MAGNETORESISTANCE PHENOMENA AND RELATED EFFECTS

JOSE MARIA DE TERESA

(CSIC - UNIVERSIDAD DE ZARAGOZA, SPAIN)

-INTRODUCTION TO MAGNETORESISTANCE (MR)

-LORENTZ MR, ANISOTROPIC MR, HALL EFFECT, SPIN-DISORDER MR AND COLOSSAL MR

-GIANT MR

-TUNNEL MR

-OTHER MAGNETORESISTIVE EFFECTS

-APPLICATIONS OF MAGNETORESISTIVE DEVICES

**EXCHANGE-BIAS FOR SPIN VALVES*

**MAGNETIC RANDOM ACCESS MEMORIES*

SPINTRONICS / MAGNETOELECTRONICS

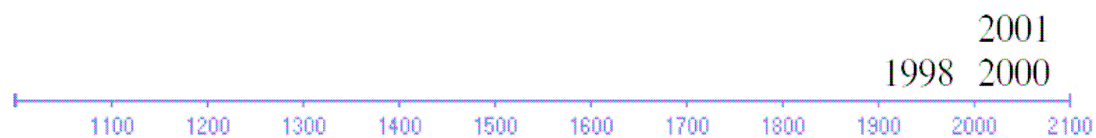
Oxford English Dictionary

Physics.

Pronunciation Etymology Quotations Date chart

[< SPIN *n.*[1] + *-tronics* (in ELECTRONICS *n.*). Cf. SPINTRONIC *a.*]

A branch of physics concerned with the storage and transfer of information by means of electron spins in addition to electron charge as in conventional electronics.



1998 *New Scientist* 28 Feb. 27/2 Over the past 18 months, DARPA has poured more than $50 million into spintronics research. **2000** *Canad. Jrnl. Physics* **78** 161 Some latest developments in magnetic sensors and magnetic RAM will be presented to emphasize the importance of spintronics in the emerging technologies of the 21st century. **2001** *Personal Computer World* Sept. 145/3 The conventional silicon chip manufacturing processes can easily be adapted to the production of spintronics systems.

INTRODUCTION TO MAGNETORESISTANCE: PRELIMINARY CONCEPTS

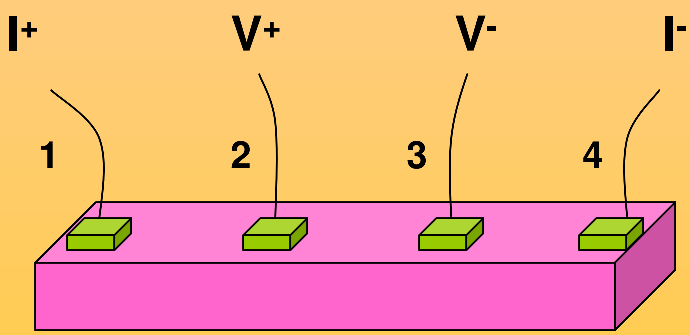
GEOMETRIES FOR THE MEASUREMENT OF RESISTANCE

Bulk samples *are normally measured in* ***bar-shaped geometry*** *and* ***four-point*** *linear contacts. Resistivity can be determined.*

$*R=I/V= I_{1-4}/ V_{2-3}$

$$\rho = F \frac{V_{2,3}}{I_{1,4}} \frac{S}{d}$$

(F can be approximated to 1 in most of the situations)



ρ(ohm x cm)

Relation between conductivity and resistivity $\sigma=1/\rho$ (Siemens)

Typical size is millimetric

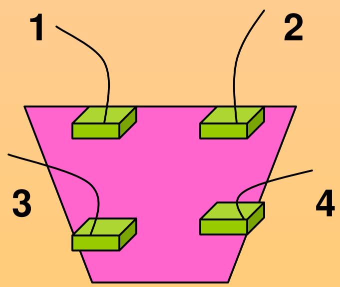
*Four-contact measurements eliminate the contact and lead resistances. One should be careful regarding offset signals such as thermoelectric effects, electronic offsets, electromotive forces, which can be minimised by current inversion in d.c. measurements or using a.c. measurements:

$*R=(R_1+R_2)/2$ with $R_1= I_{1-4}/V_{2-3}$ and $R_2=I_{4-1}/V_{3-2}$

$*R_{offset}=(R_1-R_2)/2$

GEOMETRIES FOR THE MEASUREMENT OF RESISTANCE

The van der Pauw method is used for bulk samples with arbitrary shape



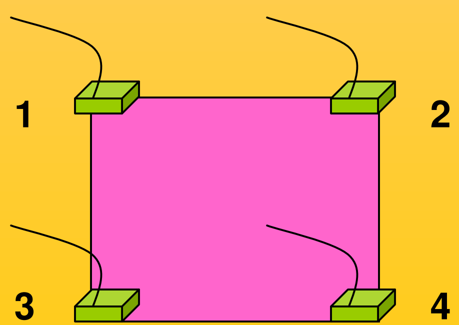
$$\rho = \frac{\rho_A + \rho_B}{2} \qquad \begin{cases} \rho_A = \dfrac{1.1331 f_A t}{I}(V_2 + V_4 - V_1 - V_3) \\ \rho_B = \dfrac{1.1331 f_B t}{I}(V_6 + V_8 - V_5 - V_7) \end{cases}$$

t=sample thickness; I=current; V=voltages; f=f(V, arc cosh function)

*V_1: $I_{2\text{-}1}$, $V_{3\text{-}4}$; V_2: $I_{1\text{-}2}$, $V_{4\text{-}3}$; V_3: $I_{3\text{-}2}$, $V_{4\text{-}1}$; V_4: $I_{2\text{-}3}$, $V_{1\text{-}4}$;

*V_5: $I_{4\text{-}3}$, $V_{1\text{-}2}$; V_6: $I_{3\text{-}4}$, $V_{2\text{-}1}$; V_7: $I_{1\text{-}4}$, $V_{2\text{-}3}$; V_8: $I_{4\text{-}1}$, $V_{3\text{-}2}$;

*The **van der Pauw method** is very useful for measurements on regular thin films



For samples with a line of symmetry:

$$\rho = \frac{\pi d}{\ln 2}\frac{V_{1,2}}{I_{3,4}}$$

220 PHILIPS TECHNICAL REVIEW VOLUME 20

A METHOD OF MEASURING THE RESISTIVITY AND HALL COEFFICIENT ON LAMELLAE OF ARBITRARY SHAPE

GEOMETRIES FOR THE MEASUREMENT OF RESISTIVITY

Devices *such as micro- and nano-devices (GMR spin-valves, magnetic tunnel junctions, nanoconstrictions,...) normally require lithography techniques to define the transport geometry and the contacts.*

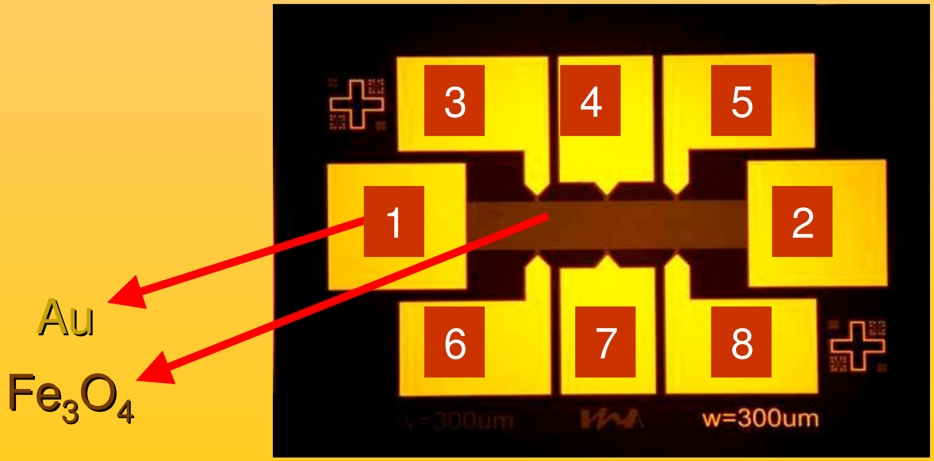
*Micrometric devices are normally patterned by means of optical lithography techniques

*Nanometric devices are normally patterned by means of electron-beam lithography, focused ion beam lithography, nanoimprinting, etc.

Design for R, MR and Hall effect measurements of a thin film

MR: I(1,2); V(3,5)

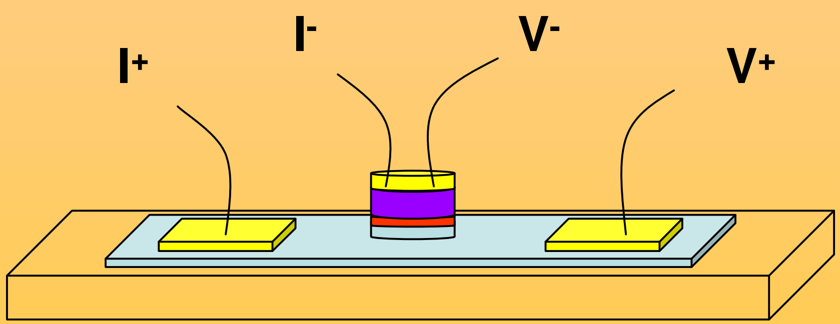
Hall: I(1,2); V(4,7)

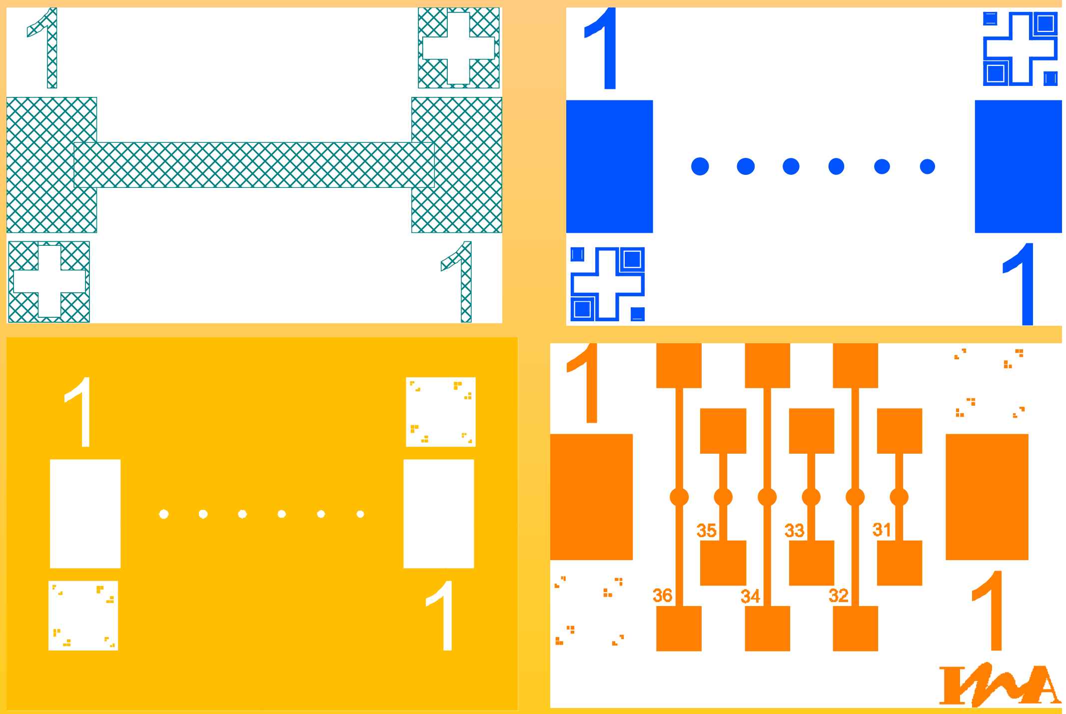


GEOMETRIES FOR THE MEASUREMENT OF RESISTIVITY

-Measurements in perpendicular geometry are difficult because they require several lithographic steps to define the current (which can be required for certain measurements in GMR-CPP configuration, magnetic tunnel junctions, etc.).

⇒ Example: masks for magnetic tunnel junctions



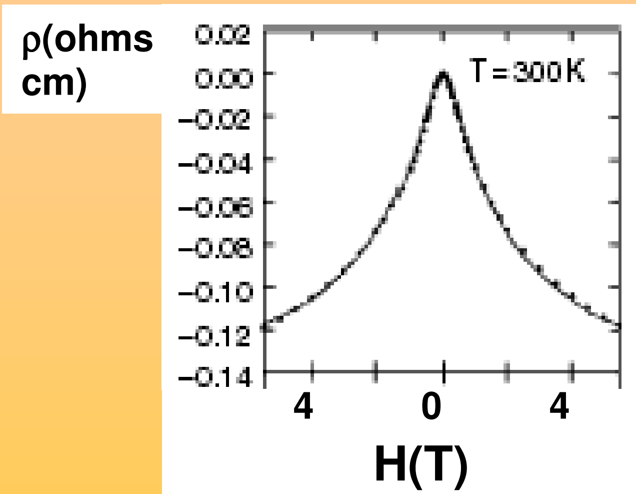


*In these nanodevices, one should be careful regarding geometrical effects arising with high resistive electrodes, large contact pads, etc.

DEFINITIONS OF MAGNETORESISTANCE

(similar definitions can be given for “magnetoconductance”)

**In the case of monotonous behaviour:*



Optimistic view:

$$\Delta\rho/\rho = \frac{\rho(H)-\rho_{\min}}{\rho_{\min}};\ MR(\%) = 100x\Delta\rho/\rho$$

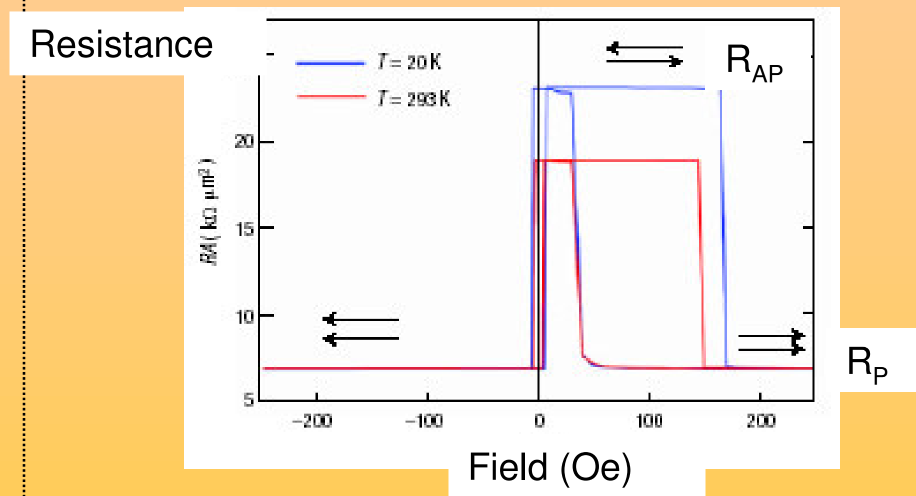
The MR ratio is unlimited

Pessimistic view:

$$\Delta\rho/\rho = \frac{\rho(H)-\rho_{\max}}{\rho_{\max}};\ MR(\%) = 100x\Delta\rho/\rho$$

The MR ratio is limited to 100%

**In the case of hysteretical behaviour:*



Optimistic view:

$$MR(\%) = 100x\frac{R_{AP}-R_P}{R_P}$$

The MR ratio is unlimited

Pessimistic view:

$$MR(\%) = 100x\frac{R_{AP}-R_P}{R_{AP}}$$

The MR ratio is limited to 100%

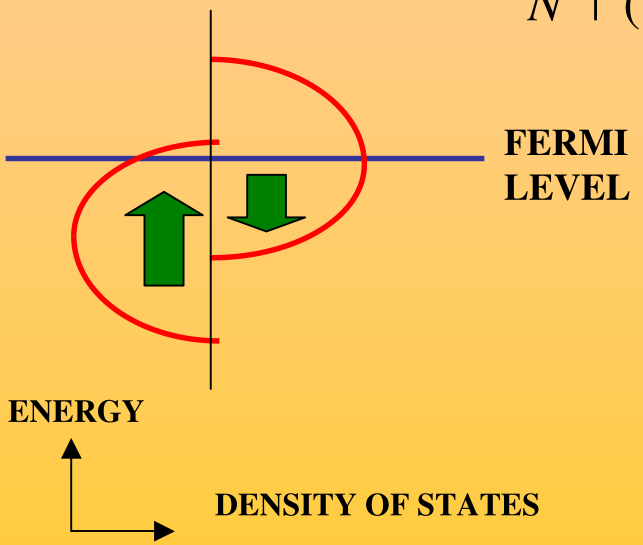
FERROMAGNETIC MATERIALS

Magnetization

$$M = N\uparrow - N\downarrow$$

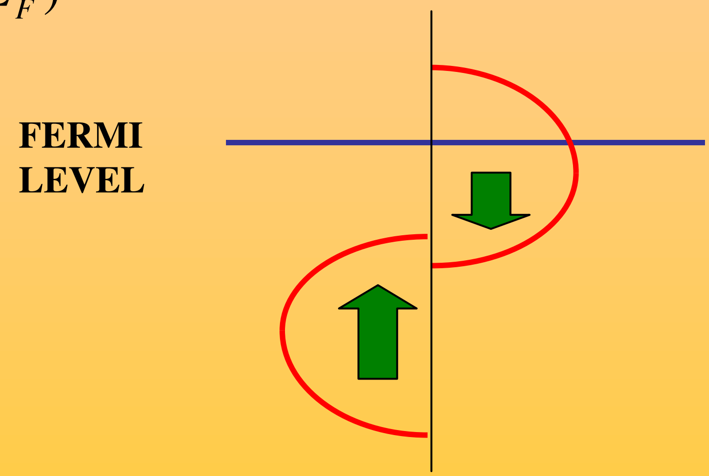
Spin Polarization

$$P(E_F) = \frac{N\uparrow(E_F) - N\downarrow(E_F)}{N\uparrow(E_F) + N\downarrow(E_F)}$$



Half metal

$P(E_F) = \pm 1$



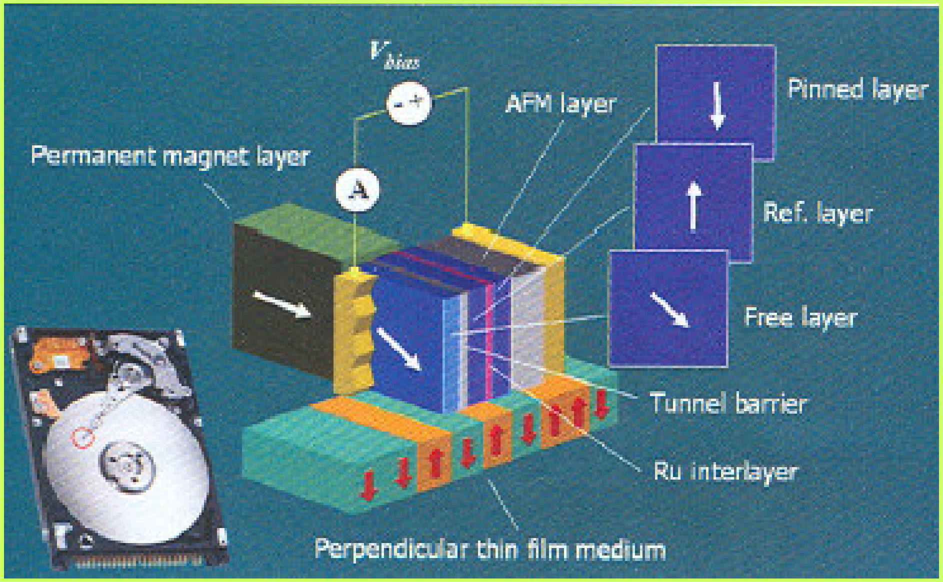
⇒Most of the magnetoresistive devices are built upon ferromagnetic materials and we will concentrate on them. Of course, magnetoresistive effects exist when using other kinds of magnetic and non-magnetic materials but here we will only consider such materials marginally.

INTEREST OF MAGNETORESISTIVE SYSTEMS NOWADAYS

APPLICATIONS IN:

Magnetic read heads, position sensors, earth magnetic field sensing, non-contact potentiometers, non-volatile memories, detection of biological activity (biosensors), spintronics,...

PARADIGMATIC EXAMPLE: GMR and TMR sensors are the active elements in the detection of the information stored in the hard disks of computers



ORIGIN OF RESISTIVITY

*Classical image of the resistivity:

-Without electric field, random movement of conduction electrons with their Fermi velocity (typically ~c/200) but null drift velocity ⇒ no conduction

-With applied electric field, a net acceleration appears and a drift velocity given by:

$\langle v \rangle = eE\tau/m^*$ (τ is the time between to scattering events). Then $J = ne\langle v \rangle$ and $\rho = E/J$

$\rho = m^* / n e^2 \tau$ (with $\tau = \lambda_{mfp}/v_F$) (Drude's formula)

Mean free path (λ_{mfp})= path between two consecutive scattering events

$$\rho(T) = \rho_0 + \rho_P(T) + \rho_m(B,T)$$

(Matthiessen's rule)

caused by defects — *caused by phonons* — *caused by Magnetism*

Normally giving rise to small MR effects

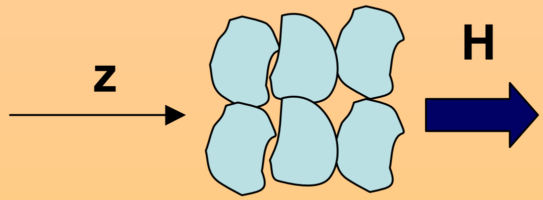
*Additional sources of resistivity (unveiled in nanodevices):

* They appear when the **sample size is comparable to significant transport parameters** such as ***the mean free path***, ***the spin diffusion length*** (distance between two consecutive scattering events which produce spin flip), ***the Fermi length of the conduction electrons***,…

In some cases the MR effects can be large even at low fields

LORENTZ MR
ANISOTROPIC MR
AND HALL EFFECT

LORENTZ MR (LMR), ANISOTROPIC MR (AMR) AND HALL EFFECT



B=**H**+4π**M**(1-D)

m=**M** / |**M**|

IN THE CASE OF A POLYCRYSTAL (ISOTROPIC MATERIAL) AND FROM SYMMETRY ARGUMENTS:

$$[\rho_{ij}] = \begin{bmatrix} \rho_\perp(B) & -\rho_H(B) & 0 \\ \rho_H(B) & \rho_\perp(B) & 0 \\ 0 & 0 & \rho_\parallel(B) \end{bmatrix}$$

When we apply current → $$E_i = \sum_j \rho_{ij} J_j$$

$$\rho_{ij}(B) = \rho_{ij} + \rho^*_{ij}(B)$$

At B=0 →

$\rho_\parallel$ = resistivity for **J** parallel to **M** at B=0

$\rho_\perp$ = resistivity for **J** perpendicular to **M** at B=0

ρ_H = extraordinary Hall resistivity

$$\vec{E} = \rho_\perp(B)\vec{J} + \left[\rho_\parallel(B) - \rho_\perp(B)\right]\left[\vec{m}.\vec{J}\right]\vec{m} + \rho_H(B)\vec{m}x\vec{J}$$

E_1: ***Lorentz magnetoresistance***

E_2: ***Anisotropic magnetoresistance effect***

E_3: ***Hall effect***

Campbell and Fert, Magnetic Materials 3 (1982) 747

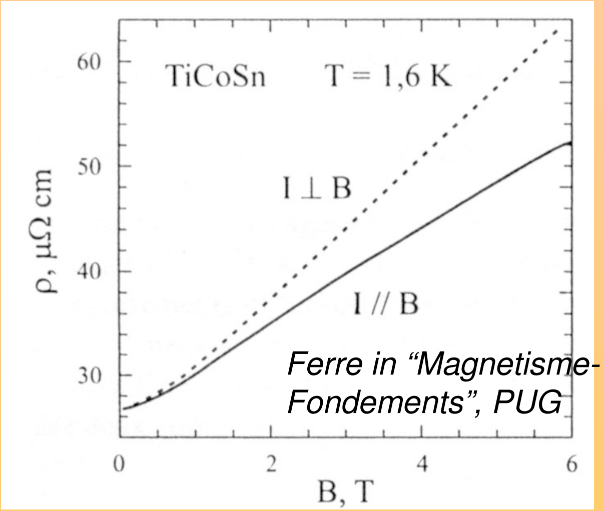
LMR, AMR AND HALL EFFECT

LORENTZ MR

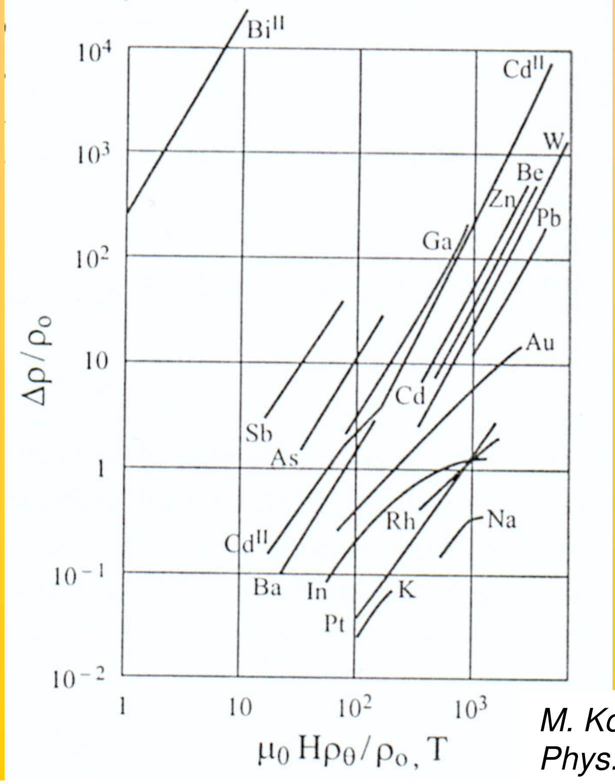
$$\vec{E}_1 = \rho_\perp(B)\vec{J}$$

-DUE TO THE CURVING OF THE CARRIER TRAJECTORY BY THE LORENTZ FORCE ($q\vec{v}x\vec{B}$)

-VERY SMALL IN MOST METALS EXCEPT AT LOW TEMPERATURES OR FOR CERTAIN ELEMENTS

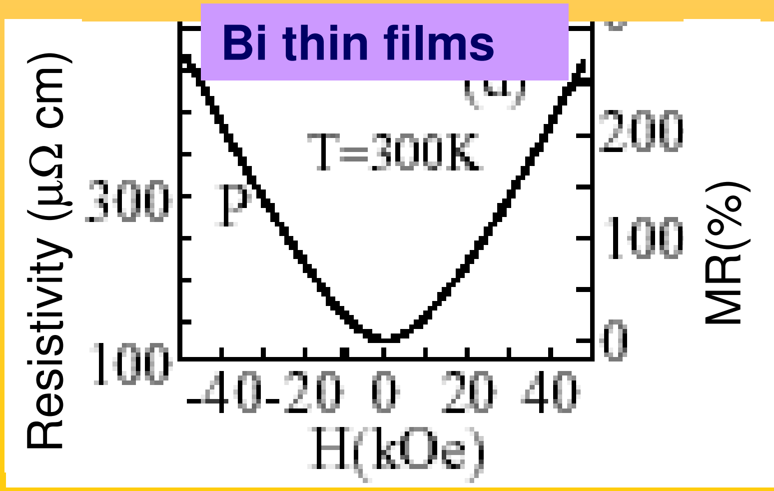


Ferre in "Magnetisme-Fondements", PUG



M. Kohler, Ann. Phys. 6 (1949) 18107

⇒ *The fundamental quantity for LMR is $\omega_c\tau$, the mean angle turned along the helical path between collisions, where ω_c is the cyclotron frequency (ω_c=eB/m*c)*

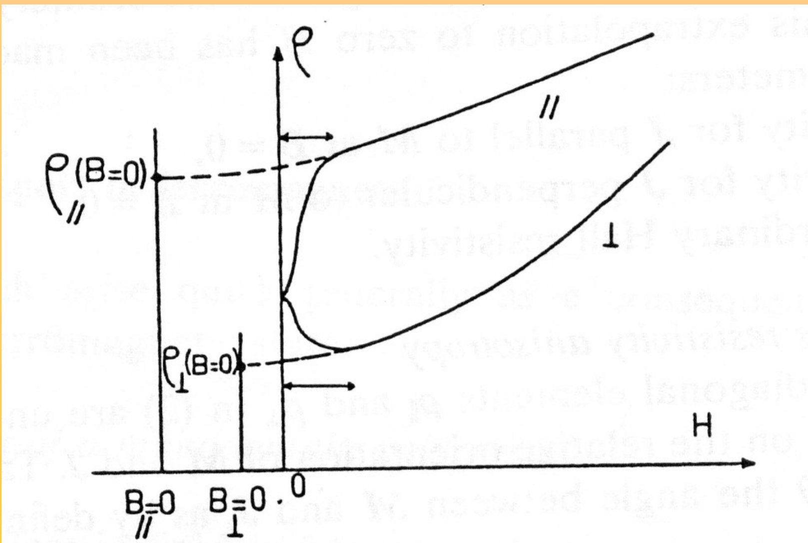


F.Y. Yang et al., Phys. Rev. Lett. 82 (1999) 3328

LMR, AMR AND HALL EFFECT

ANISOTROPIC MR

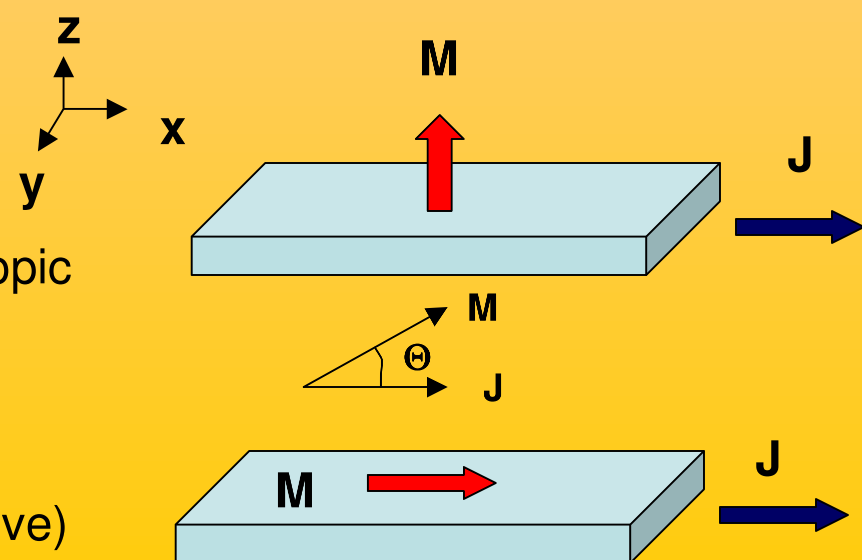
$$\vec{E}_2 = \left(\rho_{\parallel}(B) - \rho_{\perp}(B)\right)\left(\vec{m}.\vec{J}\right)\vec{m}$$



-Spontaneous anisotropy of the MR (B=0):

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho_0} \qquad \frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{(1/3)\rho_{\parallel} + (2/3)\rho_{\perp}}$$

(extrapolation to B=0 required)



-Angular dependence of the anisotropic MR at magnetic saturation:

$$\rho = \rho_0 + \rho_{ani}\cos^2\Theta$$

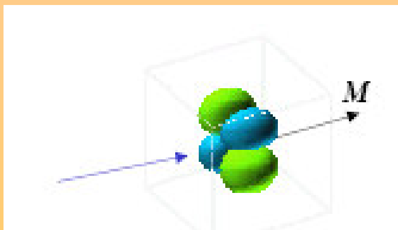
(Θ=angle between **J** and **M**)

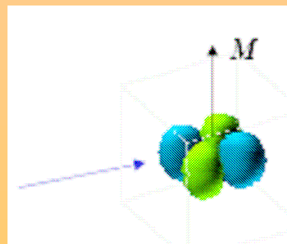
(ρ_{ani} can be either positive or negative)

LMR, AMR AND HALL EFFECT

ANISOTROPIC MR

Physical origin of the AMR: spin-orbit interaction effect: λ**L.S**

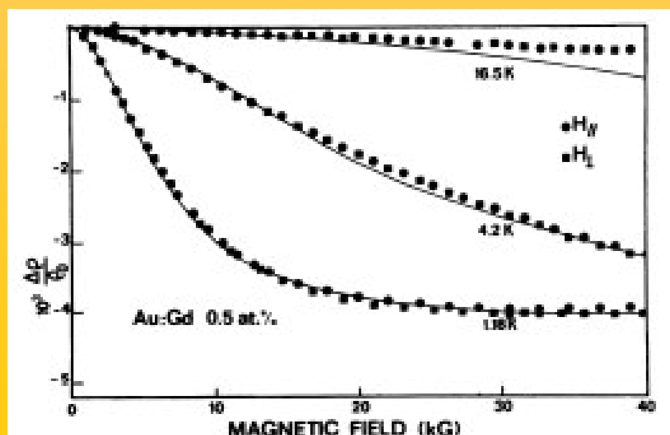


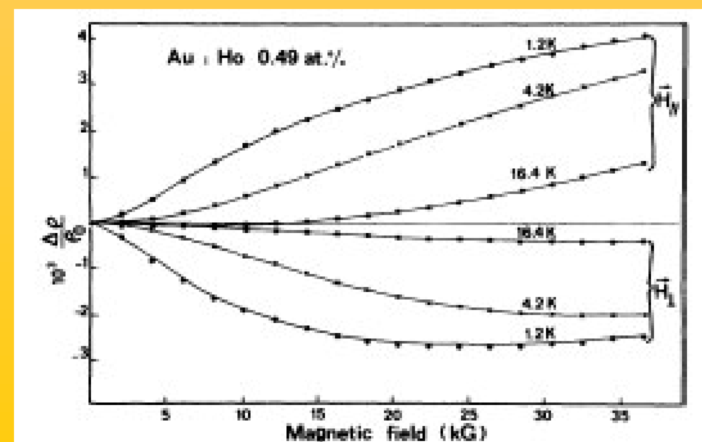


⇒It is expected to be large only in systems with large spin-orbit interaction and anisotropic charge distribution

Examples of the AMR behaviour:

1) It was shown in magnetoresistance measurements of *rare-earth-doped gold* that the AMR was large in all cases except for Gd, with L=0 (Gd^{+3}⇒ $4f^7$); (*Fert et al., Phys. Rev. B 16 (1977) 5040*)



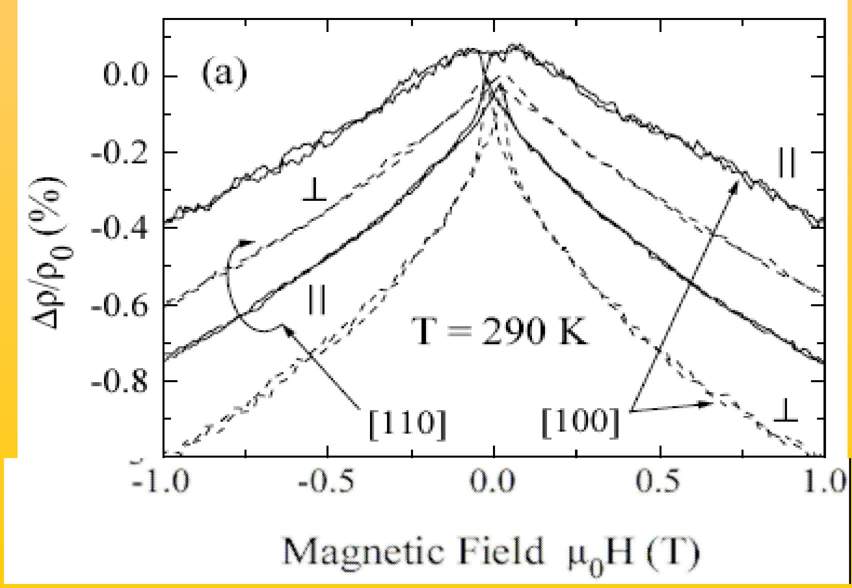


LMR, AMR AND HALL EFFECT

ANISOTROPIC MR (Examples of the AMR behaviour)

2) In transition-metal-based compounds, it is normally very small (because the orbital moment is almost quenched) except in some particular cases such as Ni-Co and Ni-Fe alloys (AMR up to 6% at 300 K). Thin films based on this kind of alloys were used for the first MR read heads. It has been found for the spontaneous AMR: $\Delta\rho / \rho = \gamma(\alpha - 1)$ (with γ=spin-orbit constant and α=ρ↑/ρ↓)

3) In single-crystals, the AMR depends on the direction of the current with respect to the crystallographic axis



Fe_3O_4 THIN FILMS

For I // [100] ⟶ $\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho_0} > 0$

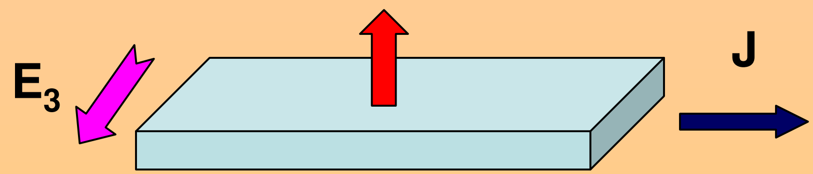
For I // [110] ⟶ $\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho_0} < 0$

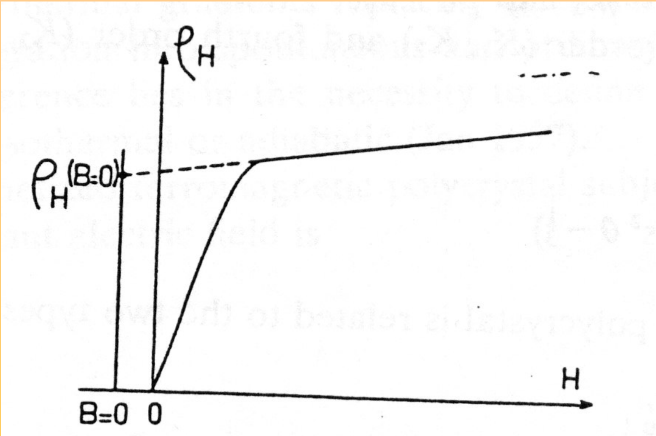
M. Ziese et al., J. Phys.: Condens. Mater. 12 (2000) 13

LMR, AMR AND HALL EFFECT

HALL EFFECT

$$\vec{E}_3 = \rho_H(B)\vec{m}x\vec{J}$$





$\rho_H \equiv \rho_{xy}$

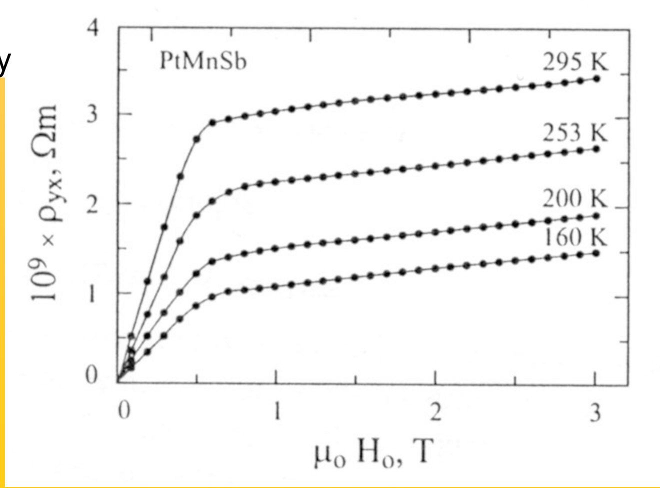


Figure from J. Ferre in "Magnetisme-Fondements" (edited by PUG)

Typical experimental dependence:

$$\rho_H(B) = \rho_H^0 B + \rho_H^{EHE} M$$

Ordinary Hall effect

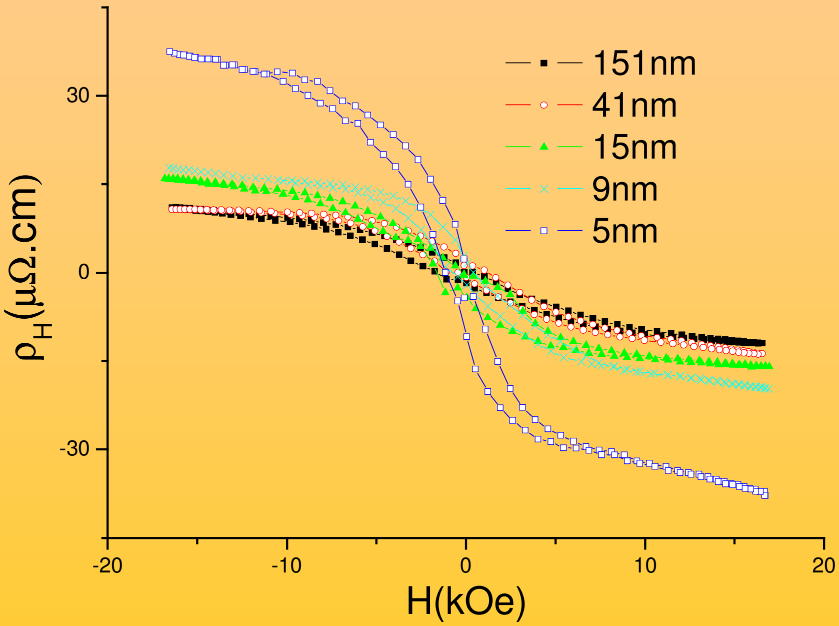
Explained by the Lorentz force (as in semiconductors). It allows one to extract the carrier density and, in combination with resistivity measurements, the carrier mobility

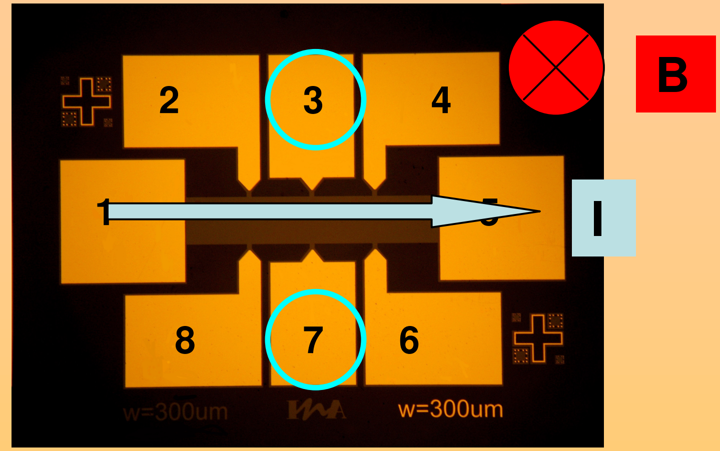
Extraordinary Hall effect (EHE)

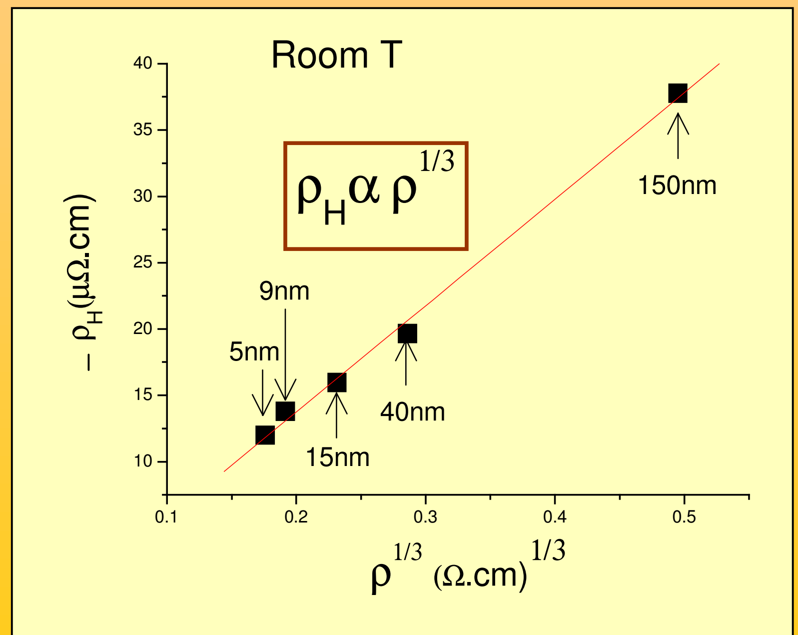
Typically, the extraordinary Hall effect is stronger than the ordinary Hall effect. Its origin is discussed either via "extrinsic" or "intrinsic" mechanisms. Spin-orbit interaction is always the key ingredient in EHE

LMR, AMR AND HALL EFFECT

EXTRAORDINARY HALL EFFECT (EHE): Example: Fe_3O_4 thin films







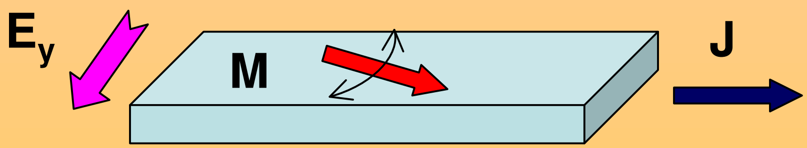
⇒*Our Group has recently found a different scaling of the EHE with $\rho^{1/3}$ in Fe_3O_4 films*

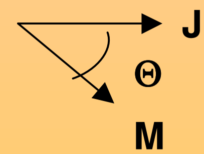
J.M. De Teresa, A. Fernández-Pacheco, L. Morellon, J. Orna, J.A. Pardo, D. Serrate, P.A. Algarabel, M.R. Ibarra, Microelectronic Engineering 84, 1660 (2007); A. Fernández-Pacheco, J.M. De Teresa, L. Morellon, J. Orna, J.A. Pardo, D. Serrate, P.A. Algarabel, M.R. Ibarra, manuscript in preparation

LMR, AMR AND HALL EFFECT

"PLANAR HALL EFFECT"

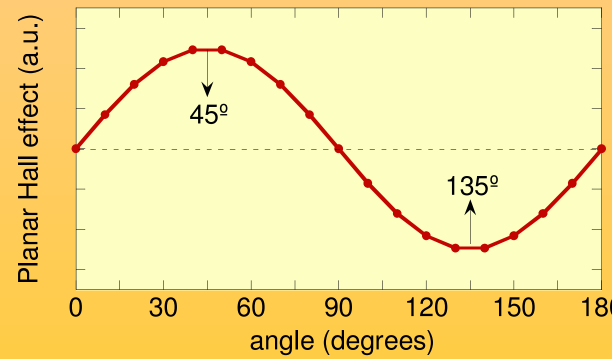
-It is due to E_2 not to E_3 ⇒ it is an AMR effect, not an actual Hall effect

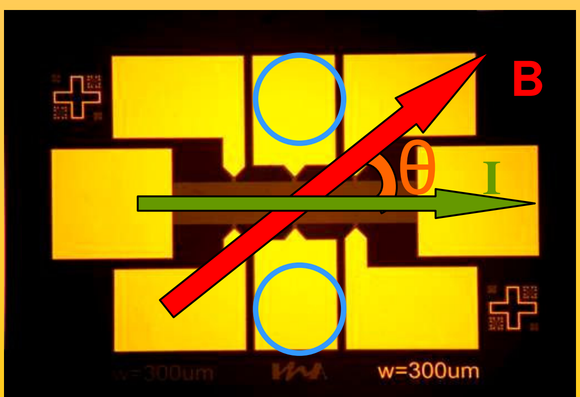


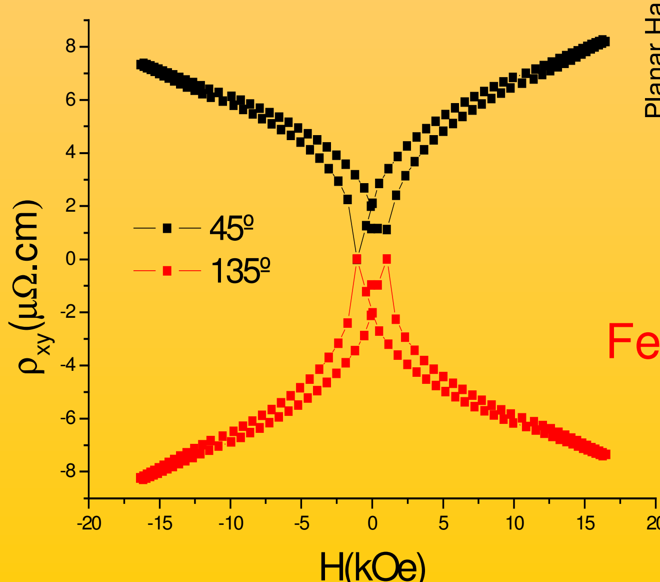


(Θ=angle between **J** and **M**)

$$E_y = \left((\rho_{\parallel} - \rho_{\perp})\cos\Theta \sin\Theta\right)J$$



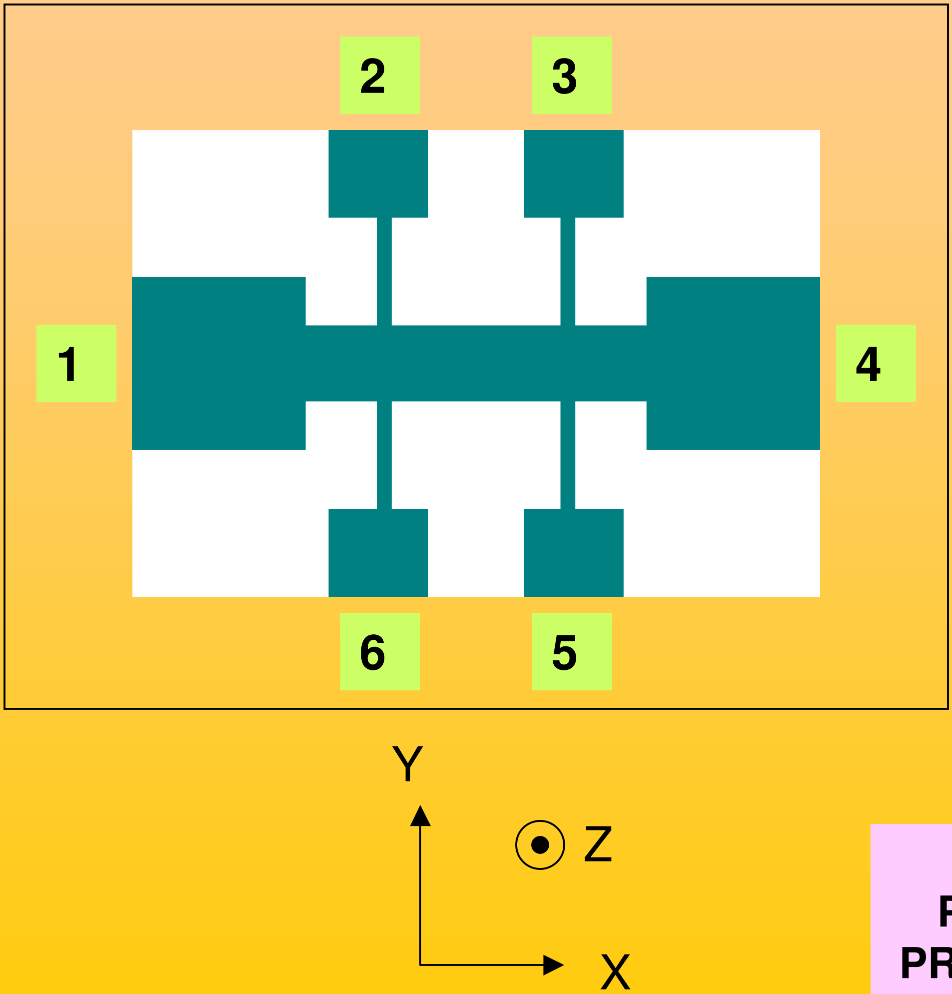




Fe_3O_4 THIN FILMS

LMR, AMR AND HALL EFFECT

SUMMARY



LORENTZ MAGNETORESISTANCE

I (1,4) ; V (2,3) ; H // y ó z

ANISOTROPIC MAGNETORESISTANCE

I (1,4) ; V (2,3) ; H // x ; H // y ó z

HALL EFFECT

I (1,4) ; V (2,6) ; H // z

PLANAR HALL EFFECT

I (1,4) ; V (2,6) ; H // (x,y) plane

⇒ ALL THESE MAGNETOTRANSPORT PHENOMENA HAVE BEEN APPLIED FOR PRACTICAL PURPOSES IN DIVERSE FIELDS

SPIN DISORDER AND COLOSSAL MAGNETORESISTANCE

SPIN-DISORDED MR (SDMR)

-With well-defined local moments, an exchange interaction between the local and conduction electrons of the type Γ**s.S** will give rise to spin-disordered scattering. At low temperatures (ferromagnetic phase) this interaction is modelled as a magnon-electron interaction.

-It gives an additional contribution to the resistivity that can be partially suppressed by applying large magnetic fields.

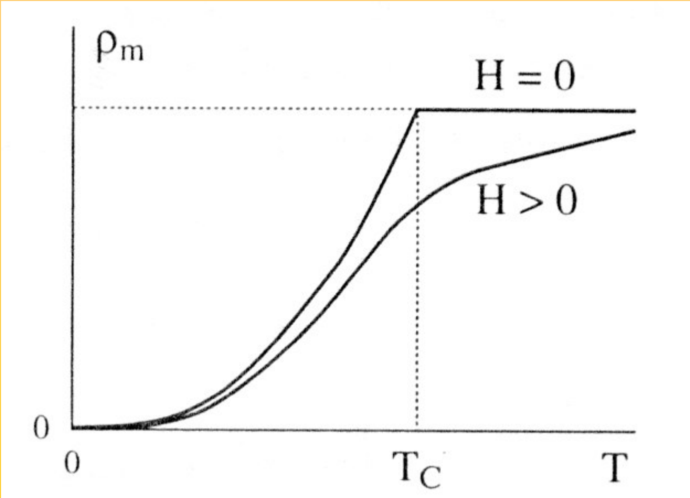


Figure from J. Ferre in "Magnetisme-Fondements" (edited by PUG)

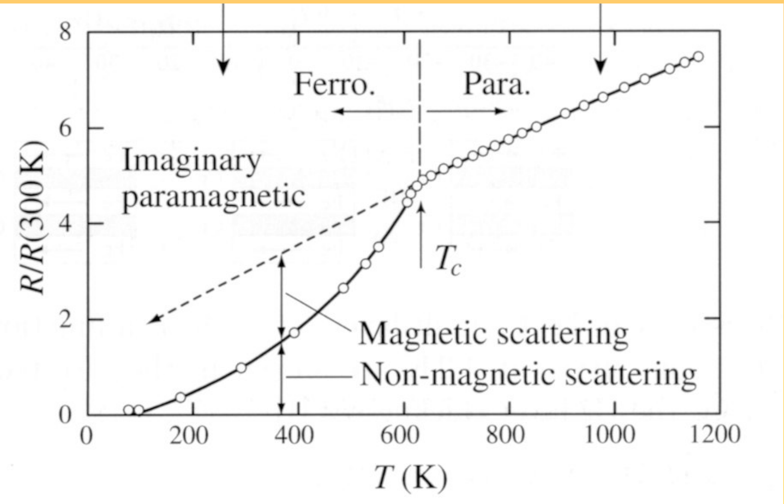
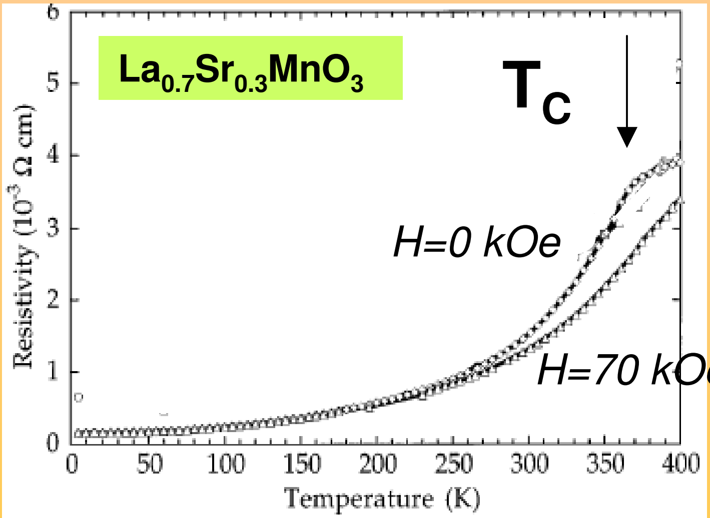


Figure from T. Shinjo in "Spin-dependent transport in magnetic nanostructures" (edited by S. Maekawa and T. Shinjo)

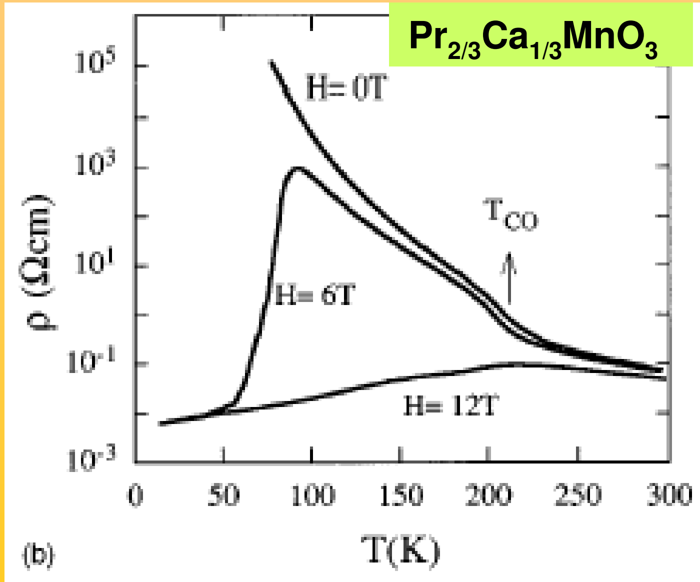
SPIN-DISORDED MR (SDMR) VERSUS COLOSSAL MR (CMR)

SDMR ocurrs in metallic systems and is the largest around Tc



Snyder et al., Phys. Rev. B 53 (1996) 14434

CMR ocurrs in certain systems showing spontaneous or field-induced metal-insulator transition



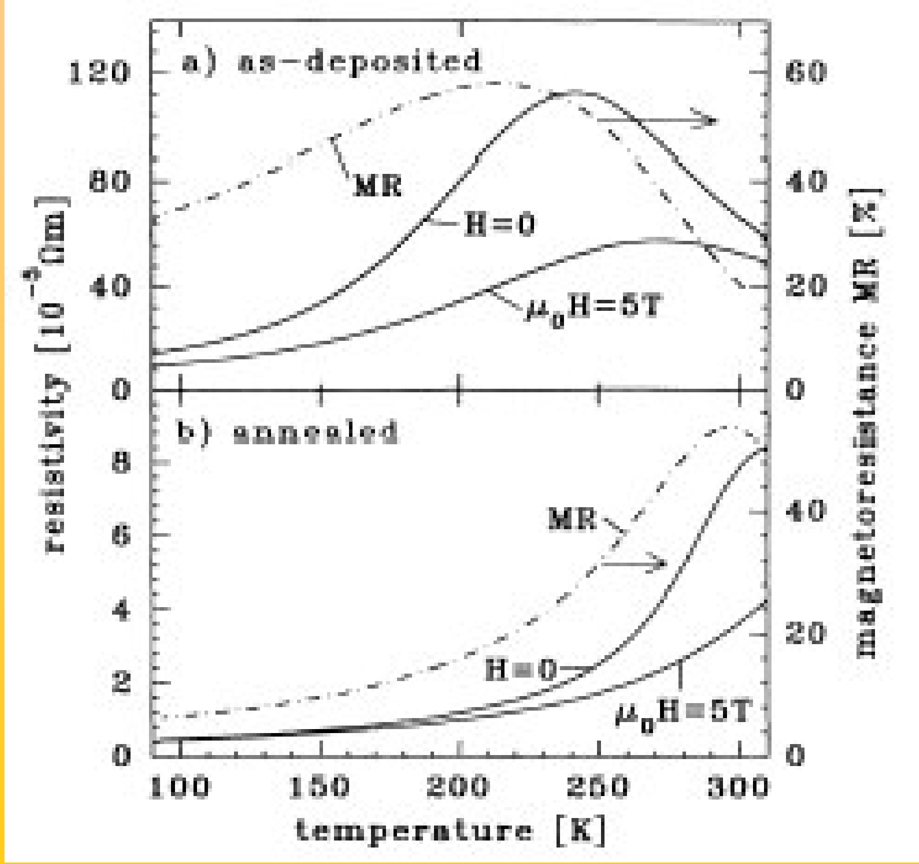
J.M. De Teresa et al., Phys. Rev. B 54 (1996) R12689

In both cases, SDMR and CMR, large magnetic fields are required for large resistance variations, which is disadvantageous for applications. It mostly remains of academic interest but with little applications

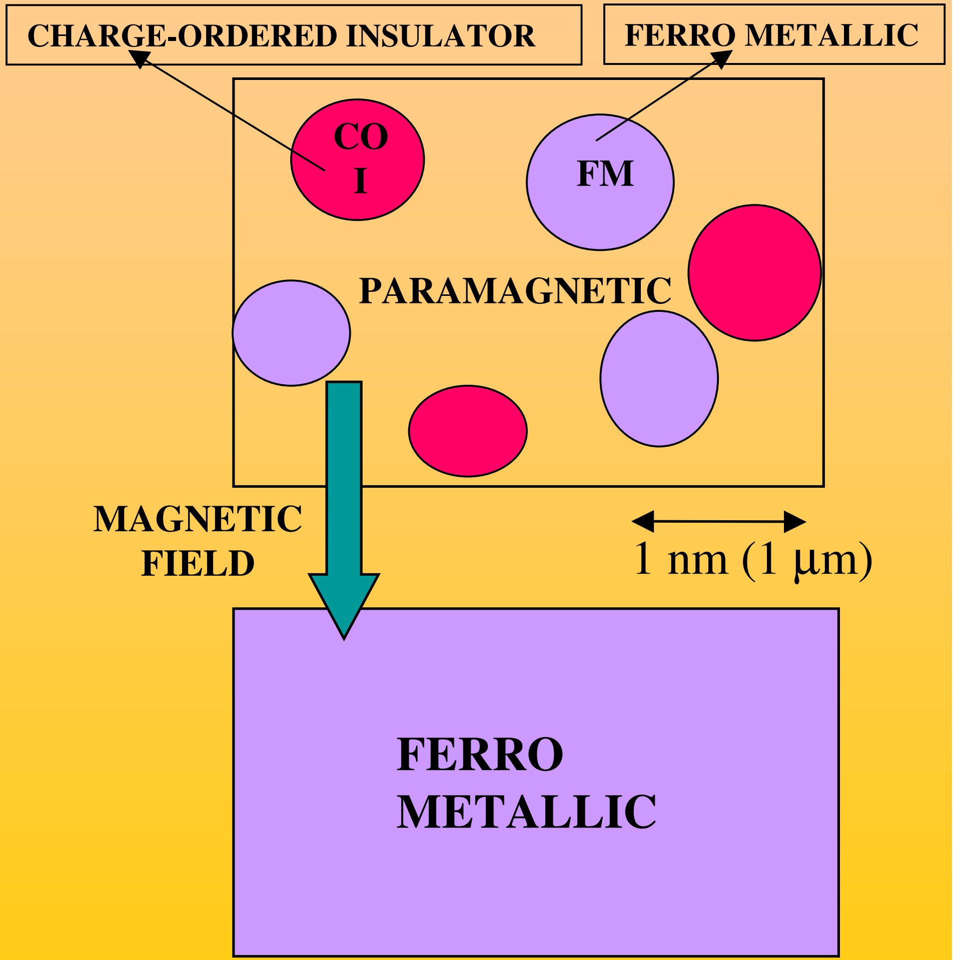
COLOSSAL MR (CMR) IN MANGANITE OXIDES ($A_{1-x}A'_xMnO_3$ type)

***KEY INGREDIENT*: STRONG COMPETITION BETWEEN INSULATING PHASES (CO, AF) AND CONDUCTIVE PHASES (FERROMAGNETIC BY DOUBLE EXCHANGE)**

$La_{2/3}Ba_{1/3}MnO_{3-d}$

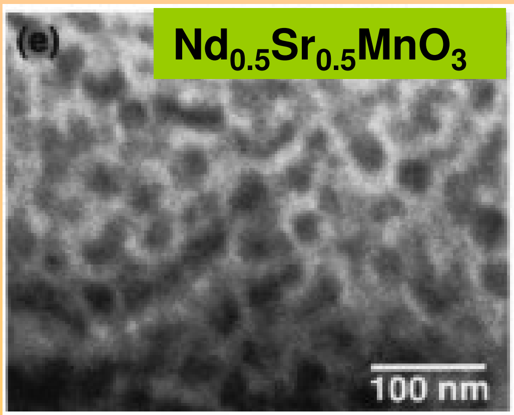


Von Helmolt et al., Phys. Rev. Lett. 71 (1993) 2331 (first report of CMR on thin films)



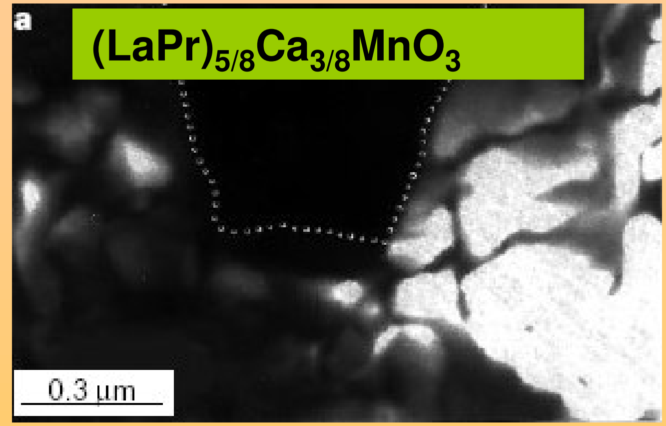
De Teresa et al., Nature 386 (1997) 256 and many other contributors

THE NANOMETRIC AND MICROMETRIC PHASE SEPARATION



Asaka et al., Phys. Rev. Lett. 89 (2002) 207203

TEM IMAGES



Uehara et al., Nature 399 (1999) 560

THEORETICAL STUDIES SHOW THAT THE SIMILAR ENERGIES OF INSULATING AND METALLIC COMPETING INTERACTIONS PLUS THE PRESENCE OF DISORDER ALLOW THE PHASE SEPARATION SCENARIO AND THE UNIQUE EFFECT OF THE MAGNETIC FIELD, WHICH FAVORS THE FERROMAGNETIC METALLIC STATE, AND CONSEQUENTLY THE CMR EFFECT

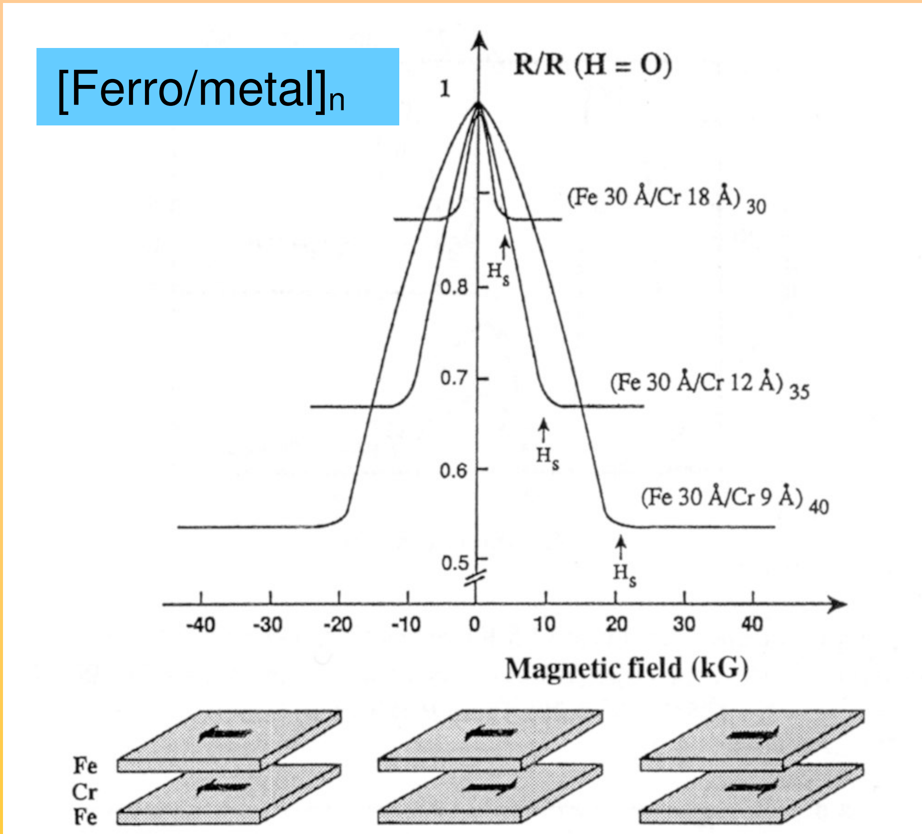
⇒ **INTRINSIC DISORDER** DUE TO THE SOLID SOLUTION WHICH CREATES RANDOM POTENTIALS

⇒**EXTRINSIC DISORDER** DUE TO SMALL LOCAL COMPOSITIONAL INHOMOGENEITIES AT THE NANOMETRIC LEVEL

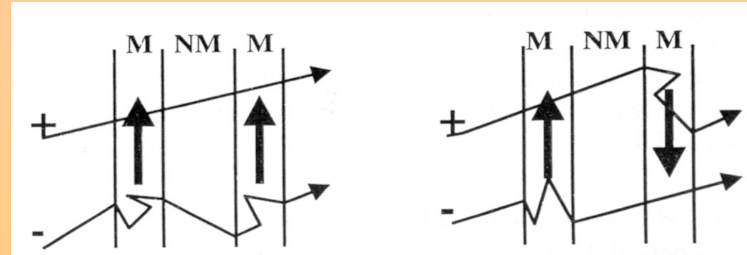
Dagotto et al., Phys. Rept. 344 (2001) 55 and references therein

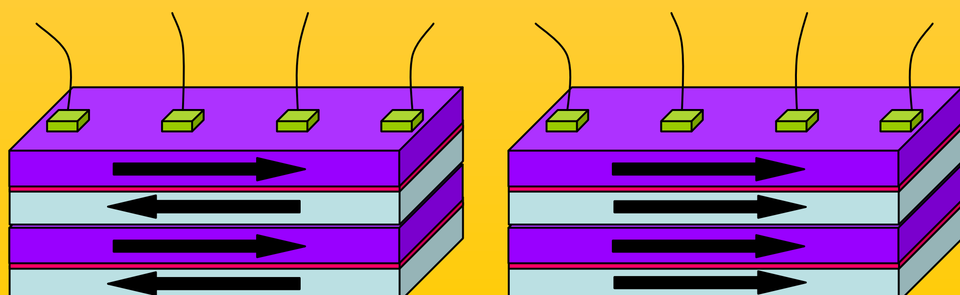
GIANT MAGNETORESISTANCE

GIANT MR (GMR)



Baibich et al., Phys. Rev. Lett. 61 (1988) 2472





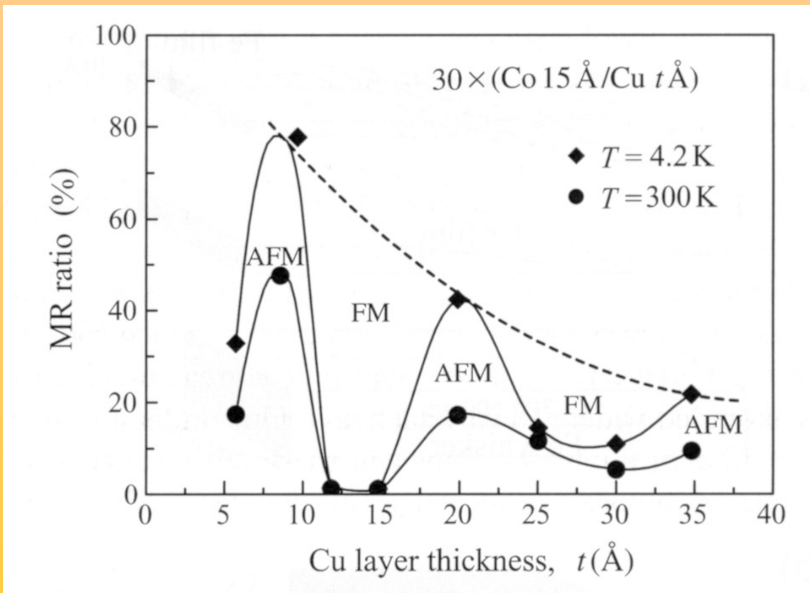
-The GMR effect was first observed in $[Fe/Cr]_n$ magnetic multilayers with layer thicknesses comparable to the mean free path.

-Theoretical explanation of the effect comes from the spin dependence of the conduction in ferromagnetic metals: “spin-up” and “spin-down” conduction electrons show different bulk and interface scattering probablility

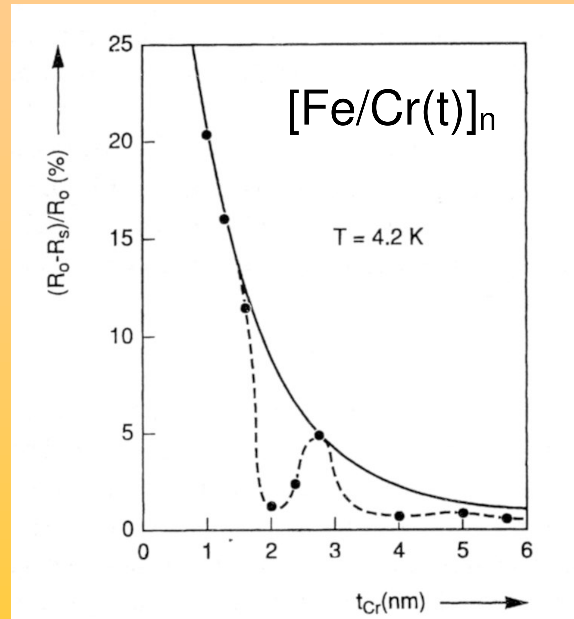
-Real applications of GMR came after the realization of the spin-valve concept (90’s), where the MR ratio is of the order of 10%

GIANT MR (GMR): some facts

-The MR effect was found to oscillate as a function of the non-magnetic layer thickness



Mosca et al., J. Magn. Magn. Mater. 94 (1991) 1

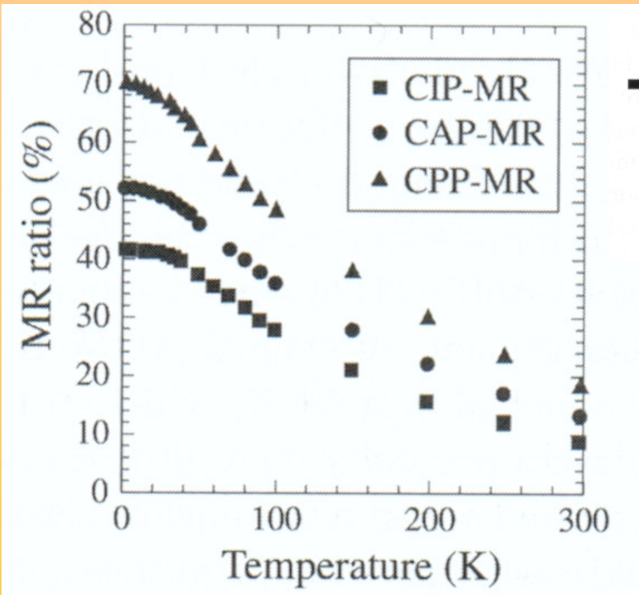


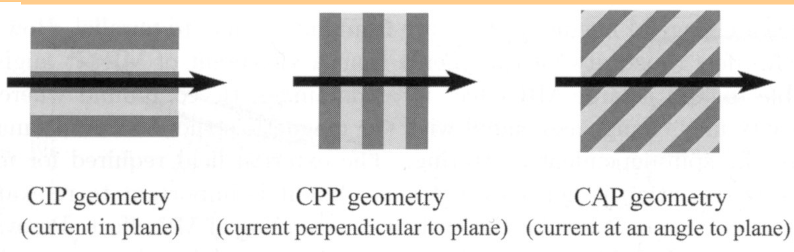
Gijs and Okada, Phys. Rev. B 46 (1992) 2908

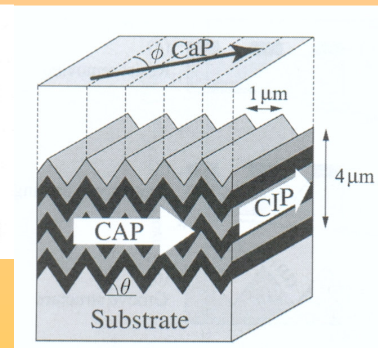
⇒THIS IS EXPLAINED BY THE ALTERNATING FERRO/ANTIFERRO MAGNETIC COUPLING OF THE MAGNETIC LAYERS THROUGH THE NON-MAGNETIC SPACER AND IS CONSISTENT WITH THE OSCILLATORY RKKY MAGNETIC INTERACTION

GIANT MR (GMR): some facts

-The MR effect is different in amplitude in the “current-in-plane” (CIP) and the “current-perpendicular to plane” (CPP) geometries







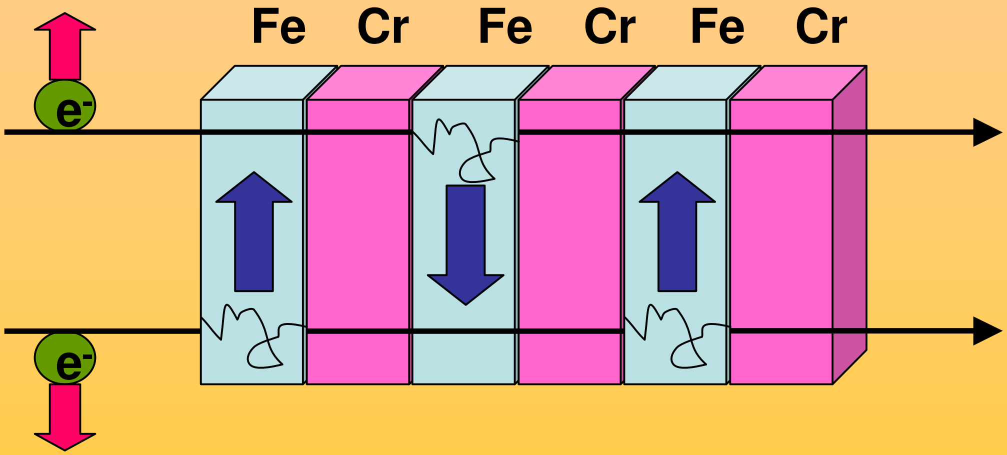
Ono et al., Phys. Rev. B 55 (1997) 14457

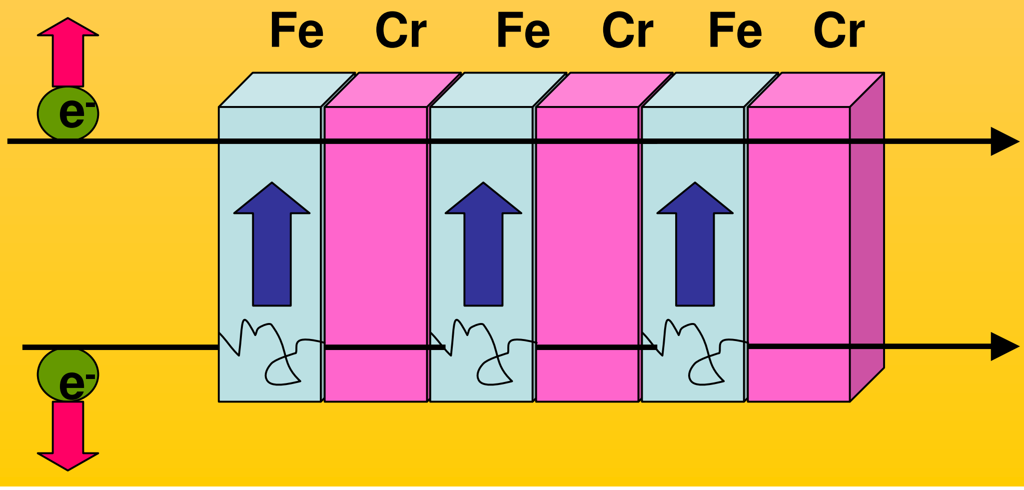
As the resistance (R) depends inversely with the area, in the CPP geometry R is very small. Normally, some lithography patterning is performed to make small areas or other tricks are applied.

⇒THE ELECTRONS INVOLVED IN THE GMR SCATTERING PROCESSES AND THE EXACT PROCESSES THEMSELVES ARE DIFFERENT DEPENDING ON THE GEOMETRY, WHICH LEADS TO DIFFERENT GMR AMPLITUDES: CPP-GMR IS FOUND TO BE LARGER THAN CIP-GMR

GIANT MR (GMR): simple picture

-If we assume that the spin-flip scattering rate of the conduction electrons is much lower than the non-flip scattering rate (as normally occurs at $T \ll T_C$), the conduction takes place through two independent parallel channels: the "spin-up" and "spin-down" electrons.





$$\rho_\uparrow = m_\uparrow / (n_\uparrow e^2 \tau_\uparrow)$$

$$\rho_\downarrow = m_\downarrow / (n_\downarrow e^2 \tau_\downarrow)$$

$$\left.\begin{aligned} \rho_\uparrow &\neq \rho_\downarrow \\ \rho_{AP} &= \frac{\rho_\uparrow + \rho_\downarrow}{4} \\ \rho_P &= \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \end{aligned}\right\}$$

$$GMR = \frac{\rho_{AP} - \rho_P}{\rho_P} = \frac{(\rho_\downarrow - \rho_\uparrow)^2}{4\rho_P \rho_{AP}}$$

GIANT MR (GMR): theoretical approaches

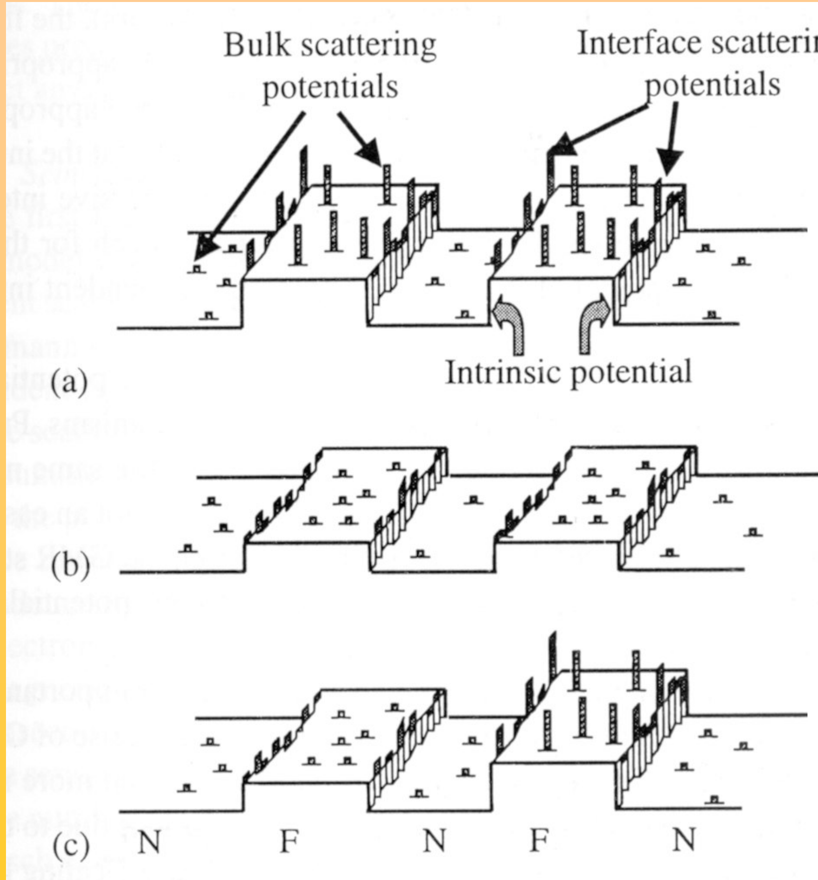
(for details see the excellent review by Barthélemy et al., Handbook of Magnetic Materials 12, 1999)

*_**THERE ARE 3 SOURCES OF SCATTERING**_:

-Bulk scattering events (spikes inside layers)

-Interface scattering events (spikes at interfaces)

-Intrinsic potential changes at the interfaces (jumps)



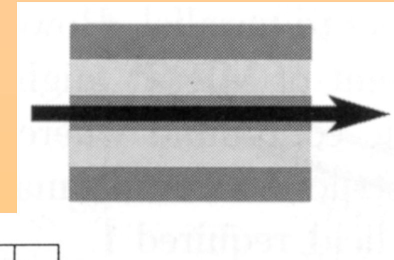
Spin "down" channel in the parallel configuration

Spin "up" channel in the parallel configuration

Spin "up" or spin "down" channels in the antiparallel configuration

- These potential jumps are important provided that the mean free path is larger than the layers thickness because they produce wavefunction specular reflections and, consequently, wavefunction interferences ("supperlattice" models). In some cases, a "layer-by-layer" approach is enough, only including bulk and interface scattering.

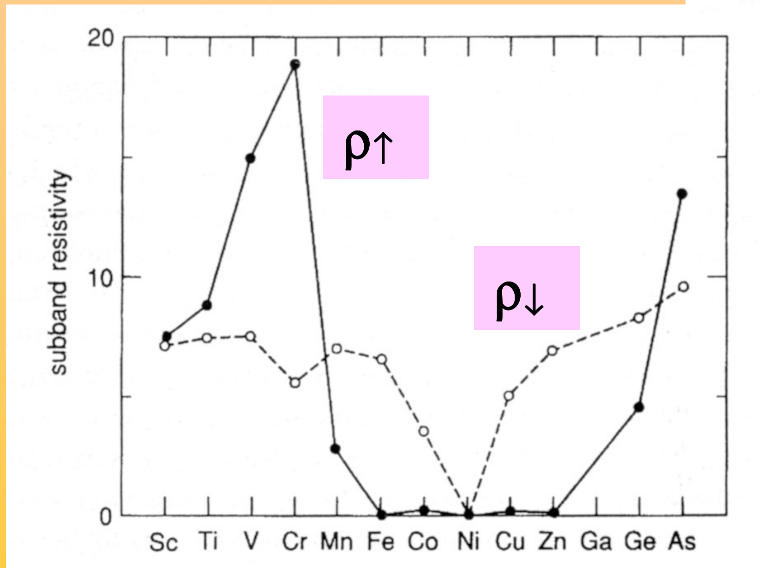
GIANT MR (GMR): theoretical approaches for CIP-GMR



-Initial models were based on free electrons scattered by **spin-dependent scatterers**. Controlled doping with impurities allows tailoring the GMR effect.

Example: impurities in Ni

$$GMR = \frac{(\rho_{\downarrow} - \rho_{\uparrow})^2}{4\rho_P \rho_{AP}}$$



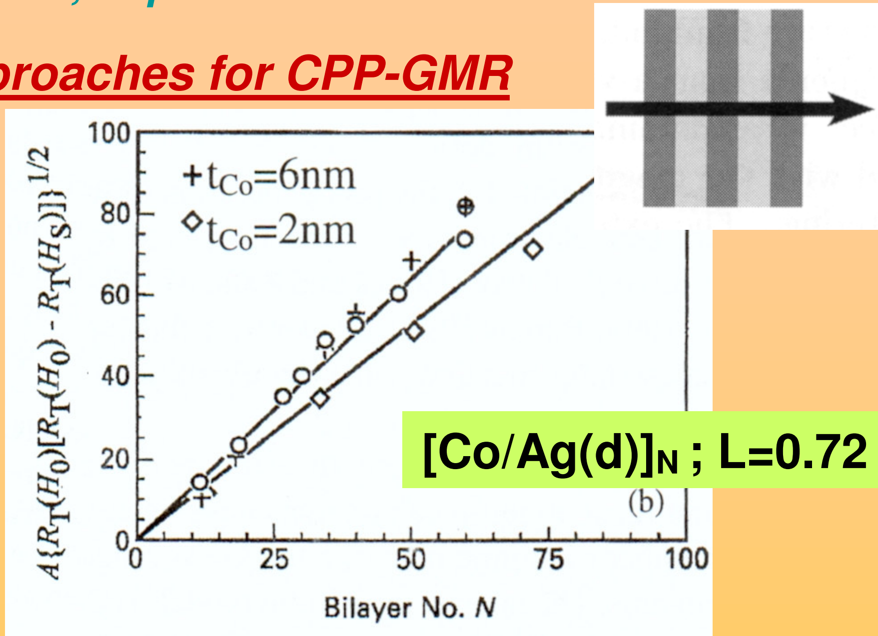
-Later, the **intrinsic potential effects** were progressively introduced into the models in addition to the scattering potentials. Interference between succesive reflections are normally not important in real experiments.

-All previous models assume **diffusive transport** (total system size larger than the mean free path). Some models have also addressed the **ballistic regime of the GMR** (to be realized in systems with very few impurities or nanocontacts)

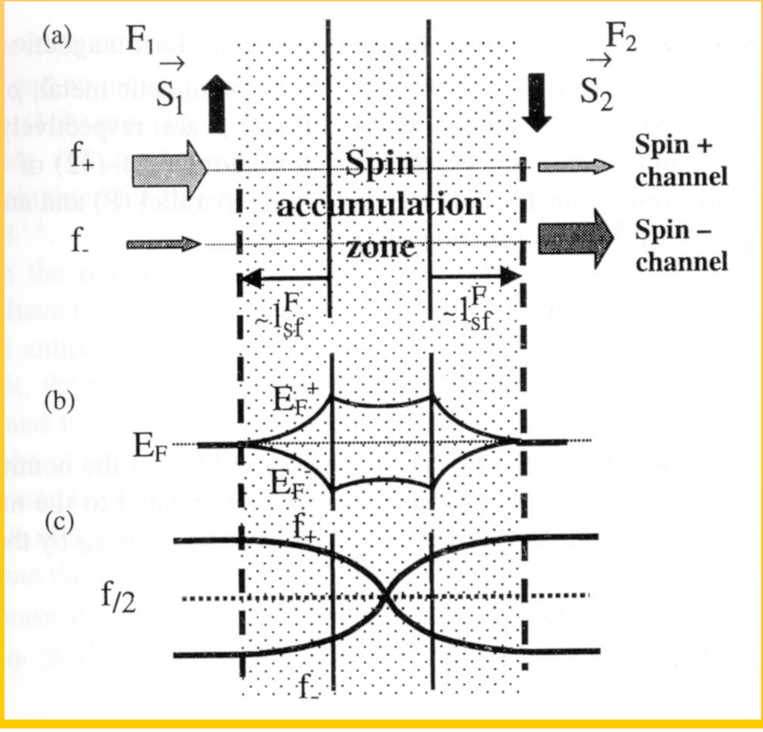
Cluj school, September 2007

GIANT MR (GMR): theoretical approaches for CPP-GMR

-The intrinsic contribution to the CPP-GMR can be normally expressed through the concept of “**interface resistance**”, which has contributions from the potential steps at the interface plus interface diffuse scattering by defects/dopants.



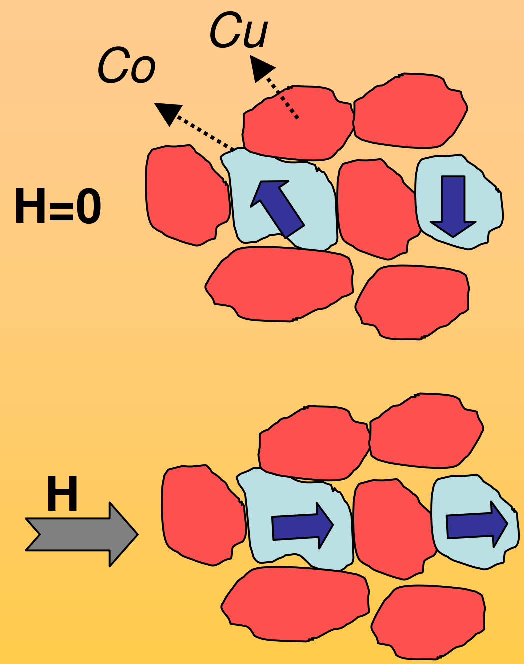
$[Co/Ag(d)]_N$; L=0.72 μm

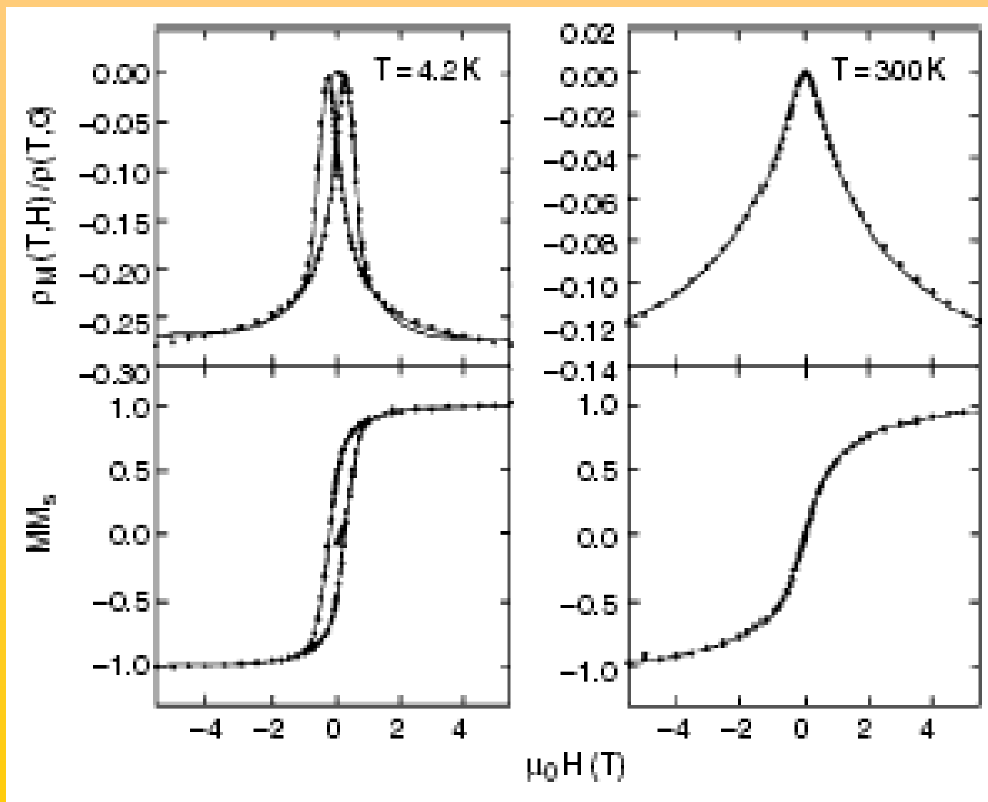


-CPP transport generates **spin accumulation** around the interfaces that must be balanced by spin relaxation (Valet and Fert theory). When spin relaxation is taken into account, the **spin diffusion length** (much larger than the mean free path) becomes the most relevant scaling length.

GIANT MR (GMR) IN GRANULAR MATERIALS

-The GMR effect can be realized in granular materials / thin films with immiscible magnetic/non-magnetic metals due to the same physical phenomena. The type of response is less suitable for applications, especially if hysteresis is present.



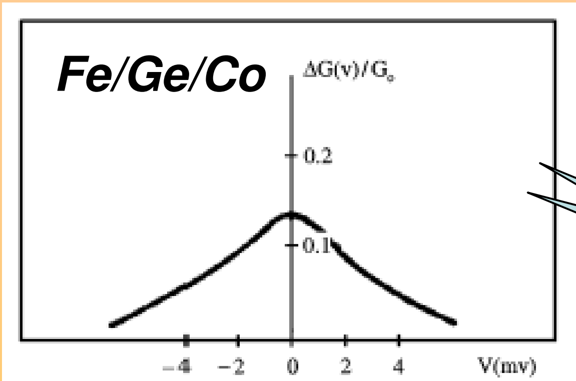


Berkowitz et al., Phys. Rev. Lett. 68 (1992) 3745; Xiao et al., Phys. Rev. Lett. 68 (1992) 3749; Wang and Xiao, Phys. Rev. B 50 (1994) 3423; Batlle and Labarta, J. Phys. D: Appl. Phys. 35 (2002) R15

TUNNEL MAGNETORESISTANCE

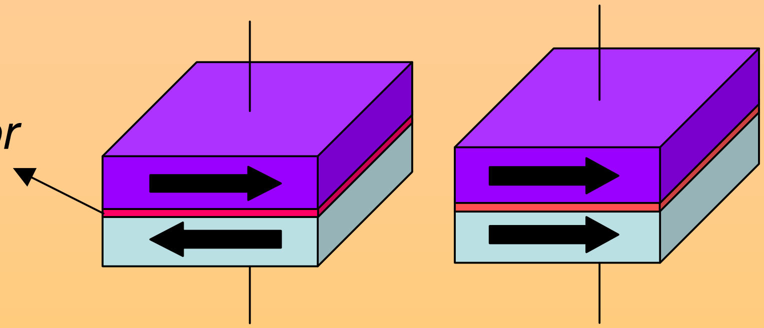
TUNNEL MAGNETORESISTANCE (TMR): how it all started

Fe/Ge/Co



1975

insulator

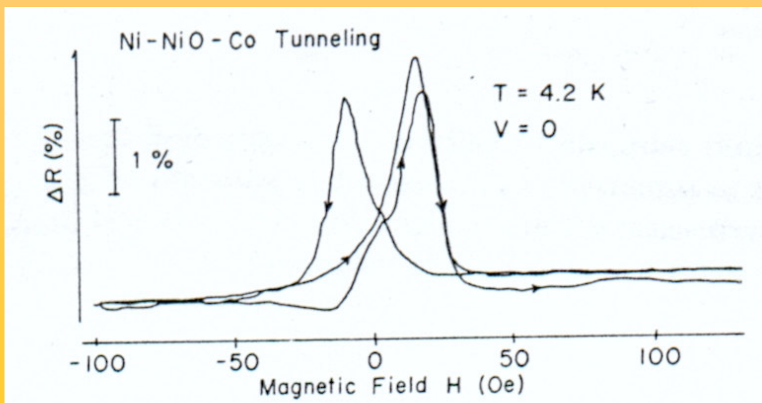


1982

Julliere, Phys. Lett. 54A (1975) 225

1995

CoFe/Al_2O_3/Co



Maekawa and Gaefvert, IEEE Transactions on Magnetics 18 (1982) 707

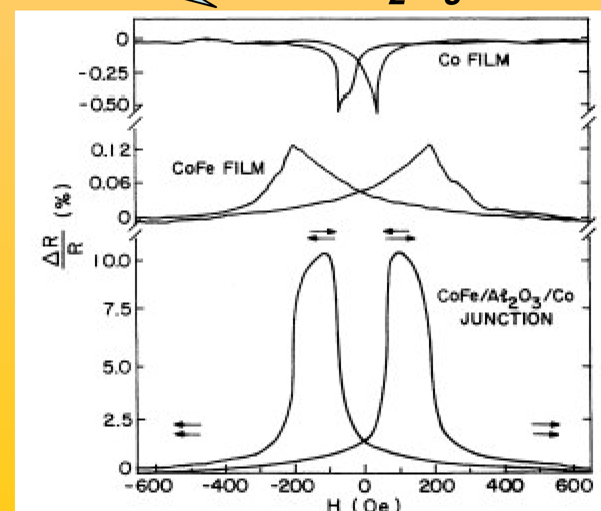
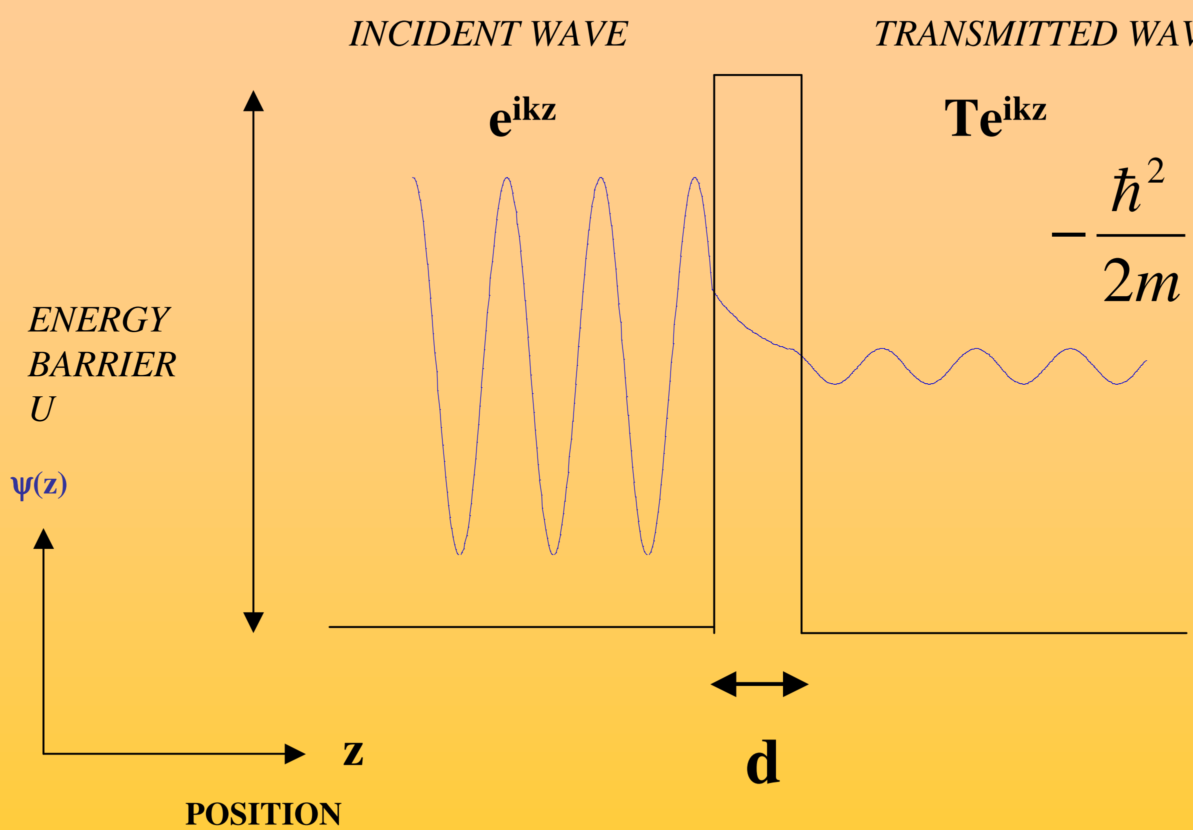


FIG. 2. Resistance of CoFe/Al_2O_3/Co junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).

Moodera et al., Phys. Rev. Lett. 74 (1995) 3273

TMR: first approach to the tunnel conductance



$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(z)}{\partial z^2}+U\psi(z)=i\hbar\frac{\partial\psi(z)}{\partial t}$$

$$\left|T_k\right|^2=\frac{16k^2k'^2}{(k^2k'^2)^2}e^{-2k'd}$$

$$k'=\sqrt{\frac{2m(U-E_z)}{\hbar^2}}$$

TUNNEL CURRENT:

$$J_k=\frac{i\hbar}{2m}\left(\psi\frac{\partial\psi^*}{\partial z}-\psi^*\frac{\partial\psi}{\partial z}\right)$$

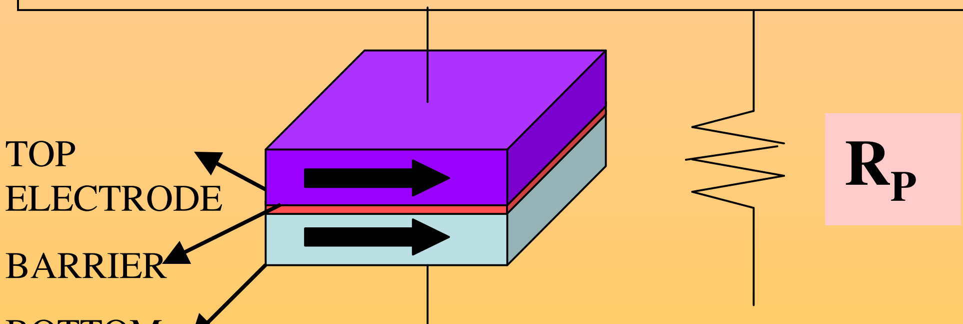
$$J_k\alpha\left|T_k\right|^2\alpha e^{-2k'd}$$

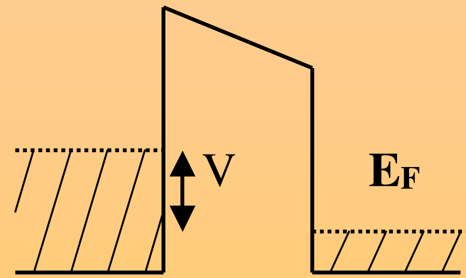
EXPONENTIAL DEPENDENCE OF THE CURRENT WITH THE BARRIER WIDTH AND THE SQUARED ROOT OF THE BARRIER HEIGHT

TMR: the basics of magnetic tunnel junctions

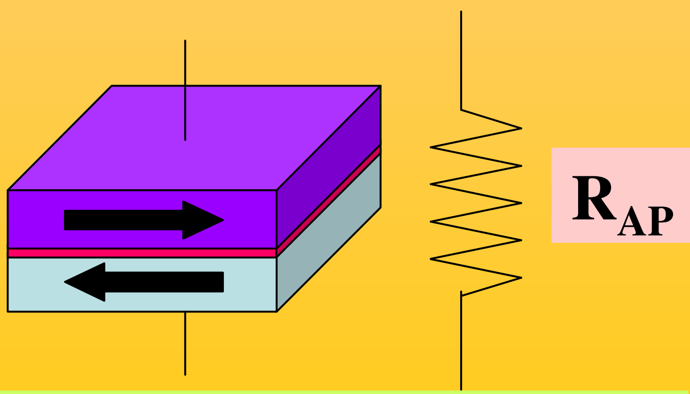
⇒ **MAGNETIC TUNNEL JUNCTIONS ARE FORMED BY TWO MAGNETIC MATERIALS (ELECTRODES) SEPARATED BY A NANOMETRIC INSULATING LAYER (BARRIER). CONDUCTION TAKES PLACE THROUGH TUNNELLING.**

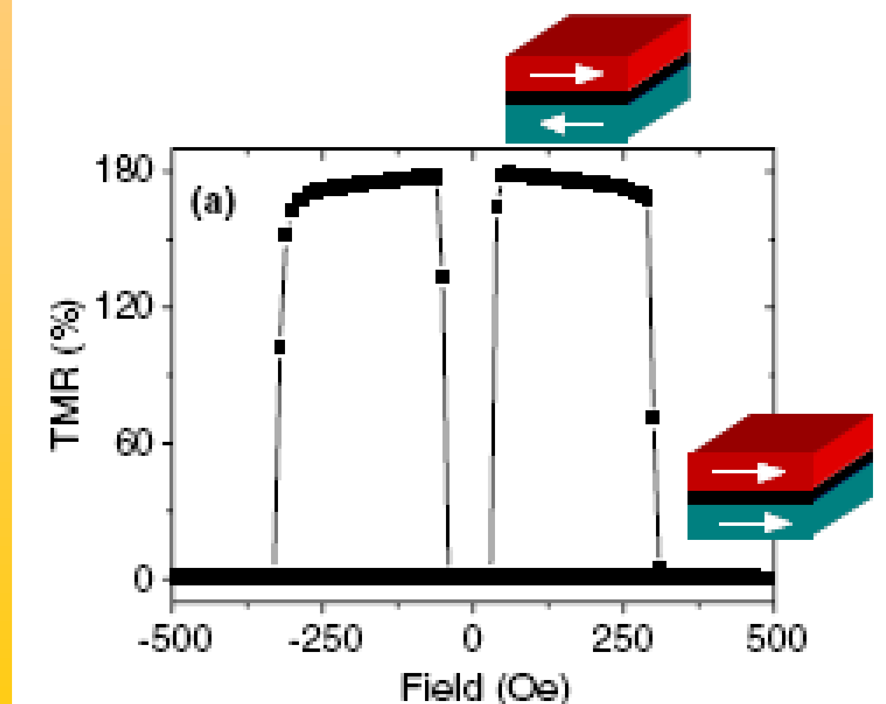
F1 / I / F2





TMR (%)= 100 x $(R_{AP}-R_P)/R_{AP}$





TMR=100 x $2P_1P_2/(1+P_1P_2)$
(Julliere's model)

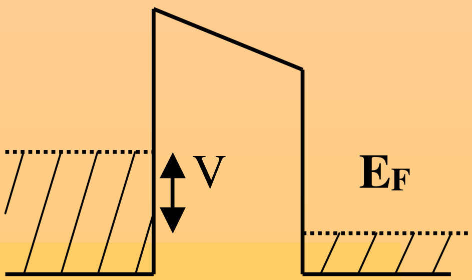
TMR: the idea behind Julliere's model

F1 / I / F2

$$I(V,E)\alpha\left|T(E)\right|^2 N_1(E-eV)N_2(E)\left[f(E-eV)-f(E)\right]$$

$$\frac{I}{V}\alpha\left|T(E_F)\right|^2 N_1(E_F)N_2(E_F) \Longrightarrow \frac{I}{V}\alpha N_1(E_F)N_2(E_F)$$

APROX.



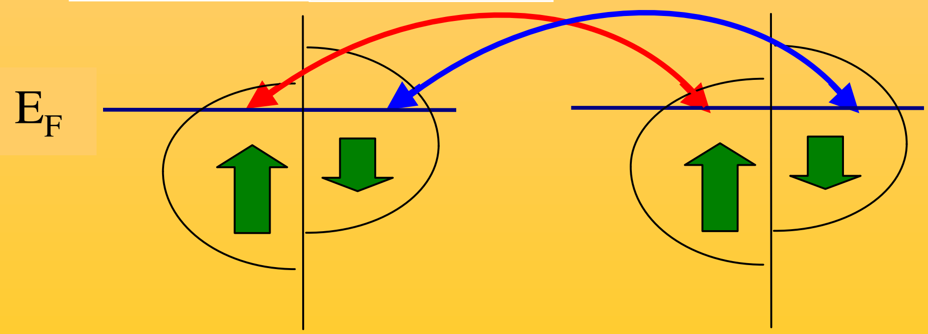
***IF THE SPIN IS CONSERVED*:**

Let $N(E_F)$= (1/2) * Total number of electrons at E_F

We define an effective spin polarization: $P=[N_\uparrow(E_F)-N_\downarrow(E_F)]/[N_\uparrow(E_F)+N_\downarrow(E_F)]$

PARALLEL MAGNETIC CONFIGURATION

MAJORITY	MINORITY

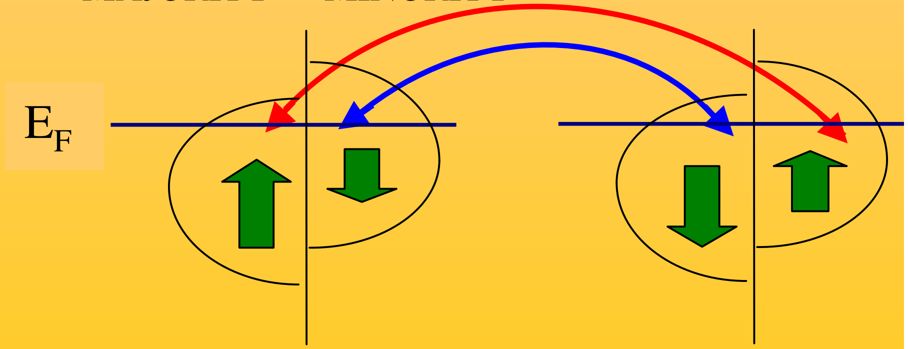


$I_P \,\alpha\, (1+P_1)(1+P_2) + (1-P_1)(1-P_2)$

$= 2(1+P_1P_2)$

ANTIPARALLEL MAGNETIC CONFIGURATION

MAJORITY MINORITY



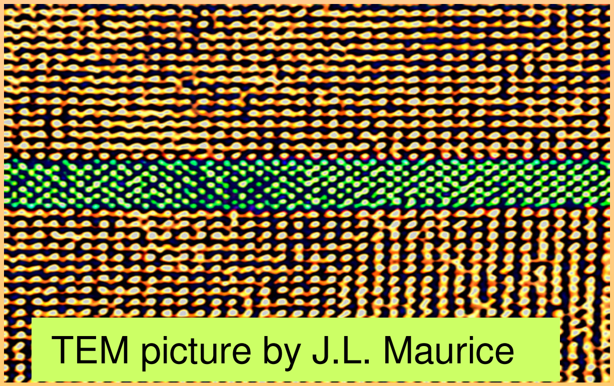
$I_{AP} \,\alpha\, (1+P_1)(1-P_2) + (1-P_1)(1+P_2)$

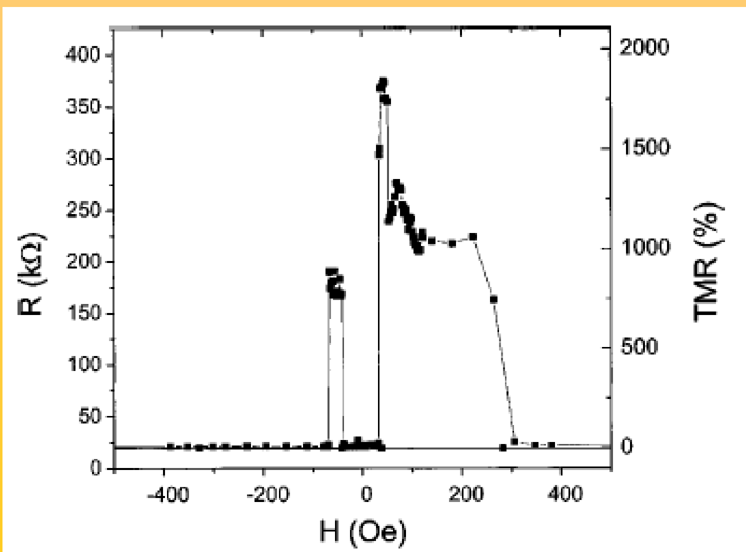
$= 2(1-P_1P_2)$

$\Rightarrow$ **$TMR=(R_{AP}-R_P)/R_{AP}=1-(I_{AP}/I_P)=2P_1P_2/(1+P_1P_2)$**

TMR: the use of half metals can give rise to huge TMR ratios

MANGANITE-based MTJs



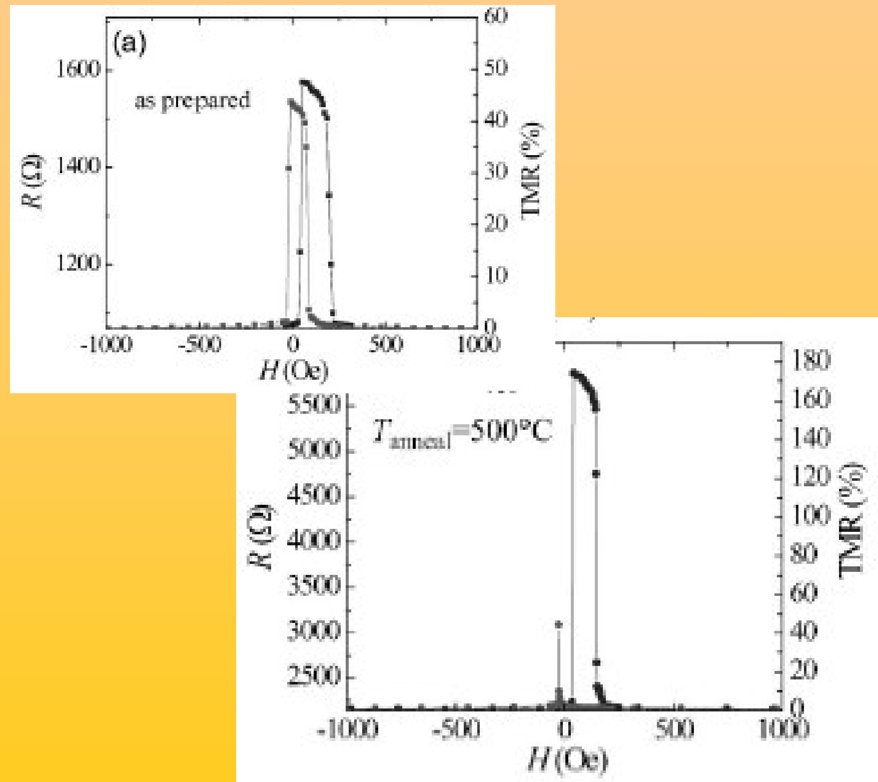


MR>1500% at 5K, which corresponds to P=0.95
(however,the MR vanishes at 300 K)

Bowen et al., Appl. Phys. Lett. 82, 233 (2003)

HEUSLER ALLOYS-based MTJs

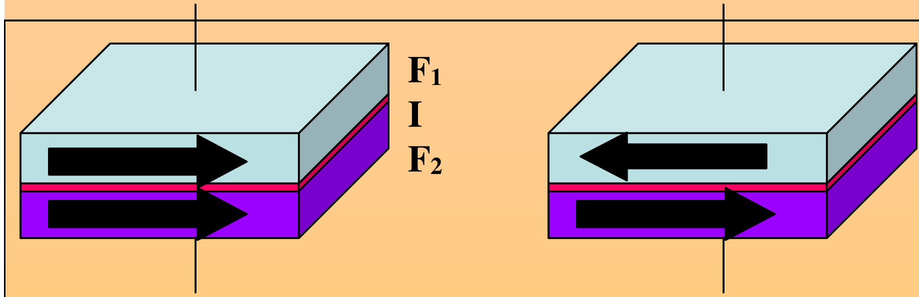
The MTJs with a stacking structure of $Co_2FeAl_{0.5}Si_{0.5}$ (30 nm)/MgO (t_{MgO} nm)/$Co_2FeAl_{0.5}Si_{0.5}$ (5 nm)/$Co_{75}Fe_{25}$ (3 nm)/$Ir_{22}Mn_{78}$ (15 nm)/capping layer (Ta) were fabricated on a Cr-buffered MgO(001) substrate. The films were pre-



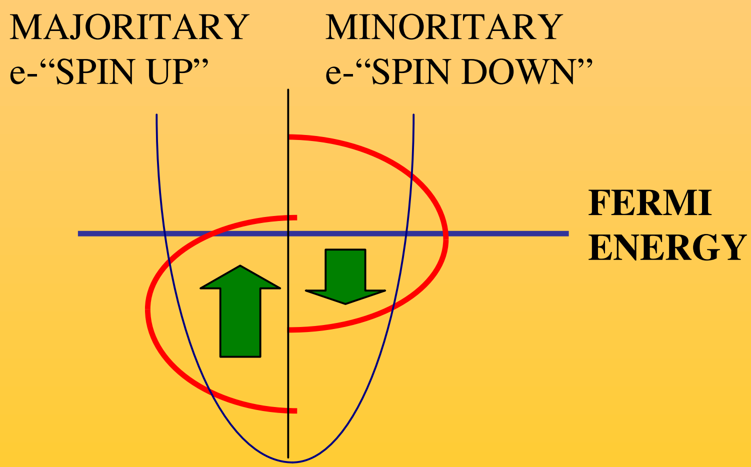
MR=175% at room temperature,
which corresponds to P=0.68

Tezuka et al., Appl. Phys. Lett. 89, 252508 (2006)

TMR: understanding the TMR effect



$$TMR\ (\%) = 200\ x \frac{P_1 P_2}{(1 + P_1 P_2)}$$ **JULLIERE'S MODEL)**



What P value is the right one to be included in Julliere's formula?

$$P = \frac{N(E_F)_\uparrow - N(E_F)_\downarrow}{N(E_F)_\uparrow + N(E_F)_\downarrow} ?$$

THE EXAMPLE OF COBALT

-**PHOTOEMISSION: INFORMATION ON**

$$P = \frac{N(E_F)_\uparrow - N(E_F)_\downarrow}{N(E_F)_\uparrow + N(E_F)_\downarrow}$$

P(Co)<0

-**TUNNEL JUNCTIONS F/I/S:**
INFORMATION ON P(Co) IN TUNNELLING

P(Co)>0 WITH Al_2O_3 BARRIER

[experiments carried out by Tedrow and Meservey: see review in Phys. Repts. 238 (1994) 173]

* ***"s-type" BANDS*** ⇒ lower density of states, positively polarized, more delocalized electrons

* ***"d-type" BANDS*** ⇒ higher density of states, negatively polarized, more localized electrons

Cluj school, September 2007

TMR: understanding the TMR effect

DESIGNED EXPERIMENT: $La_{0.7}Sr_{0.3}MnO_3$/ I /Co (I=$SrTiO_3$, Al_2O_3, CeO_2)

(experiments performed in Orsay with A. Fert's Group)

The experiment aims at probing the spin polarization of Co when using different barriers in tunnel junctions, which can be related to the preferential tunnelling of "s-type" or "d-type" electrons from Co.

$$100 * \frac{(R_{AP} - R_P)}{R_P} = TMR(\%) = 200x \frac{P_1 P_2}{(1 + P_1 P_2)}$$

* P ($La_{0.7}Sr_{0.3}MnO_3$) ≈ +100%
* P (Co) = ?

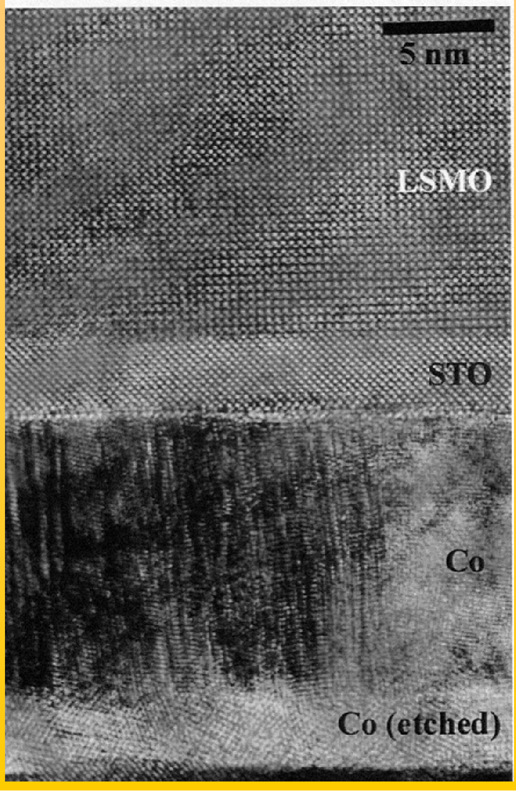
If P(Co) > 0 ⇒ TMR(%) >0

If P(Co) < 0 ⇒ TMR(%) <0

$La_{0.7}Sr_{0.3}MnO_3$

$SrTiO_3$

Co

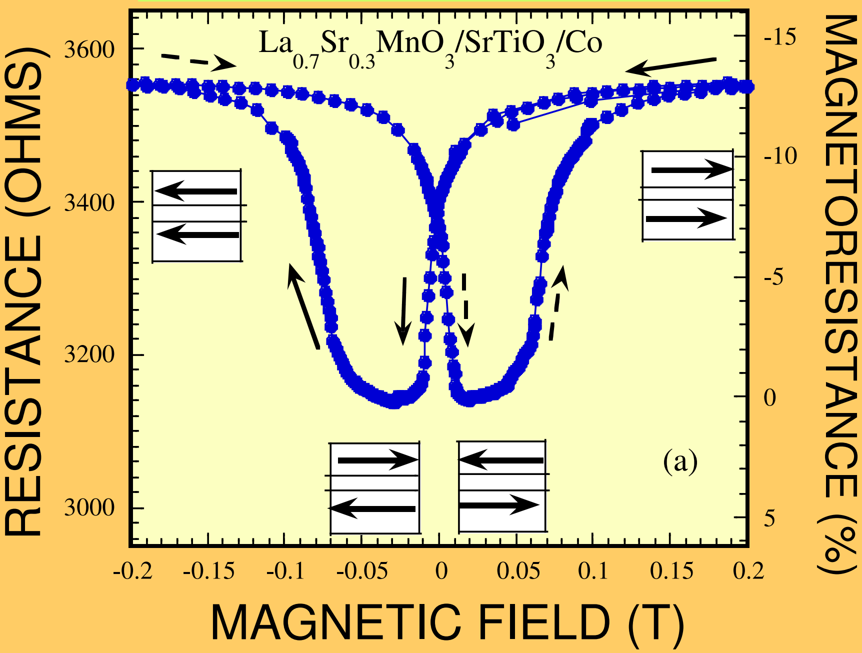


TEM IMAGE BY J.L. MAURICE

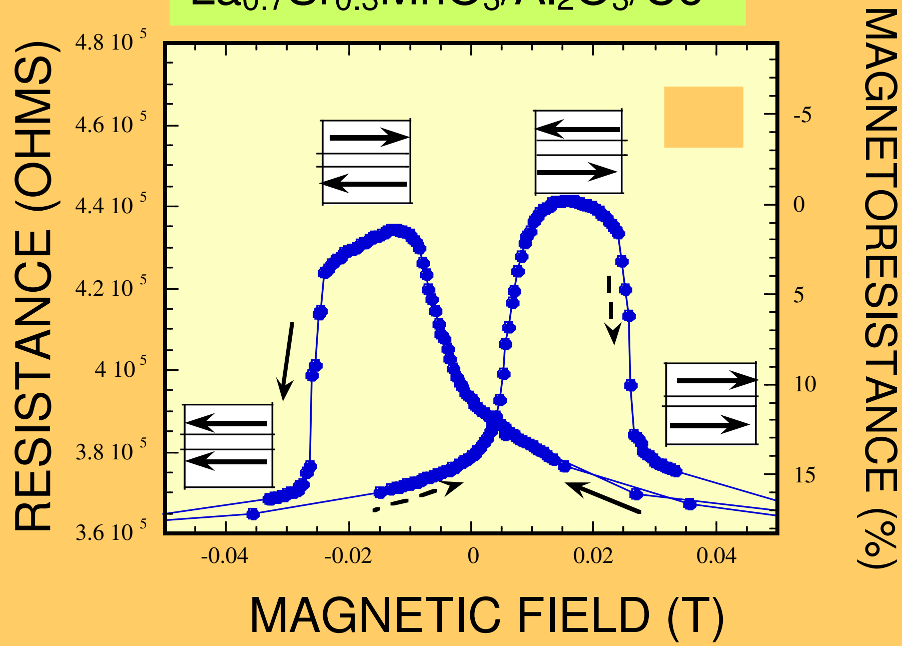
Cluj school, September 2007

TMR: understanding the TMR effect

$La_{0.7}Sr_{0.3}MnO_3/SrTiO_3/Co$



$La_{0.7}Sr_{0.3}MnO_3/Al_2O_3/Co$



INVERSE TMR

$R_{AP}<R_P$

P(Co) IS NEGATIVE

NORMAL TMR

$R_P<R_{AP}$

P(Co) IS POSITIVE

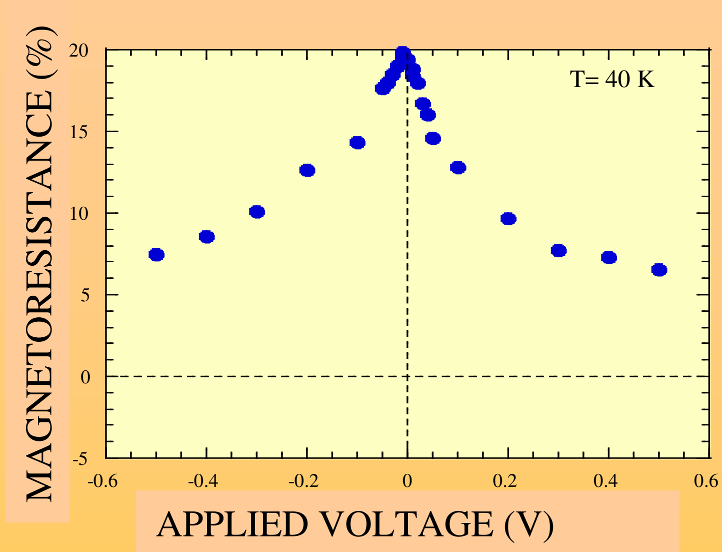
$$\mathbf{TMR \propto P_{(LSMO)}P_{(Co)}/[1+P_{(LSMO)}P_{(Co)}]; \quad with\ P_{(LSMO)} > 0}$$

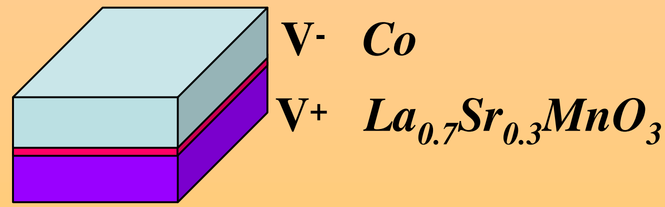
J.M. De Teresa et al., Phys. Rev. Lett. 82 (1999) 4288; J.M. De Teresa et al., Science 286 (1999) 507; Hayakawa et al., J. Appl. Phys. 91 (2002) 8792; Hayakawa et al., Jpn J. Appl. Phys. 41 (2002) 1340

Cluj school, September 2007

TMR: understanding the TMR effect

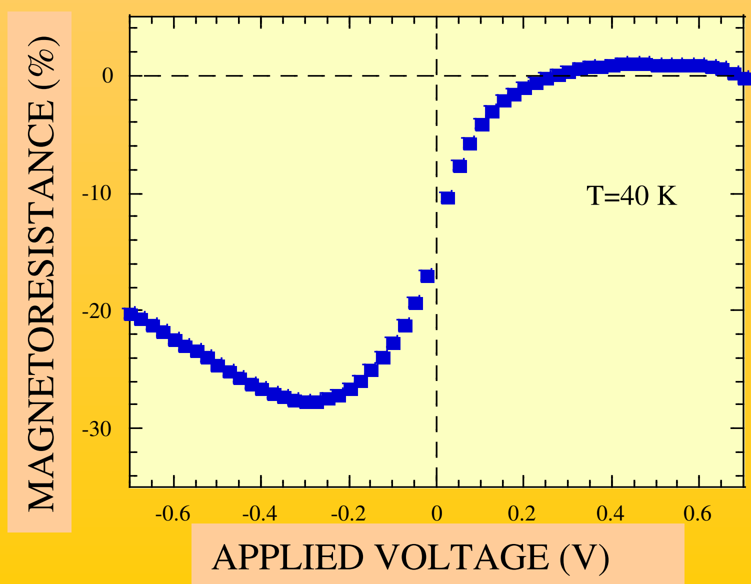
DEPENDENCE OF THE TUNNEL MAGNETORESISTANCE WITH VOLTAGE

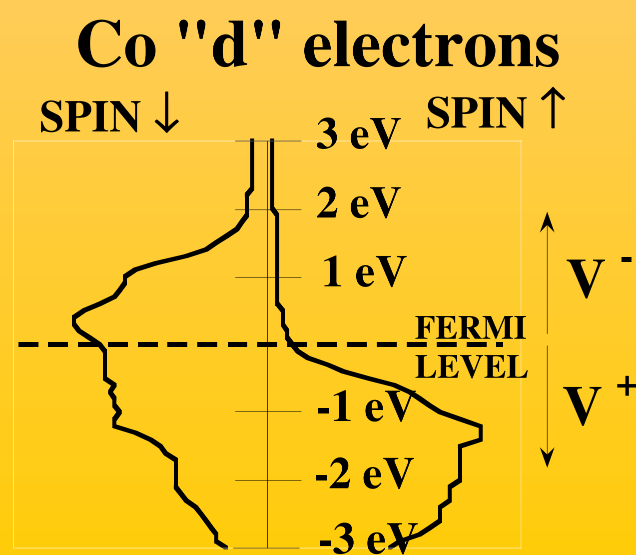




I= Al_2O_3: CURRENT BY "s-type" ELECTRONS

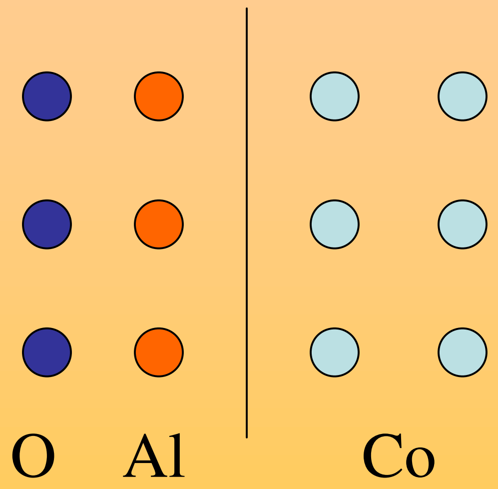
I= $SrTiO_3$: CURRENT BY "d-type" ELECTRONS





TMR: understanding the TMR effect

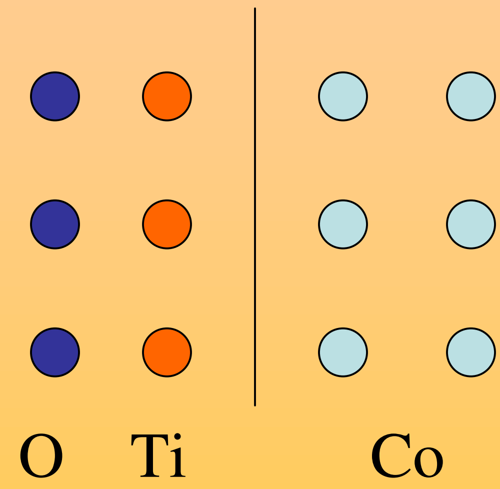
Al_2O_3/Co INTERFACE



sp-d BONDING

Selection of "s" electrons

$SrTiO_3$/Co INTERFACE



d-d BONDING

Selection of "d" electrons

THE INTERFACE CONTROLS THE STARTING POINT OF THE EVANESCENT WAVE IN THE BARRIER

(related theoretical articles supporting these experiments: Tsymbal et al., J. Phys. Condens. Matter. 9 (1997) L411; Stoeffler, J. Phys. Condens. Matter. 16 (2004) 1603; Oleinik et al., Phys. Rev. B 65 (2002) 020401; Velev et al., Phys. Rev. Lett. 95 (2005) 216601)

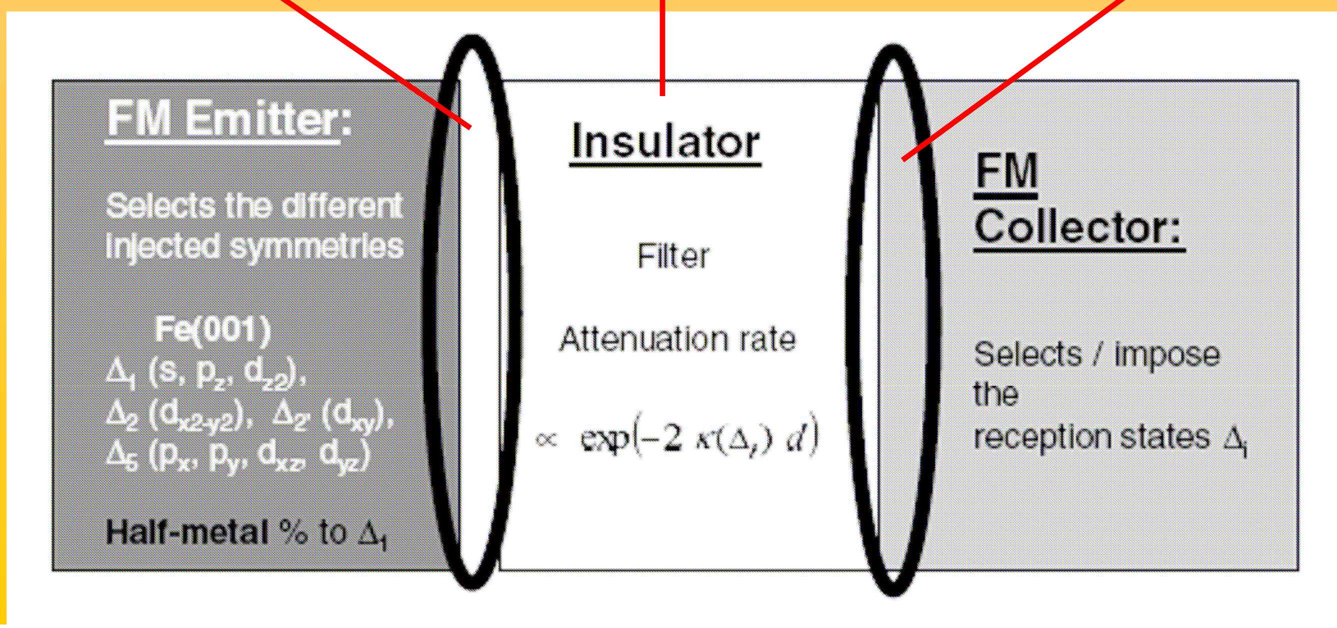
TMR: understanding the TMR effect

EXPERIMENTAL AND THEORETICAL STUDIES PERFORMED IN THE LAST YEARS INDICATE THAT RELIABLE CALCULATIONS OF THE TMR IN TUNNEL JUNCTIONS MUST TAKE INTO ACCOUNT:

-BAND STRUCTURE OF THE FERROMAGNET+INTERFACIAL RESONANT STATES (THEY CAN DEPEND ON BONDING)

-BAND STRUCTURE OF THE INSULATOR +TRANSMISSION OF THE TUNNELLING ELECTRONS

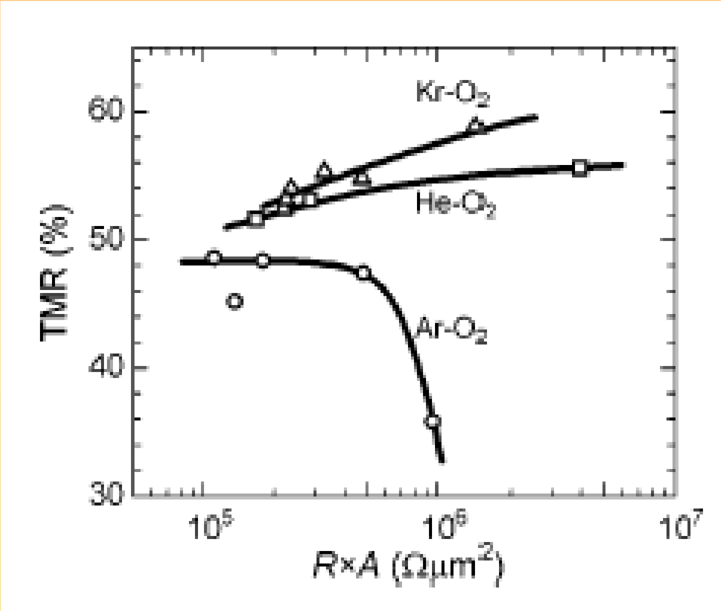
-BAND STRUCTURE OF THE FERROMAGNET+INTERFACIAL RESONANT STATES (THEY CAN DEPEND ON BONDING)



Cluj school, September 2007

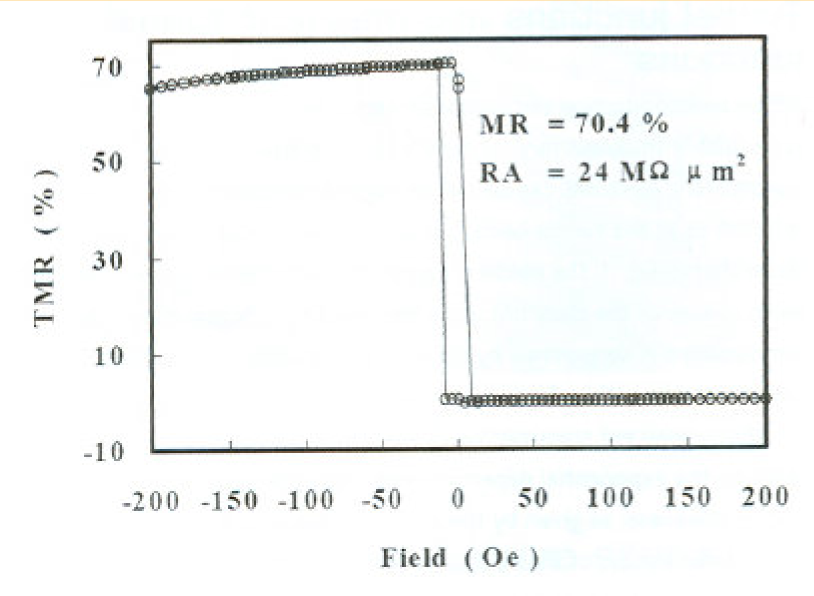
TMR: MR limitation (~70%) in Al_2O_3-based magnetic tunnel junctions

Optimization of the Al plasma-oxidation



Tsunoda et al., Appl. Phys. Lett. 17 (2002) 3135

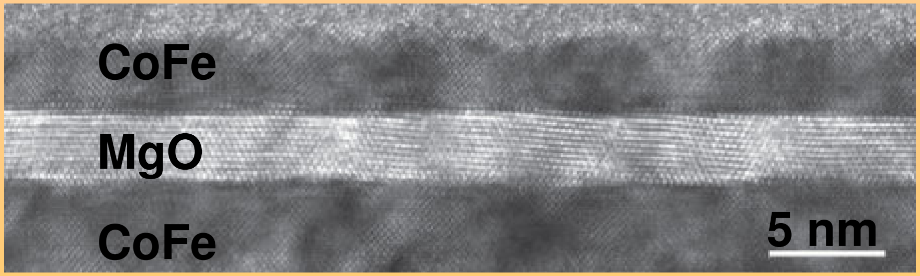
Use of CoFeB electrodes

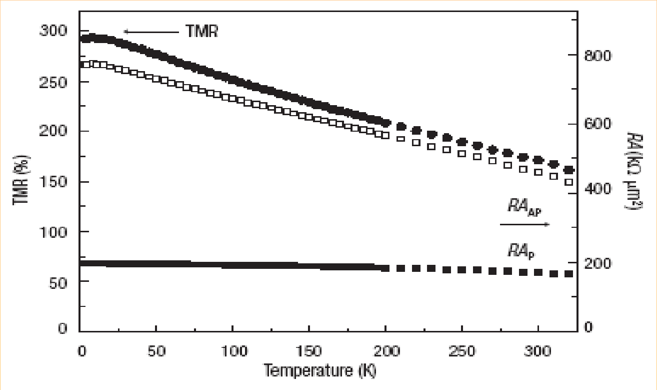


Wang et al., IEEE Trans. Magn. 40 (2004) 2269

TMR: MgO-based sputtered magnetic tunnel junctions

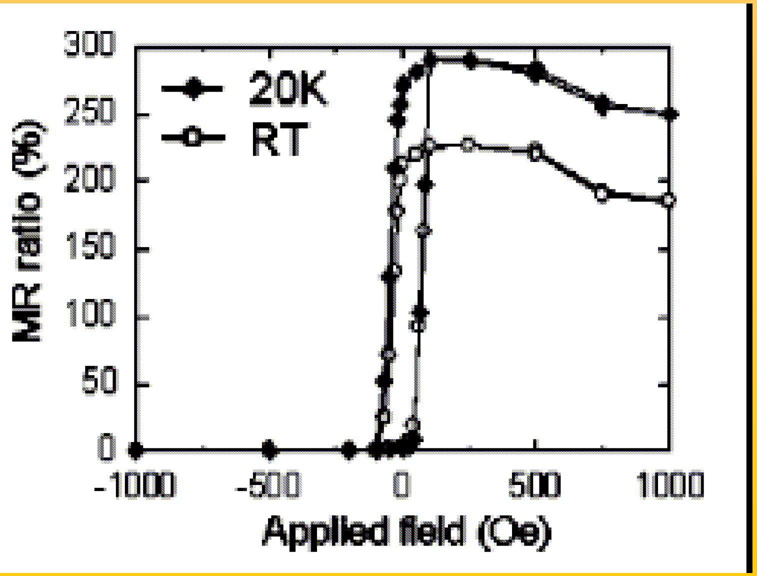
CoFe/MgO/CoFe, TMR= 150% at RT

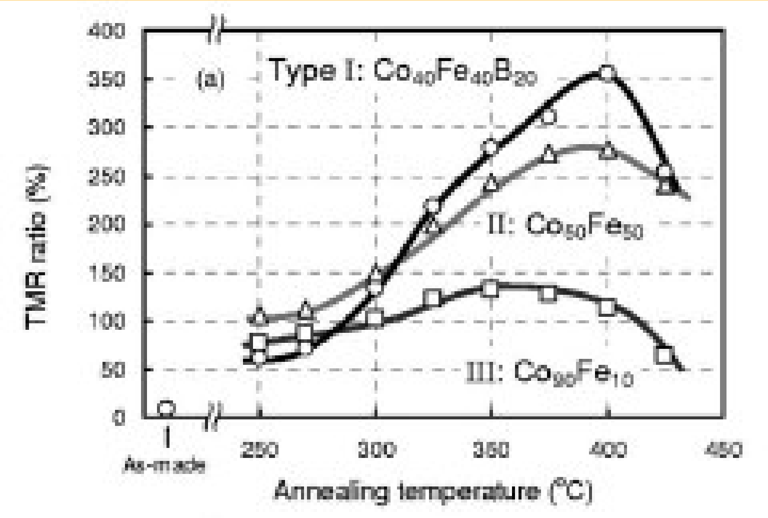




S.S.P. Parkin et al., Nature materials 3 (2004) 862

CoFeB/MgO/CoFeB, TMR= 355% at RT





Djayaprawira et al., Appl. Phys. Lett. 86 (2005) 092502

Ikeda et al., J. Appl. Phys. 99 (2006) 08A907

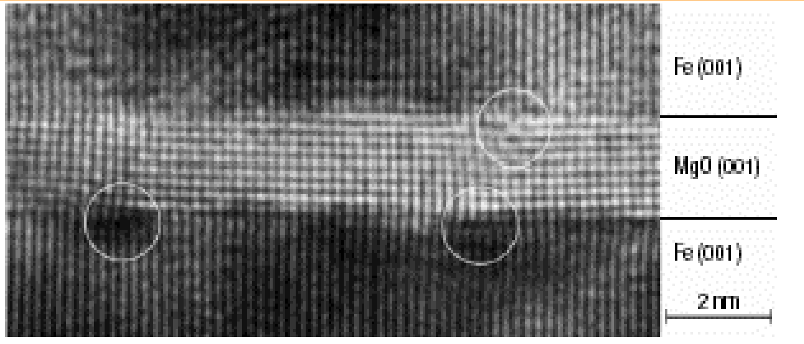
Universidad de Zaragoza

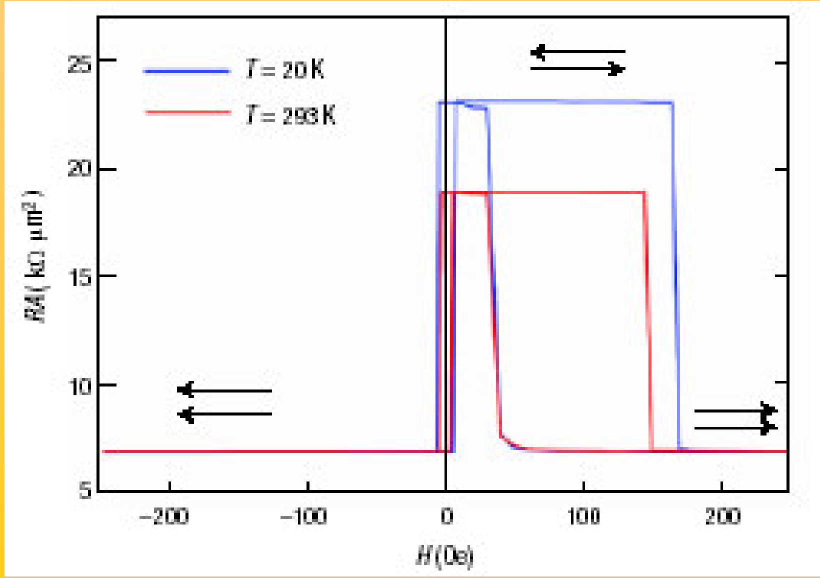
Cluj school, September 2007

CSIC

TMR: MgO-based MBE-grown single-crystal magnetic tunnel junctions

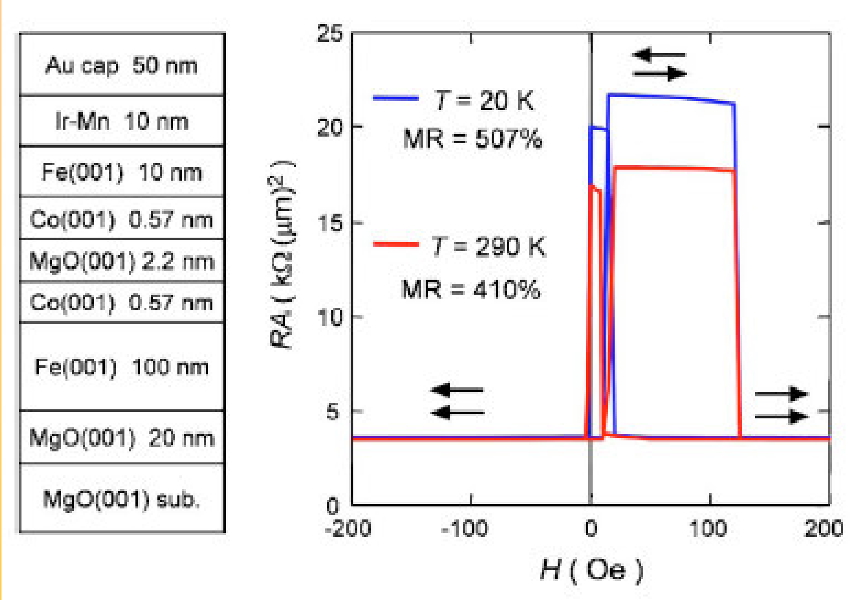
Fe/MgO/Fe, TMR= 200% at RT





Yuasa et al., Nature materials 3 (2004) 868

Co/MgO/Co, TMR= 410% at RT

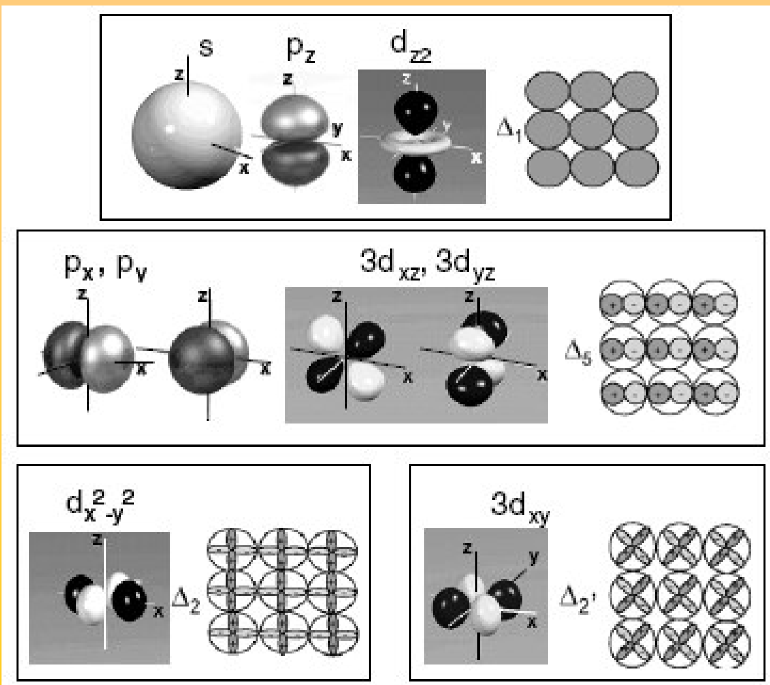


[Yuasa et al., Appl. Phys. Lett. 89 (2006) 042505]

Theoretical explanations to the TMR properties of MgO-based MTJs

***General considerations: mutilchannel conductance with conservation of spin and symmetry**

$$\Psi_{nk_i^\sigma}(r) = u_{nk_i^\sigma}(r)\exp(ik_i^\sigma r)$$

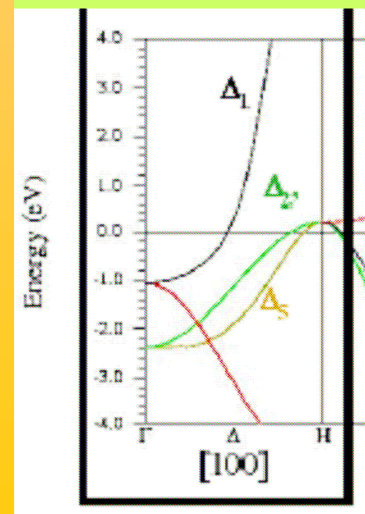


$$T \sim \exp(-2\kappa^\sigma d).$$

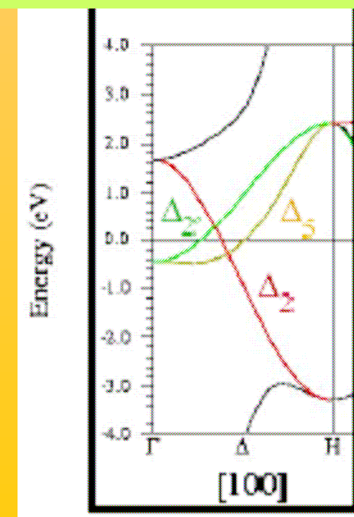
$$\kappa^\sigma = \sqrt{\frac{2m_\sigma}{\hbar^2}(V_B - E) + k_\parallel^{\sigma 2}}$$

$$\kappa_{\Delta_1} < \kappa_{\Delta_5} < \kappa_{\Delta_{2,2'}}$$

Fe, SPIN UP



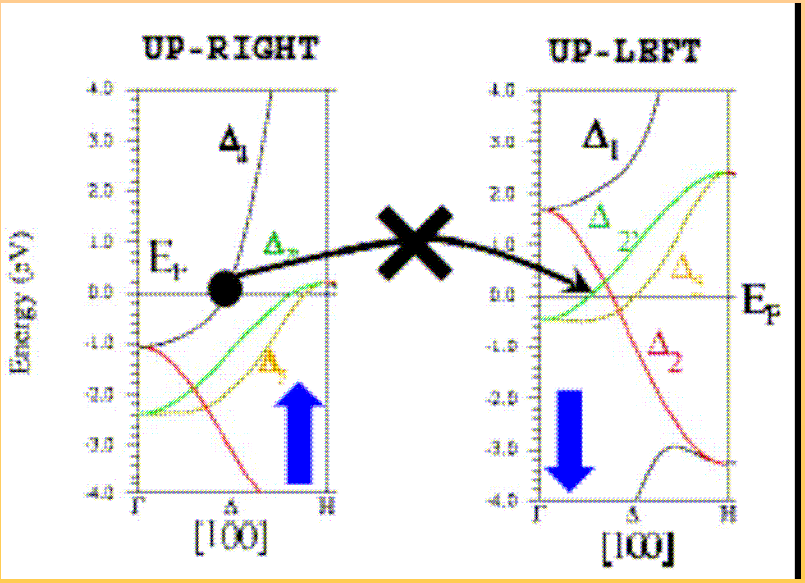
Fe, SPIN DOWN



<u>Review article</u>: *Tiusan et al., J. Phys.: Condens. Matter 19 (2007) 165201*

Theoretical explanations to the TMR properties of MgO-based MTJs

***Fe, Large MgO barrier thickness (only $k_{//}=0$ electrons tunnel efficiently)**



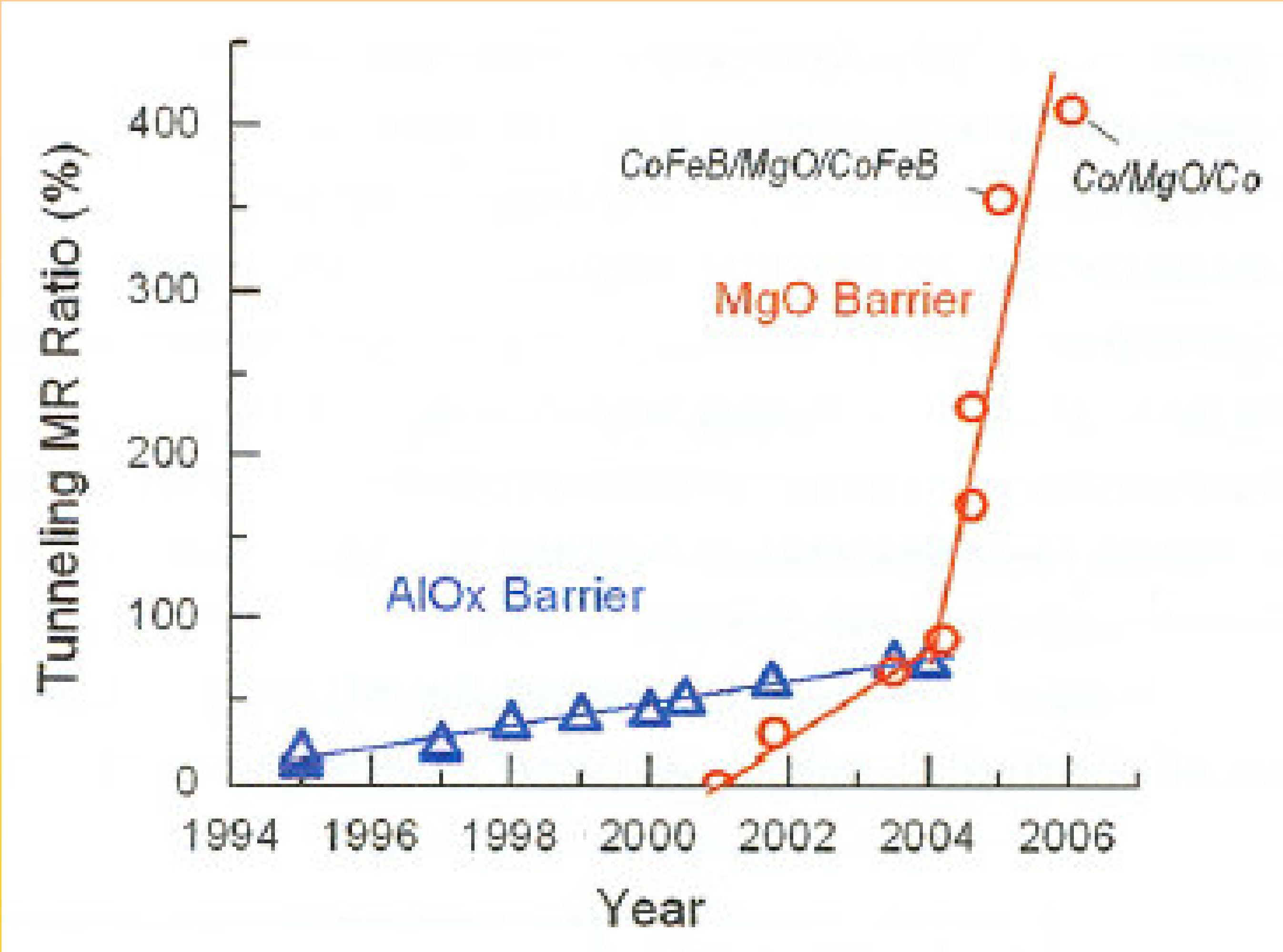
The most efficient conduction channel is through electrons arising from the band with Δ_1 symmetry, which is not available in the antiparallel magnetic configuration, giving rise to a high resistance state.

***Fe, Small MgO barrier thickness ($k_{//}\neq 0$ electrons and interfacial states important)**

Electrons arising from bands with Δ_2 and Δ_5 symmetry also contribute to the conductance as well as the Fe(100) surface state in the AP state, with Δ_1 symmetry. All this reduces the TMR at low MgO thickness.

***bcc Co: only the band with Δ_1 symmetry is present at the E_F in the spin-up subband, which implies negligible conductance in the AP configuration**

Summary of TMR record values in magnetic tunnel junctions

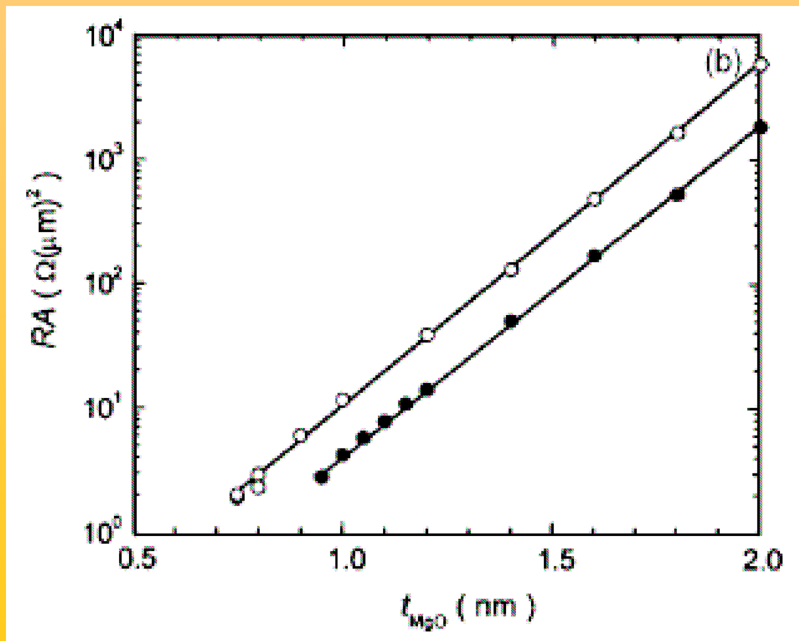


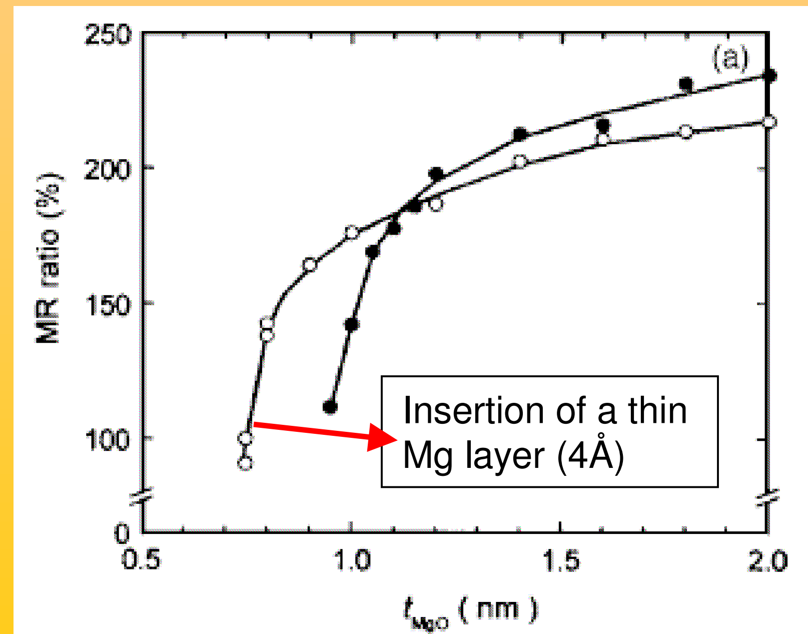
[Zhu and Park, Materials Today 9 (2006) 36]

Characteristics of magnetic tunnel junctions for real applications

In order to get a high operating frequency and low noise, the resistance-area product should be lower than 4 $\Omega\mu m^2$

Giant tunneling magnetoresistance effect in low-resistance CoFeB/MgO(001)/CoFeB magnetic tunnel junctions for read-head applications

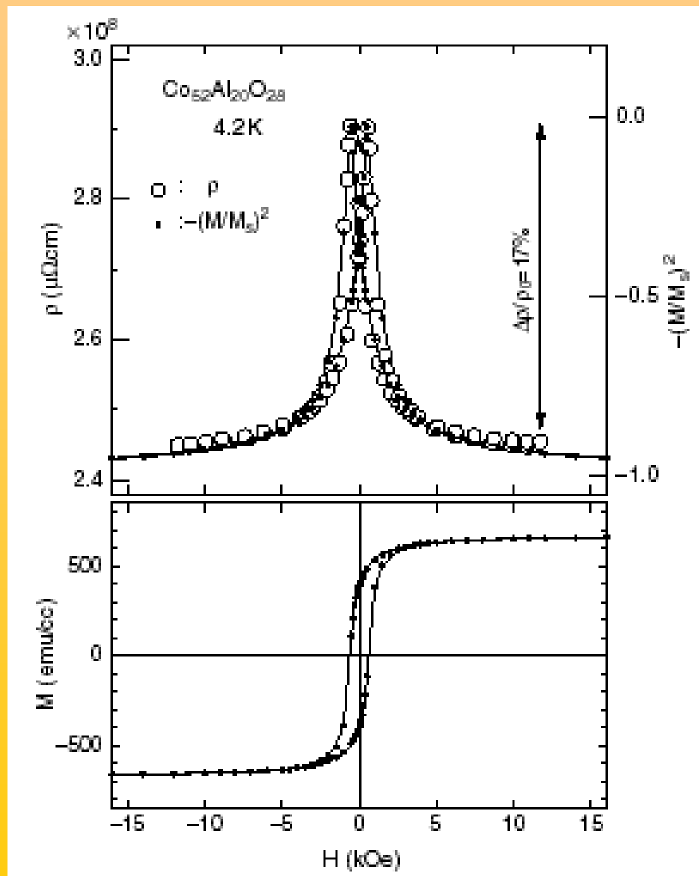


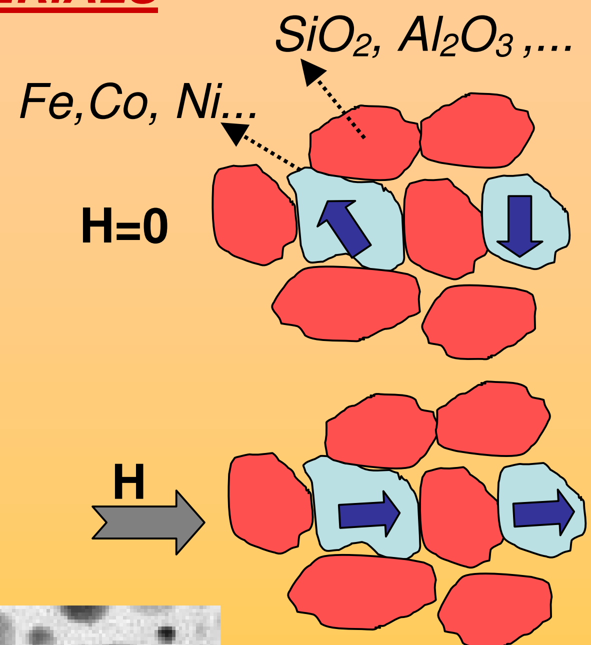


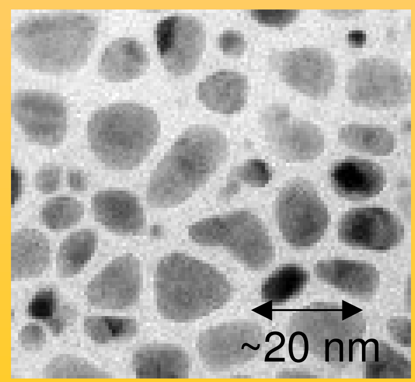
Tsunekawa et al., Appl. Phys. Lett. 87, 072503 (2005)

TUNNEL MR (TMR) IN GRANULAR MATERIALS

-The TMR effect can be realized in granular materials / thin films with immiscible magnetic metals / insulators due to the same physical phenomena.







Co in Zr_2O_3 matrix

Gittleman et al., Phys. Rev. 5 (1972) 3609; Helman and Abeles, Phys. Rev. Lett. 37 (1976) 1429;Inoue and Maekawa, Phys. Rev. B 53 (1996) R11927; Mitani et al., J. Magn. Mater. 165 (1997) 141; Batlle and Labarta, J. Phys. D: Appl. Phys. 35 (2002) R15

OTHER MAGNETORESISTIVE EFFECTS

MAGNETOTRANSPORT IN NANOCONSTRICTIONS (I)

-Transport is said to take place in a "nanoconstriction" or "point contact" if the electron mean free path, mfp ~ constriction size, d

-If the inelastic mfp > constriction size ⇒ we have "diffusive" conduction

-If the elastic and inelastic mfp > constriction size ⇒ we have "ballistic" conduction

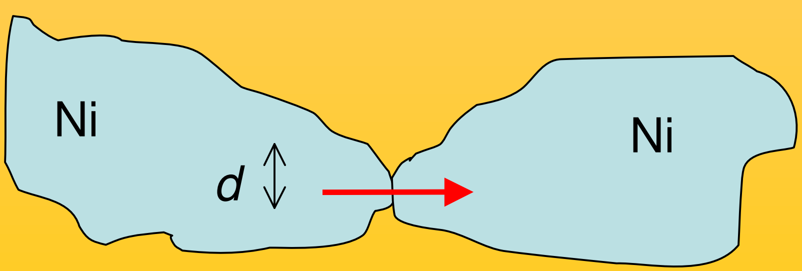
-If the Fermi length of the electrons ~ constriction size ⇒ we have "quantum" conduction

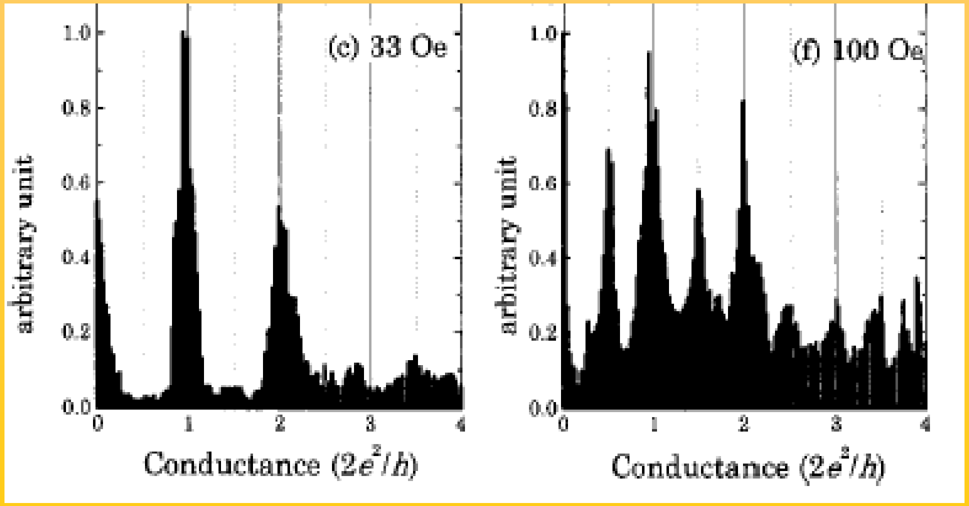
Quantum of conductance $2e^2/h = 1/(12.9\ \text{Kohm})$

$$G = \frac{e^2}{h} \sum_{i,\sigma} \mathcal{T}_{i,\sigma}$$

Wees et al., Phys. Rev. Lett. 60 (1988) 848

*See the following reviews: Halbritter et al., Adv. Phys. 53 (2004) 939; Agraït et al., Phys. Rep. 377 (2003) 81



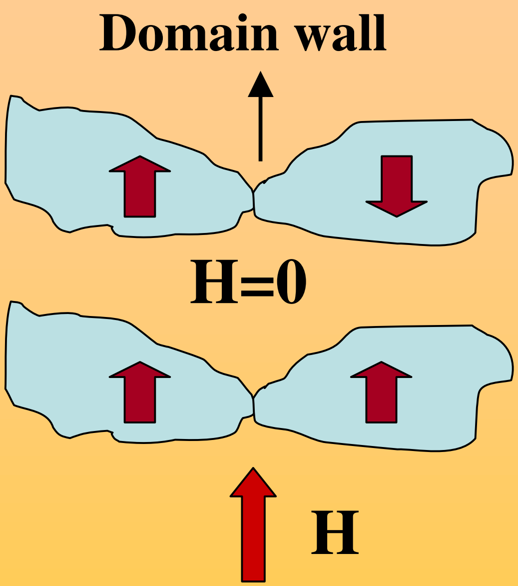


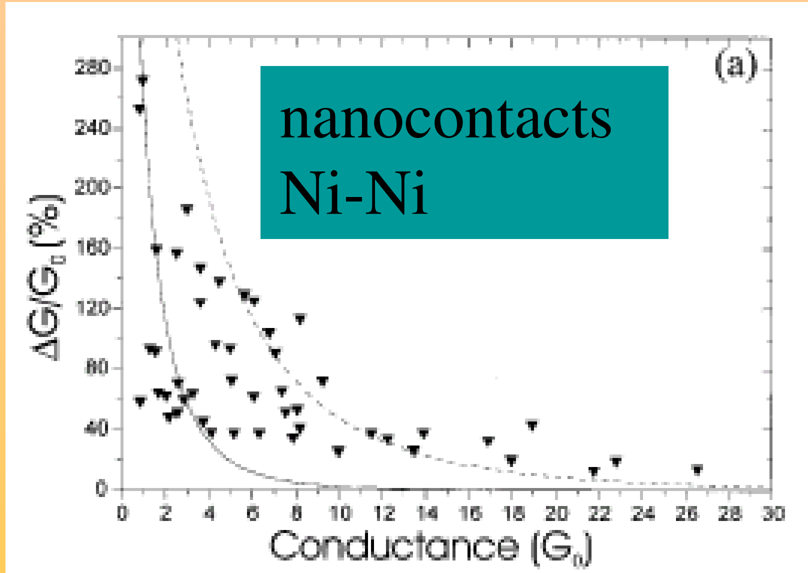
Ono et al., Appl. Phys. Lett. 75, 1622 (1999)

Cluj school, September 2007

MAGNETOTRANSPORT IN NANOCONSTRICTIONS (II)

**IS BALLISTIC MAGNETORESISTANCE (BMR) HUGE?... UNDER DISCUSSION*

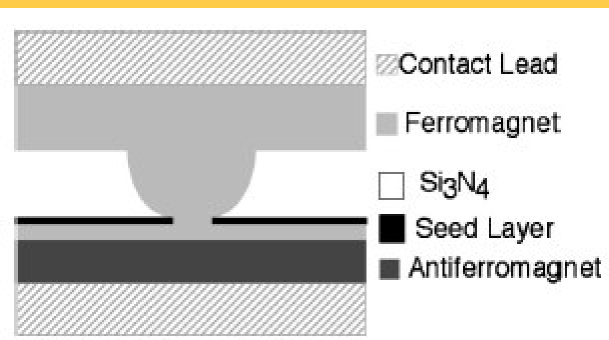


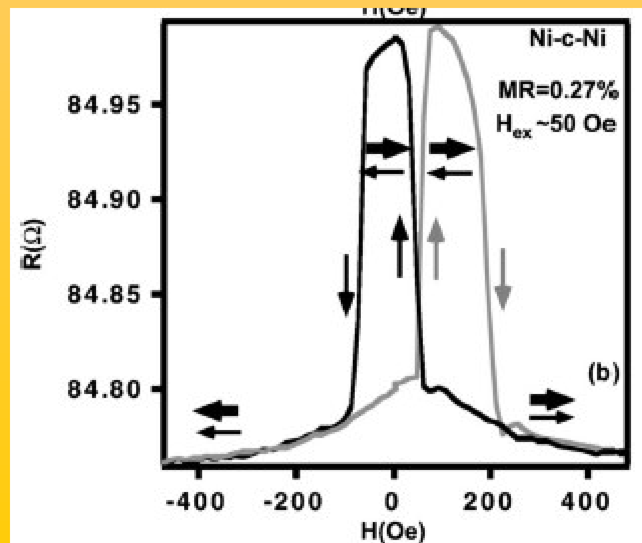


supporters

N.GARCÍA: SEE TATARA ET AL., PHYS. REV. LETT. 83 (1999) 2030

H. CHOPRA: SEE SULLIVAN ET AL., PHYS. REV. B 71 (2005) 024412





detractors

EGELHOFF: SEE EGELHOFF ET AL., J. APP. PHYS. 95 (2004) 7554

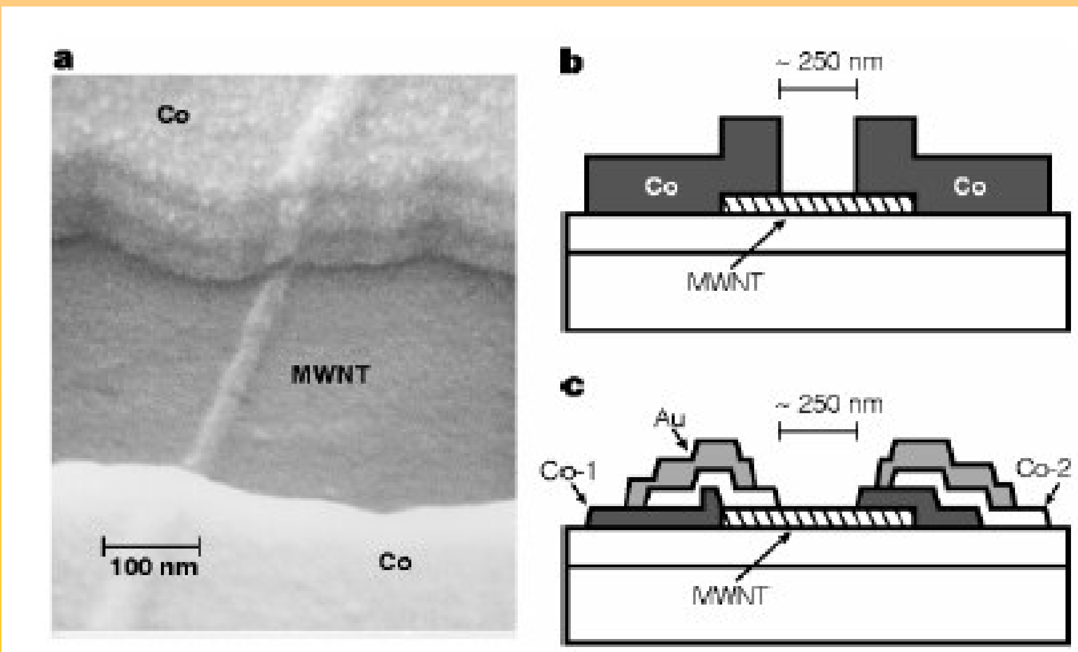
I. SCHULLER: SEE MONTERO ET AL., PHYS. REV. B 70 (2004) 184418

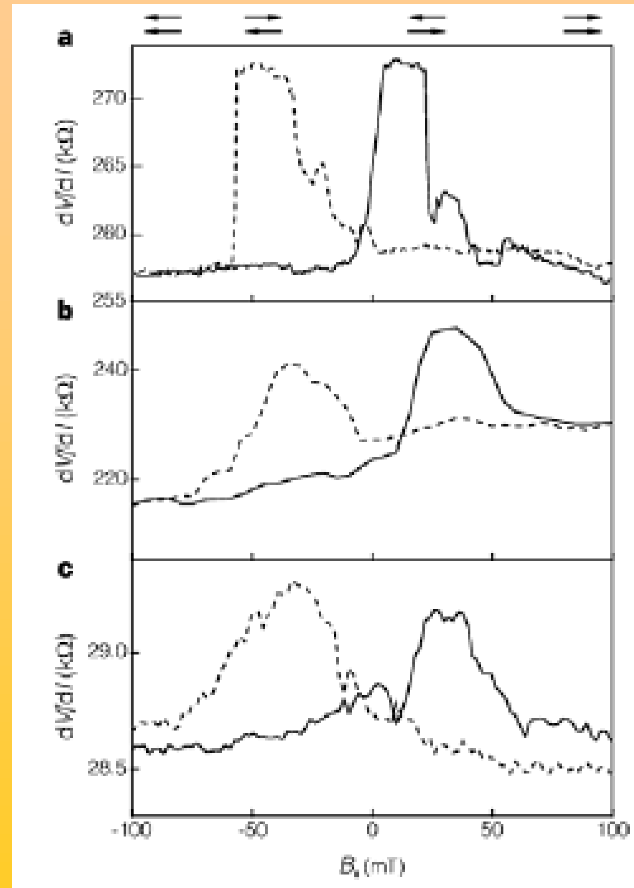
R. BUHRMAN: SEE OZATAY ET AL., J. APP. PHYS. 95 (2004) 7315

M. VIRET: SEE GABUREAC ET AL., PHYS. REV. B 69 (2004) 100401

MAGNETOTRANSPORT WITH CARBON NANOTUBES (I)

⇒ *One of the first results showing that it is possible to keep the spin information along relatively long distances through carbon nanotubes*

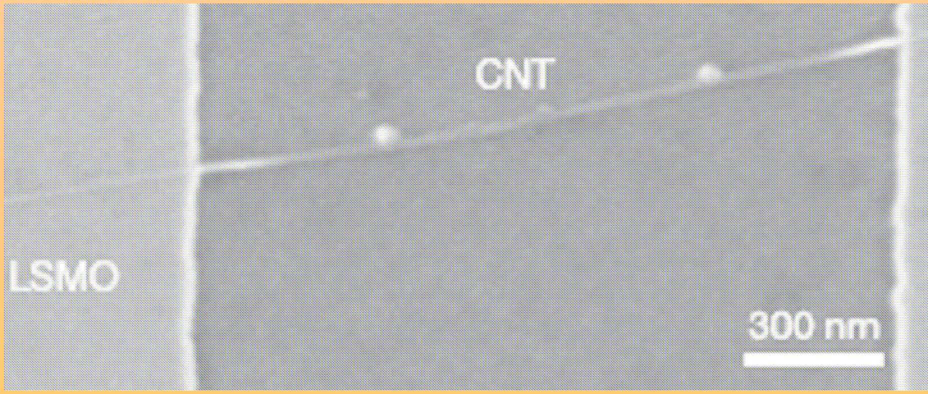




Tsukagoshi et al., Nature 401, 572 (1999)

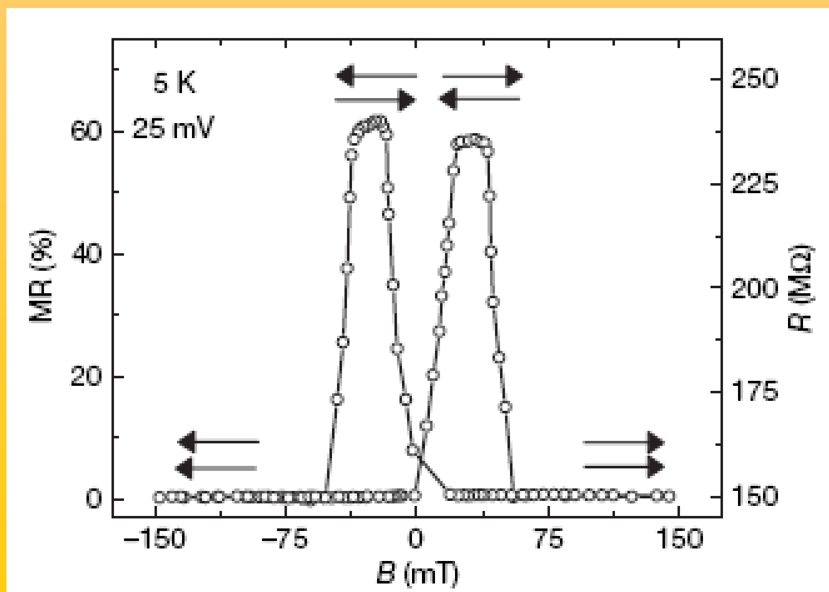
Cluj school, September 2007

MAGNETOTRANSPORT WITH CARBON NANOTUBES (II)



Transformation of spin information into large electrical signals using carbon nanotubes

Hueso et al., Nature 445, 410 (2007)



$$\mathrm{MR} = \frac{\Delta R}{R_{\mathrm{P}}} \equiv \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}} \equiv \frac{\gamma^2/(1-\gamma^2)}{1+\tau_{\mathrm{n}}/\tau_{\mathrm{sf}}}$$

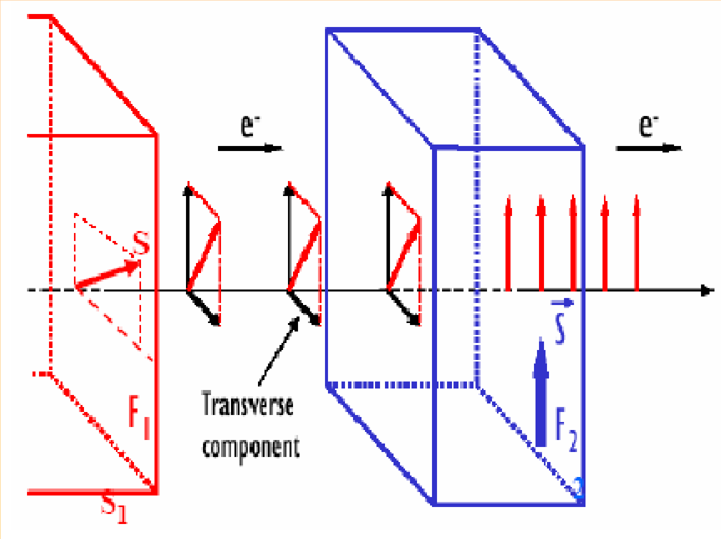
γ= spin polarizazion of the electrons transmitted at the interface

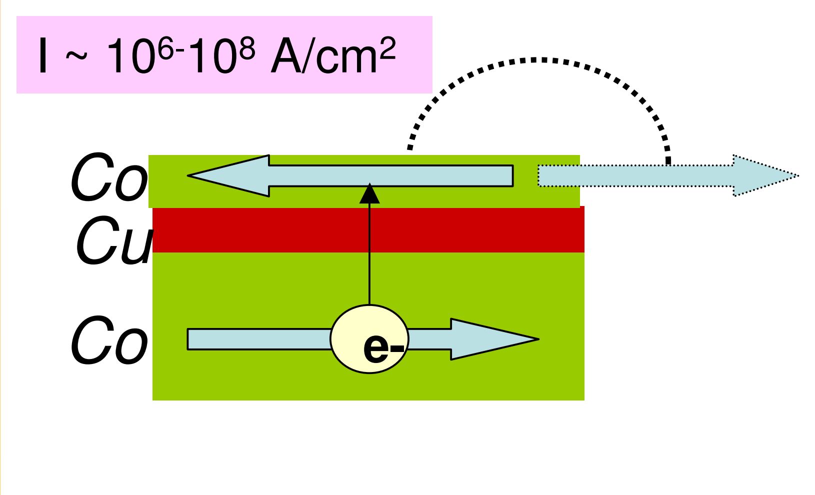
τ_n=dwell time of the electrons in the carbon nanotube

τ_{sf}= spin lifetime in the carbon nanotube

Cluj school, September 2007

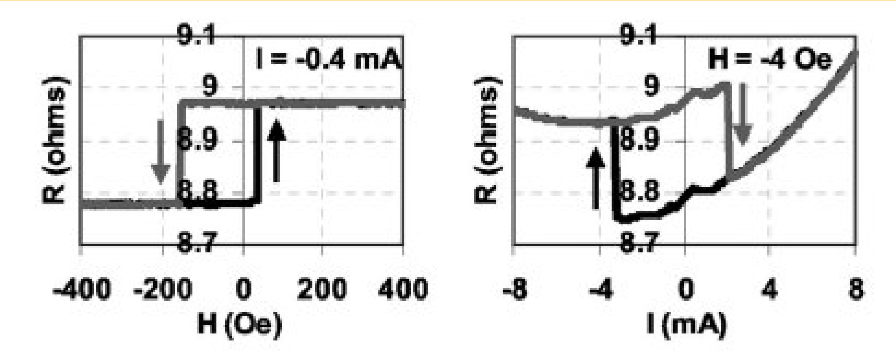
SPIN TRANSFER (current-driven magnetization reversal)





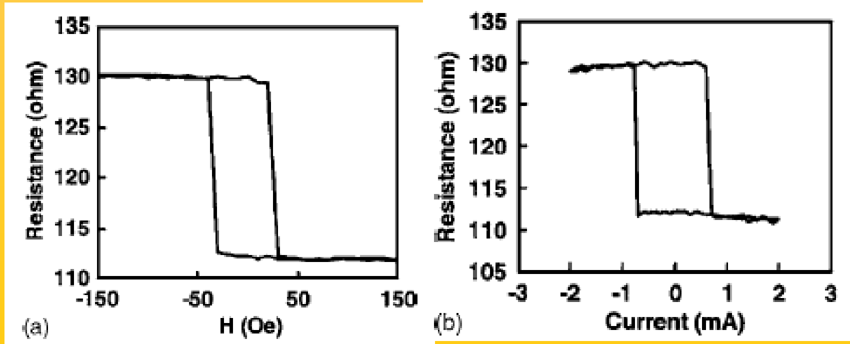
*THE MAGNETIZATION STATE AFFECTS THE CURRENT (GMR, TMR,...). CORRESPONDINGLY, THE CURRRENT CAN AFFECT THE MAGNETIZATION STATE

IN HETEROSTRUCTURES WITH GMR



Deac et al., Phys. Rev. B 73 (2006) 064414

IN HETEROSTRUCTURES WITH TMR



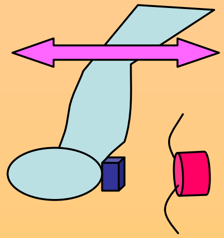
Meng et al., Appl. Phys. Lett. 88 (2006) 082504

APPLICATIONS OF MAGNETORESISTIVE DEVICES

MORE INFORMATION IN THE LESSON ON "MAGNETIC SENSORS AND ACTUATORS" (THIS AFTERNOON)

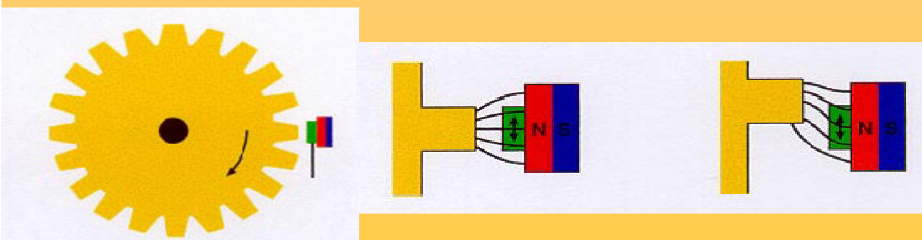
OVERVIEW OF THE APPLICATION OF MR DEVICES FOR SENSING

AUTOMOTIVE INDUSTRY:
Example: tracking the pedals positions

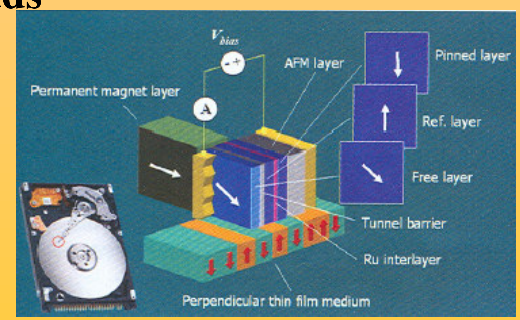



AERONAUTICS:
Example: measuring the earth's magnetic field

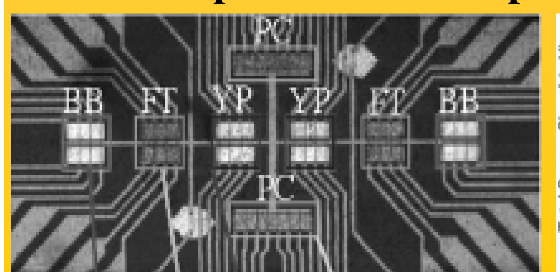
MANUFACTURING INDUSTRY:
Example: measuring the rotation velocity

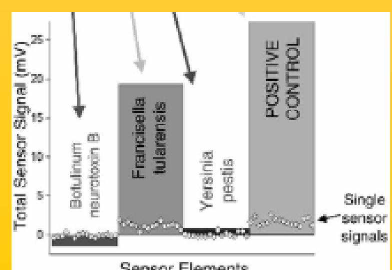


MAGNETIC STORAGE INDUSTRY:
Example: read heads

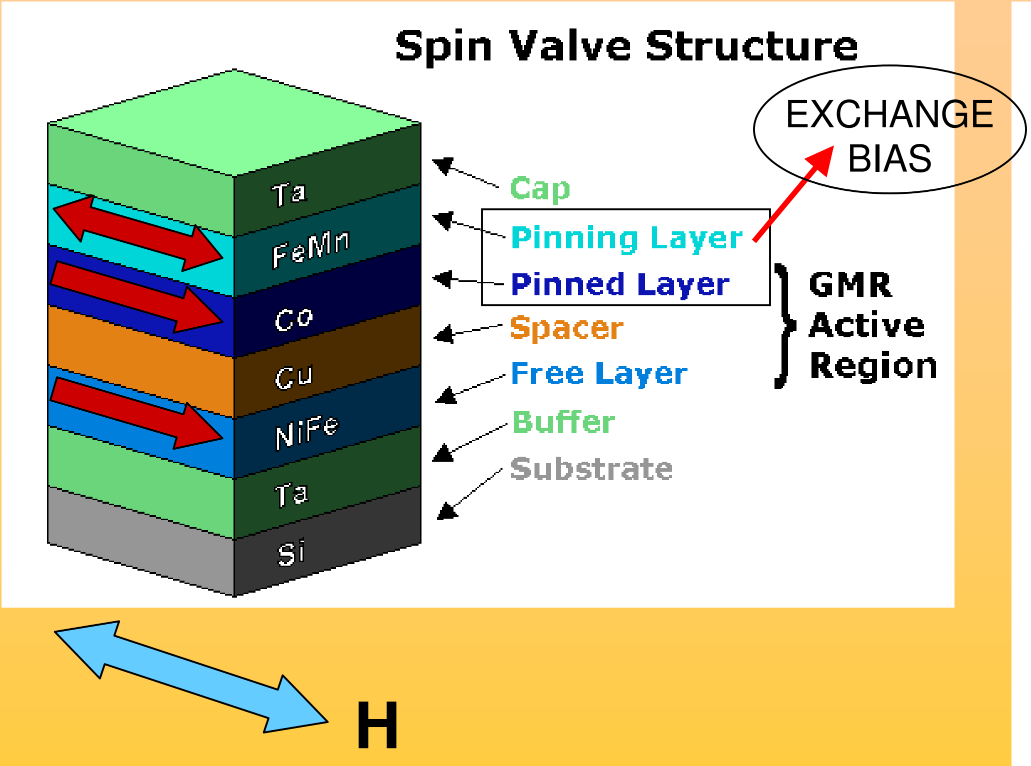
BIOSENSORS:
Example: DNA biochips

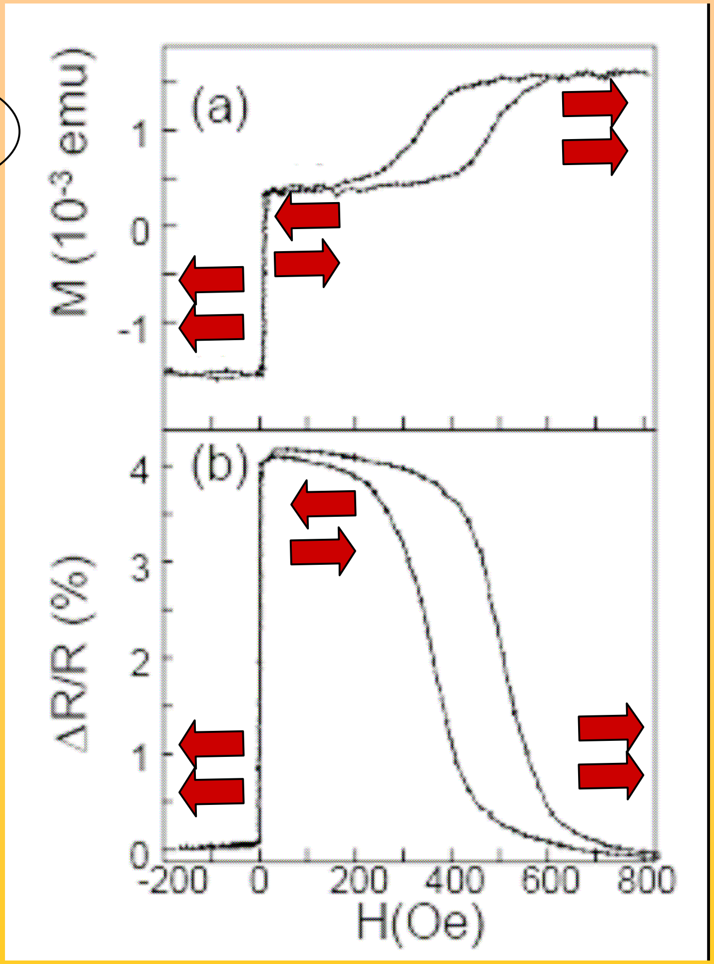




HUMAN ELECTROMAGNETIC ACTIVITY:
Example: brain/heart electromagnetic fields

GMR AND TMR: THE SPIN-VALVE CONFIGURATION



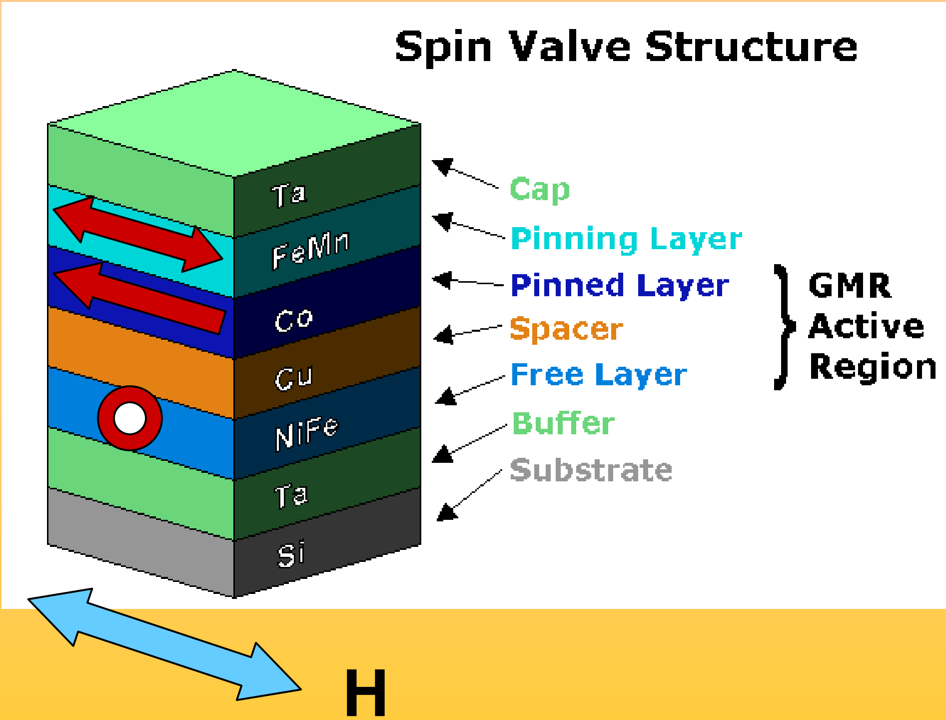


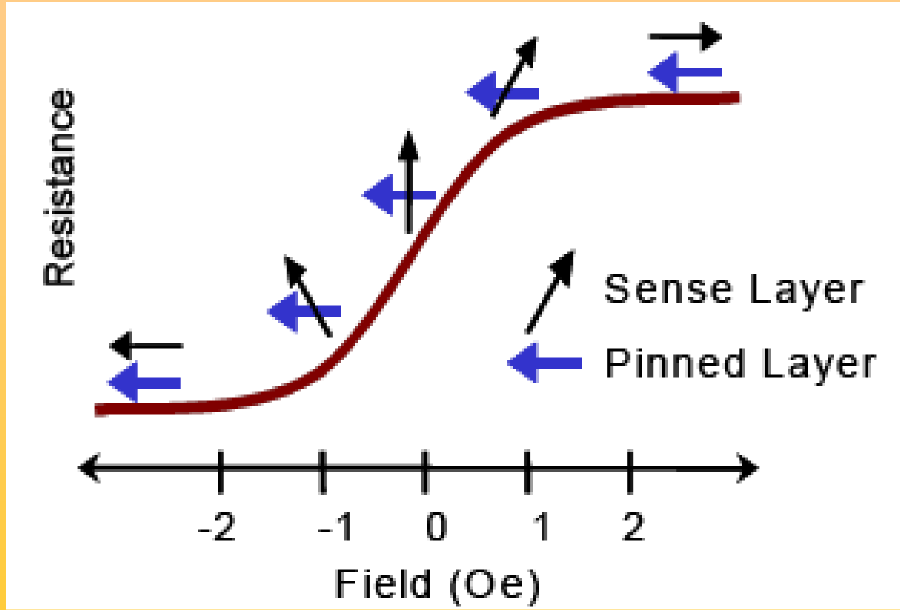
B. Dieny et al., J. Appl. Phys. 69 (1991) 4774

⇒THIS CONCEPT IS VERY USEFUL FOR APPLICATIONS DUE TO THE LOW FIELD REQUIRED TO GET A SIGNIFICANT MR RESPONSE BUT THE AMPLITUDE OF THE EFFECT IS SIGNIFICANTLY REDUCED

The spin-valve concept has also been applied to TMR-based devices

GMR AND TMR: CROSSED GEOMETRY OF THE EASY DIRECTIONS OF ELECTRODES FOR LINEAR RESPONSE AT LOW FIELDS



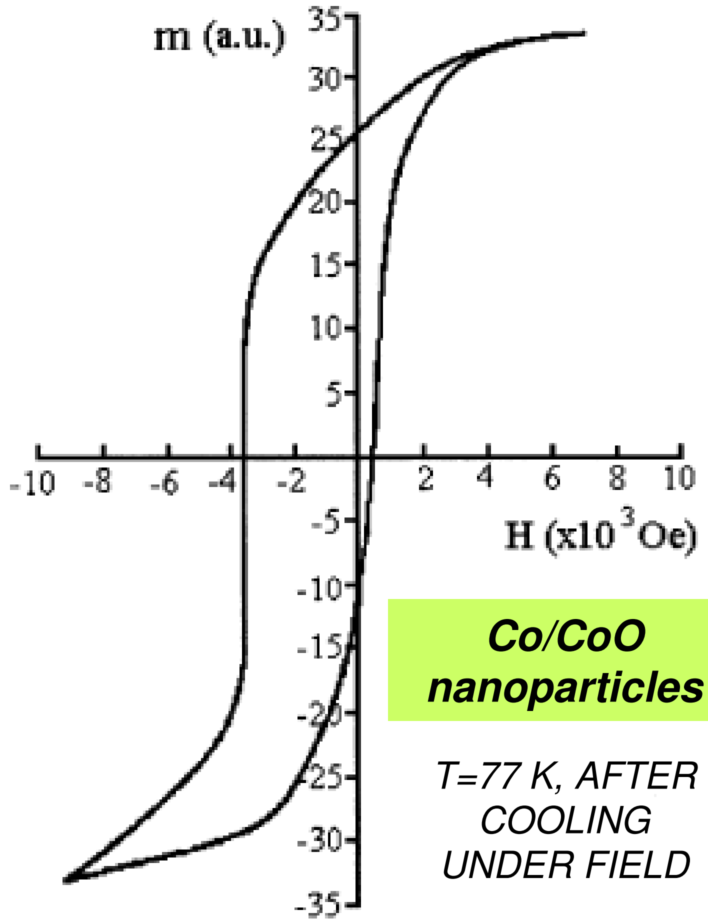


⇒THE LINEAR RESPONSE AS A FUNCTION OF THE APPLIED MAGNETIC FIELD IS VERY USEFUL TO SENSE LOW MAGNETIC FIELDS OF APPLICATION IN CERTAIN MAGNETIC SENSORS

The crossed-geometry concept has also been applied to TMR-based devices

*EXCHANGE BIAS

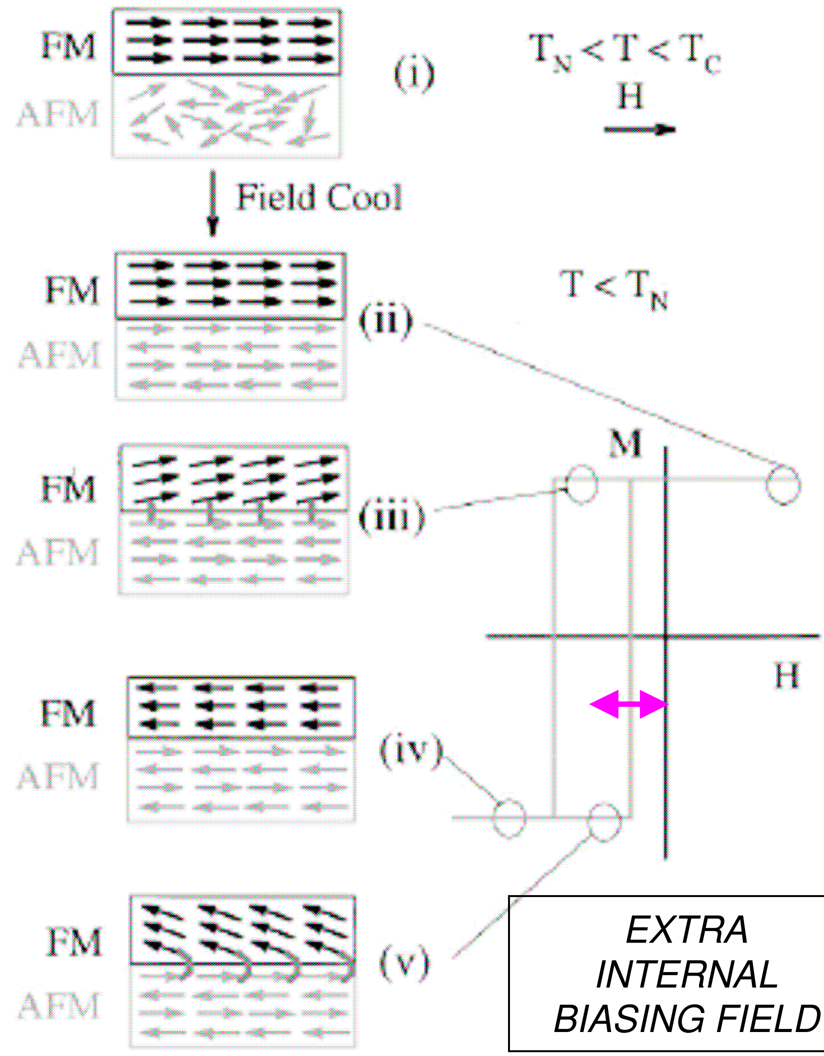
THE DISCOVERY OF EXCHANGE BIAS



Co/CoO nanoparticles

T=77 K, AFTER COOLING UNDER FIELD

W.H. Meiklejohn and C.P. Bean, Phys. Rev. 102 (1956) 1413



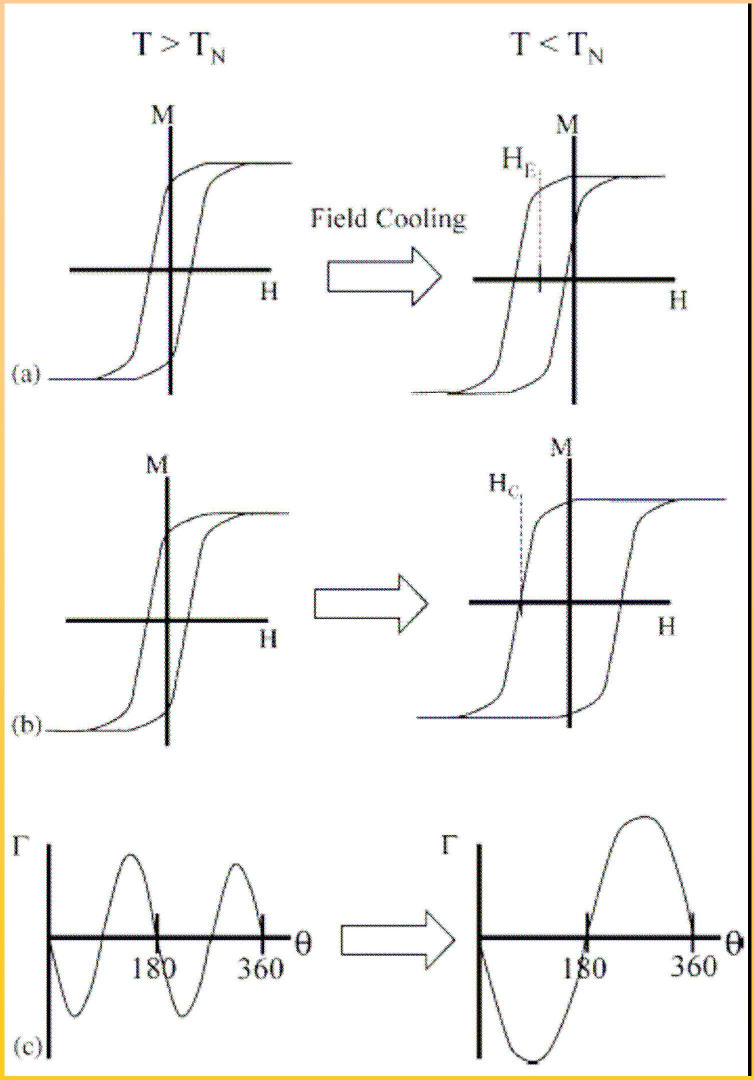
EXTRA INTERNAL BIASING FIELD

A FEW BASIC CONCEPTS IN EXCHANGE BIAS

1)SHIFT IN THE HYSTERESIS LOOP (H_E)

2)INCREASE IN THE COERCIVITY (ΔH_C)

3)UNIAXIAL ANISOTROPY (K_U)

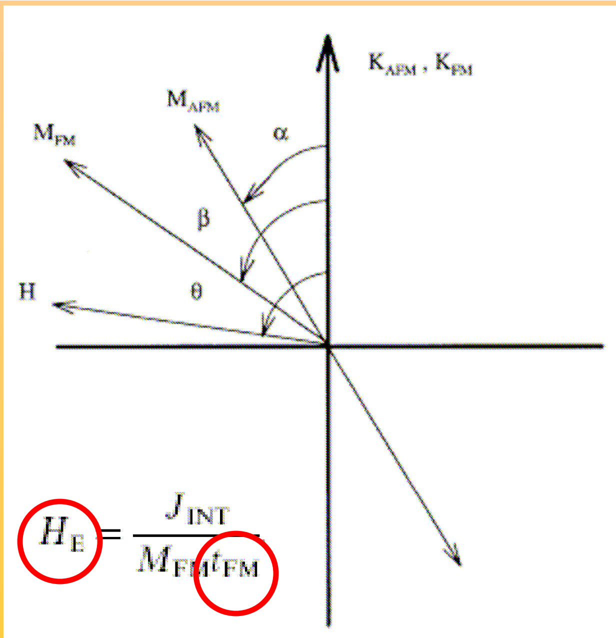


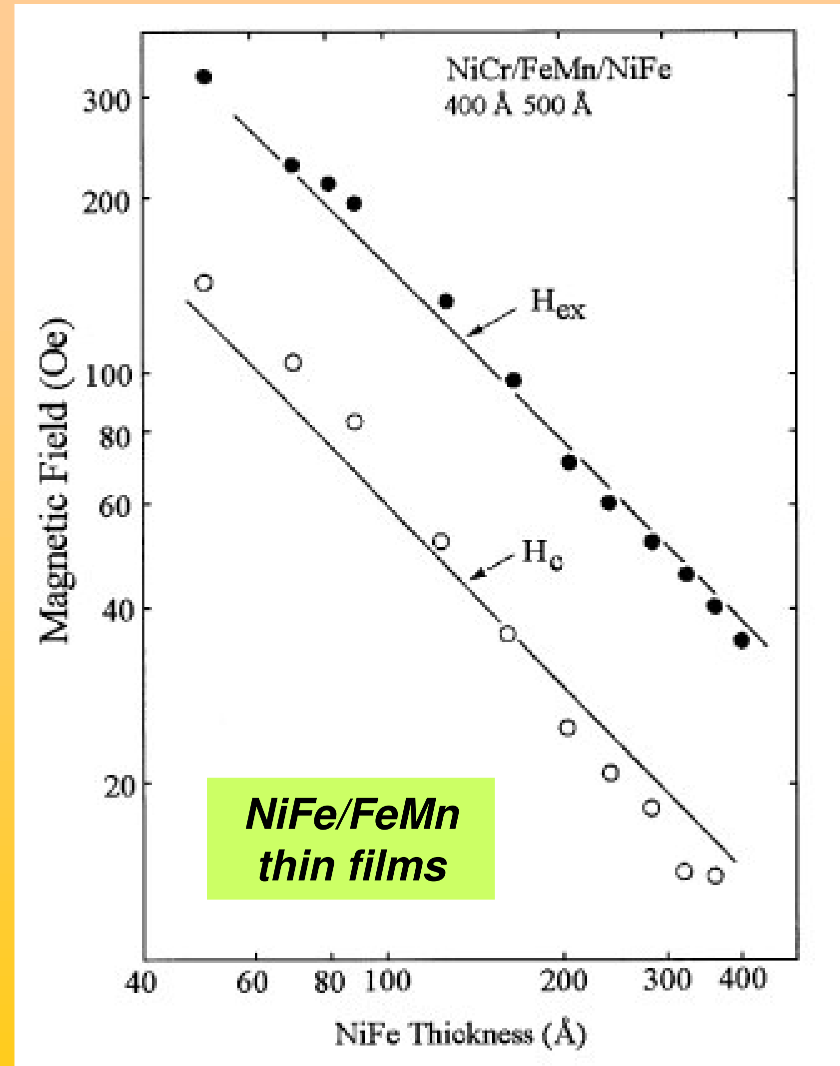
REVIEW ARTICLES ON EXCHANGE BIAS: J. Nogues et al., J. Magn. Magn. Mater. 192 (1999) 203; J. Nogues et al., Phys. Reports. 422 (2005) 65

Cluj school, September 2007

EXCHANGE BIAS IN THIN FILMS

$$E = -HM_{FM}t_{FM}\cos(\theta-\beta) + K_{FM}t_{FM}\sin^2(\beta) + K_{AFM}t_{AFM}\sin^2(\alpha) - J_{INT}\cos(\beta-\alpha),$$





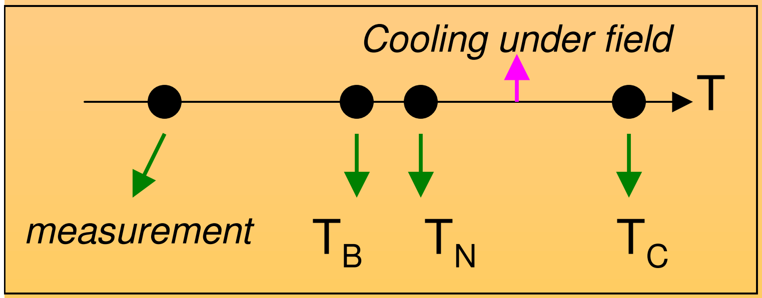
EXCHANGE BIAS IS AN INTERFACIAL EFFECT. IT STRONGLY DEPENDS ON THE SPIN CONFIGURATION AT THE INTERFACE

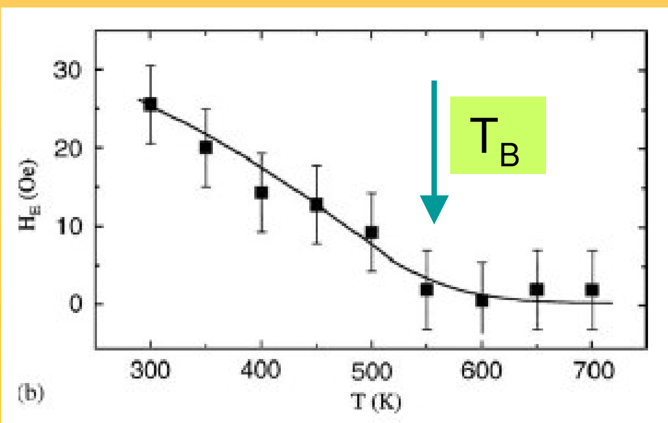
REVIEW ARTICLES ON EXCHANGE BIAS: J. Nogues et al., J. Magn. Magn. Mater. 192 (1999) 203; J. Nogues et al., Phys. Reports. 422 (2005) 65

MATERIALS FOR EXCHANGE BIAS IN THIN FILMS

FeMn

NiMn





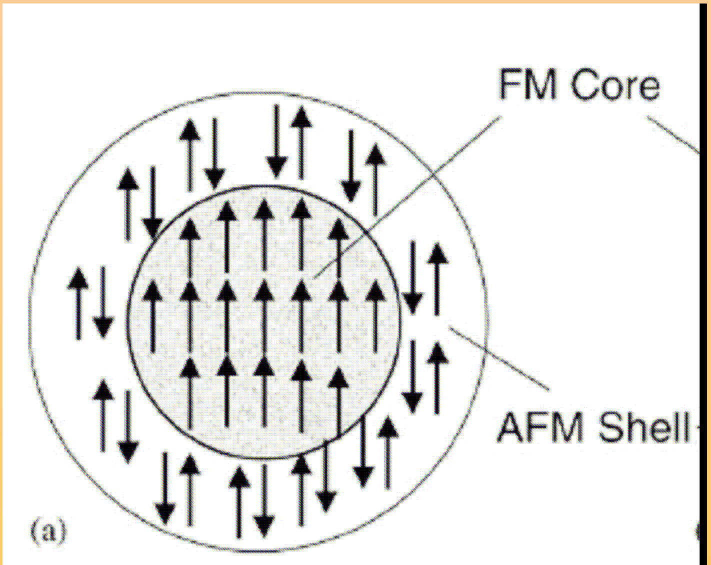
J. Nogues et al.

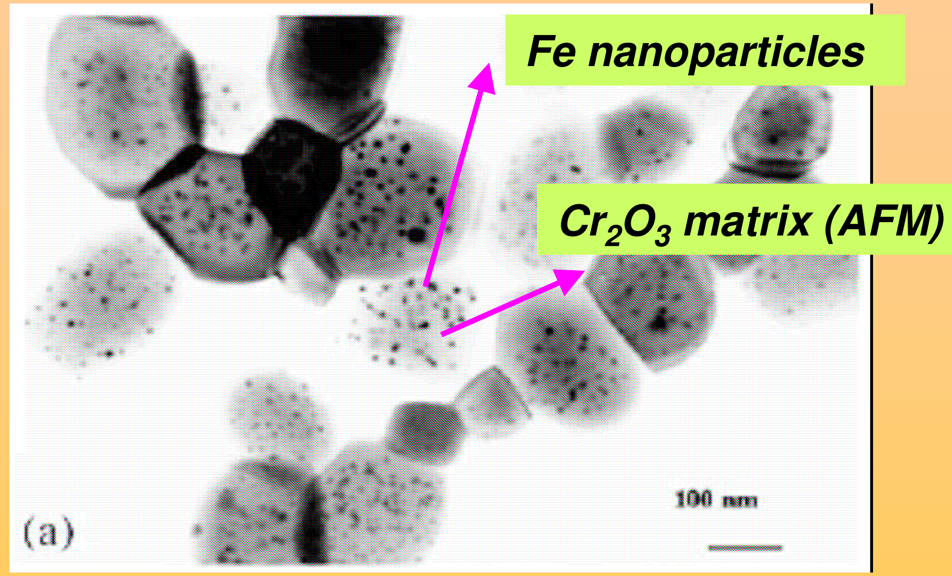
IrMn

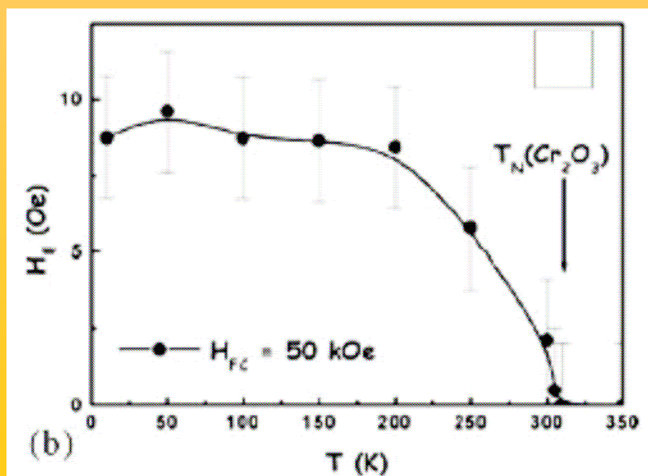
Compilation of interface energies $\Delta E = H_E t_{FM} M_{FM}$, blocking temperatures, T_B, and bulk Néel temperatures, T_N, for romagnets used in exchange bias. Note that ΔE values are at room temperature unless otherwise stated. Note that when have limited ourselves to thick enough AFM layers, where H_E and T_B are independent of t_{AFM}

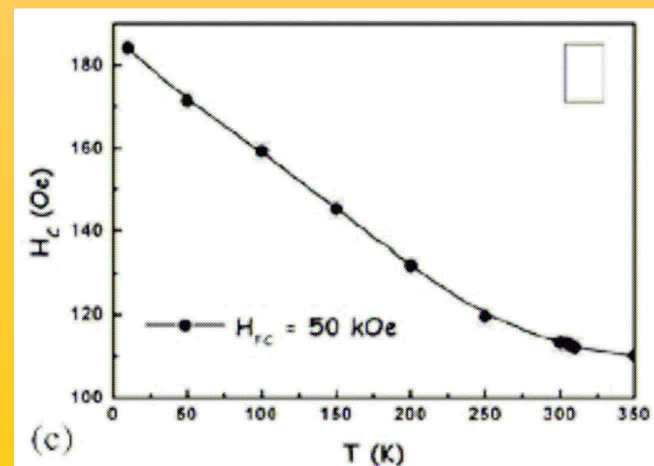
Material	ΔE (erg/cm^2)	T_B (K)	T_N (K)
$Fe_{50}Mn_{50}$ (poly)[a]	0.02–0.20	390–470	
$Fe_{50}Mn_{50}$ (poly-ann)[b]	0.05–0.47	420–570	
$Fe_{50}Mn_{50}$ (1 1 1)[c]	0.01–0.19	380–480	490
$Fe_{50}Mn_{50}$ (1 1 1-ann)[d]	0.05–0.16	–	
$Fe_{50}Mn_{50}$ (1 0 0)[e]	0.04–0.07	–	
$Fe_{50}Mn_{50}$ (1 1 0)[f]	0.04–0.06	–	
$Ni_{50}Mn_{50}$ (poly)[g]	0.002	770	
$Ni_{50}Mn_{50}$ (poly-ann)[h]	0.16–0.46	770	1070
$Ni_{50}Mn_{50}$ (1 1 1-ann)[i]	0.10–0.36	520–650	
$Ni_{25}Mn_{75}$ (1 1 1-ann)[j]	0.07	420	–
$Fe_xNi_yMn_{1-x-y}$ (poly)[k]	0.03–0.16	470–620	–
FeMnRh (poly)[l]	0.05	420	–
FeMnRh (poly-ann)[m]	0.06	420	
Rh_xMn_{1-x} (poly)[n]	0–0.13	–	–
Co_xMn_{1-x} (poly)[o]	0.14	–	–
α-Mn (poly) (5 K)[p]	0.08–0.2	50	95
Cr (poly) (4 K)[q]	0.002	–	310
Cr (1 0 0) (4 K)[r]	0	130	
$Cr_{1-x}Mn_x$ (poly)[s]	0.02	450	–
$Cr_xMn_yPt_{1-x-y}$ (poly)[t]	0.08	600	–
$Cr_xMn_yPt_{1-x-y}$ (poly-ann)[u]	0.16–0.35	600	
$Cr_xMn_yRh_{1-x-y}$ (poly)[v]	0.05–0.08	620	–
$Cr_xMn_yCu_{1-x-y}$ (poly)[w]	0.04–0.05	570	–
$Cr_xMn_yPd_{1-x-y}$ (poly)[x]	0.06–0.08	650	–
$Cr_xMn_yIr_{1-x-y}$ (poly)[y]	0.04	550	–
$Cr_xMn_yNi_{1-x-y}$ (poly)[z]	0.03	–	–
$Cr_xMn_yCo_{1-x-y}$ (poly)[a1]	0.03	–	–
$Cr_xMn_yTi_{1-x-y}$ (poly)[b1]	0.003	–	–
Pt_xMn_{1-x} (poly-ann)[c1]	0.02–0.32	400–650	480–980
Pd_xMn_{1-x} (poly)[d1]	0.06	–	–
$Pd_xPt_yMn_{1-x-y}$ (poly)[e1]	0.08–0.11	570	–
Ir_xMn_{1-x} (1 1 1)[f1]	0.01–0.19	400–520	690
Cr_xAl_{1-x} (1 1 0)[g1]	0.01–0.04	550	900

EXCHANGE BIAS WITH MAGNETIC NANOPARTICLES





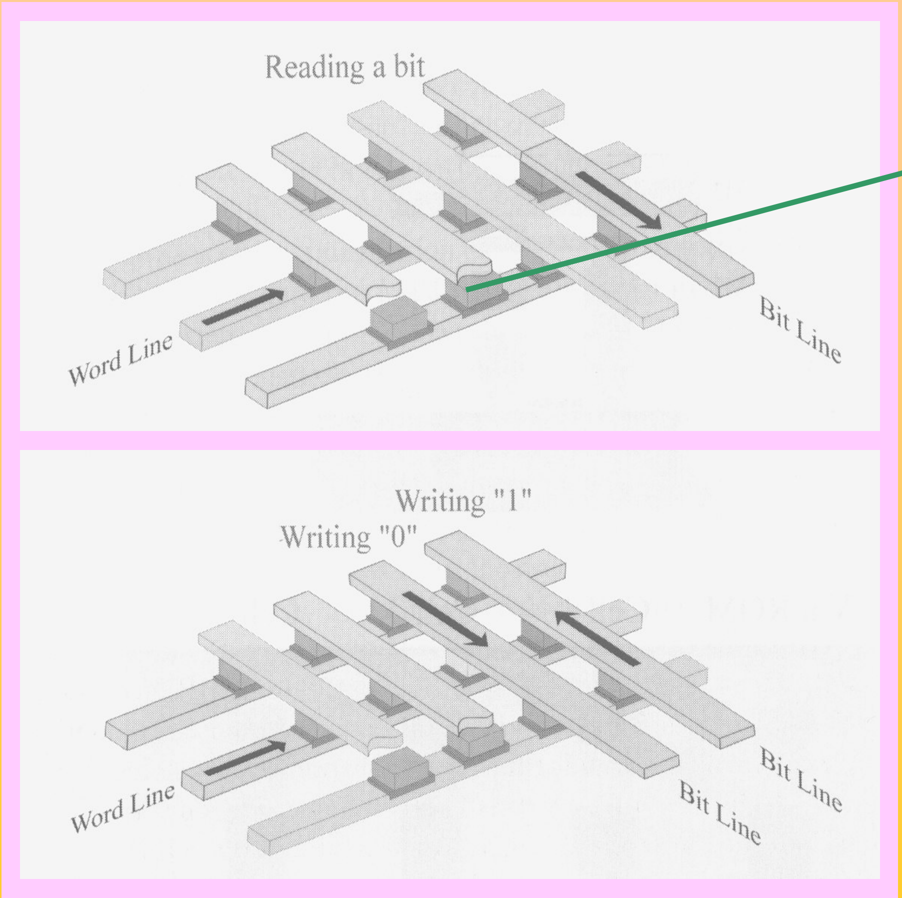




J. Nogues et al., Phys. Reports. 422 (2005) 65

*MAGNETIC RANDOM ACCESS MEMORIES

Conventional Magnetic Random Access Memories (MRAM)



MAGNETORESISTIVE ELEMENT WITH TWO WELL- DEFINED STATES

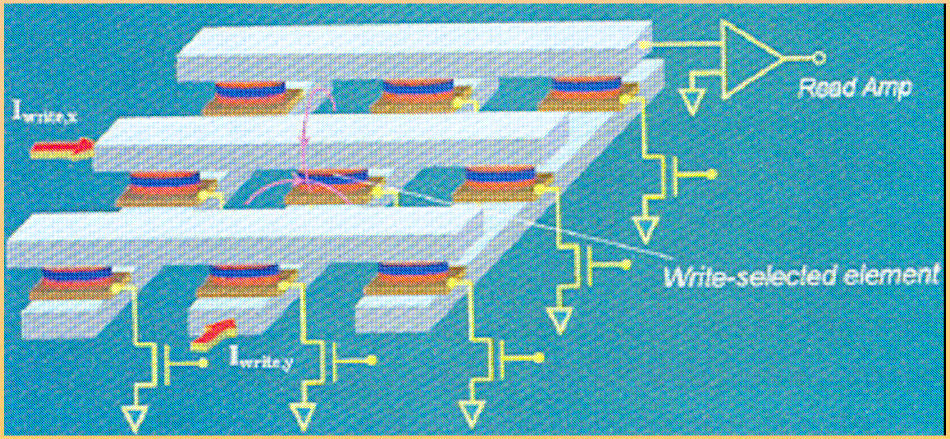
It can be realized with GMR or TMR elements

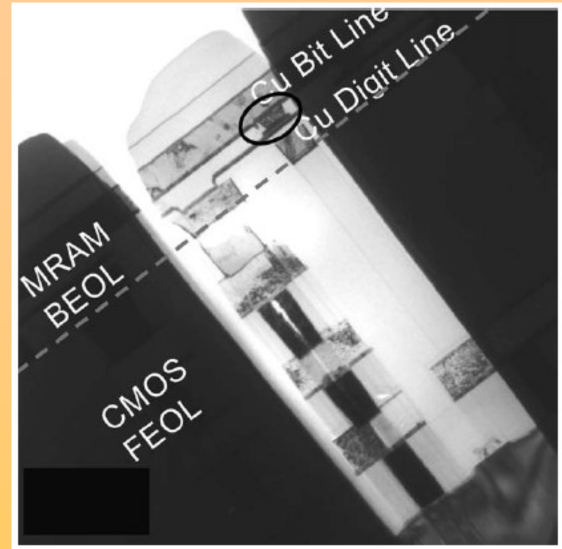
APPLICATIONS OF NON-VOLATILE MEMORIES MEMORIES :

MOBILE PHONES, DIGITAL CAMERAS, LAPTOP COMPUTERS, INTELLIGENT CARDS,...

ADVANTAGES OF MRAM: ***NON VOLATILE, HIGH DENSITY, SCALABILITY, LOW SWITCHING ENERGY, RELIABILITY, FAST ACCESS, RADIATION HARD, LOW COST OF MANUFACTURE***

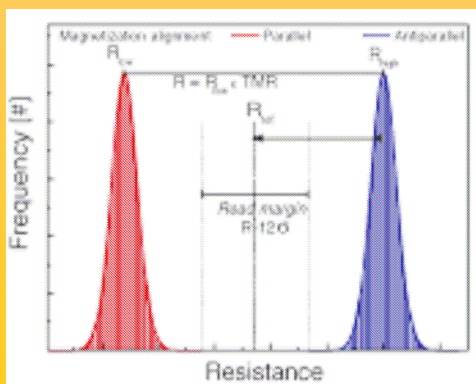
Conventional Magnetic Random Access Memories (MRAM)





A diode or a transitor is required in order to read one single bit. Thus, the memory cannot be dense.

Distribution of resistance values is crucial

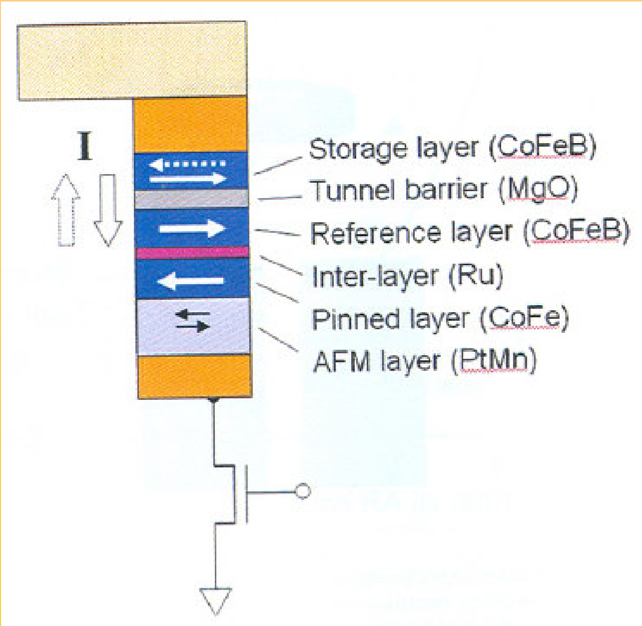


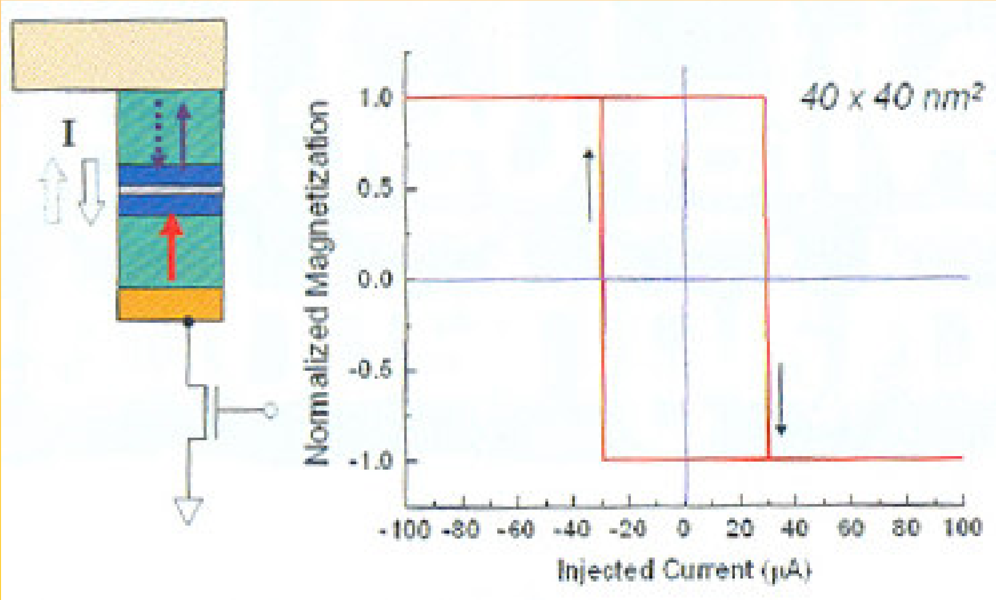
Writing is normally performed with coherent magnetization rotation with a field parallel to the easy axis plus another one perpendicular

S. Parkin in "Spin dependent transport in Magnetic Nanostructures", edited by Maekawa and Shinjo, Taylor and Francis; R. Sousa et al., C.R. Physique 6 (2005)1013; Zhu et al., Materials Today 9, 36 (2006)

Other strategies in Magnetic Random Access Memories (MRAM)

SPIN-RAM MEMORY WITH SPIN TORQUE FOR MAGNETIC SWITCHING OF THE STORAGE LAYER





R. Sousa et al., C.R. Physique 6 (2005)1013; Zhu et al., Materials Today 9, 36 (2006)

Comparison of magnetic memories

Comparison of memory technologies

Feature	DRAM	SRAM (6T)	FLASH	OUM	MRAM	FeRAM
Cell size [F^2]	8–12	50–80	4–11	5–8	6–20	4–16
Non-volatile	No	No	Yes	Yes	Yes	Yes
Endurance write/read	∞/∞	∞/∞	$10^6/\infty$	$>10^{12}/\infty$	$>10^{15}/\infty$	$>10^{12}/>10^{12}$
Non-destructive read	No	Partial	Yes	Yes	Yes	No
Direct overwrite	Yes	Yes	No	Yes	Yes	Yes
Signal margin	100–200 mV	100–200 mV	Δ current	10–100 × R	60–200% R	100–200 mV
Write/read	50 ns/50 ns	8 ns/8 ns	200 μs/60 ns	10 ns/20 ns	30 ns/30 ns	80 ns/80 ns
Erase	50 ns	8 ns	1–100 ms (block)	50 ns	30 ns	80 ns
Transistor performance	Low	High	High voltage (HV)	High	High	High
Scalability limits	Capacitor	6 Transistors	Tunnel oxide/HV	Litho.	Current density	Capacitor

*The "universal" memory should have the speed of "SRAM", the density of "DRAM" and non volatility as "FLASH". Will the MRAM attain all these features?

UPDATES TO THE MRAM GAME CAN BE FOUND AT
http://www.mram-info.com

NEWS IN APRIL 2007:

Honeywell develops non-volatile MRAM for strategic space applications. Honeywell has developed a 1 Mbit non volatile static memory component for strategic space electronics applications (see related story). Built with Honeywell's radiation-hardened, silicon-on-insulator (SOI) complementary metal oxide semiconductor (CMOS) technology, and combined with magnetic thin films, the new memory component provides high reliability for low-voltage systems operating in radiation environments. The magnetic RAM runs from a 3.3-volt power supply and has high reliability, enabling it to operate through the natural radiation found in space. It offers nearly unlimited read/write cycles (>1e15) and uses Honeywell's 150-nanometer SOI CMOS technology as well as a unique set of wafer processes developed at the company's "Trusted Foundry" in Plymouth, Minn.

NEWS IN JUNE 2007:

Freescale Semiconductor has expanded its award-winning MRAM family with the world's first 3-volt 4Mbit extended temperature range (-40 to +105℃) non-volatile RAM (nvRAM) product. This device enables entry into more rugged application environments, such as industrial, military and aerospace and automotive designs.

NEWS IN AUGUST 2007:

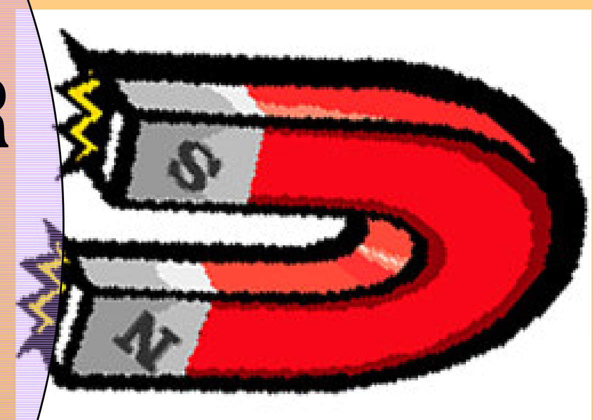
IBM has linked with Japan's TDK to develop so-called spin torque transfer RAM (random access memory) or STT-RAM. In STT-RAM, an electric current is applied to a magnet to change the direction of the magnetic field. The direction of the magnetic field (up-and-down or left-to-right) causes a change in resistance, and the different levels of resistance register as 1s or 0s.

CONCLUSIONS ANS PERSPECTIVES

MAGNETORESISTIVE DEVICES CONSTITUTE A MAGNIFICENT PLAYGROUND TO STUDY EXCITING MAGNETIC PHENOMENA

MAGNETORESISTIVE DEVICES ARE WIDELY USED IN TODAY'S TECHNOLOGY AND ARE EXPECTED TO BRING ABOUT NEW PRODUCTS IN NEXT FUTURE

THANKS FOR YOUR ATTENTION



LATEST NEWS:

SIESTA IS FORBIDDEN TODAY!