自旋电子学研究进展

姜 勇

北京科技大学材料科学与工程学院

北京市弱磁检测与应用工程技术研究中心

自旋电子学实验室主要成员

姜　勇

杰青，长江学者

徐晓光

教授，北京市科技新星

苗　君

副教授，教育部新世纪优秀人才

海外合作者

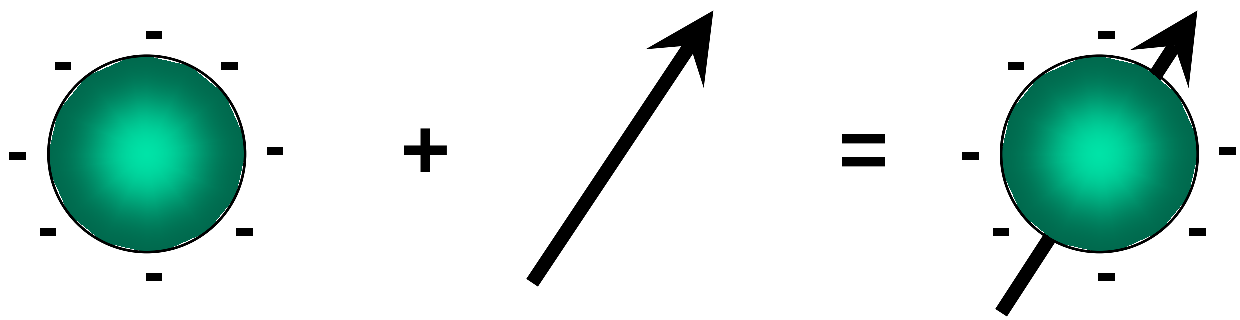
- Prof. *Koichiro Inomata* (NIMS Emeritus Fellow), National Institute for Materials Science, Tsukuba, Japan

- Assoc. Prof. *M. B. A. Jalil*, Department of Electrical and Computer Engineering, National University of Singapore, Singapore

- Prof. *Jianping Wang*, Department of Electrical and Computer Engineering, University of Minnesota

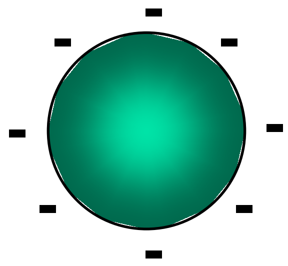
What Is an Electron ?

A particle with both a negative electric charge q= -e and a spin ½ (magnetic moment m =④$_{B}$)



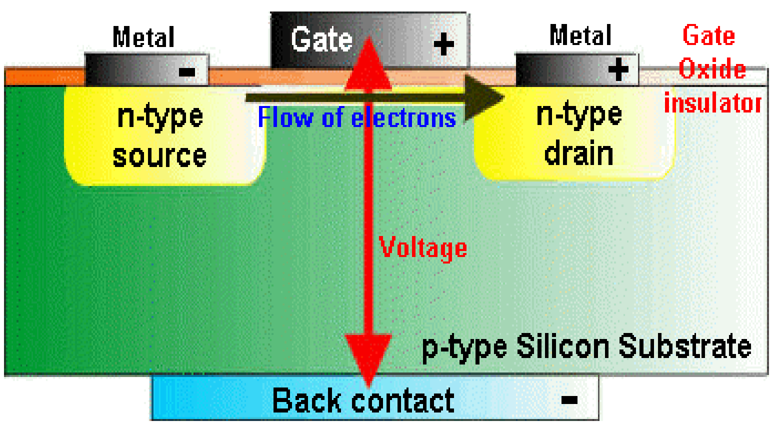
The direction of a spin is usually controlled by a magnetic field or inter-electron interactions, but there are also on-going researches to find ways to control the spin using an electric field.

Normal Electronics



An electron as seen by an electronician

Normal electronics considers the manipulation of electrons by using their charge for storage and processing of information.



MOSFET

Application:

1. Logic gates
2. Random access memory

Disadvantages:

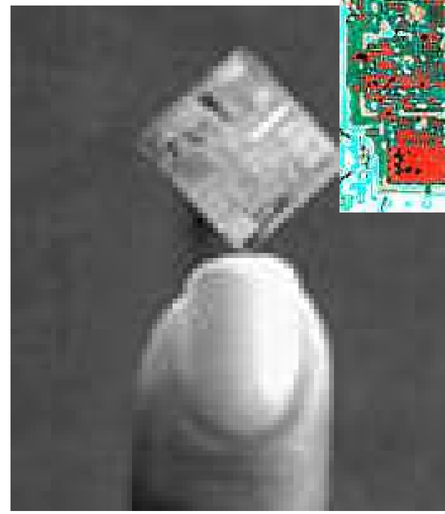
1. Volatility of the information
2. Large energy consumption
3. Limited storage density

Normal Electronics

第一只晶体管

1947, 贝尔实验室

1956年诺贝尔物理奖



第一块微处理芯片

1971， Intel 4004

2300晶体管/3x4 mm^2

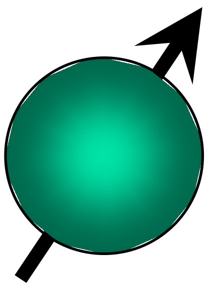
→ 信息时代

William Bradford Shockley

John Bardeen

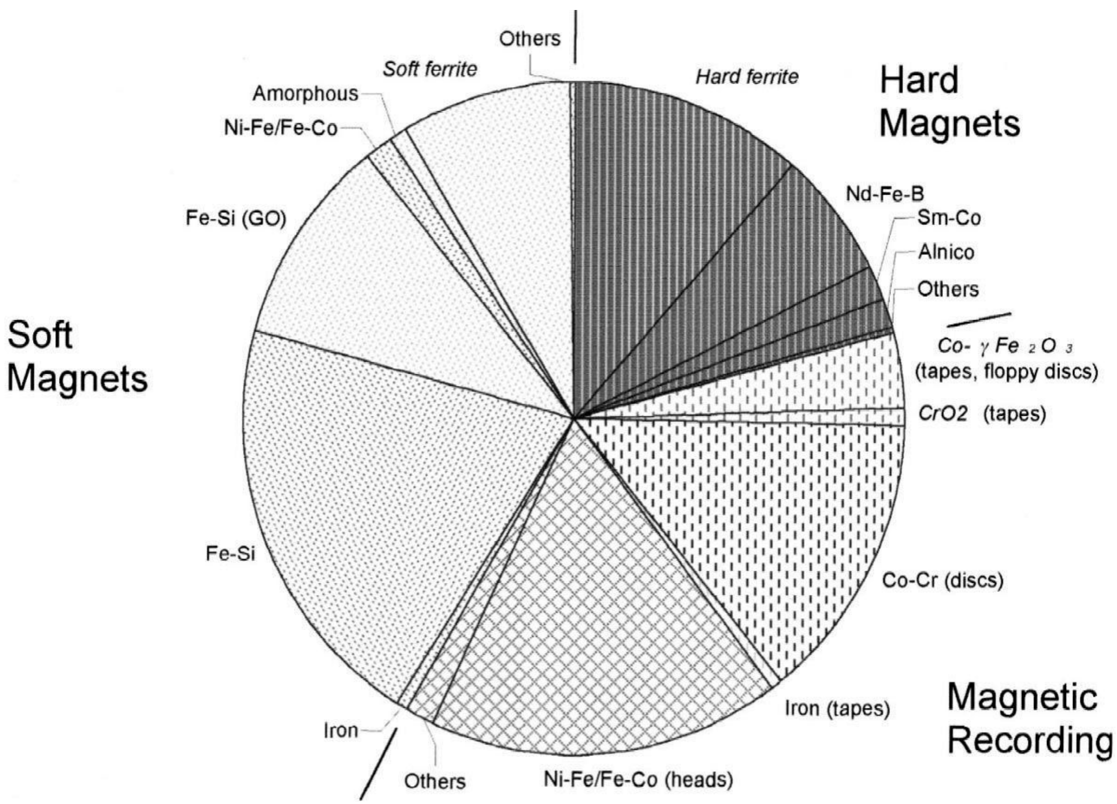
Walter Houser Brattain

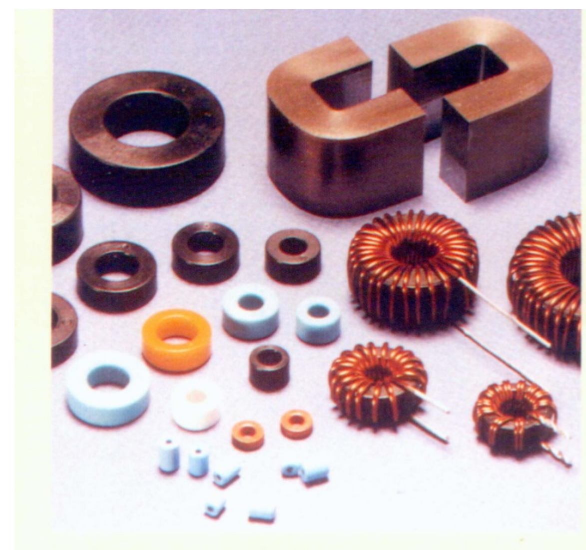
Normal Magnetism



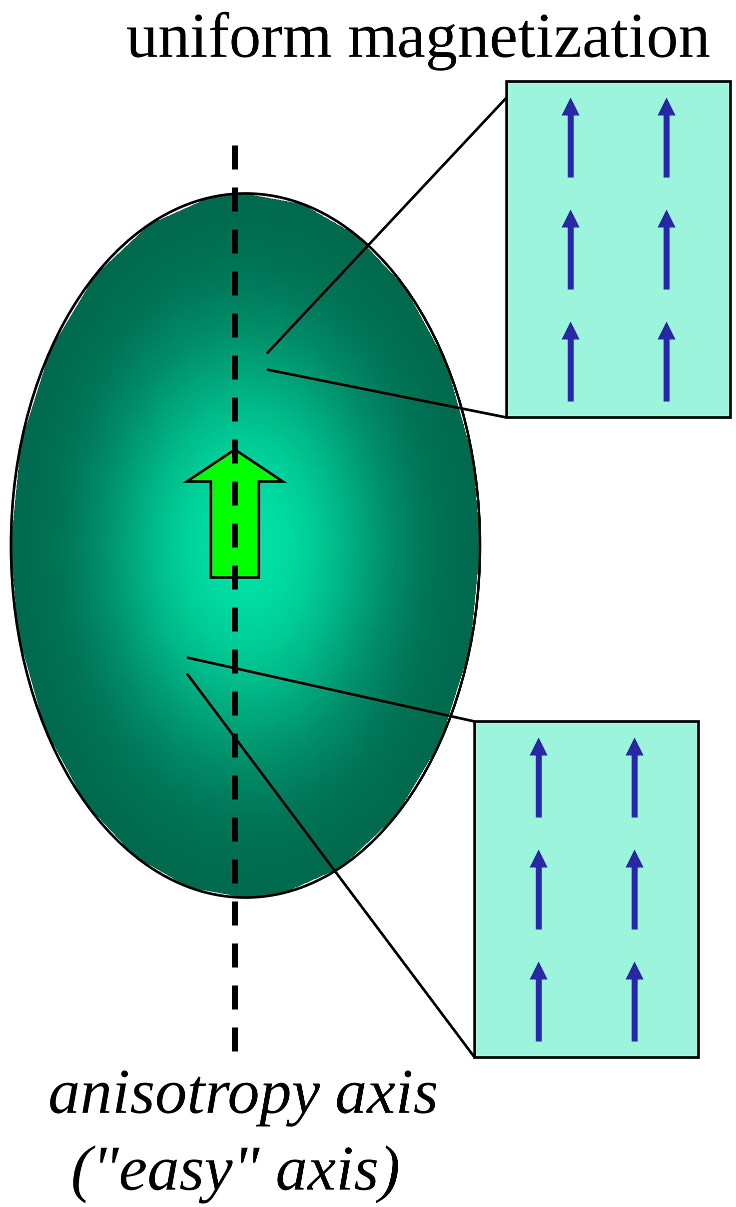
An electron as seen by a magnetician

A magnetician wants to develop materials in which the electron spins tend to align.





Ferromagnet 铁磁体



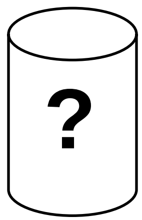
Electron magnetic moments ("spins")

Aligned by "exchange interaction"

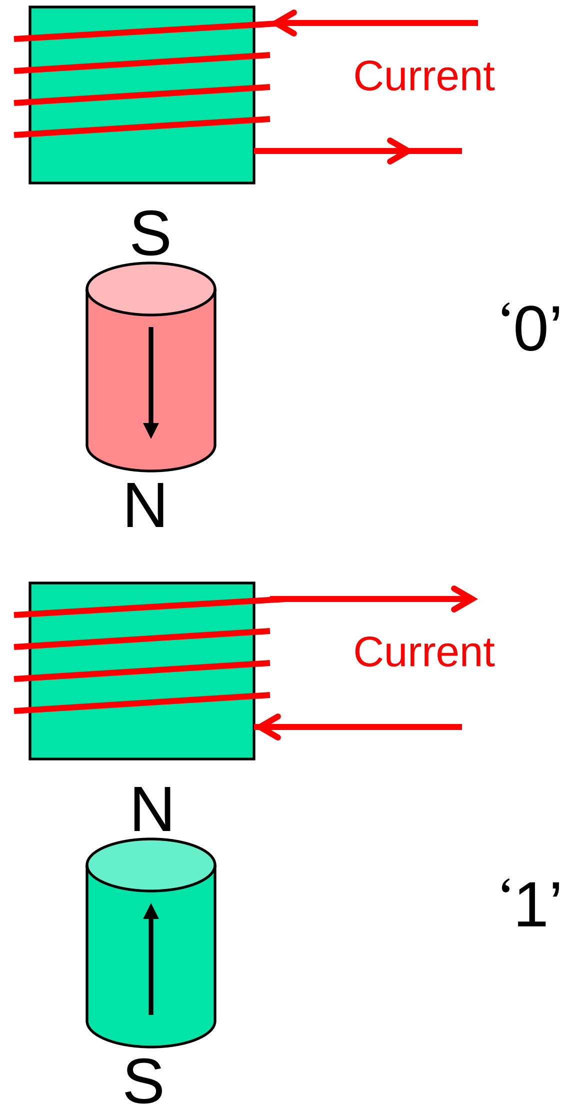
Bistable: Equivalent energy for "up" or "down" states

计算机硬盘盘片—

Ferromagnets are used to store data

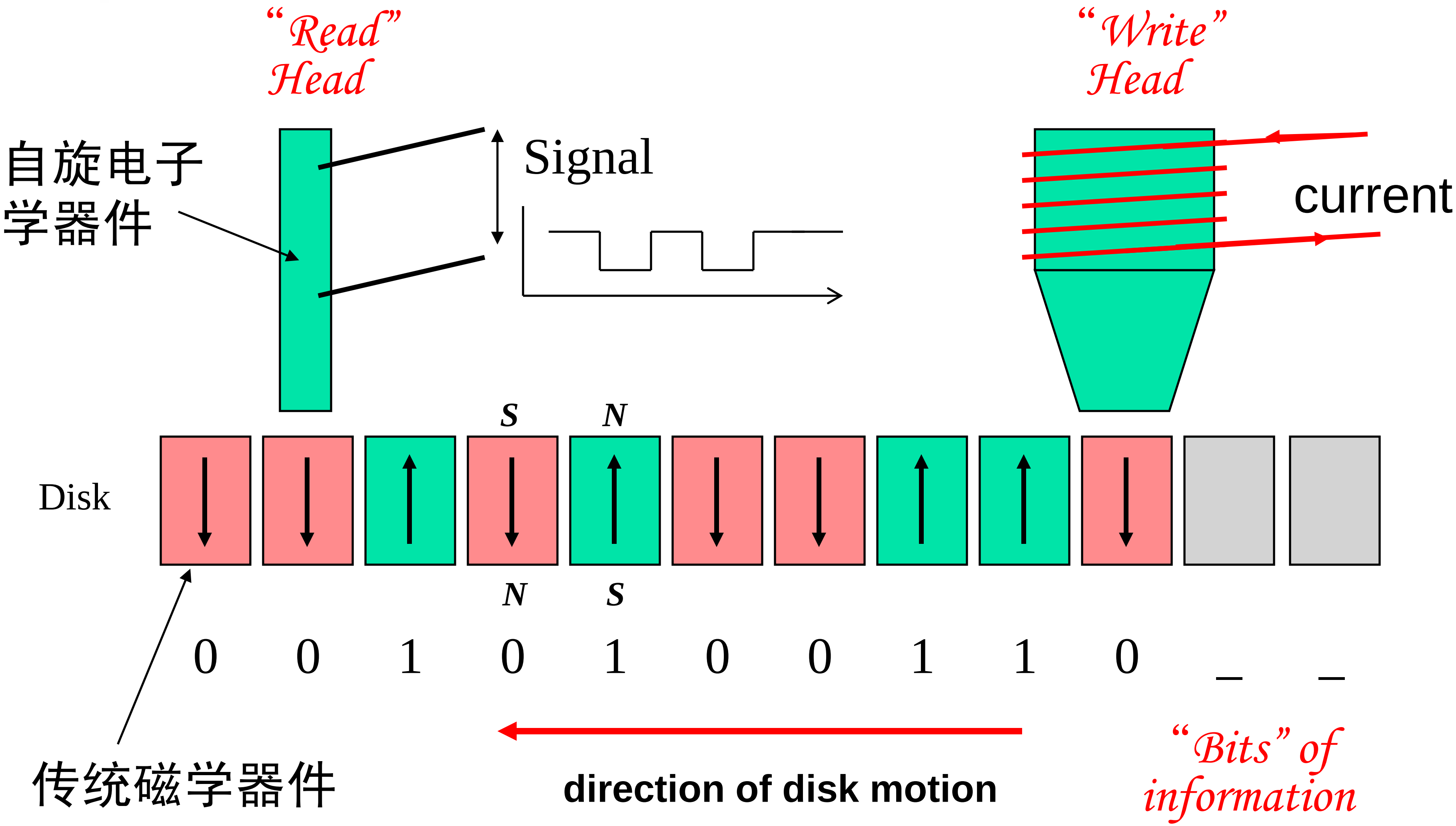


Ferromagnet with unknown magnetic state

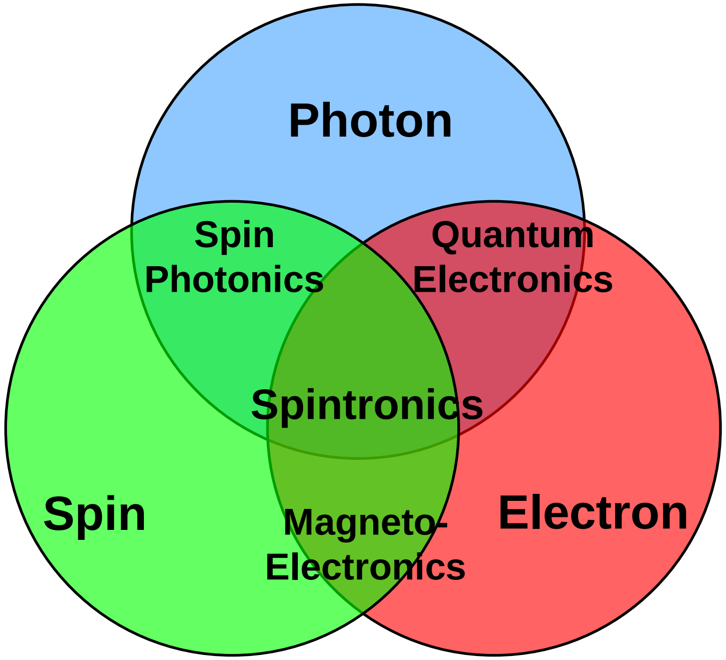


Magnetic Data Storage

A computer hard drive stores your data magnetically



Spin Electronics



Purpose of spin-electronics

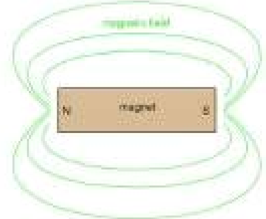
Combine electronics and magnetism in order to develop new devices in which both charge and spin of an electron play an active role.

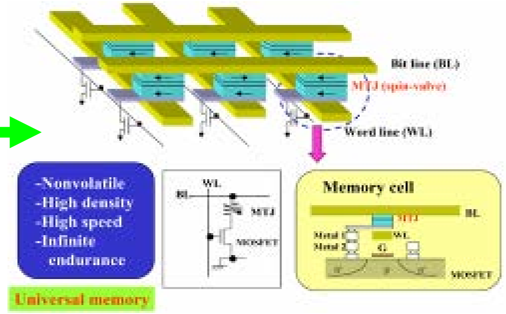
New fundamental physical questions

New phenomena

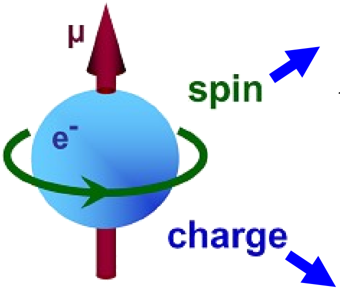
New devices and applications

自旋电子学





MRAM (Magnetic Random Access Memory) :Huge TMR



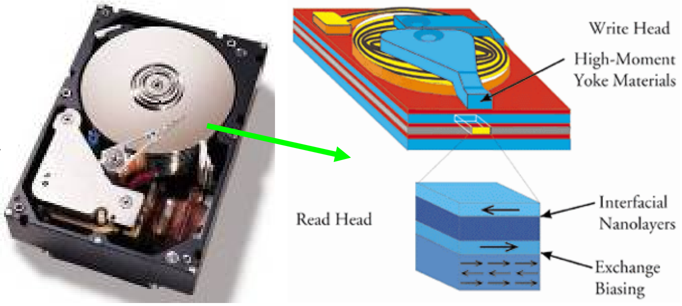
Magnetic engineering

Magnetic memory

Permanent magnet ..

spintronics

Spin + charge



HDD (Hard Disc Drive) read head

GMR → Large TMR + Low R;

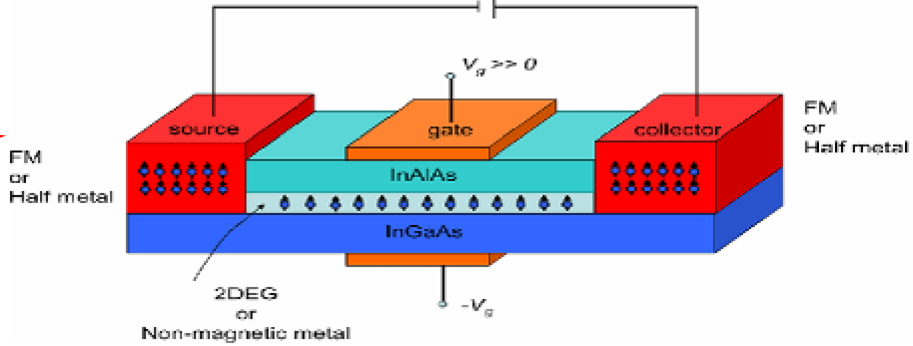
Large CPP-GMR

Electronics

Semiconductor

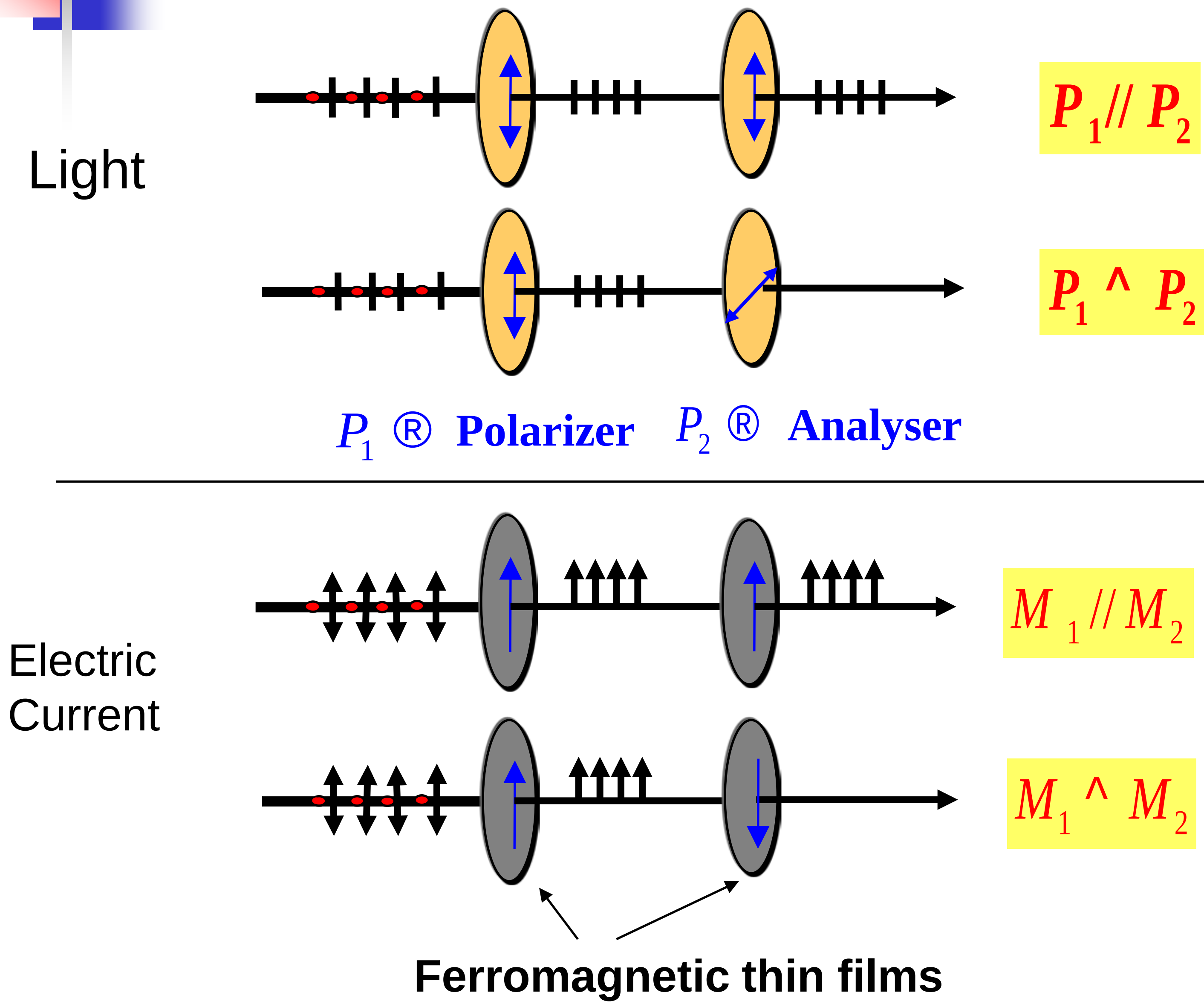
Transistor ..

spin –FET(spin –field effect transistor)

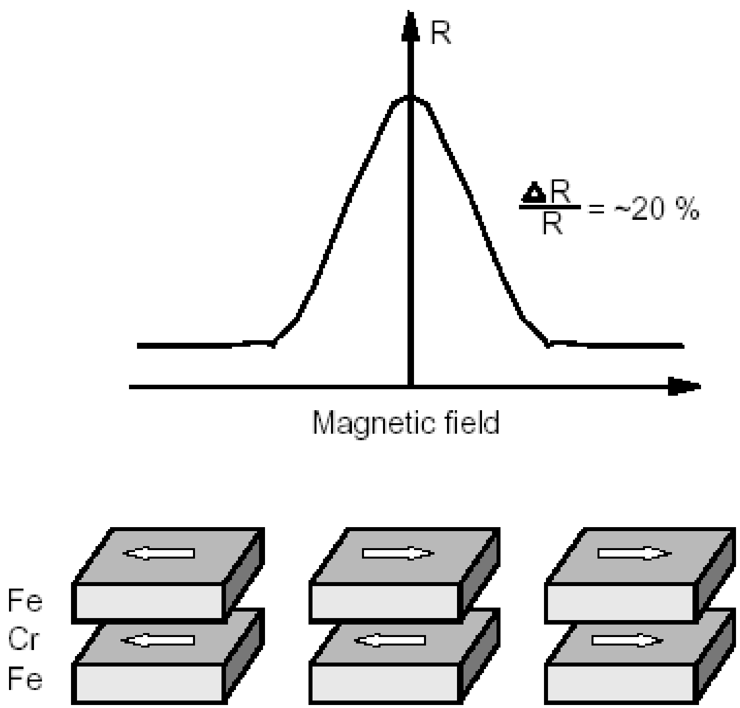


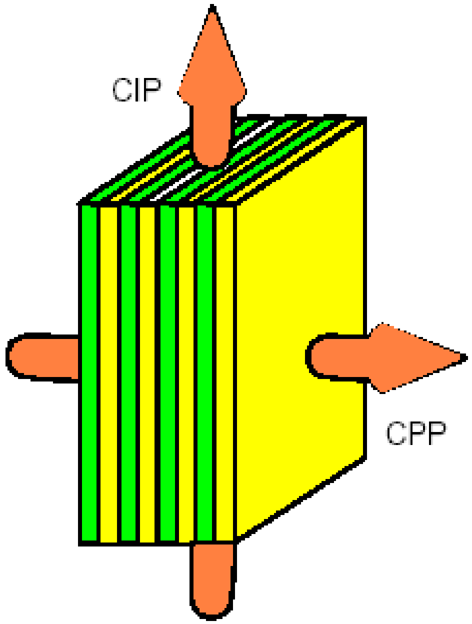
High spin injection Efficiency into semiconductor

How to Use "Spin"?

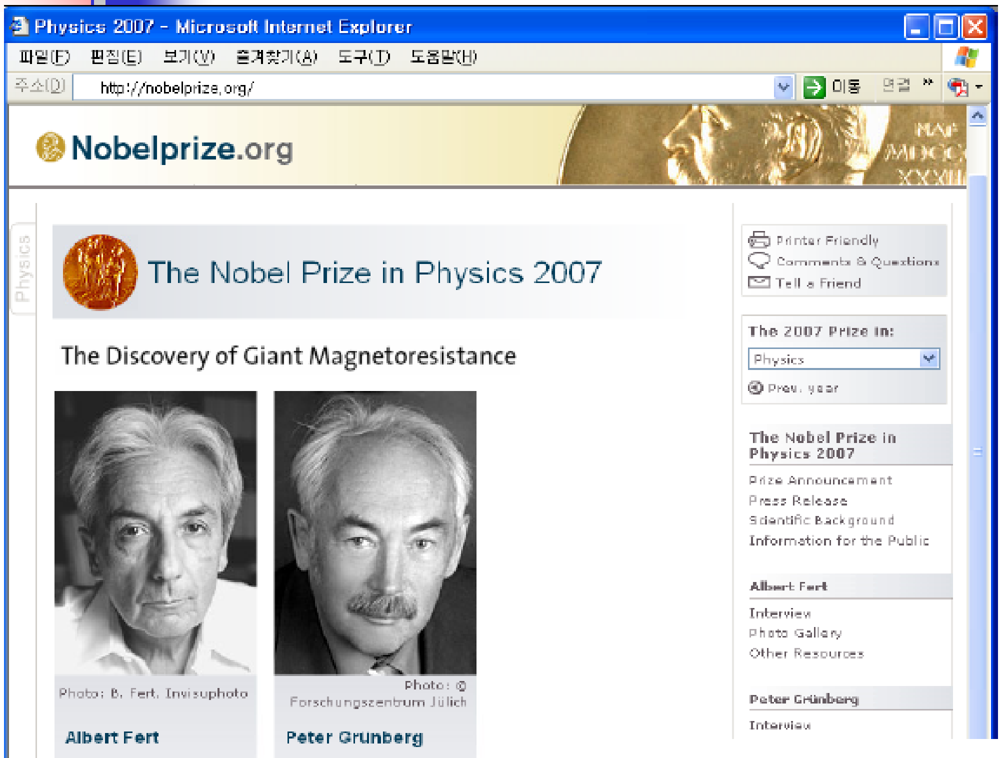


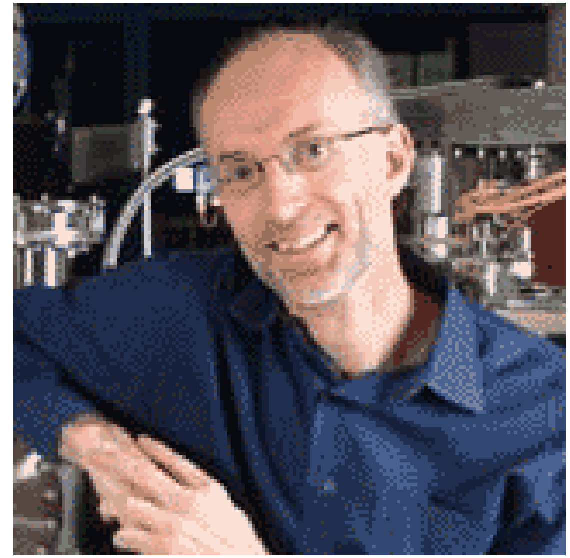
Giant Magnetoresistance (GMR，巨磁电阻)





Baibich et al., Phys. Rev. Lett, 61, 2472 (1988).

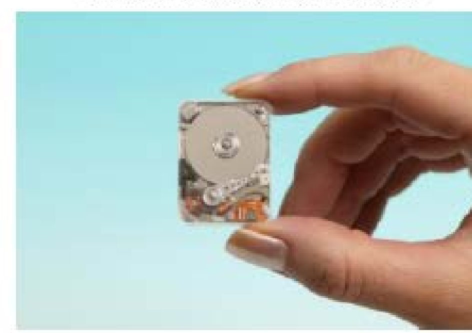




Stuart Parkin, IBM

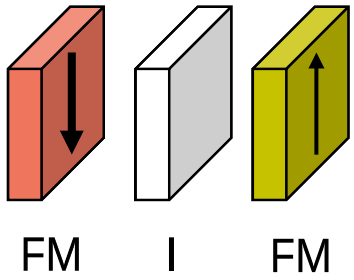
1951
mercury memory
(UNIVAC)

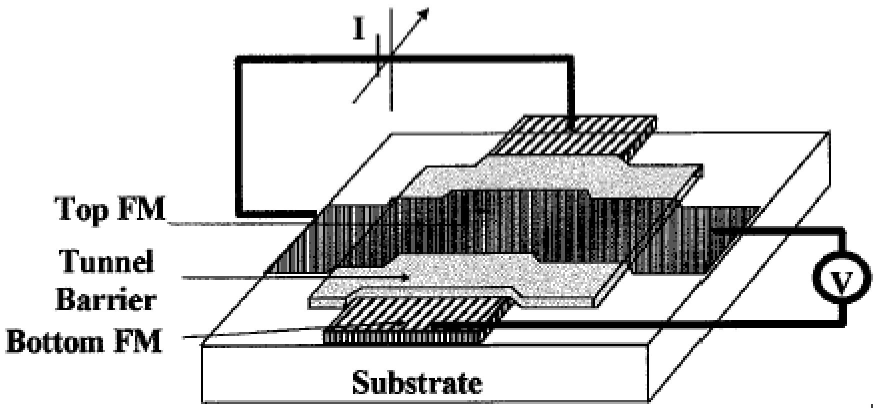
GMR Head on the HDD



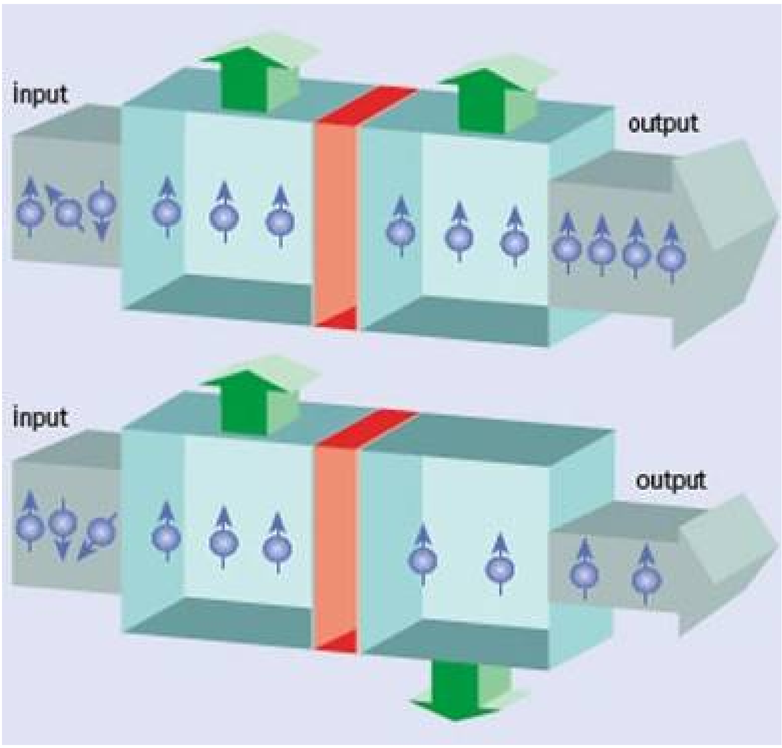
Today
0.85"HDD, 4 GBytes, 12.5 MB/sec

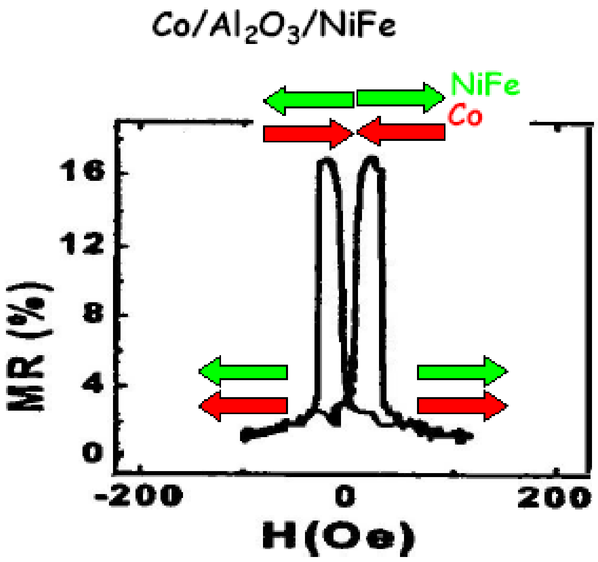
Tunneling Magnetoresistance（TMR，隧穿磁电阻）



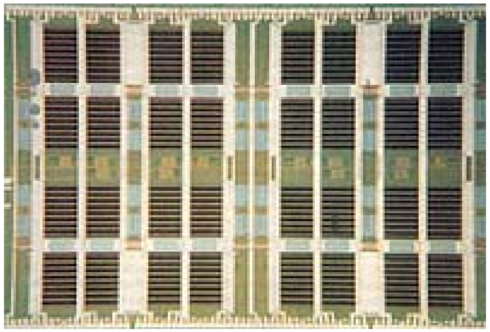


Magnetic Tunnel Junction (MTJ)

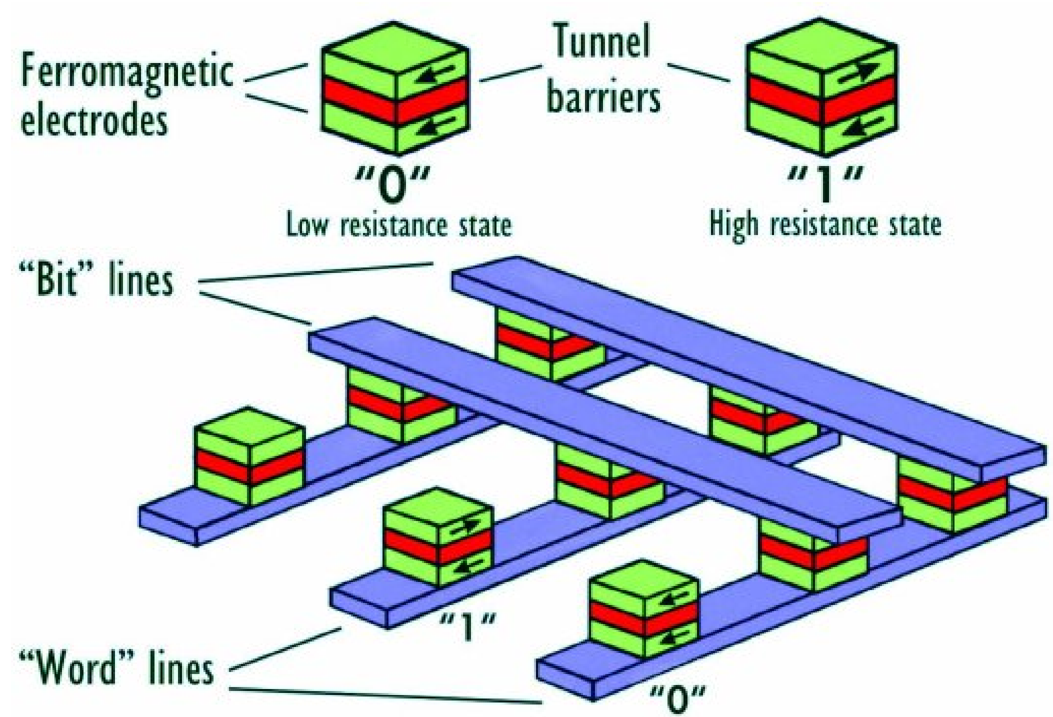


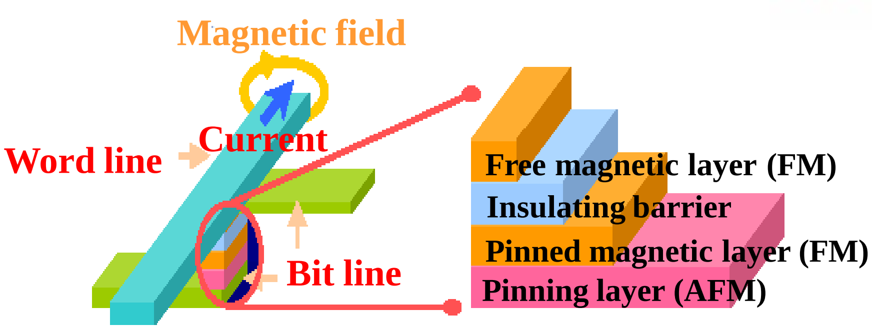


Magnetic Random Access Memory（MRAM，磁随机存储器）



4-Mbit MRAM
(Motorola)

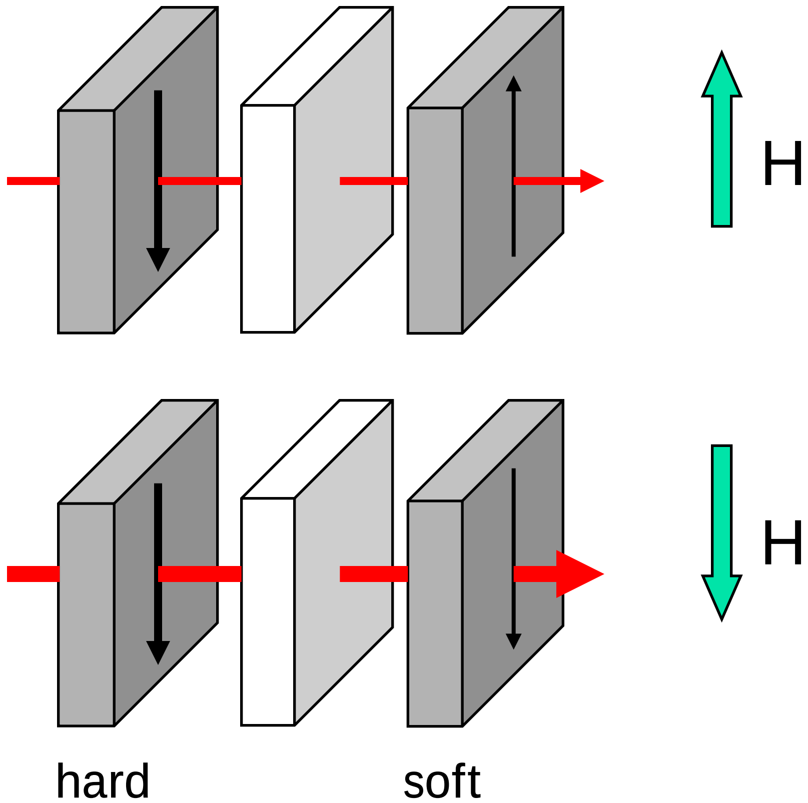




工艺复杂，能耗高，造成存储密度很难提高，目前最高记录仅有64M！

主要研发公司：Motorola, Everspin, Infineon, SONY, Toshiba, Hitachi

Spin transfer torque（STT,自旋转移力矩）

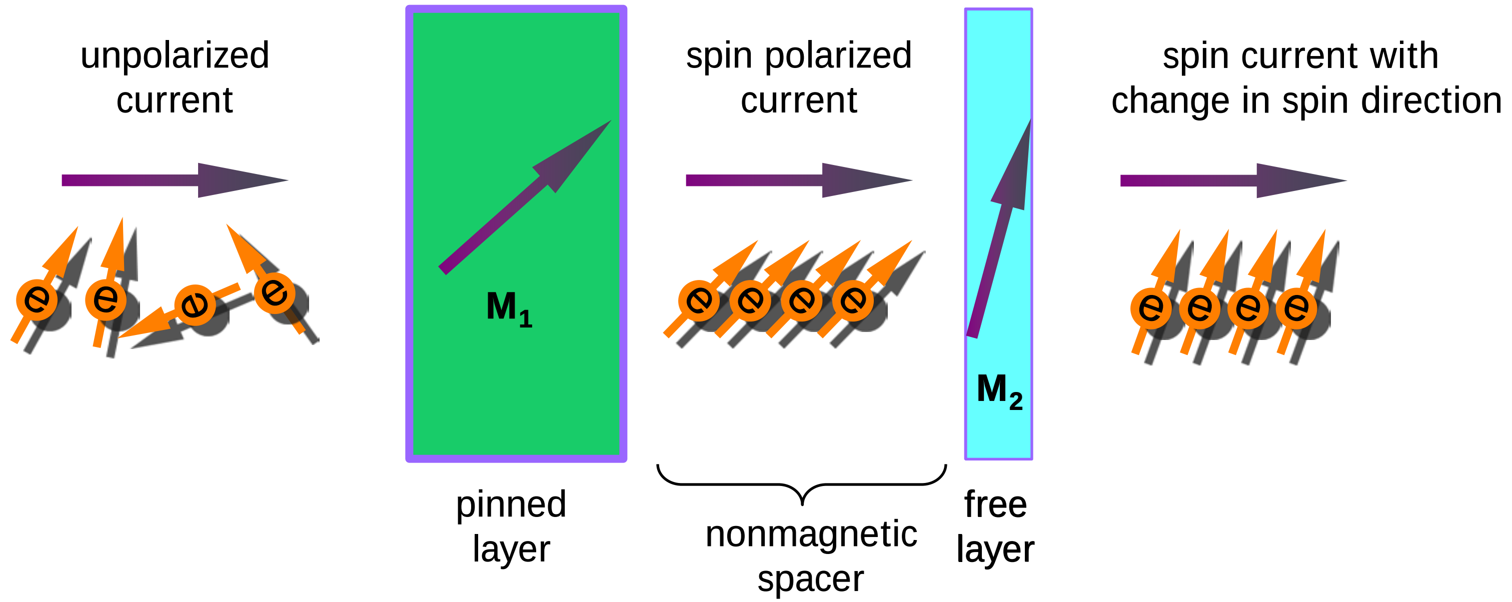


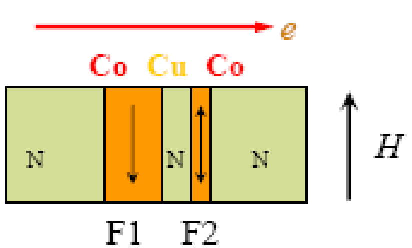
GMR & TMR: Magnetization changes current

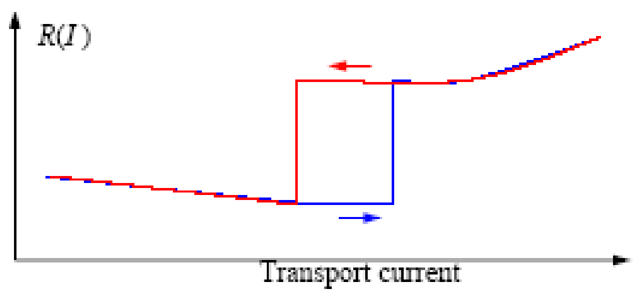
Can it be reversed?

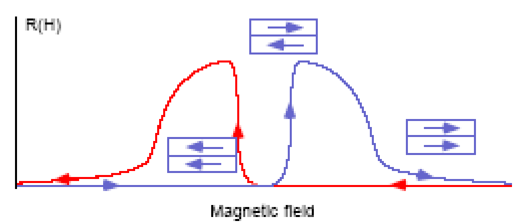
Spin transfer torque: Current changes magnetization

Spin transfer torque



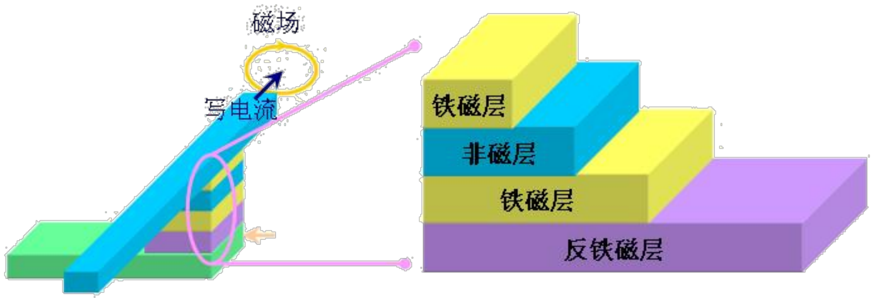


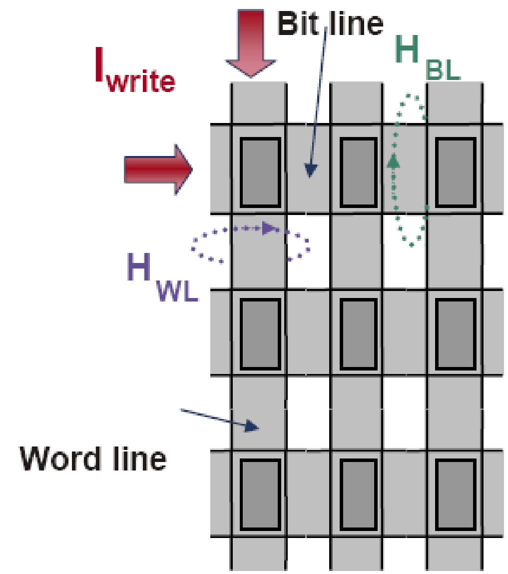


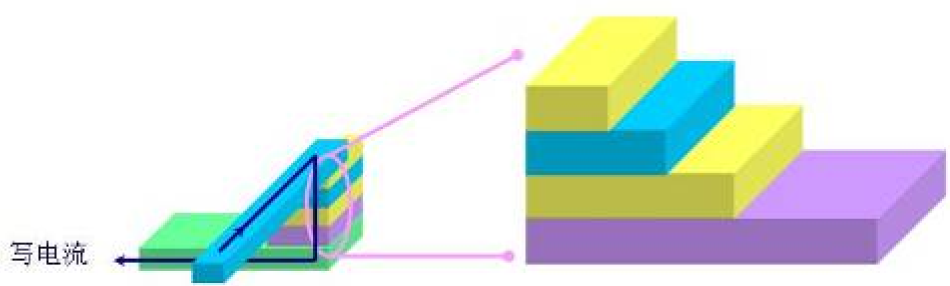


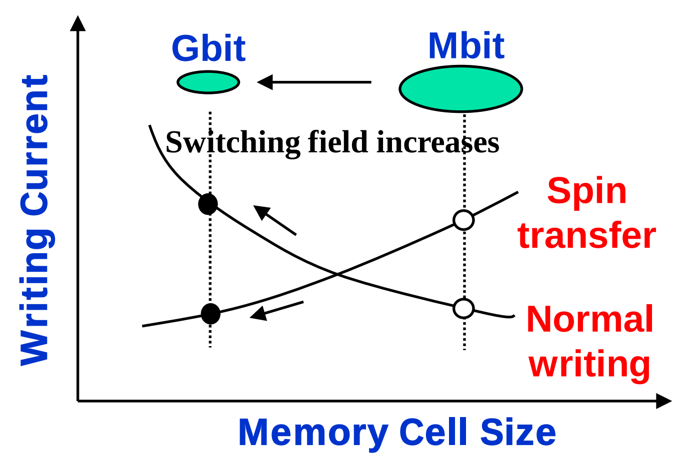
- Current is spin polarized as it passes through the pinned magnetic layer.
- If the net spin direction along M_1 is different from moments M_2 of free layer then there is a spin torque acting on the moments M_2
- M_2 **rotates** as current passes through it.

Spin torque applications





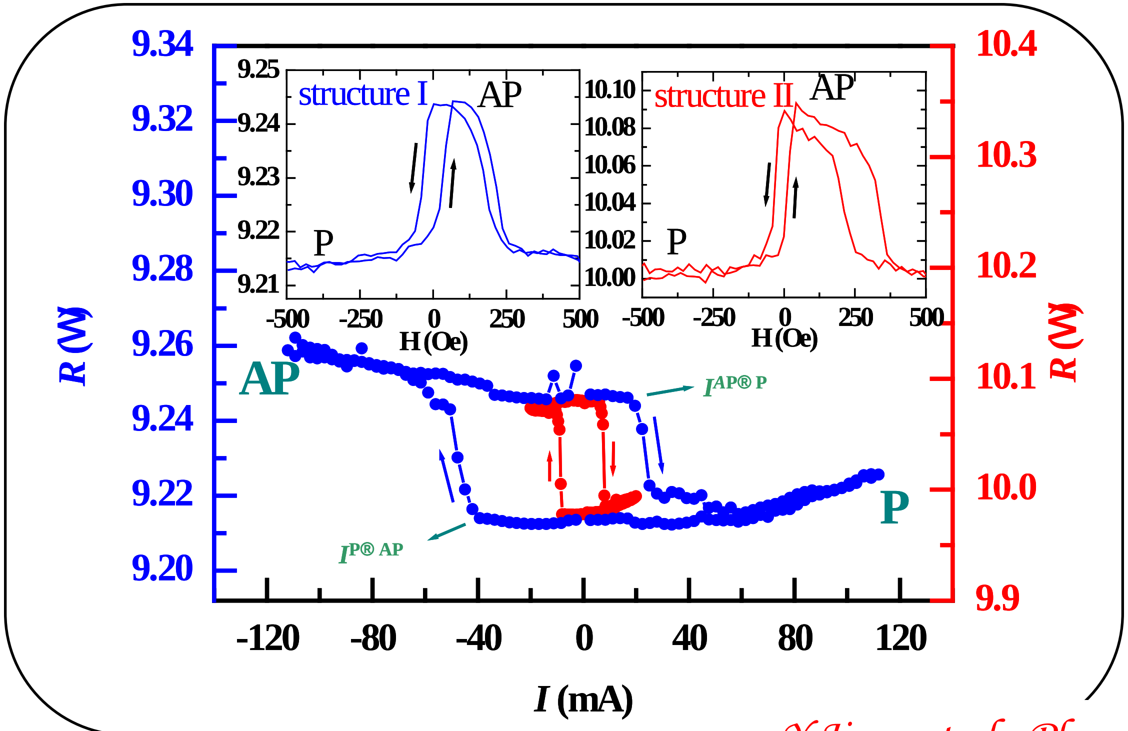




The critical current density (~10^7A/cm^2) is too high!

- 自旋转移力矩效应
- 垂直磁各向异性薄膜
- 多铁性薄膜

交换偏置自旋阀中的自旋转移力矩效应



Size: 280·90 nm^2

Y.Jiang et al., Phys. Rev. Lett. vol.92, 167204(2004).

structure I:
Cu(20)/IrMn(10)/$Co_{90}Fe_{10}$(5)/Cu(6)/$Co_{90}Fe_{10}$(2.5)/Cu(5)/Ta(2) (nm)

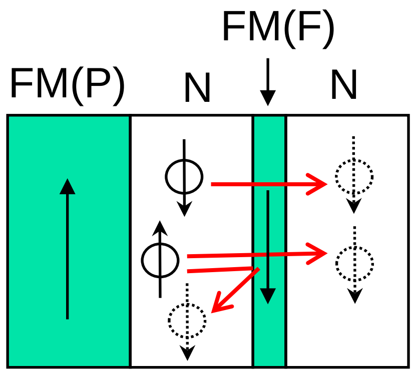
structure II:
Cu(20)/IrMn(10)/$Co_{90}Fe_{10}$(5)/Cu(6)/$Co_{90}Fe_{10}$(2.5)/**Ru**(0.45)/Cu(5)/Ta(2) (nm)

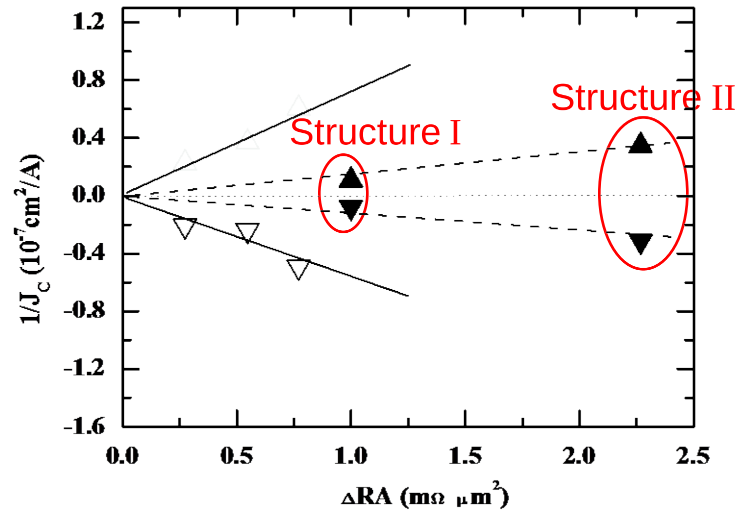
Critical current densities:
2.2·10^8 A/cm^2 (structure I);
1.8·10^7 A/cm^2 (structure II).

The Ru cap layer effectively decreases the critical current densities.

纳米厚度金属钌层增强的自旋转移力矩

Spin polarization *vs.* spin transfer





$$I_C(H_{app}) = \frac{e t_1}{\hbar \varepsilon}\left[\frac{23.4 M_S D}{2\hbar g} + 6.3 r^2 a_{LLG} M_S (H_{app} + H_{ex} - M_{eff})\right]$$

Assume $H_{app}=M_{eff}-H_{ex}$, we have

$$I_C \propto 1/\varepsilon.$$

ε is spin transfer efficiency. Then

$$\frac{\varepsilon(structureII)}{\varepsilon(structureI)} = \frac{I_{C1}}{I_{C2}} = \frac{J_{C1}}{J_{C2}} = \frac{1.8\times 10^8}{2.2\times 10^7} \approx 8.2$$

If ε(*structure II*)=0.5, ε(*structure I*) is only 0.06.

△ $Fe_{50}Mn_{50}$ cap in the pseudo-spin valves by *Urazhdin et al.*

▲ Ru cap in the spin valves (*our results*)

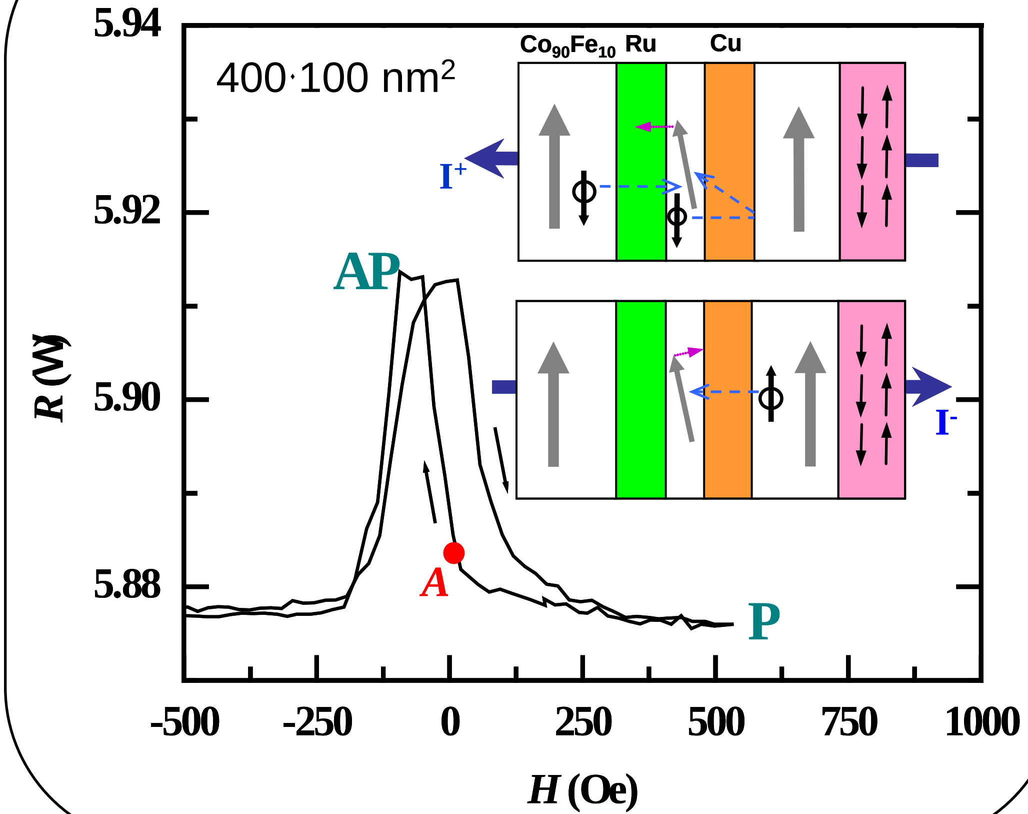
$$1/J_c \propto \Delta RA \propto P$$

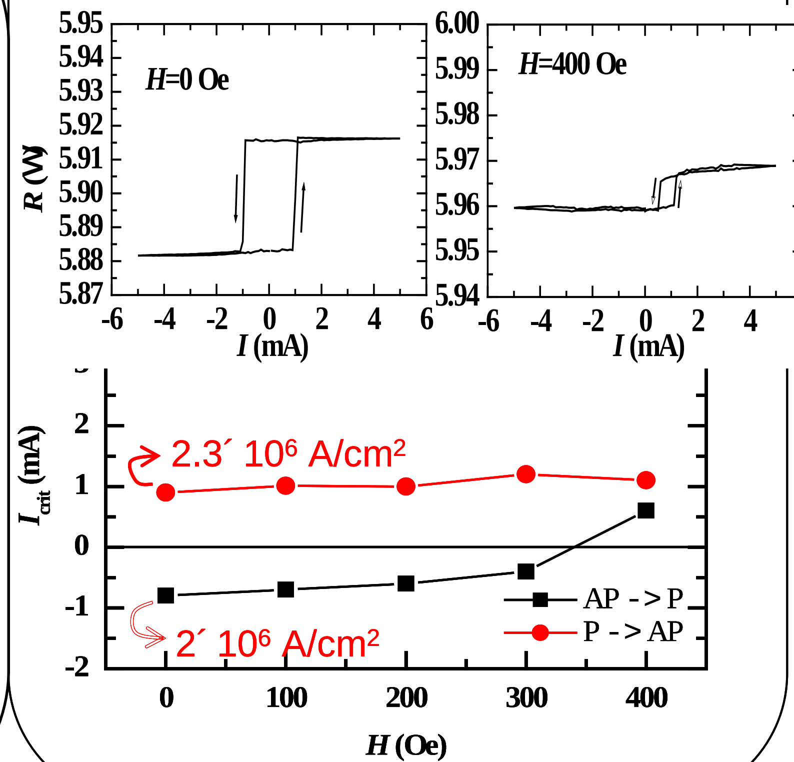
P ■ spin polarization

Y.Jiang et al., Phys.Rev.Lett. 92, 167204(2004).

Different spin transfer efficiencies between the two structures

反对称自旋阀结构中STT临界电流密度的大幅度降低





Y.Jiang et al., Nature Materials, vol.3, 361(2004).

Structure III:
Ta(6)/Cu(50)/$Co_{90}Fe_{10}$(5)/Ru(6)/$Co_{90}Fe_{10}$(2.5)/Cu(6)/$Co_{90}Fe_{10}$(5)/IrMn(10)/Cu(5)/Ta(2) (nm)

反对称自旋阀结构中STT临界电流密度的大幅度降低

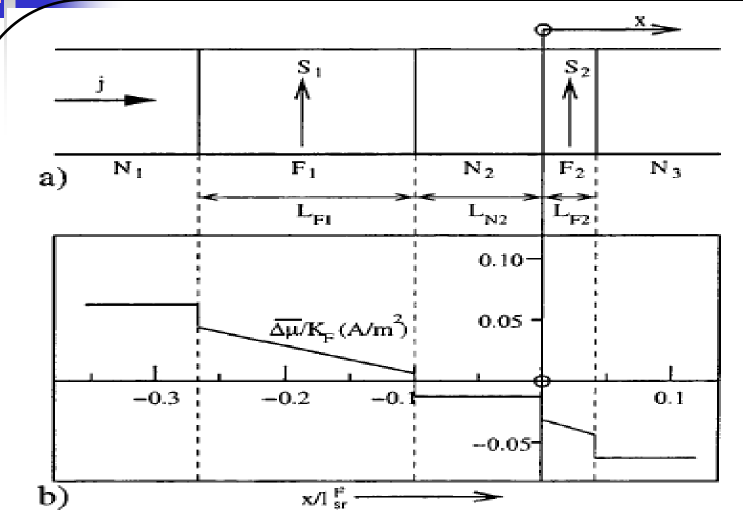


FIG. 1. (a) Asymmetric configuration of layers; (b) values of $\overline{\Delta\mu}/K_F$ are plotted vs x/l_{sr}^F, assuming $L_{F_1}=10$ nm and $j=1$ A/m^2.

Asymmetric configuration

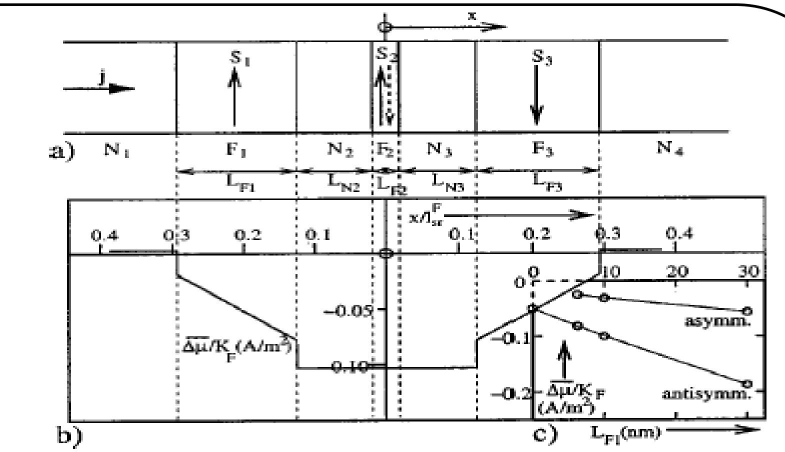
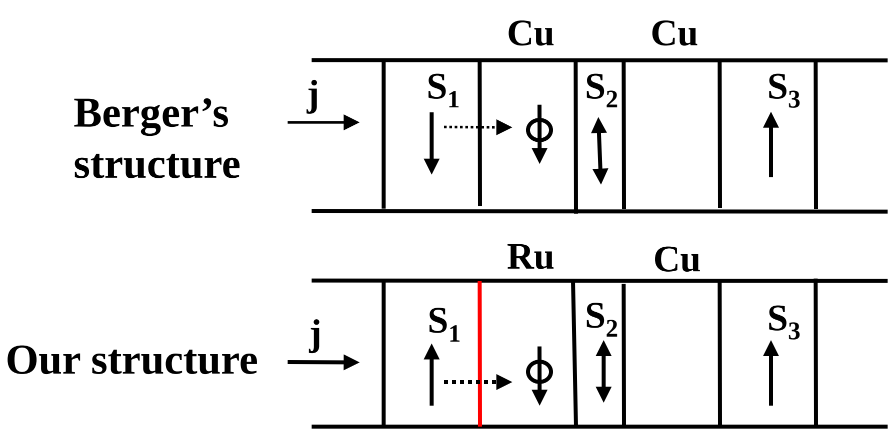


FIG. 2. (a) Antisymmetric configuration of layers. The two possible directions of S_2 are shown; (b) values of $\overline{\Delta\mu}/K_F$ are plotted vs x/l_{sr}^F for the

Six times higher spin accumulation!

Antisymmetric configuration

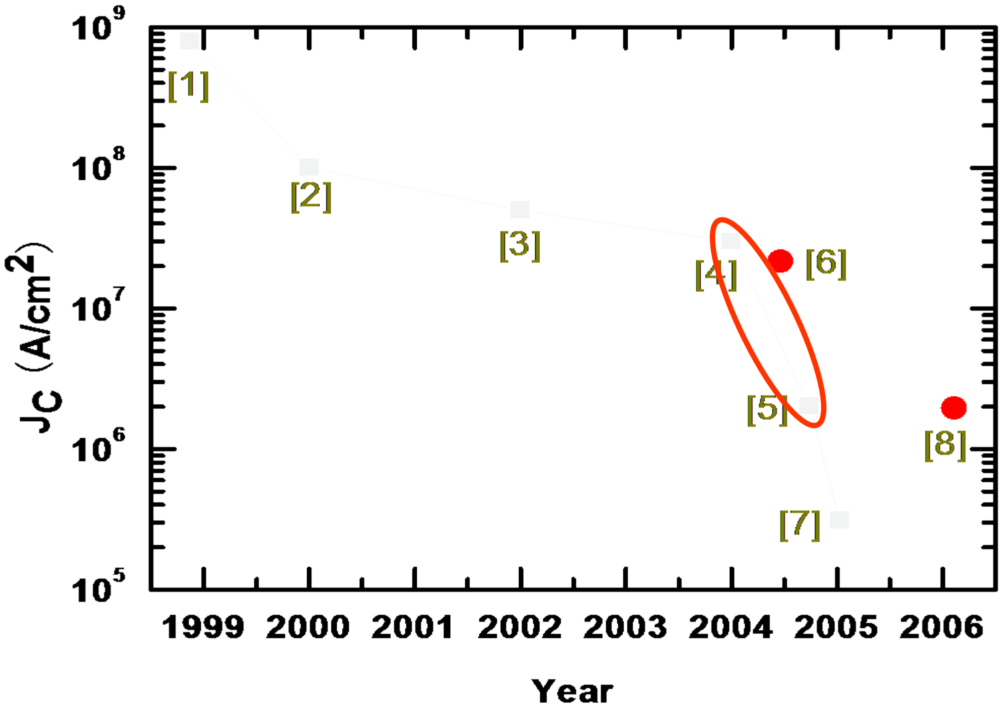
L.Berger,J.Appl.Phys. 93, 7693(2003)



According to the equations of *Berger*, in our structure:

When S_1//S_3, $\left.\frac{\overline{Dm}}{K}\right|_{Ru}$ has the same sign as $\left.\frac{\overline{Dm}}{K}\right|_{Cu}$, therefore enhance spin transfer.

When S_1//-S_3, $\left.\frac{\overline{Dm}}{K}\right|_{Ru}$ has an opposite sign as $\left.\frac{\overline{Dm}}{K}\right|_{Cu}$, spin transfer cannot be enhanced.



1. E. B. Myers *et al.,* Science **285**, 867 (1999).
2. J. A. Katine *et al.*,PRL **84**, 3149 (2000).
3. F. J. Albert *et al.*, PRL **89**, 226802, (2002).
4. **Y. Jiang *et al.*, PRL 92, 167204 (2004).**
5. **Y. Jiang *et al.*, Nat. Mater. 3, 361 (2004).**
6. G. D. Fuchs *et al.*, APL **85**, 1205 (2004).
7. M. Yamanouchi *et al.*, Nature **428**, 539 (2004).
8. H. Meng et al., APL, 88, 082504(2006).

论文被Nature及其子刊正面引用6次，
且被12篇综述文章正面引用。

IBM公司Thomas J. Watson研发中心科学家Jonathon Sun博士在《IBM器件研发》上发表综述文章

Spin angular momentum transfer in current-perpendicular nanomagnetic junctions

J. Z. Sun

IBM J. RES. & DEV. VOL. 50 NO. 1 JANUARY 2006

One proposal for reducing the current required to switch a nanomagnet was presented by Berger [80]. **Figure 15** illustrates the proposal. For a free nanomagnet sandwiched between two oppositely fixed magnetic polarizer layers, Berger predicted a sizable enhancement of the spin-transfer effect, and an approximately sixfold net reduction of the threshold current. Several recent experiments [81] seem to confirm the existence of this enhancement, although a quantitative comparison with model results has yet to be made.

81. Y. Jiang, T. Nozaki, S. Abe, T. Ochiai, A. Hirohata, N. Tezuka, and K. Inomata, *Nature Mater.* **3**, 361 (2004).

美国Carnegie Mellon大学数据存储中心主任，国际著名磁记录专家Jian-Gang Zhu(IEEE Fellow)教授发表的综述文章

Magnetoresistive Random Access Memory: The Path to Competitiveness and Scalability

Memory devices with magnetoresistive properties have had limited commercial success but new spin torque driven magnetization switching designs may provide greatly expanded storage capacity.

By Jian-Gang Zhu, *Fellow IEEE*

developing effort of STT-MRAM technology. Many schemes have bee suggested to reduce the Gilbert damping constant of a storage layer. Experimental studies have found that an Ru layer, or Ru-based composite layers, deposited on top of the storage layer, could lower switching current thresholds, and reduction of the Gilbert damping has been suggested to be the responsible mechanism [55].

[55] Y. Jiang *et al.*, "Substantial reduction of critical current for magnetization switching in an exchange-biased spin valve," *Nat. Mater.*, vol. 3, p. 361, 2004.

《Proceedings of the IEEE》

ITRS International Technology Roadmap for Semiconductors

研究结果被写入《国际半导体技术蓝图》

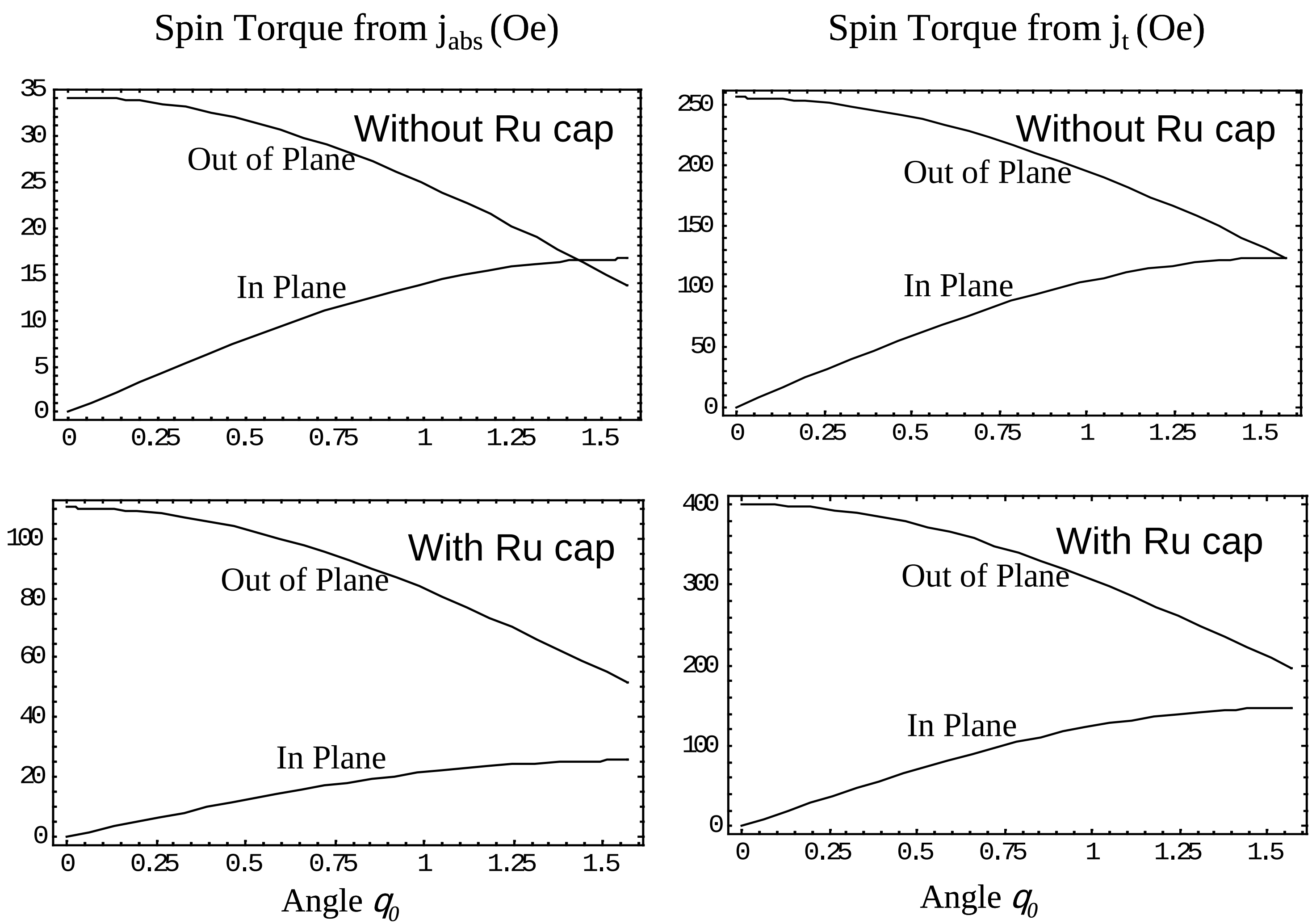
		DRAM		SRAM [A]	[B]		SONOS	FeRAM	MRAM	PCM
		Stand-alone	Embed-ded		NOR	NAND				
Storage Mechanism										Reversibly changing amorphous and crystalline phases
Cell Elements										1T1R
Feature size F, nm	**2005**									90
	2018									18
Cell Area	**2005**									$7.2F^2$
	2018	$5F^2$	$12F^2$	$140\ F^2$	$10\ F^2$	$5\ F^2$	$5.5F^2$	$16F^2$	$16F^2$	$4.7F^2$
Read Time	**2005**	<15 ns	1 ns	0.4 ns	14 ns	70 ns	14 ns	80 ns [D]	<25 ns [G]	60 ns [I]
	2018	<15 ns	<1 ns	70 ps	2.5 ns	12 ns	2.5 ns	<20 ns [E]	<0.5 ns	< 60 ns
W/E time	**2005**	<15 ns	1 ns	0.4 ns	1 µs/ 10 ms	1 ms/ 0.1 m				
	2018	<15 ns	0.2 ns	<0.1 ns	1 µs/ 10 ms	1 ms/ 0.1 m				
Retention Time	**2005**	64 ms	64 ms	[C]	>10 y	> 10				
	2018	64 ms	64 ms	[C]	>10 y	> 10				
Write Cycles	**2005**	>3E16	>3E16	>3E16	>1E5	>1E5				
	2018	>3E16	>3E16	>3E16	>1E5	>1E5				
Write operating voltage (V)	**2005**	2.5	2.5	1.2	12	15				
	2018	1.5	1.5	0.7	12	15	4.0 – 4.5	0.7 – 1	<	<3
Read operating voltage (V)	**2005**	2.5	2.5	1.2	2.5	2.5	2.5	0.9 – 3.3	1.	3
	2018	1.5	1.5	0.8	1.2	1.2	2.5	0.7 – 1	<	<3
Write energy (J/bit)	**2005**	1E-16	1E-16	7E-16	8E-15	8E-15	2E-15	2E-14	1	1E-10
	2018	4E-17	4E-17	2E-17	3E-15	3E-15	3E-16	4E-15	2	Not known
Comments								Destructive read-out	Spin-polarized Write has a potential to lower Write current density and energy [K]	

自旋极化电流具有降低写入电流密度和能耗的潜力[Y.Jiang et al.]。

[K] Jiang, Y., T. Nozaki, S. Abe, T. Ochiai, A. Hirohata, N. Tezuka, K. Inomata. "Substantial reduction of critical current for magnetization switching in an exchange-biased spin valve", Nature Materials. 3 (2004) 361-364.

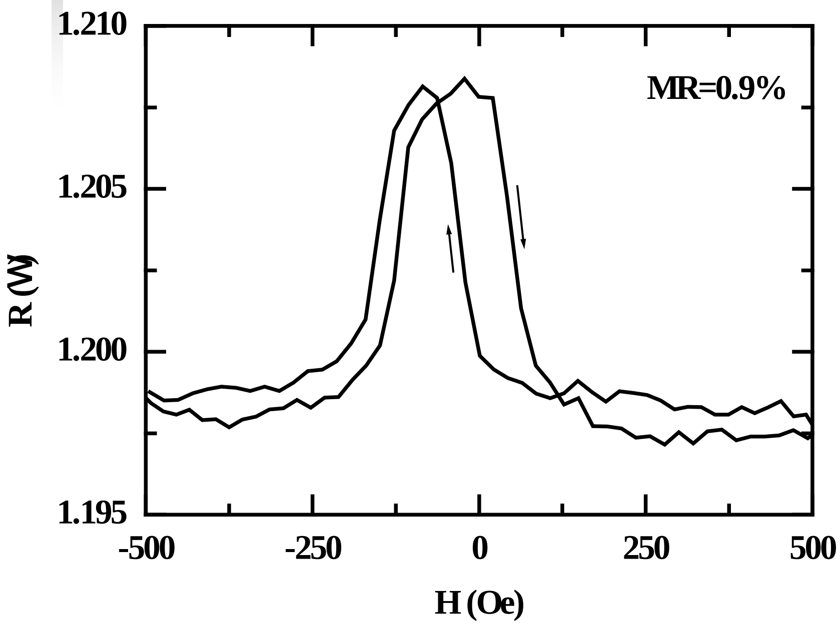
成果被至少10部外文专著正面引用

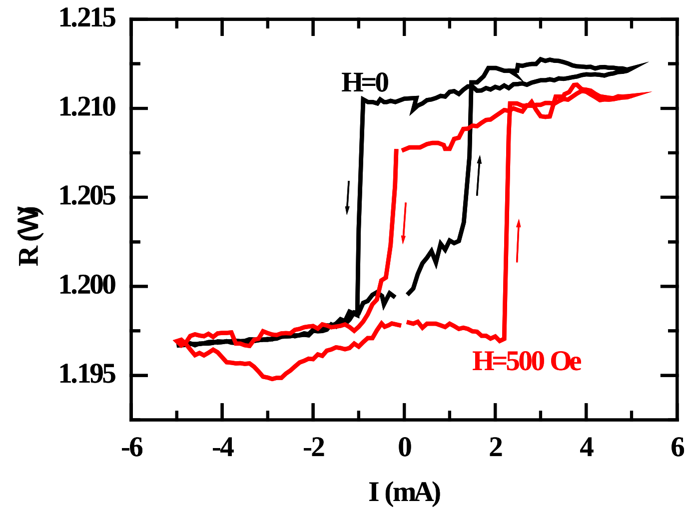
Spin transfer torque (STT)

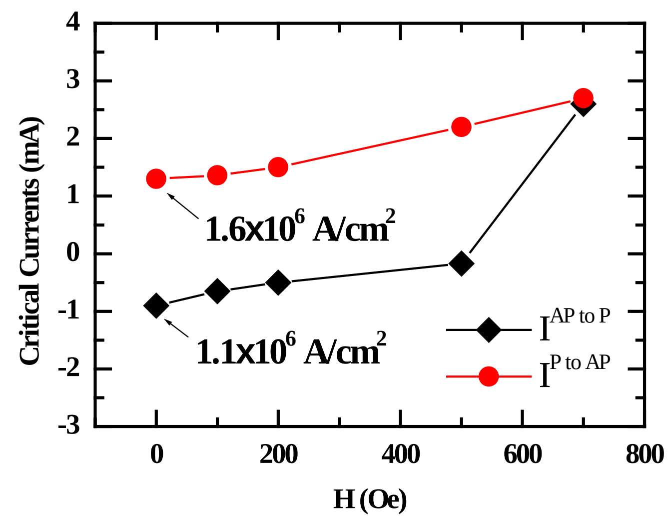


Phys. Rev. B, 72, 064439 (2005).

Effect of the Ru thickness on STT





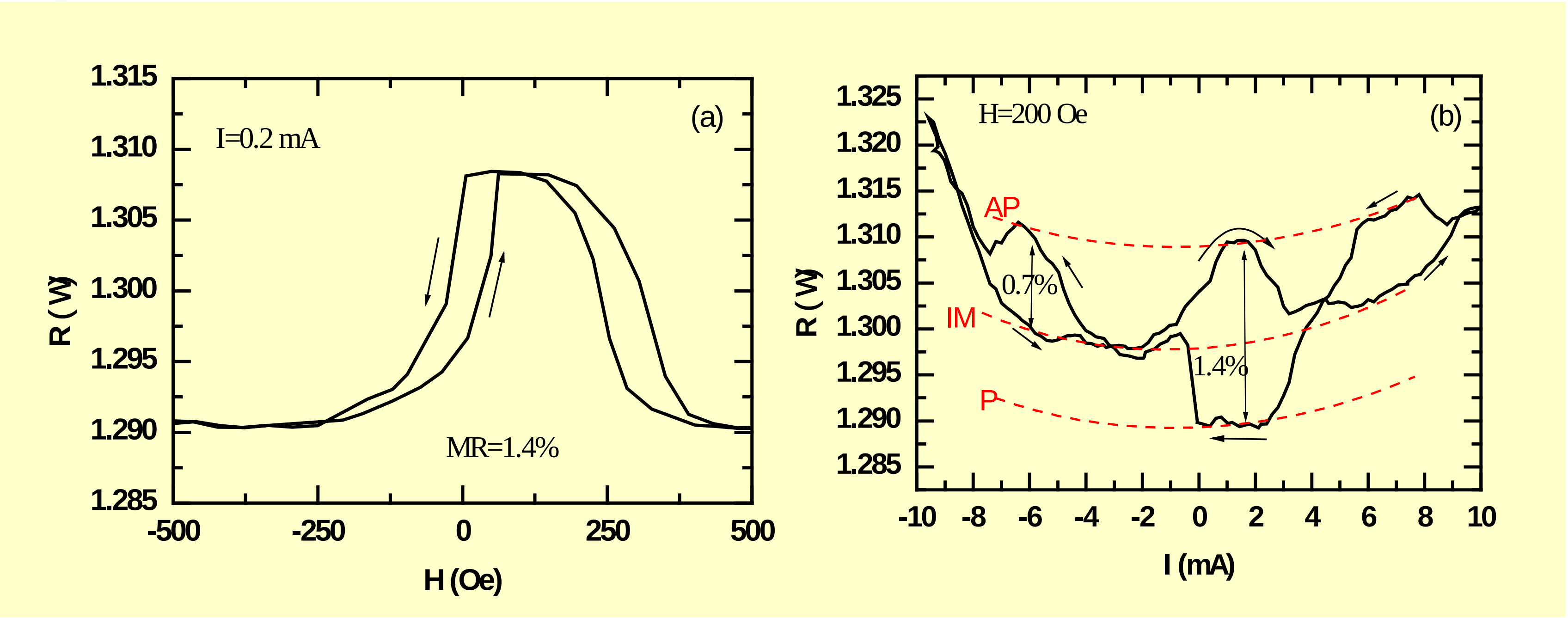


Structure IV:
Ta(2)/Cu(80)/$Co_{90}Fe_{10}$(5)/Ru(4.5)/$Co_{90}Fe_{10}$(2.5)/Cu(6)/$Co_{90}Fe_{10}$(5)/IrMn(10)/Cu(5)/Ta (2) (nm)

Size:
400·200 nm^2

Appl. Phys. Lett. 86, 192515(2005).

STT in SPVs with a low aspect ratio of 1



Size: 100·100 nm^2

Structure: Ta/Cu/IrMn (10)/$Co_{90}Fe_{10}$ (5)/Cu (6)/$Co_{90}Fe_{10}$ (2.5) /Cu (5)/Ta (2) (nm)

Appl. Phys. Lett. 89, 122514(2006).

Current-induced domain wall motion

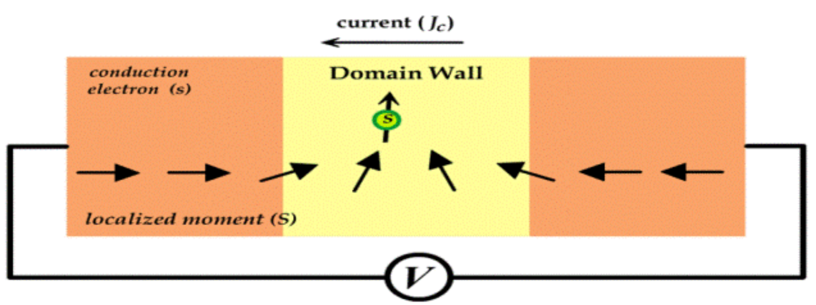
Spin transfer torque (STT)

Spin-transfer torque MRAM (Current induced magnetization switching)

Oscillator and spin diode

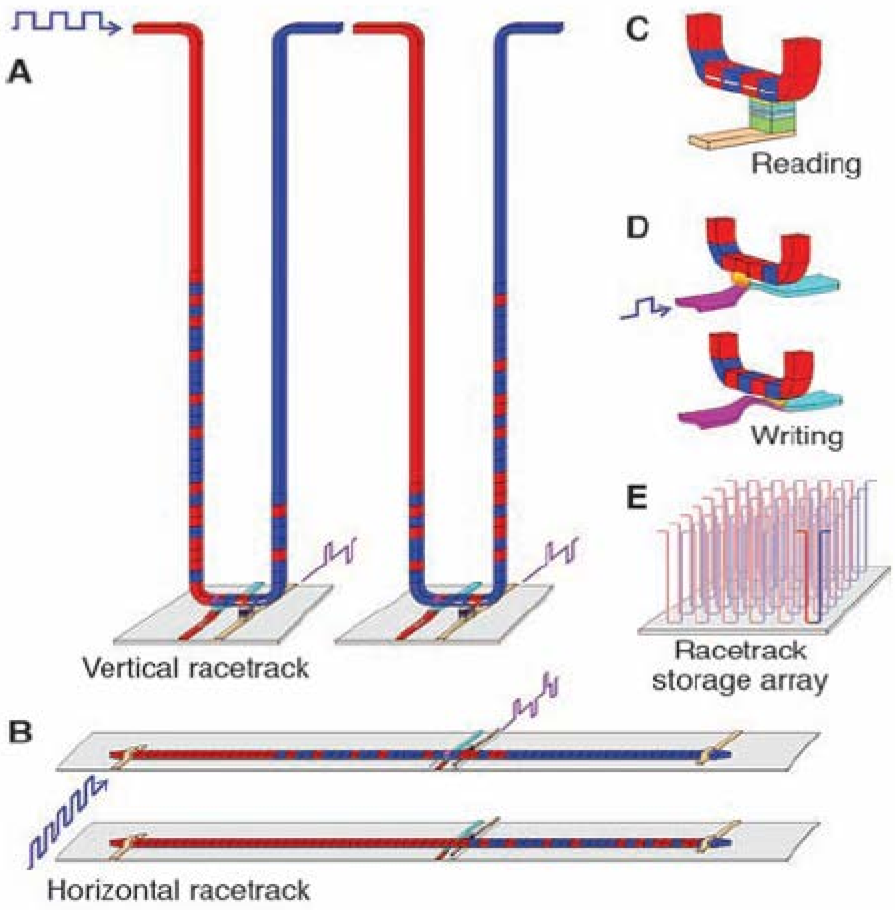
Magnetic racetrack memory

Current-induced domain wall motion



From S. Maekawa

Magnetic domain-wall racetrack memory



Courtesy of *Stuart Parkin*.

Micromagnetic simulations

Object Oriented MicroMagnetic Framework (OOMMF)

LLG equation with the STT contribution

$$\frac{d\mathbf{m}}{dt} = -|\gamma|\mathbf{H}\times\mathbf{m} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt} - (u\cdot\nabla)\mathbf{m} + \beta\mathbf{m}\times\left[(u\cdot\nabla)\mathbf{m}\right]$$

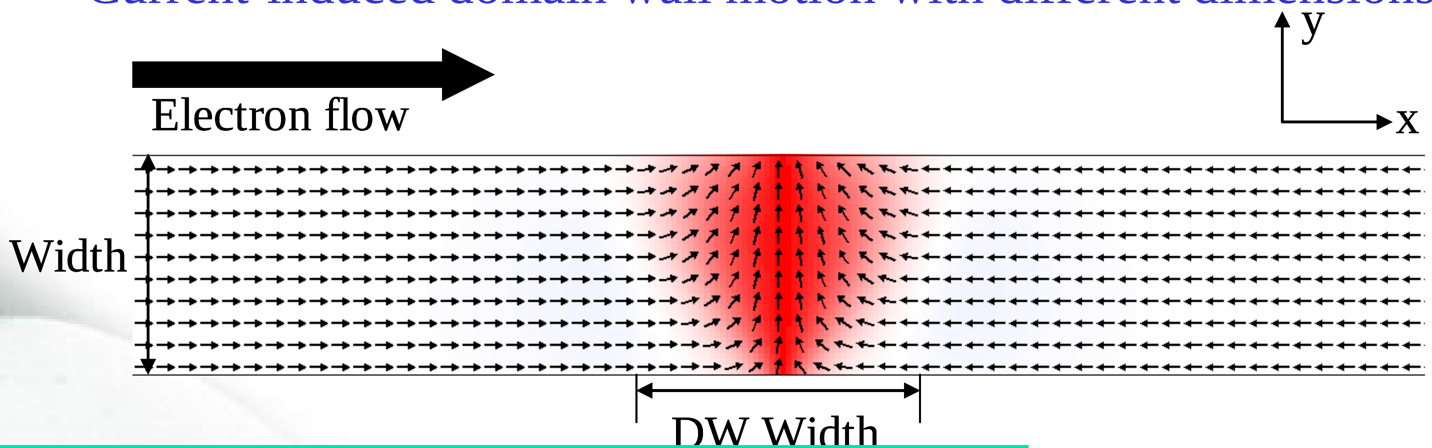
Precession term | **Damping term** | **Adiabatic term** | **Nonadiabatic term**

$$u = JPg\mu_B / 2eM_S$$

Where J is the current density and *P* is the current polarization.

Electrons flowing toward the right means that u > 0.

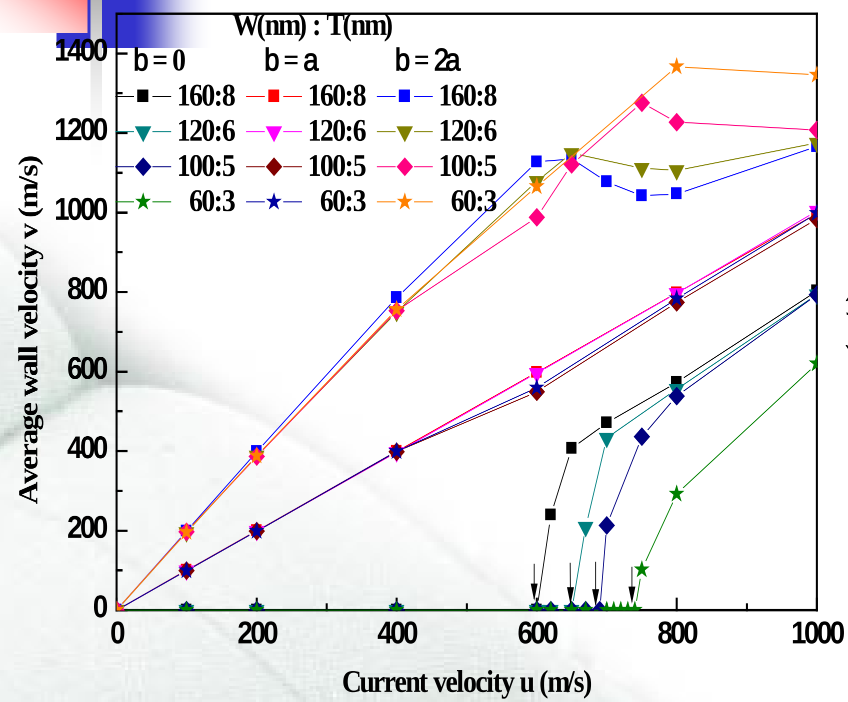
Current-induced domain wall motion with different dimensions

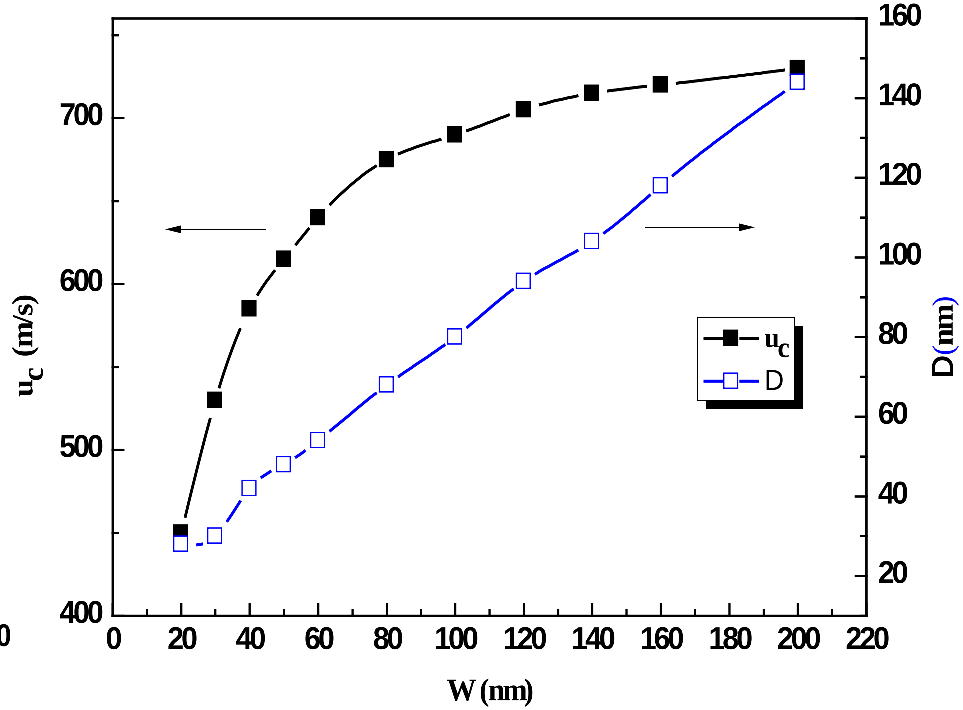


Length L = 5 ④m
Width W = 20-200 nm
Thickness T = 3-8 nm.
Material parameters of Permalloy
Saturation magnetization: $M_S = 8 \times 10^5$ A/m
Exchange energy coefficient: A = 1.3×10^{-11} J/m
Gilbert gyromagnetic ratio: γ= 221000 m /(A·s)
Damping constant $a = 0.02$
Maximum cell size of 4×4×T nm3

$$\langle v \rangle = \frac{L}{2} \frac{\langle M_x \rangle}{M_S t_{total}}$$

$$M_x / M_S = - \tanh(2x / D)$$



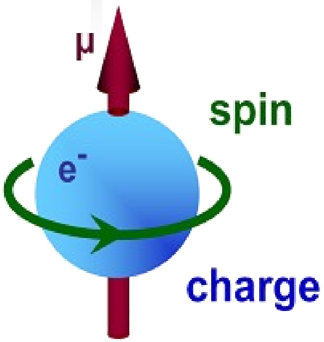


➢1、The critical current density increases with the decreases in both the width and thickness of nanowires due to the enhanced hard-axis anisotropy.

➢2、While the thickness is fixed, the critical current density decreases with the decreasing width of nanowires due to the domination of reducing domain wall width.

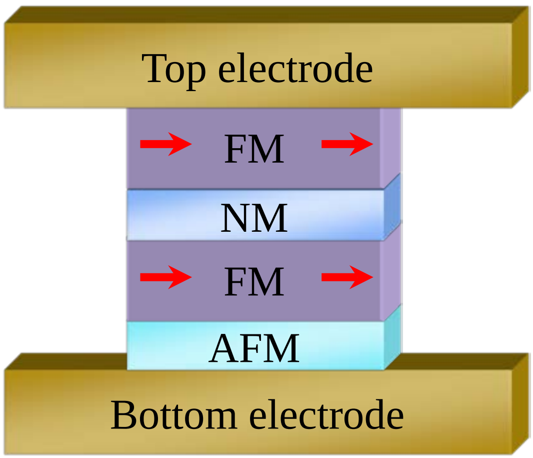
- 自旋转移力矩效应
- 垂直磁各向异性薄膜
- 多铁性薄膜

垂直磁各向异性（PMA）薄膜

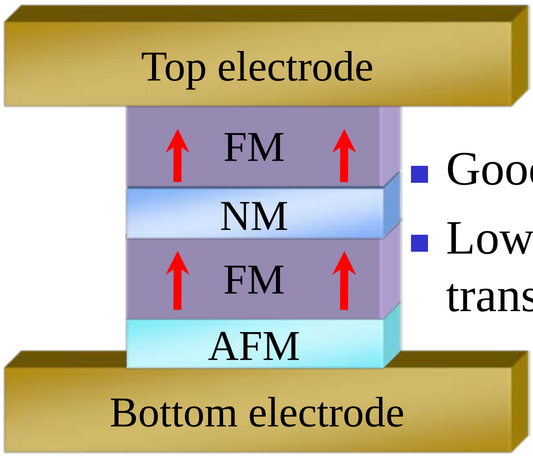


Hard disk drive (HDD) read head

Magnetic random access memory (MRAM)



Conventional



Perpendicular

- Good thermal stability
- Low critical current for spin transfer torque

I. **Rare-earth/transition-metal alloys**

II. **$L1_0$-ordered CoPt (or FePt) alloys**

III. **Co-based multilayers**

Strong PMA;
Low thermal stability;
TbCoFe,GdCoFe and SmCo ,et al.

Strong PMA;
High thermal stability;
High fabricate temperature.

Strong PMA;
Low thermal stability;
reduced spin polarization (SP)
$[Co/Ni]_n$, $[Co/Pt]_n$ and $[Co/Pd]_n$

Low SP

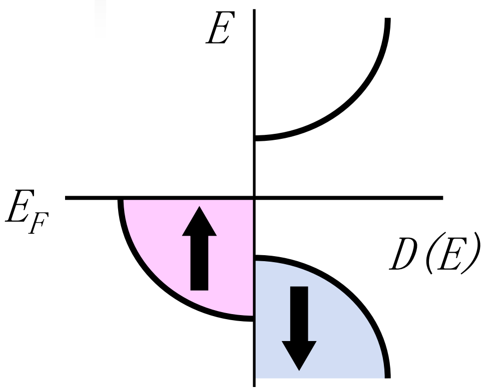
Small TMR effect

SP value is a key factor to determine TMR ratio according to Julliere's model.

M. Julliere, Phys. Lett. A.54, 225(1975).

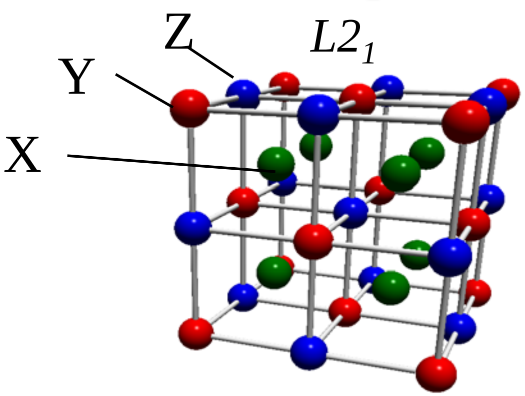
Half-metallic full-Heusler alloys

Half-metal: P = 1



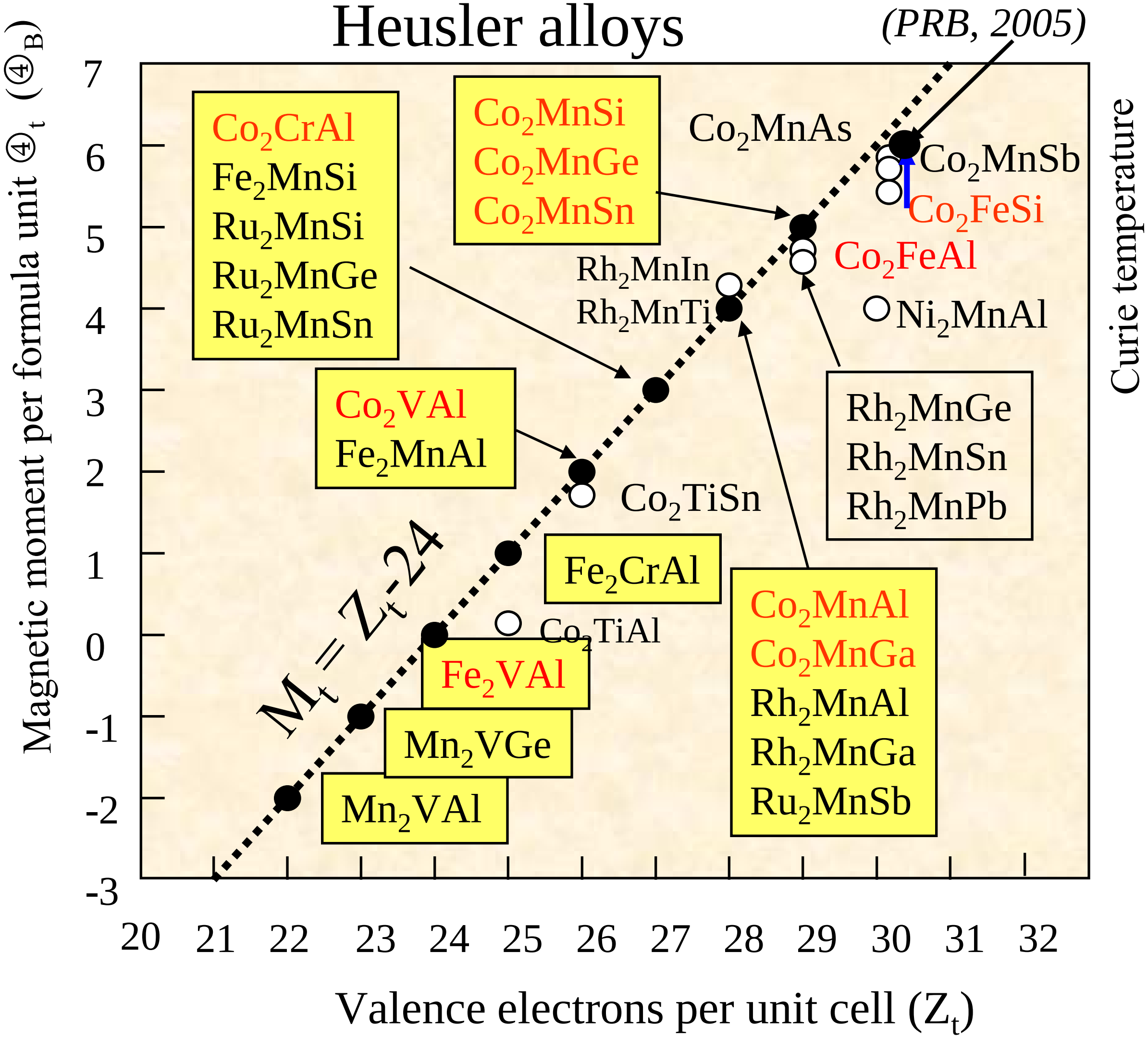
$$TMR = 2P_1P_2/(1-P_1P_2)$$
$$TMR = \infty \text{ for } P = 1$$

Heusler alloys X_2YZ



Courtesy of K. Inomata

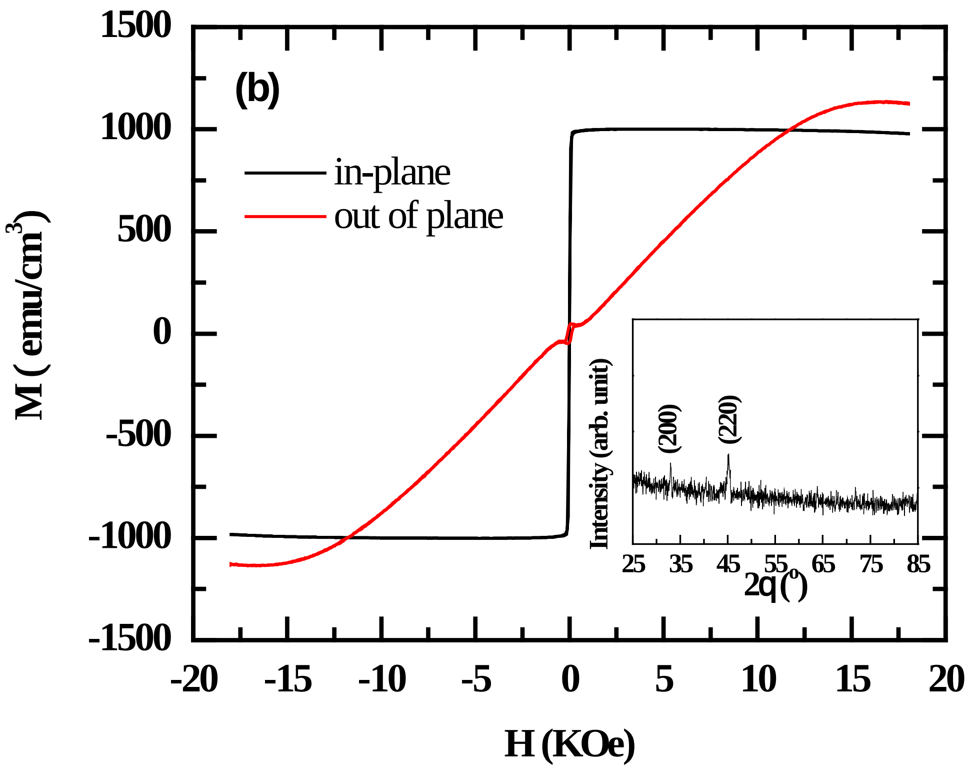
S. Wumehl, C. Felser *et al* *(PRB, 2005)*



I. Galanakis, *PRB* 66, 174429 (2002).

PMA thin films

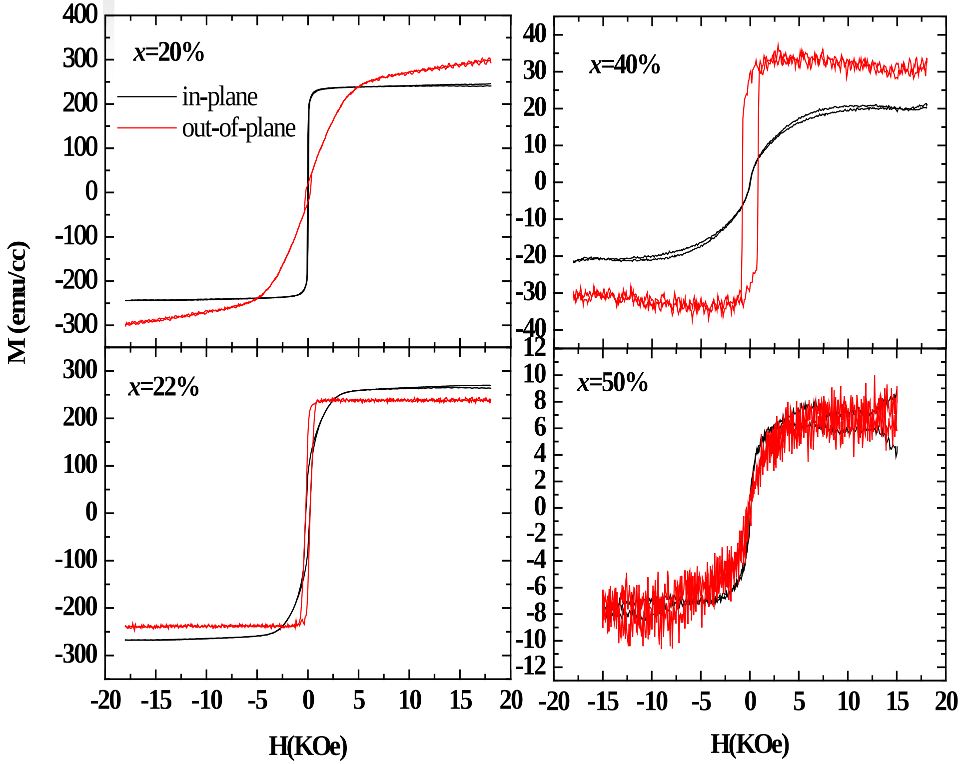
The Co_2FeAl thin film is always in-plane magnetized.

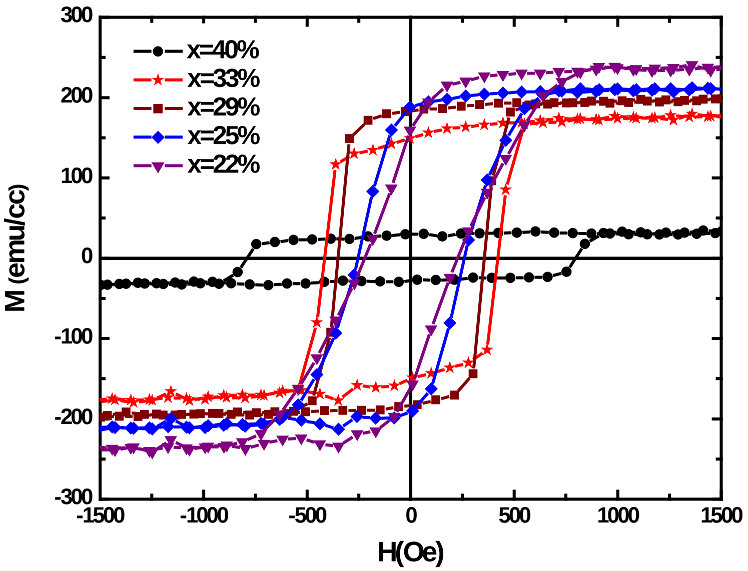


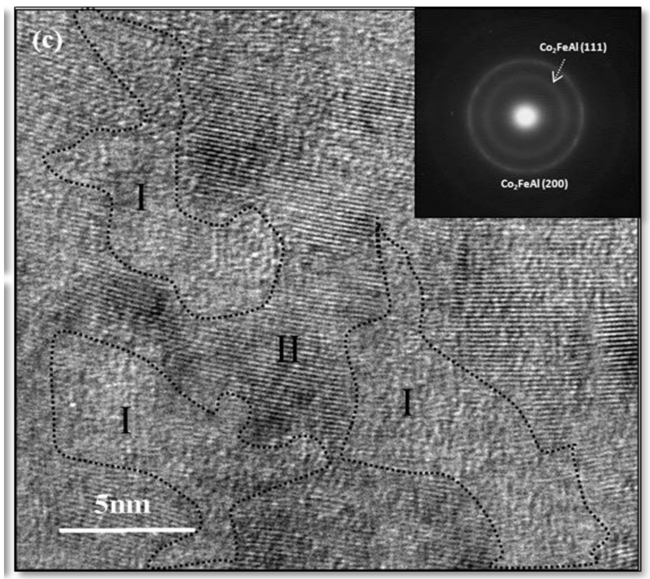
Magnetization curves for a Co_2FeAl film with a thickness of 30 nm. The magnetic field was aligned in the film (black lines) or perpendicular to the film (red lines).

Can full-Heusler alloy films be perpendicularly magnetized?

Tb-Co_2FeAl 薄膜



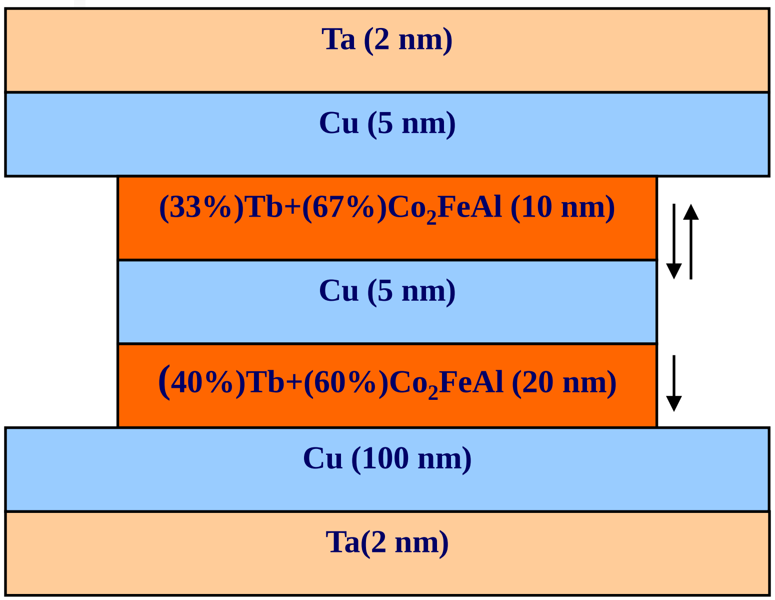


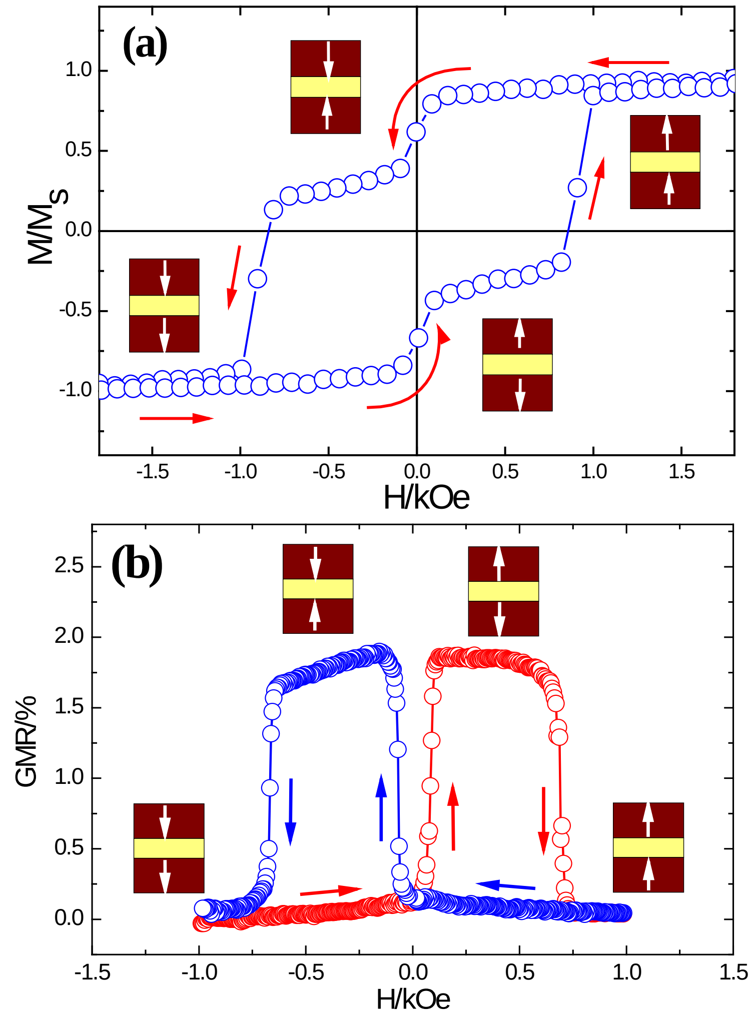


[*x* Tb+ (1-*x*) CFA] (0≤*x*≤1)

Appl. Phys. Lett. 96, 142505(2010).

Tb-CFA based CPP SPVs





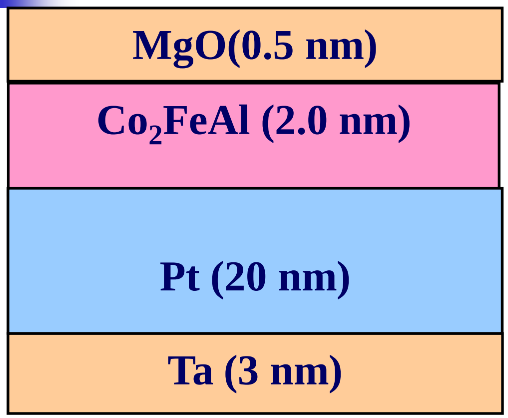
Schematic of spin valve with TCFA as the free and reference layer.

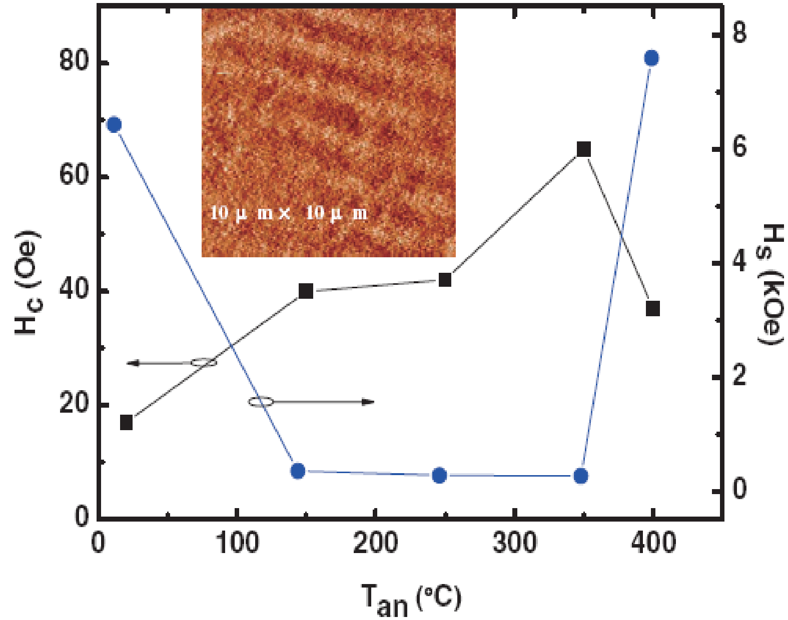
PSPV was patterned into a pillar of 0.5× 1 μm²

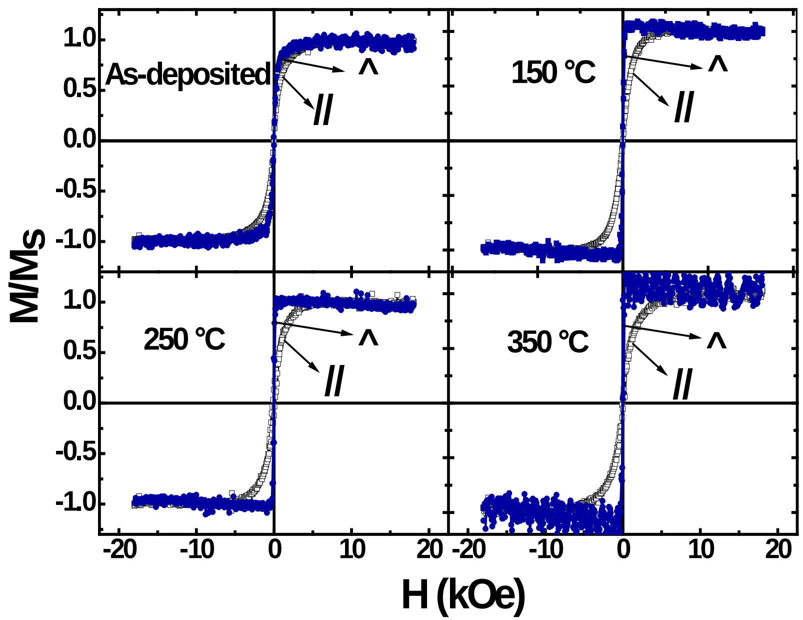
Appl. Phys. Lett. 96, 142505(2010).

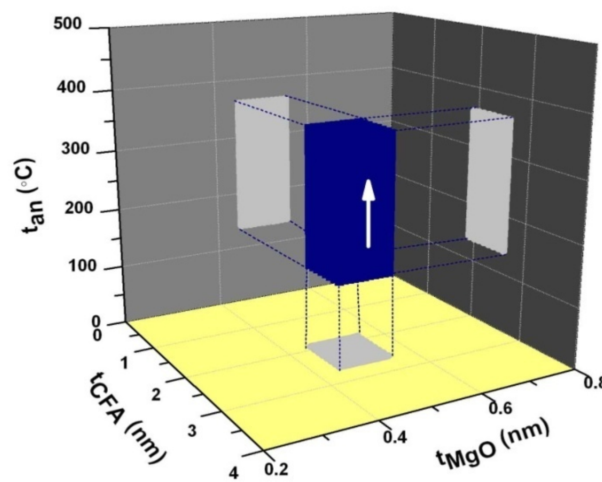
CPP GMR=1.8%

Pt/CFA/MgO 三层膜结构



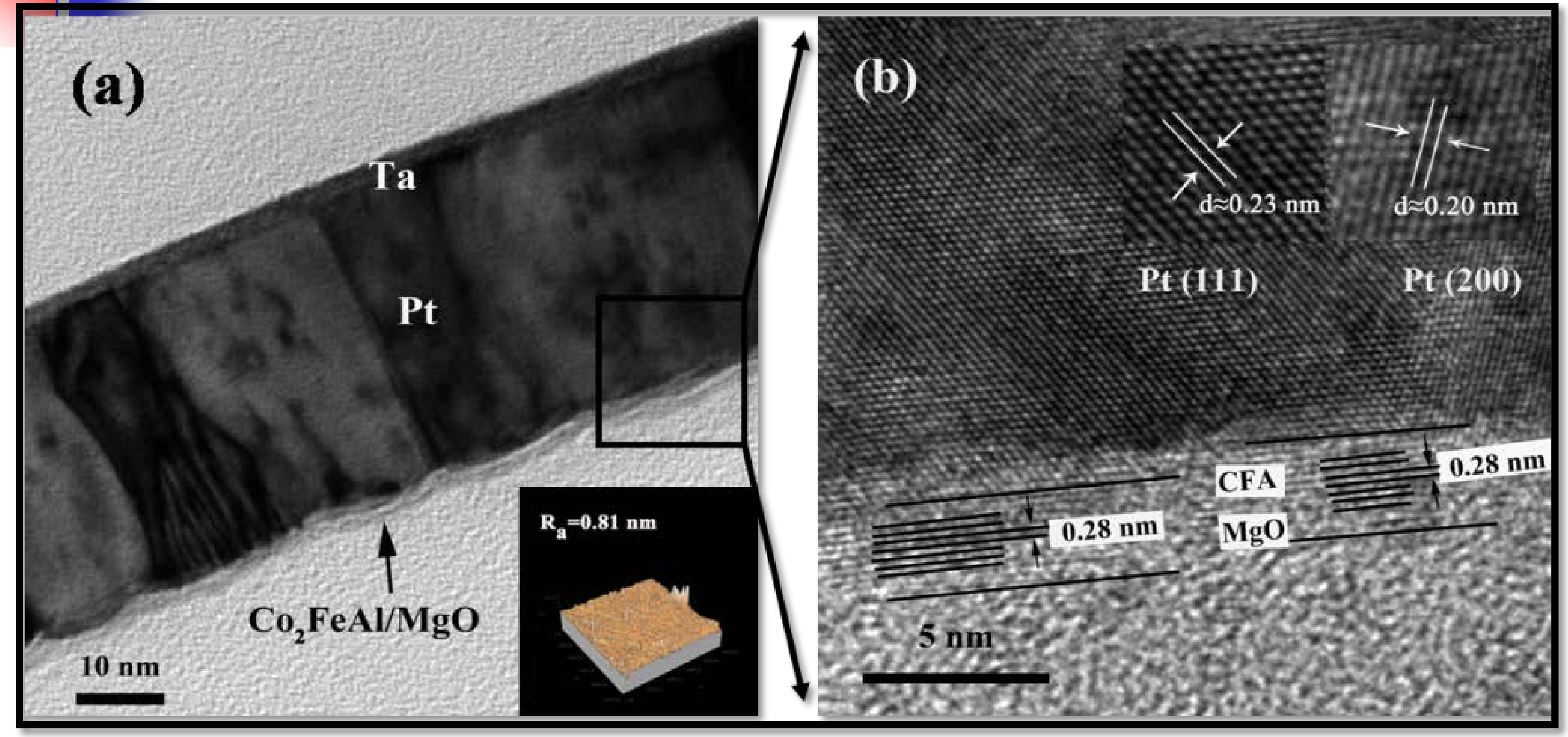






Appl. Phys. Express, 4, 043006 (2011)

$K_u = M_s H_k /2 \approx 1.3\times 10^6$ erg/cm^3

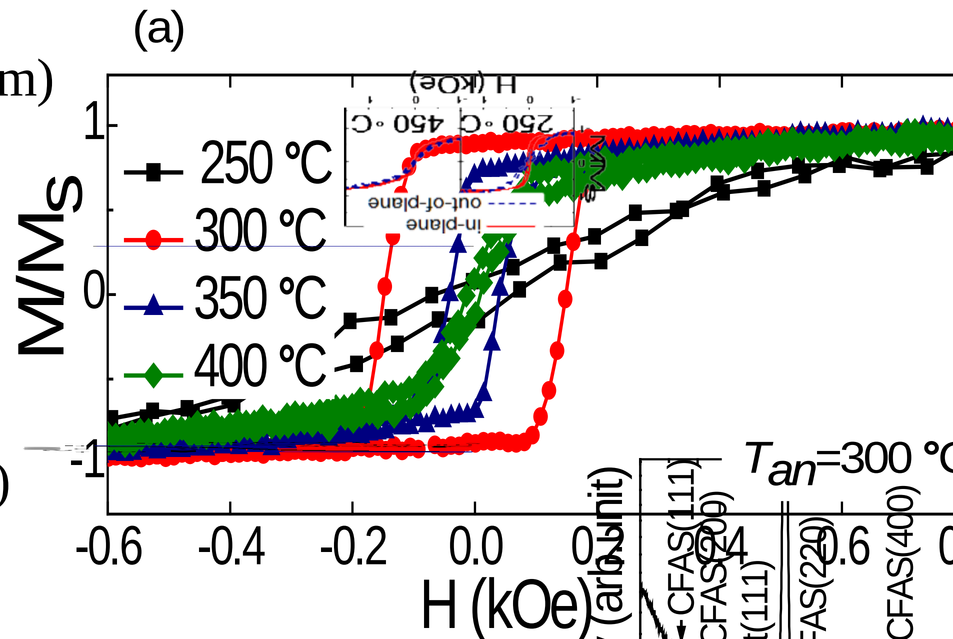


$d_{\mathrm{CFA}(200)} \approx 0.28$ nm

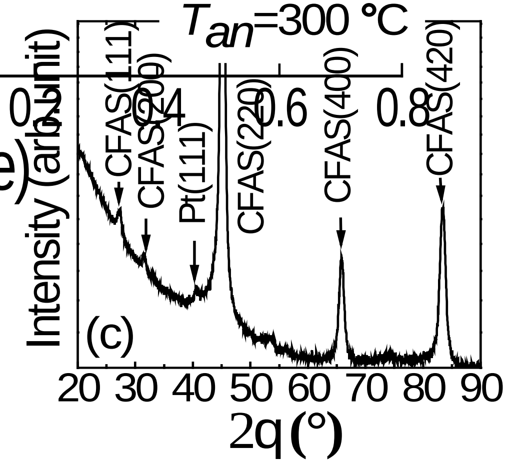
Pt/CFA/MgO interface

B2-ordered structure in CFA after annealing.

Pt(10)/CFAS(2.5)/MgO(0.5)/Pt(5) (nm)



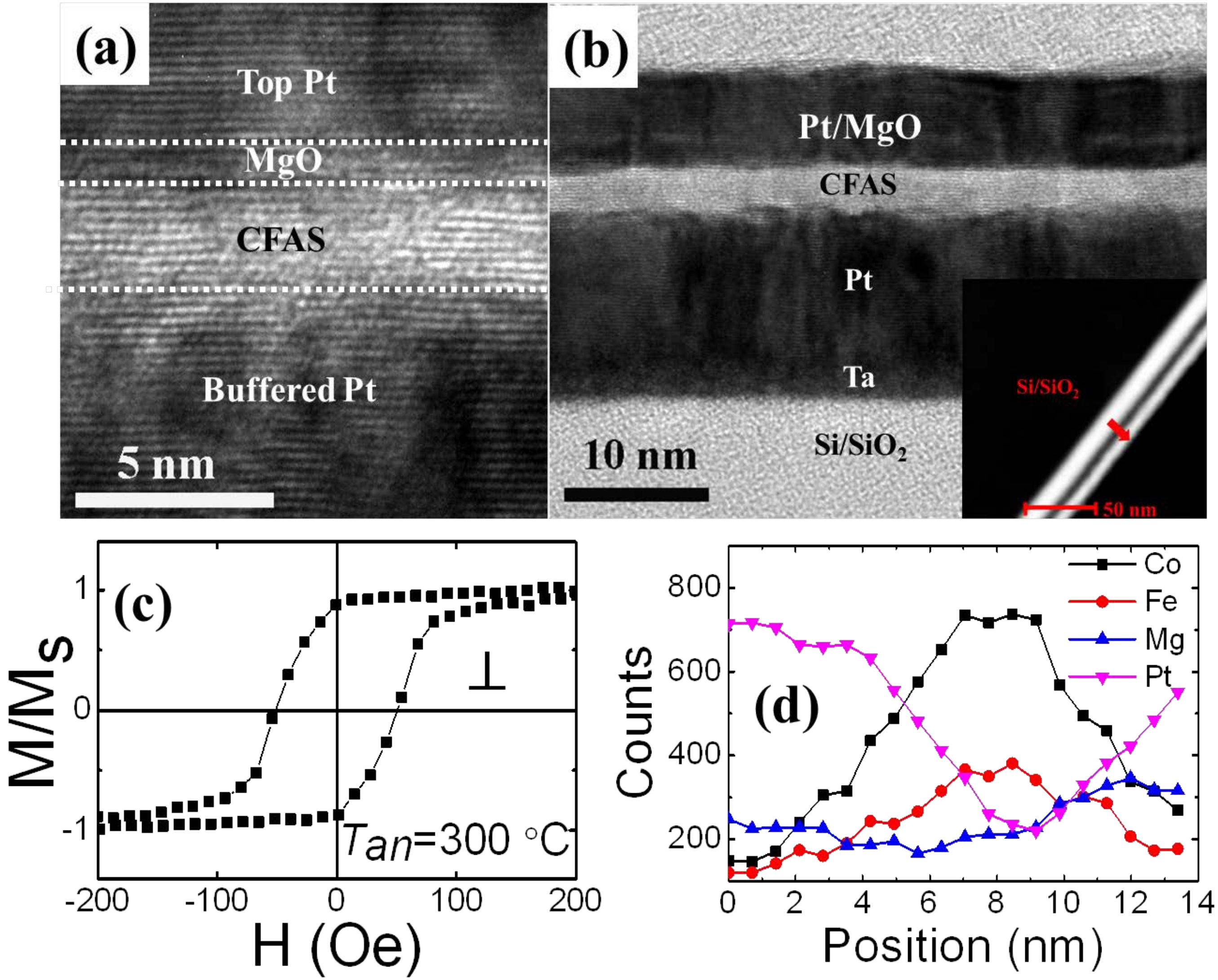
Pt(10)/CFAS(4.8)/MgO(2)/Pt(5) (nm)



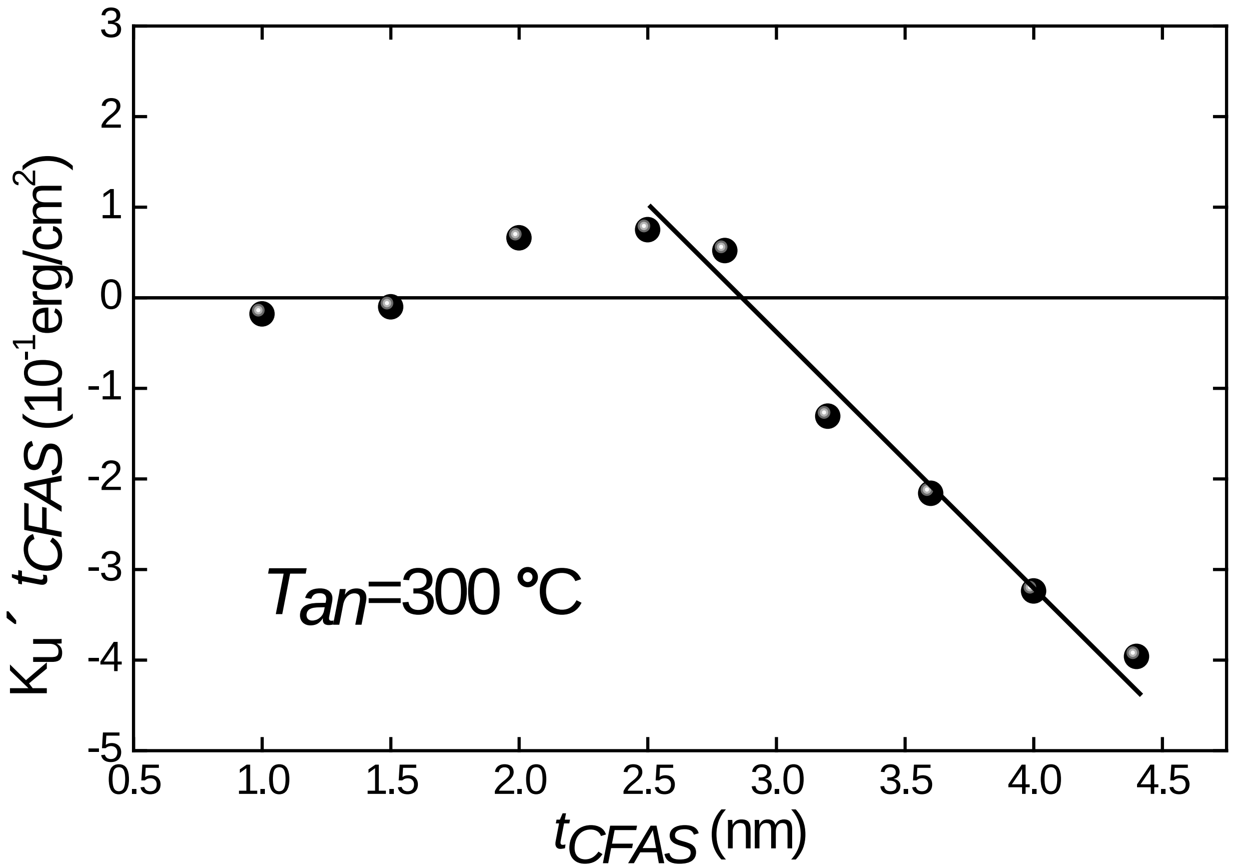
Advantages:

1. Strong PMA K_u=2～3×10^6 erg/cc
2. Thicker CFAS with PMA
3. Good thermal stability (even annealed at 400 ℃）
4. The structure could be used as the bottom electrodes in MgO-based MTJs

300 °C annealed Ta (3)/Pt (10)/CFAS (2.5)/ MgO (1.0)/Pt (5) (nm)



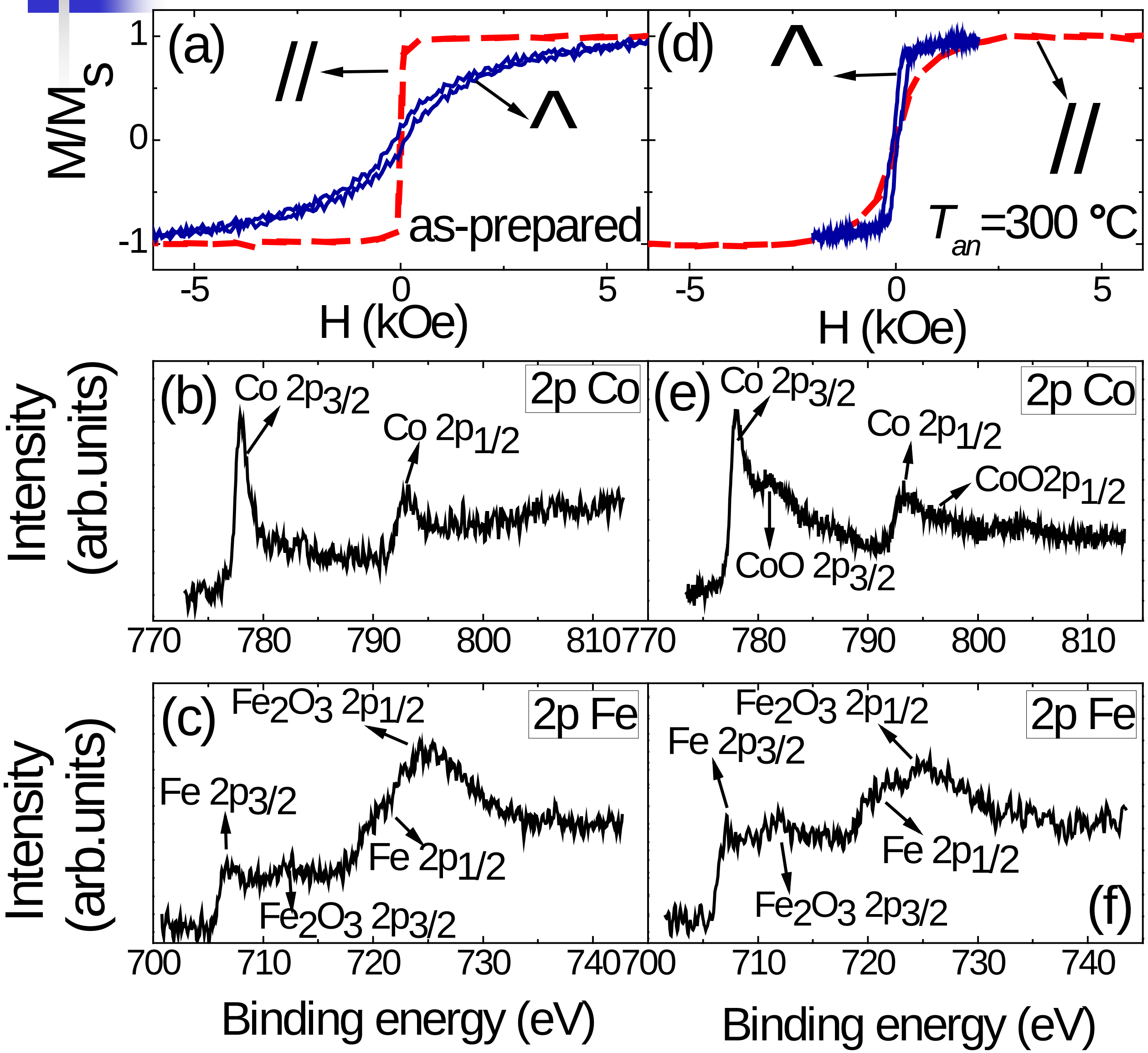
Ta (3)/Pt (10)/CFAS (t_{CFAS})/ MgO (0.5)/Pt (5) (nm)



$K_u \times t_{CFAS} = (K_v - 2\pi M_s^2) \times t_{CFAS} + K_s$, where K_v and K_s are bulk and interfacial anisotropy density, respectively.

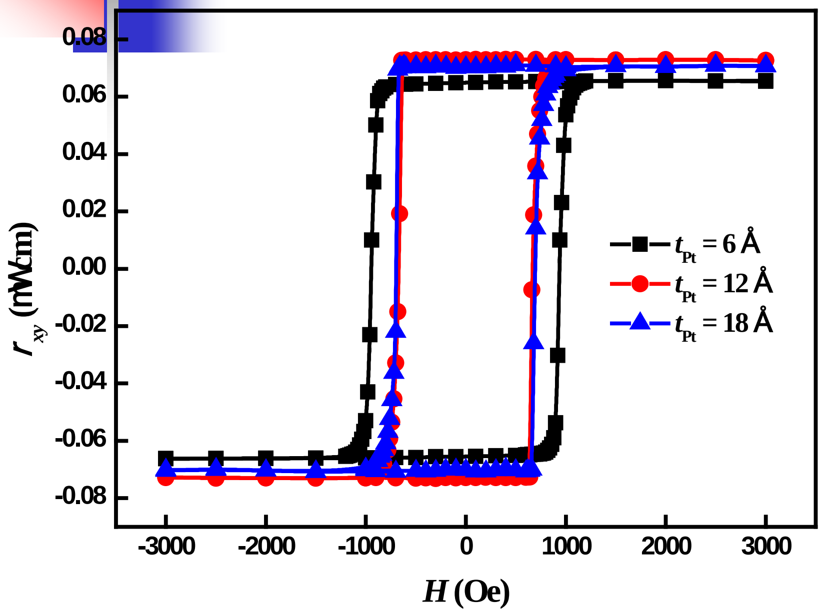
K_s ~0.8 erg/cm^2
K_v ~-2.6 erg/cm^3

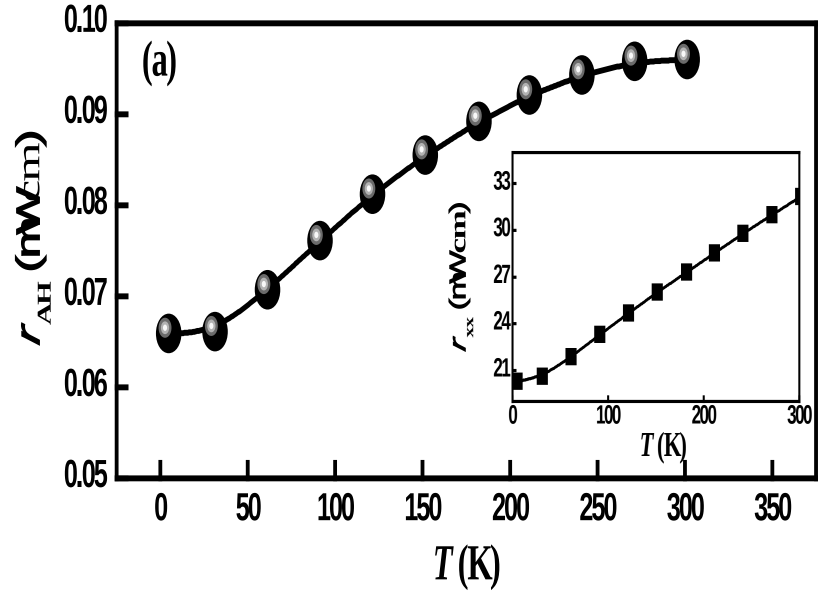
Ta (3)/Pt (10)/CFAS (2.5)/MgO (0.5)/Pt (2) (nm)

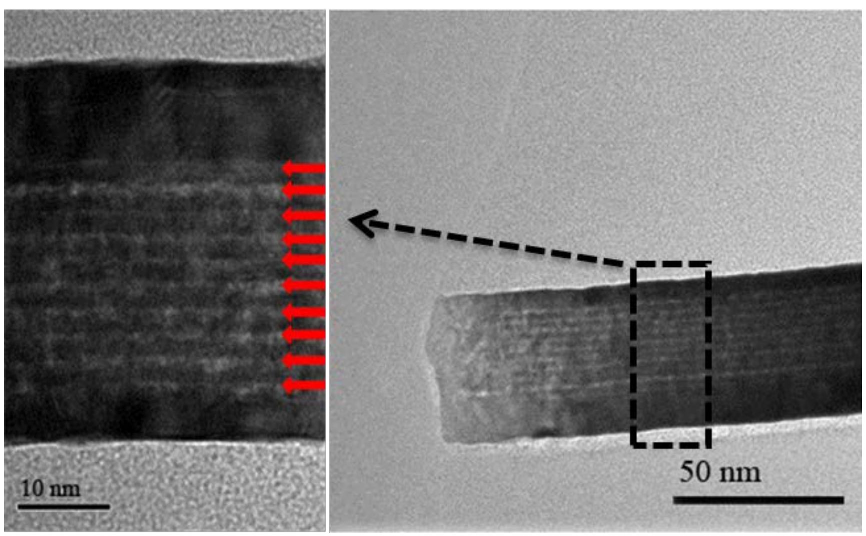


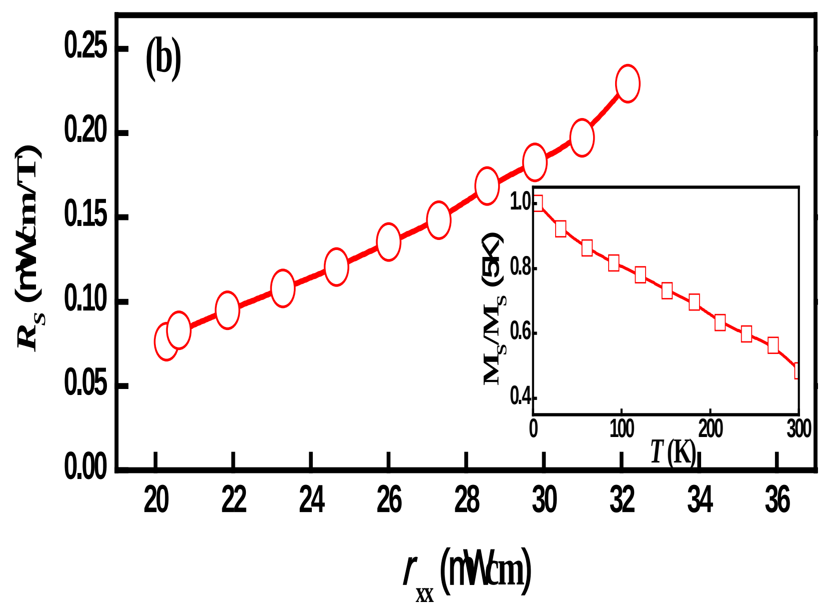
The oxidation of Co at the CFAS/MgO interface is more important to PMA?

[CFAS (6 Å)/Pt (t Å)]$_n$中的反常霍尔效应





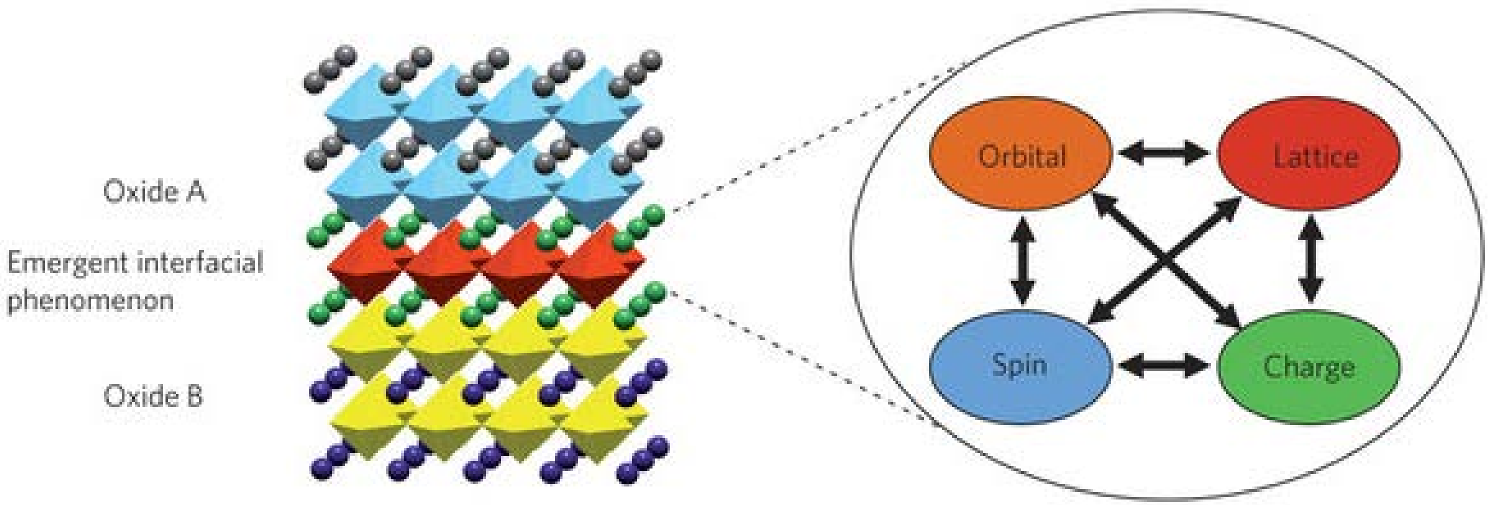


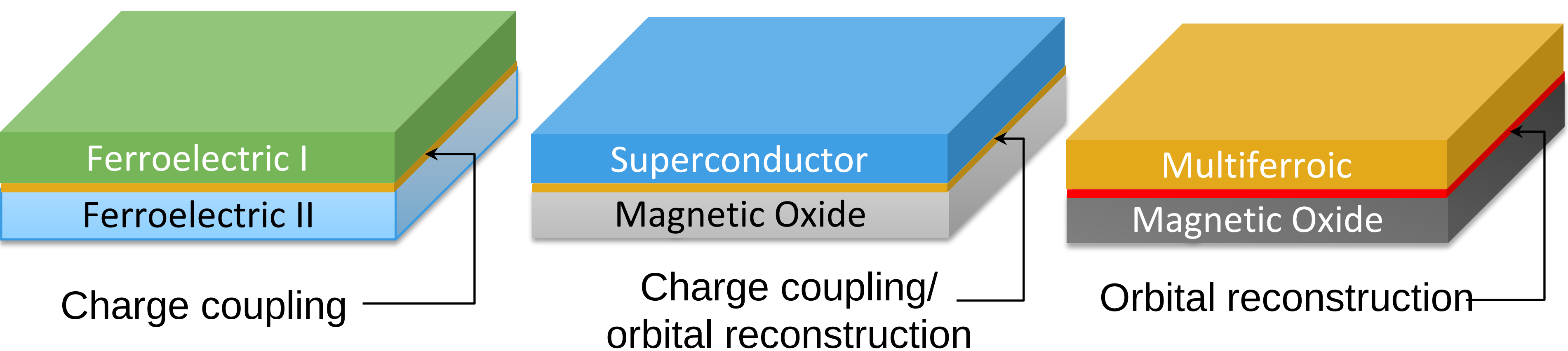


Appl. Phys. Express, 6, 113003(2013)

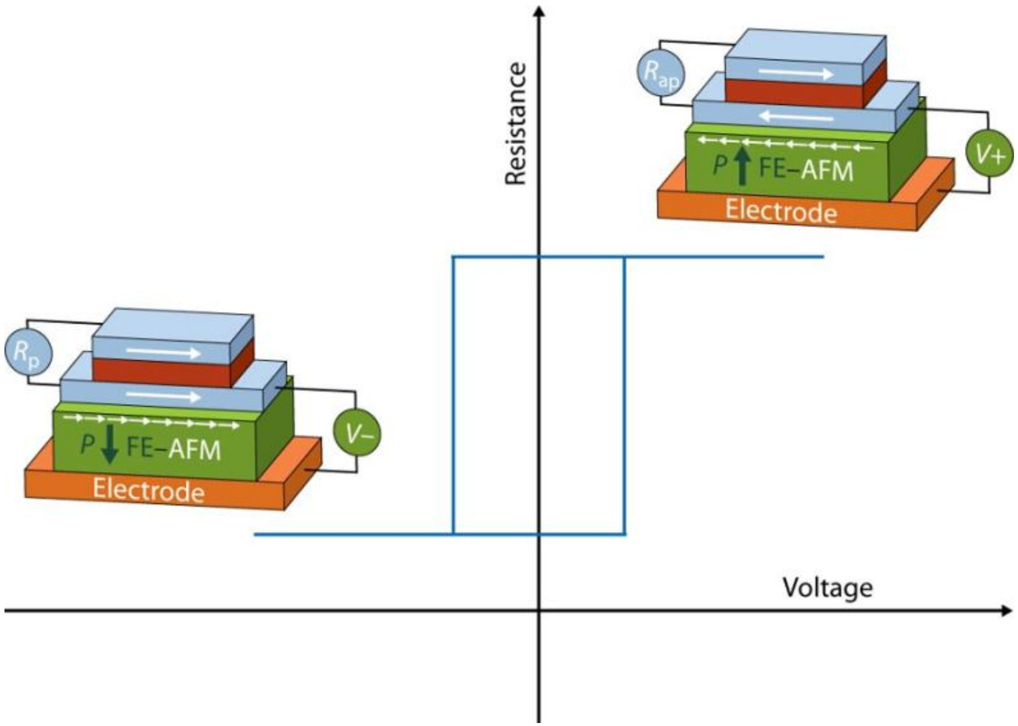
- 自旋转移力矩效应
- 垂直磁各向异性薄膜
- 多铁性薄膜

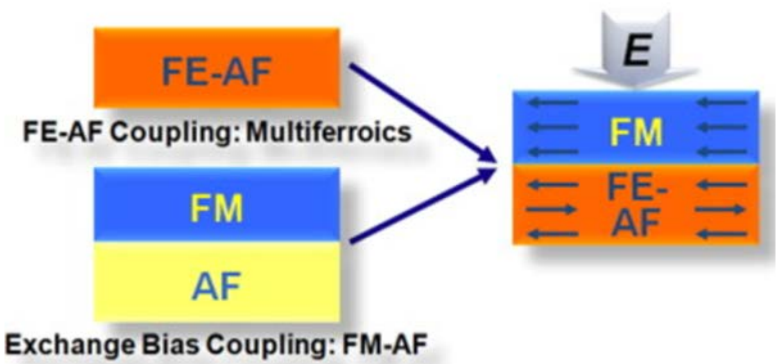
Background & motivations

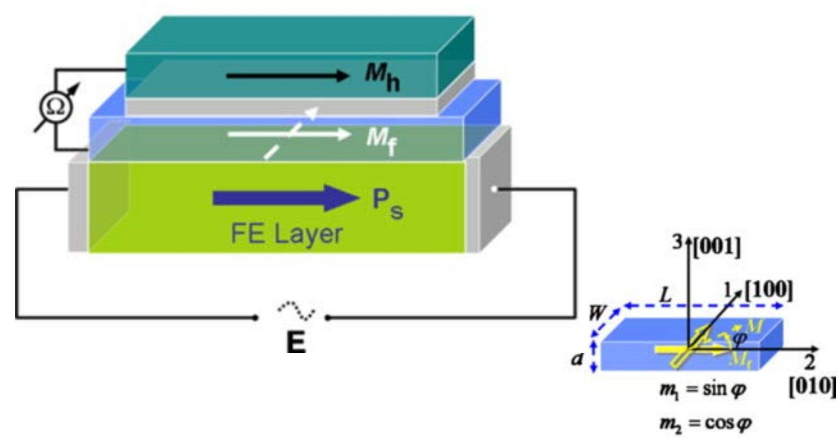


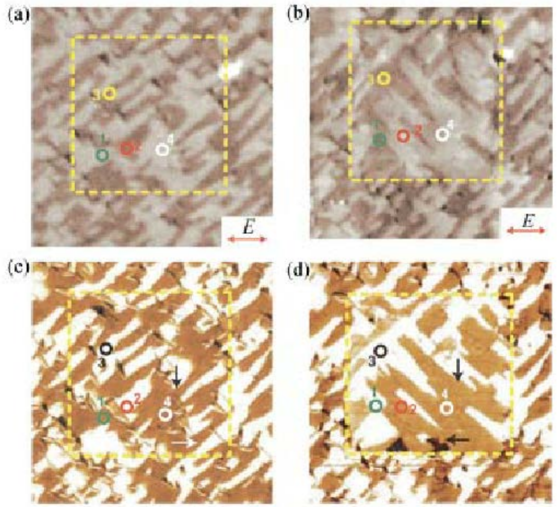


Electric-field controlled magnetism - Future Memory

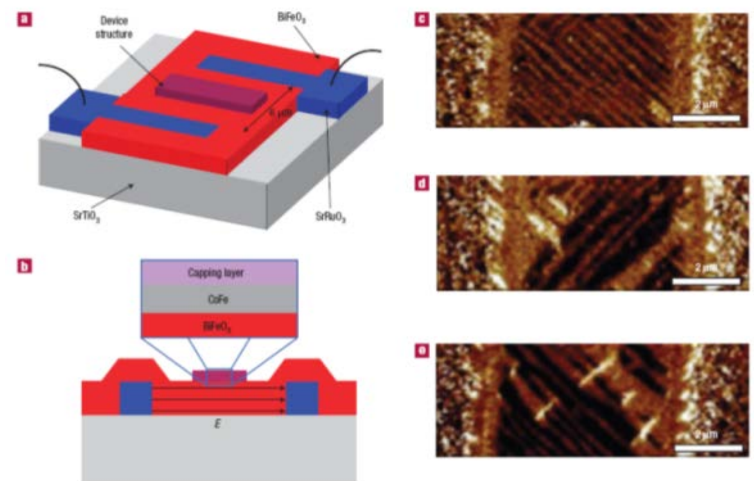




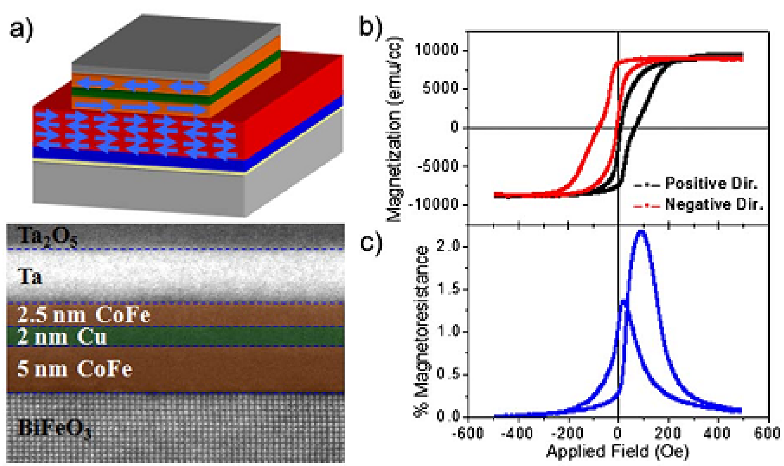




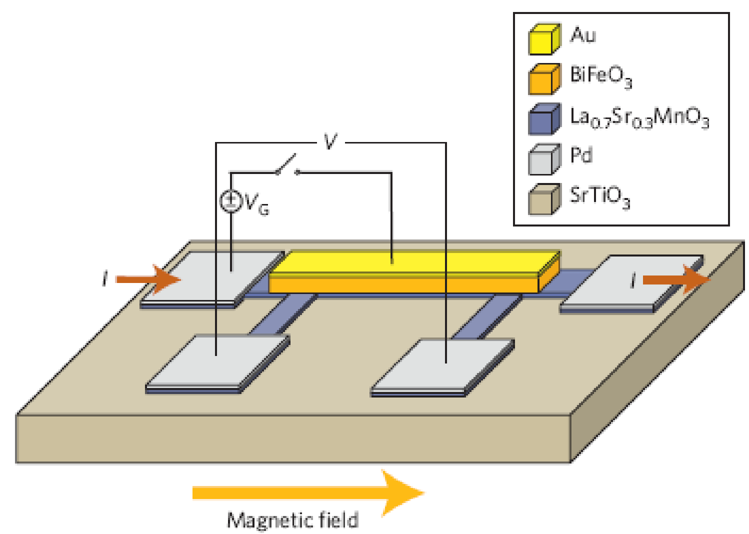
Zhao *et al*, Nature Mater 5, 823-829 (2006).



Chu *et al*, Nature Mater 7, 478-482 (2008).

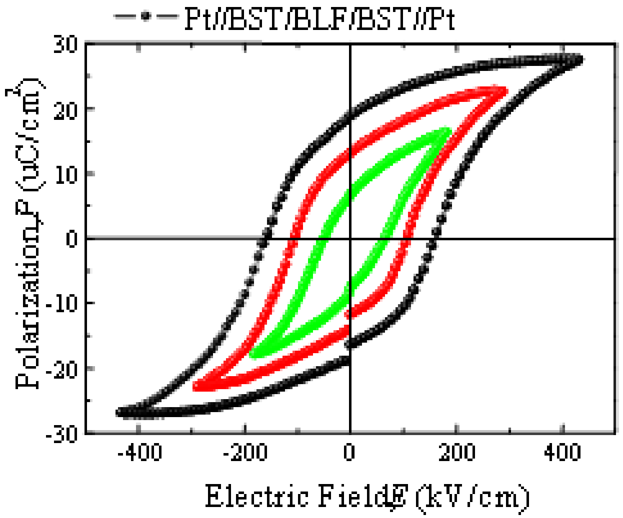


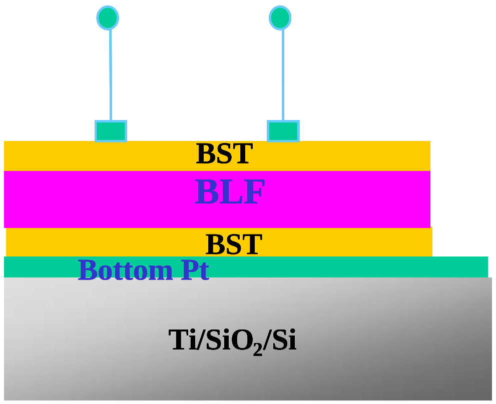
Martin *et al*, Appl. Phys. Lett. 91, 172513 (2007).



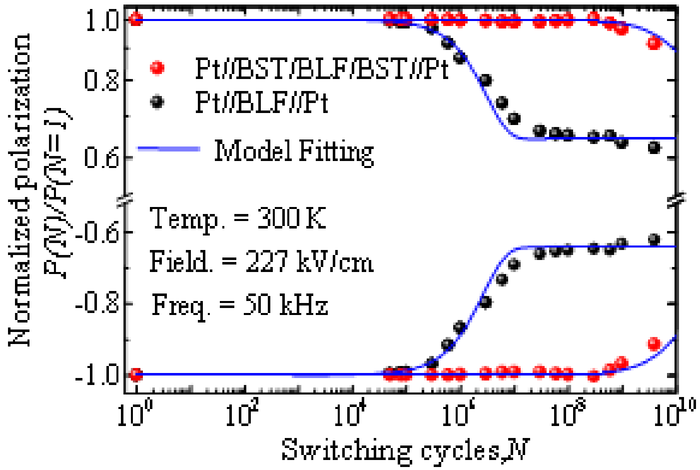
Wu *et al*, Nature Mater 9, 756-761 (2010).

Multiferroic BST/BLFO/BST sandwich





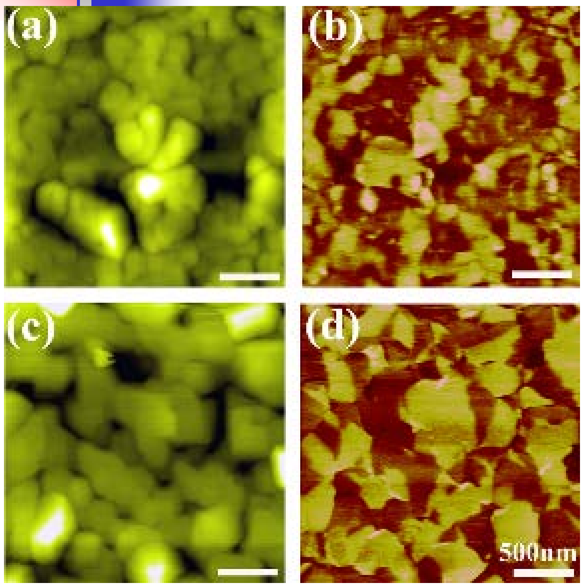
<u>(Ba,Sr)TiO$_3$/Bi(La, Fe)O$_3$/(Ba,Sr)TiO$_3$ structure</u>

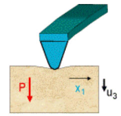


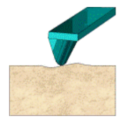
- "Fatigue-free" multiferroic properties.
- Enhanced ferroelectric loops.
- Reduced concentration of oxygen vacancies due to the BST buffer layer.

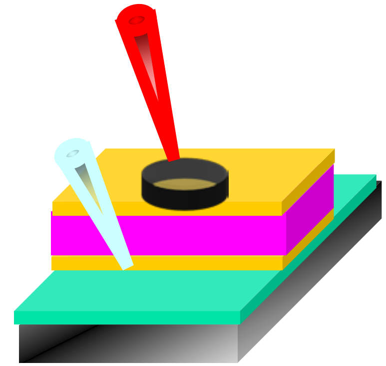
Appl. Phys. Lett, 92, 062902 (2008).

KNNO/LSMO multiferroic heterostructure

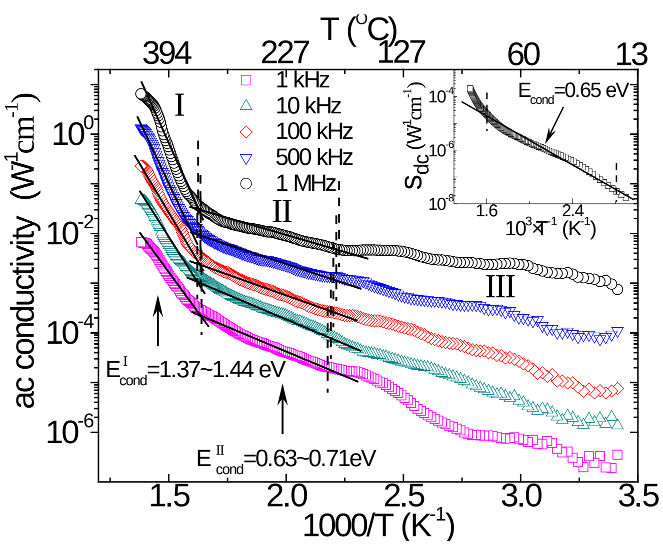








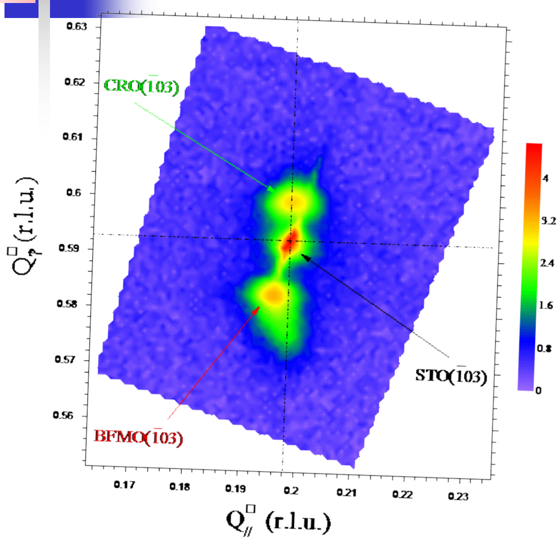
(K,Na)NdO$_3$/(La$_{0.5}$Sr$_{0.5}$)MnO$_3$ structure



- Strong coupling between ferroelectric and ferromagnetic.
- relaxor behavior in high temperature
- “Giant Polarization” due to the field-assisted hopping conduction.

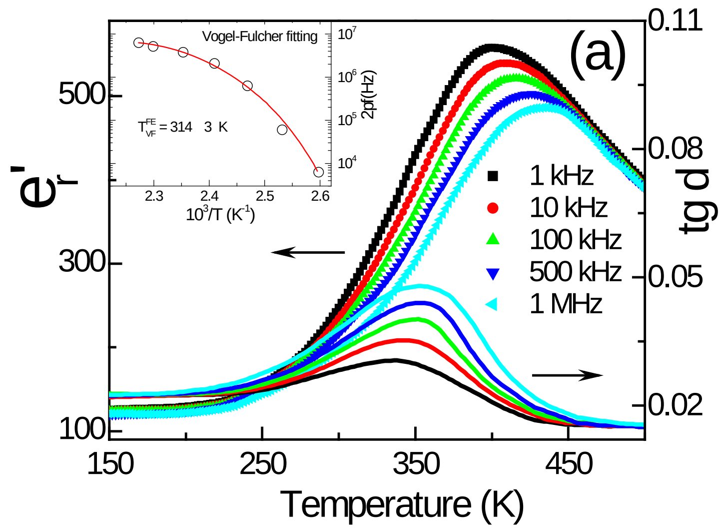
Appl. Phys. Lett, 95, 132905 (2009).

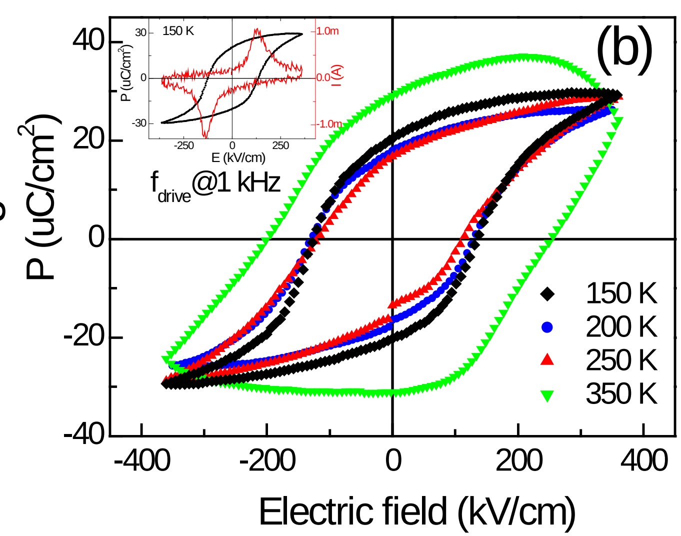
Bi-relaxor multiferroic behavior



$BiFe_{0.5}Mn_{0.5}O_3/CaRuO_3$ heterostructures

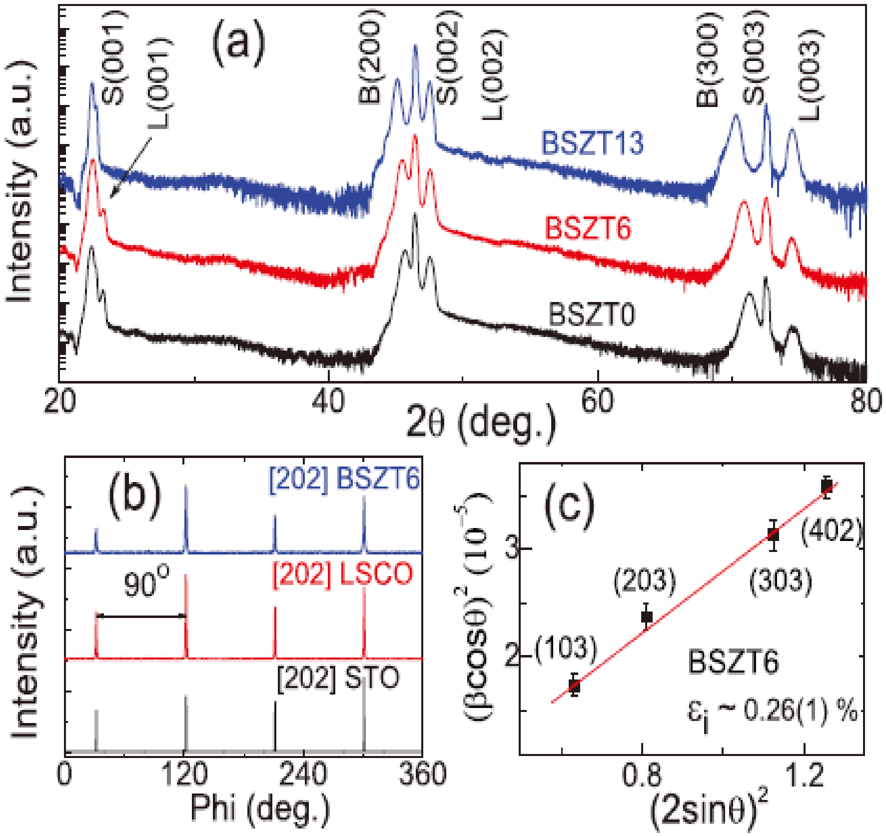
- Double-perovskite $BiFe_{0.5}Mn_{0.5}O_3$
- Fully epitaxial growth (RSM)
- Dielectric relaxor behavior in 400K.
- PNRs and magnetic relaxor behavior in 140K.

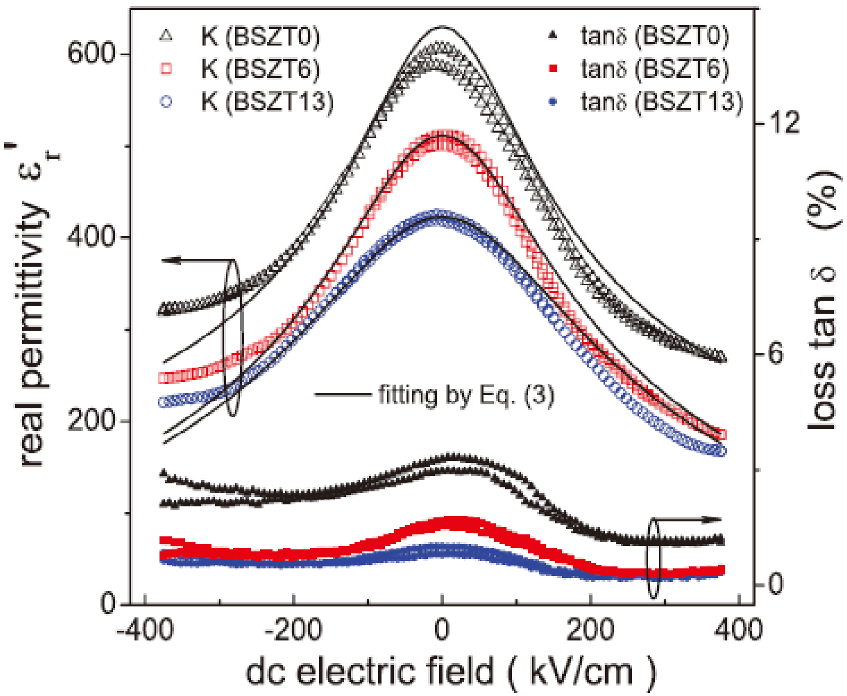




Appl. Phys. Lett, 99, 062905 (2011).

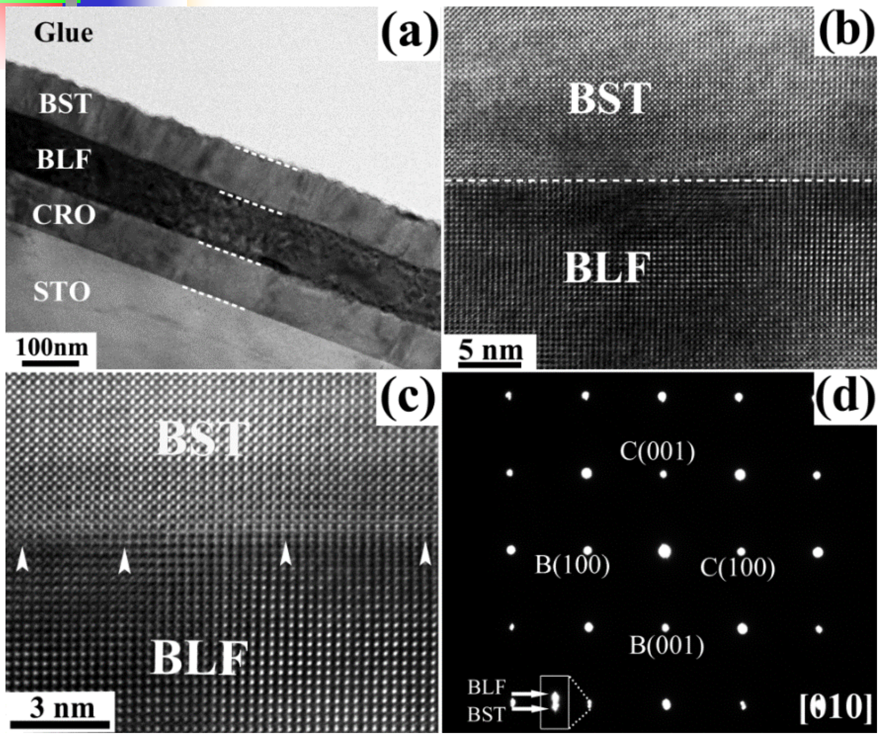
Defects control in Co-doped BSZT films





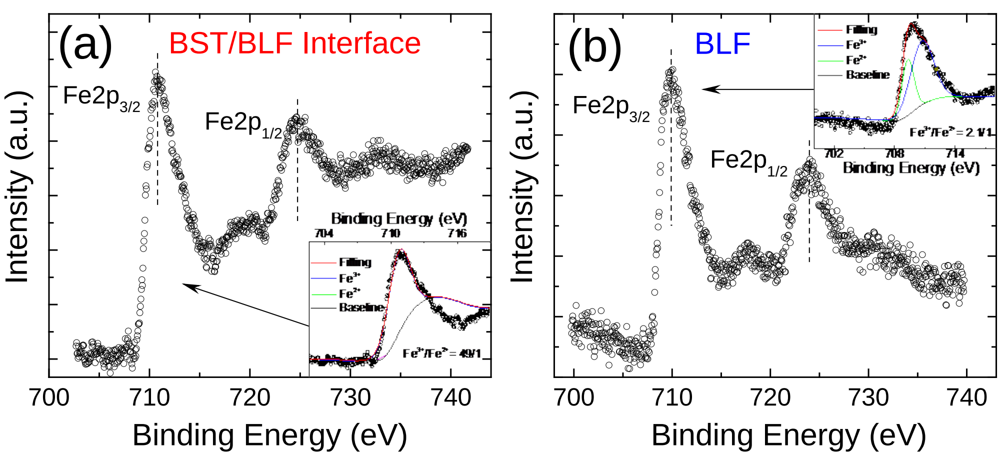
Appl. Phys. Lett, 99, 232910 (2011).

$(BaSr)TiO_3/(BiLa)FeO_3$ multiferroic heterostructure



Relations: [001]/[100]/[001]

Lattice correlated



Fe^{2+} - $V_O^{\cdot\cdot}$ - Fe^{3+} ~ 0.97 eV

$V_O^{\cdot\cdot}$ ~ 0.39 - 0.47 eV

Appl. Phys. Lett, 102, 232902(2013).

Electric-field-induced change of magnetoresistance in multiferroic spin valves

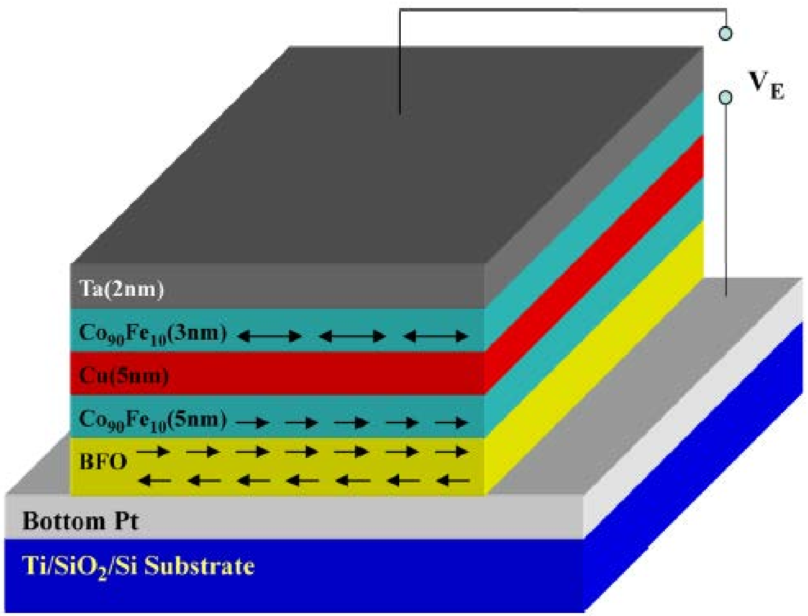


Fig. 1. The schematic illustration of the multiferroic spin valve structure.

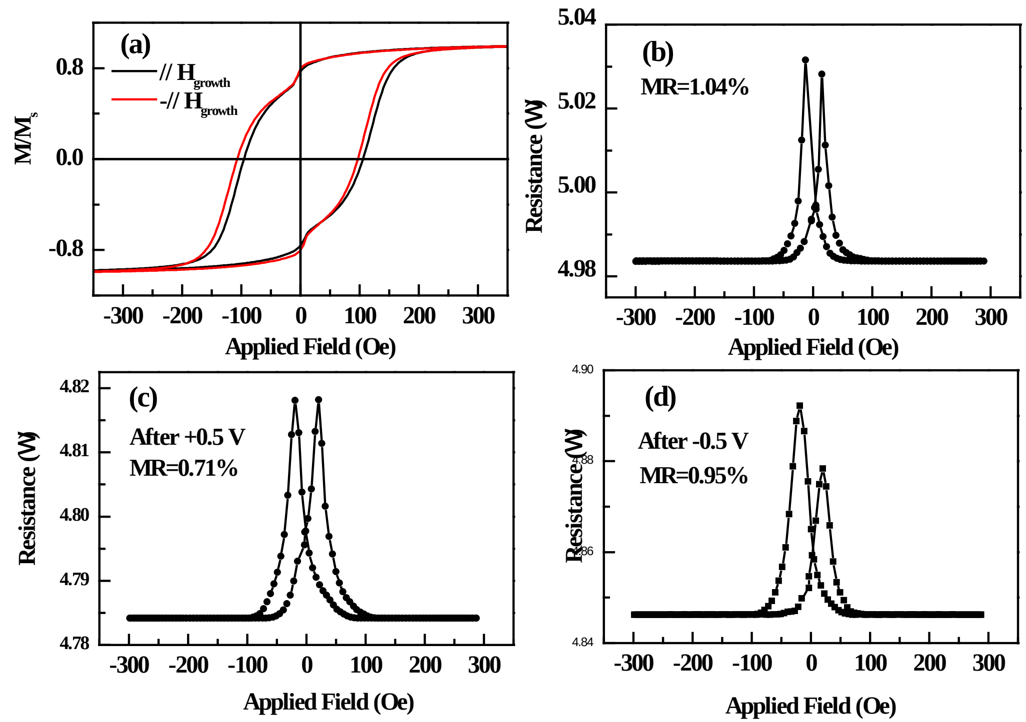


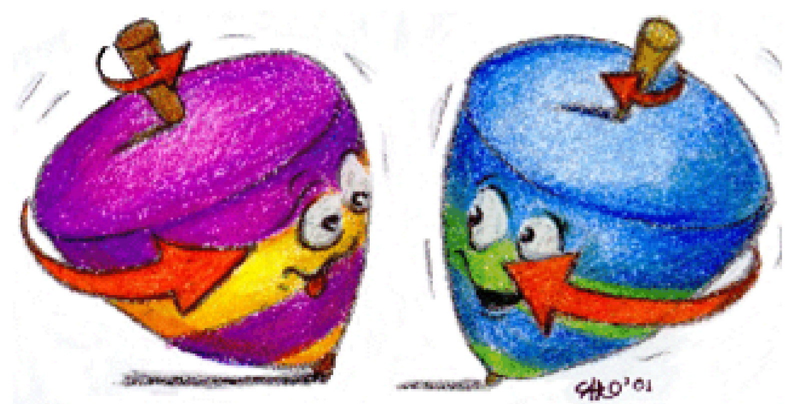
Fig. 5. CoFe/Cu/CoFe spin valve structures based on BFO film.

(a) Magnetic hysteresis loops; and current-in-plane magnetoresistance measurements with (b) no applied voltage, (c) applying 0.5 V, and (d) applying −0.5 V at room temperature.

V_E was applied to change the magnetization of BFO layer

IEEE T. Magn. Vol. 47, No. 10, 2011.

Thanks for your attention !



The electron as "Spinning top"