Spin-dependent transport in layered magnetic metals

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Summary:

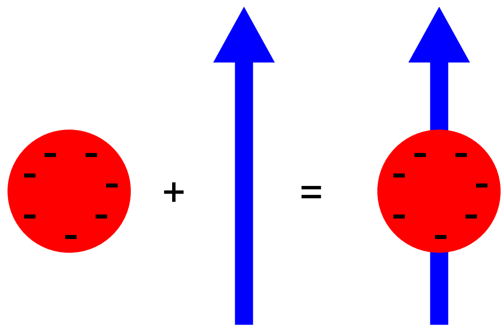
- introduction: what is spin-electronics
- giant magnetoresistance (GMR)
- tunneling magnetoresistance (TMR)
- hot-electron spin-transistor
- magnetization switching due to spin-injection
- *ab initio* calculations of perpendicular current GMR
- domain wall magnetoresistance
- theory of TMR

introduction: what is spin-electronics ?

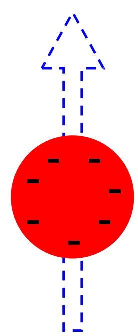
what is an electron ?

particle with negative electric charge $q = -e$

and spin 1/2 (magnetic moment $m = \mu_B$)

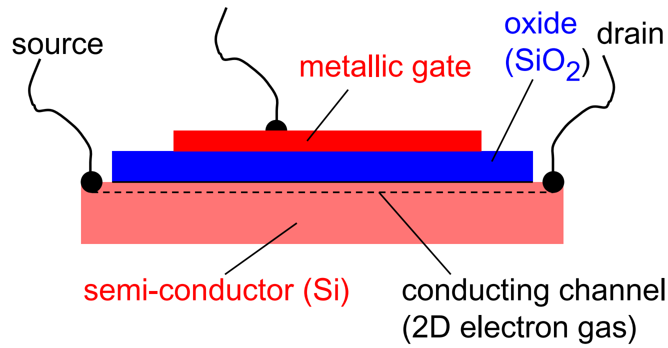


electron as seen by an electronician:



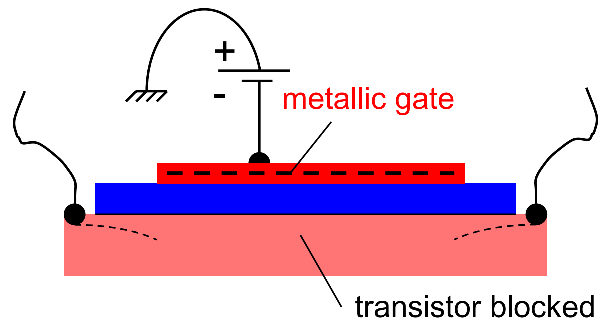
electronics = manipulation of electrons by using their charge for storage and processing of information

the spin is (almost) completely neglected principal electronic device: MOSFET



application:

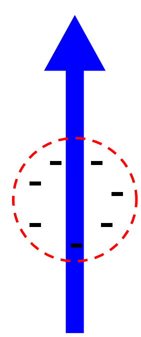
- logic gates
- random access memory



inconvenients:

- volatility of the information
- energy consumption
- limited density of information

electron as seen by a magnetician:



purpose of magnetism: develop materials in which the electron spins tend to align parallel to each (magnets)

the charge of the electrons plays a secondary role

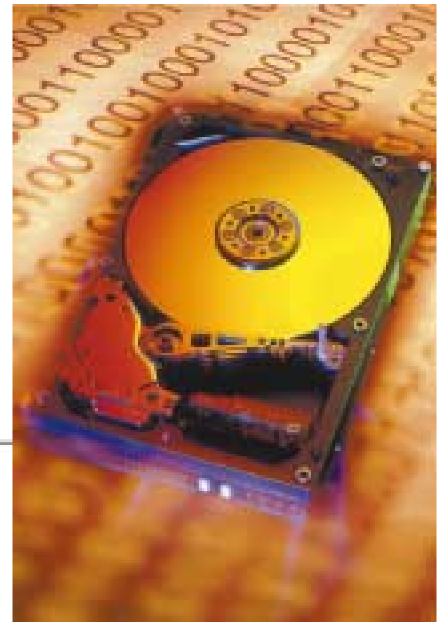
application: mass storage of information (magnetic disks and tapes)

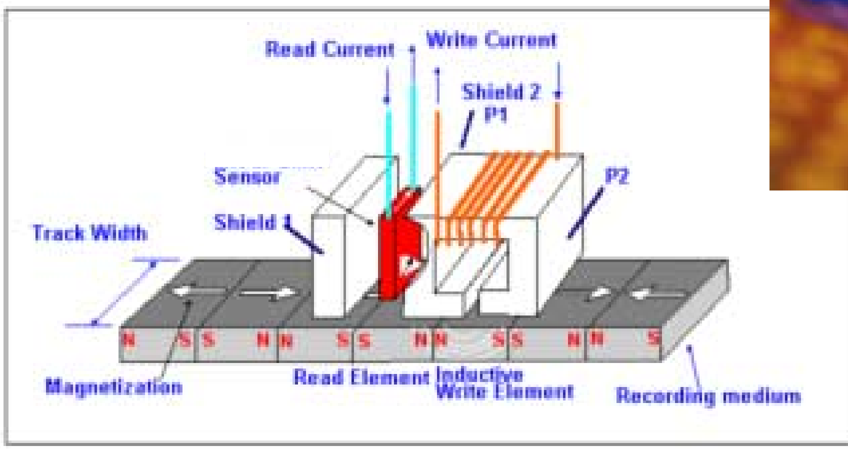
advantages:

- non-volatility
- high storage density
- no energy consumption

inconvenients:

- mechanical access to information





$\mu\Phi$

Purpose of spin-electronics: ***``Teaching electrons new tricks´´***

combine electronics and magnetism in order to make new devices in which both the charge and the spin of the electron play an active role

new fundamental physical questions

new phenomena

new devices and applications

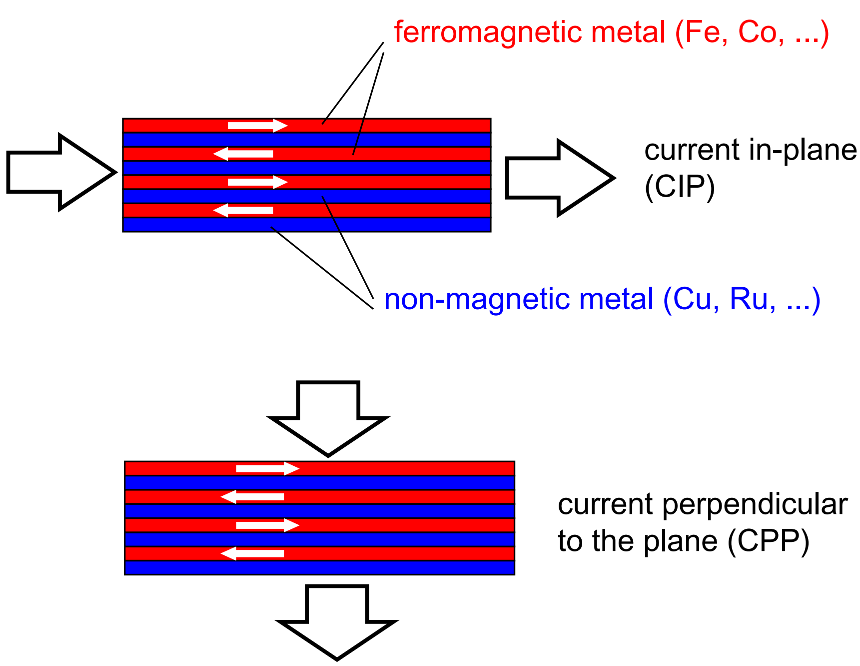
$\mu\Phi$

giant-magnetoresistance

Giant magneto-resistance (GMR)

Baibich *et al.*, PRL **61**, 2472 (1988)

Binasch *et al.*, PRB **39**, 4828 (1989)



VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
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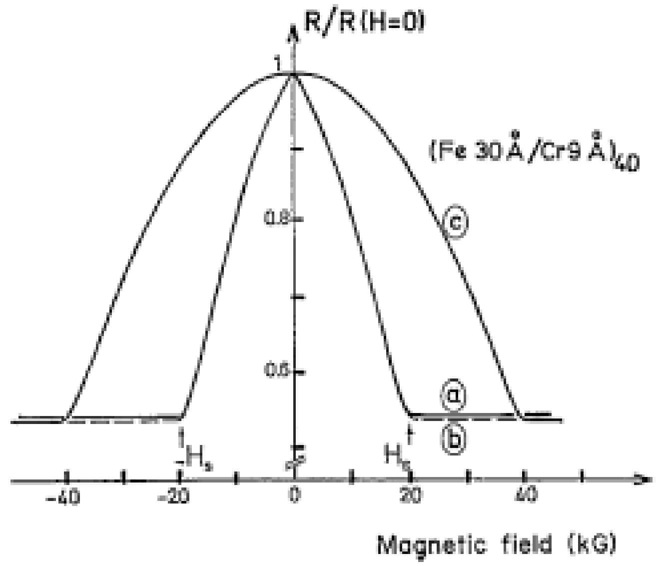
P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France
(Received 24 August 1988)



PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

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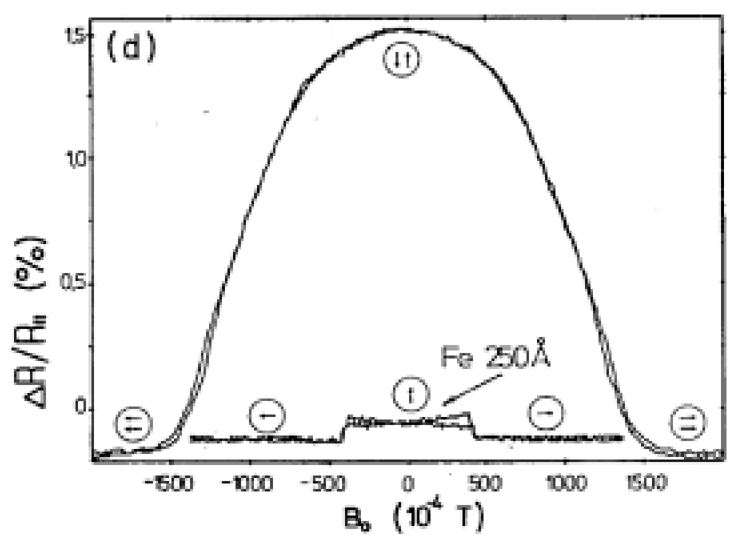
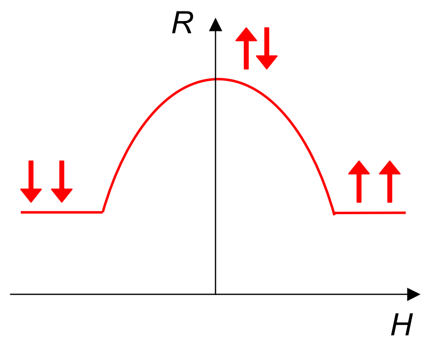
(Received 31 May 1988; revised manuscript received 12 December 1988)



definition conventions for the magnetoresistance ratio

$$A = \frac{R_{AP} - R_P}{R_P}$$ ``optimistic´´ definition

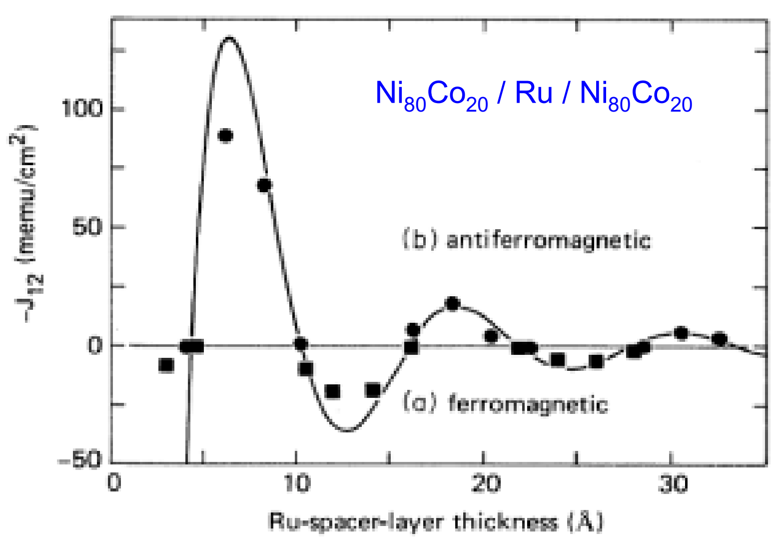


$$A = \frac{R_{AP} - R_P}{R_{AP}}$$ ``pessimistic´´ definition

$$A = \frac{R_{AP} - R_P}{R_{AP} + R_P}$$ reasonable definition

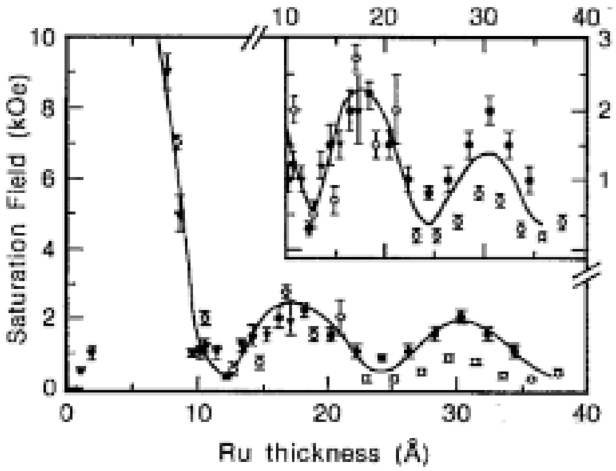
$\mu\Phi$

interlayer exchange coupling

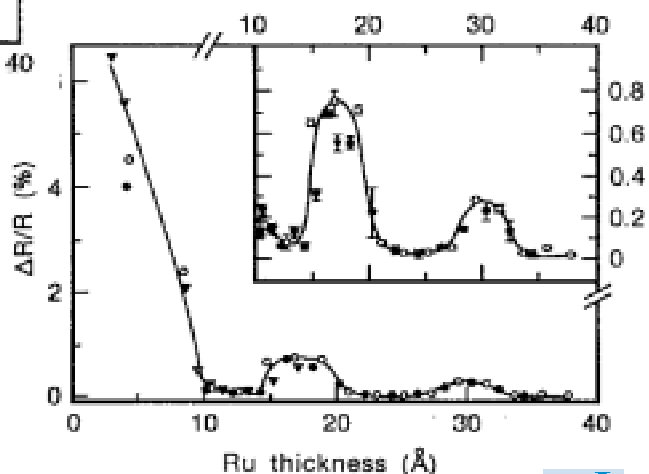


Parkin and Mauri, PRB **44**, 7131 (1991)

$\mu\Phi$



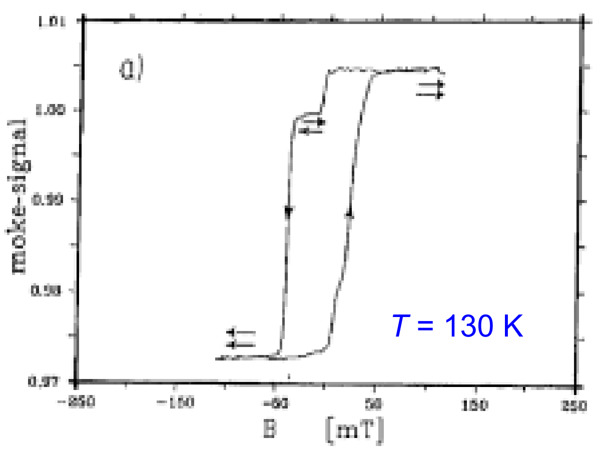
Co / Ru / Co

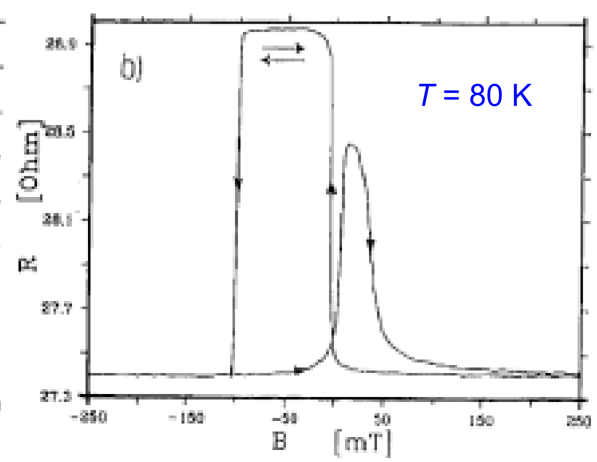


Parkin *et al.*, PRL **64**, 2304 (1990)

GMR without interlayer exchange coupling

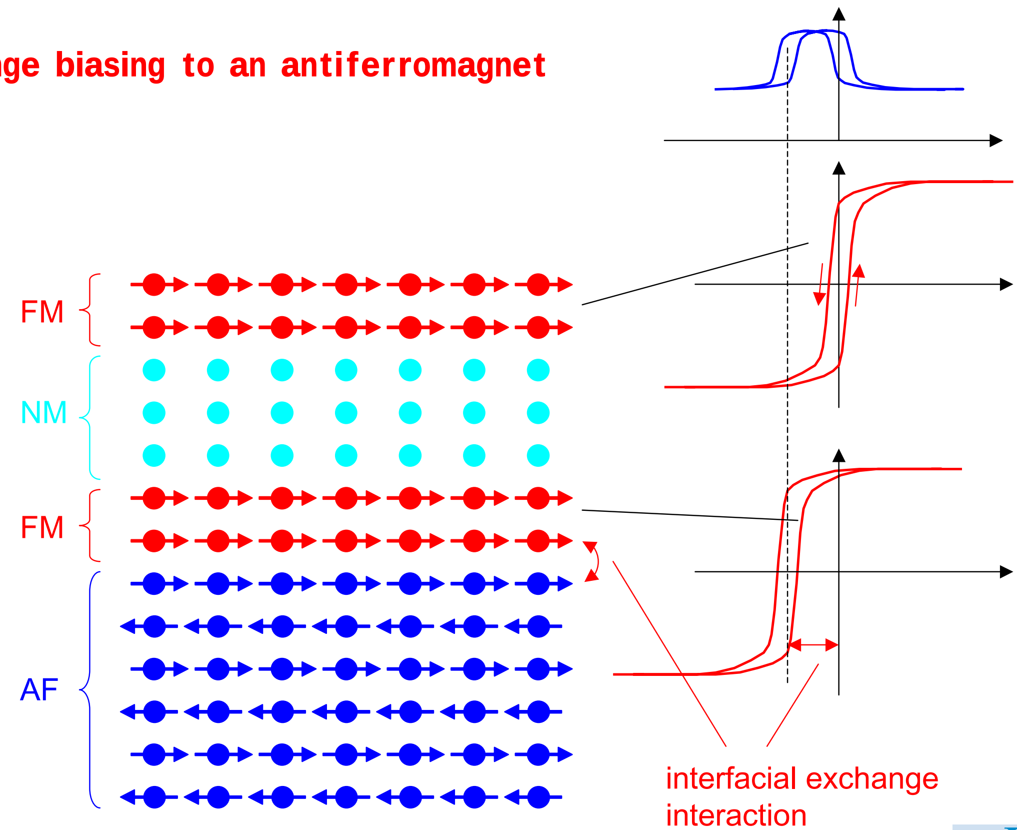
Co / Au / Co / Au(111)

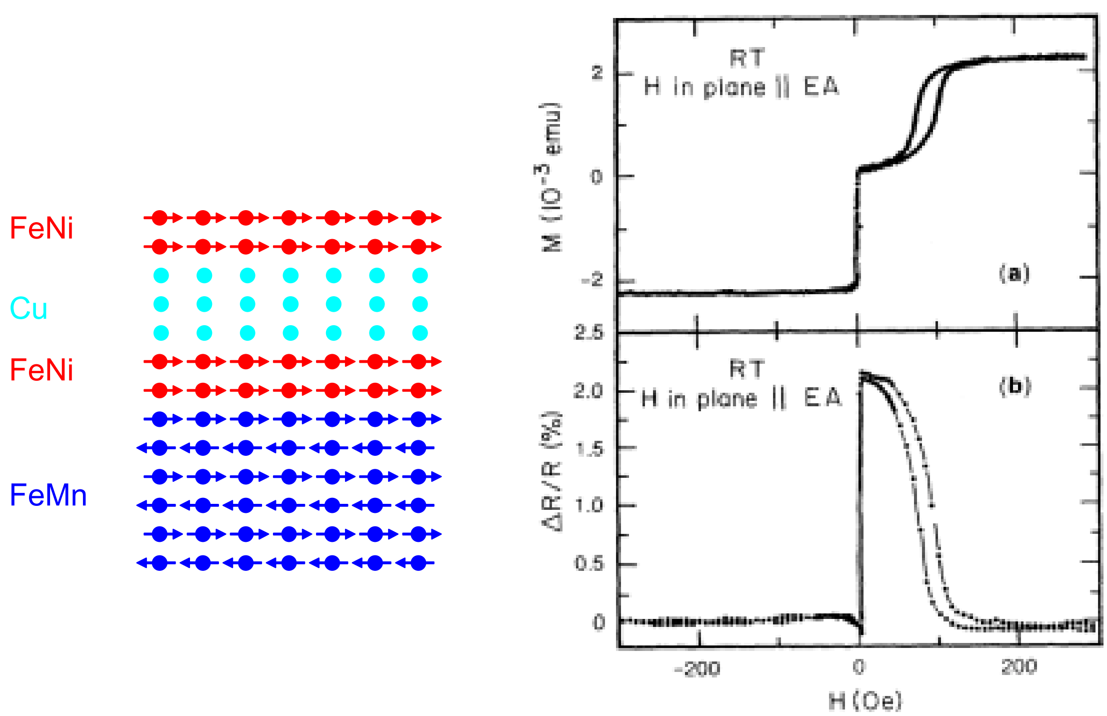




Barnas *et al.*, Vacuum 41, 1241 (1990)

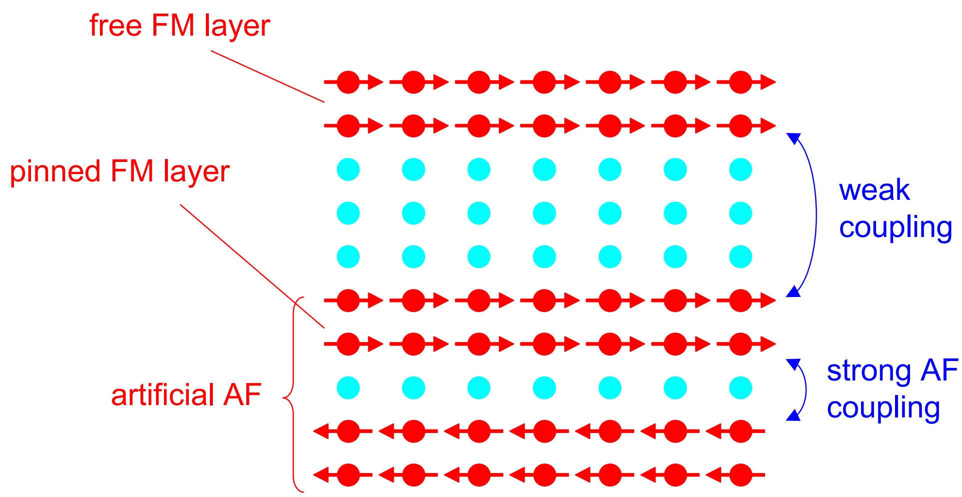
Exchange biasing to an antiferromagnet





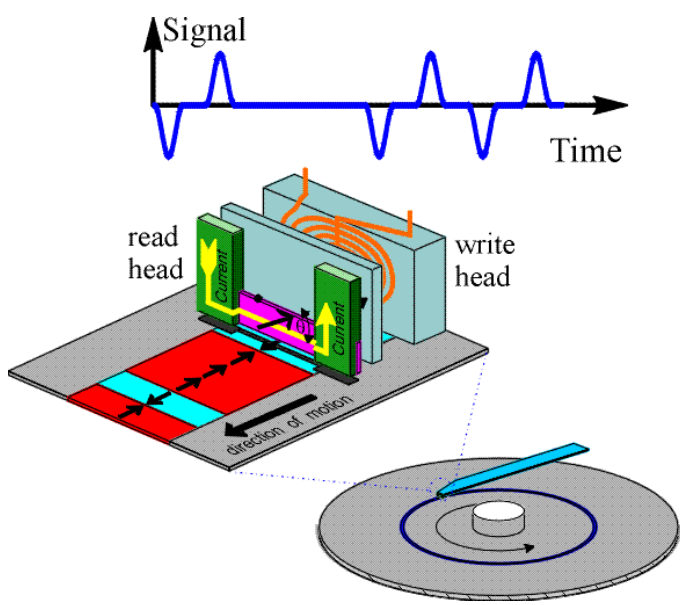
Diény *et al.*, PRB **43**, 1297 (1991)

Biasing by artificial antiferromagnet



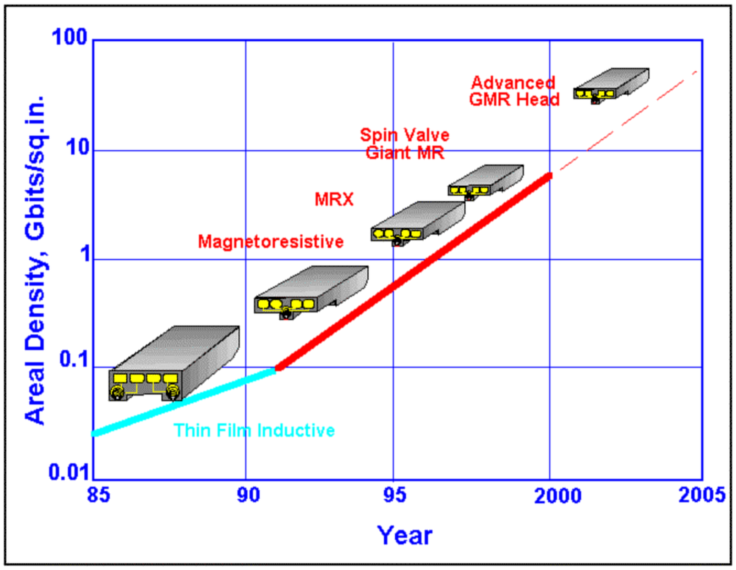
μΦ

Applications of GMR: reading head for magnetic disks



μΦ

Evolution of magnetic storage density

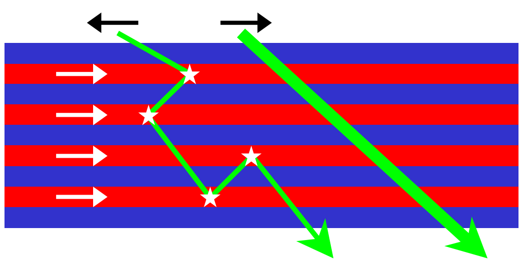


1 GByte drive

$\mu\Phi$

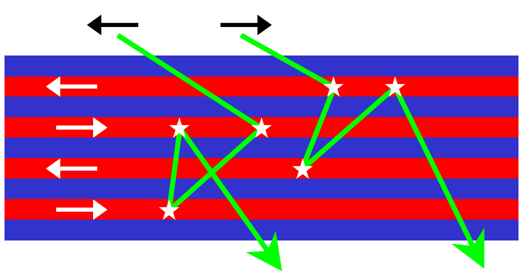
- **mechanism of GMR: spin-dependent scattering**

two-current model



ferromagnetic (F) configuration

$R_F < R_{AF}$

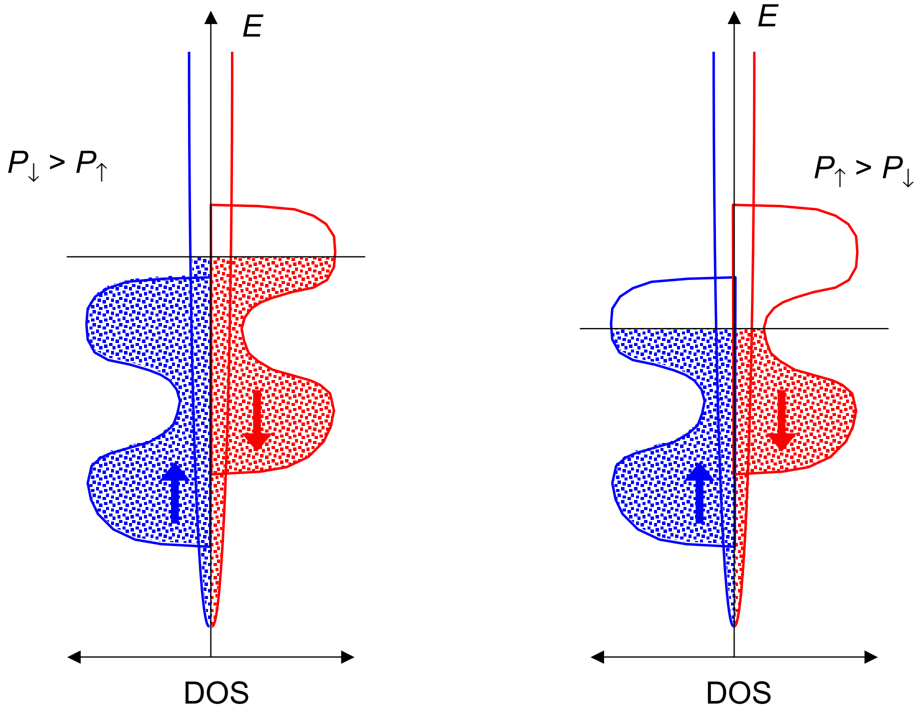


antiferromagnetic (AF) configuration

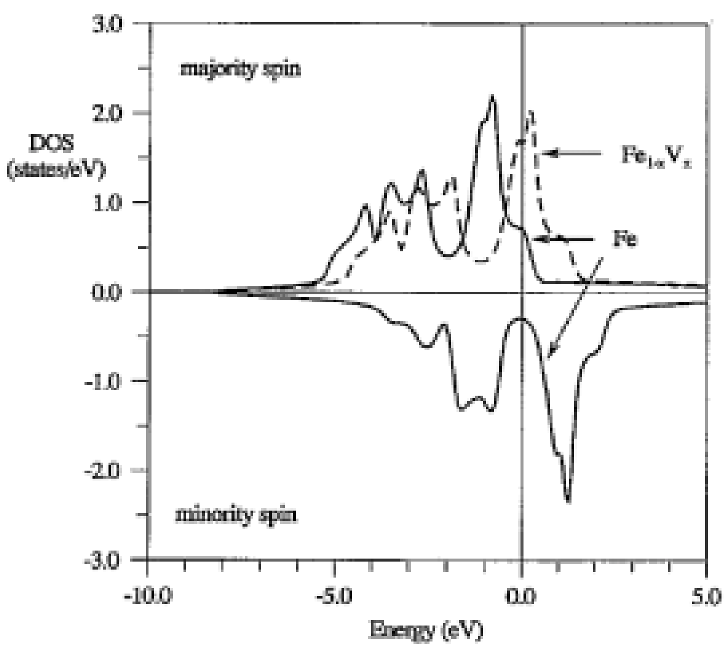
$$A \equiv \frac{R_{AF} - R_F}{R_{AF} + R_F}$$ → can be larger than 50%

$\mu\Phi$

spin-dependent scattering probability

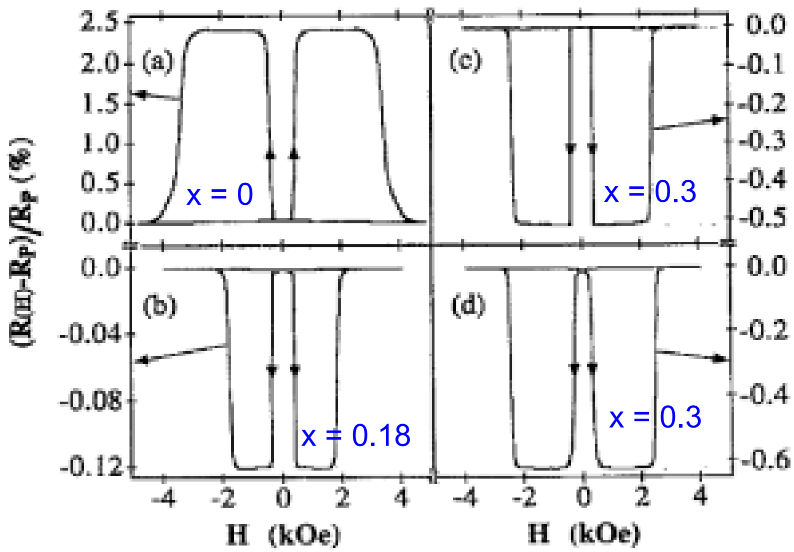


$\mu\Phi$



$\mu\Phi$

$Fe_{1-x}V_x$ / Au / Co



Renard *et al.*, PRB **51**, 12821 (1995)

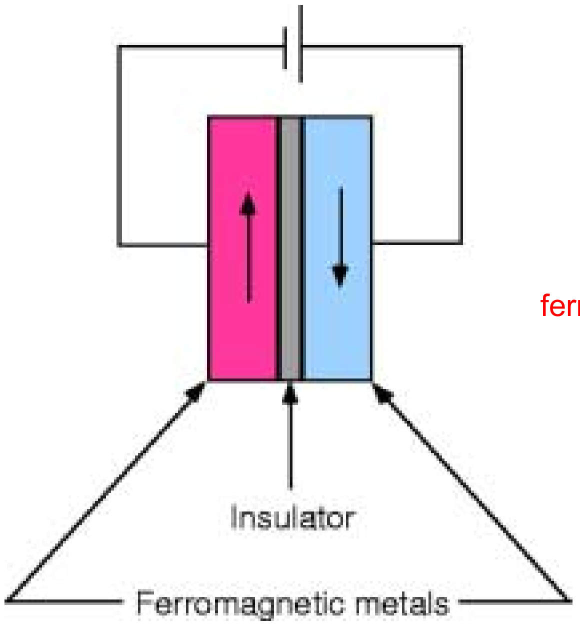
μΦ

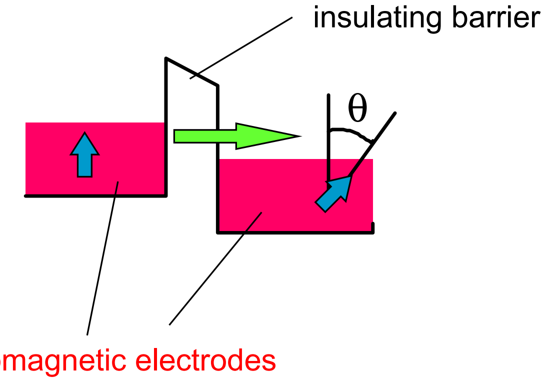
tunneling-magnetoresistance

μΦ

Tunneling magneto-resistance (TMR)

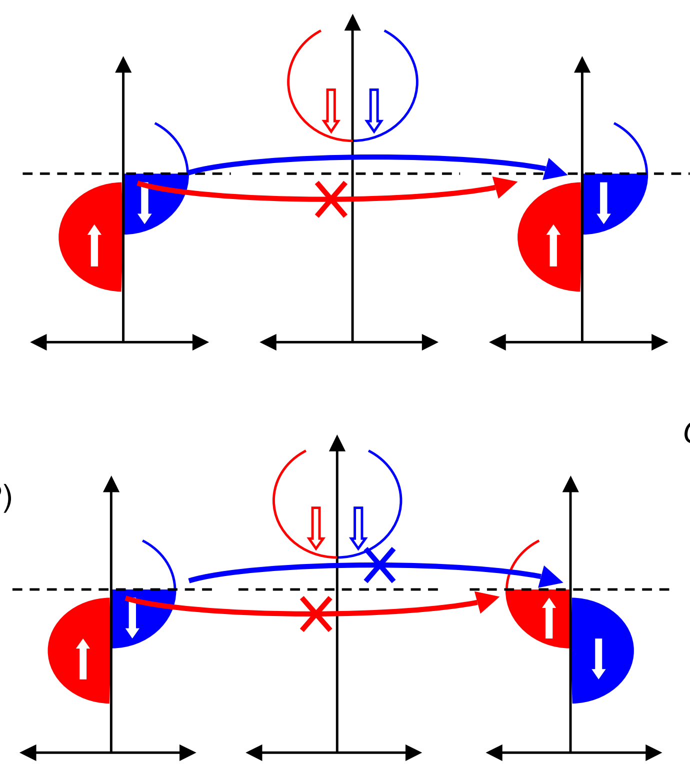
Jullière, Phys. Lett. **54A**, 225 (1975)
Moodera *et al*., PRL **74**, 3273 (1995)





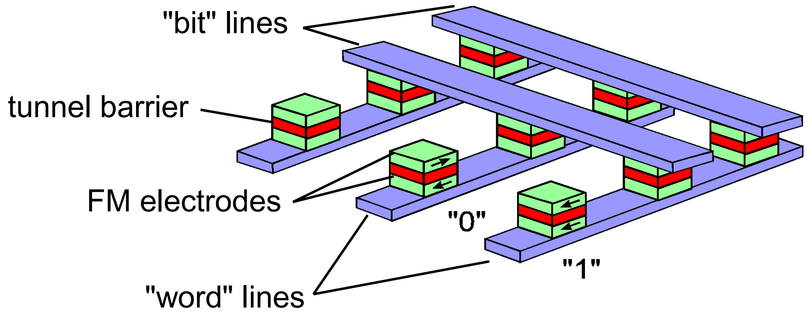
μΦ

Mechanism of tunneling magneto-resistance



μΦ

Applications of TMR: magnetic random access memories (M-RAM)

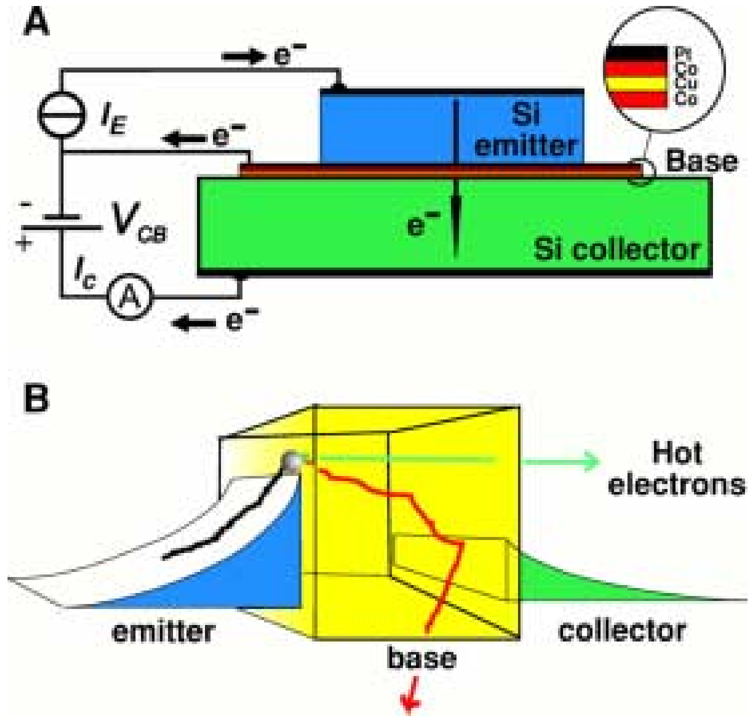


$\mu\Phi$

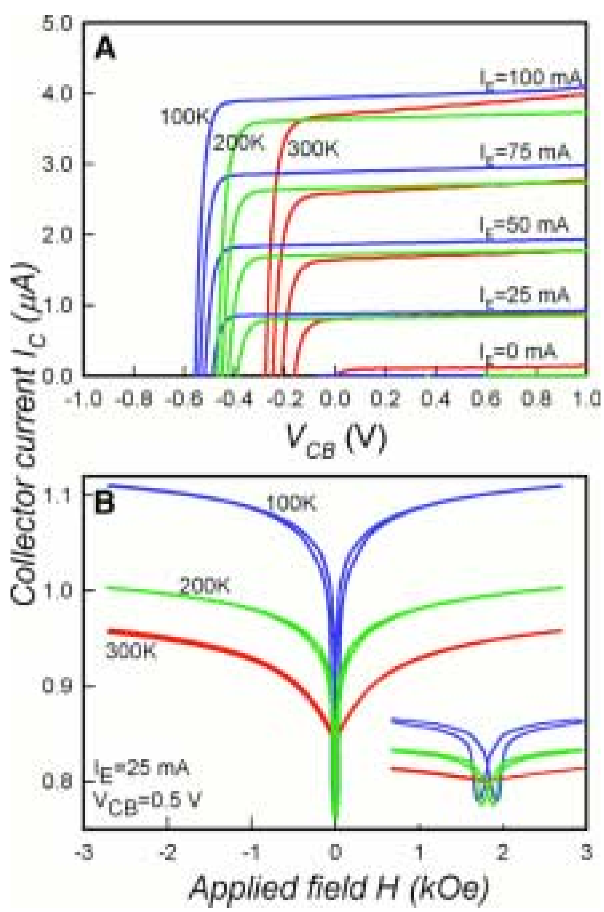
hot-electron spin-transistor

$\mu\Phi$

hot-electron spin-transistor



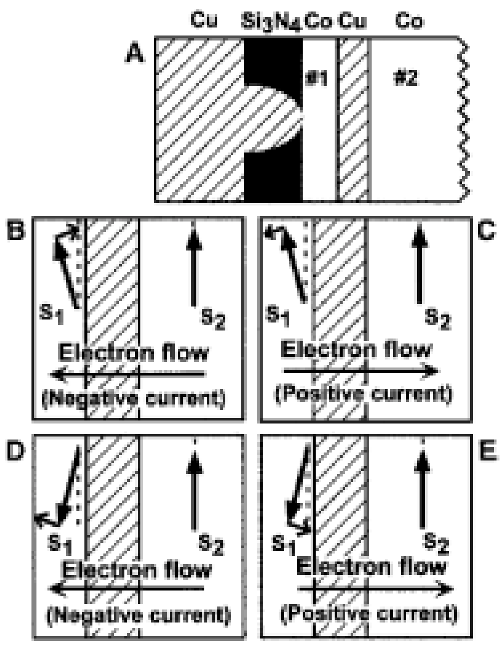
Monsma *et al.* PRL **74**, 5260 (1995)
Science **281**, 407 (1998)



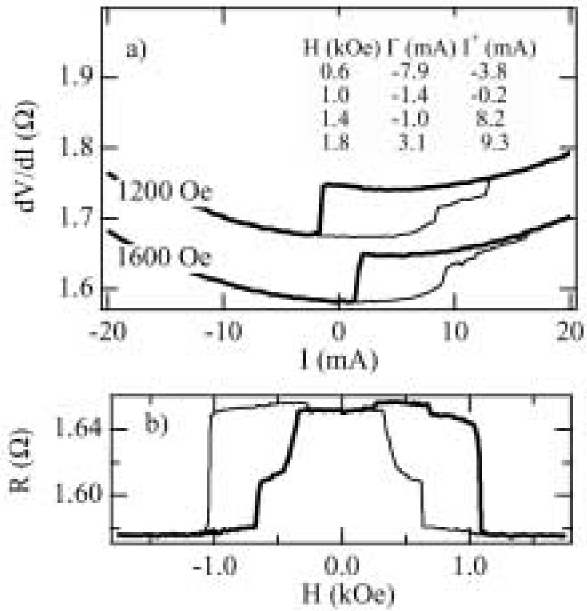
magnetization switching due to spin-injection

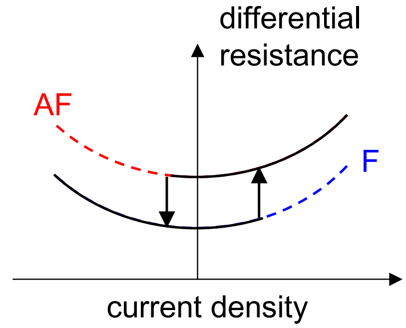
$\mu\Phi$

Magnetization switching due to spin-injection



$\mu\Phi$

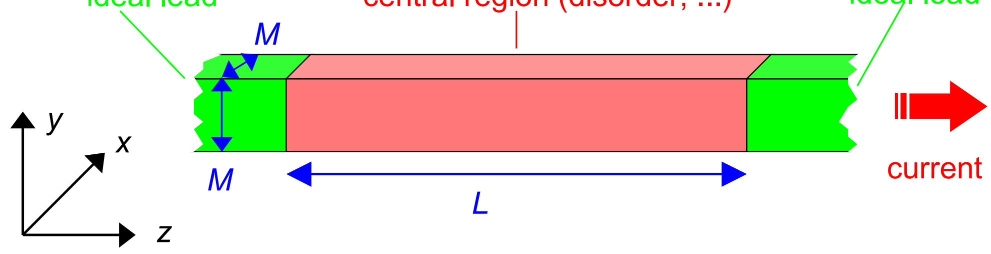




Myers *et al.*, Science **285**, 867 (1999)
Katine *et al.*, PRL 84, 3149 (2000)

ab initio calculations of perpendicular current GMR

model considered:



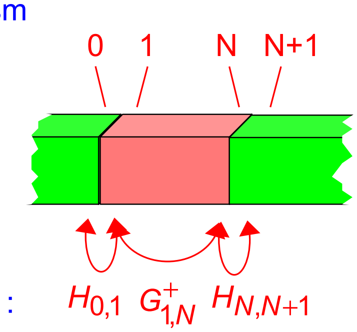
periodic repetition of the supercell in x and y directions

$\mu\Phi$

Conductances within the Landauer-Büttiker formalism

$C = C^{\uparrow} + C^{\downarrow}$ (spin-colinear case)

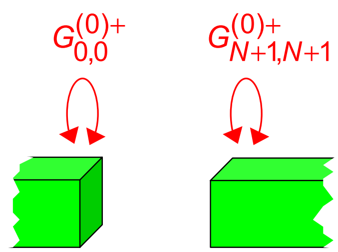
$$C^{\sigma} = \frac{e^2}{h}\frac{1}{N_{//}}\sum_{\mathbf{k}_{//}} T^{\sigma}(\mathbf{k}_{//}, \varepsilon_F)$$



transmittance for spin σ, wavevector $\boldsymbol{k}_{//}$ and energy ε_F :

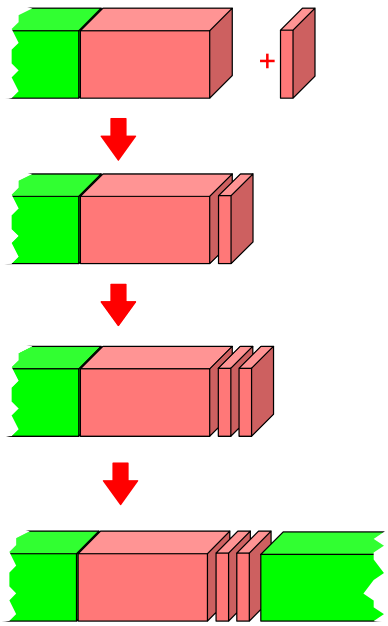
$$T^{\sigma}(\mathbf{k}_{//}, \varepsilon_F) = \mathrm{Tr}\left[\Gamma_1 G^{+}_{1,N}\, \Gamma_N\, G^{-}_{N1}\right]$$

$$\Gamma_1 = i\, H_{1,0}\left(G^{(0)+}_{0,0} - G^{(0)-}_{0,0}\right) H_{0,1}$$

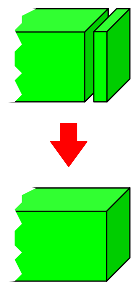


$\mu\Phi$

recursive calculation of
the Green's function

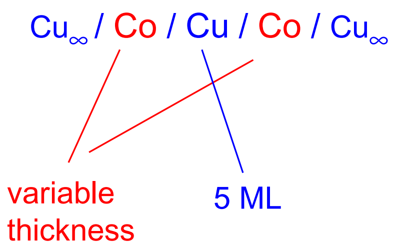


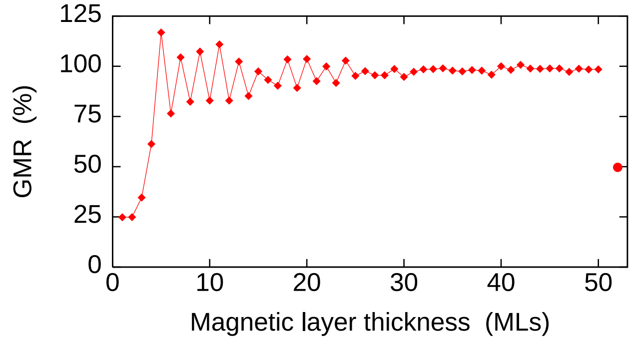
calculation of the surface Green's function:
layer addition (or removal) invariance
$\rightarrow$ self-consistent (Dyson-like) equation

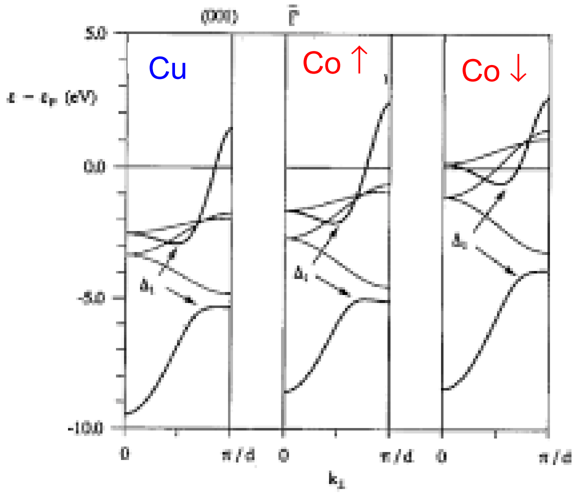


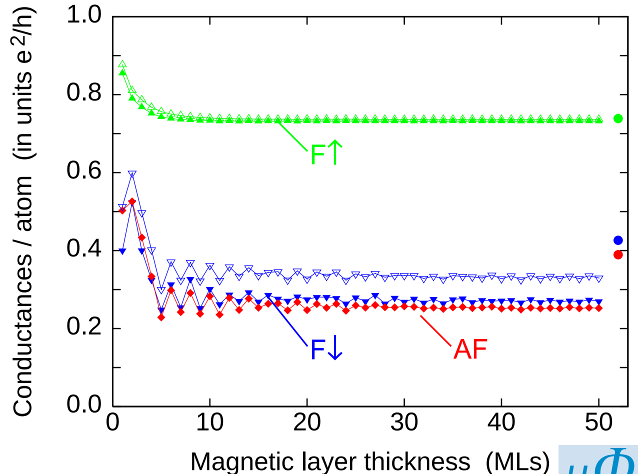
Computational details:

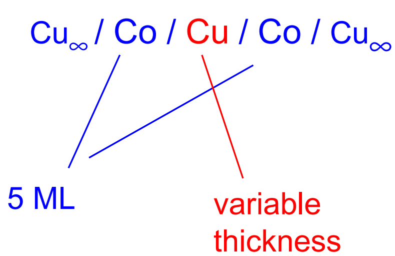
- density functional theory (local density approximation)
- TB-LMTO method (Green's function)
  well adapted to surface problems
- imaginary energy for GF calculations: 10^{-7} Ry
- disordered systems:
  - 5 x 5 supercell averaged over 5 configurations, or
    7 x 7 supercell averaged over 3 configurations
  - on-site potential parameters obtained from (layer dependent) CPA method
- $k_{//}$ -integration: 10 000 points in the full fcc(001) SBZ
- definition of GMR ratio: $GMR \equiv \dfrac{C_F - C_{AF}}{C_{AF}}$

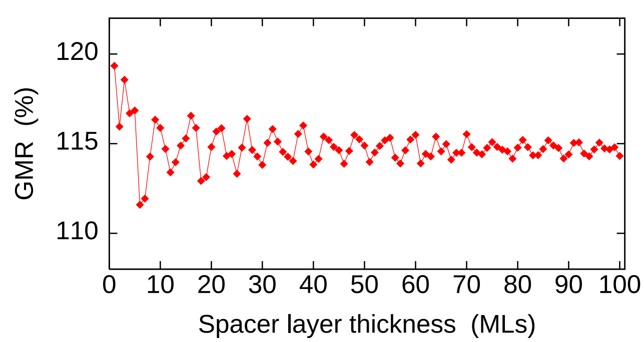

Cu_∞ / Co / Cu / Co / Cu_∞
variable thickness
5 ML

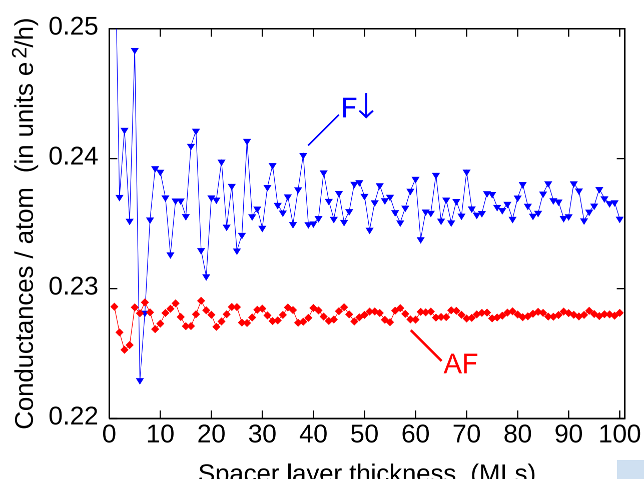

GMR (%)
125
100
75
50
25
0
0
10
20
30
40
50
Magnetic layer thickness (MLs)

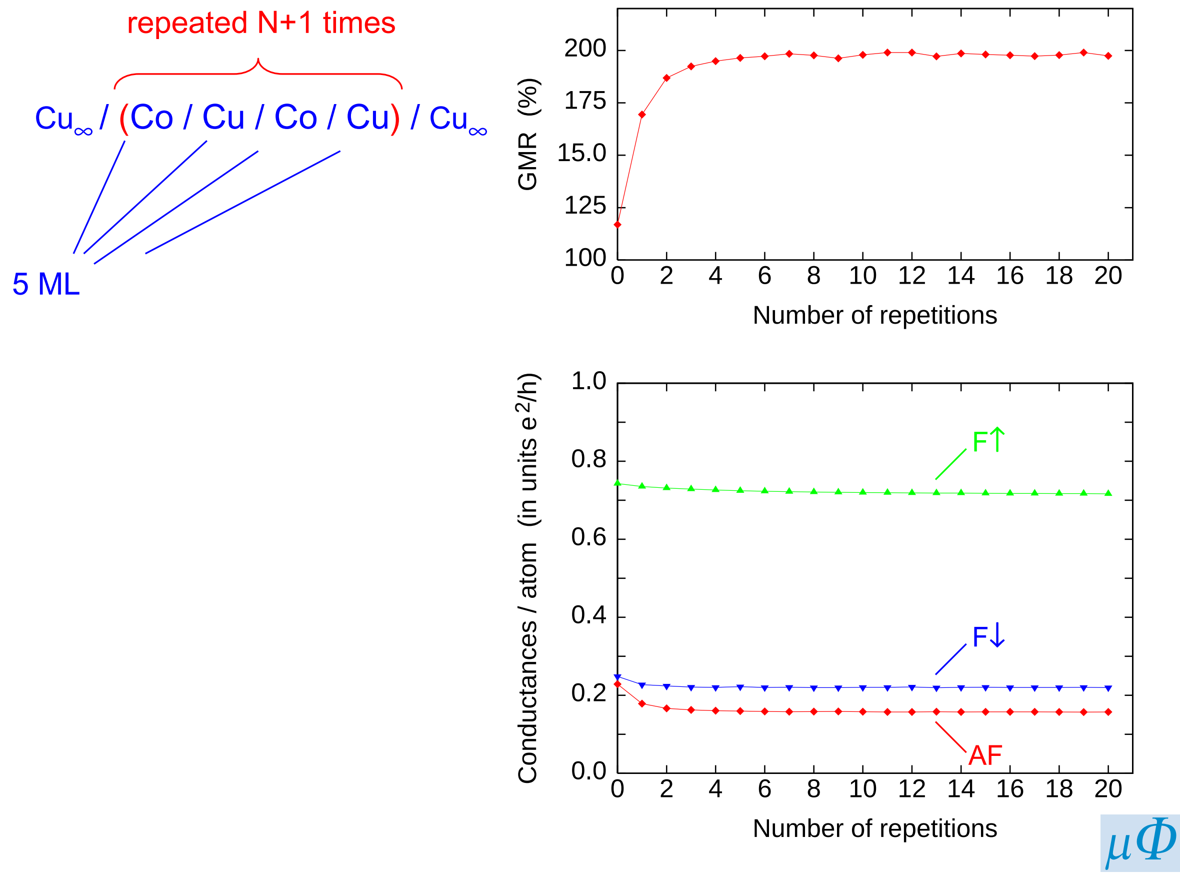

(001)
$\bar{\Gamma}$
5.0
0.0
-5.0
-10.0
$\varepsilon - \varepsilon_F$ (eV)
Cu
Co ↑
Co ↓
Δ_1
0
π/d
$k_\perp$


Conductances / atom (in units e^2/h)
1.0
0.8
0.6
0.4
0.2
0.0
F↑
F↓
AF
0
10
20
30
40
50
Magnetic layer thickness (MLs)

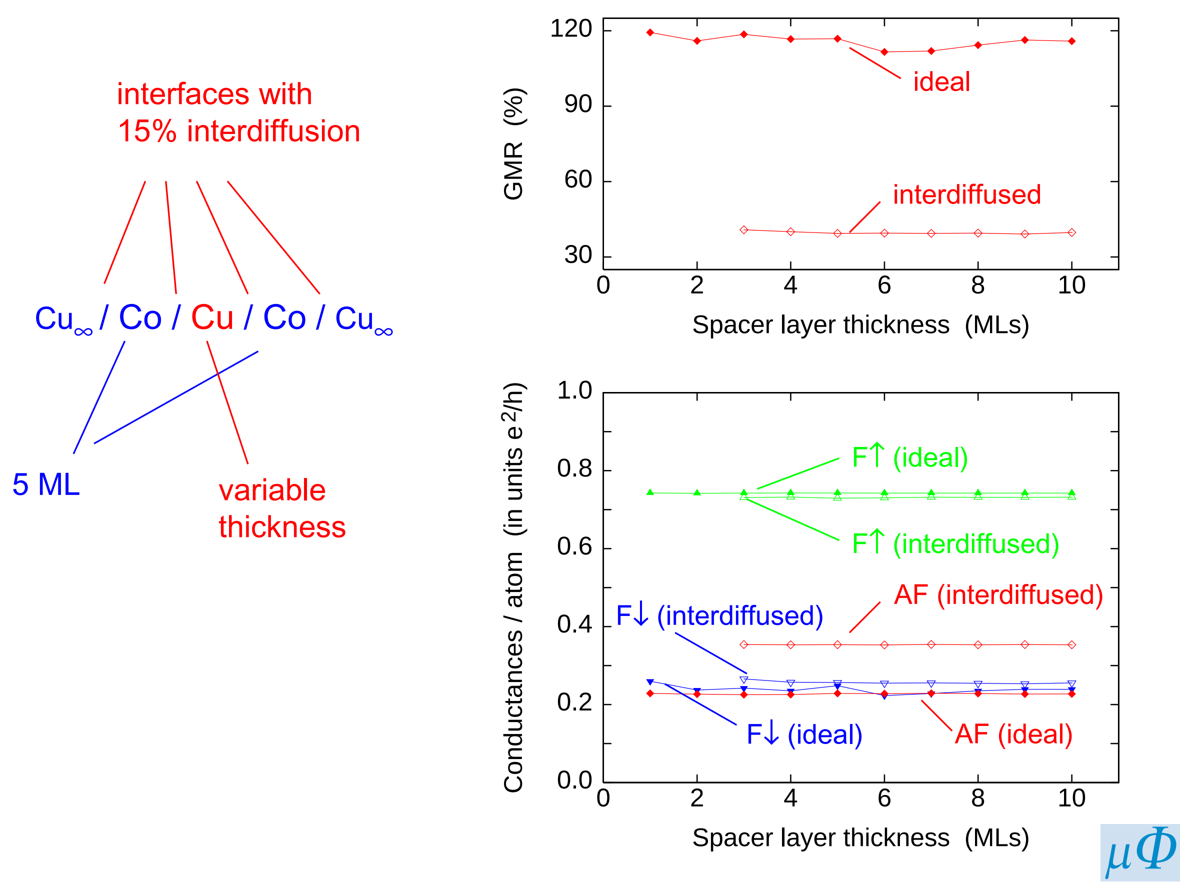

Cu_∞ / Co / Cu / Co / Cu_∞
5 ML
variable thickness


GMR (%)
120
115
110
0
10
20
30
40
50
60
70
80
90
100
Spacer layer thickness (MLs)

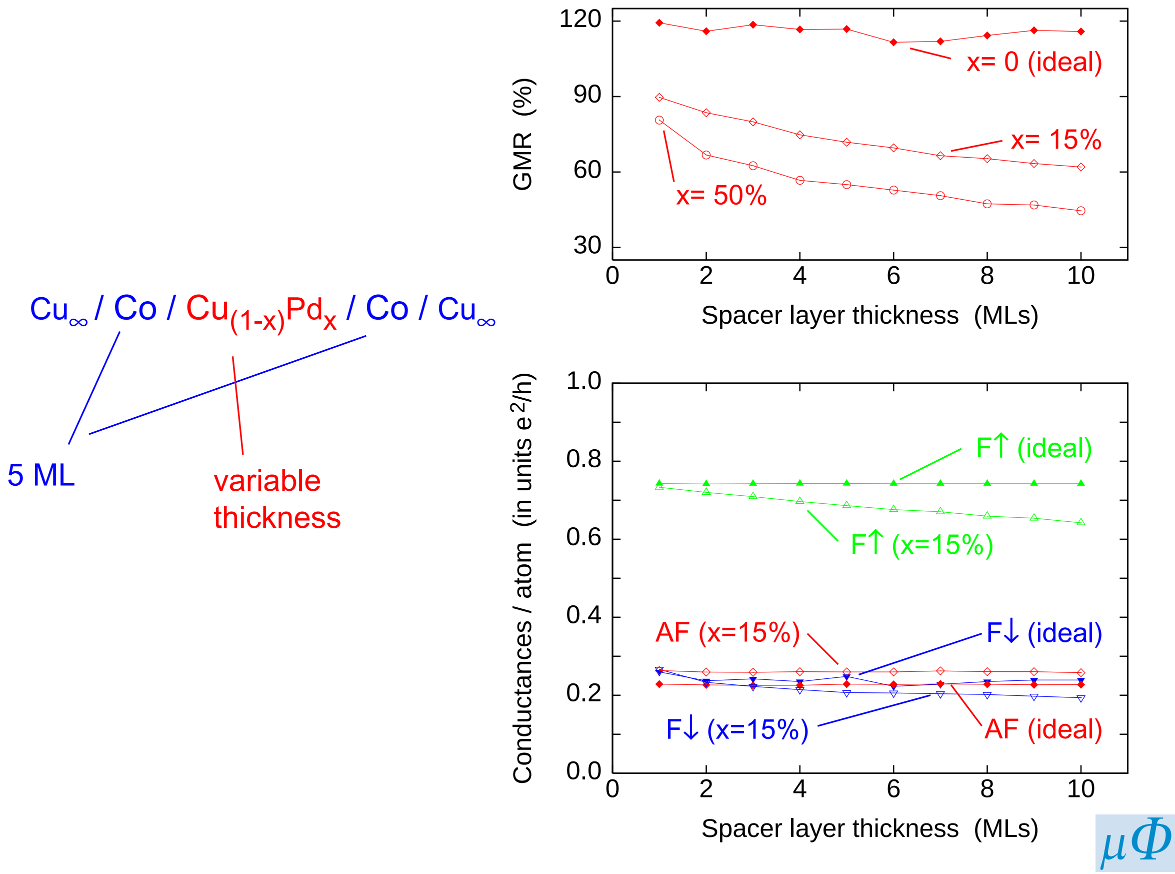

Conductances / atom (in units e^2/h)
0.25
0.24
0.23
0.22
F↓
AF
0
10
20
30
40
50
60
70
80
90
100
Spacer layer thickness (MLs)



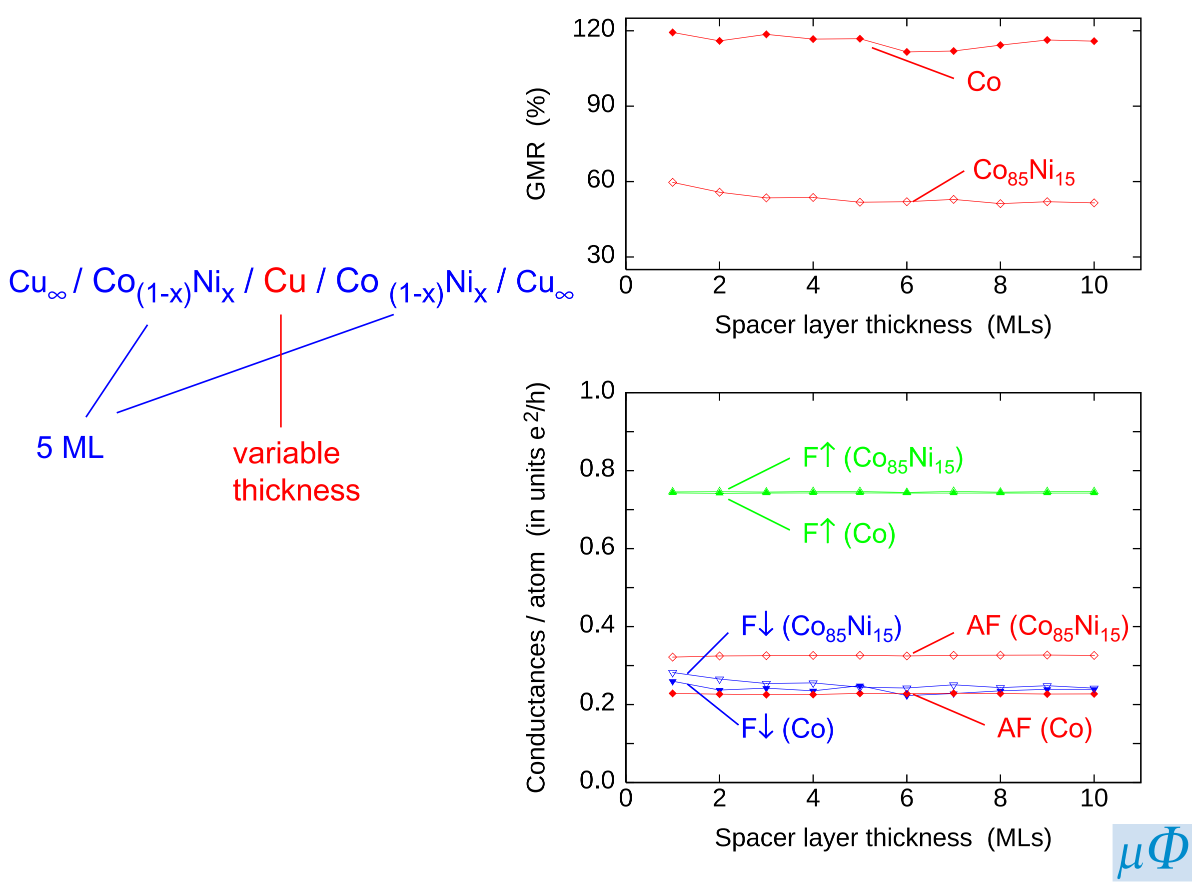
repeated N+1 times
Cu∞ / (Co / Cu / Co / Cu) / Cu∞
5 ML
GMR (%)
200
175
15.0
125
100
0
2
4
6
8
10
12
14
16
18
20
Number of repetitions
Conductances / atom (in units e²/h)
1.0
0.8
0.6
0.4
0.2
0.0
F↑
F↓
AF
Number of repetitions
μΦ



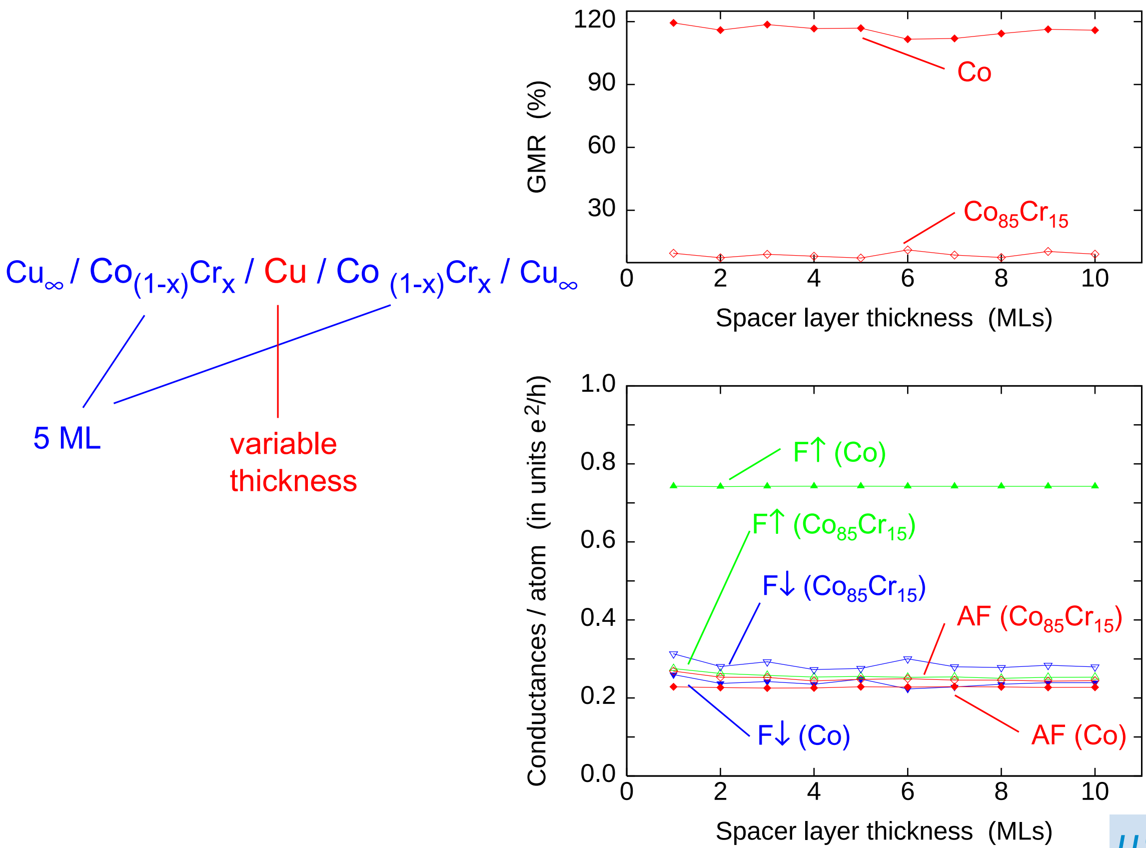
interfaces with
15% interdiffusion
Cu∞ / Co / Cu / Co / Cu∞
5 ML
variable
thickness
GMR (%)
120
90
60
30
0
2
4
6
8
10
ideal
interdiffused
Spacer layer thickness (MLs)
Conductances / atom (in units e²/h)
1.0
0.8
0.6
0.4
0.2
0.0
F↑ (ideal)
F↑ (interdiffused)
AF (interdiffused)
F↓ (interdiffused)
F↓ (ideal)
AF (ideal)
Spacer layer thickness (MLs)
μΦ



Cu∞ / Co / Cu(1-x)Pdx / Co / Cu∞
5 ML
variable thickness
GMR (%)
x= 0 (ideal)
x= 15%
x= 50%
Spacer layer thickness (MLs)
Conductances / atom (in units e2/h)
F↑ (ideal)
F↑ (x=15%)
AF (x=15%)
F↓ (ideal)
F↓ (x=15%)
AF (ideal)
Spacer layer thickness (MLs)



Cu∞ / Co(1-x)Nix / Cu / Co (1-x)Nix / Cu∞
5 ML
variable thickness
GMR (%)
Co
Co85Ni15
Spacer layer thickness (MLs)
Conductances / atom (in units e2/h)
F↑ (Co85Ni15)
F↑ (Co)
F↓ (Co85Ni15)
AF (Co85Ni15)
F↓ (Co)
AF (Co)
Spacer layer thickness (MLs)

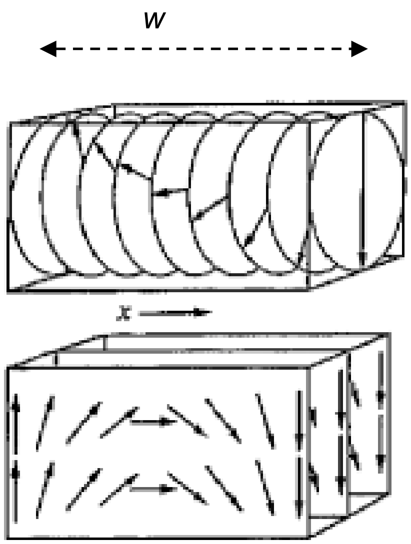


μΦ

domain wall magnetoresistance

μΦ

easy axis

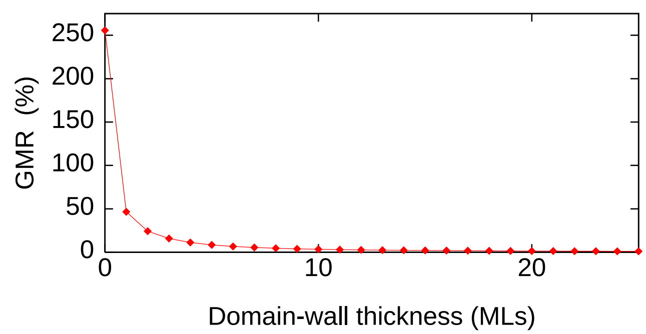


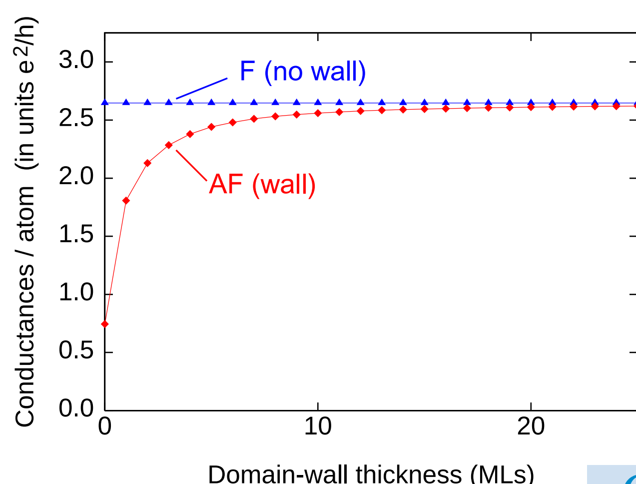
Bloch wall $w \propto \sqrt{\dfrac{A}{K}}$

Néel wall $w \propto \sqrt{\dfrac{A}{2\pi M^2}}$

Co_∞ / Co / Co_∞

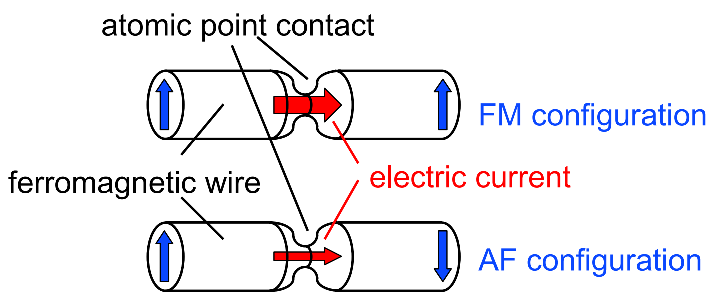
magnetic wall of variable thickness
(linear rotation of magnetization)





μΦ

Giant magnetoresistance of ferromagnetic atomic point contacts



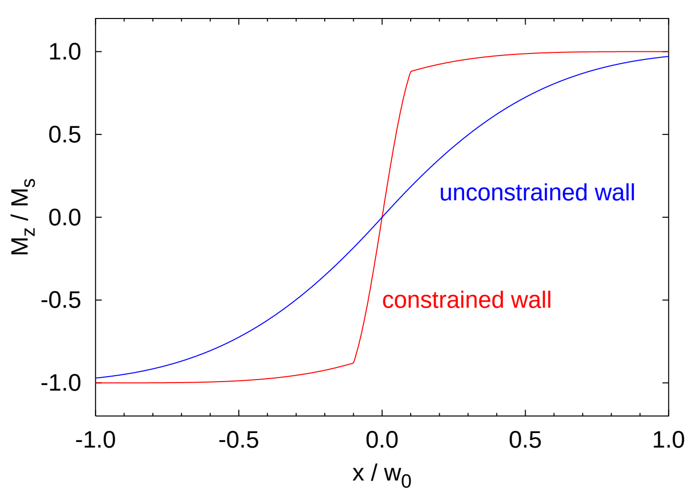
explaination requires:

- narrow magnetic wall in an atomic point contact
- large resistance due to a narrow wall

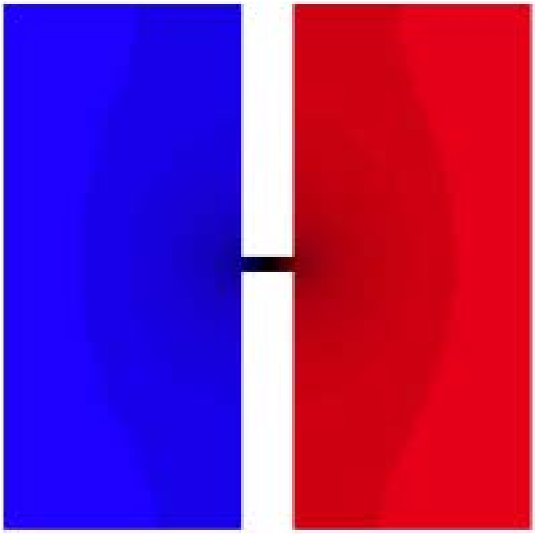
geometrical constriction → new kind of magnetic wall:

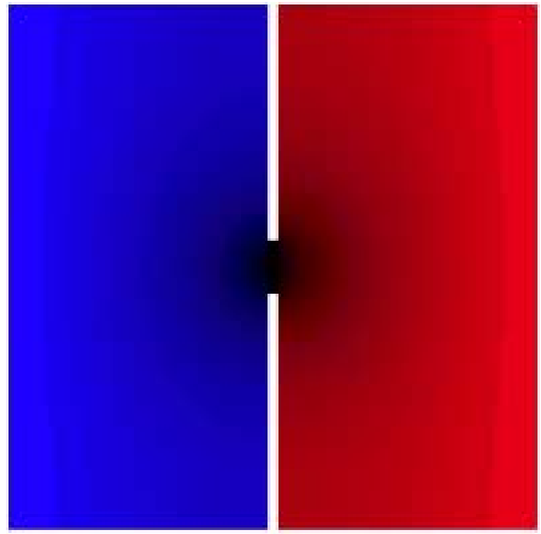
- structure (almost) entirely determined by the constriction geometry
- energy = (almost) pure exchange energy
- width determined by the characteristic size of the constriction

→ wall can be extremely narrow in an atomic point contact



P. Bruno, PRL **83**, 2425 (1999)

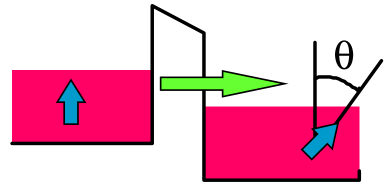




20 nm X 20 nm

theory of tunneling magnetoresistance

simple approach: Jullière model

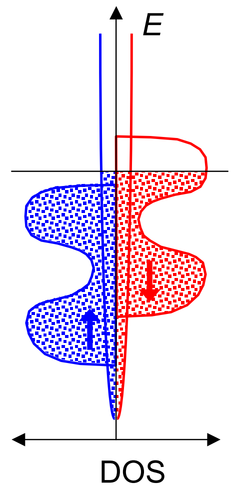


assumptions: $G = G_\uparrow + G_\downarrow$

$G\sigma \propto \rho_1^\sigma(\varepsilon_F)\,\rho_2^\sigma(\varepsilon_F)$

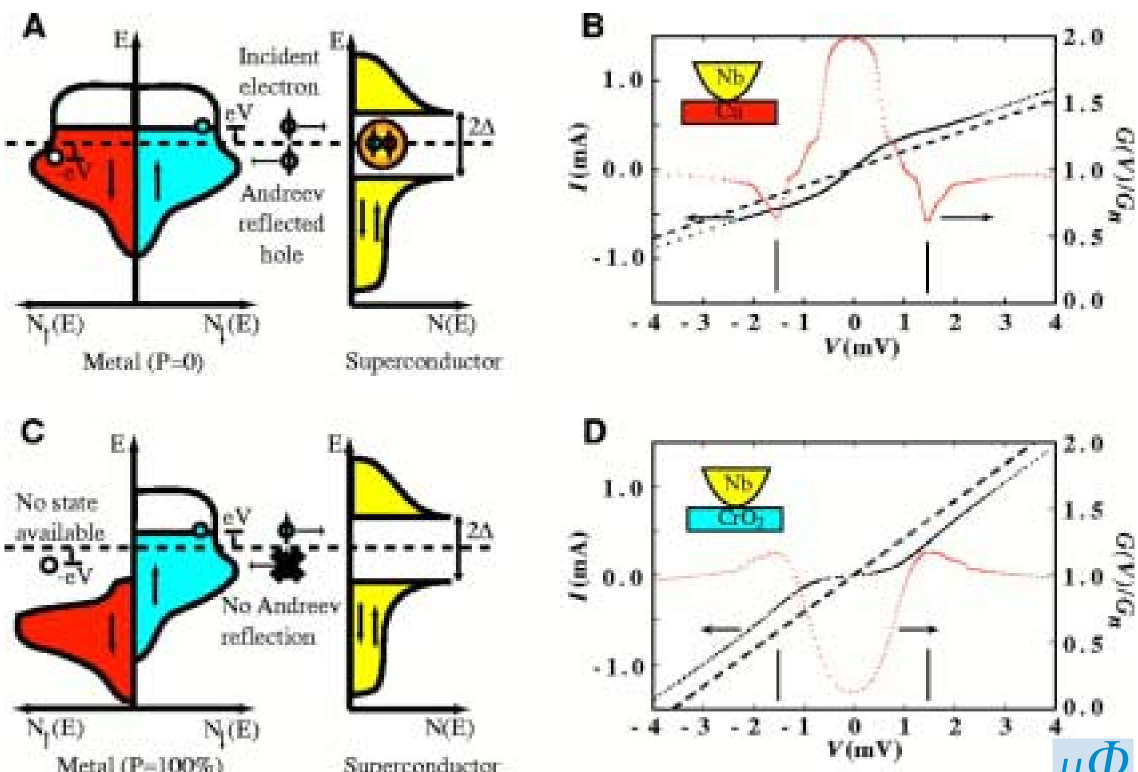
→ $$A \equiv \frac{G_{AP} - G_P}{G_{AP} + G_P} = P_1 P_2$$

with $$P \equiv \frac{\rho^\uparrow(\varepsilon_F) - \rho^\downarrow(\varepsilon_F)}{\rho^\uparrow(\varepsilon_F) + \rho^\downarrow(\varepsilon_F)}$$

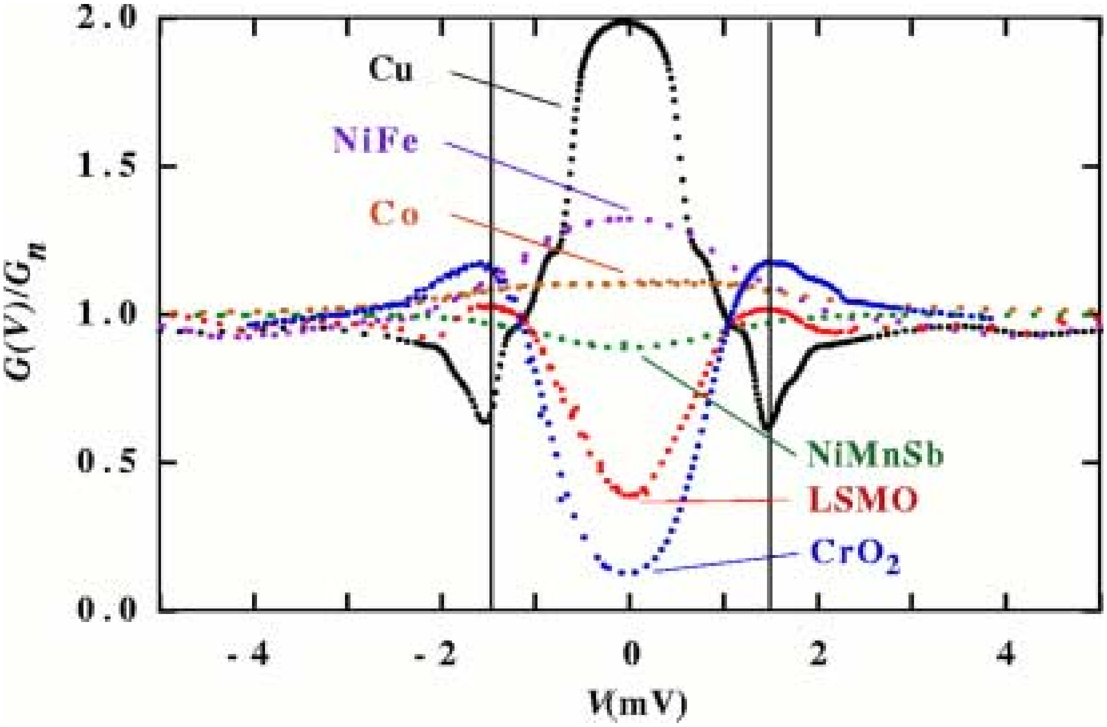


μΦ

measurement of the spin-polarization by spin-injection into a superconductor



μΦ



Soulen *et al.*, Science **282**, 85 (1998)

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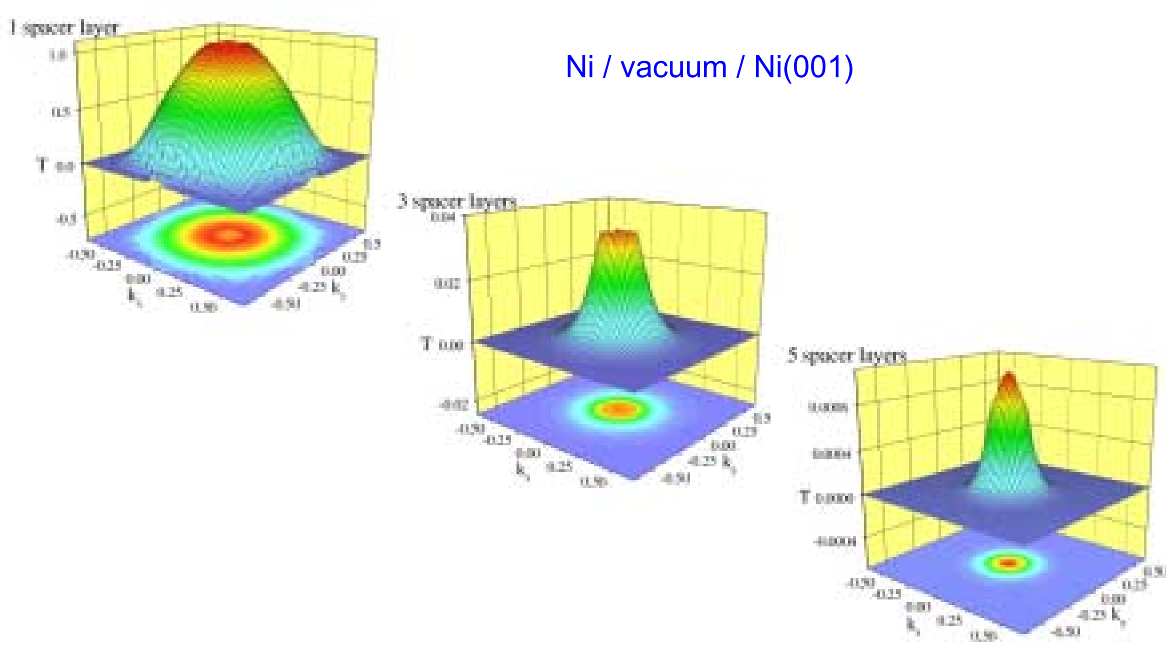
ab initio calculation of tunnel conductance

Ni / vacuum / Ni(001)



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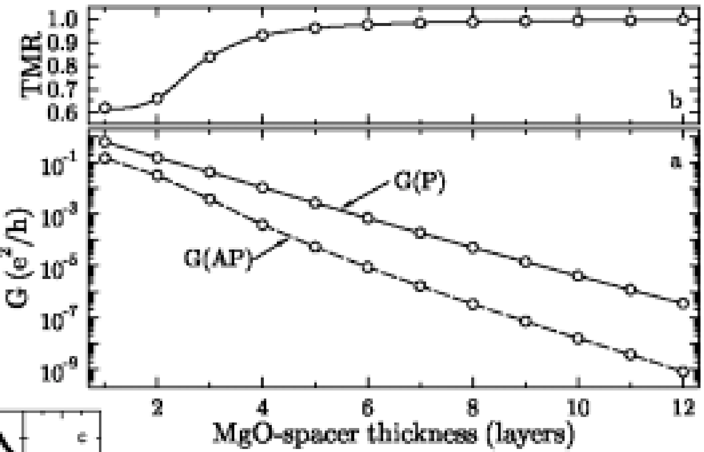
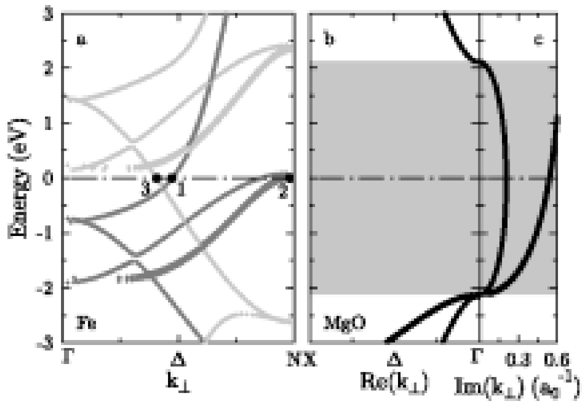
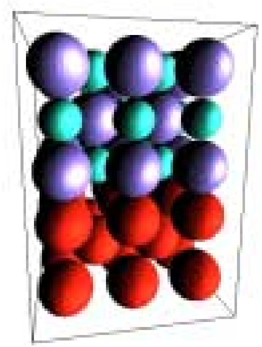
Fe / MgO / Fe(001)







MgO

Fe

J. Henk (MPI Halle)

$\mu\Phi$