



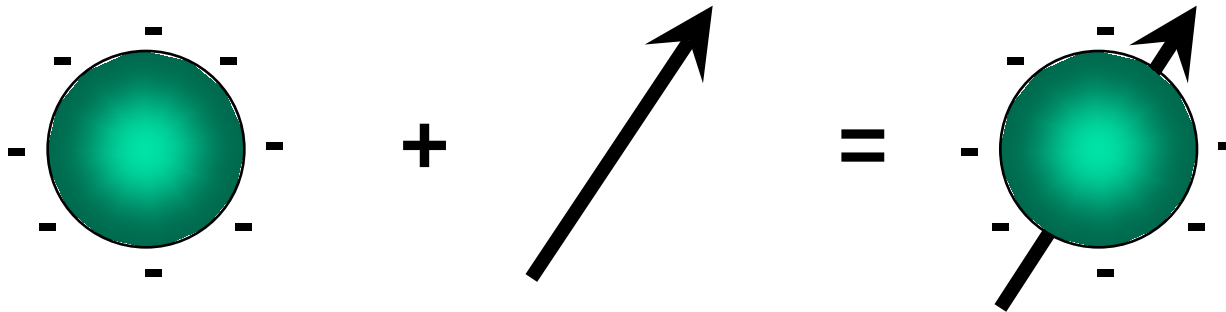
自旋电子学研究进展



- 
- 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

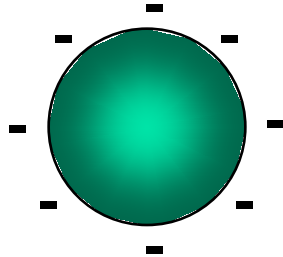
What Is an Electron ?

A particle with both a negative electric charge $q = -e$ and a spin $\frac{1}{2}$ (magnetic moment $m = \frac{e\hbar}{2m_e} \hat{S}$)



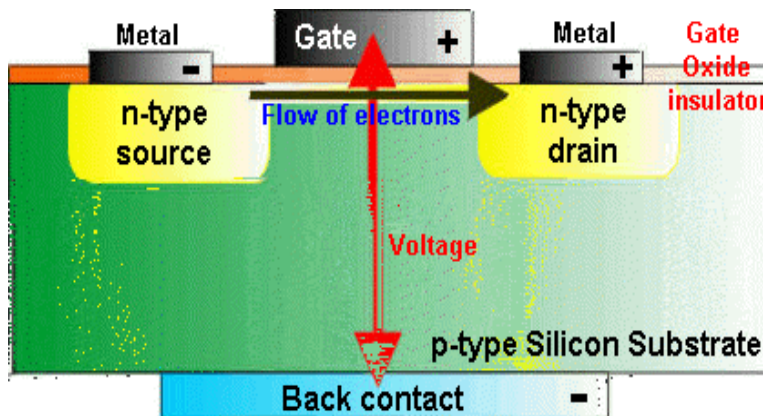
The direction of a spin is usually controlled by a magnetic field or inter-electron interactions, but there are also on-going researches to find ways to control the spin using an electric field.

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:

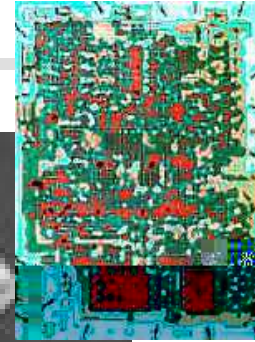
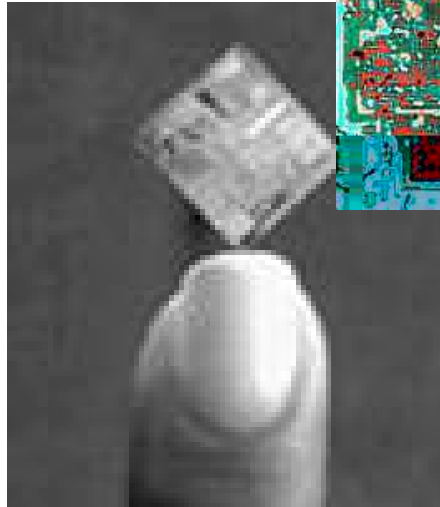
1. Volatility of the information
2. Large energy consumption
3. Limited storage density

Normal Electronics



1947,

1956



1971 Intel 4004
2300 /3x4 mm²



William Bradford Shockley



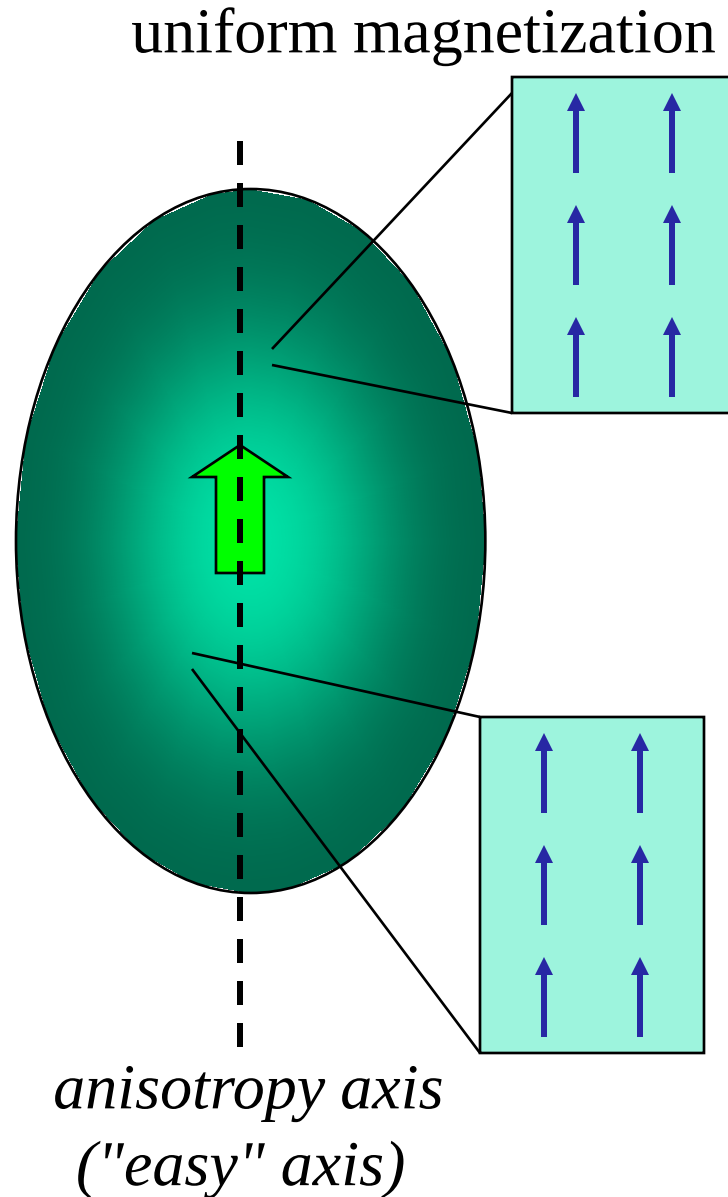
John Bardeen



Walter Houser Brattain



Ferromagnet

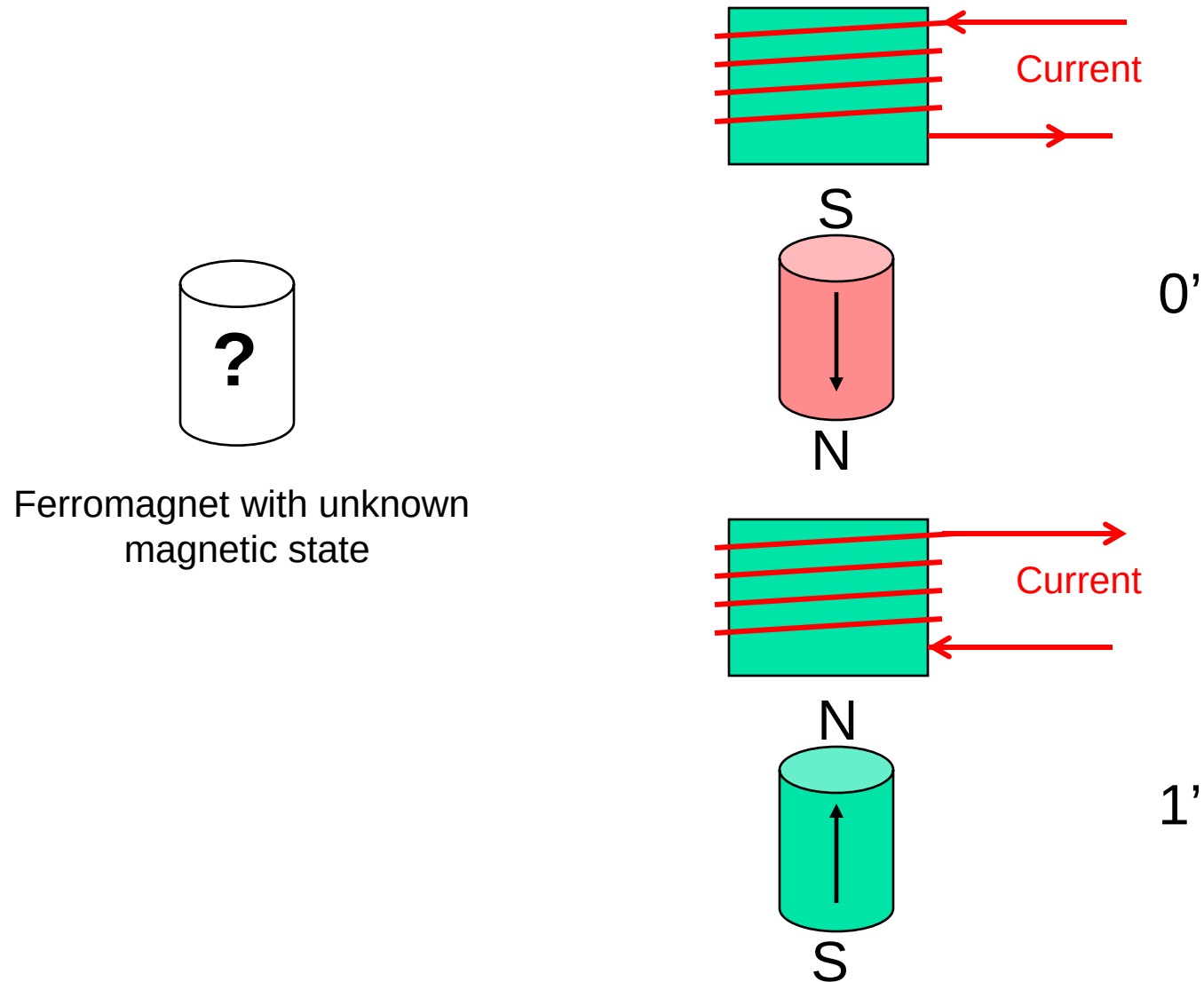


Electron magnetic
moments ("spins")

Aligned by
"exchange interaction"

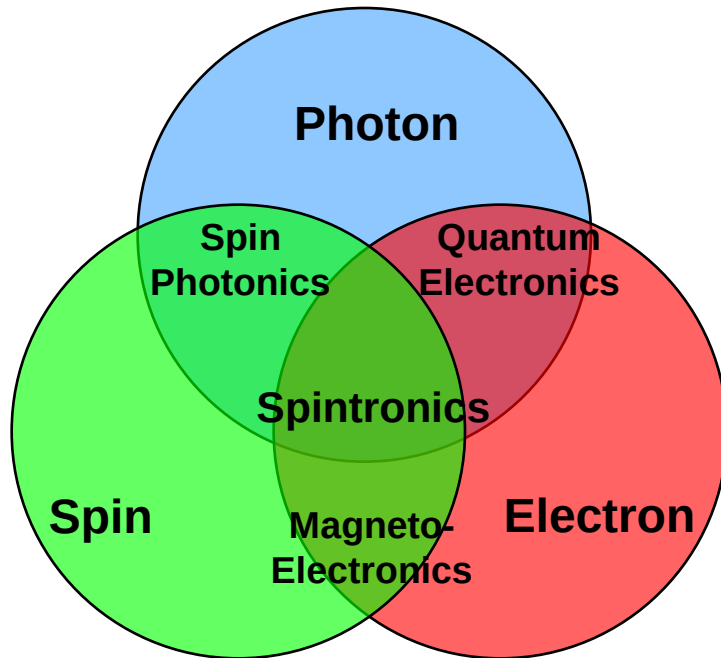
Bistable:
Equivalent
energy for
"up" or "down"
states

Ferromagnets are used to store data





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.

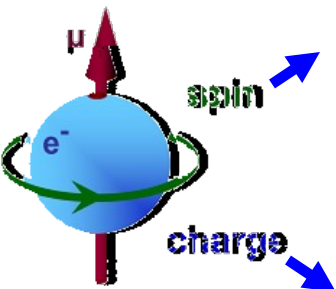
New fundamental physical questions

New phenomena

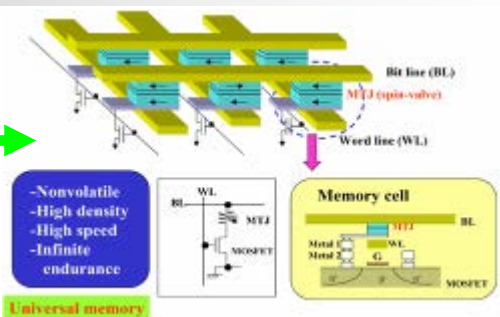
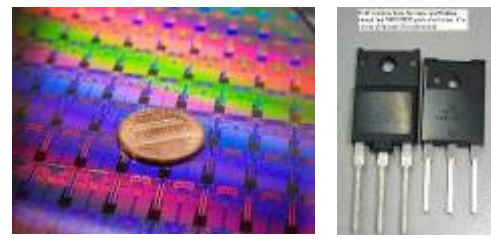
New devices and applications



Magnetic engineering
Magnetic memory
Permanent magnet..



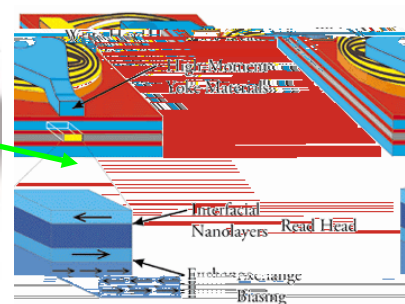
Electronics
Semiconductor
Transistor ..



-Nonvolatile
 -High density
 -High speed
 -Infinite endurance
Universal memory

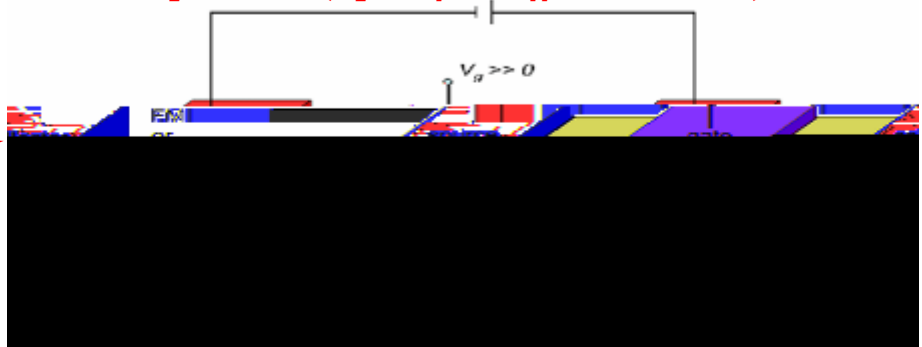
MRAM (Magnetic Random Access Memory) Huge TMR

spintronics
Spin + charge



HDD (Hard Disc Drive) read head
GMR → Large TMR + Low R;
Large CPP-GMR

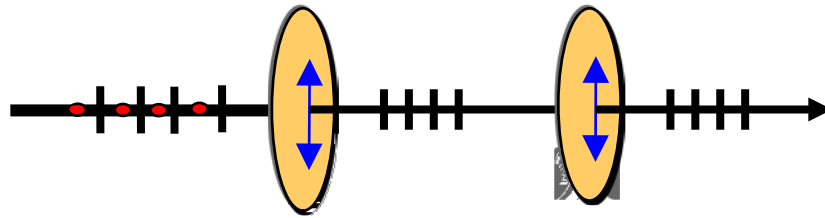
spin -FET(spin -field effect transistor)



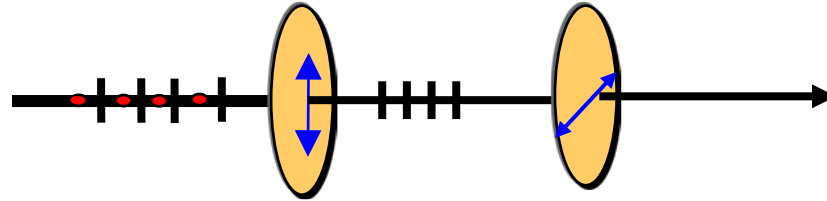
High spin injection
Efficiency into semiconductor

How to Use “Spin”?

Light

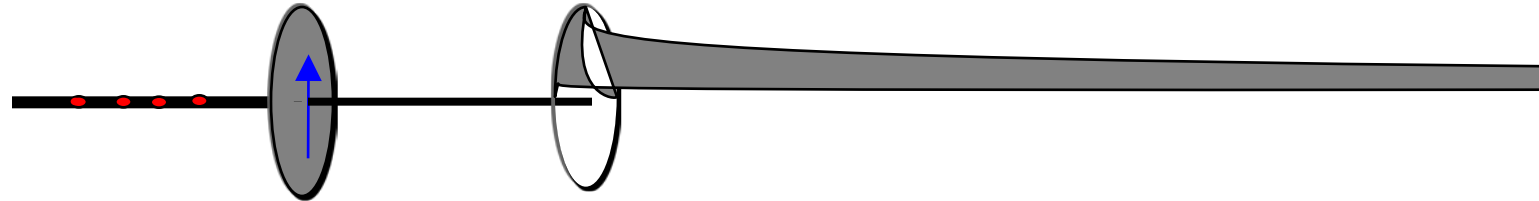
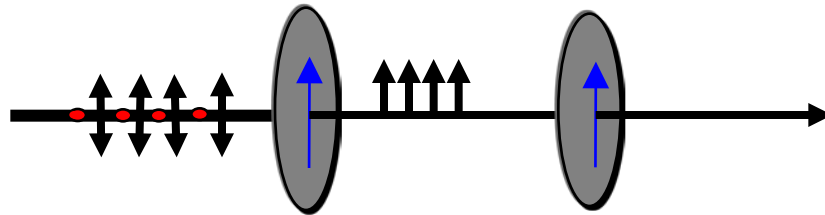


$P_1 // P_2$



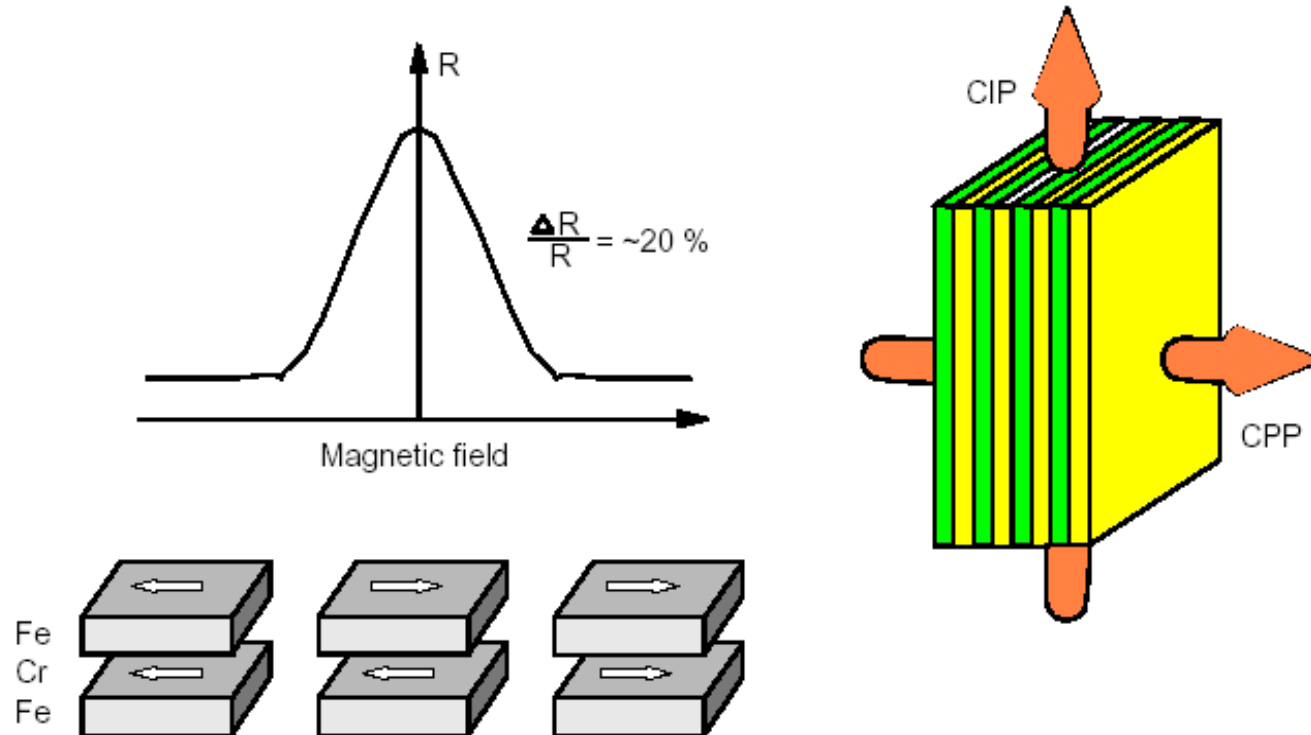
$P_1 \wedge P_2$

P_1 ® Polarizer P_2 ® Analyser

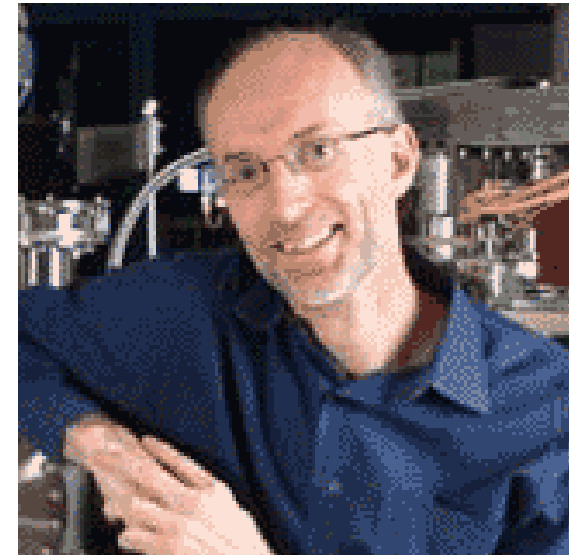
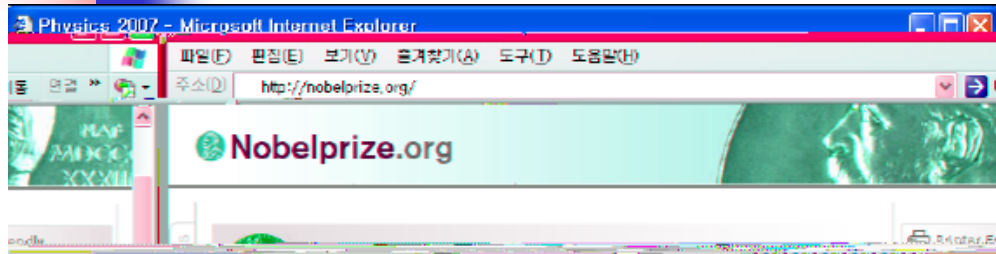


Giant Magnetoresistance (GMR)

)



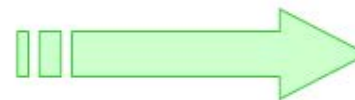
Baibich et al., Phys. Rev. Lett, 61, 2472 (1988).



Stuart Parkin, IBM



1951
mercury memory
(UNIVAC)

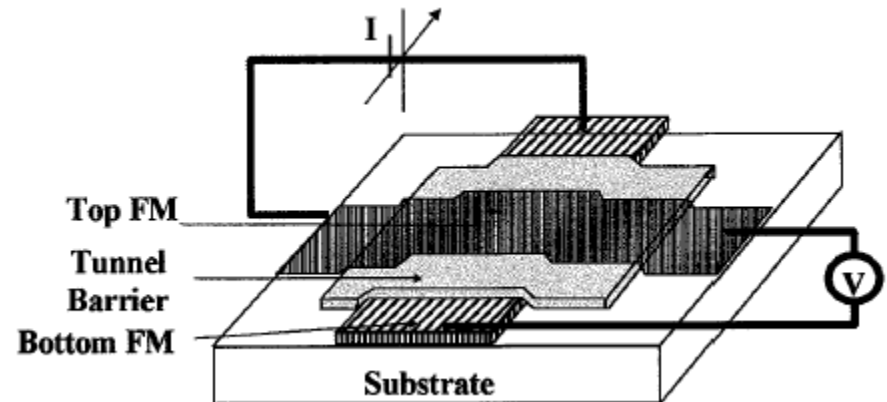
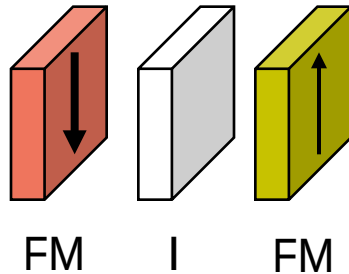


GMR Head on the HDD

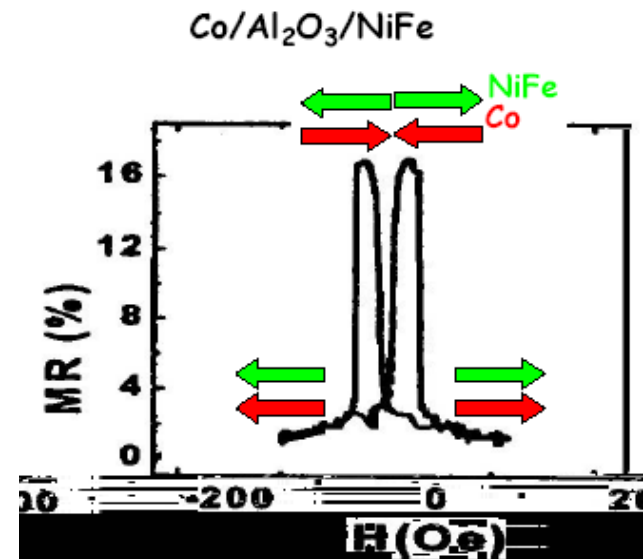
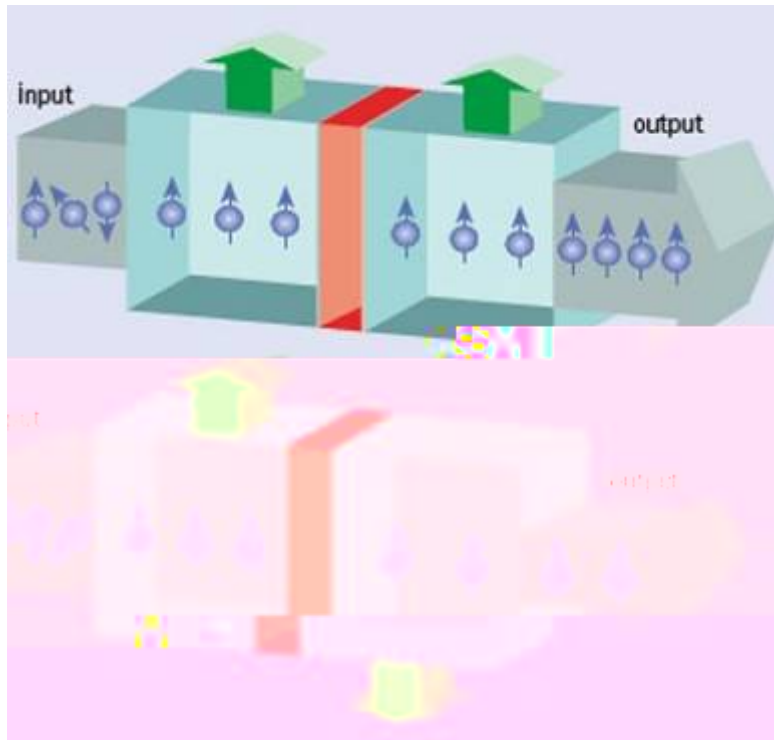


Today
0.85" HDD, 4 GBytes, 12.5 MB/sec

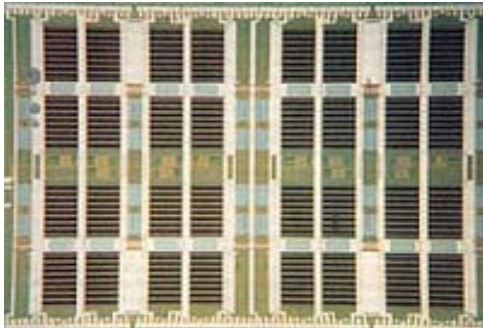
Tunneling Magnetoresistance TMR



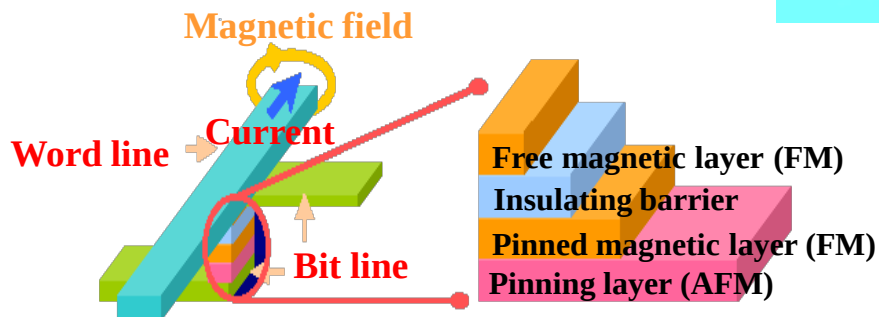
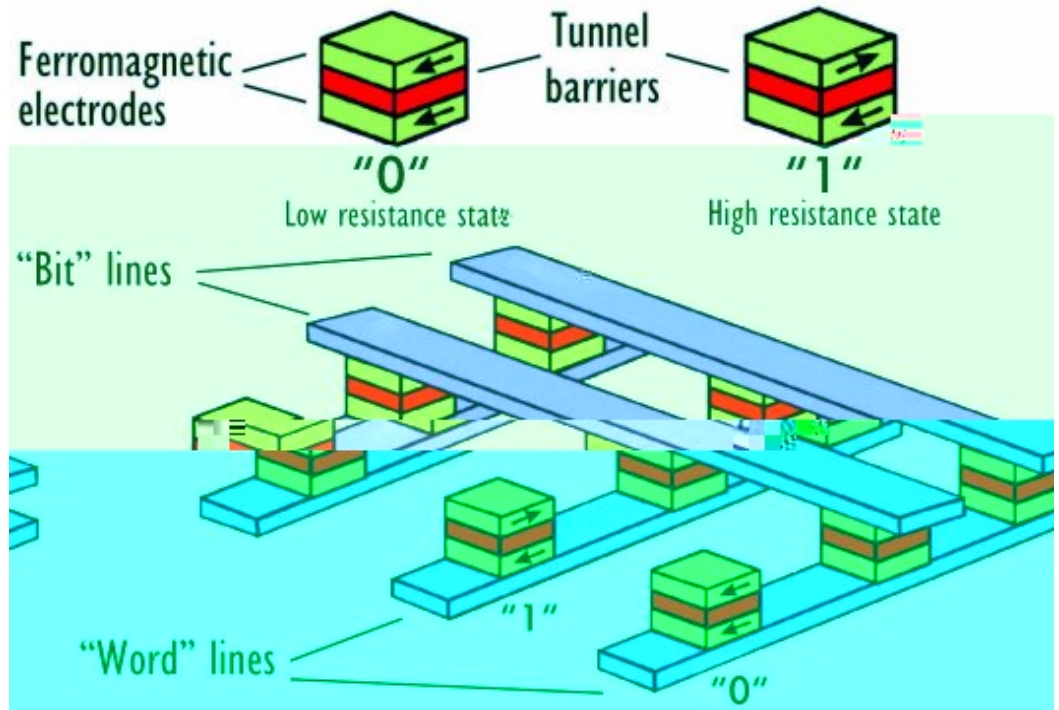
Magnetic Tunnel Junction (MTJ)



Magnetic Random Access Memory MRAM



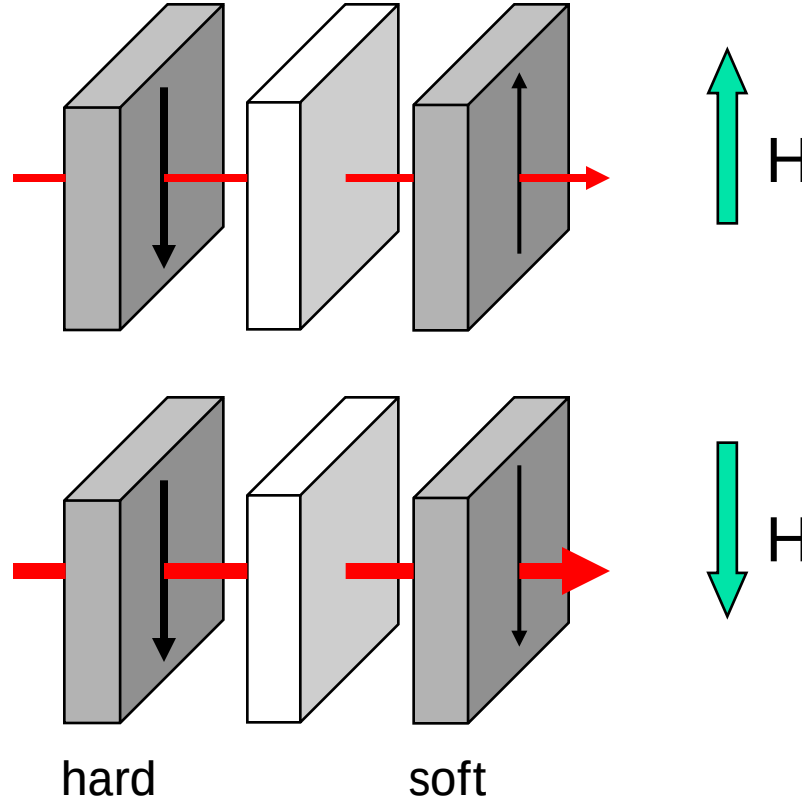
4-Mbit MRAM
(Motorola)



64M!

Motorola, Everspin, Infineon, SONY, Toshiba, Hitachi

Spin transfer torque STT,

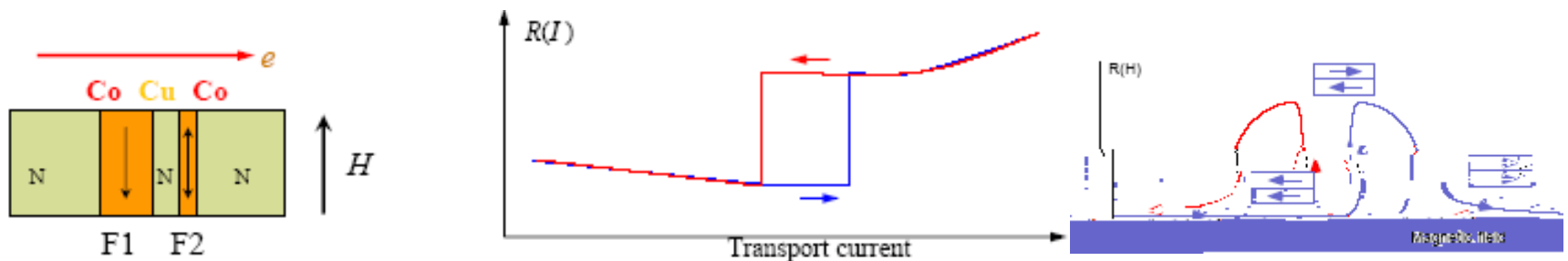
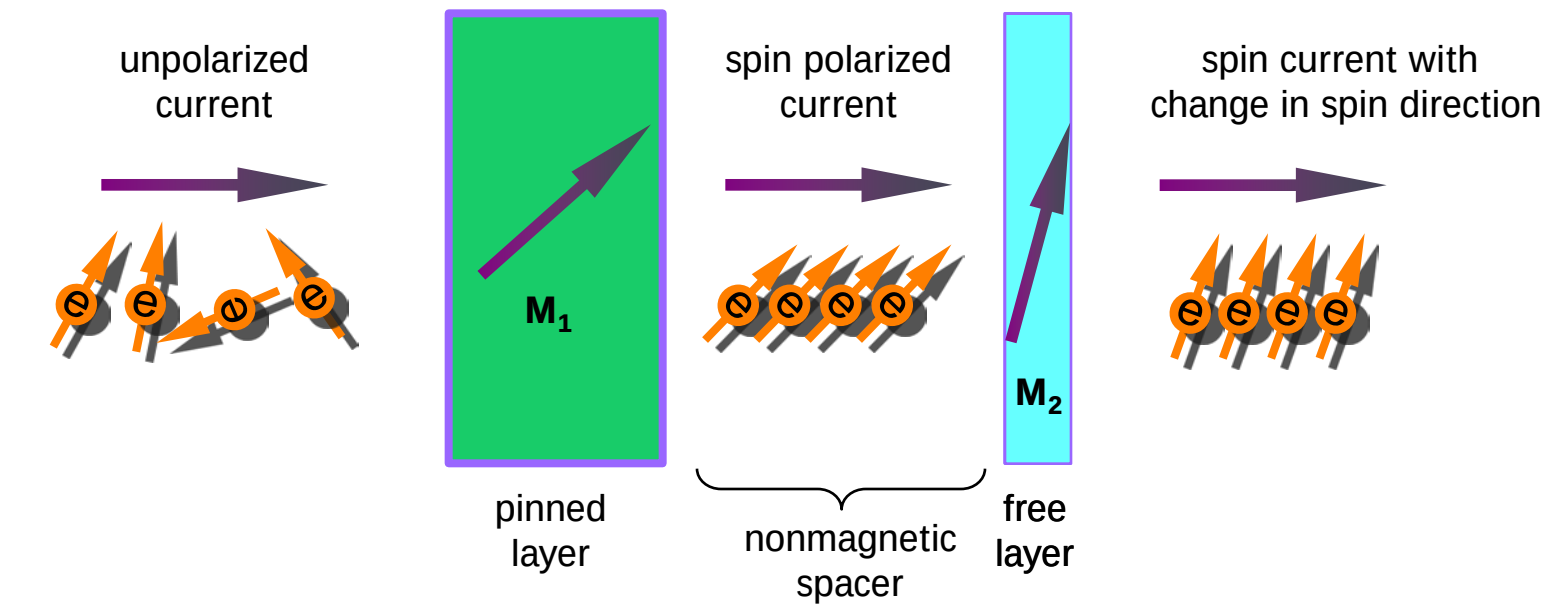


GMR & TMR: Magnetization changes current

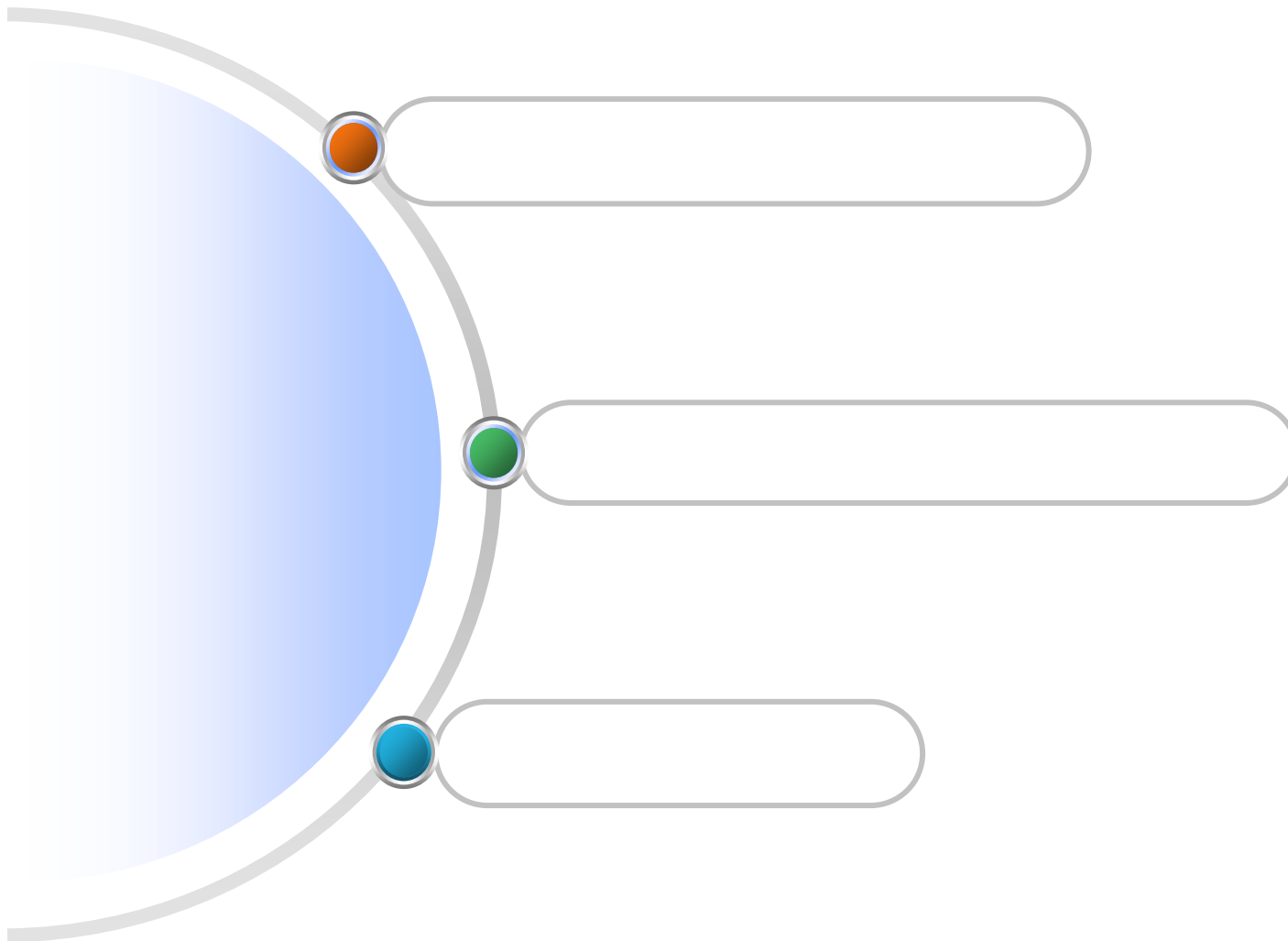
Can it be reversed?

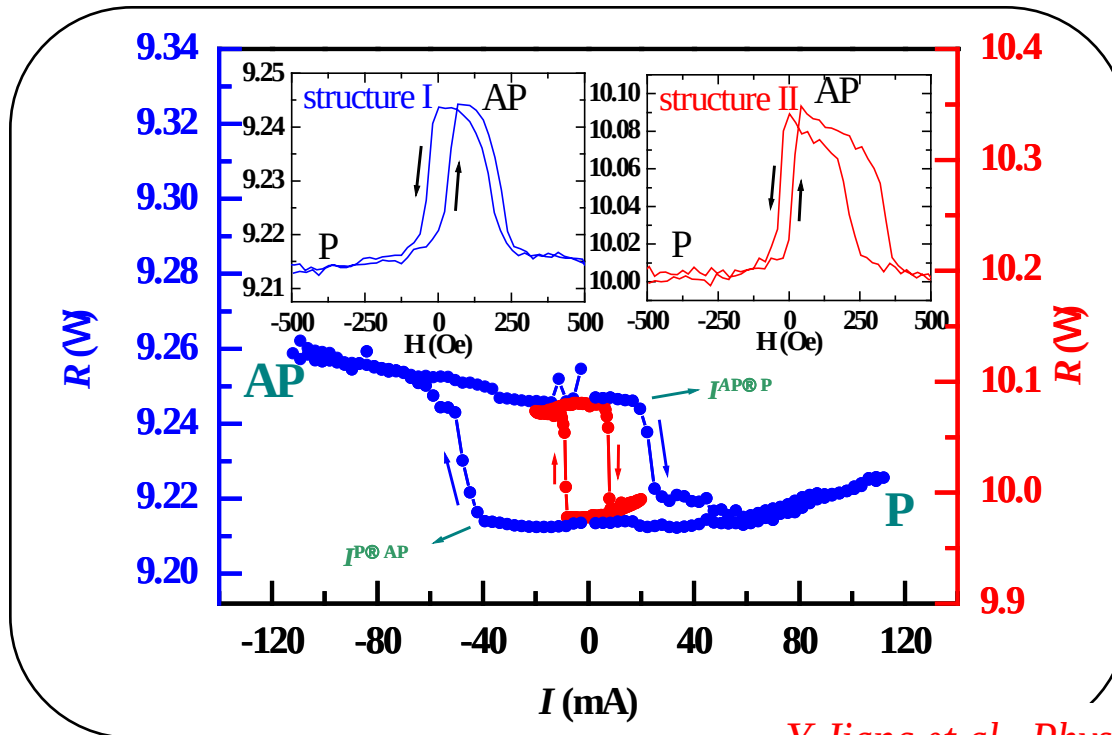
Spin transfer torque: Current changes magnetization

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.





Size: 280·90 nm²

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

structure I:

Cu(20)/IrMn(10)/Co₉₀Fe₁₀(5)/Cu(6)/Co₉₀Fe₁₀(2.5)/Cu(5)/Ta(2) (nm)

structure II:

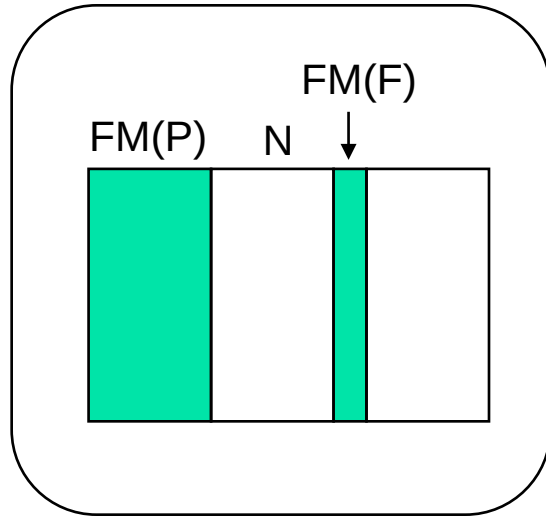
Cu(20)/IrMn(10)/Co₉₀Fe₁₀(5)/Cu(6)/Co₉₀Fe₁₀(2.5)/**Ru(0.45)**/Cu(5)/Ta(2) (nm)

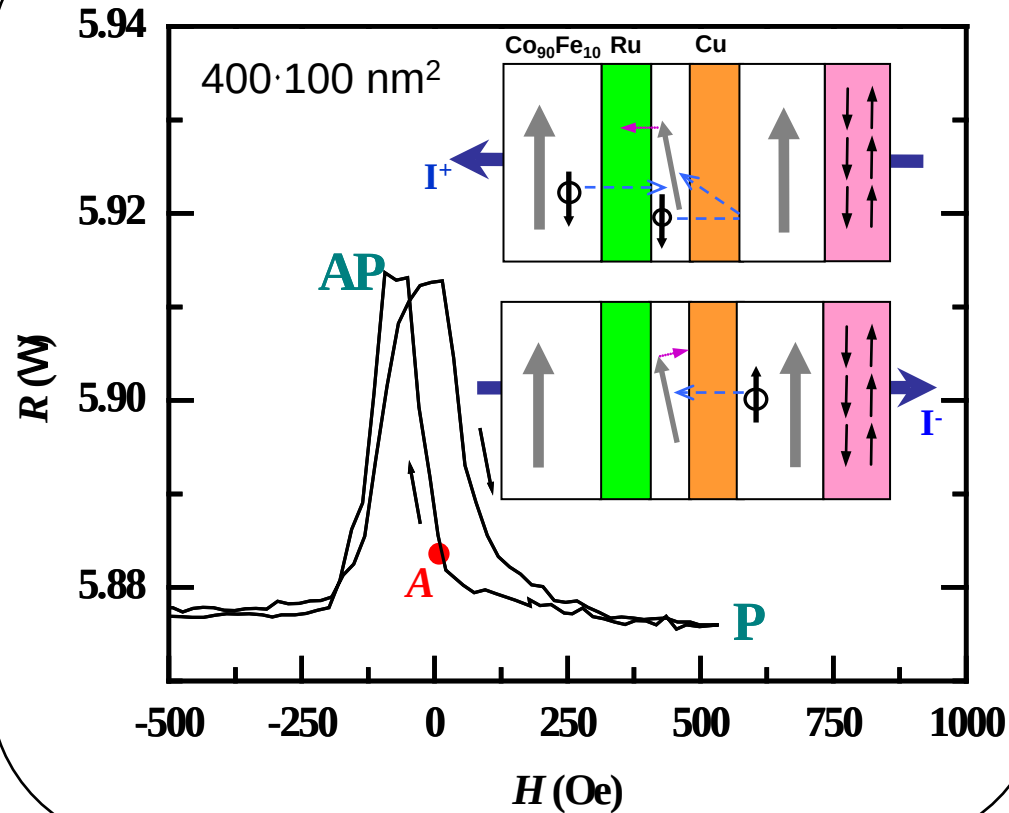
Critical current densities:

2.2·10⁸ A/cm² (structure I);

1.8·10⁷ A/cm² (structure II).

The Ru cap layer effectively decreases the critical current densities.

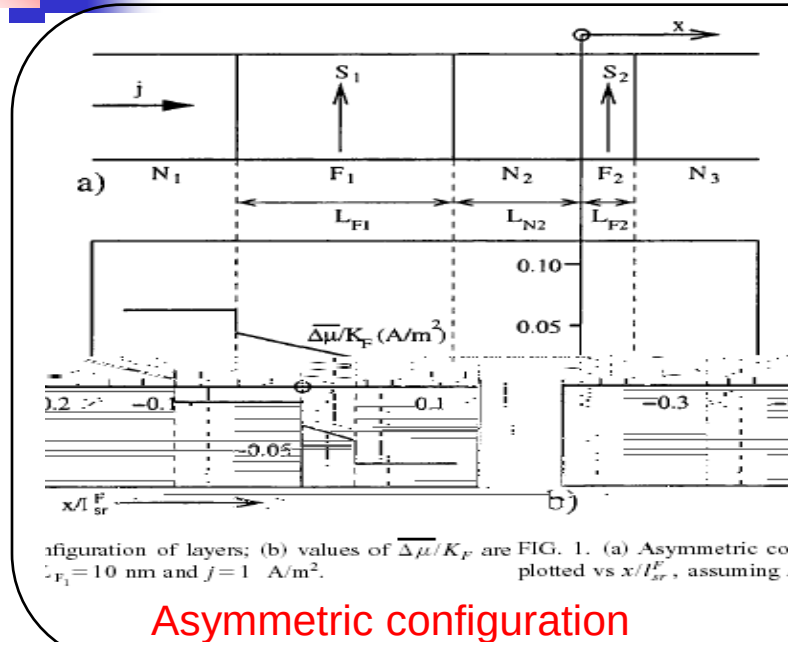




Y.Jiang et al., Nature Materials, vol.3, 361(2004).

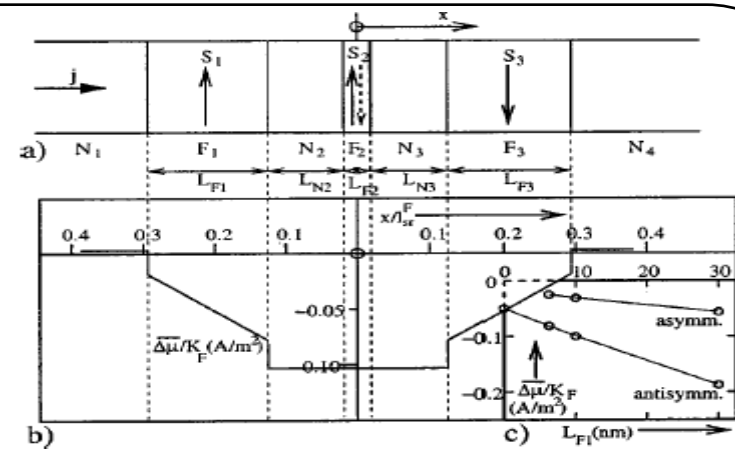
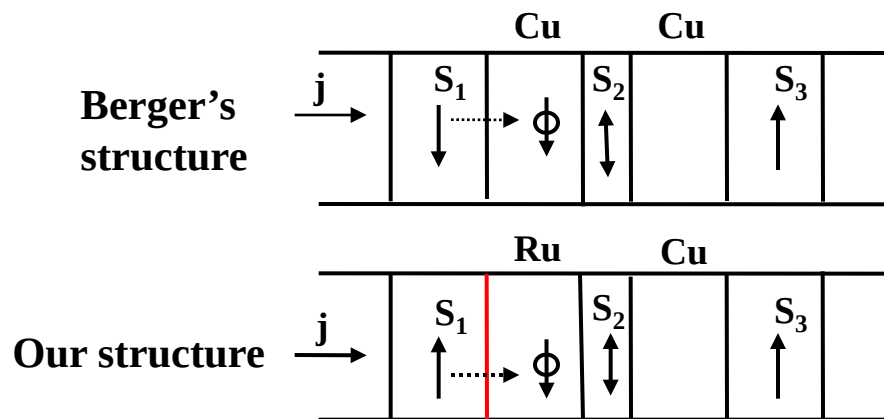
Structure III:

Ta(6)/Cu(50)/ $\text{Co}_{90}\text{Fe}_{10}$ (5)/Ru(6)/ $\text{Co}_{90}\text{Fe}_{10}$ (2.5)/Cu(6)/ $\text{Co}_{90}\text{Fe}_{10}$ (5)/IrMn(10)/Cu(5)/Ta(2) (nm)



Asymmetric configuration

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



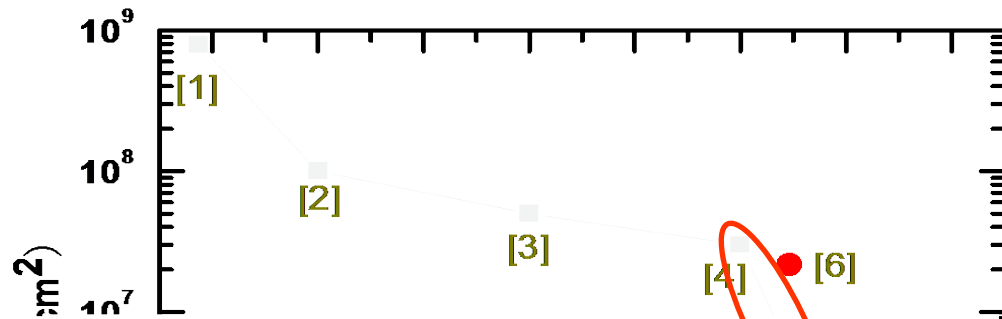
Six times higher spin accumulation!

Antisymmetric configuration

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

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

When $S_1 // -S_3$, $\frac{\overline{Dm}}{K} \big|_{Ru}$ has an opposite sign as $\frac{\overline{Dm}}{K} \big|_{Cu}$, 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).

Nature
12

6



IBM

Thomas J. Watson
Jonathon Sun

IBM

Spin angular momentum transfer in current-perpendicular nanomagnetic junctions

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).



Carnegie Mellon

Jian-Gang
Zhu(IEEE Fellow)

Magnetoresistive Random Access Memory: The Path to Competitiveness and Scalability

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

JIAN ZHU, Fellow IEEE

By JIAN-C

developing effort of STT-MRAM technology. Many schemes have been suggested to reduce the Gilbert damping constant of a storage layer. Experimental studies have focused on a Permalloy-based device. However, lower layers, deposited on top of the storage layer, could lower Gilbert switching current thresholds, and reduction of the Gilbert damping has been suggested to be the resonant 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

8 Emerging Research Devices



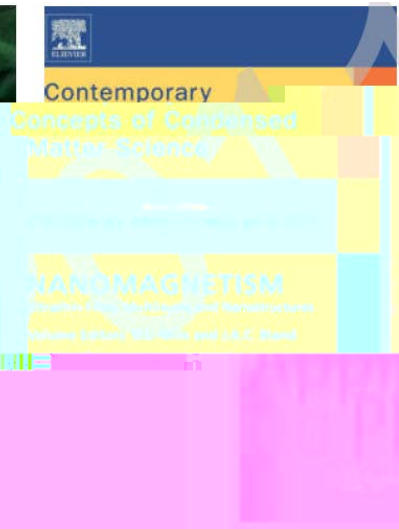
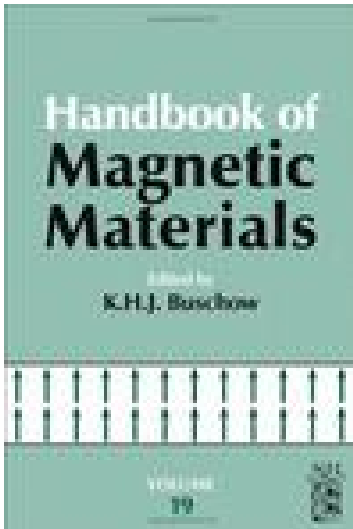
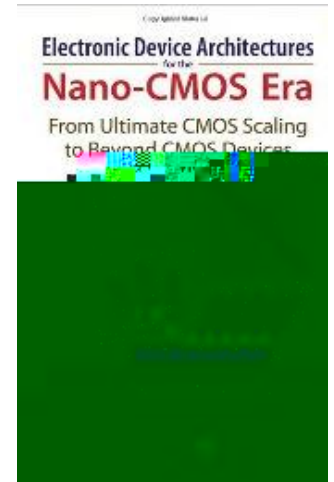
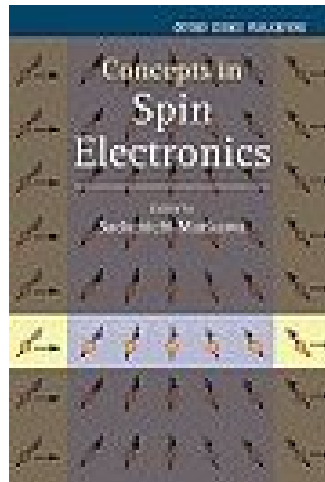
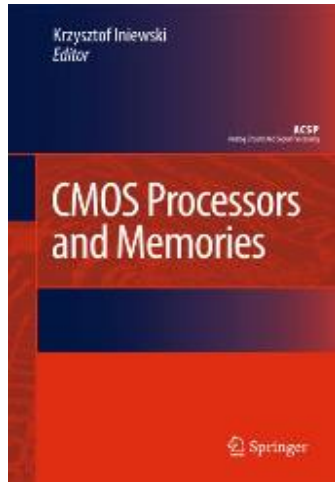
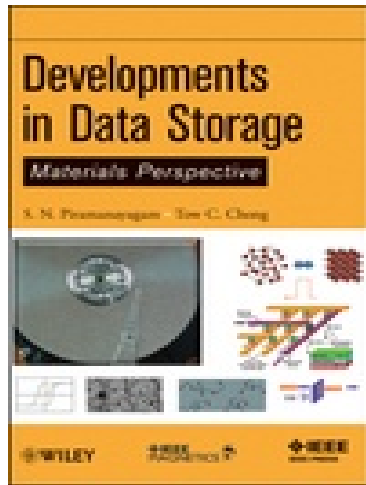
International Technology Roadmap for Semiconductors

		DRAM		SRAM [A]	[B]		SONOS	FeRAM	MRAM	PCM								
		Stand-alone	Embed-ded		NOR	NAND												
<i>Storage Mechanism</i>										Reversibly changing amorphous and crystalline phases								
<i>Cell Elements</i>																		1T1R
<i>Feature size F, nm</i>	2005																	90
	2018																	18
<i>Cell Area</i>	2005																	7.2F ²
	2018	1.5F ²	1.0F ²	1.0F ²	1.0F ²	0.5F ²	0.5F ²	1.0F ²	1.0F ²	1.0F ²								

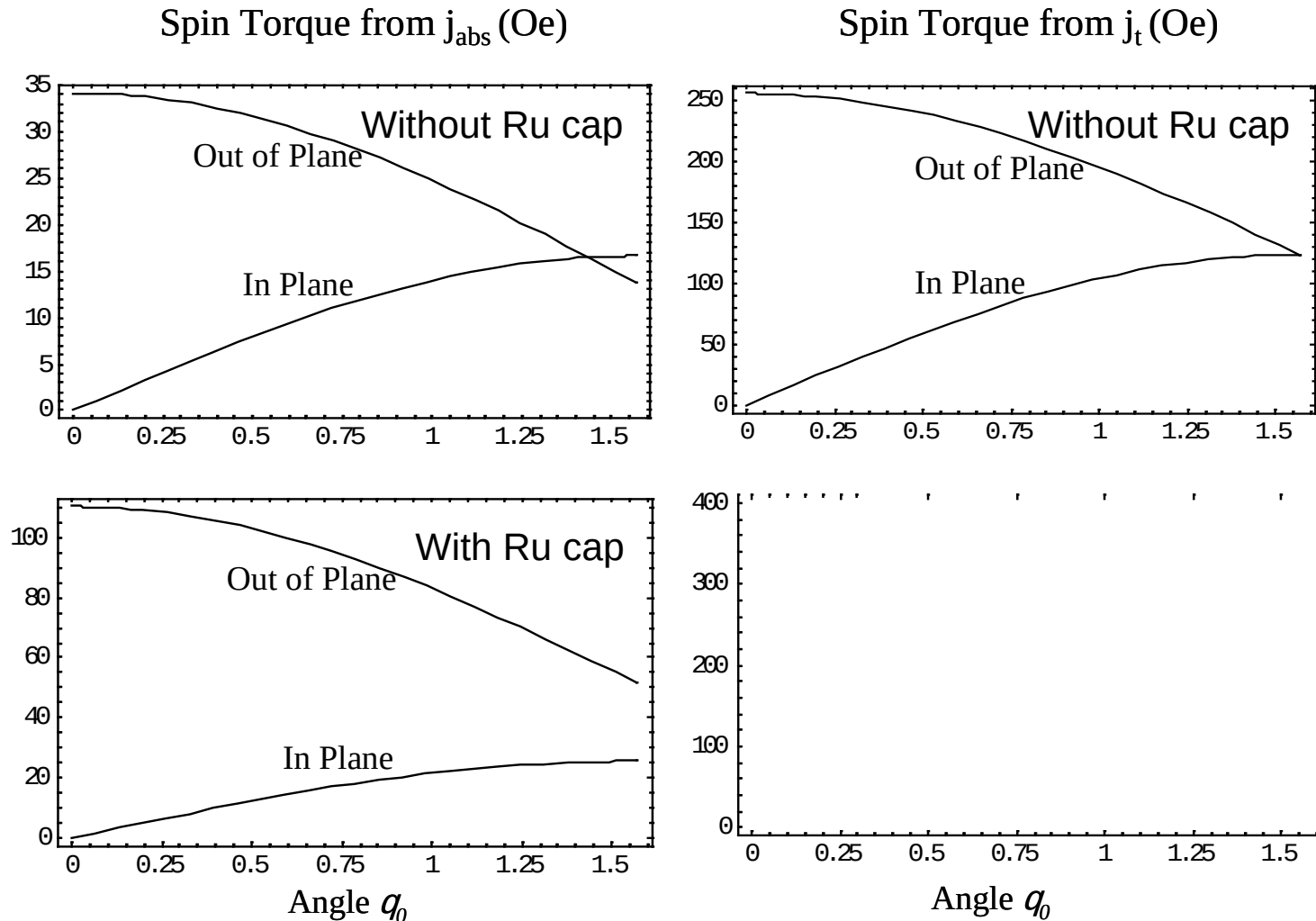
[Y.Jiang et al.]

[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.

10

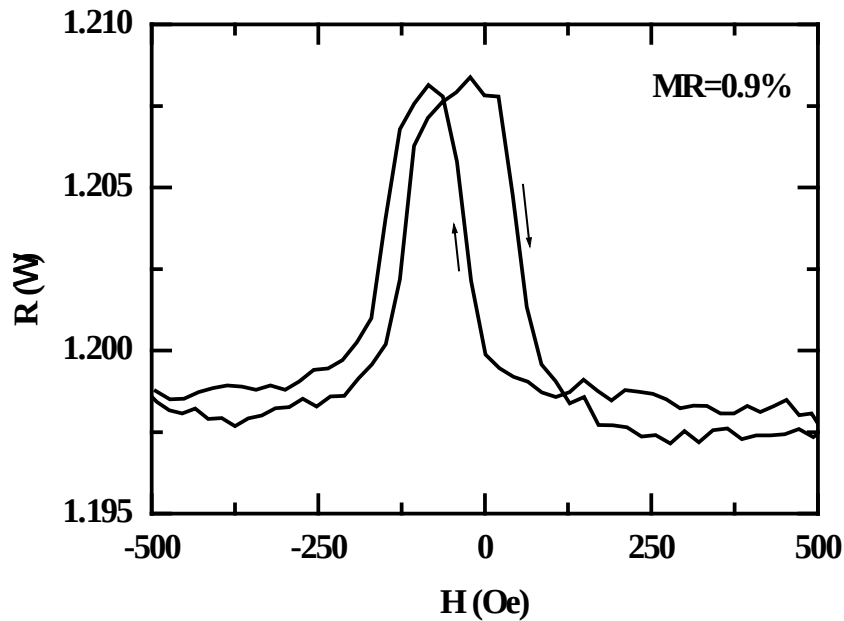


Spin transfer torque (STT)



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

Effect of the Ru thickness on STT

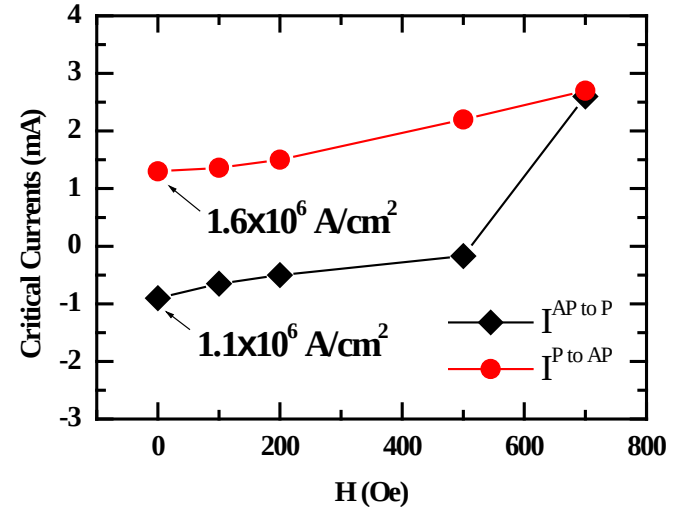
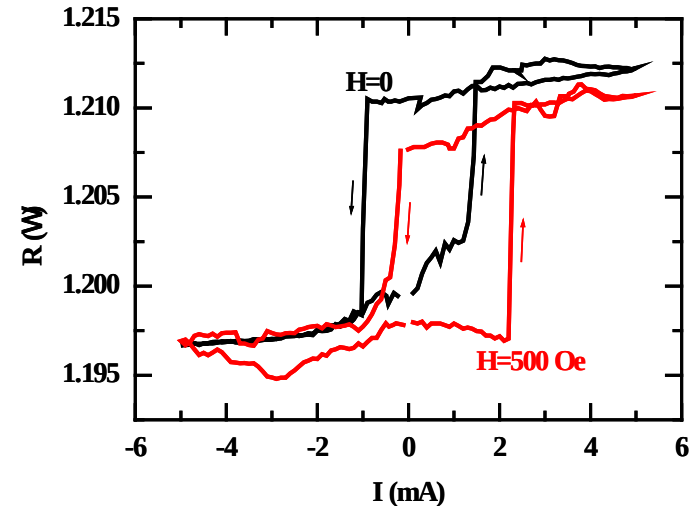


Structure IV:

Ta(2)/Cu(80)/Co₉₀Fe₁₀(5)/Ru(4.5)/Co₉₀Fe₁₀(2.5)/Cu(6)/Co₉₀Fe₁₀(5)/IrMn(10)/Cu(5)/Ta (2) (nm)

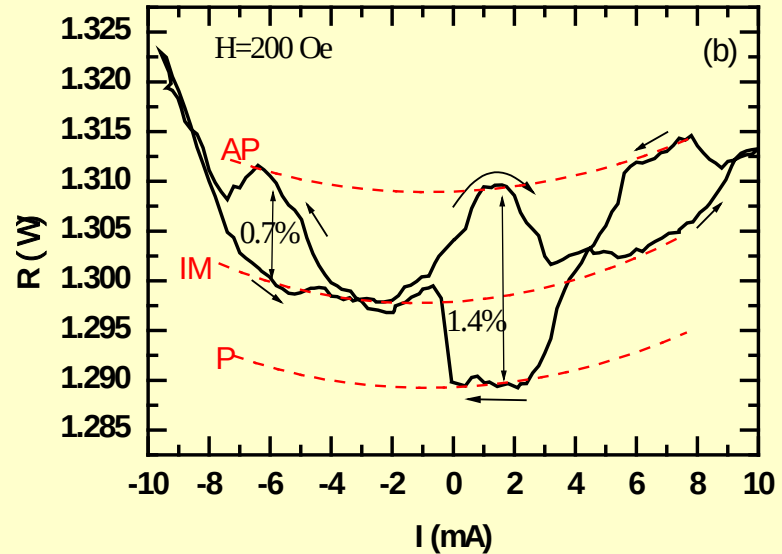
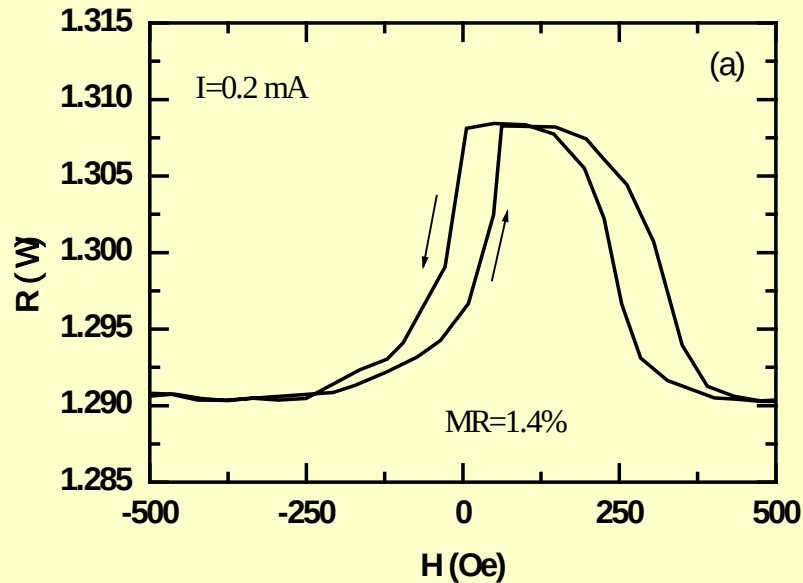
Size:

400·200 nm²



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

STT in SPVs with a low aspect ratio of 1



Size: 100·100 nm²

Structure: Ta/Cu/IrMn (10)/Co₉₀Fe₁₀ (5)/Cu (6)/Co₉₀Fe₁₀ (2.5) /Cu (5)/Ta (2) (nm)

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

Current-induced domain wall motion

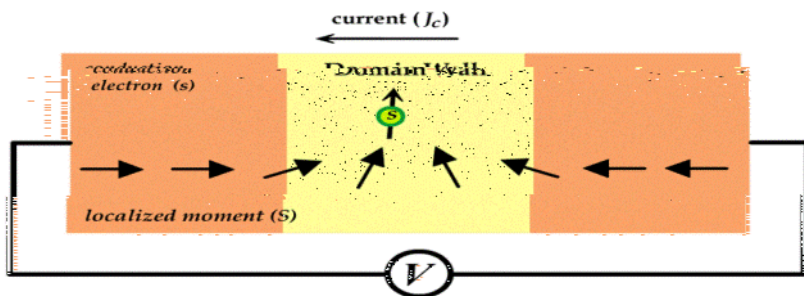
Spin transfer torque (STT)

Spin-transfer torque MRAM
(Current induced magnetization switching)

Oscillator and spin diode

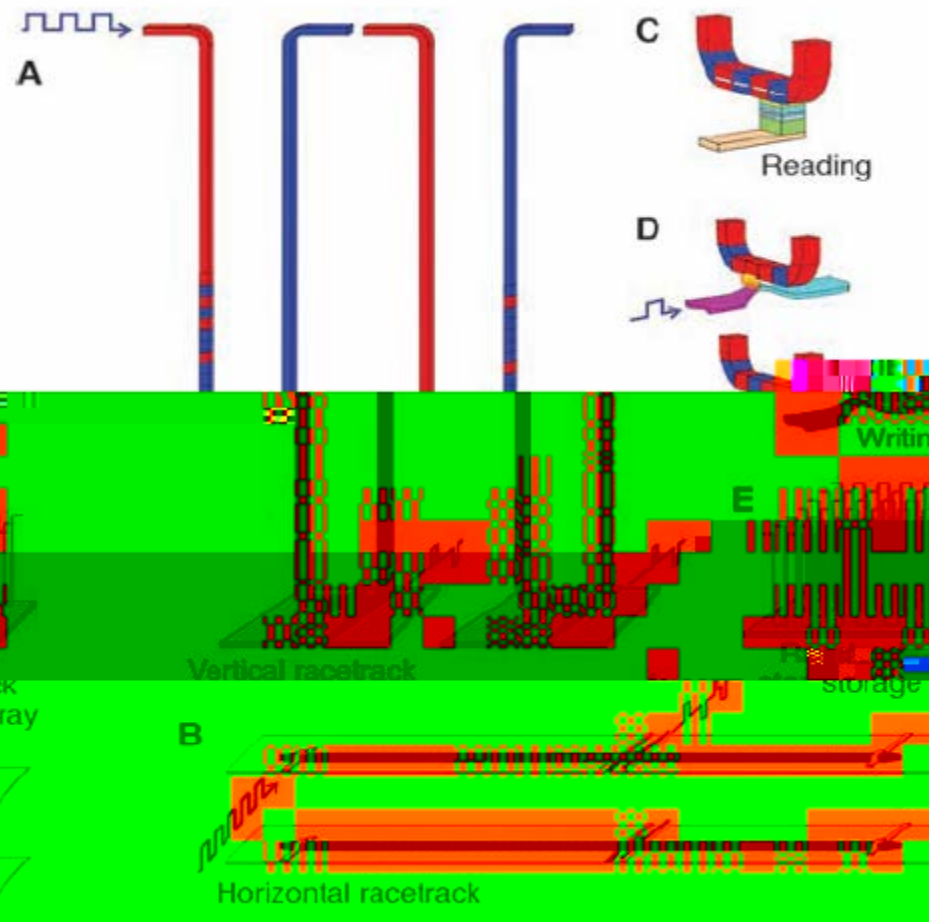
Magnetic racetrack memory

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

$$\frac{d\mathbf{m}}{dt} = -|g|\mathbf{H}' \times \mathbf{m} + a\mathbf{m}' \cdot \frac{d\mathbf{m}}{dt} - (u \times \tilde{\mathbf{N}}) \times \mathbf{m} + b\mathbf{m}' \cdot \frac{d}{dt} (u \times \tilde{\mathbf{N}}) \times \mathbf{m}$$

Precession term

Damping term

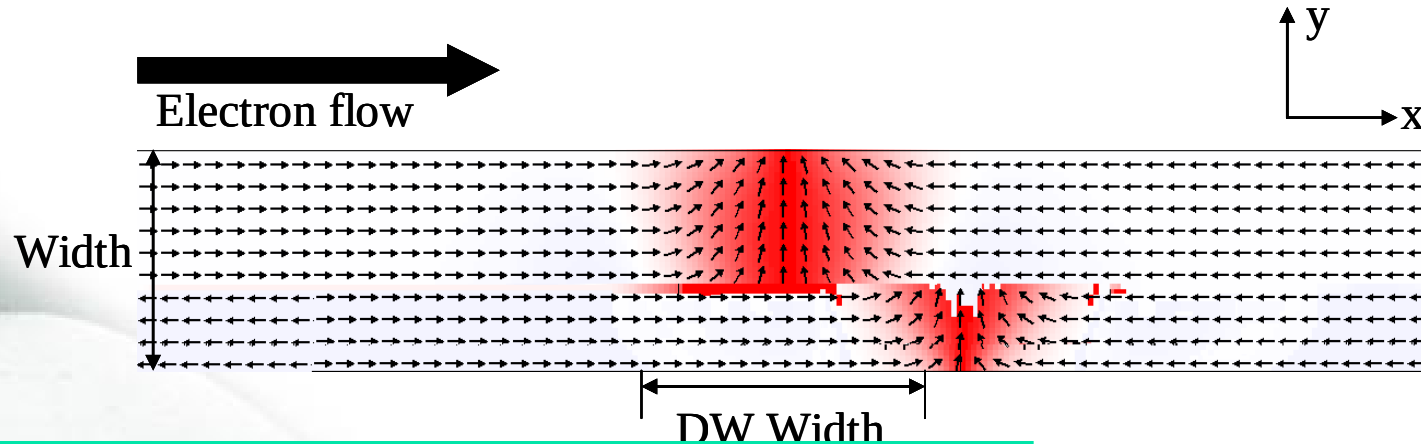
Adiabatic term

Nonadiabatic term

$$u = JPg m_B / 2eM_s$$

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 $L = 5 \text{ } \mu\text{m}$

Width $W = 20\text{-}200 \text{ nm}$

Thickness $T = 3\text{-}8 \text{ nm}$.

Material parameters of Permalloy

Saturation magnetization: $M_S = 8 \cdot 10^5 \text{ A/m}$

Exchange energy coefficient: $A = 1.3 \cdot 10^{-11} \text{ J/m}$

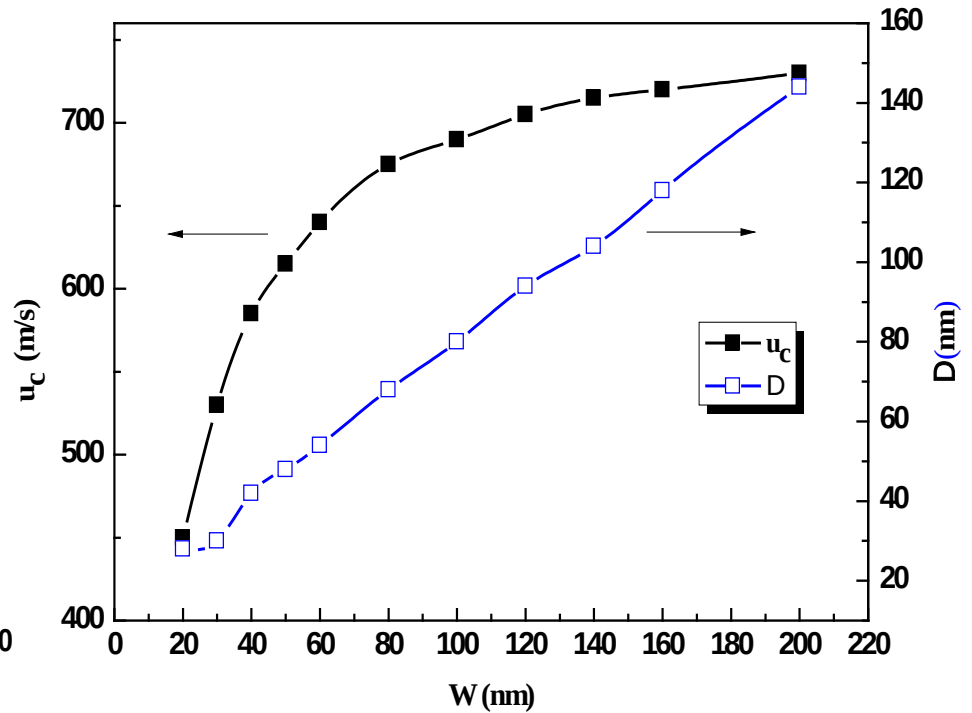
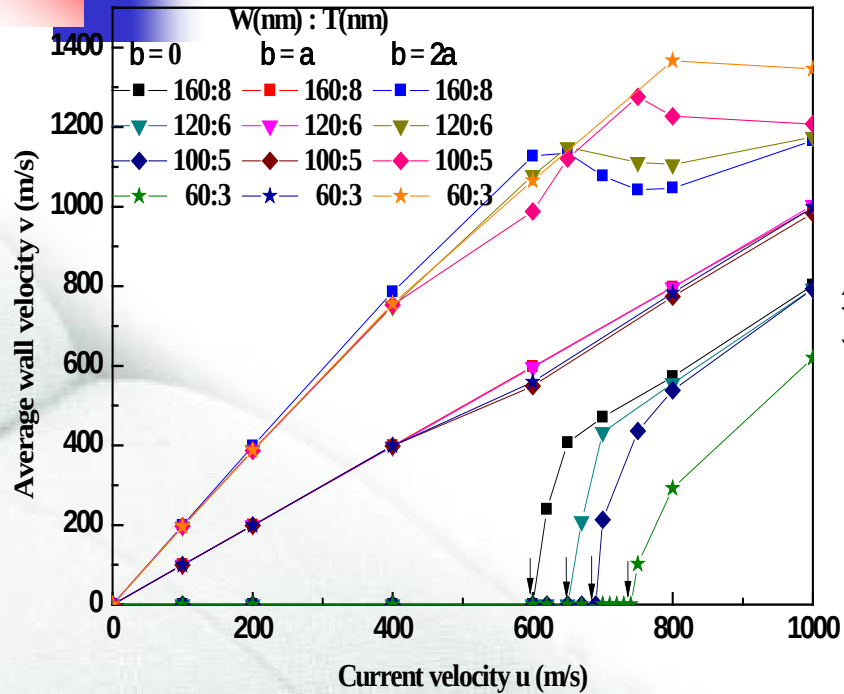
Gilbert gyromagnetic ratio: $\gamma = 221000 \text{ m/(A}\cdot\text{s)}$

Damping constant $\alpha = 0.02$

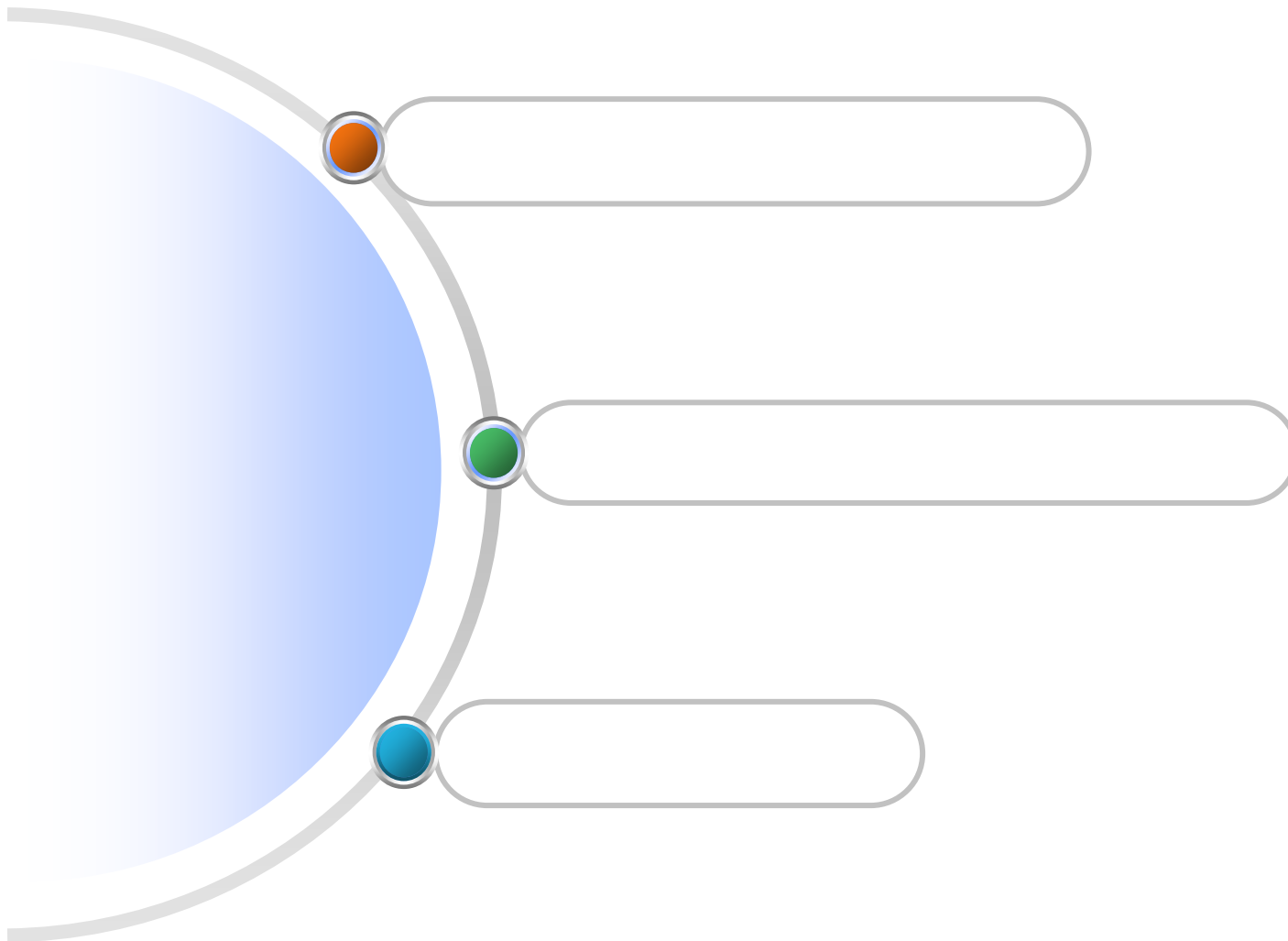
Maximum cell size of $4 \times 4 \text{ T nm}^3$

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

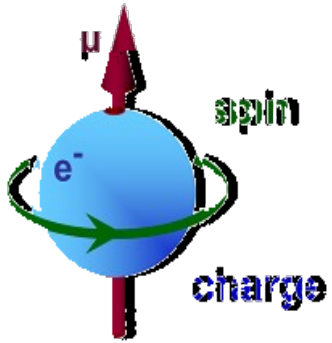
$$M_x / M_S = - \tanh(2x / D)$$



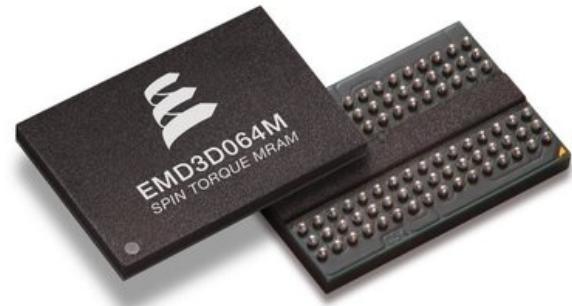
- 1 The critical current density increases with the decreases in both the width and thickness of nanowires due to the enhanced hard-axis anisotropy.
- 2 While the thickness is fixed, the critical current density decreases with the decreasing width of nanowires due to the domination of reducing domain wall width.



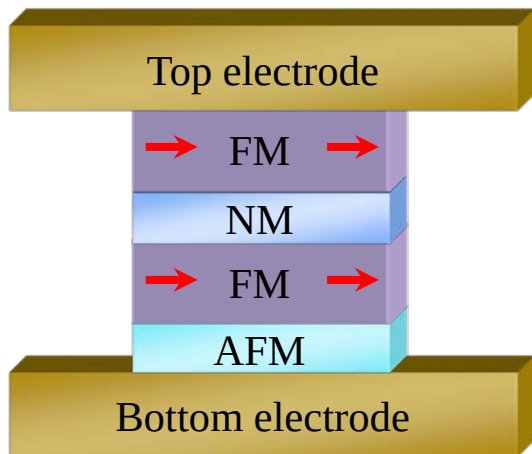
PMA



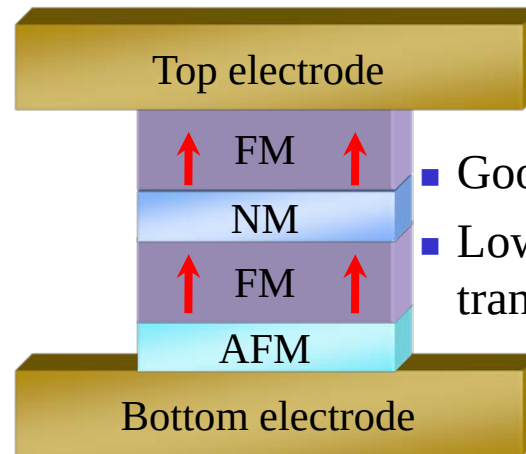
Hard disk drive (HDD)
read head



Magnetic random access
memory (MRAM)



Conventional



Perpendicular

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



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

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

II. **L1₀-ordered CoPt (or FePt) alloys**

Strong PMA;
High thermal stability;
High fabricate temperature.

III. **Co-based multilayers**

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

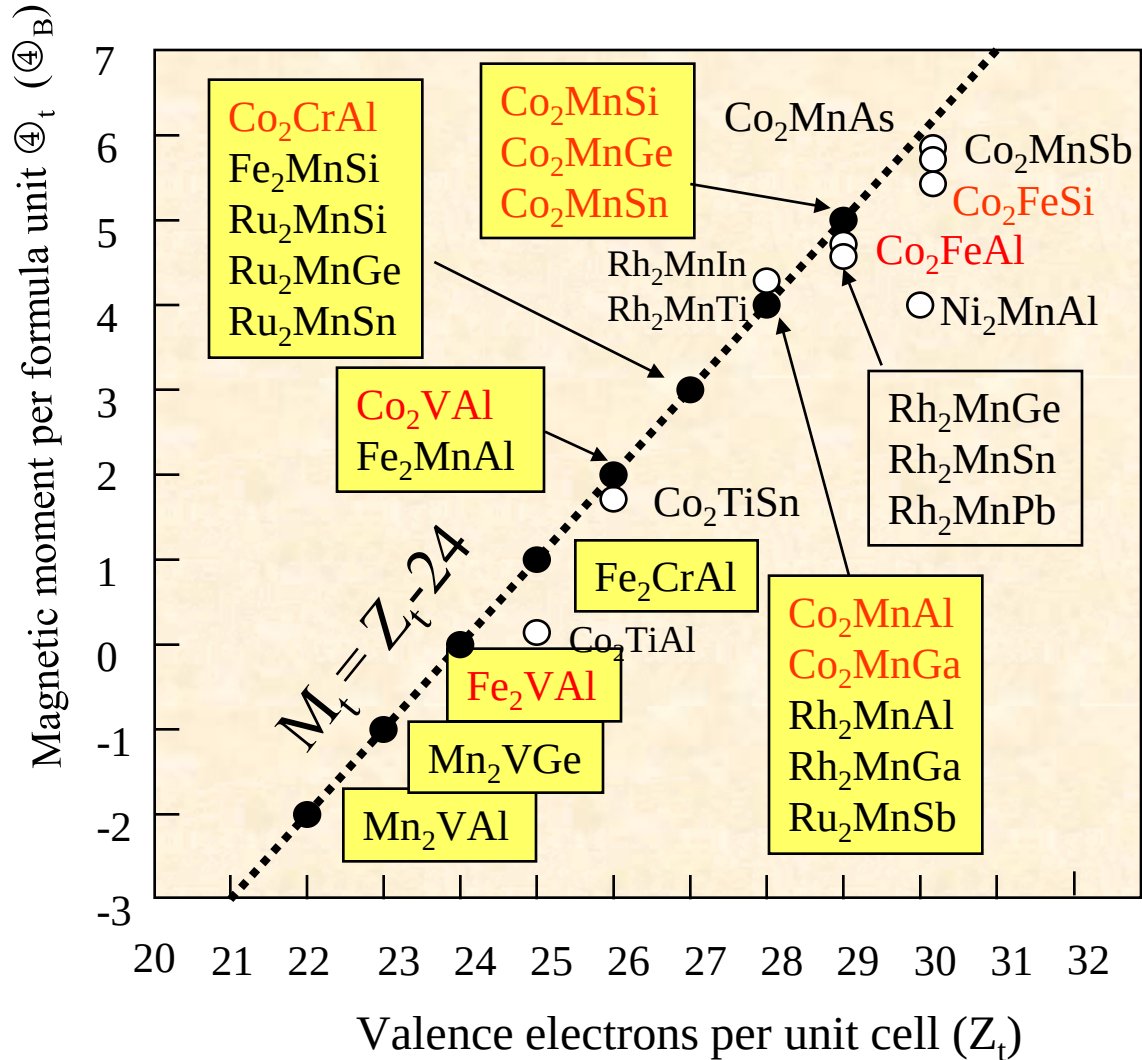
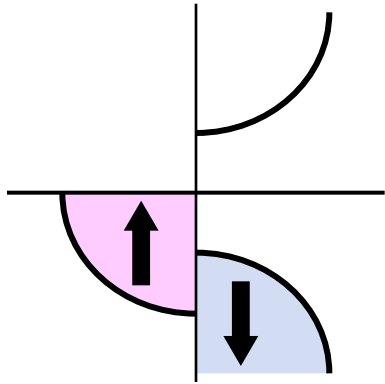
Low SP

Small TMR effect

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

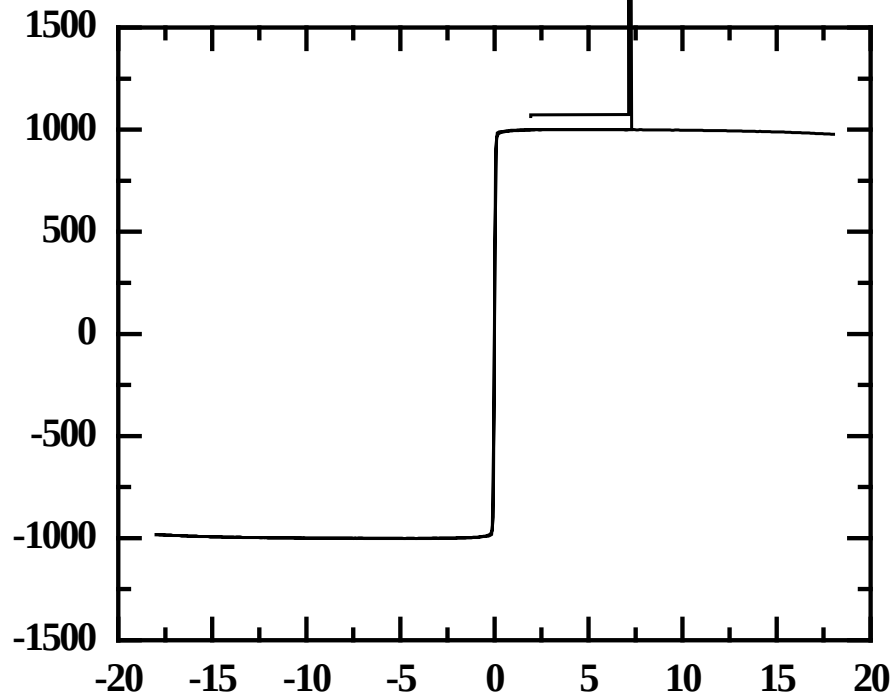
M. Julliere, Phys. Lett. A.54, 225(1975).

Half-metallic full-Heusler alloys



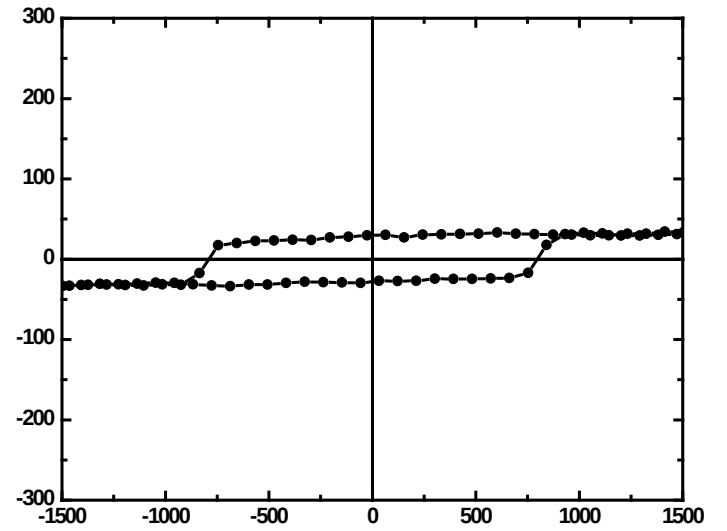
PMA thin films

The Co_2FeAl thin film is always in-plane magnetized.

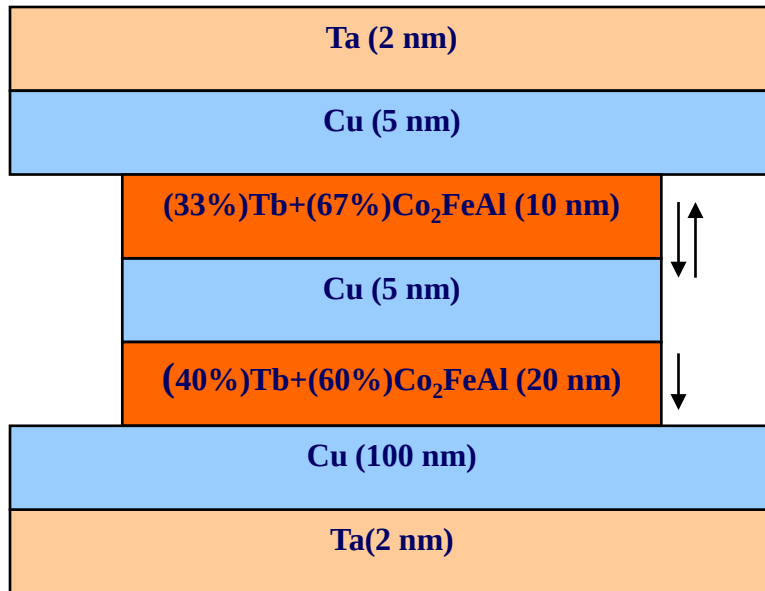


Magnetization curves for a Co_2FeAl film with a thickness of 30 nm. The magnetic field was aligned in the film (black lines) or perpendicular to the film (red lines).

Tb-Co₂FeAl

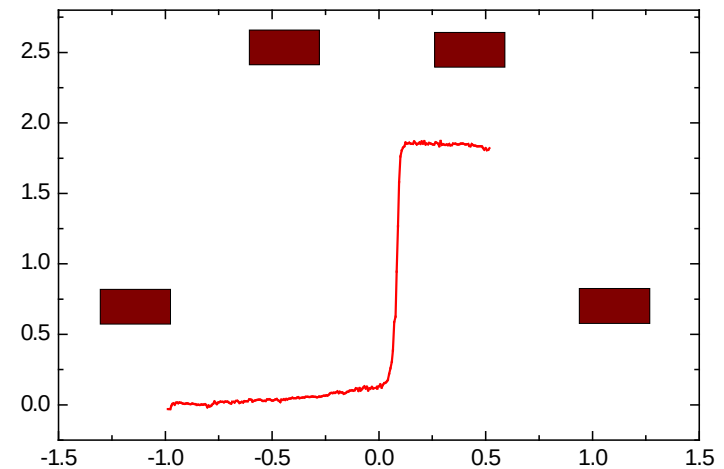


Tb-CFA based CPP SPVs



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

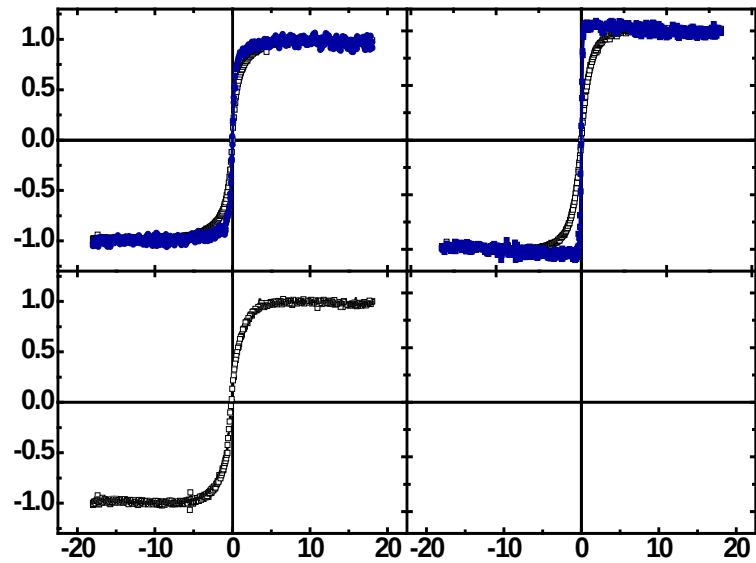
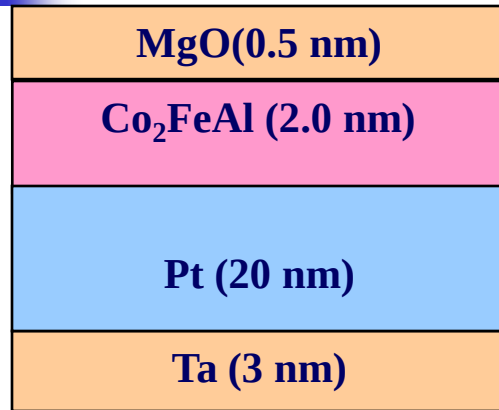
Appl. Phys. Lett. 96, 142505(2010).

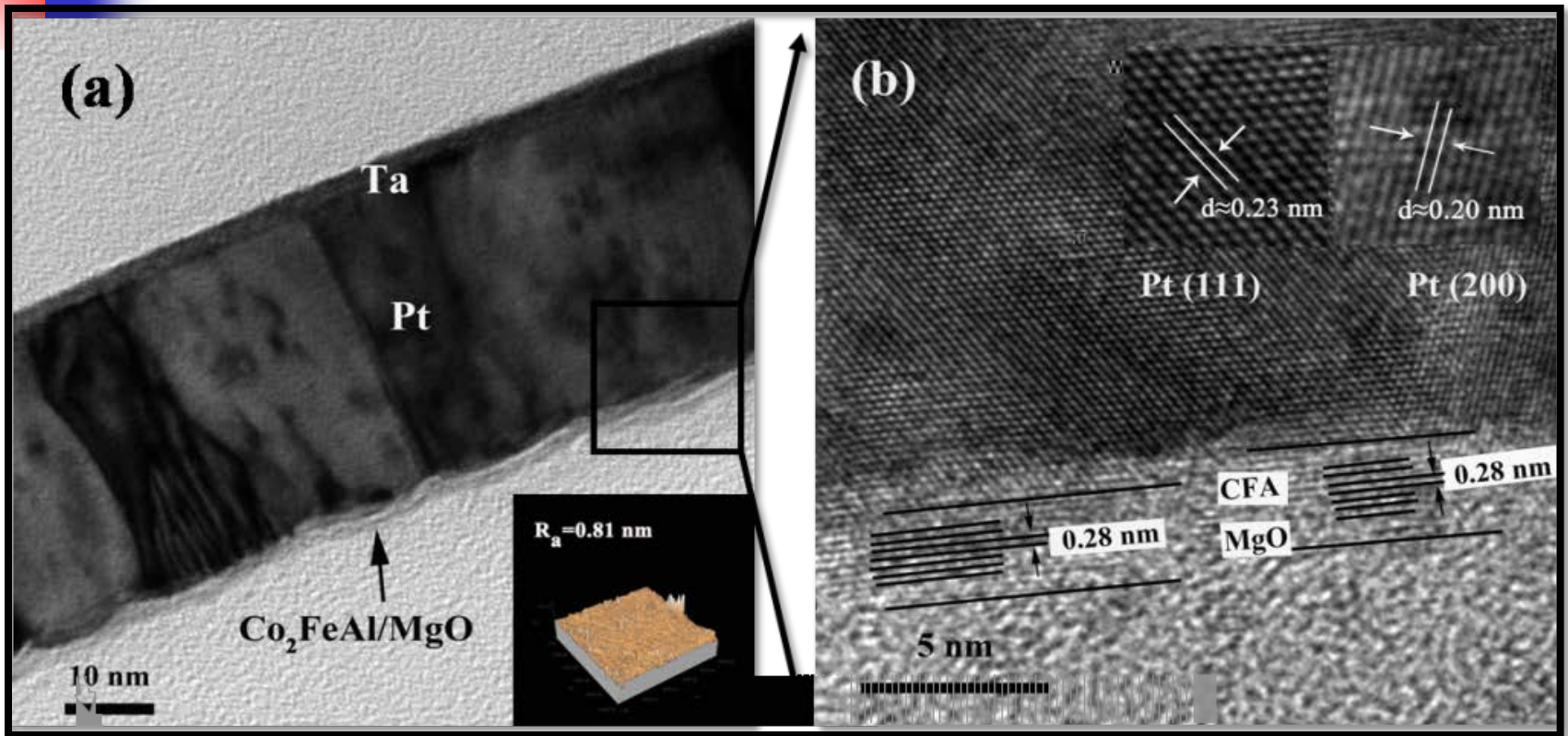


PSPV was patterned into a pillar of 0.5 × 1 μm²

CPP GMR=1.8%

Pt/CFA/MgO





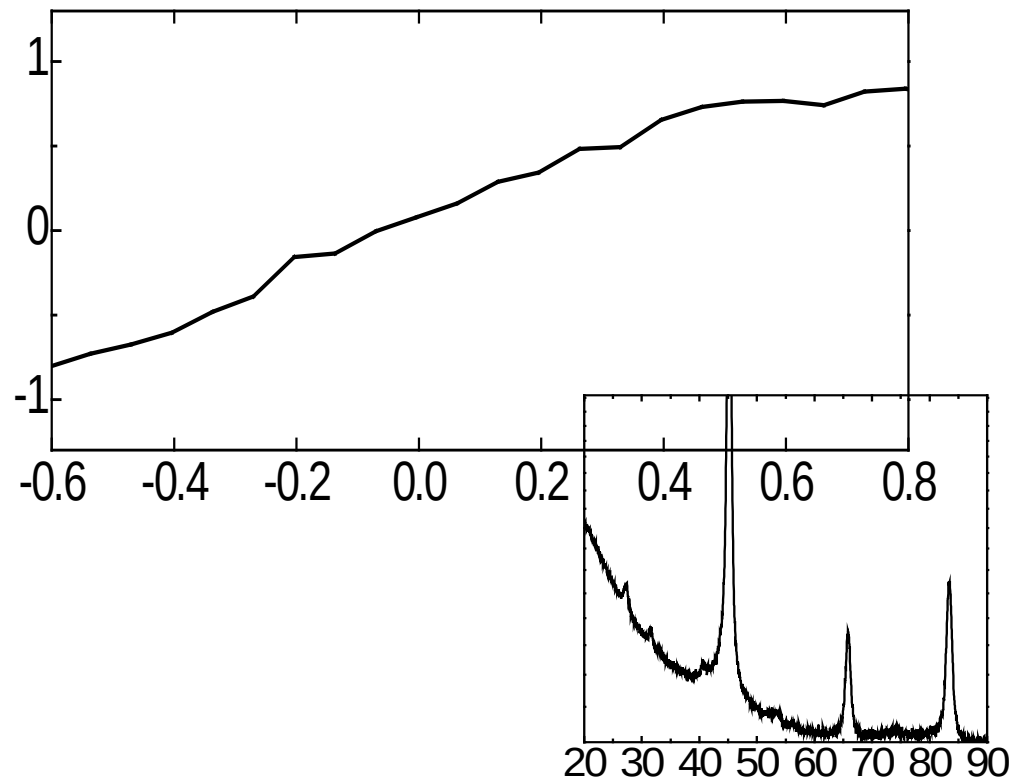
Pt/CFA/MgO interface

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

B2-ordered structure in CFA after annealing.



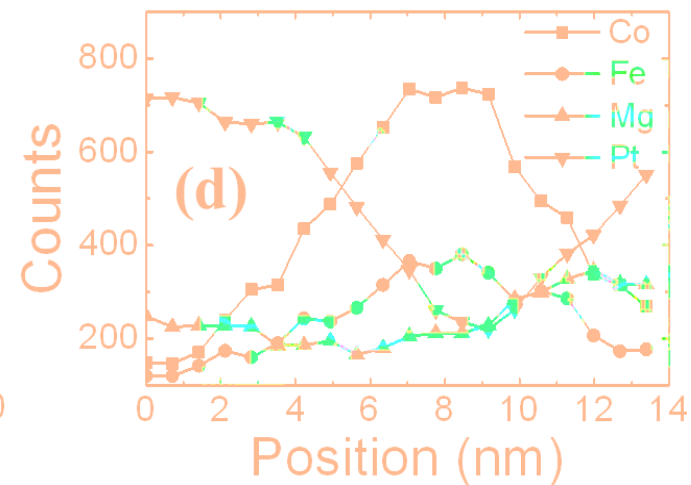
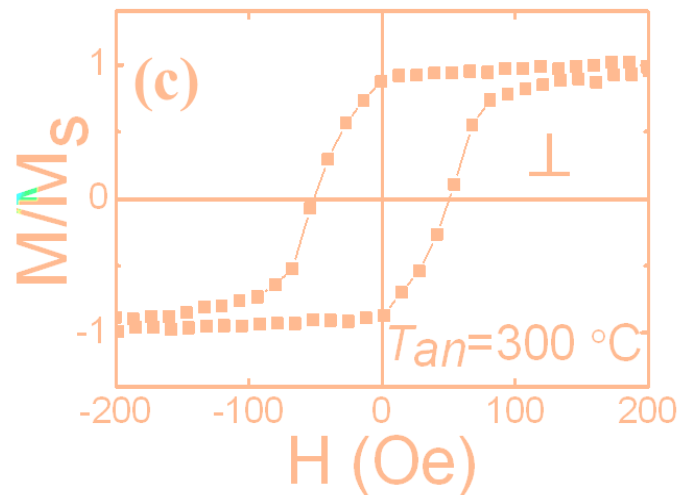
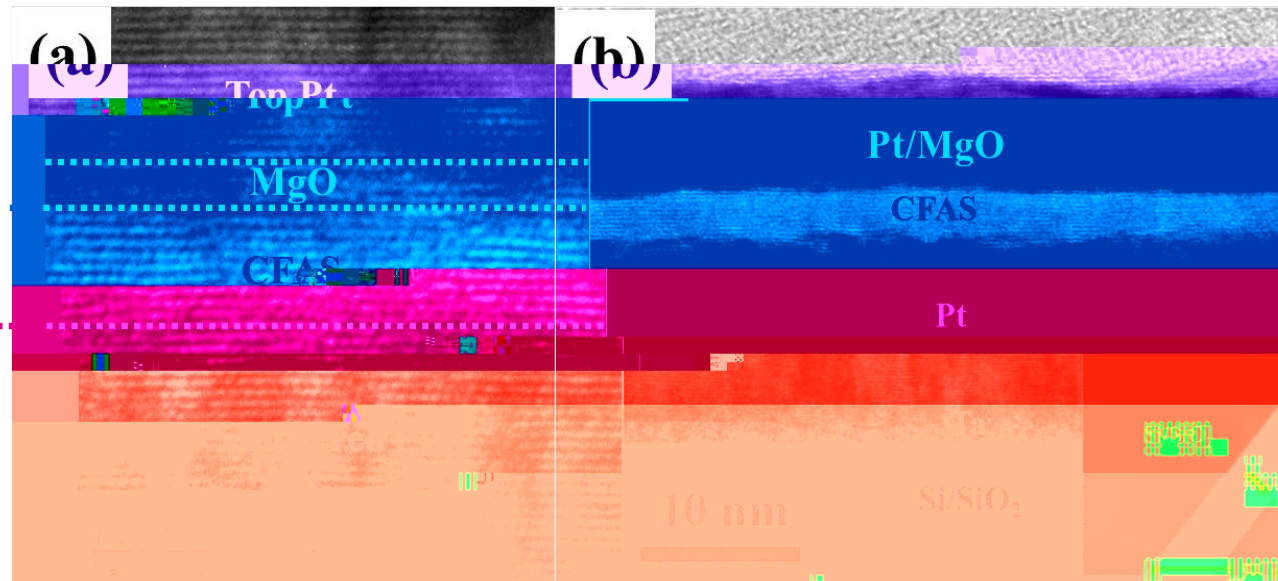
Pt(10)/CFAS(2.5)/MgO(0.5)/Pt(5) (nm)



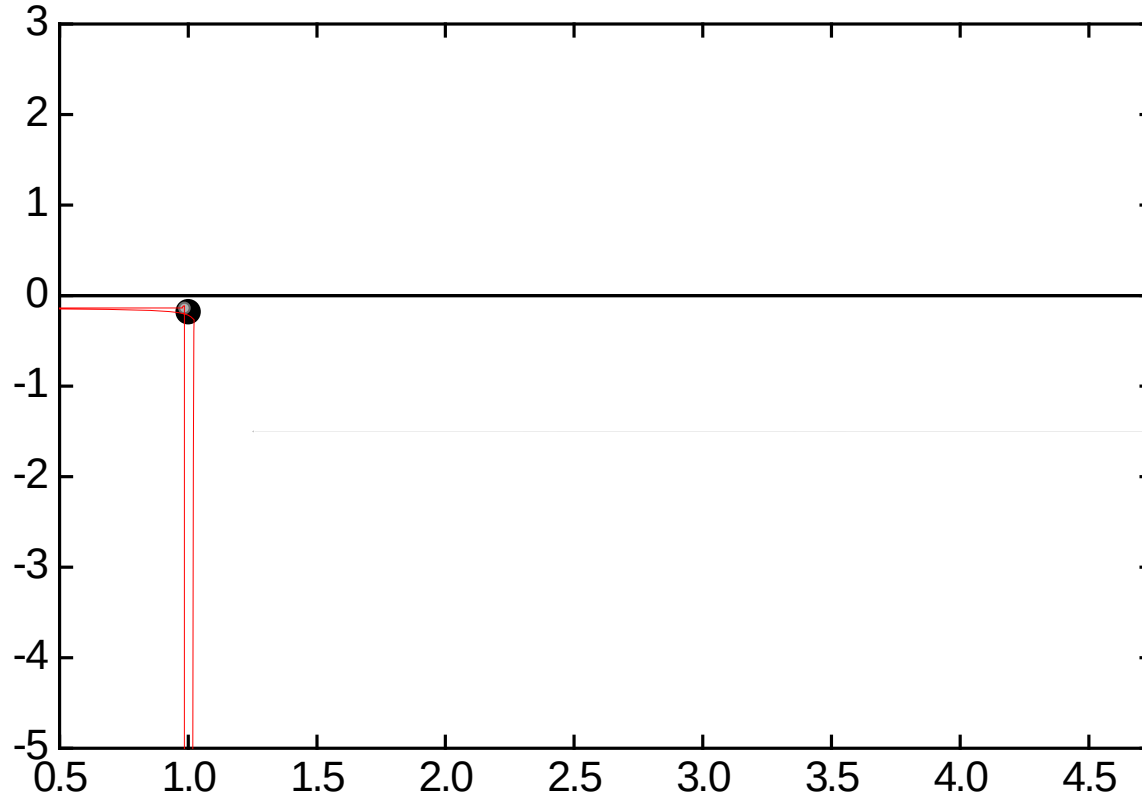
Advantages:

1. Strong PMA $K_u = 2 \sim 3 \times 10^6$ 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)

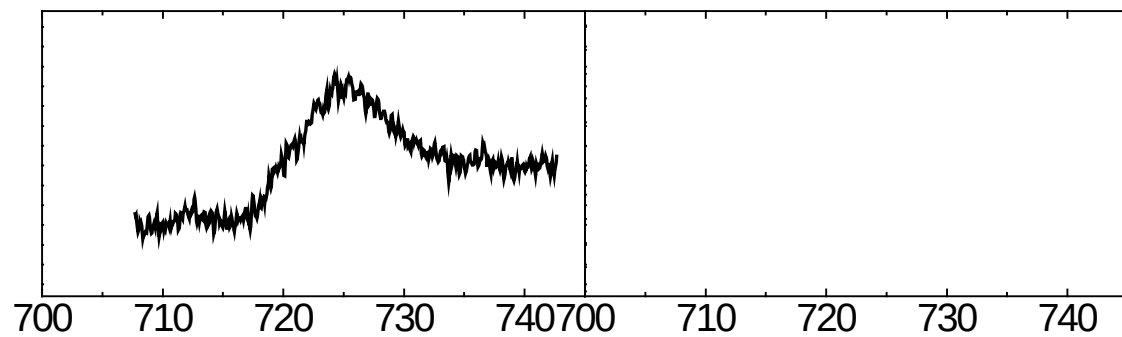
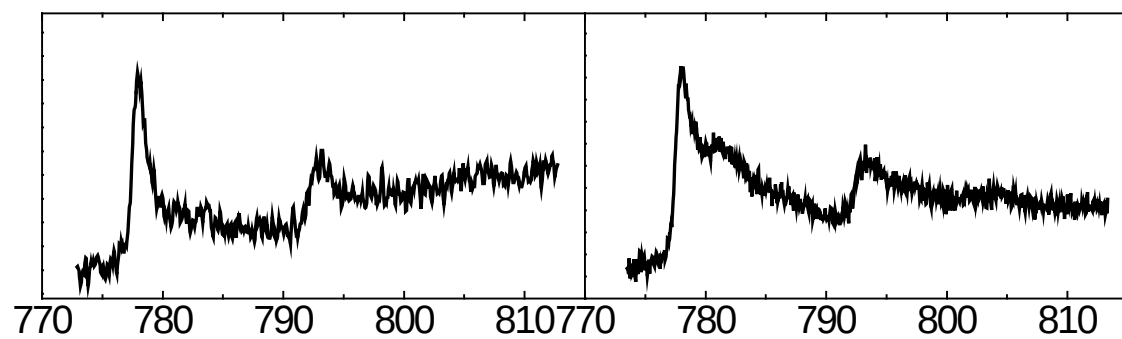
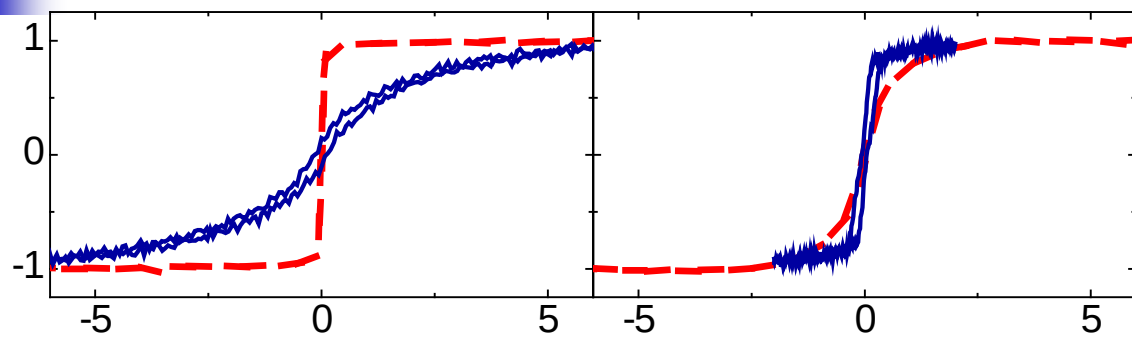


Ta (3)/Pt (10)/CFAS (t_{CFAS})/ MgO (0.5)/Pt (5) (nm)

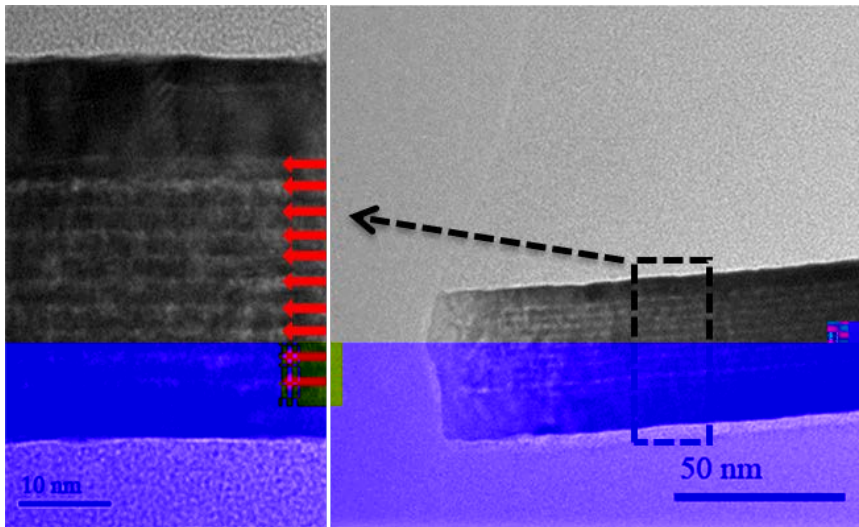
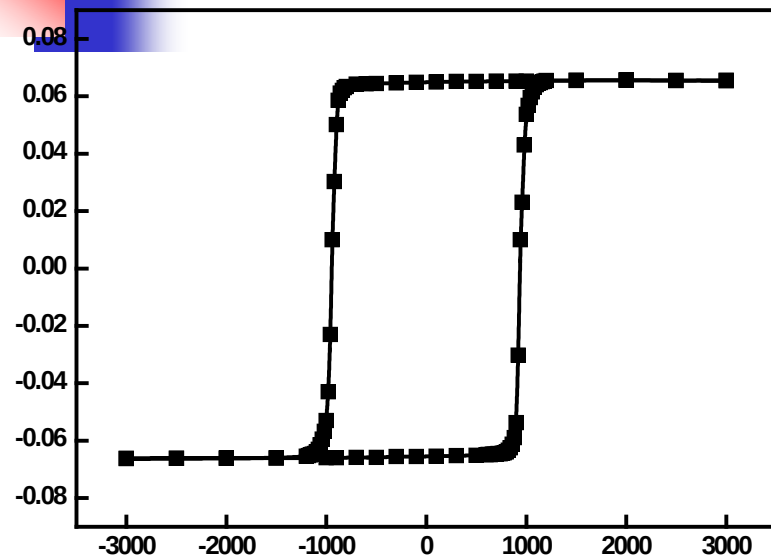


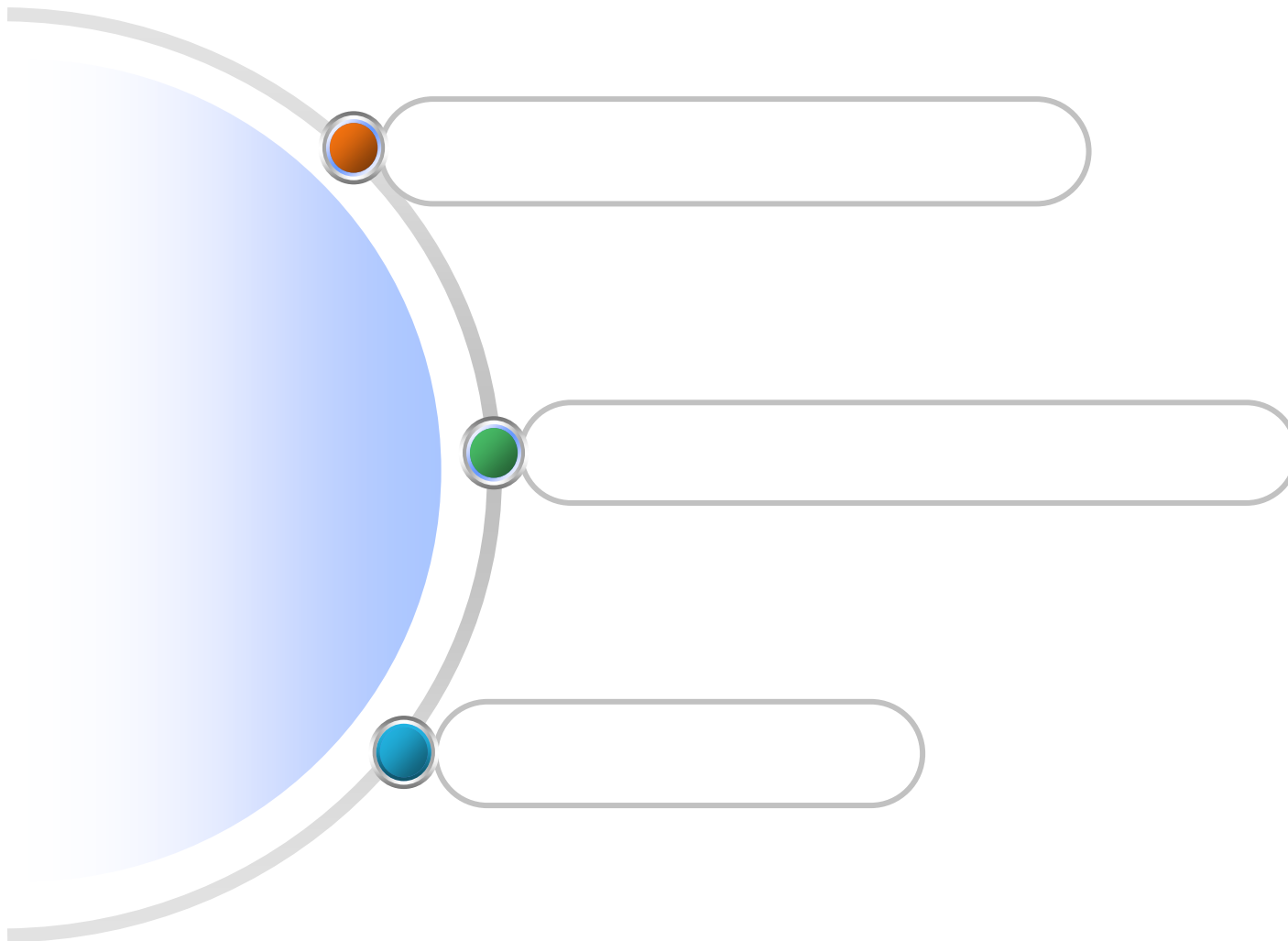
$K_u - t_{CFAS} = (K_v - 2\pi M_s^2) t_{CFAS} + K_s$, where K_v and K_s are bulk and interfacial anisotropy density, respectively.

$K_s \sim 0.8 \text{ erg/cm}^2$
 $K_v \sim -2.6 \text{ erg/cm}^3$

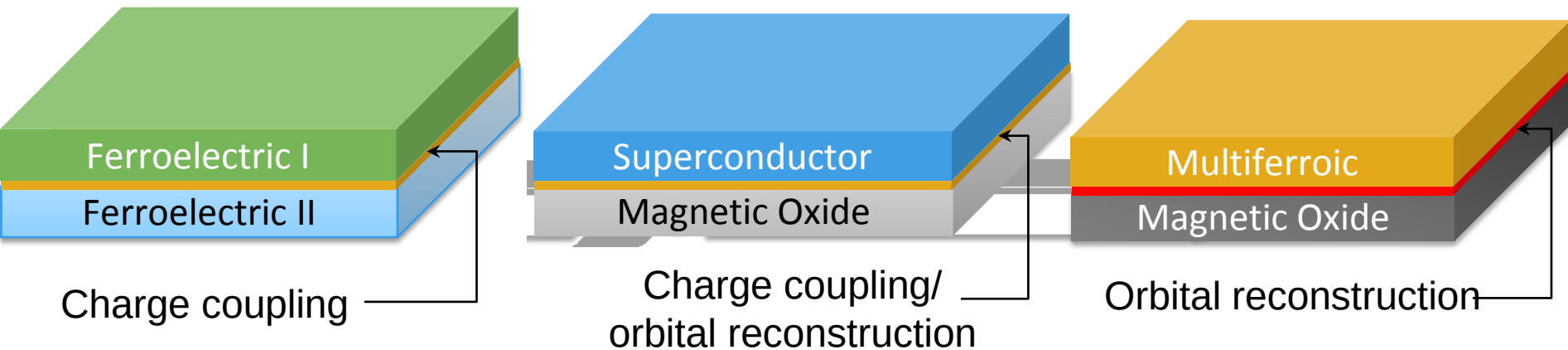
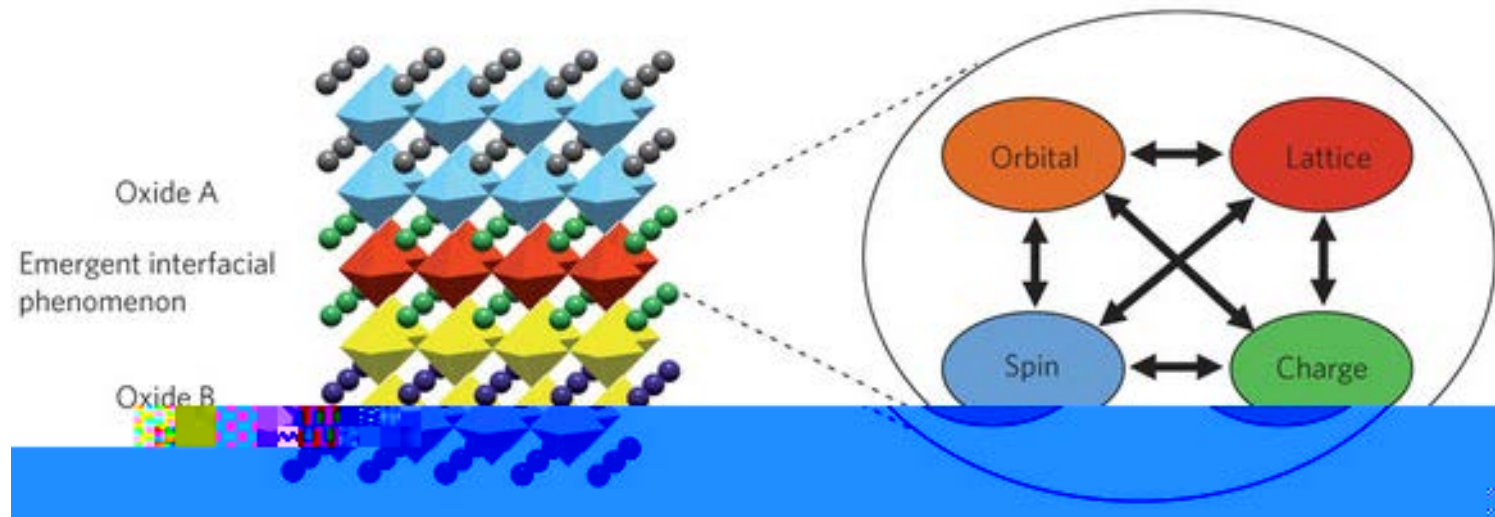


[CFAS (6 Å)/Pt (t Å)]_n

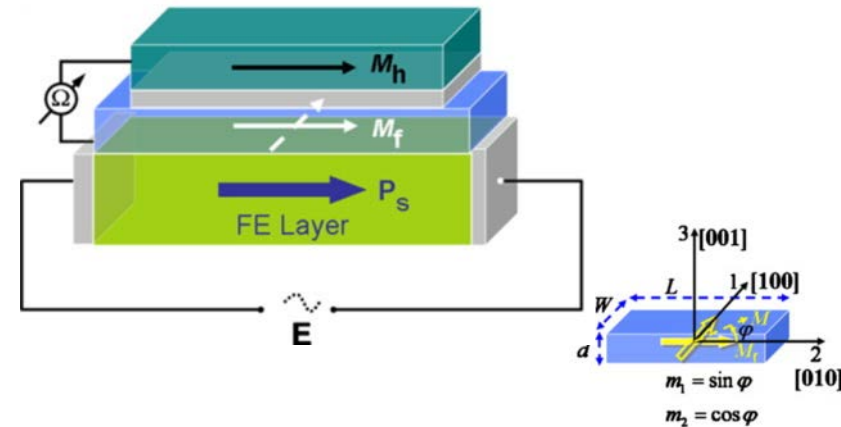
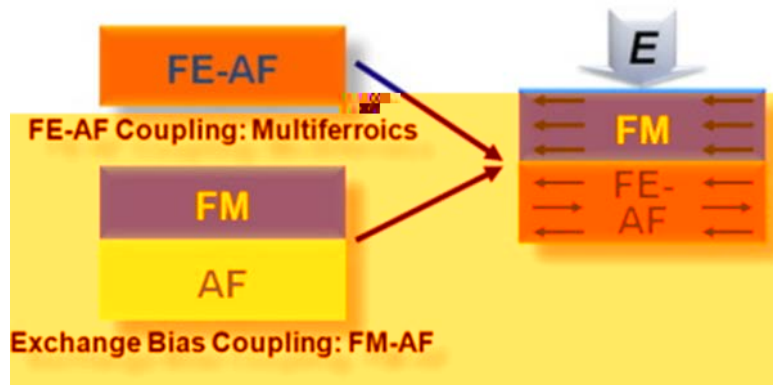
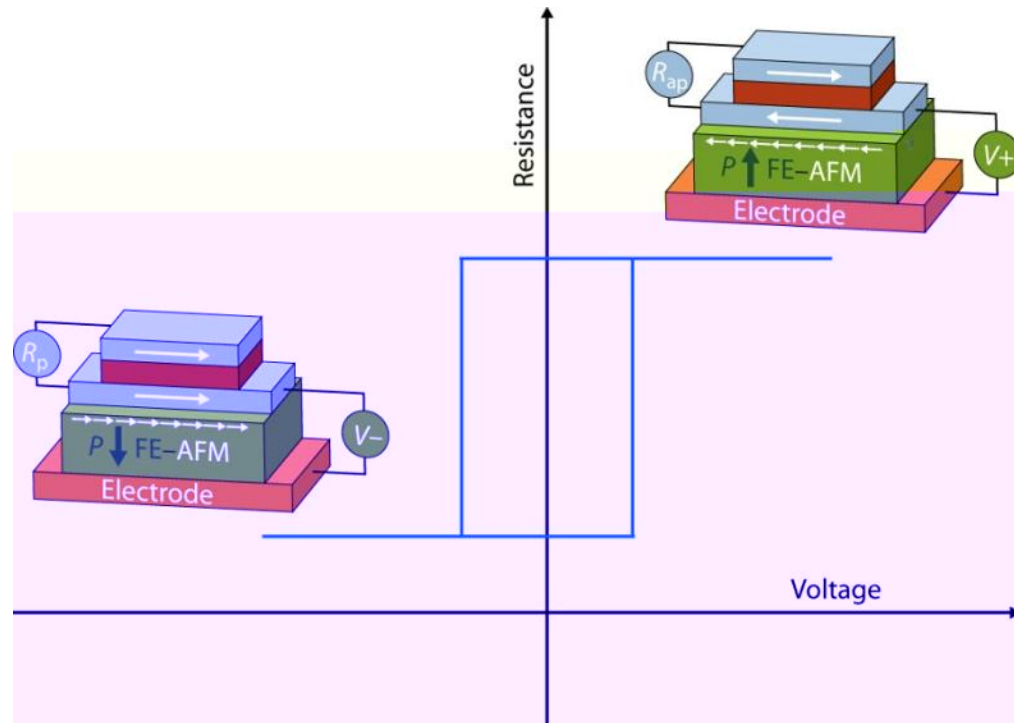


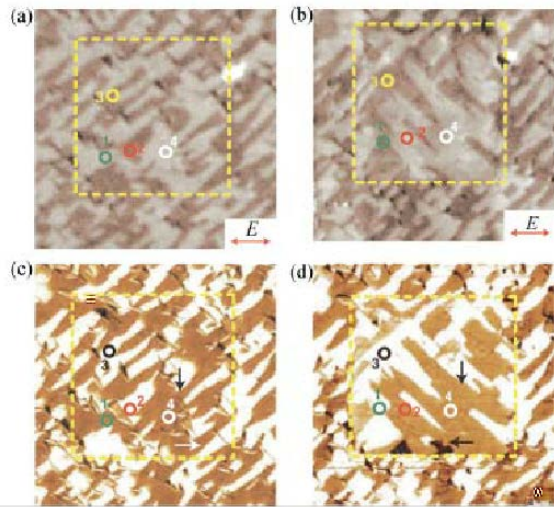


Background & motivations

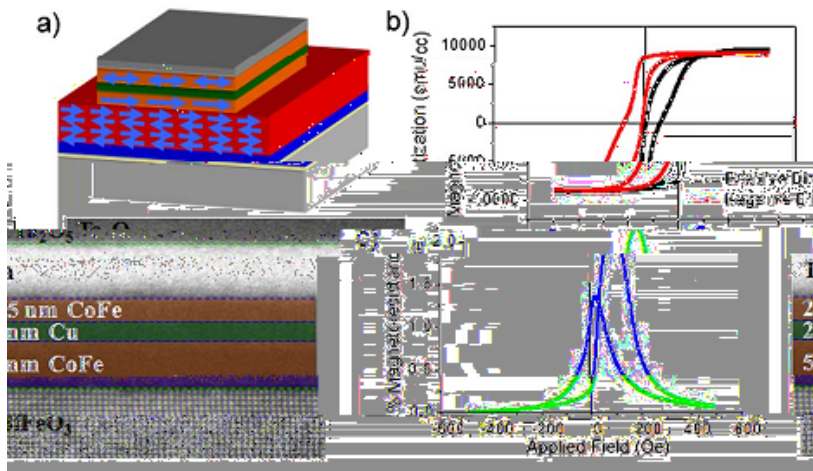


Electric-field controlled magnetism - Future Memory

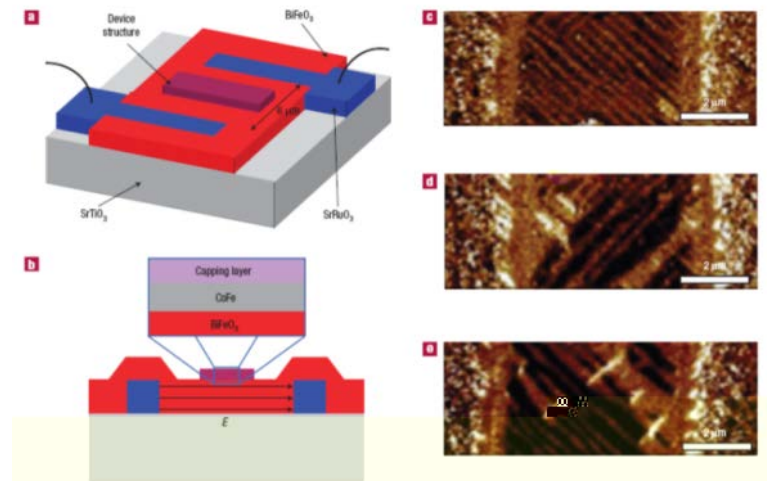




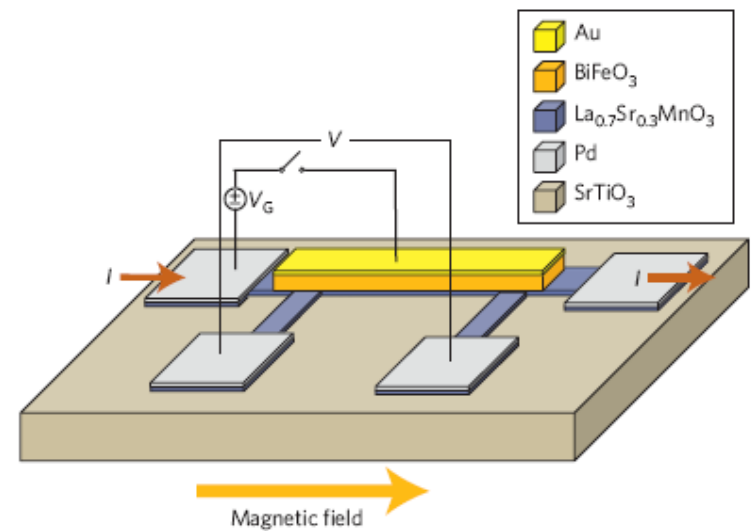
Zhao et al, *Nature Mater* 5, 823-829 (2006).



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

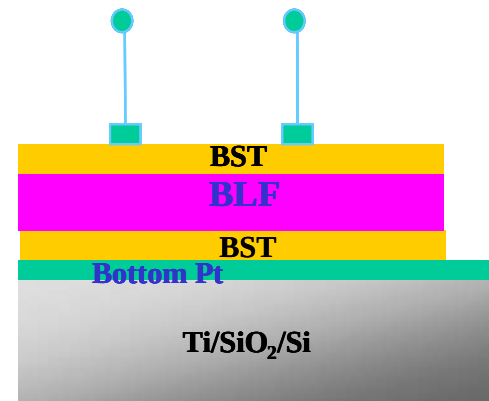
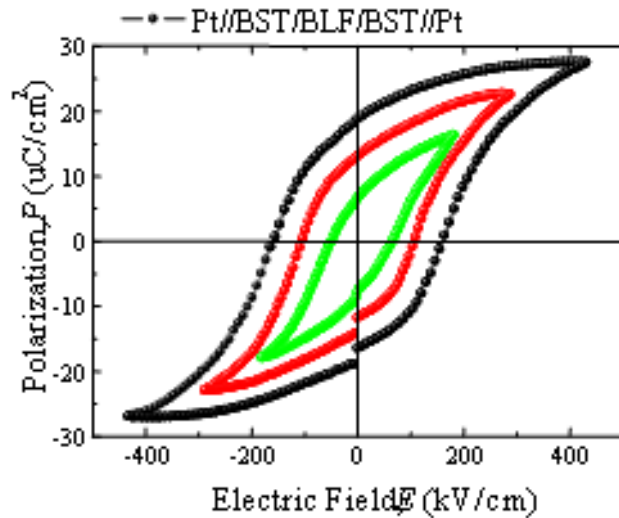


Chu et al, *Nature Mater* 7, 478-482 (2008).

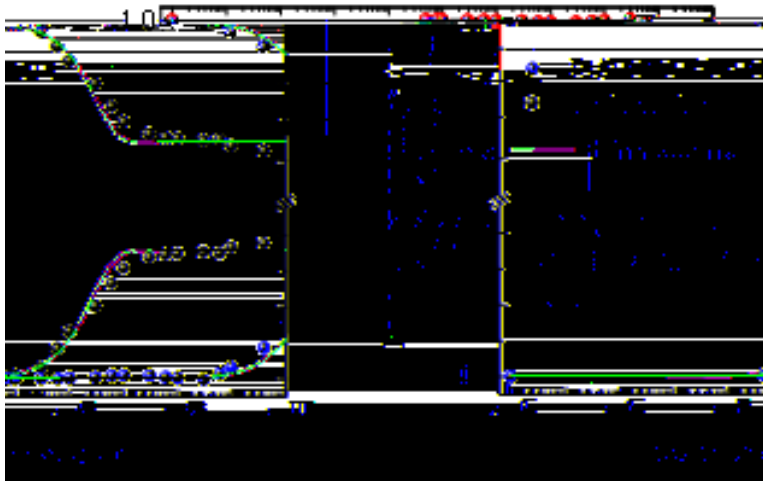


Wu et al, *Nature Mater* 9, 756-761 (2010).

Multiferroic BST/BLFO/BST sandwich

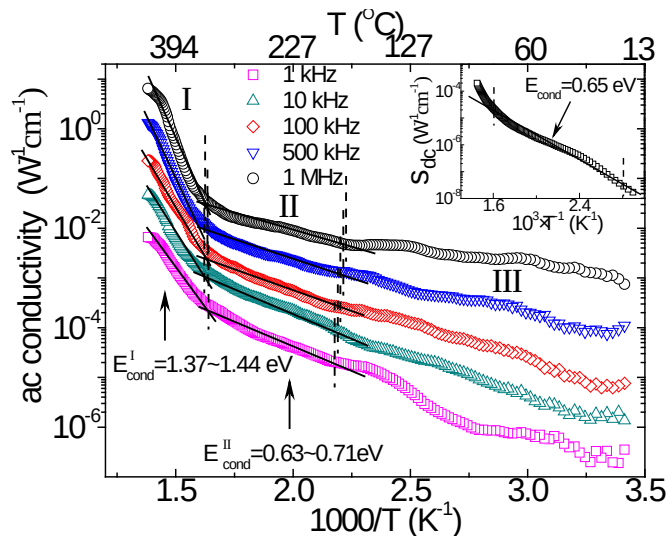
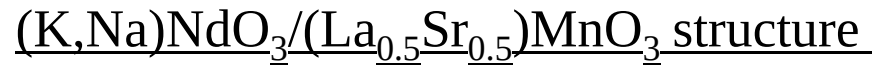


(Ba,Sr)TiO₃/Bi(La, Fe)O₃/(Ba,Sr)TiO₃ structure



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

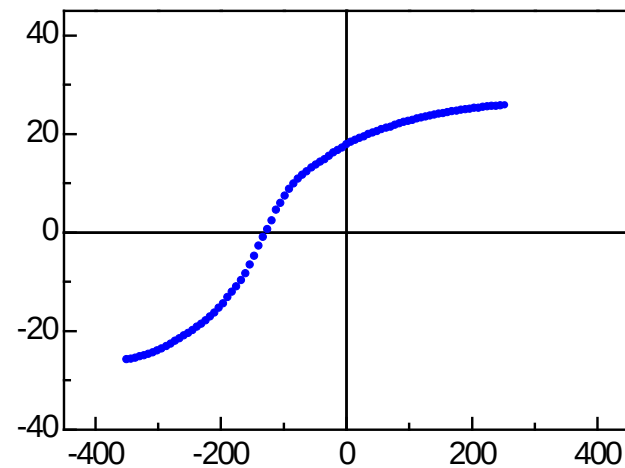
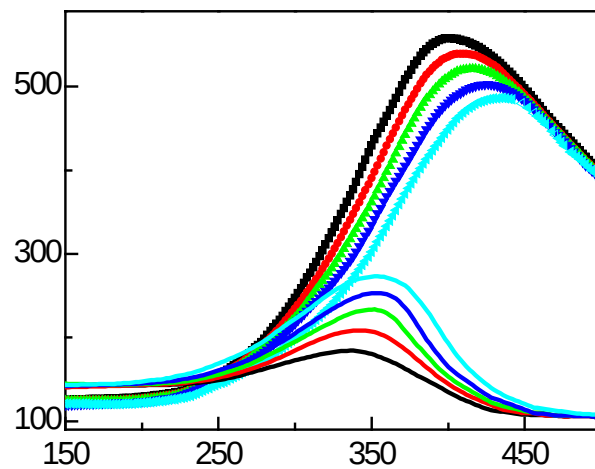
Appl. Phys. Lett, 92, 062902 (2008).



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

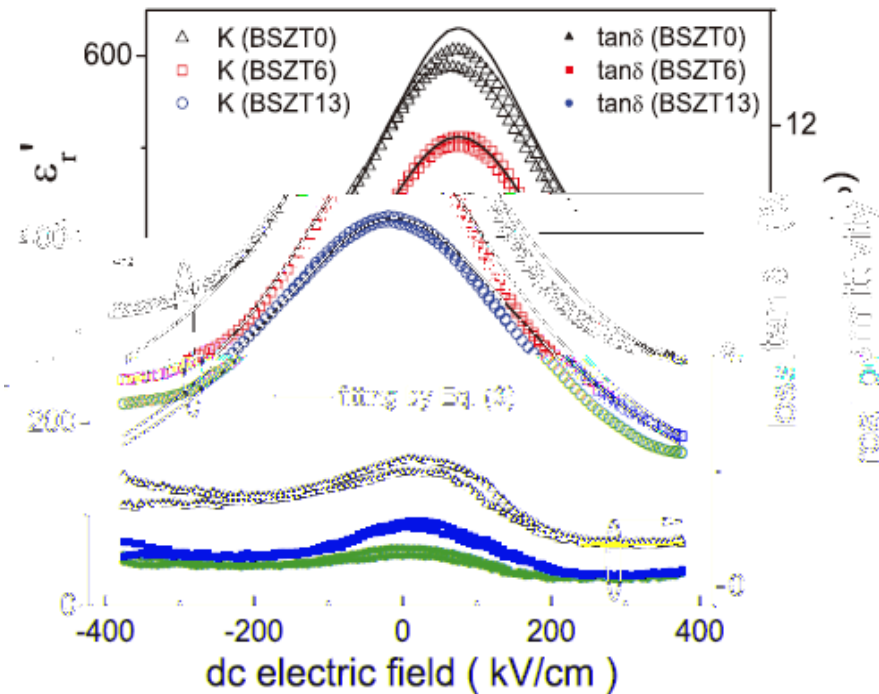
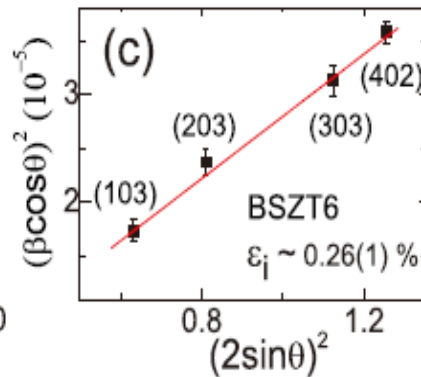
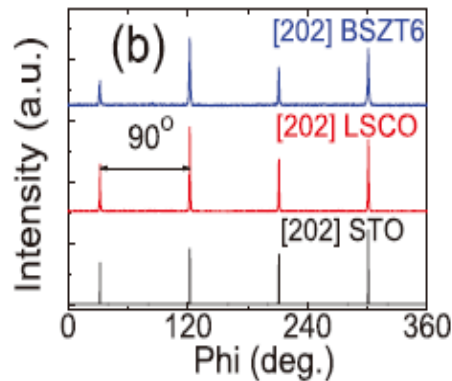
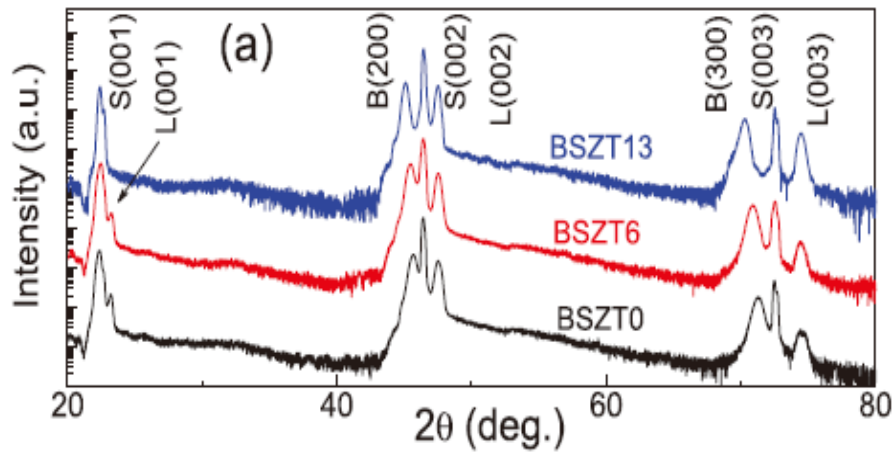
Appl. Phys. Lett, 95, 132905 (2009).

$\text{BiFe}_{0.5}\text{Mn}_{0.5}\text{O}_3/\text{CaRuO}_3$ heterostructures



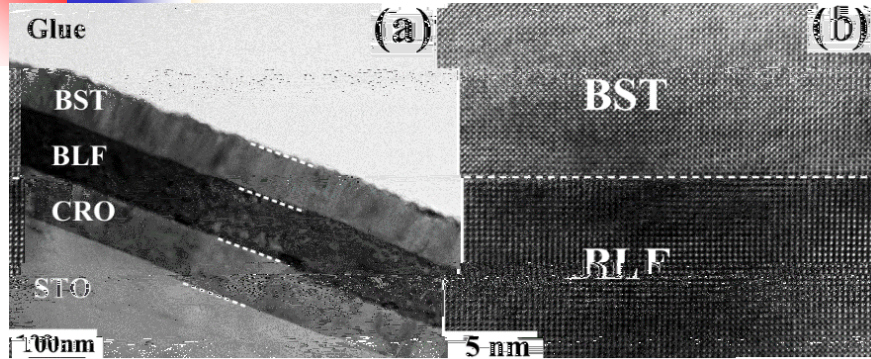
Appl. Phys. Lett, 99, 062905 (2011).

Defects control in Co-doped BSZT films



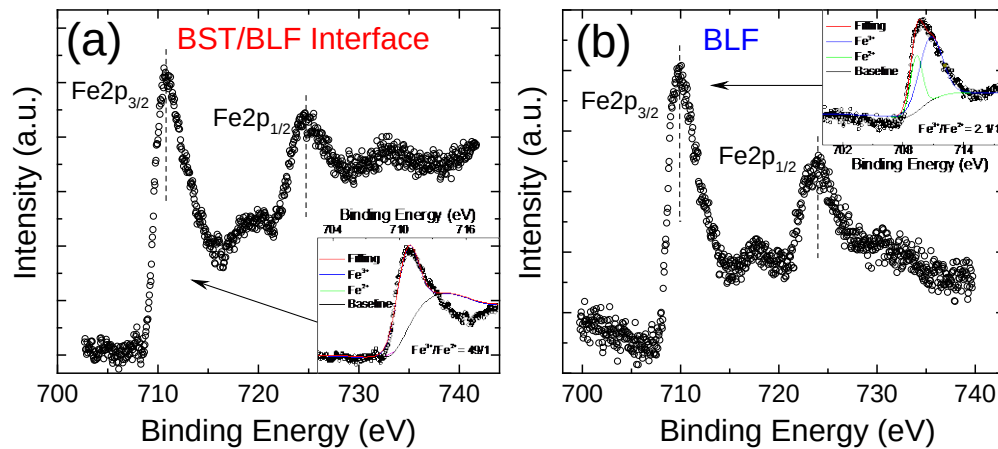
Appl. Phys. Lett, 99, 232910 (2011).

(BaSr)TiO₃/(BiLa)FeO₃ multiferroic heterostructure



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

Lattice correlated



$$Fe^{2+} - V_O^{\bullet\bullet} - Fe^{3+} \sim 0.97 \text{ eV}$$

$$V_O^{\bullet\bullet} \sim 0.39 - 0.47 \text{ eV}$$

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



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

*Thanks for your
attention !*

