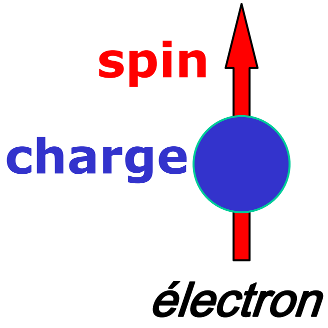
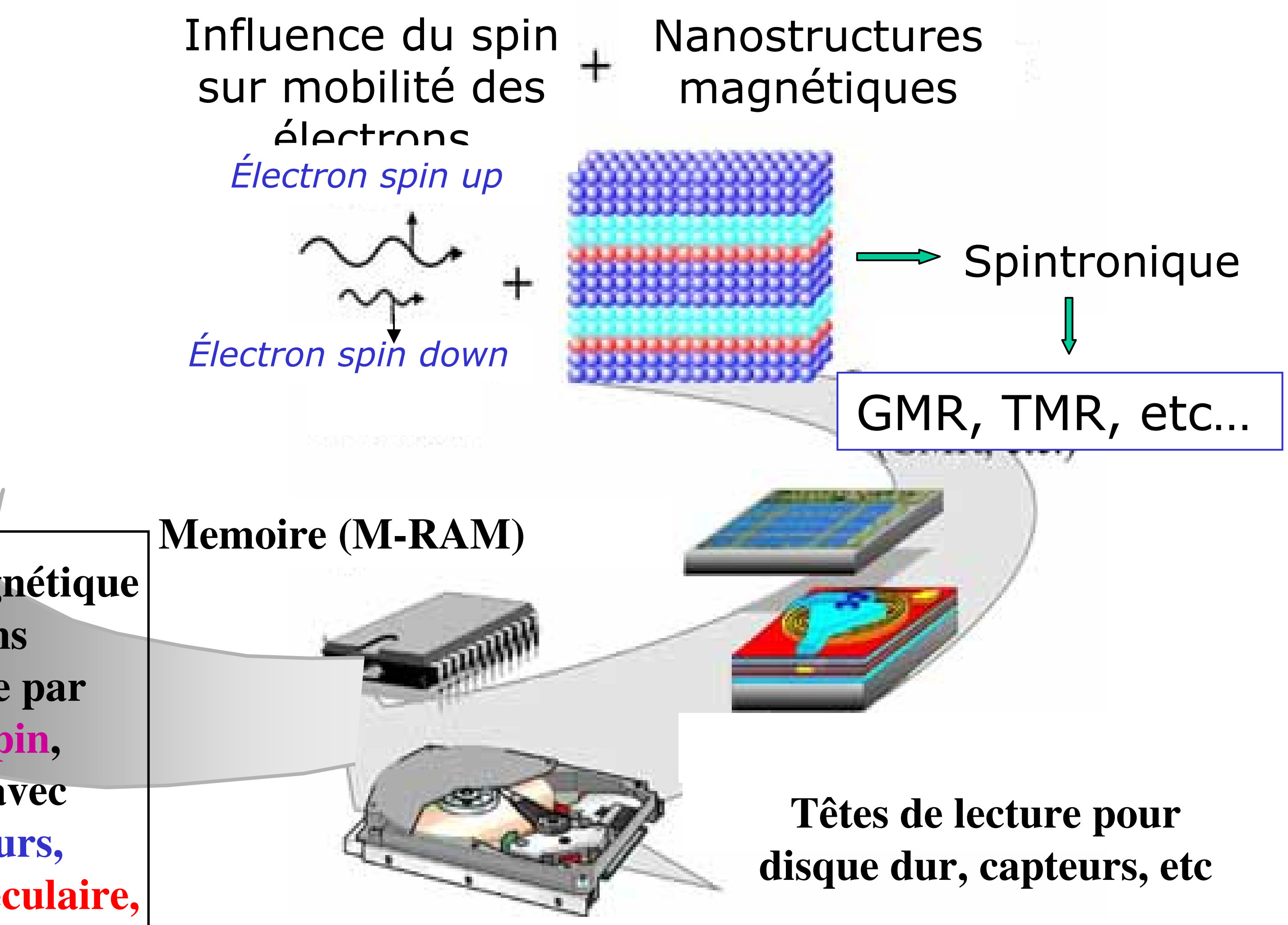
Présent et Futur de la Spintronique



spin

charge

électron



Influence du spin sur mobilité des électrons + Nanostructures magnétiques

Électron spin up

Électron spin down

\+

→ Spintronique

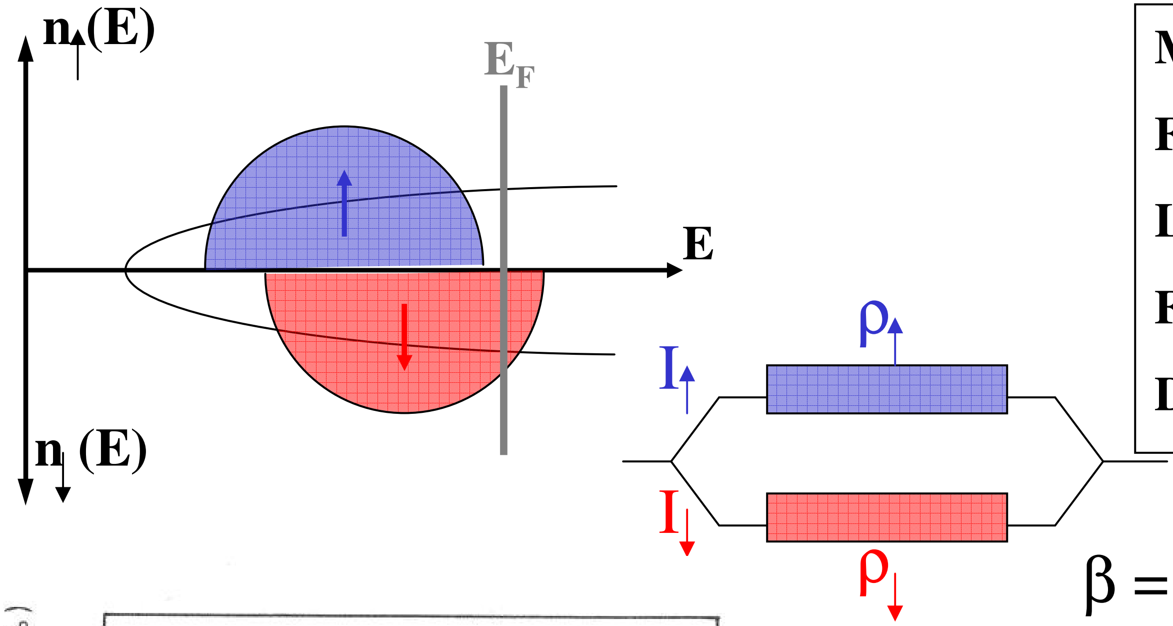
GMR, TMR, etc…

Memoire (M-RAM)

Têtes de lecture pour disque dur, capteurs, etc

commutation magnétique et oscillations hyperfréquence par transfert de spin, spintronique avec semiconducteurs, spintronique molèculaire, etc

Influence du spin sur la mobilité des électrons dans un métal ferromagnétique



Mott, Proc.Roy.Soc A153, 1936

Fert et al, PRL 21, 1190, 1968

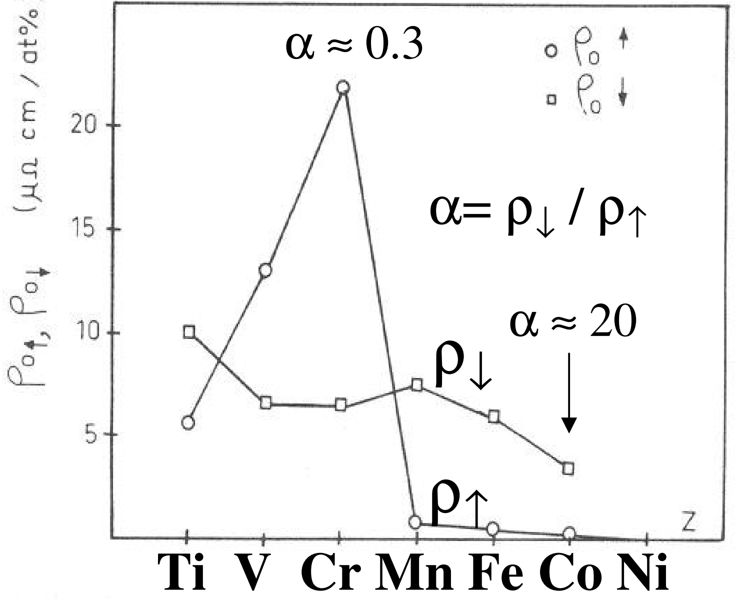
Loegel-Gautier, JPCS 32, 1971

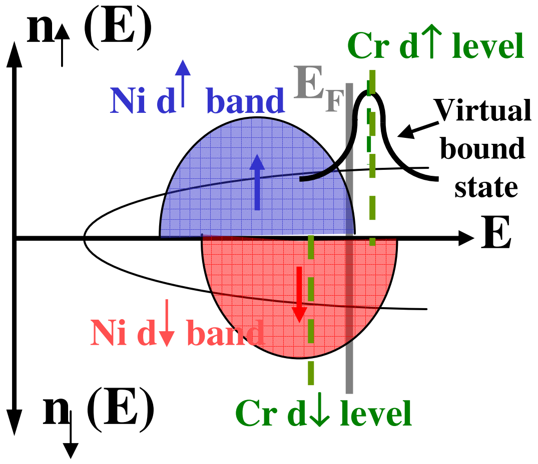
Fert et al,J.Phys.F6, 849, 1976

Dorlejin et al, ibid F7, 23, 1977

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

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





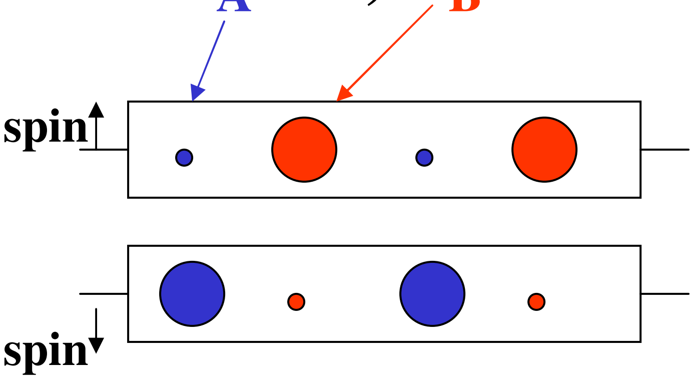
Mixing impurities A and B with opposite or similar spin asymmetries: *the pre-concept of GMR*

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

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

1st case

$\alpha_A > 1, \alpha_B < 1$

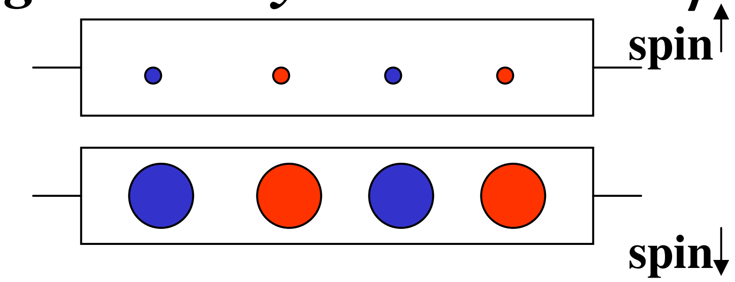


$\rho_{AB} >> \rho_A + \rho_B$

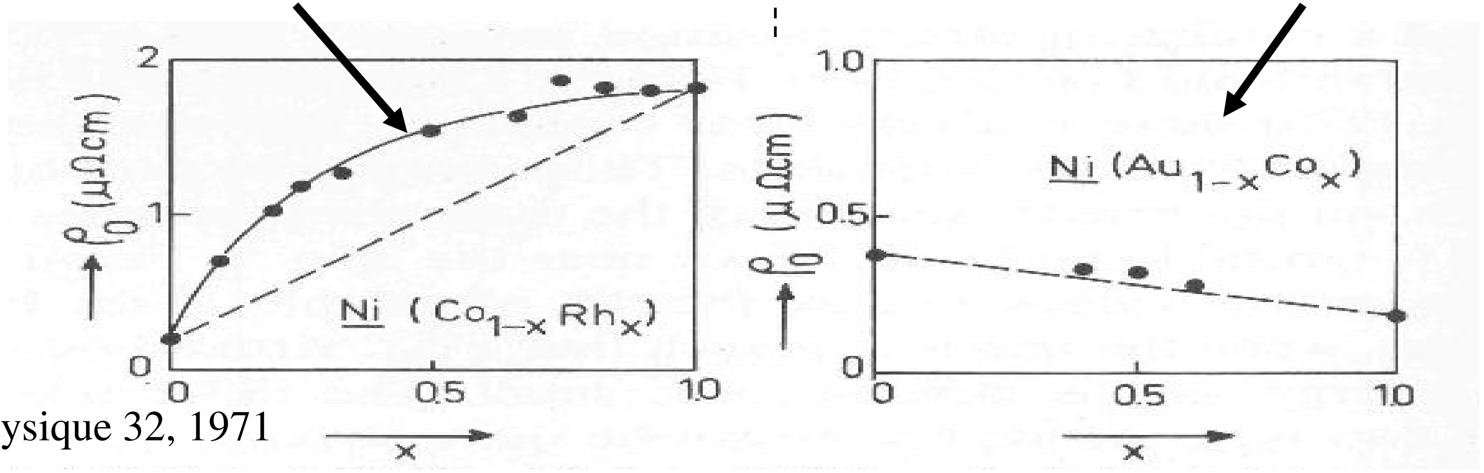
2d case

α_A **and** $\alpha_B > 1$

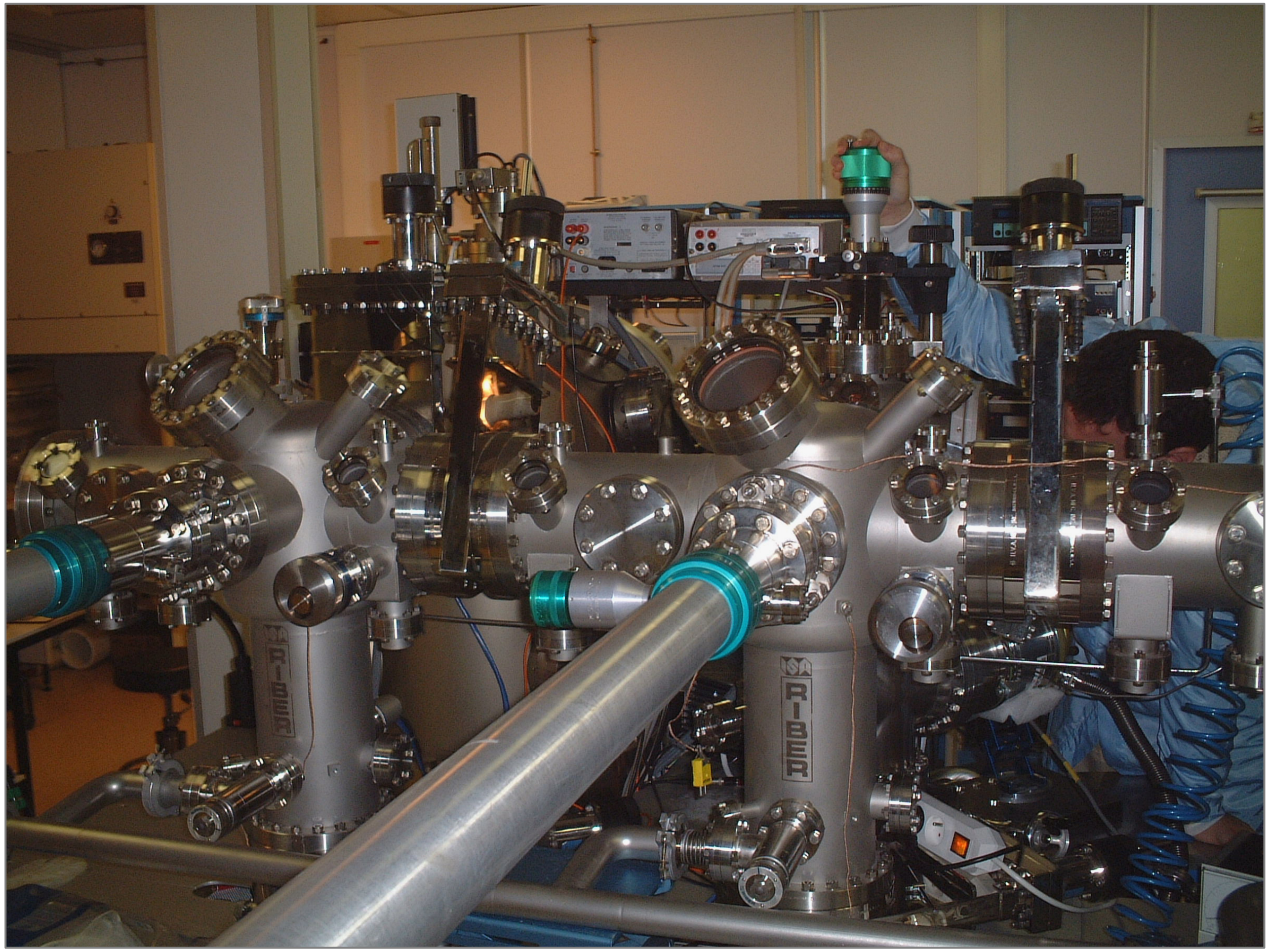
High mobility channel→low ρ



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

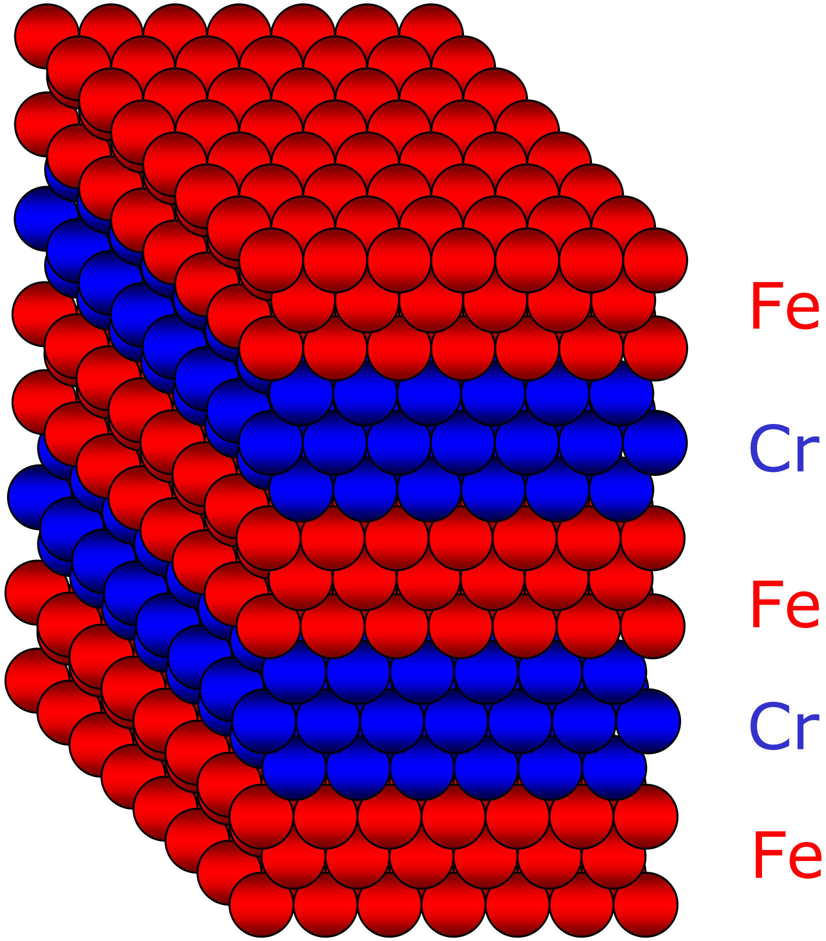


J. de Physique 32, 1971

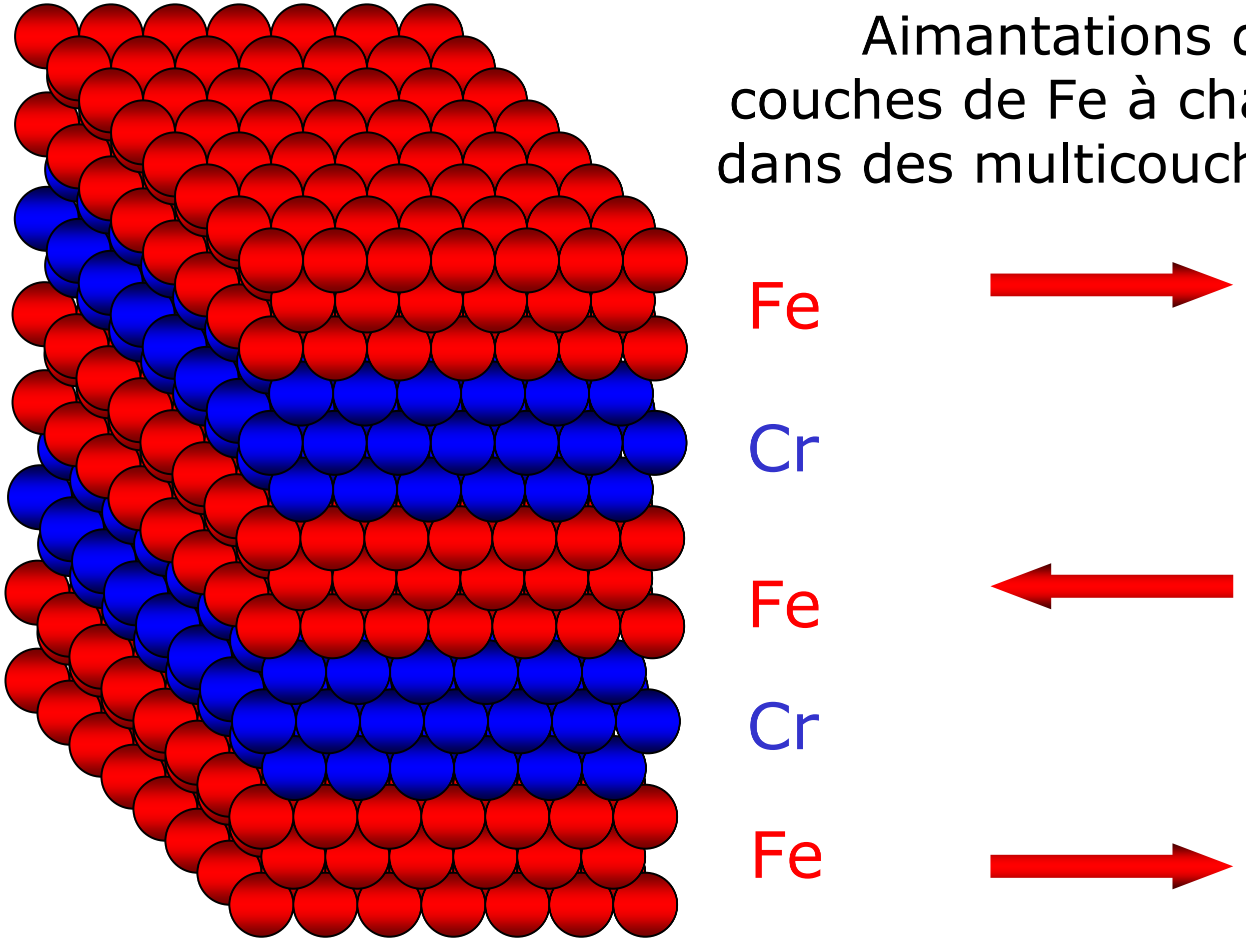


Epitaxie par jet moléculaire
(croissance de multicouches métalliques)

Multicouches magnétiques



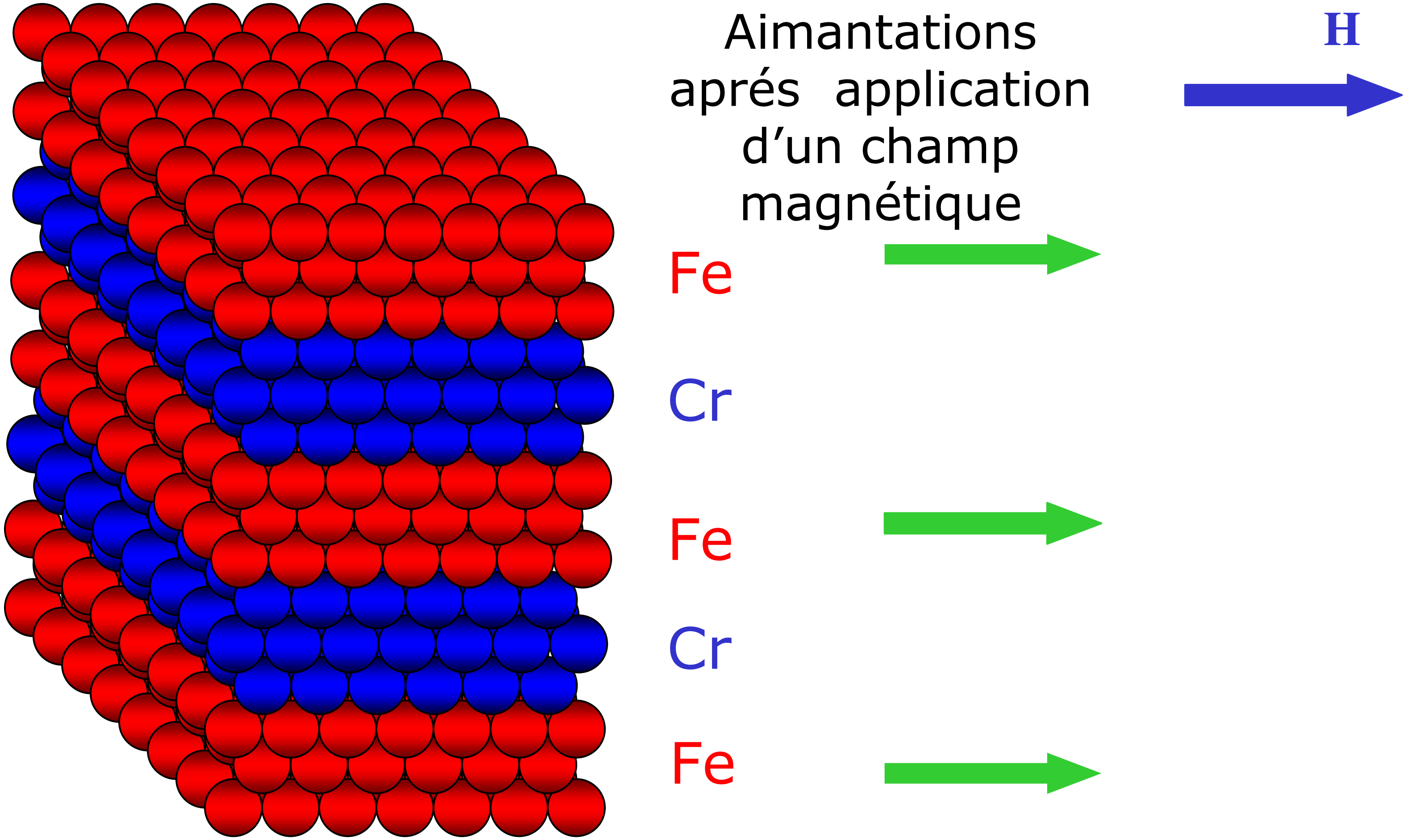
• Multicouches magnétiques



Aimantations des
couches de Fe à champ nul
dans des multicouches Fe/Cr

P. Grünberg, 1986 → couplage antiferromagnétique entre couches

•Multicouches magnétiques



Aimantations
aprés application
d'un champ
magnétique

H

Fe

Cr

Fe

Cr

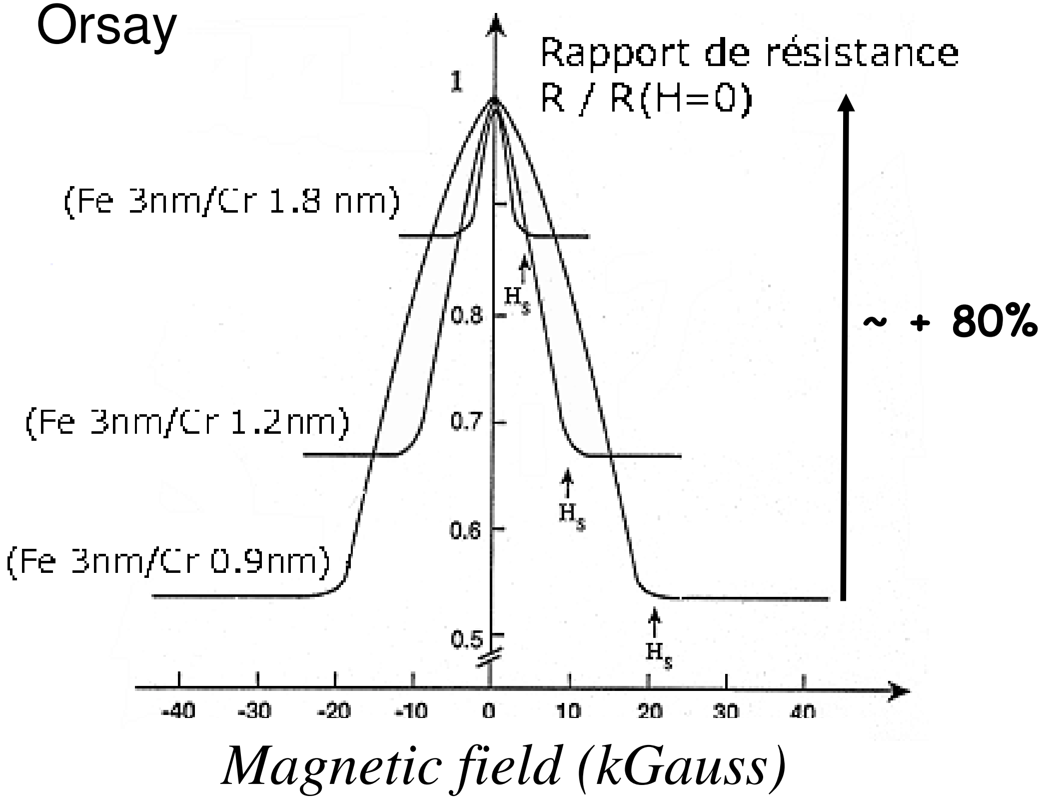
Fe

P. Grünberg, 1986 → couplage antiferromagnétique entre couches

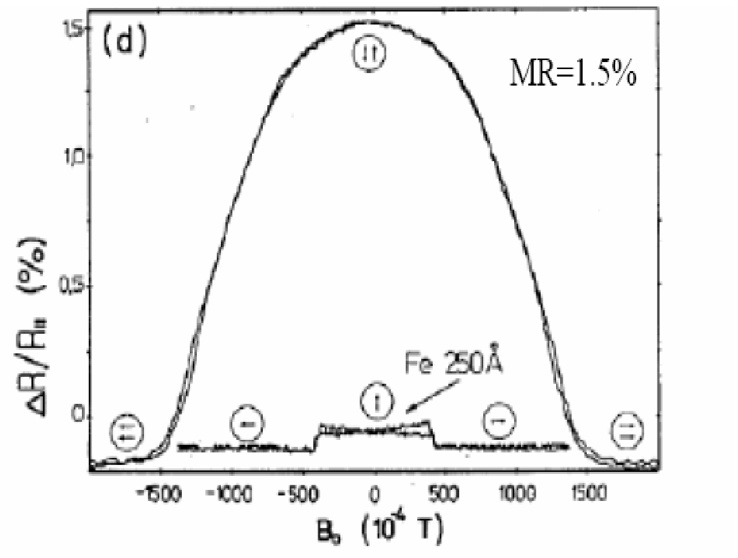
• Magnetoresistance Géante (GMR)

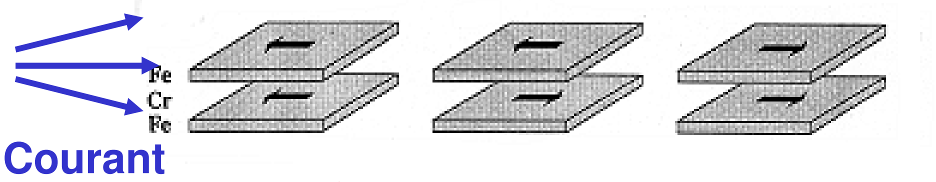
(Orsay, 1988, multicouches Fe/Cr, Jülich, 1989,tricouches Fe/Cr/Fe)

Orsay

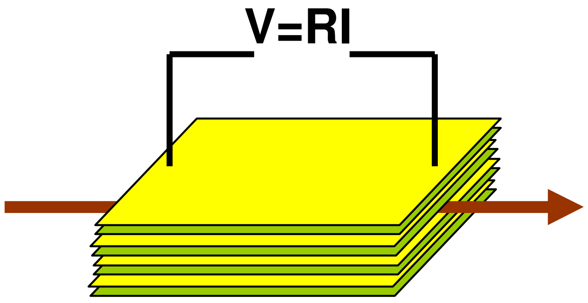


Jülich





AP (AntiParallèle) **P** (Parallèle)



• Magnetoresistance Géante (GMR)

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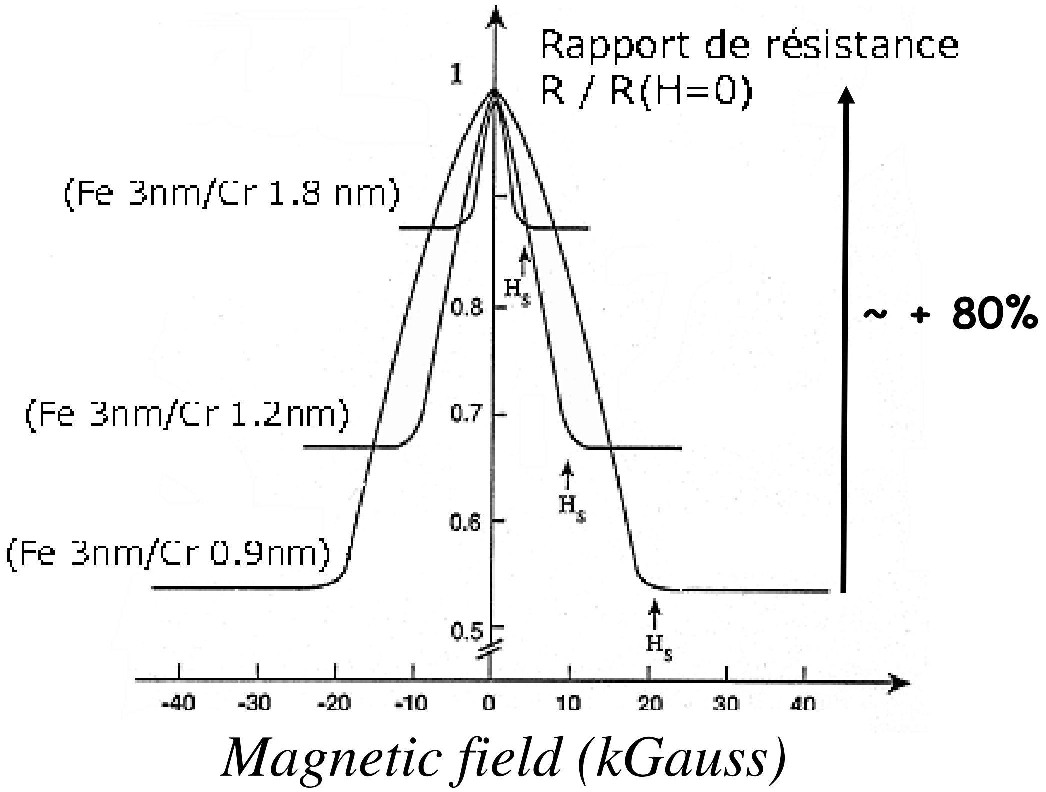
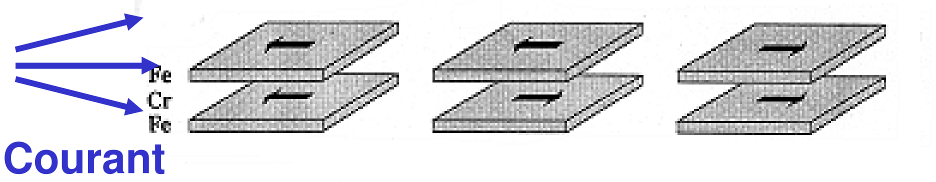
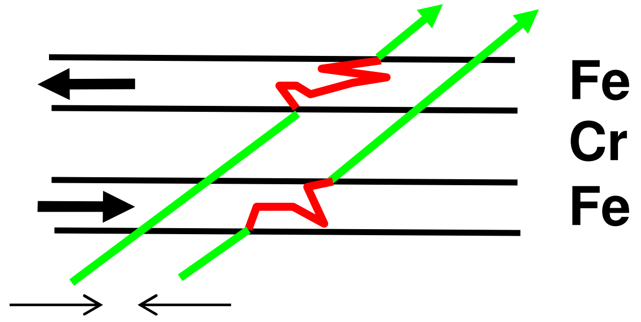


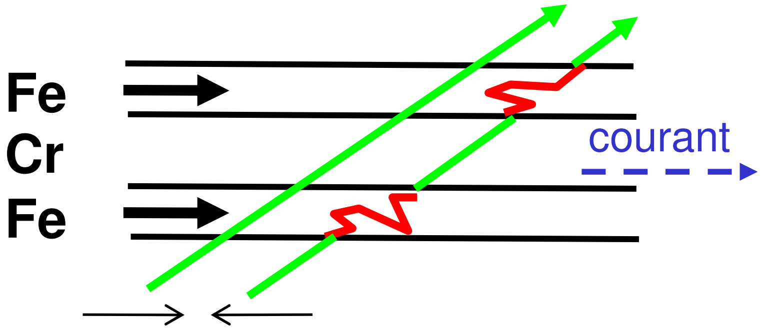


AP (AntiParallèle) **P** (Parallèle)

Aimantations anti-parallèles
(champ nul, forte résistance)

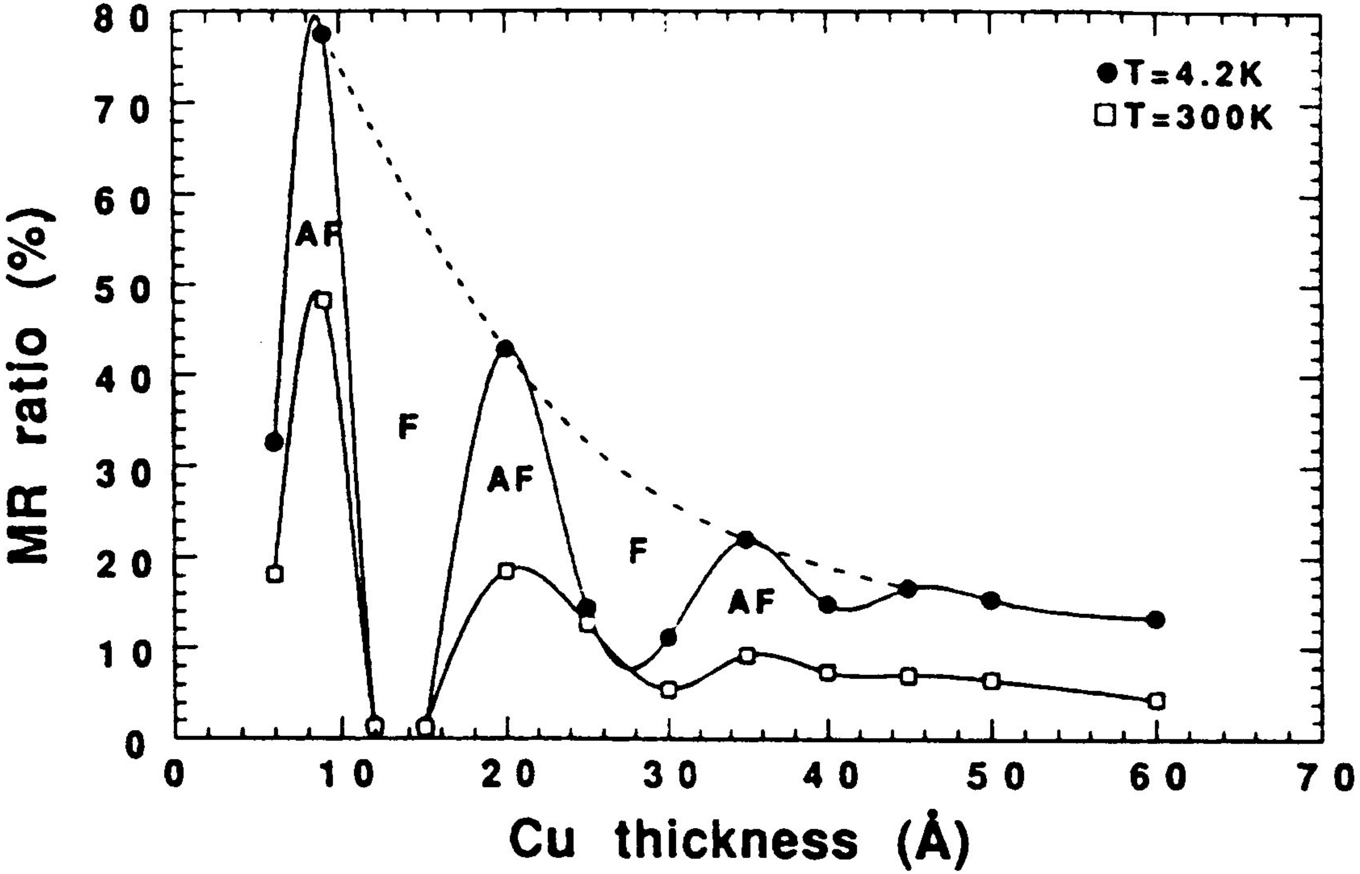


Aimantations parallèles
(champ appl., petite resist.)



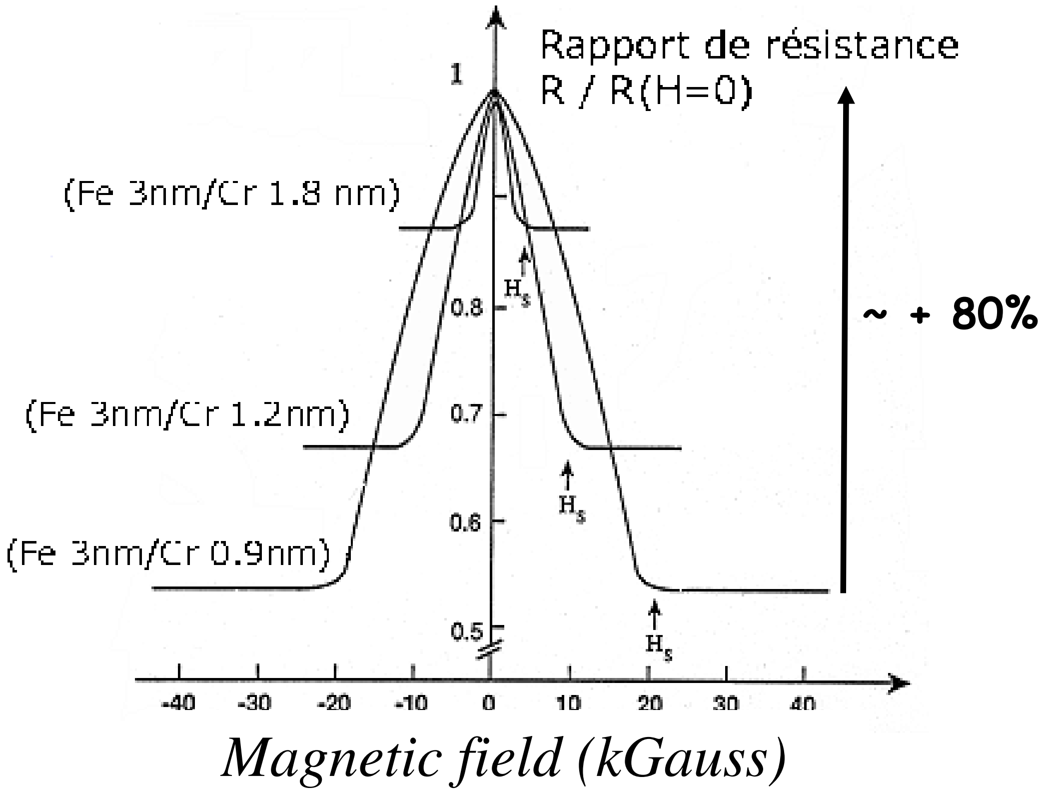
Condition pour GMR:
épaisseurs ≈ nm

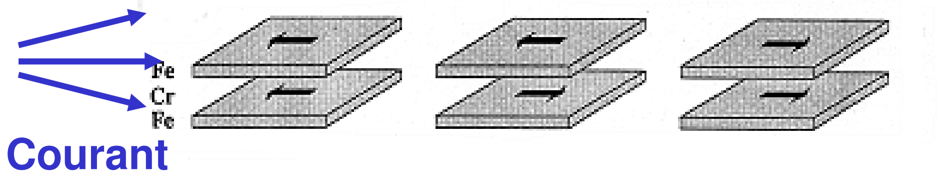
GMR oscillations in Co/Cu (Orsay 1991, Mosca, AF et al)



• Magnetoresistance Géante (GMR)

(Orsay, 1988, multicouches Fe/Cr, Jülich, 1989,tricouches Fe/Cr/Fe)





AP (AntiParallèle) **P** (Parallèle)

Aimantations anti-parallèles
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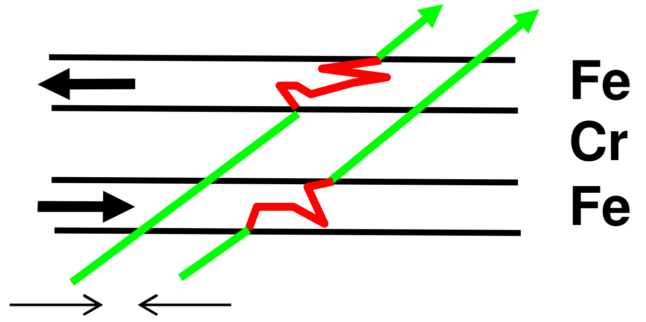
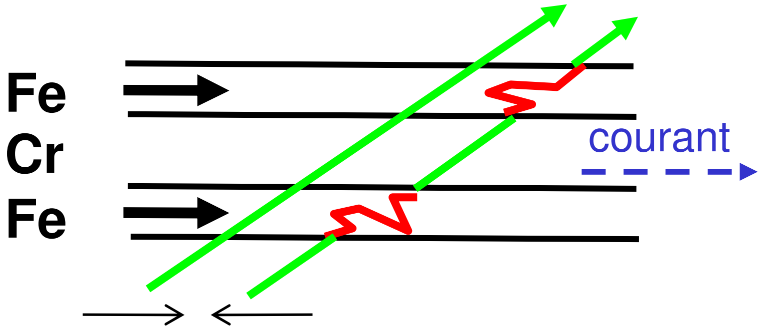
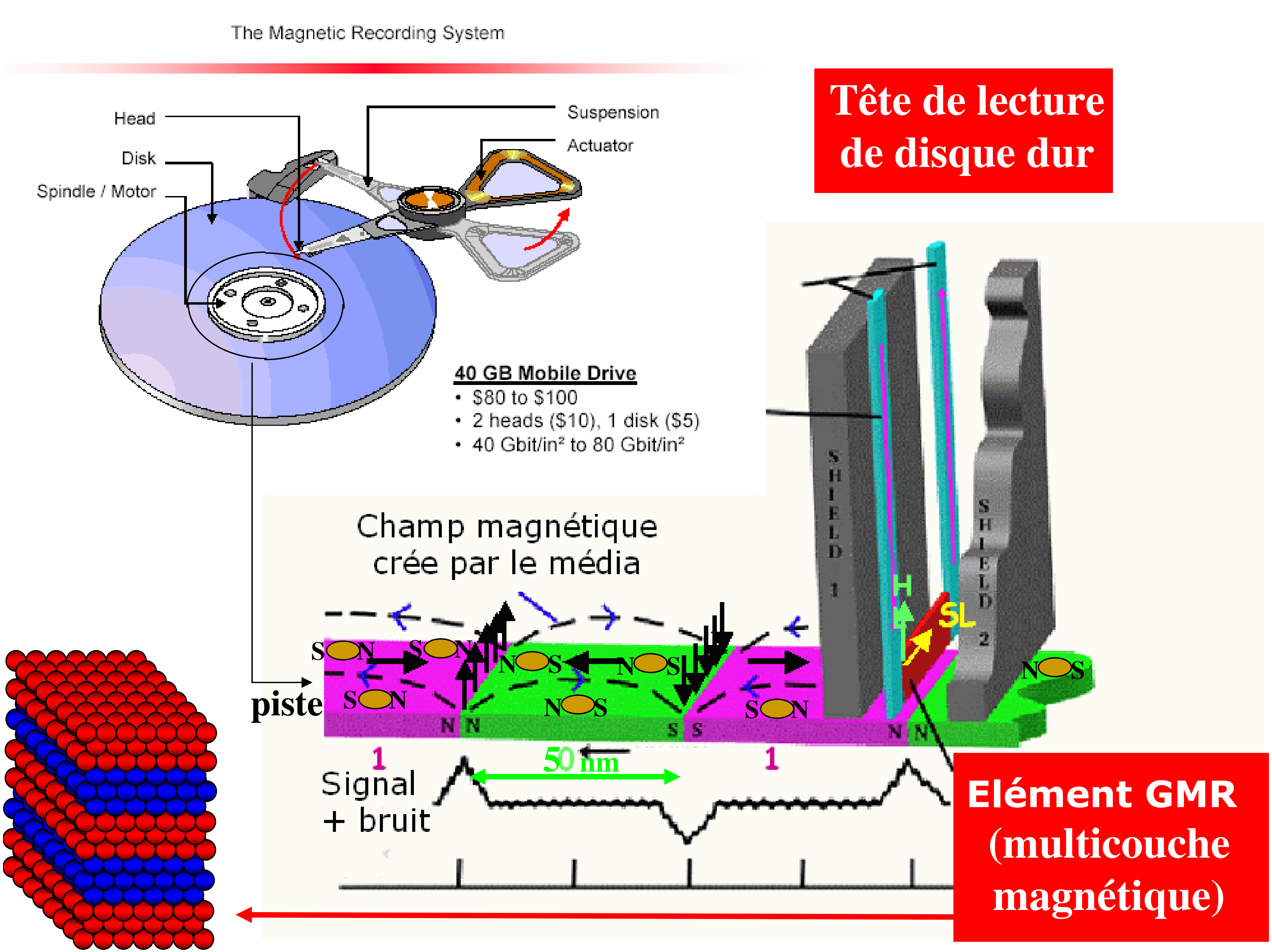


Aimantations parallèles
(champ appl., petite resist.)



Condition pour GMR:
épaisseurs ≈ nm

Tête de lecture de disque dur



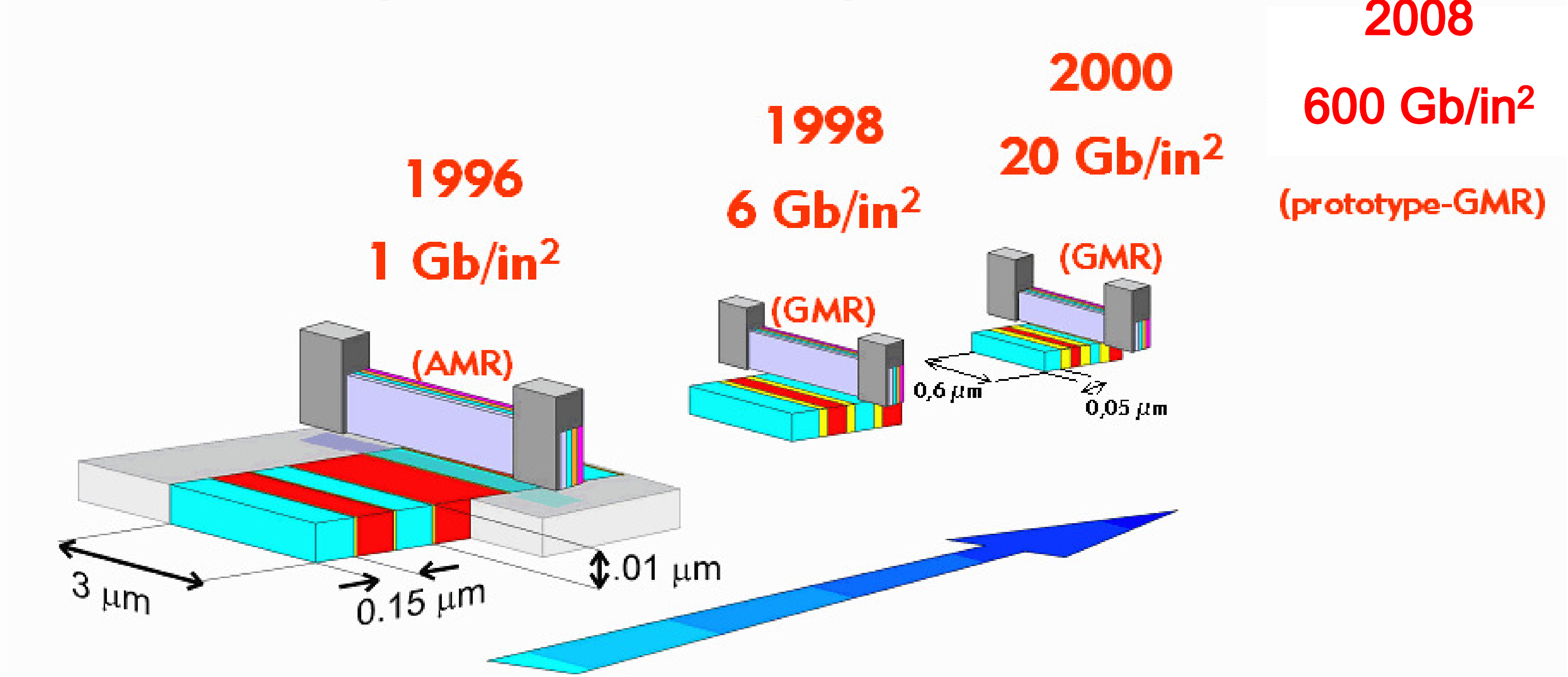
40 GB Mobile Drive

- $80 to $100
- 2 heads ($10), 1 disk ($5)
- 40 Gbit/in² to 80 Gbit/in²

Elément GMR (multicouche magnétique)

- **Enregistrement magnétique:**

➢ *évolution des densités surfaciques (de l'AMR à la GMR)*

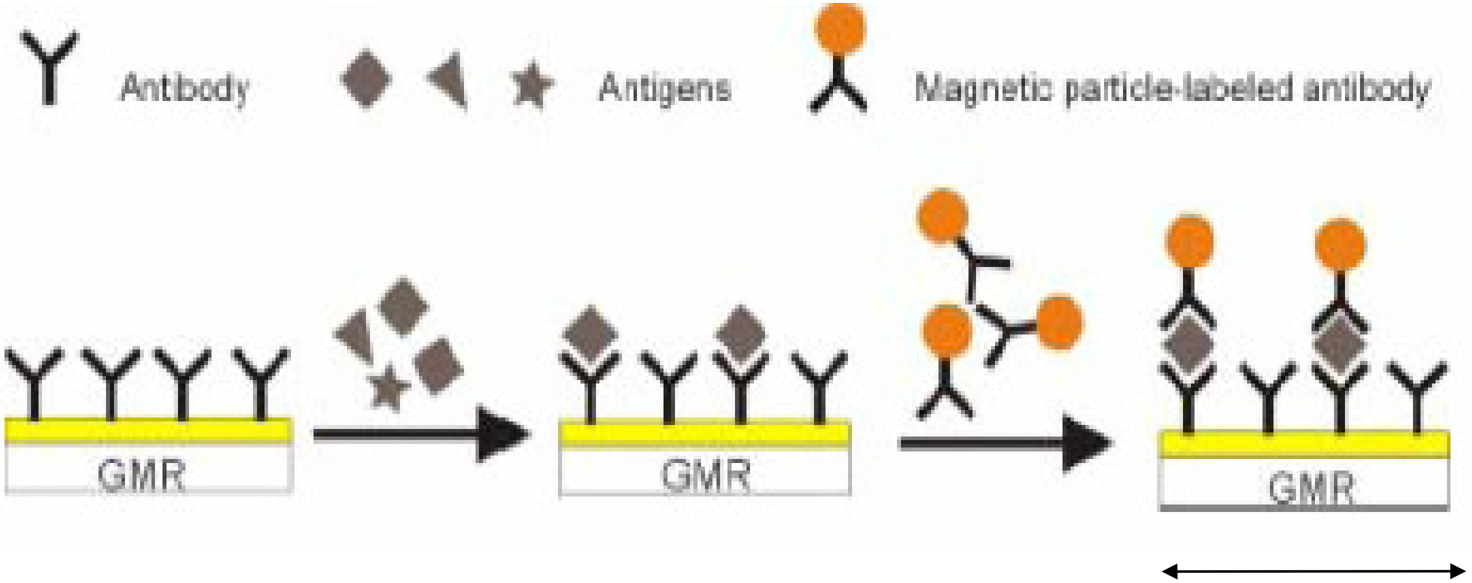


1 disque dur de 400 Giga-octet peut contenir une information équivalente
à environ 800.000 livres (format livre de poche)
ou à 1 million de photographies (de définition moyenne)
ou à 8000 CD audio (compression MP3)
ou à 300 heures video, ou 36 heures video haute def.

- **Enregistrement magnétique:**

➢ ***Disque 5 GB Microdrive***

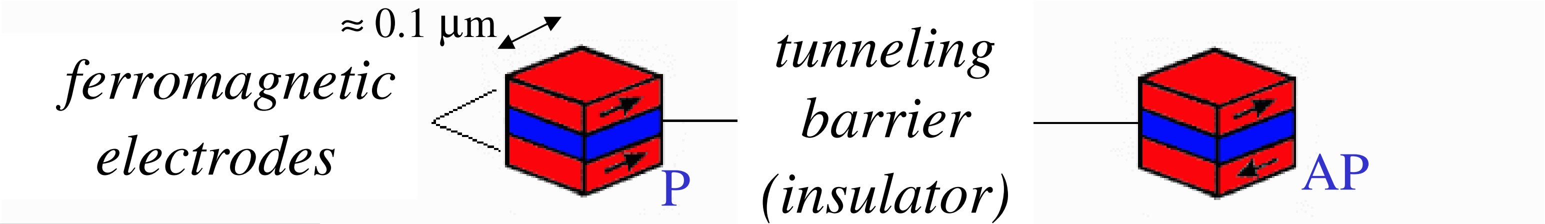
Analyse biologique « biochips »



quelques microns

(prototypes avec réseaux de capteurs pour détecter un millier de cibles différentes)

• Magnetic Tunnel Junctions,Tunneling Magnetoresistance (TMR)



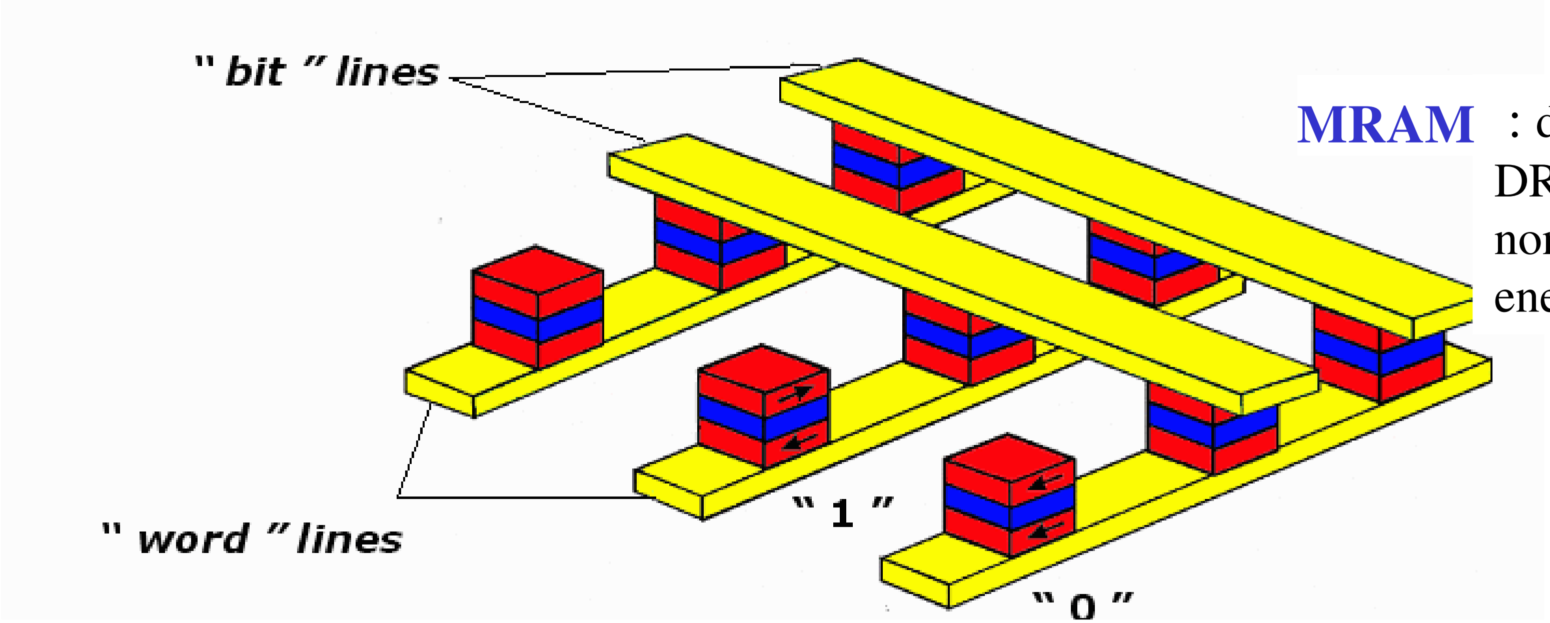
Low resistance state *High resistance state*

Jullière, 1975, low T, hardly reproducible

Moodera et al, 1995, Miyasaki et al,1995, CoFe/Al$_2$O$_3$/Co, MR ≈30-40%

Applications: - read heads of Hard Disc Drive

- M-RAM (Magnetic Random Access Memory)

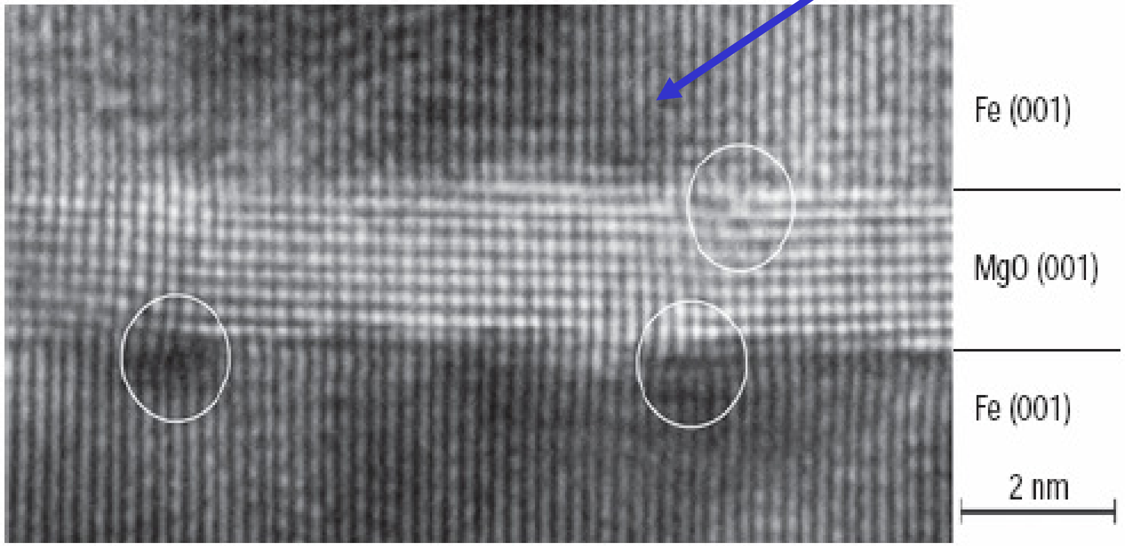


MRAM : density/speed of DRAM/SRAM + nonvolatilty + low energy consumption

1)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 »?

2) Directions pour une TMR plus élevée

Ferromagnétiques à polarisation en spin 100% (composés demi-metalliques)

Exemple: **$La_{2/3}Sr_{1/3}MnO_3$ (LSMO)**

jonctions tunnel LSMO/$SrTiO_3$/LSMO (CNRS/Thales): TMR de 1800% correspondant à 95% de polarisation de spin

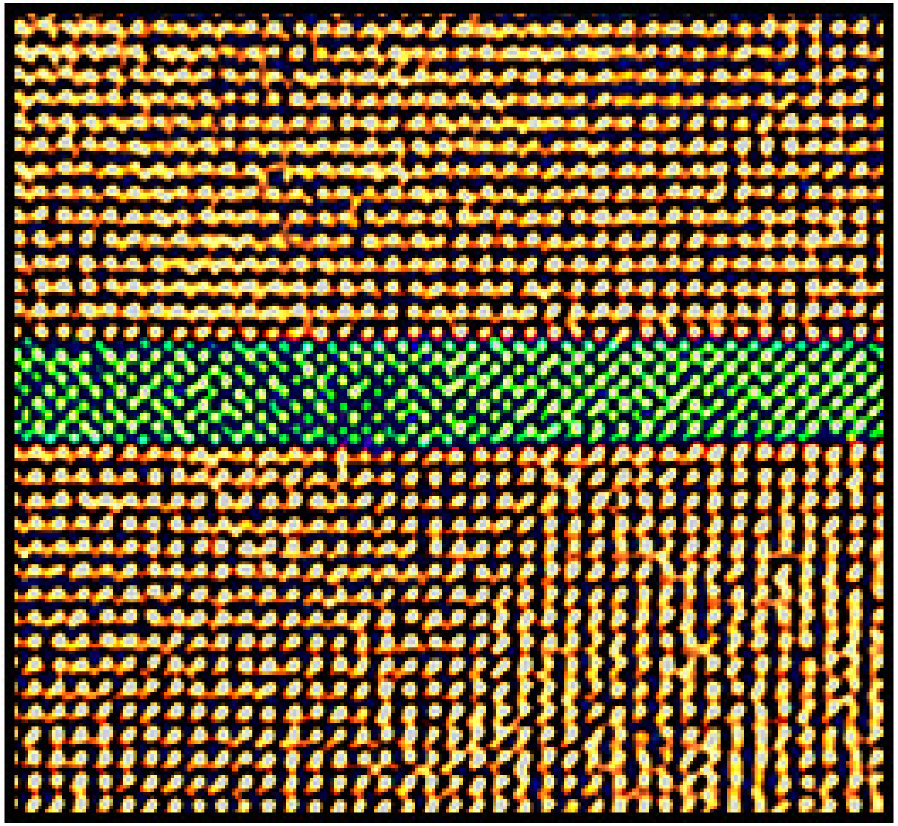


Image de microscopie électronique par J-L. Maurice, UMR CNRS/Thales

Transfert de spin
(renversement d’aimantation, génération de micro-ondes)

Spintronique avec semi-conducteurs

Spintronique moléculaire

Transfert de spin
(renversement d'aimantation, génération de micro-ondes)

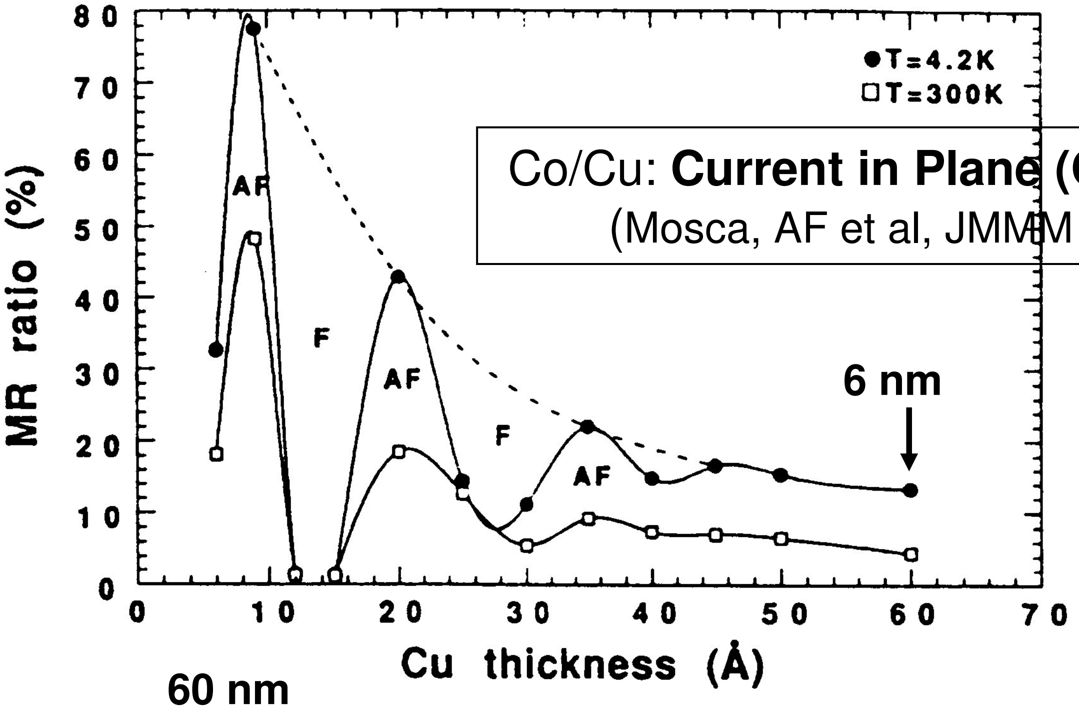
Spintronique avec semi-conducteurs

Spintronique moléculaire

Introduction:

accumulation de spin

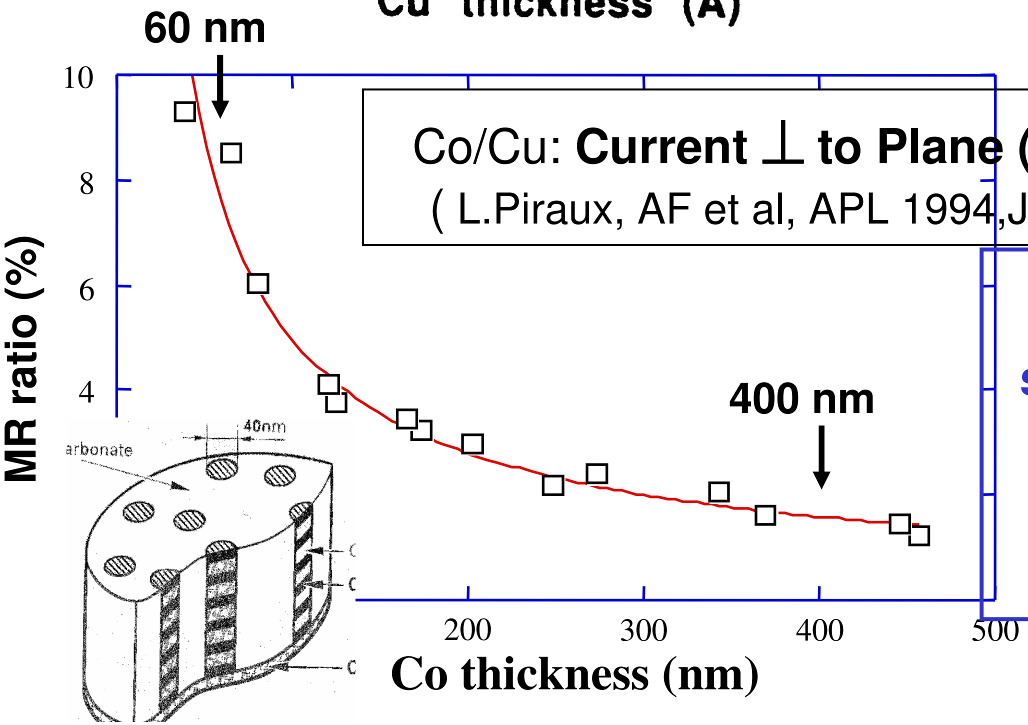
et courant de spin



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)

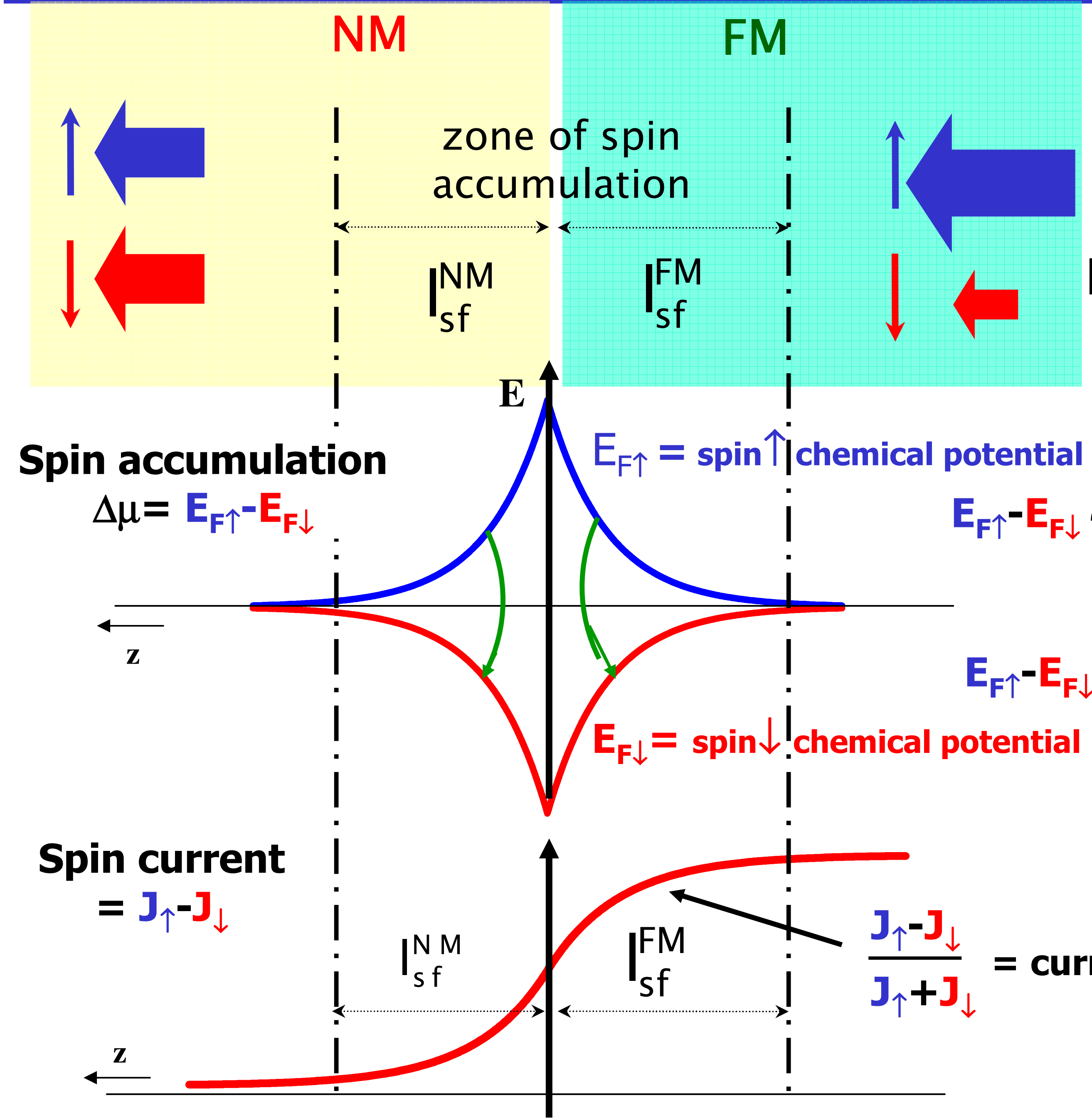
Spin injection/extraction at a NM/FM interface (beyond ballistic range)

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

$l_{s\,f}^{F\,M}$ = spin diffusion length in FM

$l_{s\,f}^{N\,M}$ = spin diffusion length in NM

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



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

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

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

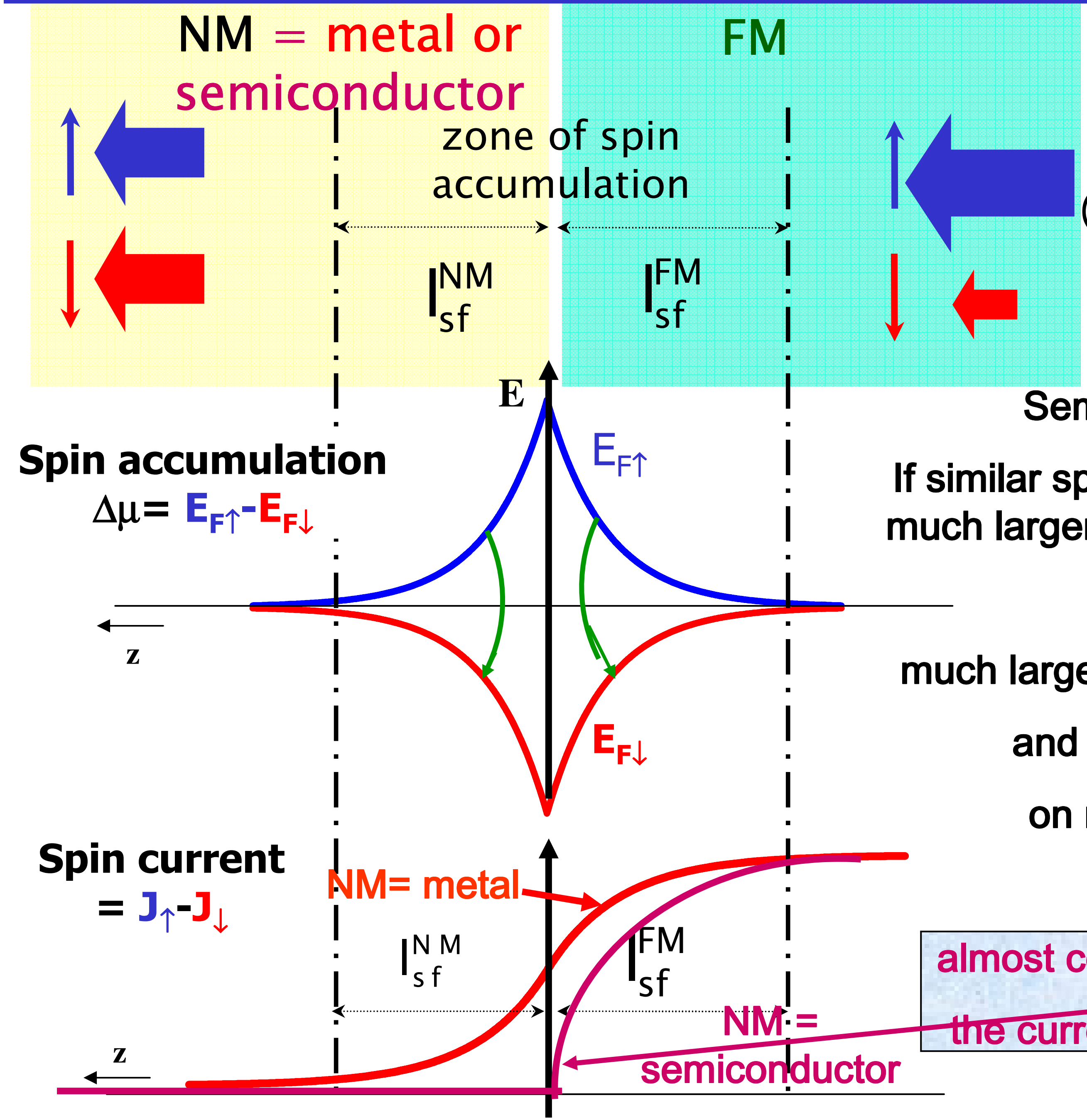
$E_{F\uparrow} - E_{F\downarrow} \sim \exp(z/\,l_{s\,f}^{F\,M})$ **in FM**

$E_{F\uparrow} - E_{F\downarrow} \sim \exp(-z/\,l_{s\,f}^{N\,M})$ **in NM**

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

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

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

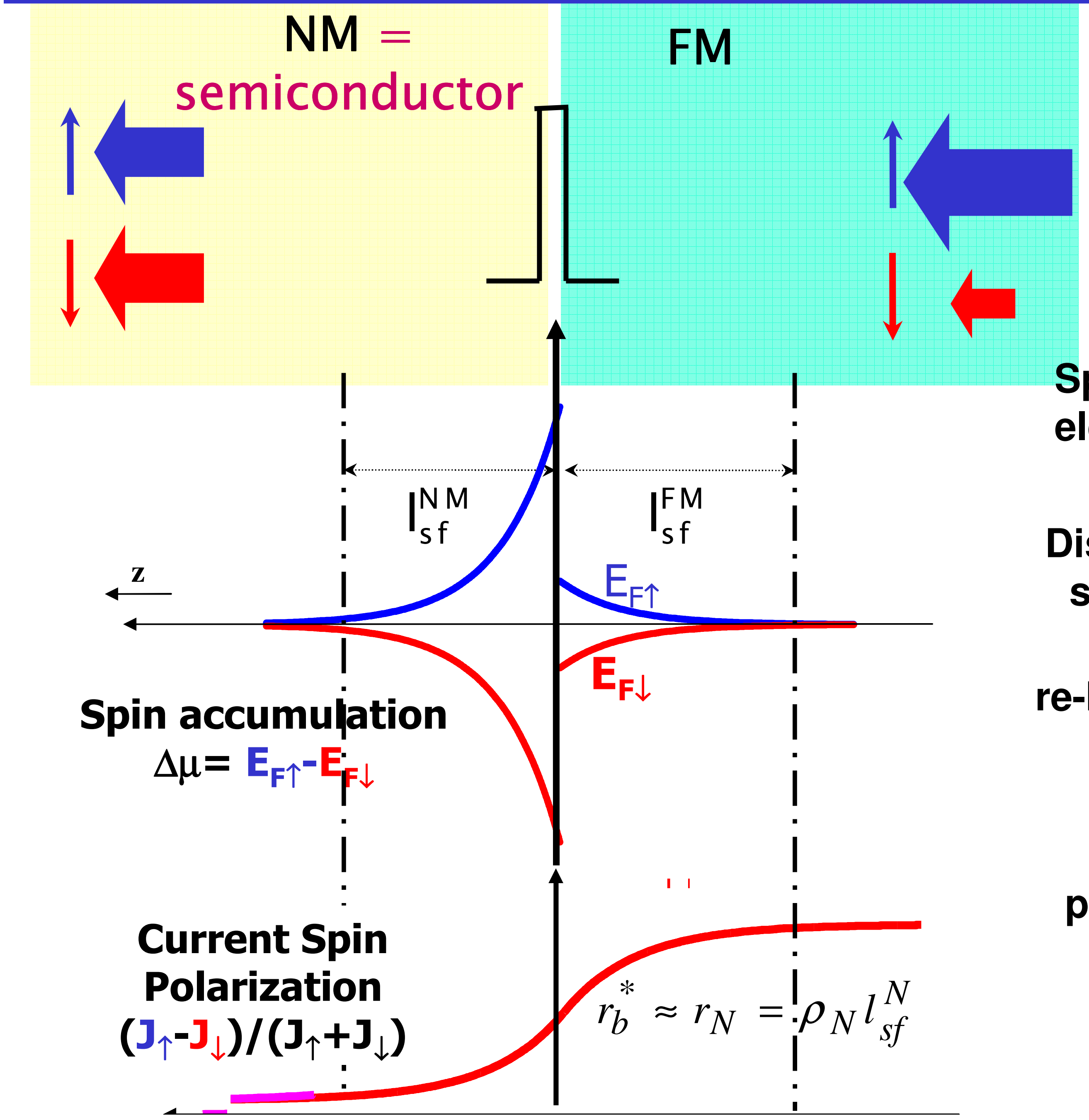
much larger spin accumulation density

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

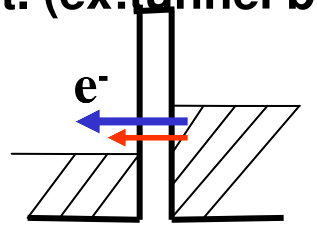


Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$

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

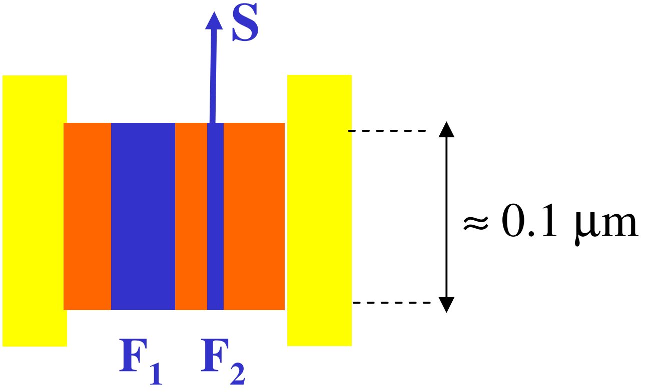
re-balanced spin relaxations in F and NM

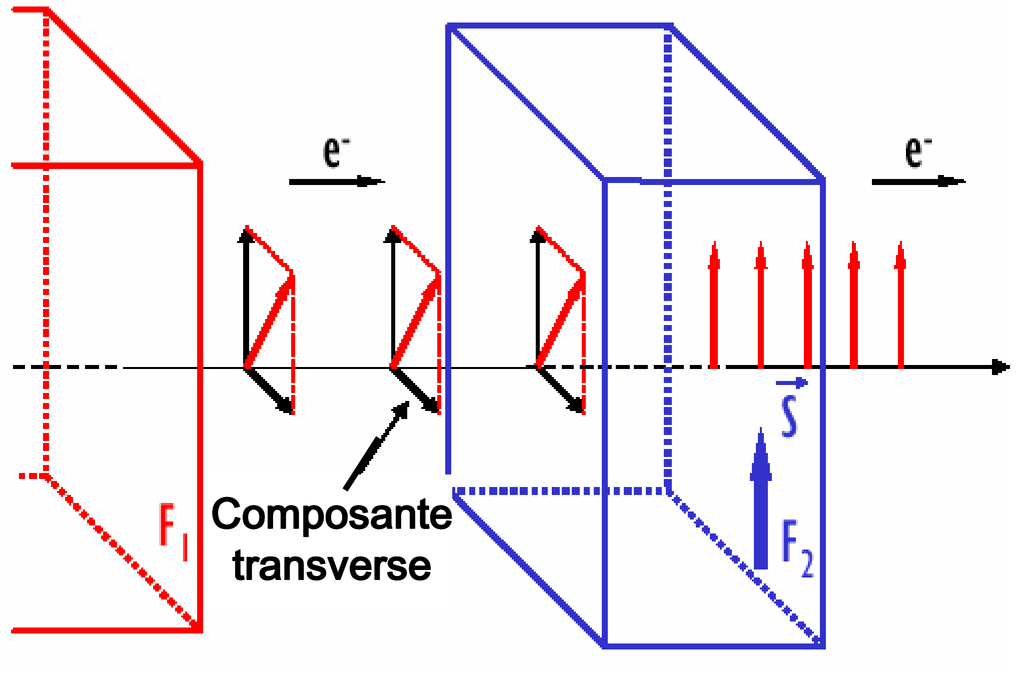
extension of the spin-polarized current into the semiconductor

Rasbah, PR B 2000

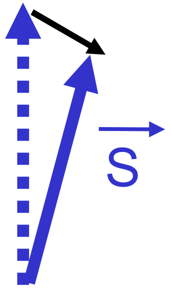
A.F-Jaffrès, PR B 2001

Concept du transfert de spin (Slonczewski 1996)

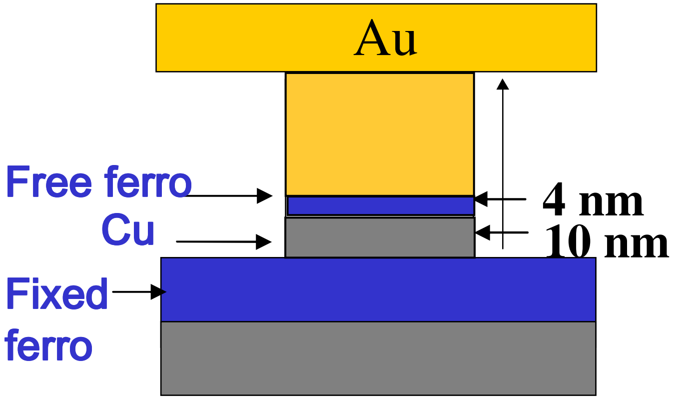




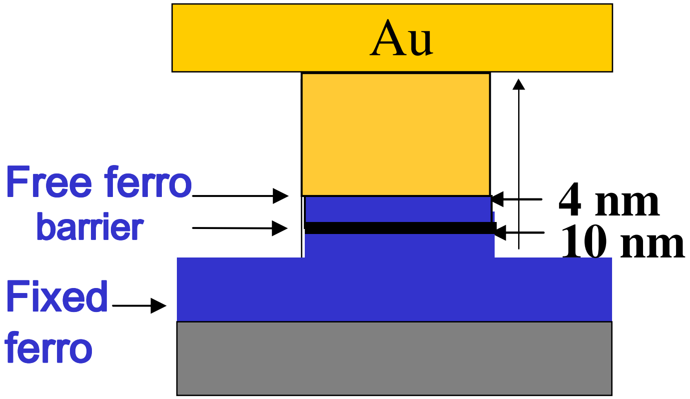
La composante transverse du spin est perdue par les électrons du courant, mais est en fait transférée au SPIN global $\vec{S}$ de la couche → rotation de $\vec{S}$



Experiments on pillars

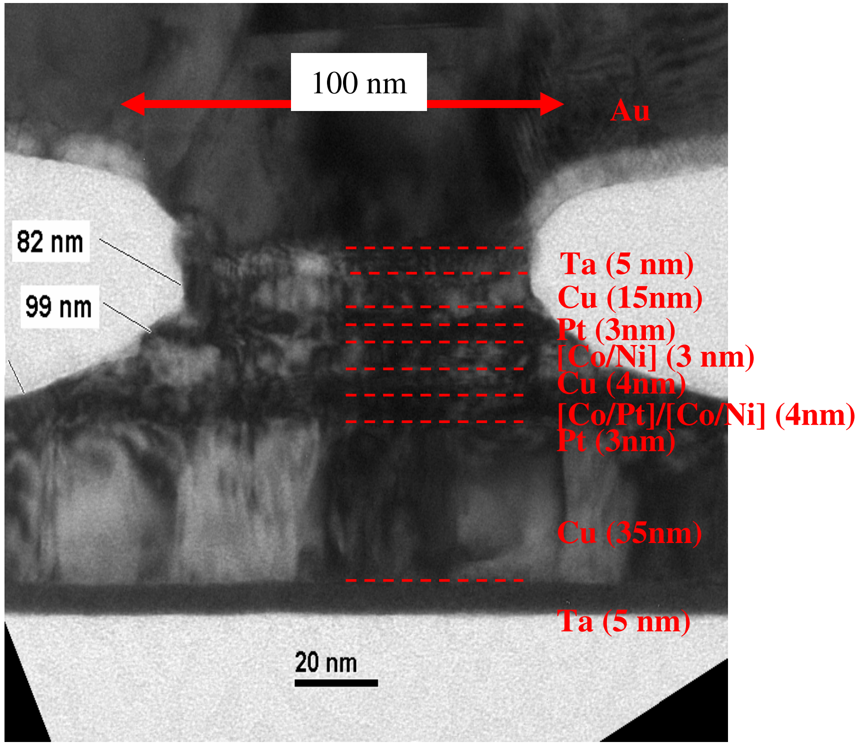


Metallic pillar ≈ 50x150 nm²



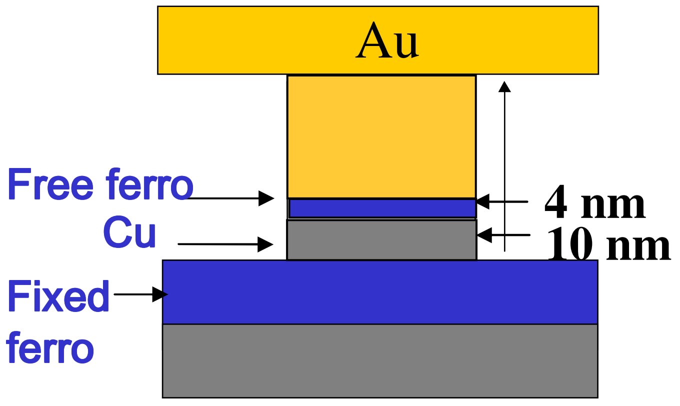
Tunnel junction

E-beam lithography + etching

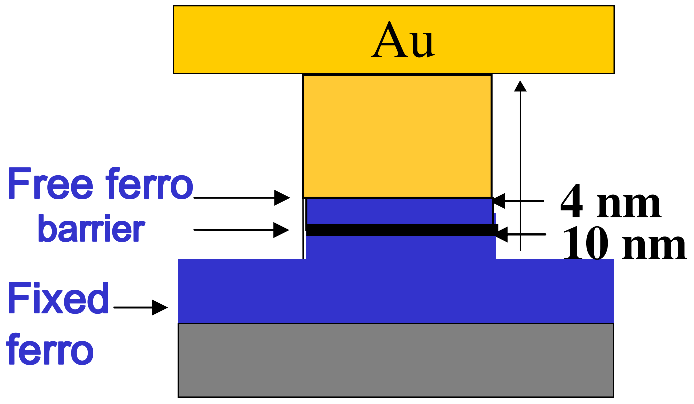


courtesy of S. Mangin
University of Nancy

Experiments on pillars



Metallic pillar ≈ 50x150 nm²



Tunnel junction

E-beam lithography + etching

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

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

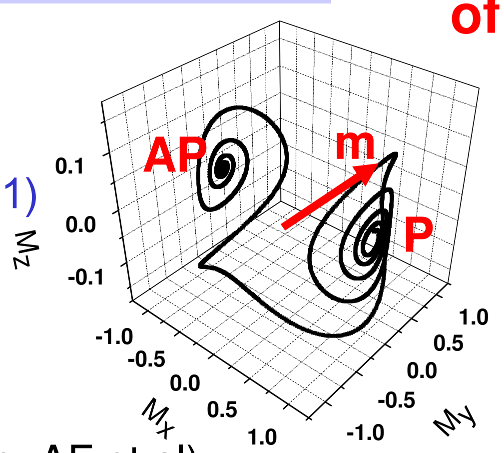
Regime of irreversible magnetic switching

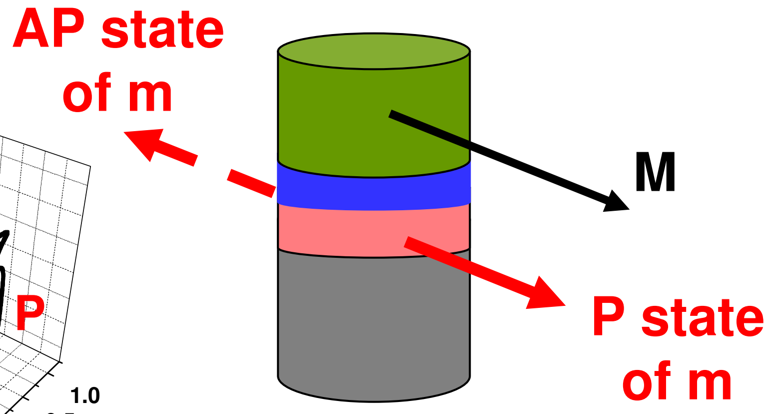
First experiments on pillars:

Cornell (Katine et al, PRL 2000)

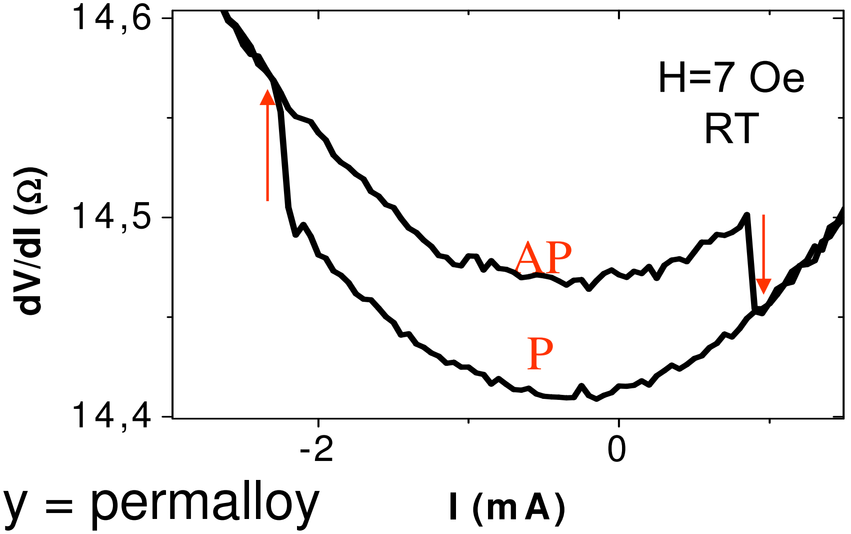
CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)





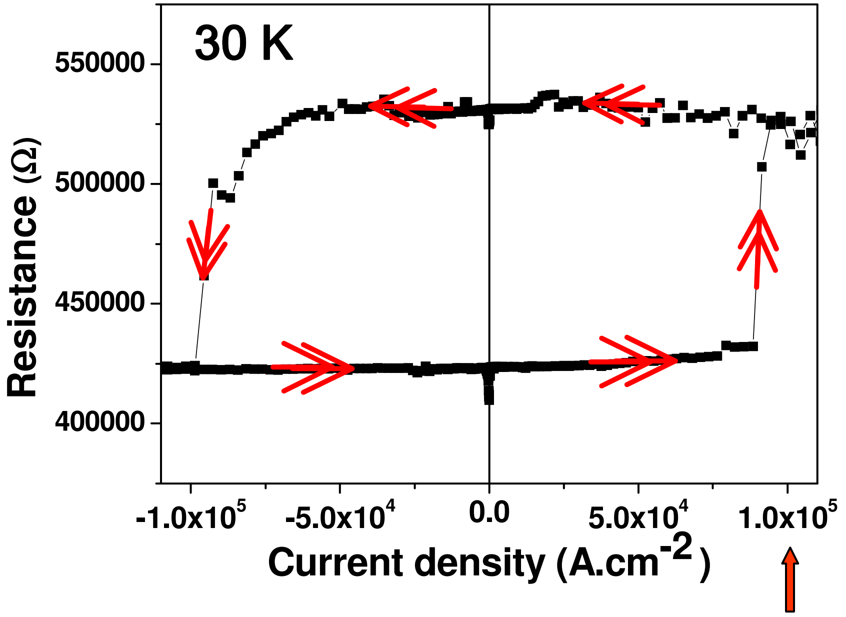
Py/Cu/Py 50nmX150nm (Boulle, AF et al)



Py = permalloy

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

(Elsen, AF et al, PR B 2006)



1×10^5 A/cm^2

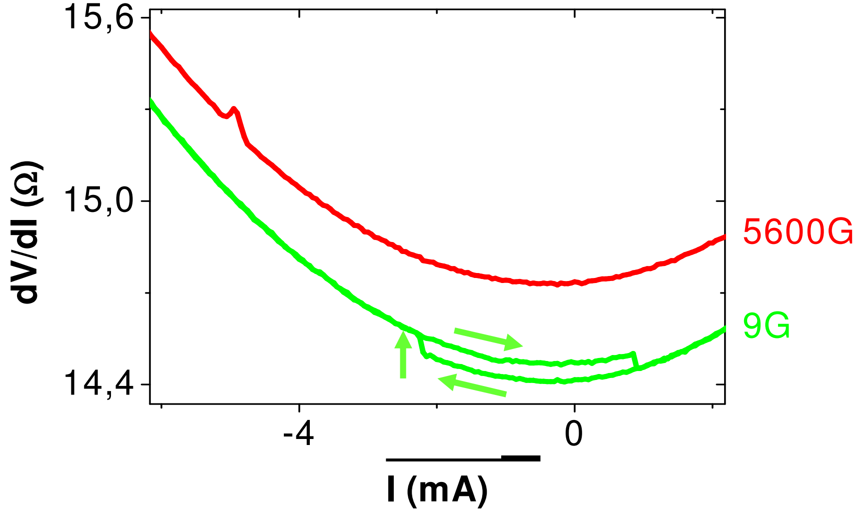
typical switching current ≈ 10^7A/cm^2

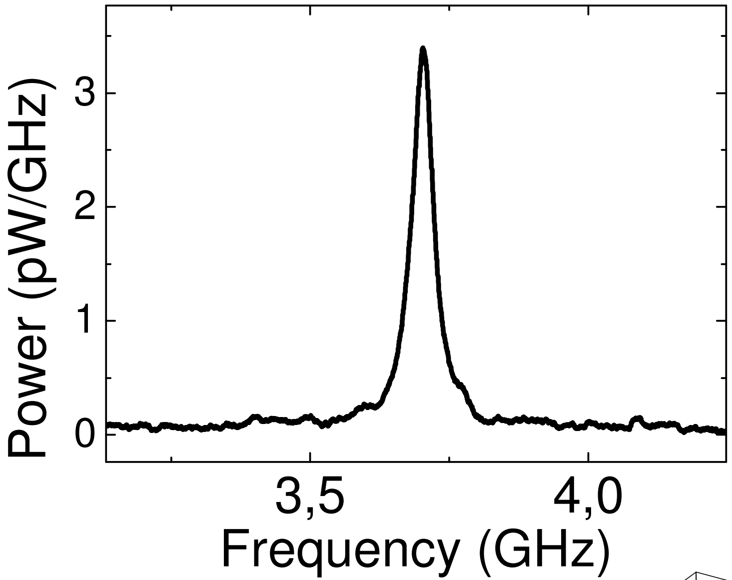
switching time can be as short as 0.1 ns (Chappert et al)

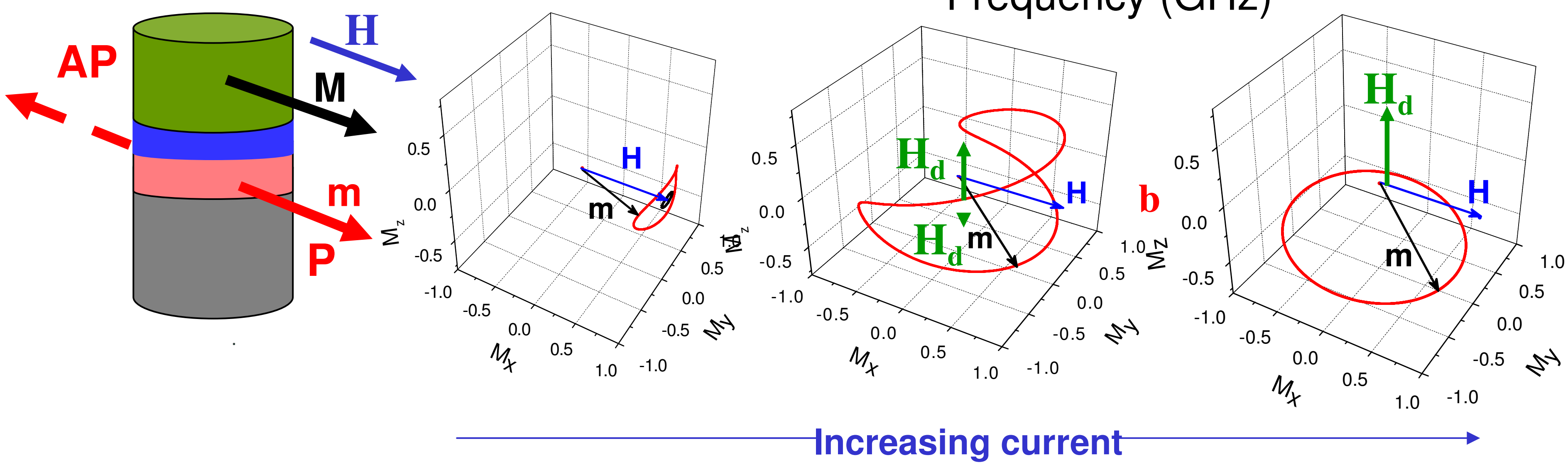
Regime of steady precession (microwave frequency range)

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

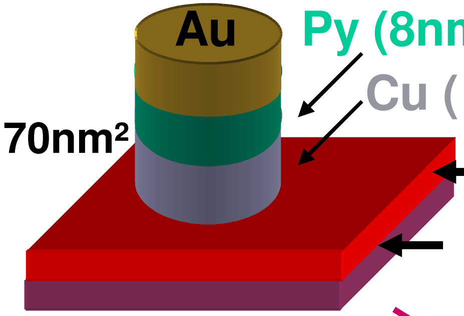
(Py = permalloy)







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



Py (8nm, free)

Cu (8nm)

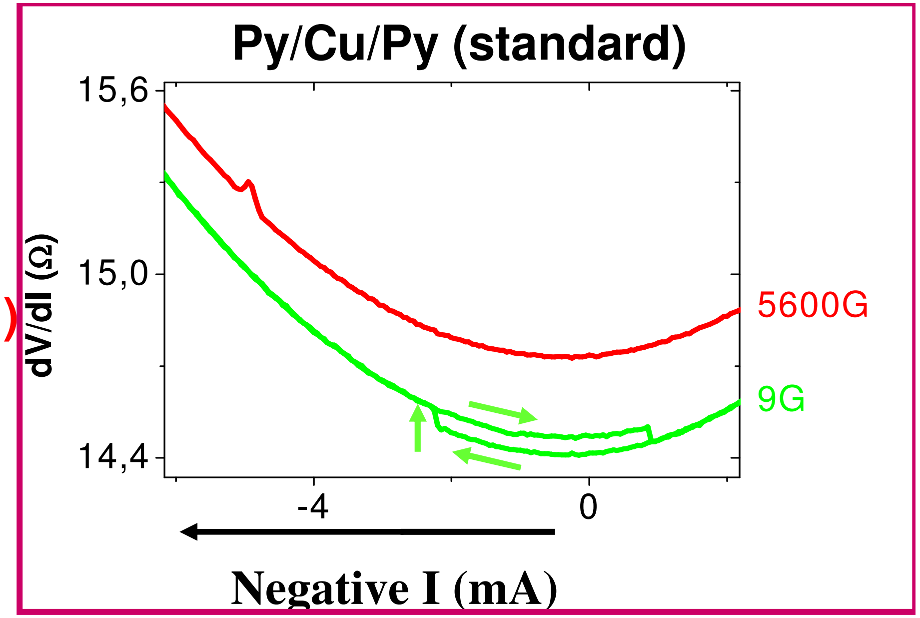
100x170nm²

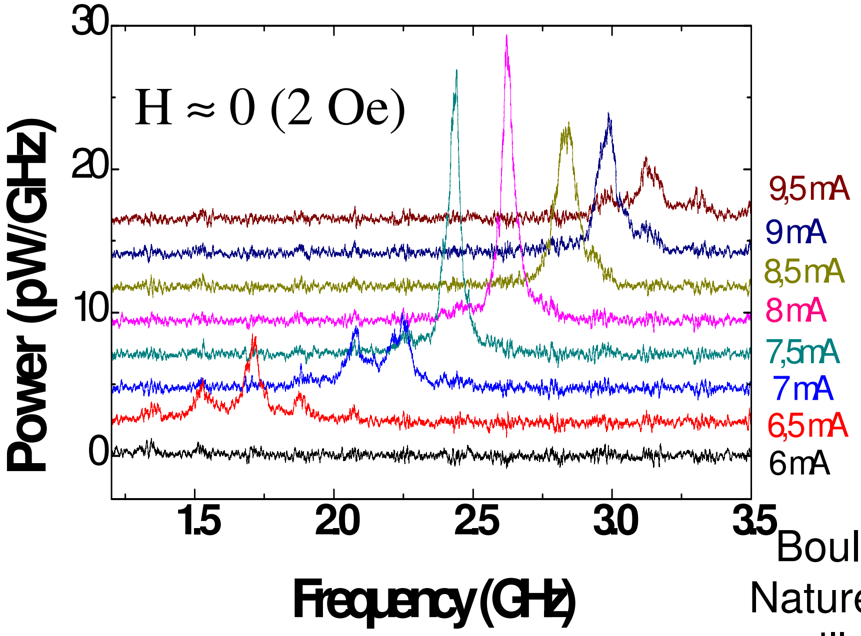
Co (8nm, fixed)

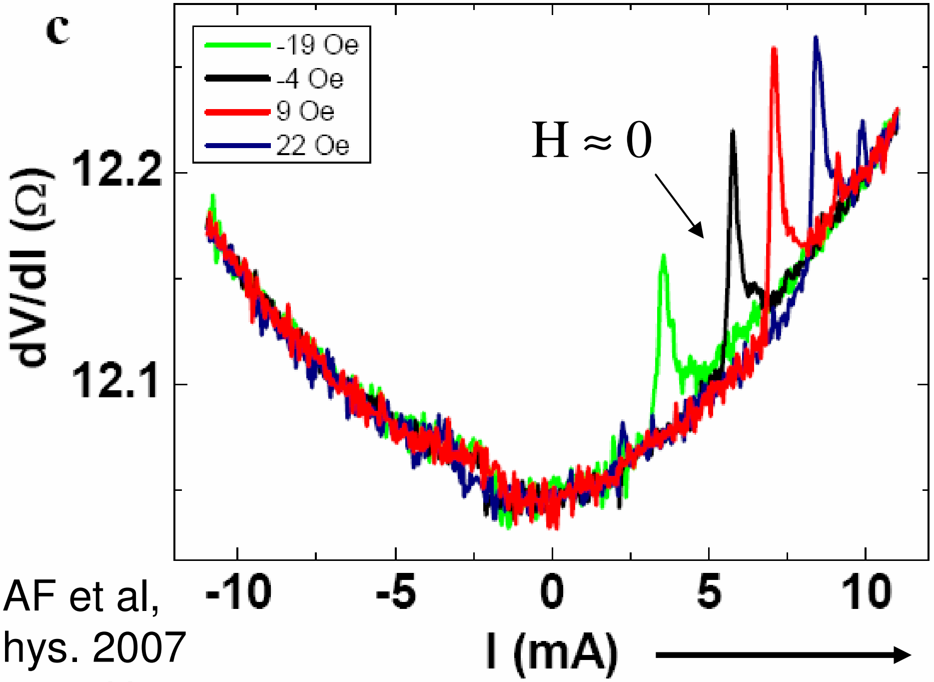
IrMn (15nm) or CoO or Cu

free Py:fast spin relaxation

fixed Co: slower spin relaxation







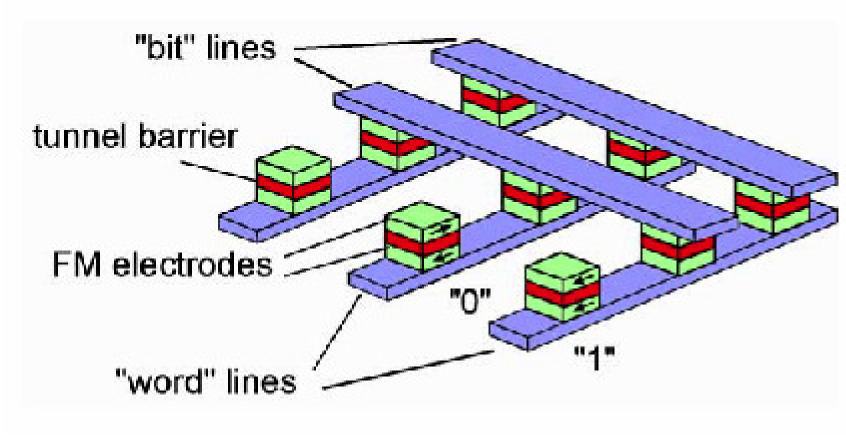
Positive I

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

Application du transfert de spin: commutation de mémoires MRAM et d'électronique logique reconfigurable

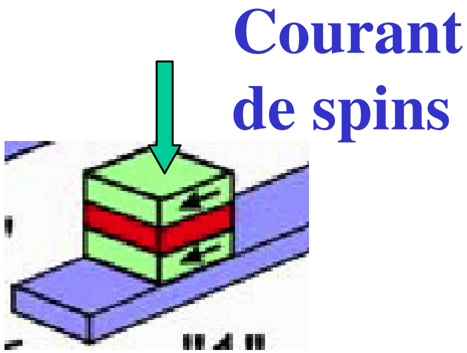
Aujourd'hui :

commutation par un champ magnetique appliqué de l'extérieur (non local) →



Demain, électroniquement

° par transfusion de spins →



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

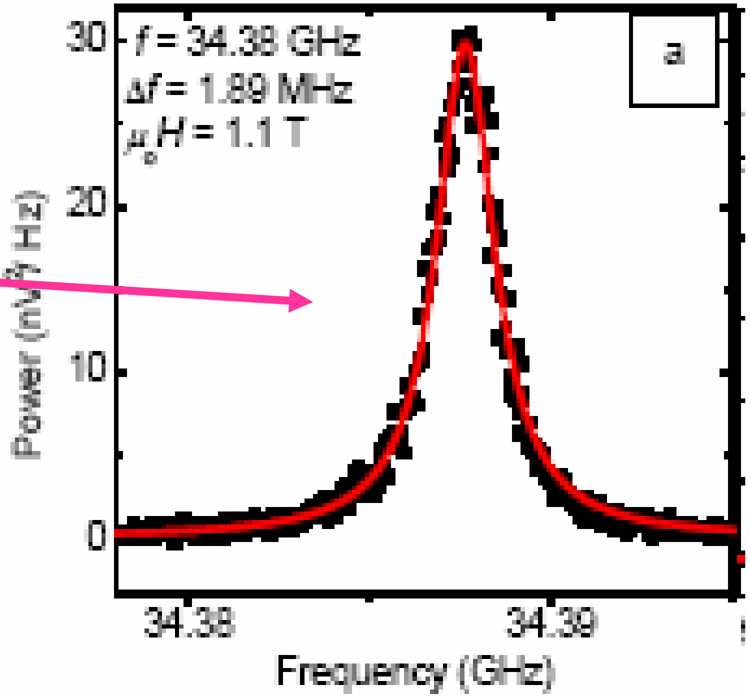
- small size ($\approx 0.1\mu m$) (on-chip integration)

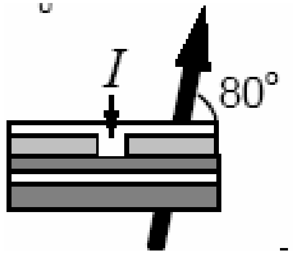
-oscillations without applied field

-Needed improvements

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

$f/f\Delta f \cong 18000$



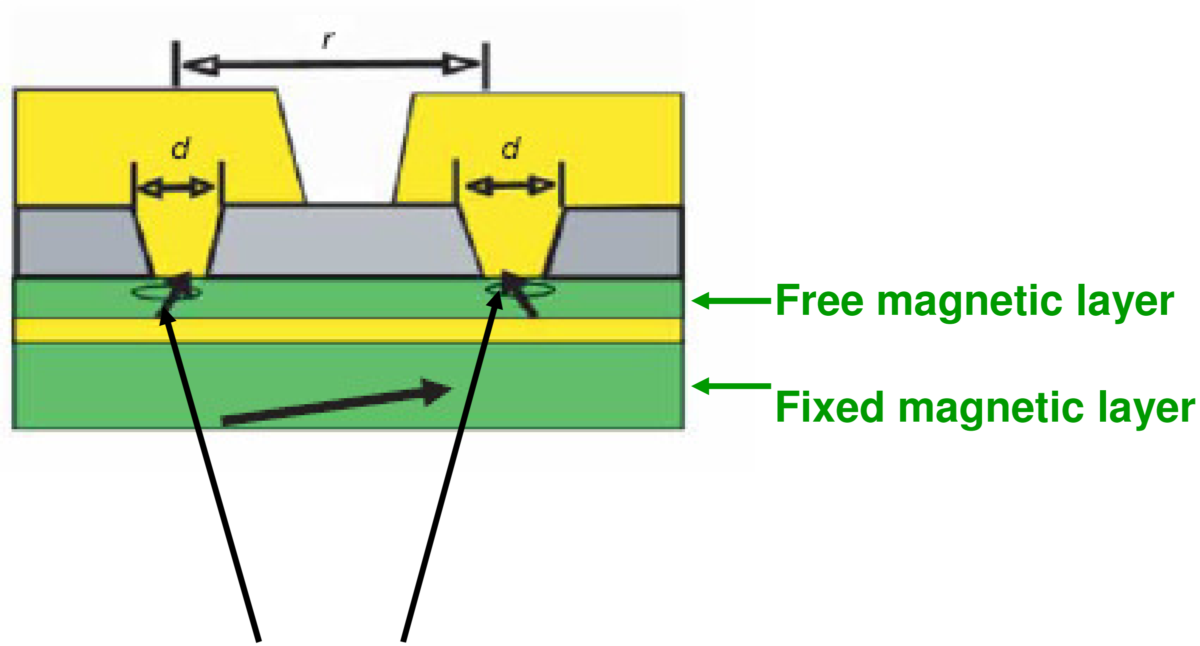


Rippart et al,
PR B70, 100406,
2004

Synchronization of STOs

Synchronization **by exchange coupling** (magnetic elasticity)

- **Kaka et al (NIST Boulder) Nature 2005**
  (similar results by Freescale)



Free magnetic layer

Fixed magnetic layer

Phase locking of oscillations for r ≈ 500 nm

Experiments of STO synchronization by electrical connection

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