Spintronics I

1. Introduction
2. Mott paradigm: two currents model
3. AMR
4. Giant MagnetoResistance

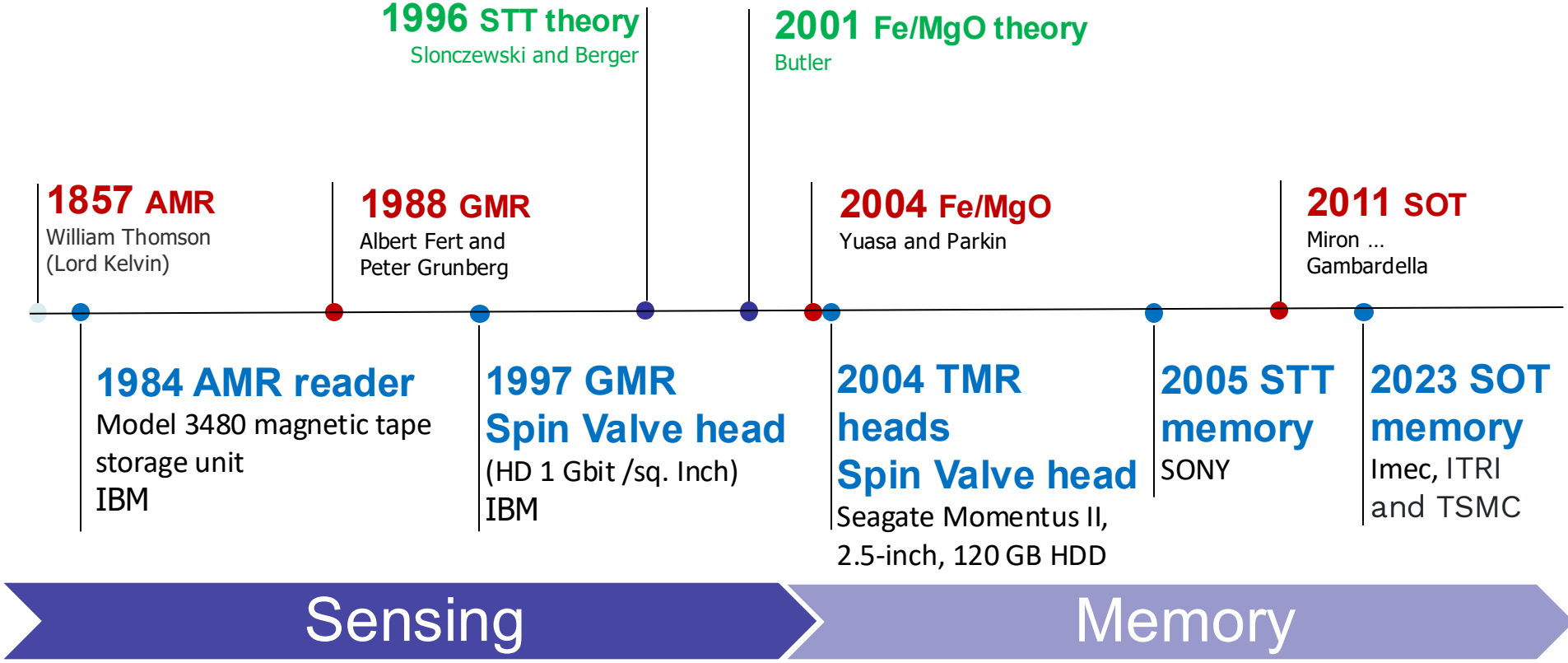
Italian School of Magnetism
Perugia, 22 Ottobre 2025

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Outlook

- 1. Introduction
- 2. Conventional spintronics: two currents model
- 3. Anisotropic Magnetoresistance
- 4. Giant MagnetoResistance

The story of spintronics



The Nobel Prize in Physics 2007



Photo: U. Montan

Albert Fert

Prize share: 1/2



Photo: U. Montan

Peter Grünberg

Prize share: 1/2

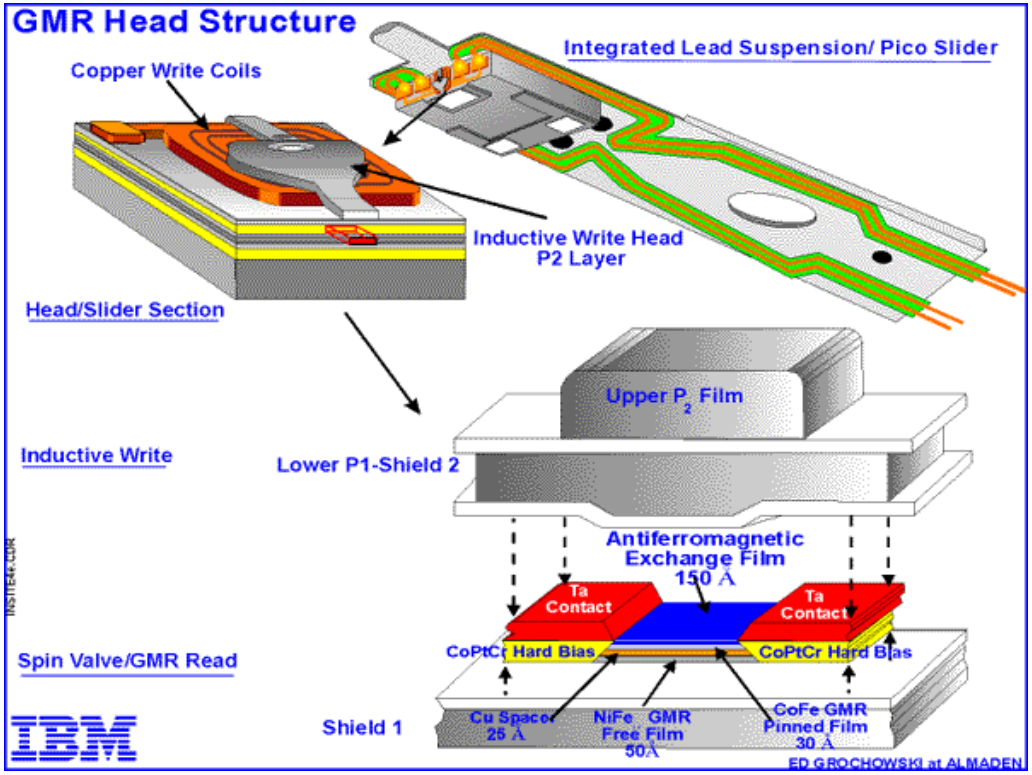
Giant

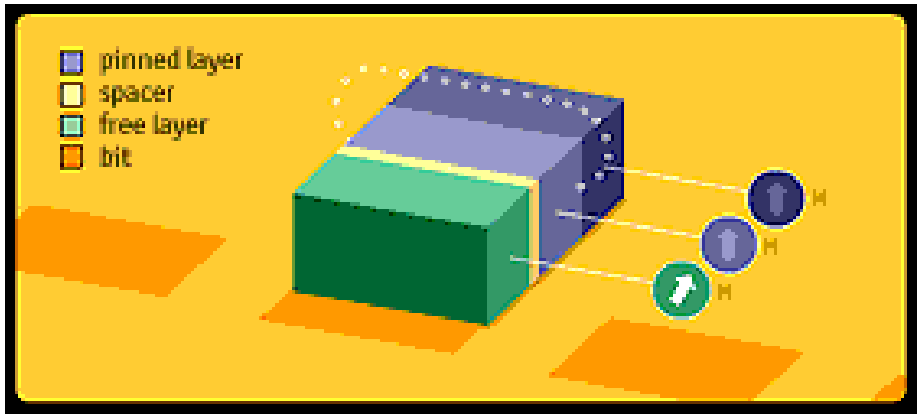
Magneto

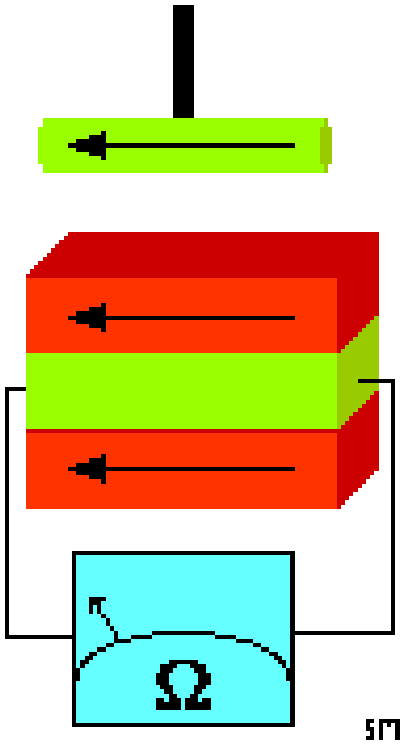
Resistance

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

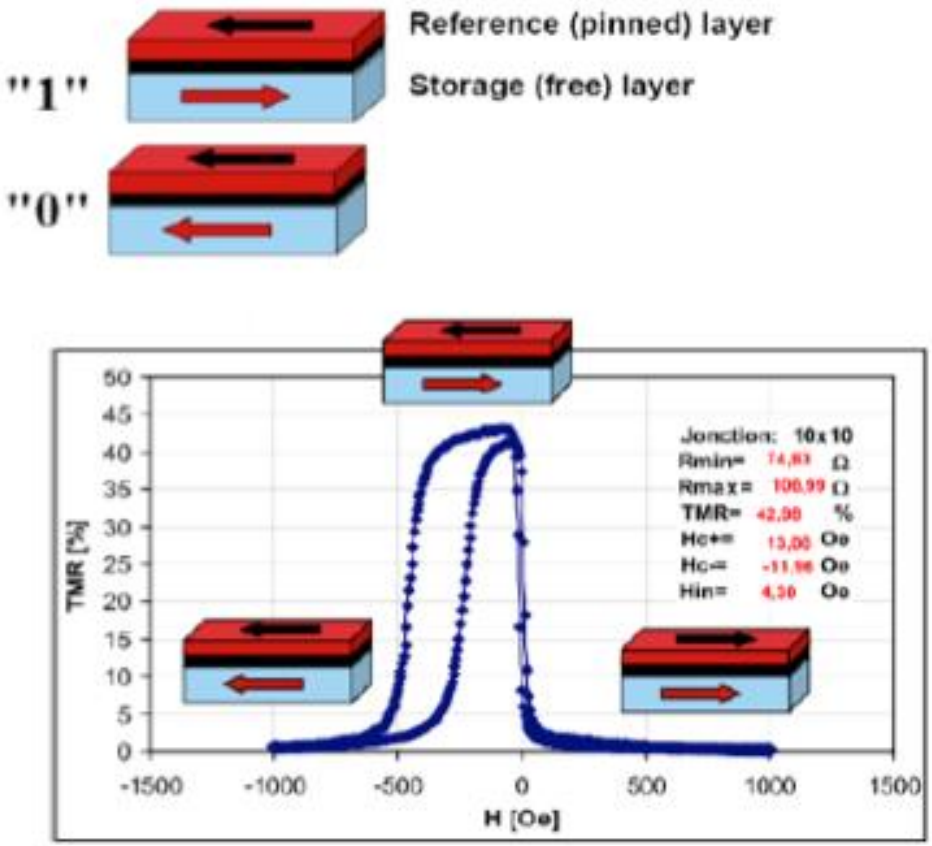
GMR for magnetic recording

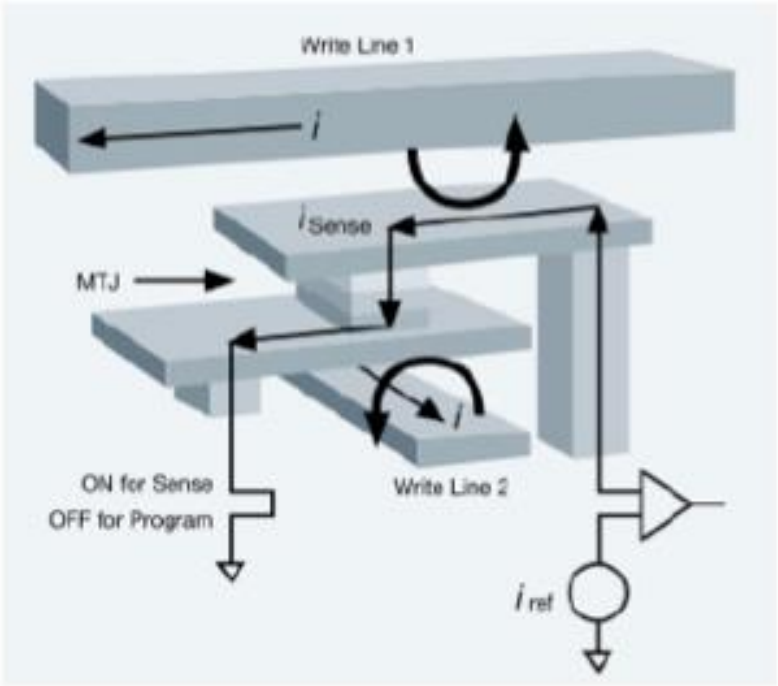






Non Volatile RAMs





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

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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: spin channel

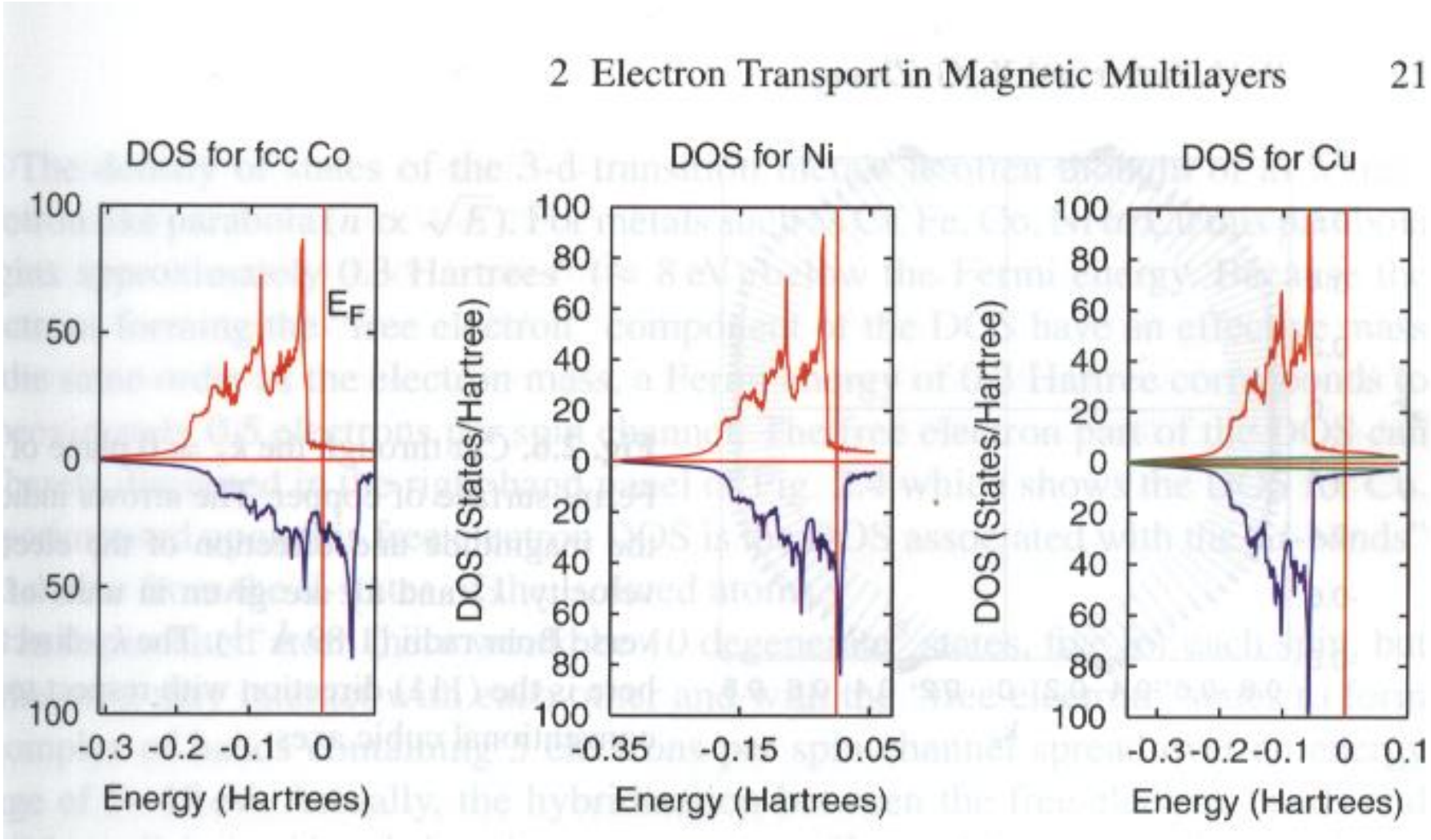
Eigenvalues: $\varepsilon_{j,s}(\mathbf{k})$

Spin up and down bands

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:

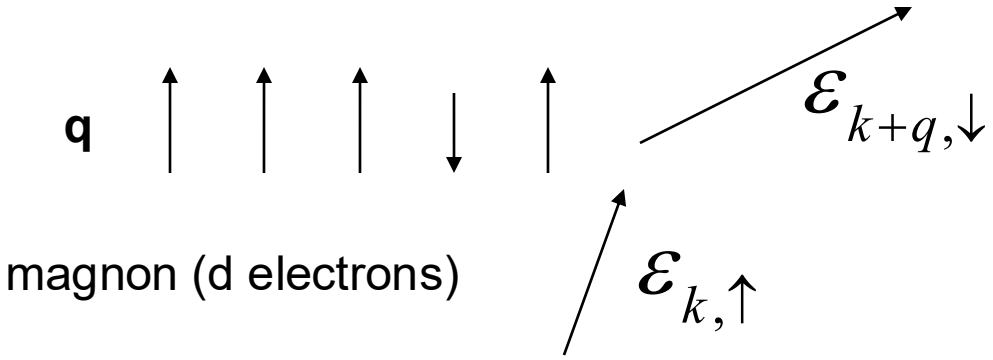
$$\chi_1 = \cos\vartheta/2\, \chi_1' + \sin\vartheta/2\, e^{i\varphi} \chi_2'$$

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

$$f(\mathbf{k}) \cong f_0(\mathbf{k}) + \tau e\mathbf{E}/\hbar \cdot \nabla_{\mathbf{k}} f_0(\mathbf{k}) \cong f_0(k + \tau(\mathbf{k}) e\mathbf{E}/\hbar)$$

Shift of the distribution Function: conduction!

Channel up

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

Channel down

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

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

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

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

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

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:

$$\rho_\downarrow > \rho_\uparrow$$

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Anisotropic Magneto Resistance (AMR)



$\rho_{//} > \rho_{\perp}$

Physica XVI, no 6 Juni 1951

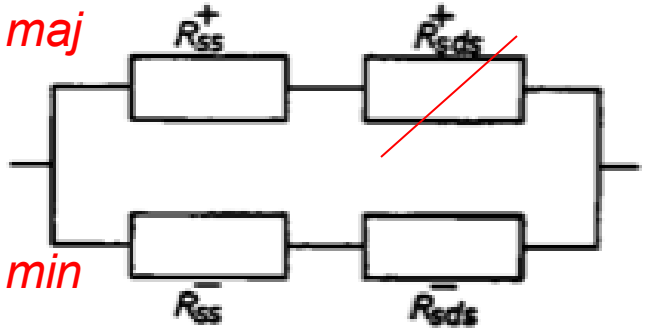
Scattering of s electrons interacting with the orbital magnetic moment of 3d electrons.

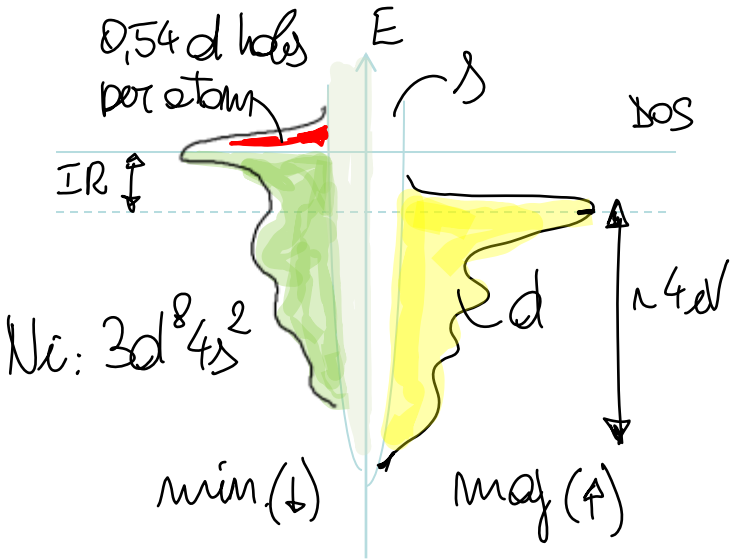
MAGNETORESISTANCE OF FERROMAGNETIC METALS AND ALLOYS AT LOW TEMPERATURES

by J. SMIT *)

Communication No. 286a from the Kamerlingh Onnes Laboratory, Leiden, Nederland

Consider Ni in the Two-currents model





- ✓ 4s electrons are responsible for conduction
- ✓ $\rho_{\uparrow} > \rho_{\downarrow}$ due to the large d-DOS at E_F in the minority channel
- ✓ In the equivalent circuit above there is a "short" in the majority channel (+): the total resistance is mainly due to R_{ss}^{+} as R_{sds}^{+} can be neglected if there are no d-states at E_F in the majority channel

But spin-orbit (SO) interaction gives some mixing of minority and majority states.

Thus even at T=0K we expect some unoccupied majority d-states available for scattering, not equally distributed over the five possible states.

It turns out that there is a deficit of majority holes with motion in the plane perpendicular to magnetization, where the probability of scattering of electrons travelling parallel to the magnetization is null.

The SO interaction operator is of the form:

$$A(\mathbf{L}.\mathbf{S}) = A\{L_z S_z + \tfrac{1}{2}(L_x - iL_y)(S_x + iS_y) + \tfrac{1}{2}(L_x + iL_y)(S_x - iS_y)\}$$

The magnetization is along z, so that pure spin states are: $\chi_+ = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $\chi_- = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

The spin raising and lowering operators $S^+ = S_x + iS_y$ $S^- = S_x - iS_y$
mix the up and down states as they are no more eigenvalues of the SO term.

Let's find the new eigenvalues by using first order perturbation theory:

$$\Psi_n = \varphi_n + \sum_k \frac{\langle \varphi_k | H' | \varphi_n \rangle}{E_n^0 - E_k^0} \varphi_k$$

The unperturbed states are obtained by multiplying d-states

$$\varphi_1 = yz\, f(r)\ \varphi_2 = xz\, f(r)\ \varphi_3 = xy\, f(r)\ \varphi_4 = \tfrac{1}{2}(x^2 - y^2)\, f(r),\ \varphi_5 = \\ = \tfrac{1}{2}3^{-\frac{1}{2}}(r^2 - 3z^2)\, f(r).$$

by the spinors, so as to obtain: $\varphi_i^{\pm} = \varphi_i \chi_{\pm}$

As we are interested in majority d-holes made available to scattering of s-electrons in the majority channel, we simply consider the term of the SO Hamiltonian:

$$H' = \frac{1}{2} L^- S^+$$

PERTURBED MINORITY WAVEFUNCTIONS

$$\psi_\mu^- = \varphi_\mu^- + \frac{A}{2}\sum_k \frac{\langle \varphi_k | L^- S^+ + L^+ S^- | \varphi_\mu^- \rangle}{E_\mu^0 - E_k}\varphi_k = \qquad (L^+ S^- |\varphi_\mu^-\rangle = \phi)$$

$$= \varphi_\mu^- + \frac{A}{2}\sum_k \frac{\langle \varphi_k^+ | L^- S^+ | \varphi_\mu^- \rangle}{E_\mu^0 - E_k}\varphi_k^+ \qquad \langle \varphi_k^- | L^- S^+ | \varphi_\mu^- \rangle = 0$$

↑ NEW maj. states appear

$E_\mu^0 - E_k = 2\delta$ exchange splitting

PERTURBED MAJORITY WAVEFUNCTIONS

$$\psi_\mu^+ = \varphi_\mu^+ + \frac{A}{2}\sum_k \frac{\langle \varphi_k^- | L^+ S^- | \varphi_\mu^+ \rangle}{E_\mu^0 - E_k}\varphi_k^-$$

↑ NEW min. states appear

As we are interested in new maj (+) states appearing at E_F, we focus on $L^- S^+$

Remember: $S_z|\chi\rangle = \pm|\chi\rangle$

$$S^+ = S_x + iS_y = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + i\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = \begin{bmatrix} 0 & 2 \\ 0 & 0 \end{bmatrix}$$

$$S^+\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \phi \qquad S^+\begin{bmatrix} 0 \\ 1 \end{bmatrix} = 2\begin{bmatrix} 1 \\ 0 \end{bmatrix} \Rightarrow \frac{S^+}{2}|\varphi_\mu^-\rangle = |\varphi_\mu^+\rangle$$

$$\left\{ \bar{L} = \bar{r} \times \bar{p} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ x & y & z \\ p_x & p_y & p_z \end{vmatrix} \qquad L_x = y p_z - z p_y \quad L_y = z p_x - x p_z \right\}$$

For dimensionless operators used in Smit paper

$$L^- = \frac{1}{\hbar}\left[L_x - i L_y\right] = \frac{-i\hbar}{\hbar}\left[\left(y\frac{\partial}{\partial z} - z\frac{\partial}{\partial y}\right) - i\left(z\frac{\partial}{\partial x} - x\frac{\partial}{\partial z}\right)\right] = -i\left(y\frac{\partial}{\partial z} - z\frac{\partial}{\partial y}\right) - \left(z\frac{\partial}{\partial x} - x\frac{\partial}{\partial z}\right)$$

For $\psi_1^- = \varphi_1^- + \frac{A}{2}\sum_k \frac{\langle \varphi_k^+ | L^- S^+ | \varphi_1^- \rangle}{E_1^0 - E_k} \varphi_k^+$

$\varphi_1 = yz \cdot f(x)$

$\varphi_2 = xz \cdot f(x)$

$\varphi_3 = xy \cdot f(x)$

$\varphi_4 = \frac{1}{2}(x^2 - y^2) \cdot f(x)$

$\varphi_5 = \frac{x^2 - 2z^2}{2\sqrt{3}} f(x)$

$$\langle \varphi_2^+ | \frac{A}{2} L^- S^+ | \varphi_1^- \rangle = \langle \varphi_2^+ | A L^- | \varphi_1^+ \rangle \simeq A \langle xz | L^- | yz \rangle$$

$$= A \langle xz | -i(y^2 - z^2) + xy \rangle = \phi$$

$$\langle \varphi_3^+ | \frac{A}{2} L^- S^+ | \varphi_1^- \rangle = \langle \varphi_3^+ | A L^- | \varphi_1^+ \rangle \simeq A \langle xy | -i(y^2 - z^2) + xy \rangle$$

$$= A \langle xy | xy \rangle = A$$

$$\langle \varphi_4^+ | \frac{A}{2} L^- S^+ | \varphi_1^- \rangle \simeq A \langle \tfrac{1}{2}(x^2 - y^2) | -i(y^2 - z^2) + xy \rangle = -i\frac{A}{2} \langle x^2 - y^2 | y^2 - z^2 \rangle$$

$$= -i\frac{A}{2} \int (x^2 y^2 - y^4 - z^2 x^2 + z^2 y^2) d^3x$$

$$\int \varepsilon^2 \times \varepsilon^3 dx = \int \frac{\rho_2^2}{f^2(x)} d^3\eta$$

$$\langle \varphi_4^+ | \tfrac{A}{2} L^- S^+ | \varphi_1^- \rangle = -i\tfrac{A}{2} \int (x^2y^2 - y^4) f^2(r)\, d^3r$$

Note that $\frac{1}{4}\int (x^2-y^2)^2 f^2(r)\, d^3r = 1$

$$\frac{1}{4}\left[\int x^4 f^2(r) d^3r + \int y^4 f^2(r) d^3r - 2\int x^2y^2 f^2(r) d^3r\right] = 1$$

$$\frac{1}{4}\left[2\int y^4 f^2(r) d^3r - 2\int \varphi_3^2 d^3r\right] = 1$$

thus $\int y^4 f^2(r) d^3r = 3$

$$\langle \varphi_4^+ | \tfrac{A}{2} L^- S^+ | \varphi_1^- \rangle = -i\tfrac{A}{2}(1-3) = iA$$

For L^-S^+ term, only matrix elements of the form

$$\left\langle \varphi_k^+ \left| \frac{1}{2} L^- S^+ \right| \varphi_n^- \right\rangle$$

are different from zero, due to the spin raising operator. Thus the new mixed states will be a combination of φ_k^+ *and* φ_n^-

$$\psi_1^- = \varphi_1^- + (A/2\delta)\,(\varphi_3^+ - i\varphi_4^+ + i\sqrt{3}\,\varphi_5^+)$$
$$\psi_2^- = \varphi_2^- + (A/2\delta)\,(i\varphi_3^+ - \varphi_4^+ - \sqrt{3}\,\varphi_5^+)$$
$$\psi_3^- = \varphi_3^- + (A/2\delta)\,(\varphi_1^+ - i\varphi_2^+)$$
$$\psi_4^- = \varphi_4^- + (A/2\delta)\,(i\varphi_1^+ + \varphi_2^+)$$
$$\psi_5^- = \varphi_5^- + (A/2\delta)\,(i\sqrt{3}\,\varphi_1^+ + \sqrt{3}\,\varphi_2^+)$$

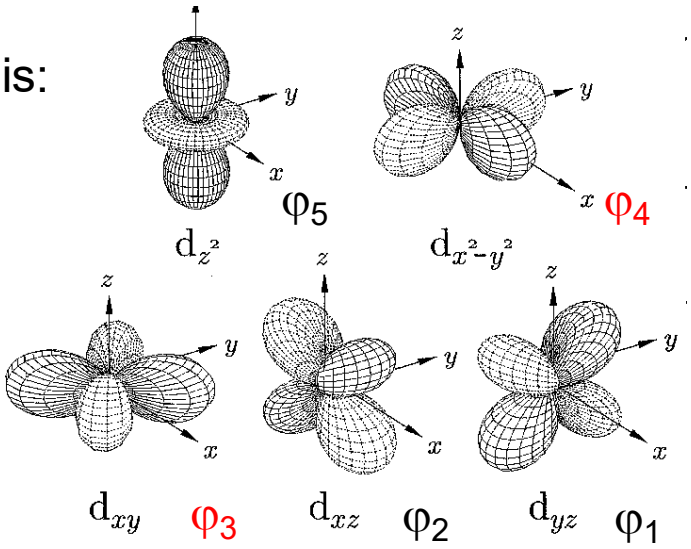
There is a deficit of φ_3^+, φ_4^+ states, which correspond to a motion of the electrons in a plane perpendicular to M.

The transition probability from an s- to a φ_3 state is:

$$P_{sd} \sim |\iiint e^{-i\mathbf{kr}} . V . xy\ f(r)\ dxdydz\ |^2$$

P_{sd}= 0 if :
- V has spherical symmetry
- k_x=k_y=0 while $k_z \neq 0$,

because in this case the function within the integral is odd with respect to x,y.

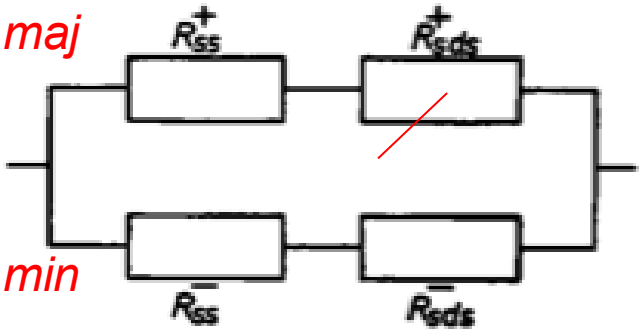


Also the transition probability from an s-state and φ_4 vanishes for $k_x=k_y=0$, $k_z\neq 0$,

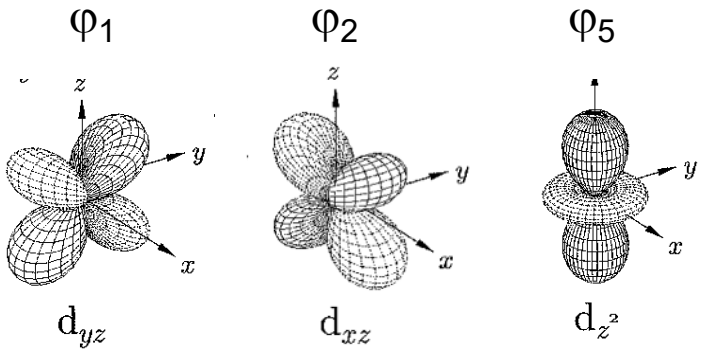
The transition probability from an s-state into a majority d-state φ_3, φ_4 vanishes if the s electron is moving parallel to M.

R_{sds}^{+} is proportional to the sum of the transition probabilities into d states.

If an electron is moving along M, there will be a deficit of available d-states φ_3, φ_4 for the transition probability is small. Most available states will be (φ_1, φ_2,φ_5) with a non vanishing transition probability. As a result the total *resistivity will be high for motion parallel to M*.

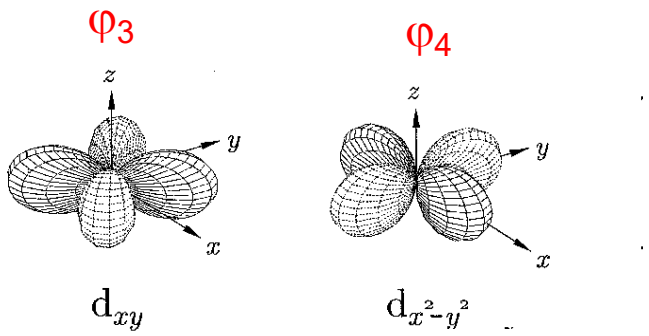


M



Abundant maj (+) states due to SOI

Orbital motion in a plane perpendicular to M



Deficit of these (+) states due to SOI

$J_{//}$

$P_{sd} \neq 0$

Large probability of scattering into abundant d+ states:
HIGH RESISTANCE

$P_{sd} = 0$

Null probability of scattering into scarce d+ states:
No contribution

If the s electron is moving perpendicular to M, e.g. along x

The transition probability from an s- to a φ_1 (yz) is:

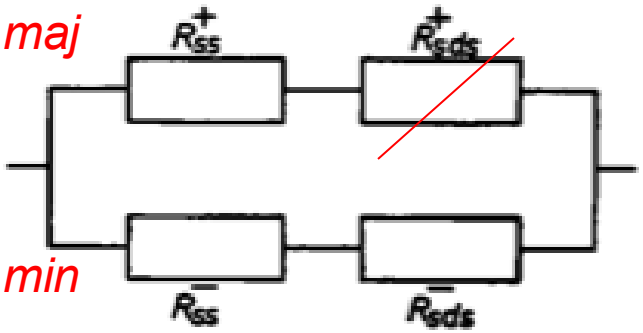
$$P_{sd} \propto \left| \iiint e^{-i\mathbf{k}\cdot\mathbf{r}} V\, yz\, f(r)\, dx dy dz \right|^2 \simeq K_y^2 K_z^2$$

P_{sd}= 0 if :

- V has spherical symmetry and $k_z=k_y=0$ while $k_x \neq 0$,

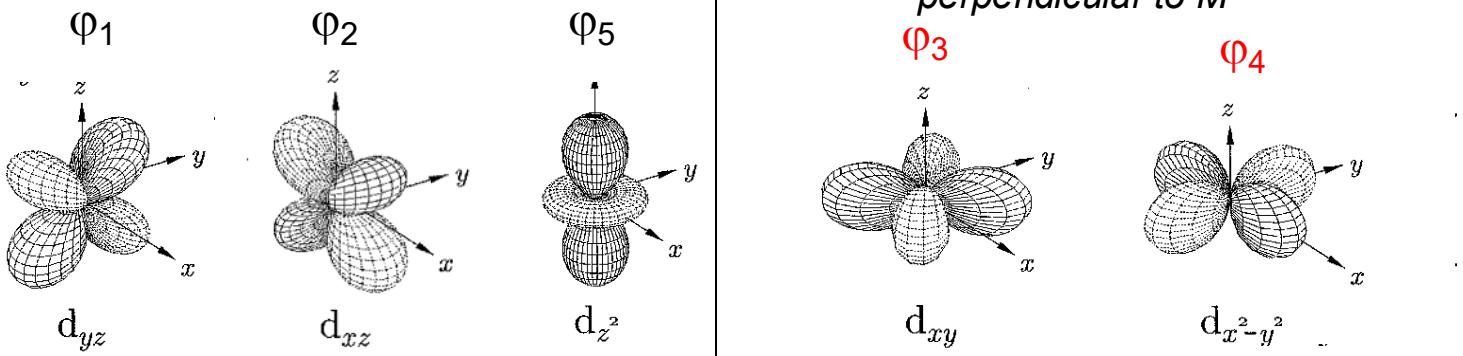
(the function within the integral is odd with respect to z,y)

Small probability of scattering into abundant $\varphi_1, \varphi_2, \varphi_5$, states, so the R_{sds}^{+} term (and *the overall resitivity) will be unchanged for motion perpendicular to M*.



To summarize

Orbital motion in a plane perpendicular to M



Abundant maj (+) states due to SOI

Deficit of these (+) states due to SOI

$J_{//}$

$P_{sd} \neq 0$

Large probability of scattering into abundant d+ states:
HIGH RESISTANCE

$P_{sd} = 0$

Null probability of scattering into scarce d+ states:
No contribution

$J_{\perp}$

$P_{sd} = 0$

Null probability of scattering into abundant d+ states

$P_{sd} \neq 0$

Large probability of scattering into scarce d+ states

SOI does not significantly alter the unperturbed case: **LOW RESISTANCE**

Angular dependence of AMR and Planar Hall Effect

The AMR is generally defined as:

$$AMR = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho} \qquad \rho = \frac{(\rho_{\parallel} + 2\rho_{\perp})}{3}$$

We consider a sheet of ferromagnetic material of width w and thickness t with an easy axis along the x-axis where the magnetization vector is rotated an angle θ with respect to the easy axis (see Fig. 3.12). A uniform and constant current density $\mathbf{J} = J\hat{\mathbf{x}}$ flows along

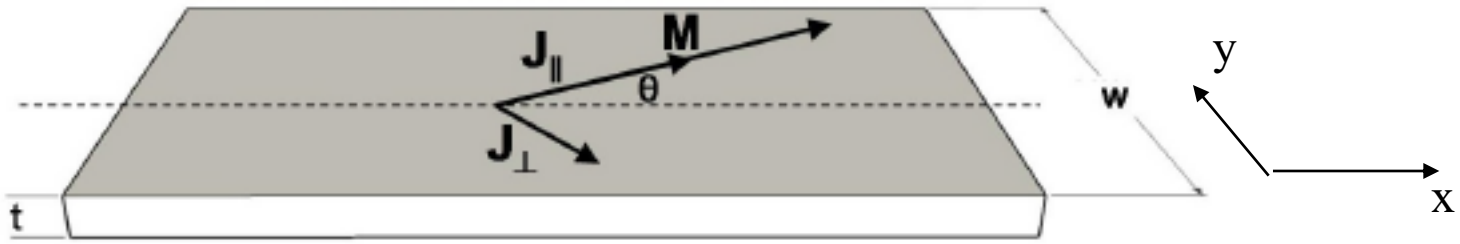


Figure 3.12: Sketch of **M** and **J** relative to the easy axis of a ferromagnetic material

the easy axis. The current density is now decomposed in two projections, one parallel to the magnetization and one perpendicular to it which can be written as

$$\mathbf{J}_{\parallel} = \left(\mathbf{J} \cdot \hat{\mathbf{M}}\right) \hat{\mathbf{M}} \tag{3.18}$$

$$\mathbf{J}_{\perp} = \mathbf{J} - \mathbf{J}_{\parallel} \tag{3.19}$$

$$\mathbf{J}_{\parallel} = \frac{\mathbf{E}_{\parallel}}{\rho_{\parallel}} \quad \text{and} \quad \mathbf{J}_{\perp} = \frac{\mathbf{E}_{\perp}}{\rho_{\perp}} \tag{3.20}$$

Combining these expressions and solving for $\mathbf{E}$ yield

$$\mathbf{E}_{\text{AMR}} = \mathbf{E}_{\parallel} + \mathbf{E}_{\perp} = \rho_{\parallel}\mathbf{J}_{\parallel} + \rho_{\perp}\mathbf{J}_{\perp} \tag{3.21}$$

While the sum $\mathbf{J}_{\parallel} + \mathbf{J}_{\perp}$ yields a vector parallel to the x-axis, the combination $\rho_{\parallel}\mathbf{J}_{\parallel} + \rho_{\perp}\mathbf{J}_{\perp}$ does not. Since $\rho_{\parallel} \neq \rho_{\perp}$ the electric field will have a y-component as well. This component, perpendicular to the current flow produce the *planar hall effect* (PHE), resulting in a pile-up of charge on the edge of the material, until this effect produces another field to exactly cancel the y-component of $\mathbf{E}_{\text{AMR}}$. Thus the current still flows only in the x-direction once equilibrium is established. To find the associated PHE voltage, we first combine Eq. (3.18) Eq. (3.19) and Eq. (3.21):

$$\begin{aligned}
\mathbf{E}_{\text{AMR}} &= \rho_{\parallel}\left(\mathbf{J}\cdot\hat{\mathbf{M}}\right)\hat{\mathbf{M}} + \rho_{\perp}\left(\mathbf{J} - \mathbf{J}_{\parallel}\right) \\
&= \left(\rho_{\parallel} - \rho_{\perp}\right)\left(\mathbf{J}\cdot\hat{\mathbf{M}}\right)\hat{\mathbf{M}} + \rho_{\perp}\mathbf{J} \\
&= \left(\rho_{\parallel} - \rho_{\perp}\right)(J\cos\theta)\left(\cos\theta\hat{\mathbf{x}} + \sin\theta\hat{\mathbf{y}}\right) + \rho_{\perp}J\hat{\mathbf{x}} \\
&= \frac{I}{tw}\left[\left(\left(\rho_{\parallel} - \rho_{\perp}\right)\cos^2\theta + \rho_{\perp}\right)\hat{\mathbf{x}} + \left(\rho_{\parallel} - \rho_{\perp}\right)\sin\theta\cos\theta\hat{\mathbf{y}}\right]
\end{aligned} \tag{3.22}$$

The longitudinal x-component of the field gives the angular dependence of AMR

$$\rho(\theta) = (\rho_{\parallel} - \rho_{\perp}) \cos^2 \theta + \rho_{\perp}$$

The transverse component gives the Planar Hall Effect

$$\begin{aligned} V_{\mathrm{PHE}} &= -\int_{(0,-\frac{w}{2})}^{(0,\frac{w}{2})} \mathbf{E}_{\mathrm{AMR}} \cdot d\ell \\ &= -\int_{-\frac{w}{2}}^{\frac{w}{2}} \frac{\rho_{\parallel} - \rho_{\perp}}{tw} I \sin\theta \cos\theta \, dy \\ &= -\frac{\rho_{\parallel} - \rho_{\perp}}{t} I \sin\theta \cos\theta \end{aligned} \tag{3.23}$$

This can be re-written as:

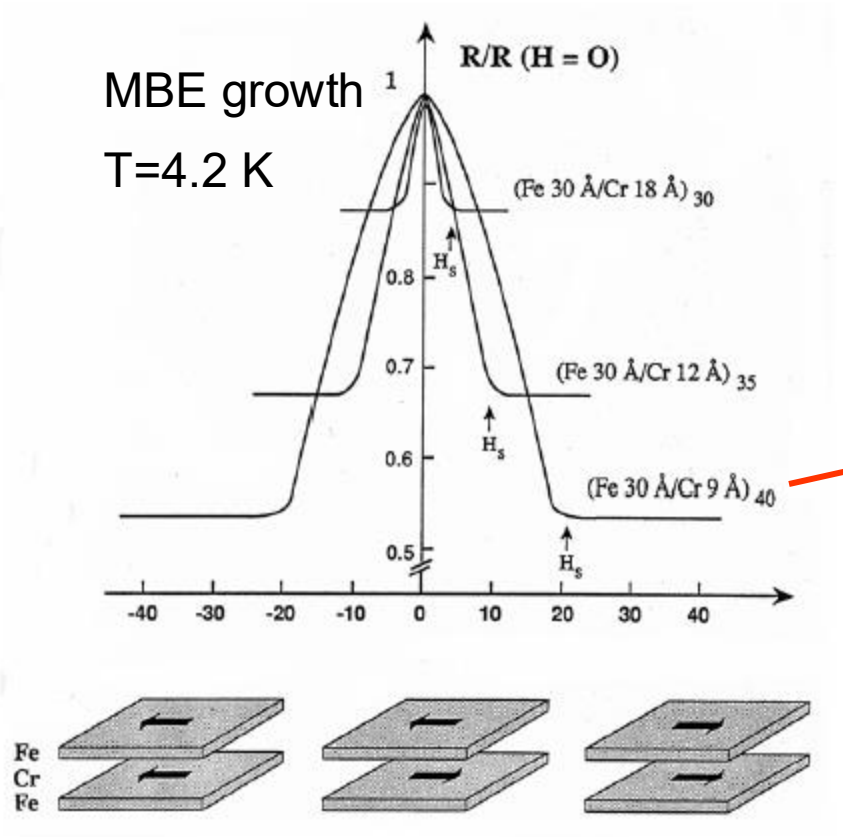
$$V_{\mathrm{PHE}} = -\frac{\mathrm{AMR}\,\rho}{t} I \sin\theta \cos\theta \tag{3.24}$$

Thus, the hall voltage is independent of the width w and only the current, I, and the direction of the magnetization influence the observed voltage.

Outlook

- 1. Introduction
- 2. Conventional spintronics: two currents model
- 3. Anisotropic Magnetoresistance
- 4. Giant MagnetoResistance

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)

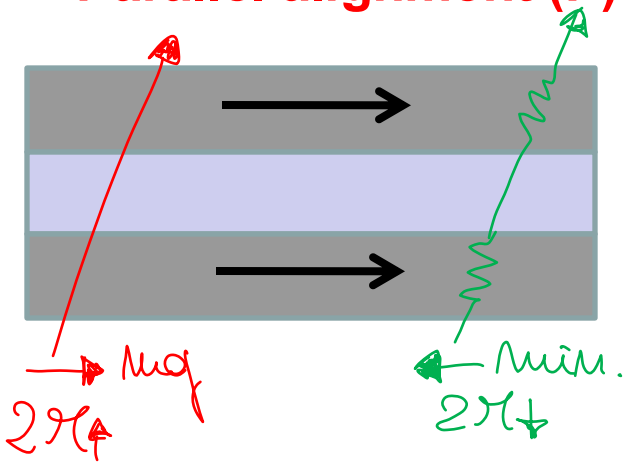
[2] G. Binash, P. Grünberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989) *(trilayer)*

GMR: a simple model

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

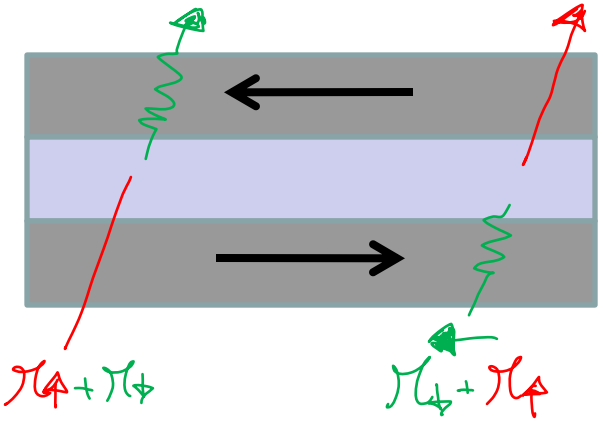
Hp2: *Consider a CPP configuration*

Parallel alignment (P)



Hp: $r_\uparrow \ll r_\downarrow$
($G_1 N_1$, ---)

Antiparallel alignment (AP)



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

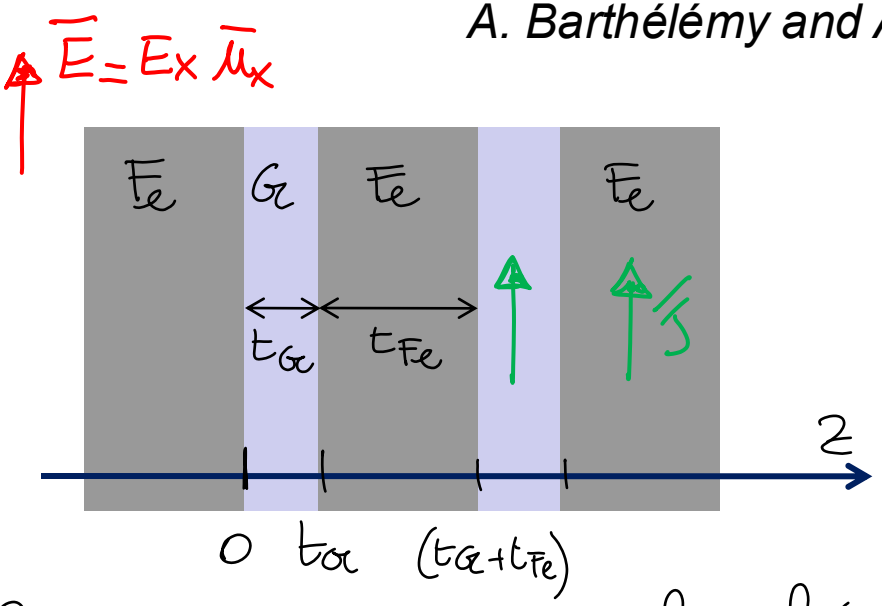
$$r_{AP} = \frac{r_\uparrow + r_\downarrow}{2}$$

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

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

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 $f(\vec{v}, z)$ (unidimensional problem)

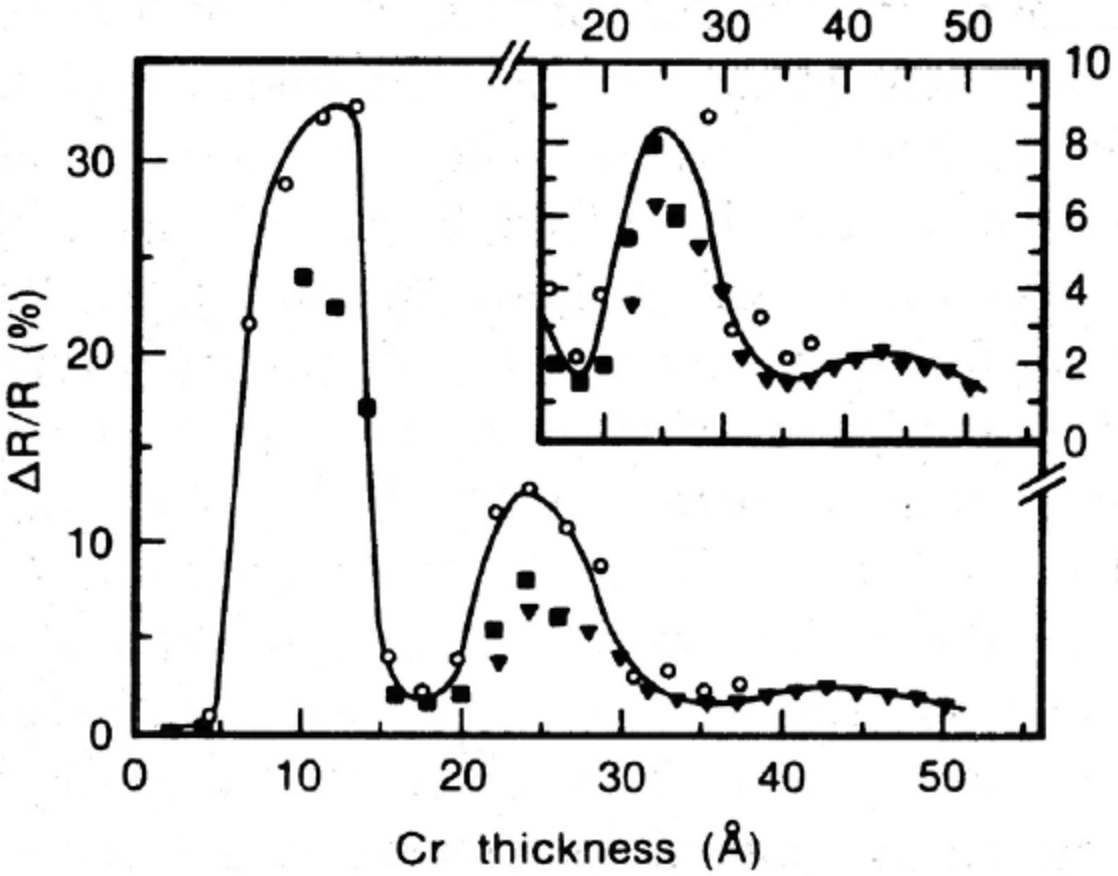
$$\frac{\partial f}{\partial t} + \vec{v}\,\vec{\nabla}_r f - \frac{e\vec{E}}{m}\vec{\nabla}_v f = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

steady state

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

The relevant length scale is the inelastic mean free path λ

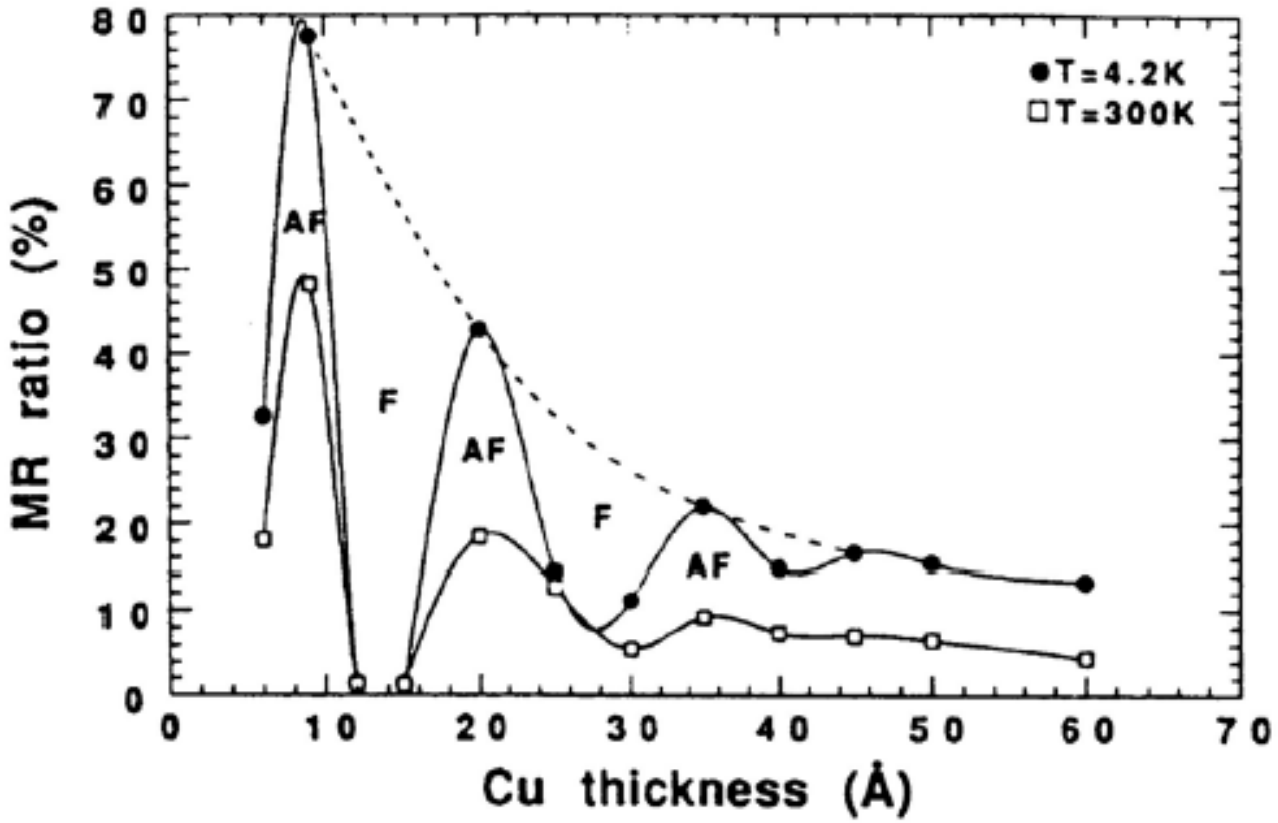
GMR oscillations



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].

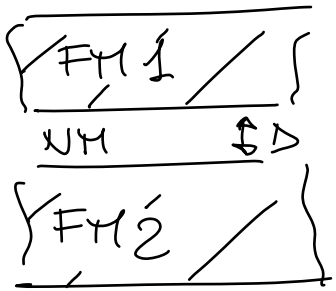
GMR oscillations Co/Cu



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



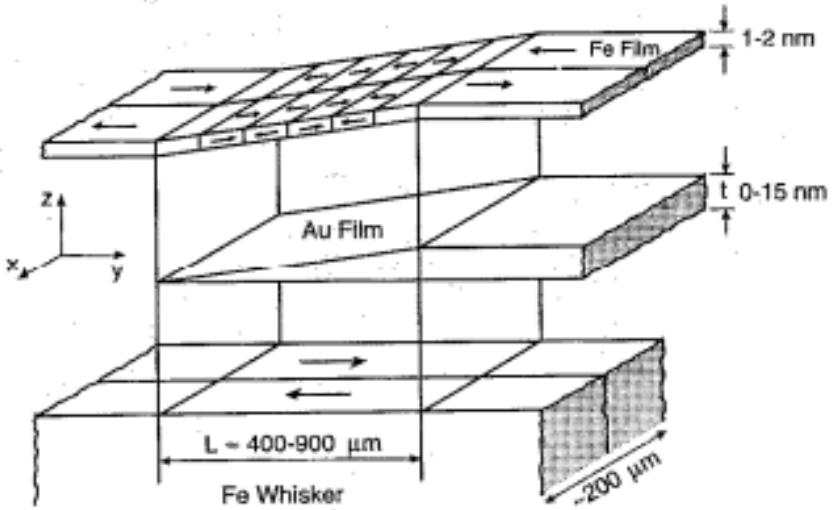
$$\frac{E}{A} = -J\,\vec{M}_1 \cdot \vec{M}_2$$

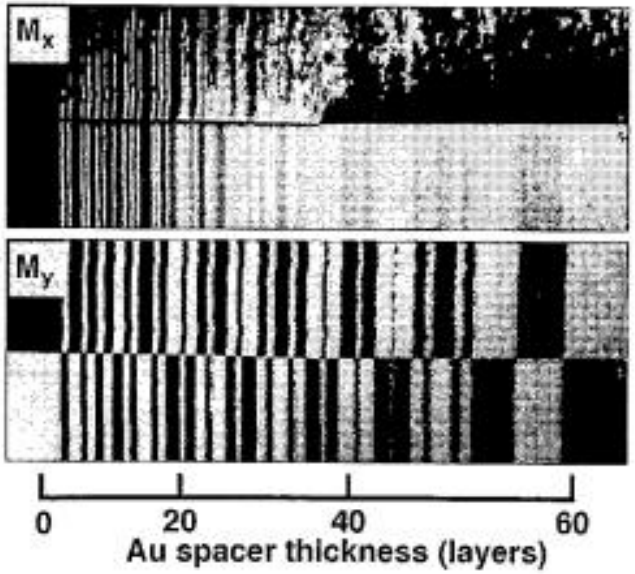
depends on the product of both $\vec{M}_1$ and $\vec{M}_2$ ($\rightarrow$ BILINEAR)

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

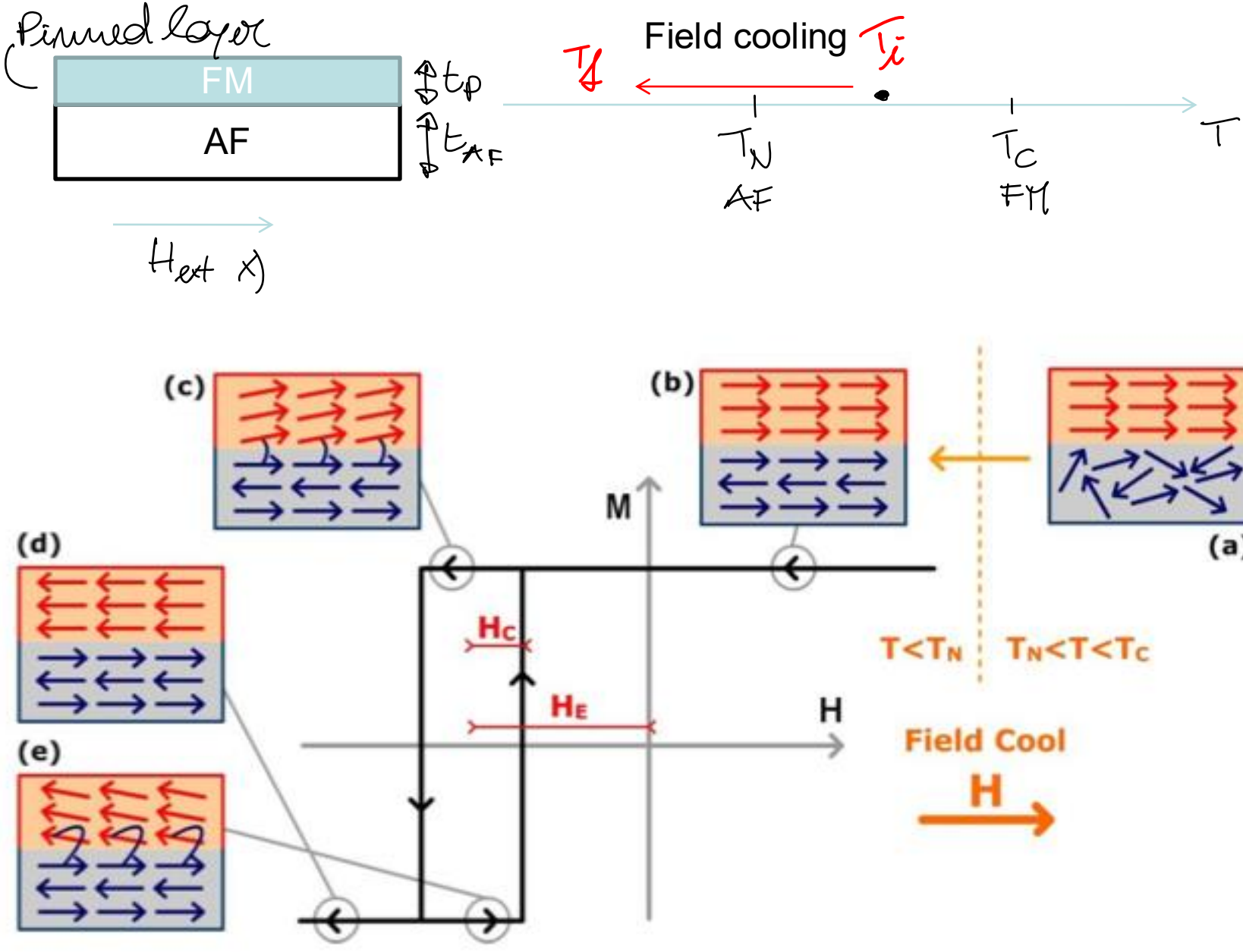
J. Appl. Phys. **75** (10), 15 May 1994



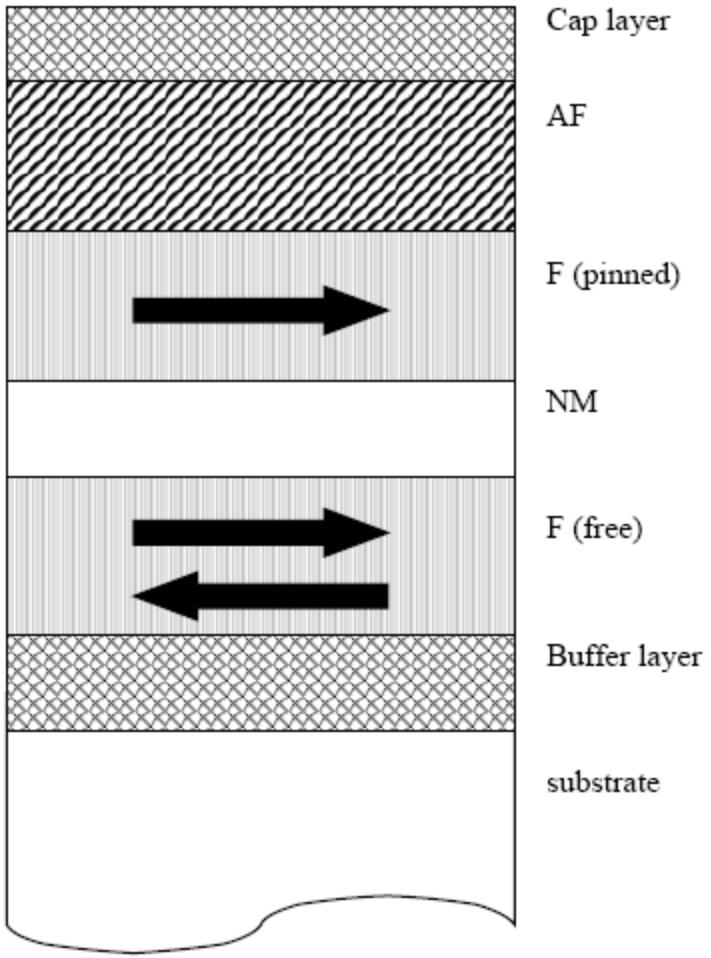


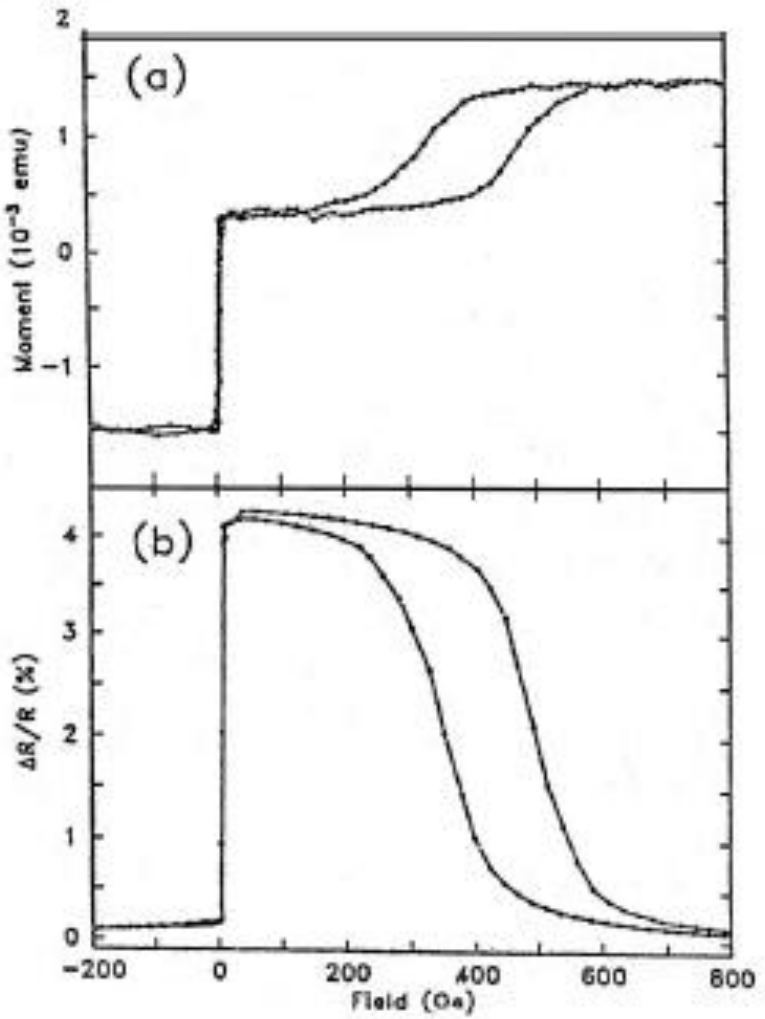
http://cnst.nist.gov/epg/Pubs/pdf/epg625.pdf

Direct exchange coupling , exchange bias

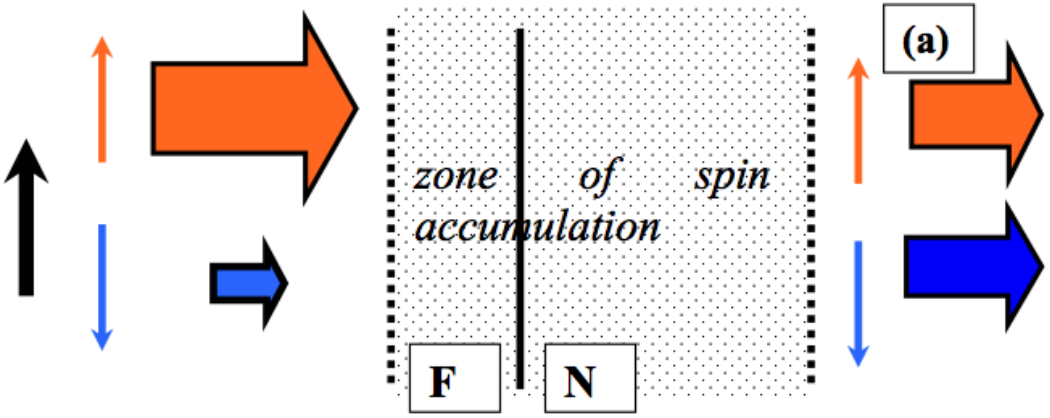


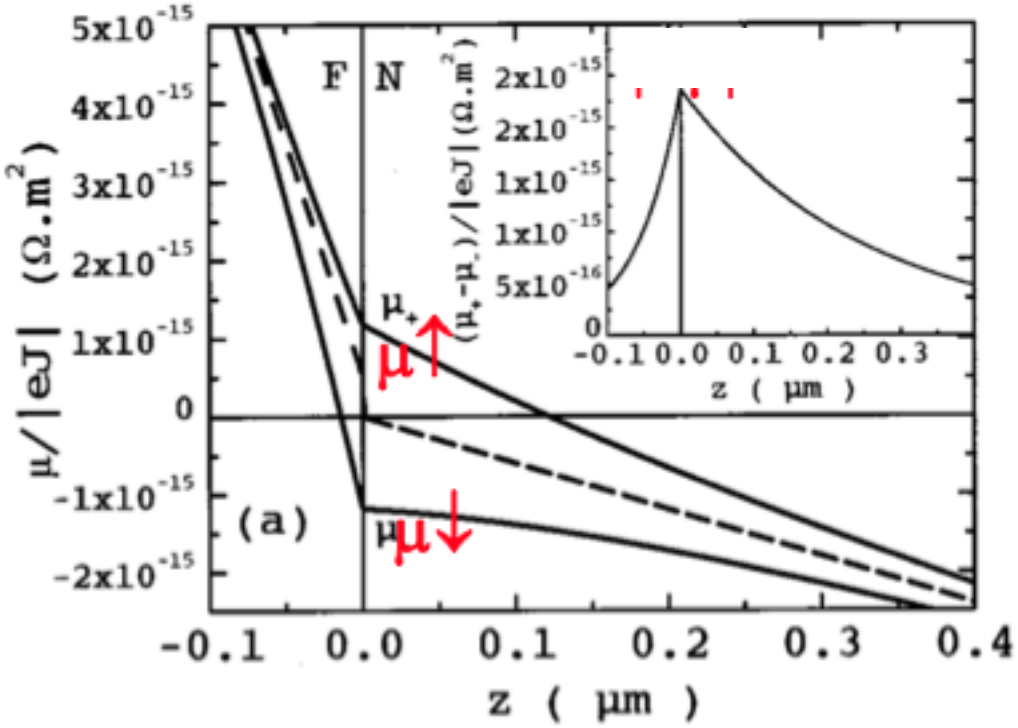
Spin valve (1991)





CPP GMR and Spin-accumulation

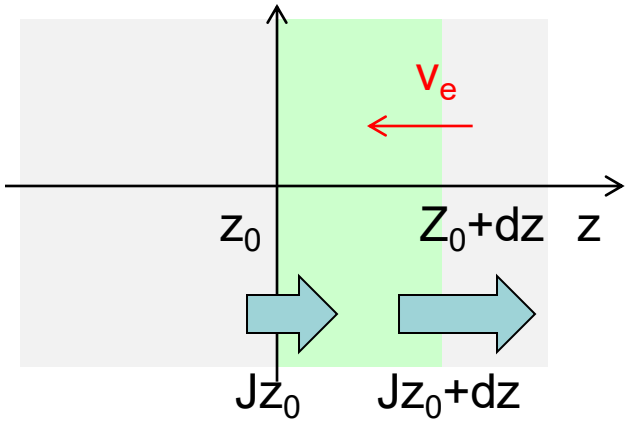




Co/cu interface:
$\beta = 0.46 > 0$
$\rho+ < \rho-$

In the bulk of Co
J+ > J-

Equilibrium condition



$$\nabla \cdot J_{\downarrow} = -\frac{\partial \rho_{\downarrow}}{\partial t} = -\frac{\partial \left(-en_{\downarrow}\right)}{\partial t} = e\frac{\partial n_{\downarrow}}{\partial t}$$

If divJ>0 There's an electron accumulation in the green zone: non stationary case!

To find a stationary state the excess of spin up electrons entering from the right side must undergo a spin flip towards the spin down channel. This corresponds to the spin flip term added to the Boltzmann equation:

$$\left(\frac{\partial f_{\uparrow}}{\partial t}\right)_{sf} = -\frac{f_{\uparrow}(\mathbf{v}) - f_{\downarrow}(\mathbf{v})}{\tau_{sf}}$$

Spin-flip rate towards the spin up channel from the spin down channel

$$\frac{\partial n_{\downarrow}}{\partial t} = \underbrace{\frac{1}{e}(\nabla \cdot J_{\downarrow})}_{\text{Acc. rate due to currents}} \underbrace{-\frac{n_{\downarrow} - n_{\uparrow}}{\tau_{sf}}}_{\text{Acc. rate due to spin-flip}} = 0$$

End of the first lecture