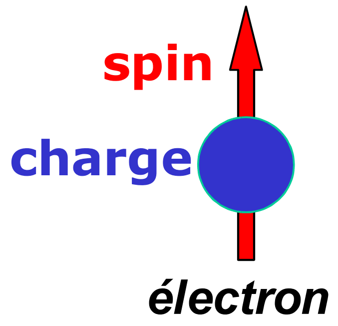
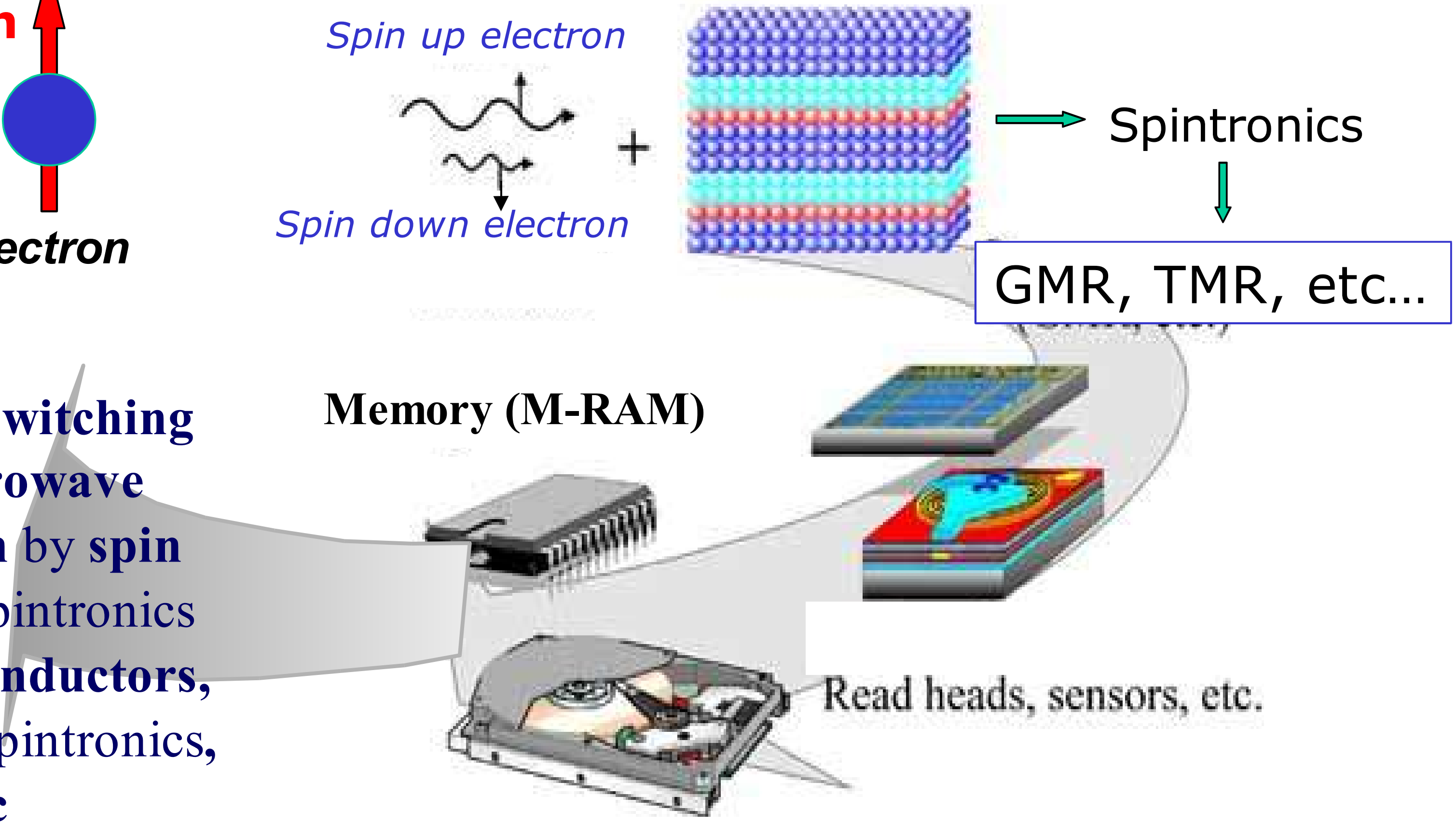
Albert Fert, UMR CNRS/Thales, Palaiseau, and Université Paris-Sud, Orsay, France

The origin, the development and the future of spintronics



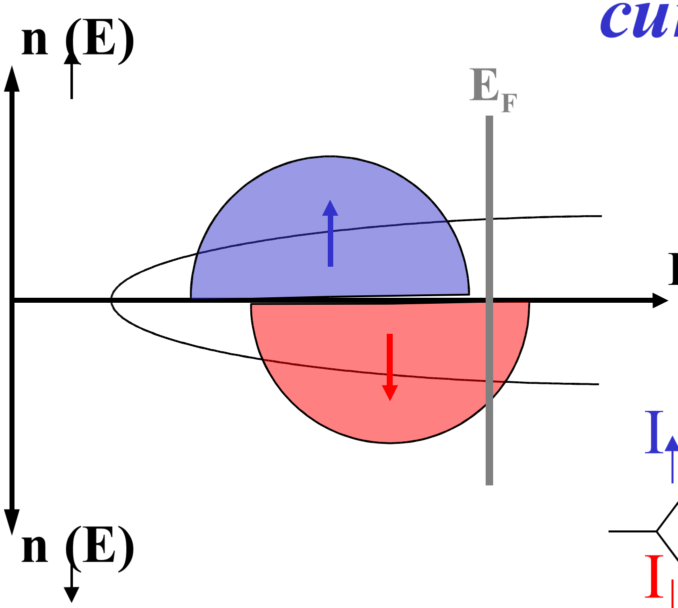
Influence of spin on conduction + Magnetic nanostructures



Magnetic switching and **microwave generation** by **spin transfer,** spintronics with **semiconductors, molecular** spintronics, **etc**

Spin dependent conduction in ferromagnetic metals

current model)



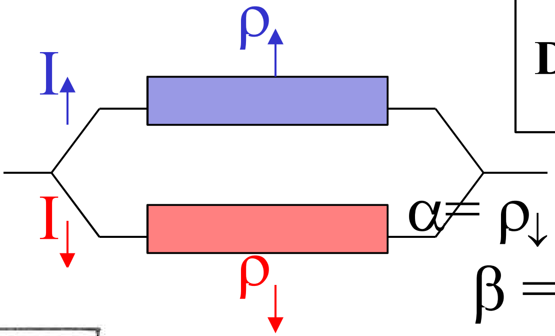
Mott, Proc.Roy.Soc A153, 1936

Fert et al, PRL 21, 1190, 1968

Loegel-Gautier, JPCS 32, 1971

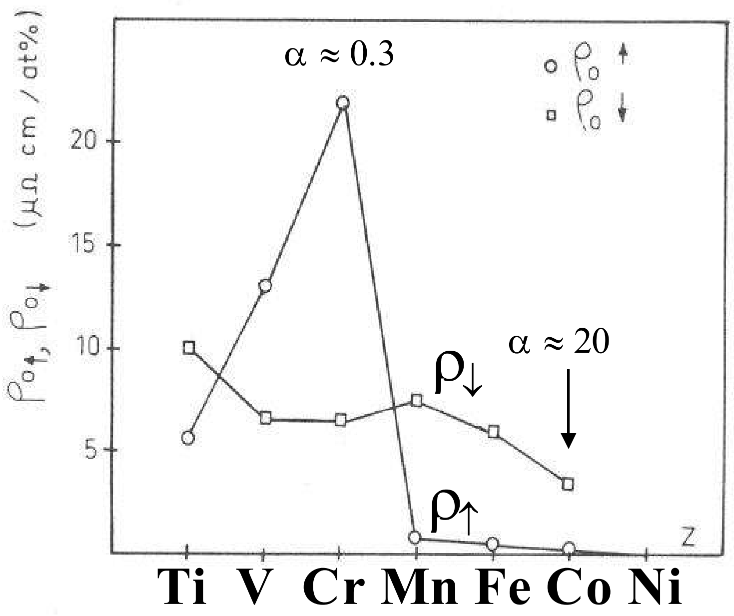
Fert et al,J.Phys.F6, 849, 1976

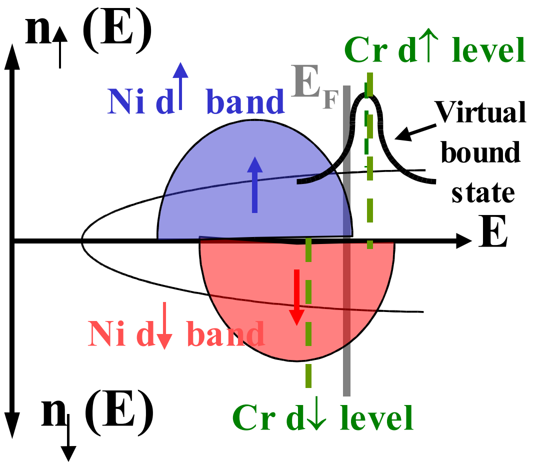
Dorlejin et al, ibid F7, 23, 1977



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

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





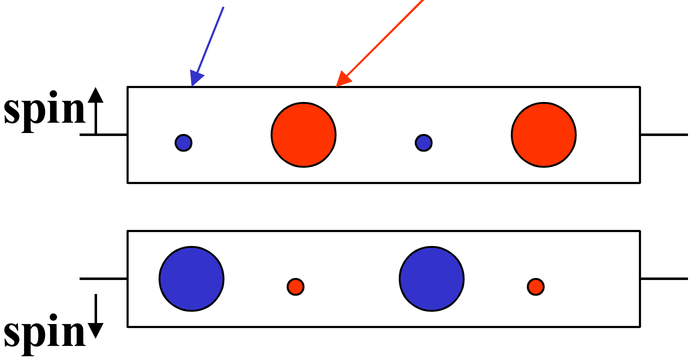
Mixing impurities A and B with opposite or similar spin asymmetries: ***the pre-concept of GMR***

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

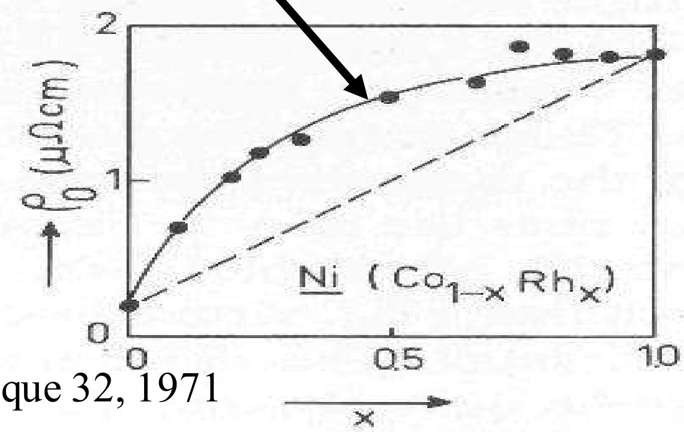
$\alpha = \rho_\downarrow / \rho_\uparrow$

1st case

$\alpha_A > 1, \alpha_B < 1$



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

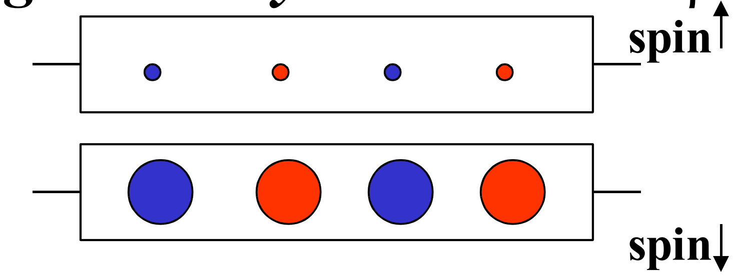


J. de Physique 32, 1971

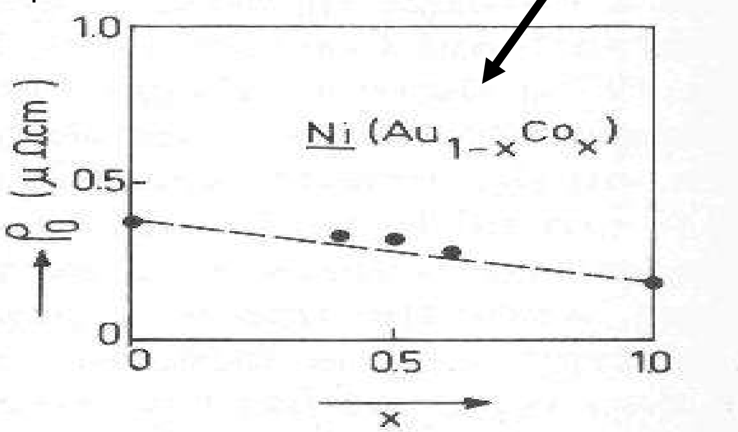
2d case

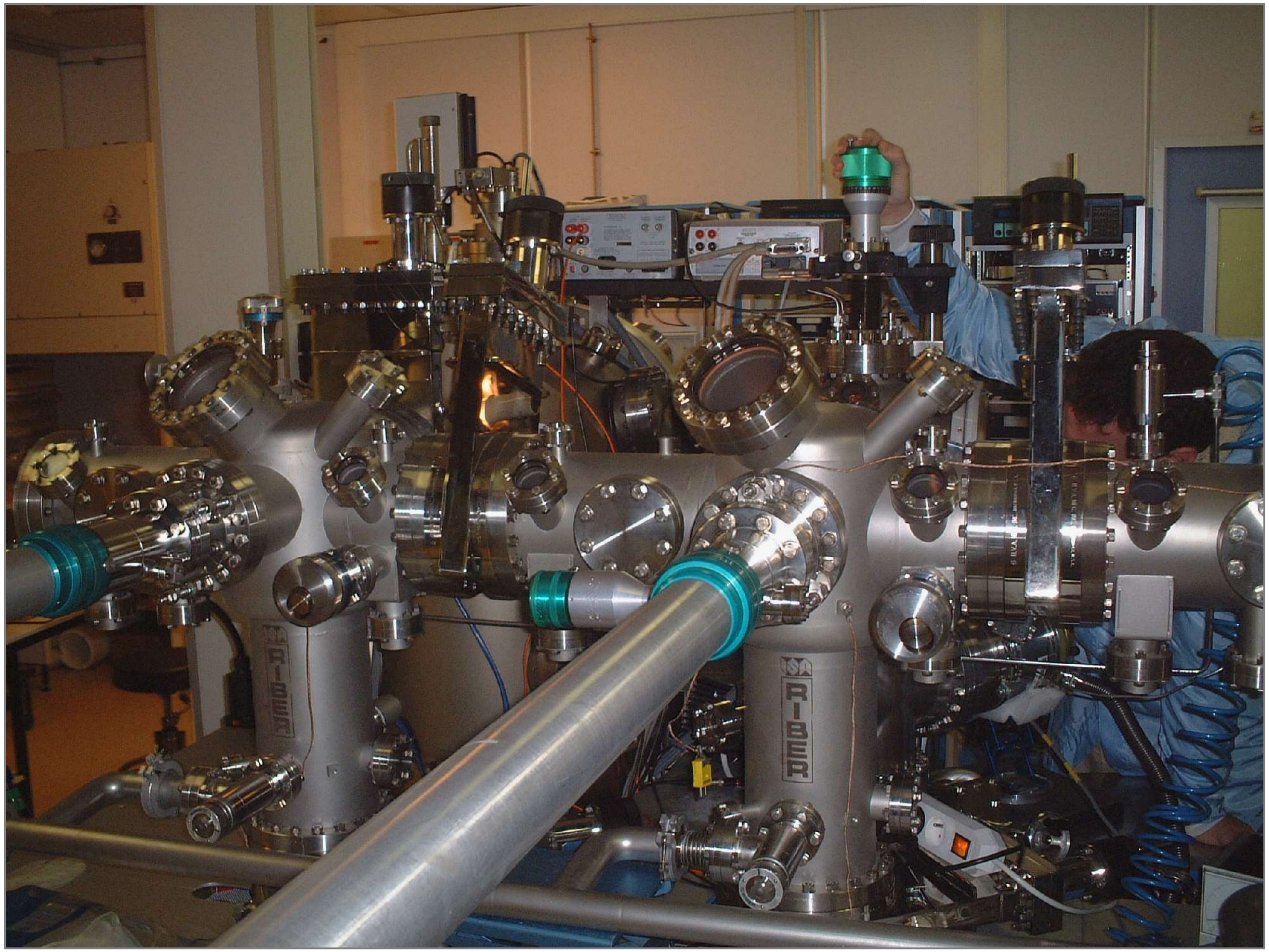
α_A **and** $\alpha_B > 1$

High mobility channel → low ρ



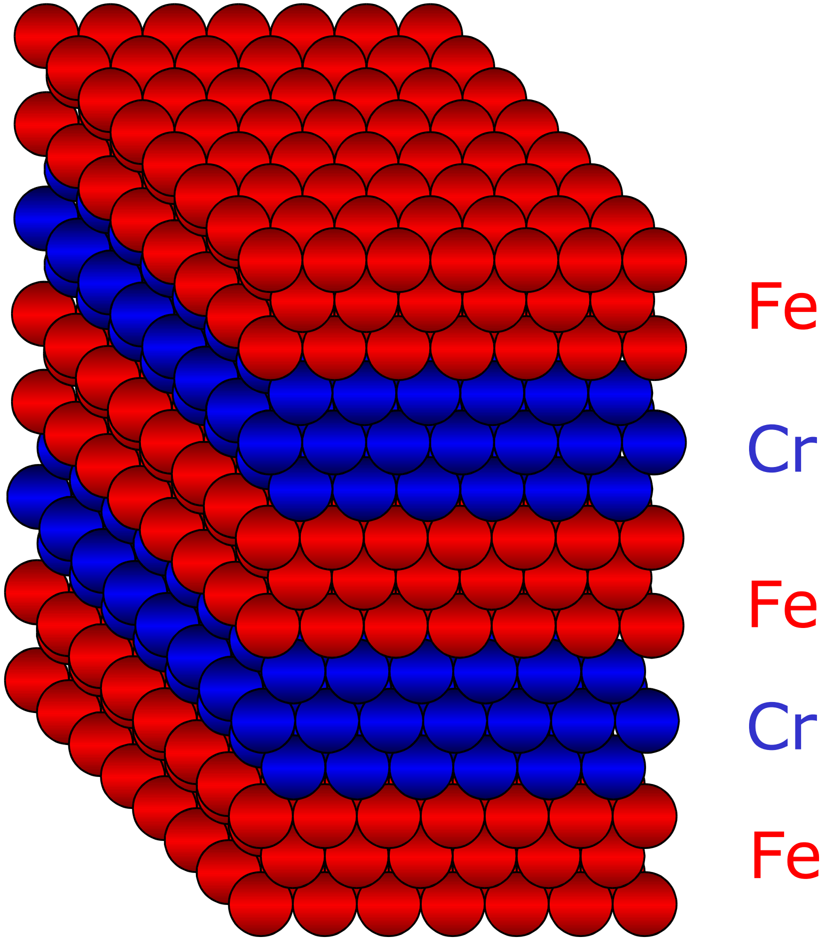
$\rho_{AB} \approx \rho_A + \rho_B$





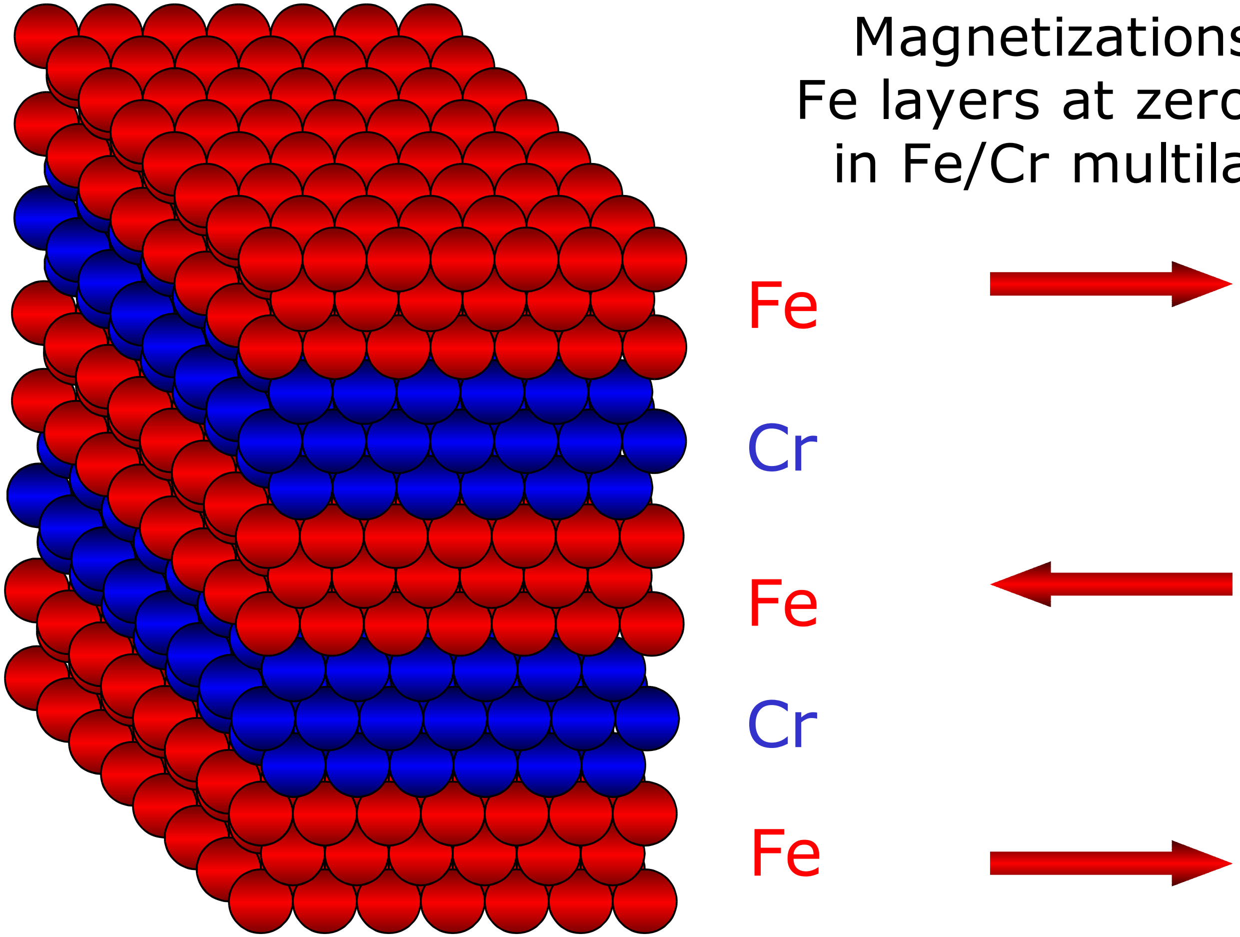
Molecular Beam Epitaxy
(growth of metallic multilayers)

- **Magnetic multilayers**



- **Magnetic multilayers**

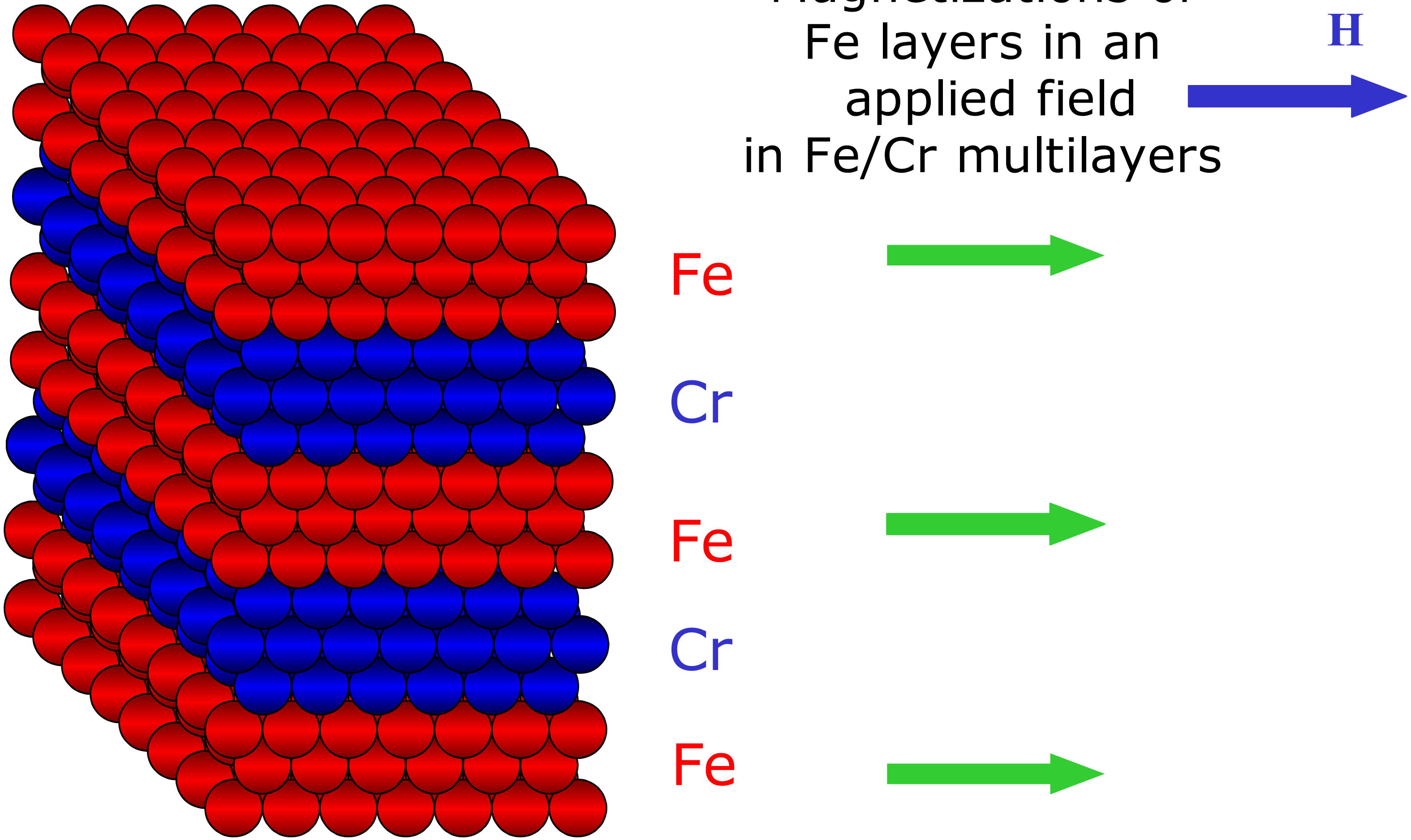
Magnetizations of
Fe layers at zero field
in Fe/Cr multilayers



P. Grünberg, 1986 → antiferromagnetic interlayer coupling

- **Magnetic multilayers**

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

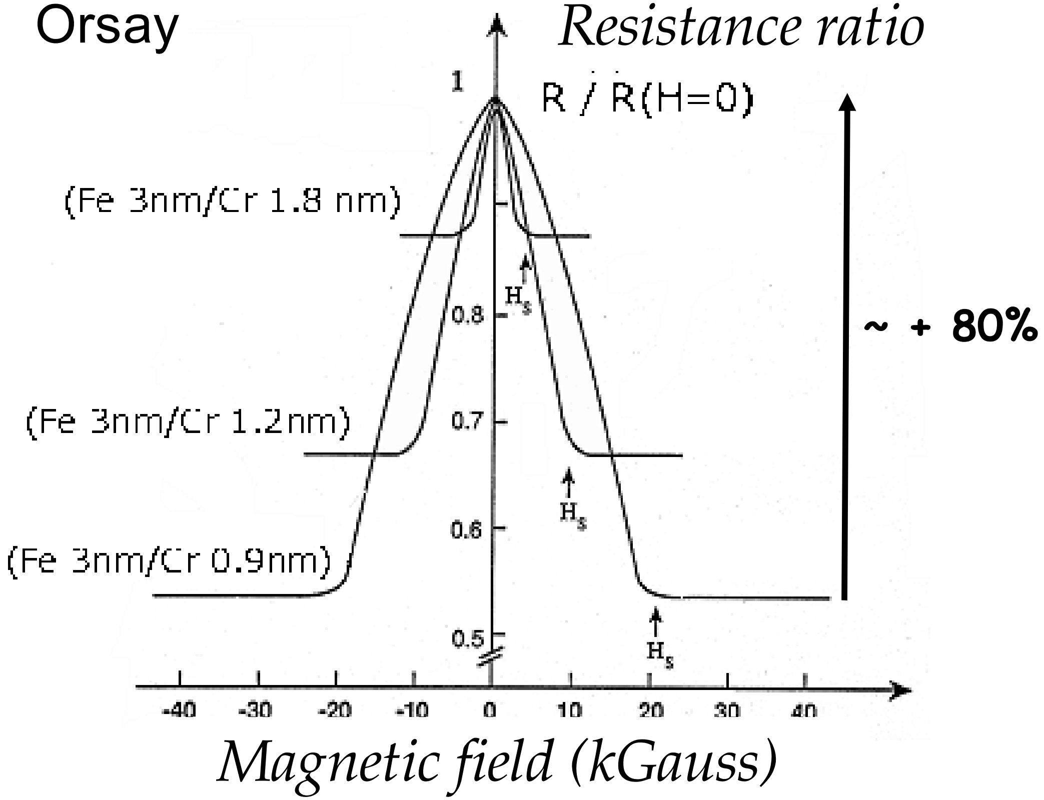


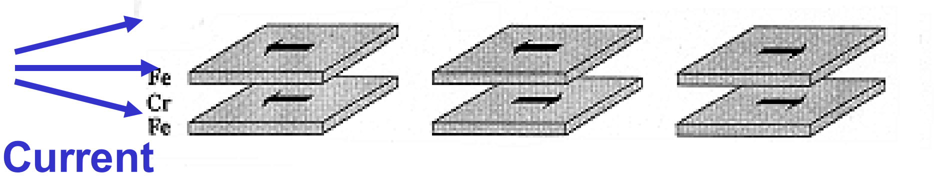
P. Grünberg, 1986 → antiferromagnetic interlayer coupling

• Giant Magnetoresistance (GMR)

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

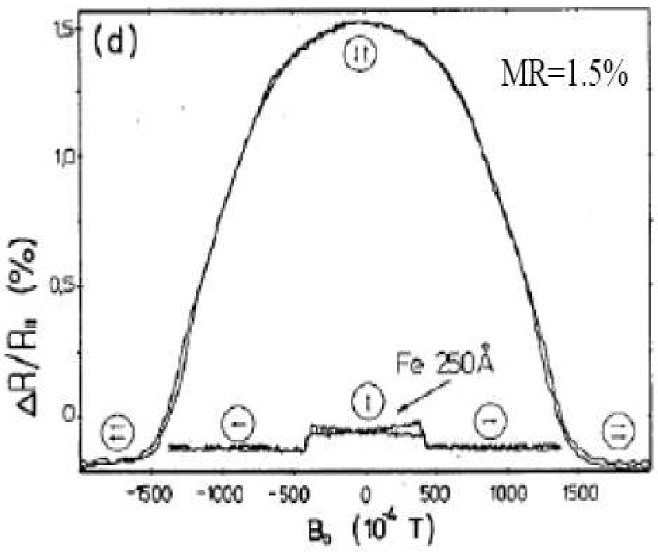
Orsay

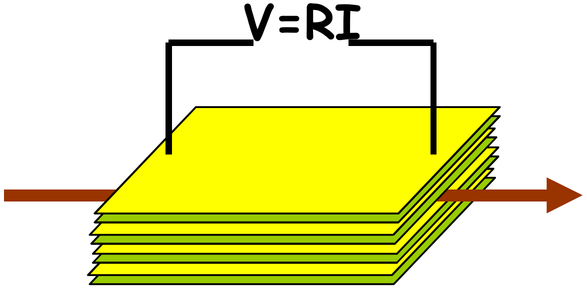




AP (AntiParallel) **P** (Parallel)

Jülich





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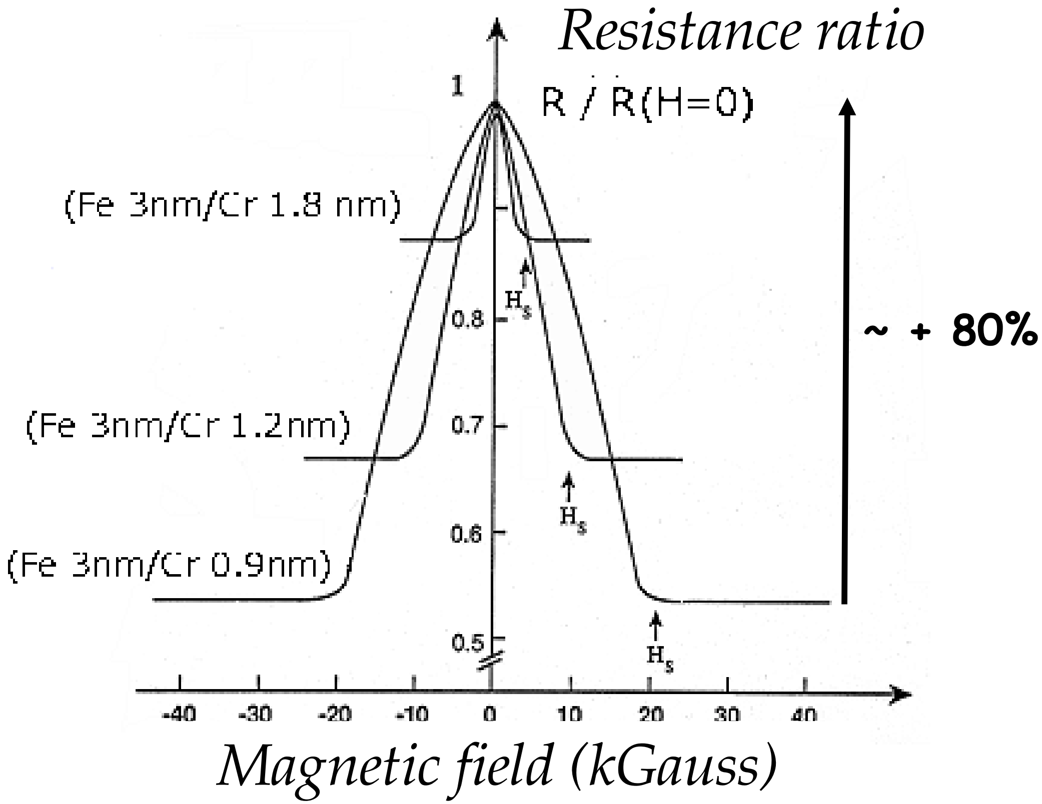
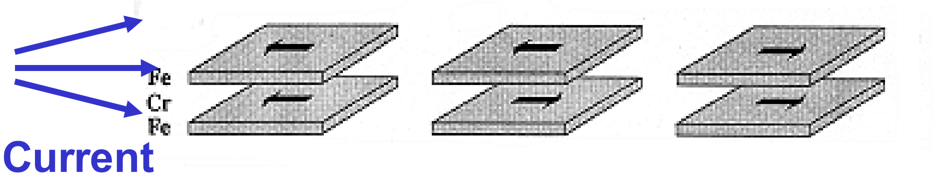
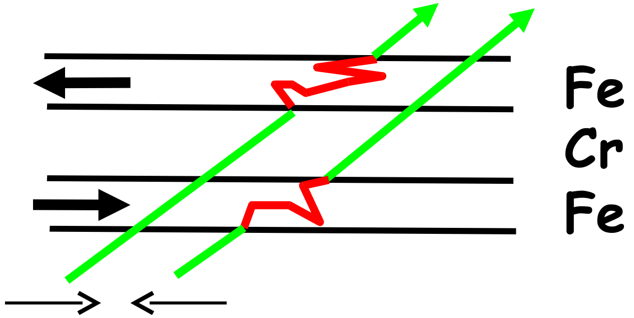


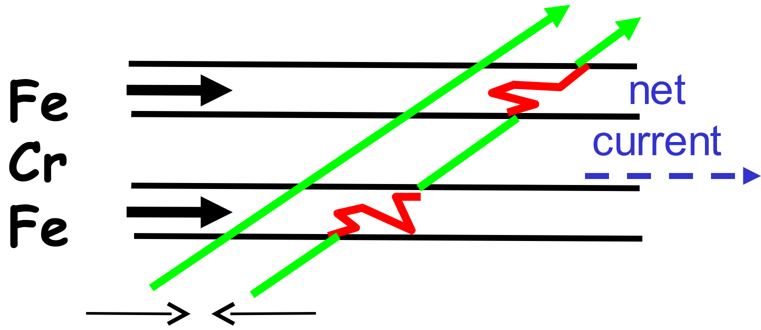


AP (AntiParallel) **P** (Parallel)

Anti-parallel magnetizations
(zero field, **high** resistance)

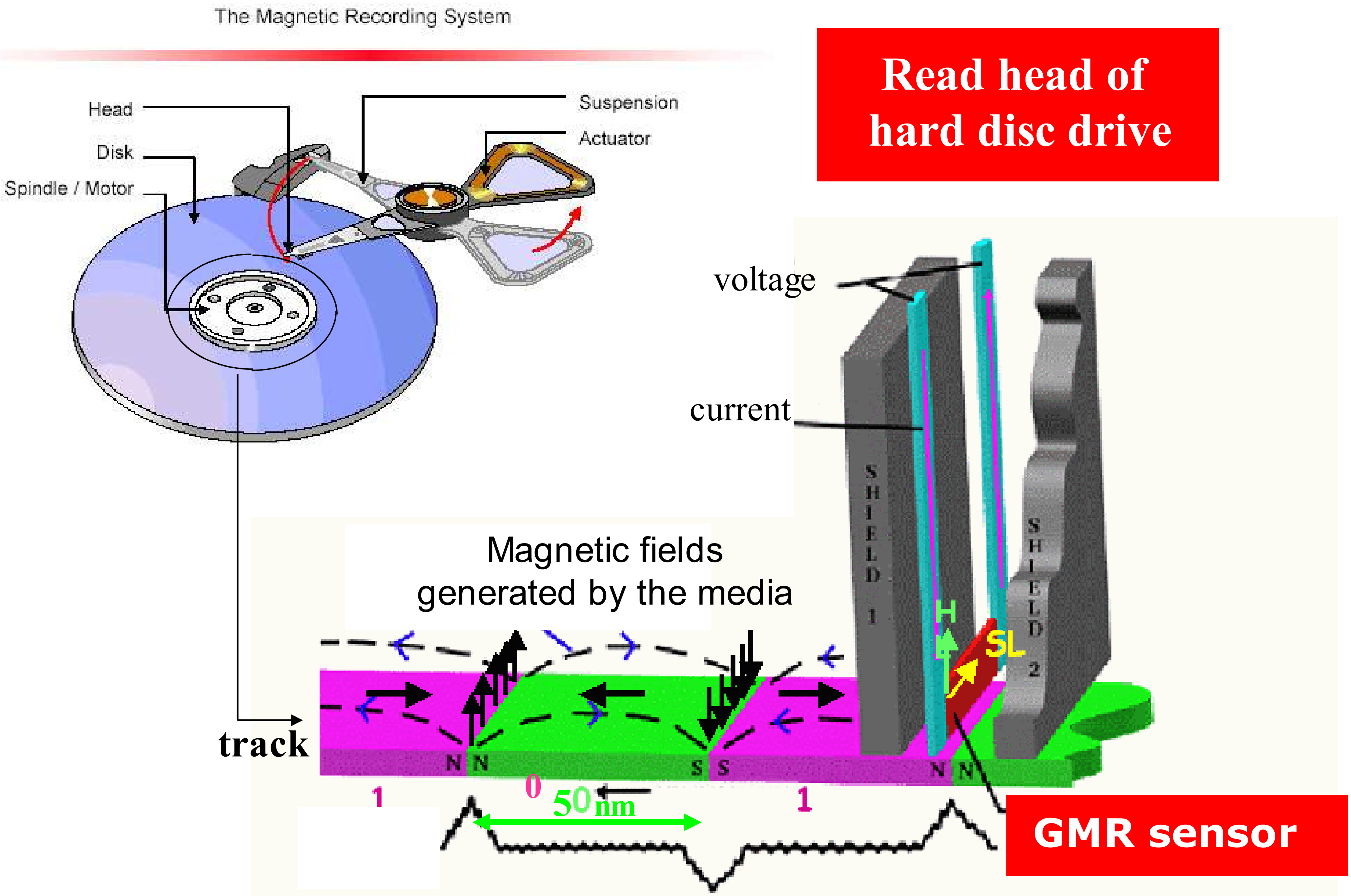


Parallel magnetizations
(appl. field, **low** resist.)



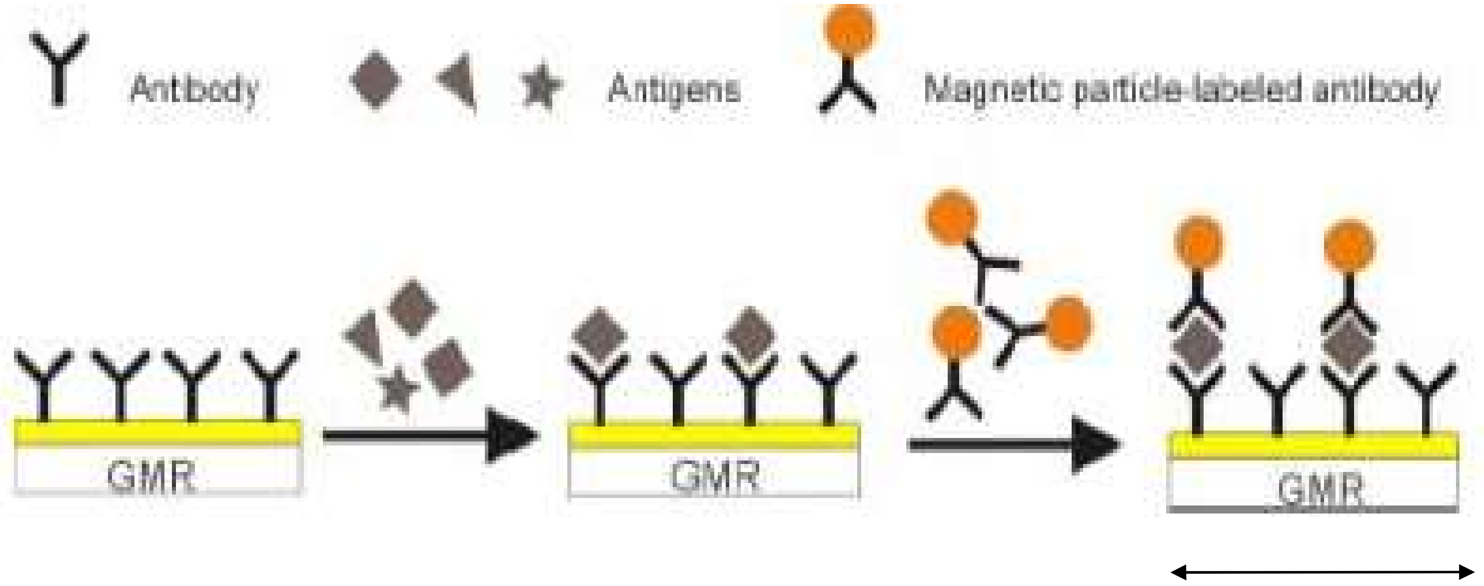
Condition for GMR:
layer thickness ≈ nm

Read head of hard disc drive



1997 (before GMR) : 1 Gbit/in^2 , 2007 : GMR heads ~ 300 Gbit/in^2

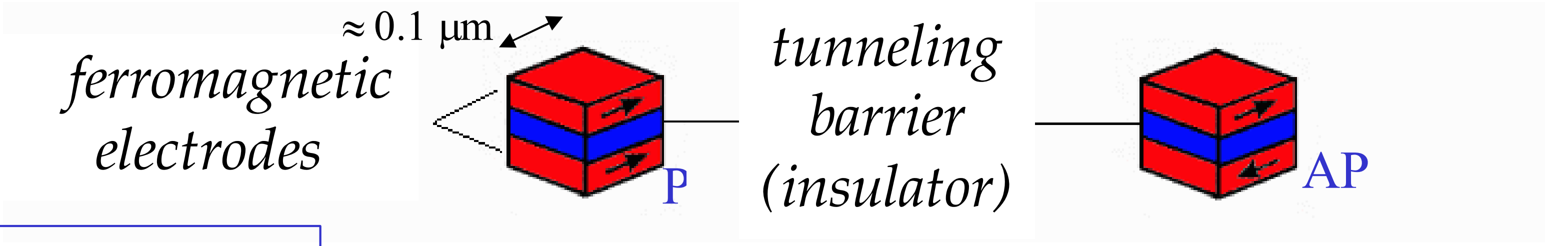
Arrays of GMR biochips for analysis of biomolecules (example: antigens are trapped by antibodies and also decorated by other antibodies labelled by magnetic nanoparticles which are detected by a GMR sensor)



9 µm (Philips), 1µm (Santa Barbara)

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

Magnetic Tunnel Junctions,Tunneling Magnetoresistance (TMR)



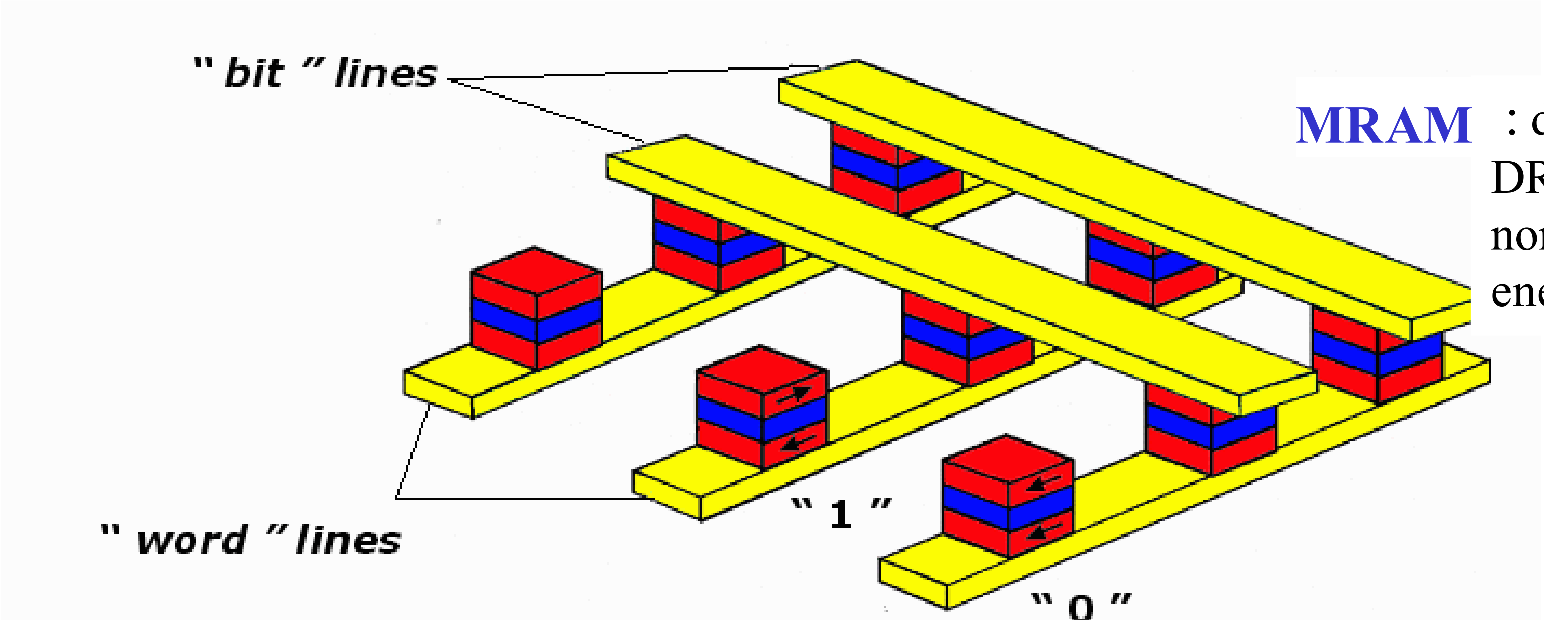
Low resistance state *High resistance state*

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)

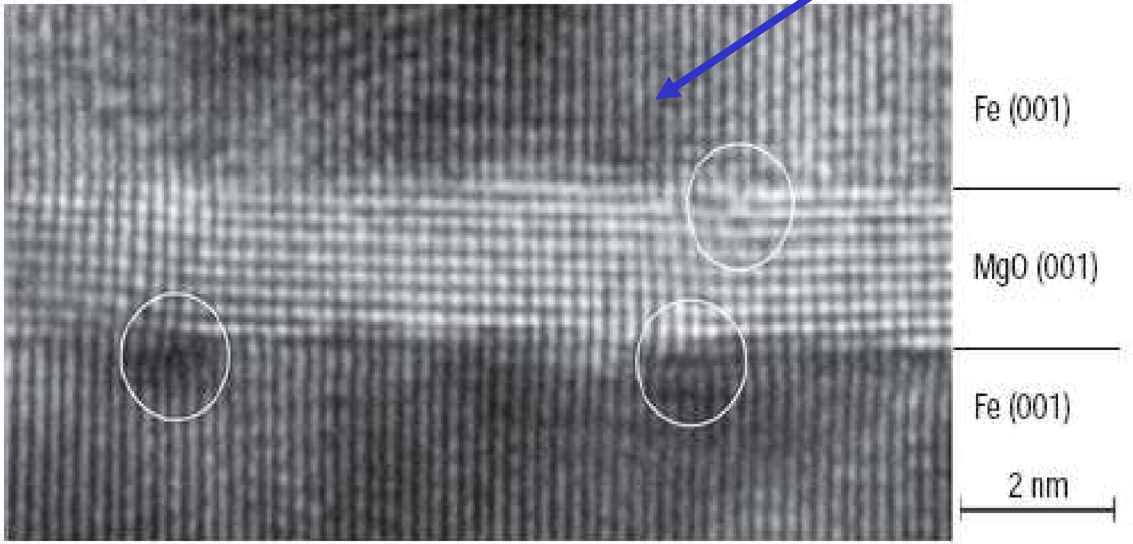


MRAM : density/speed of DRAM/SRAM + nonvolatilty + low energy consumption

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)]

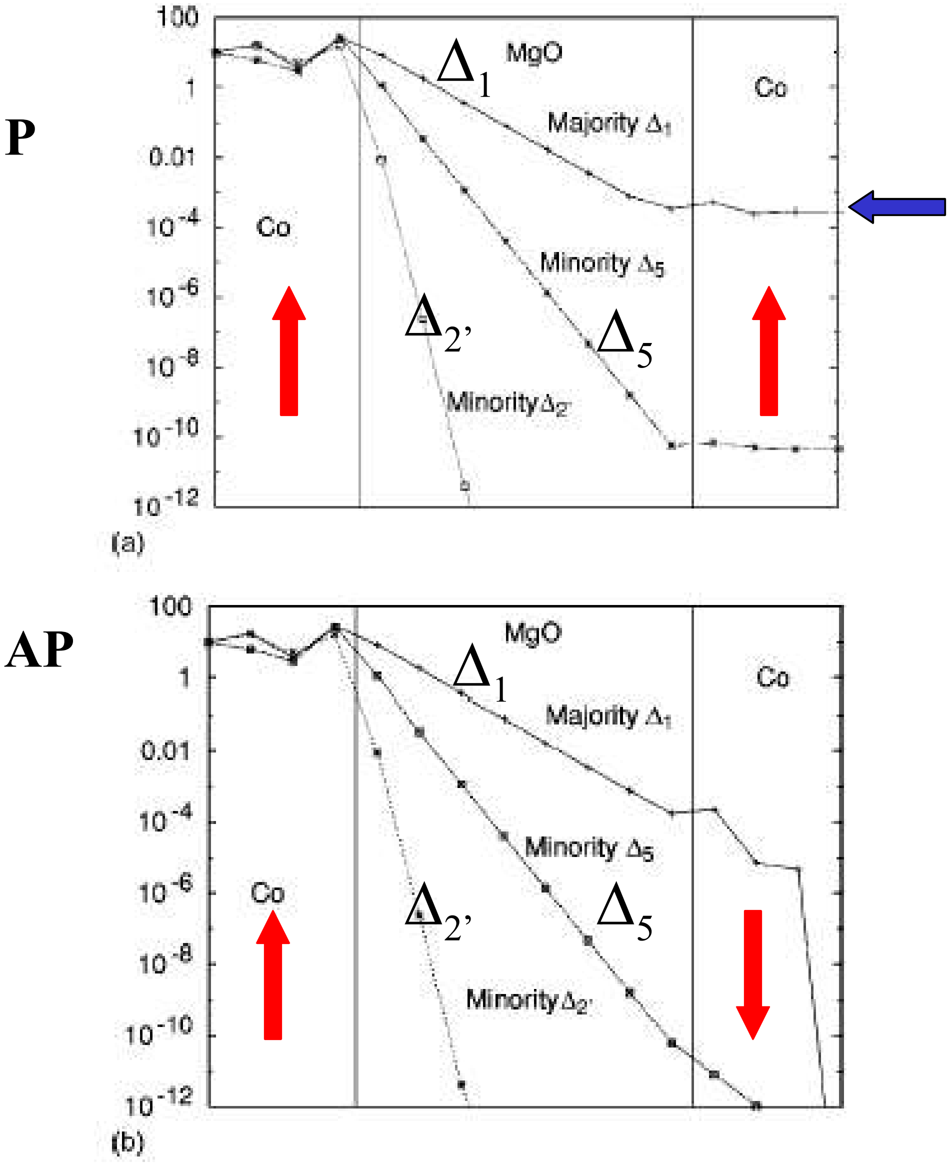
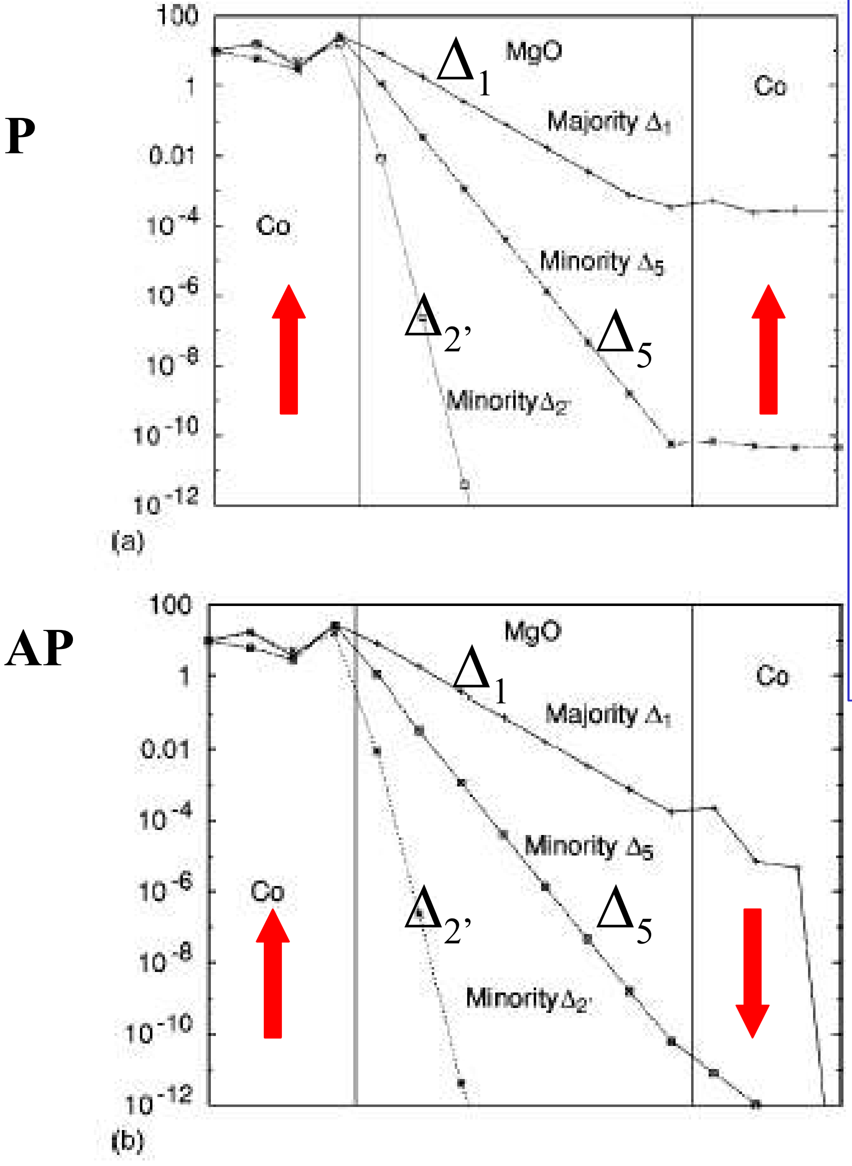


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel = 0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

Zhang and Butler, PR B 2004



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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)

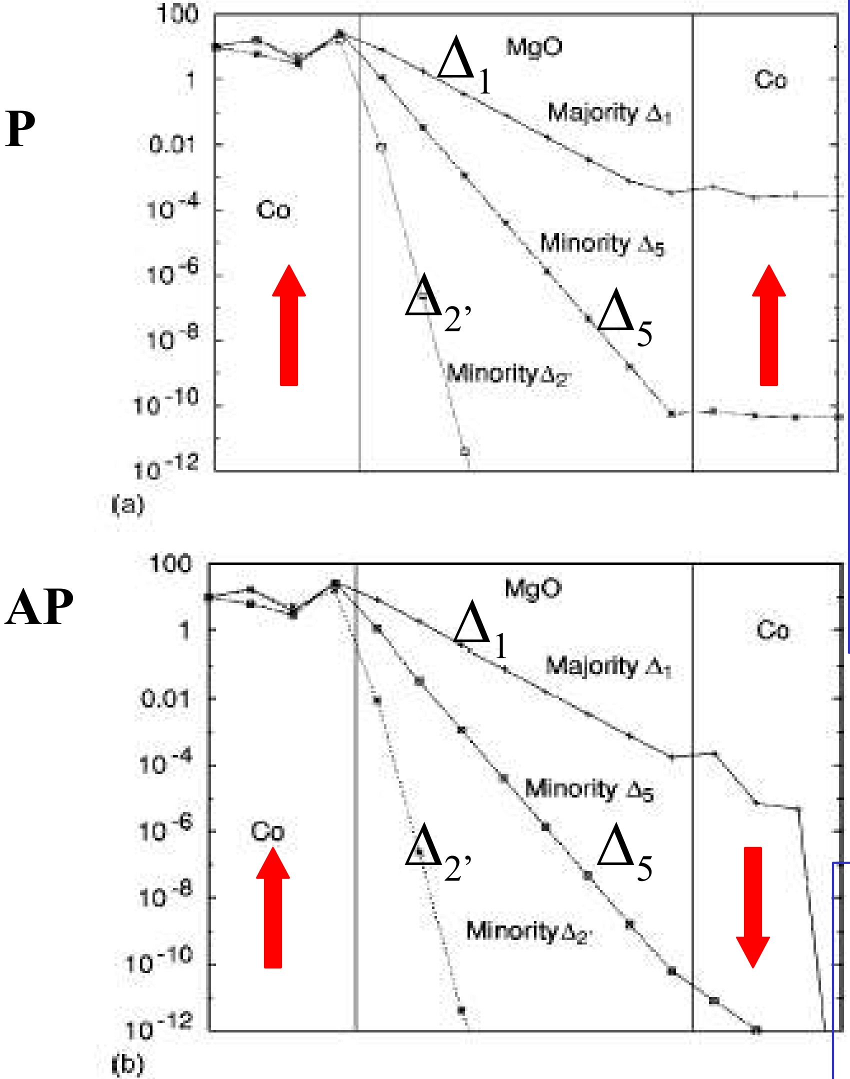
→Δ_5 symmetry (d) slowly decaying

→ 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



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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)

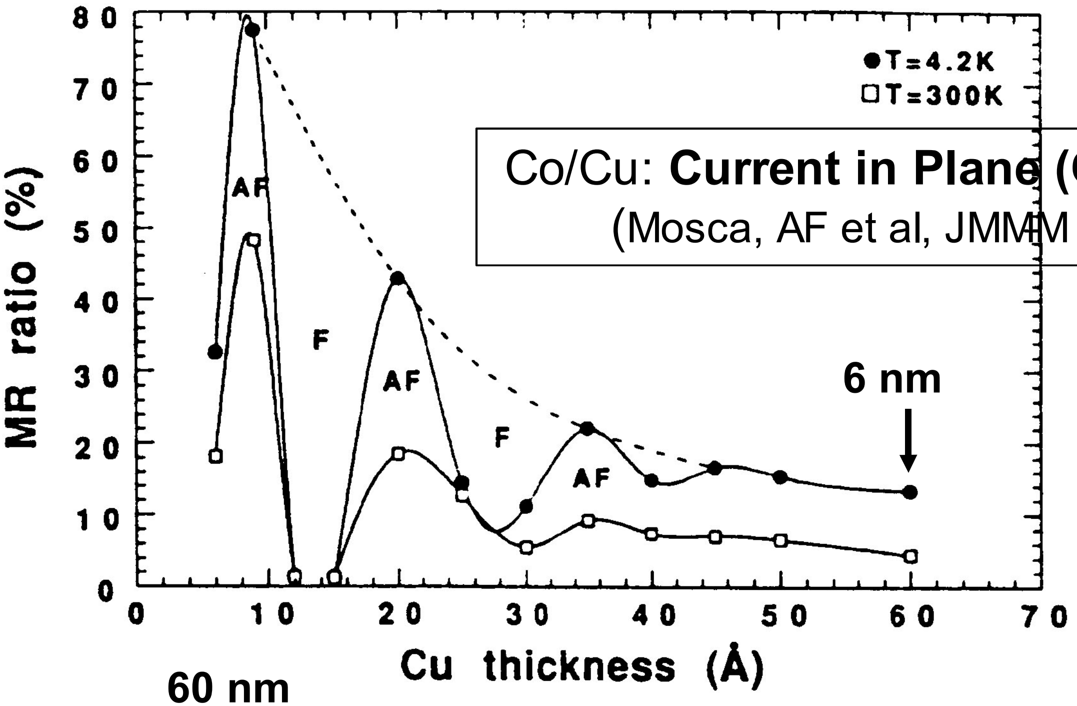
Spintronics with semiconductors

Spintronics with molecules

Introduction:

spin accumulation

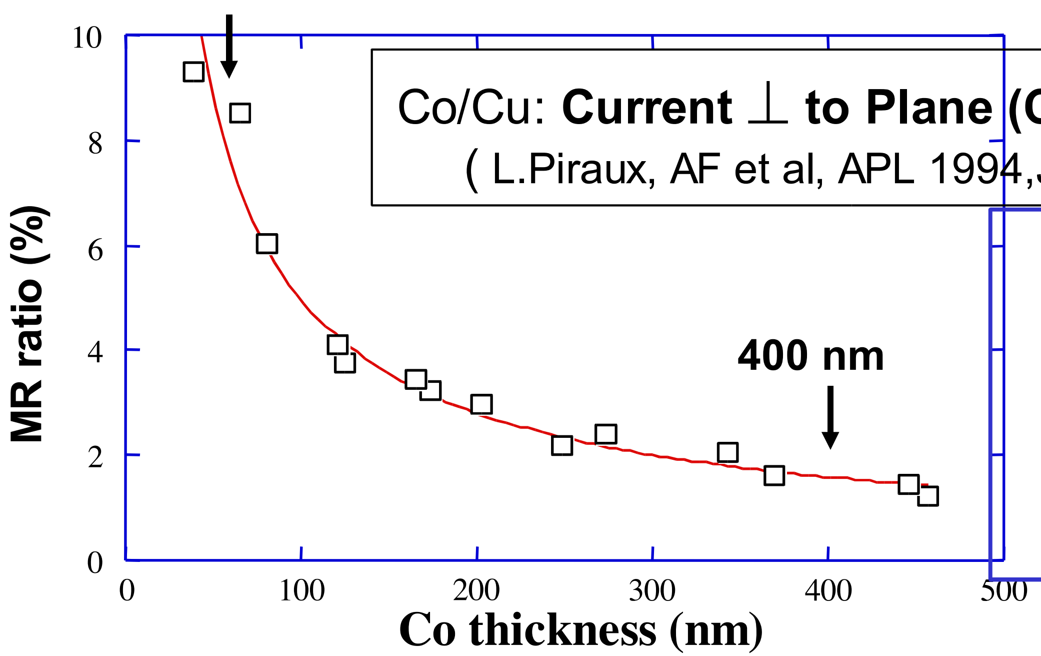
and spin currents



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)

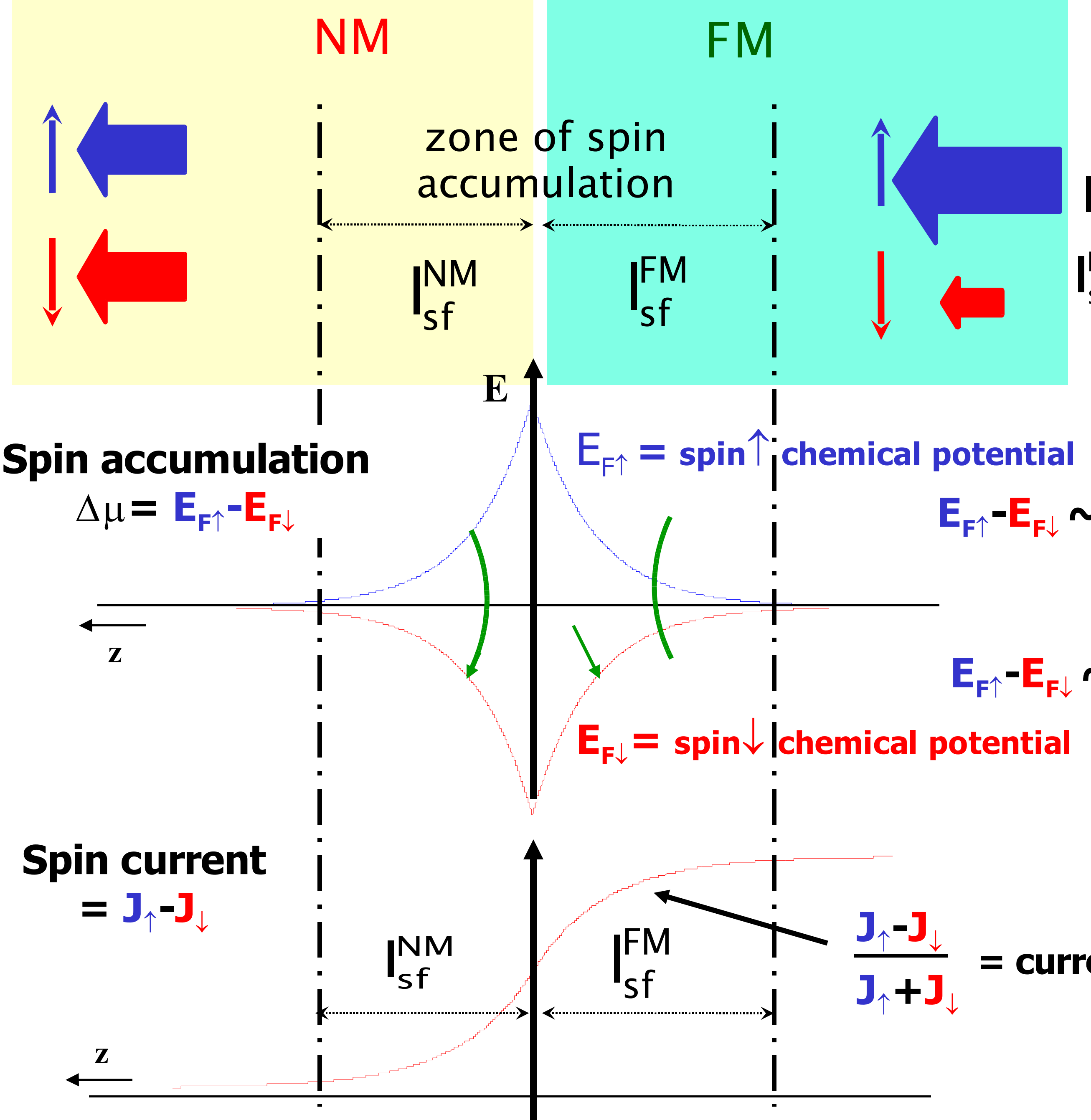
Spin injection/extraction at a NM/FM interface (beyond ballistic range)

(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)



Spin accumulation

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

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

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

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

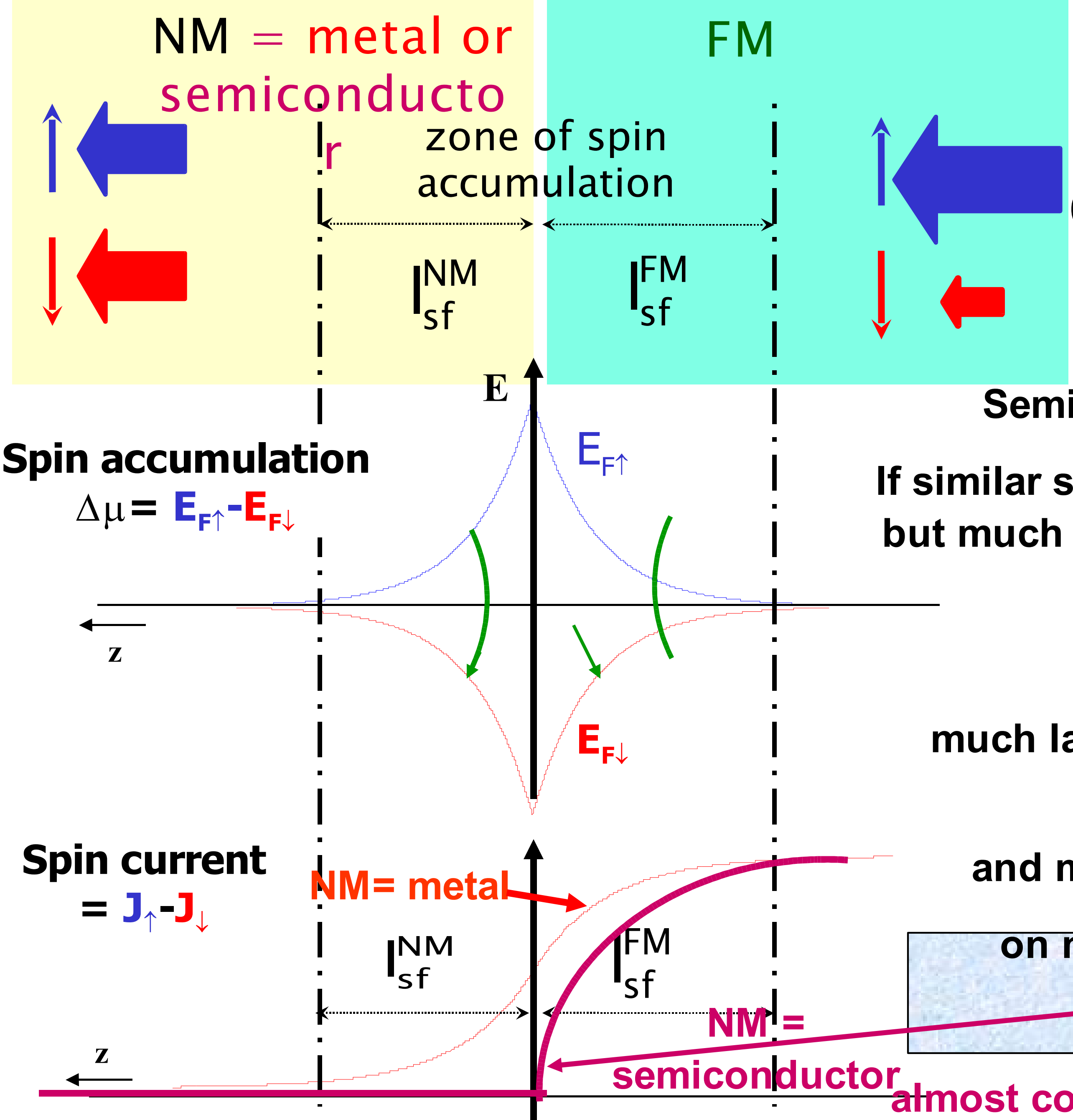
$E_{F\uparrow} - E_{F\downarrow} \sim \exp(-z/\ l_{sf}^{NM})$ **in NM**

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



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

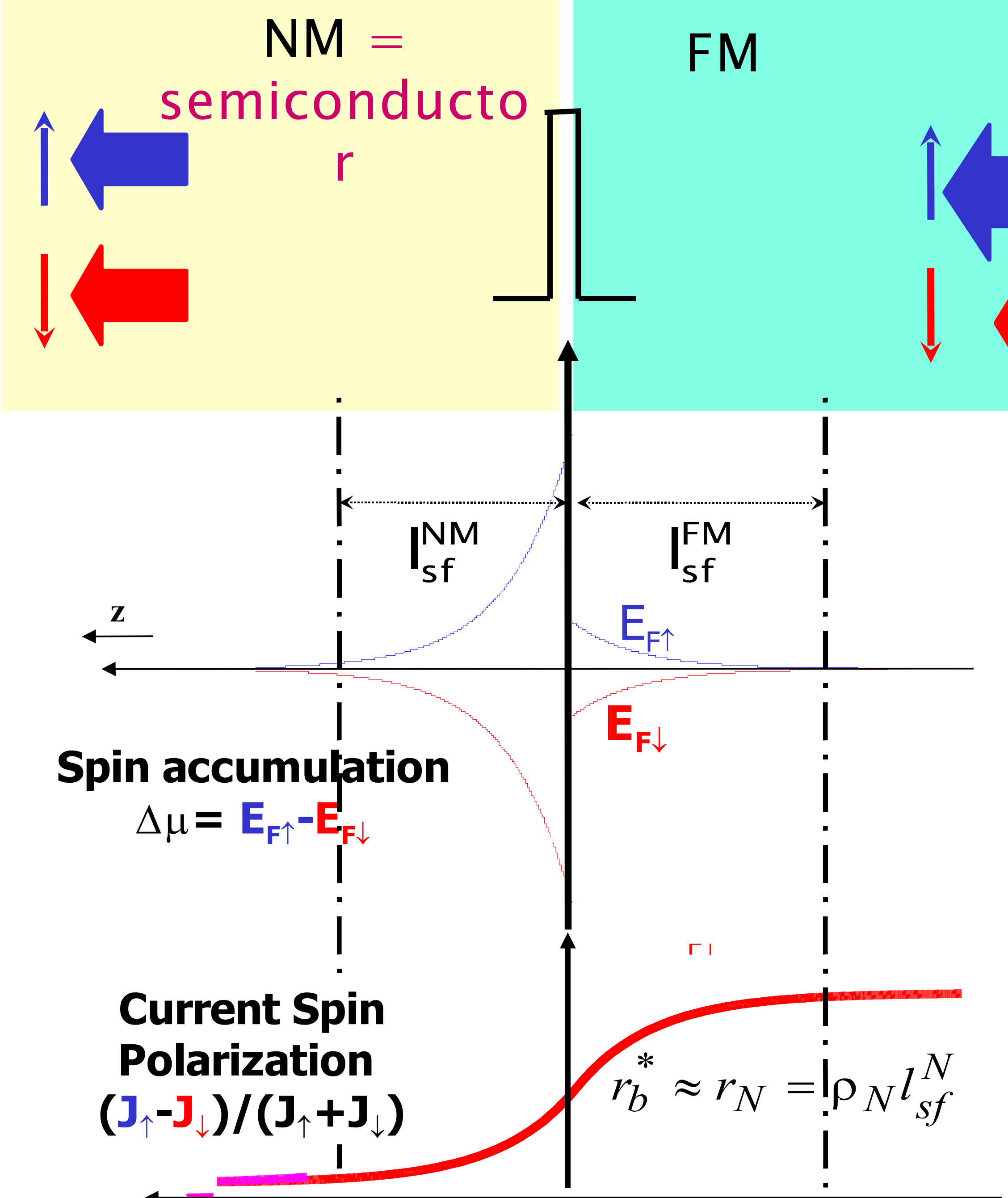
↓

and much more spin flips

on magnetic metal side

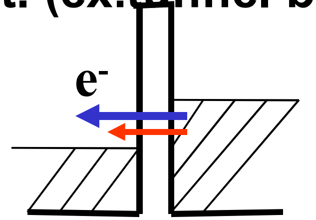
almost complete depolarization of

Spin injection/extraction at a Semiconductor/FM interface



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

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

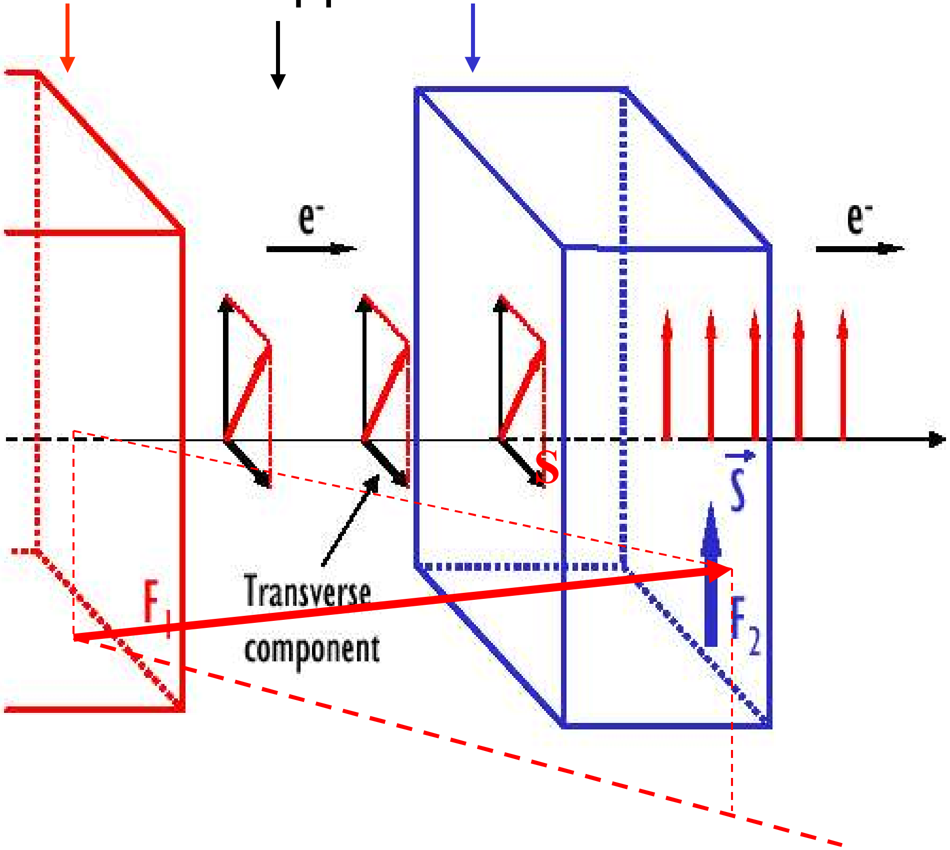
Rasbah, PR B 2000

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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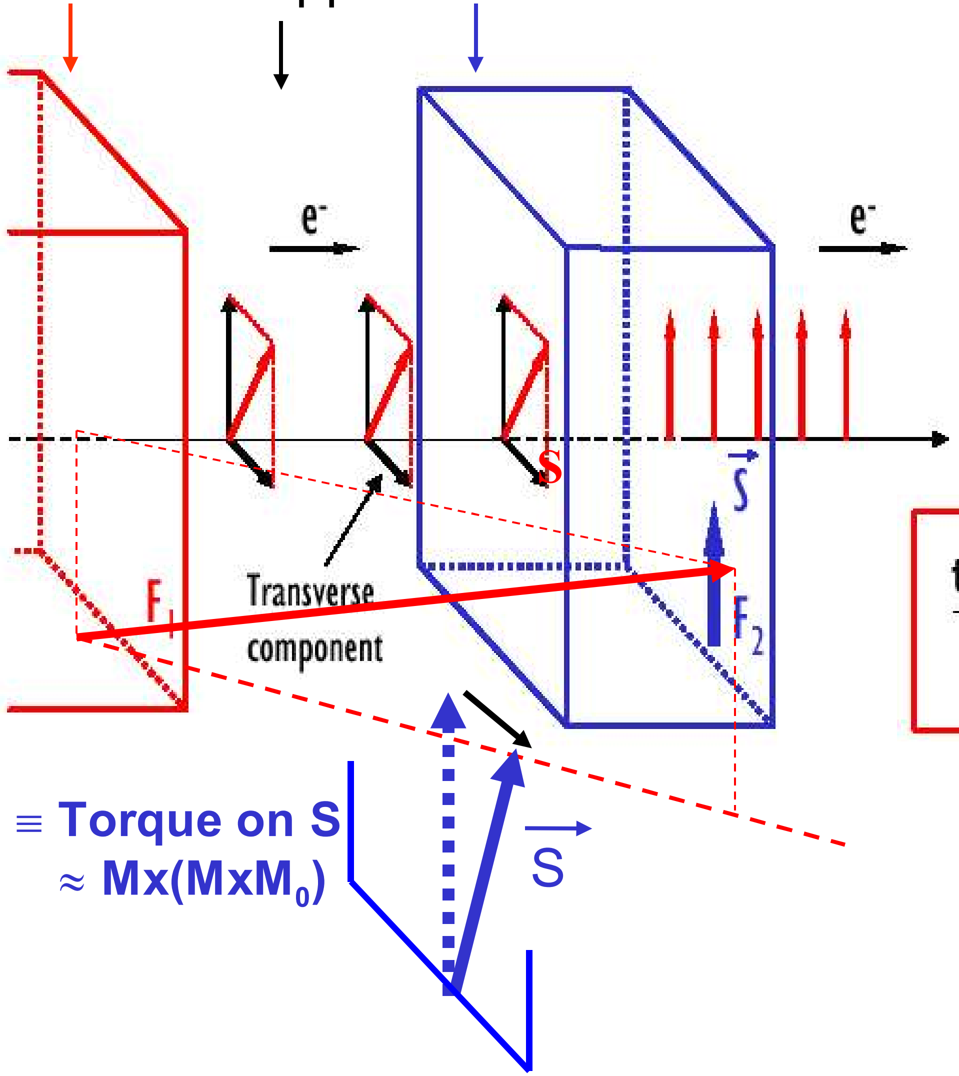
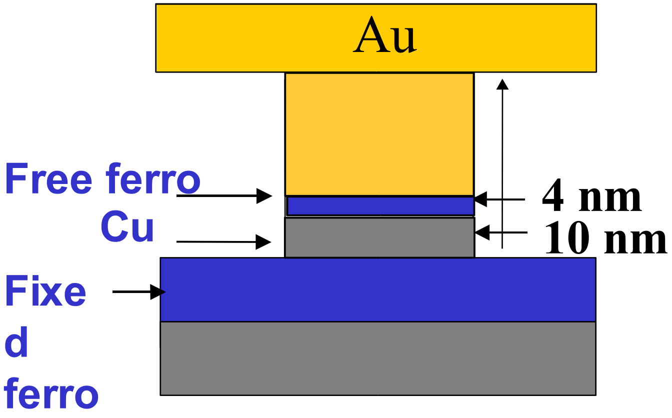


≡ **Torque on S**
≈ **$Mx(MxM_0)$**

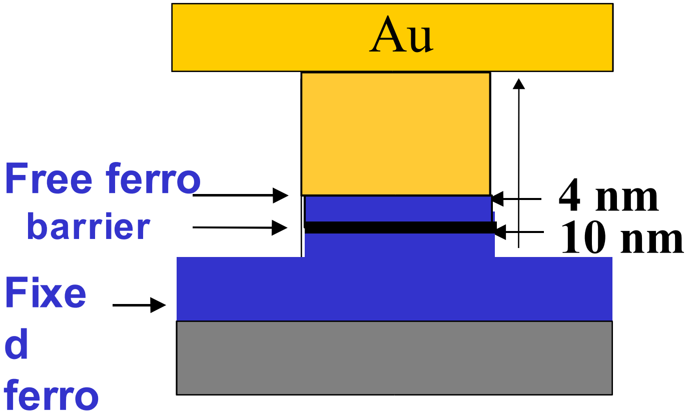
The transverse component of the spin current is absorbed and transferred to the total spin of the layer

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

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)**

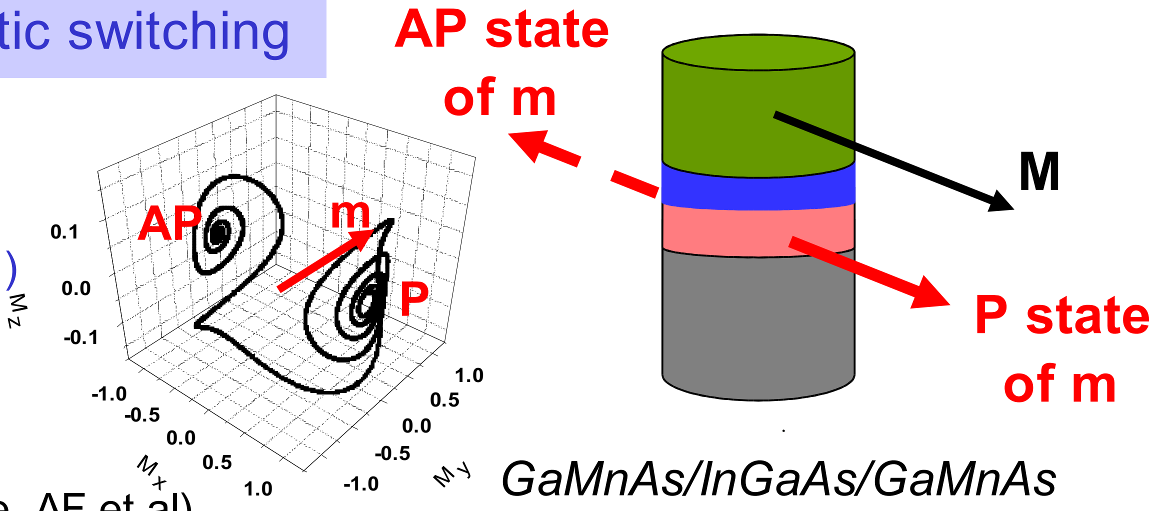
Regime of irreversible magnetic switching

First experiments on pillars:

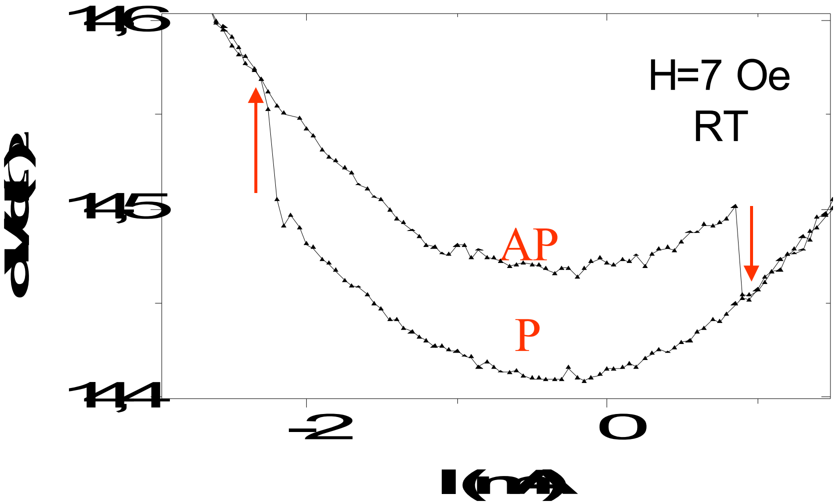
Cornell (Katine et al, PRL 2000)

CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)

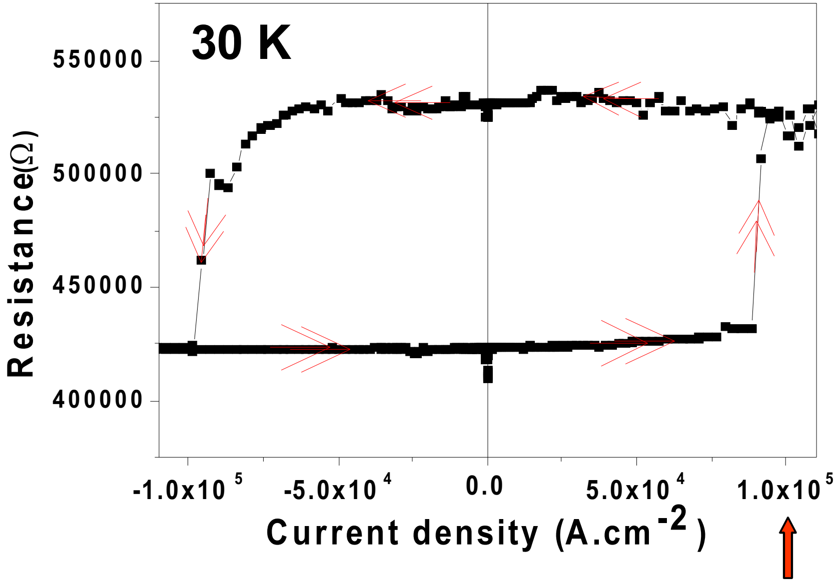


Py/Cu/Py 50nmX150nm (Boulle, AF et al)



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

(Elsen, AF et al, PR B 2006)



1 x 10^5 A/cm^2

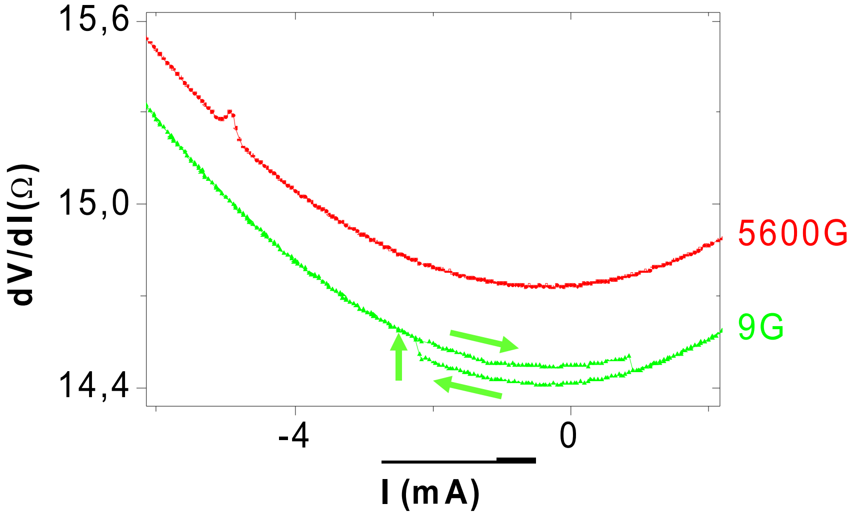
typical switching current ≈ 10^7A/cm^2

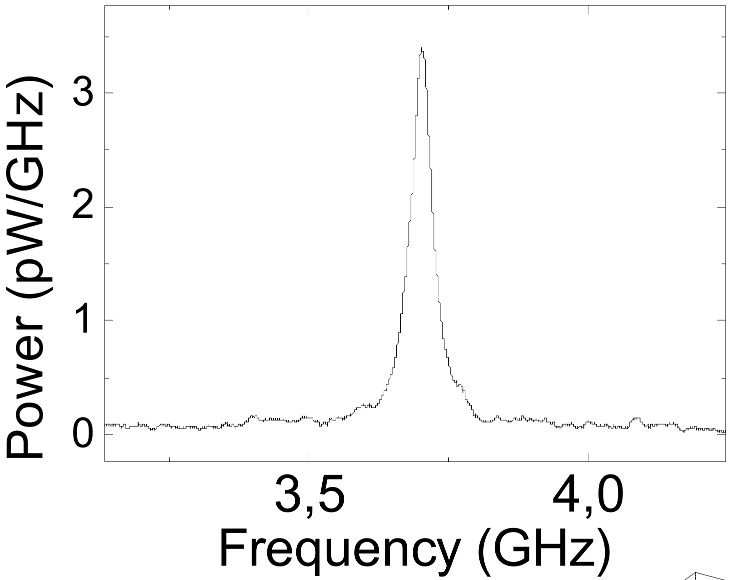
switching time can be as short as 0.1 ns (Chappert et al)

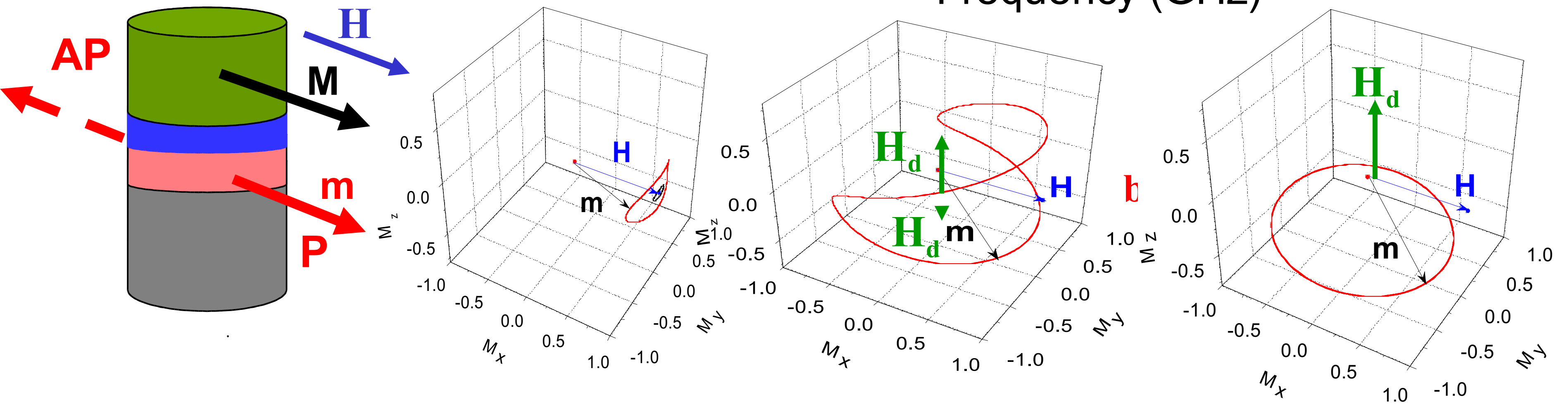
Regime of steady precession (microwave frequency range)

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

(Py = permalloy)

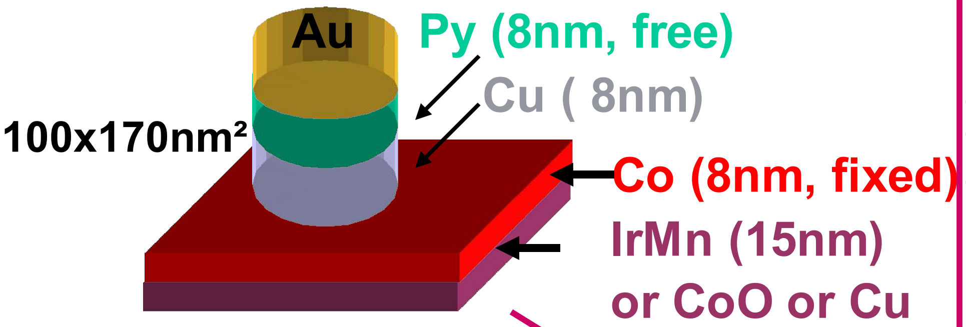


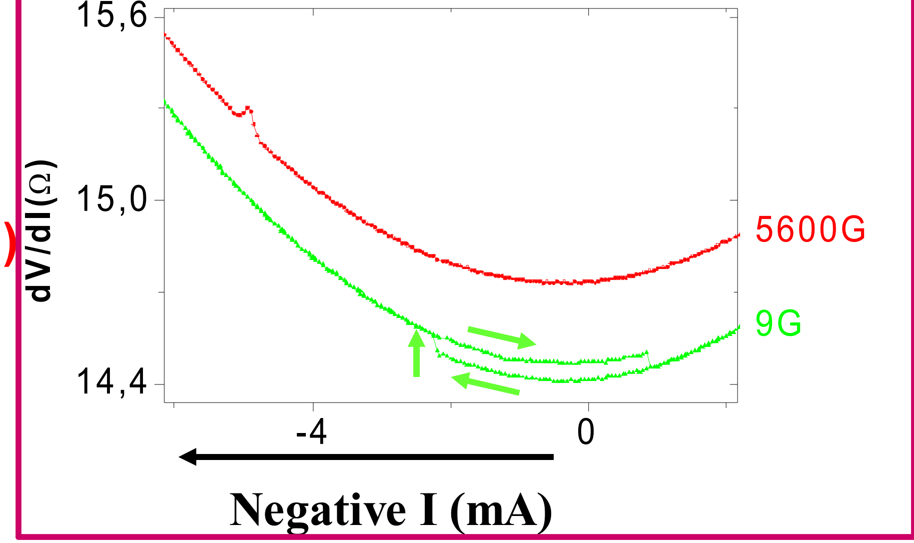




Increasing current

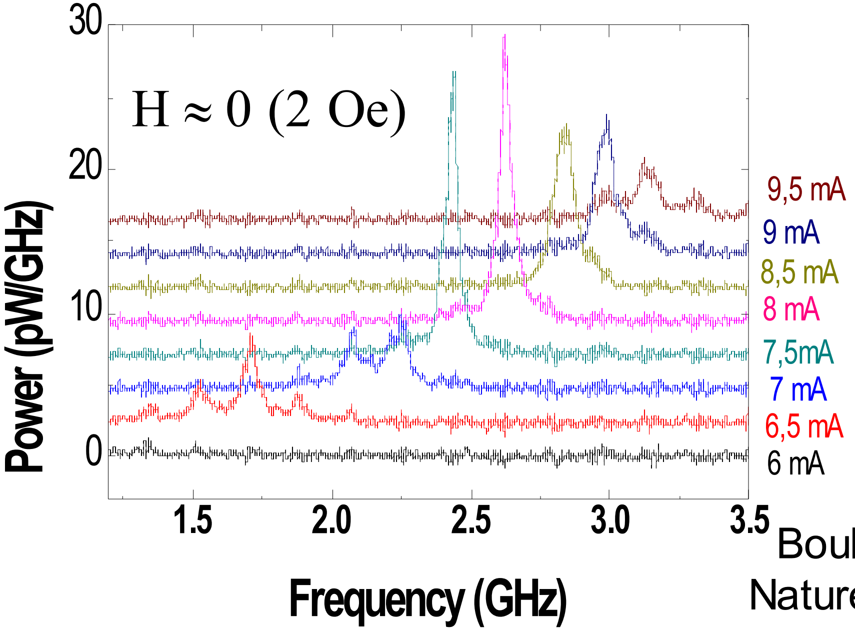
Co/Cu/Py (« wavy » angular variation calculated by Barnas, AF et al, PR B 2005)

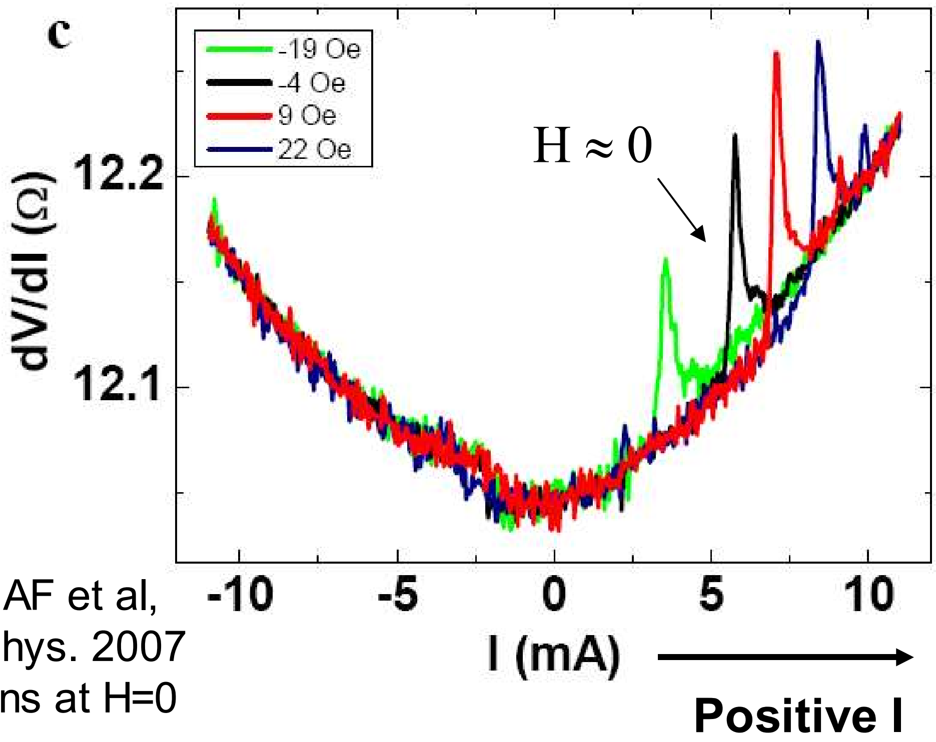



Py/Cu/Py (standard)

free Py: fast spin relaxation

fixed Co: slower spin relaxation



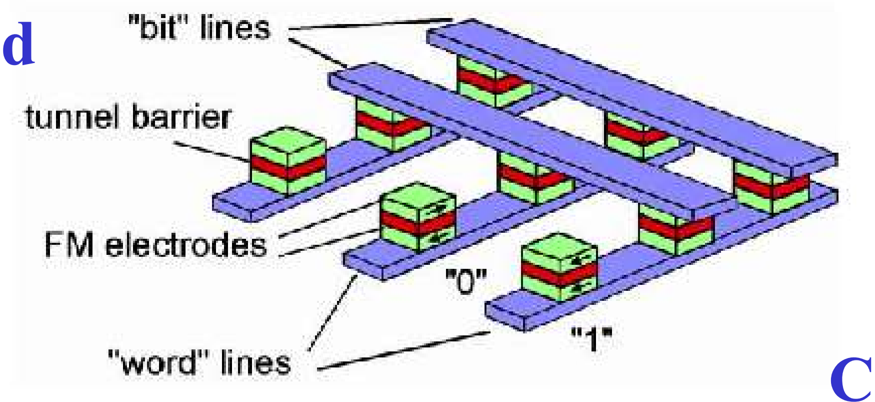


Boulle, AF et al, Nature Phys. 2007 oscillations at H=0

Switching of reprogrammable devices (example: MRAM)

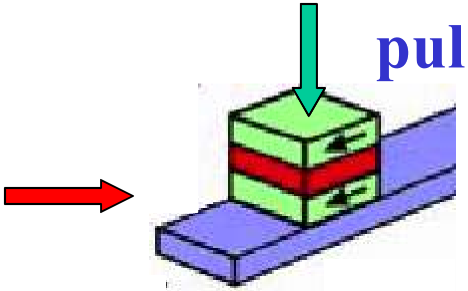
1) By external magnetic field

(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)

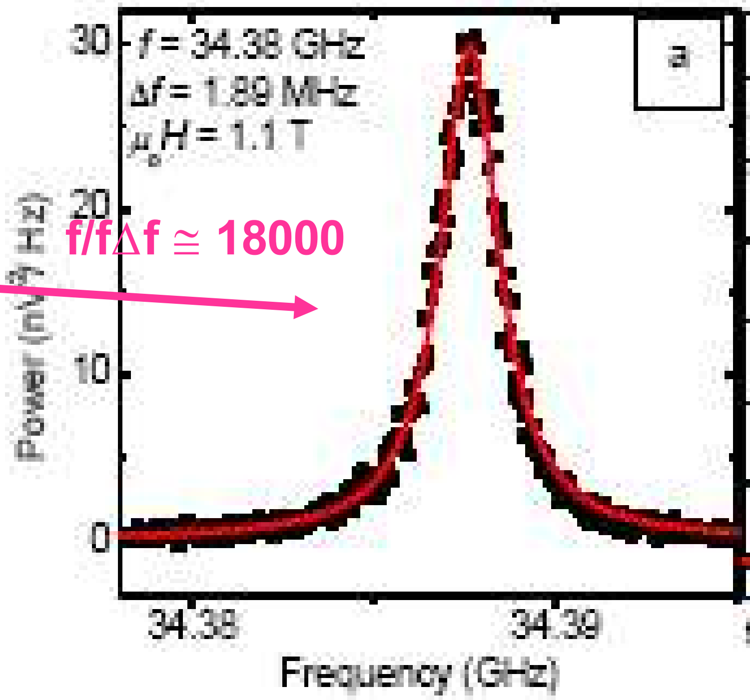
- high quality factor

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

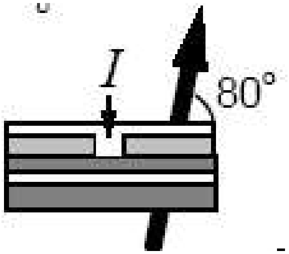
-oscillations without applied field

-Needed improvements

- - increase of power by synchronization of



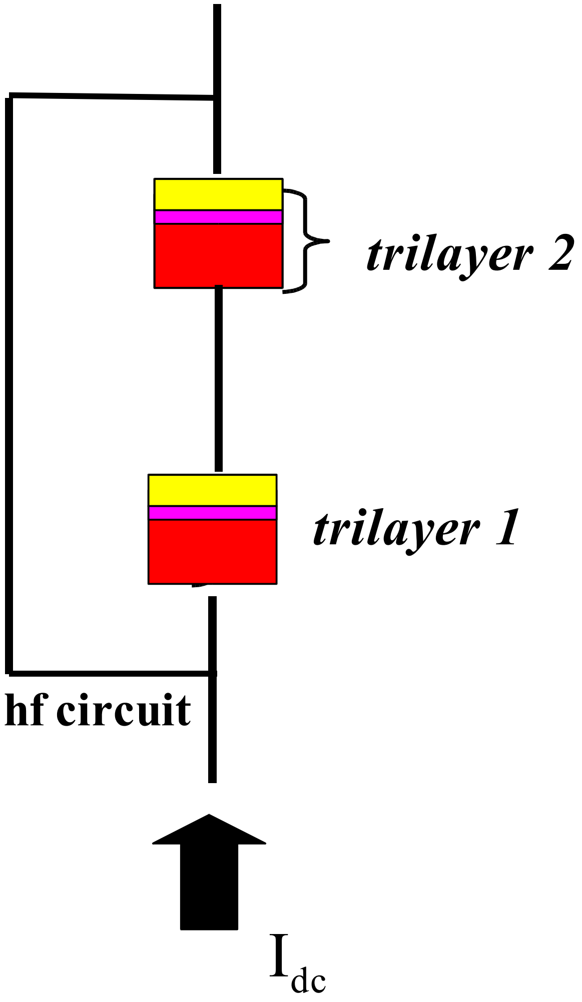
f/fΔf ≅ 18000



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)**



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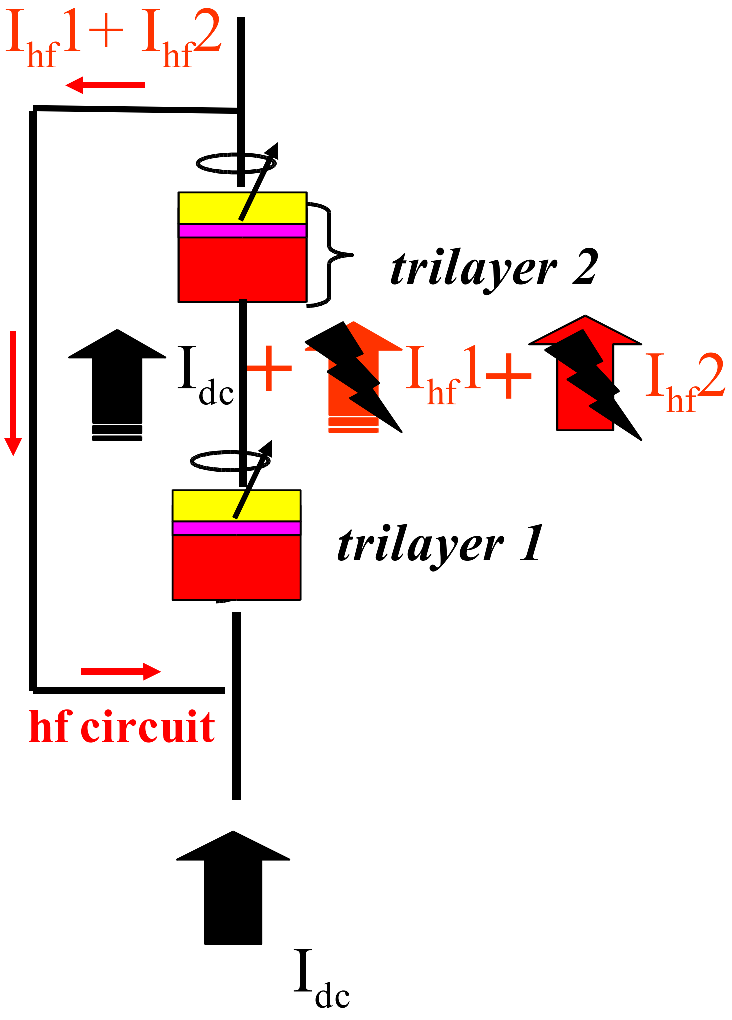

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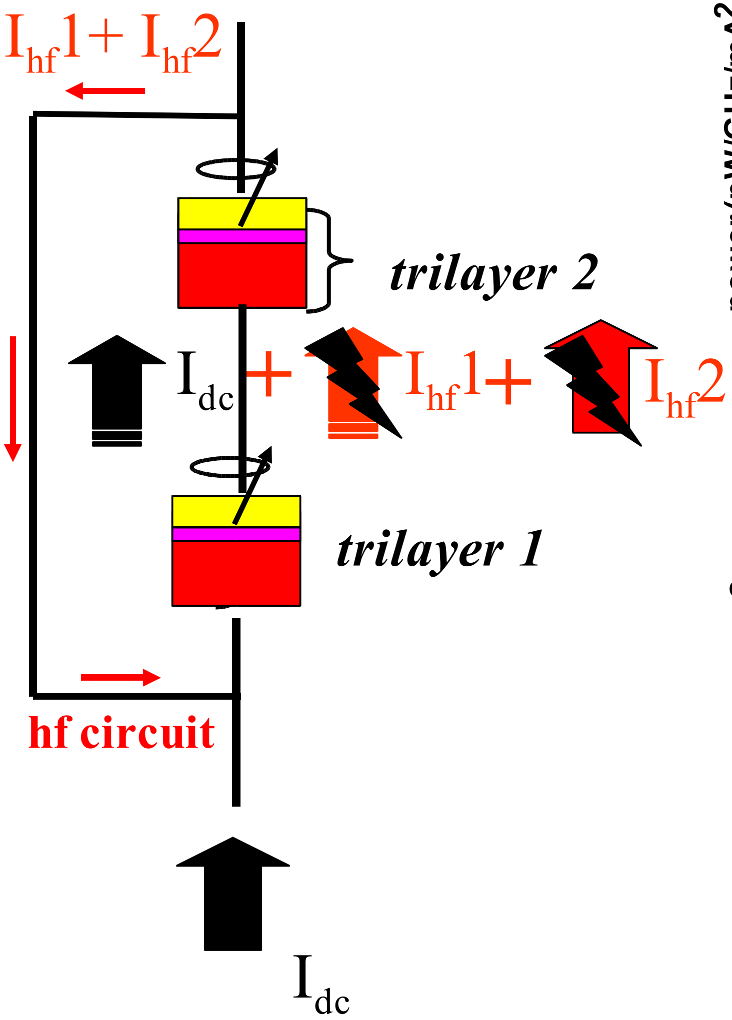
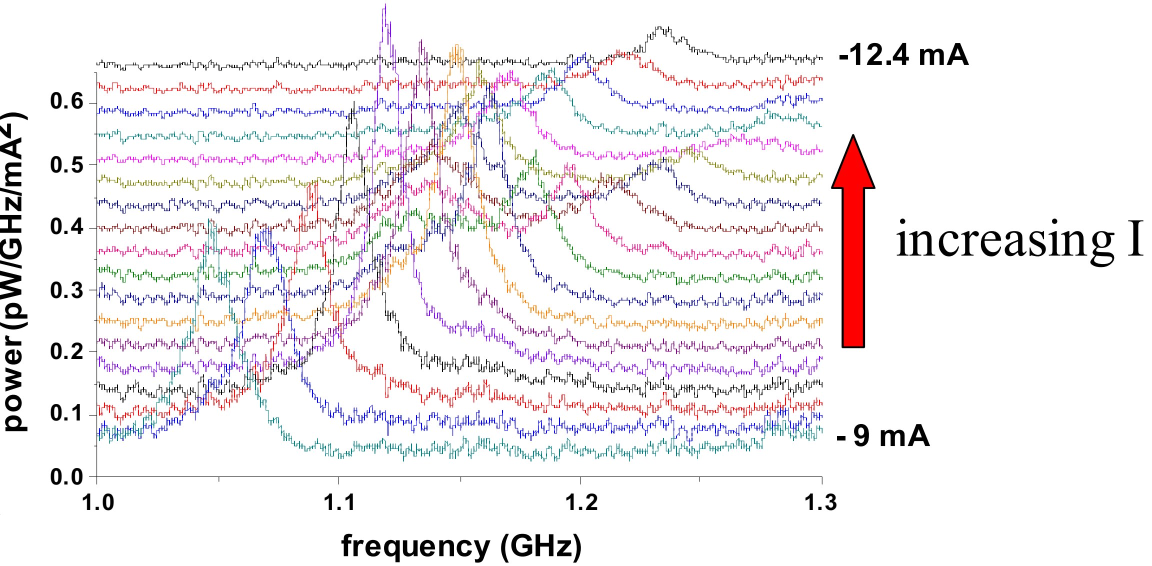
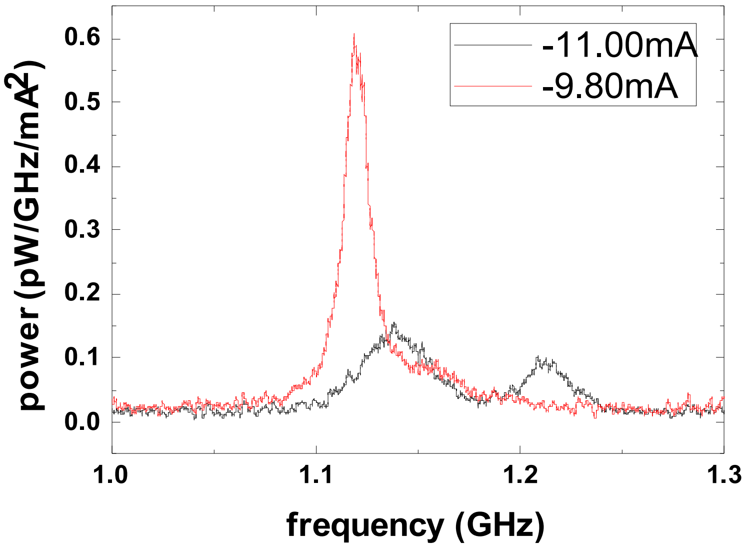




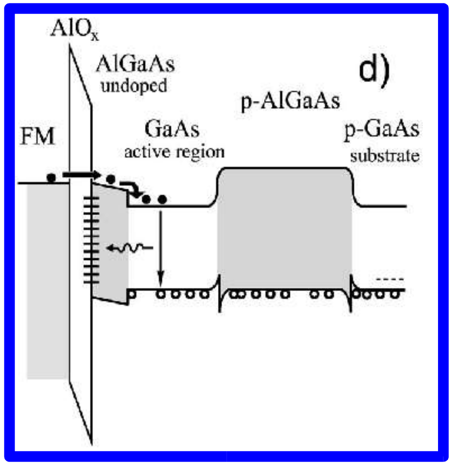


Spintronics with semiconductors and molecules

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→170K) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

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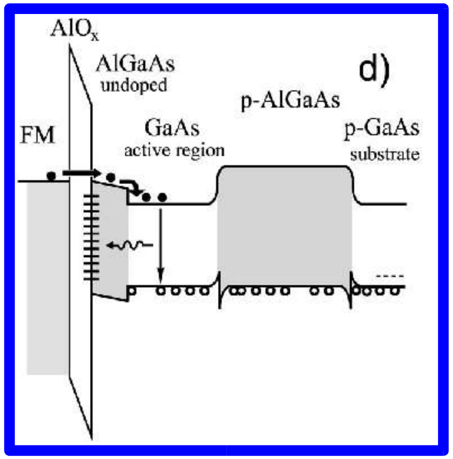

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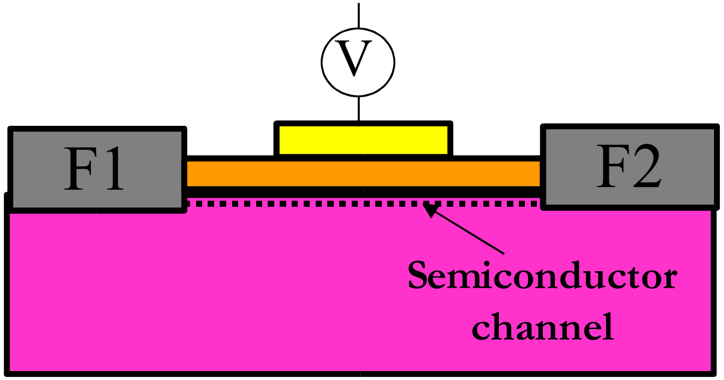
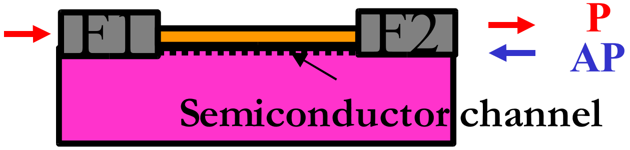
Spin Field Effect Transistor ?



Semiconductor 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*

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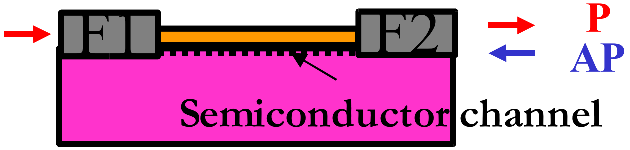

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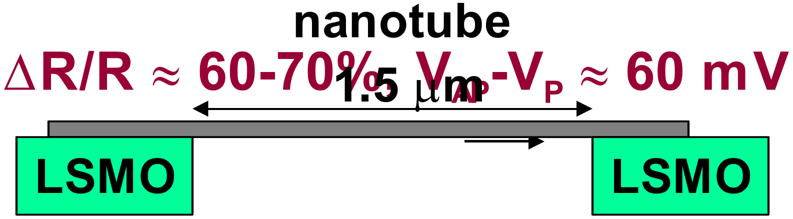
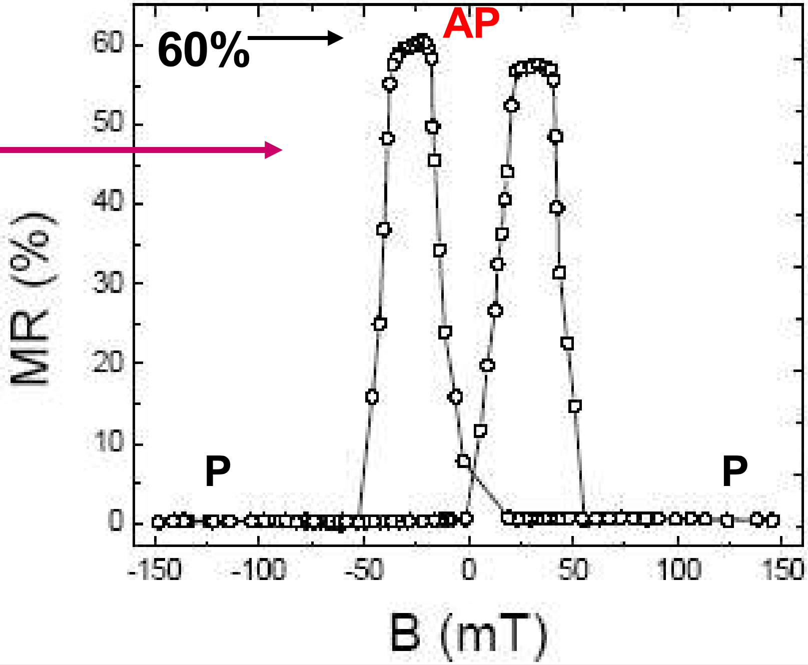
Carbon nanotubes:

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



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

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



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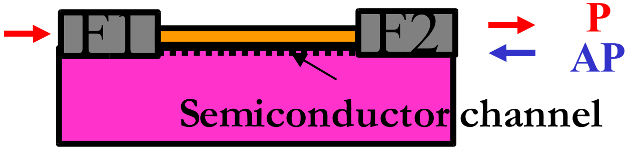

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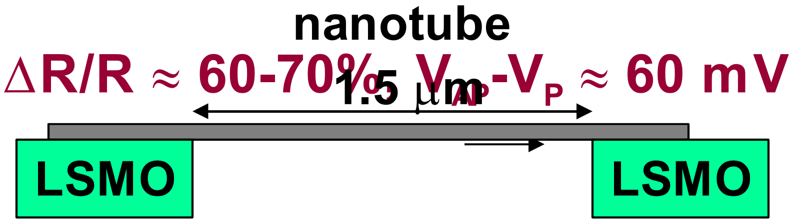

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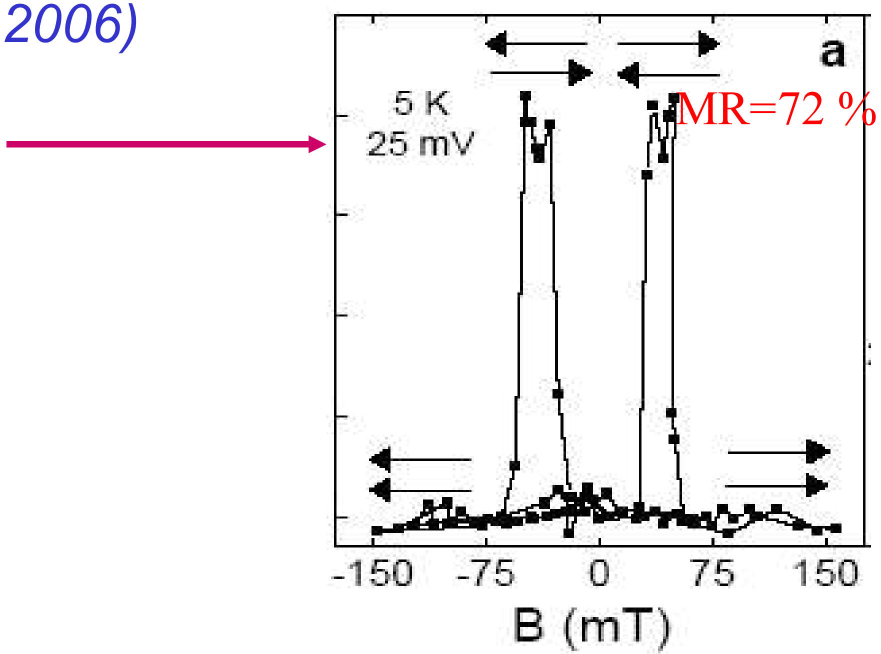


Two interface spin transport problem (diffusive regime)

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

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

Condition for

spin injection

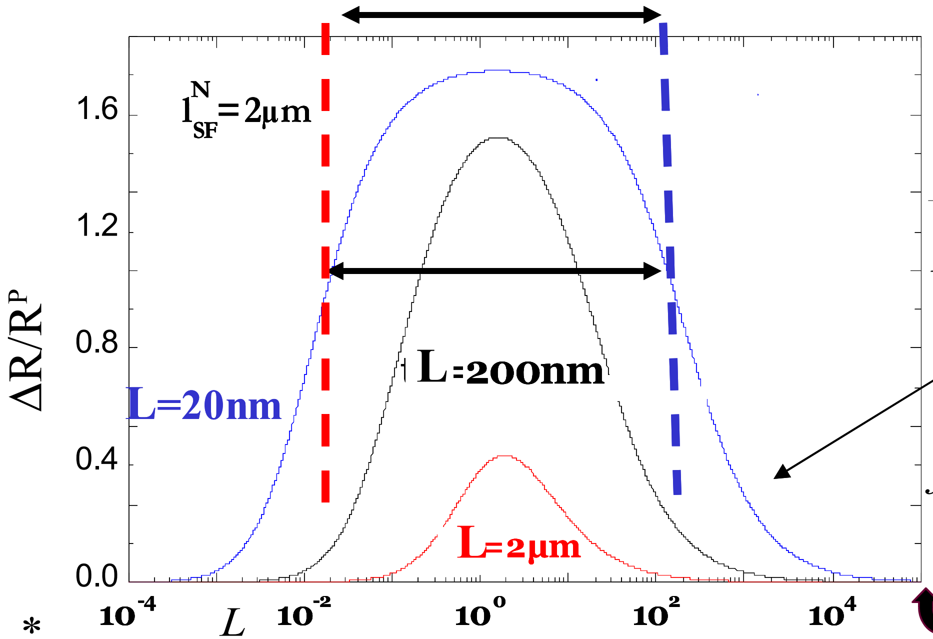
Condition

dwell time τ_n < spin lifetime

τ_{sf} *dwell time*

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

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



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

$$r_b^* / r_N$$

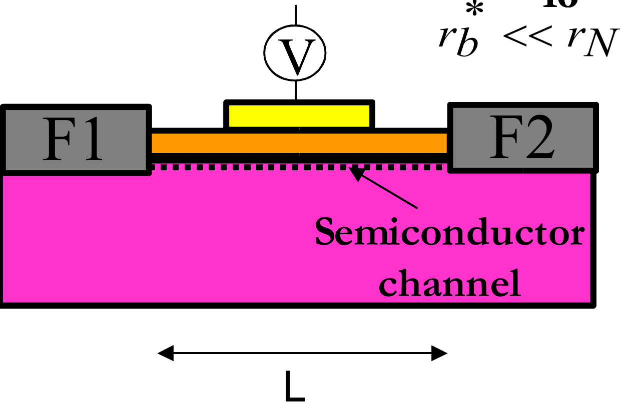
$$\frac{\Delta R}{R^P} = \frac{\gamma^2/(1-\gamma^2)}{1+\tau_n/\tau_{sf}}$$

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) :

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

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

Semiconductors:

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

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Solution for semiconductors:

shorter L ?, larger transmission t_r ?

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Next challenge for molecules:

spin control by gate

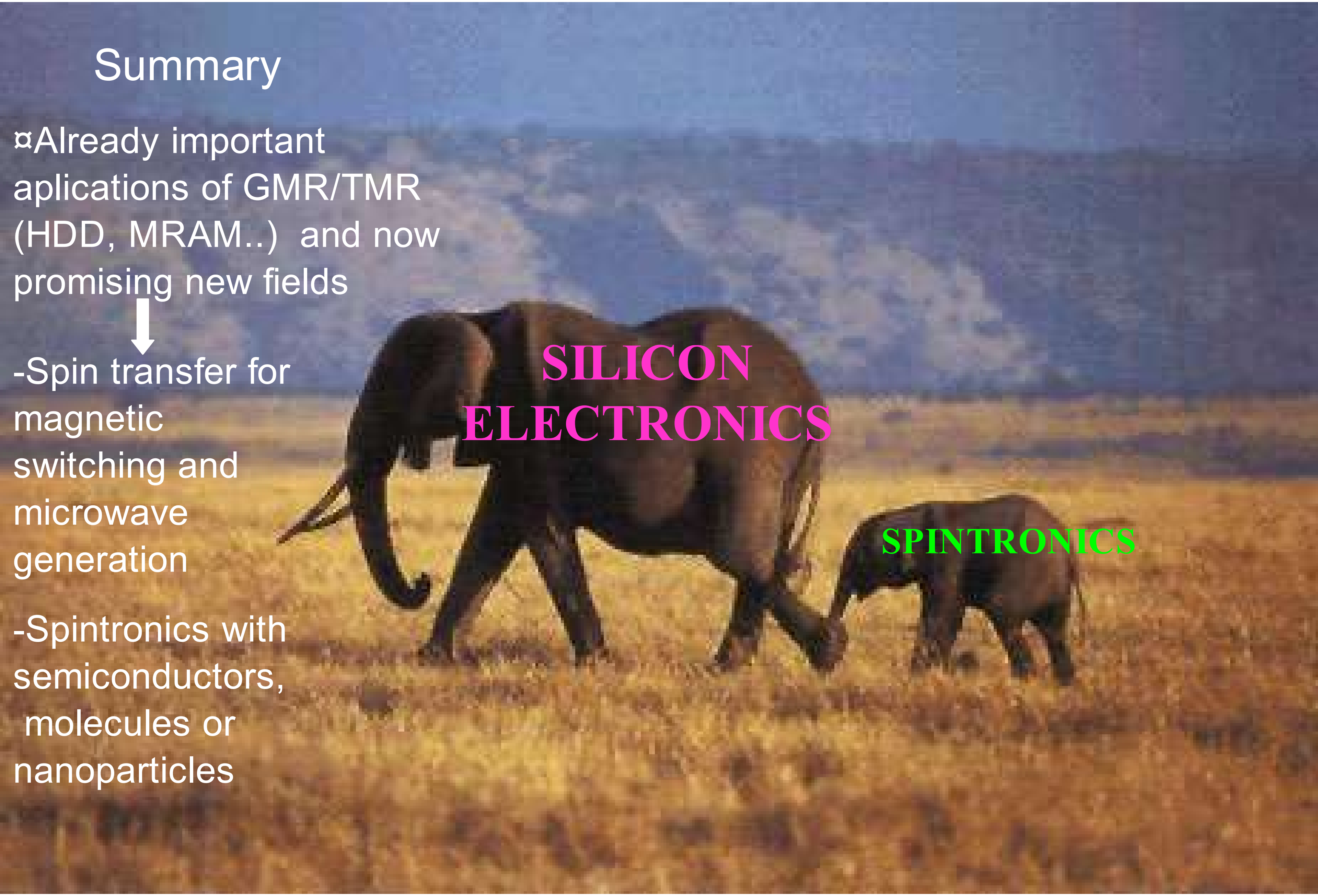
Summary

¤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



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L. Hueso, N.Mathur, Cambridge

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