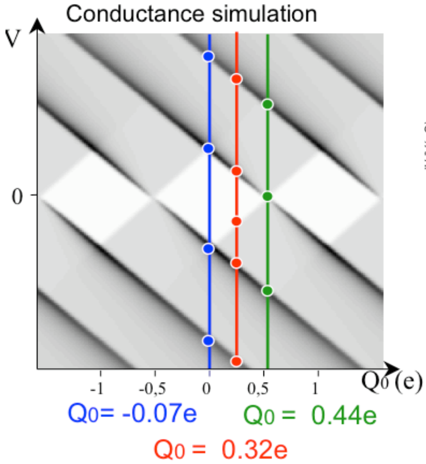
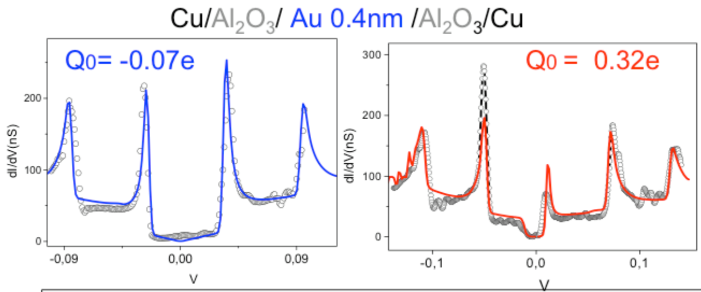
Background charge effect

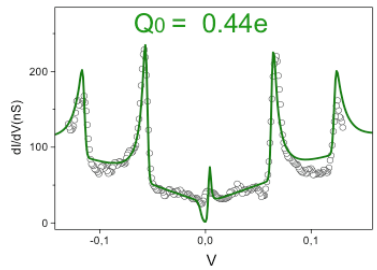


Fixed parameters :

C_1= 2.5aF R_1= 1MΩ
C_2= 2.7aF R_2= 16MΩ

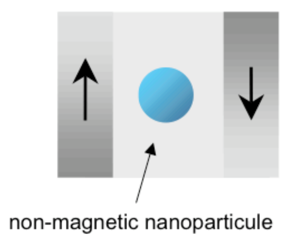


→We are able to connect a single cluster



Spin accumulation

- Effet of spin accumulation in a single non magnetic nanoparticle

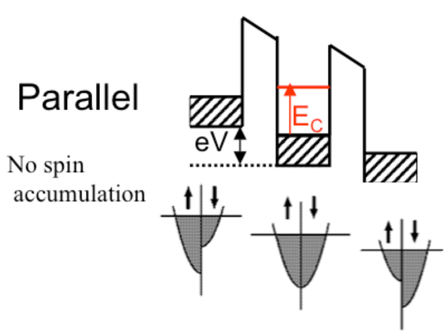


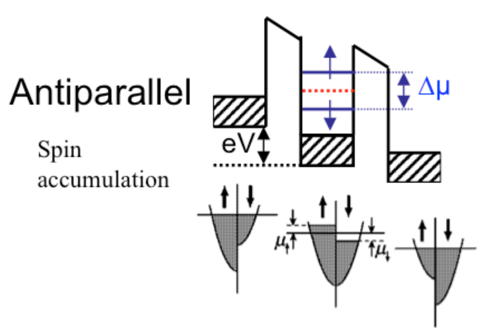
First theoretical predictions:

Barnas Fert, 1998,
Maekawa, 1998,
Braatas et al, 1999

But few experiments

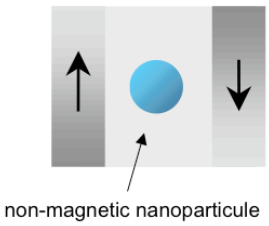
Bernand-Mantel et al. APL 89 062502 (2006)
Wei et al. Cond-mat 0703139 (2007)





Spin accumulation

• Effet of spin accumulation in a single non magnetic nanoparticle



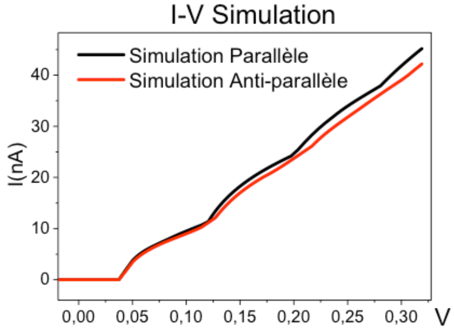
First theoretical predictions:

Barnas Fert, 1998,
Maekawa, 1998,
Braatas et al, 1999

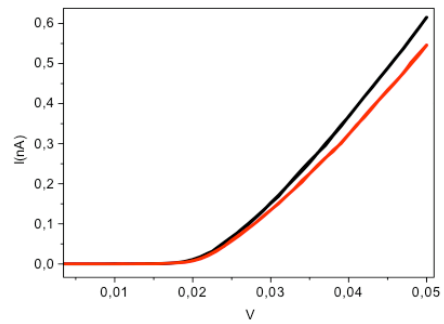
But few experiments

Bernand-Mantel, PS et al. APL 06
Wei et al. Cond-mat 0703139 (2007)

I-V Simulation



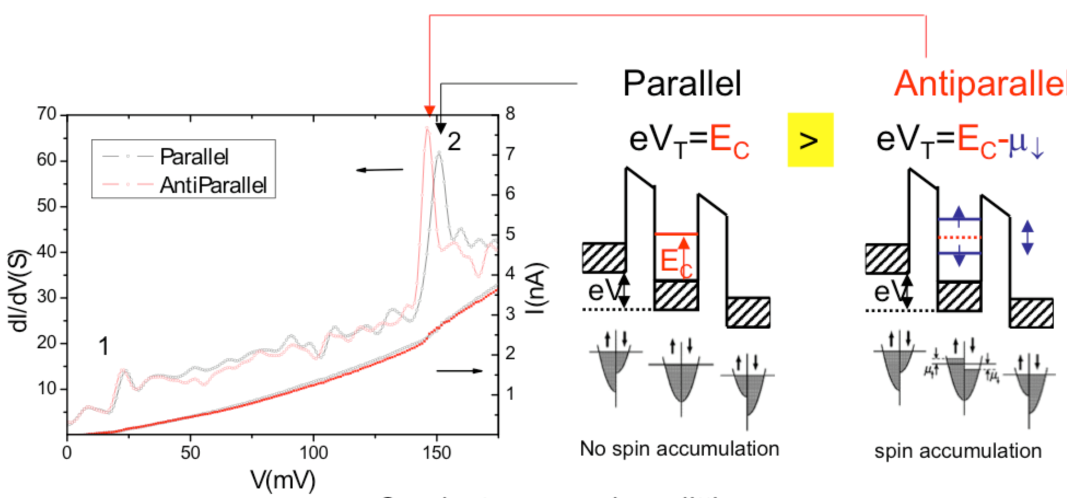
Co/Al_2O_3/ Al cluster /Al_2O_3/Co



Directly probing the spin accumulation

Co/Al_2O_3/2~3nm Au Cluster/Al_2O_3/Co

Spin accumulation in non-magnetic gold clusters



Conductance peaks splitting:
Due to spin accumulation, controled by spin lifetime τ_{sf}

Direct probe for the spin lifetime

❷ Quantitatively: balancing spin currents

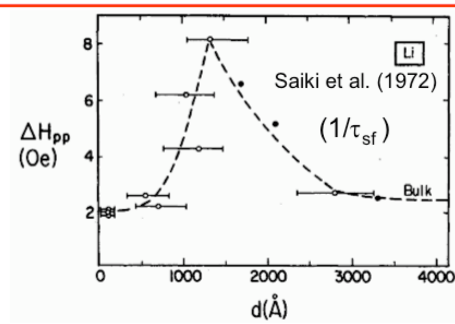
$$I_{2\uparrow} = I_{1\uparrow} + \frac{eN\mu_{\downarrow}}{\tau_{sf}} - \frac{eN\mu_{\uparrow}}{\tau_{sf}} \longrightarrow \Delta\mu = \frac{\tau_{sf} P_{Co}}{eN} I$$

$$\longrightarrow \tau_{sf} = \frac{eN}{IP_{Co}} \Delta\mu$$

Cluster Au 2.5nm: $\tau_{sf} \approx 800 ps >> few\ 100 fs$ (thin films...)

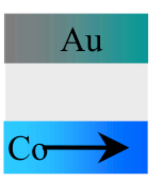
No impurity or Quantum size effects!?

The Lithium Case (ESR):



Anisotropic magnetoresistance in tunneling

Anisotropic Magneto Resistance (TAMR)



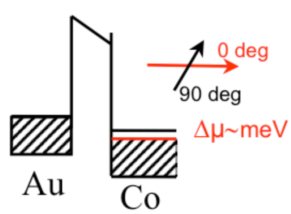
First observation: GaMnAS, Molenkamp PRL '04

→ Spin-Orbit interaction makes the electronic structure anisotropic; acts on transmission

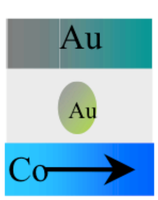
With metals? Only theory

Jungwirth PRB '06, Krupin PRB '05, Tsymbal PRL '07

→ Effect hardly detectable in metal based MTJs



Anisotropic Magneto Resistance effect on Coulomb blockade:



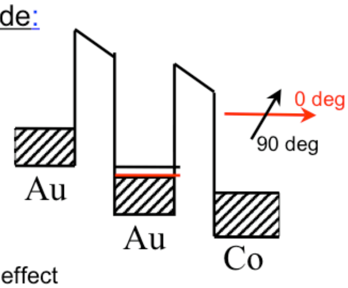
First observation: GaMnAS, Wunderlich PRL '06

→ CB systems are highly sensitive to small energy change

With metals? Only theory

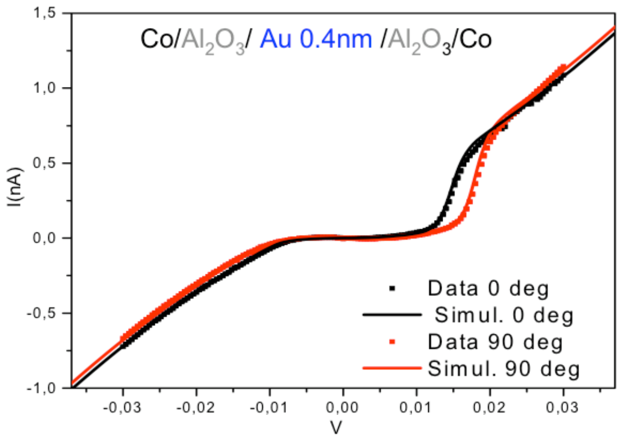
Jungwirth PRB '06

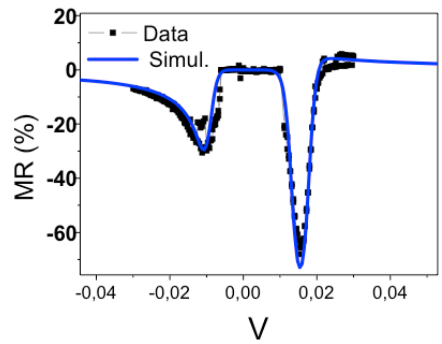
→ CBAMR can give rise to a strong Magnetoresistance effect



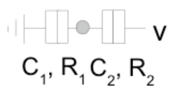
Magneto-Coulomb effect: anisotropy

Anisotropic Magneto-transport





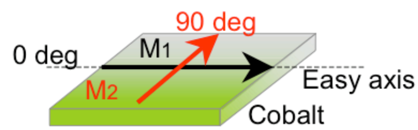
Parameters :



C_1= 2.9aF R_1= 0.3MΩ

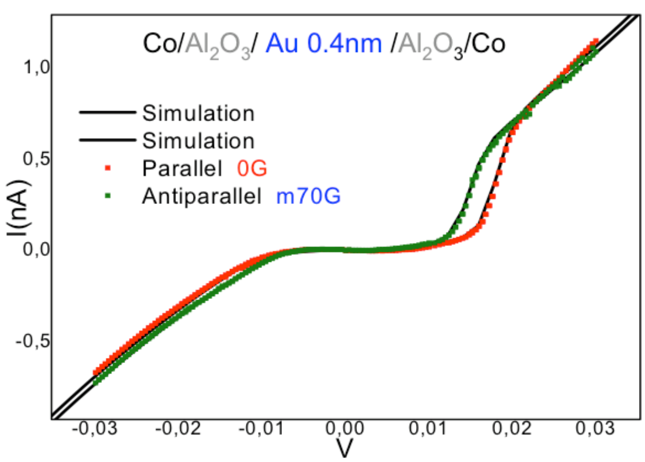
C_2= 1.7aF R_2= 30MΩ

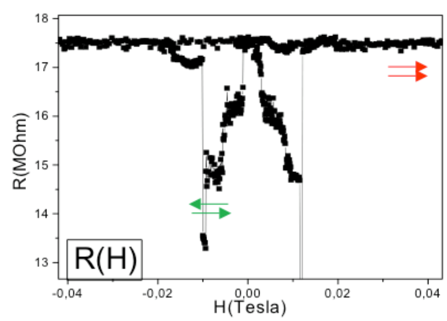
Q_0=0.31e + Δ Q

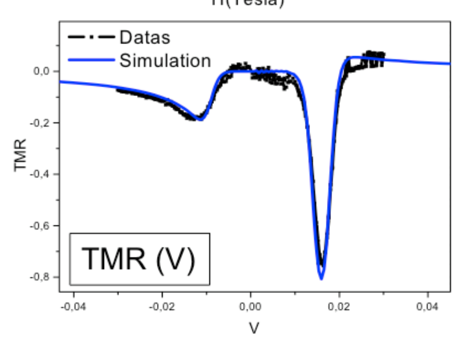


MR done close to 90°

→ The same curve can be obtained in a R vs H close to 90°







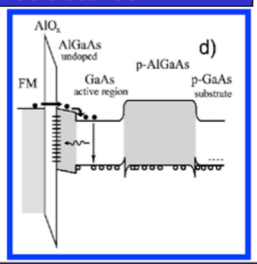
→ The magnetic electrode act as a gate on the system

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)

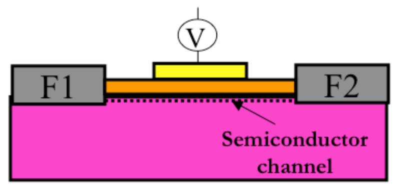
GaMnAs ($T_c \rightarrow$170K) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition

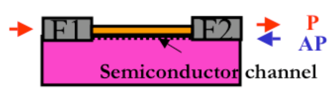
Spin Field Effect Transistor ?



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:

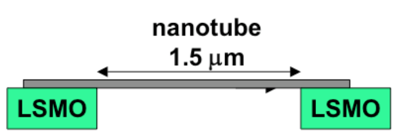


« Measured effects of the order of **0.1-1%** have been reported for the change in voltage or resistance (between P and AP)…. », *from the review article « Electrical Spin Injection and Transport in Semiconductors » by BT Jonker and ME Flatté in Nanomagnetism (ed.: DL Mills and JAC Bland, Elsevier 2006)*

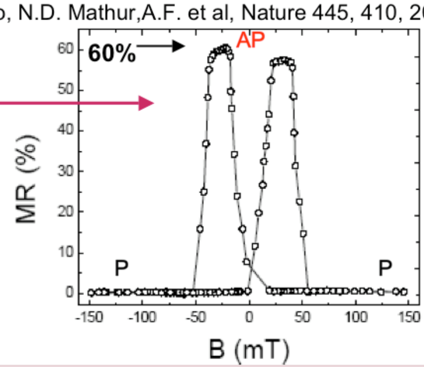
L.Hueso, N.D. Mathur,A.F. et al, Nature 445, 410, 2007

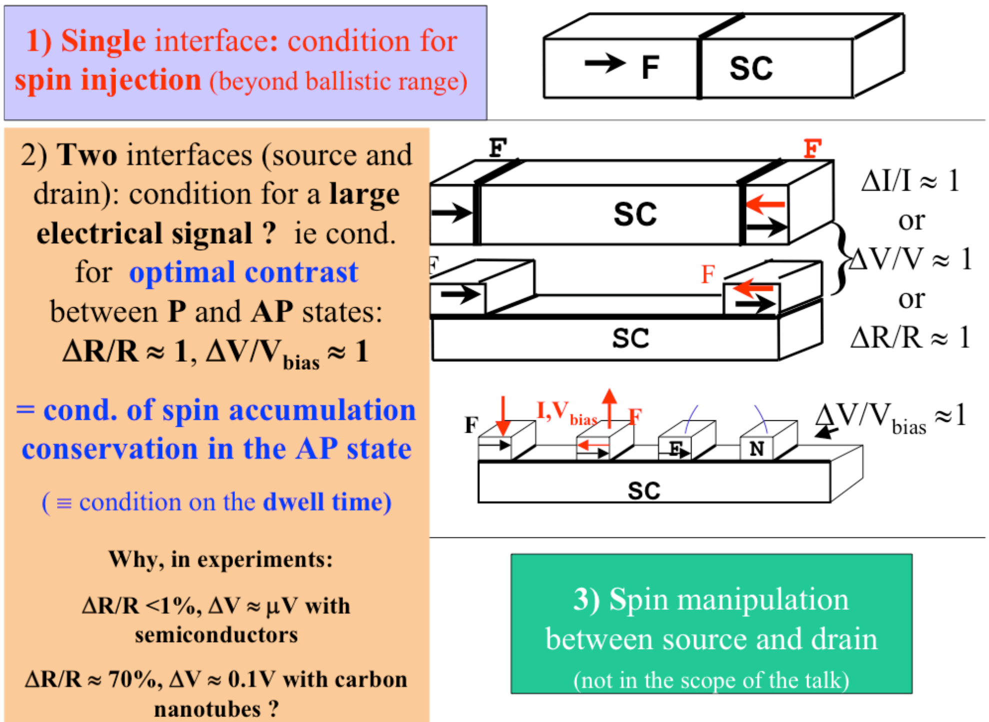
Carbon nanotubes:

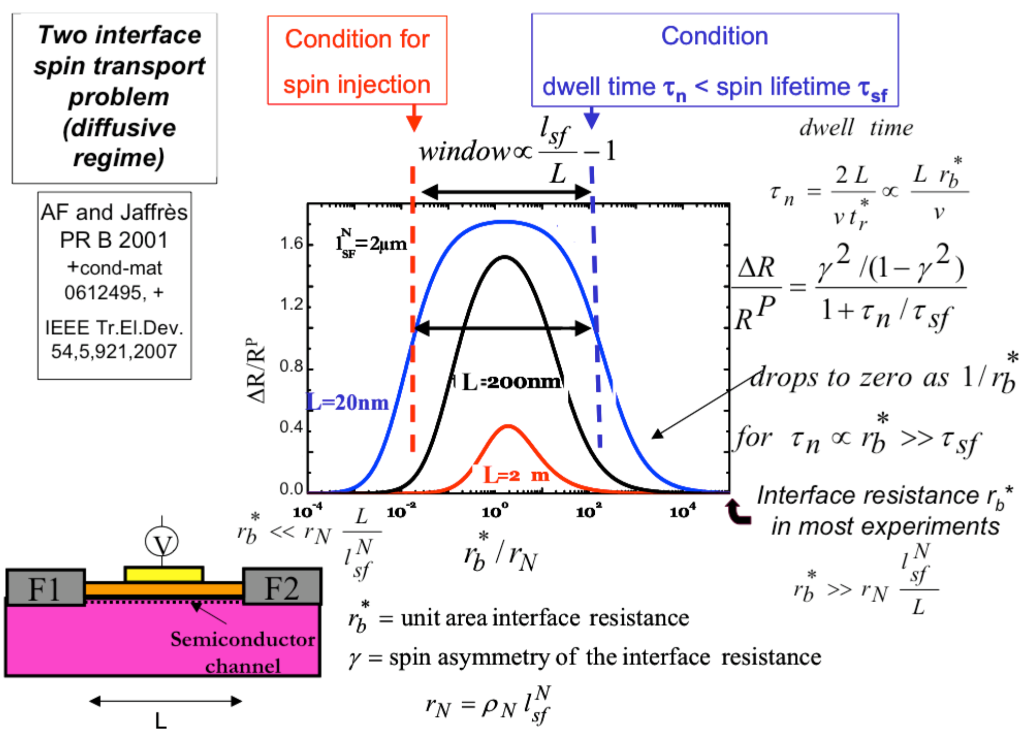
$\Delta R/R \approx$ 60-70%, V_{AP}-$V_P \approx$ 60 mV



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

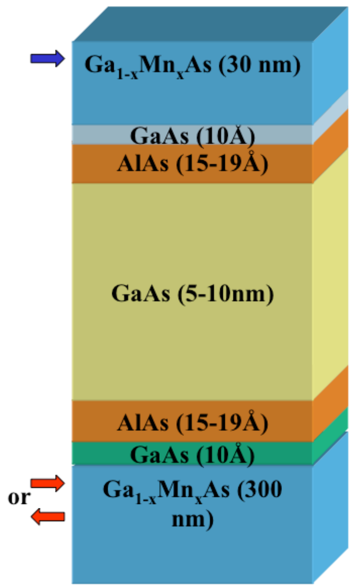


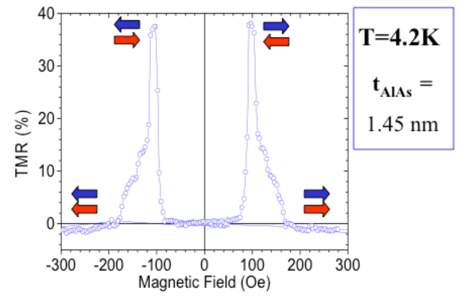

1) Single interface: condition for spin injection (beyond ballistic range)
F
SC
2) Two interfaces (source and drain): condition for a large electrical signal ? ie cond. for optimal contrast between P and AP states: ΔR/R ≈ 1, ΔV/V_bias ≈ 1
= cond. of spin accumulation conservation in the AP state
(≡ condition on the dwell time)
Why, in experiments:
ΔR/R <1%, ΔV ≈ µV with semiconductors
ΔR/R ≈ 70%, ΔV ≈ 0.1V with carbon nanotubes ?
F
F
SC
ΔI/I ≈ 1
or
ΔV/V ≈ 1
or
ΔR/R ≈ 1
F
SC
I,V_bias
N
ΔV/V_bias ≈1
3) Spin manipulation between source and drain
(not in the scope of the talk)

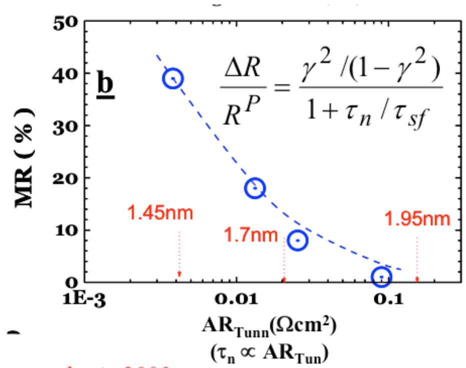

Two interface spin transport problem (diffusive regime)
AF and Jaffrès PR B 2001 +cond-mat 0612495, + IEEE Tr.El.Dev. 54,5,921,2007
Condition for spin injection
Condition
dwell time τ_n < spin lifetime τ_sf
dwell time
window ∝ l_sf/L − 1
τ_n = 2L/(v t_r*) ∝ L r_b*/v
ΔR/R^P = γ²/(1−γ²) / (1 + τ_n/τ_sf)
drops to zero as 1/r_b*
for τ_n ∝ r_b* >> τ_sf
Interface resistance r_b* in most experiments
r_b* >> r_N l_sf^N/L
ΔR/R^P
l_SF^N=2µm
L=20nm
L=200nm
L=2 m
1.6
1.2
0.8
0.4
0.0
10^-4
10^-2
10^0
10^2
10^4
r_b* << r_N L/l_sf^N
r_b*/r_N
V
F1
F2
Semiconductor channel
L
r_b* = unit area interface resistance
γ = spin asymmetry of the interface resistance
r_N = ρ_N l_sf^N

b) Experimental results

$(R_{AP}-R_P)/R_P$ as a function of R_{Tunnel}

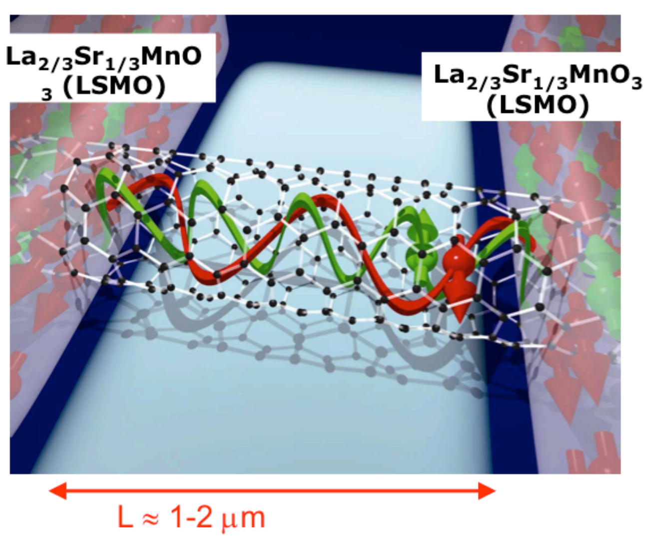


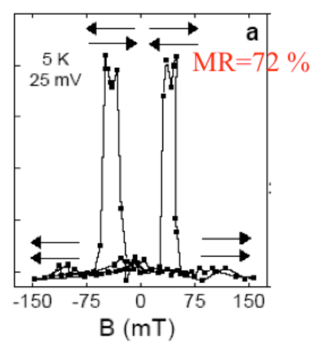


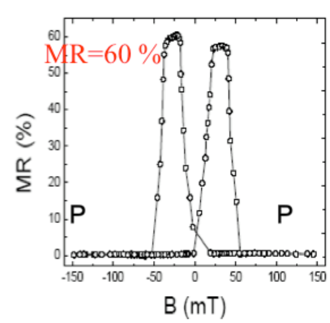


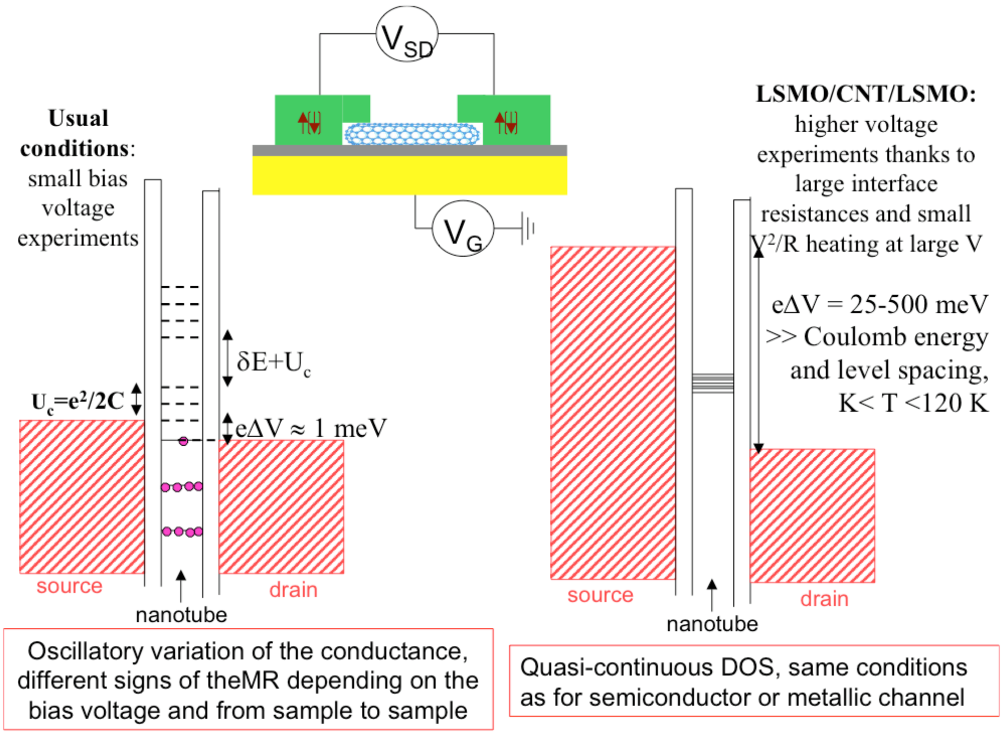
Mattana, A .F. et al, PRL 90, 166601, 2003; Mattana, thesis 2003

Carbon nanotubes between spin-polarized sources and drains

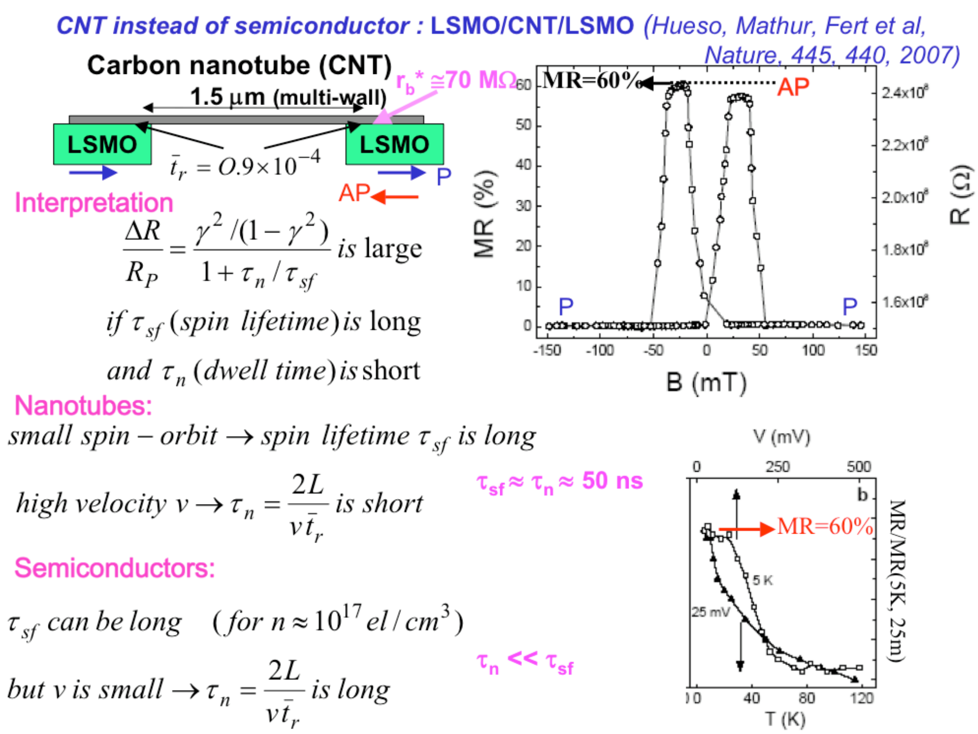








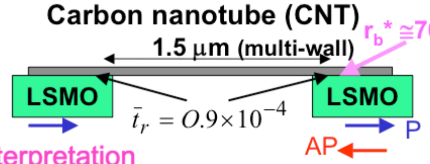
V_SD
V_G
Usual conditions: small bias voltage experiments
δE+U_c
U_c=e²/2C
eΔV ≈ 1 meV
source
drain
nanotube
Oscillatory variation of the conductance, different signs of theMR depending on the bias voltage and from sample to sample
LSMO/CNT/LSMO: higher voltage experiments thanks to large interface resistances and small V²/R heating at large V
eΔV = 25-500 meV >> Coulomb energy and level spacing, K< T <120 K
source
drain
nanotube
Quasi-continuous DOS, same conditions as for semiconductor or metallic channel

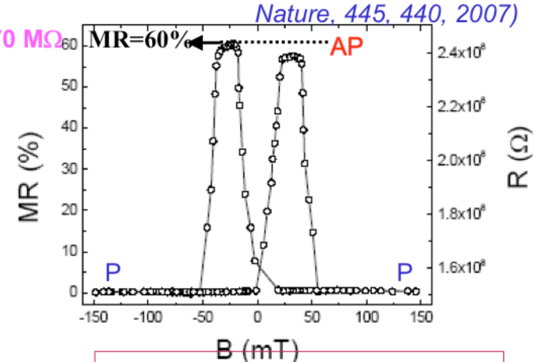


CNT instead of semiconductor : LSMO/CNT/LSMO (Hueso, Mathur, Fert et al, Nature, 445, 440, 2007)
Carbon nanotube (CNT)
1.5 μm (multi-wall)
r_b* ≅70 MΩ
LSMO
LSMO
t̄_r = 0.9×10⁻⁴
P
AP
Interpretation
ΔR/R_P = γ²/(1−γ²) / (1+τ_n/τ_sf) is large
if τ_sf (spin lifetime) is long
and τ_n (dwell time) is short
Nanotubes:
small spin − orbit → spin lifetime τ_sf is long
high velocity v → τ_n = 2L/(v t̄_r) is short
τ_sf ≈ τ_n ≈ 50 ns
Semiconductors:
τ_sf can be long (for n ≈ 10¹⁷ el/cm³)
but v is small → τ_n = 2L/(v t̄_r) is long
τ_n << τ_sf
MR=60%
AP
P
P
MR (%)
R (Ω)
B (mT)
V (mV)
b
MR=60%
5 K
25 mV
MR/MR(5K, 25m)
T (K)

***CNT instead of semiconductor* : LSMO/CNT/LSMO** *(Hueso, Mathur, Fert et al, Nature, 445, 440, 2007)*

Carbon nanotube (CNT)





Interpretation

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

$$\text{if } \tau_{sf}\,(\text{spin lifetime}) \text{ is long}$$

$$\text{and } \tau_n\,(\text{dwell time}) \text{ is short}$$

Nanotubes:

$$\text{small spin-orbit} \rightarrow \text{spin lifetime } \tau_{sf} \text{ is long}$$

$$\text{high velocity } v \rightarrow \tau_n = \frac{2L}{v\bar{t}_r} \text{ is short}$$

Semiconductors:

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

$$\text{but } v \text{ is small} \rightarrow \tau_n = \frac{2L}{v\bar{t}_r} \text{ is long}$$

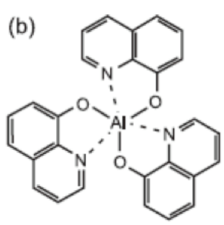
Potential of molecular spintronics (nanotubes, graphene and others

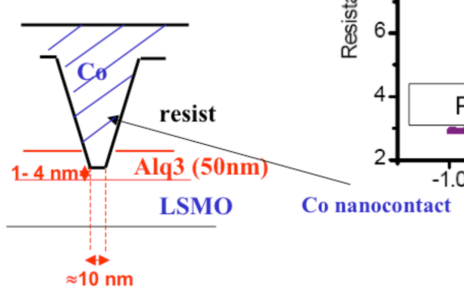
Next challenge for molecules: spin control by gate

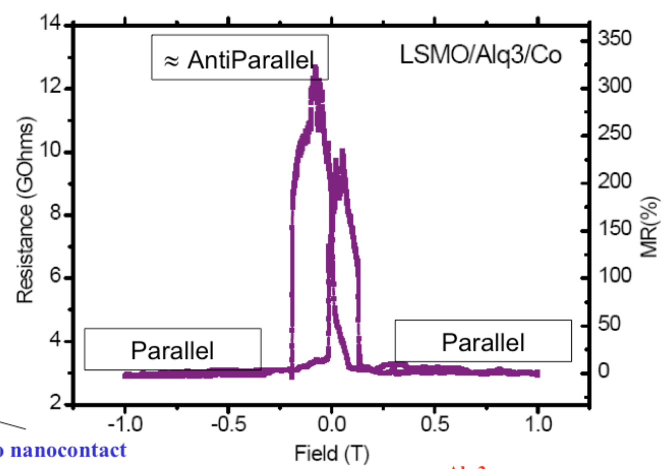
Solution for semiconductors: shorter L ?, larger transmission t_r ?

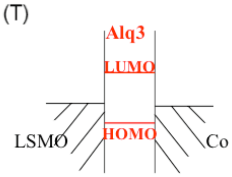
MR of LSMO/Alq3/Co structures (preliminary results)

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

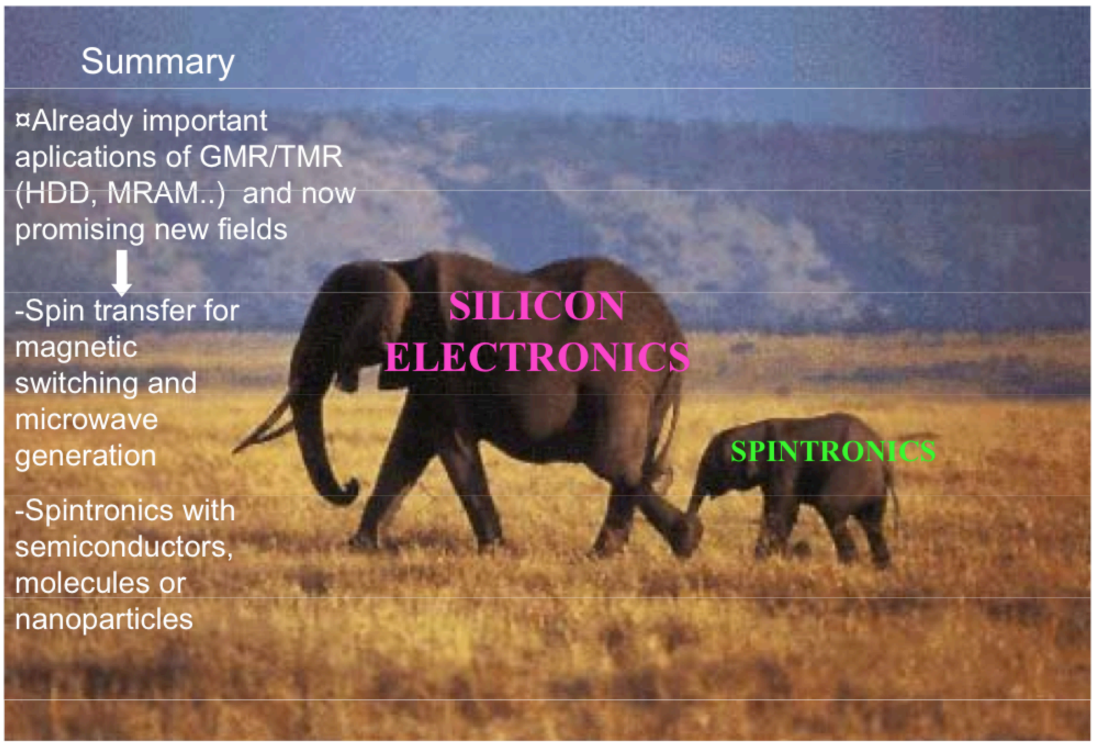








Alq3 = π - conjugated 8-hydroxy-quinoline aluminium


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
SILICON ELECTRONICS
SPINTRONICS