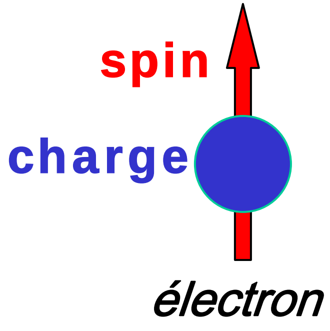
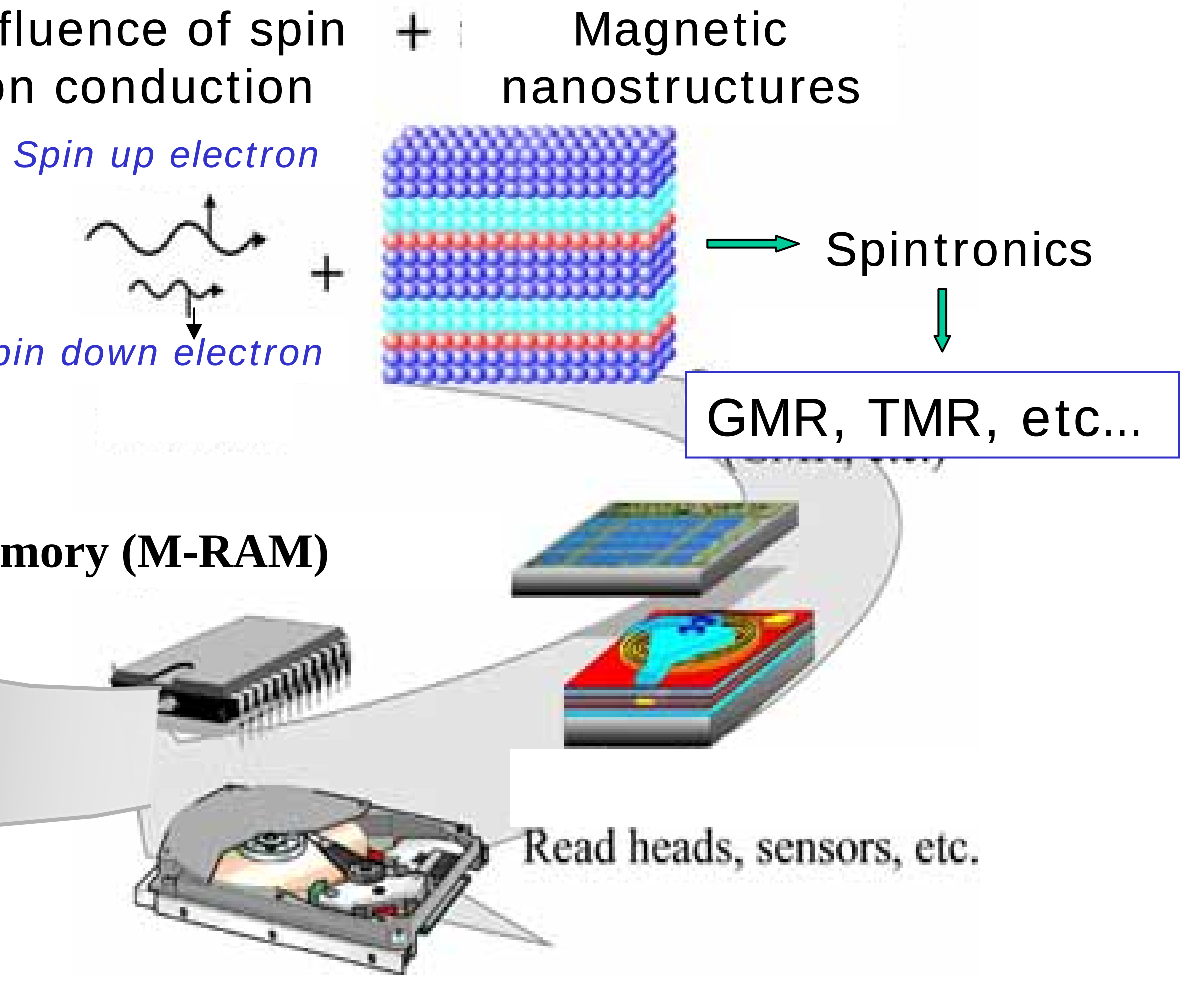
Présent et futur de la spintronique (LAAS, 17/12/ 08)




Influence of spin on conduction + Magnetic nanostructures

Spin up electron

Spin down electron

→ Spintronics

GMR, TMR, etc...

Memory (M-RAM)

Read heads, sensors, etc.

Spin transfer :

- writing by electrical transport of magnetic information,

- microwave generation

spintronics with semiconductors,

molecular spintronics,

Single-electron spintronics, etc

Introduction :

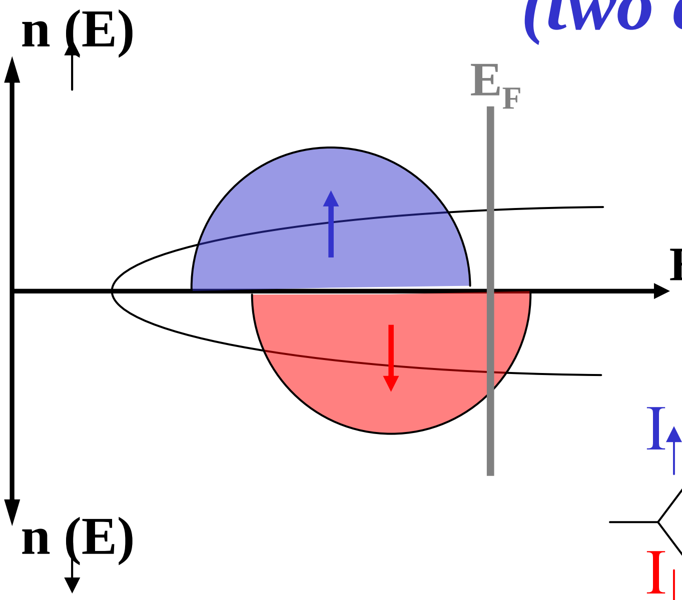
Spin dependent conduction in ferromagnetic conductors,

Giant Magnetoresistance (GMR),

Tunnel Magnetoresistance (TMR)

Spin dependent conduction in ferromagnetic metals

(two current model)



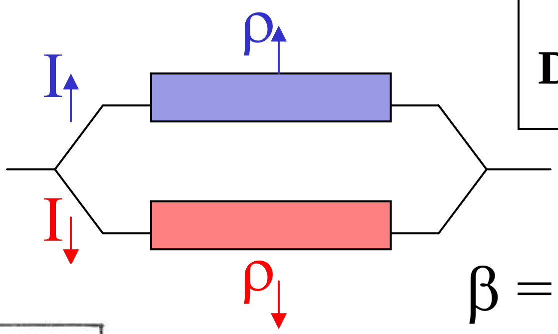
Mott, Proc.Roy.Soc A153, 1936

Fert et al, PRL 21, 1190, 1968

Loegel-Gautier, JPCS 32, 1971

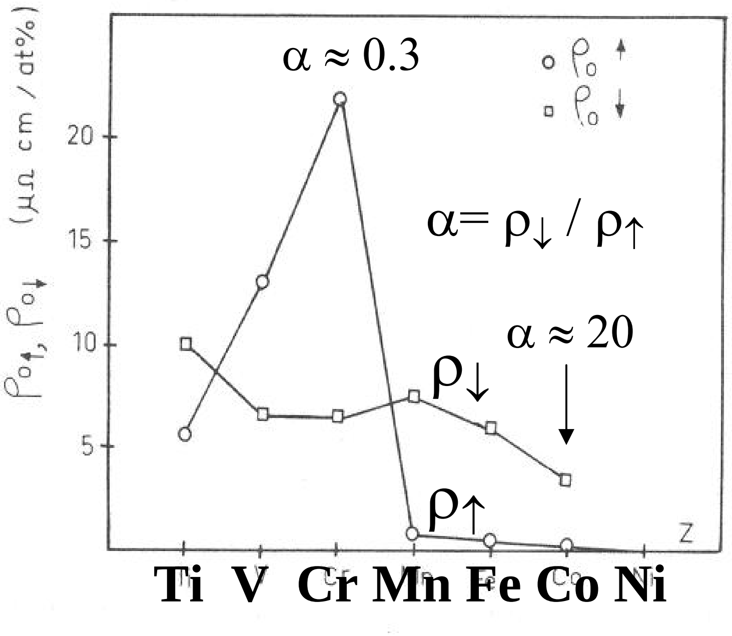
Fert et al,J.Phys.F6, 849, 1976

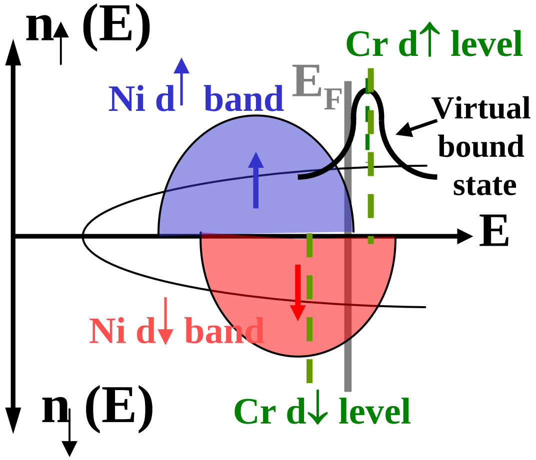
Dorlejin et al, ibid F7, 23, 1977



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

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





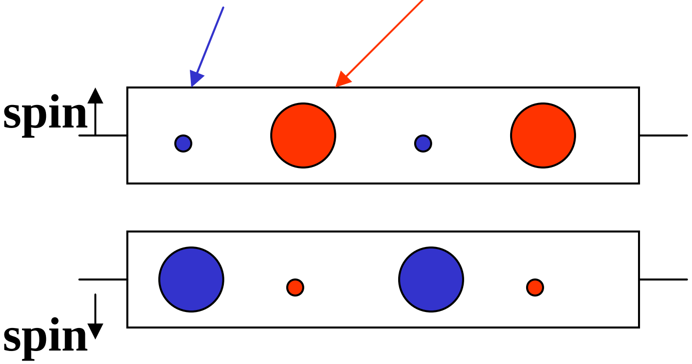
Mixing impurities A and B with opposite or similar spin asymmetries: *the pre-concept of GMR*

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

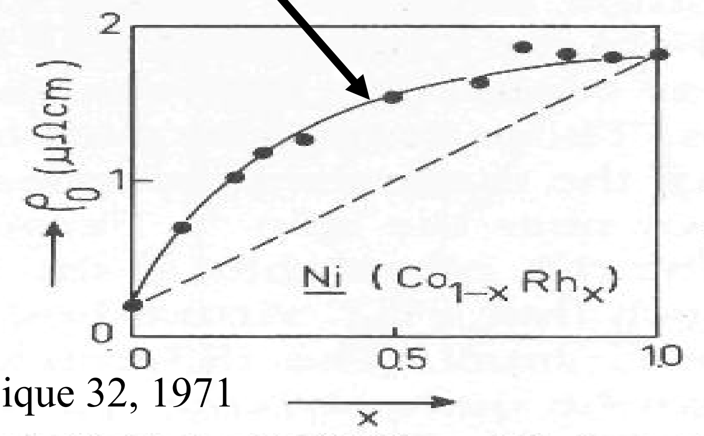
$\alpha = \rho_{\downarrow}/\rho_{\uparrow}$

1st case

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



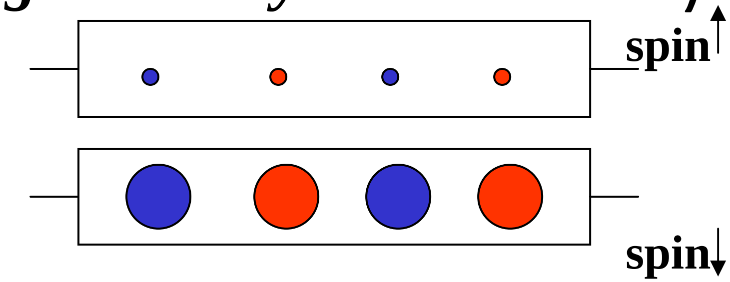
$\rho_{AB} >> \rho_A + \rho_B$



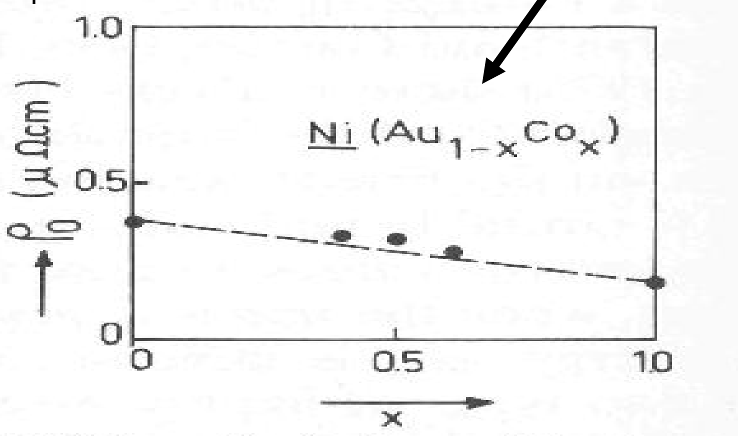
2d case

α_A and $\alpha_B > 1$

High mobility channel → low ρ

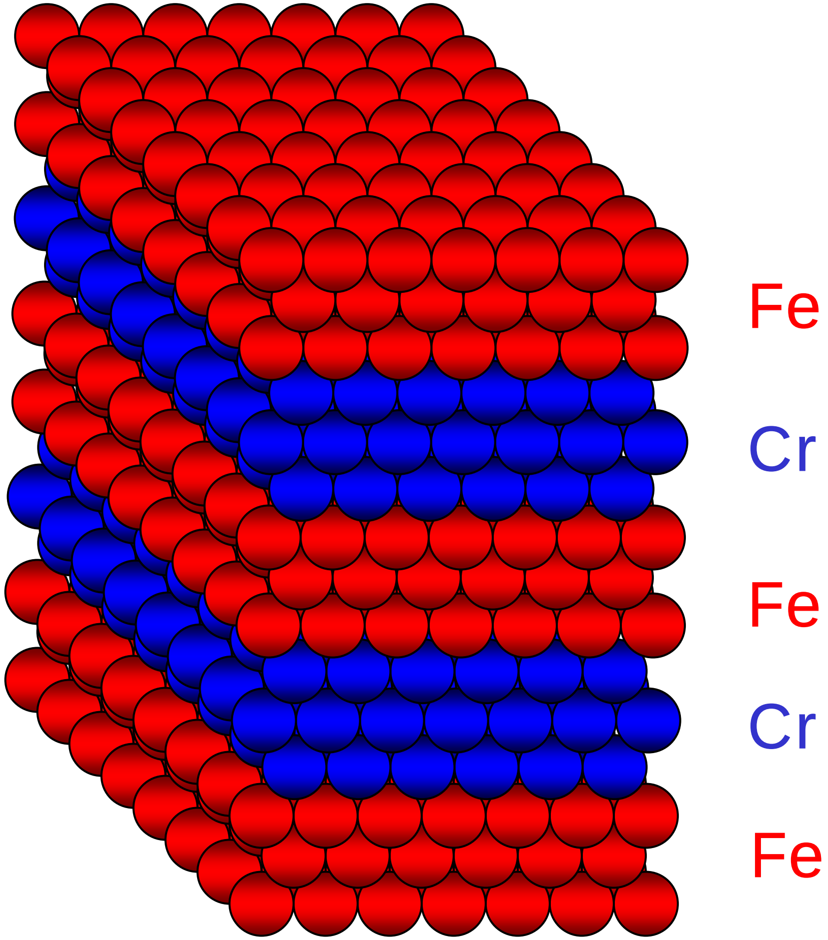


$\rho_{AB} \approx \rho_A + \rho_B$

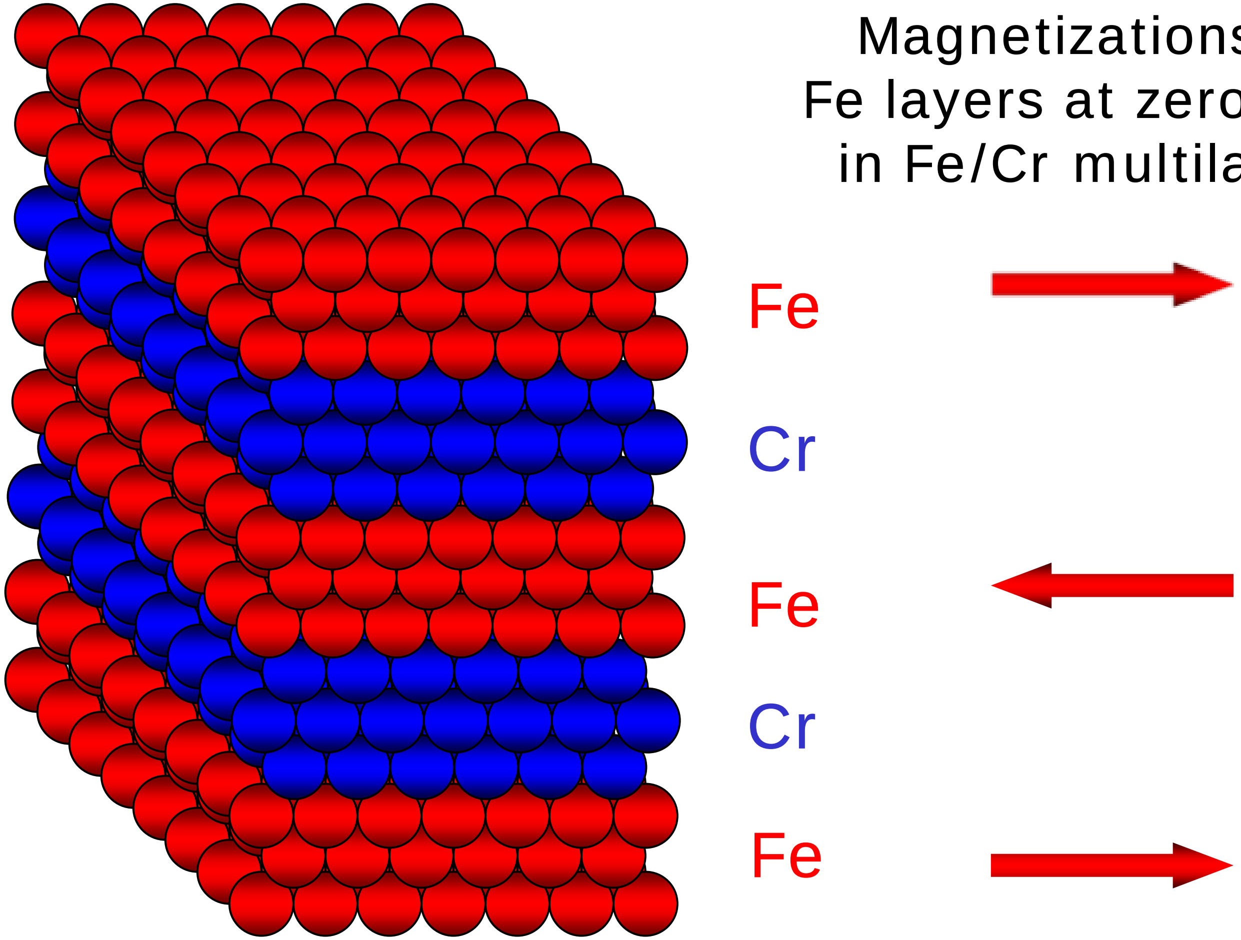


J. de Physique 32, 1971

- **Magnetic multilayers**



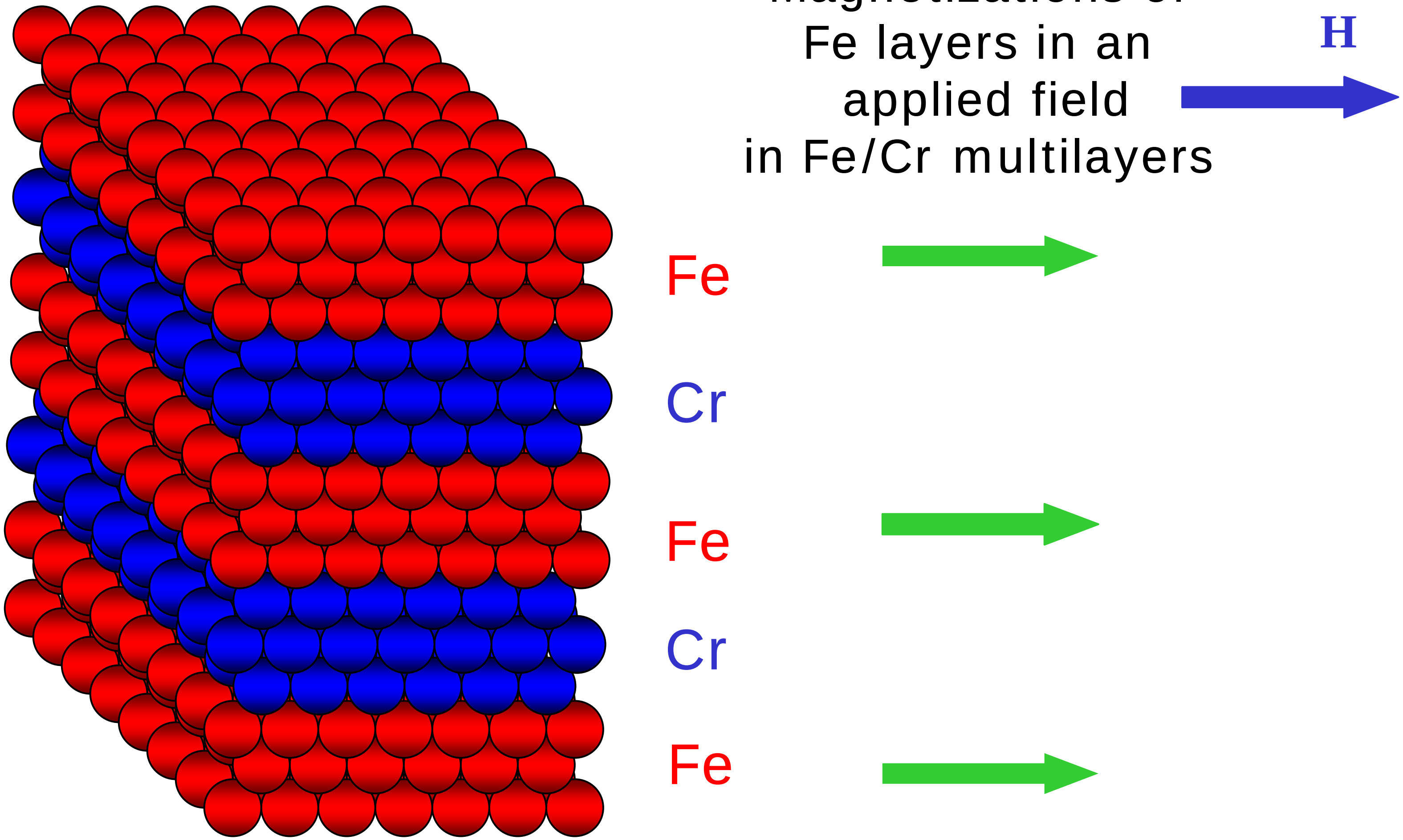
- **Magnetic multilayers**



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

P. Grünberg, 1986 → antiferromagnetic interlayer coupling

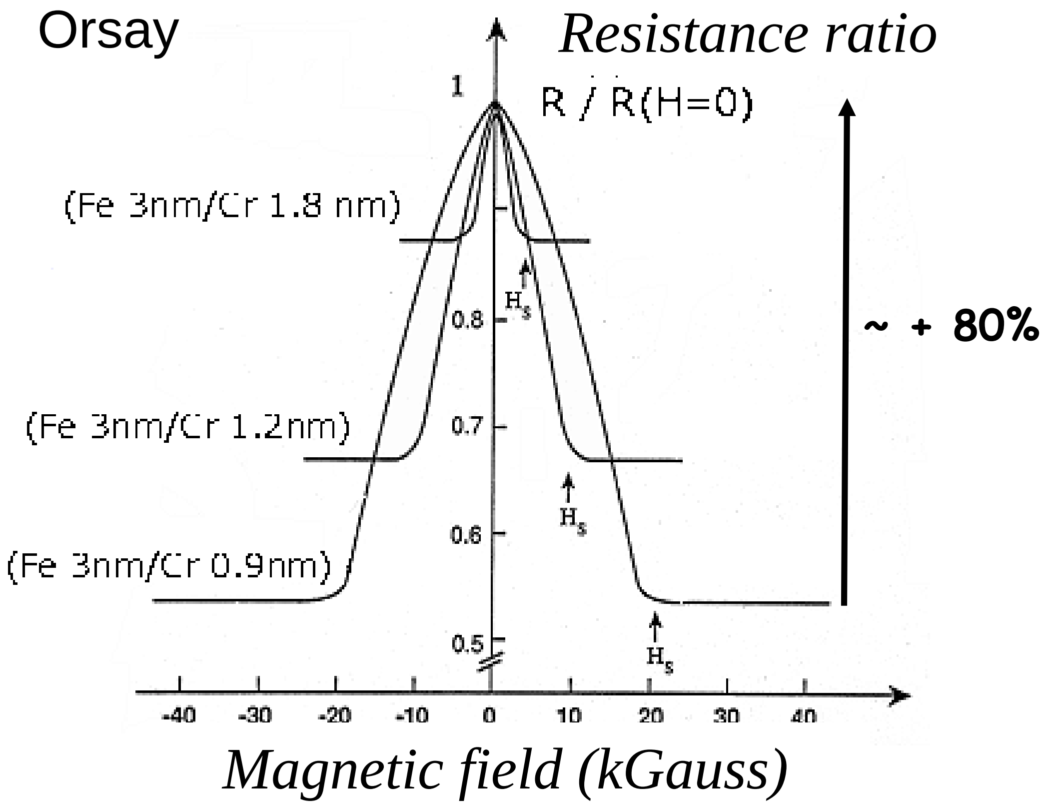
- **Magnetic multilayers**

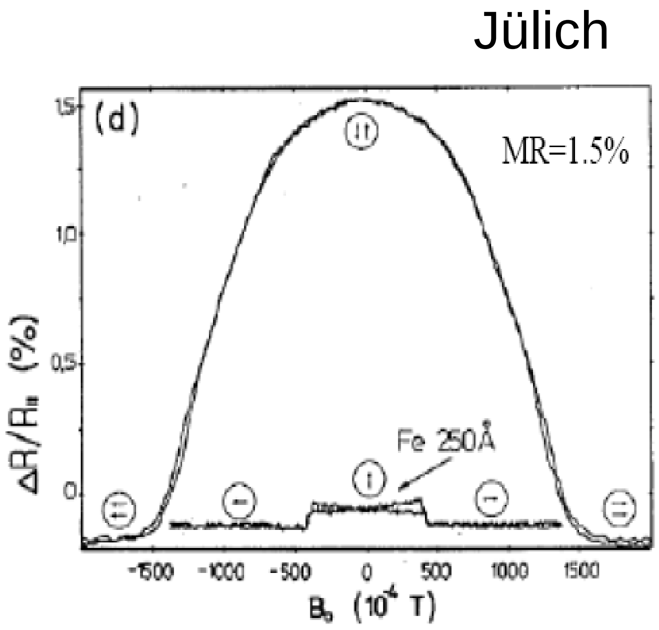

Magnetizations of
Fe layers in an
applied field
in Fe/Cr multilayers

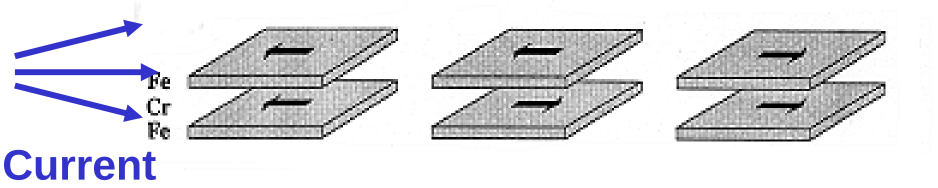
P. Grünberg, 1986 → antiferromagnetic interlayer coupling

Giant Magnetoresistance (GMR)

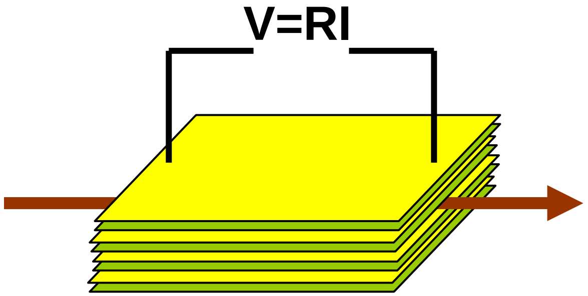
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)





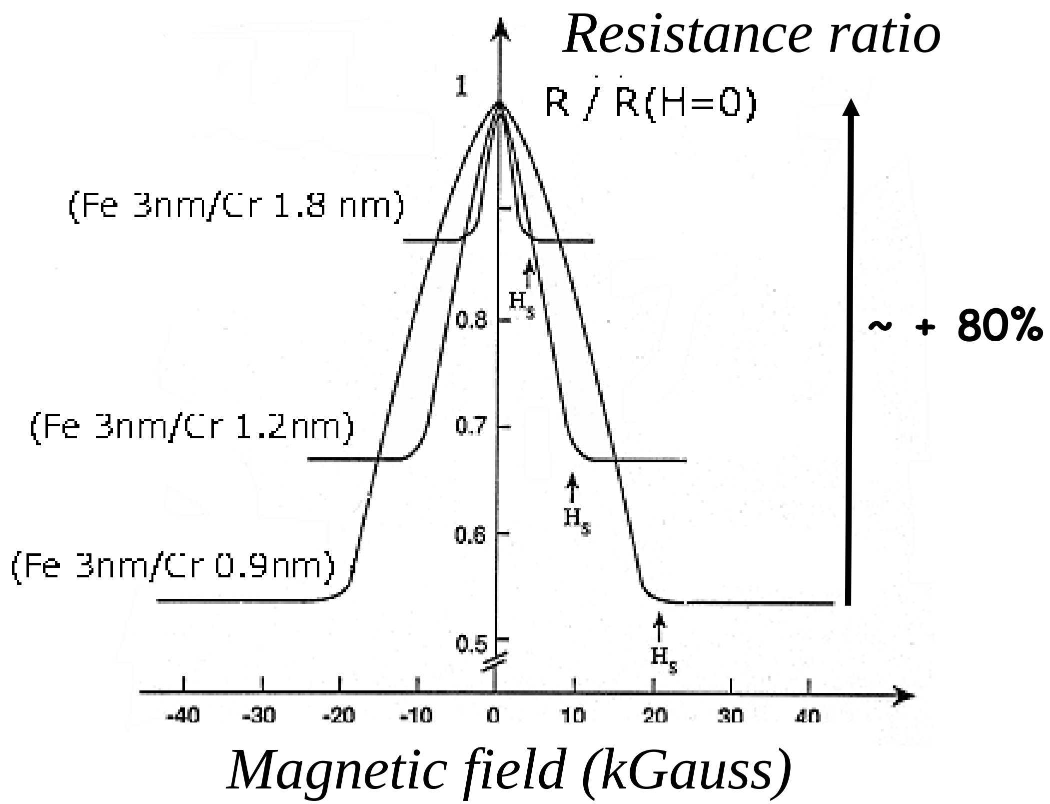


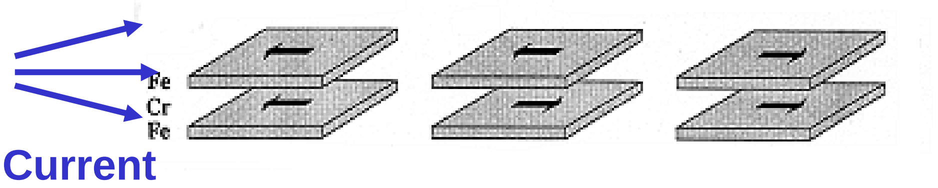
AP (AntiParallel) **P** (Parallel)



• Giant Magnetoresistance (GMR)

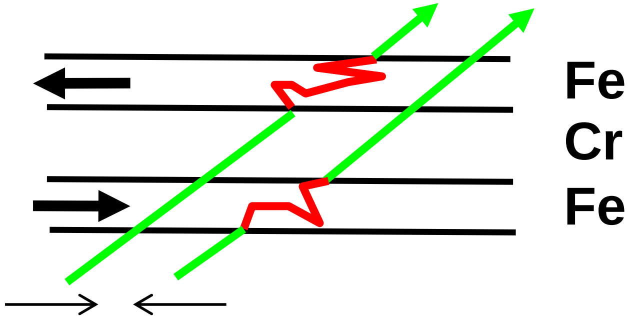
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)



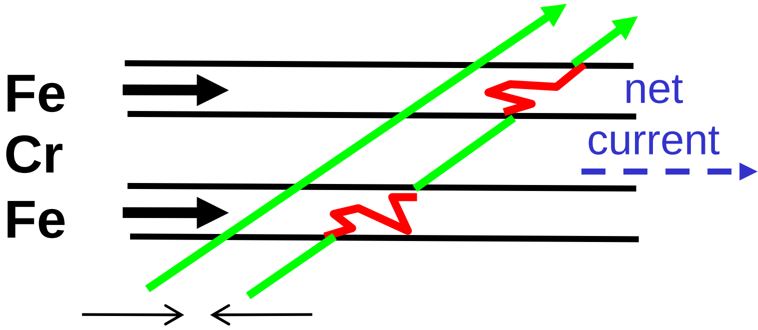


AP (AntiParallel) **P** (Parallel)

Anti-parallel magnetizations
(zero field, high resistance)

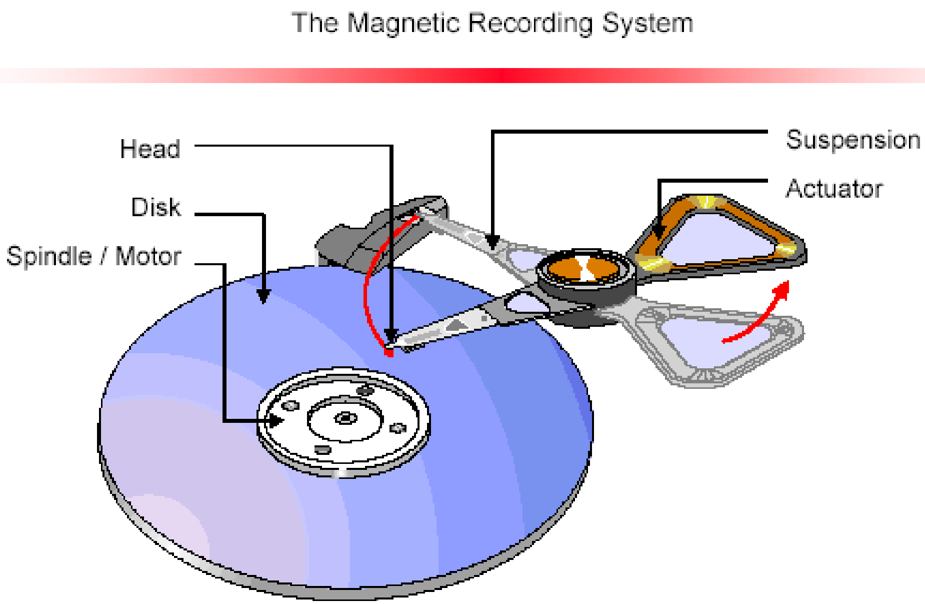


Parallel magnetizations
(appl. field, low resist.)

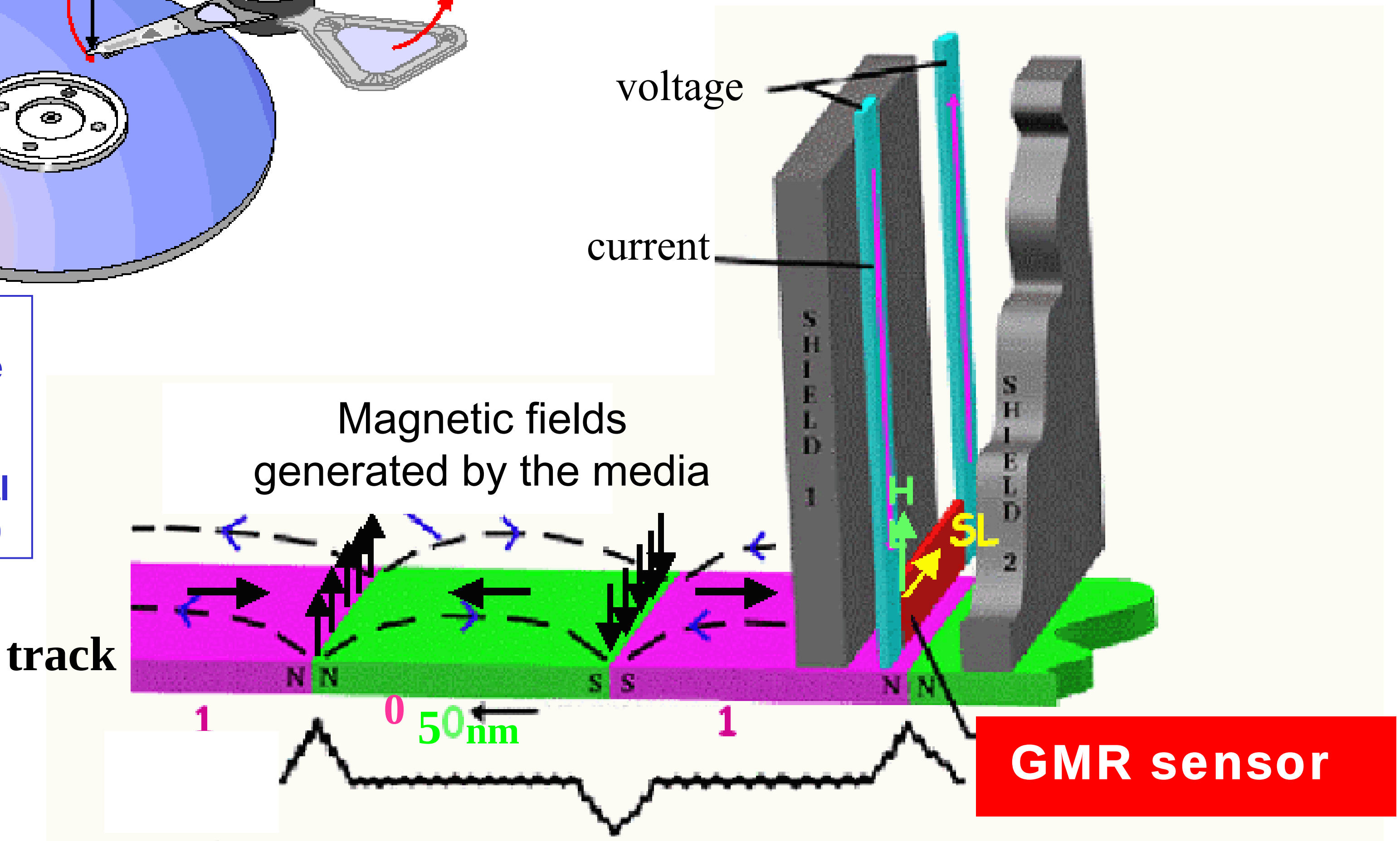


Condition for GMR:
layer thickness ≈ nm

Read head of hard disc drive

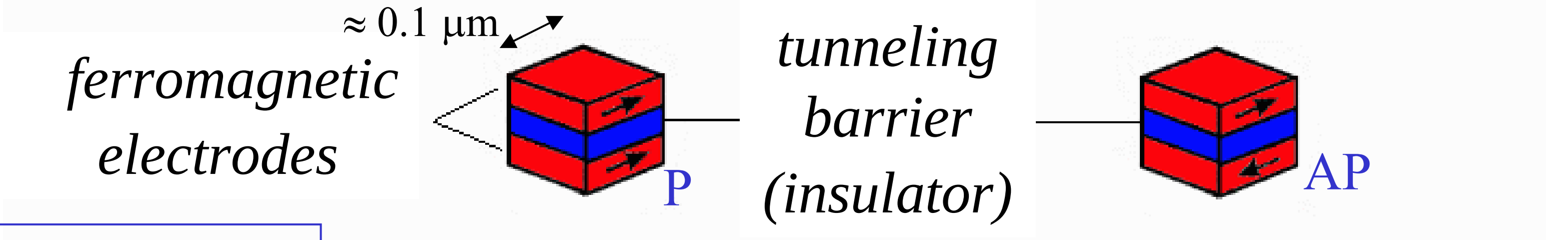


Recent review :
« The emergence of spintronics in data storage »
Chappert, AF et al
Nat. Mat.(Nov.07)



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

P

tunneling barrier (insulator)

AP

Low resistance state

High resistance state

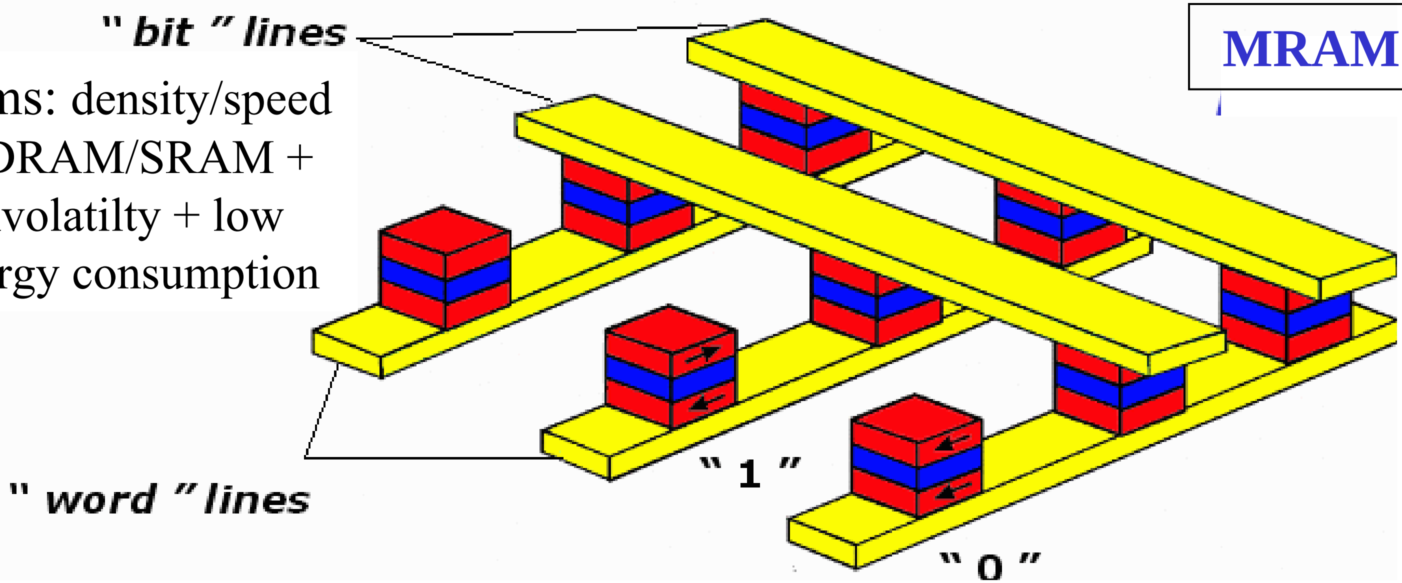
Jullière, 1975, low T, hardly reproducible

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

CoFeB/MgO/CoFeB,
ΔR/R ≈ **500%** at RT in 2006-2007

Applications: - read heads of Hard Disc Drive

- M-RAM (Magnetic Random Access Memory) and STT-RAM



" *bit* " *lines*

" *word* " *lines*

" 1 "

" 0 "

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

MRAM (2006, Freescale)

STT-RAM (in demonstration)

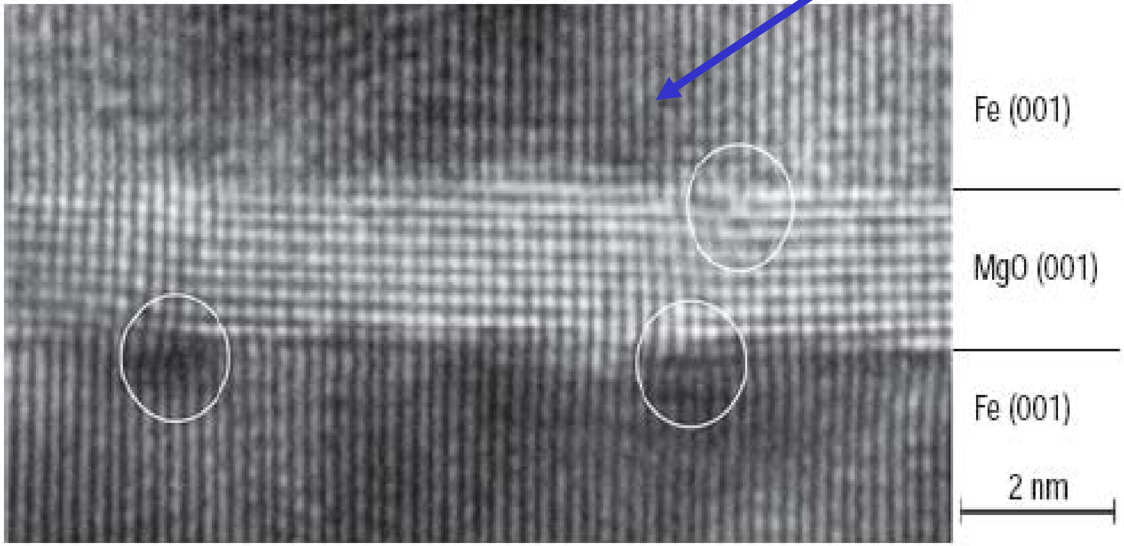
with MgO tunnel junctions

+ writing by spin transfer

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 »?

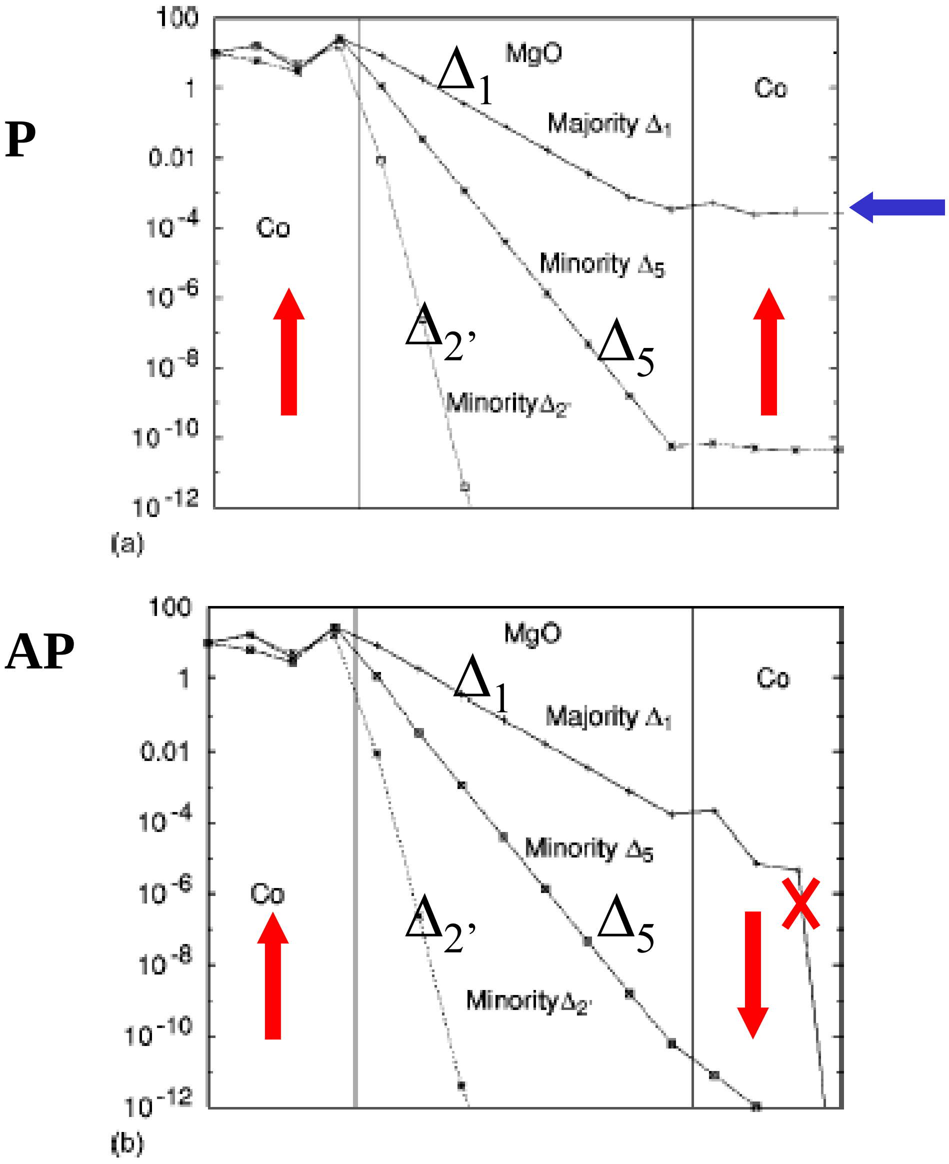
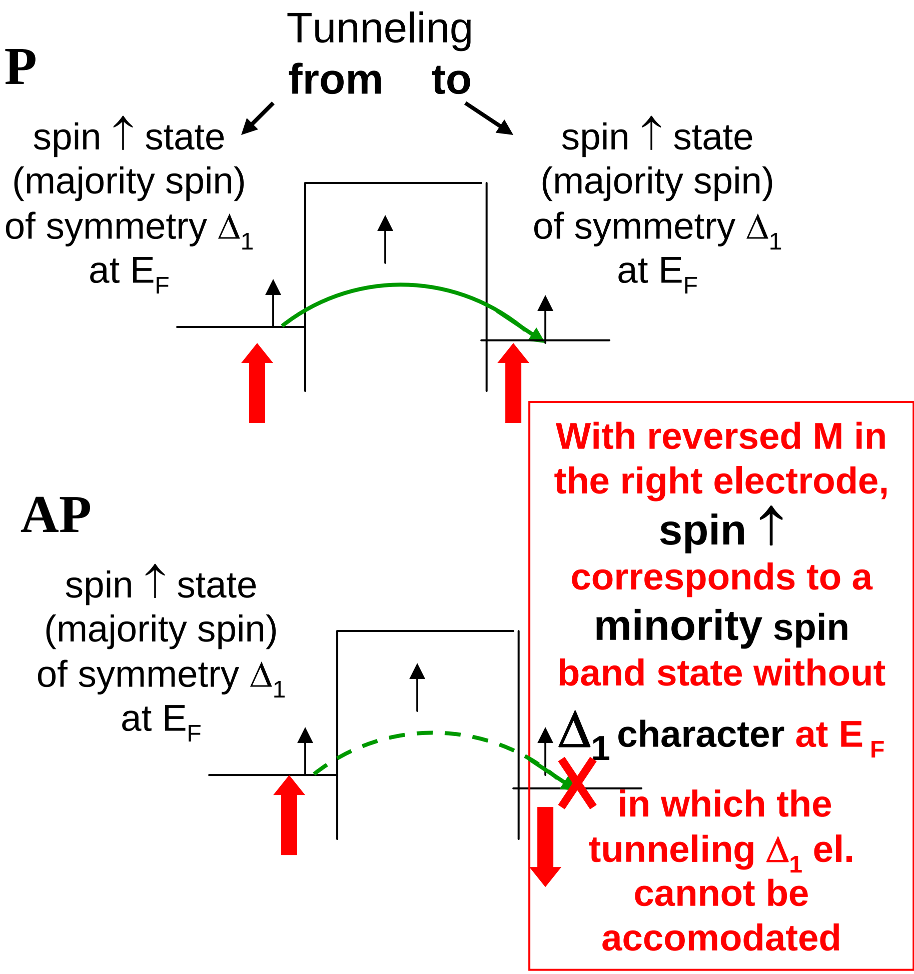


FIG. 2. Tunneling density of states on each atomic layer at $k_\parallel = 0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment

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)]



P

Tunneling **from to**

spin ↑ state (majority spin) of symmetry Δ_1 at E_F

spin ↑ state (majority spin) of symmetry Δ_1 at E_F

AP

spin ↑ state (majority spin) of symmetry Δ_1 at E_F

With reversed M in the right electrode, spin ↑ corresponds to a minority spin band state without Δ_1 character at E_F in which the tunneling Δ_1 el. cannot be accomodated

Spin Transfer

(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules

Common physics:

spin accumulation

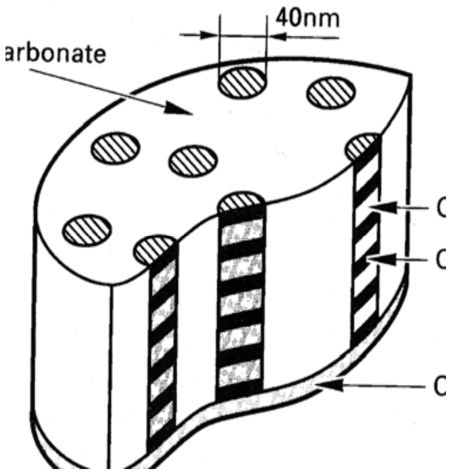
↓

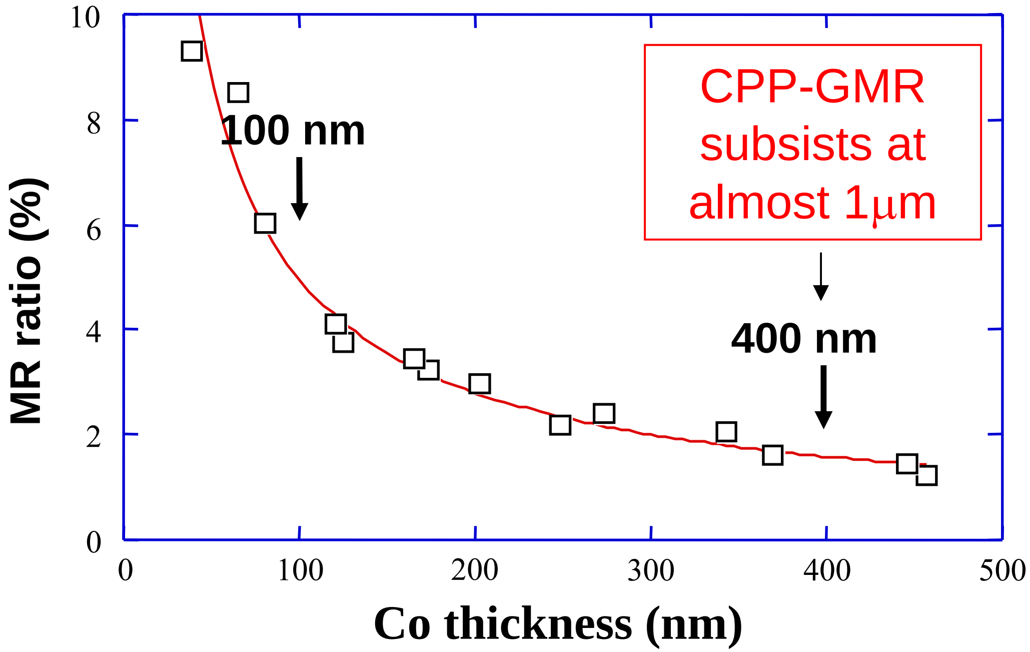
spins injected to long distances

by diffusion

Co/Cu: **Current ⊥ to Plane (CPP) -GMR of multilayered nanowires**

(L.Piraux, AF et al, APL 1994,JMMM 1999)





CPP-GMR
subsists at
almost 1μm

CIP-GMR

scaling length = mean free path

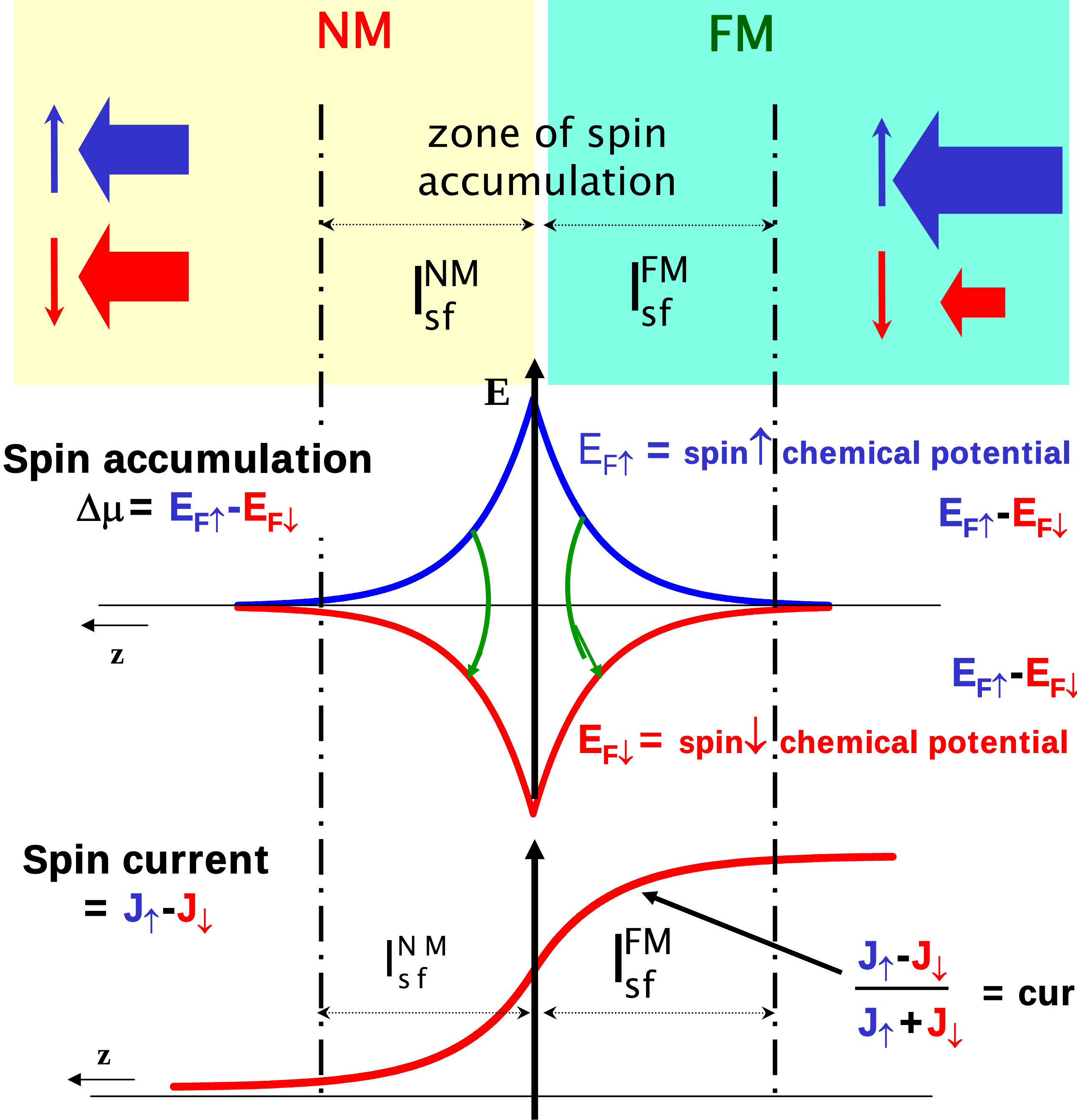
CPP-GMR

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)



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

l^{FM}_{sf} = spin diffusion length in FM

l^{NM}_{sf} = spin diffusion length in NM

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

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

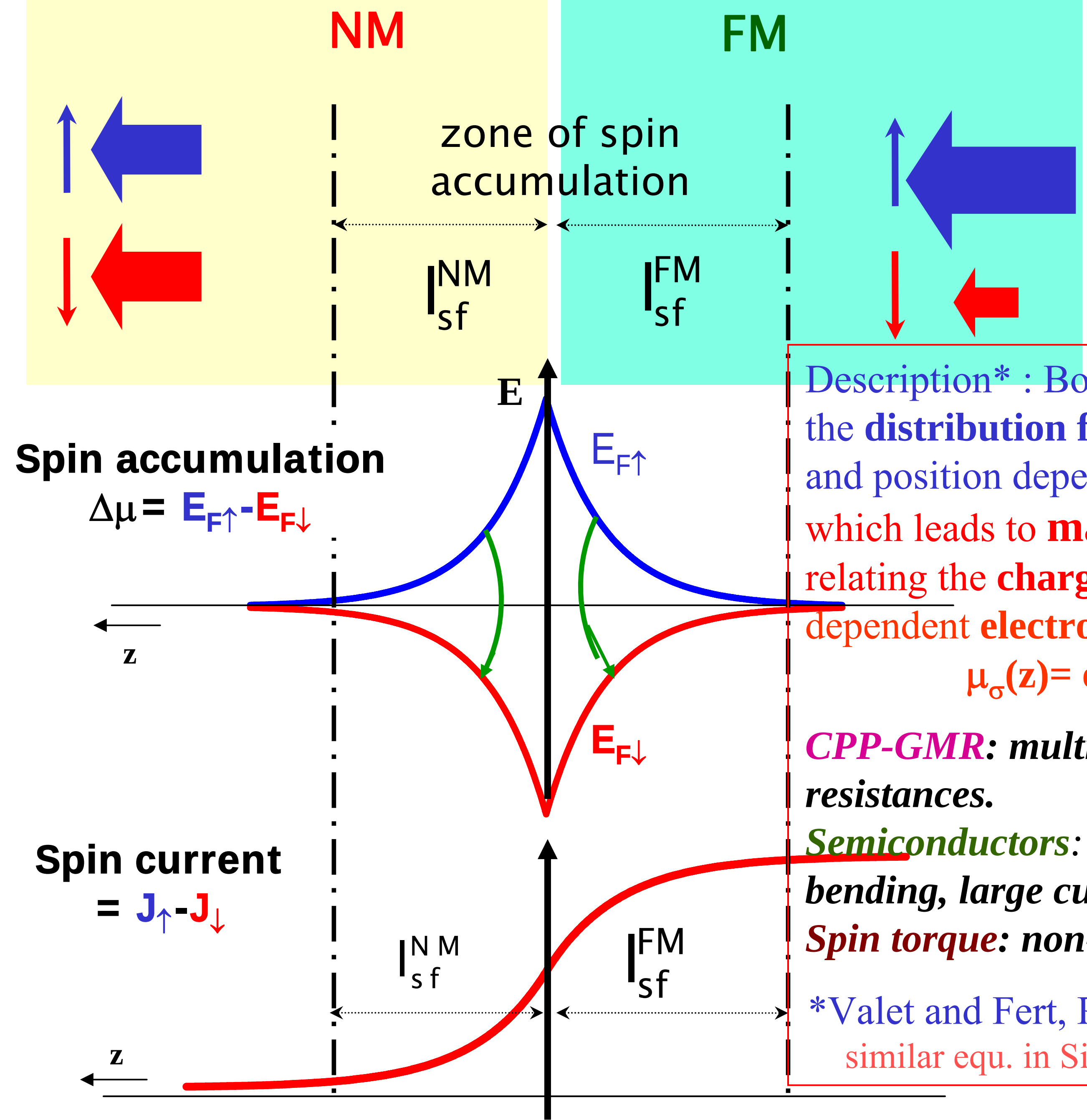
$E_{F\uparrow} - E_{F\downarrow} \sim \exp(z / l^{FM}_{sf})$ **in FM**

$E_{F\uparrow} - E_{F\downarrow} \sim \exp(-z / l^{NM}_{sf})$ **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 NM/FM interface (beyond ballistic range)



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

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

Description* : Boltzmann-type formalism with the **distribution function** associated to a spin and position dependent chemical pot. $E_{F\sigma}(z)$ which leads to **macroscopic equations**** relating the **charge and spin currents to** a spin dependent **electro-chemical potential**

$$\mu_{\sigma}(z) = eV(z) + E_{F\sigma}(z)$$

***CPP-GMR*: multi-interface with interface resistances.**

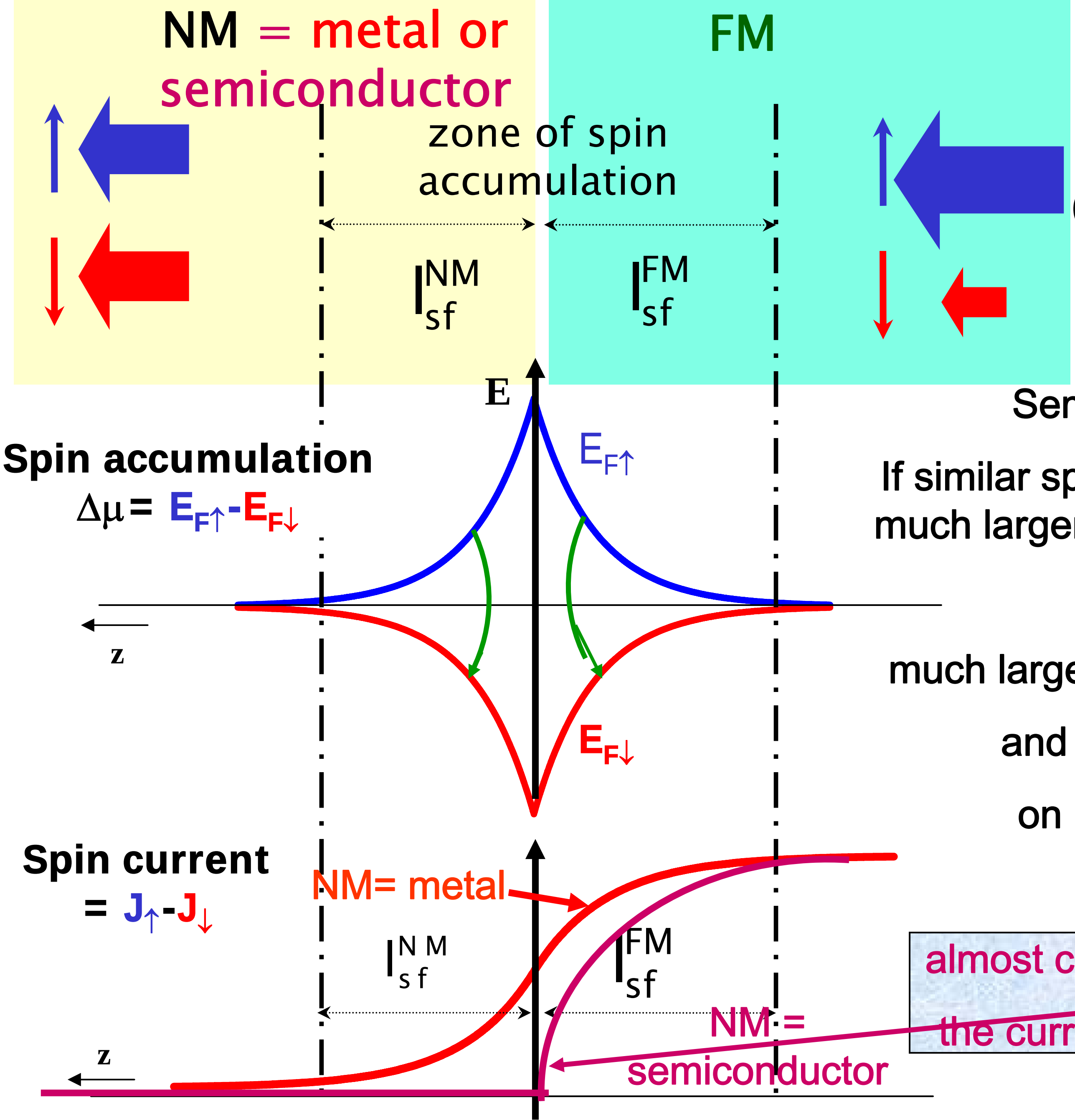
***Semiconductors*: new problems with band bending, large currents, "conductivity mism."**

***Spin torque*: non-colinear situation**

*Valet and Fert, PR B 48, 7099, 1993.

** similar equ. in Silsbee-Johnson and van Son et al

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

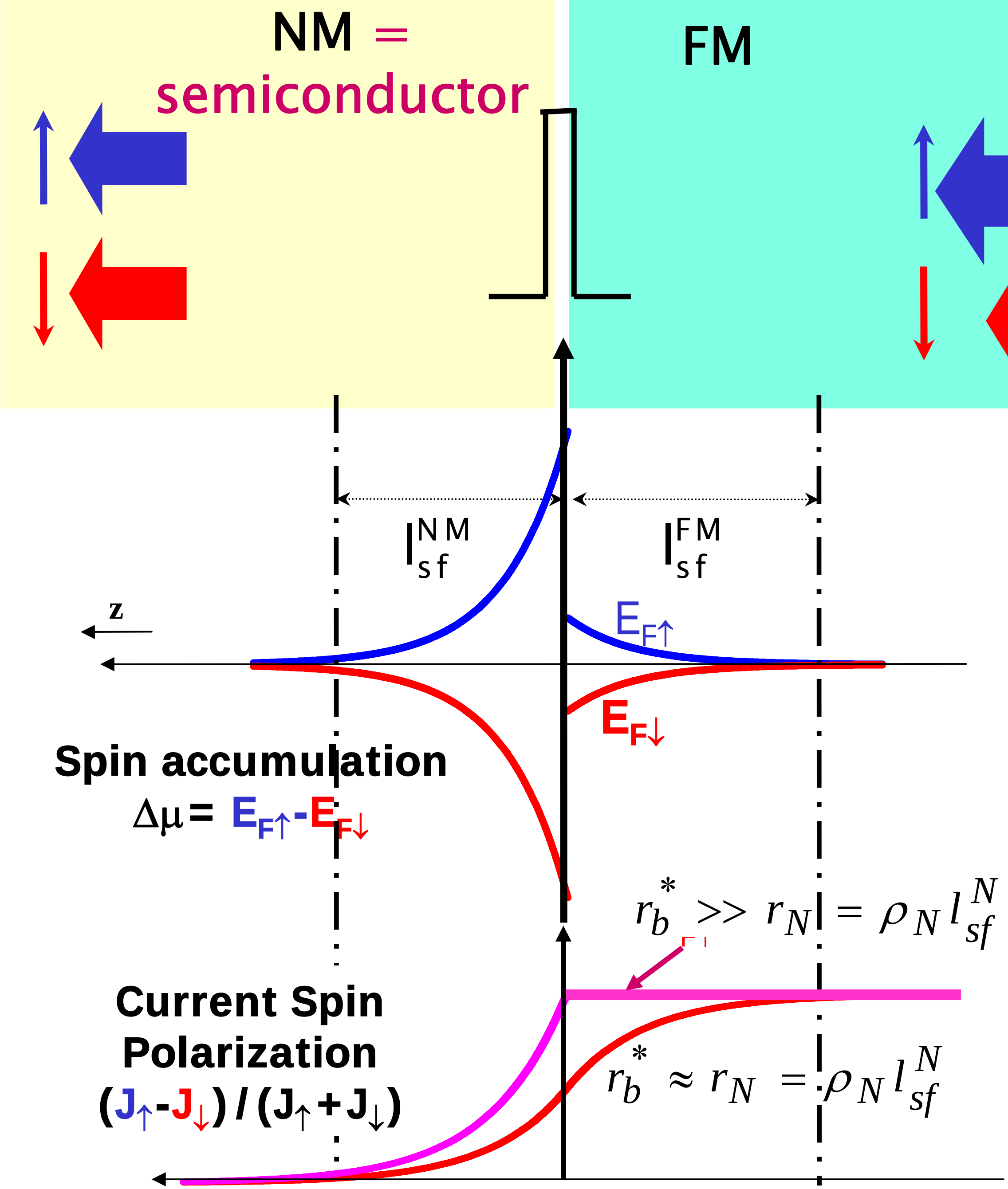
and much more spin flips

on magnetic metal side

↓

almost complete depolarization of the current before it enters the SC

Spin injection/extraction at a Semiconductor/FM interface



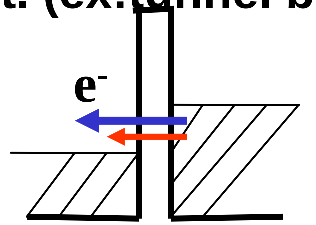
Spin accumulation
$\Delta\mu = E_{F\uparrow} - E_{F\downarrow}$

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

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

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

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



Spin dependent drop of the electro-chemical potential

Discontinuity increases the spin accumulation in NM

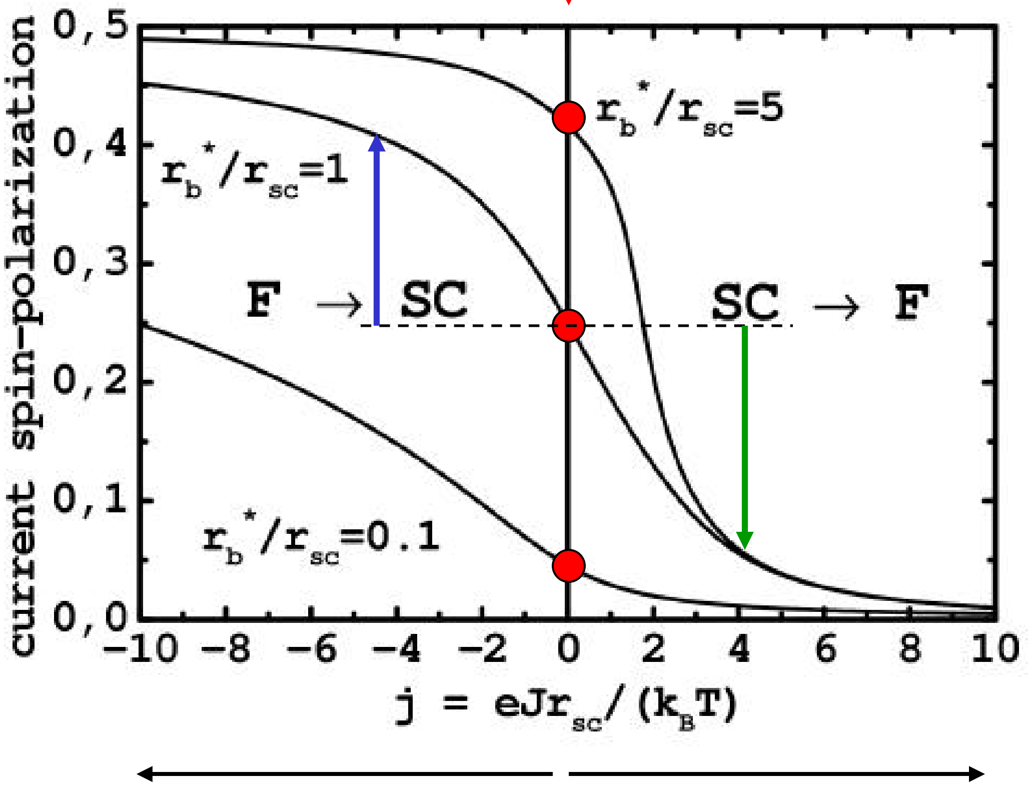
re-balanced spin relaxations in F and NM

extension of the spin-polarized current into the semiconductor

Rasbah, PR B 2000
A.F-Jaffrès, PR B 2001

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)

Spin transfer

(tranport of magnetization by an electrical curent)

- fundamentals

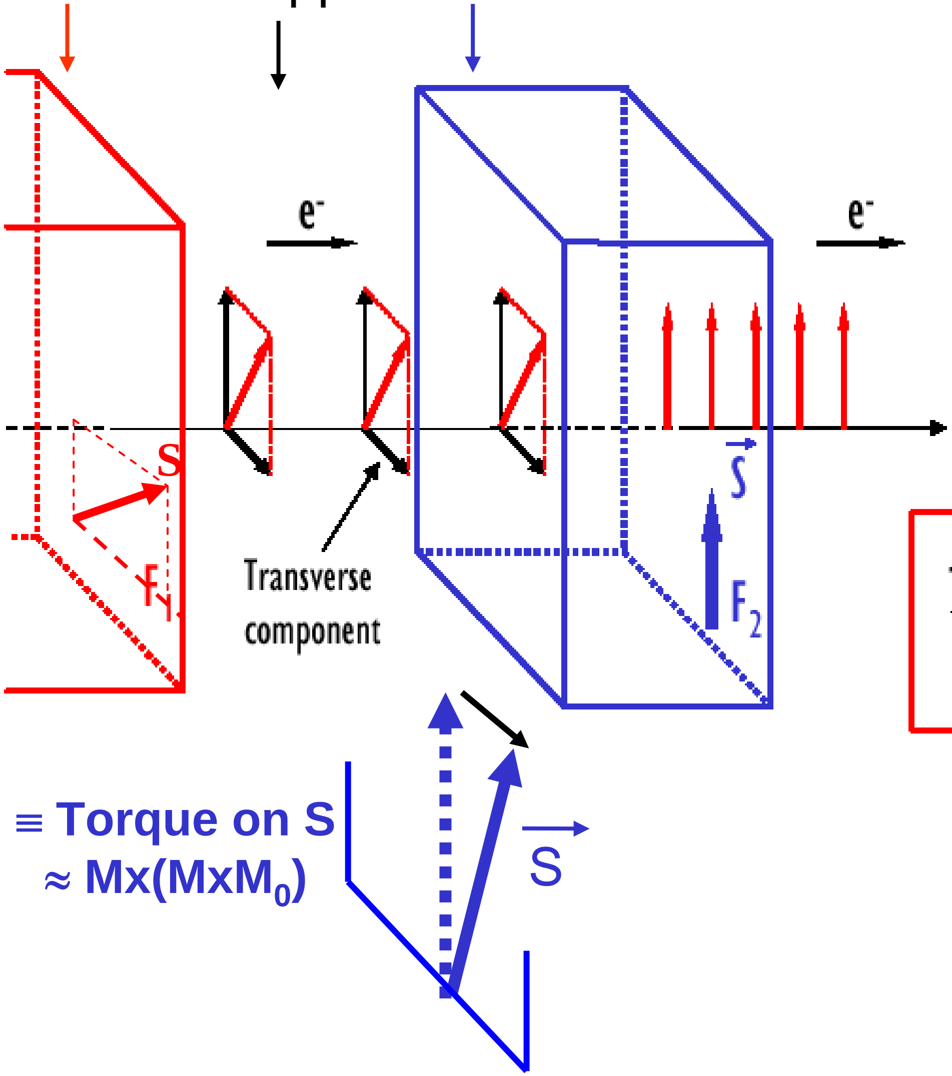
- switching of magnetization by spin transfer and applications (STT-RAM, reprogrammable devices)

- microwave oscillations by spin transfer and applications to telecommunications.s

Spin transfer

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

Ex:Cobalt/Copper/ Cobalt

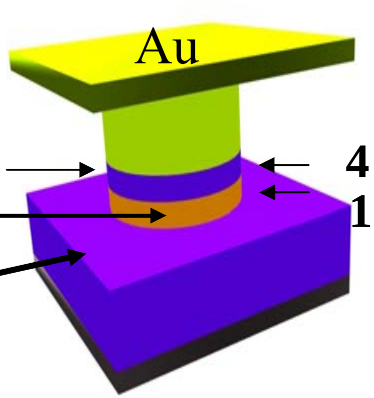


≡ Torque on S
≈ Mx(MxM$_0$)

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

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

Trilayered pillar or tunnel junction



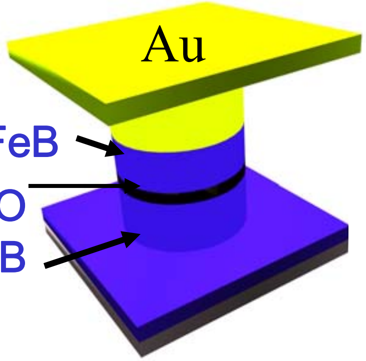
Free magn. layer

Cu

Polarizer

Metallic pillar ≈ 50x150 nm^2

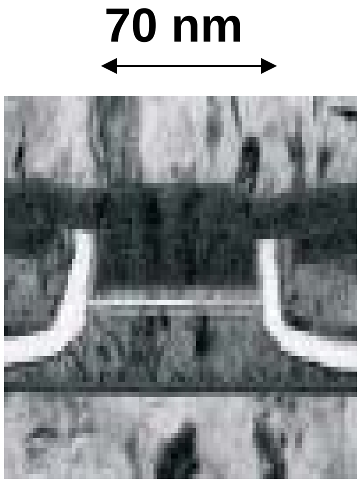
Tunnel junction ≈ 50x170 nm^2



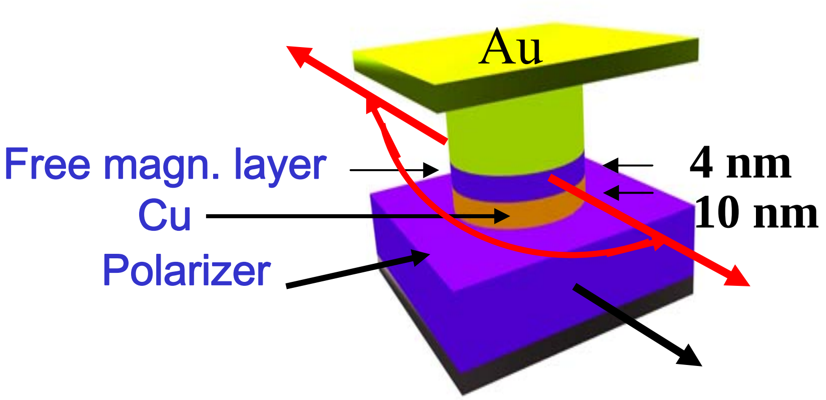
CoFeB

MgO

CoFeB

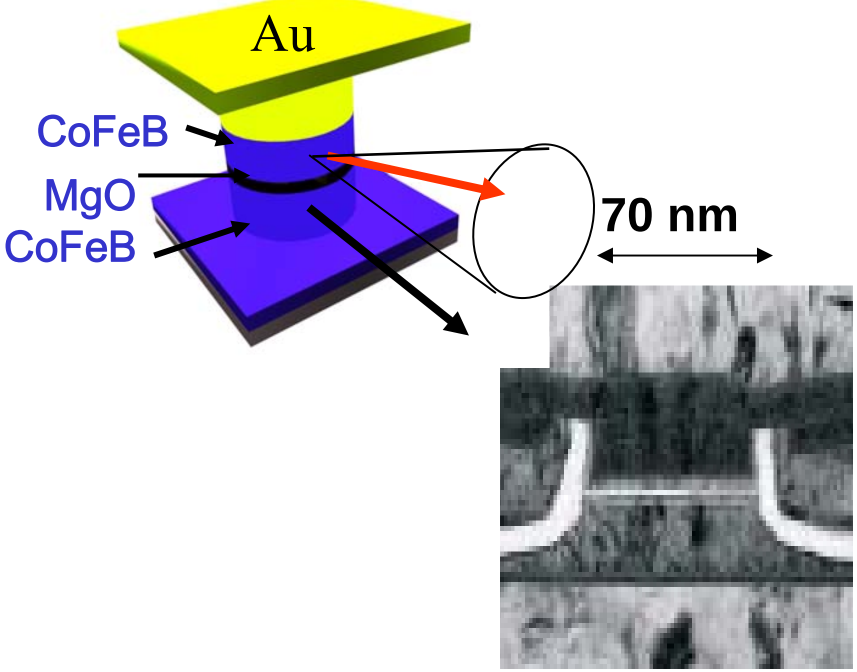


Trilayered pillar or tunnel junction



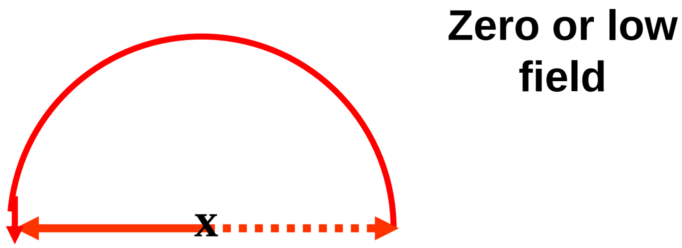
Metallic pillar ≈ 50x150 nm²

Tunnel junction ≈ 50x170 nm²



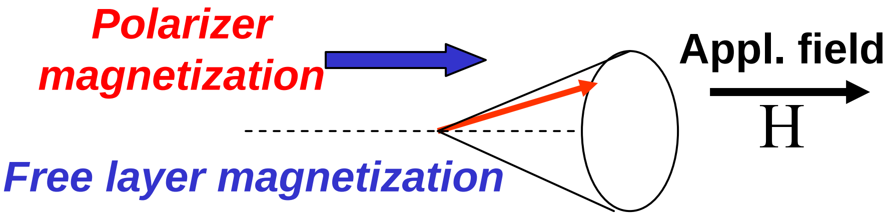
Two regimes of spin transfer

1) Magnetization switching by spin transfer



Applications: writing a memory, etc

2) Sustained precession of the magnetization of the free layer and generation of radio-frequency oscillations



Applications: spin transfer nano-oscillators (NSTOs) for communications (telephone, radio, radar)

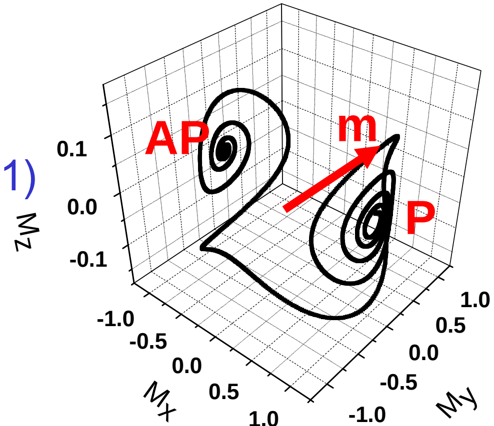
Regime of irreversible magnetic switching

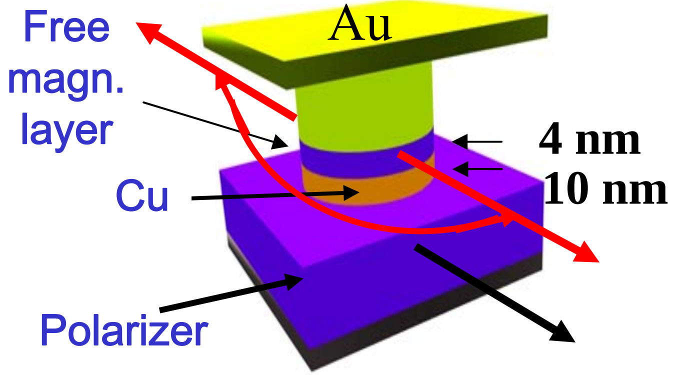
First experiments on pillars:

Cornell (Katine et al, PRL 2000)

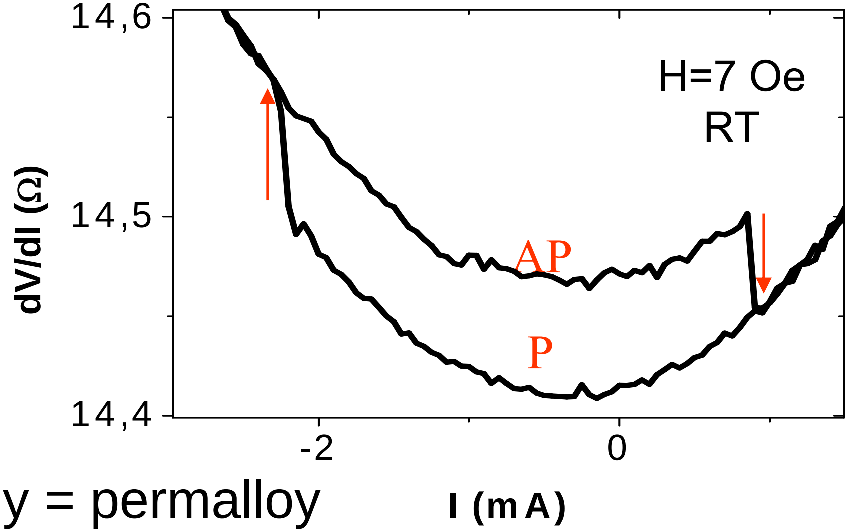
CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)



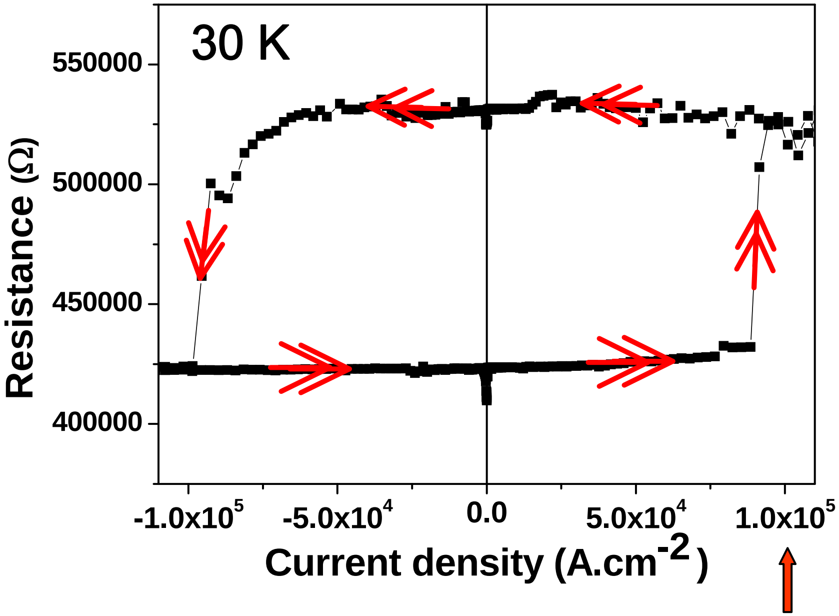


Py/Cu/Py 50nmX150nm (Boulle, AF et al)



Py = permalloy

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

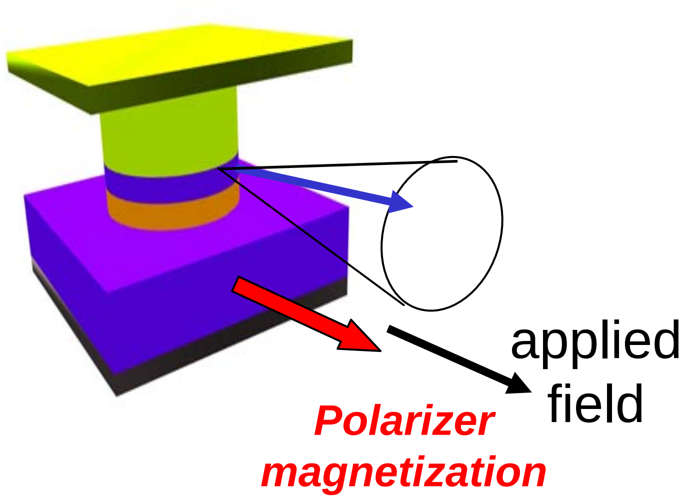


1×10^5 A/cm^2

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

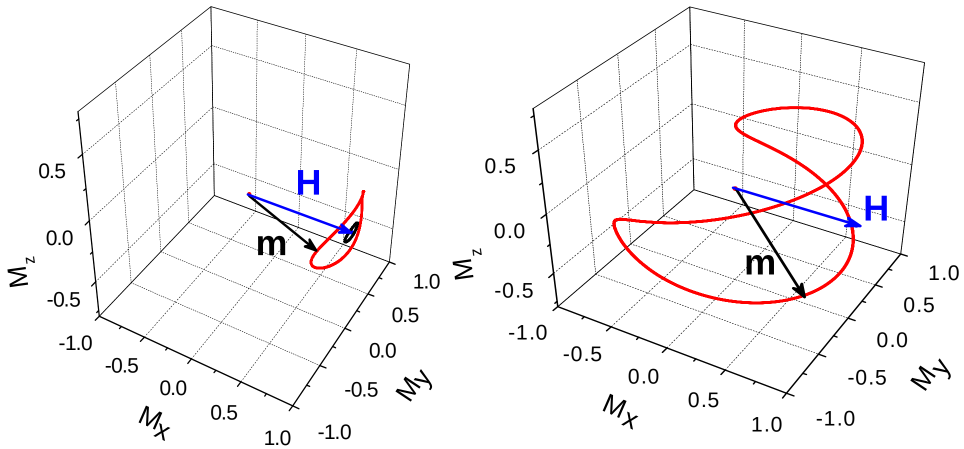
switching time can be as short as 0.1 ns (Chappert et al)

Regime of steady precession (microwave frequency range)

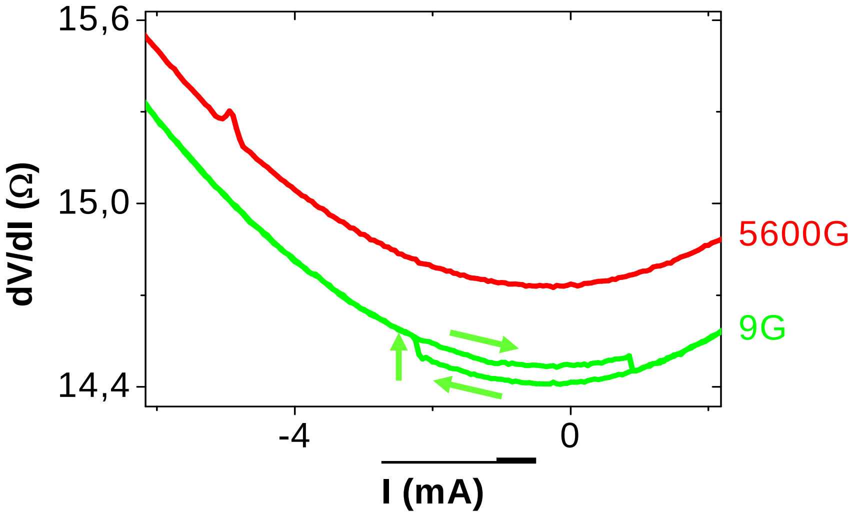


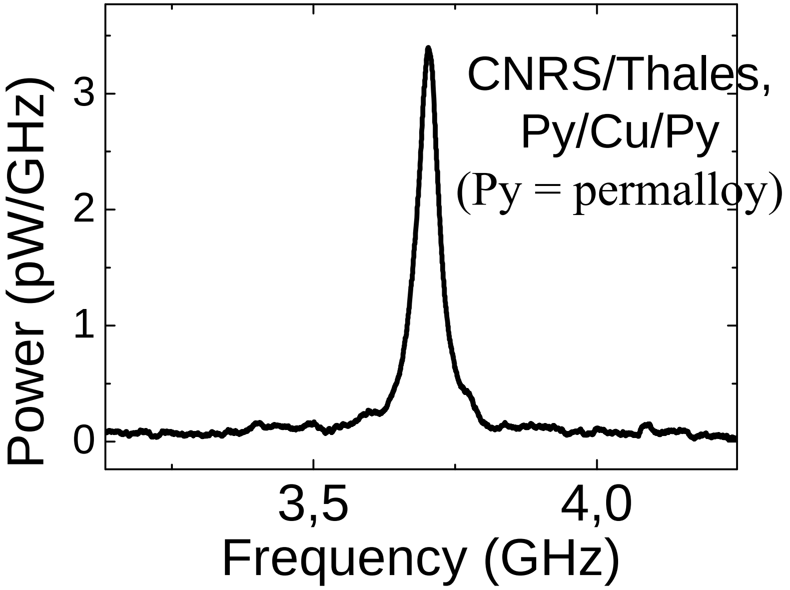
applied field

Polarizer magnetization



Increasing current



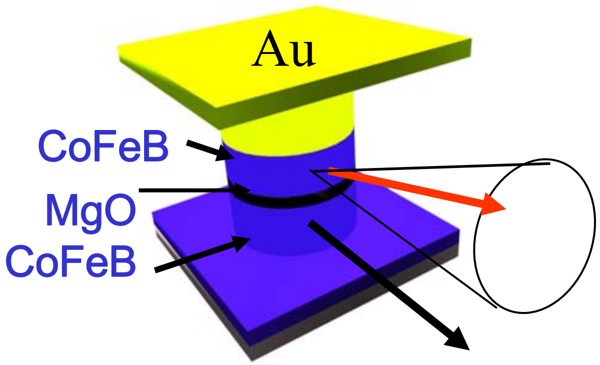


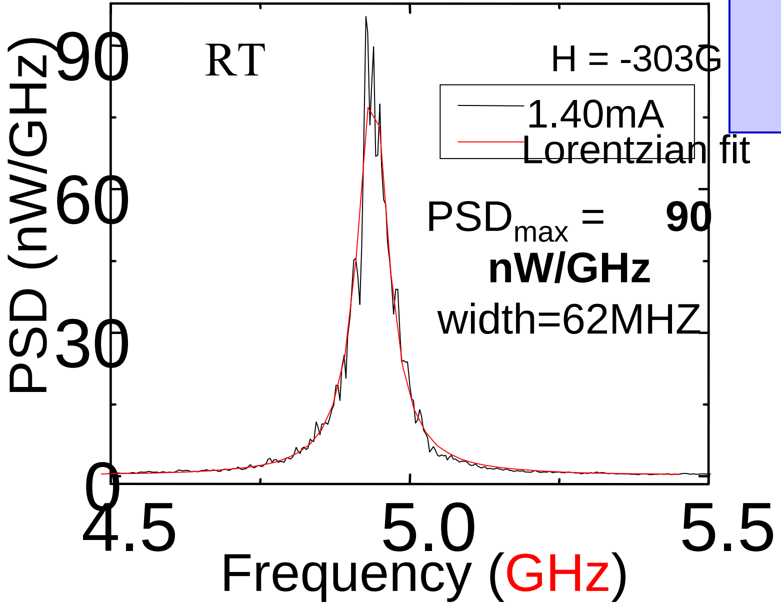
CNRS/Thales,
Py/Cu/Py
(Py = permalloy)

Microwave power spectrum of the oscillations of a permalloy-based pillar

Regime of steady precession for tunnel junctions

Tunnel junction ≈ 50x170 nm²





Spin Transfer mixes very different (and interacting) problems:

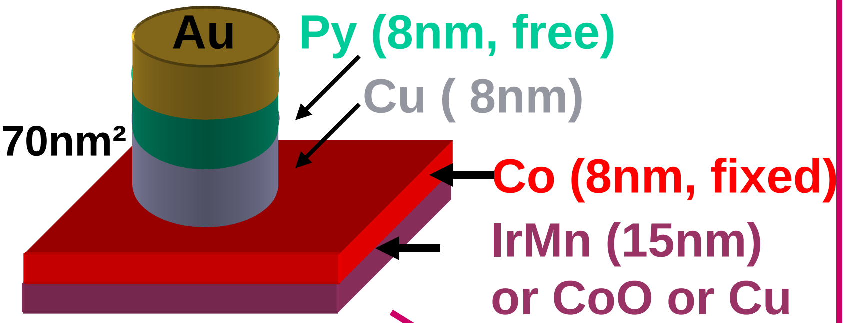
transport (in metallic pillars, tunnel junctions, point contacts)

problems of non-linear dynamics

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

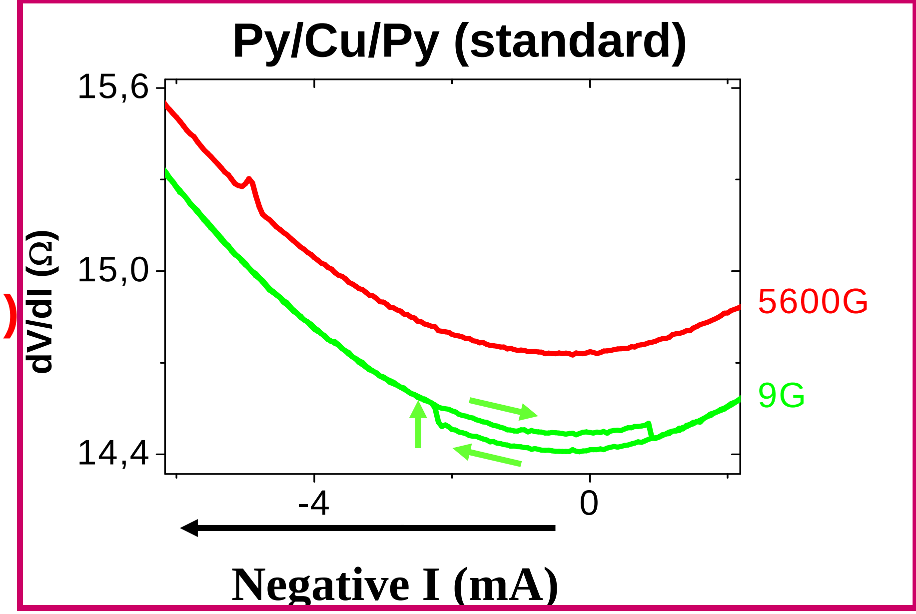
CoFeB/MgO/CoFeB junction **(J.Grollier, AF et al 2008, collaboration S. Yuasa et al, AIST)**

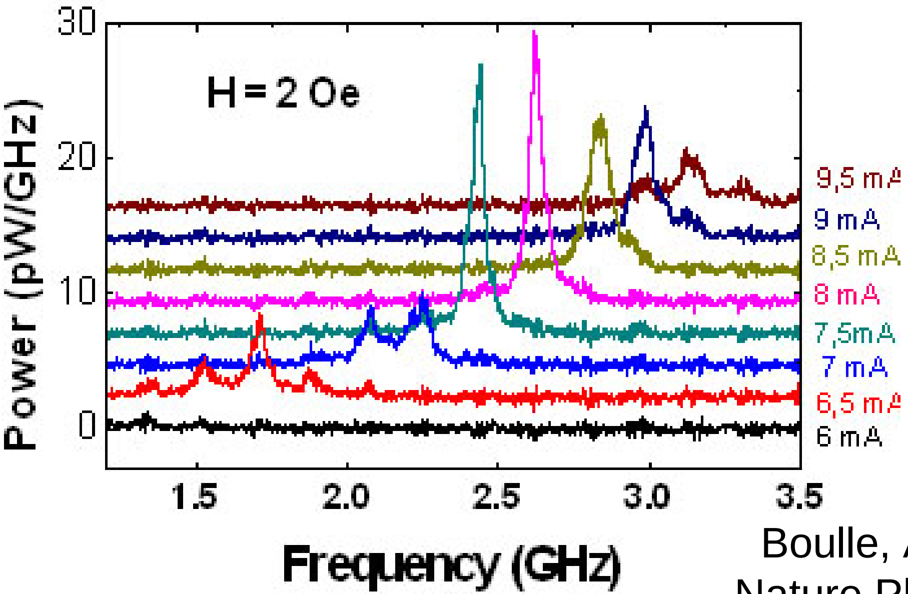
Co/Cu/Py (« wavy » angular variation calculated by Barnas, AF et al, PR B 2005)

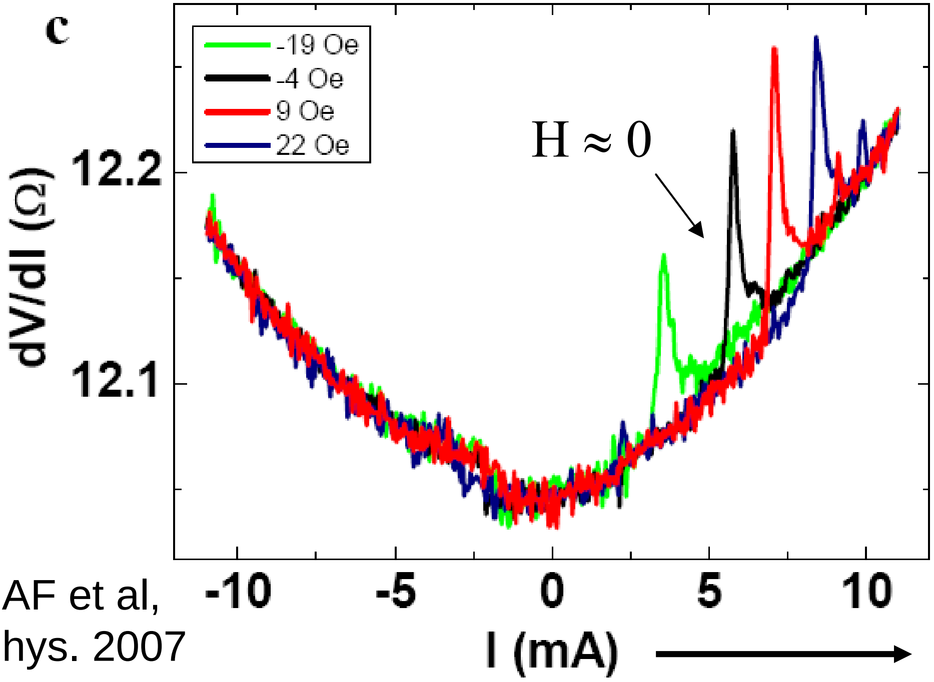


free Py:fast spin relaxation

fixed Co: slower spin relaxation







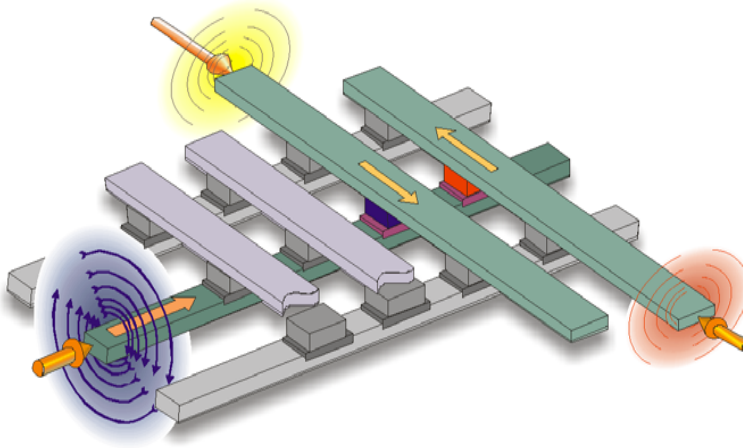
Boulle, AF et al, Nature Phys. 2007
oscillations at H=0

Positive I

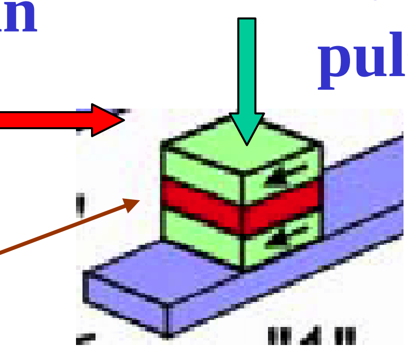
Applications of magnetic switching by spin transfer

Switching of reprogrammable devices (example: STT-RAM)

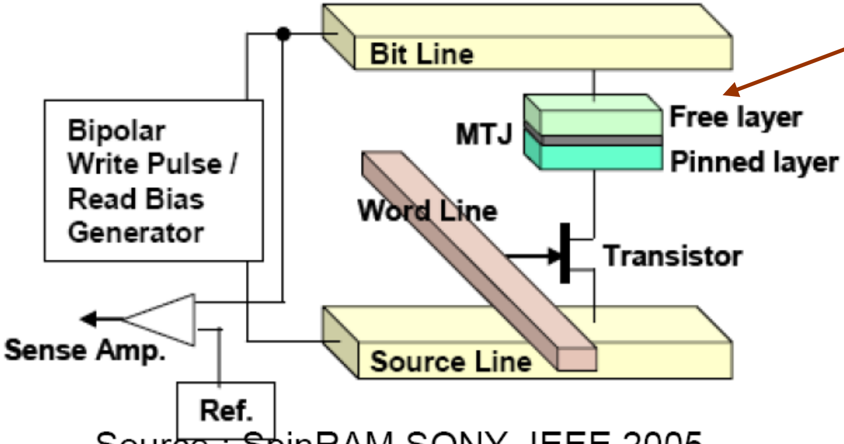
To replace M-RAM (switching by external magnetic field : ***nonlocal, risk of « cross-talk » limiting integration, too large currents)***



STT-RAM :«Electronic» reversal by spin transfer from an electrical current



Current pulse



Source : SpinRAM SONY, IEEE 2005

Applications of magnetic switching by spin transfer

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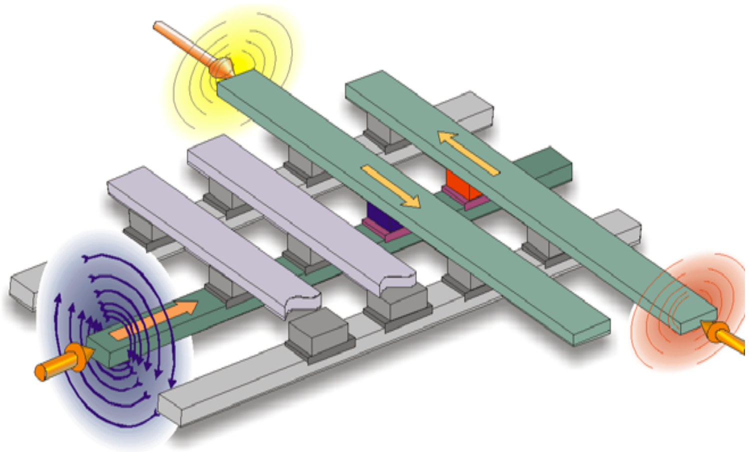

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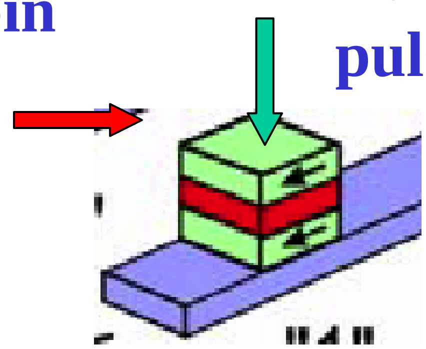
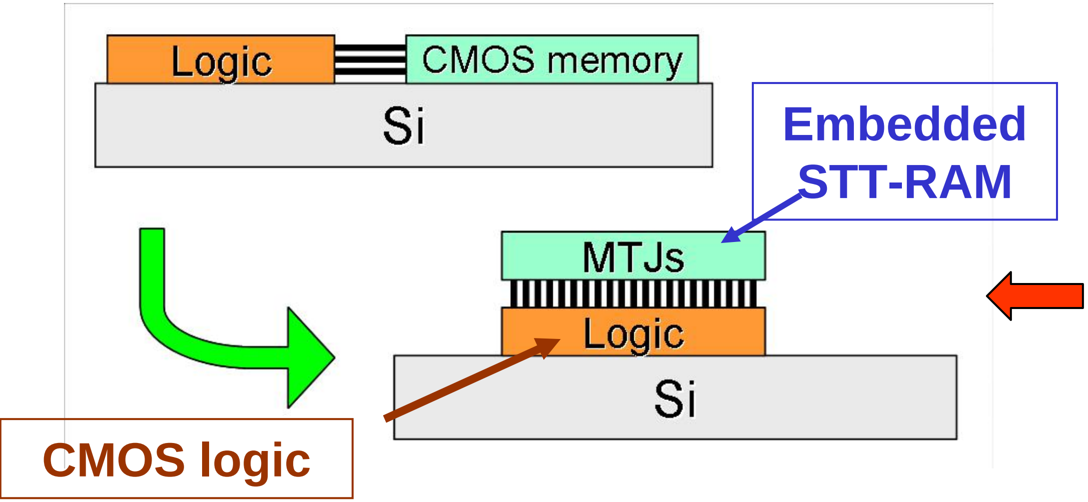
Current pulse





Embedded STT-RAM

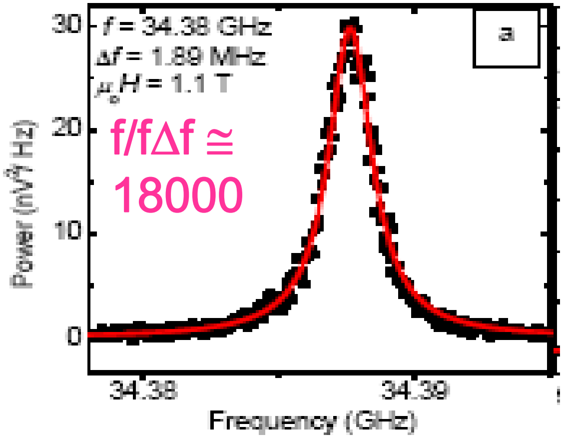
CMOS logic

Non volatile FPGA Logic Circuits

Flash and SRAM would be replaced by a non volatile memory (<10F^2) embedded directly inside the look up table (Sony, IEEE Proc. 07)

Spin Transfer Oscillators (STOs)

(telecommunications, radar, chip to chip communication…)



$f/f\Delta f \cong$ 18000

Advantages:

-direct oscillation in the microwave range (0.5-40 GHz)

-agility: control of frequency by dc current amplitude

- high quality factor

- small size (≈ 0.1μm) (on-chip integration, chip to chip com., microwave assisted writiing in HDD)

-Needed improvements

-- Increase of power by synchronization of a large number N of STOs (x N^2)

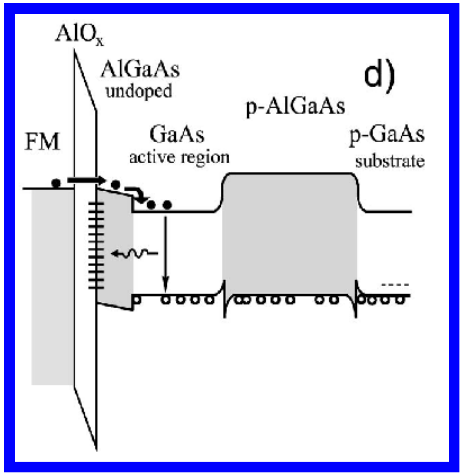
-Optimization of the emission linewidth

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)

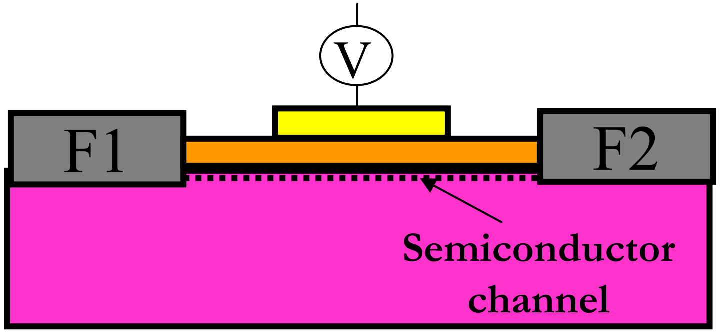
GaMnAs ($T_c \rightarrow 170K$) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

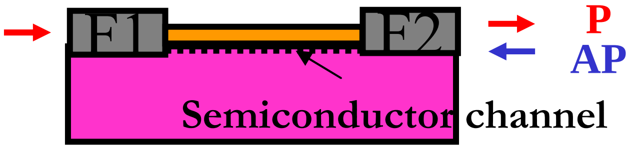
Logic devices, spin transistor ?



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:

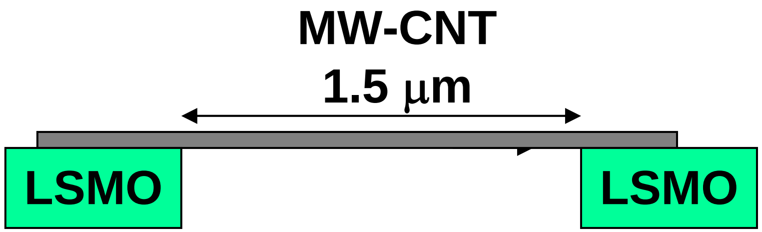


« Measured effects of the order of **0.1-1%** have been reported for the change in voltage or resistance (between P and AP)…. », *from the review article « Electrical Spin Injection and Transport in Semiconductors » by BT Jonker and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 2006)*

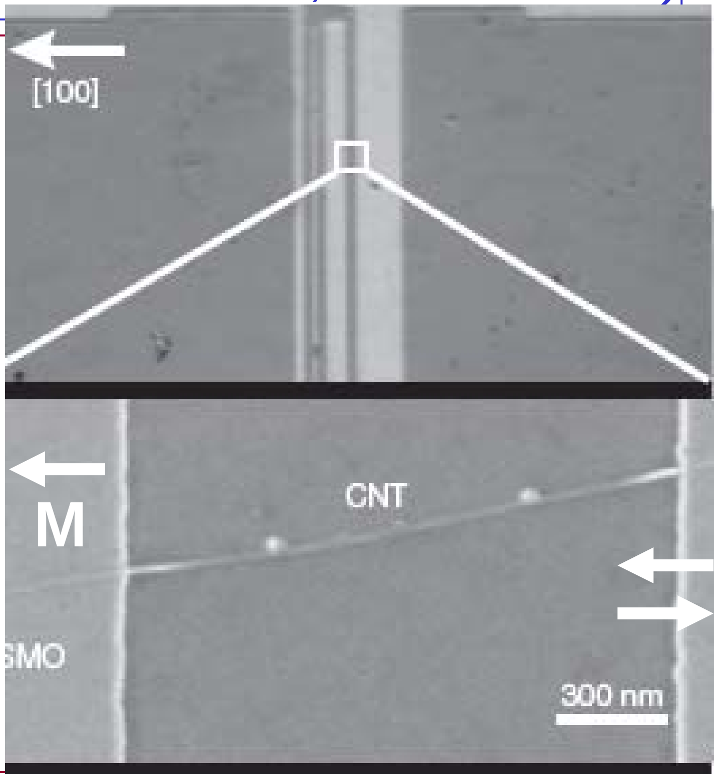
L.Hueso, N.D. Mathur,A.F. et al, Nature 445, 410, 2007

Carbon nanotubes:

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



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



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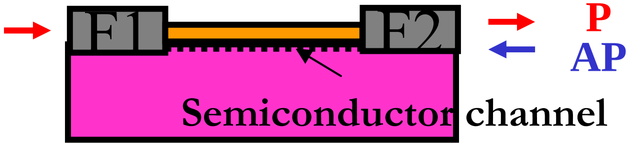

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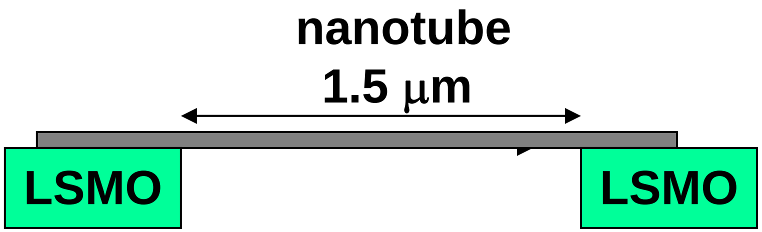

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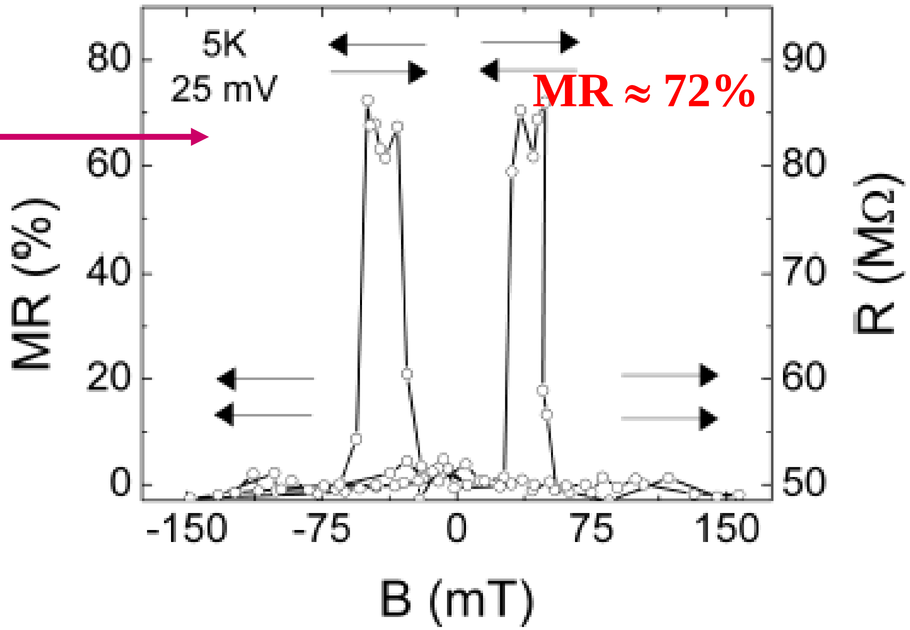

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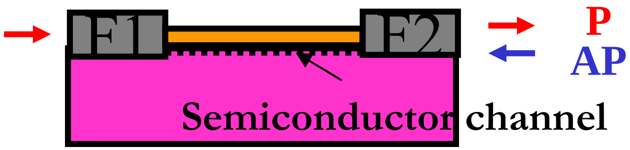

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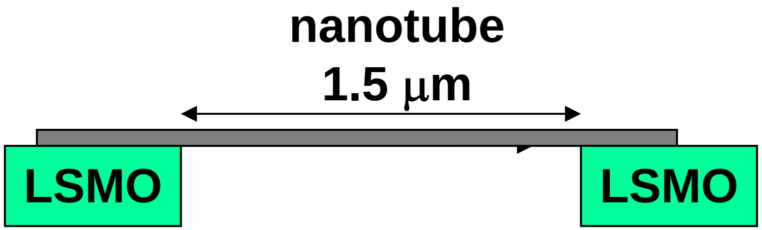

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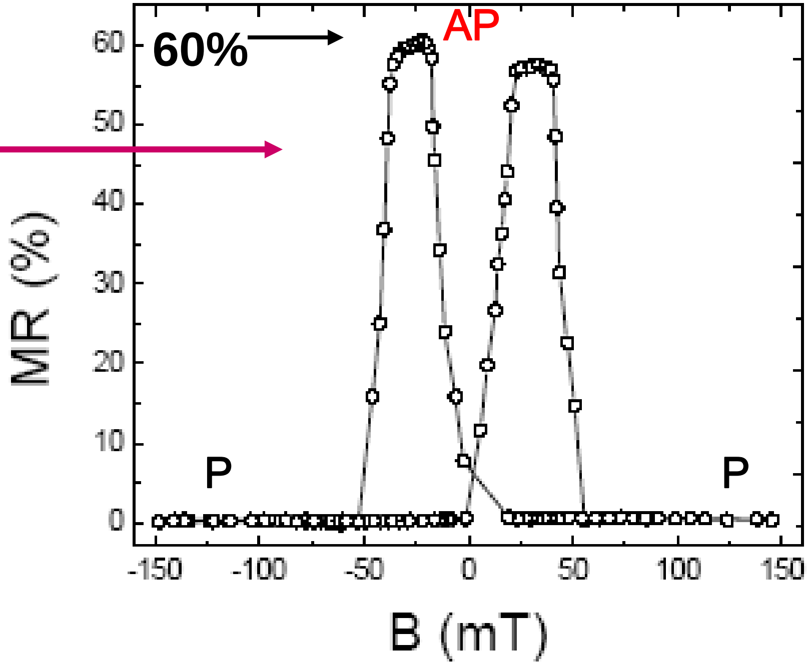


L.Hueso, N.D. Mathur,A.F. et al, Nature 445, 410, 2007

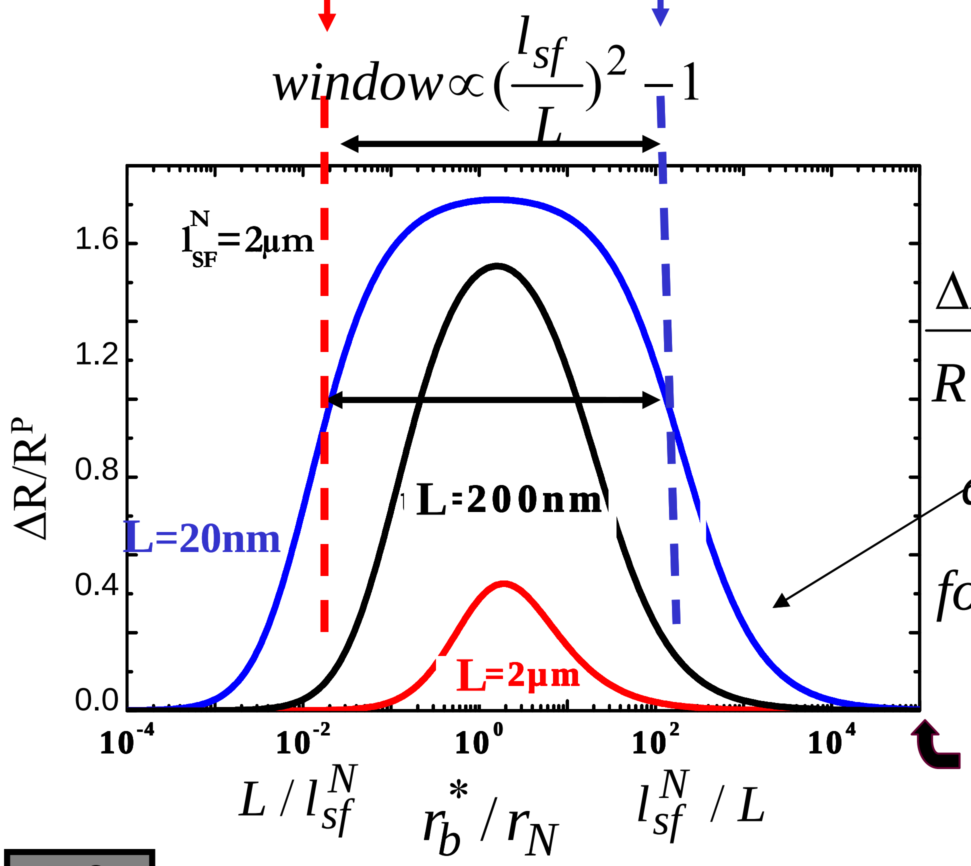
Two interface spin transport problem (diffusive regime)

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

IEEE
Transactions.on
Electronic
Devices.
54,5,921,2007

Condition for
spin injection

Condition
dwell time τ_n < spin lifetime τ_{sf}



dwell time

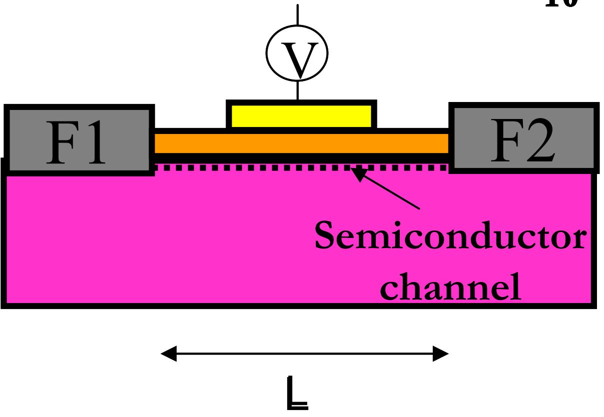
$$\tau_n = \frac{2L}{t_r^* v} \propto \frac{L\ r_b^*}{v}$$

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

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 (calc.with $\gamma = 0.8$)

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

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

Two interface spin transport problem (diffusive regime)

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

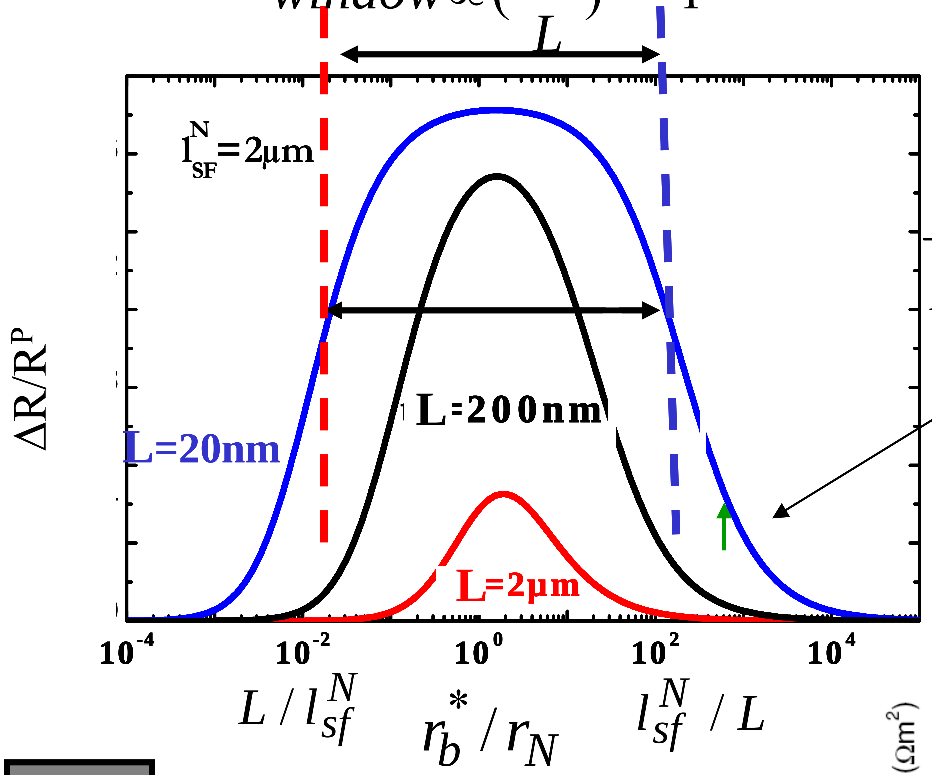
IEEE Tr.El.Dev*.
54,5,921,2007

*calculation. for
Co and GaAs
at RT

Condition for
spin injection

Condition
dwell time τ_n < spin lifetime τ_{sf}

$$window \propto \left(\frac{l_{sf}}{L}\right)^2 - 1$$



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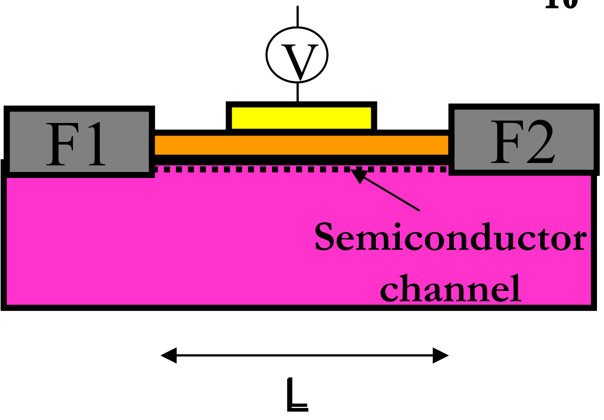
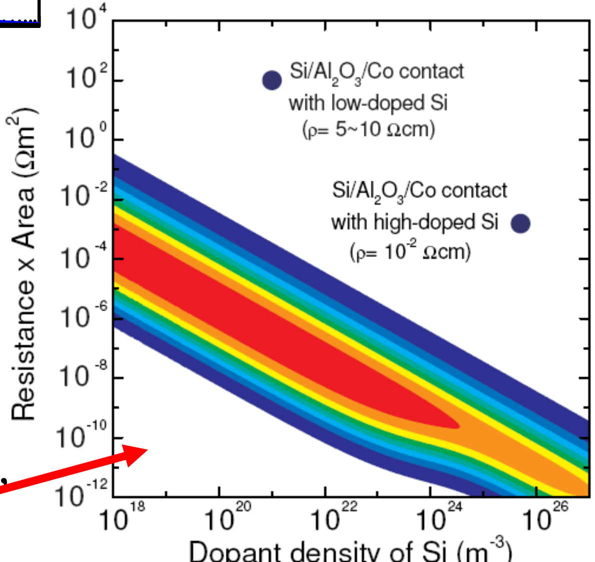


Window only for $l_{sf}(N) > L$

Min, Motihashi, Lodder and Jansen,
Nature Mat. 5, 817, 2006



Two interface spin transport problem (diffusive regime)

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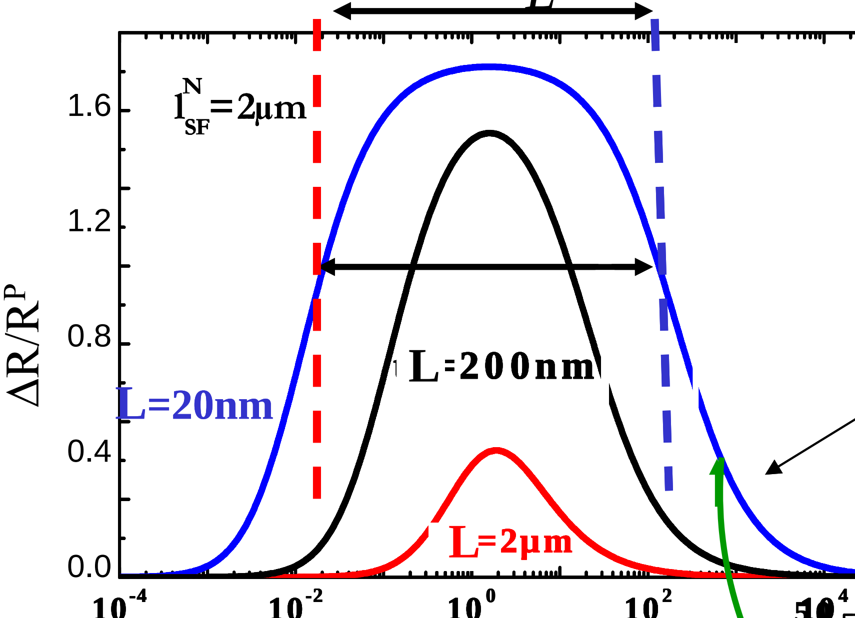
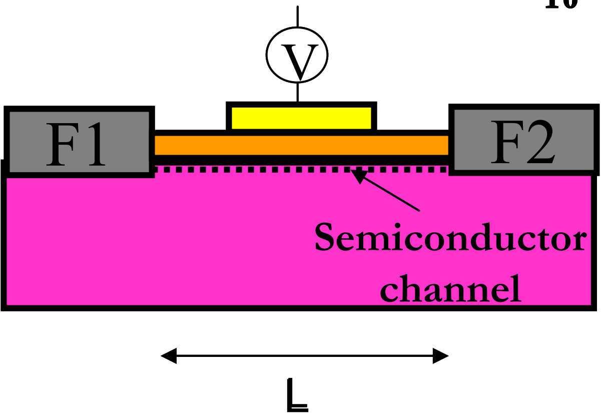


dwell time

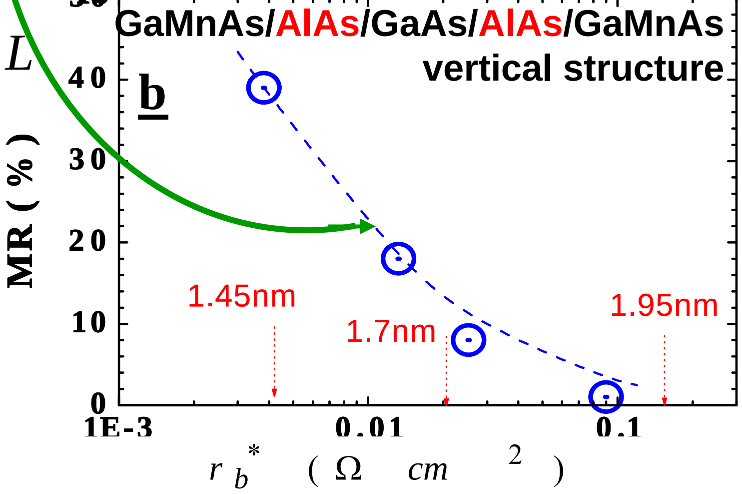
$$\tau_n = \frac{2L}{t_r^* v} \propto \frac{L\, r_b^*}{v}$$

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

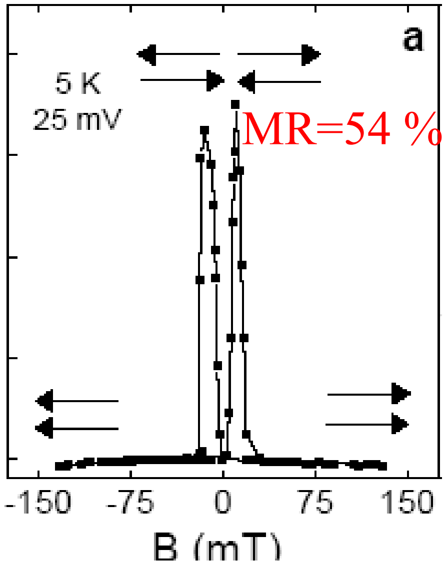
drops to zero as $1/r_b^*$ *as in this example (Mattana, AF et al)*

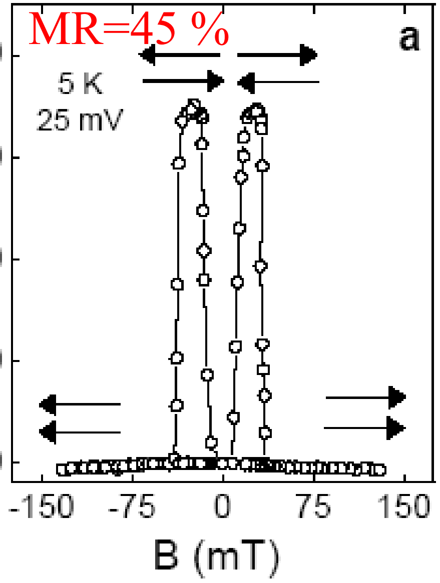


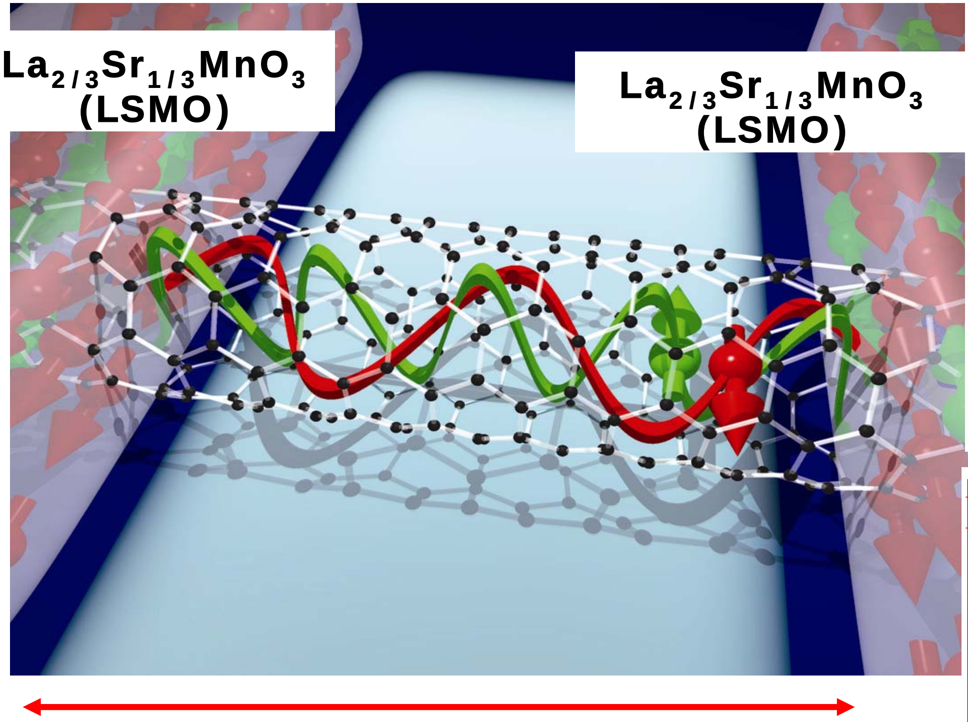
Window only for $l_{sf}(N) > L$



Carbon nanotubes between spin-polarized sources and drains

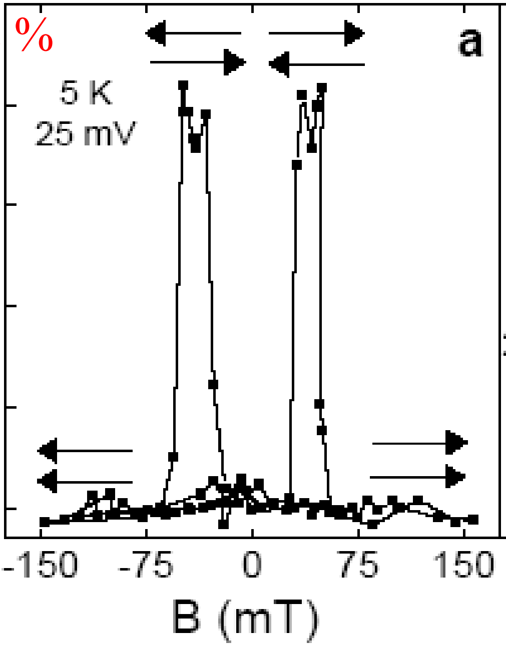


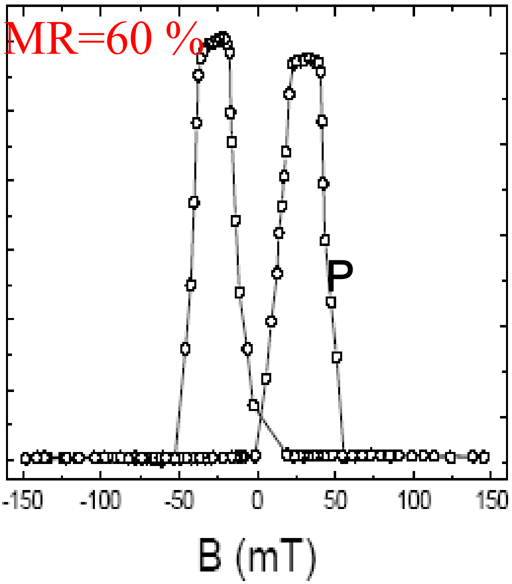




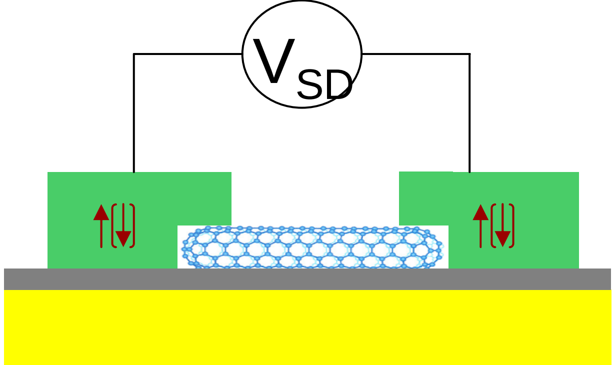
L ≈ 1-2 μm

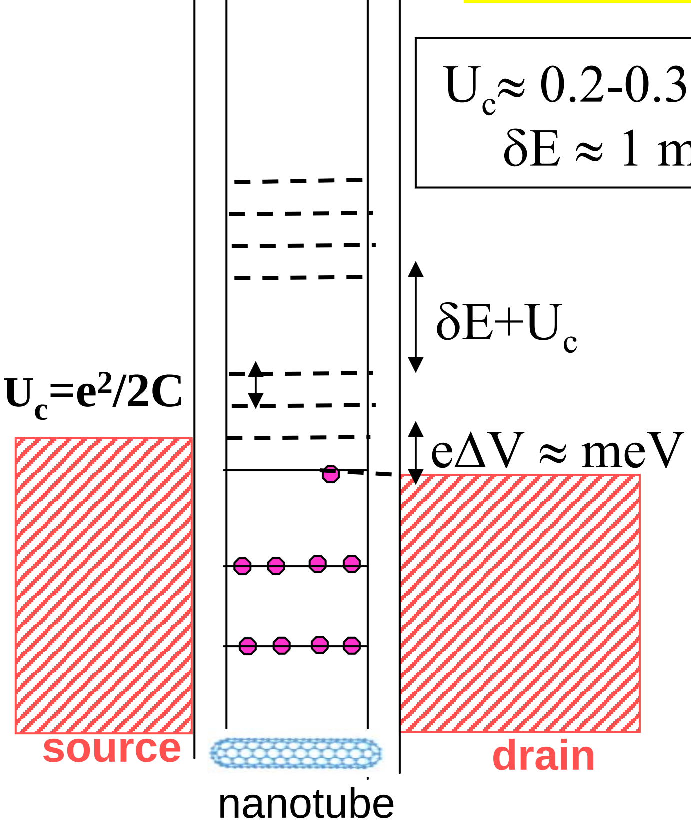
Artist: Takis Kontos





Usual conditions: experiments at small bias voltage

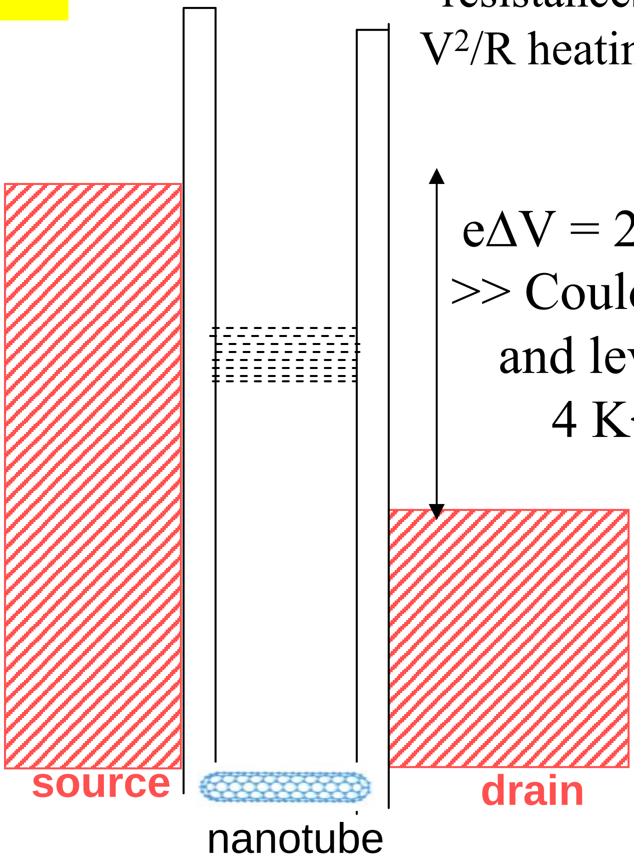




$U_c \approx$ 0.2-0.3 meV,
$\delta E \approx$ 1 meV

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

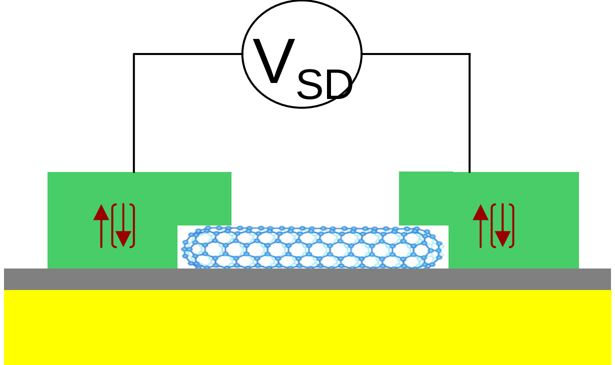
LSMO/CNT/LSMO: experiments at higher voltage, thanks to relatively large interface resistances and small V^2/R heating at large V

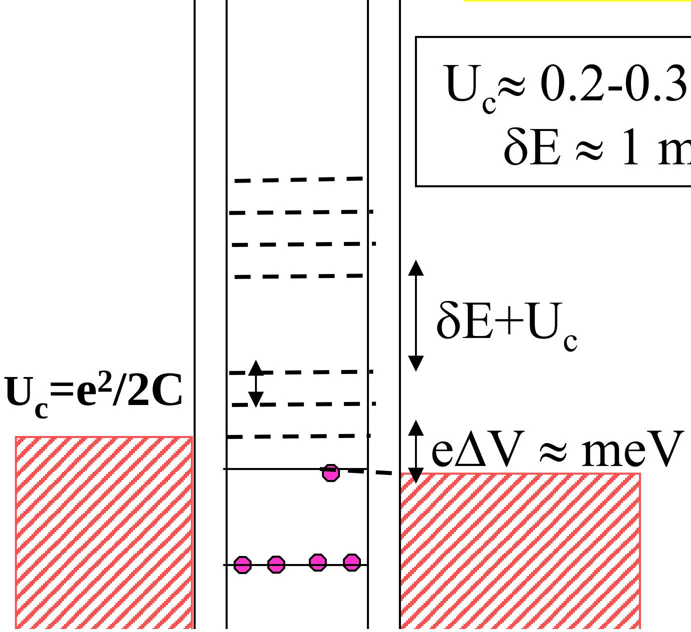


$e\Delta V$ = 25-500 meV >> Coulomb energy and level spacing, 4 K< T <120 K

Quasi-continuous DOS, same conditions as for semiconducting or metallic channel (also diffusive transport regime)

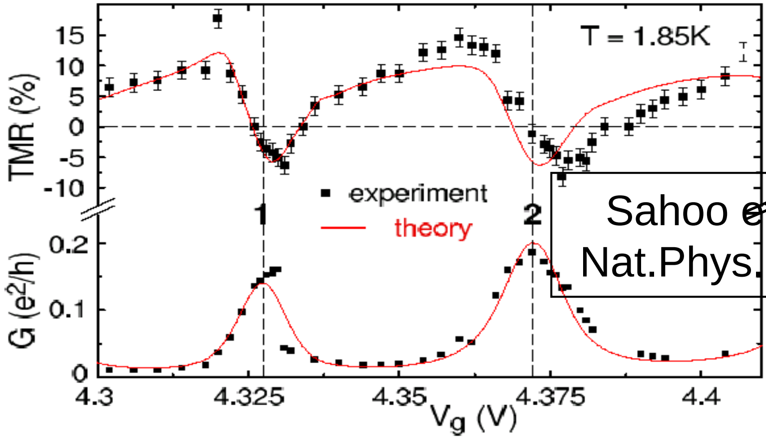
Usual conditions: experiments at small bias voltage





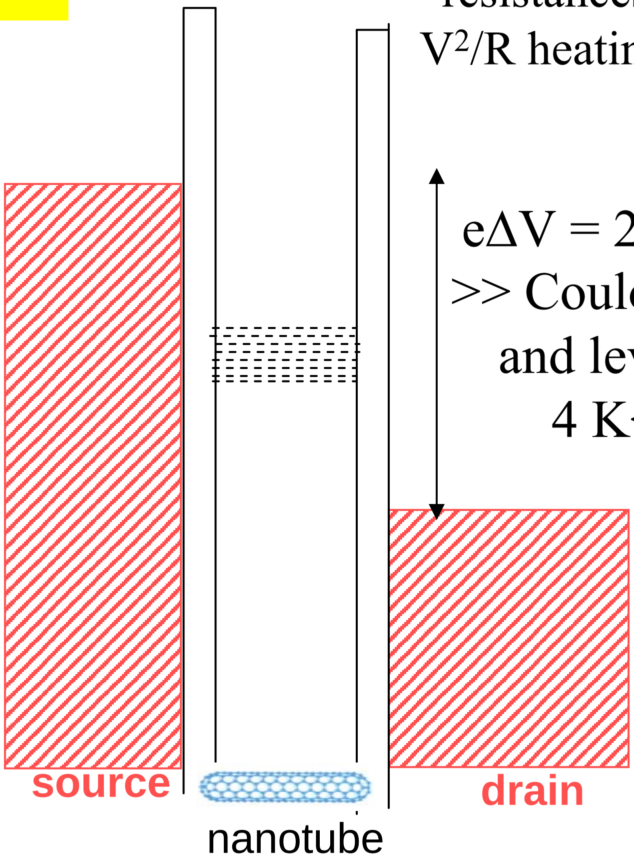
$U_c≈$ 0.2-0.3 meV, δE ≈ 1 meV

$U_c=e^2/2C$



Sahoo et al, Nat.Phys.2005

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



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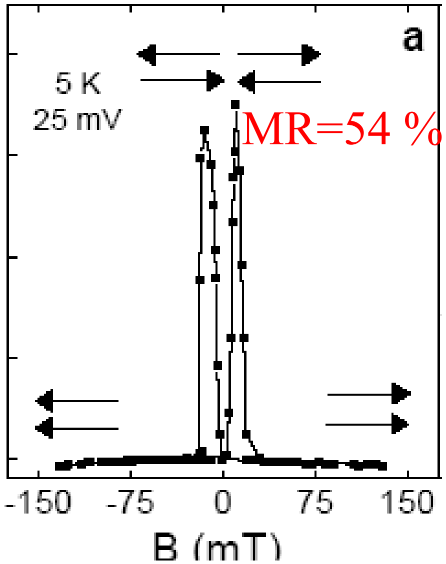
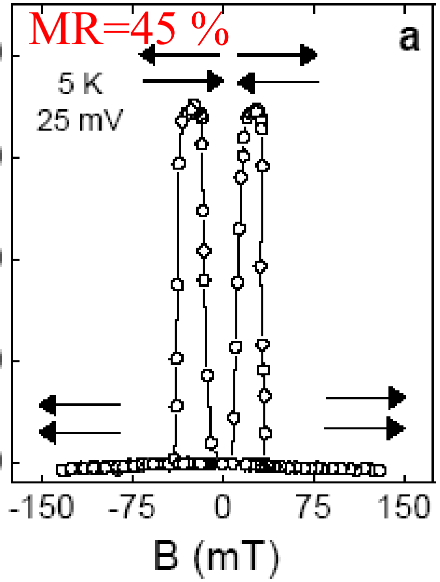
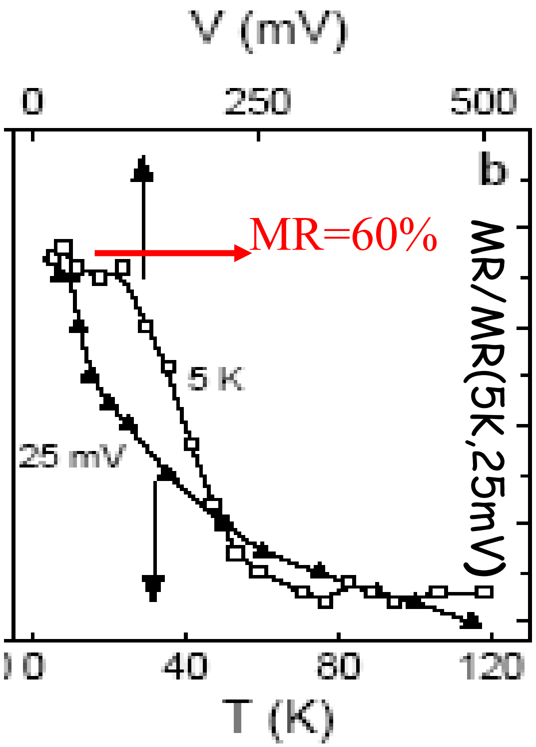


MR=54 %

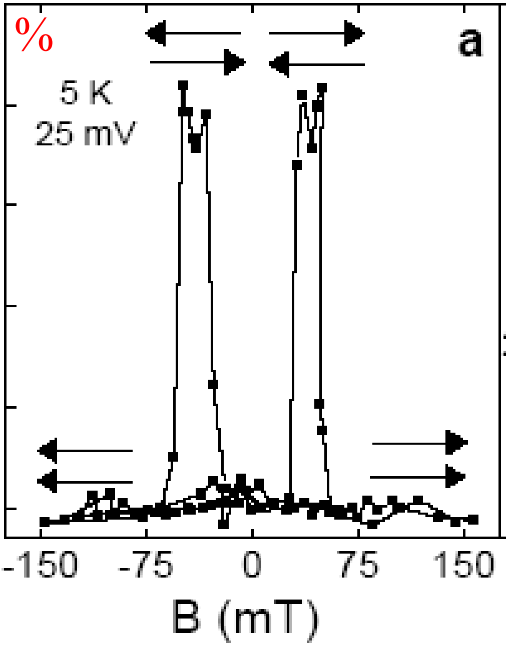


MR=45 %

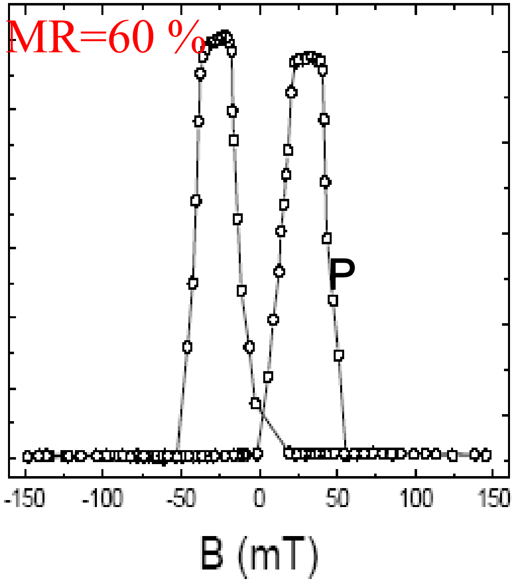


MR=60%

Bias and temperature dependence of MR



MR=72 %



MR=60 %

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* $\tau_n < \tau_{sf}$

with $\tau_n \approx$ 60ns*
(from interface resist.)
fit with $\tau_{sf} \approx$ 30ns
(l_{sf}=48μm) and γ = 0.8
→ $\tau_n \approx \tau_{sf}$
(Hueso, AF et al,Nat.07)

Nanotubes (also graphene, other molecules) :

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

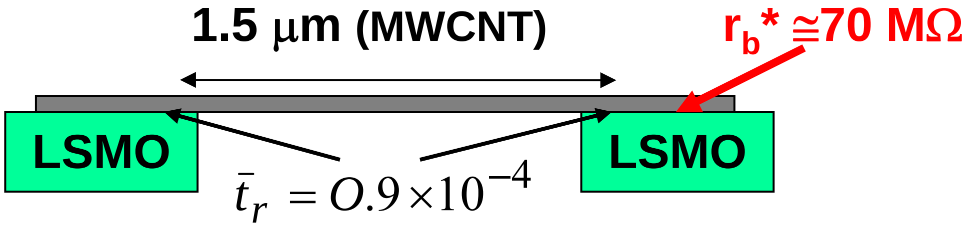
$high\ \ velocity\ \ v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r}$ *can be relatively short* (60 *ns*)*

Semiconductors:

τ_{sf} *can be as long as in CNT* (*for* $n \approx 10^{16-17}\ el/cm^3$)

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 r_b^*



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) :

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

Semiconductors:

$$\tau_{sf}\ \ can\ be\ as\ long\ as\ in\ CNT\ \ (for\ \ n \approx 10^{16-17}\ el\,/\,cm^3)$$

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

- $\tau_n \approx$ 60ns*,

τ_{sf} > 4 ns if γ < 0.95

or $\tau_{sf} \approx$ 30ns

(l_{sf}=48µm) for γ = 0.8

$\rightarrow \tau_n \approx \tau_{sf}$

(Hueso, AF et al,Nat.07)

Solution for semiconductors:

shorter L ?, larger transmission t_r ?

Improvement for nanotubes:

slightly larger transmission t_r and **longer spin lifetime** with the **spin polarization directed along the tube**

Nanotubes, graphene..

Next challenge for nanotubes (or graphene…):

spin control by a gate potential

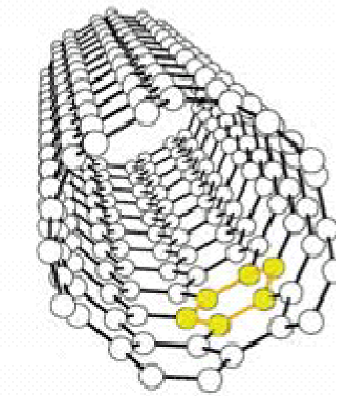
Molecules in general

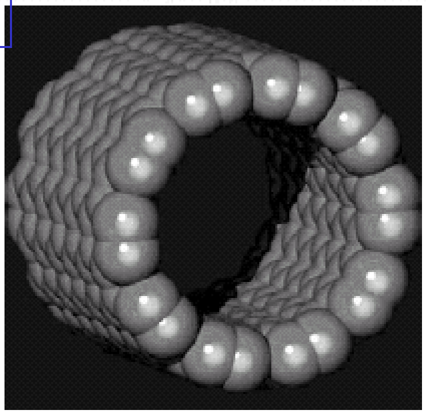
Promising potential of molecular spintronics

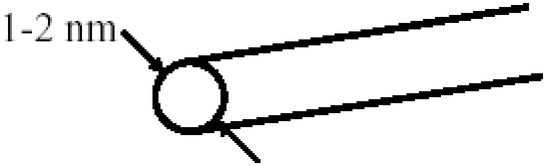
New materials for spintronics (carbon nanotubes, graphene, molecules, ….)

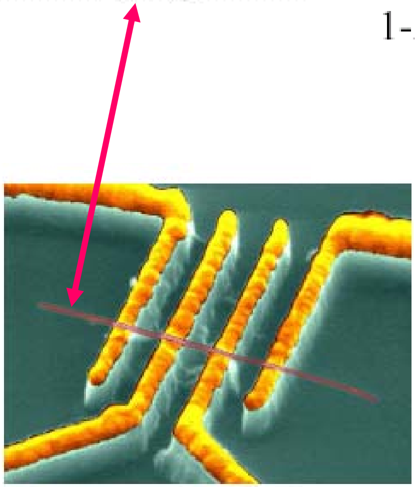
Examples of new materials

Carbon nanotubes

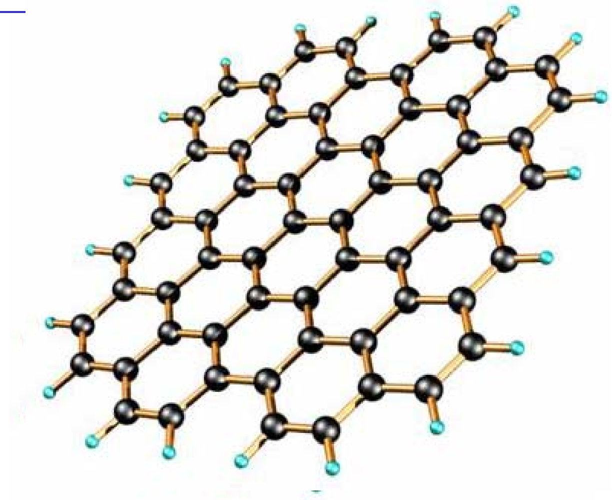


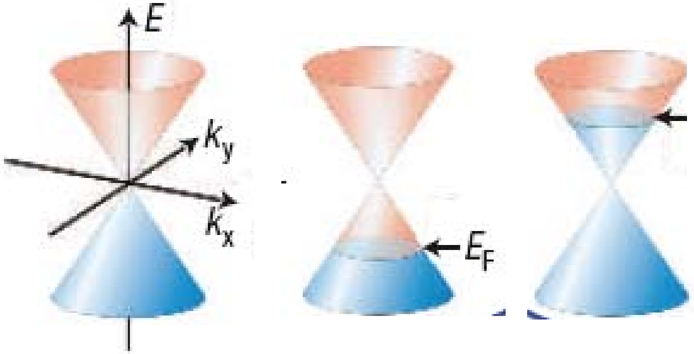


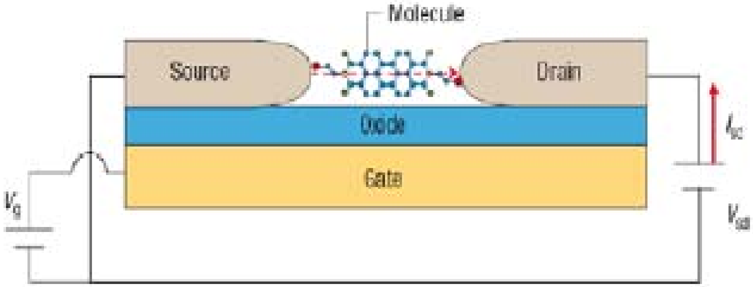




Graphene



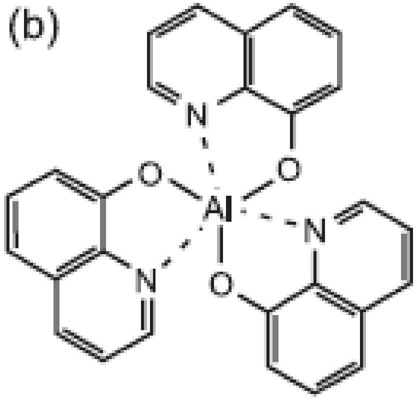


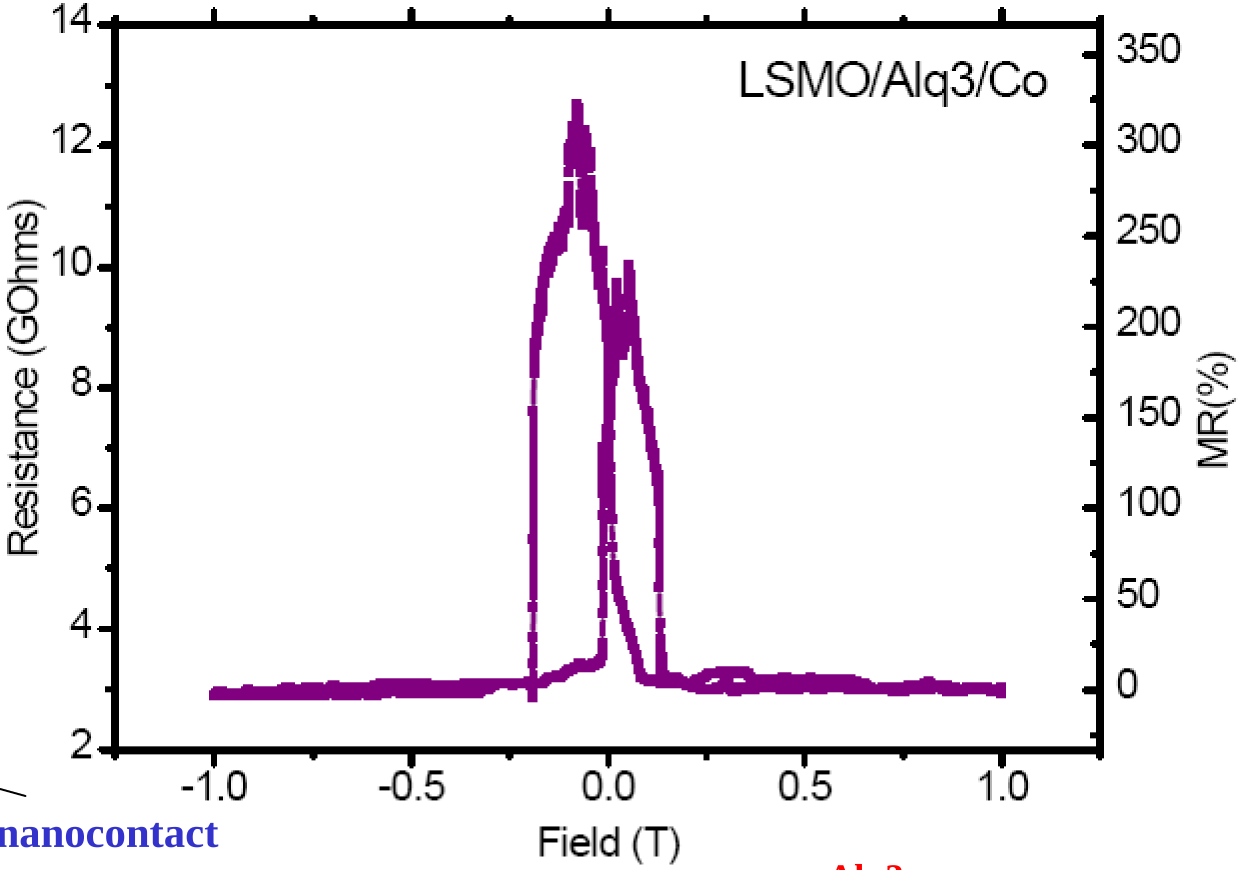


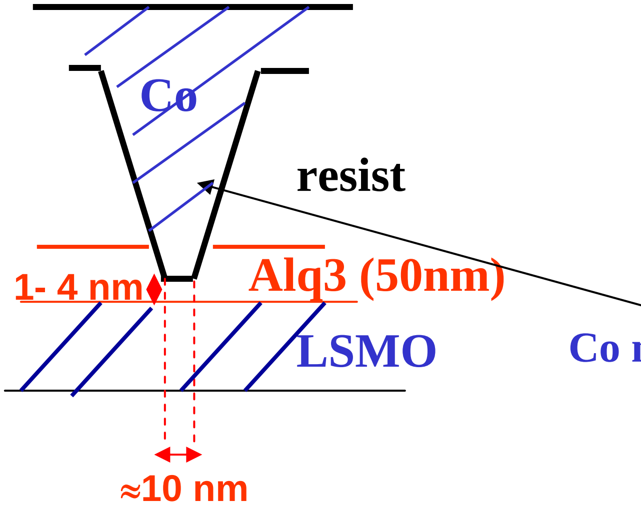
Molecules

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

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







Co

resist

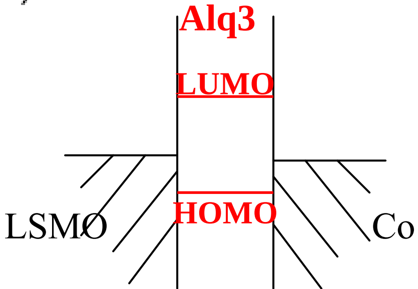
1- 4 nm

Alq3 (50nm)

LSMO

Co nanocontact

≈10 nm



Alq3

LUMO

HOMO

LSMO

Co

Alq3 = π - conjugated 8-hydroxy-quinoline aluminium

The Japan Applied Physics Society Academic Roadmap on Spintronics

Quantum Information

Physics
Physics of spin 1 qubit system
Achieving long coherence time

Progress in qubit media
Superconducting qubits,
photon qubits

→

Hybrid qubit media
Integration of spin, superconductor, photon qubits

Spin quantum computation and quantum memory

Integrated QC

→

Multiple qubits

Quantum communication network
All the backbone networks are protected by quantum cryptography

Quantum computation
Simulations from molecules through proteins to earth-scale ones that could not be done by classical computers are now being done by quantum computers

Spin Photonics

Integration of
High speed electronics
Spintronics
Photonics

→

Spin photo-diodes
Spin light-emitting diodes
Reconfigurable logic elements
Variable polarization diodes

→

High frequency spintronics
Spin photonics

Storage

Density (bits/in^2)

100G	→	1T	→	10T	→	100T
35x180		25x25		8x8		2.5x2.5

bit size (nm x nm)

“Fujitsu” Jan. 2007

TMR →TMR/CPP-GMR → CPP-GMR (new materials, half-metals) →new sensors (new principles (molecular/atomic))
perpend. granular →patterned media (litho) →patterned media (litho+self-assembly) →multibit patterned media

Spin Memory & Logic

MRAM technology F

180 nm	45 nm	32 nm	22 nm
25F^2	20F^2	18F^2	16F^2

MRAM write energy

100 pJ	50 pJ	25 pJ	20 PJ

→

All medical records securely stored in a card allowing patients for full and total treatment

SRAM for Mobiles/ Car electronics →Replace SRAMs in PC → Nonvolatile Logic → Soft brain-like info. processing
→Replace part of DRAM → Nonvolatile reconfigurable logic

Material & New Physics

Materials Research
Multiferroic, transparent, half-metal
RT ferromagnetic semiconductors,
Environment friendly,
Computational design of new materials

→

Spin transistors
Spin current devices/ domain wall devices

Multibit tech. enabled by domain control, multiferroics, ferro. molec. mag.

→

Materials with self-correction
High-μ without rare elements
High moment alloys

New Physics
Current-driven physics
Spin-current, nanomagnetism

Crystal growth with atomic manipulation
Application of strongly correlated materials

2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035

By H. Akinaga, J. Okabayashi, G. Yusa, and H. Oshima

Translated by H. Ohno

http://www.jsap.or.jp/jsap75/academic_roadmap.html (in Japanese)

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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