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Séminaire Poincaré

Recent Developments and Perspectives in Spintronic

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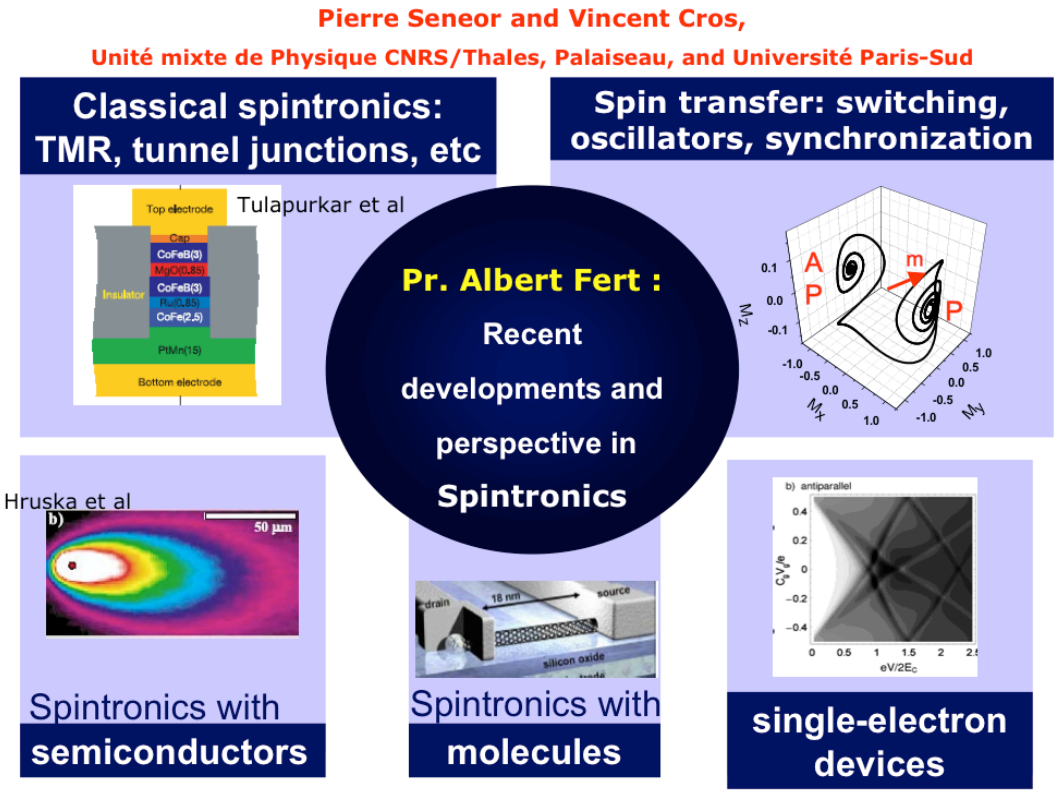
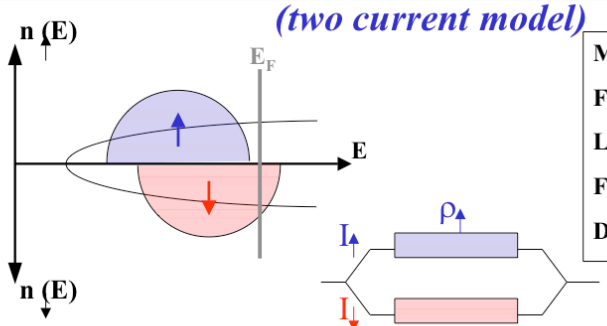
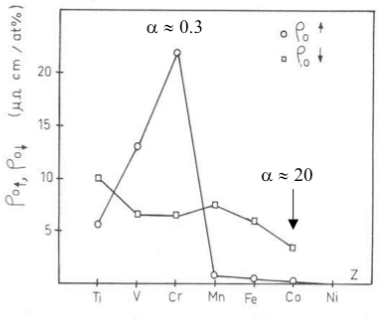


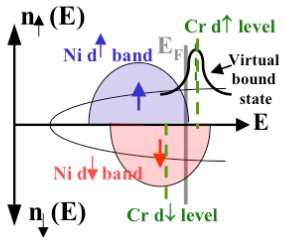
Spin dependent conduction in ferromagnetic metals (two current model)



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



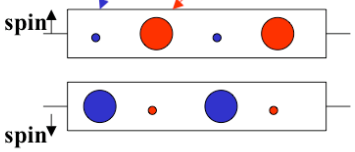


Mixing impurities A and B with opposite or similar spin asymmetries:
the pre-concept of GMR

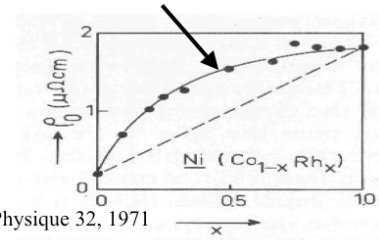
Example: Ni + impurities A and B *(Fert-Campbell, 1970)*

1st case

$\alpha_A > 1, \alpha_B < 1$



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

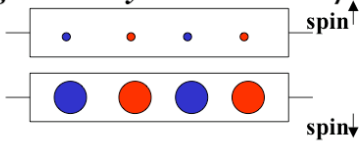


J. de Physique 32, 1971

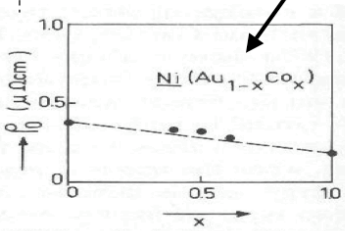
2d case

α_A and $\alpha_B > 1$

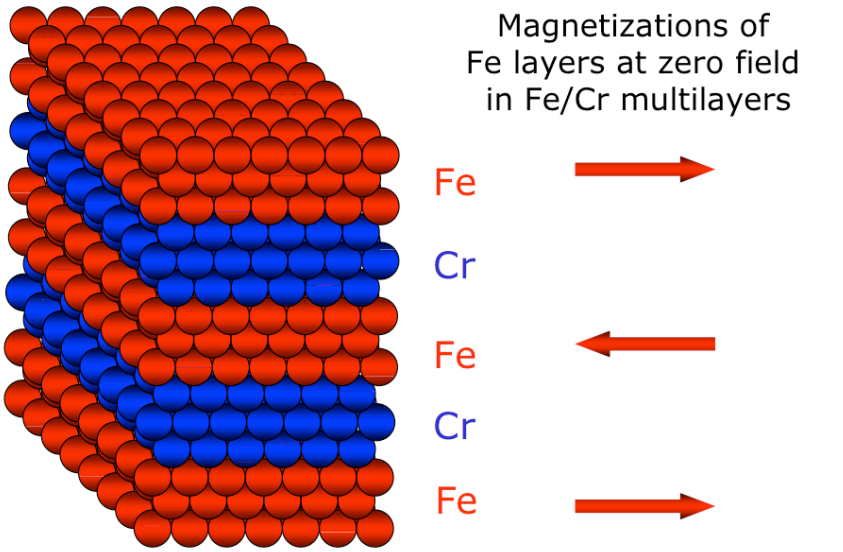
High mobility channel → low ρ



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

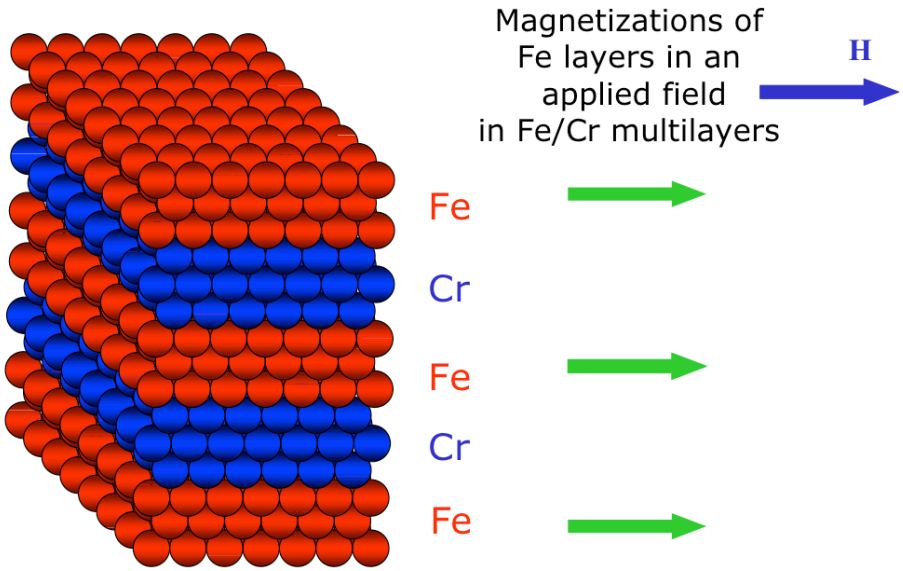


- **Magnetic multilayers**



P. Grünberg, 1986 → antiferromagnetic interlayer coupling

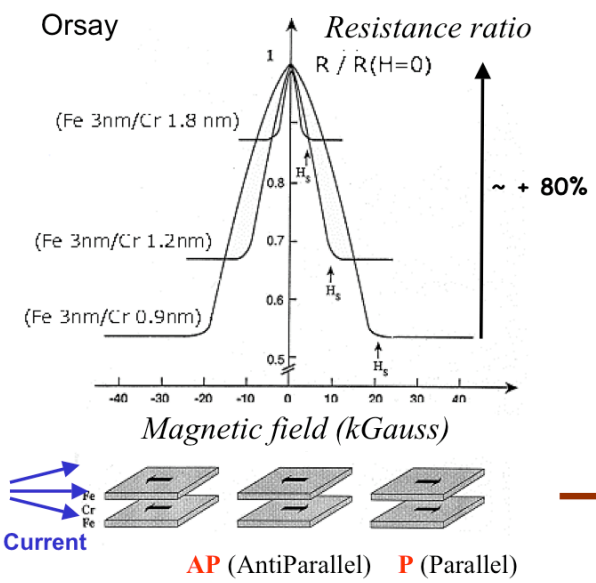
- **Magnetic multilayers**

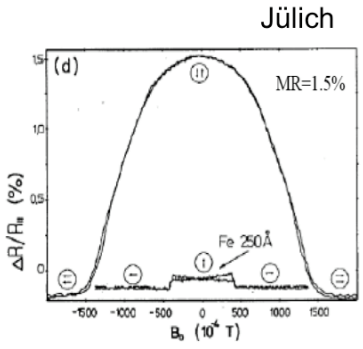


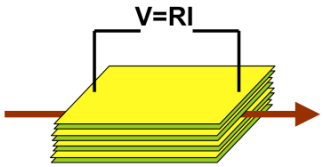
P. Grünberg, 1986 → antiferromagnetic interlayer coupling

• Giant Magnetoresistance (GMR)

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







AP (AntiParallel) P (Parallel)

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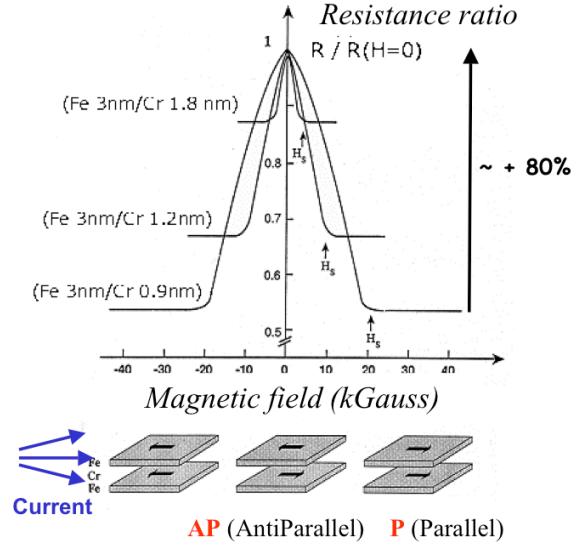
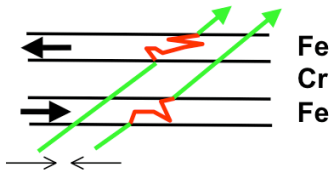
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

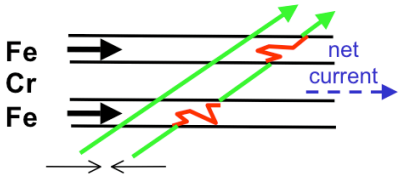


AP (AntiParallel) P (Parallel)

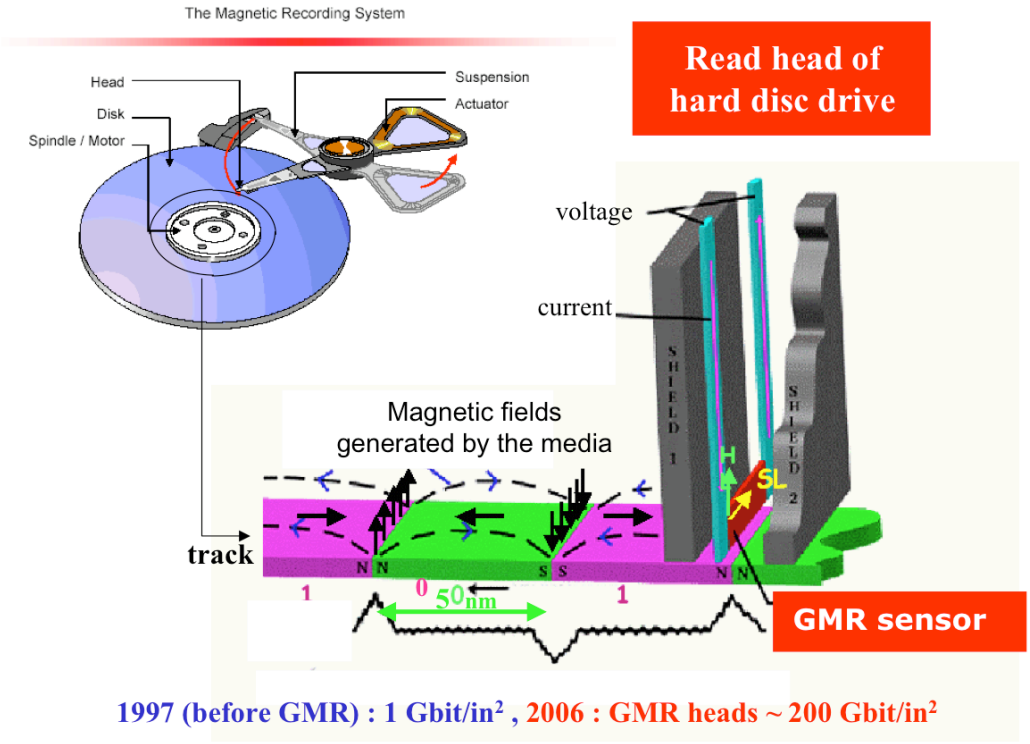
Anti-parallel magnetizations
(zero field, high resistance)



Parallel magnetizations
(appl. field, low resist.)

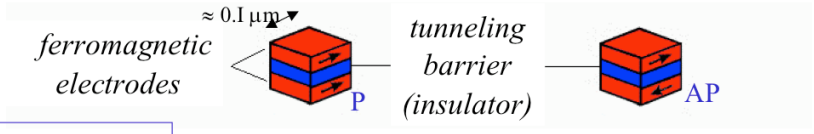


Condition for GMR:
layer thickness ≈ nm



1997 (before GMR) : 1 Gbit/in^2 , 2006 : GMR heads ~ 200 Gbit/in^2

• Magnetic Tunnel Junctions,Tunneling Magnetoresistance (TMR)



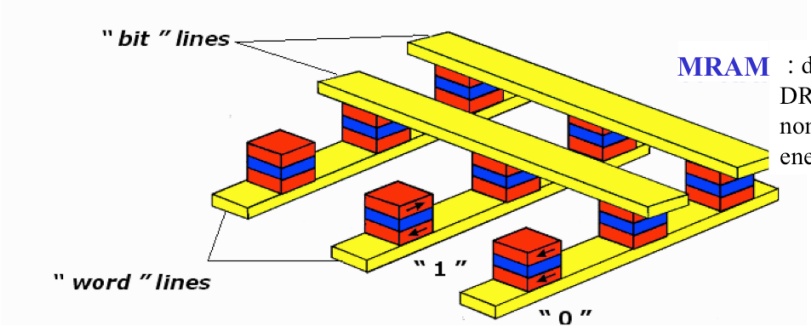
Jullière, 1975, low T, hardly reproducible

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)

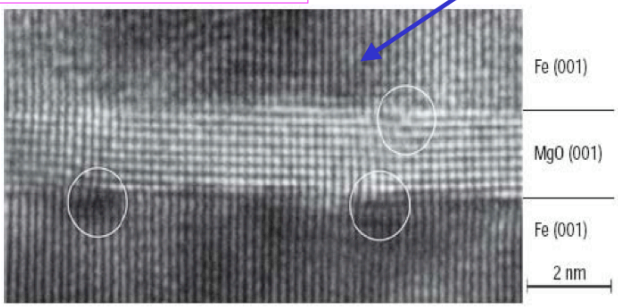


MRAM : density/speed of DRAM/SRAM + nonvolatilty + low energy consumption

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



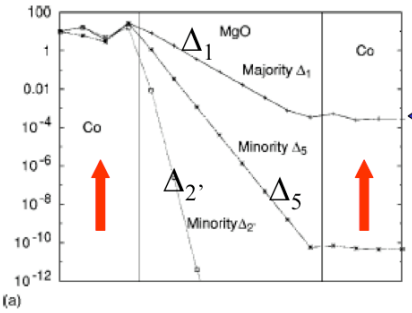
2006-2007

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

+

Clearer picture of the physics of TMR

P



AP

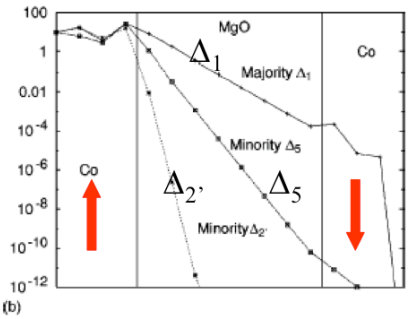


FIG. 2. Tunneling density of states on each atomic layer at $k_{\parallel}$ =0 for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

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)]

Zhang and Butler, PR B 2004

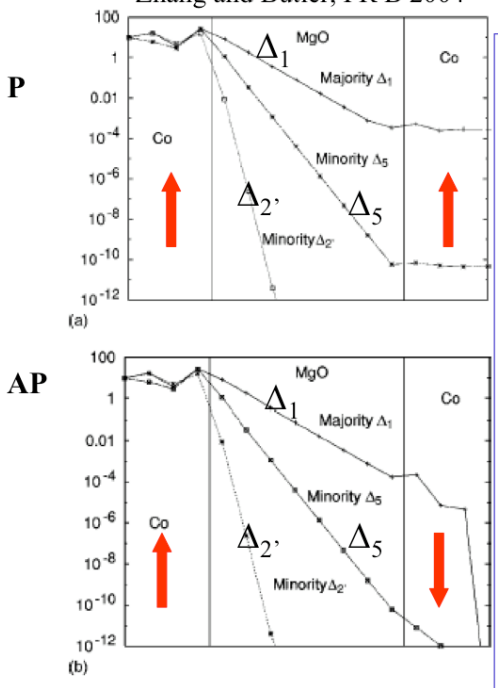


FIG. 2. Tunneling density of states on each atomic layer at $k_{\parallel}$ =0 for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

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)

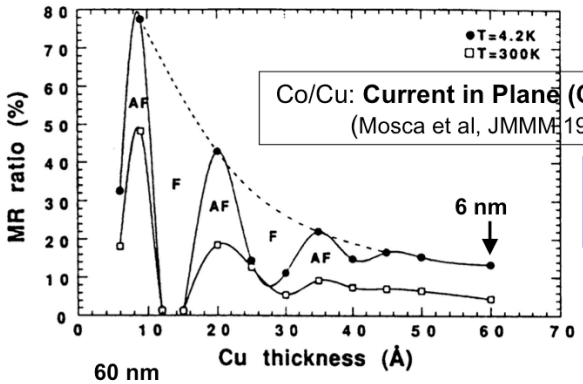
Highest TMR: best fit between the symmetry selected by the barrier and the symmetry for which the spin polarization is the highest in the electrodes

Spin Transfer
(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules

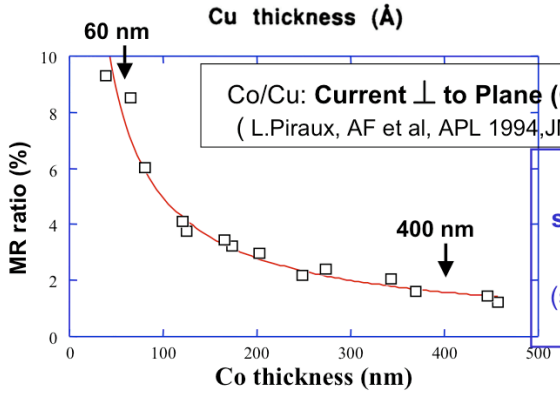
Introduction:
spin currents and
spin accumulation



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

CIP-GMR

scaling length = mean free path

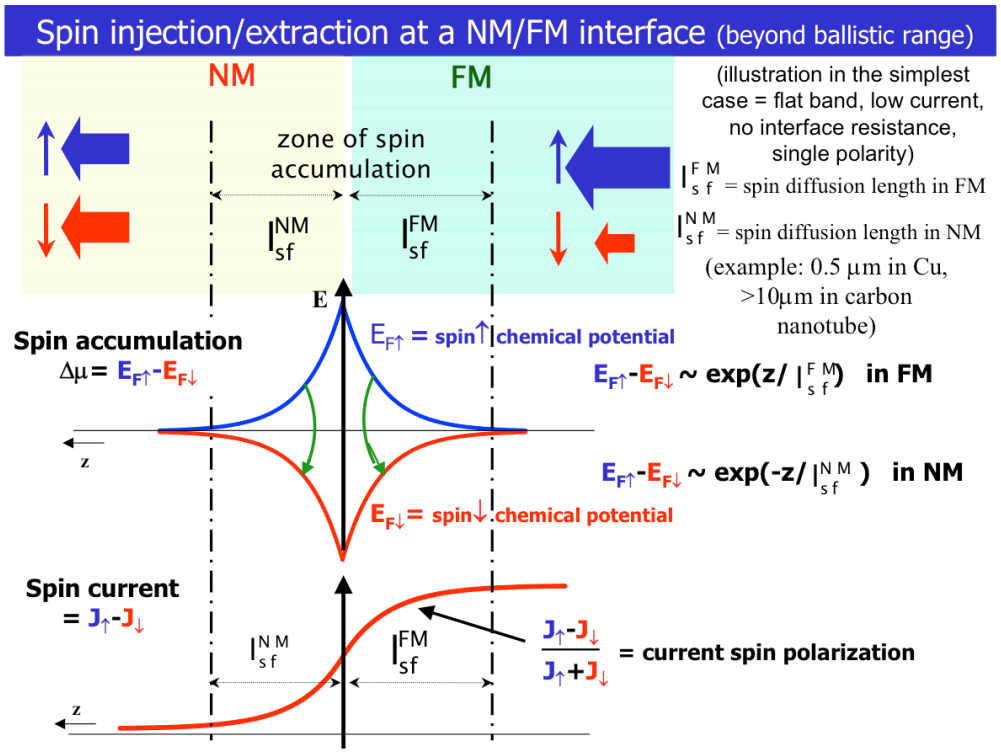


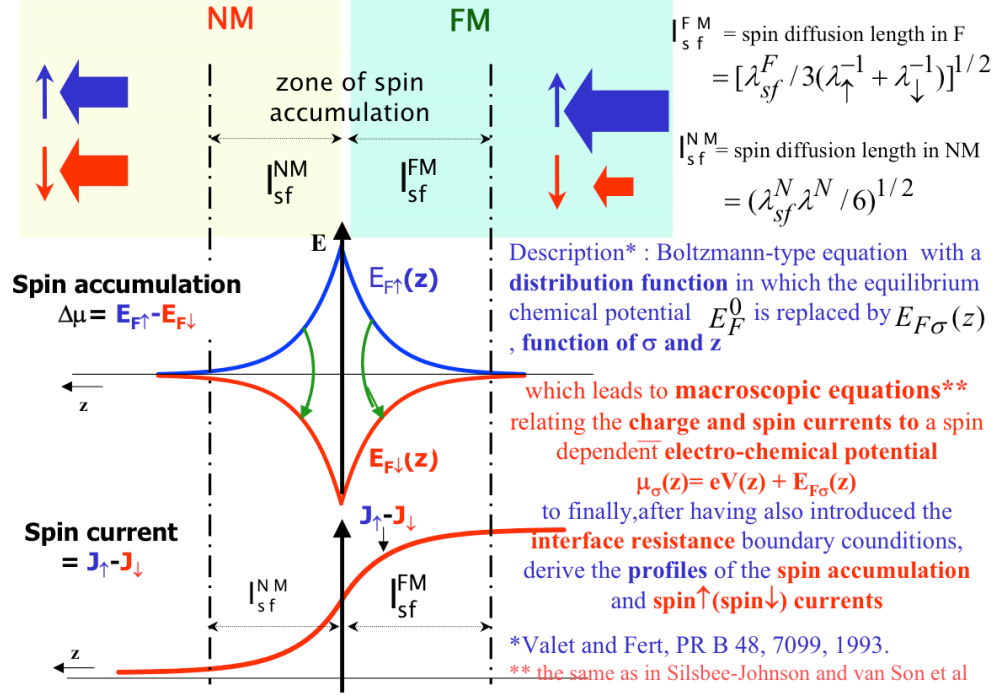
Co/Cu: **Current ⊥ to Plane (CPP) GMR**
(L.Piraux, AF et al, APL 1994,JMMM 1999)

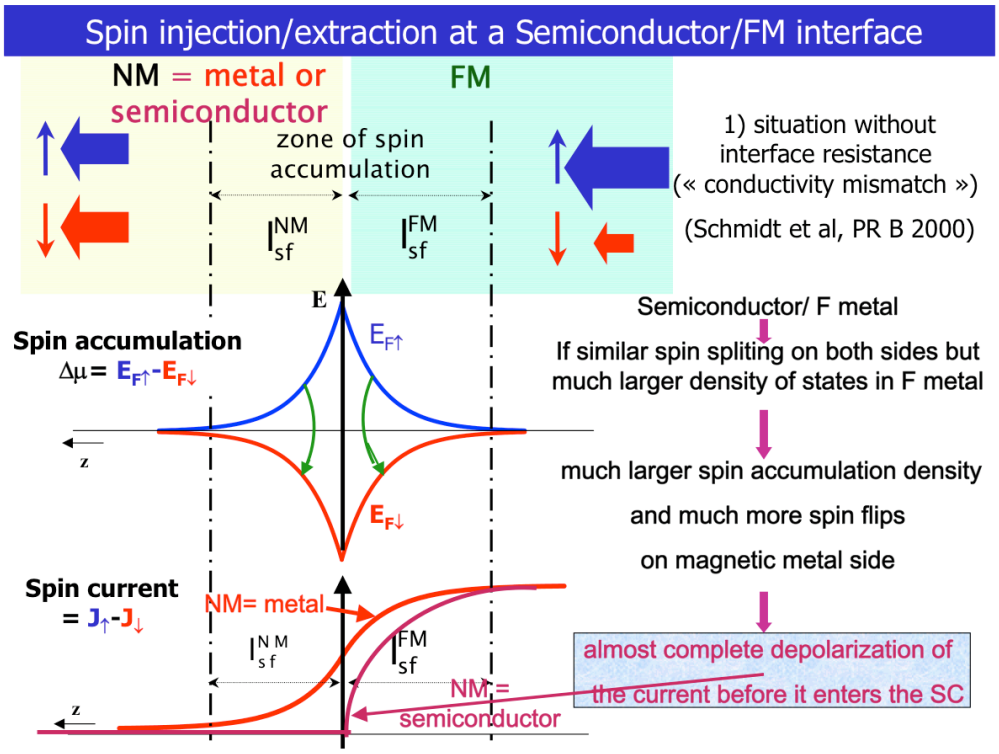
CPP-GMR

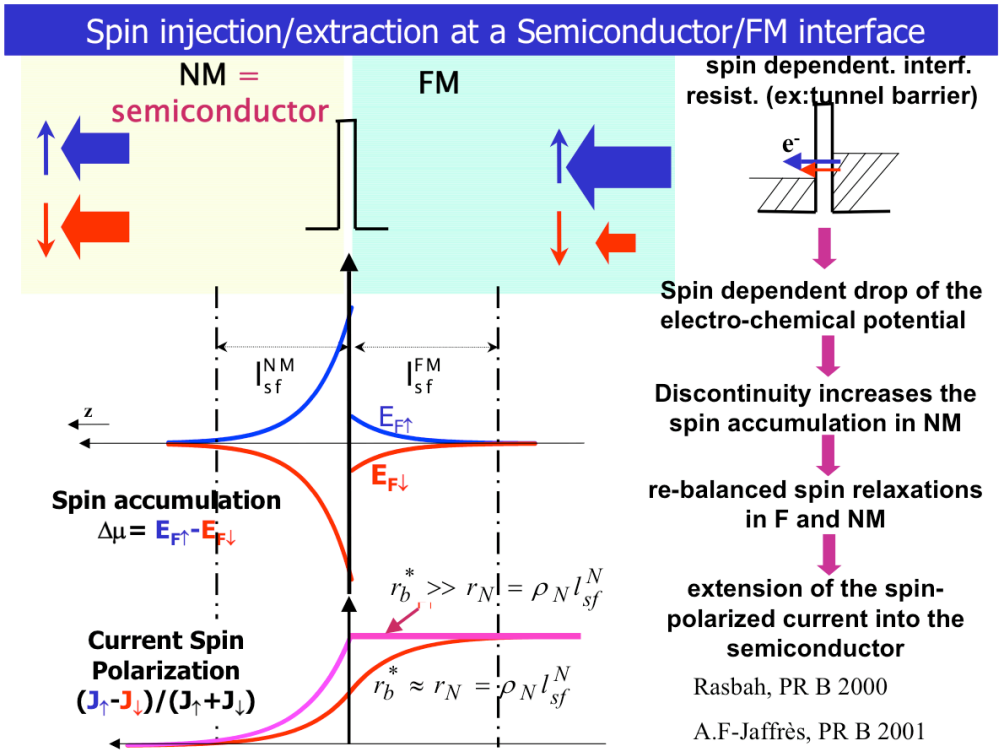
scaling length = spin diffusion length >> mean free path

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


Spin injection/extraction at a NM/FM interface (beyond ballistic range)
NM
FM
zone of spin accumulation
l_{sf}^{NM}
l_{sf}^{FM}
(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
Spin accumulation
Δμ= $E_{F↑}$-$E_{F↓}$
$E_{F↑}$ = spin↑ chemical potential
$E_{F↑}$-$E_{F↓}$ ~ exp(z/ l_{sf}^{FM}) in FM
$E_{F↑}$-$E_{F↓}$ ~ exp(-z/ l_{sf}^{NM}) in NM
$E_{F↓}$= spin↓ chemical potential
z
Spin current
= $J_↑$-$J_↓$
$J_↑$-$J_↓$ / $J_↑$+$J_↓$ = current spin polarization


Spin injection/extraction at a NM/FM interface (beyond ballistic range)
NM
FM
zone of spin accumulation
l_{sf}^{NM}
l_{sf}^{FM}
l_{sf}^{FM} = spin diffusion length in F
$= [\lambda_{sf}^{F}/3(\lambda_{\uparrow}^{-1}+\lambda_{\downarrow}^{-1})]^{1/2}$
l_{sf}^{NM} = spin diffusion length in NM
$= (\lambda_{sf}^{N}\lambda^{N}/6)^{1/2}$
E
Spin accumulation
Δμ= $E_{F↑}$-$E_{F↓}$
$E_{F↑}(z)$
$E_{F↓}(z)$
z
Spin current
= $J_↑$-$J_↓$
$J_↑$-$J_↓$
Description* : Boltzmann-type equation with a distribution function in which the equilibrium chemical potential E_F^0 is replaced by $E_{F\sigma}(z)$, function of σ and z
which leads to macroscopic equations** relating the charge and spin currents to a spin dependent electro-chemical potential
$\mu_\sigma(z)= eV(z) + E_{F\sigma}(z)$
to finally,after having also introduced the interface resistance boundary counditions, derive the profiles of the spin accumulation and spin↑(spin↓) currents
*Valet and Fert, PR B 48, 7099, 1993.
** the same as in Silsbee-Johnson and van Son et al


Spin injection/extraction at a Semiconductor/FM interface
NM = metal or semiconductor
FM
zone of spin accumulation
l_{sf}^{NM}
l_{sf}^{FM}
1) situation without interface resistance (« conductivity mismatch »)
(Schmidt et al, PR B 2000)
E
$E_{F\uparrow}$
$E_{F\downarrow}$
Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$
z
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
Spin current
$= J_\uparrow - J_\downarrow$
NM= metal
NM = semiconductor
almost complete depolarization of the current before it enters the SC


Spin injection/extraction at a Semiconductor/FM interface
NM = semiconductor
FM
spin dependent. interf. resist. (ex:tunnel barrier)
e-
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
l_{sf}^{NM}
l_{sf}^{FM}
z
$E_{F\uparrow}$
$E_{F\downarrow}$
Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$
$r_b^* >> r_N = \rho_N l_{sf}^N$
$r_b^* \approx r_N = \rho_N l_{sf}^N$
Current Spin Polarization
$(J_\uparrow - J_\downarrow)/(J_\uparrow + J_\downarrow)$
Rasbah, PR B 2000
A.F-Jaffrès, PR B 2001