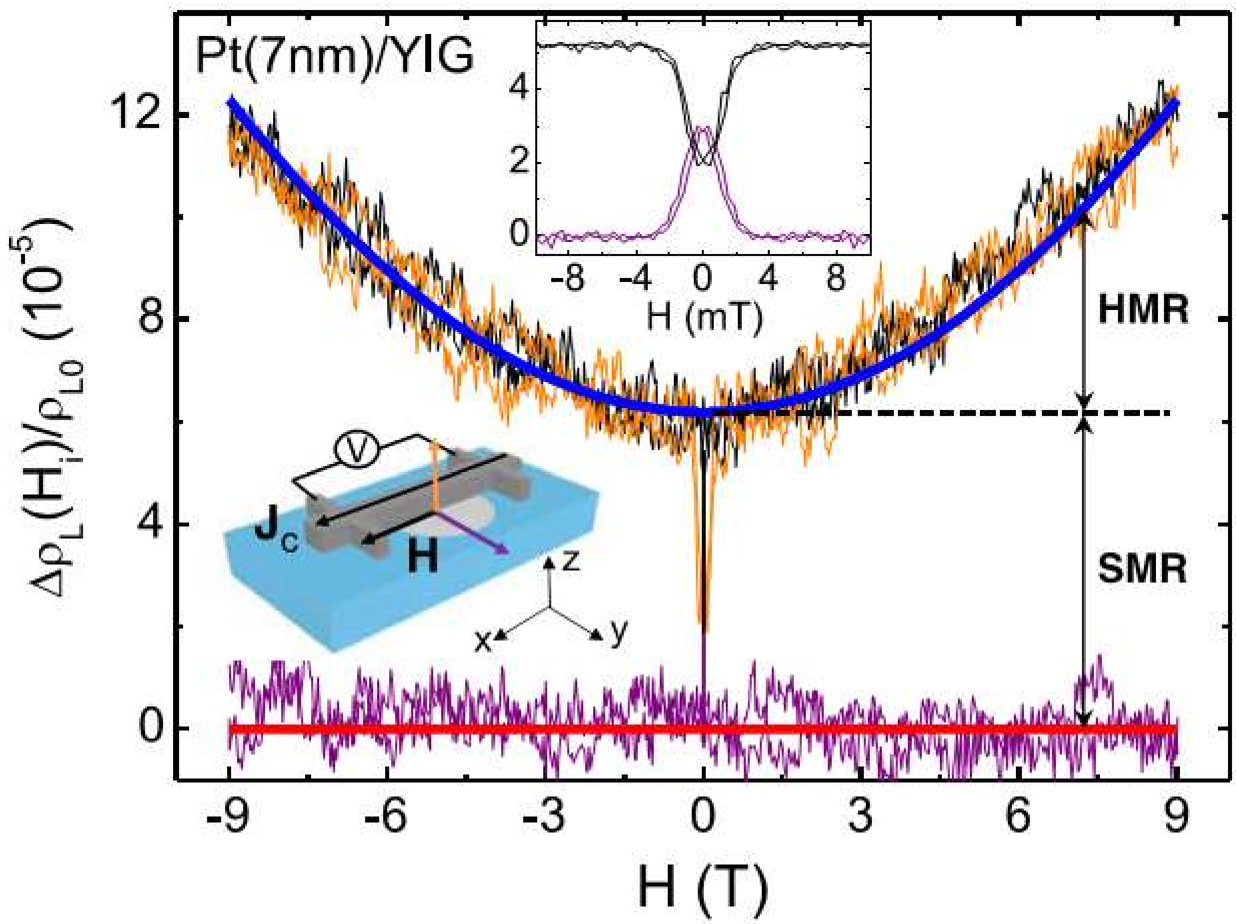
Hanle MR



- **Hanle effect on the spin accumulation**

Vélez,, et al, PRL (2016)

Hanle MR



- **Resistance change**

$$\boldsymbol{H} \perp \boldsymbol{S}$$

- **No resistance change**

$$\boldsymbol{H} \,//\, \boldsymbol{S}$$

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. 18th

Chapter 4: Spin Valves

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

谢谢！