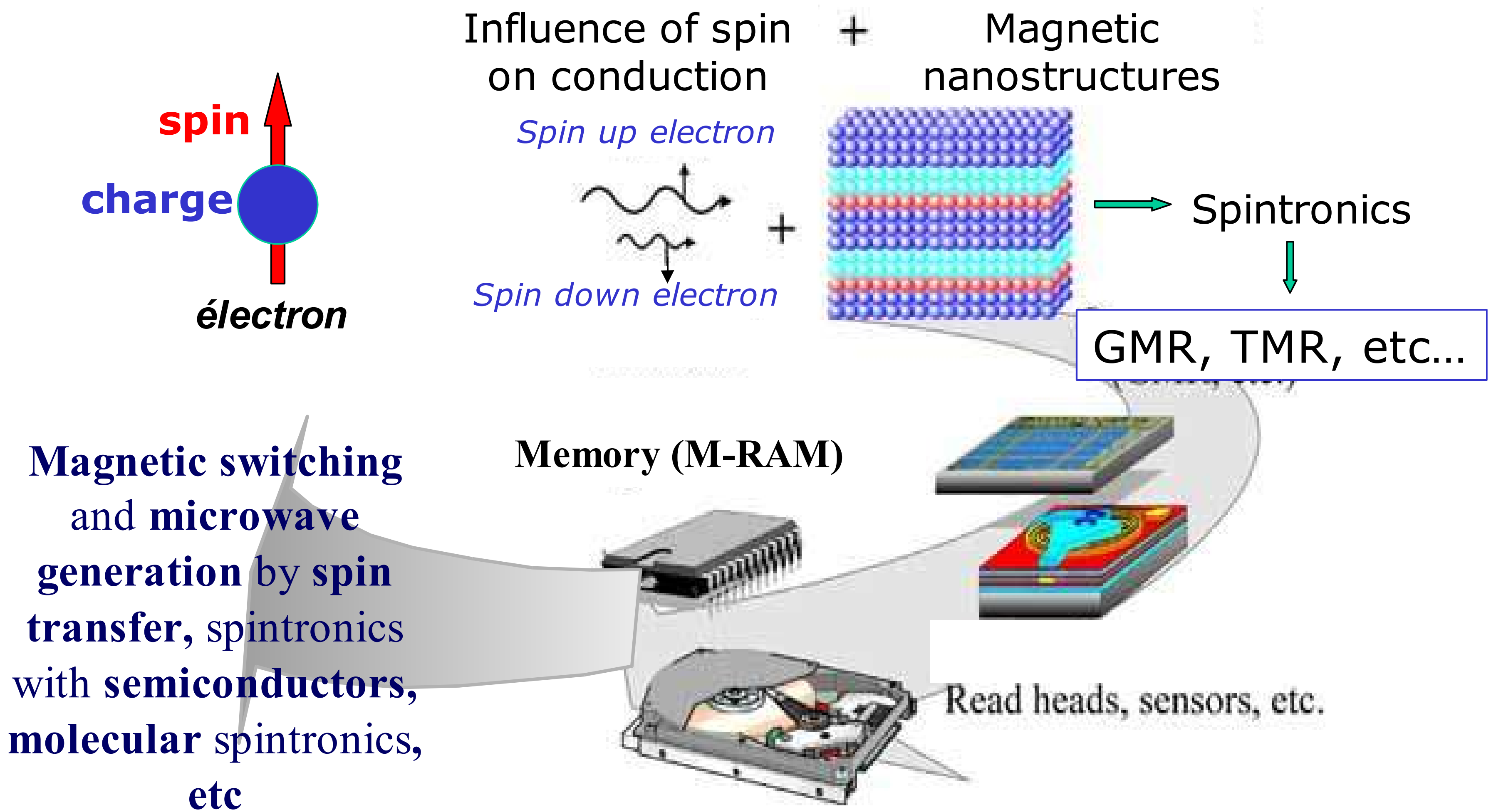
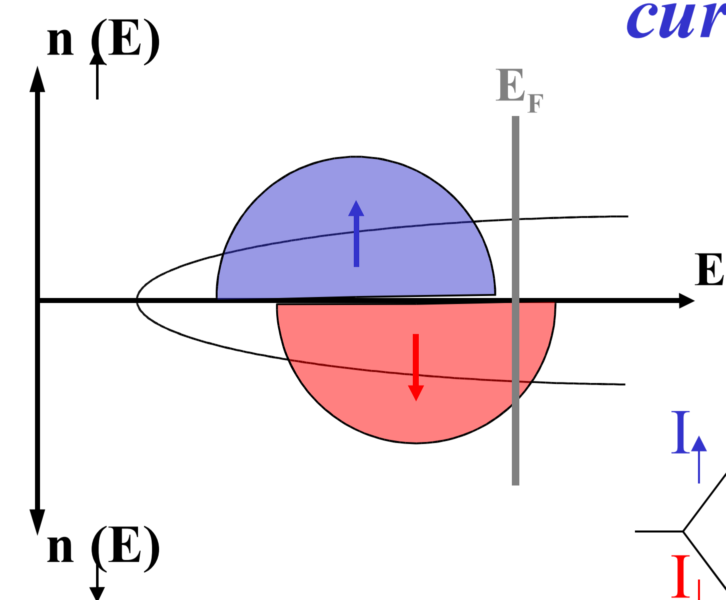
Albert Fert, UMR CNRS/Thales, Palaiseau, and Université Paris-Sud, Orsay, France

The origin, the development and the future of spintronics



Spin dependent conduction in ferromagnetic metals

current model)



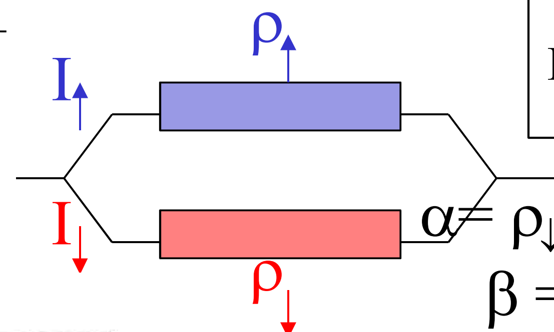
Mott, Proc.Roy.Soc A153, 1936

Fert et al, PRL 21, 1190, 1968

Loegel-Gautier, JPCS 32, 1971

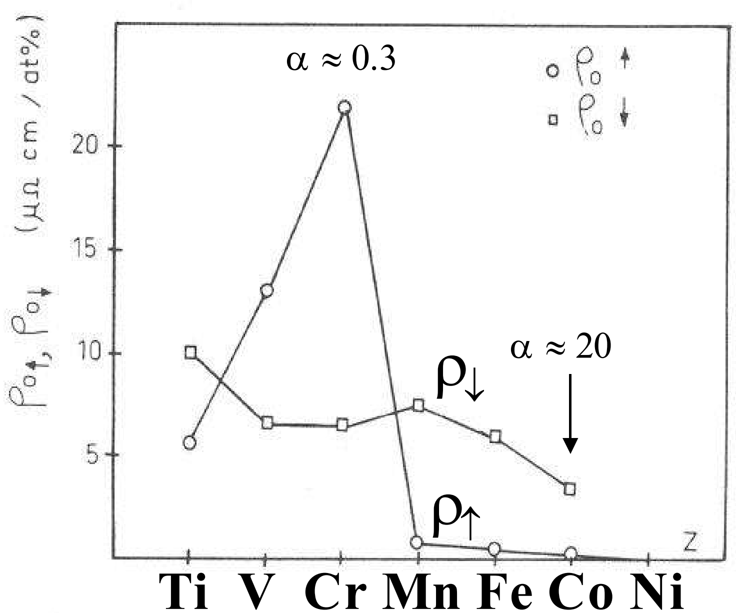
Fert et al,J.Phys.F6, 849, 1976

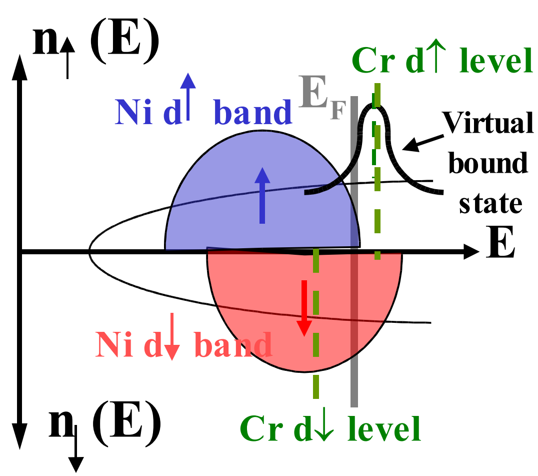
Dorlejin et al, ibid F7, 23, 1977



$\alpha = \rho_\downarrow / \rho_\uparrow$ or

$$\beta = (\rho_\downarrow - \rho_\uparrow)/(\rho_\downarrow + \rho_\uparrow) = (\alpha - 1)/(\alpha + 1)$$



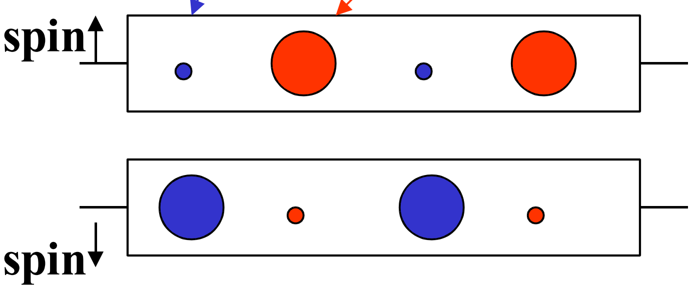


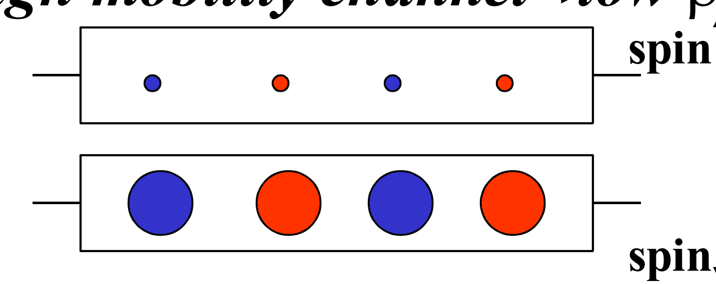
Mixing impurities A and B with opposite or similar spin asymmetries: ***the pre-concept of GMR***

Example: Ni + impurities A and B *(Fert-Campbell, 1968, 1971)*

$\alpha = \rho_{\downarrow}/\rho_{\uparrow}$

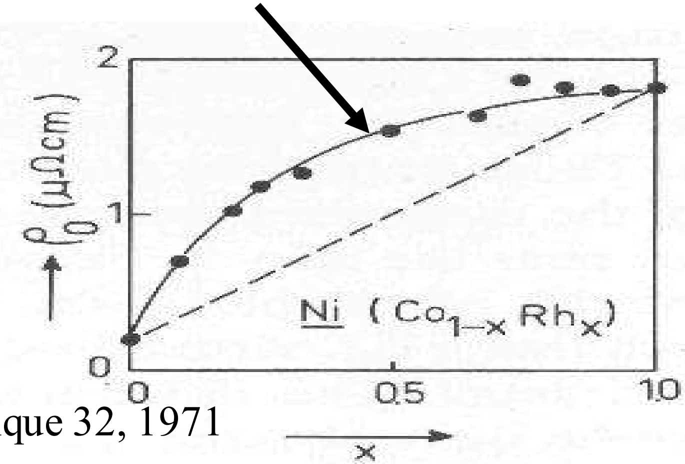
1st case	***2d case***
$\alpha_A > 1$, $\alpha_B < 1$	α_A **and** $\alpha_B > 1$
	High mobility channel→low ρ

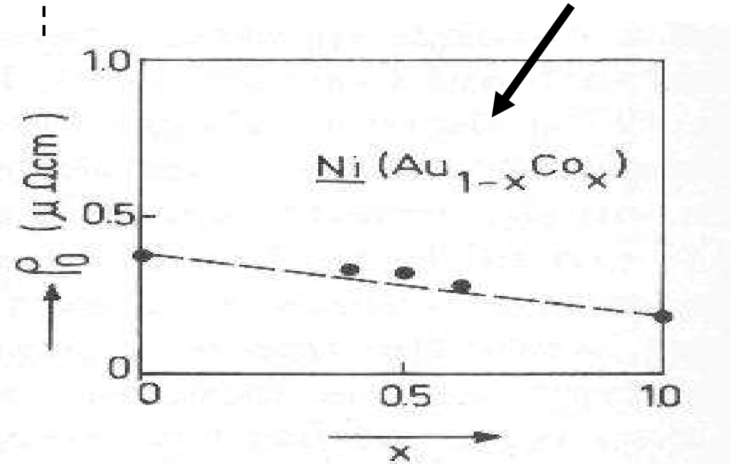




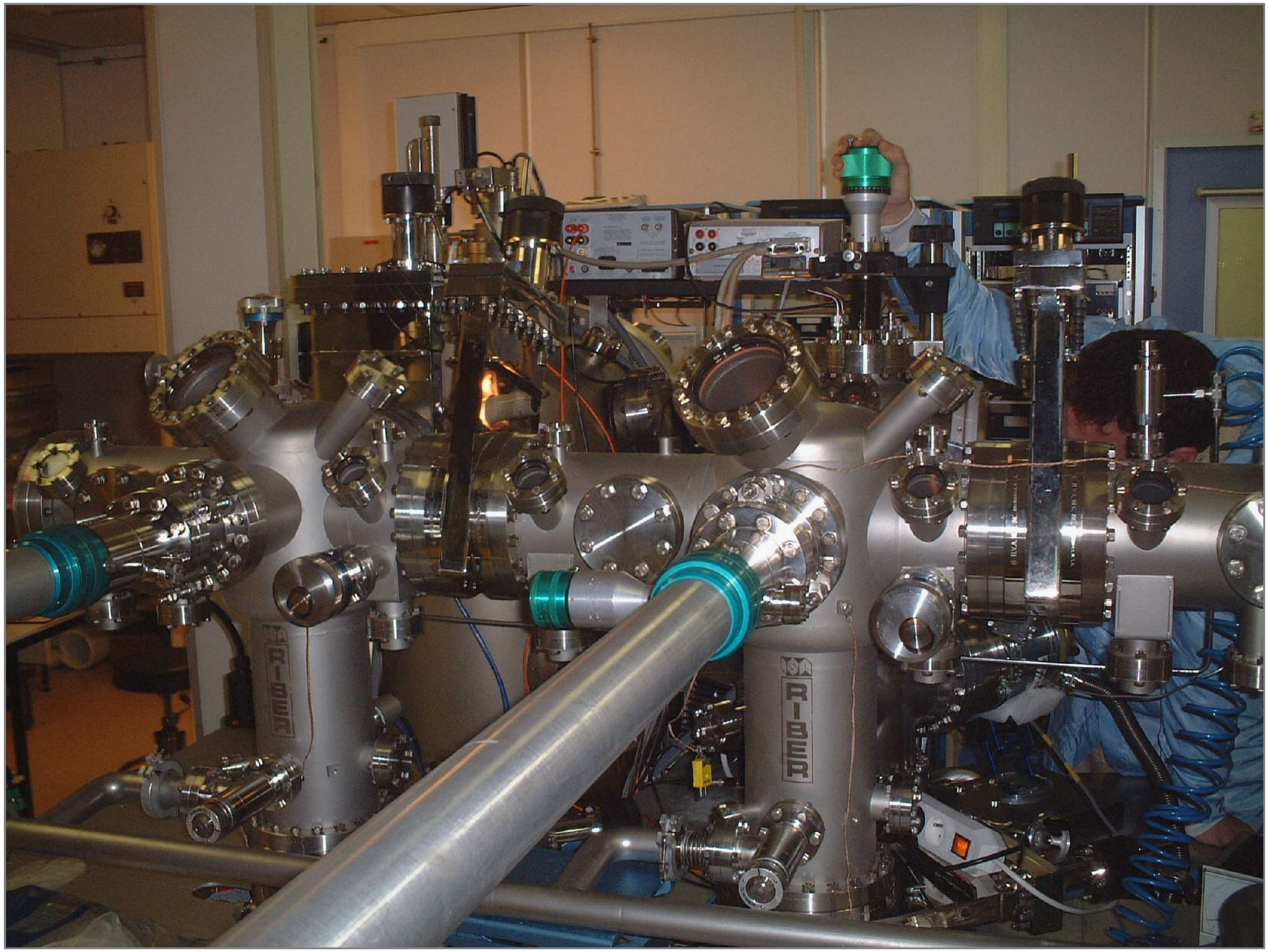
$\rho_{AB} >> \rho_A + \rho_B$

$\rho_{AB} \approx \rho_A + \rho_B$



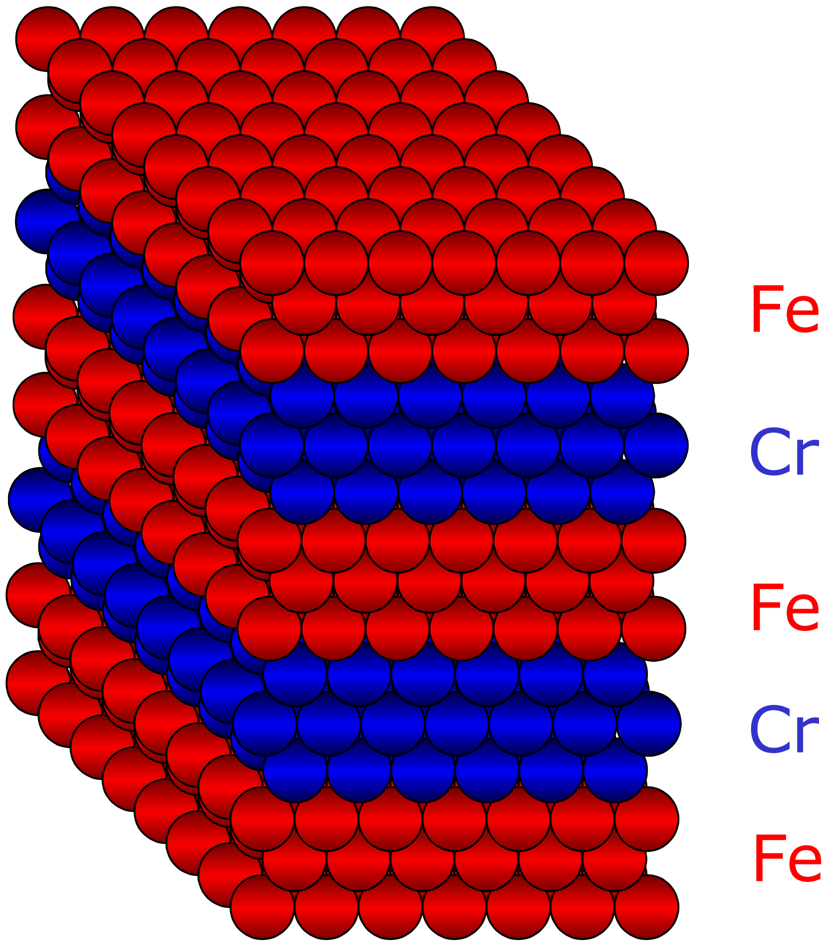


J. de Physique 32, 1971



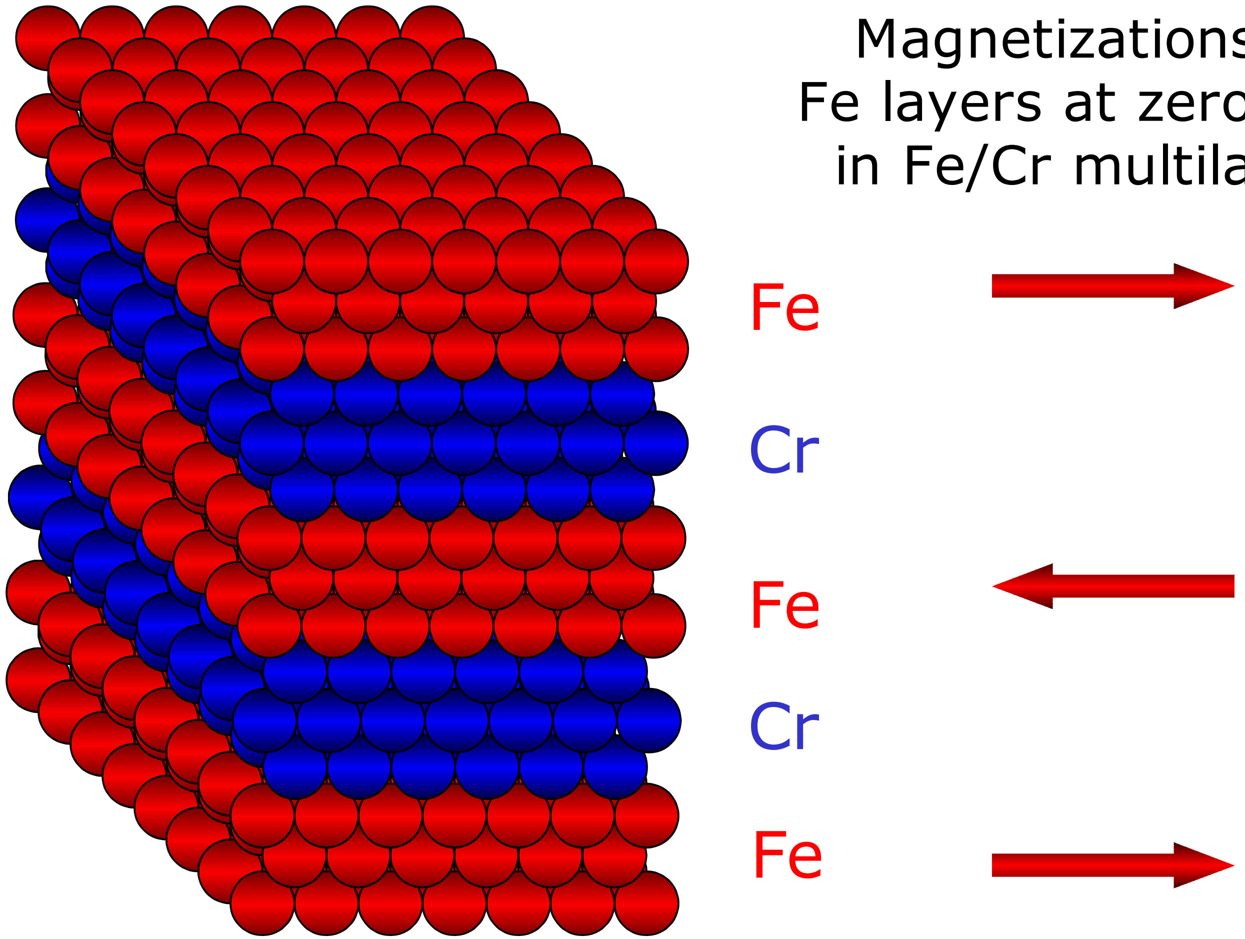
Molecular Beam Epitaxy
(growth of metallic multilayers)

- **Magnetic multilayers**



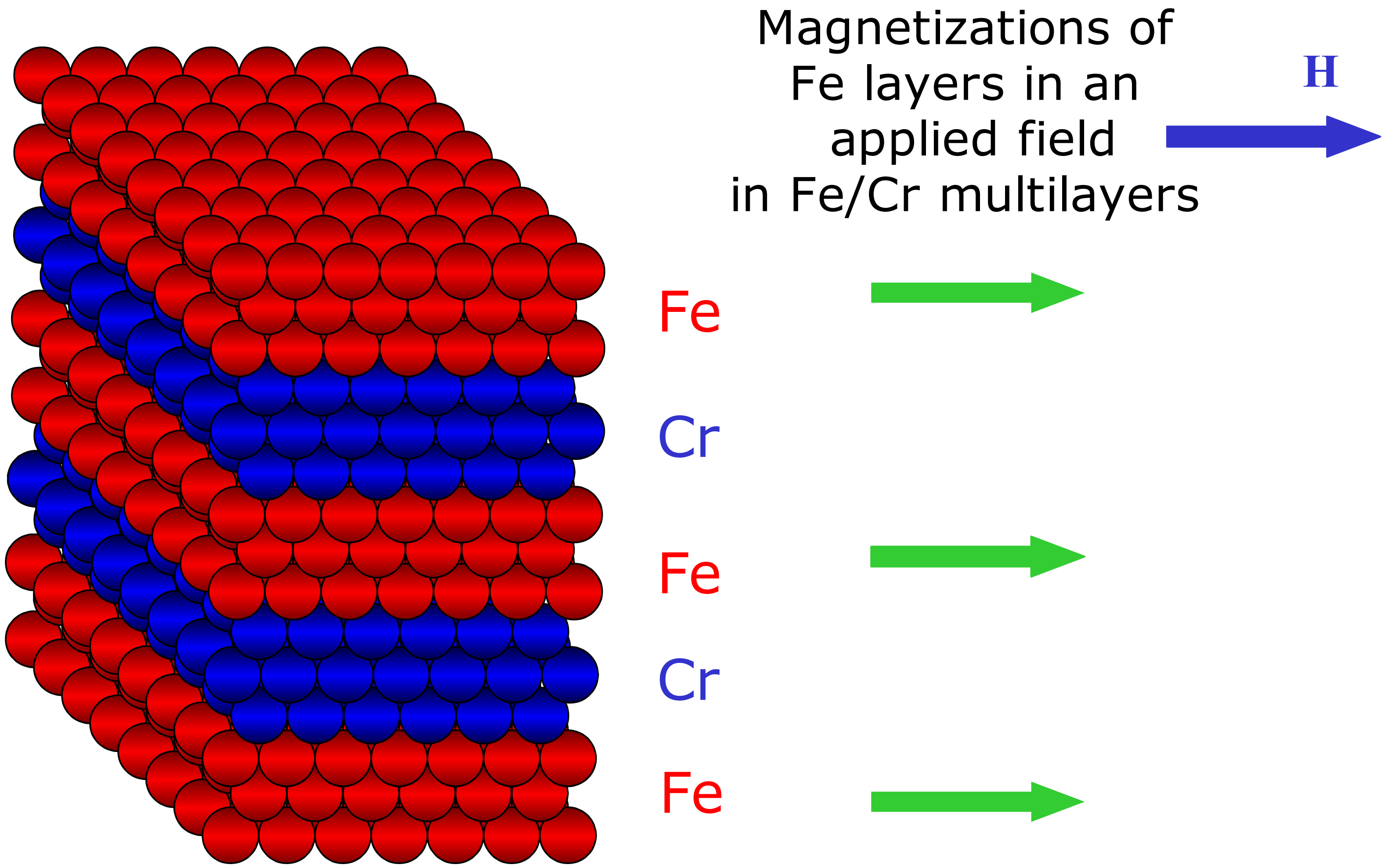
- **Magnetic multilayers**

Magnetizations of
Fe layers at zero field
in Fe/Cr multilayers



P. Grünberg, 1986 → antiferromagnetic interlayer coupling

- **Magnetic multilayers**

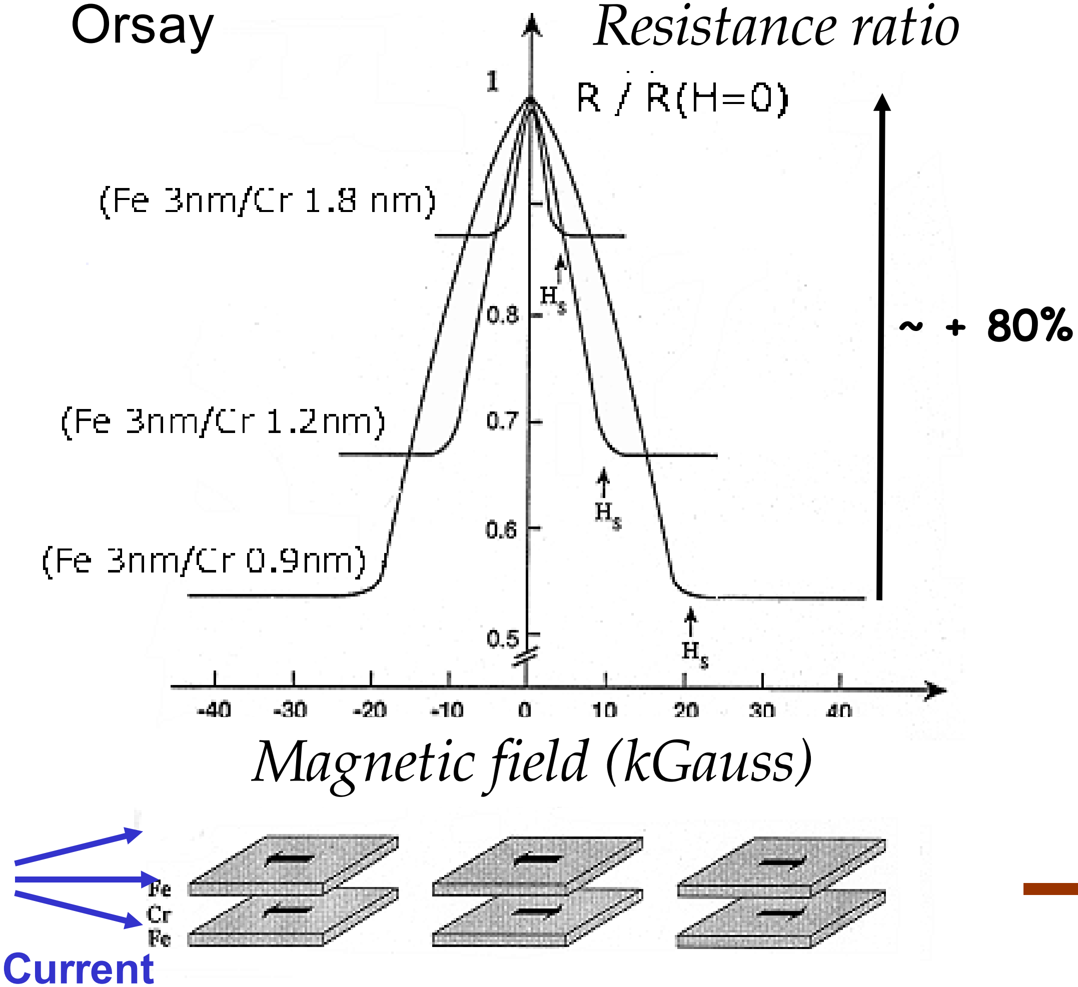


P. Grünberg, 1986 → antiferromagnetic interlayer coupling

• Giant Magnetoresistance (GMR)

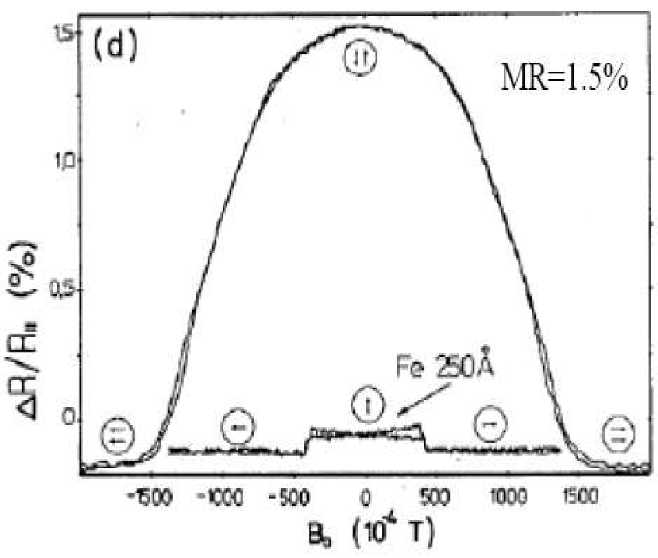
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

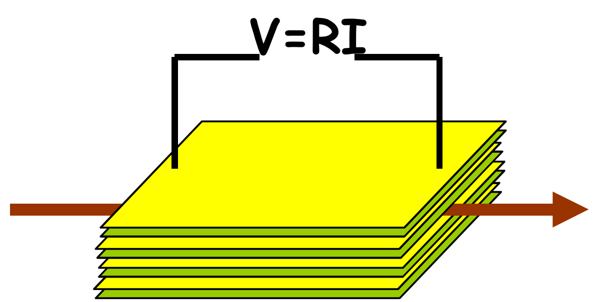
Orsay



AP (AntiParallel) **P** (Parallel)

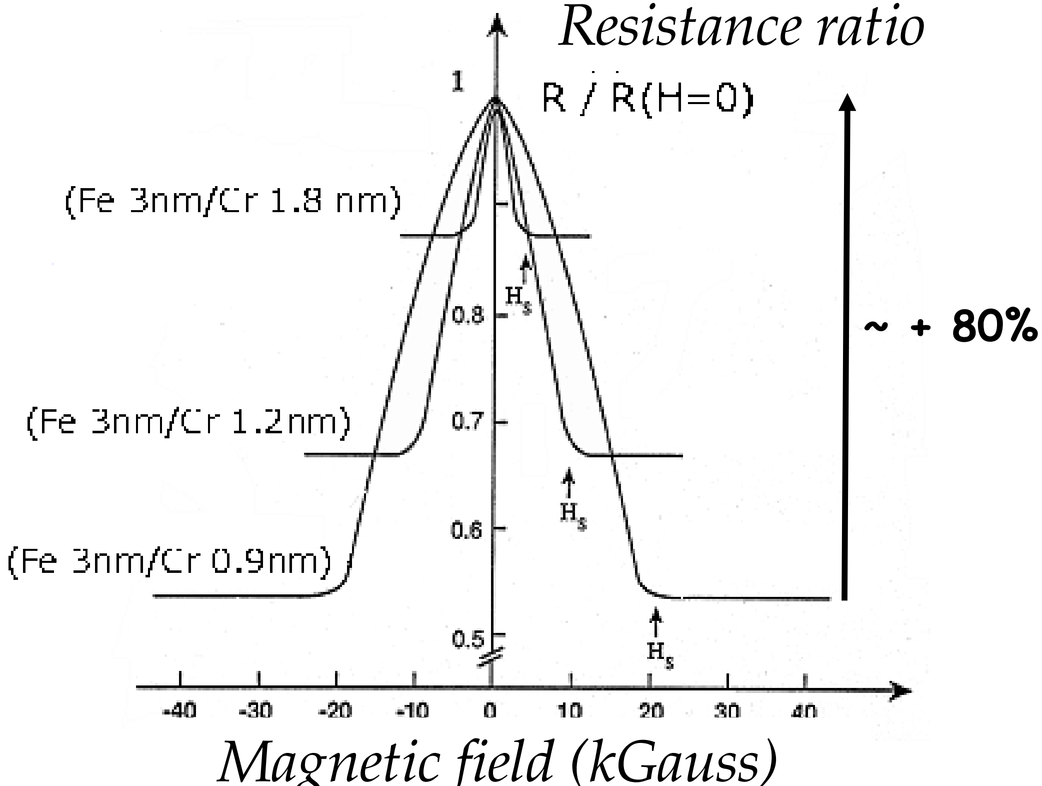
Jülich

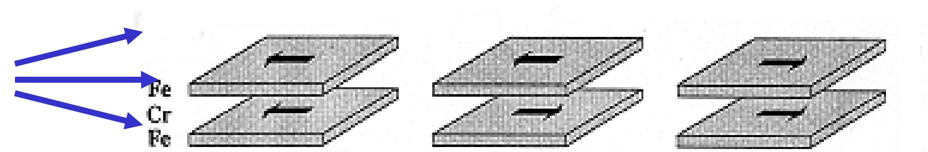




• Giant Magnetoresistance (GMR)

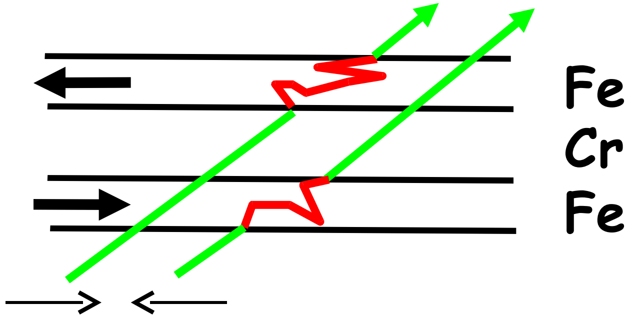
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)



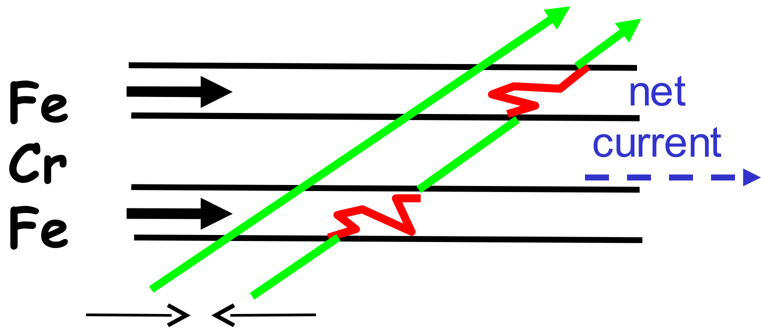


AP (AntiParallel) **P** (Parallel)

Anti-parallel magnetizations
(zero field, high resistance)

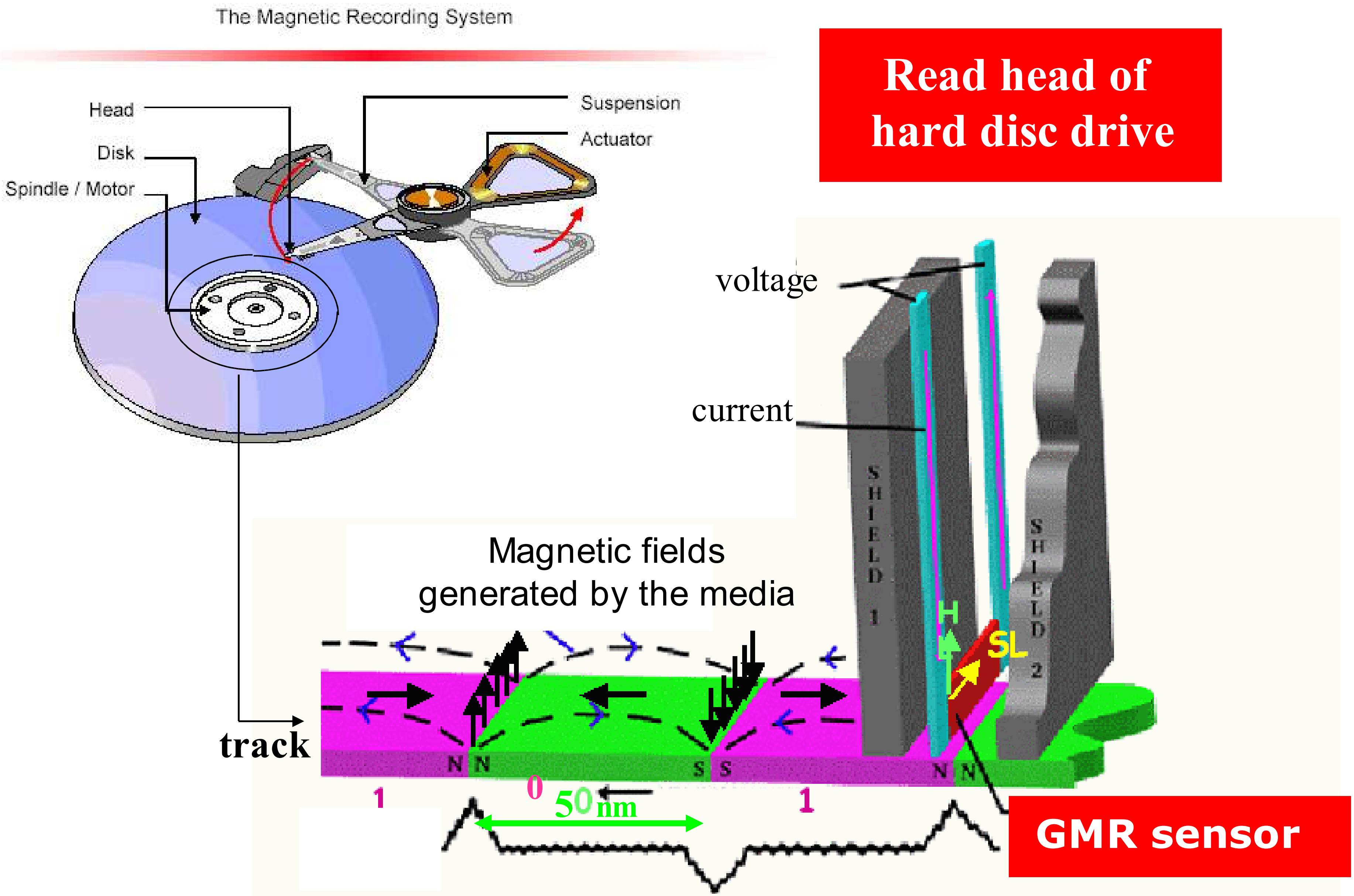


Parallel magnetizations
(appl. field, low resist.)



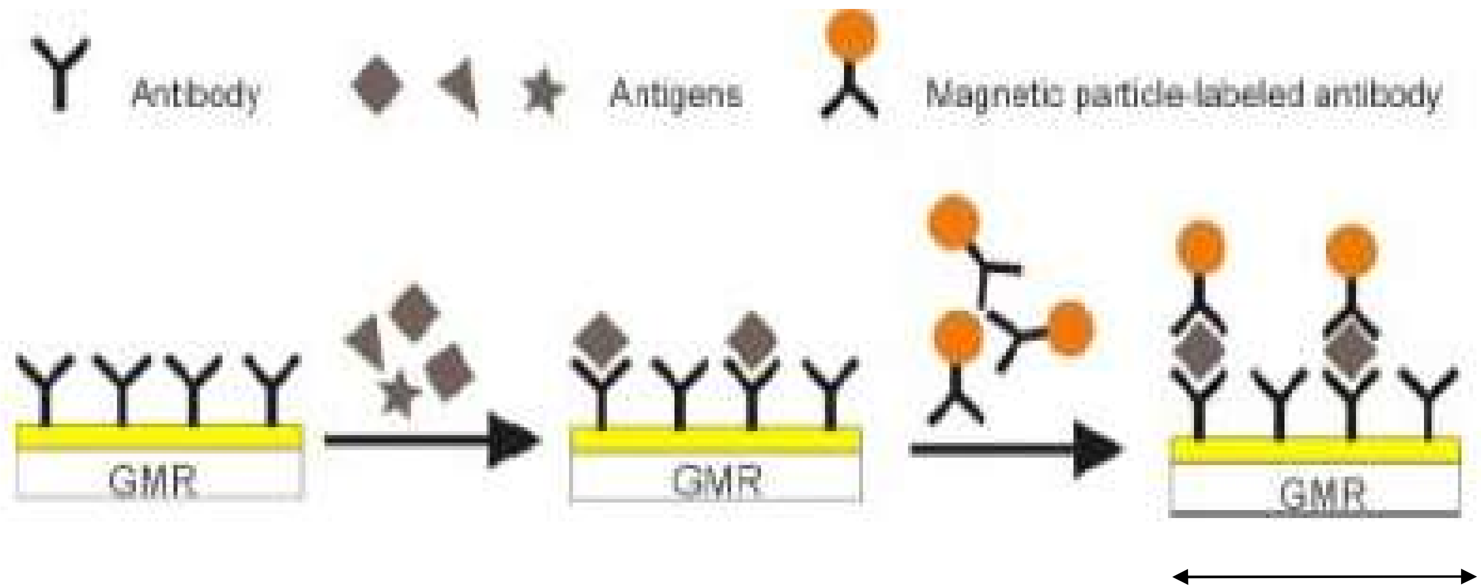
Condition for GMR:
layer thickness ≈ nm

Read head of hard disc drive



1997 (before GMR) : 1 Gbit/in² , 2007 : GMR heads ~ 300 Gbit/in²

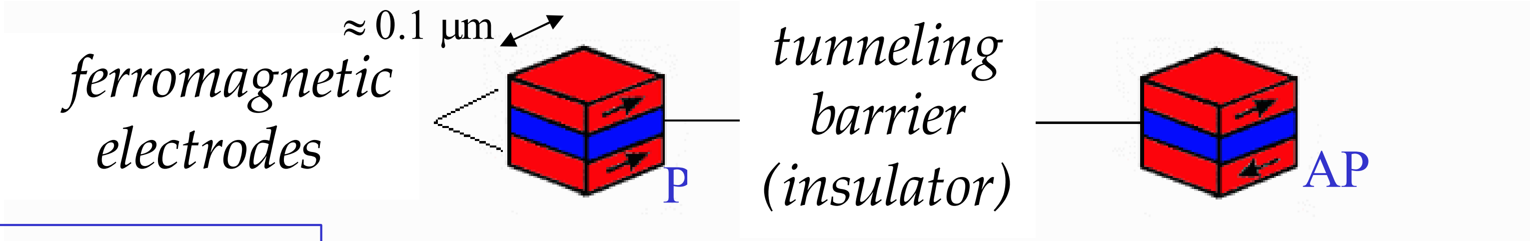
Arrays of GMR biochips for analysis of biomolecules (example: antigens are trapped by antibodies and also decorated by other antibodies labelled by magnetic nanoparticles which are detected by a GMR sensor)



9 μm (Philips), 1μm (Santa Barbara)

→ Probe arrays for analysis of thousands of different targets in parallel

• Magnetic Tunnel Junctions, Tunneling Magnetoresistance (TMR)



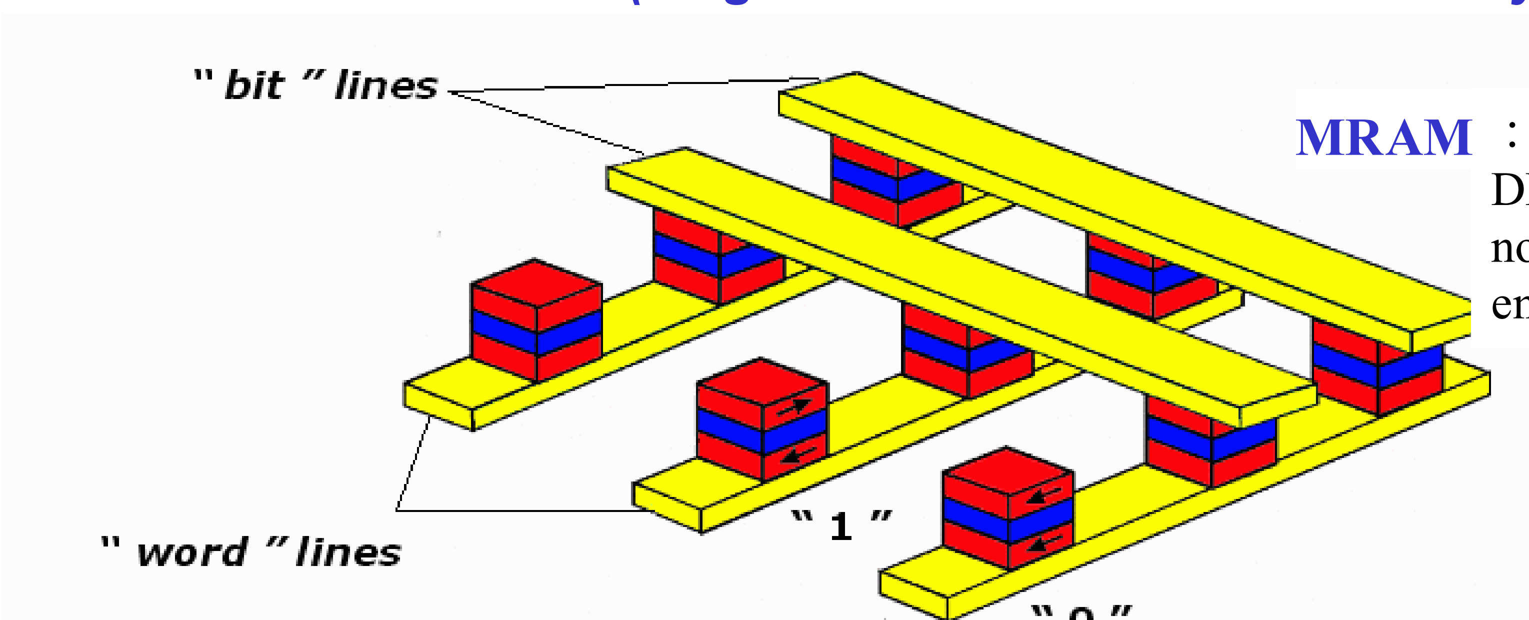
Low resistance state *High resistance state*

Jullière, 1975, low T, hardly reproducible

Moodera et al, 1995, Miyasaki et al, 1995, $CoFe/Al_2O_3/Co$, MR ≈30-40%

Applications: - read heads of Hard Disc Drive

- M-RAM (Magnetic Random Access Memory)

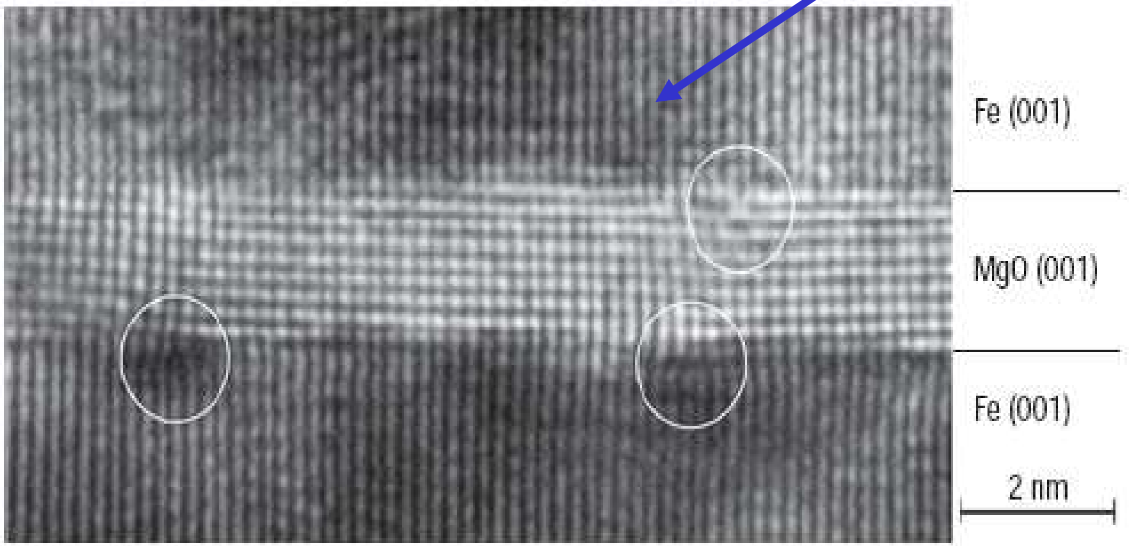


MRAM : density/speed of DRAM/SRAM + nonvolatilty + low energy consumption

Epitaxial magnetic tunnel junctions (MgO, etc)

First examples on Fe/MgO/Fe(001):
CNRS/Thales (Bowen, AF et al, APL2001) Nancy (Faure-Vincent et al, APL 2003) Tsukuba (Yuasa et al, Nature Mat. 2005) IBM (Parkin et al, Nature Mat. 2005) ….etc

Yuasa et al, Fe/MgO/Fe
Nature Mat. 2005
$\Delta R/R = (R_{AP}-R_P)/ R_P \approx$ **200%** at RT



2006-2007

CoFeB/MgO/CoFeB,

$\Delta R/R \approx$ **500%** at RT in several laboratories in 2006-2007

+

Clearer picture of the physics of TMR:
what is inside the word « spin polarization »?

Mathon and Umerski, PR B 1999
Mavropoulos et al, PRL 2000 Butler et al , PR B 2001
Zhang and Butler, PR B 2004 [bcc Co/MgO/bcc Co(001)]

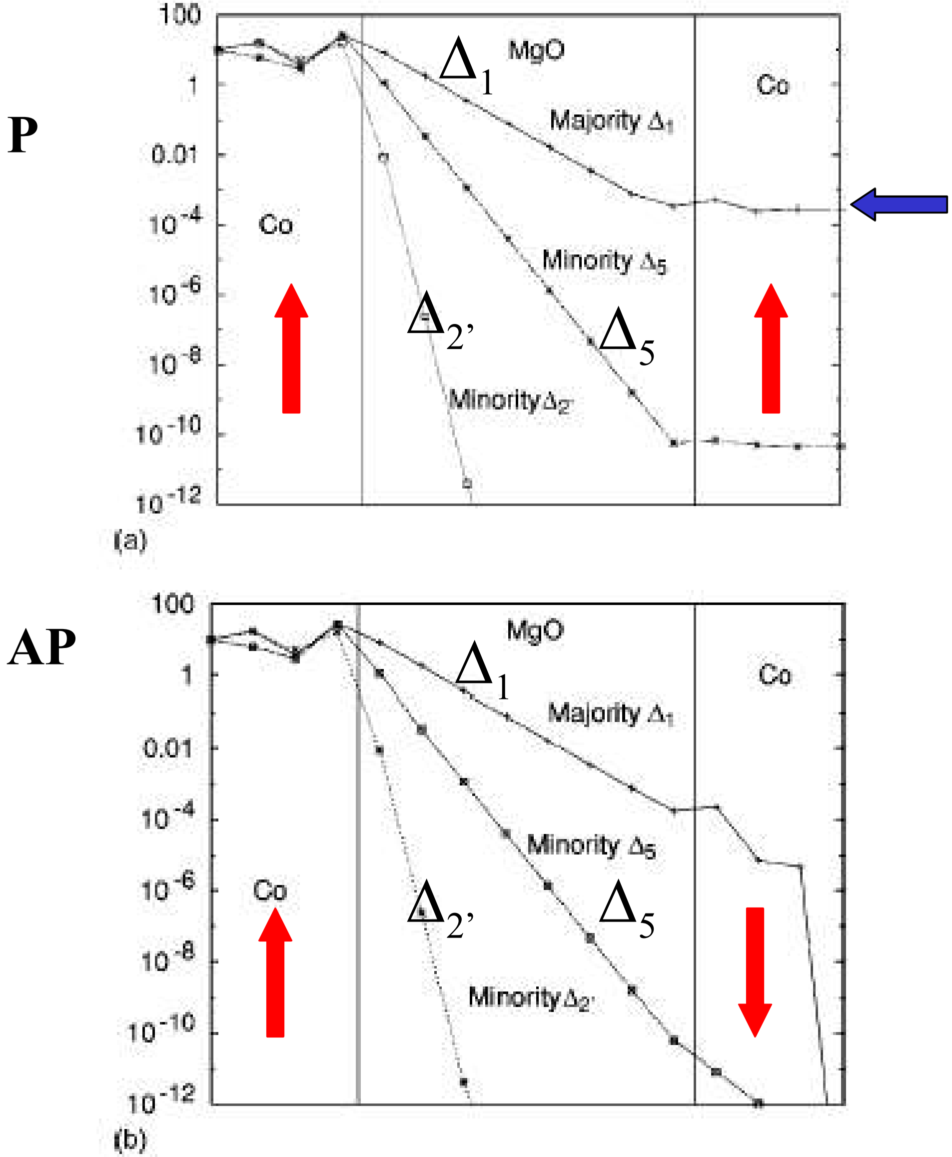


FIG. 2. Tunneling density of states on each atomic layer at $k_{\|}=0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

Zhang and Butler, PR B 2004

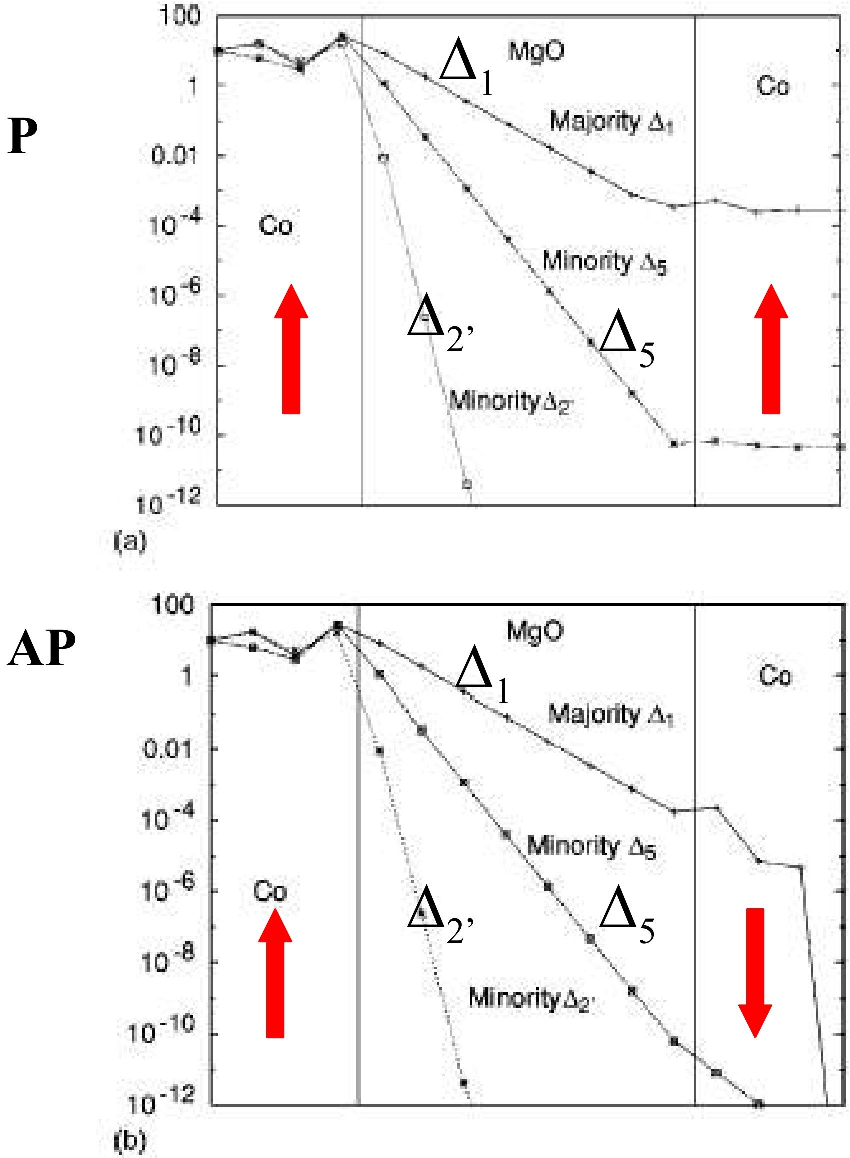


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel=0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

Beyond MgO

MgO, ZnSe ***(Mavropoulos et al, PRL 2000),*** **etc**

→ Δ_1 symmetry (sp) slowly decaying

→ tunneling of Co majority spin electrons

$SrTiO_3$ and other d-bonded insulators

(Velev et al , PRL 95, 2005; Bowen et al, PR B 2006)

→ Δ_5 symmetry (d) slowly decaying

→ tunneling of Co minority spin electrons

in agreement with the negative polarization of Co found in TMR with $SrTiO_3$, TiO_2 and $Ce_{1-x}La_xO_2$ barriers

(de Teresa, A.F. et al, Science 1999)

Zhang and Butler, PR B 2004

P

AP

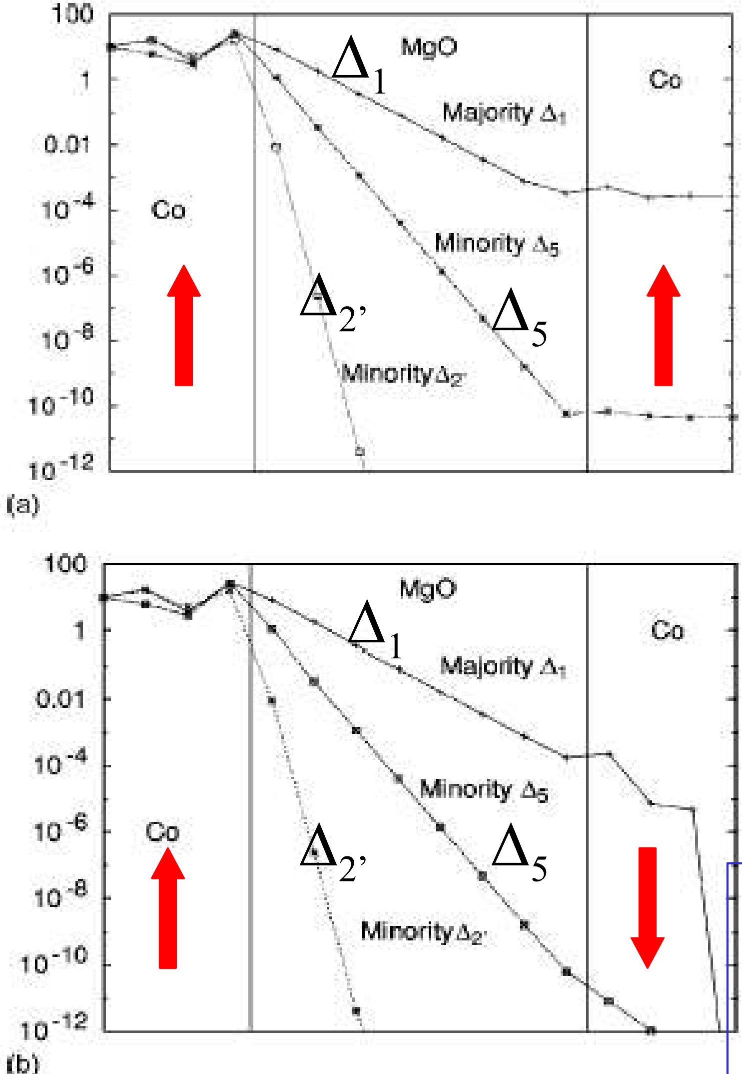


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel=0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

Beyond MgO

MgO, ZnSe ***(Mavropoulos et al, PRL 2000),*** **etc**

→ Δ_1 symmetry (sp) slowly decaying

→ tunneling of Co majority spin electrons

$SrTiO_3$ and other d-bonded insulators

(Velev et al , PRL 95, 2005; Bowen et al, PR B 2006)

→Δ_5 symmetry (d) slowly decaying

→ tunneling of Co minority spin electrons

in agreement with the negative polarization of Co found in TMR with $SrTiO_3$, TiO_2 and $Ce_{1-x}La_xO_2$ barriers

(de Teresa, A.F. et al, Science 1999)

Physical basis of « **spin polarization** » (SP)

¤Tunneling: SP of the DOS for the **symmetry selected by the barrier**

¤Electrical conduction: SP depends on **scatterers, impurities**,..

Spin Transfer

(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules

Spin Transfer

(magnetic switching, microwave generation)

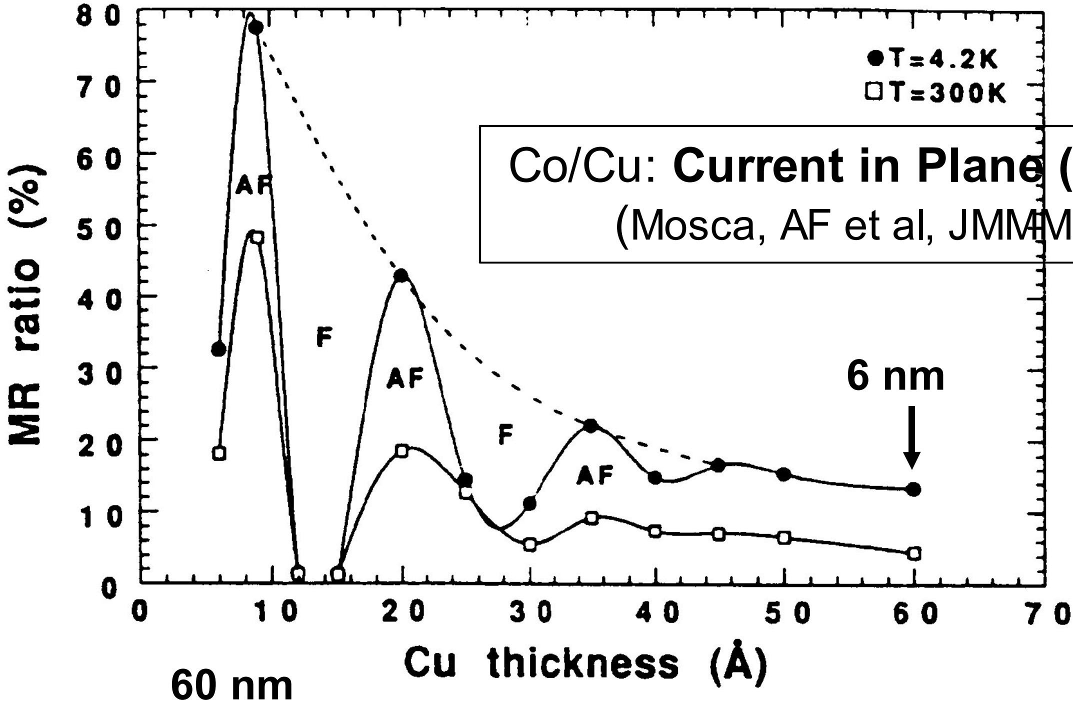
Spintronics with semiconductors

Spintronics with molecules

Introduction:

spin accumulation

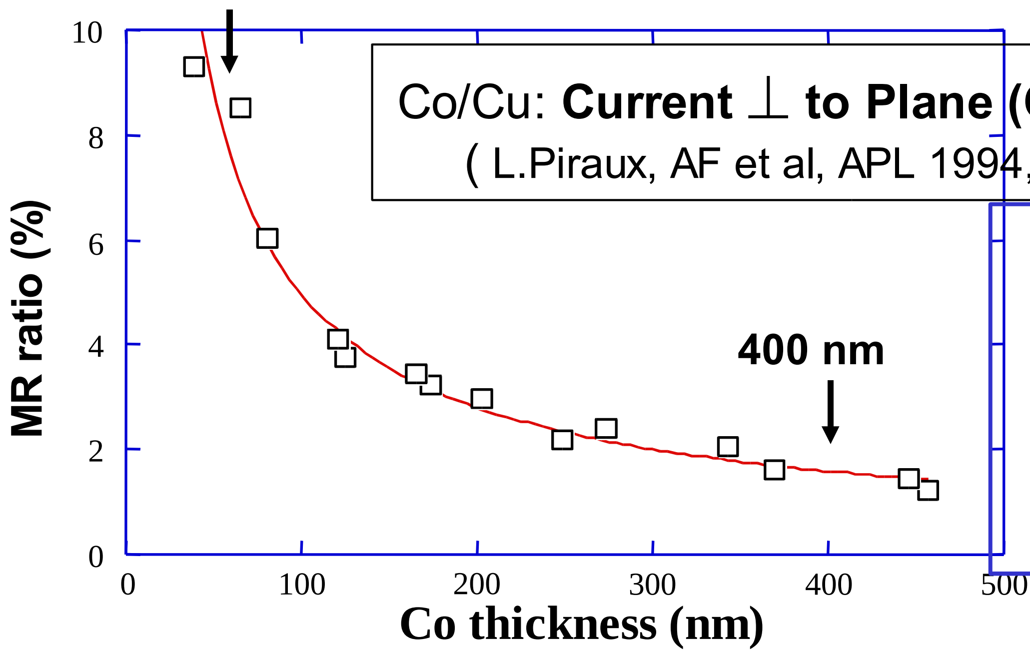
and spin currents



Co/Cu: **Current in Plane (CIP)-GMR**
(Mosca, AF et al, JMMM 1991)

CIP-GMR

scaling length = mean free path



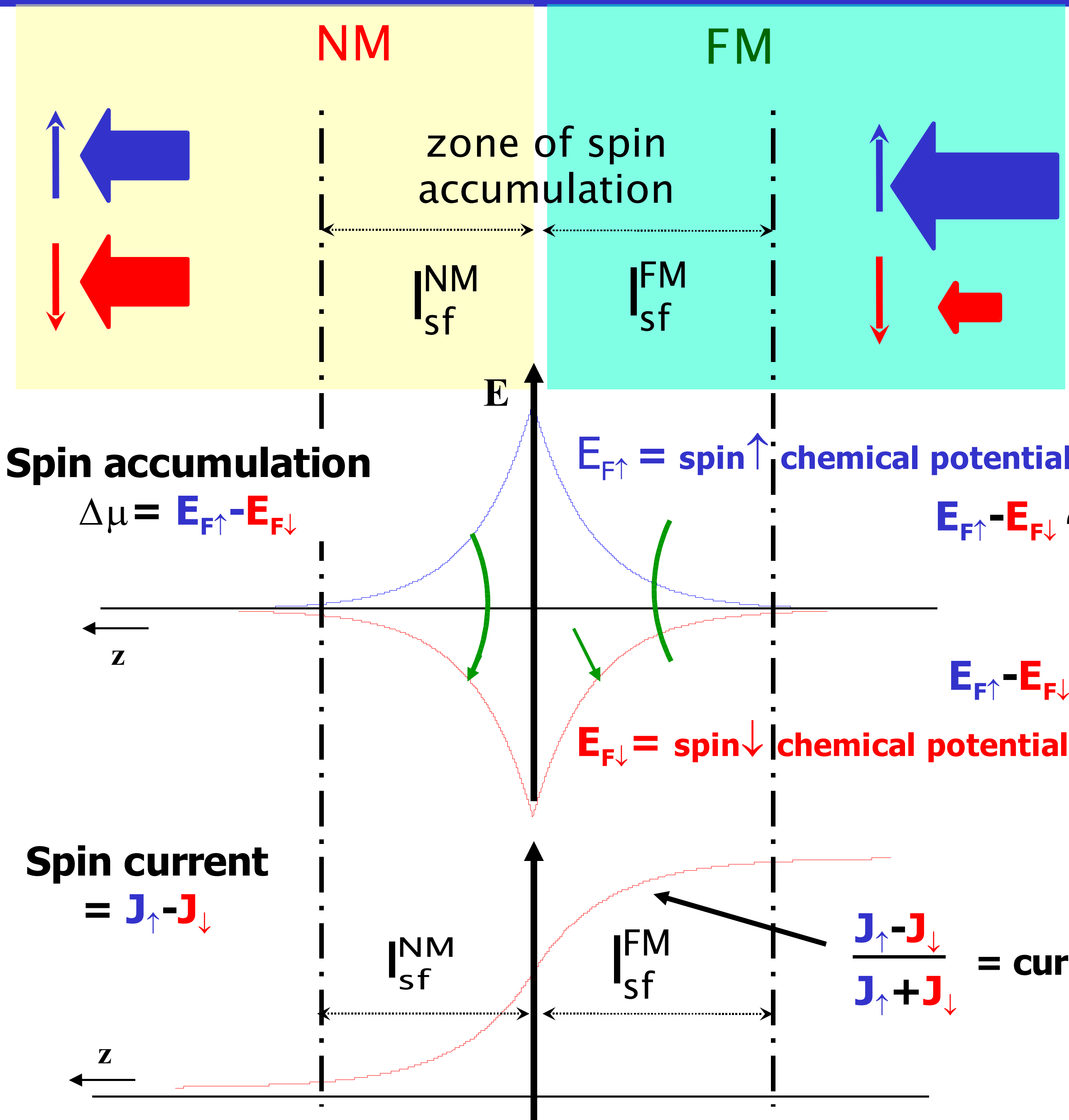
Co/Cu: **Current ⊥ to Plane (CPP) GMR**
(L.Piraux, AF et al, APL 1994,JMMM 1999)

CPP-GMR

scaling length = spin diffusion length >> mean free path

spin accumulation theory,
(Valet-Fert, PR B 1993)

Spin injection/extraction at a NM/FM interface (beyond ballistic range)



(illustration in the simplest case = flat band, low current, no interface resistance, single polarity)

l_{sf}^{FM} = spin diffusion length in FM

l_{sf}^{NM} = spin diffusion length in NM

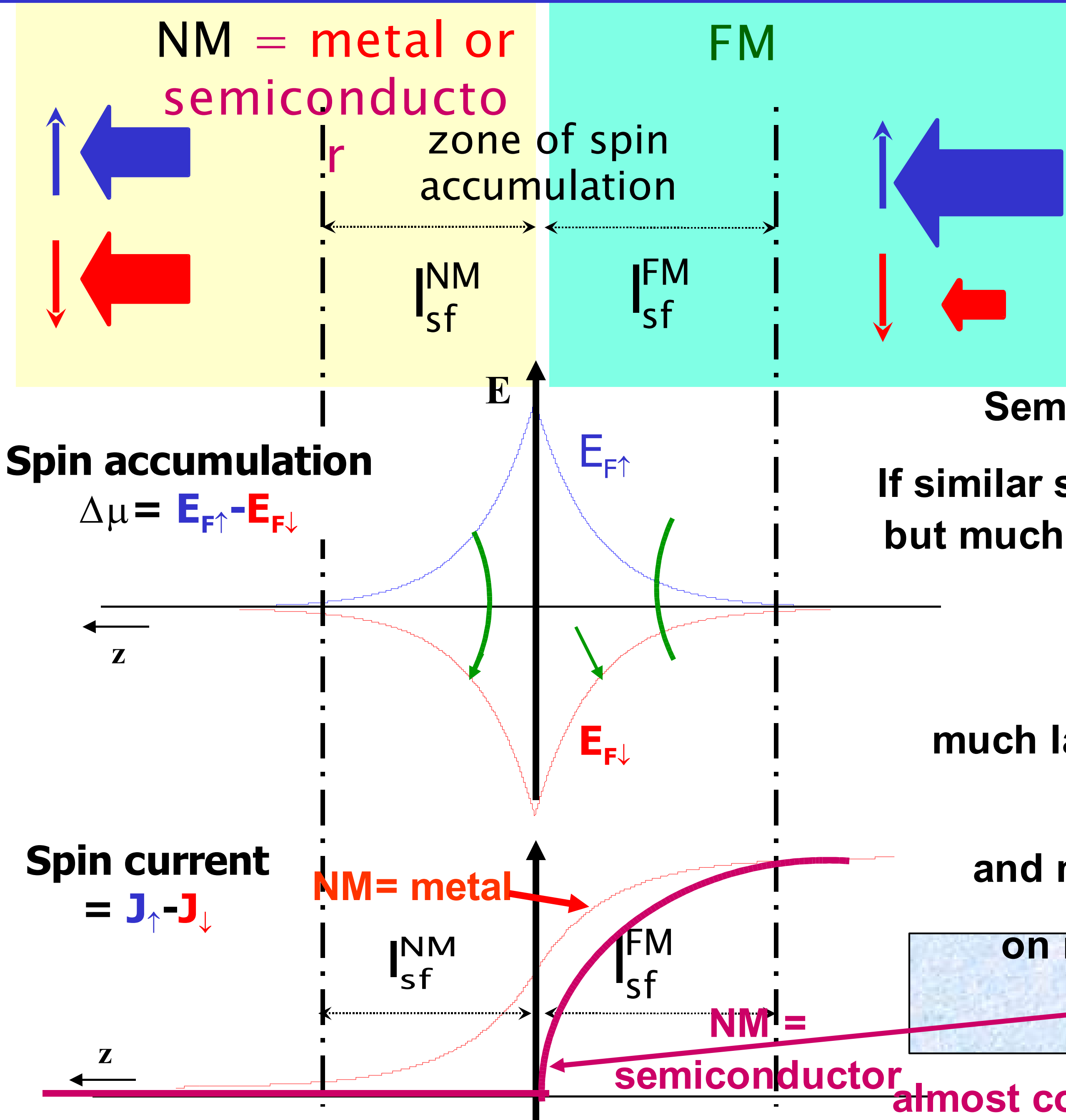
(example: 0.5 μm in Cu, >10μm in carbon nanotube)

$E_{F\uparrow} - E_{F\downarrow} \sim \exp(z/\ l_{sf}^{FM})$ in FM

$E_{F\uparrow} - E_{F\downarrow} \sim \exp(-z/\ l_{sf}^{NM})$ in NM

$\dfrac{J_{\uparrow} - J_{\downarrow}}{J_{\uparrow} + J_{\downarrow}}$ = current spin polarization

Spin injection/extraction at a Semiconductor/FM interface



1) situation without interface resistance (« conductivity mismatch »)

(Schmidt et al, PR B 2000)

Semiconductor/ F metal

If similar spin spliting on both sides but much larger density of states in F metal

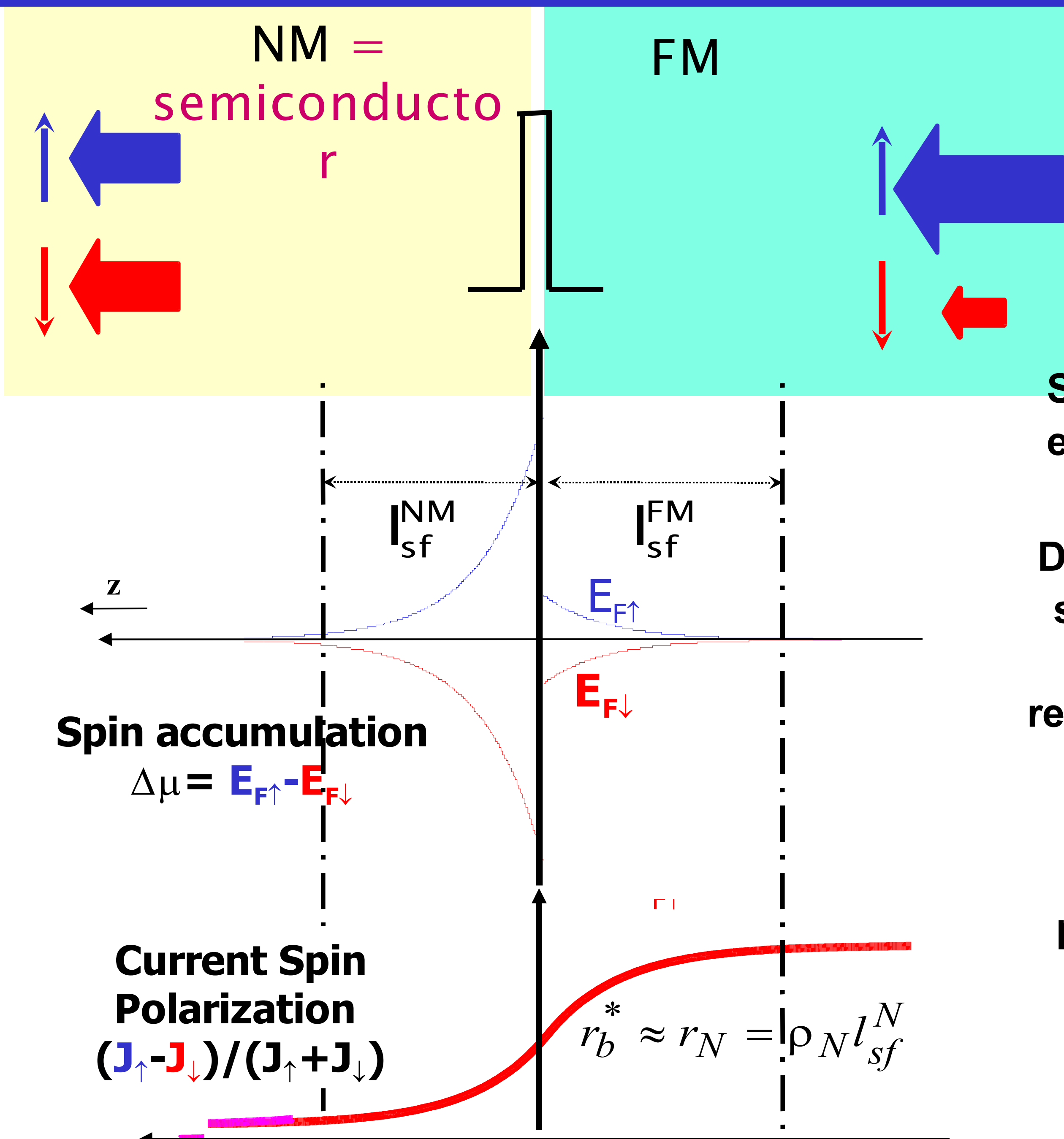
much larger spin accumulation density

and much more spin flips

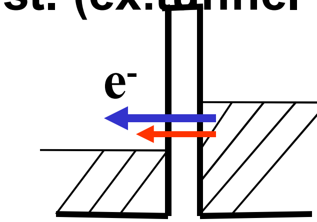
on magnetic metal side

almost complete depolarization of

Spin injection/extraction at a Semiconductor/FM interface



spin dependent. interf. resist. (ex:tunnel barrier)



Spin dependent drop of the electro-chemical potential

Discontinuity increases the spin accumulation in NM

re-balanced spin relaxations in F and NM

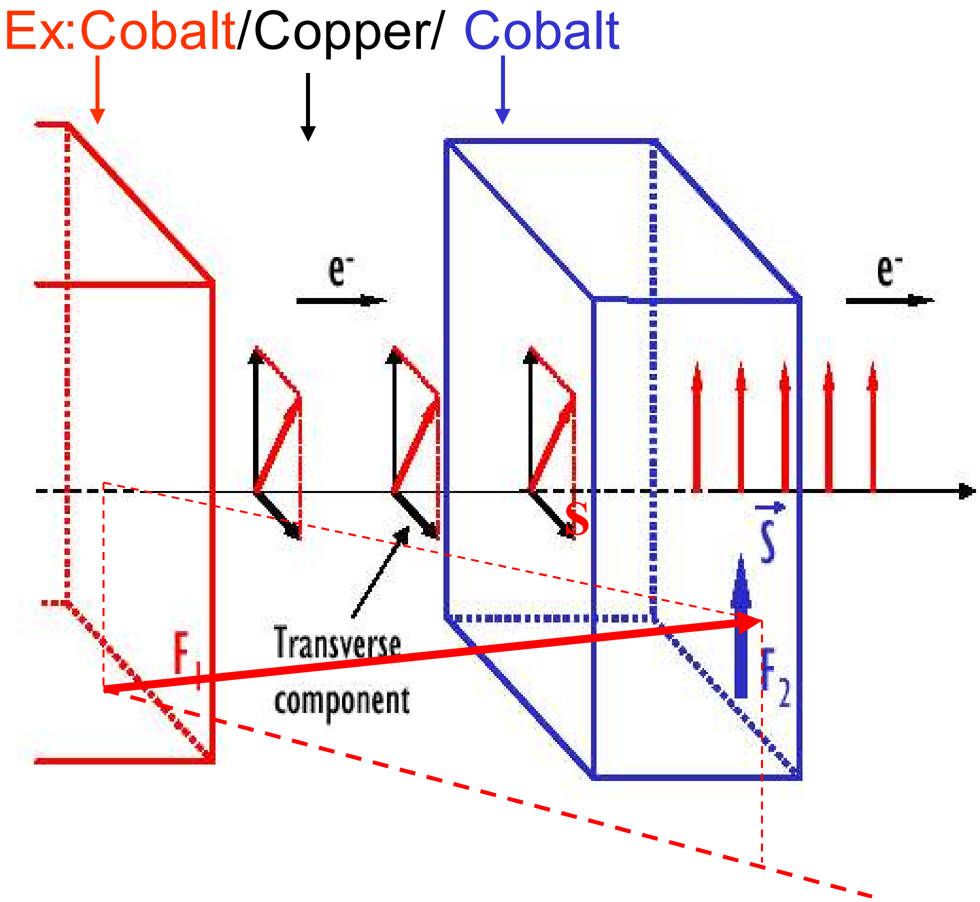
extension of the spin-polarized current into the semiconductor

Rasbah, PR B 2000

A.F-Jaffrès, PR B 2001

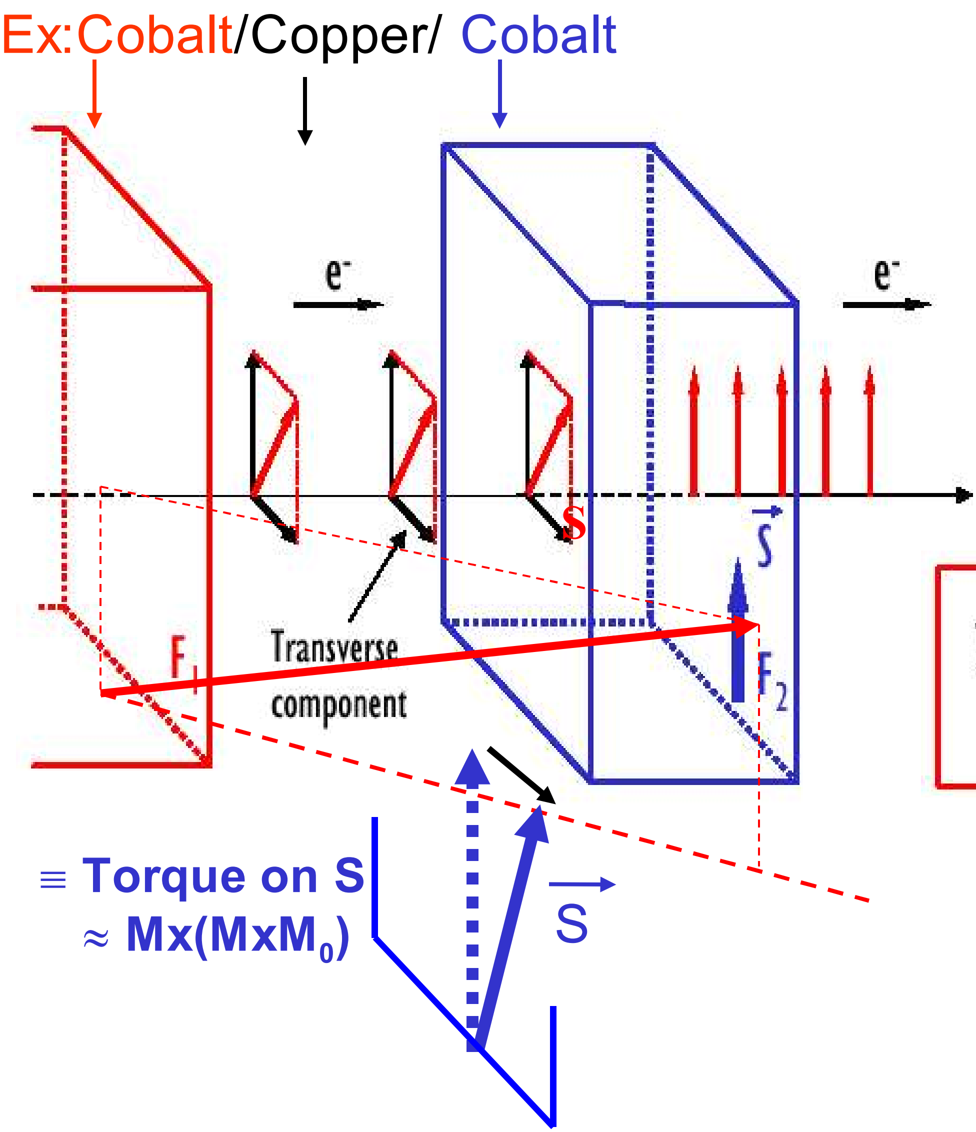
Spin transfer

(J. Slonczewski, JMMM 1996, L. Berger, PR B 1996)



Spin transfer

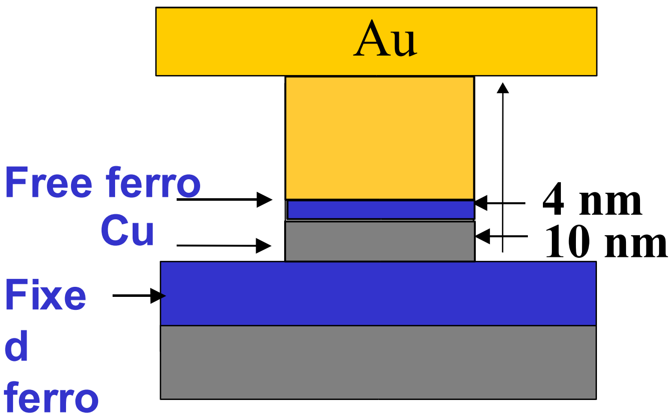
(J. Slonczewski, JMMM 1996, L. Berger, PR B 1996)



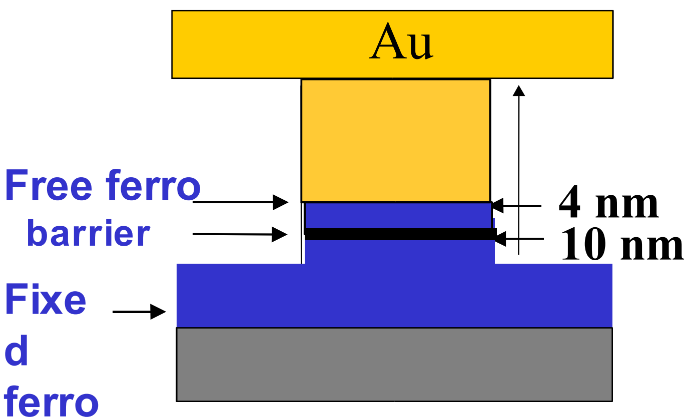
The transverse component of the spin current is absorbed and transferred to the total spin of the layer

$$\frac{\text{torque}}{\hbar} = \left(\frac{d\vec{S}}{dt}\right)_j = \text{absorbed transverse spin current} \propto j\, M \times (M \times M_0)$$

Experiments on pillars



Metallic pillar ≈ 50x150 nm^2



Tunnel junction

E-beam lithography + etching

a) First regime (low H): irreversible switching (CIMS)

b) Second regime (high H): steady precession (microwave generation)

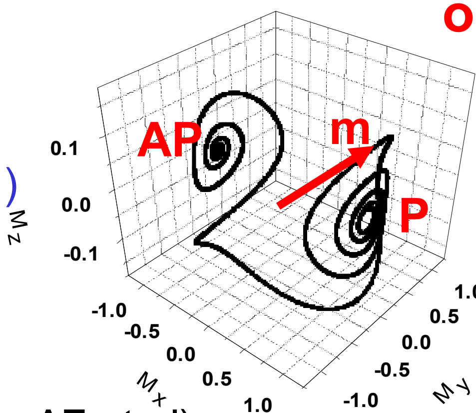
Regime of irreversible magnetic switching

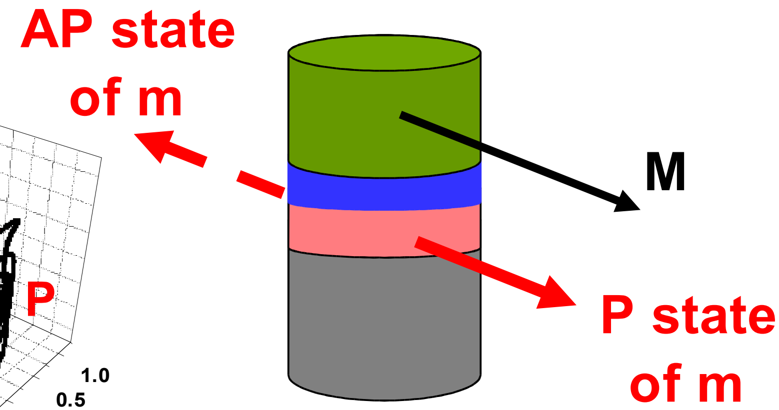
First experiments on pillars:

Cornell (Katine et al, PRL 2000)

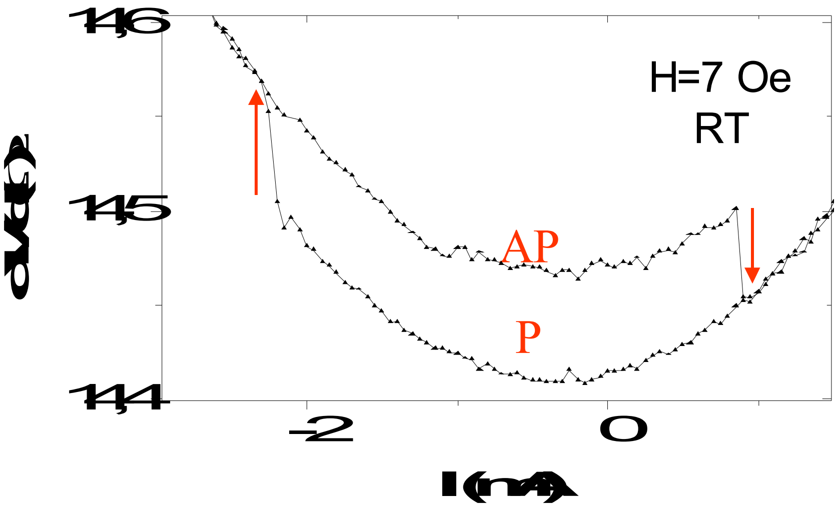
CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)

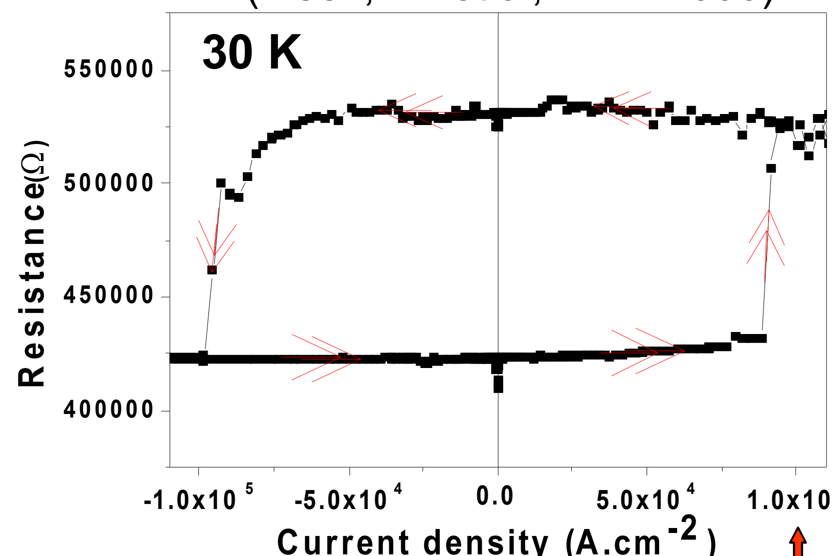




Py/Cu/Py 50nmX150nm (Boulle, AF et al)



GaMnAs/InGaAs/GaMnAs tunnel junction ***(MR=150%)***
(Elsen, AF et al, PR B 2006)



1×10^5 A/cm^2

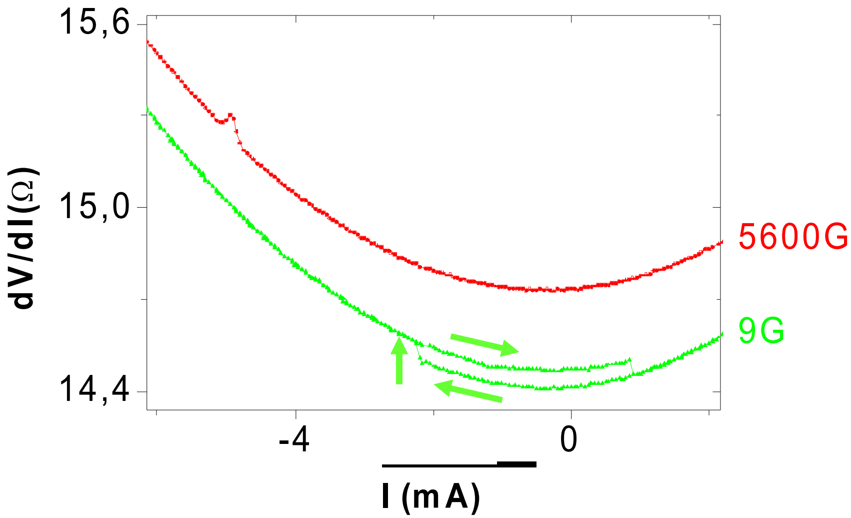
typical switching current ≈ 10^7A/cm^2

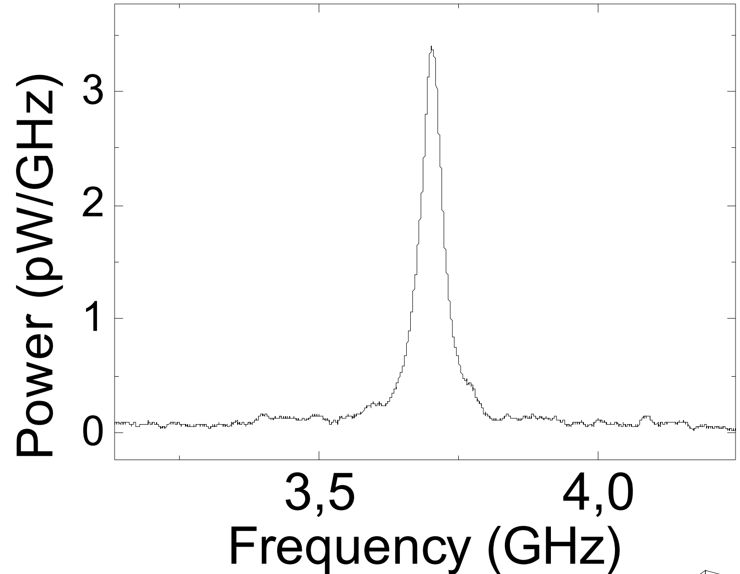
switching time can be as short as 0.1 ns (Chappert et al)

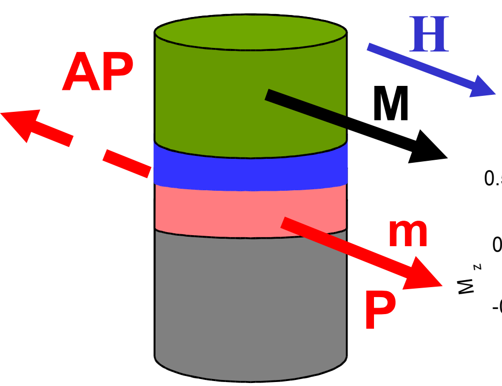
Regime of steady precession (microwave frequency range)

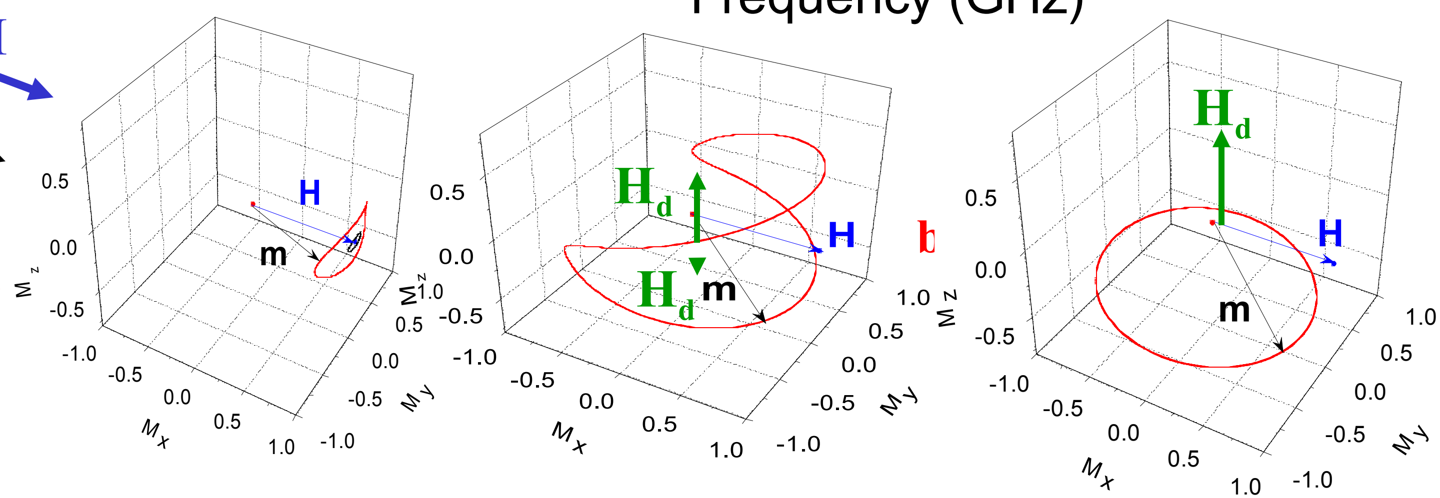
CNRS/Thales, Py/Cu/PY (Grollier et al)

(Py = permalloy)



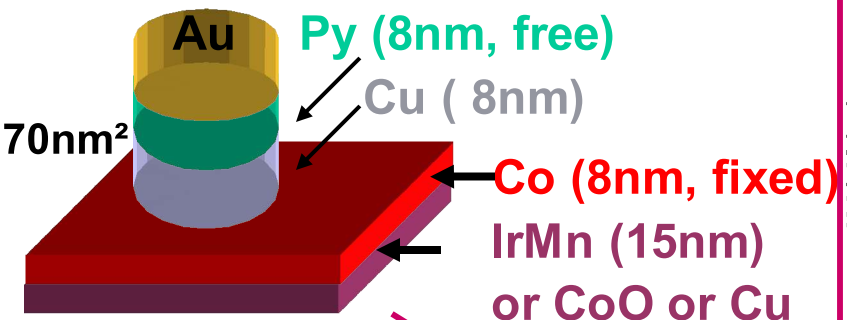


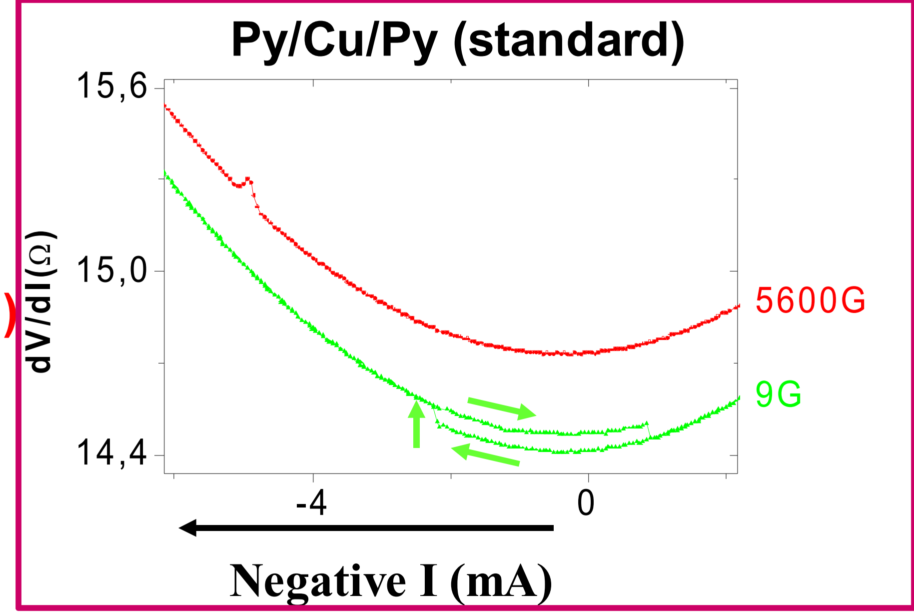




Increasing current

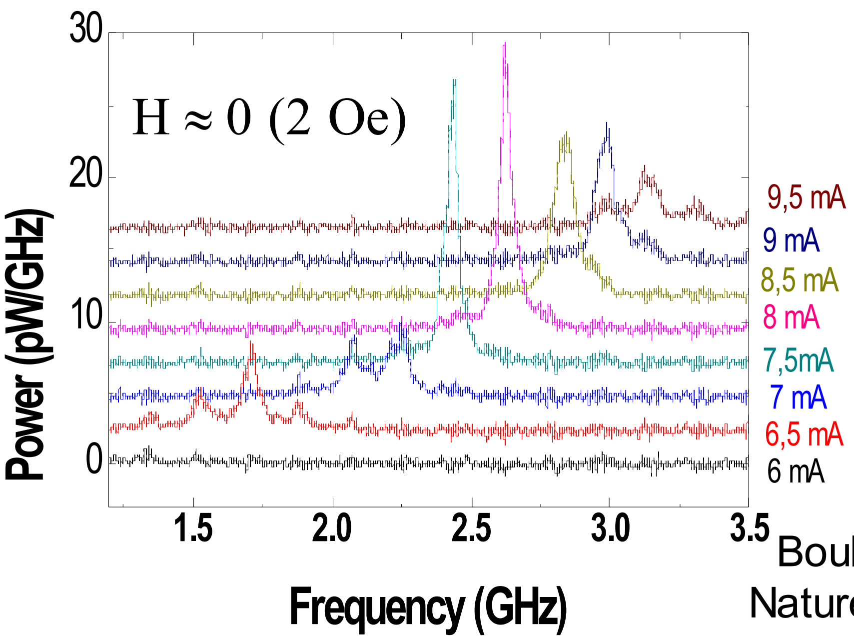
Co/Cu/Py (« wavy » angular variation calculated by Barnas, AF et al, PR B 2005)



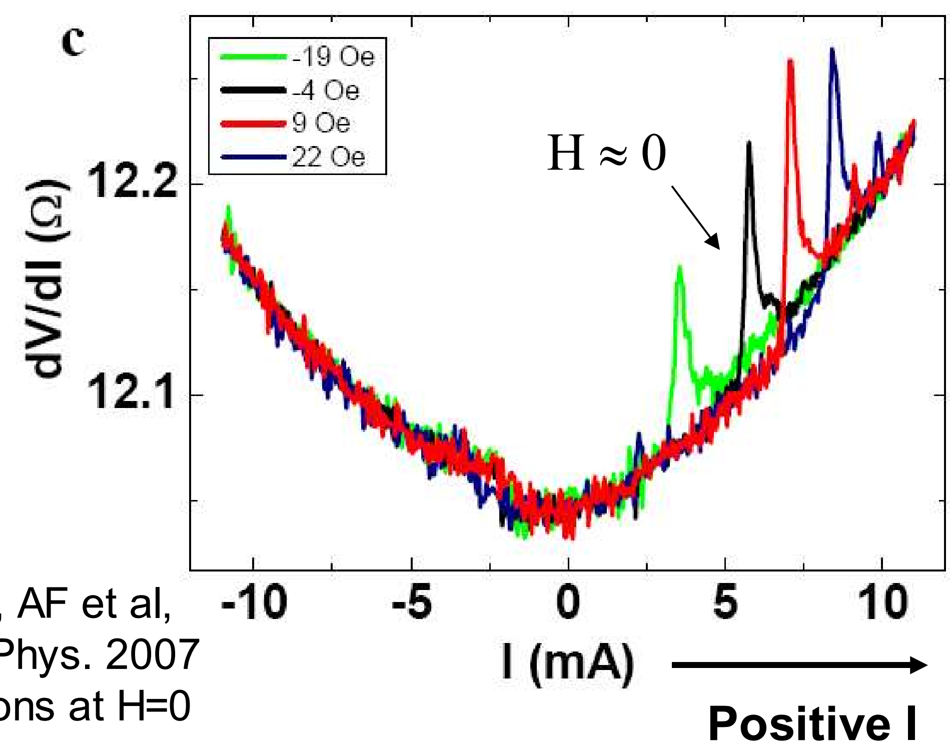


free Py: fast spin relaxation

fixed Co: slower spin relaxation



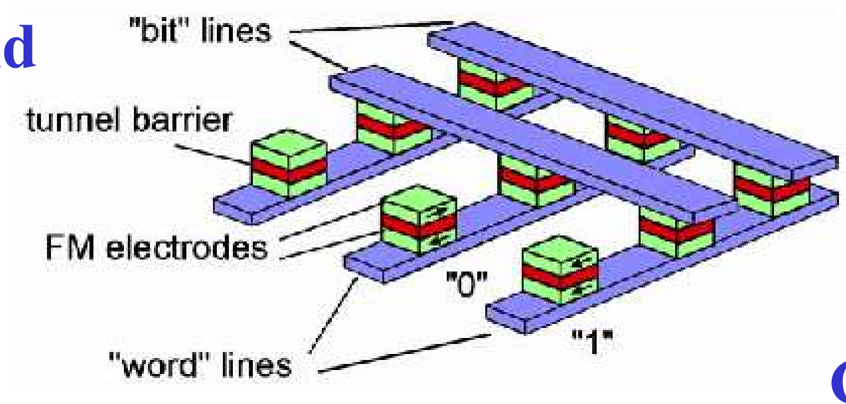
Boulle, AF et al, Nature Phys. 2007 oscillations at H=0



Switching of reprogrammable devices (example: MRAM)

1) By external magnetic field

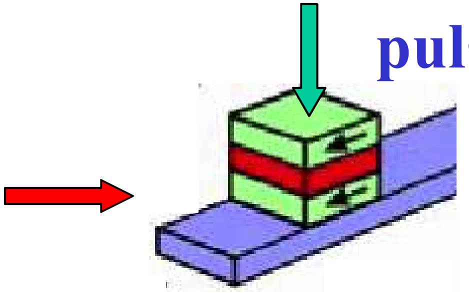
(present generation of MRAM, nonlocal, risk of « cross-talk » limits integration)



2) «Electronic» reversal by spin transfer from current

(for the next generation of MRAM, with already promising demonstrations by several companies)

Current pulse



Spin Transfer Oscillators (STO) (communications, microwave pilot)

Advantages:

-direct oscillation in the microwave range (5-40 GHz)

-agility: control of frequency by dc current amplitude, (frequency modulation , fast switching)

- high quality factor

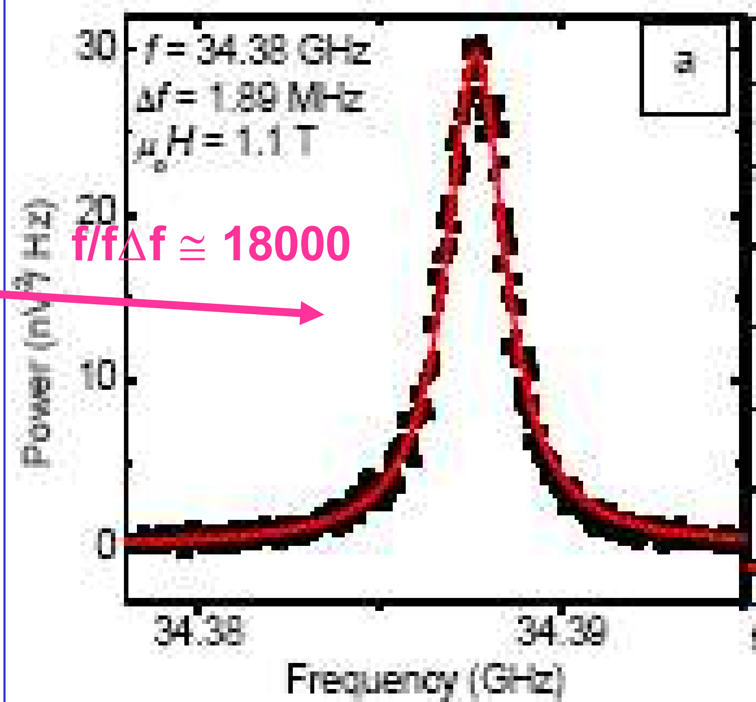
- small size (≈ 0.1μm) (on-chip integration)

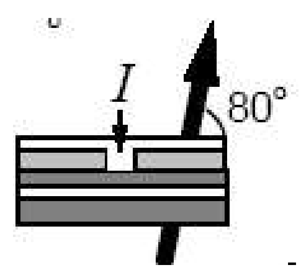
-oscillations without applied field

-Needed improvements

- - increase of power by synchronization of

f/fΔf ≅ 18000

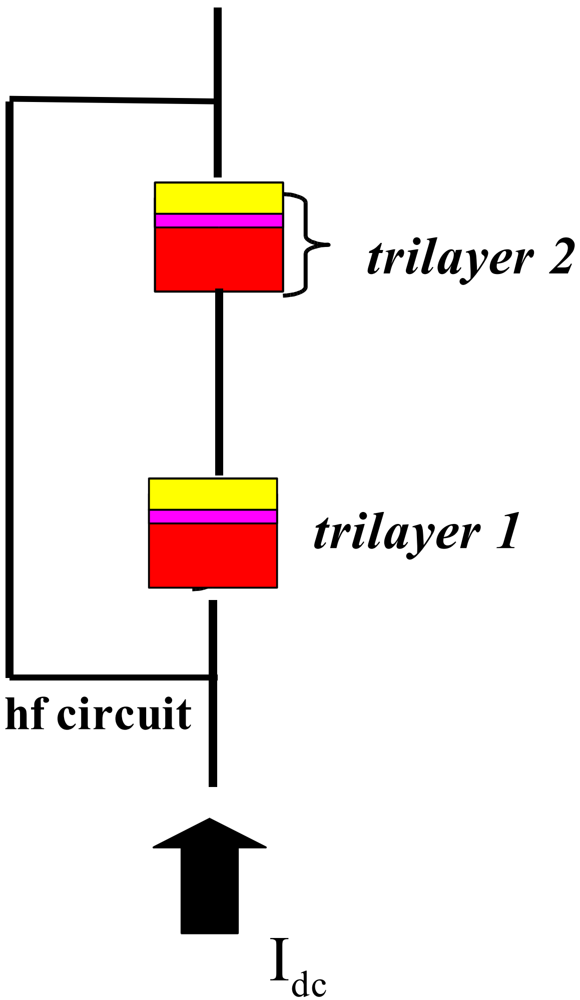




Rippart et al, PR B70, 100406, 2004

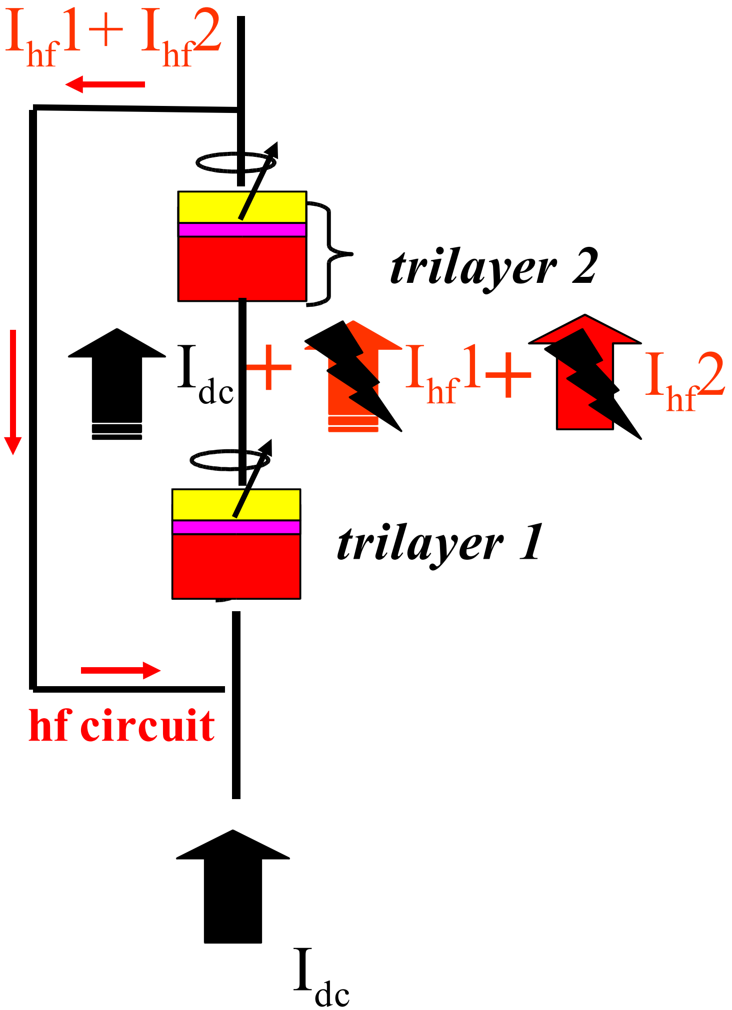
Experiments of STO synchronization by electrical connection

(B.Georges, AF et al, **CNRS/Thales and LPN-CNRS, preliminary results)**



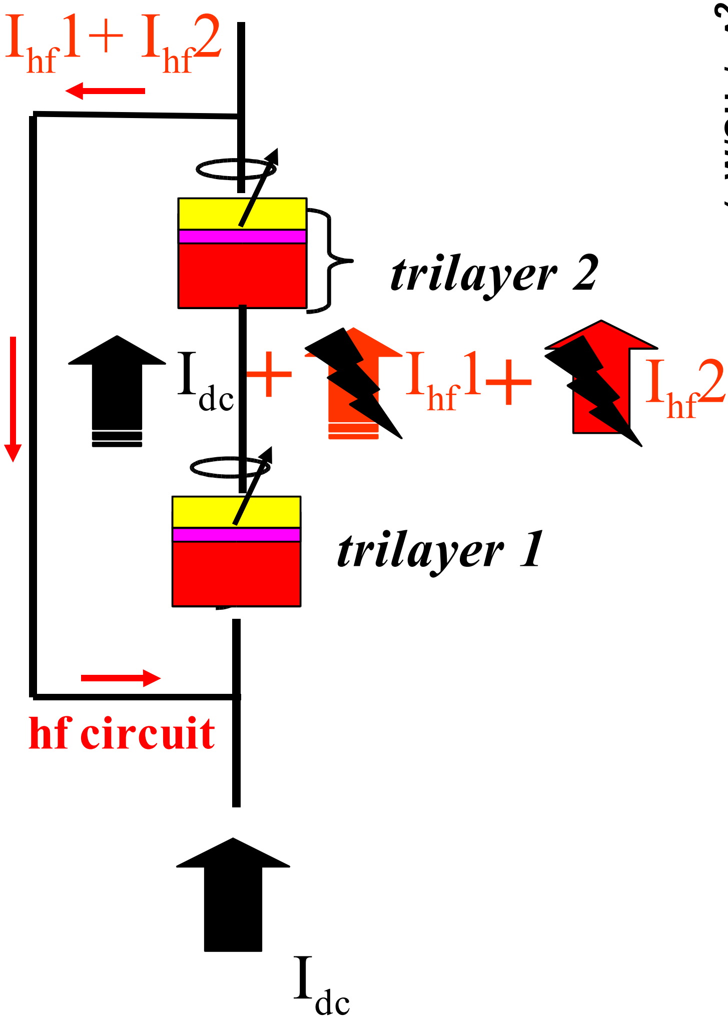
Experiments of STO synchronization by electrical connection

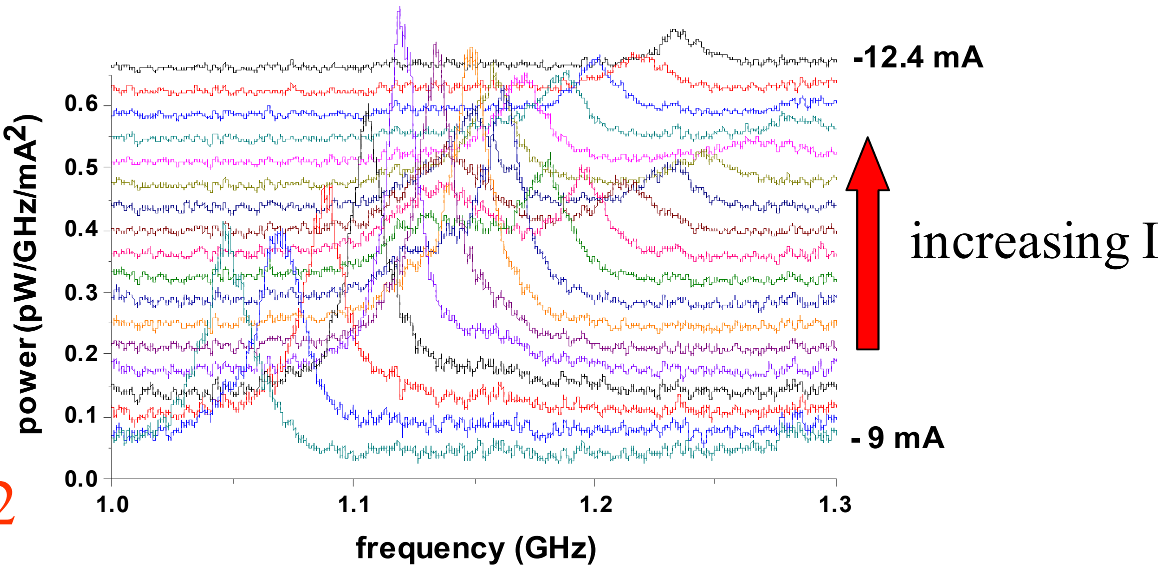
(B.Georges, AF et al, **CNRS/Thales and LPN-CNRS, preliminary results)**

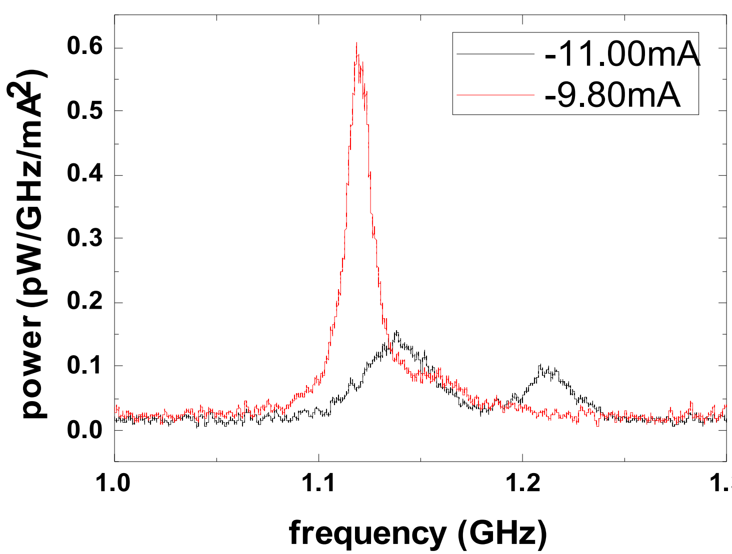


Experiments of STO synchronization by electrical connection

(B.Georges, AF et al, **CNRS/Thales and LPN-CNRS, preliminary results)**





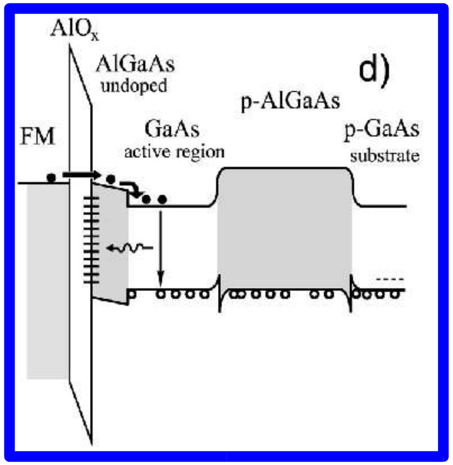


Spintronics with semiconductors and molecules

Spintronics with semiconductors

Magnetic metal/semiconductor hybrid structures

Example: spin injection from Fe into LED (Mostnyi et al, PR. B 68, 2003)



Ferromagnetic semiconductors (FS)

GaMnAs ($T_c \rightarrow 170K$) and R.T. FS

Electrical control of ferromagnetism

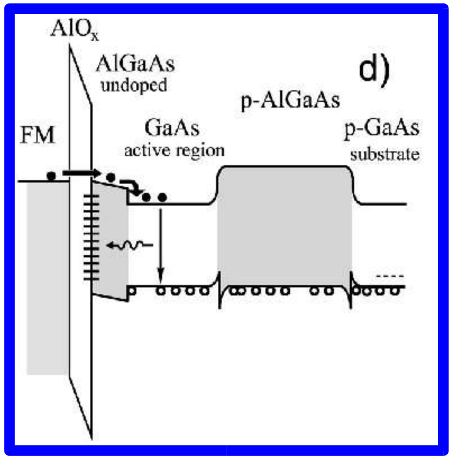
TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

Spintronics with semiconductors

Magnetic metal/semiconductor hybrid structures

Example: spin injection from Fe into LED (Mostnyi et al, PR. B 68, 2003)



Ferromagnetic semiconductors (FS)

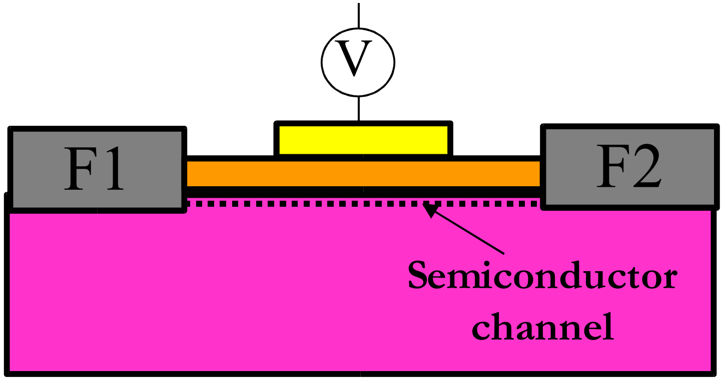
GaMnAs ($T_c \rightarrow 170K$) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

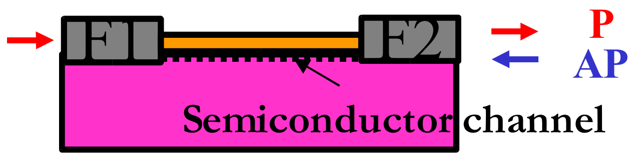
Spin Field Effect Transistor ?



Semiconductor channel between spin-polarized source and drain transforming spin information into large (?) and tunable (by gate voltage) electrical signal

Nonmagnetic lateral channel between spin-polarized source and drain

Semiconductor channel:



« Measured effects of the order of **0.1-1%** have been reported for the change in

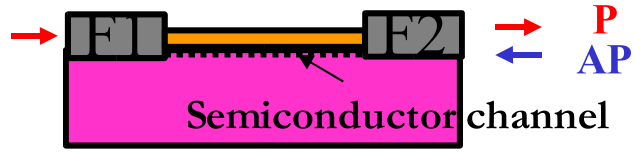
voltage or resistance (between P and AP)…. », *from the review article*

« Electrical Spin Injection and Transport in Semiconductors » by BT Jonker

and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 2006)

Nonmagnetic lateral channel between spin-polarized source and drain

Semiconductor channel:



« Measured effects of the order of **0.1-1%** have been reported for the change in

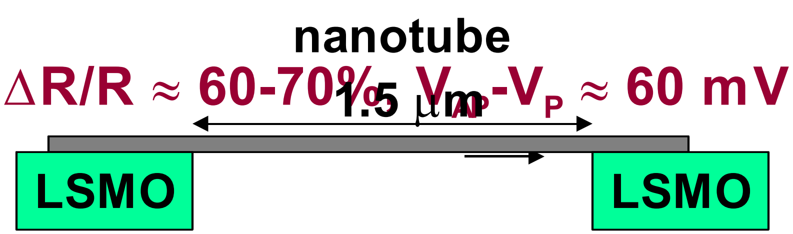
voltage or resistance (between P and AP)…. », *from the review article*

« Electrical Spin Injection and Transport in Semiconductors » by BT Jonker and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 20

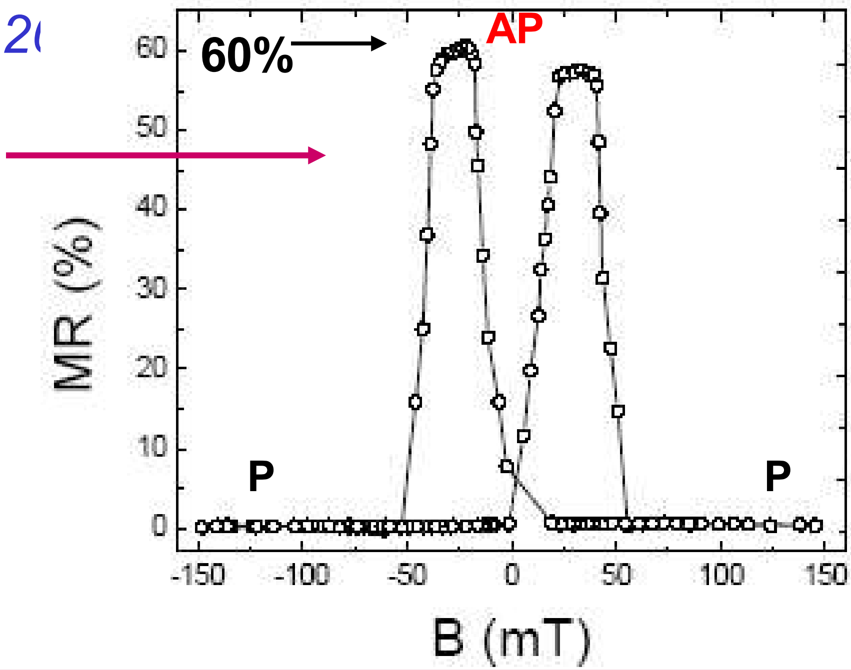
L.Hueso, N.D. Mathur, A.F. et al, Nature 445, 410, 2007

Carbon nanotubes:

$\Delta R/R \approx$ 60-70%, V_{AP}-$V_P \approx$ 60 mV

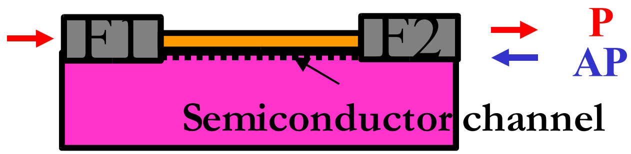


LSMO = $La_{2/3}Sr_{1/3}O_3$



Nonmagnetic lateral channel between spin-polarized source and drain

Semiconductor channel:

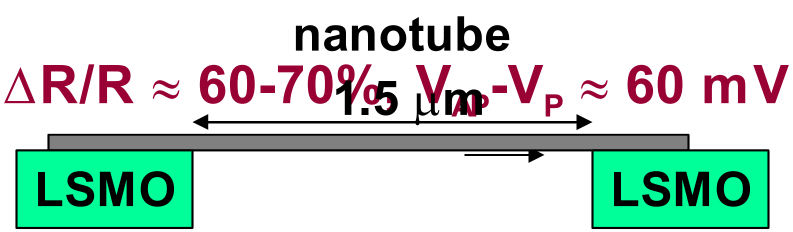


« Measured effects of the order of **0.1-1%** have been reported for the change in voltage or resistance (between P and AP)…. », *from the review article « Electrical Spin Injection and Transport in Semiconductors » by BT Jonker and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 2006)*

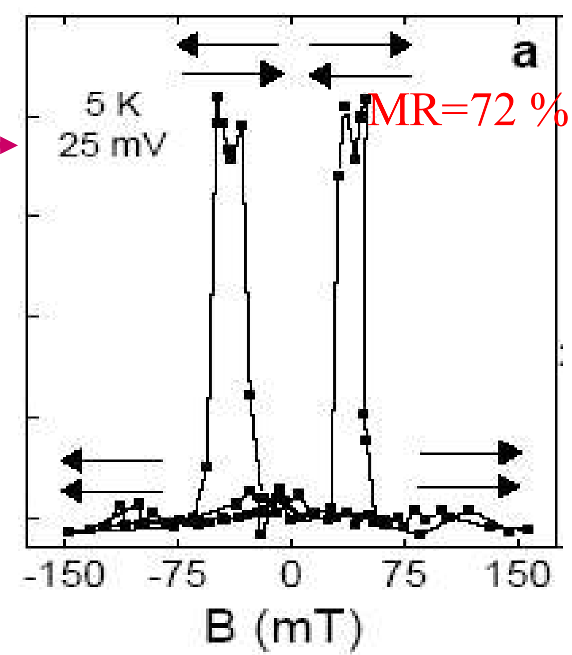
L.Hueso, N.D. Mathur, A.F. et al, Nature 445, 410, 2007

Carbon nanotubes:

$\Delta R/R \approx$ 60-70%, $V_{AP}-V_P \approx$ 60 mV



LSMO = $La_{2/3}Sr_{1/3}O_3$



Two interface spin transport problem (diffusive regime)

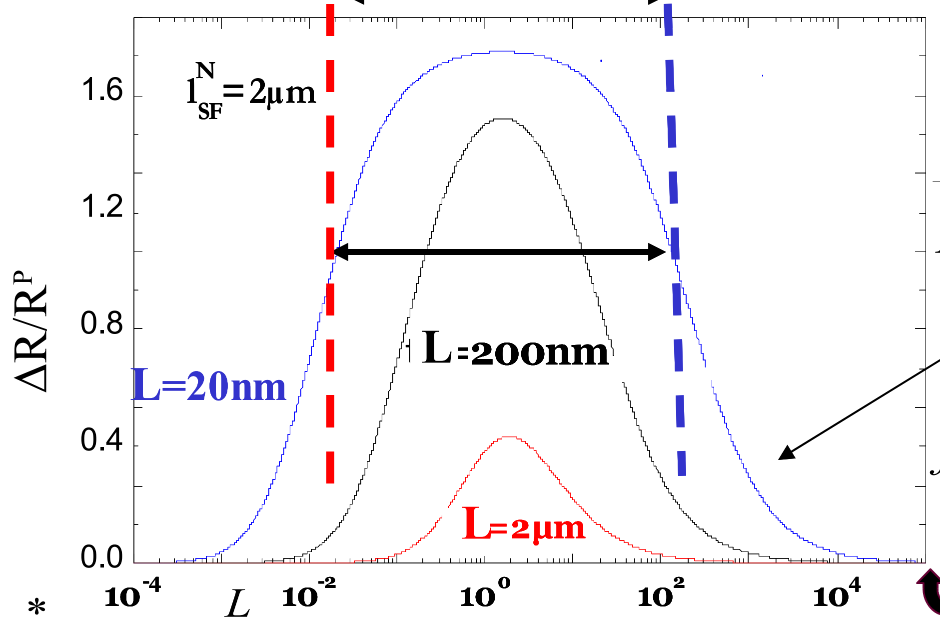
AF and Jaffrès
PR B 2001
+cond-mat
0612495, +
IEEE Tr.El.Dev.
54,5,921,2007

Condition for spin injection

Condition dwell time τ_n < spin lifetime τ_{sf} *dwell time*

$$window \propto \frac{l_{sf}}{L} - 1$$

$$\tau_n = \frac{2L}{v t_r^*} \propto \frac{L\, r_b^*}{v}$$



$$r_b^* \ll r_N \frac{L}{l_{sf}^N}$$

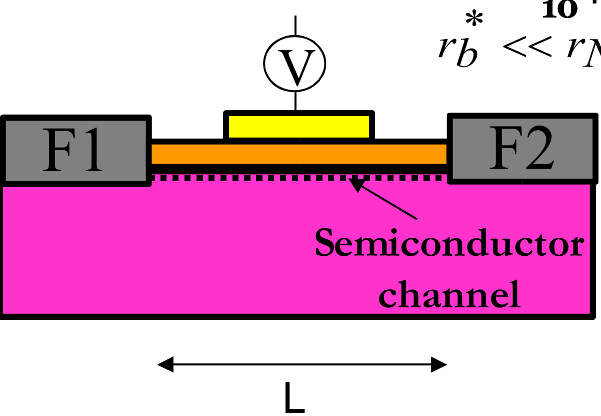
$$r_b^* / r_N$$

$$\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$$

drops to zero as $1/r_b^*$ *for* $\tau_n \propto r_b^* \gg \tau_{sf}$

Interface resistance r_b^* *in most experiments*

$$\tau_n \gg \tau_{sf}$$



r_b^* = unit area interface resist. $\propto 1/\text{trans.coeff } t_r^*$

γ = spin asymmetry of the interface resistance

$$r_N = \rho_N\, l_{sf}^N$$

Transport between SP source and drain : τ_n = dwell time, τ_{sf} = spin lifetime, γ = injection SP

: the contrast between P (on) and AP (off), $\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$, is large *if* $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules) :

$$small\ spin-orbit \rightarrow spin\ lifetime\ \tau_{sf}\ is\ \text{long}\ (\approx 50\text{ns})$$

$$high\ velocity\ v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ short\ (<\tau_{sf})$$

Semiconductors:

$$\tau_{sf}\ can\ be\ \text{long}\quad (for\ n \approx 10^{17}\ el/cm^3)$$

$$but\ v\ is\ small \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ \text{long}\ (>>\tau_{sf})$$

Transport between SP source and drain : τ_n = dwell time, τ_{sf} = spin lifetime, γ = injection SP

: the contrast between P (on) and AP (off), $\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$, is large if $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules) :

$$small\ spin-orbit \rightarrow spin\ \ lifetime\ \tau_{sf}\ is\ \text{long}(\approx 50\text{ns})$$

$$high\ velocity\ \ v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ short\ (<\ \tau_{sf}\ )$$

Semiconductors:

$$\tau_{sf}\ can\ be\ \text{long}\quad (for\ n \approx 10^{17}\ el/cm^3)$$

$$but\ v\ is\ \ small \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ \text{long}(>>\tau_{sf}\ )$$

Solution for semiconductors:

shorter L ?, larger transmission t_r ?

Transport between SP source and drain : τ_n = dwell time, τ_{sf} = spin lifetime, γ = injection SP

: the contrast between P (on) and AP (off), $\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$, is large *if* $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules) :

$$small\ spin-orbit \rightarrow spin\ \ lifetime\ \tau_{sf}\ is\ \text{long}\,(\approx 50\text{ns})$$

$$high\ velocity\ \ v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ short\ (<\ \tau_{sf})$$

Semiconductors:

$$\tau_{sf}\ can\ be\ \text{long}\quad (for\ n \approx 10^{17}\, el/cm^3)$$

$$but\ v\ is\ small \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ \text{long}\,(>>\tau_{sf})$$

Solution for semiconductors:

shorter L ?, larger transmission t_r ?

Potential of molecular spintronics (nanotubes, graphene and others)

Transport between SP source and drain : τ_n = dwell time, τ_{sf} = spin lifetime, γ = injection SP

: the contrast between P (on) and AP (off), $\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$, is large *if* $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules) :

$$small\ spin-orbit \rightarrow spin\ \ lifetime\ \tau_{sf}\ is\ \text{long}\,(\approx 50\text{ns})$$

$$high\ velocity\ \ v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ short\ (<\ \tau_{sf}\ )$$

Semiconductors:

$$\tau_{sf}\ can\ be\ \text{long}\quad (for\ n \approx 10^{17}\,el/cm^3)$$

$$but\ v\ is\ small \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}\ is\ \text{long}\,(>>\tau_{sf}\ )$$

Solution for semiconductors:

shorter L ?, larger transmission t_r ?

Potential of molecular spintronics (nanotubes, graphene and others)

Next challenge for molecules:

spin control by gate


Summary
¤Already important aplications of GMR/TMR (HDD, MRAM..) and now promising new fields
-Spin transfer for magnetic switching and microwave generation
-Spintronics with semiconductors, molecules or nanoparticles
SILICON ELECTRONICS
SPINTRONICS

Acknowledgements to

M. Anane, C. Barraud, A. Barthélémy, H. Bea, A. Bernand-Mantel, M. Bibes, O. Boulle, K.Bouzehouane, O. Copi, V.Cros, C. Deranlot, B. Georges, J-M. George, J.Grollier, H. Jaffrès, S. Laribi, J-L. Maurice, R. Mattana, F. Petroff, P. Seneor, M. Tran F. Van Dau, A. Vaurès

Université Paris-Sud and Unité Mixte de Physique CNRS-Thales, Orsay, France

P.M. Levy, New York University, **A.Hamzic,** Zagreb University

B. Lépine, A. Guivarch and G. Jezequel

Unité PALMS, Université de Rennes , Rennes, France

G. Faini, R. Giraud, A. Lemaître: CNRS-LPN, Marcoussis, France

L. Hueso, N.Mathur, Cambridge

J. Barnas, M. Gimtra, I. Weymann, Poznan University