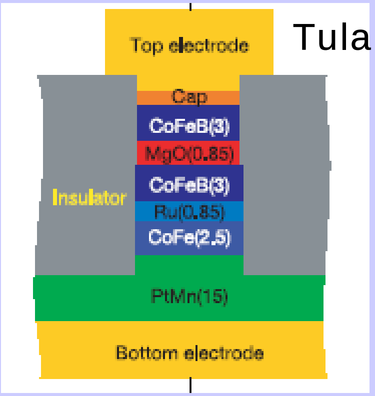
Zagreb, May 2008, A. Fert, CNRS/Thales, Palaiseau, and Université Paris-Sud

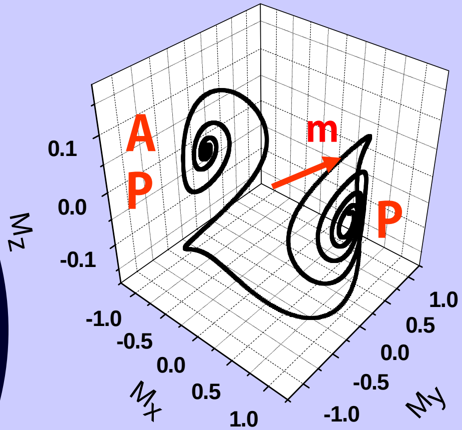
The present and future of Spintronics

In classical spintronics: new types of MTJ

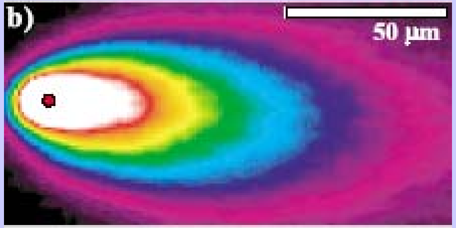


Tulapurkar et al

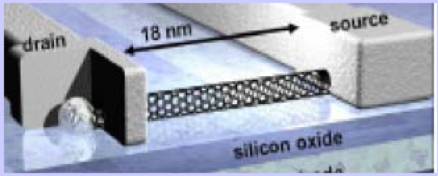
Spin transfer: switching, oscillators, synchronization



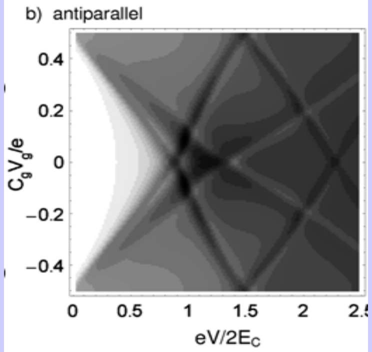
Hruska et al



Spintronics with **semiconductors**



Spintronics with **molecules**



single-electron devices

Introduction :

Spin dependent conduction in ferromagnetic conductors,

Giant Magnetoresistance (GMR),

Tunnel Magnetoresistance (TMR)

Spin dependent conduction in ferromagnetic metals (two current model)

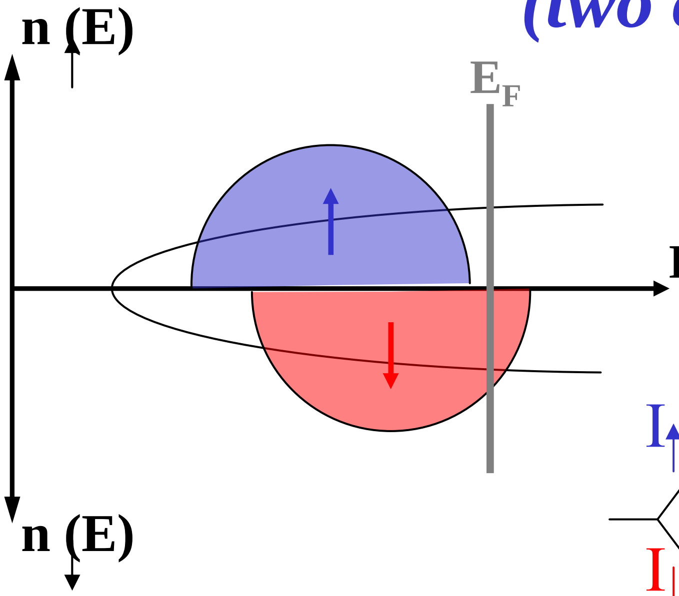
Mott, Proc.Roy.Soc A153, 1936

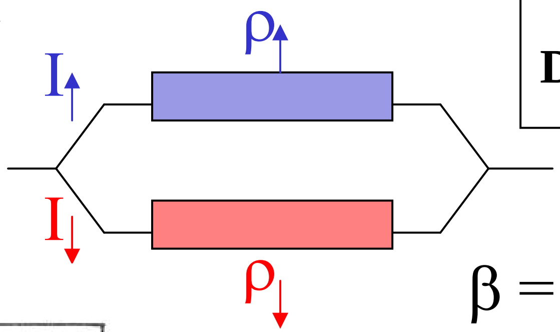
Fert et al, PRL 21, 1190, 1968

Loegel-Gautier, JPCS 32, 1971

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

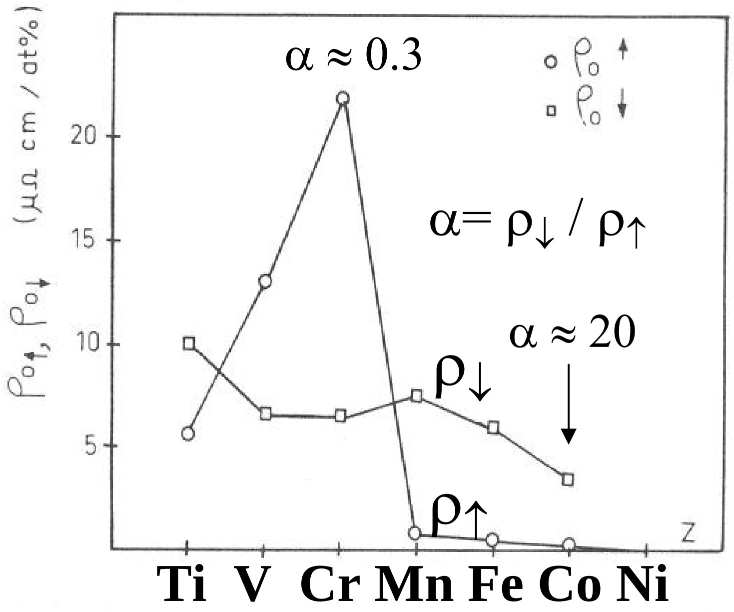
Dorlejin et al, ibid F7, 23, 1977

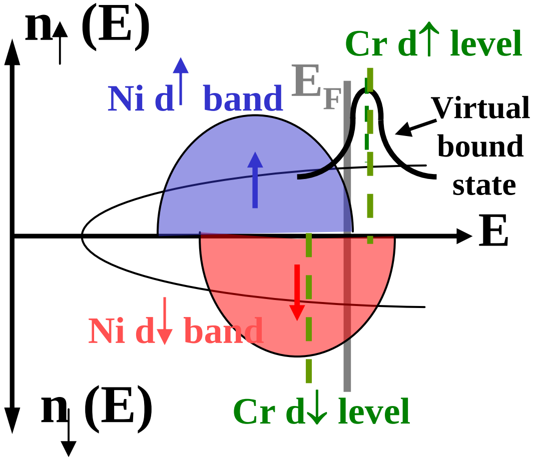




$\alpha = \rho_\downarrow / \rho_\uparrow$ or

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





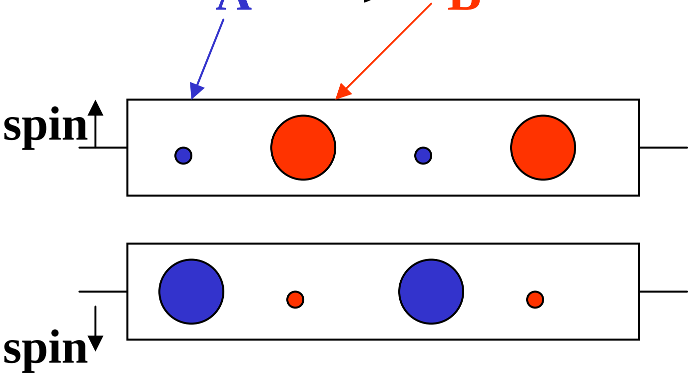
Mixing impurities A and B with opposite or similar spin asymmetries: *the pre-concept of GMR*

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

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

1st case

$\alpha_A > 1$, $\alpha_B < 1$

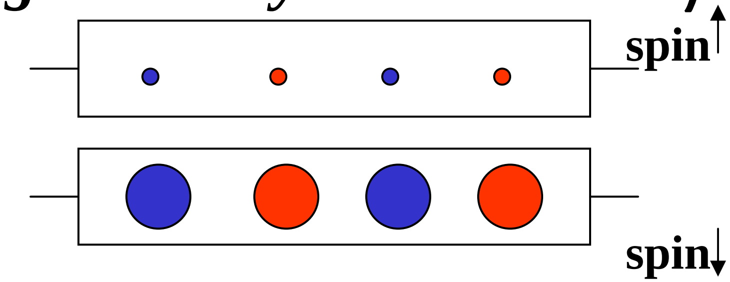


$\rho_{AB} >> \rho_A + \rho_B$

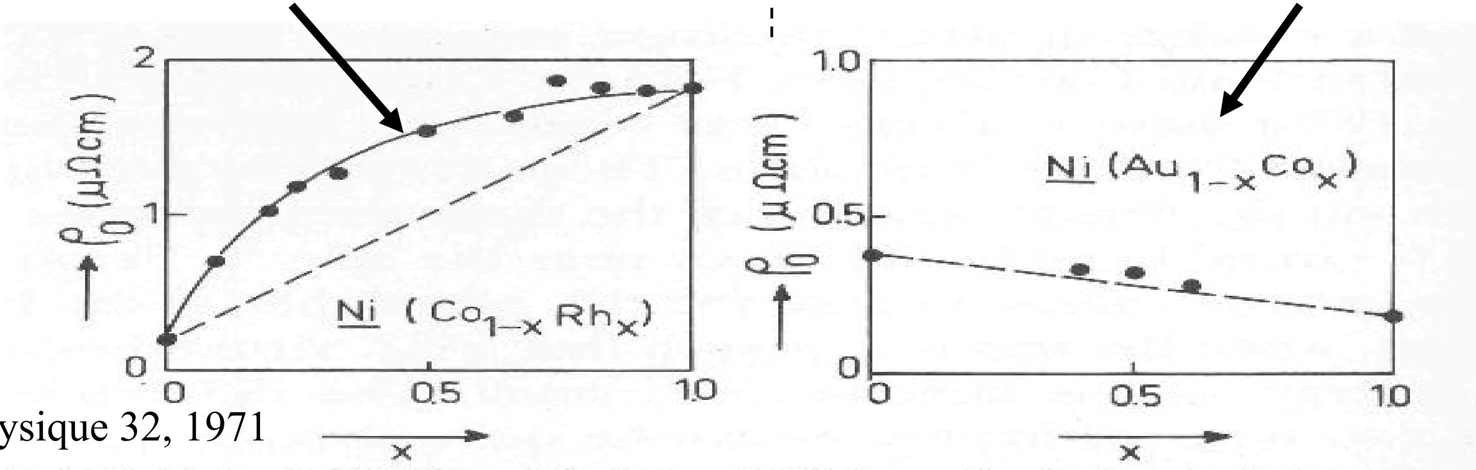
2d case

α_A **and** $\alpha_B > 1$

High mobility channel → low ρ

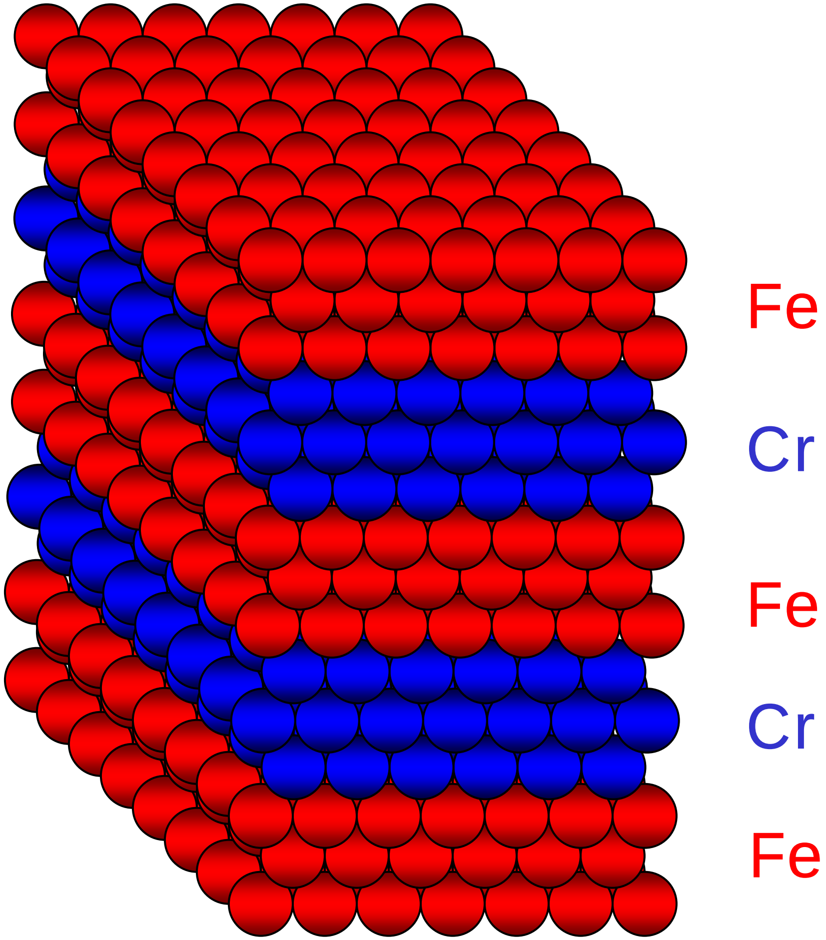


$\rho_{AB} \approx \rho_A + \rho_B$



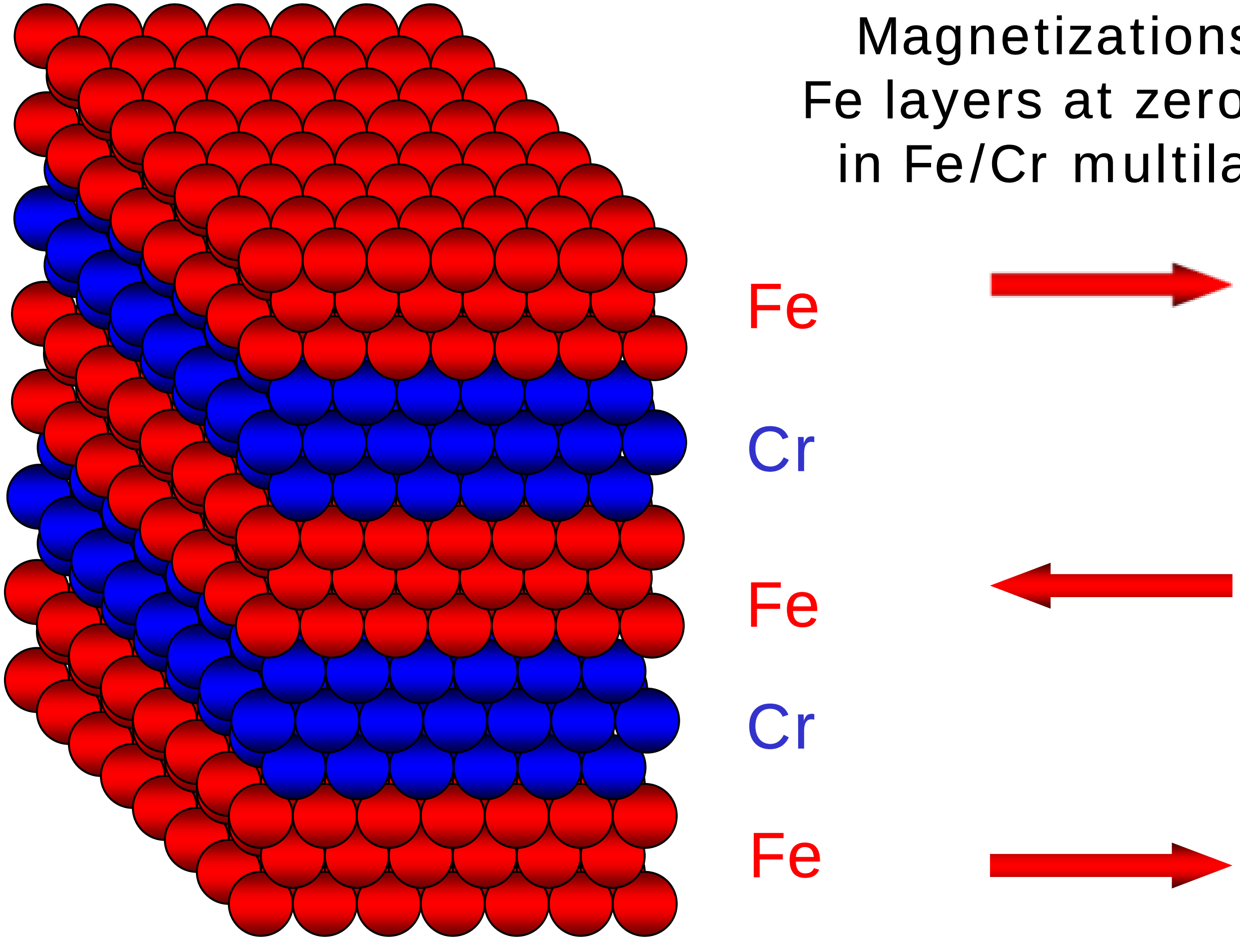
J. de Physique 32, 1971

- **Magnetic multilayers**



Magnetic multilayers

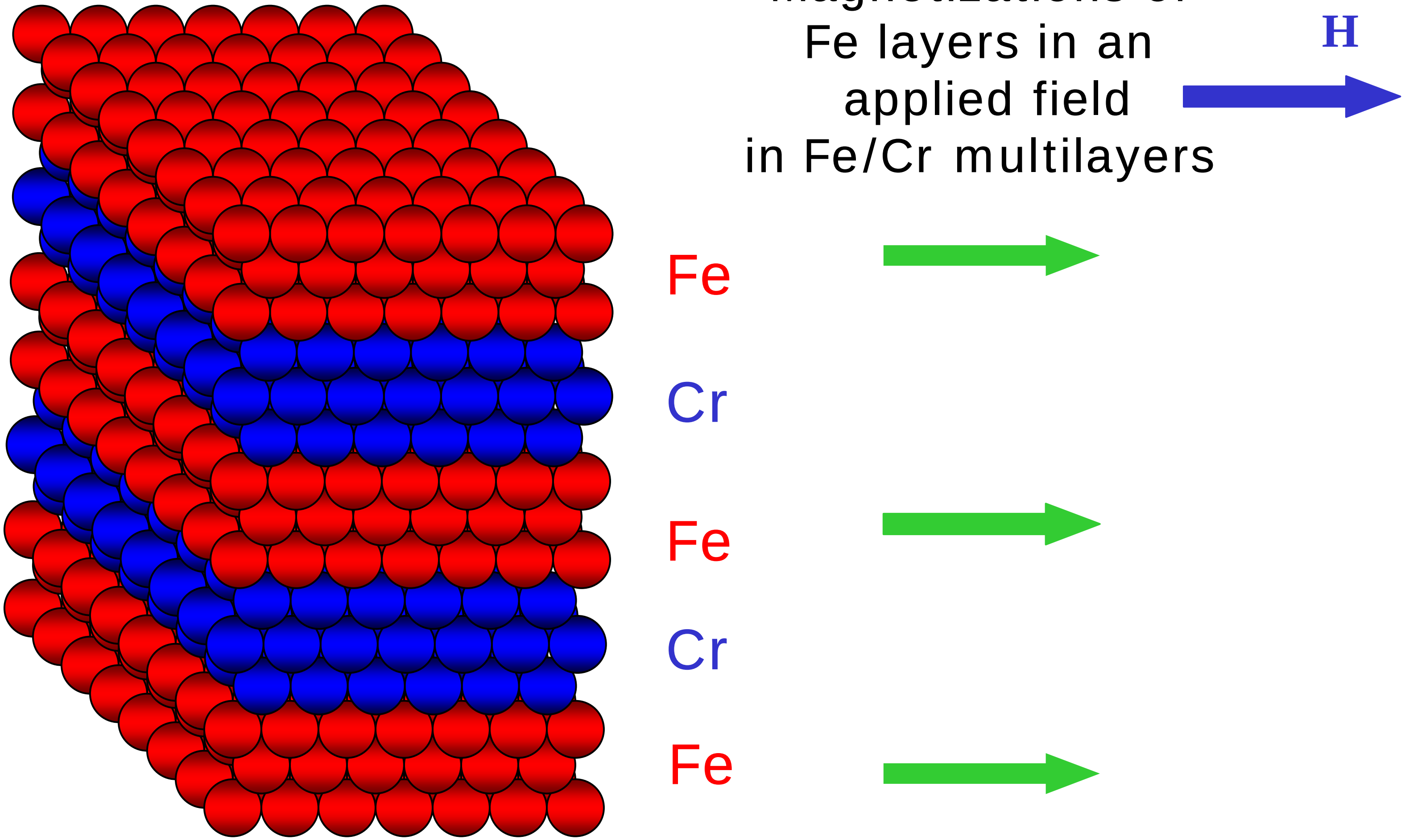
Magnetizations of
Fe layers at zero field
in Fe/Cr multilayers



P. Grünberg, 1986 → antiferromagnetic interlayer coupling

- **Magnetic multilayers**

Magnetizations of
Fe layers in an
applied field
in Fe/Cr multilayers

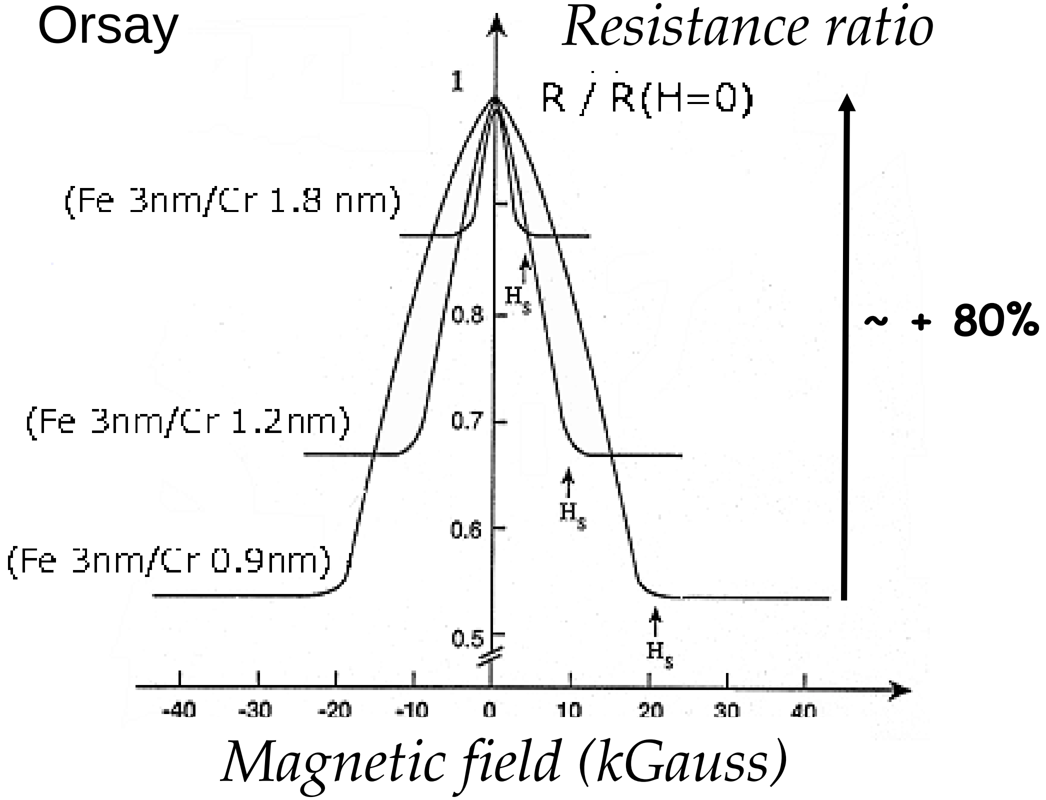


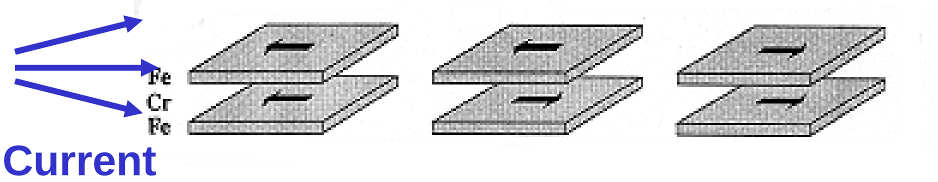
P. Grünberg, 1986 → antiferromagnetic interlayer coupling

• Giant Magnetoresistance (GMR)

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

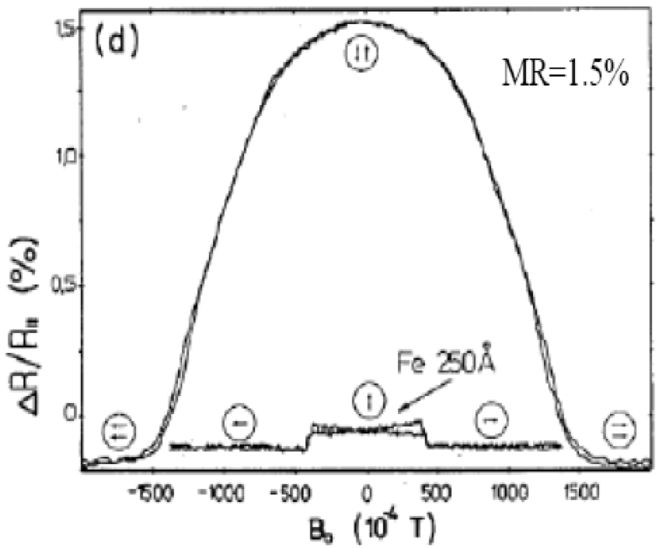
Orsay

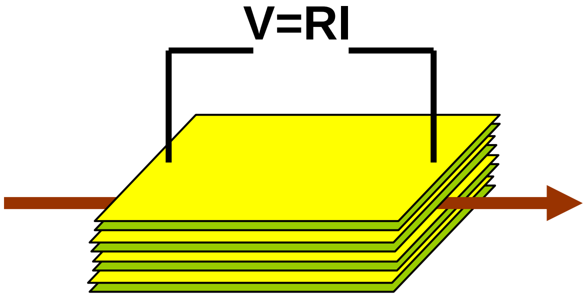




AP (AntiParallel) **P** (Parallel)

Jülich





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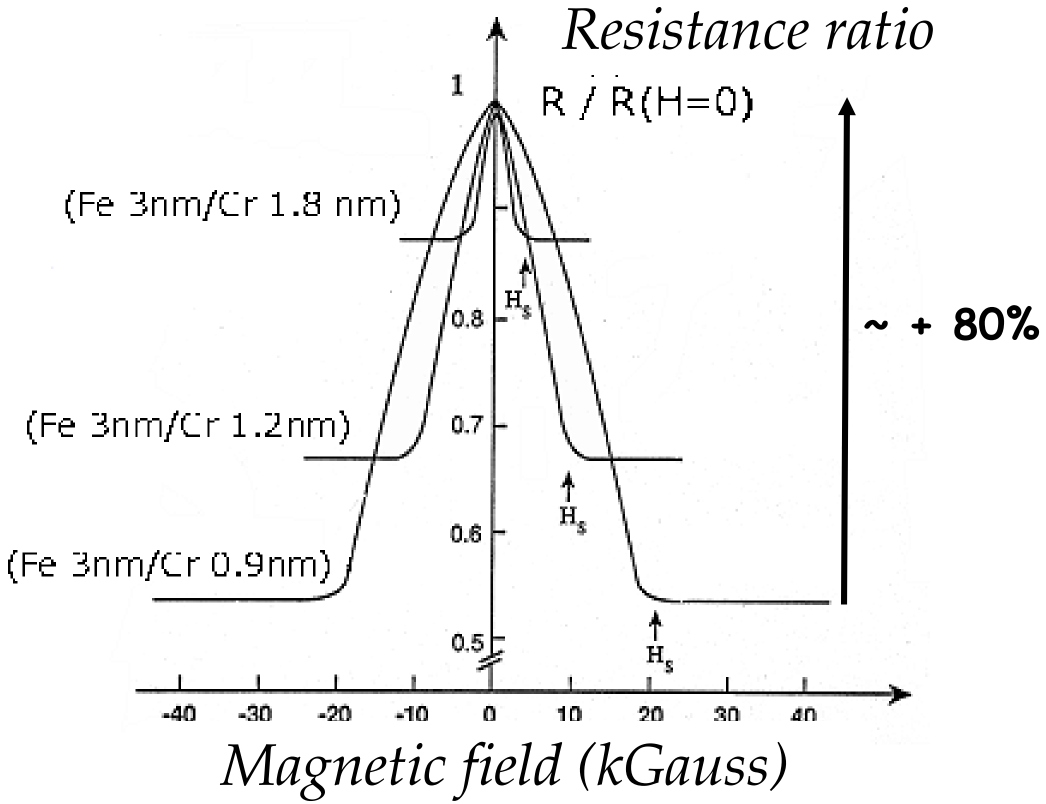
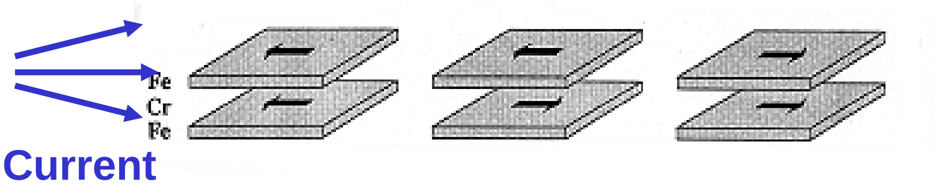
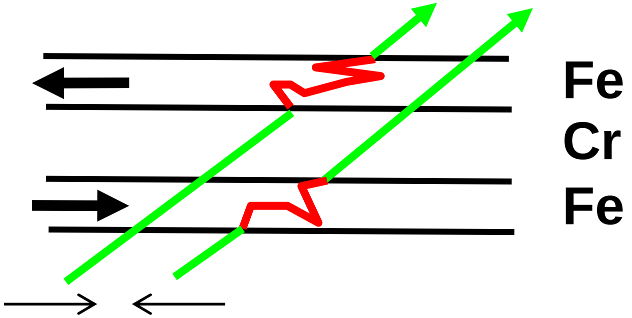
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)



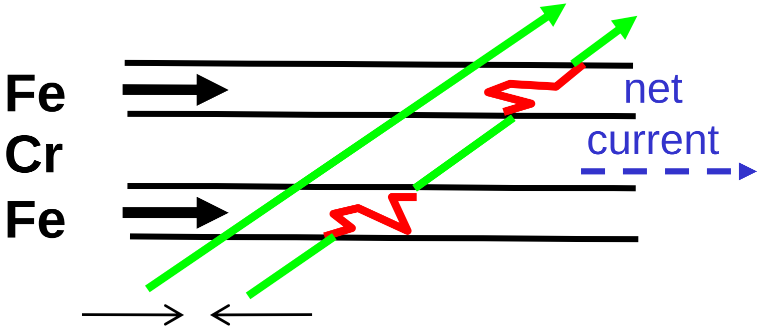


AP (AntiParallel) **P** (Parallel)

Anti-parallel magnetizations
(zero field, high resistance)

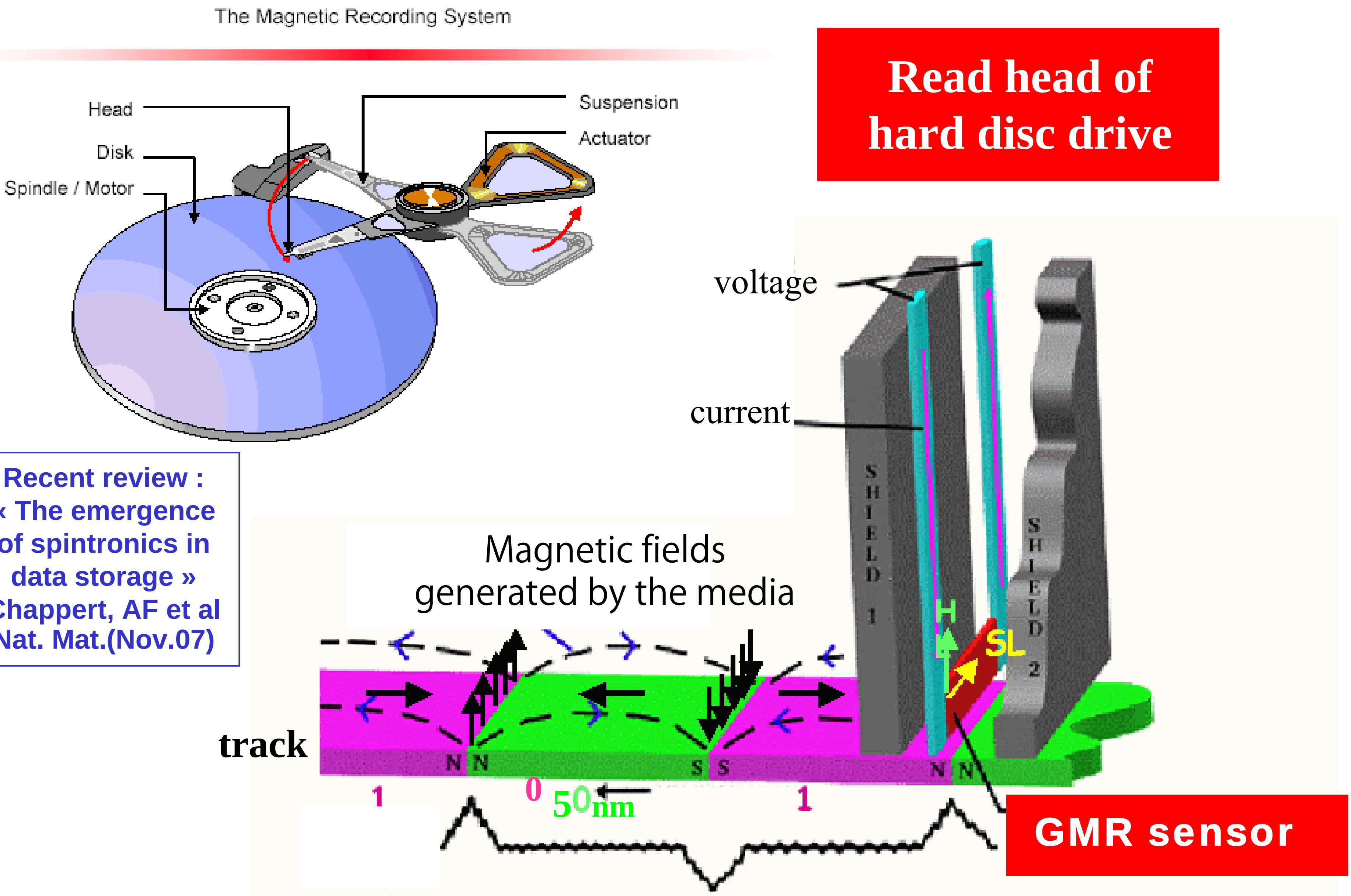


Parallel magnetizations
(appl. field, low resist.)



Condition for GMR:
layer thickness ≈ nm

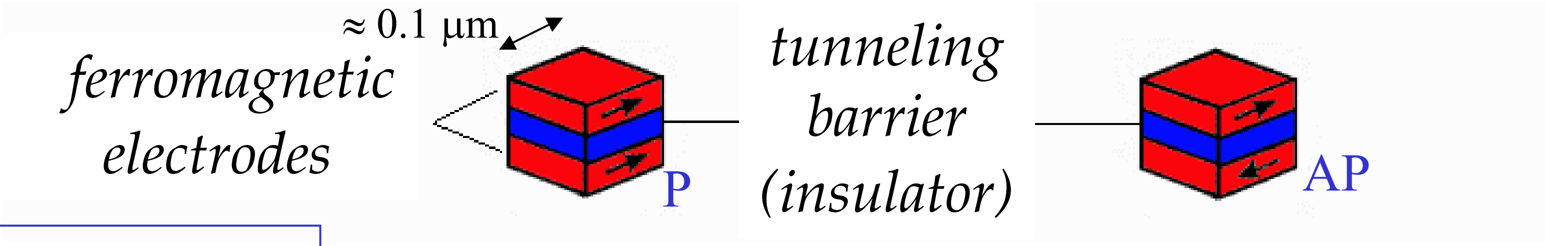
Read head of hard disc drive



Recent review :
« The emergence of spintronics in data storage »
Chappert, AF et al
Nat. Mat.(Nov.07)

1997 (before GMR) : 1 Gbit/in^2 , 2007 : GMR heads ~ 600 Gbit/in^2

• Magnetic Tunnel Junctions,Tunneling Magnetoresistance (TMR)



≈ 0.1 µm

ferromagnetic electrodes

tunneling barrier (insulator)

P

AP

Jullière, 1975, low T, hardly reproducible

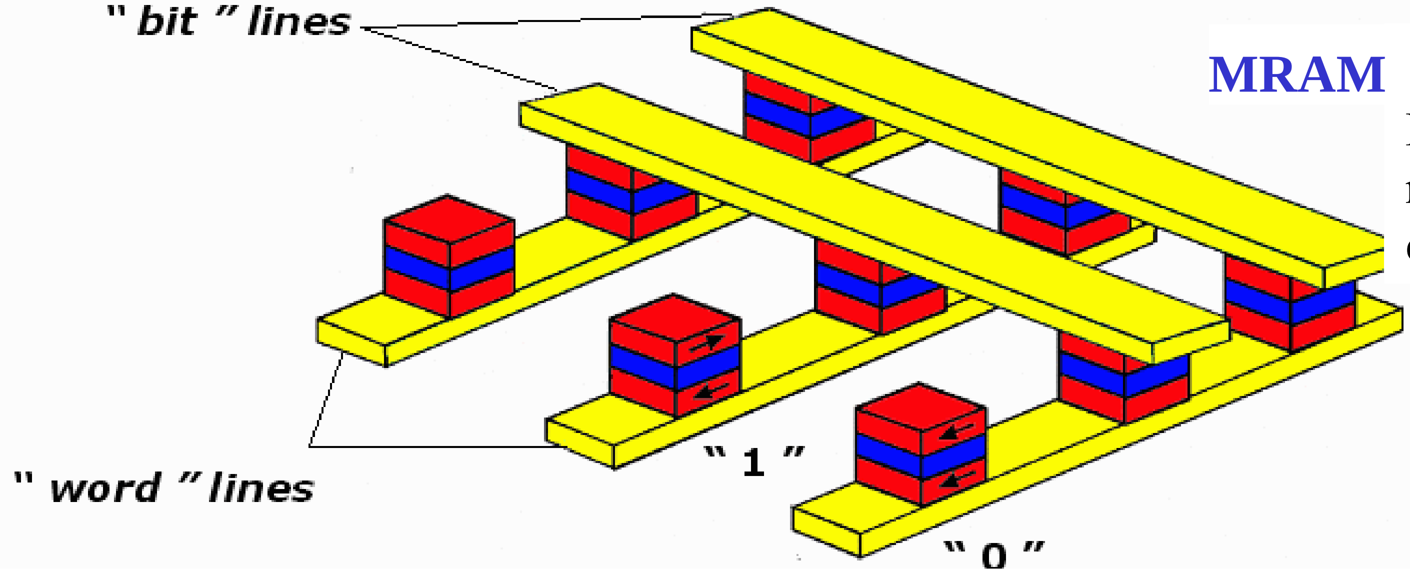
Low resistance state

High resistance state

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)

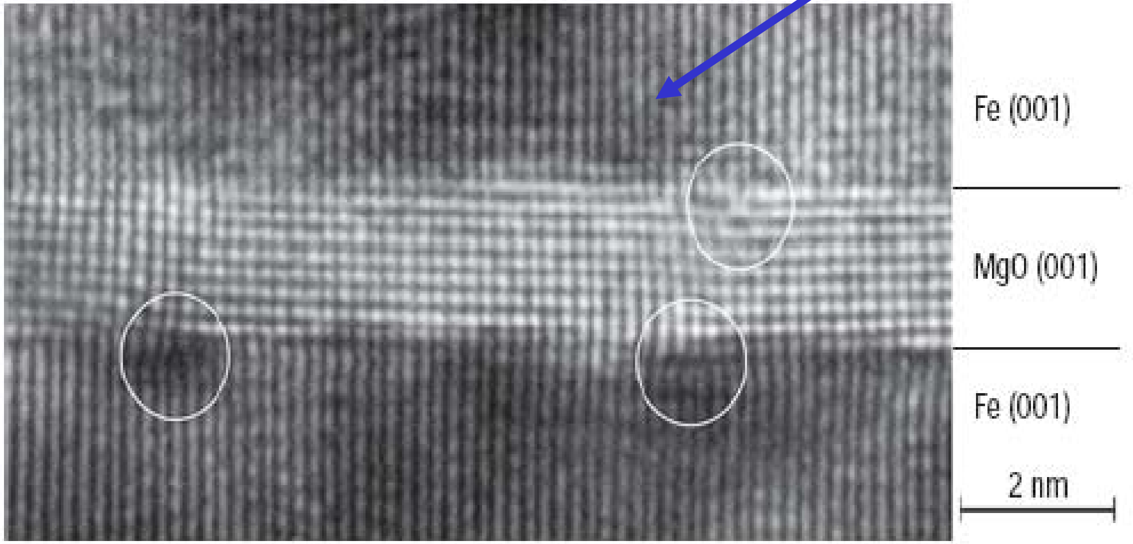


MRAM : density/speed of DRAM/SRAM + nonvolatilty + low energy consumption

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)]

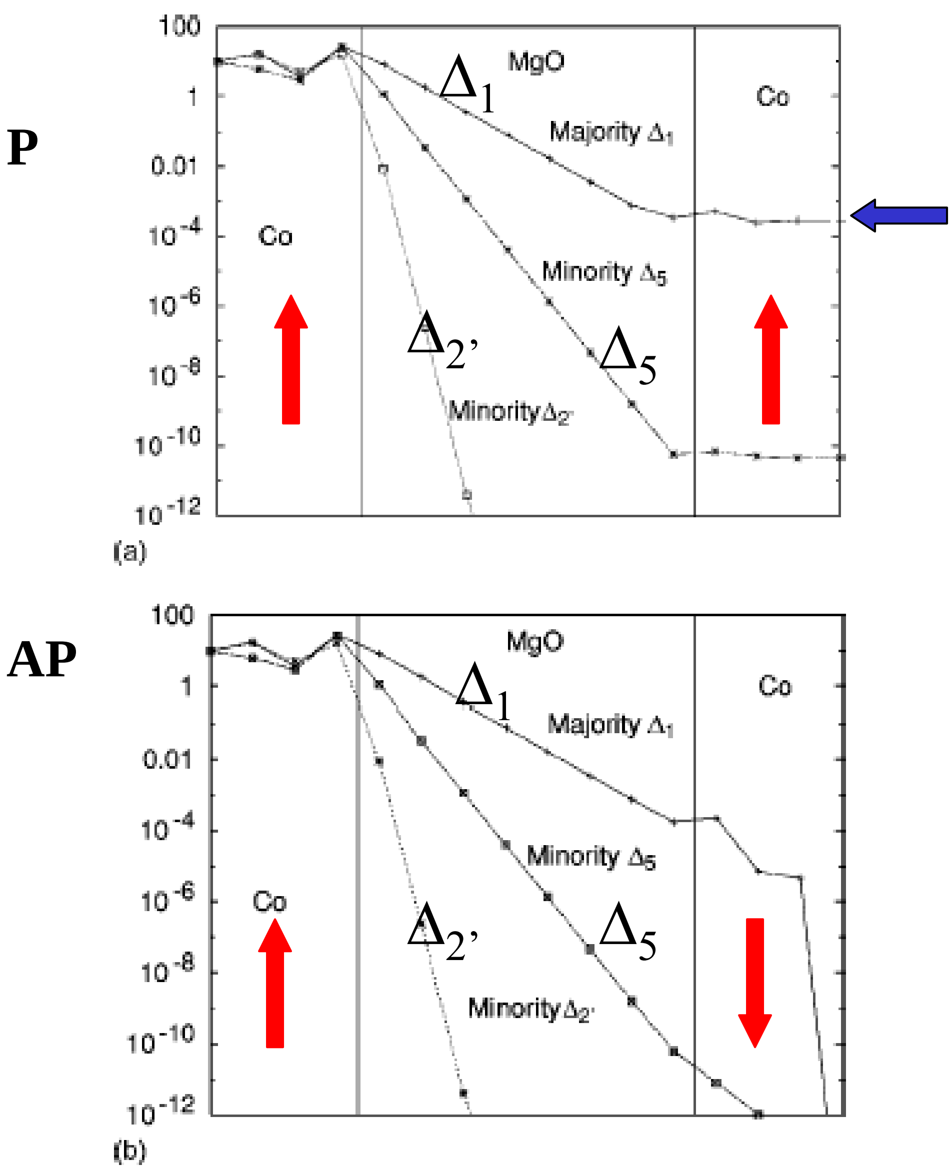


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel=0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

Beyond MgO

Zhang and Butler, PR B 2004

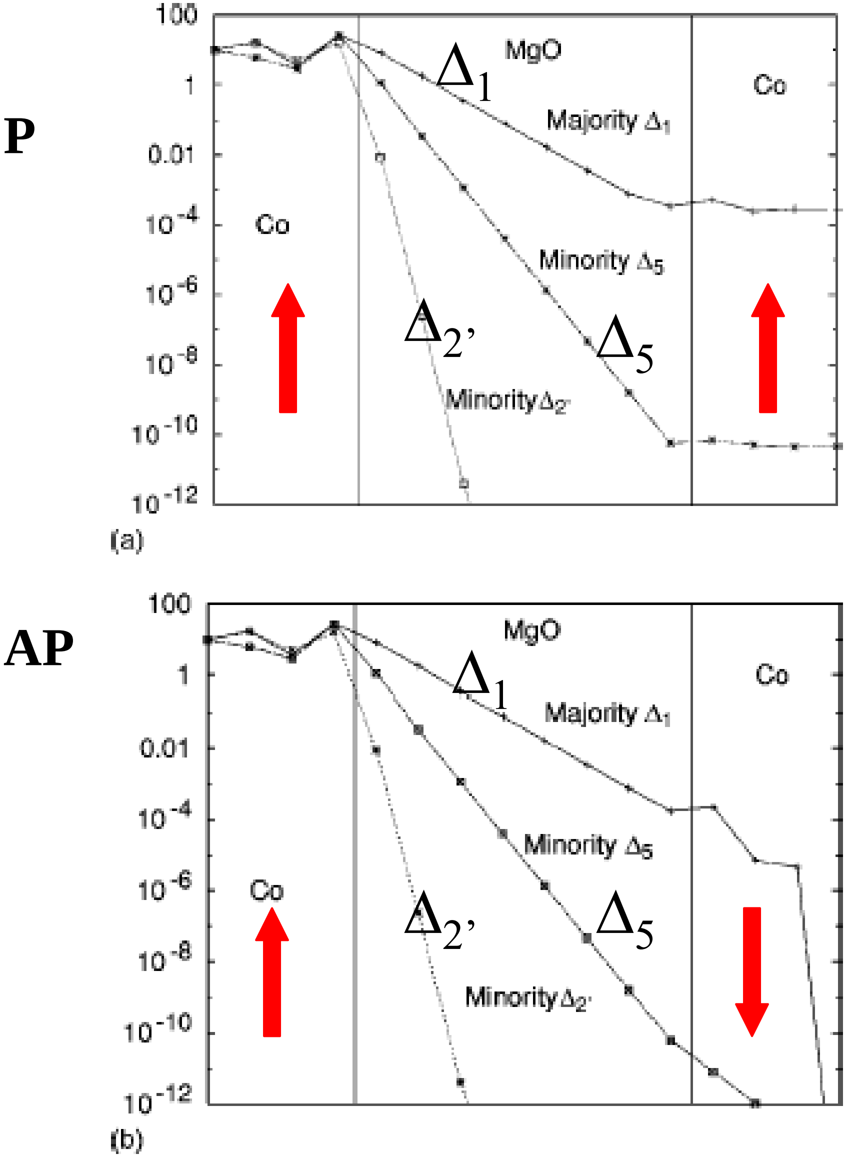


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel = 0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

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)

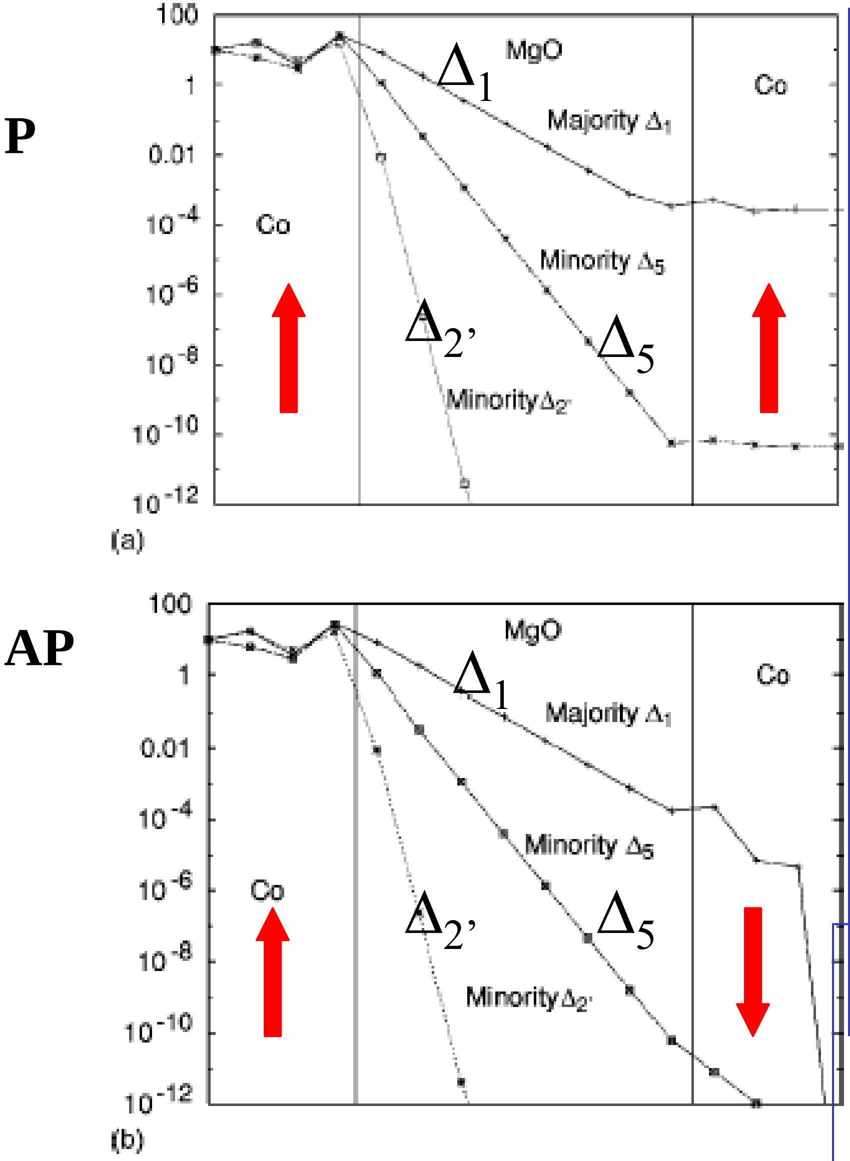
→Δ_5 symmetry (d) slowly decaying

→ 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)

Beyond MgO

Zhang and Butler, PR B 2004



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(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

Common physics:

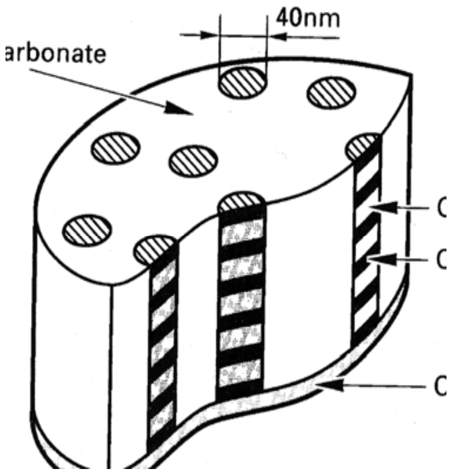
spin accumulation

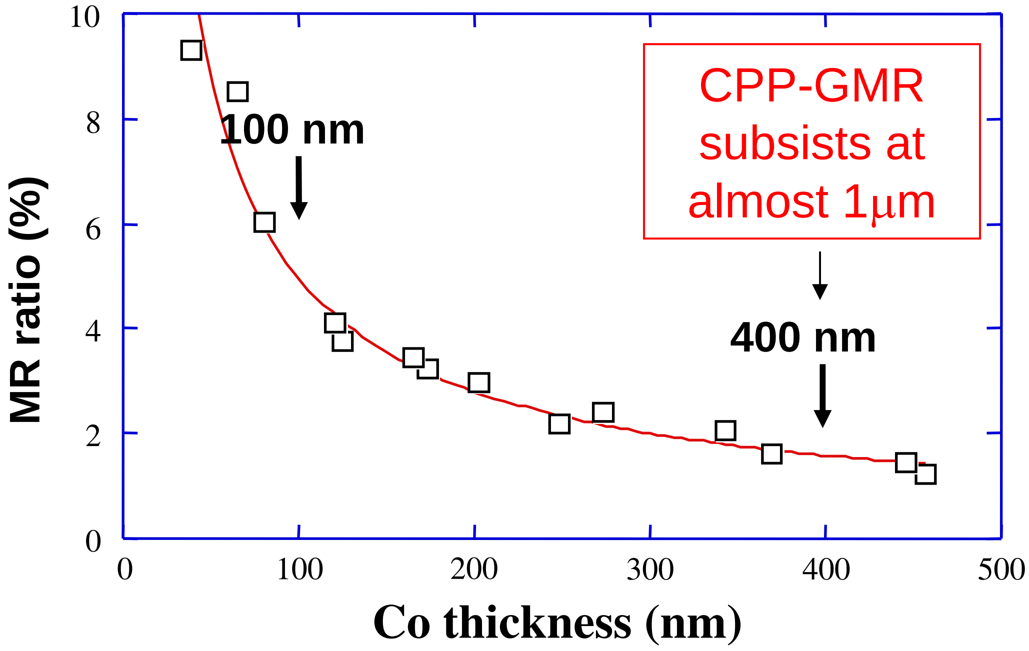
↓

spins injected to long distances

by diffusion

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





100 nm

CPP-GMR subsists at almost 1μm

400 nm

CIP-GMR

scaling length = mean free path

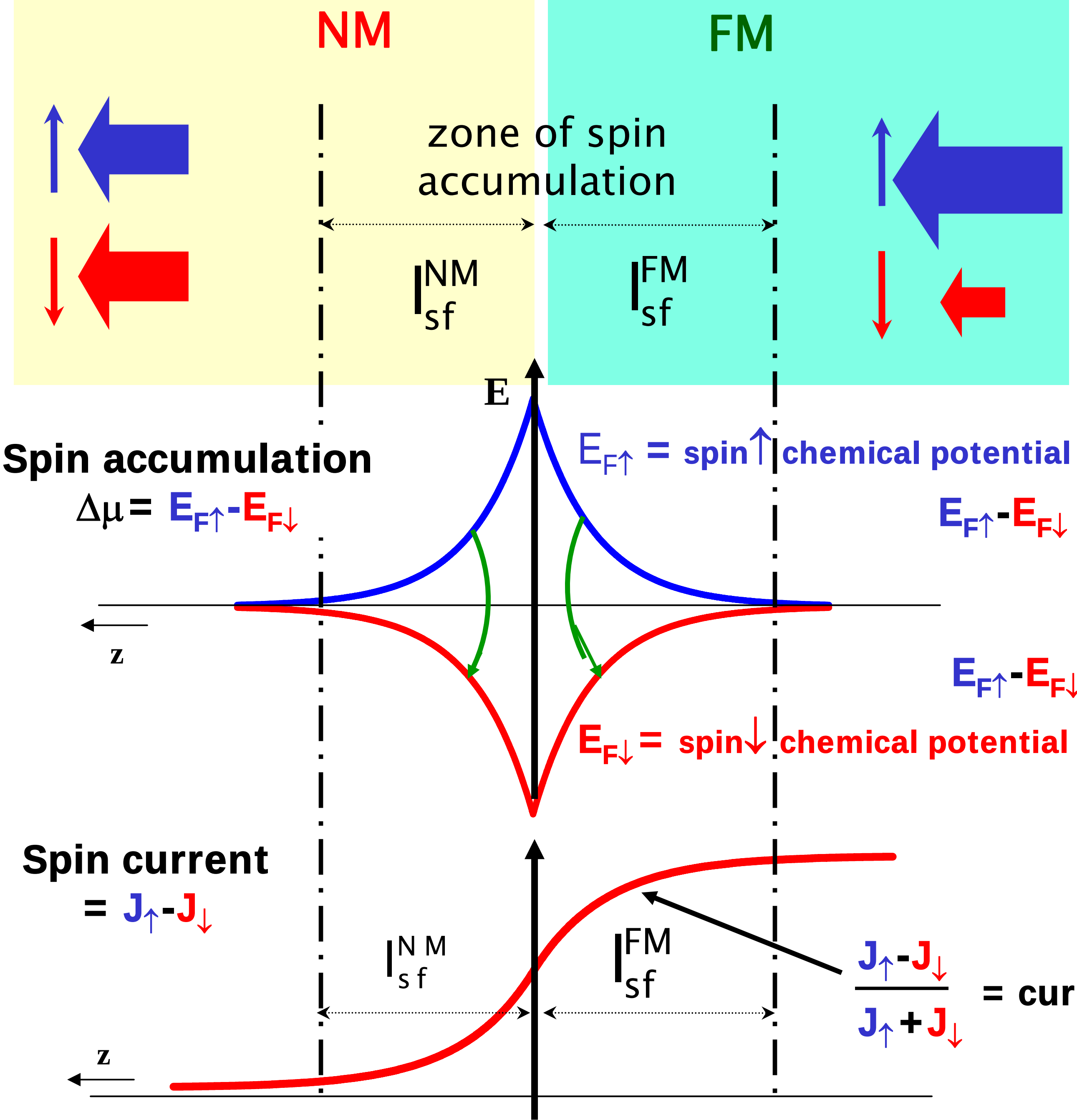
CPP-GMR

scaling length = spin diffusion length >> mean free path

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

Other results: MSU group, PRL 1991, JMMM 1999

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



zone of spin accumulation

l_{sf}^{NM} l_{sf}^{FM}

Spin accumulation

$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$

$E_{F\uparrow}$ = spin↑ chemical potential

$E_{F\downarrow}$ = spin↓ chemical potential

Spin current

$= J_{\uparrow} - J_{\downarrow}$

(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

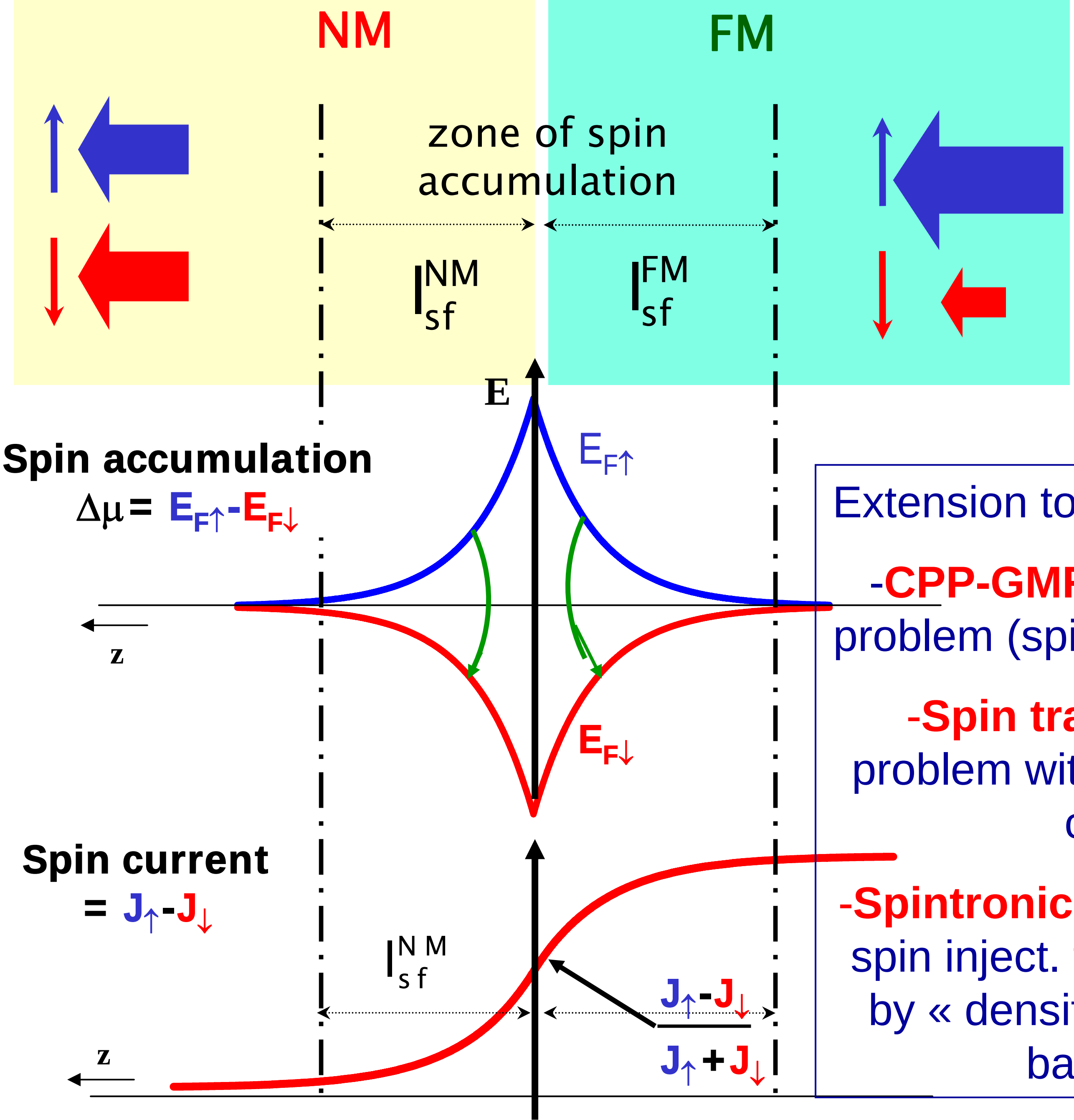
(example: 0.5 μm in Cu, >10μm in carbon nanotube)

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

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

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

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



Spin accumulation

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Spin current

$= J_\uparrow - J_\downarrow$

(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)

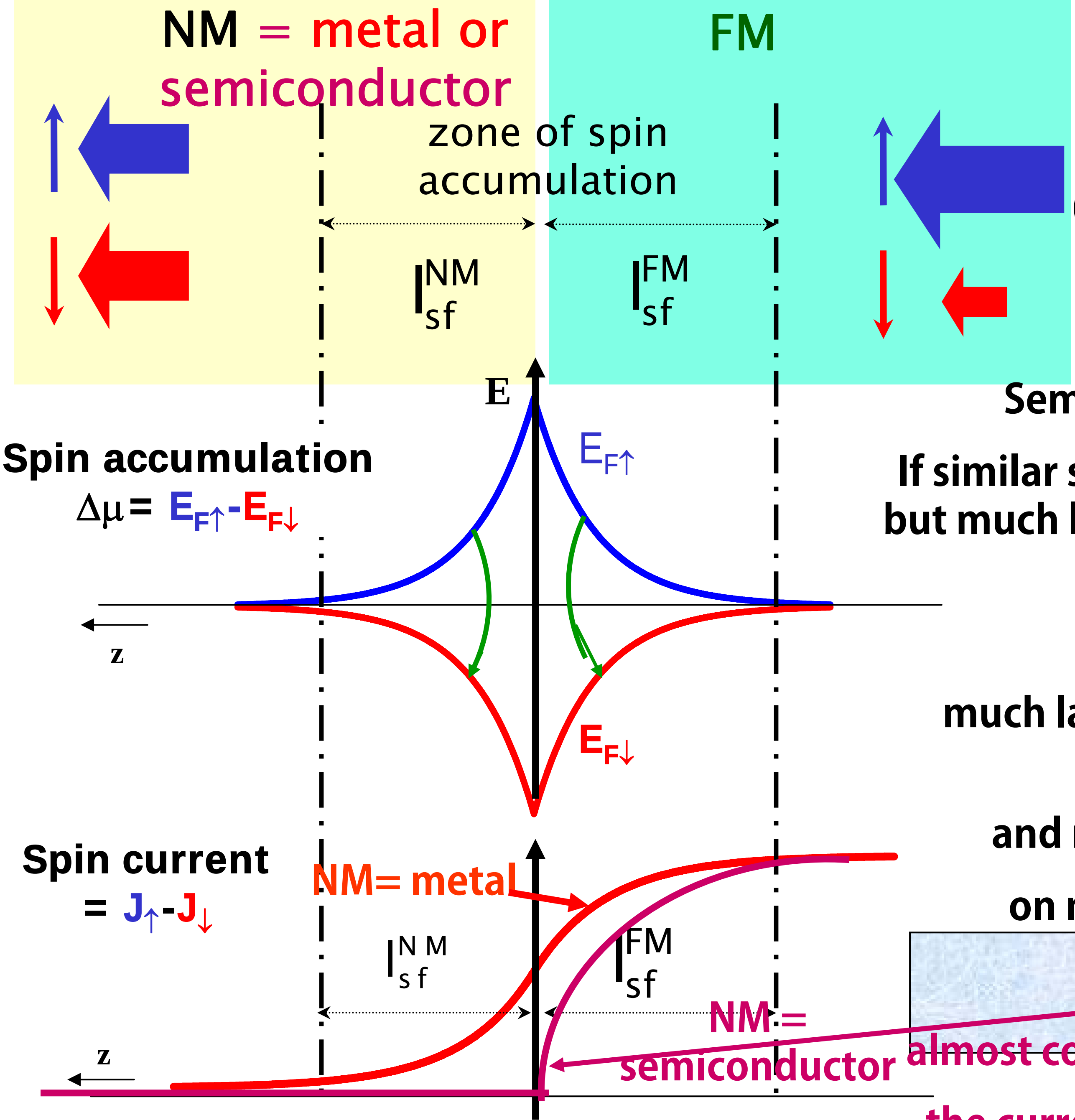
Extension to more complex situations

-**CPP-GMR**: typical multi-interface problem (spin accumulation overlaps)

-**Spin transfer**: multi-interface problem with non-colinear magnetic configurations

-**Spintronics with semiconductors**: spin inject. from metals complicated by « density of states mismatch », band bending, etc

Spin injection/extraction at a Semiconductor/FM interface



Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$

Spin current
$= J_{\uparrow} - J_{\downarrow}$

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

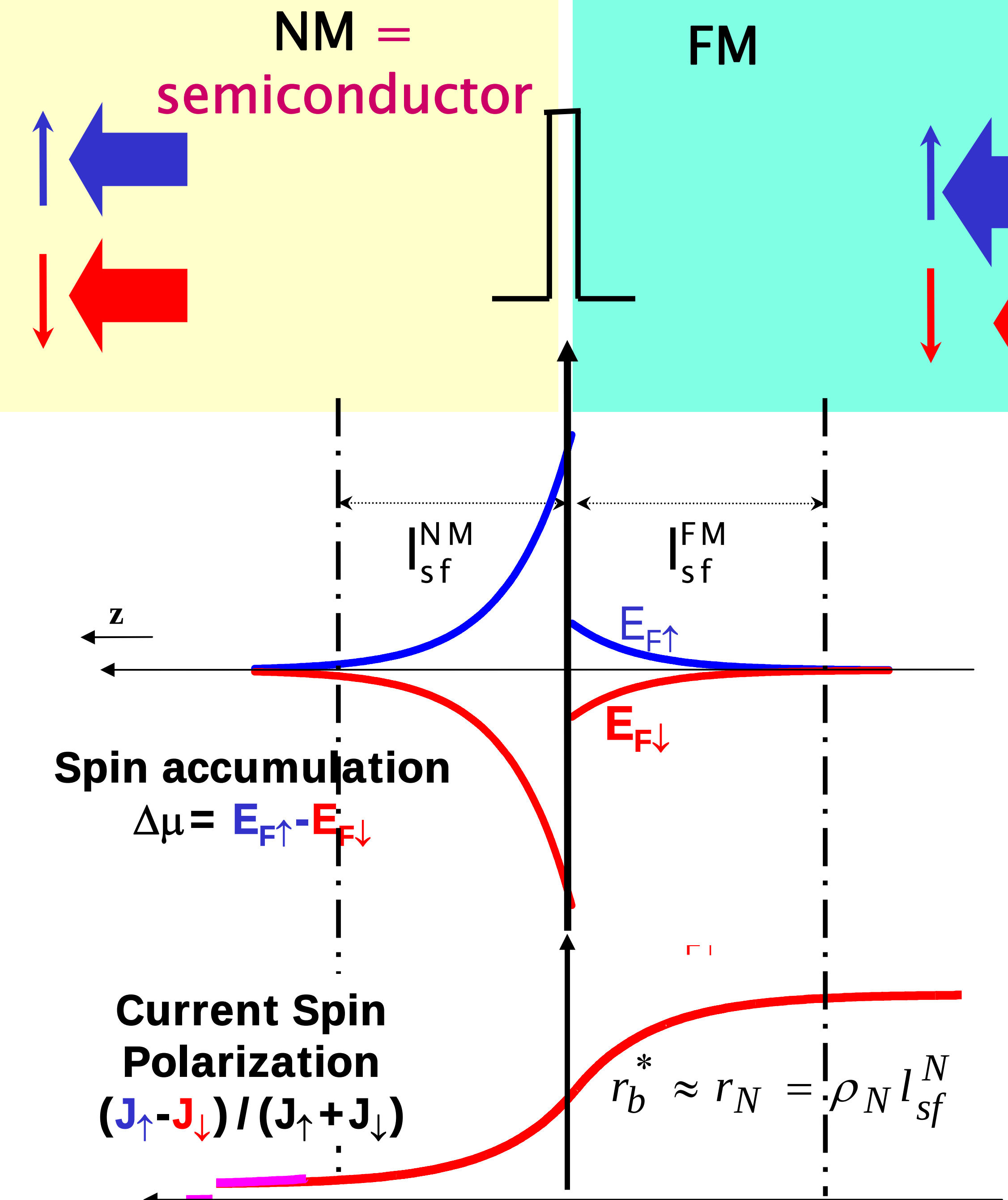
and much more spin flips

on magnetic metal side

↓

almost complete depolarization of the current before it enters the SC

Spin injection/extraction at a Semiconductor/FM interface

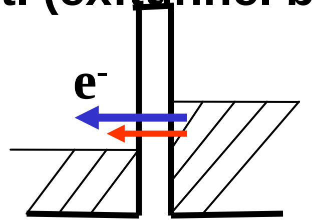


Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$

Current Spin Polarization
$(J_\uparrow - J_\downarrow) / (J_\uparrow + J_\downarrow)$

$$r_b^* \approx r_N = \rho_N l_{sf}^N$$

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

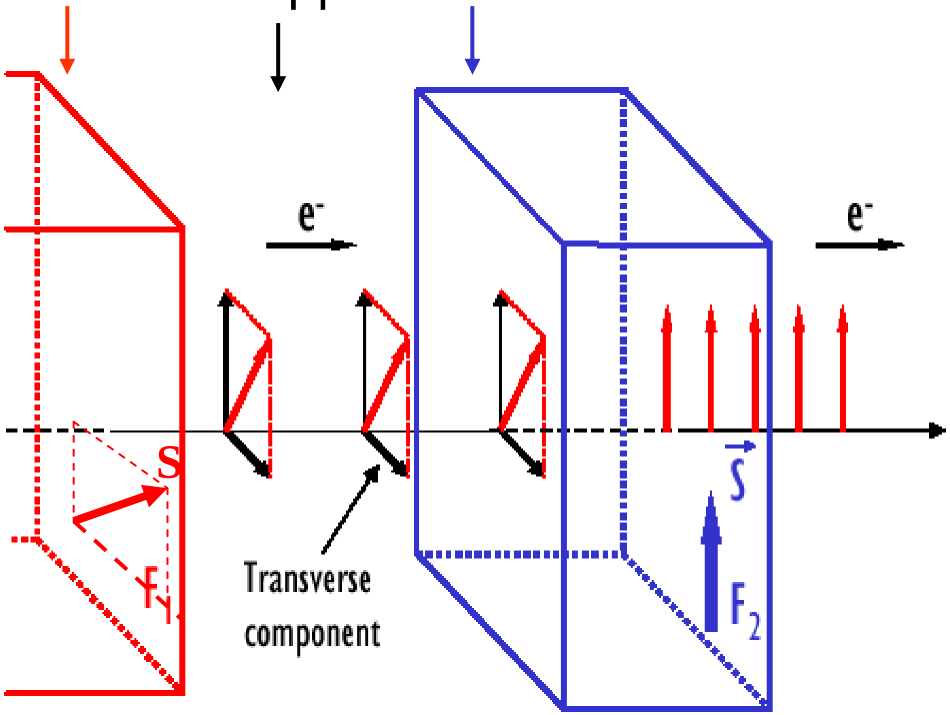
Rasbah, PR B 2000

A.F-Jaffrès, PR B 2001

Spin transfer

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

Ex:Cobalt/Copper/ Cobalt



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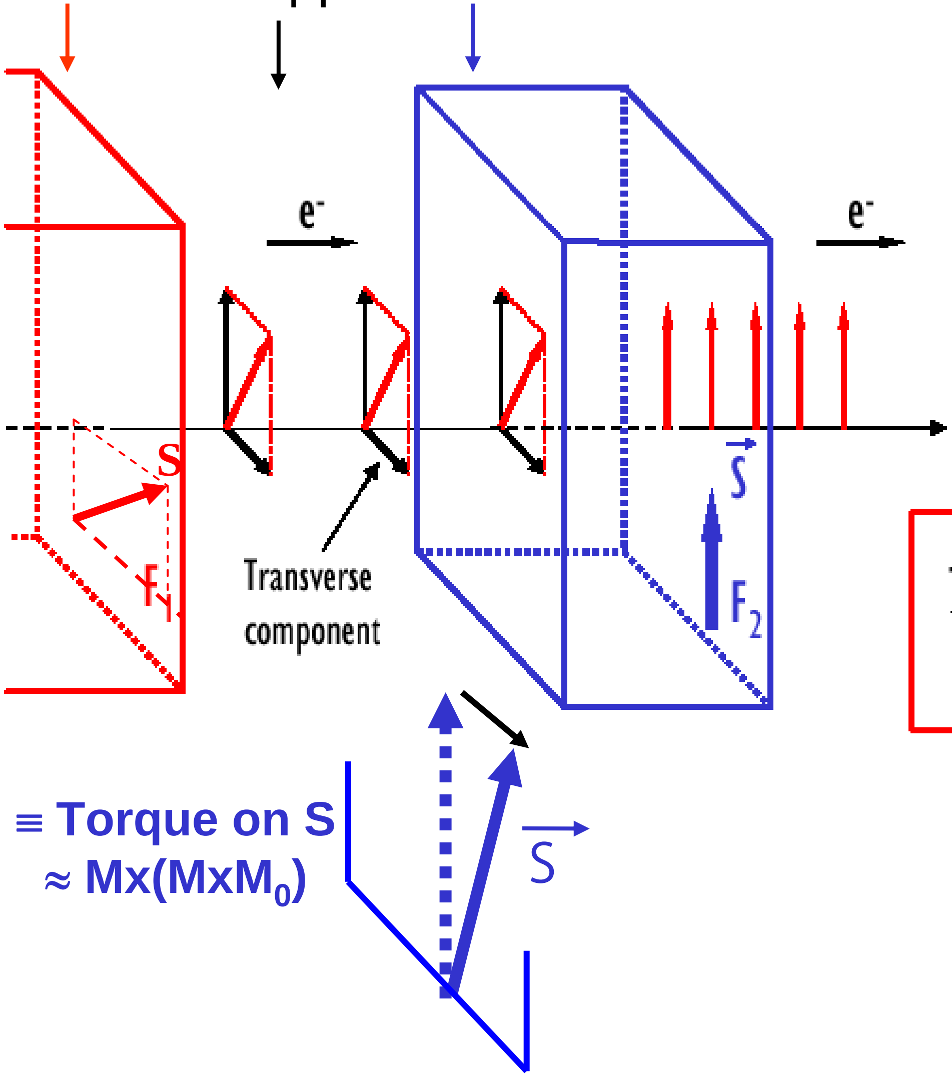


≡ **Torque on S**

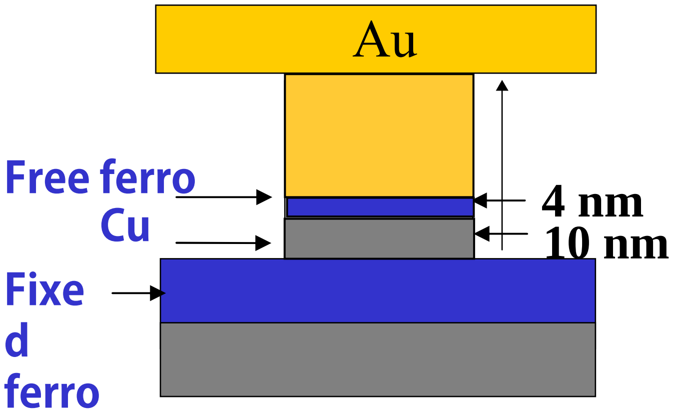
≈ **$Mx(MxM_0)$**

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

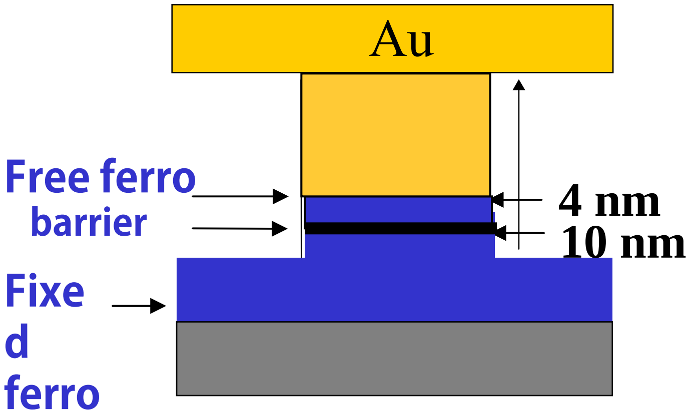
$$\frac{\text{torque}}{\hbar} = \left(\frac{d\vec{S}}{dt}\right)_i = \text{absorbed transverse spin current}$$

$$\propto j\ M \text{ x } (M \text{ x } M_0)$$

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)

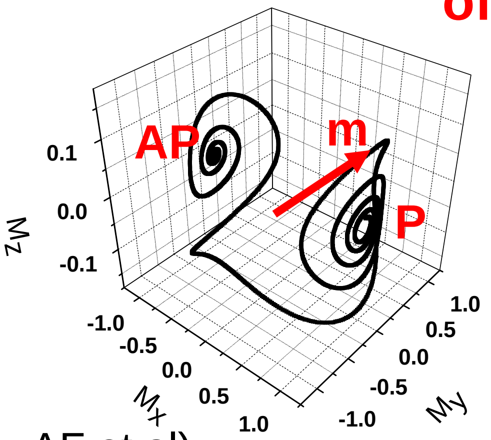
Regime of irreversible magnetic switching

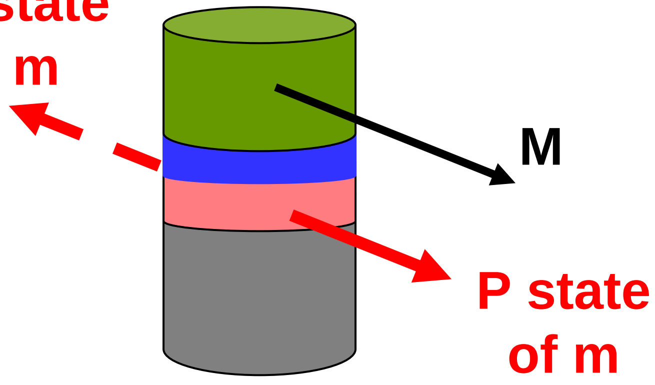
First experiments on pillars:

Cornell (Katine et al, PRL 2000)

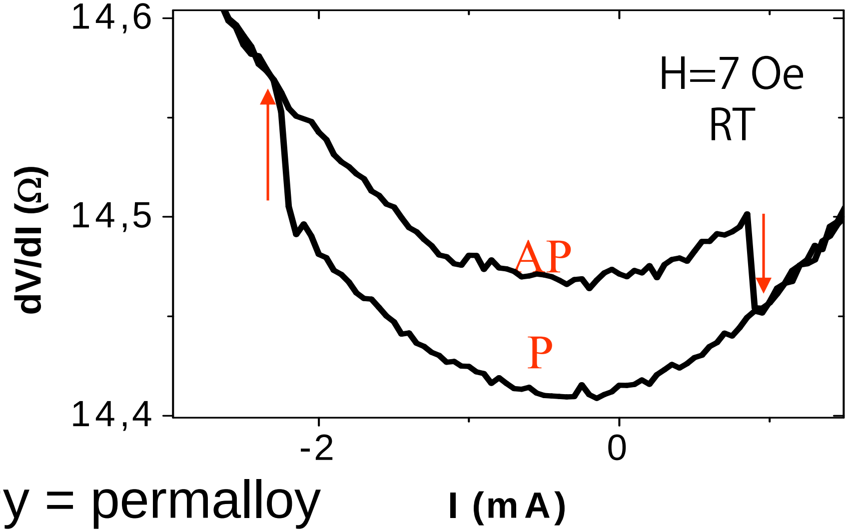
CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)





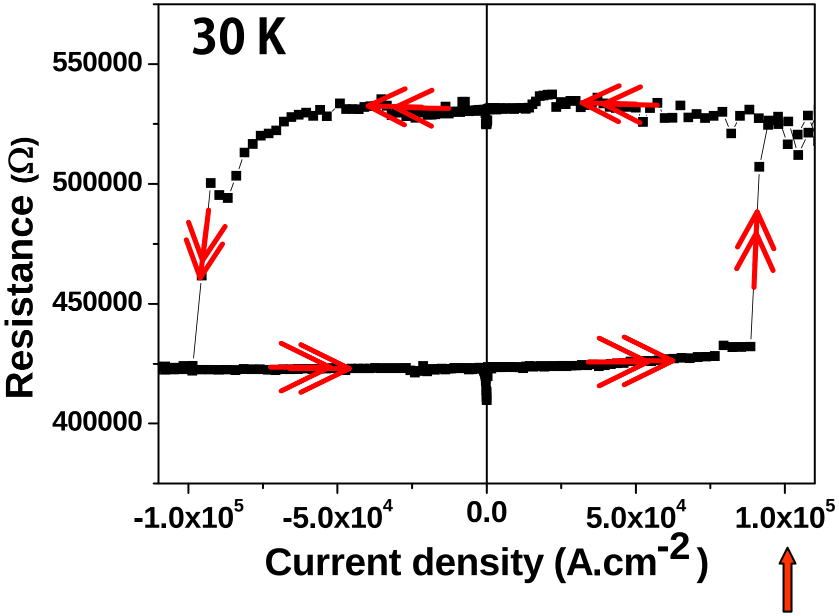
Py/Cu/Py 50nmX150nm (Boulle, AF et al)



Py = permalloy

GaMnAs/InGaAs/GaMnAs tunnel junction ***(MR=150%)***

(Elsen, AF et al, PR B 2006)



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

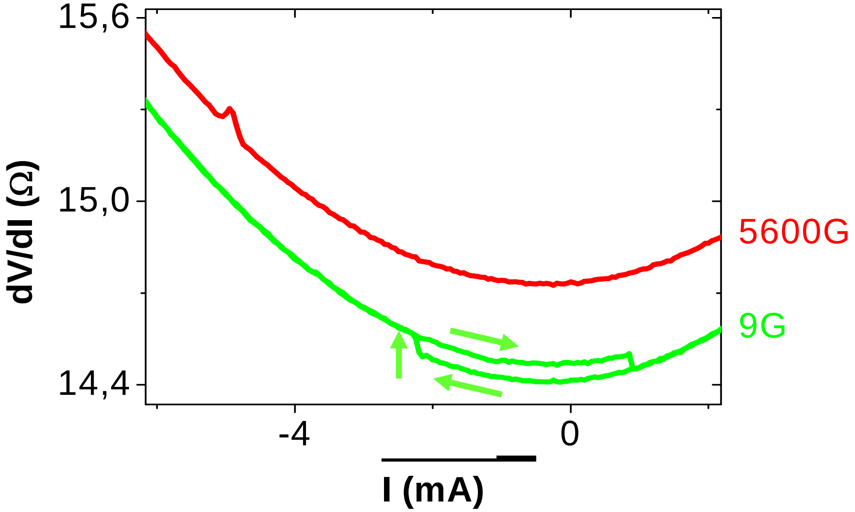
switching time can be as short as 0.1 ns (Chappert et al)

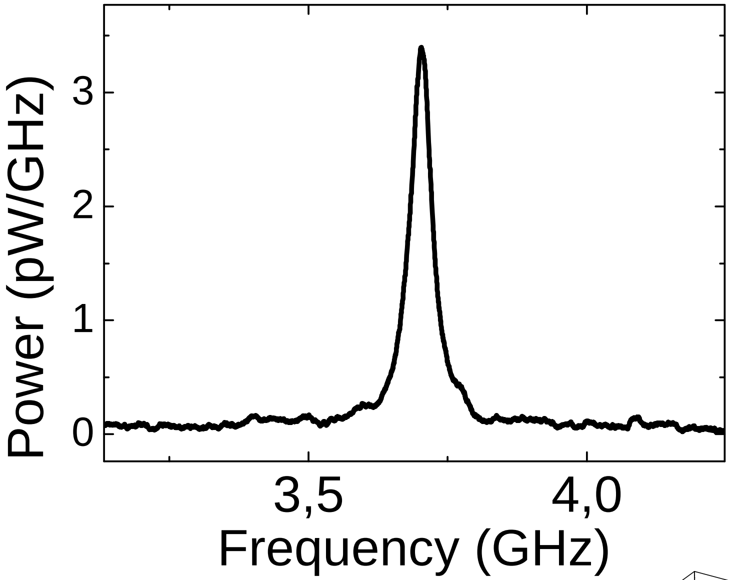
$1 \times 10^5\ A/cm^2$

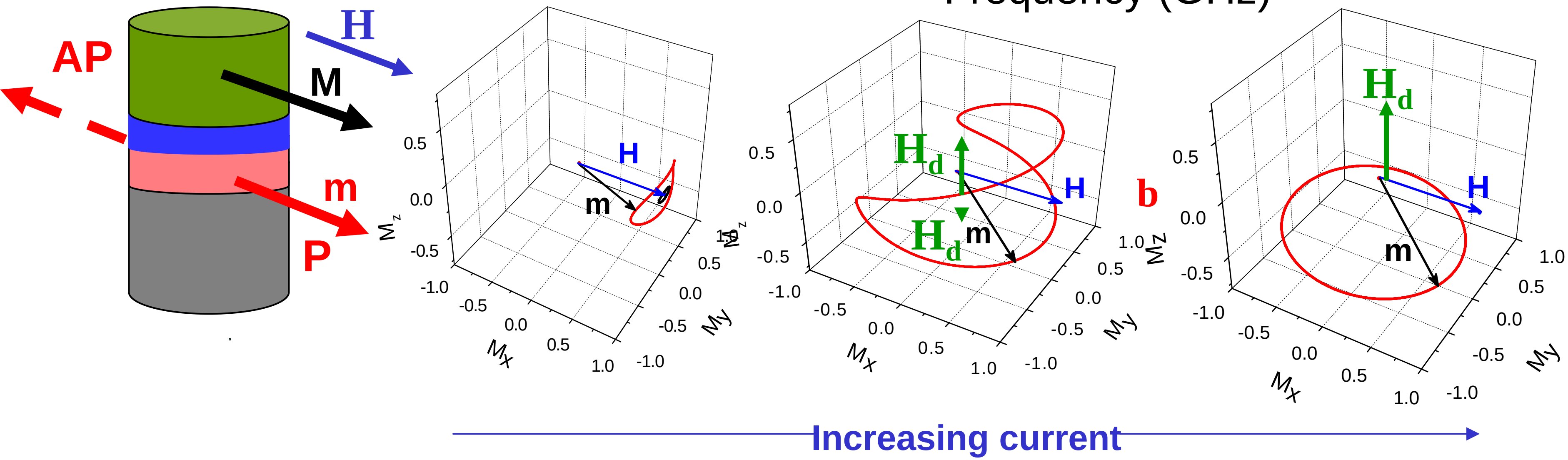
Regime of steady precession (microwave frequency range)

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

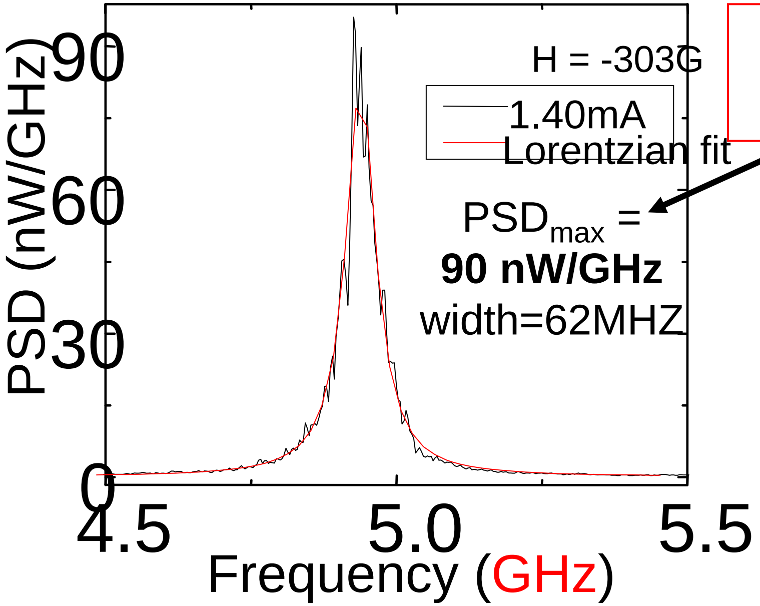
(Py = permalloy)





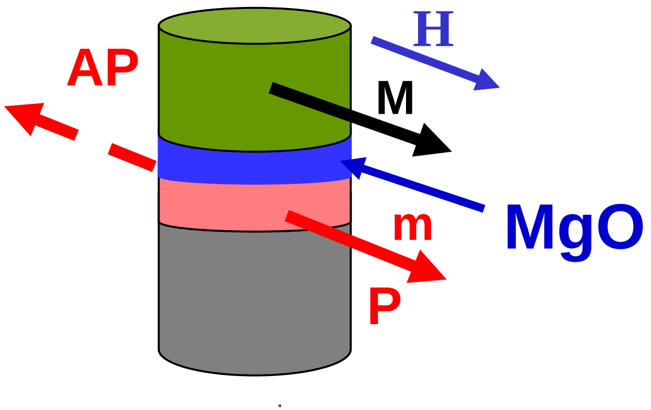


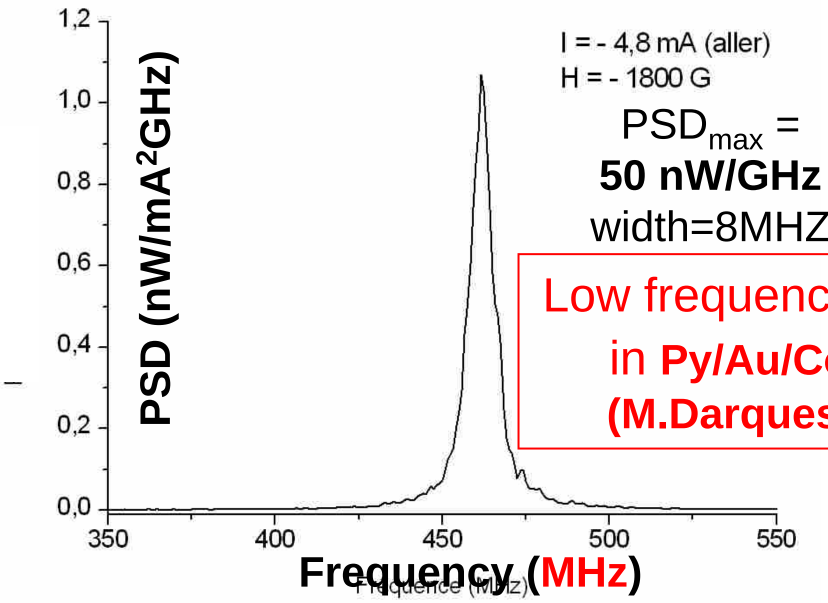
Regime of steady precession or vortex motion(microwave frequency range)



PSD_{max} = **90 nW/GHz** width=62MHZ

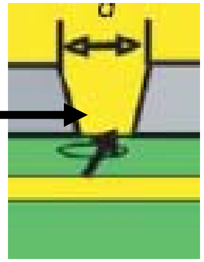
CoFeB/MgO/CoFeB junction **(J.Grollier, AF et al 2008, collaboration S. Yuasa et al, AIST)**



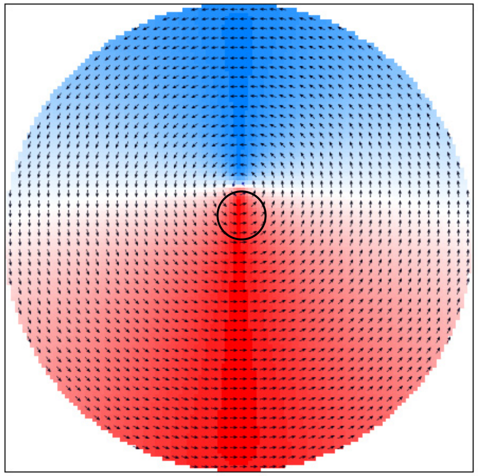


PSD_{max} = **50 nW/GHz** width=8MHZ

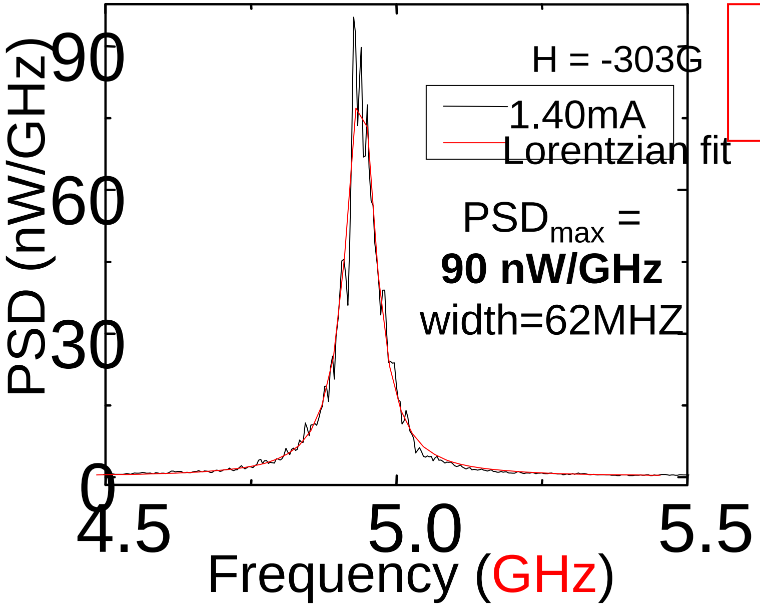
Low frequency vortex excitation in **Py/Au/Co** nanocontacts **(M.Darques, AF et al, 2008)**



Φ ~ 20 – 30 nm



Regime of steady precession or vortex motion(microwave frequency range)



PSD_{max} =
90 nW/GHz
width=62MHZ

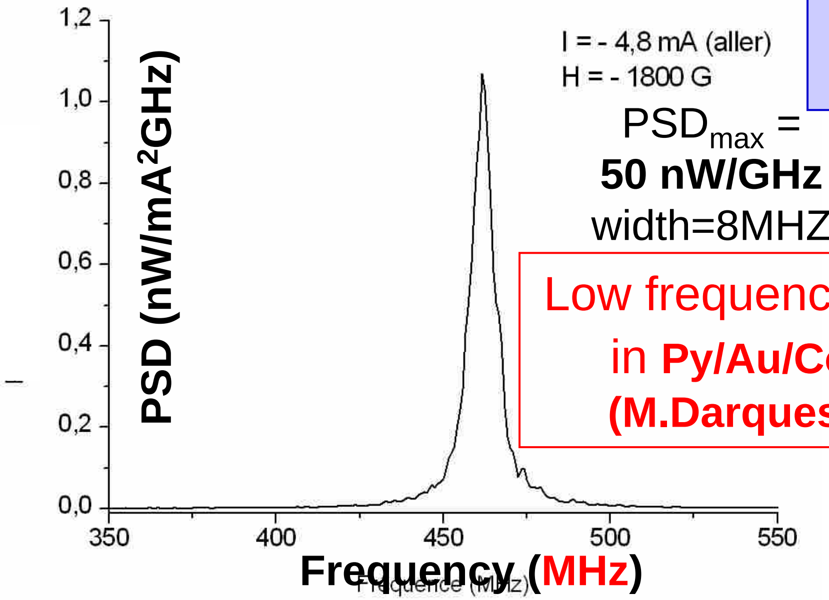
CoFeB/MgO/CoFeB junction (J.Grollier, AF et al 2008, collaboration S. Yuasa et al, AIST)

Spin Transfer mixes very different (and interacting) problems:

transport (in metallic pillars, tunnel junctions, point contacts)

problems of non-linear dynamics

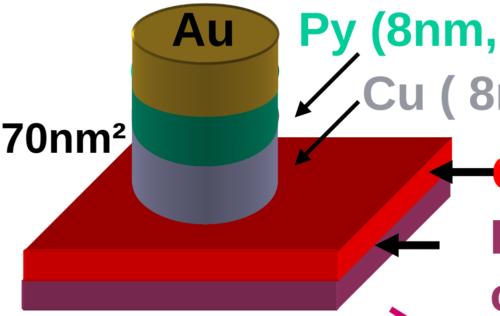
micromagnetism (non-uniform excitations, vortex motion..)



PSD_{max} =
50 nW/GHz
width=8MHZ

Low frequency vortex excitation
in **Py/Au/Co** nanocontacts
(M.Darques, AF et al, 2008)

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



100x170nm²

Py (8nm, free)

Cu (8nm)

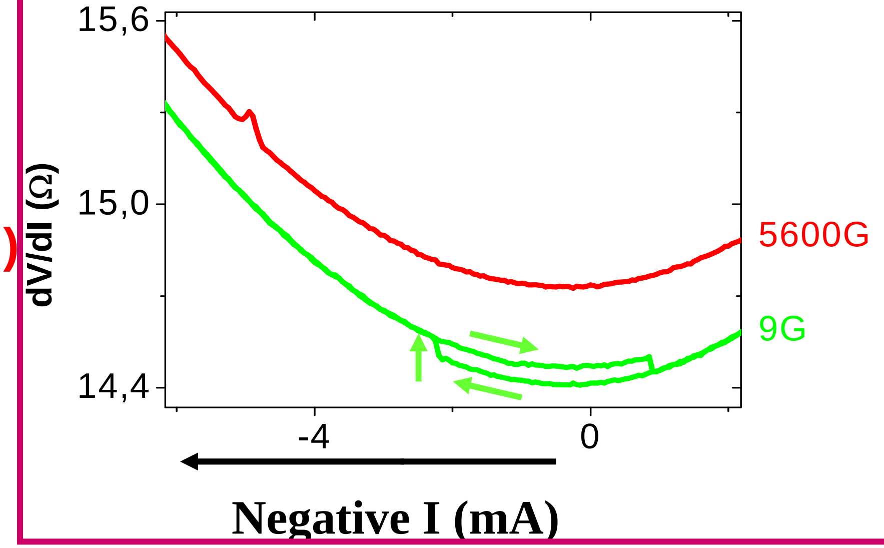
Co (8nm, fixed)

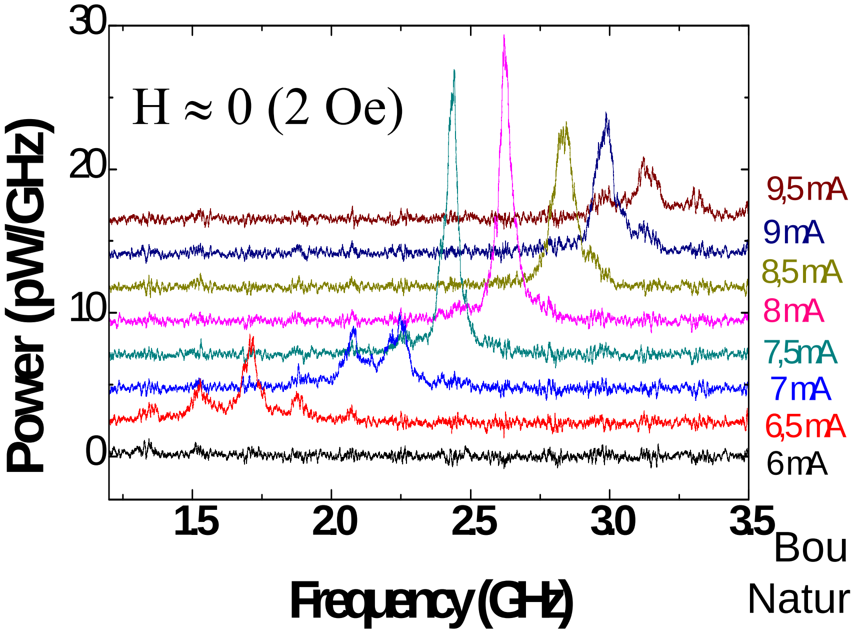
IrMn (15nm)
or CoO or Cu

free Py:fast spin relaxation

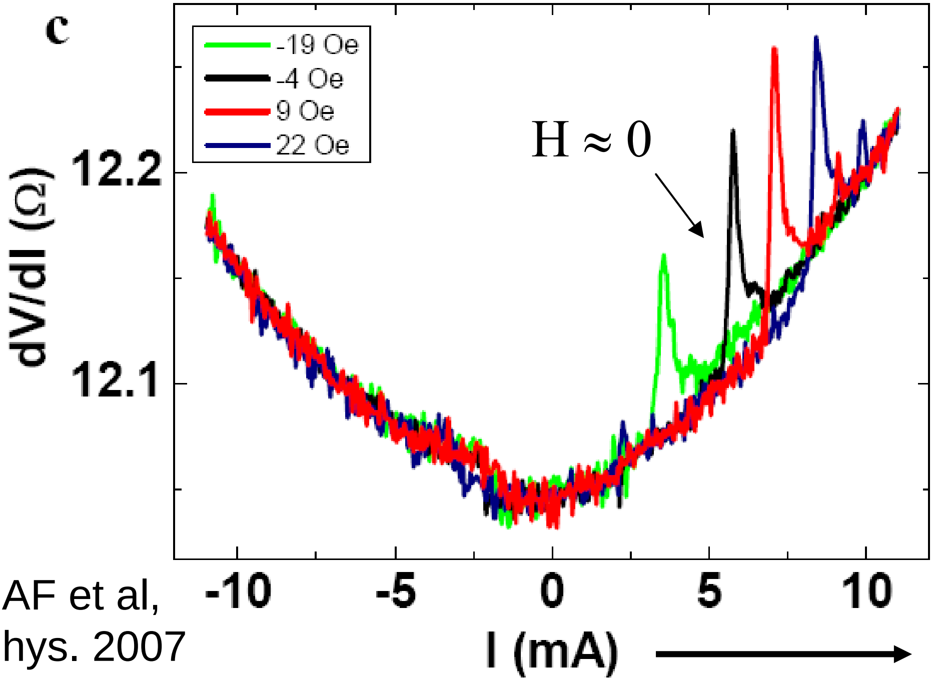
fixed Co: slower spin relaxation

Py/Cu/Py (standard)





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

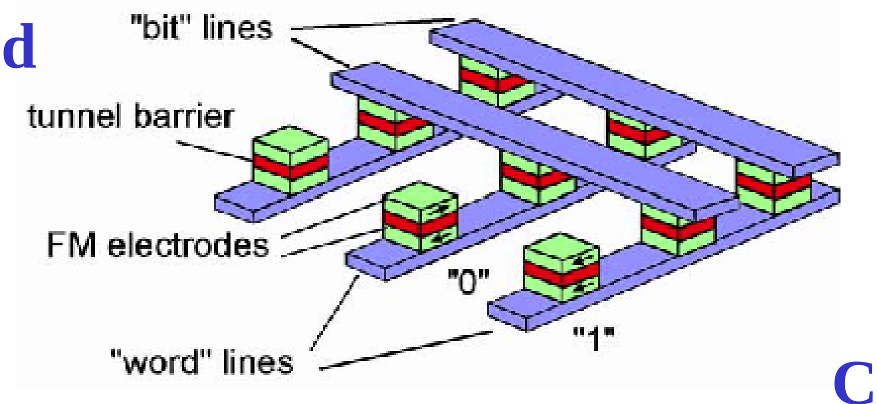


Positive I

Switching of reprogrammable devices (example: MRAM)

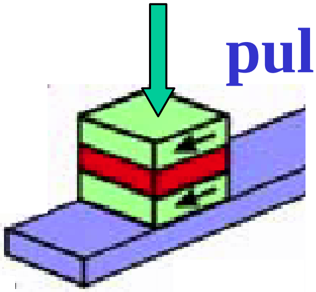
1) By external magnetic field

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



2) «Electronic» reversal by spin transfer from current

(ST-MRAM: next generation of MRAM, with demonstrations by Sony, Hitachi, NEC, etc)



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**

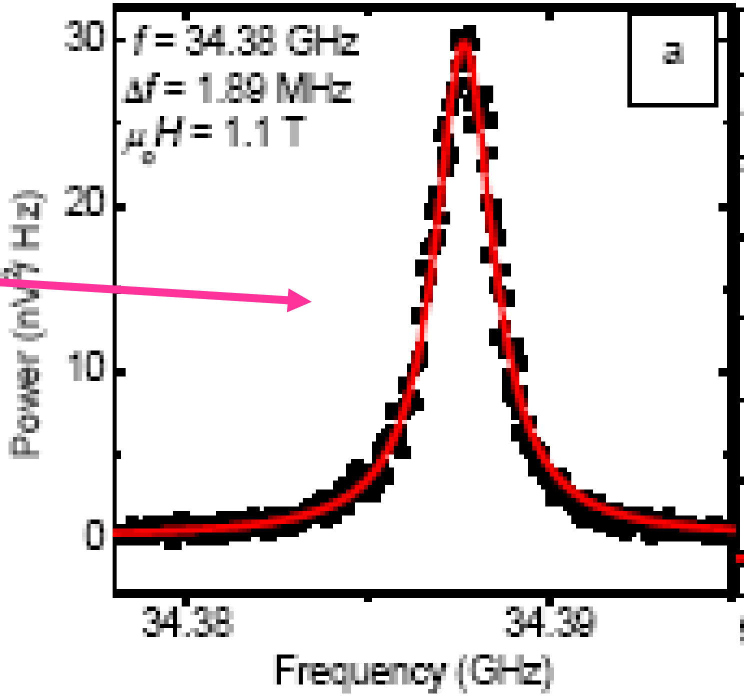
- **small size (≈ 0.1μm)** (on-chip integration)

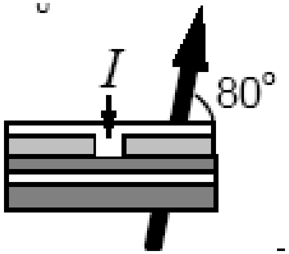
-**oscillations without applied field**

-**Needed improvements**

- - **increase of power by synchronization of a large of number N of STO (x N^2)**

$f/f\Delta f \cong 18000$

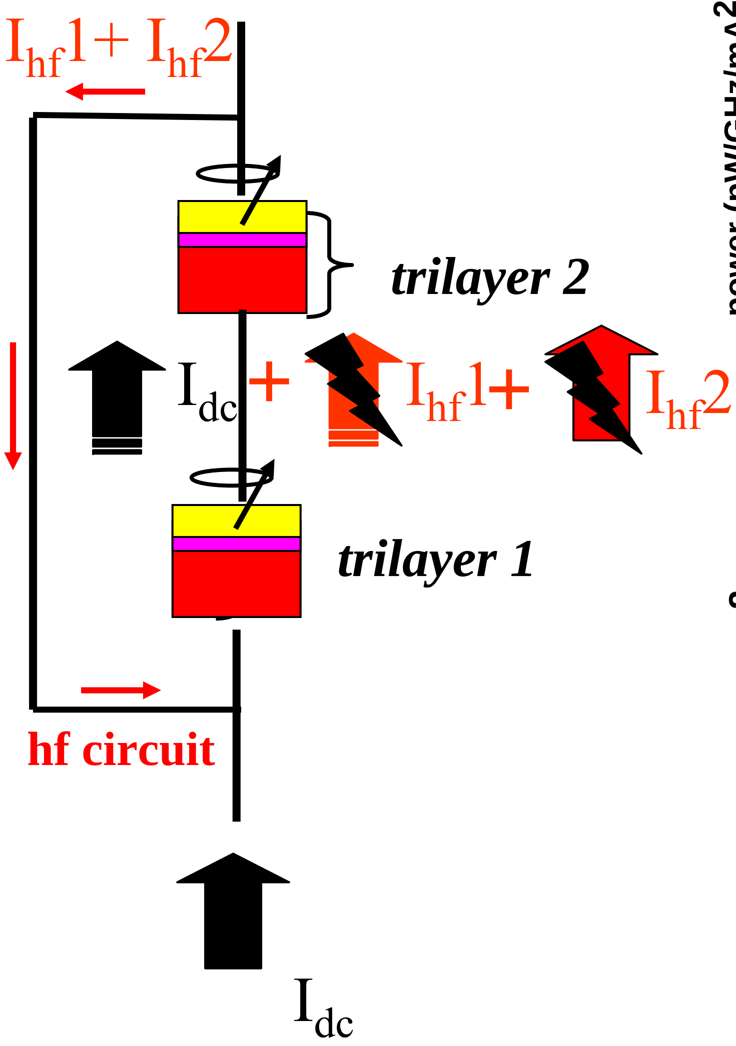


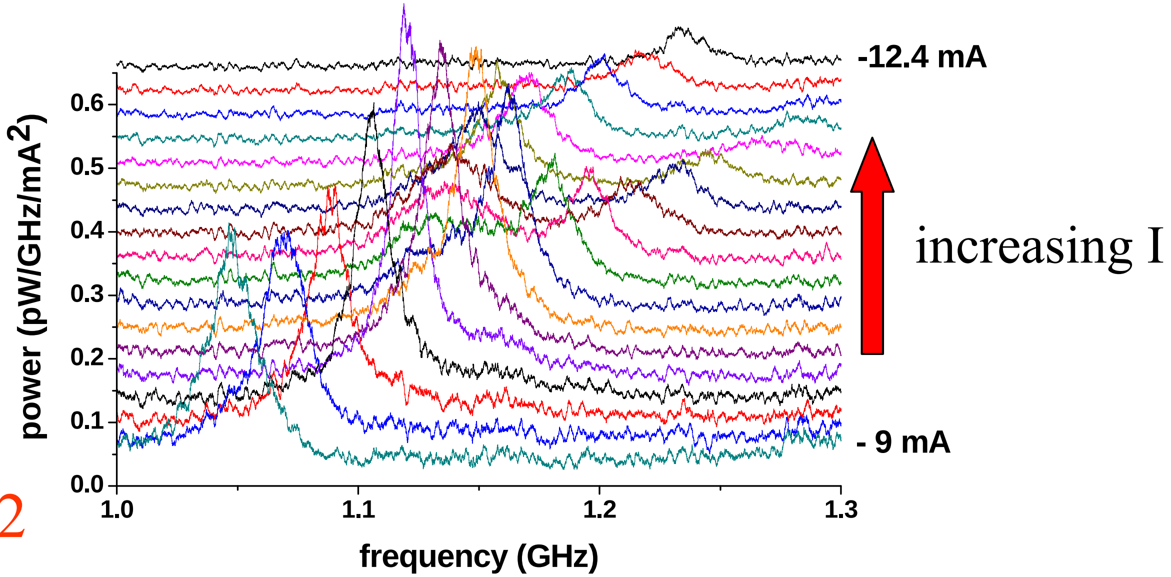


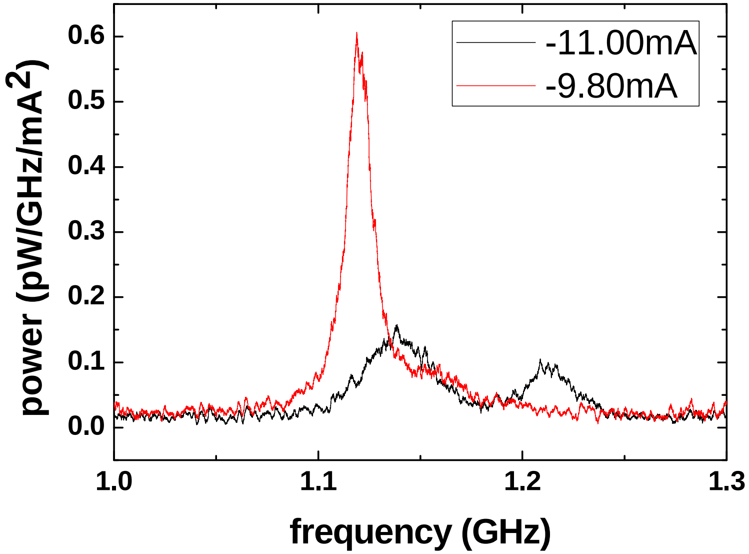
Rippart et al,
PR B70, 100406,
2004

Experiments of STO synchronization by electrical connection

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





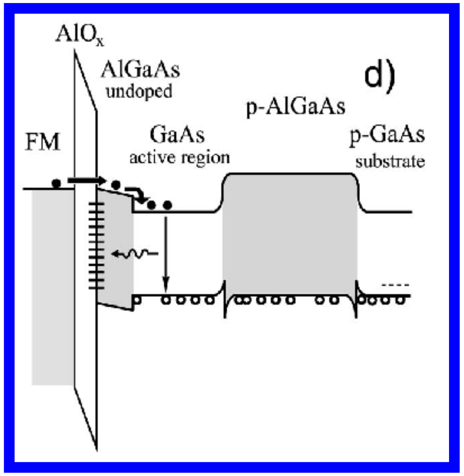


Spintronics with semiconductors and molecules

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

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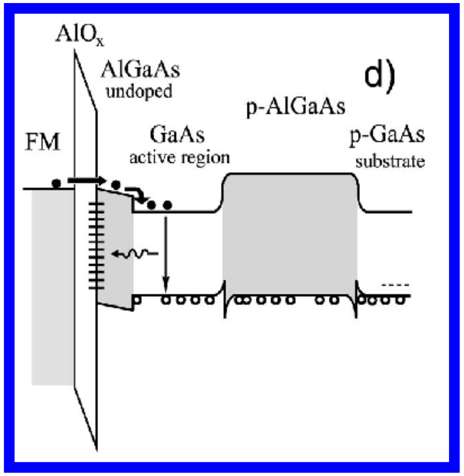

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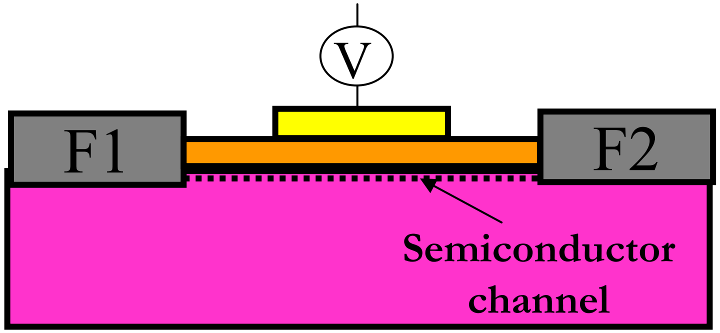
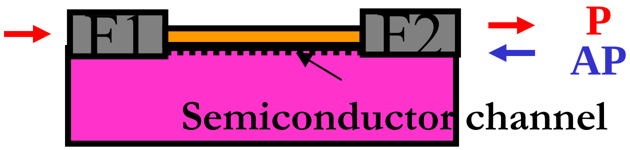
Spin Field Effect Transistor ?



Semiconductor lateral 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)*

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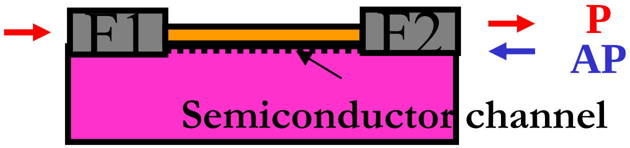

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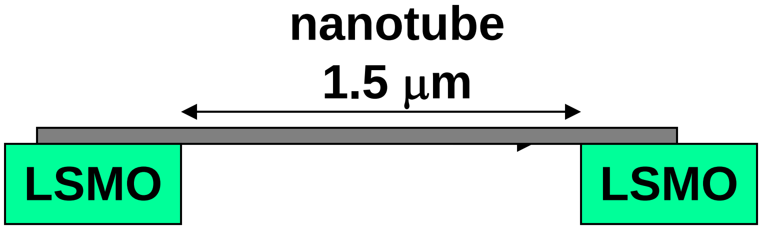
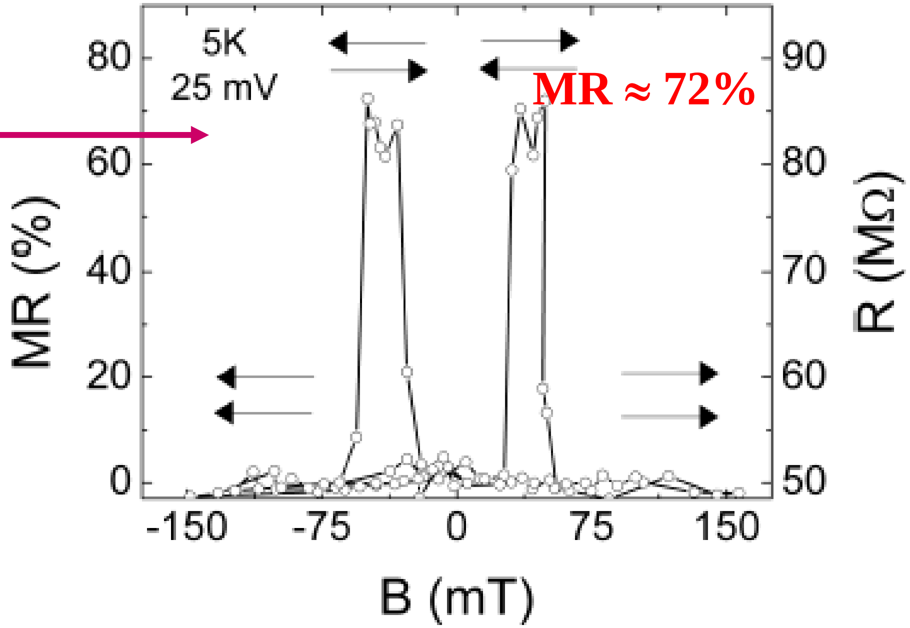
L.Hueso, N.D. Mathur,A.F. et al, Nature 445, 410, 2007

Carbon nanotubes:

$\Delta R/R \approx$ 60-70%, V_{AP}-$V_P \approx$ 20-60 mV



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



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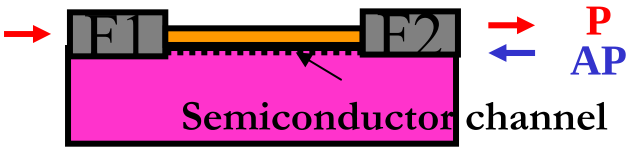

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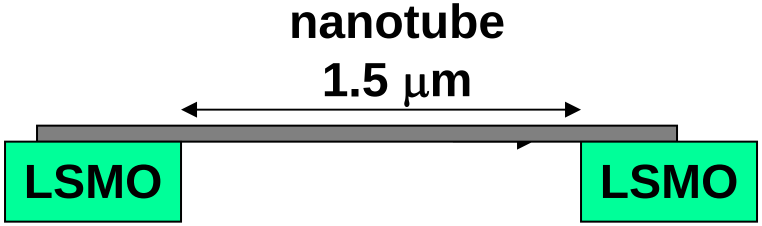

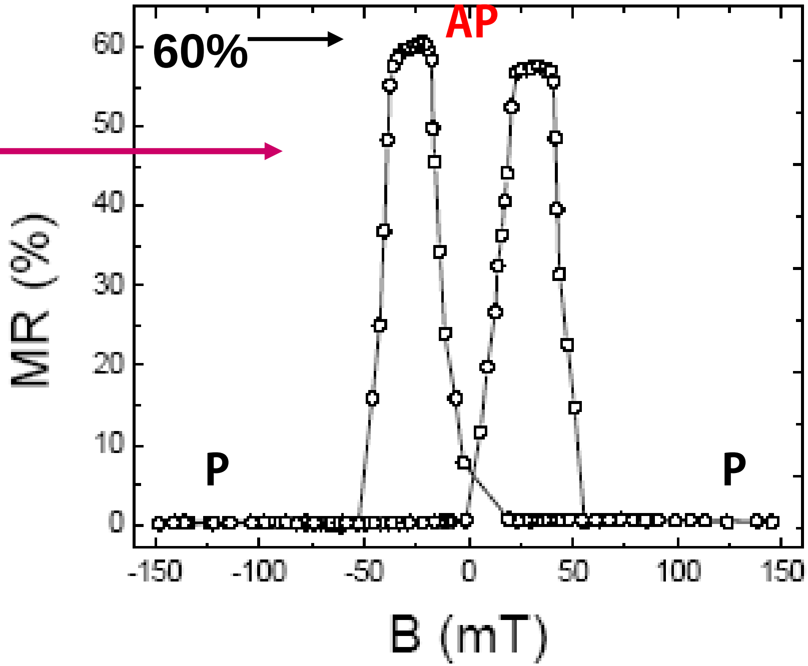

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Two interface spin transport problem (diffusive regime)

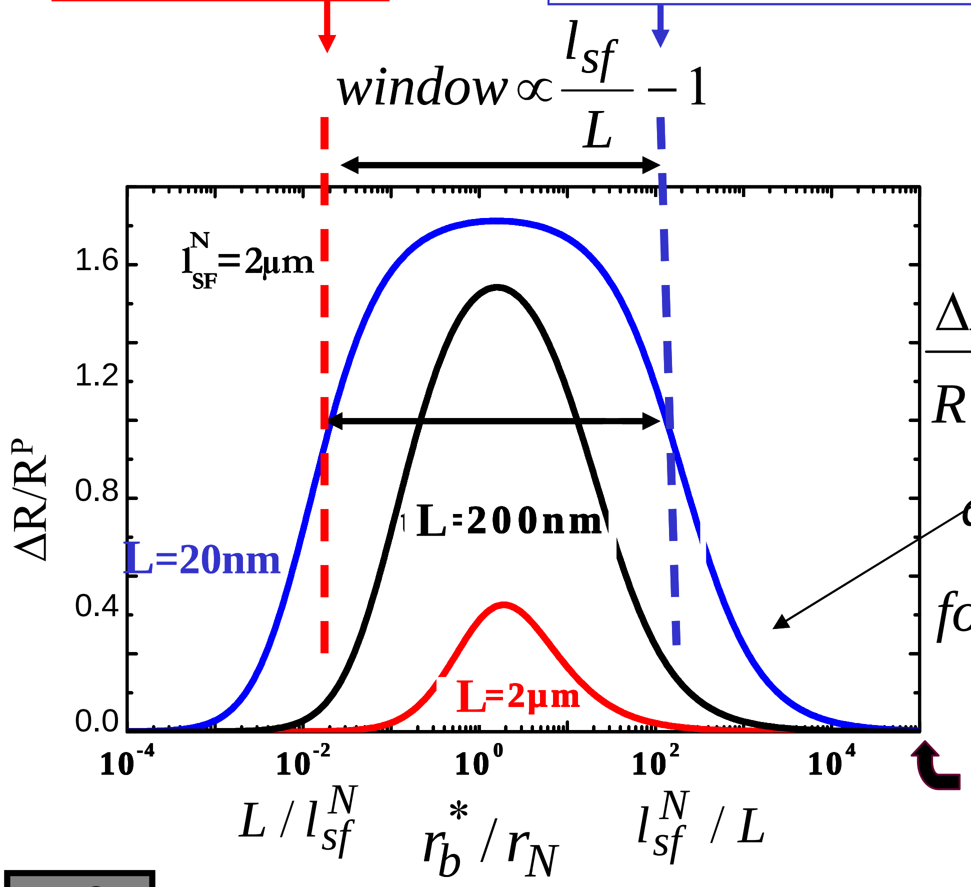
AF and Jaffrès
PR B 2001*
+cond-mat
0612495, +

IEEE Tr.El.Dev*.
54,5,921,2007

*calculation. for
Co and GaAs
at RT

Condition for spin injection

Condition
dwell time τ_n < spin lifetime τ_{sf}



dwell time

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

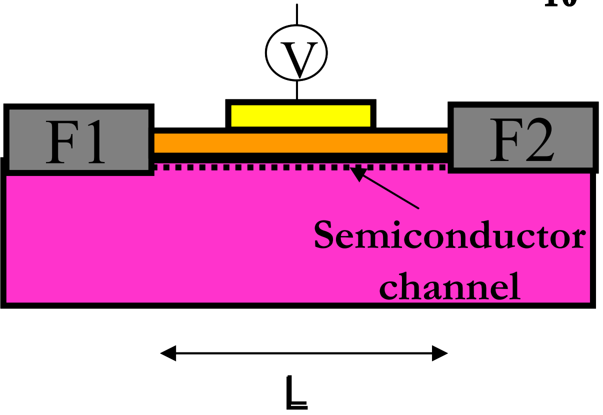
$$\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$$

drops to zero as $1/r_b^*$

for $\tau_n \propto r_b^* >> \tau_{sf}$

Interface resistance r_b in most experiments*

$\tau_n >> \tau_{sf}$



r_b^* = unit area interface resist. ∝ 1/trans.coeff t_r^*

γ = spin asymmetry of the interface resistance

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

Window only for l_{sf}(N) > L

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 → *spin lifetime* τ_{sf} *is* long (≈ 5 – 50ns)

high velocity $v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}$ *can be relatively short* ($\approx 60ns^{*} \approx \tau_{sf}$)

Semiconductors :

τ_{sf} *can be as long as in CNT* (*for* $n \approx 10^{17}\ el/cm^3$)

but v *is smaller* → *long* $\tau_n = \frac{2L}{v\bar{t}_r} >> \tau_{sf}$

---

[*] CNT : τ_n = 60ns from L, v of CNT and $\bar{t}_r$ derived from interface resistance

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

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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

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Nanotubes (also graphene, other molecules) :

small spin – orbit → *spin lifetime* τ_{sf} *is* long ($\approx 5 - 50\text{ns}$)

high velocity v → $\tau_n = \frac{2L}{v\bar{t}_r}$ *can be relatively short* ($\approx 60ns^* \approx \tau_{sf}$)

Semiconductors :

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Potential of molecular spintronics (nanotubes, graphene and others)

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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

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

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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

Two interface spin transport problem (diffusive regime)

AF and Jaffrès PR B 2001*
+cond-mat 0612495, +
IEEE Tr.El.Dev*. 54,5,921,2007
*calculation. for Co and GaAs at RT

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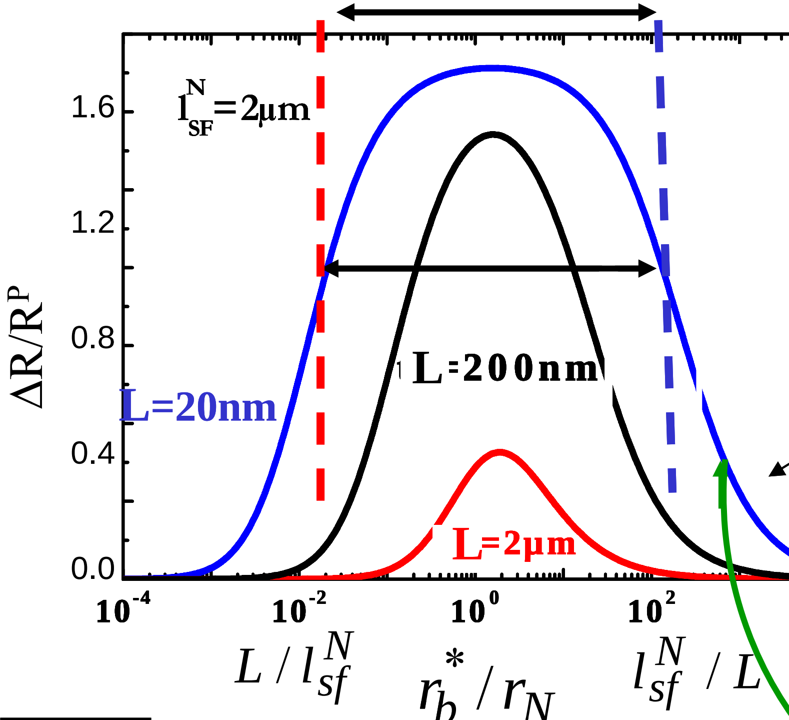
dwell time τ_n < spin lifetime τ_{sf}

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



dwell time

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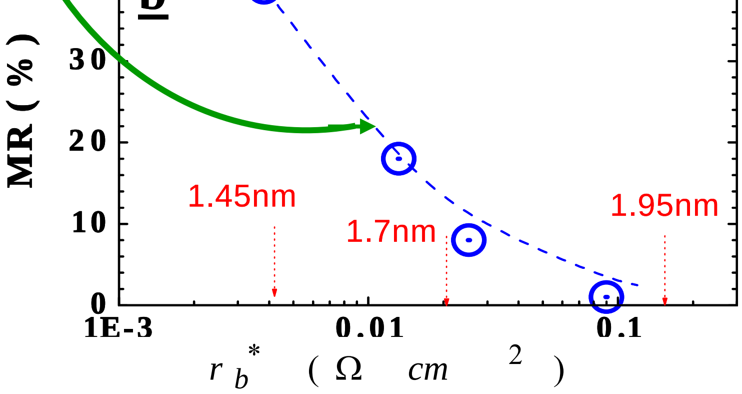
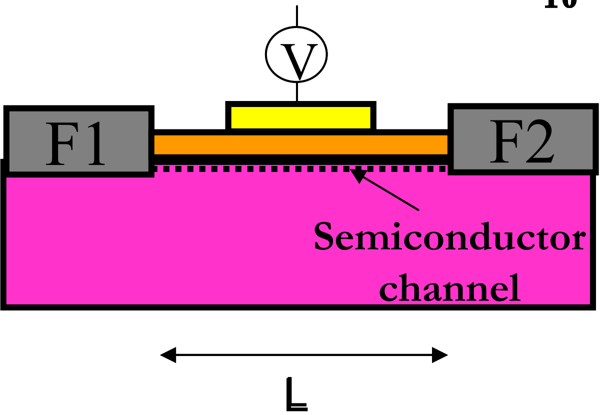
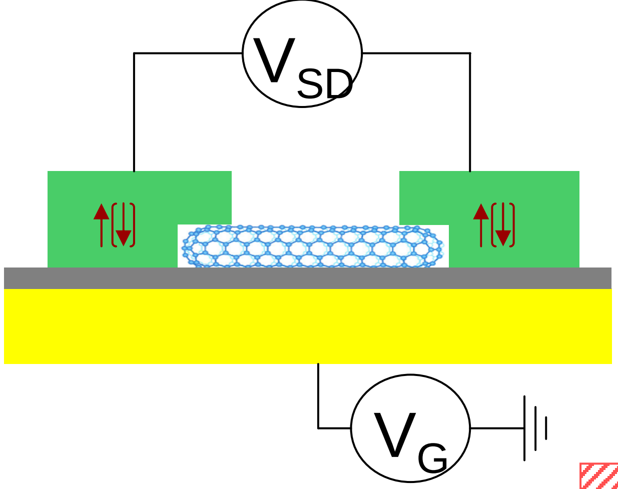
$$\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$$

drops to zero as $1/r_b^*$
as in this example
(Mattana, AF et al)

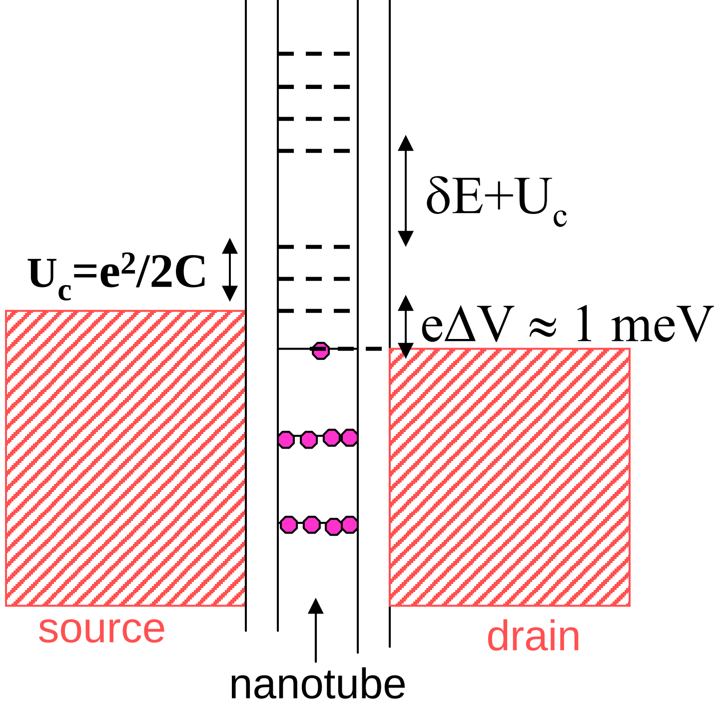




Window only for $l_{sf}(N) > L$



Usual conditions: small bias voltage experiments


$U_c=e^2/2C$

$\delta E+U_c$

$e\Delta V \approx 1$ meV

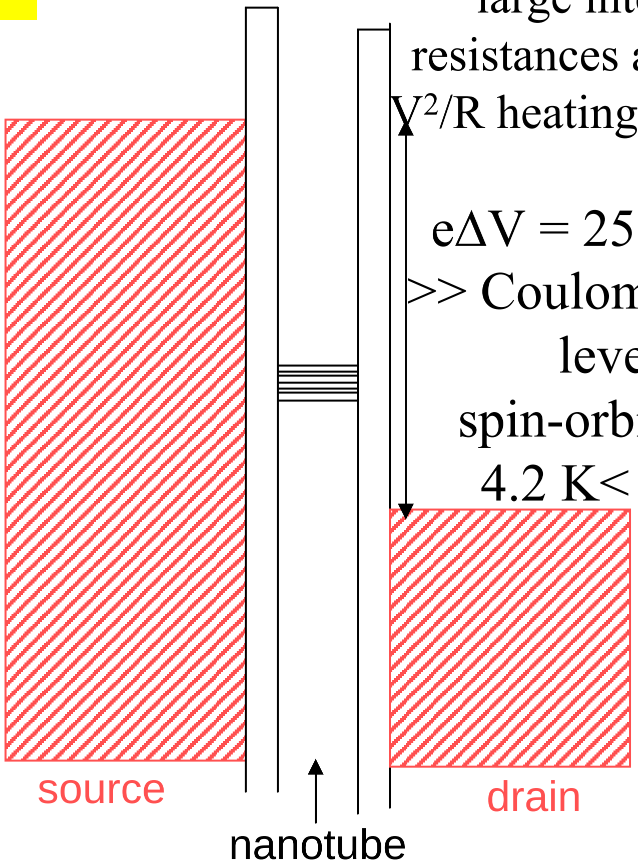
source

nanotube

drain

Oscillatory variation of the conductance, different signs of theMR depending on the bias voltage and from sample to sample

LSMO/CNT/LSMO: higher voltage experiments thanks to large interface resistances and small V^2/R heating at large V


$e\Delta V$ = 25-500 meV >> Coulomb energy, level spacing, spin-orbit spliting, 4.2 K< T <120 K

source

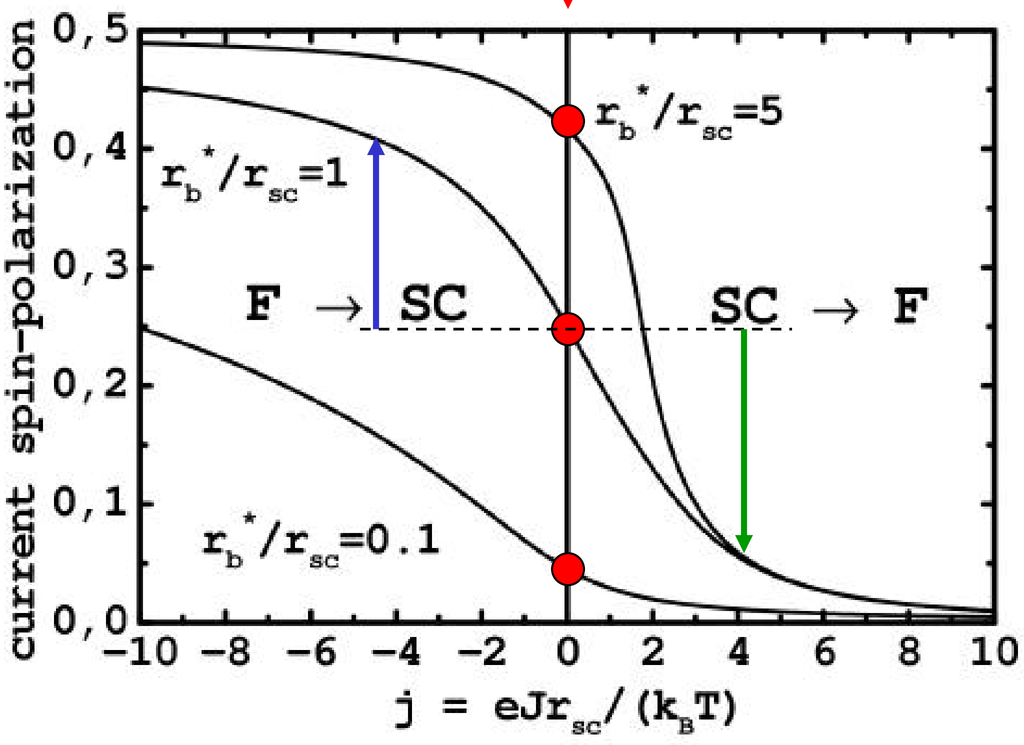
nanotube

drain

Quasi-continuous DOS, same conditions as for semiconductor or metallic channel

Deviations from $\frac{J_\uparrow - J_\downarrow}{J_\uparrow + J_\downarrow} = \frac{\beta r_F + \gamma r_b^*}{r_F + r_N + r_b^*}$ at large current density (drift effect)

● = *low current limit*



current density

↑ ↓ = deviations from the low current limit (nondegenerate semiconductor)

from Jaffrès and A.F.

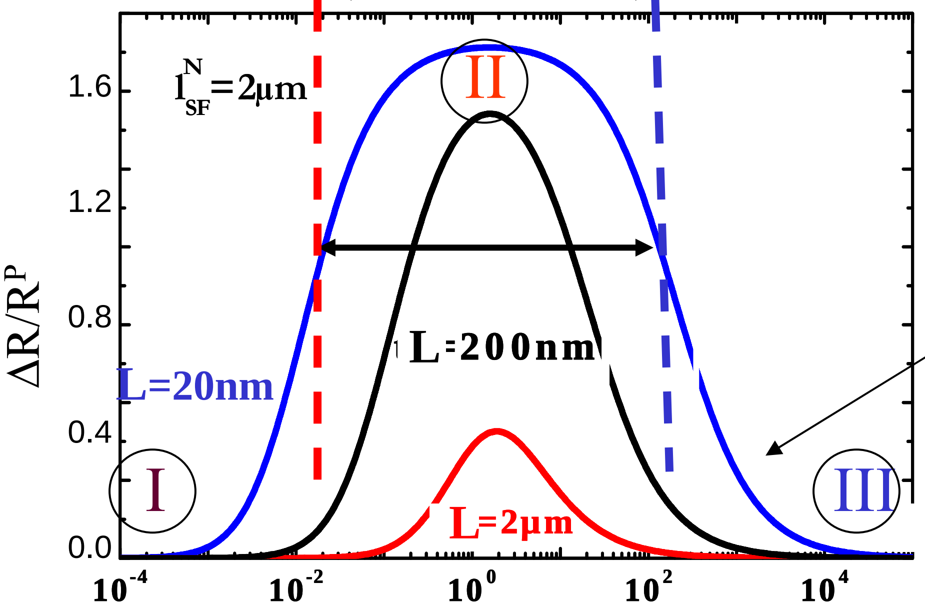
(see also Yu and Flatté)

Condition for spin injection

Condition

dwell time τ_n < spin lifetime τ_{sf}

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



r_b^*/r_N

dwell time

$$\tau_n = 2L/(v\bar{t}_r) \propto r_b^*$$

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

drops to 0 as $1/r_b^*$

for $\tau_n \propto r_b^* >> \tau_{sf}$

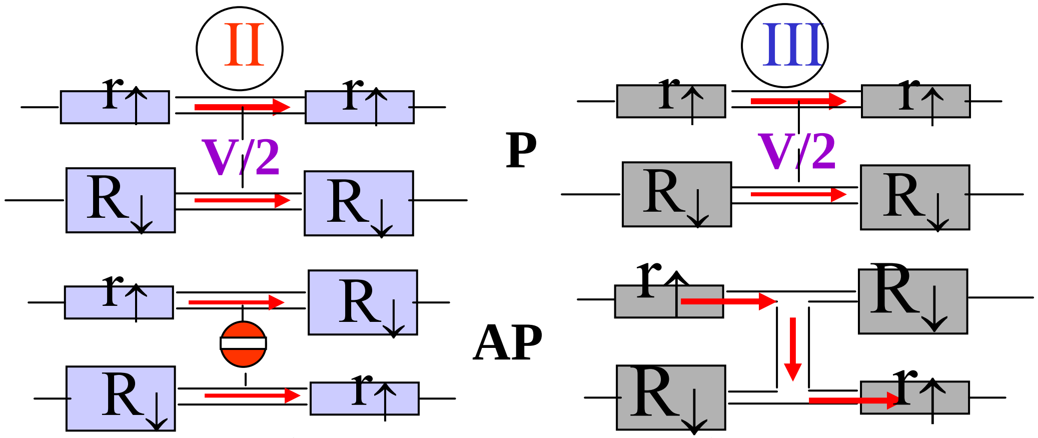
$R_{\uparrow(\downarrow)}$, $r_{\uparrow(\downarrow)}$= interface resistance

(equal for source and drain)

I

Unpolarized current in the semiconductor (depolarization in the source and repolarization in the drain)

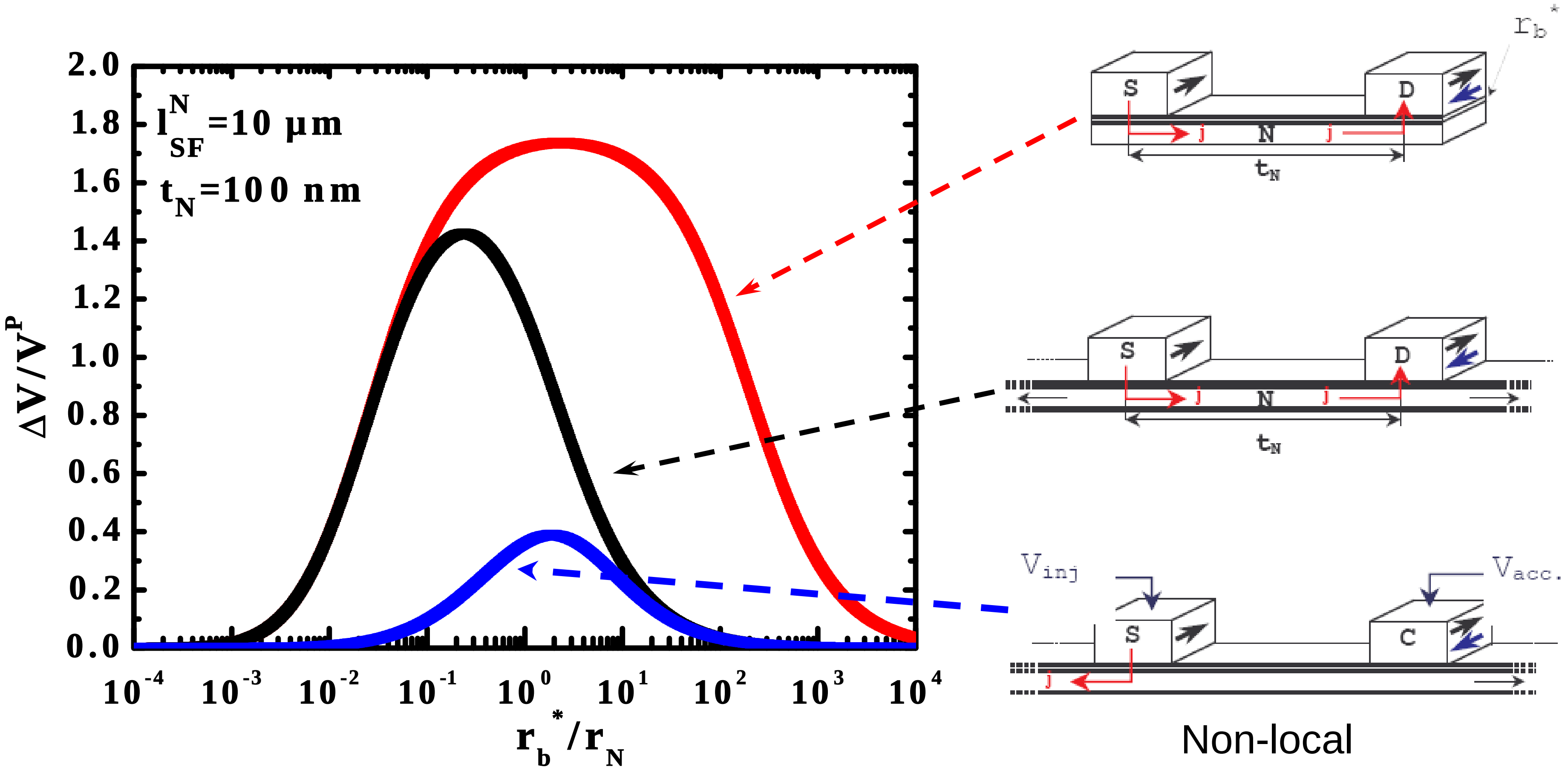
ΔR/R = 0



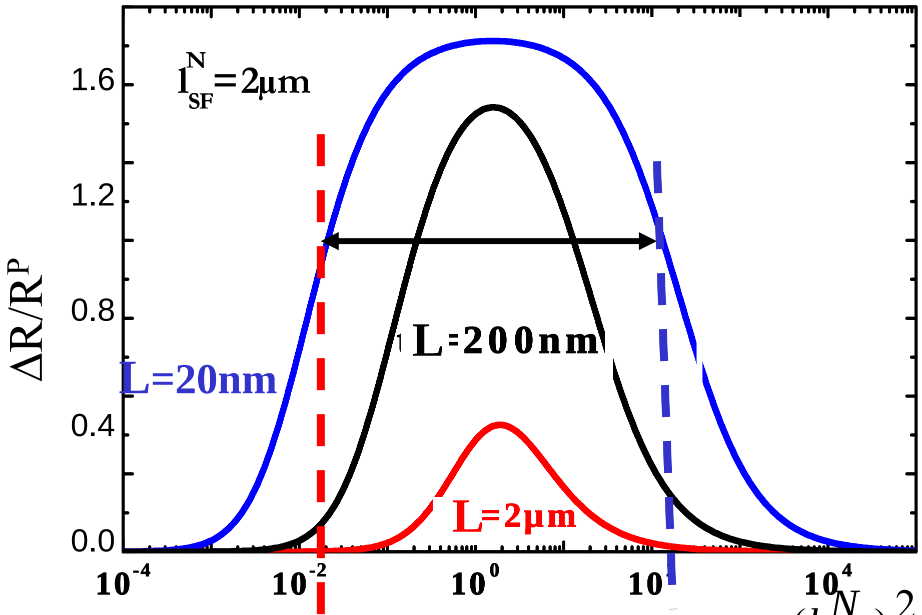
Optimal ΔR/R

ΔR/R = 0

$\Delta V/V_{bias}$ for local (2 types) and non-local geometries

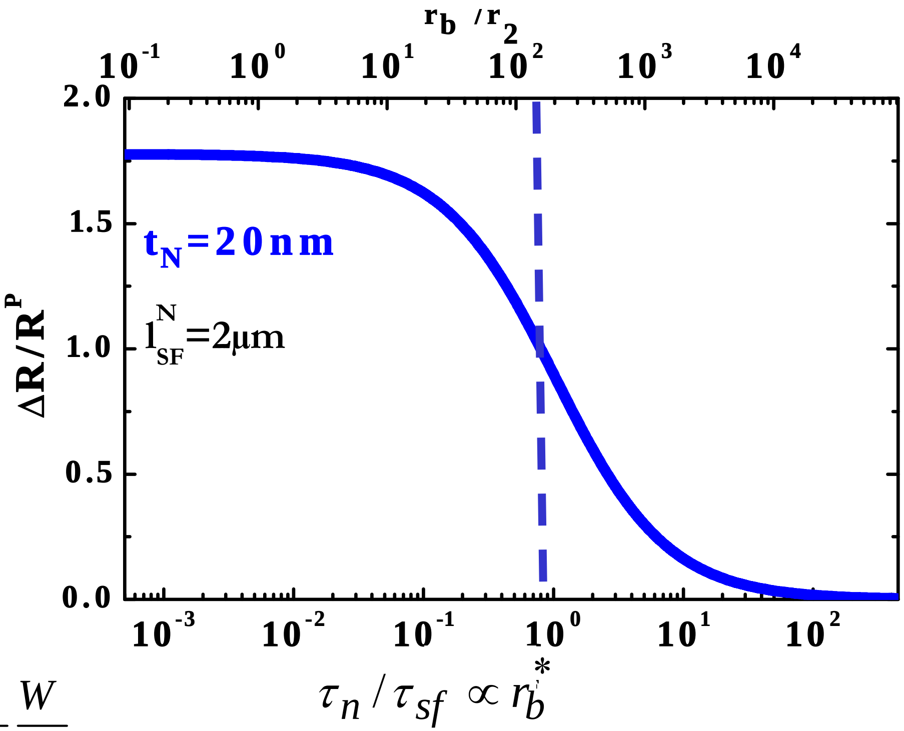


Diffusive transport

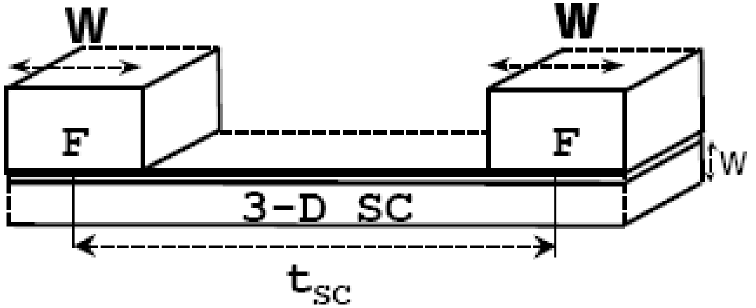


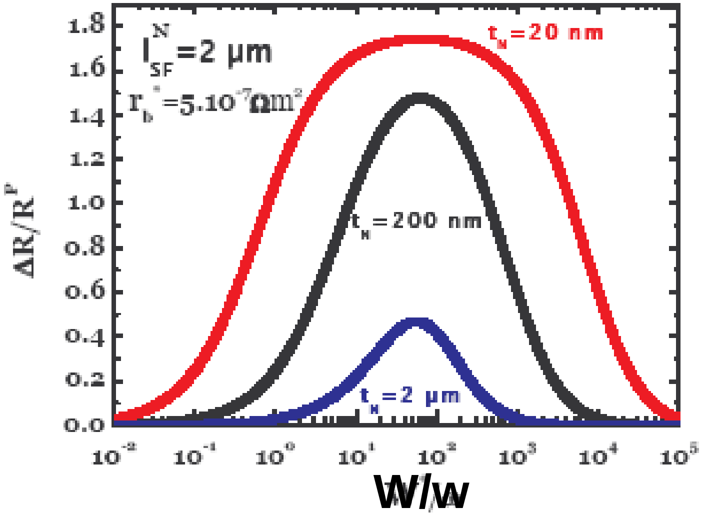
$$r_b^* = \rho_N^* \, t_N \, \frac{W}{w} \qquad r_b^* / r_N \qquad r_b^* = \rho_N^* \, \frac{(l_{sf}^N)^2}{t_N} \, \frac{W}{w}$$

Ballistic transport



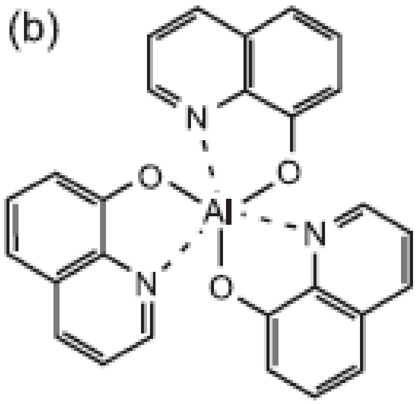
+ additional geometrical parameters when the number of conduction channels is different for the injection and in the channel (W ≠ w in the example)

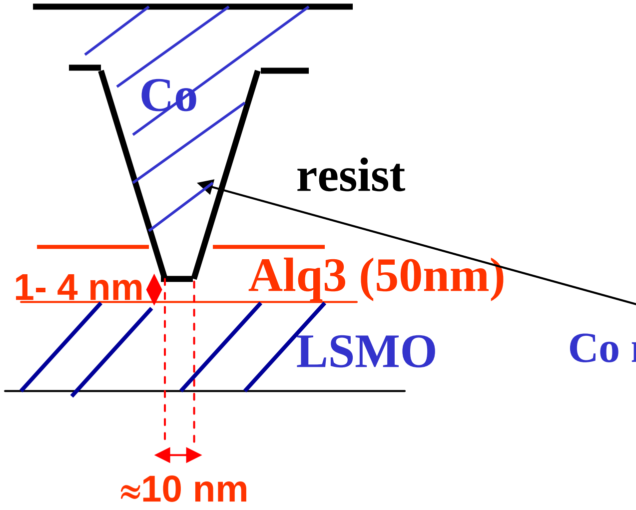




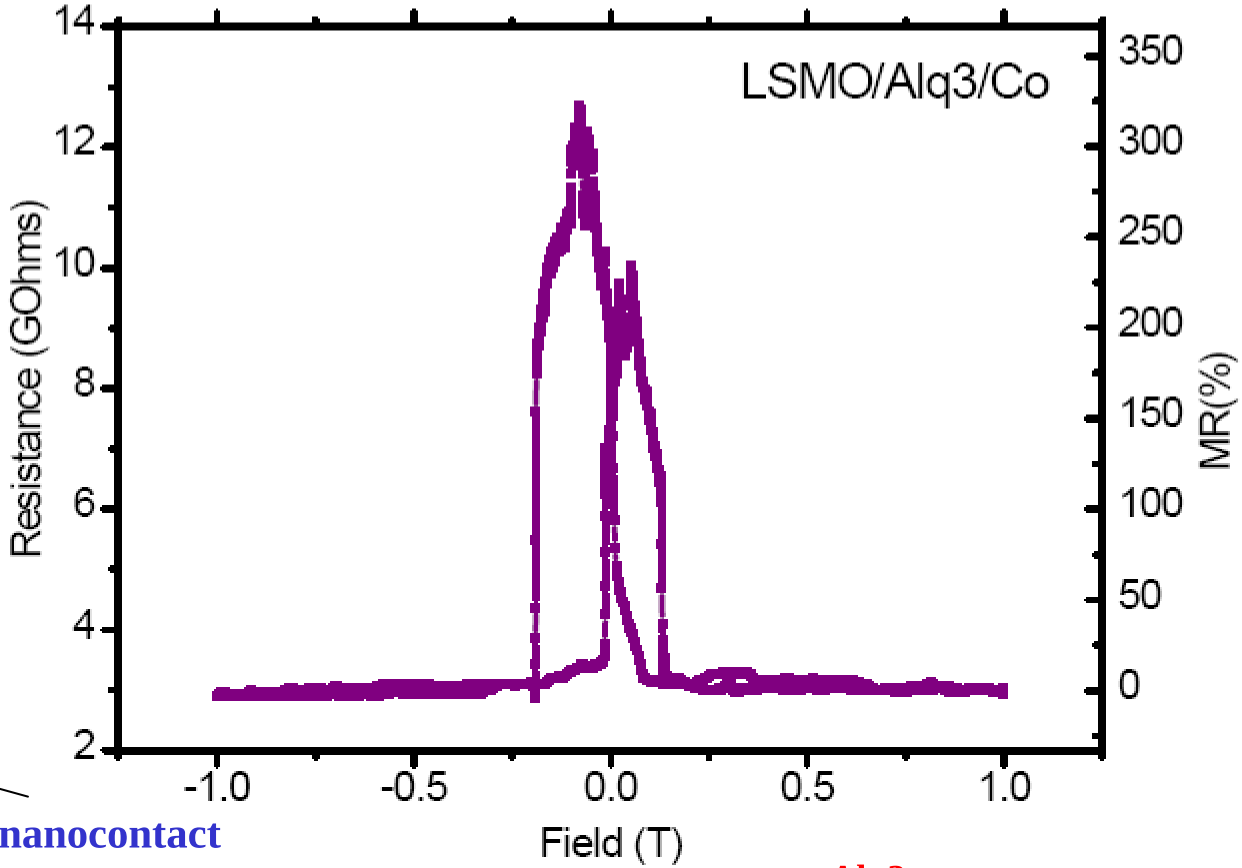
MR of LSMO/Alq3/Co structures (preliminary results)

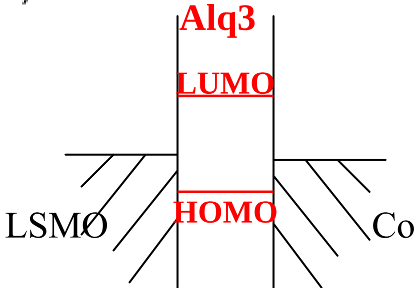
Collaboration CNRS/Thales [C. Barraud, P. Seneor et al) and CNR Bologna (Dediu et al)]





Co nanocontact





Alq3 = π - conjugated 8-hydroxy-quinoline aluminium