Spintronics I

1. Introduction
3. Mott paradigm: two currents model
4. Giant MagnetoResistance: story and basic principles
5. Semiclassical model for CIP GMR

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Outlook

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The Nobel Prize in Physics 2007

Photo: U. Montan

Albert Fert

Prize share: 1/2

Photo: U. Montan

Peter Grünberg

Prize share: 1/2

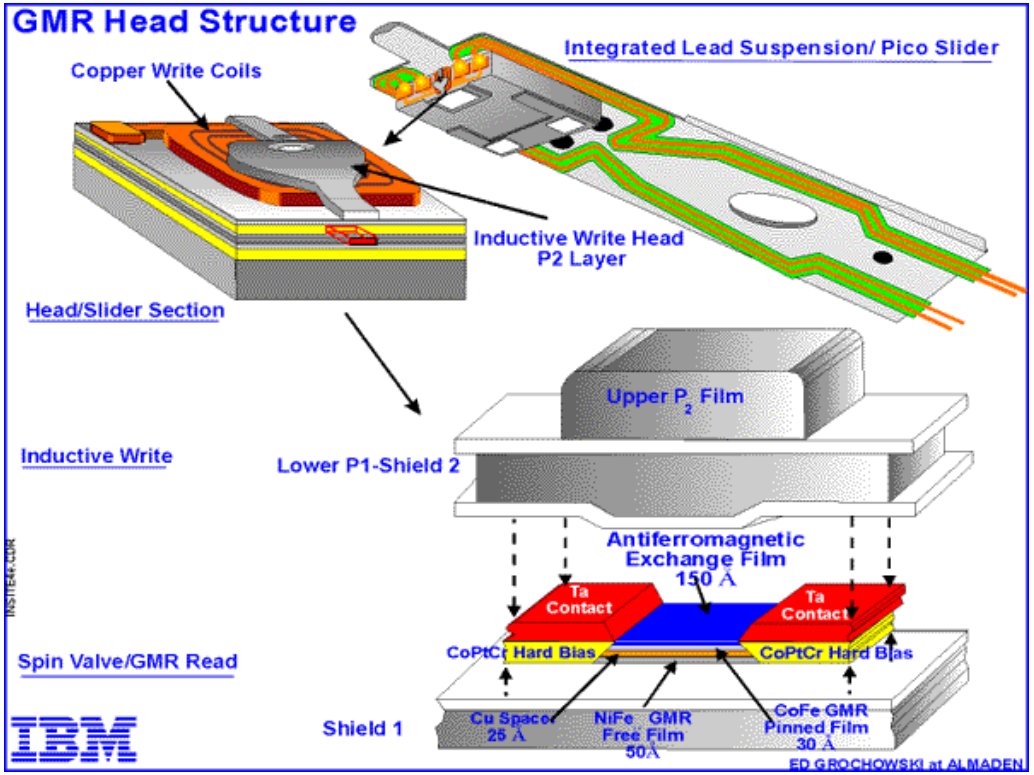
The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

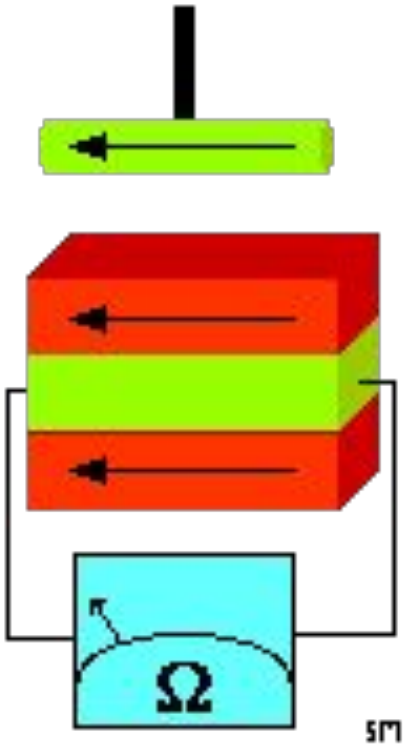
Giant

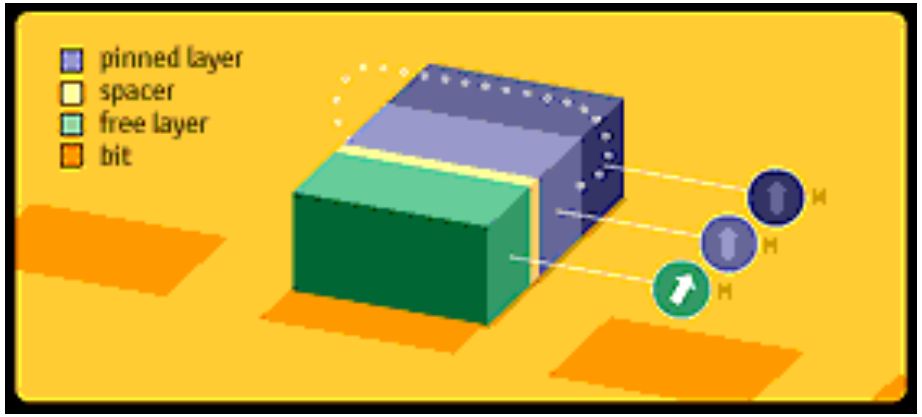
Magneto

Resistance

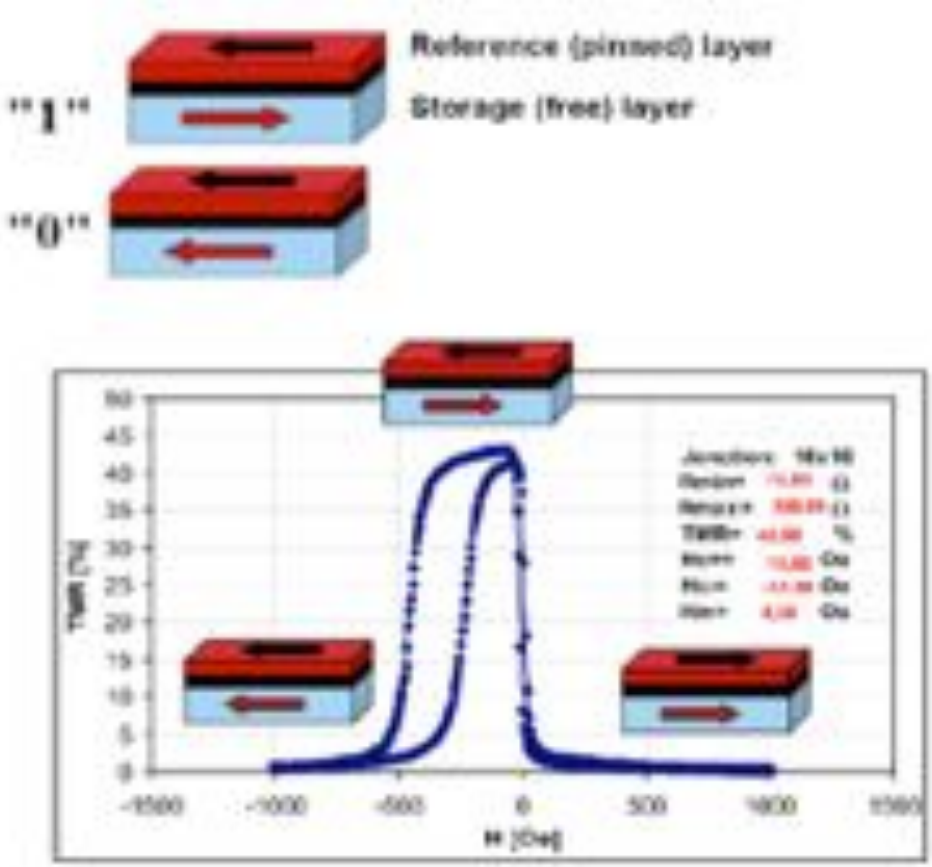
GMR for magnetic recording

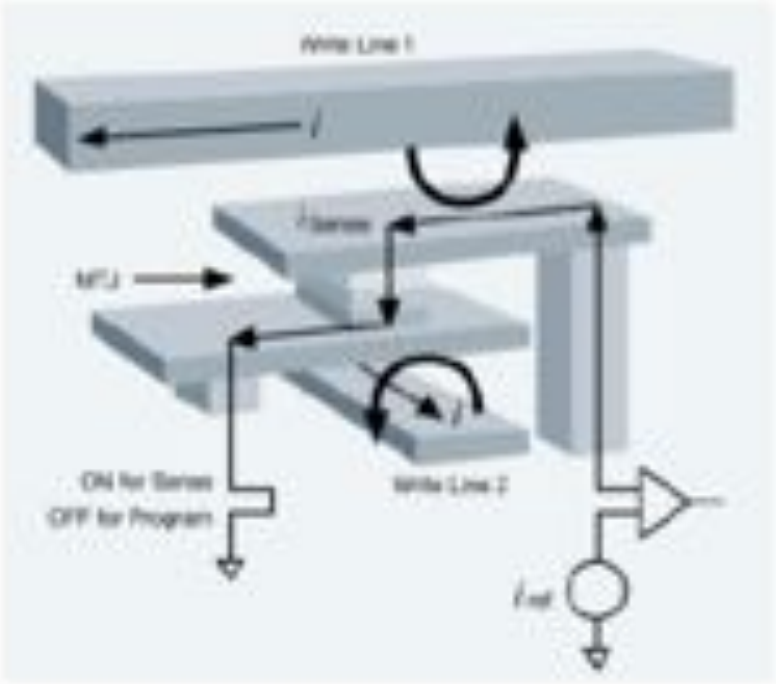






Non Volatile RAMs





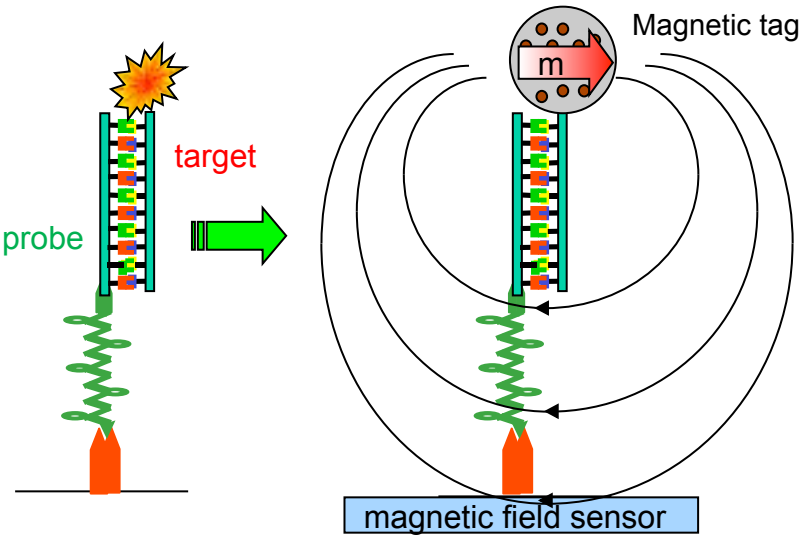
[Courtesy of J.P. Nozieres (Spintec)]

GMR/TMR for medicine and biology

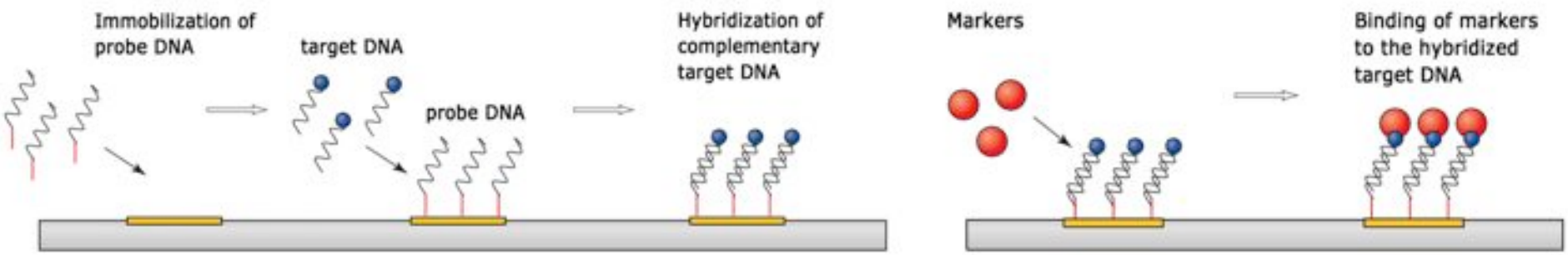
Magnetic sensor for read-out of biomolecular recognition at their surface

✓No quenching
✓Direct electrical read-out: easily integrable
✓ No magnetic background

[V. C. Martins, F. A. Cardoso et al., Biosensors & bioelectronics, 2009]
[R. S. Gaster et al., Lab Chip 2011 and Nat. Nanotech. 2011]

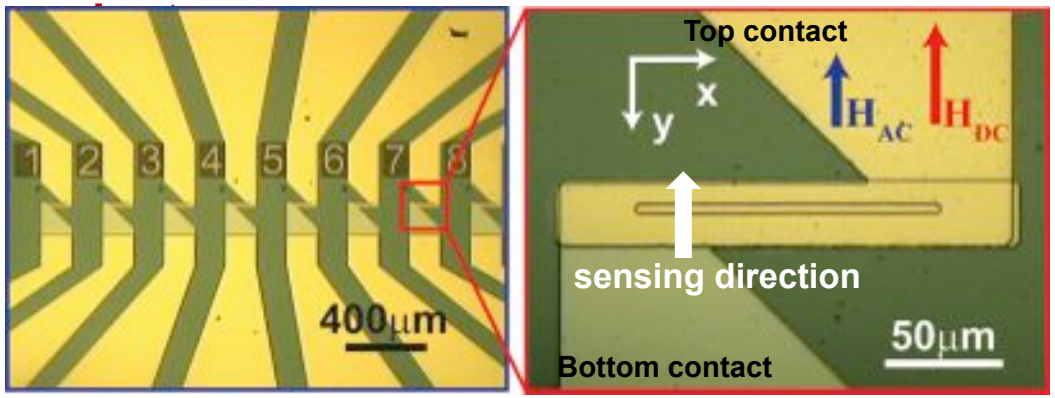


Surface functionalization, molecular recognition and marker binding scheme

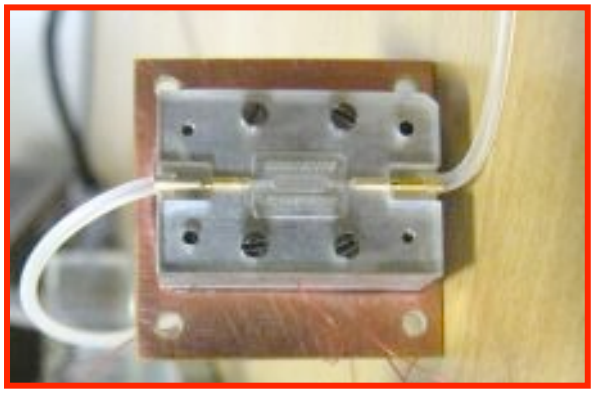


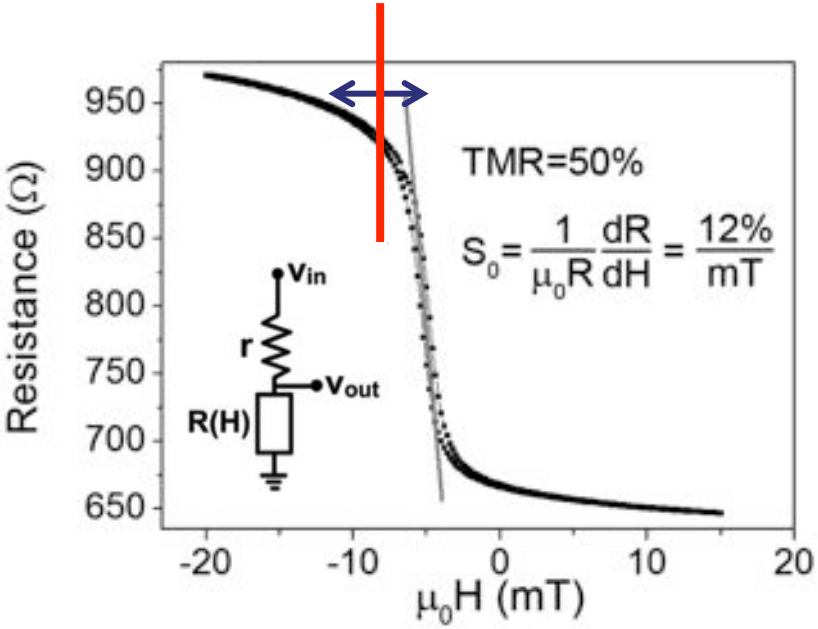
Microarrays of spintronic transducers

***Multiplexing:* up to 8 sensors sequential**



Integration with microfluidics





Double modulation technique

- ✓**AC junction current: reduces 1/f noise (f_1=51kHz)**

$$V(t) = V_s \cos(2\pi f_1 t)$$

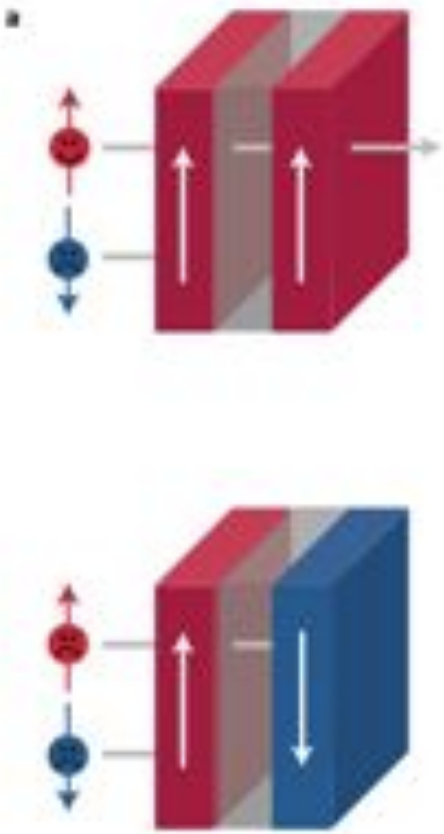
- ✓**H_{AC} oscillatory magnetic excitation (f_2=111Hz)**

$$H_{AC}(t) = h\cos(2\pi f_2 t)$$

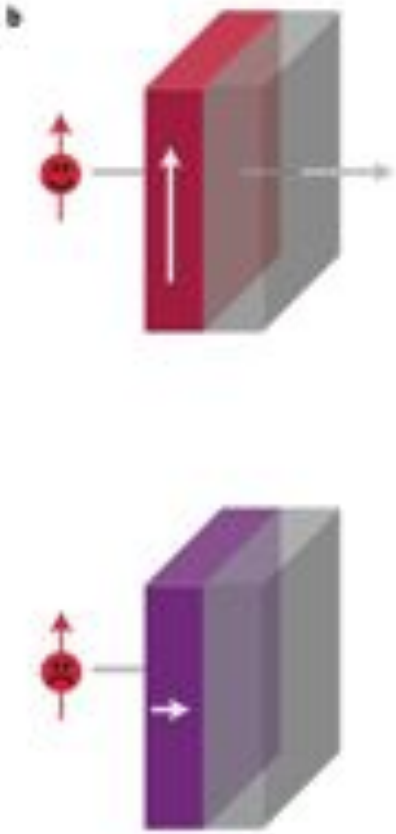
- ✓**H_{DC} bias for selecting the working point**
- ✓**Lock-in demodulation @ $f_1 + f_2$**

Spintronic paradigms

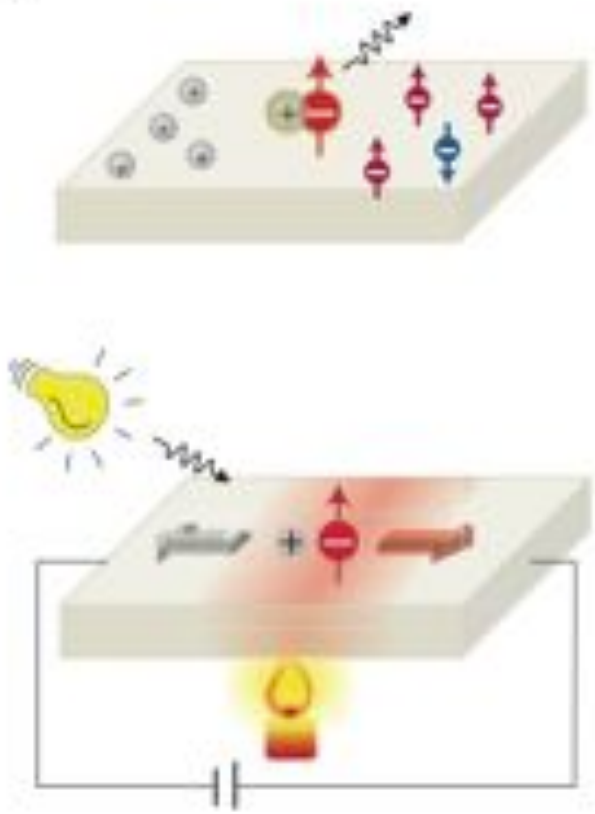
Mott



Dirac



Shockley



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MOTT spintronics: Two currents model

Original idea: N. F. Mott, Proc. Roy. Soc. A153, 699 (1936)

First experimental evidence for spin dependent transport:
A. Fert and I. A. Campbell, Phys. Rev. Lett. 21, 1190 (1968) – Ni/Fe alloys

Basic idea: conduction in independent parallel channels by the spin↑ (majority) and spin↓ (minority) electrons. *The spin flip scattering of the conduction electrons by magnons is frozen out, the spin mixing rate is much smaller than the momentum relaxation rate.*

Eigenstates: $\psi_{j,s,\mathbf{k}}(\mathbf{r})$

j : layer in the structure
s: canale di spin

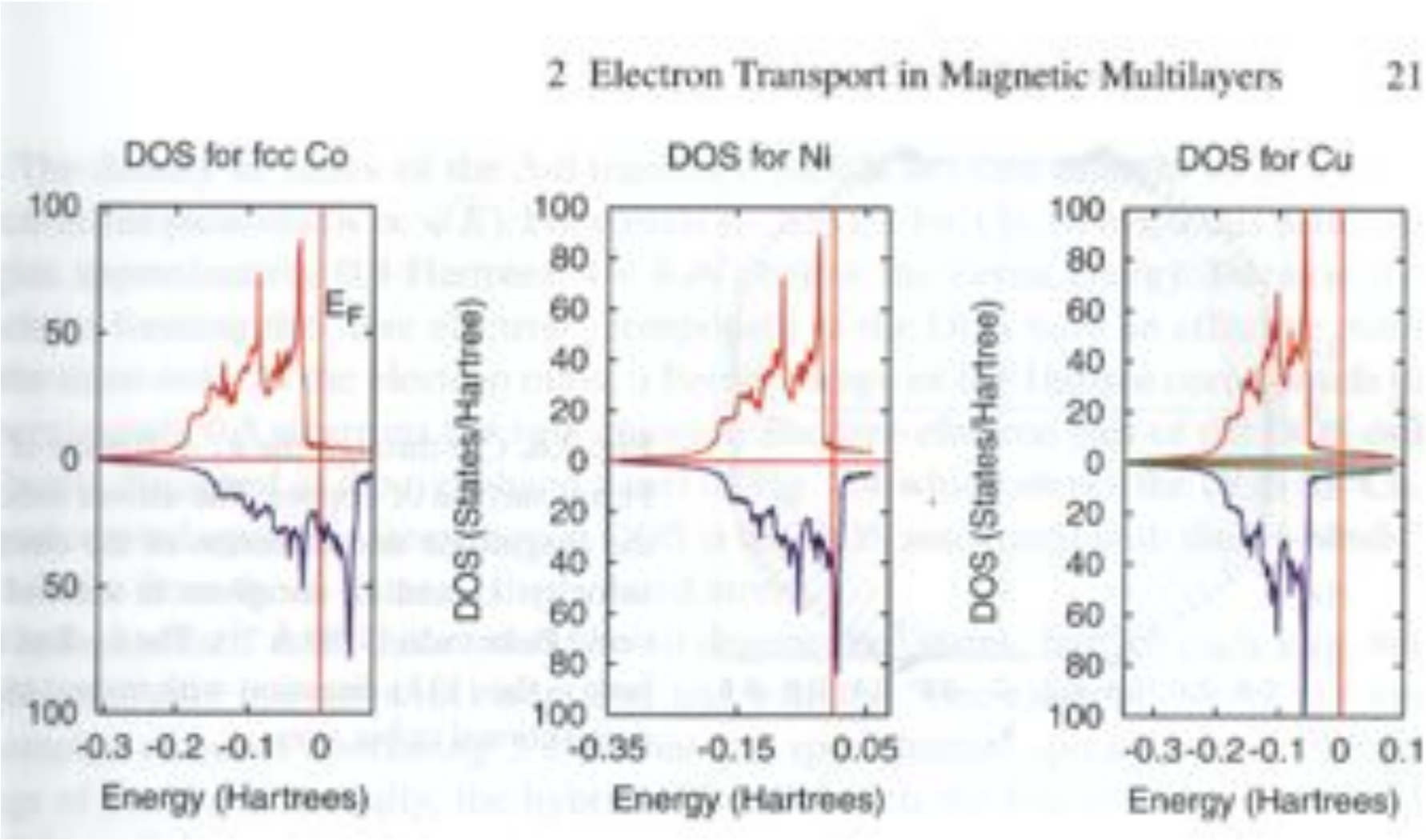
Eigenvalues: $\varepsilon_{j,s}(\mathbf{k})$

Bande up e down

DOS (up and down): $$n_{j,s}(E) = \sum_{\mathbf{k}} \delta(E - \varepsilon_{j,s}(\mathbf{k}))$$

This is the Stoner description or band description of a ferromagnet

Spin dependent electronic structure



Ultrathin Magnetic Nanostructures III, Springer Verlag (2005)

Validity of the two current model /1

1) Negligible spin-orbit interaction

The spin-orbit contribution in the Hamiltonian should contain a term like:

$$H_{SO} = \frac{\hbar^2}{2m^2c^2r}\frac{dV}{dr}\mathbf{L}\cdot\mathbf{S}$$

The Hamiltonian would depend ont the angle between **L** and **S**, and the eigenstates could not be indexed as up or down with respect to a quantization axis.

Validity of the two current model /2

2) The magnetization in the different layers of a multilayer should be parallel or antiparallel to a given quantization axis

If in two adjacent layers M_1 and M_2 form an angle different from $n\pi$ an up electron in the layer 1 must be described as a mixture of states up and down in the layer 2, where the quantization axis is rotated by θ.

Exercise: Consider M_2 ($\theta = 0$) ; M_1 (θ, ϕ) ; **e** : unit vector in the direction (θ, ϕ). Find out the equations connecting the pure states of spin in the two layers.

The spinors describing the eigenstates in M_1 satisfy the equation:

$$(\boldsymbol{\sigma} \cdot \mathbf{e})\chi = \lambda\chi$$

$$\boldsymbol{\sigma} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\mathbf{u}_x + \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\mathbf{u}_y + \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\mathbf{u}_z$$

Eigenstates in the first layer:

$$\chi_1 = \begin{bmatrix} \cos\vartheta/2 \\ \sin\vartheta/2\, e^{i\varphi} \end{bmatrix}$$

λ = 1 spin up

$$\chi_2 = \begin{bmatrix} \sin\vartheta/2 \\ -\cos\vartheta/2\, e^{i\varphi} \end{bmatrix}$$

λ = -1 spin down

Eigenstates in the second layer:

$$\chi_1' = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \chi_2' = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

There is a mixing of the spin channels in the first layer when passing in the second layer:

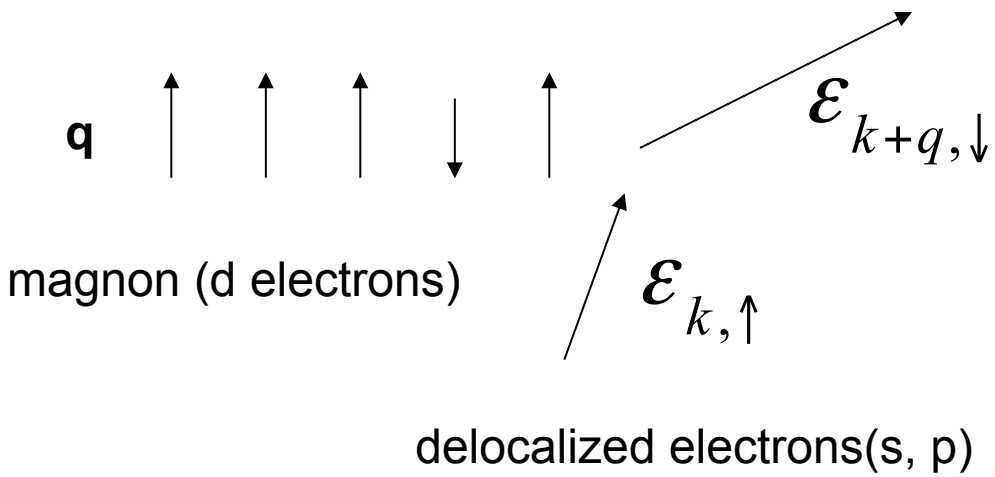
$$\chi_1 = \cos\vartheta/2\, \chi_1' + \sin\vartheta/2\, e^{i\varphi} \chi_2'$$

Validity of the two current model /3

3) T << Tc

Magnon scattering, inducing spin flip and mixing of the two spin channels, can be neglected only at low temperature, well below Tc.

Example: An electron up undergoes a spin flip event and becomes down upon annihilation of a magnon.



Conservation of total momentum and spin.

Transport in the two current model

Channel up

$$-eE_x/\hbar \cdot \frac{\partial f_0}{\partial k_x} = -\frac{f_\uparrow(\mathbf{k}) - f_0(\mathbf{k})}{\tau_\uparrow(\mathbf{k})}$$

$$\sigma_\uparrow \cong \frac{e^2 \tau_\uparrow(\varepsilon_F) n_\uparrow}{m_\uparrow{}^*}$$

Channel down

$$-eE_x/\hbar \cdot \frac{\partial f_0}{\partial k_x} = -\frac{f_\downarrow(\mathbf{k}) - f_0(\mathbf{k})}{\tau_\downarrow(\mathbf{k})}$$

$$\sigma_\downarrow \cong \frac{e^2 \tau_\downarrow(\varepsilon_F) n_\downarrow}{m_\downarrow{}^*}$$

Two channels in parallel

$$\rho = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$$

Spin asymmetry coefficients:

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

$$\beta = \frac{\rho_\downarrow - \rho_\uparrow}{\rho_\downarrow + \rho_\uparrow} = \frac{\alpha - 1}{\alpha + 1}$$

Within the two current model

$$\frac{1}{\tau_{\uparrow,\downarrow}(\varepsilon_F)} \approx \left|\langle \mathbf{k} | V_{\uparrow,\downarrow} | \mathbf{k}' \rangle\right|^2 n_{\uparrow,\downarrow}(\varepsilon_F)$$

Spin dependence of:

$$\rho_{\uparrow,\downarrow} = \frac{m_{\uparrow,\downarrow}}{e^2 n_{\uparrow,\downarrow} \tau_{\uparrow,\downarrow}}$$

a) Intrinsic origins

For transition metal the most relevant term is $1/\tau \sim n(\varepsilon_F)$, where the density of d electrons must be considered. A major part of the current is carried by light electrons of s character and these electrons are more strongly scattered when they can be scattered into heavy states of the d band for which the DOS is large.

Co, Ni, NiFe, CoFe have a d↑ band completely occupied, thus leading to:

$n\, d\uparrow (\varepsilon_F) = 0 \qquad n\, d\downarrow (\varepsilon_F) \neq 0$

There is a relevant s-d scattering only in the minority channel:

$$\rho_{\downarrow} > \rho_{\uparrow}$$

b) Estrinsic origins

The perturbation potential due to impurities depends on the spin.

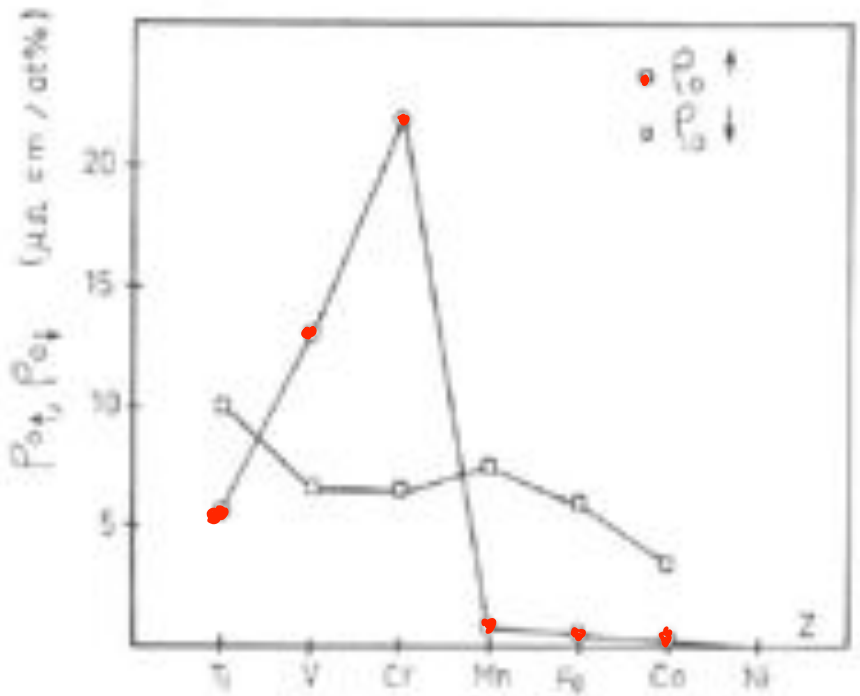


Fig. 1: Resistivities, ρ↑and ρ↓, induced by 1% of several types of impurity in the spin↓ and spin↑ channels of Ni [7,14].

A. Fert and I.A. Campbell, J. Phys. F, 6, 849 (1976)

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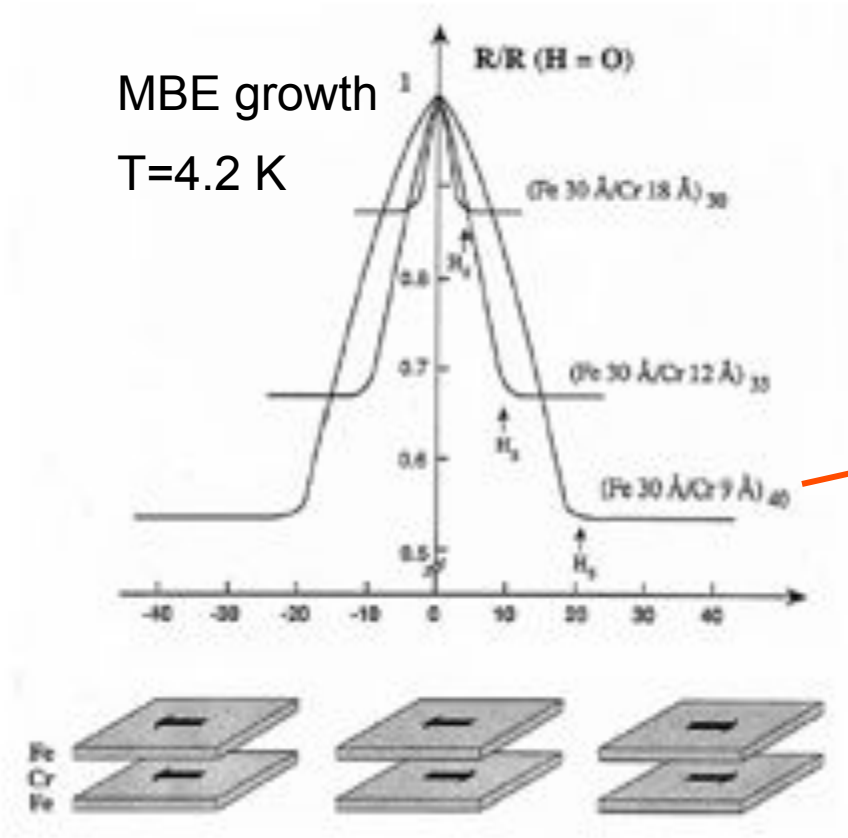
Giant Magneto Resistance (GMR)



$$MR = \frac{\rho_{AP} - \rho_P}{\rho_P}$$

79% at 4.2 K
20% at 300 K

Record: 220%
Fe/Cr multilayers
Schad et al. (1994)

[1] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J.Chazelas, Phys. Rev. Lett. **61**, 2472 (1988)

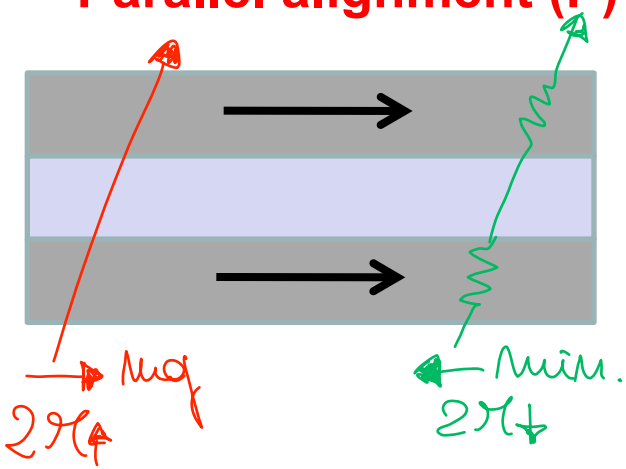
[2] G. Binash, P. Grünberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989) *(trilayer)*

GMR: a simple model

Hp1: Spin dependent scattering due to defects and impurities in magnetic layers as well as at interfaces

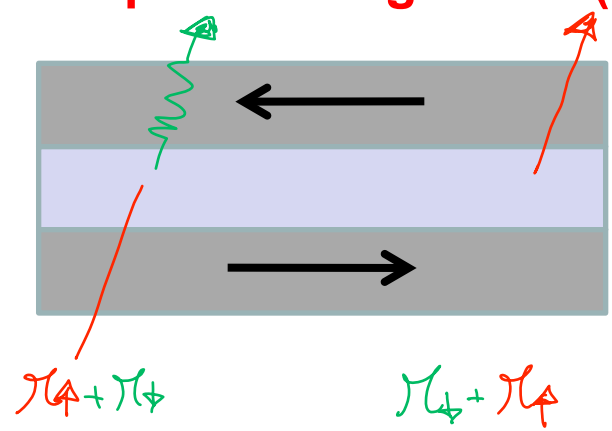
Hp2: Consider a CPP configuration

Parallel alignment (P)



Hp: $r_\uparrow \ll r_\downarrow$
(Co, Ni, ...)

Antiparallel alignment (AP)



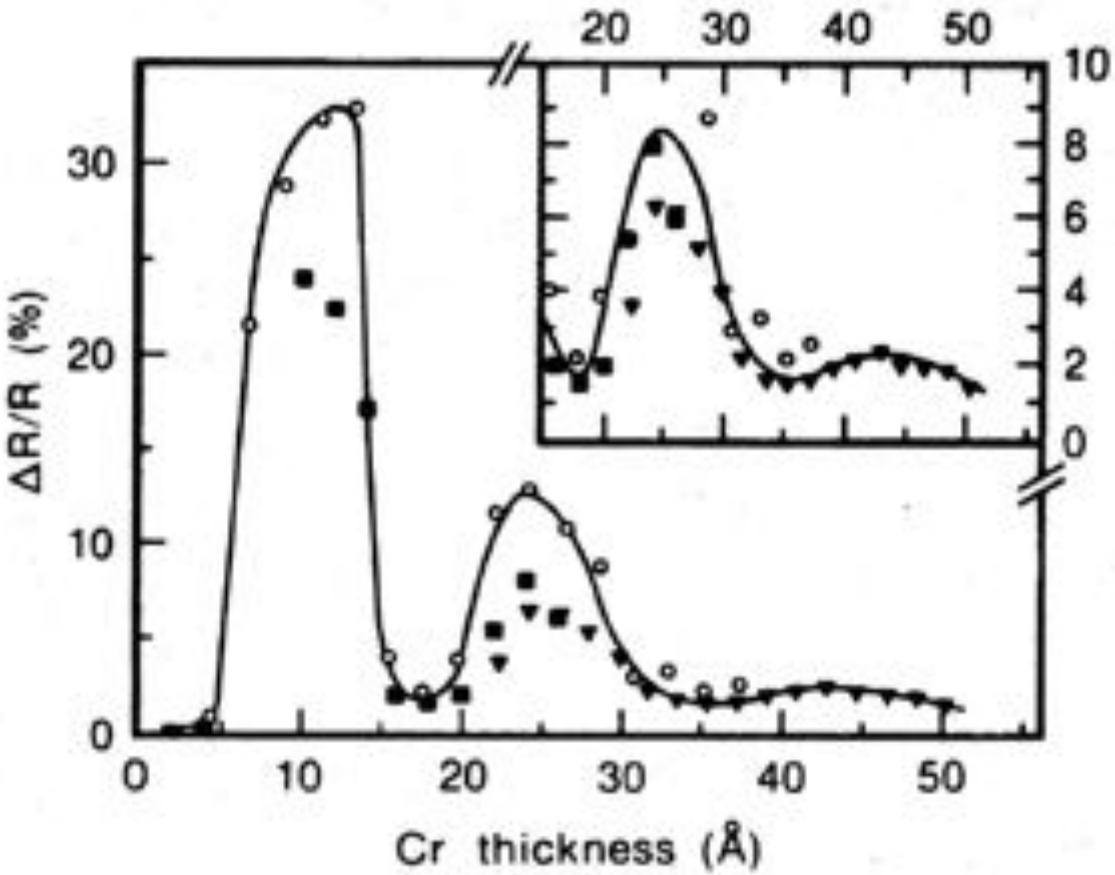
$$r_P = \frac{2 r_\uparrow r_\downarrow}{r_\uparrow + r_\downarrow} \simeq 2 r_\uparrow$$

$$r_{AP} = \frac{r_\uparrow + r_\downarrow}{2}$$

$r_{AP} \gg r_P$ because in P config. there is a "SHORT" in the maj. channel

$$GMR = \frac{r_{AP} - r_P}{r_P} = \frac{\frac{r_\uparrow + r_\downarrow}{2} - \frac{2 r_\uparrow r_\downarrow}{r_\uparrow + r_\downarrow}}{\frac{2 r_\uparrow r_\downarrow}{r_\uparrow + r_\downarrow}} = \frac{(r_\uparrow + r_\downarrow)^2 - 4 r_\uparrow r_\downarrow}{4 r_\uparrow r_\downarrow} = \frac{(r_\uparrow - r_\downarrow)^2}{4 r_\uparrow r_\downarrow}$$

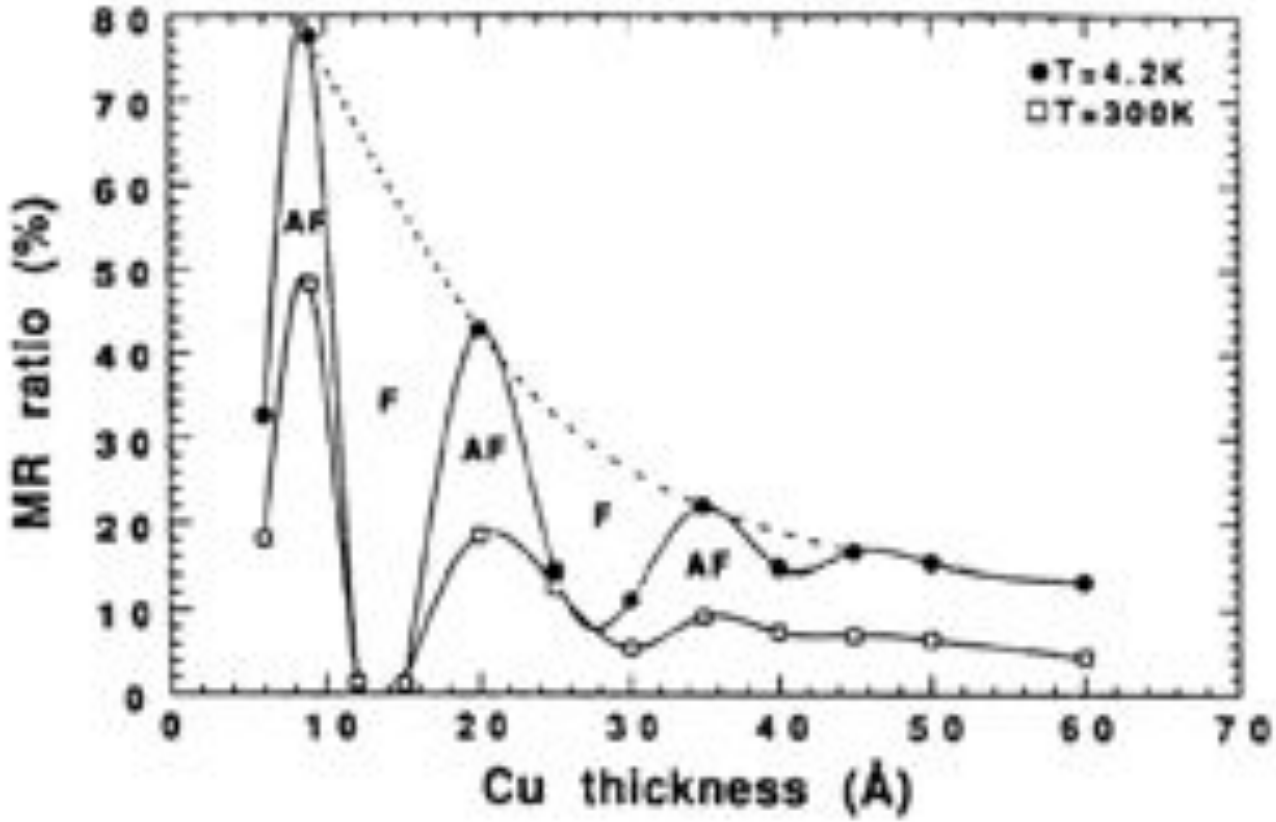
GMR oscillations



S. S. P. Parkin, N. More, K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990)

GMR ratio of (Fe 2nm/Cr) multilayers at T=4.5 K as a function of the thickness of the Cr layers. Different symbols correspond to different deposition temperatures. From Parkin et al. [16].

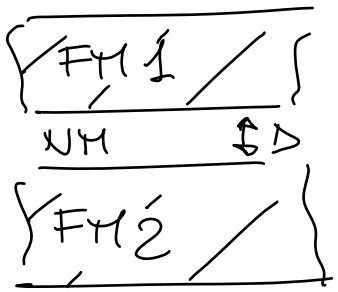
GMR oscillations Co/Cu



MR ratio of (Co 1.5nm/Cu) multilayers as a function of the thickness of Cu layers.

D. H. Mosca, F. Petroff, A. Fert, P. A. Schroeder, W. P. Pratt, R. Loloee,
J. Magn. Magn. Mater. **94**, L1 (1991)

Interlayer exchange coupling or bilinear coupling



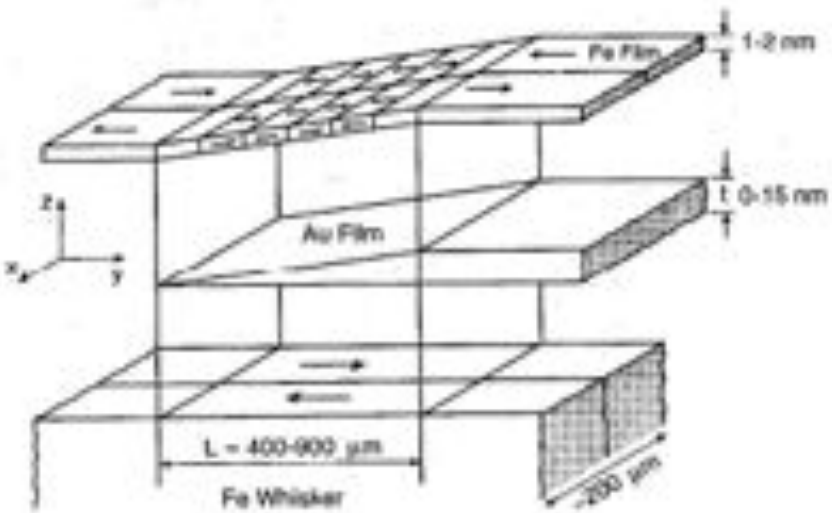
$$\frac{E}{A} = -J\,\bar{m}_1 \cdot \bar{m}_2$$

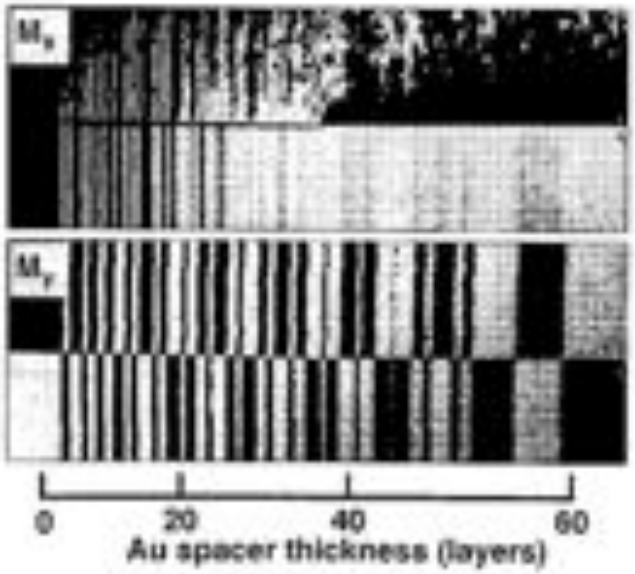
depends on the product of both $\bar{m}_1$ and $\bar{m}_2$ ($\rightarrow$ BILINEAR)

Oscillatory exchange coupling in Fe/Au/Fe(100)

J. Unguris, R. J. Celotta, and D. T. Pierce
Electron Physics Group, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

J. Appl. Phys. **75** (10), 15 May 1994





http://cnst.nist.gov/epg/Pubs/pdf/epg625.pdf

Physical origin of bilinear coupling

$$\frac{E}{A} = -J\,\bar{m}_1\cdot\bar{m}_2 \Rightarrow J = \frac{1}{2A}\left(E_{AP} - E_P\right)$$

FORCE THEOREM: If the approximation for the mean potential is good enough, the difference between energies calculated as sum of single-particle energies is very close to the difference of energies calculated in a self consistent way

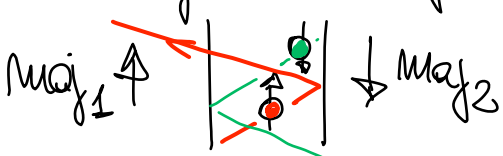
$$\Delta\left(\sum_i E_i\right) \simeq \Delta E_{TOT}$$

SPIN DEPENDENT QW STATES MAKE THE DIFFERENCE

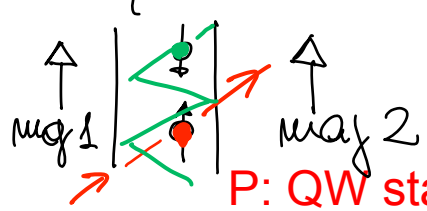
Simple model: NOBLE / 3d metal interface

→ Good matching of d bands for majority, not for minority electrons

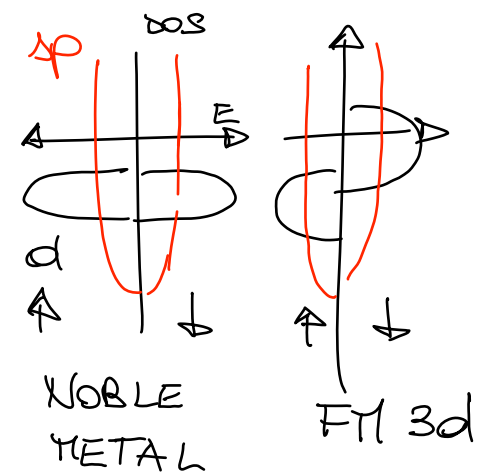
Reflection of minority el.



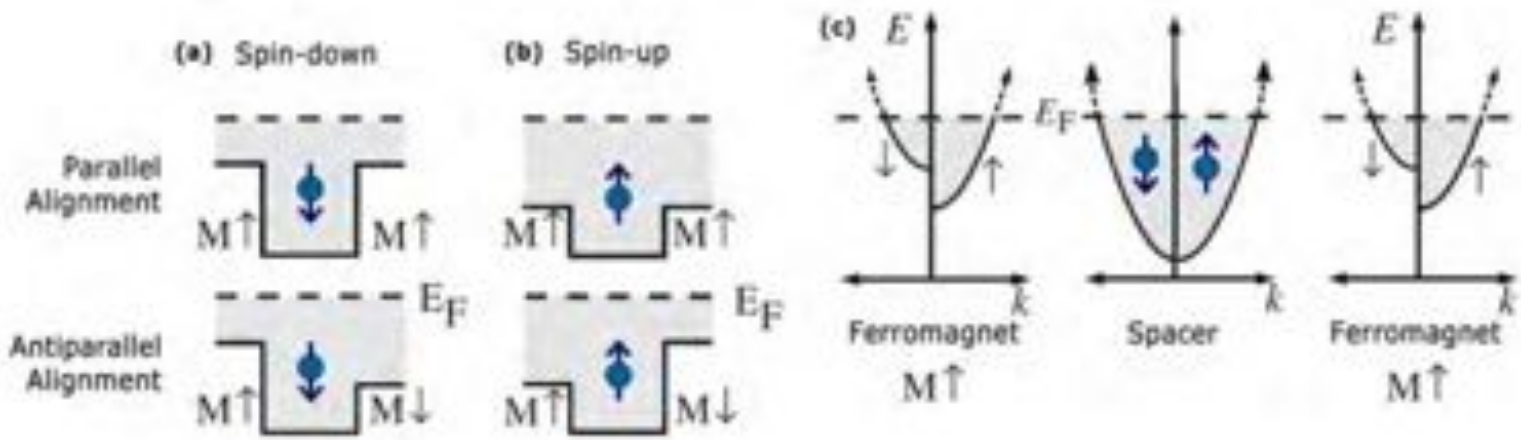
AP: no QW states



P: QW states only for ↓



$(E_{AP} - E_P)$ depends on the energy of QW states for P and AP configuration



Phase accumulation model (barrier not ∞)

A_0 initial amplitude

$$A_1 = \left(e^{ikD} R_R e^{ikD} R_L\right) A_0$$ after 1 round trip

R_R, R_L: spin dependent reflection coefficients

$$A_\infty = A_0 \sum_{n=1}^{\infty} \left(e^{i2kD} R_R R_L\right)^n = \frac{e^{i2kD} R_R R_L}{1 - R_R R_L e^{i2kD}} A_0$$

$$R_R = \alpha_R e^{i\phi_R} \qquad R_L = \alpha_L e^{i\phi_L}$$

Constructive interference for minima of $1 - \alpha_R \alpha_L e^{i2kD} e^{i\phi_R} e^{i\phi_L}$

$$2kD + \phi_R + \phi_L = 2m\pi$$

$|R|$ → RESONANCES, wide in energy

→ narrow RESONANCES, bound states

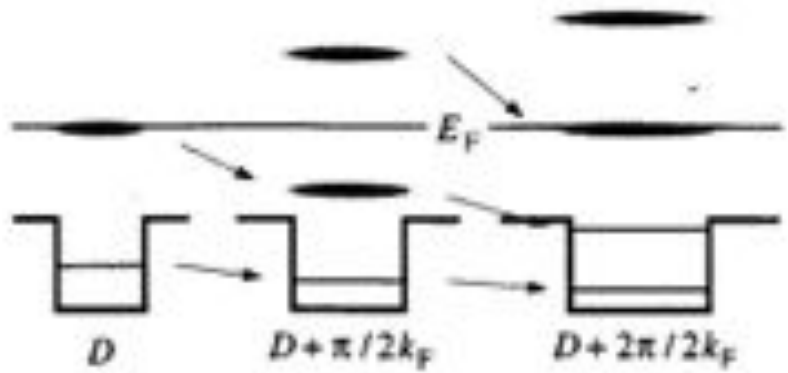


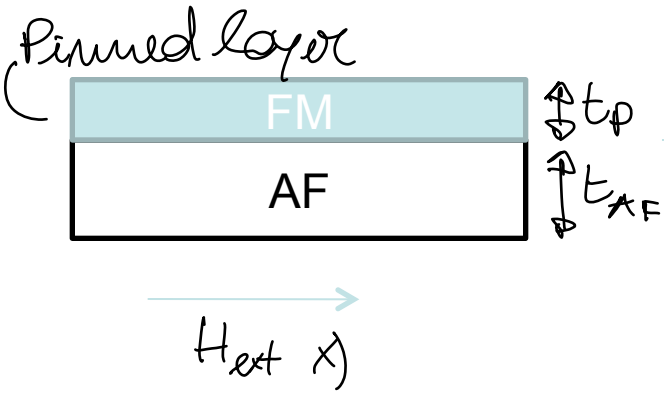
Fig. 4.5. Evolution of quantum well resonances with spacer layer thickness. The three panels illustrate the bound states (*lines*) and resonances (*fuzzy ellipses*) for quantum wells of increasing thickness. The arrows indicate how each resonance evolves as the thickness is increased

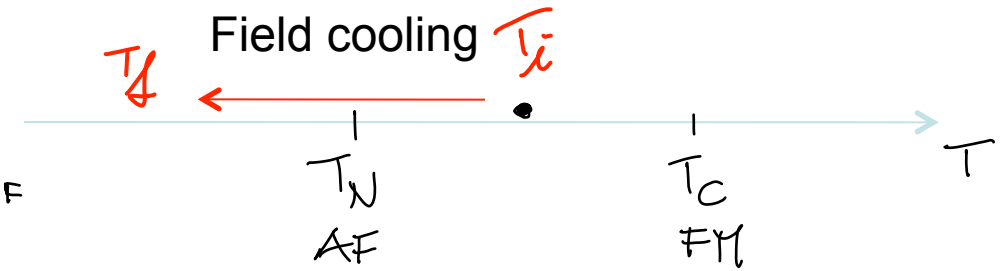
Resonances crosses E_F (when D increases) with a period determined by $2k_F$

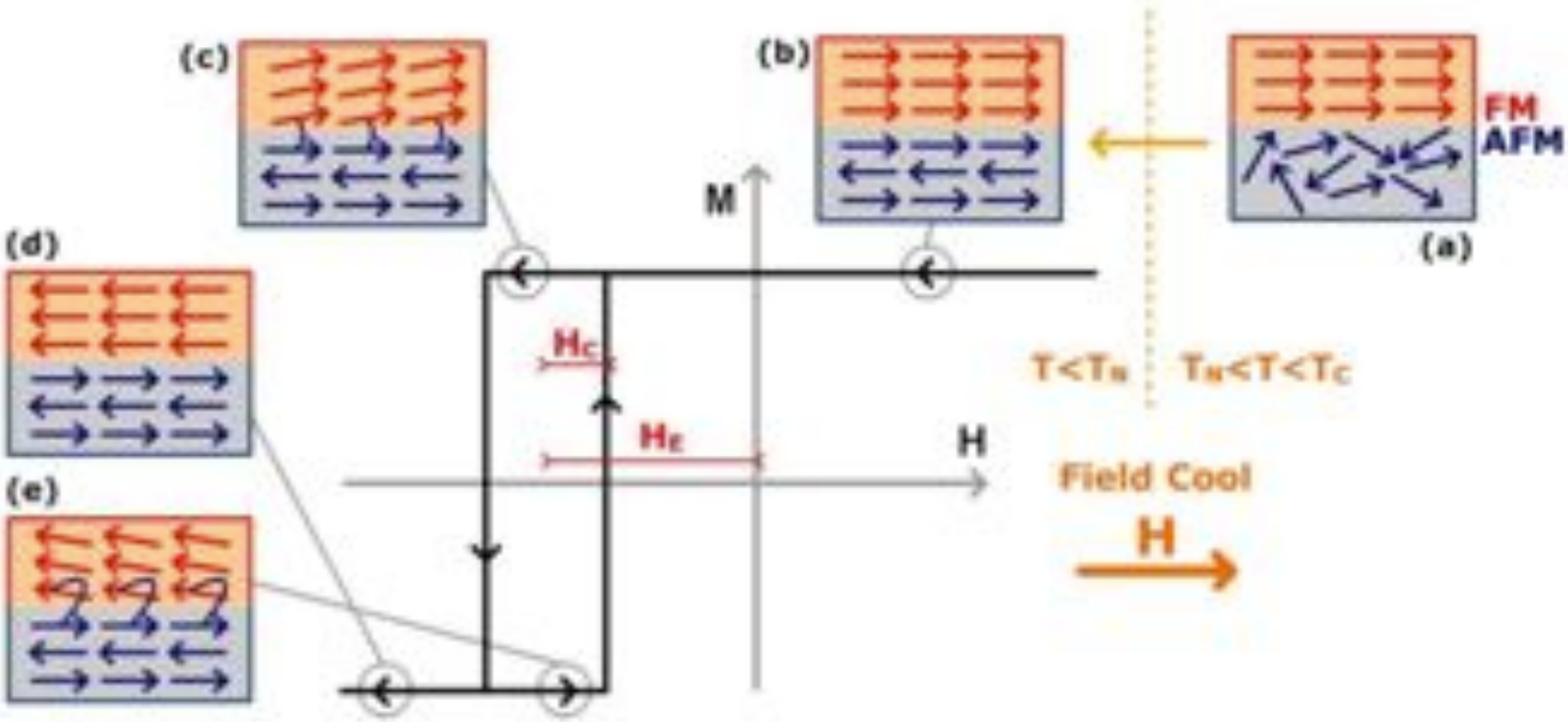
$$\Delta = \frac{2\pi}{2k_F} = \frac{2\pi}{\text{SPANNING VECTOR}}$$

⇒ The energy associated to QWs oscillates "with" $2k_F$

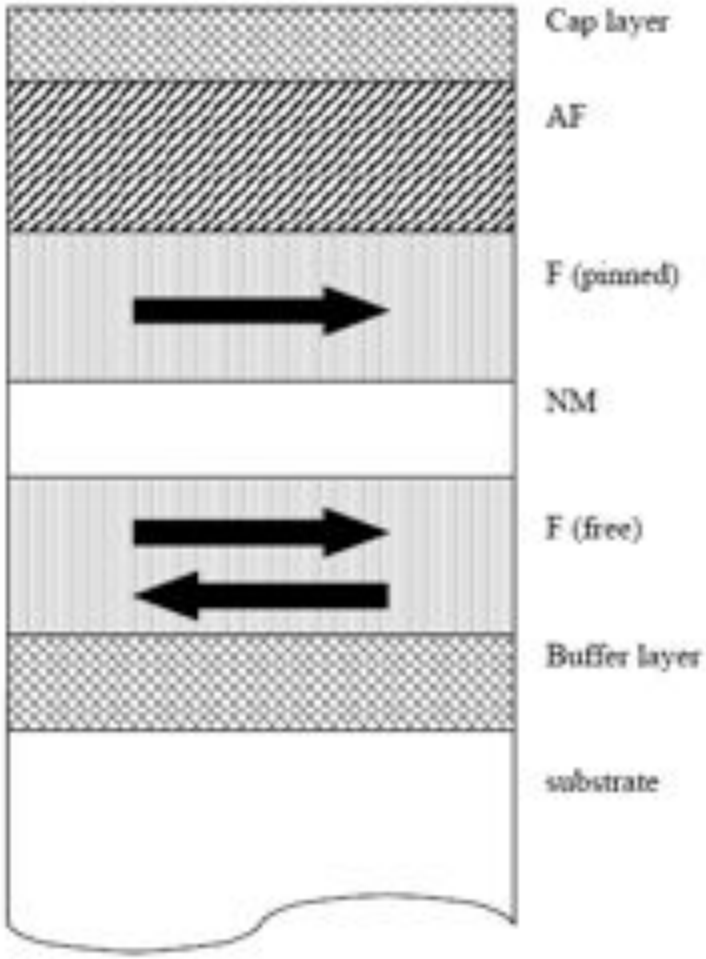
Direct exchange coupling , exchange bias

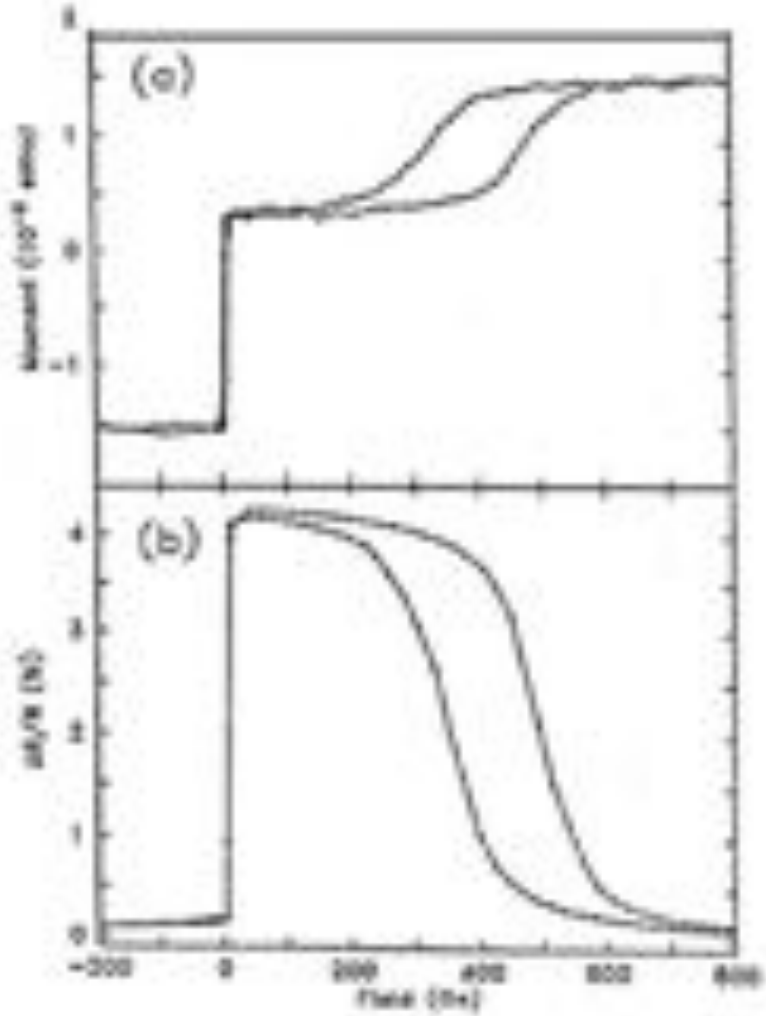






Spin valve (1991)





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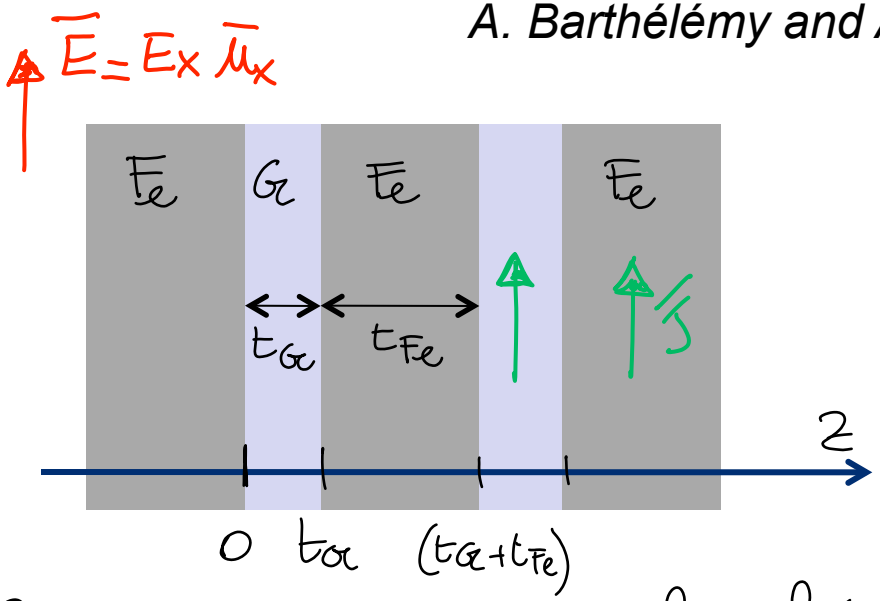
- 2. Mott spintronics: two currents model
- 3. Giant MagnetoResistance: story and basic principles
- 4. Semiclassical model for CIP GMR

Semiclassical model for CIP GMR

A. Barthélémy and A. Fert, Phys. Rev. B 43, 13124 (1991)



Hp: only intrinsic spin dependent scattering at interface

(No impurities or defects leading to spin dependent scattering in the bulk.)

Ok for thin layers, so that bulk scattering can be neglected

Boltzmann equation for $f(\bar{v}, z)$ (Unidimensional problem)

$$\frac{\partial f}{\partial t} + \bar{v}\,\bar{\nabla}_r f - \frac{e\bar{E}}{m}\bar{\nabla}_v f = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

steady state

$$\bar{\nabla}_r f = \frac{\partial f}{\partial z}\bar{u}_z \; ; \; \bar{E} = E_x \bar{u}_x$$

$$v_z \frac{\partial f}{\partial z} - \frac{e E_x}{m}\frac{\partial f}{\partial v_x} = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

Let us introduce the perturbation to eq. distrib: $f = f_0 + g(v, z)$

$$\frac{\partial f}{\partial z} = \cancel{\frac{\partial f_0}{\partial z}} + \frac{\partial g}{\partial z}$$

$$\left(\frac{\partial f}{\partial t}\right)_{coll} = -\frac{f - f_0}{\tau} = -\frac{g}{\tau}$$ (RELAXATION TIME APPROXIMATION)

$$\frac{\partial f}{\partial v_x} = \frac{\partial f_0}{\partial v_x} - \cancel{\frac{\partial g}{\partial v_x}} \simeq \frac{\partial f_0}{\partial v_x}$$ Approximation for linearizing the Boltzmann equation

$$v_z \frac{\partial g}{\partial z} - \frac{eE_x}{m}\frac{\partial f_0}{\partial v_x} = -\frac{g}{\tau}$$

(1) $$\boxed{\frac{\partial g_\sigma}{\partial z} + \frac{g_\sigma}{\tau v_z} = \frac{eE_x}{m v_z}\frac{\partial f_0}{\partial v_x}}$$ σ: spin $\uparrow$ or $\downarrow$

diffusive term

Hp: The relaxation time τ is the same in FM and NM and independent on the spin (ONLY SURFACE SPIN DEP. SCATT.)

BOUNDARY CONDITIONS (Spin dependent transmission $0 < T_\sigma < 1$)

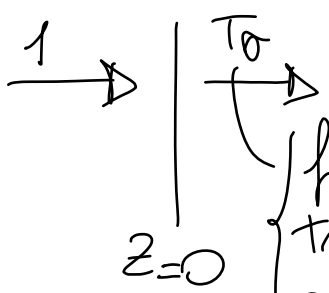
$v_z > 0$ (+)

$$g_\sigma^+(\bar{v}, z=0^+) = T_\sigma g_\sigma^+(\bar{v}, z=0^-)$$

$v_z < 0$ (−)

$$g_\sigma^-(\bar{v}, z=0^-) = T_\sigma g_\sigma^-(\bar{v}, z=0^+)$$

For $v_z > 0$



$(1-T_\sigma)$ { fraction of electrons suffering scattering at interface

{ fraction of el. transmitted coherently which stay OUT OF EQUILIBRIUM after crossing the interface

The dependence on the spin of T_σ gives the magnetoresistance

Let us solve eq. (1): $\frac{\partial g_\sigma}{\partial z} + \frac{g_\sigma}{\tau v_z} = \frac{eE_x}{m v_z}\frac{\partial f_0}{\partial v_x}$

A solution is:

$$g_\sigma = \frac{eE\tau}{m}\cdot\frac{\partial f_0}{\partial v_x} = eE\tau v_x \frac{\partial f_0}{\partial \varepsilon} \qquad \varepsilon = \frac{1}{2}m\left(v_x^2 + v_y^2 + v_z^2\right)$$

The general solution of the homogeneous eq. is:

$$g_\sigma = \alpha\, e^{-\frac{z}{\tau v_z}}$$

THE GENERAL SOLUTION IS: $\overset{\pm}{}(\vec{v}, z) = e\tau E v_x \frac{\partial f_0}{\partial \varepsilon}\, G_\sigma^{\pm}(v_z, z)$

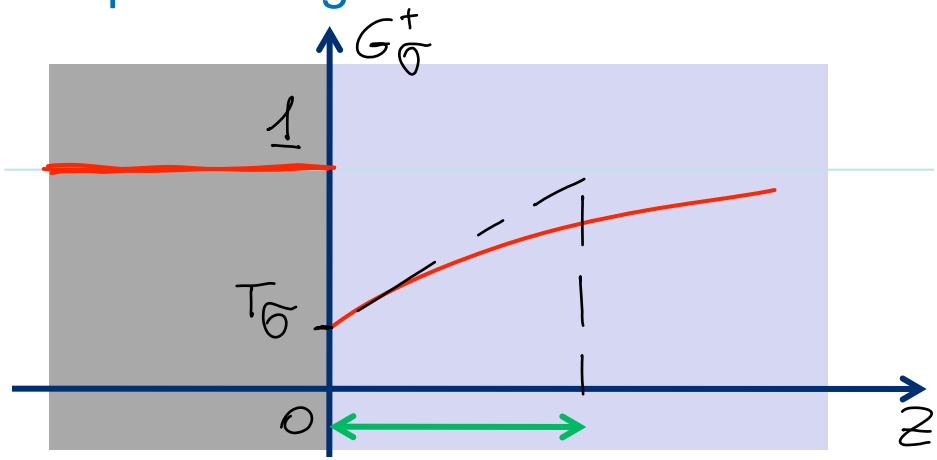
$$\overset{\pm}{\sigma}(v_z, z) = 1 - A^{(\pm)} \exp\left(\mp \frac{z}{|v_z|}\right)$$

Normalized perturbation

Example 1: homogeneus material

$G = 1 \qquad g_\sigma^\pm = e\tau E v_x \frac{\partial f_0}{\partial \varepsilon}$ usual conduction in a field E

Example 2: single interface at z=0



$\lambda_\sigma = \tau v_z \leq \lambda = \tau v_F$

MEAN FREE PATH

Case of GMR for a multilayer

Hp: $t_{Fe} \gg t_{Cr}, \lambda \Rightarrow G_\sigma$ recovers the asymptotic value within the Fe layer

In the PRL of 1988 $t_{Fe} = 30\,\text{Å}$; $t_{Cr} = 9\,\text{Å}$; $\lambda \simeq 14\,\text{Å}$

$T_\uparrow$: transmission for maj.

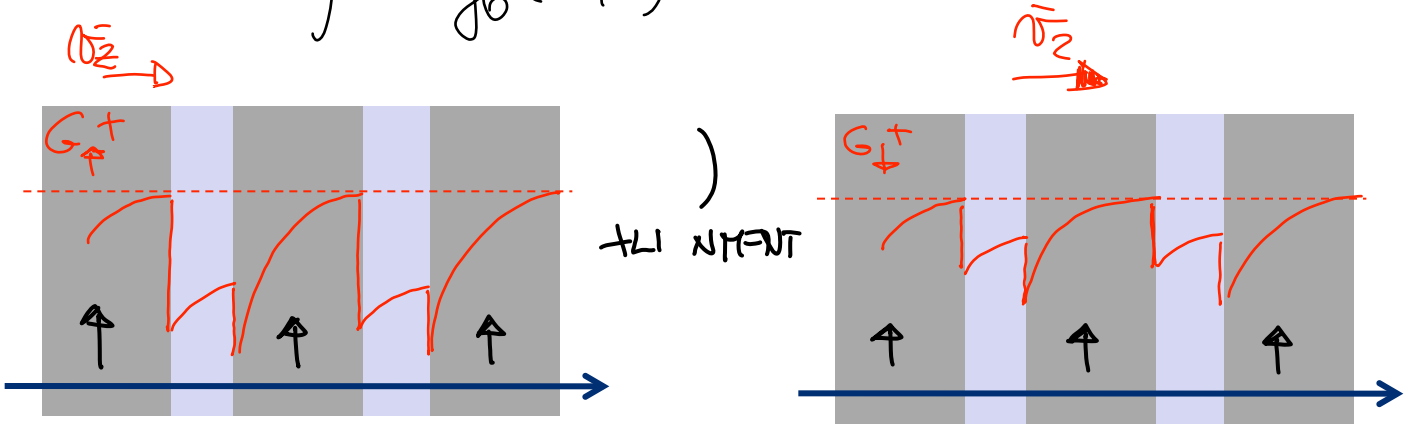
$T_\downarrow$: " " min.

For the Fe/Cr system the scattering in the majority channel is more efficient $\Rightarrow T_\uparrow < T_\downarrow$ $(\rho_\uparrow > \rho_\downarrow)$

HOW TO CALCULATE GMR?

$$g = g_\uparrow + g_\downarrow = (g_\uparrow^+ + g_\uparrow^-) + (g_\downarrow^+ + g_\downarrow^-)$$

$$J = \Sigma \int v_x \, g_\sigma(v, z) \, d^3v \, dz$$



ALIGNMENT

$G_\downarrow^+$ is closer to 1 than $G_\uparrow^+$

$(J_\uparrow \ll J_\downarrow) \rightarrow \rho_\uparrow > \rho_\downarrow$

Within the TWO CURRENTS MODEL

(P): $\rho_\uparrow > \rho_\downarrow$

(AP): $\rho_\uparrow = \rho_\downarrow$

Considering the parallel: $\rho_P < \rho_{AP}$

For $t_G \gg \lambda$:

$$\frac{\Delta R}{R(\mathrm{AF})} = \frac{3}{2}(T_\downarrow - T_\uparrow)^2 \frac{\exp\left[-\frac{t_{\mathrm{Cr}}}{\lambda}\right]}{\left[\frac{t_{\mathrm{Fe}}}{\lambda}\right]\left[\frac{t_{\mathrm{Cr}}}{\lambda}\right]^2} . \qquad (33)$$

(This is not exactly GMR; but $GMR \propto \exp\left(-\frac{t_{Cr}}{\lambda}\right)$