MAGNETORESISTANCE PHENOMENA IN MAGNETIC MATERIALS AND DEVICES

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-INTRODUCTION TO MAGNETORESISTANCE (MR)

-LORENTZ MR (LMR), ANISOTROPIC MR (AMR), HALL EFFECT (OHE, EHE)

-SPIN-DISORDER MR (SDMR) AND COLOSSAL MR (CMR)

-GIANT MR (GMR)

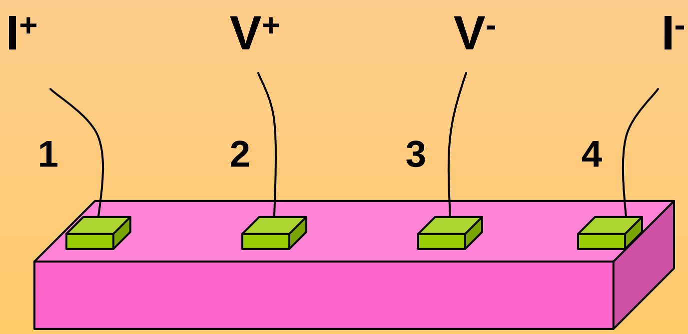
-TUNNEL MR (TMR)

-PERSPECTIVES

INTRODUCTION TO MAGNETORESISTANCE: PRELIMINARY CONCEPTS

GEOMETRY OF MEASUREMENT

Bulk samples *are normally measured in bar-shaped geometry and four-point linear contacts. The van der Pauw method is used for samples with arbitrary shape*



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

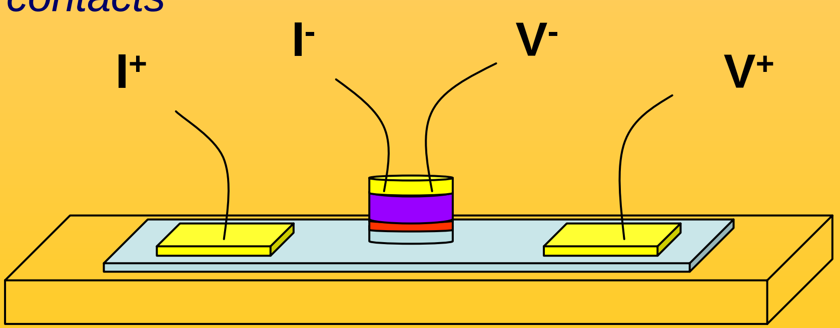
(F can be approximated to 1 in most of the situations)

*In this geometry one should be careful regarding offset signals such as thermoelectric effects, electronic offsets, electromotive forces,...

Devices *such as magnetic tunnel junctions, GMR in CPP geometry, etc. Normally require lithography techniques to define the contacts*

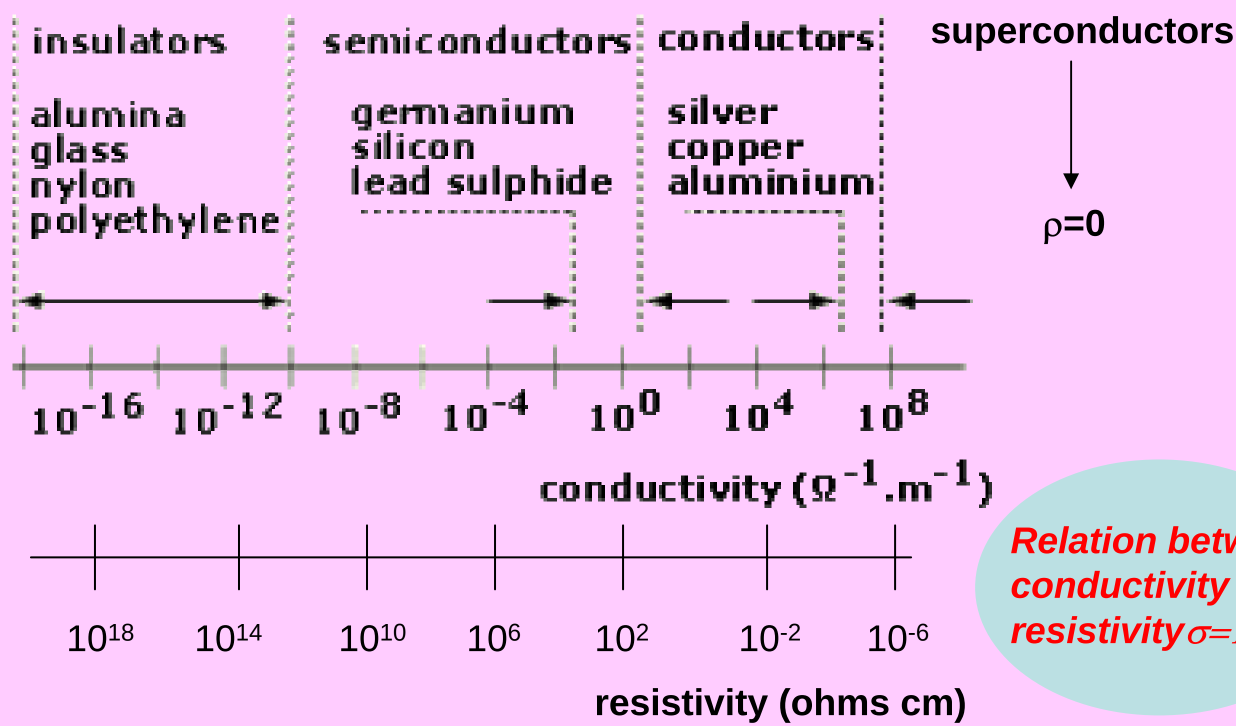
(results are normally expressed in the form of "resistance" or "resistance x surface")

*In this geometry one should be careful regarding geometrical effects arising with high resistive electrodes.



⇒ In all cases d.c. as well as a.c. measurements are possible

TYPES OF MATERIALS IN TERMS OF CONDUCTION BEHAVIOUR



***Relation between conductivity and resistivity** $\sigma=1/\rho$*

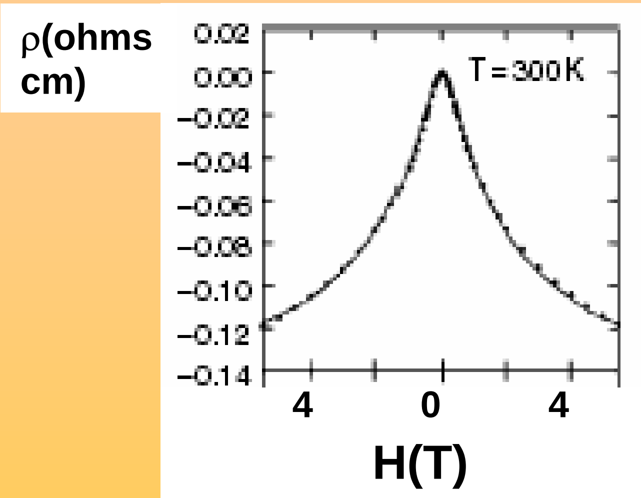
⇒All kinds of these materials (in terms of conductivity properties) have found applications in different technological domains

⇒From a basic point of view, the electrical properties indirectly inform the researcher on the band structure, phase transitions, ground state, magnetic effects, impurities in the sample, etc. The dependence of the resistivity under magnetic field gives additional and important information on all these aspects

DEFINITIONS OF MAGNETORESISTANCE

(similar definitions can be given for "magnetoconductance")

*In the case of monotonous behaviour:



Optimistic view:

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

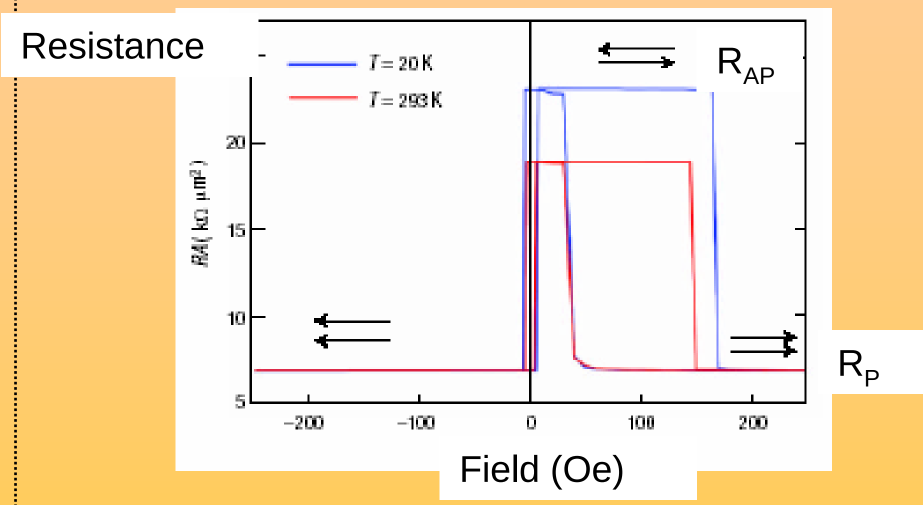
The MR ratio is unlimited

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

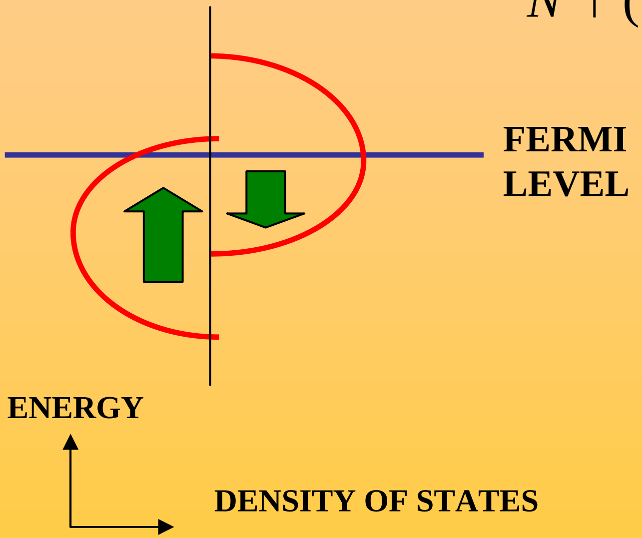
$$M = N\uparrow - N\downarrow$$

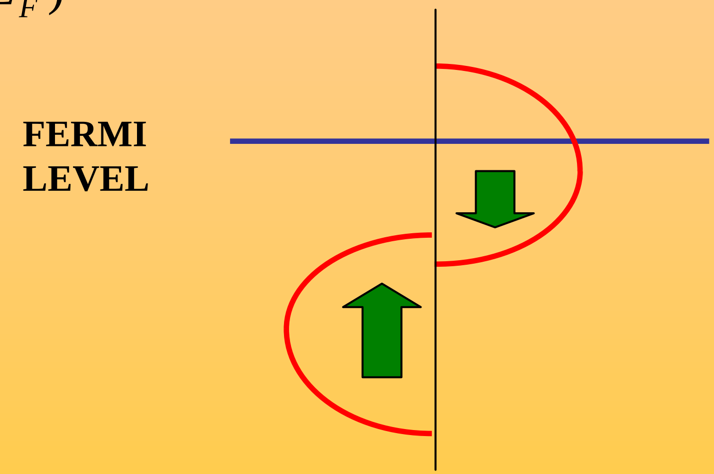
Spin Polarization

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

Half metal

$P(E_F) = \pm 1$





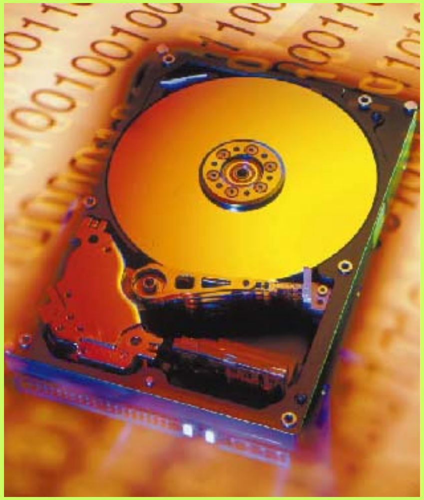
⇒Most of the magnetoresistive devices are built upon ferromagnetic materials and we will concentrate on them. Of course, magnetoresistive effects exist when using other kinds of magnetic and non-magnetic materials but here we will only consider such materials marginally.

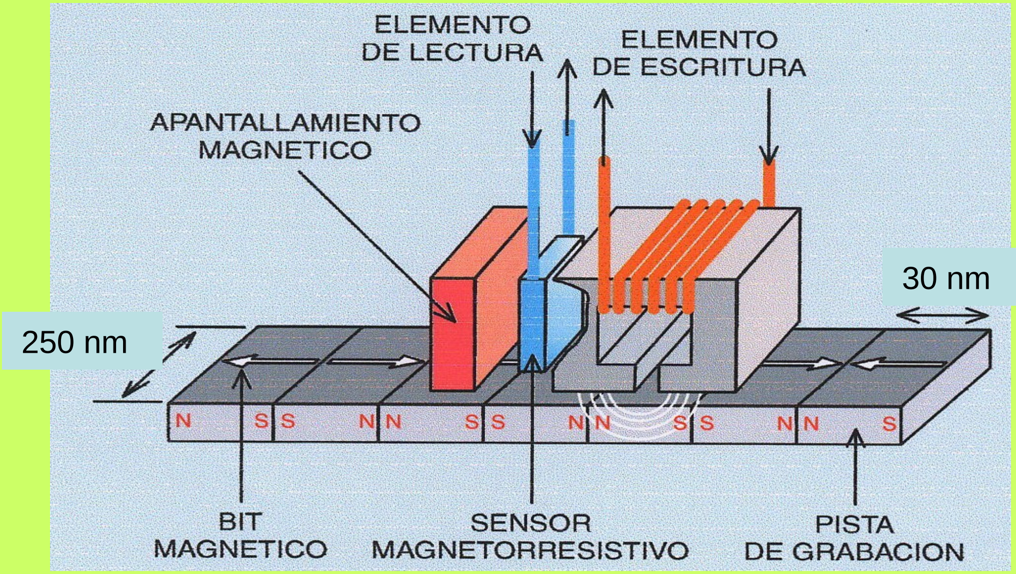
INTEREST OF MAGNETORESISTIVE SYSTEMS NOWADAYS

APPLICATIONS IN:

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

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





RESISTIVITY OF NON-MAGNETIC METALS

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

(Matthiessen's rule)

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

*Classical image of the resistivity:

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

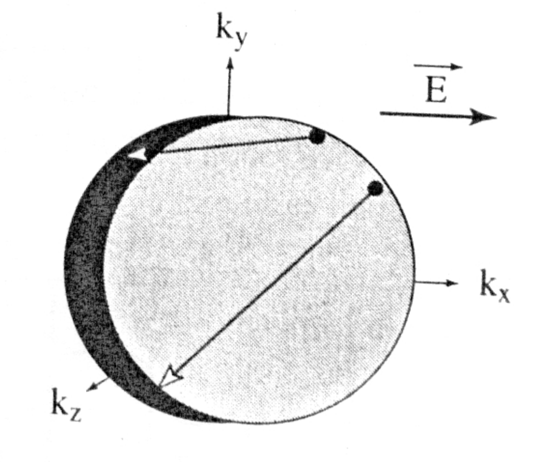
-With applied electric field, a net acceleration appears and a drift velocity given by:

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

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

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

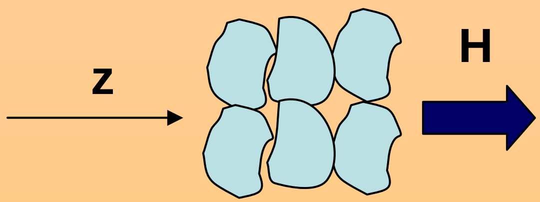
Spin diffusion length (l_{SD})= distance between two consecutive scattering events which produce spin flip. **$l_{SD} >> \lambda_{mfp}$**



*Key role played by the electrons at the Fermi level in the conduction process:

ANISOTROPIC MAGNETORESISTANCE 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:

When we apply current

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

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

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

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

Lorentz magnetoresistance

Anisotropic magnetoresistance effect

Hall effect

Campbell and Fert, Magnetic Materials 3 (1982) 747

LMR, AMR AND HALL EFFECT

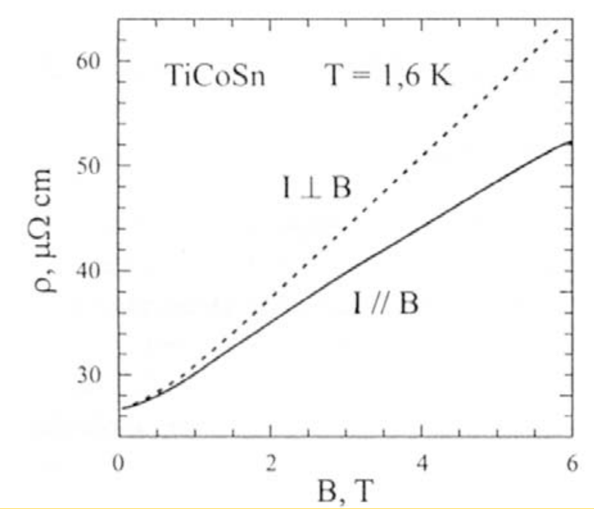
LORENTZ MR

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

-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

-IT FOLLOWS THE DEPENDENCE $\Delta\rho/\rho=f(B/\rho_0)$ (Kohler's RULE) AND AT LOW FIELDS $\frac{\Delta\rho}{\rho} = \left(\frac{1}{\rho}\right)\left(\frac{1}{ne}\right)B^2$

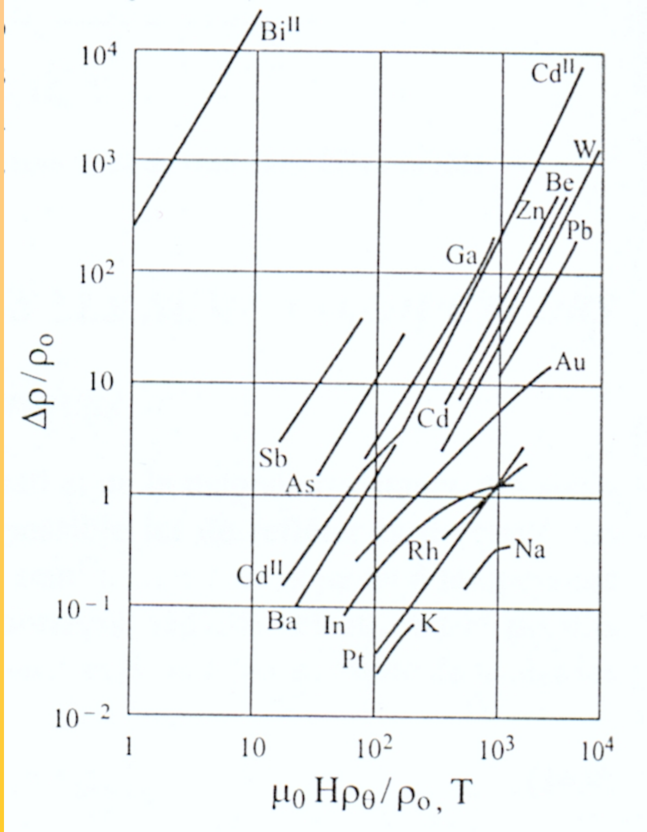


Ferre in "Magnetisme-Fondements" (edited by PUG)

$\Rightarrow$ 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)

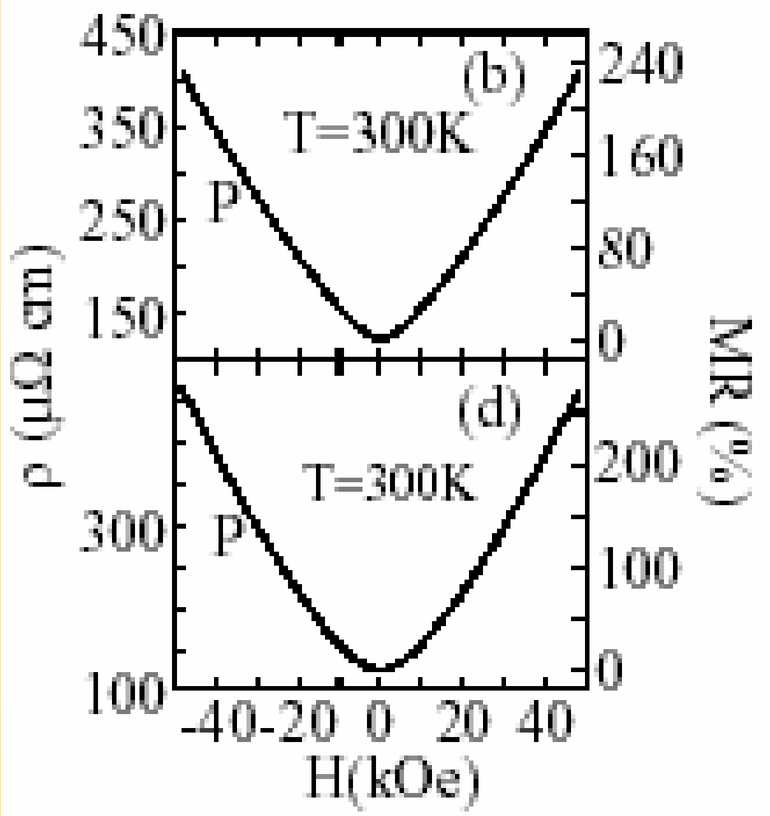
LMR, AMR AND HALL EFFECT

LORENTZ MR



M. Kohler, Ann. Phys. 6 (1949) 18107 and J. Ferre in “Magnetisme-Fondements” (edited by PUG)

Bi thin films

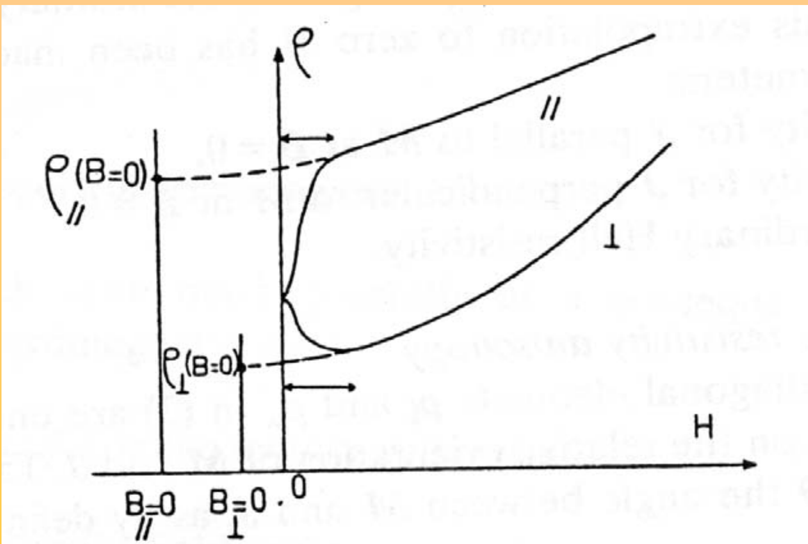


F.Y. Yang et al., Phys. Rev. Lett. 82 (1999) 3328

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):

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

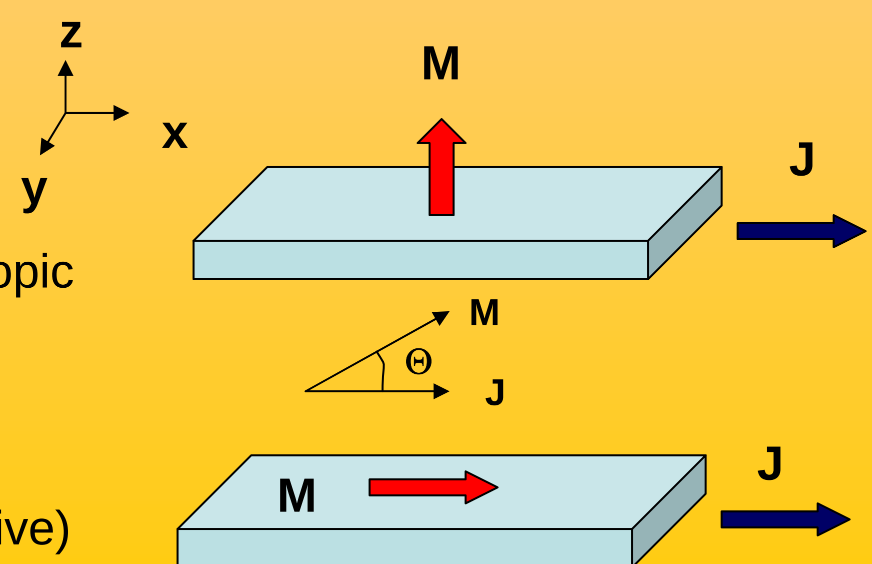
(extrapolation to B=0 required)

-Angular dependence of the anisotropic MR at magnetic saturation:

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

(Θ=angle between **J** and **M**)

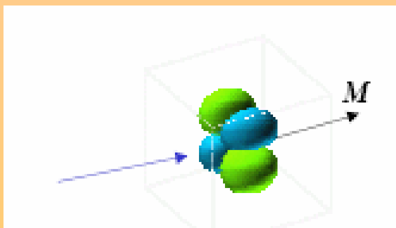
(ρ_{ani} can be either positive or negative)

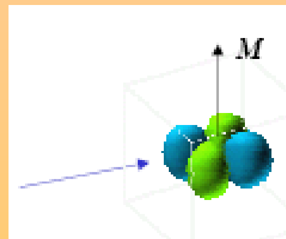


LMR, AMR AND HALL EFFECT

ANISOTROPIC MR

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

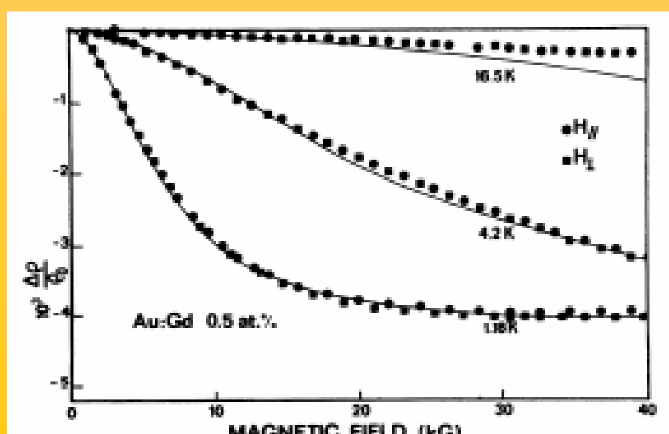


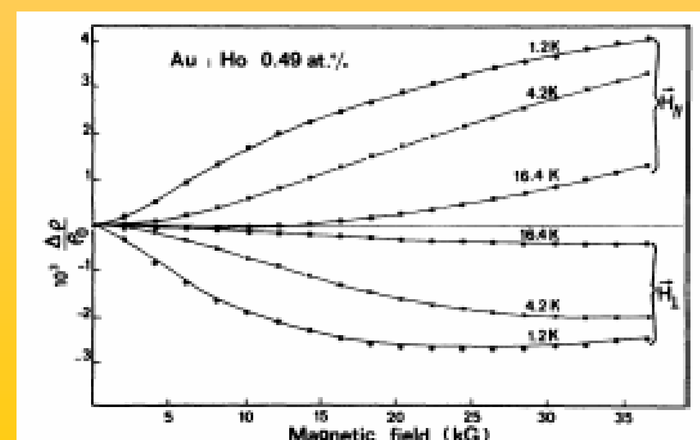


⇒It is expected to be large only in systems with large spin-orbit interaction and anisotropic charge distribution

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 ($Gd^{+3} \Rightarrow 4f^7$); (*Fert et al., Phys. Rev. B 16 (1977) 5040*)





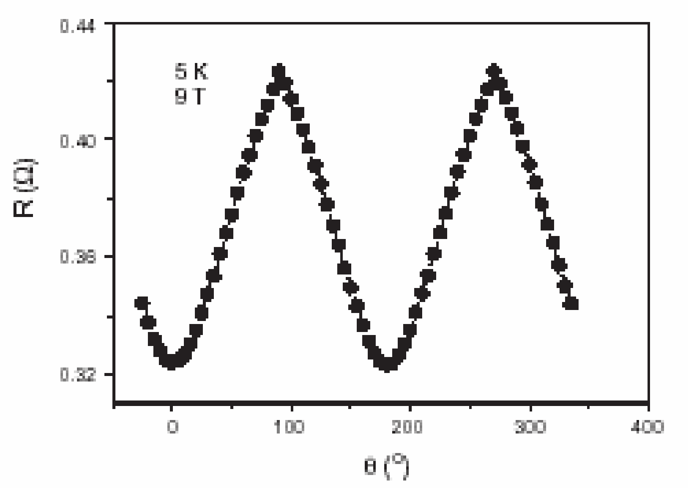
LMR, AMR AND HALL EFFECT

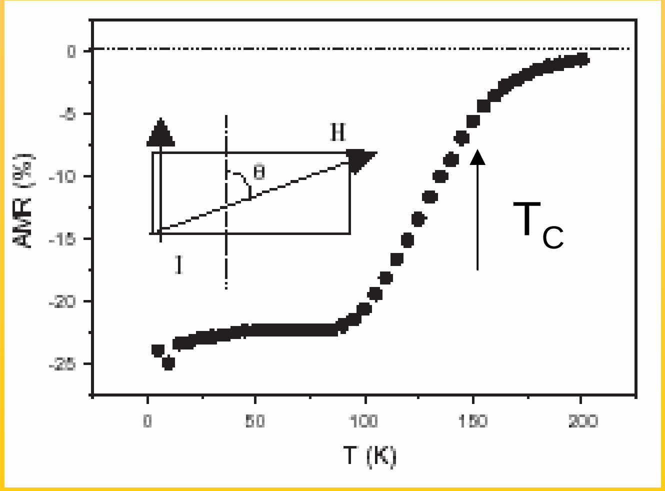
ANISOTROPIC MR

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 $\alpha=\rho\uparrow/\rho\downarrow$)

3) In magnetic oxides, AMR is also small except for systems having large orbital moment such as $SrRuO_3$ (*Herranz et al., J. Magn. Magn. Mater. 272-276 (2004) 517*)

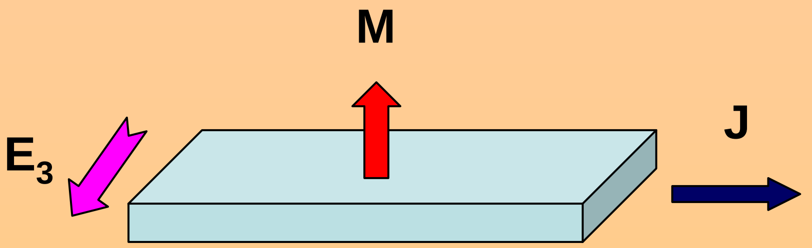


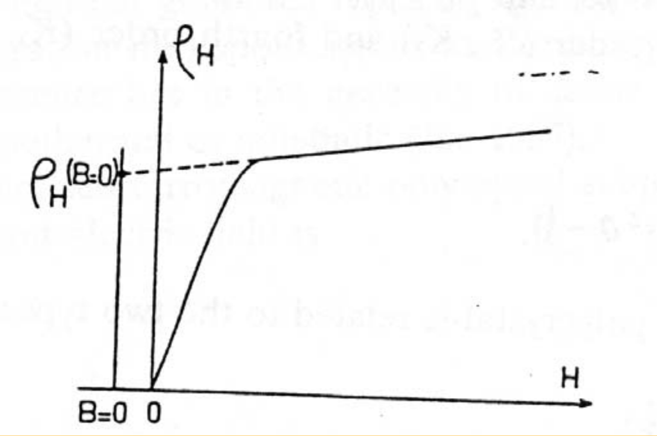


LMR, AMR AND HALL EFFECT

HALL EFFECT

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





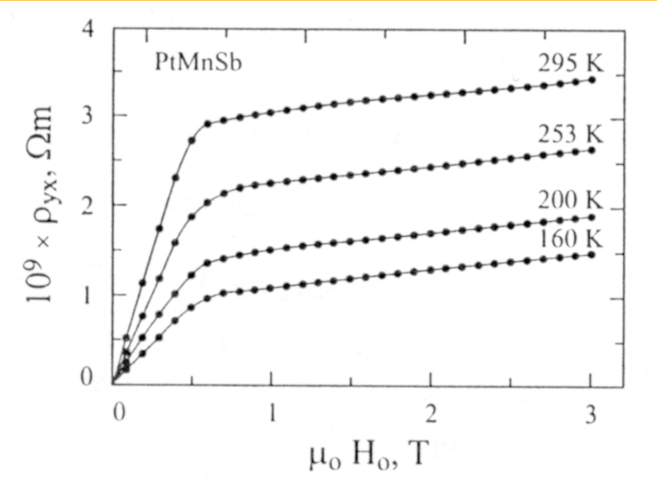


Figure from J. Ferre in "Magnetisme-Fondements" (edited by PUG)

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

Ordinary Hall effect

$$\rho_H^0 = -\frac{1}{nec}$$

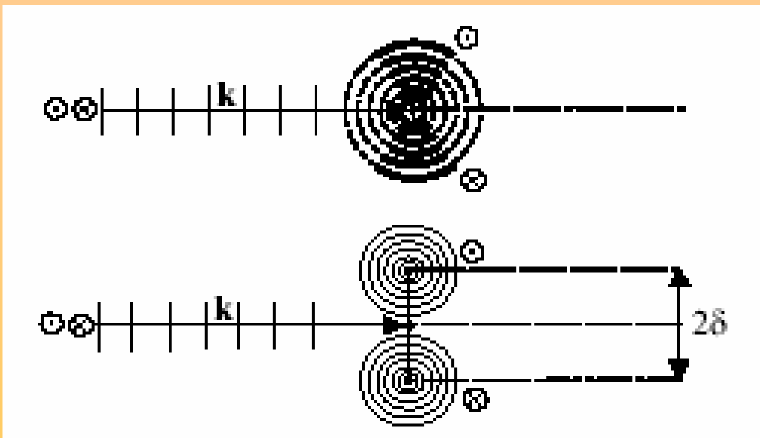
Explained by the Lorentz force (as in semiconductors).

Extraordinary Hall effect (EHE)

Its origin has been related to spin-orbit coupling in the presence of carrier spin polarization. Typically, it is stronger than the ordinary Hall effect.

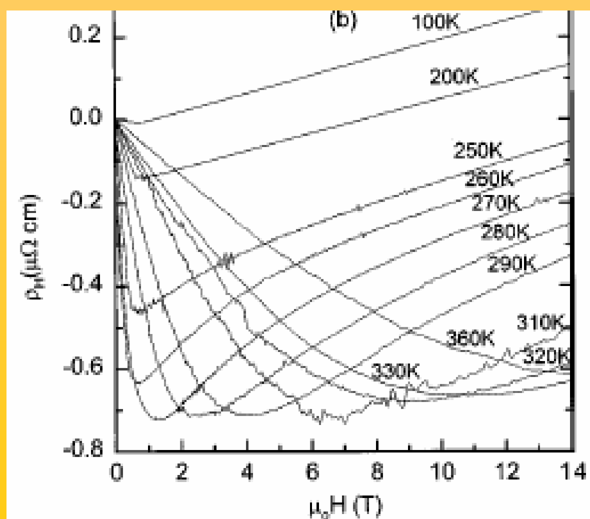
LMR, AMR AND HALL EFFECT

EXTRAORDINARY HALL EFFECT (EHE)



-An asymmetric interaction of the carriers with the scattering centers occur because the carriers have a spin. At least, two kinds of processes contribute to this effect: “skew scattering” and “jump scattering”

Crepieux and Bruno, Phys. Rev. B 64 (2001) 014416



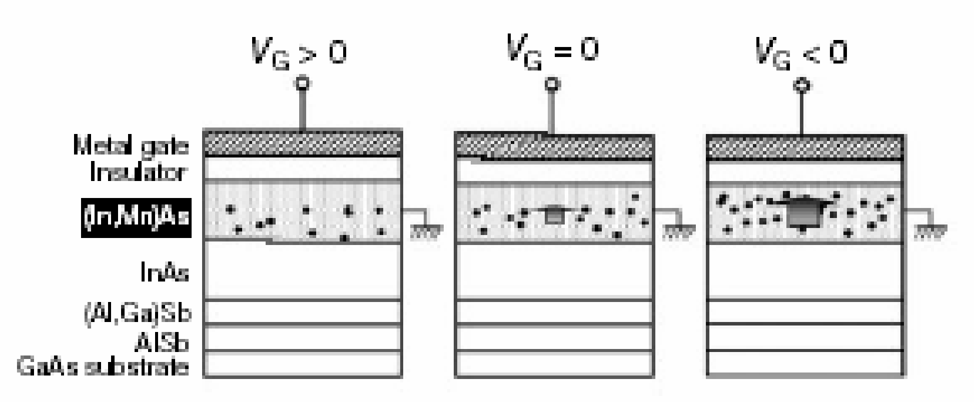
-The EHE effect is strongly temperature dependent and typically exhibits a peak below T_C. Its sign can be even opposite to that of the ordinary Hall effect.

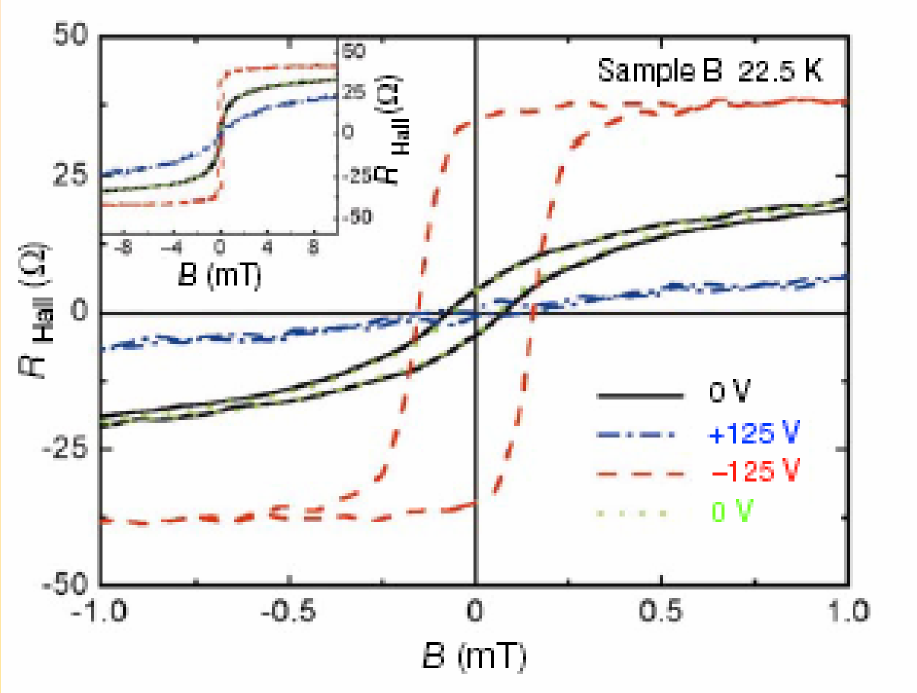
EHE in $La_{2/3}Ca_{1/3}MnO_3$, Matl et al., Phys. Rev. B 57 (1998) 10248

LMR, AMR AND HALL EFFECT

EXTRAORDINARY HALL EFFECT (EHE)

⇒*The extraordinary Hall effect has been used to obtain the magnetization from transport measurements*





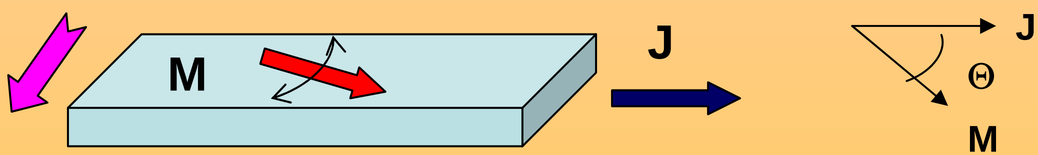
Ohno et al., Nature 408 (2000) 944

⇒Other applications of t*he extraordinary Hall effect are: the study of dynamics of magnetic domains (*Belmeguenai et al., J. Magn. Magn. Mater. 290 (2005) 514*), perpendicular anisotropy (*Cheng et al., Phys. Rev. Lett. 94 (2005) 017203*), etc.*

LMR, AMR AND HALL EFFECT

"PLANAR HALL EFFECT"

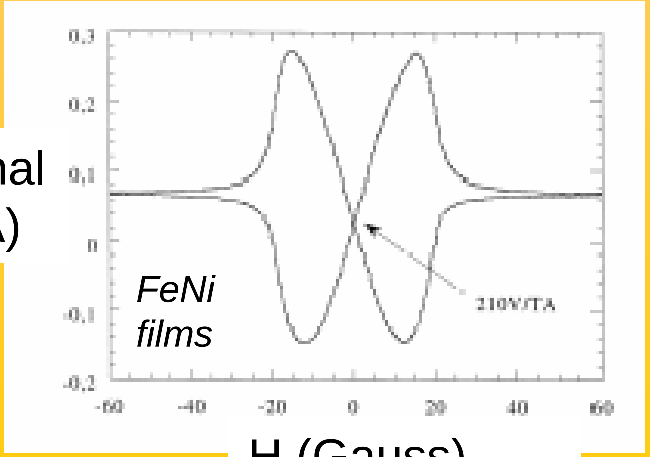
-It is due to E_2 not to $E_3 \Rightarrow$ it is an AMR effect, not an actual Hall effect

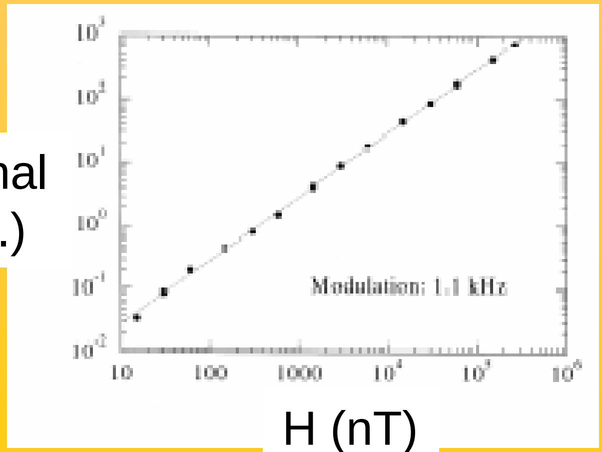


$$E_y = \left((\rho_{\parallel} - \rho_{\perp})\cos\Theta \sin\Theta\right) J$$

(Θ=angle between **J** and **M**)

-It has been used for precise magnetic sensing (thermal noise is minimized)



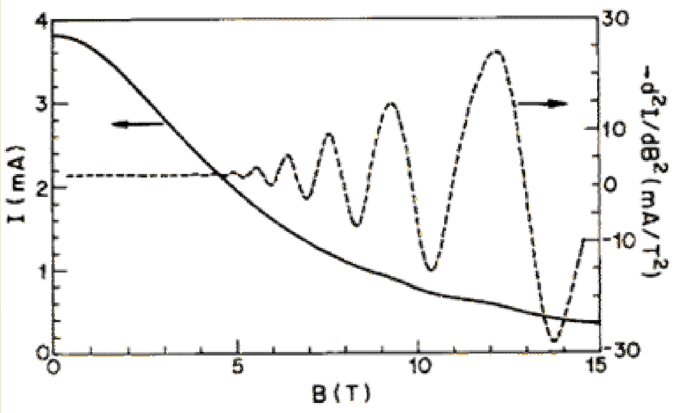


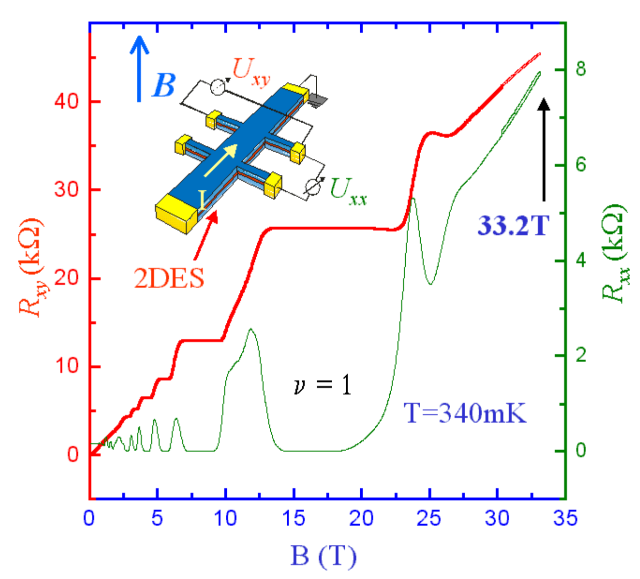
Montaigne et al., Sensors and Actuators 81 (2000) 324

LMR, AMR AND HALL EFFECT

"QUANTUM HALL EFFECTS" *(not time to be studied in detail here)*

-At low temperatures and large magnetic fields ($\omega_c\tau >> 1$), quantum effects give rise to oscillations in the resistivity (**Shubnikov-de Haas effect**)





-In 2D gases (formed with suitable semiconductor layers) it was discovered the **Quantum Hall effect**, where the longitudinal and Hall resistances increase non-monotonously following certain quantum rules

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.

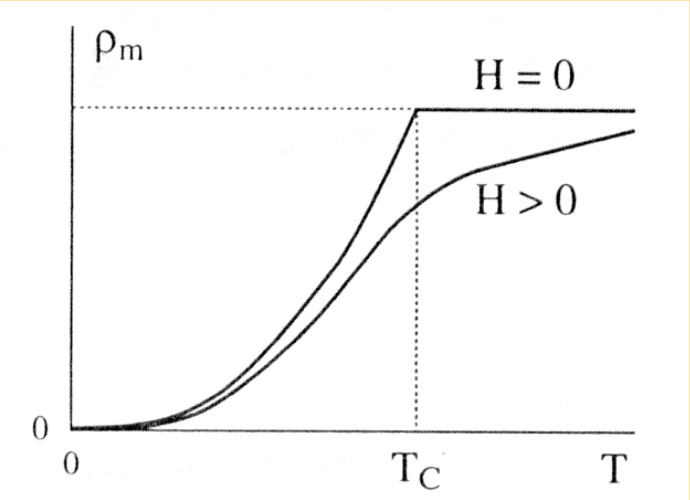


Figure from J. Ferre in "Magnetisme-Fondements" (edited by PUG)

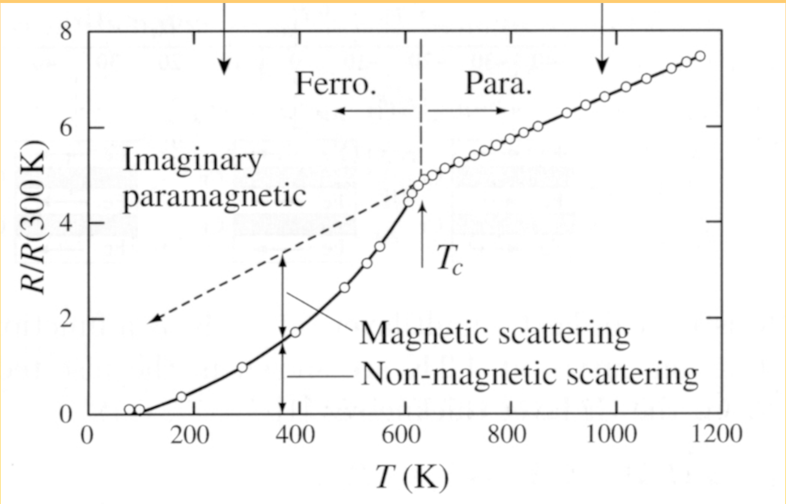
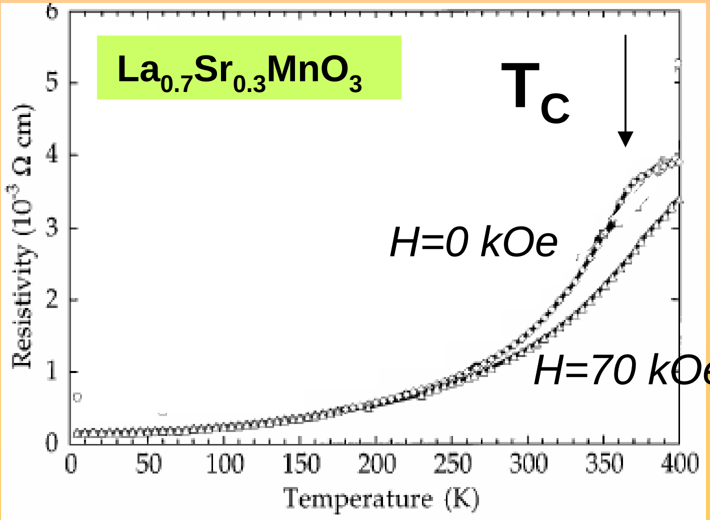


Figure from T. Shinjo in "Spin-dependent transport in magnetic nanostructures" (edited by S. Maekawa and T. Shinjo)

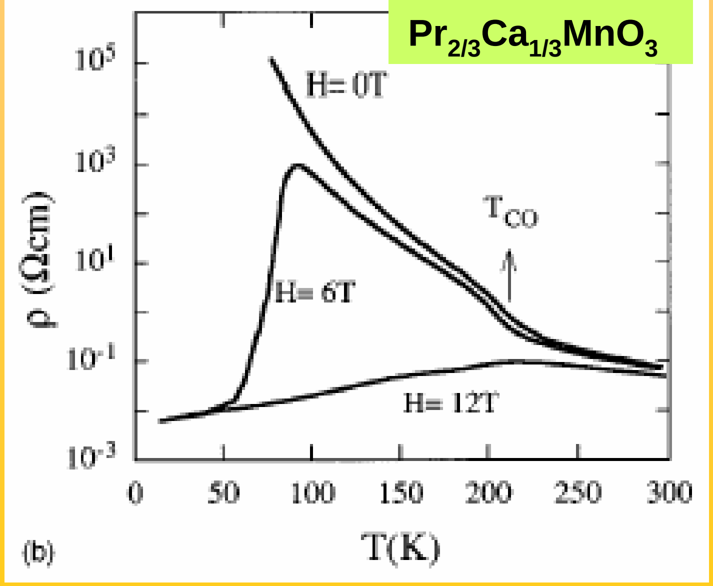
SPIN-DISORDED MR (SDMR) VERSUS COLOSSAL MR (CMR)

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



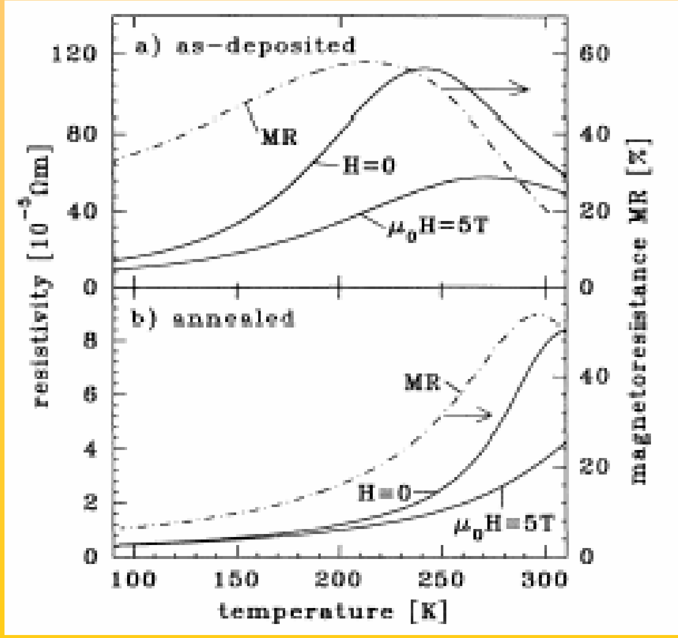
J.M. De Teresa et al., Phys. Rev. B 54 (1996) R12689

COLOSSAL MR (CMR)

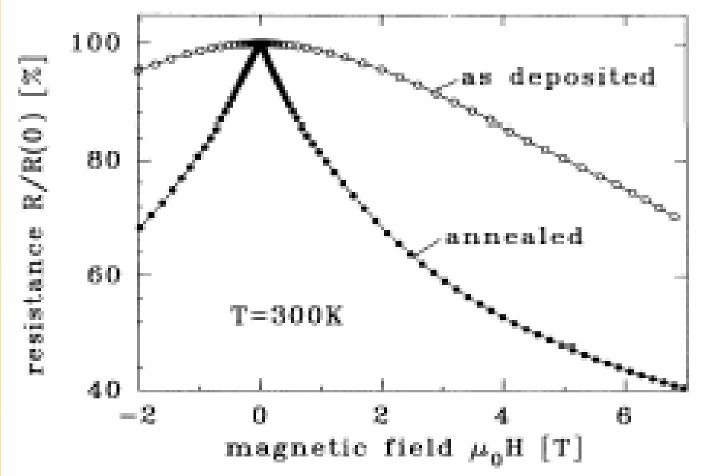
-This CMR effect has been observed in certain manganite single perovskite oxides ($A_{1-x}A'_xMnO_3$ type)

-In these materials the electrical resistivity can change up to several orders of magnitude by application of large magnetic fields

-The drawback for applications in MR devices is that this effect calls for high magnetic fields and occurs mainly below room temperature.

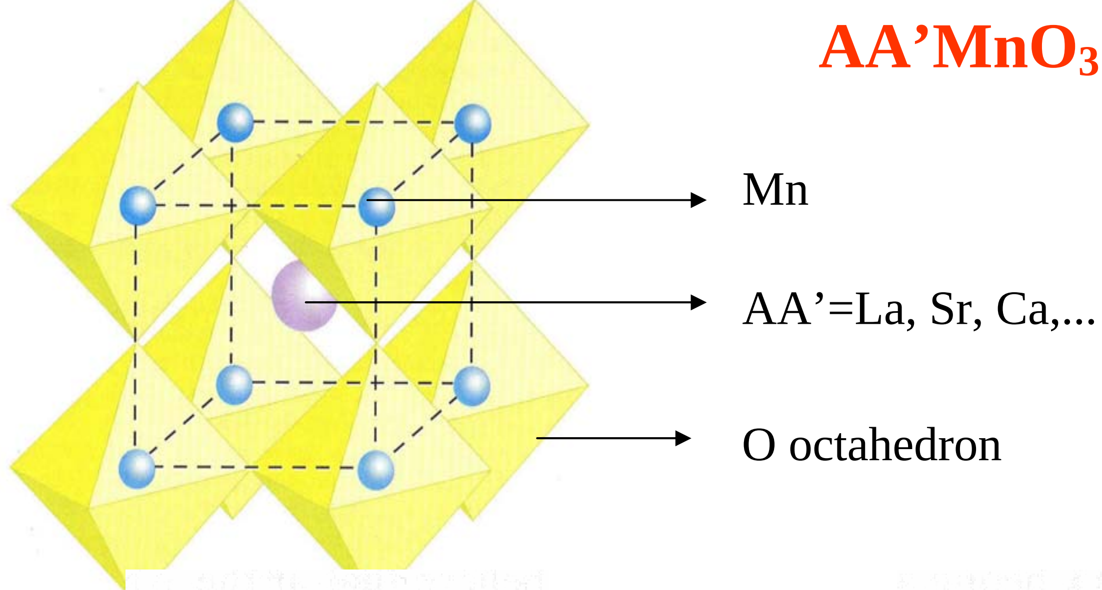


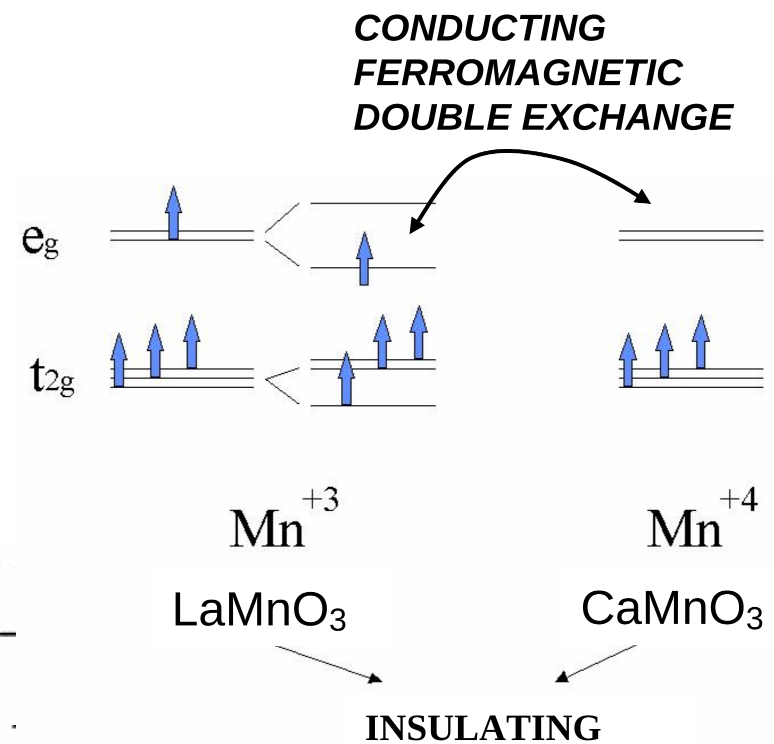
$La_{2/3}Ba_{1/3}MnO_{3-d}$

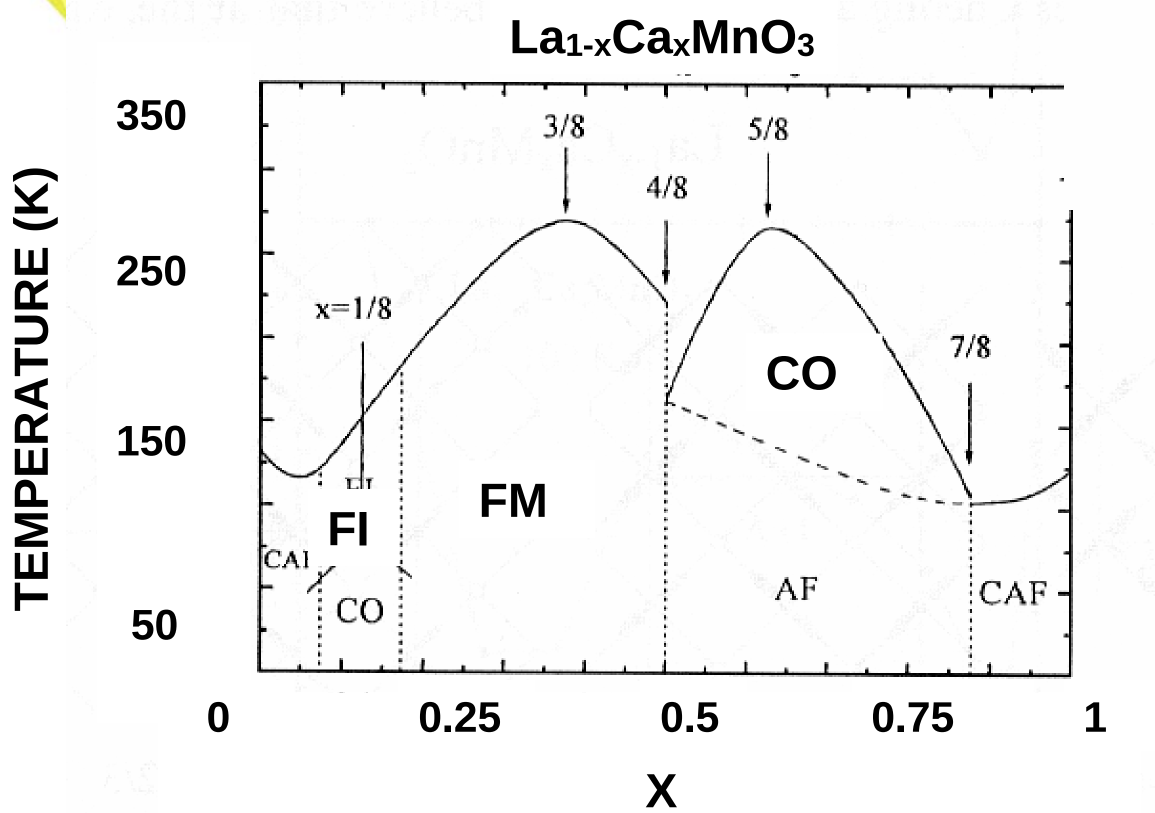


Von Helmolt et al., Phys. Rev. Lett. 71 (1993) 2331 (first report of CMR on thin films)

$AA'MnO_3$



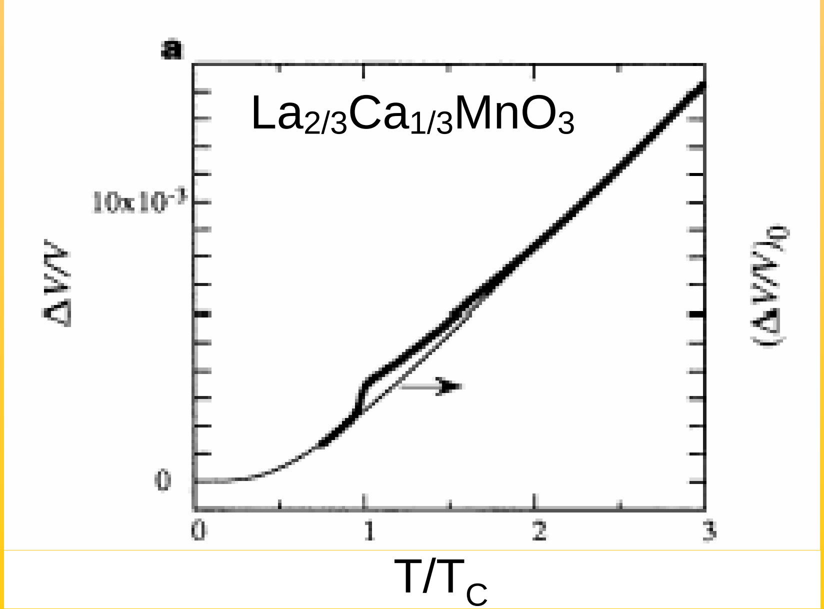


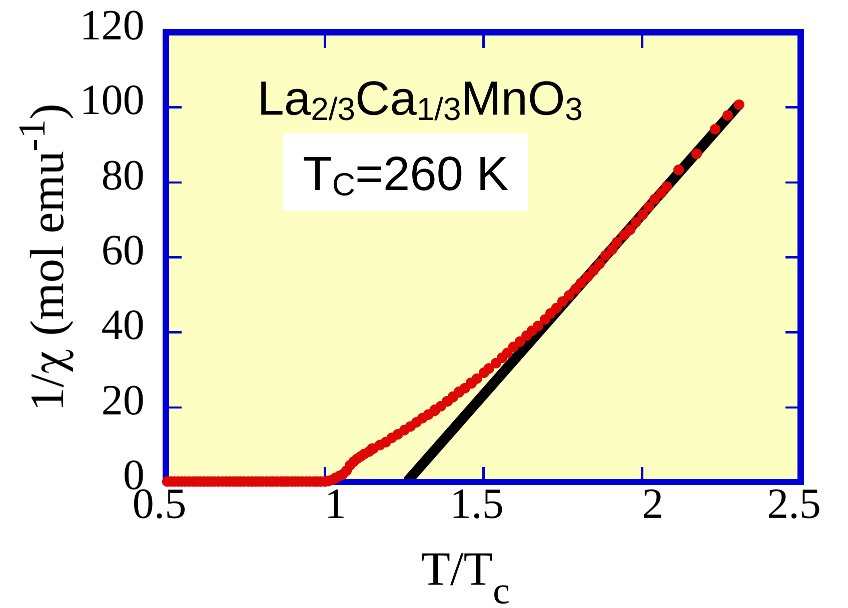


STRONG COMPETITION BETWEEN INSULATING PHASES (CO, AF) AND CONDUCTIVE PHASES (FERROMAGNETIC BY DOUBLE EXCHANGE)

CMR IN MANGANESE PEROVSKITES

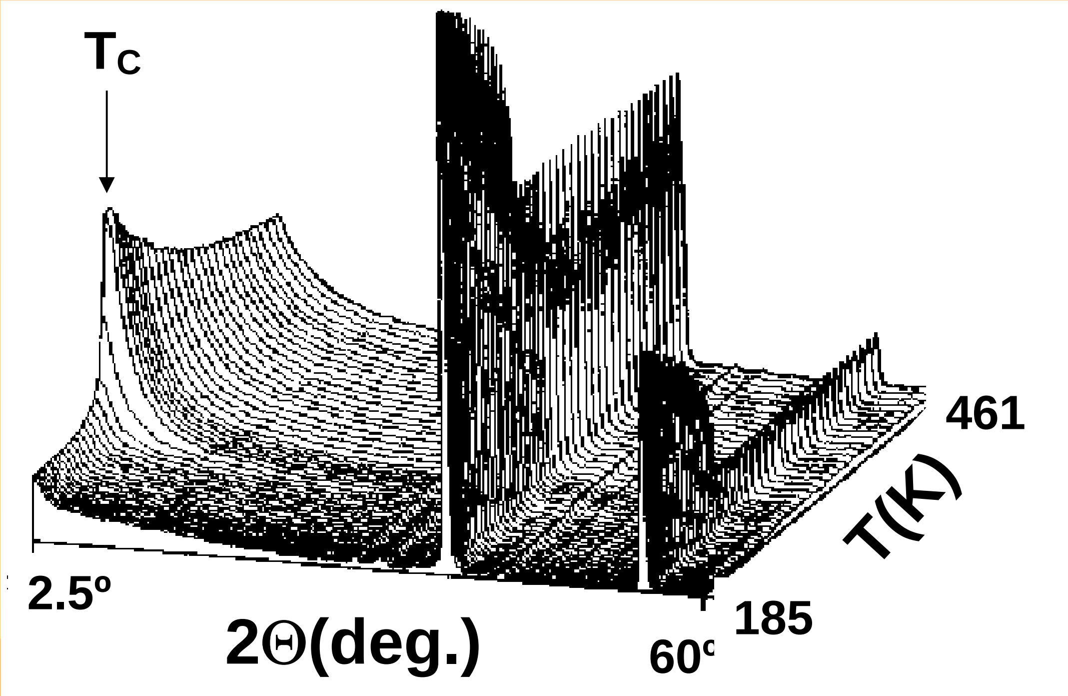
-One of the most studied issues is the origin of the semiconducting/ insulating state in the paramagnetic phase. Many groups have contributed to this issue.Our group was one of the firsts to show the existence of a continuous ***electronic localization process*** which disappears at T_C (in coincidence with the insulator-metal transition) or by application of large magnetic field. This process was related to the strong electron-phonon interaction (polaronic effect), which localizes the carriers. Magnetic susceptibility above T_C also shows strong short-range order effects.



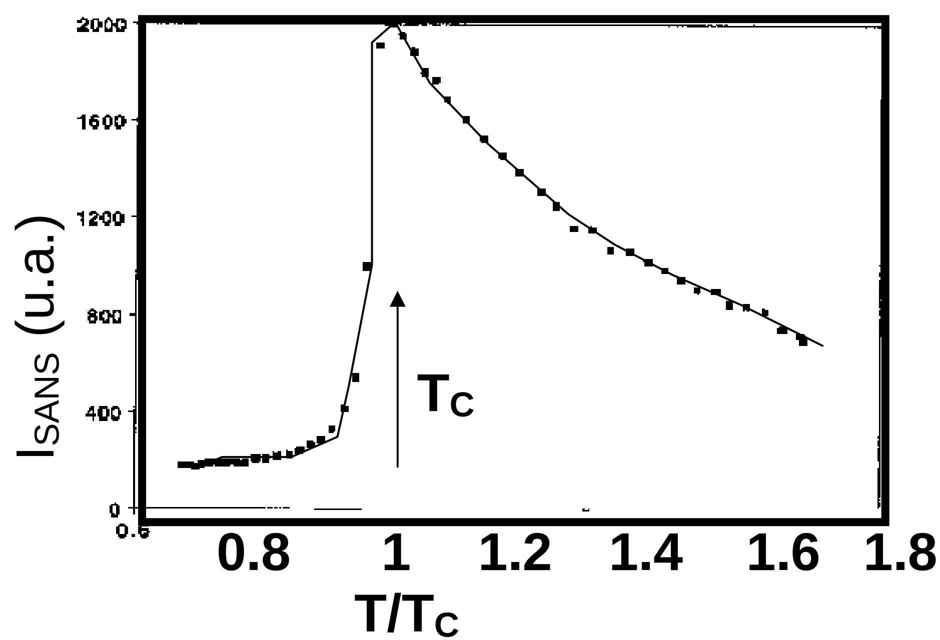


De Teresa et al., Nature 386 (1997) 256

Small-angle neutron scattering (SANS) in $La_{2/3}Ca_{1/3}MnO_3$



LARGE SANS INTENSITY EXISTS ABOVE T_C WHICH WE FOUND TO BE RELATED TO A MAGNETIC INHOMOGENEITY OF ~1 nm



De Teresa et al., Phys. Rev. B 54 (1996) 1187

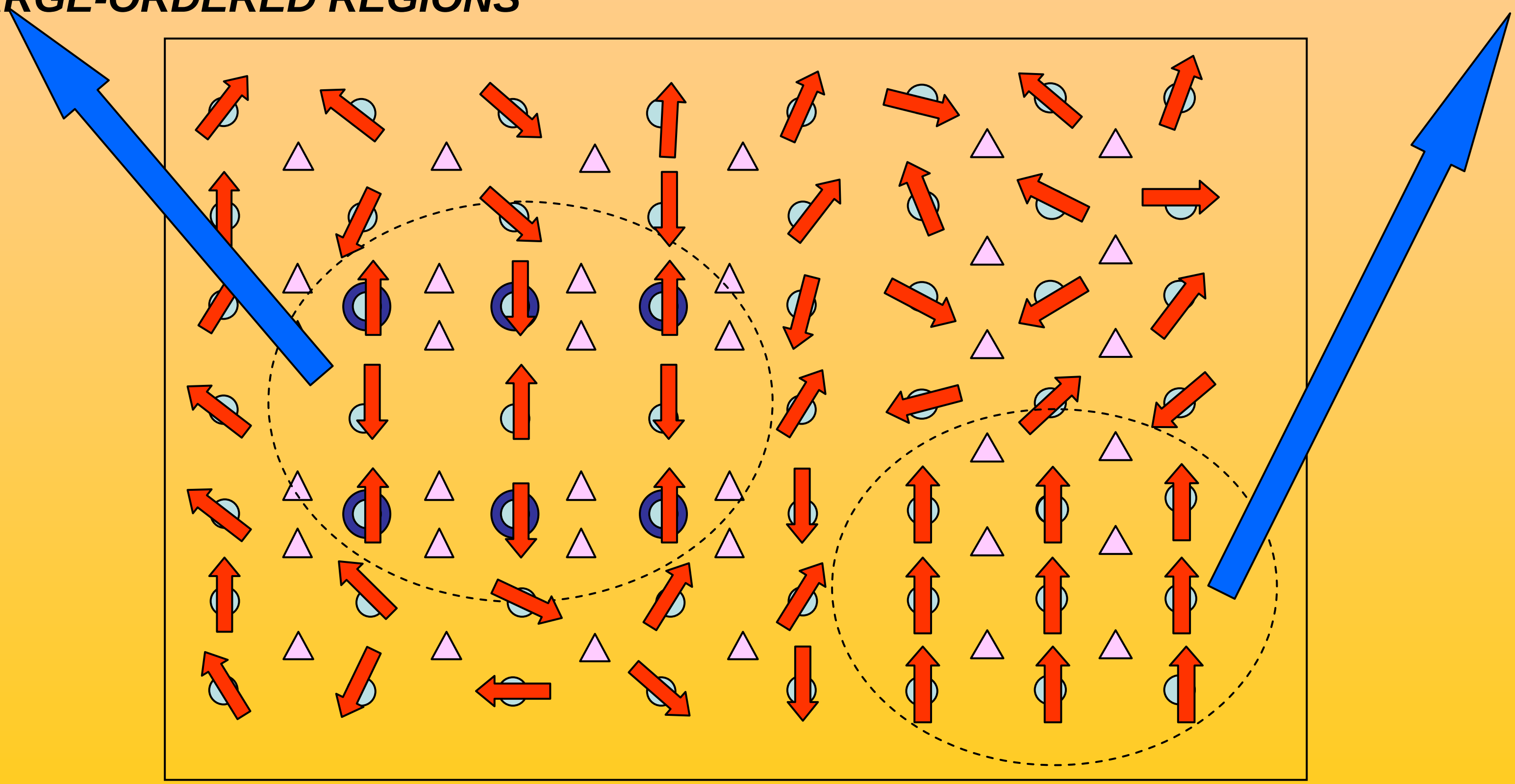
De Teresa et al., Nature 386 (1997) 256

THE REFINED PHASE SEPARATION SCENARIO

COEXISTENCE OF:

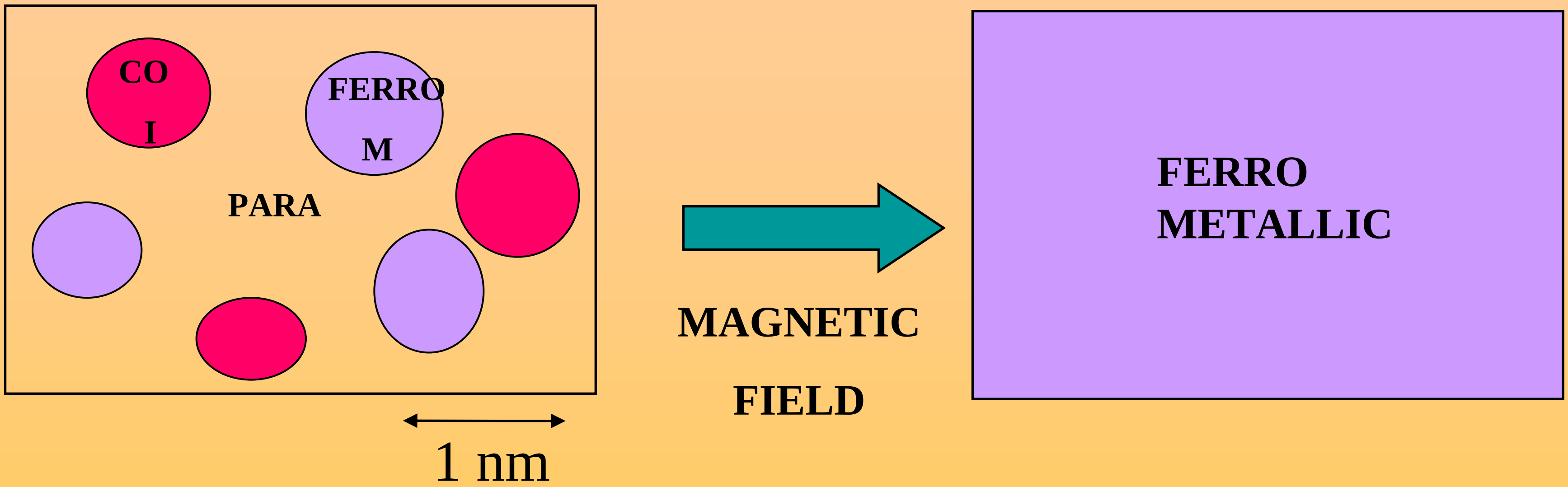
SHORT-RANGE ANTIFERROMAGNETIC CHARGE-ORDERED REGIONS

DOUBLE-EXCHANGE FERROMAGNETIC REGIONS

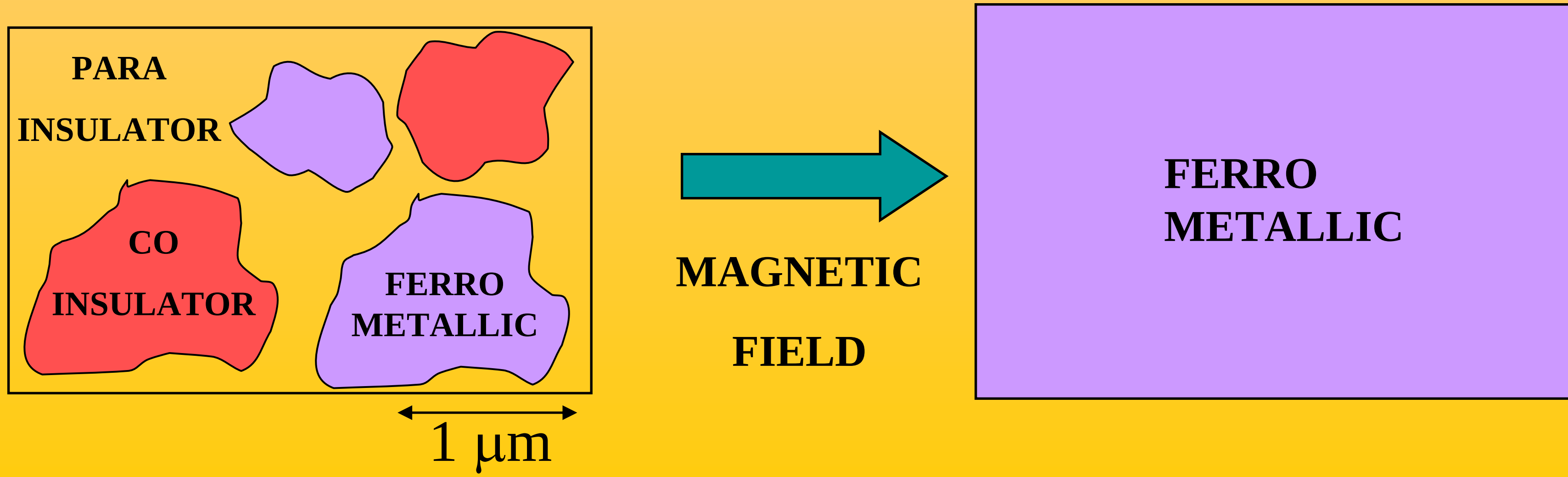


UNIFIED PICTURE OF THE CMR

NANOMETRIC PHASE SEPARATION: $La_{2/3}Ca_{1/3}MnO_{3}$, $La_{0.6}Y_{0.07}Ca_{0.33}MnO_{3}$, $Sm_{0.55}Sr_{0.45}MnO_{3}$



MICROMETRIC PHASE SEPARATION: $(La\text{-}Nd\text{-}Pr\text{-}Tb)_{2/3}Ca_{1/3}MnO_{3}$



IS THE PHASE SEPARATION SCENARIO FEASIBLE?

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

⇒THEORETICAL CALCULATIONS PREDICT THAT NANOMETRIC ELECTRONIC PHASE SEPARATION IS FAVOURED IN MODELS OF MANGANITES. HOWEVER MICROMETRIC ELECTRONIC PHASE SEPARATION IS FORBIDDEN.

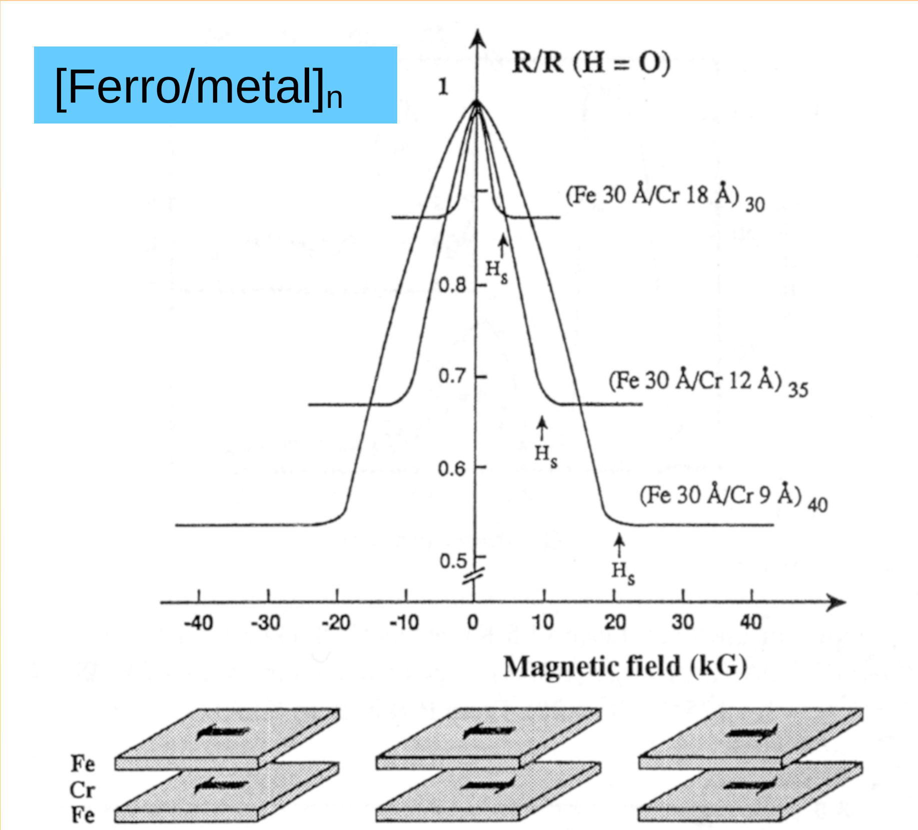
⇒RECENT EXPERIMENTS AND THEORETICAL CALCULATIONS SUGGEST THAT PHASE SEPARATION CAN BE ACHIEVED BY ***COMPETITION OF TWO INTERACTIONS PLUS THE PRESENCE OF DISORDER***

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

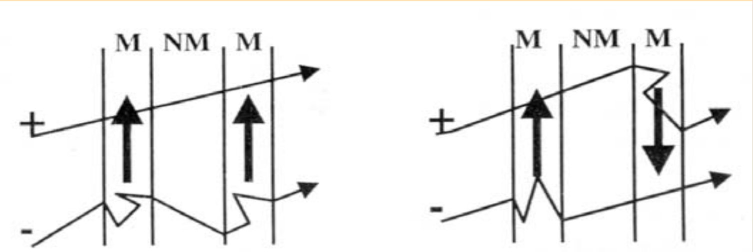
⇒**EXTRINSIC DISORDER** DUE TO SMALL LOCAL COMPOSITIONAL INHOMOGENEITIES AT THE NANOMETRIC LEVEL

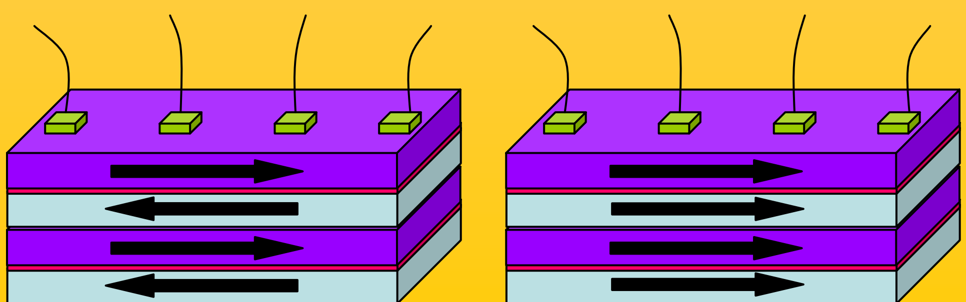
GIANT MAGNETORESISTANCE

GIANT MR (GMR)



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





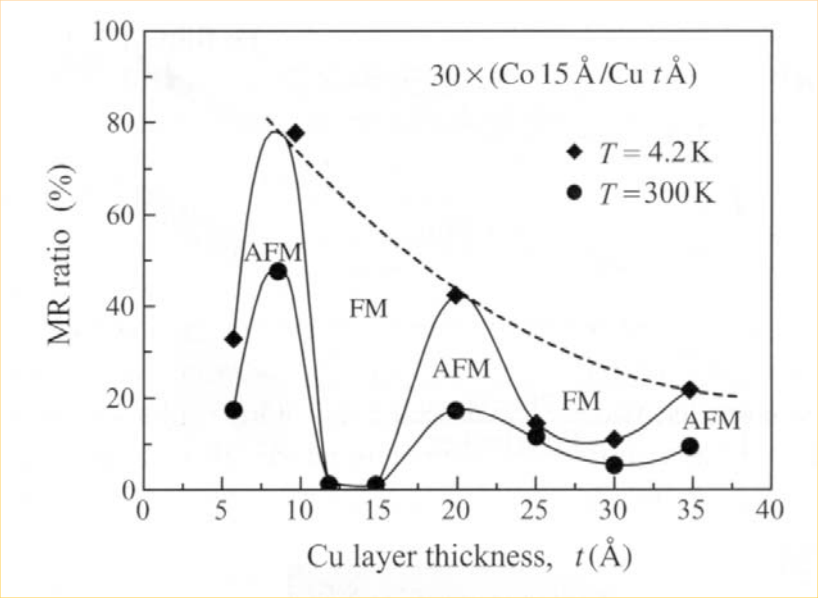
-The GMR effect was first observed in $[Fe/Cr]_n$ magnetic multilayers with layer thicknesses smaller than the electron mean free path.

-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

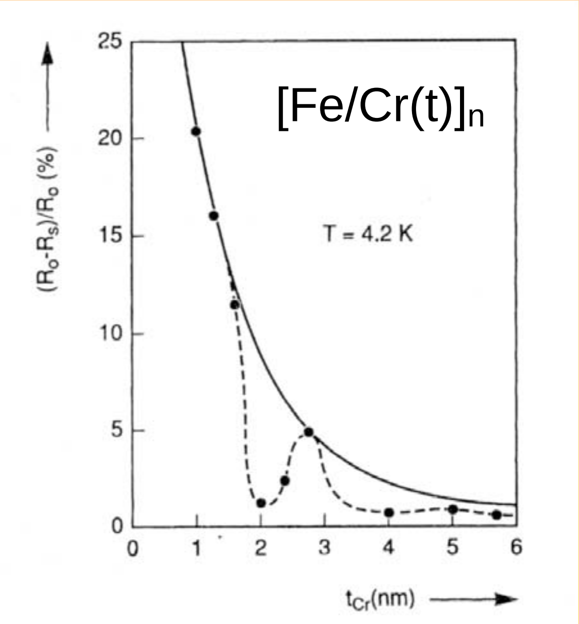
-Real applications of GMR came after the realization of the spin-valve concept, where the MR ratio is of the order of 10%

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

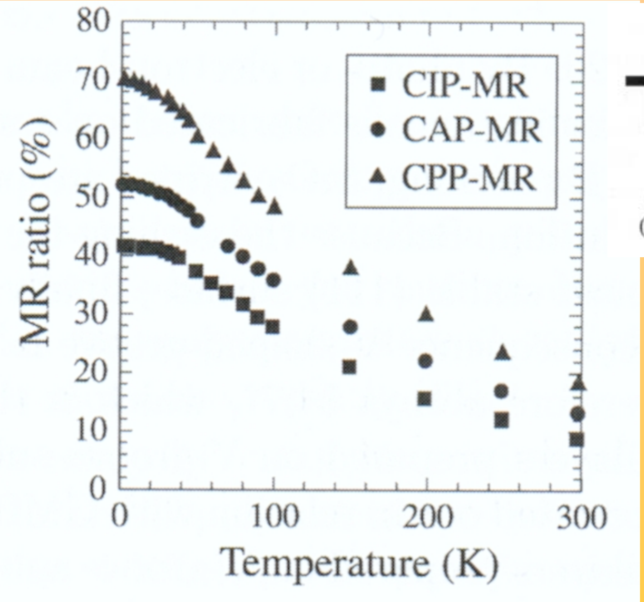


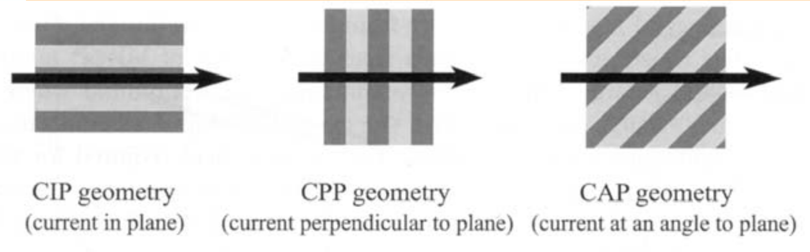
Gijs and Okada, Phys. Rev. B 46 (1992) 2908

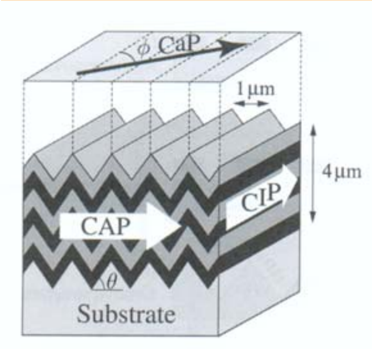
⇒THIS IS EXPLAINED BY THE ALTERNATING FERRO/ANTIFERRO MAGNETIC COUPLING OF THE MAGNETIC LAYERS THROUGH THE NON-MAGNETIC SPACER AND IS CONSISTENT WITH THE OSCILLATORY RKKY MAGNETIC INTERACTION

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







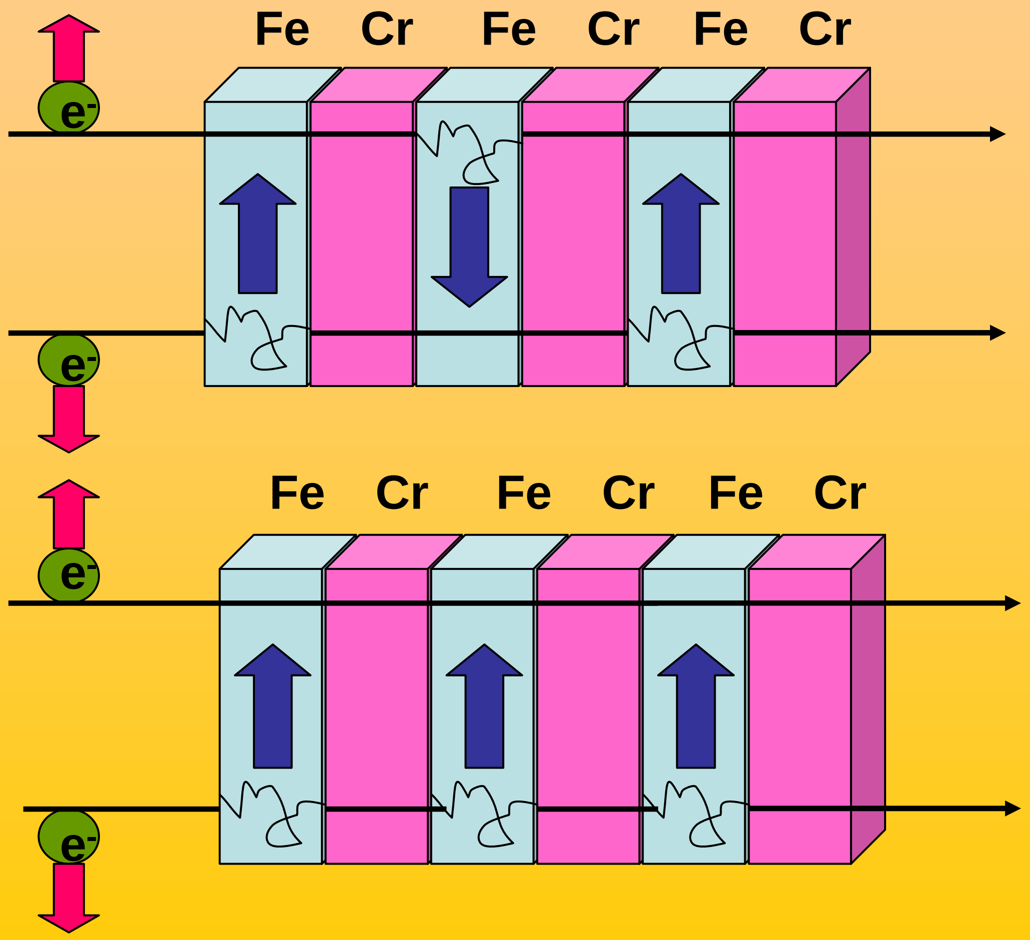
Ono et al., Phys. Rev. B 55 (1997) 14457

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.



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

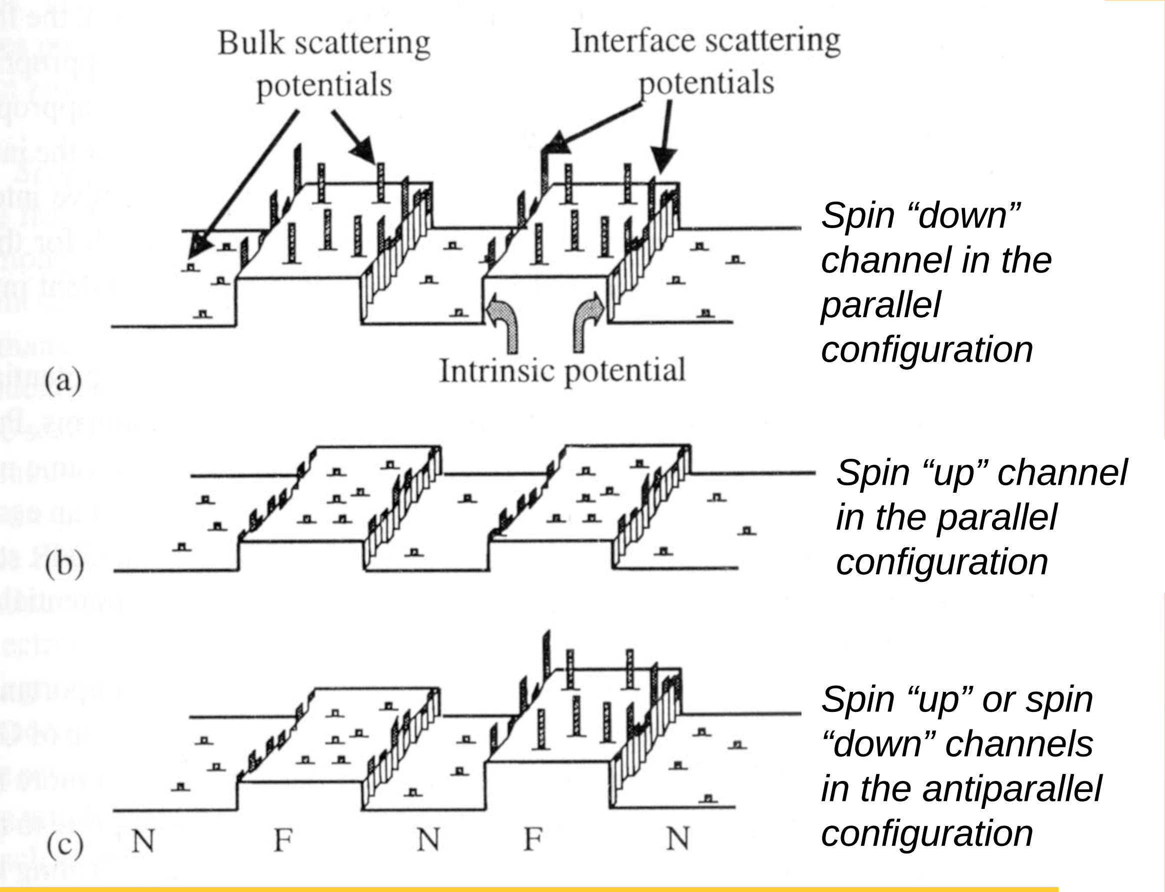
$$\rho_\downarrow = m_\downarrow / (n_\downarrow e^2 \tau_\downarrow)$$

$$\left.\begin{array}{r} \rho_\uparrow \neq \rho_\downarrow \\[1em] \rho_{AP} = \dfrac{\rho_\uparrow + \rho_\downarrow}{4} \\[1em] \rho_P = \dfrac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \end{array}\right\}$$

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

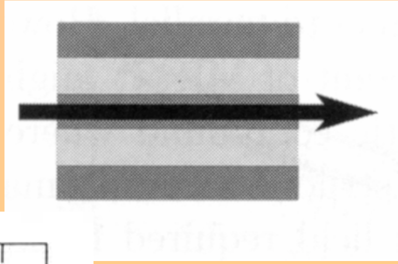
GIANT MR (GMR): theoretical approaches

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



-If the mean free path is shorter than the layers thickness, a "layer-by-layer" approach is enough. Otherwise, "supperlattice" models are required where interference between succesive reflections must be considered.

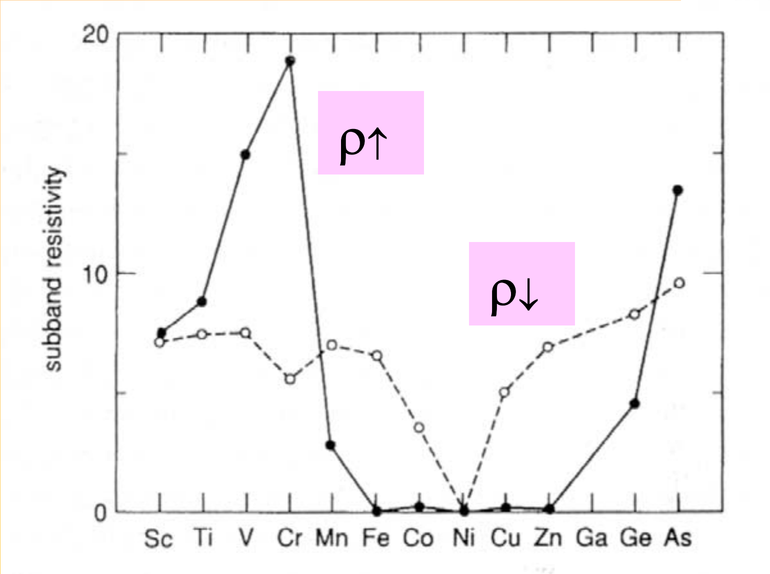
GIANT MR (GMR): theoretical approaches for CIP-GMR



-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

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

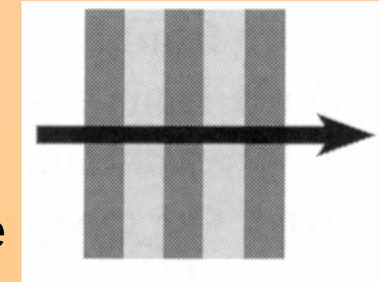


-Later, the **intrinsic potential effects** were progressively introduced into the models in addition to the scattering potentials. Interference between succesive reflections are normally not important in real experiments.

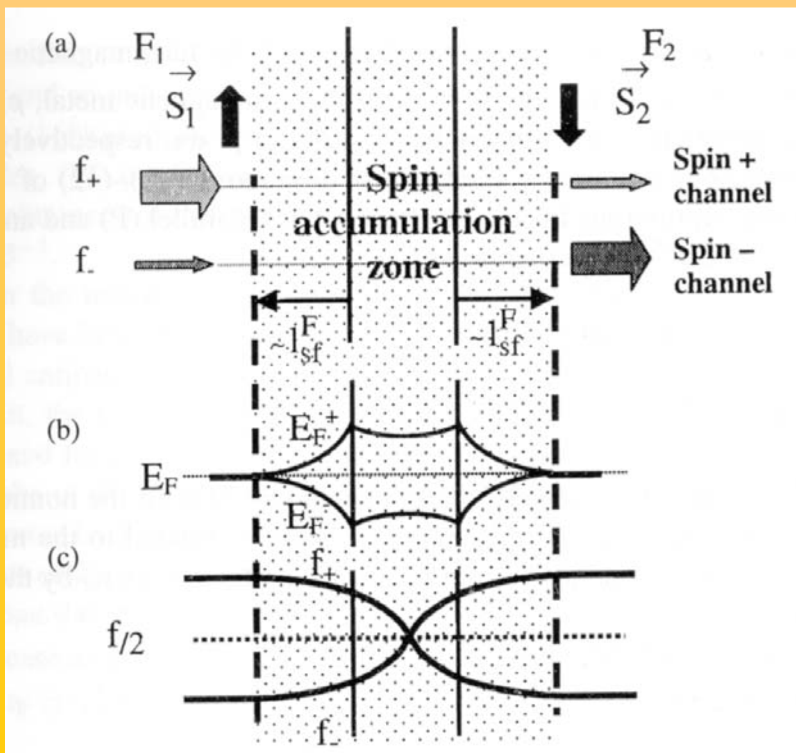
-All previous models assume **diffusive transport** (system size larger than the mean free path). Some models have also addressed the **ballistic regime of the GMR** (to be realized in systems with very few impurities or nanocontacts)

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

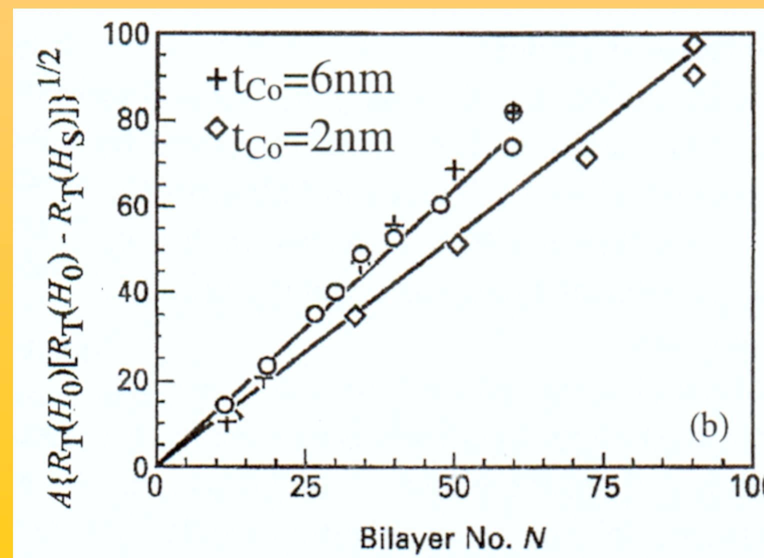
-The intrinsic contribution to the CPP-GMR can be normally expressed through the concept of "**interface resistance**", which has contributions from the potential steps at the interface plus interface diffuse scattering by defects/dopants.



-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** becomes the most relevant scaling length.

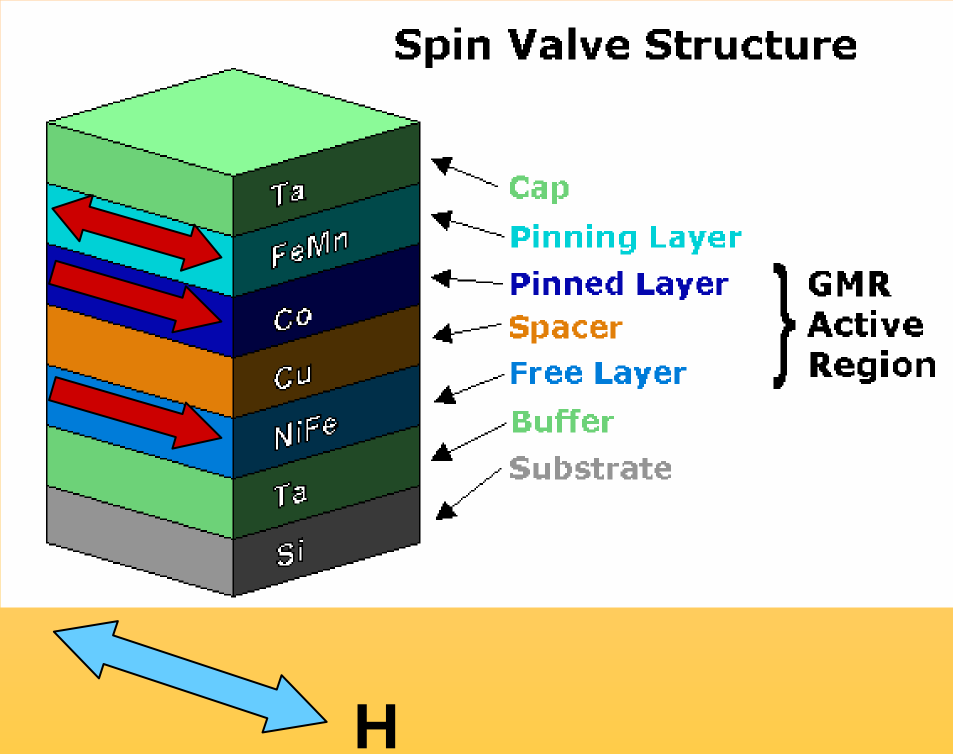


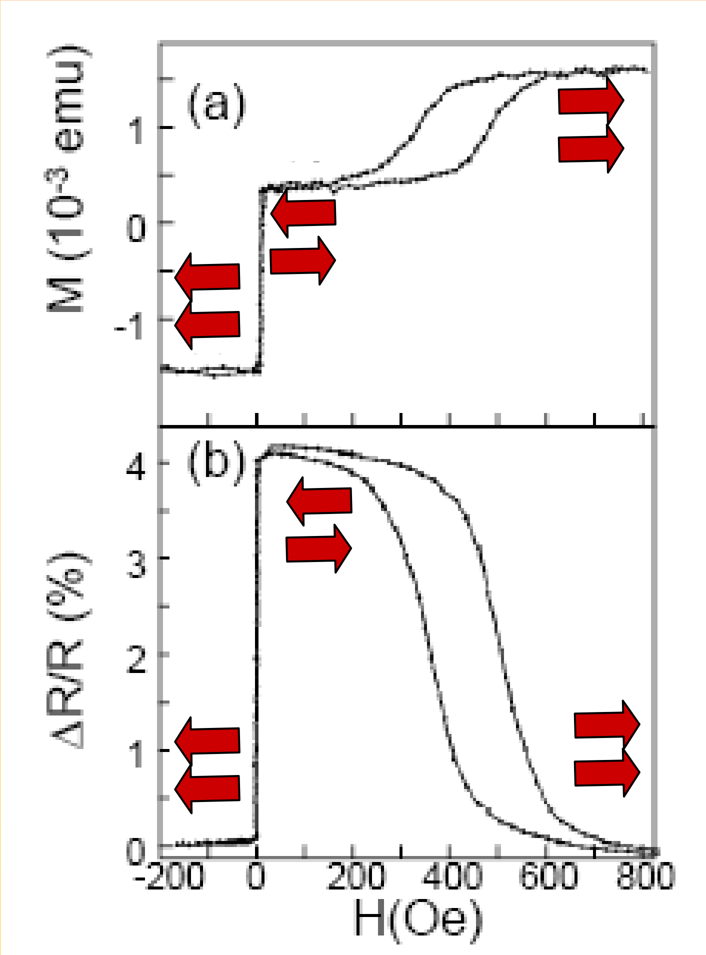
[Co/Ag(d)]$_N$; L=0.72 μm



(for detailed formulas, please read the abovementioned review)

GIANT MR (GMR): THE SPIN-VALVE CONFIGURATION





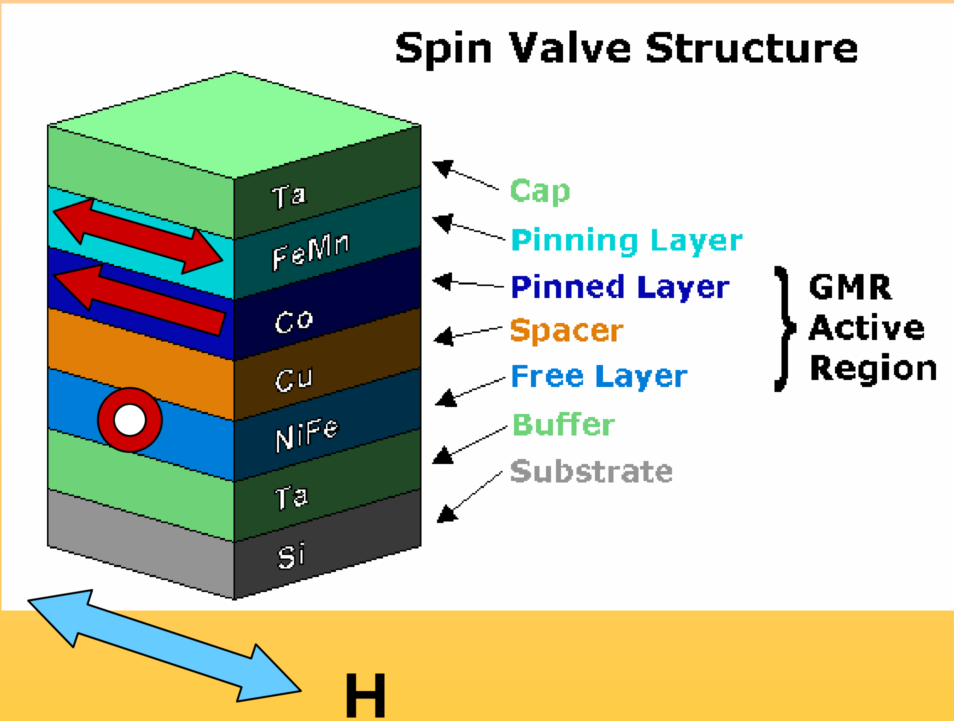
B. Dieny et al., J. Appl. Phys. 69 (1991) 4774

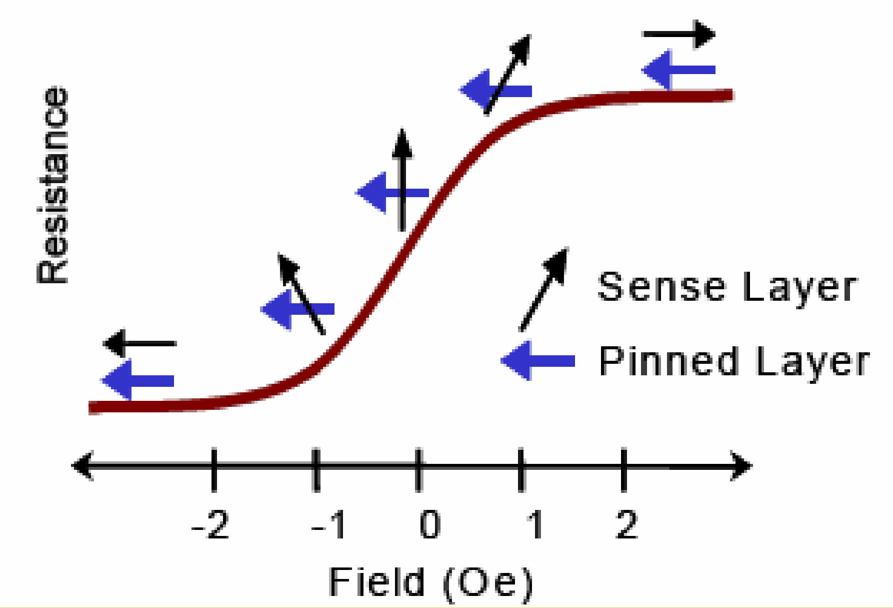
⇒THIS CONCEPT IS VERY USEFUL FOR APPLICATIONS DUE TO THE LOW FIELD REQUIRED TO GET A SIGNIFICANT MR RESPONSE BUT THE AMPLITUDE OF THE EFFECT IS SIGNIFICANTLY REDUCED

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

GIANT MR (GMR)

****CROSSED GEOMETRY OF THE EASY DIRECTIONS OF ELECTRODES FOR GMR-BASED DEVICES**



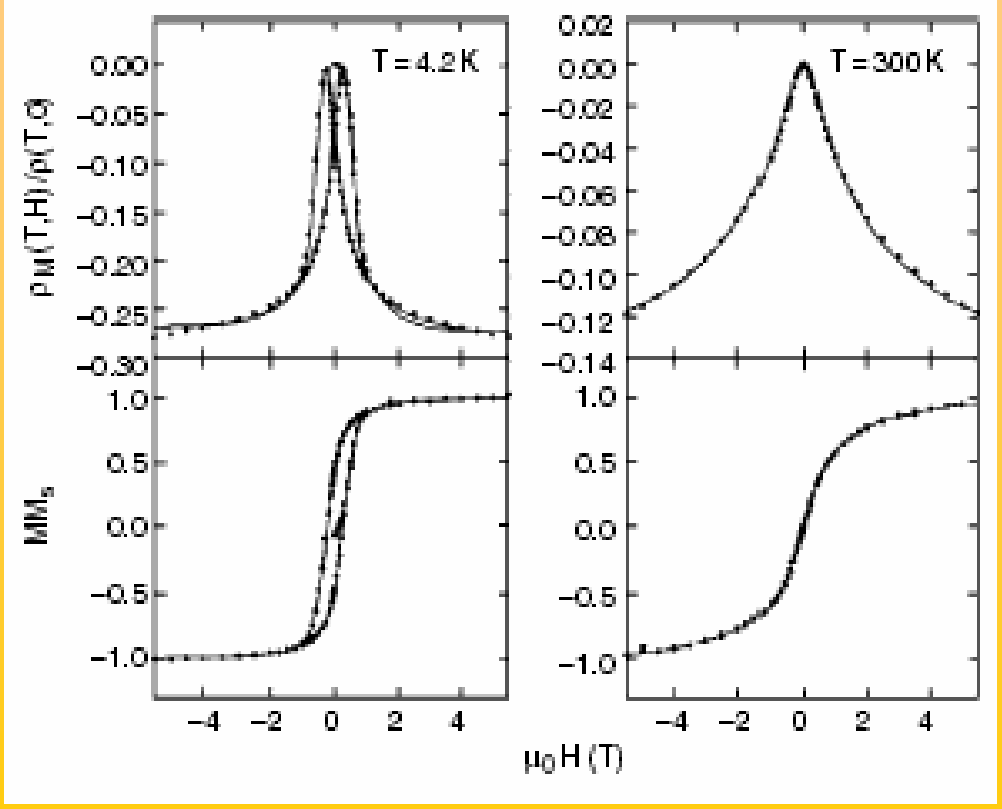


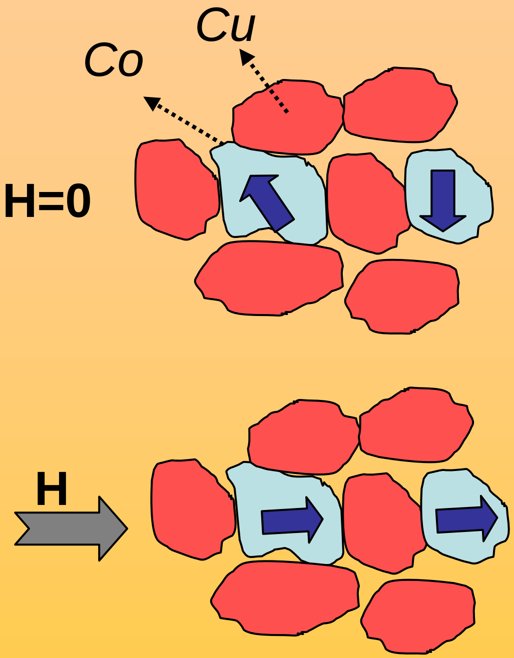
⇒*THE LINEAR RESPONSE AS A FUNCTION OF THE APPLIED MAGNETIC FIELD IS VERY USEFUL TO SENSE LOW MAGNETIC FIELDS OF APPLICATION IN CERTAIN MAGNETIC SENSORS*

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

GIANT MR (GMR) IN GRANULAR MATERIALS

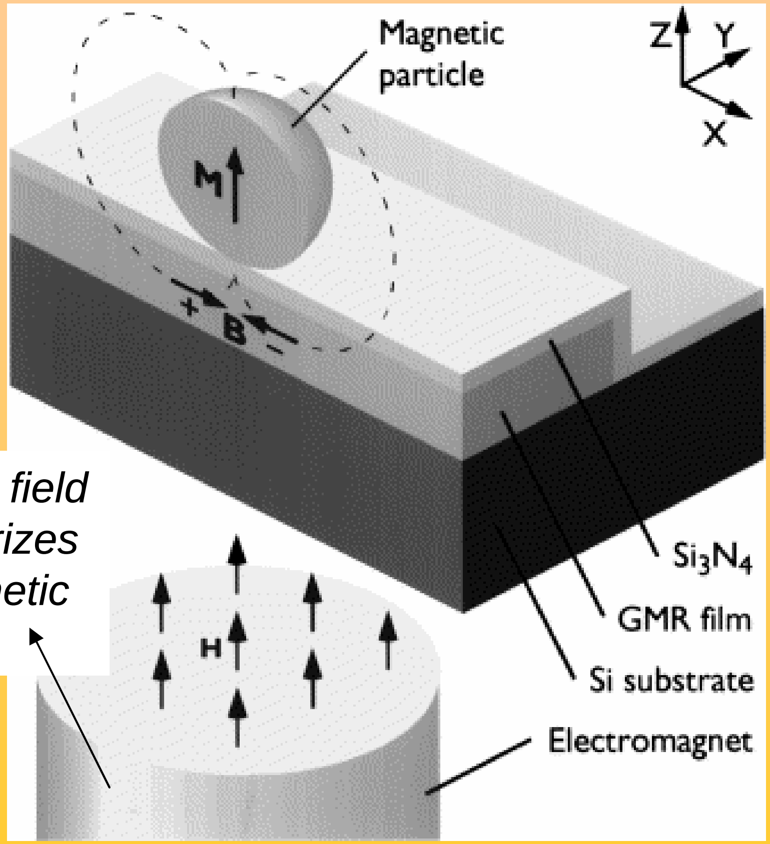
-The GMR effect can be realized in granular materials / thin films with immiscible magnetic/non-magnetic metals due to the same physical phenomena. The type of response is less suitable for applications





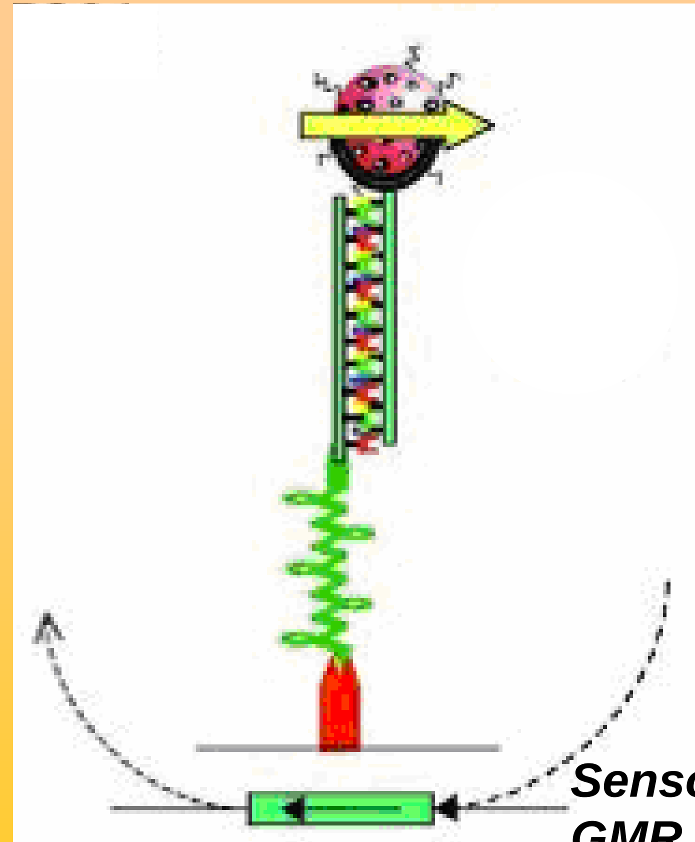
Berkowitz et al., Phys. Rev. Lett. 68 (1992) 3745; Xiao et al., Phys. Rev. Lett. 68 (1992) 3749; Wang and Xiao, Phys. Rev. B 50 (1994) 3423; Batlle and Labarta, J. Phys. D: Appl. Phys. 35 (2002) R15

GMR: application in the detection of biological activity



Magnetic field that polarizes the magnetic particles

D.R. Baselt et al., Biosensors and Bioelectronics 13 (1998) 731

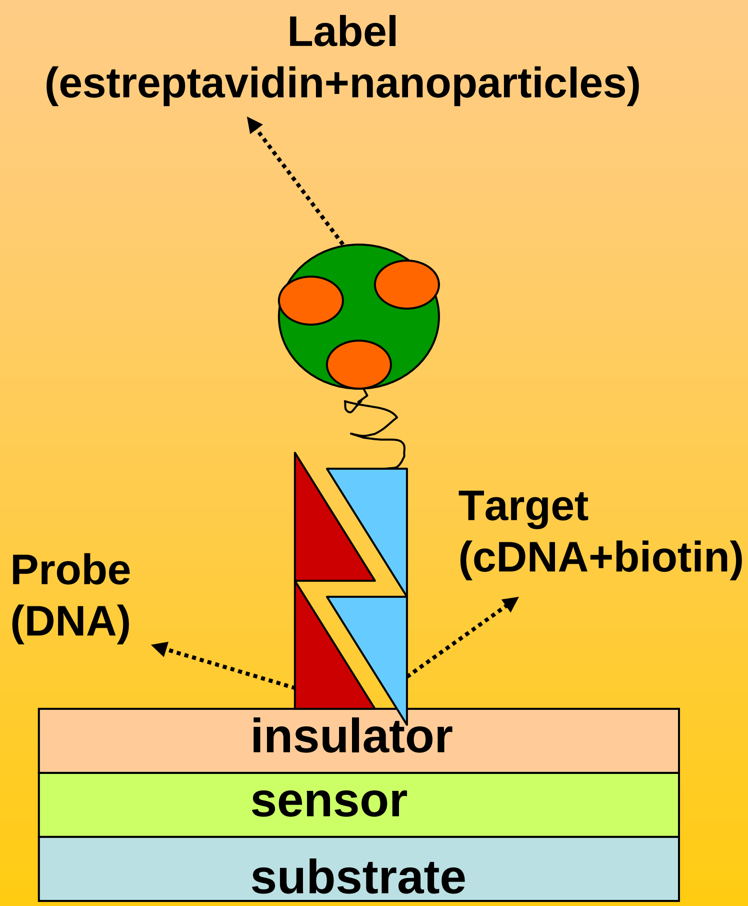


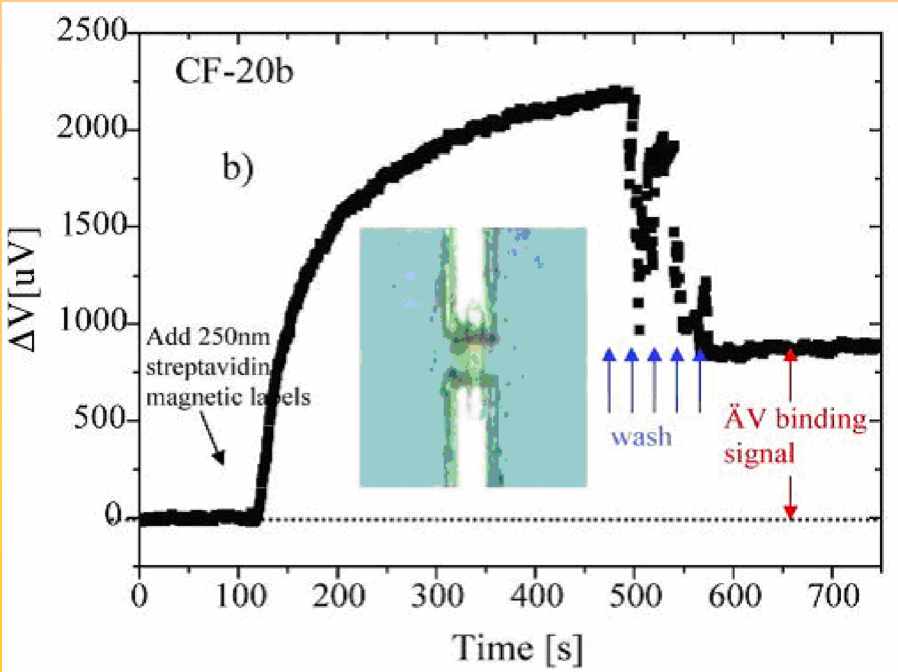
Sensor GMR

P.P Freitas et al., Europhysics News 34 (2003) 224

GMR: application in the detection of biological activity

DETECTION OF THE GENE RESPONSIBLE FOR CYSTIC FIBROSIS CFTR (via DNA-cDNA hybridization, labelled with estreptavidin+nanoparticles)



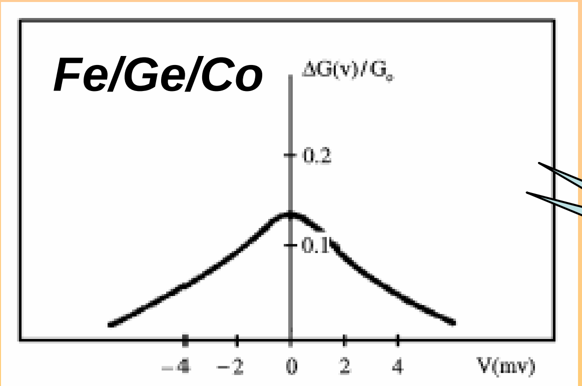


P.P Freitas et al., Europhysics News 34 (2003) 224

TUNNEL MAGNETORESISTANCE

TUNNEL MAGNETORESISTANCE (TMR): how it all started

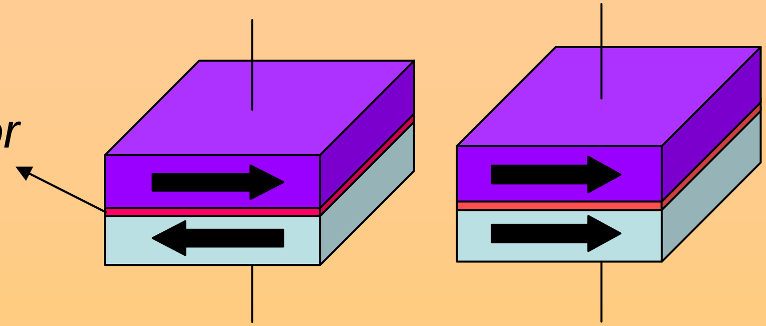
Fe/Ge/Co



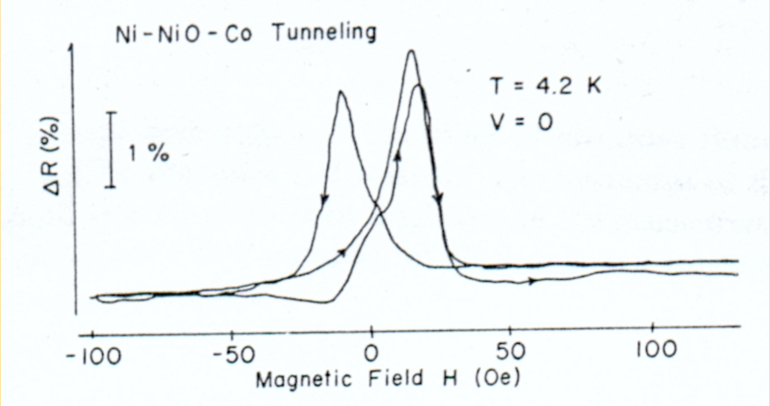
Julliere, Phys. Lett. 54A (1975) 225

1975

insulator



1982



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

1995

$CoFe/Al_2O_3/Co$

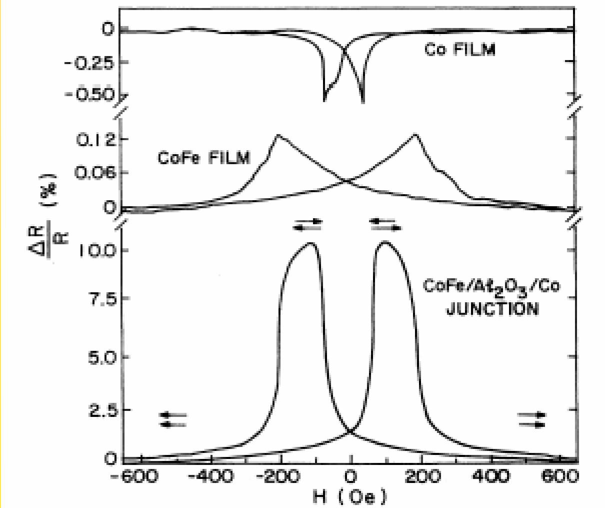
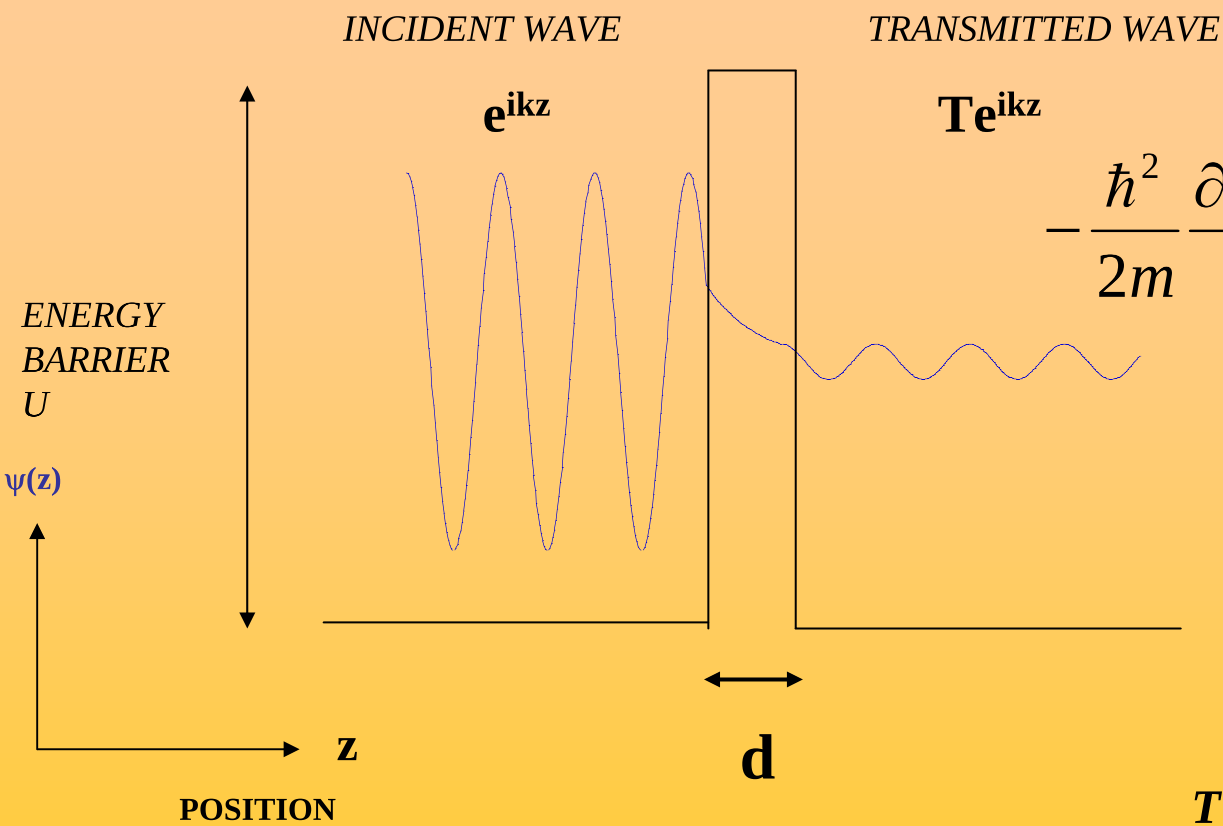


FIG. 2. Resistance of CoFe/Al$_2$O$_3$/Co junction plotted as a function of H in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of M in the two films (see text).

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:

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

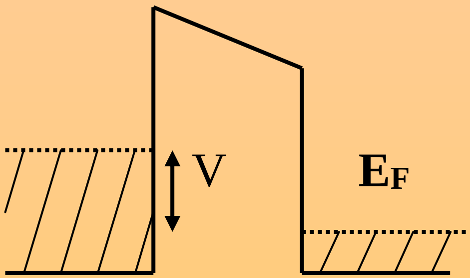
$$J_k\,\alpha\left|T_k\right|^2\alpha e^{-2k'd}$$

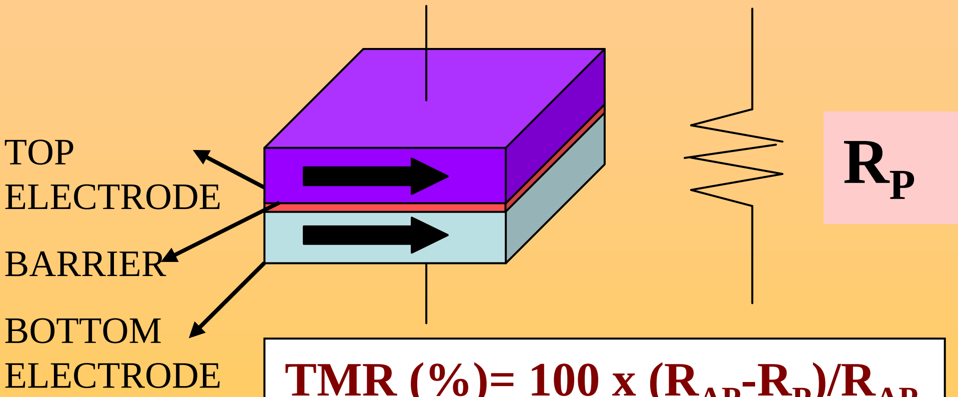
EXPONENTIAL DEPENDENCE OF THE CURRENT WITH THE BARRIER WIDTH AND THE SQUARED ROOT OF THE BARRIER HEIGHT

TMR: the basics of magnetic tunnel junctions

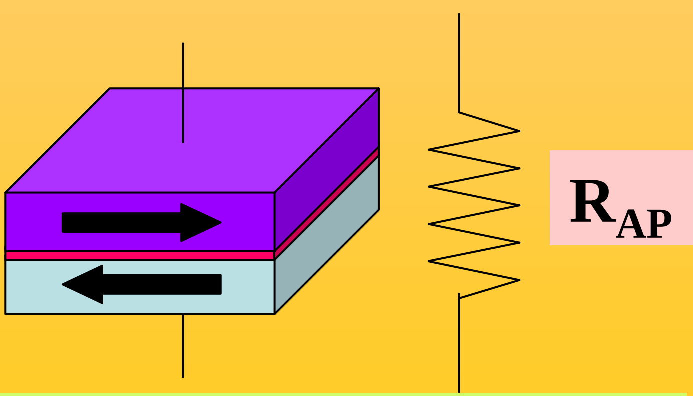
F1 / I / F2

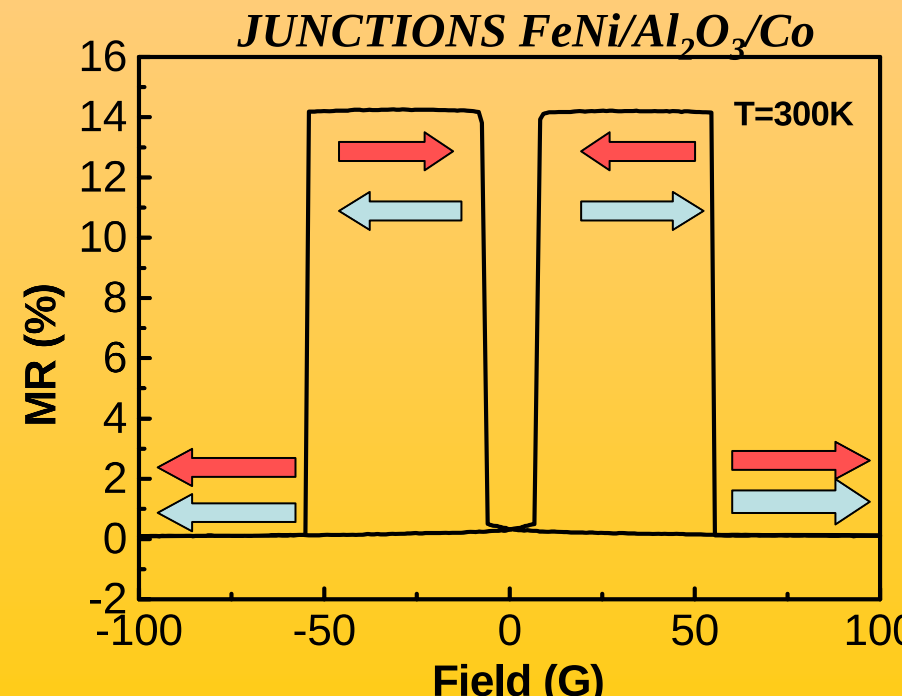
⇒ **MAGNETIC TUNNEL JUNCTIONS ARE FORMED BY TWO MAGNETIC MATERIALS (ELECTRODES) SEPARATED BY A NANOMETRIC INSULATING LAYER (BARRIER). CONDUCTION TAKES PLACE THROUGH TUNNELLING.**





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





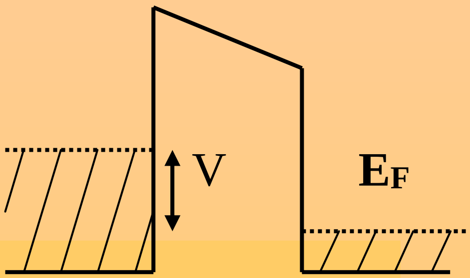
TMR=100 x $2P_1P_2/(1+P_1P_2)$
(Julliere's model)

TMR: the idea behind Julliere's model

F1 / I / F2

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

$$\frac{I}{V}\alpha\left|T(E_F)\right|^2 N_1(E_F)N_2(E_F) \xrightarrow{\text{APROX.}} \frac{I}{V}\alpha N_1(E_F)N_2(E_F)$$



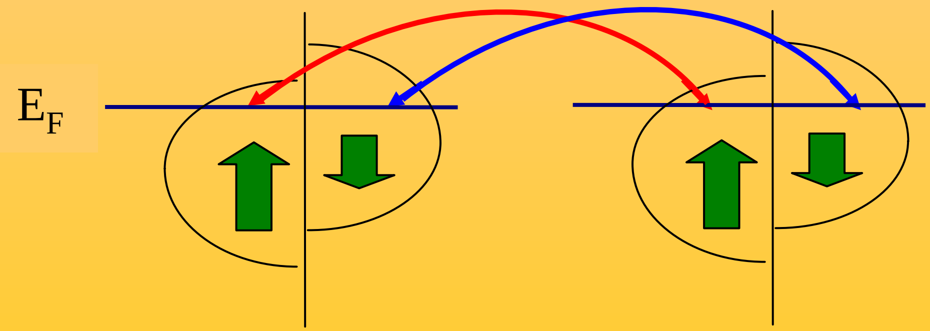
***IF THE SPIN IS CONSERVED*:**

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

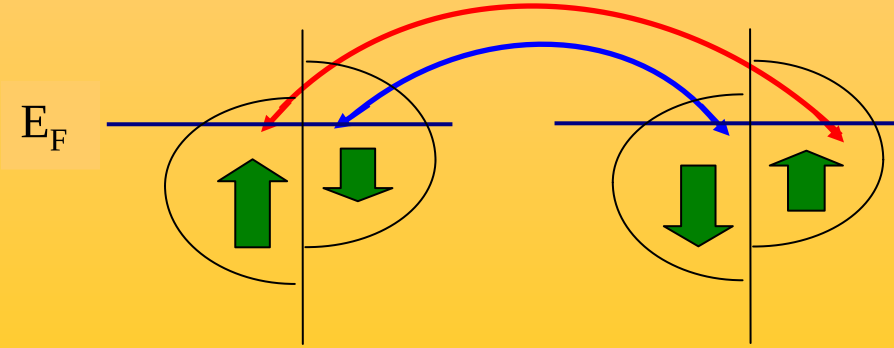
MAJORITY	MINORITY



$I_P \,\alpha\, (1+P_1)(1+P_2) + (1-P_1)(1-P_2) = 2(1+P_1P_2)$

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: other features

⇒**SIMMONS' FORMULAS FOR THE GENERAL CALCULATIONS OF THE UNPOLARIZED TUNNELLING CONDUCTANCE [J. Appl. Phys. 34 (1963) 1793]: I vs V linear at low voltages, non-linear at intermediate voltage levels. Breakdown occurs at high voltage.**

⇒**SLONCZEWSKI'S MODEL FOR SPIN-DEPENDENT TUNNELLING OF FREE ELECTRONS [Phys. Rev. B 39 (1989) 6995]: unlike the original Julliere's model, the expected TMR depends on the type of barrier.**

For further details and full formulas on these previous models, please download the following file (slides corresponding to the presentation on spin tunnel and spin polarization by L. Ranno in the previous european school on magnetism in Brasov in 2003):

http://lab-neel.grenoble.cnrs.fr/euronanomag/2003-brasov/slides/ranno-slides-1.pdf

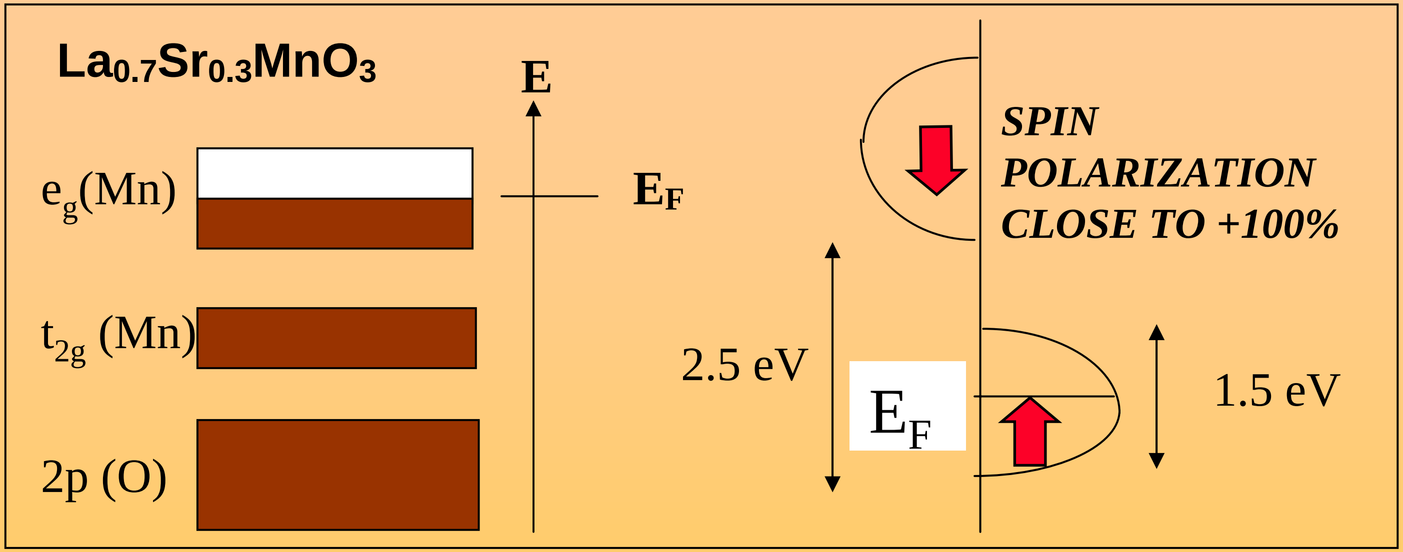
⇒**MACLAREN ET AL. SHOW THAT JULLIERE'S AND SLONCZEWSKI'S MODELS ARE ONLY ROUGH APPROXIMATIONS [Phys. Rev. B 56 (1997) 11827]: detailed calculations should incorporate true band structures in the presence of the interfaces as well as the dependence on the barrier properties**

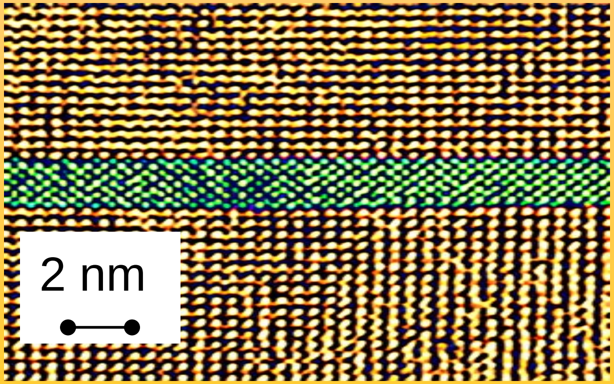
⇒**IT IS EXPERIMENTALLY OBSERVED THAT THE RESISTANCE AS WELL AS THE MAGNETORESISTANCE DECREASE WHEN INCREASING THE TEMPERATURE.**

⇒**IN ORDER TO ASCERTAIN THE TUNNELLING EFFECT VERSUS PINHOLES CONDUCTION, SOME CRITERIA HAVE BEEN ESTABLISHED [Akerman et al., Appl. Phys. Lett. 79 (2001) 3104].**

Constanta, European School on Magnetism 2005

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



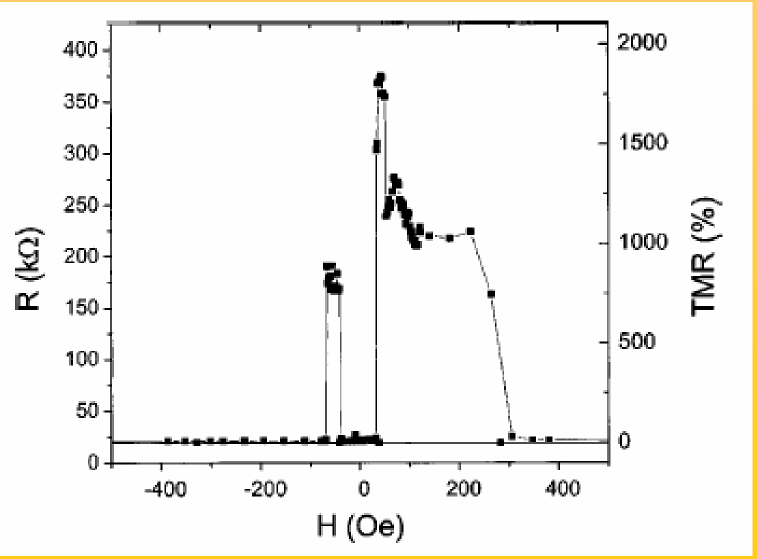


$La_{0.7}Sr_{0.3}MnO_3$

$SrTiO_3$

$La_{0.7}Sr_{0.3}MnO_3$

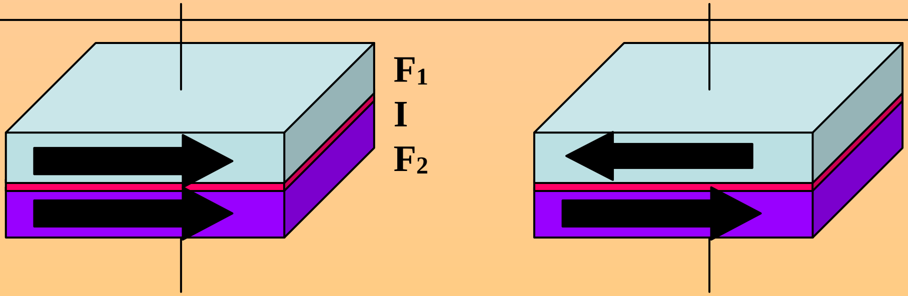
TEM picture by J.L. Maurice



Bowen., Appl. Phys. Lett. 82, 233 (2003) and references therein

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

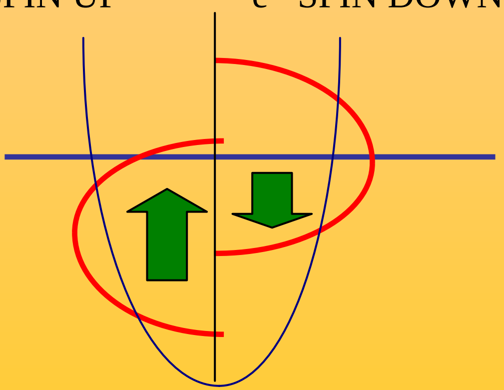
TMR: understanding the TMR effect



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

MAJORITARY e-"SPIN UP"

MINORITARY e-"SPIN DOWN"



FERMI ENERGY

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 $\Rightarrow$ lower density of states, positively polarized, more delocalized electrons

"d-type" BANDS $\Rightarrow$ higher density of states, negatively polarized, more localized electrons

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.

$$100*\frac{(R_{AP}-R_P)}{R_P}=TMR(\%)=200x\frac{P_1P_2}{(1+P_1P_2)}$$

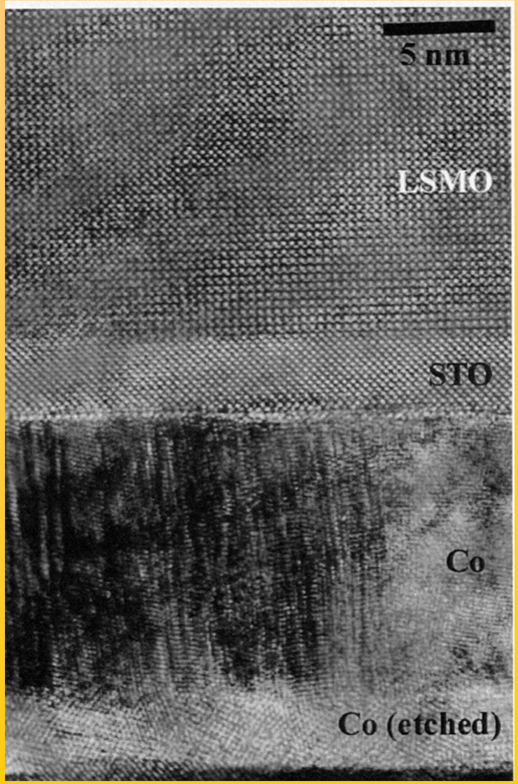
$$\begin{cases} * \ P\,(La_{0.7}Sr_{0.3}MnO_3) \approx +100\% \\ * \ P\,(Co) = ? \end{cases}$$

$\boxed{\begin{array}{l} \text{If } P(Co) > 0 \Rightarrow TMR(\%) > 0 \\ \text{If } P(Co) < 0 \Rightarrow TMR(\%) < 0 \end{array}}$

$La_{0.7}Sr_{0.3}MnO_3$

$SrTiO_3$

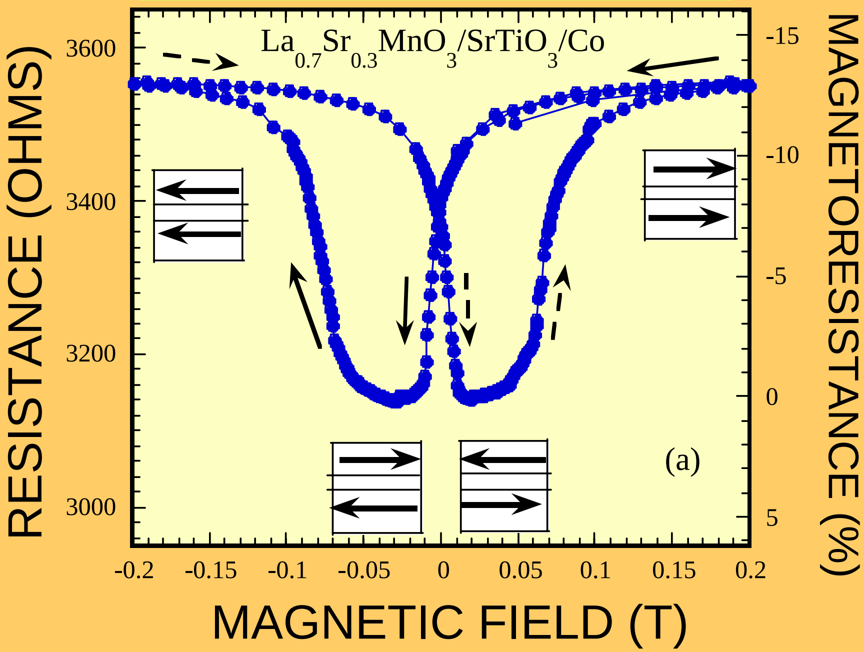
Co



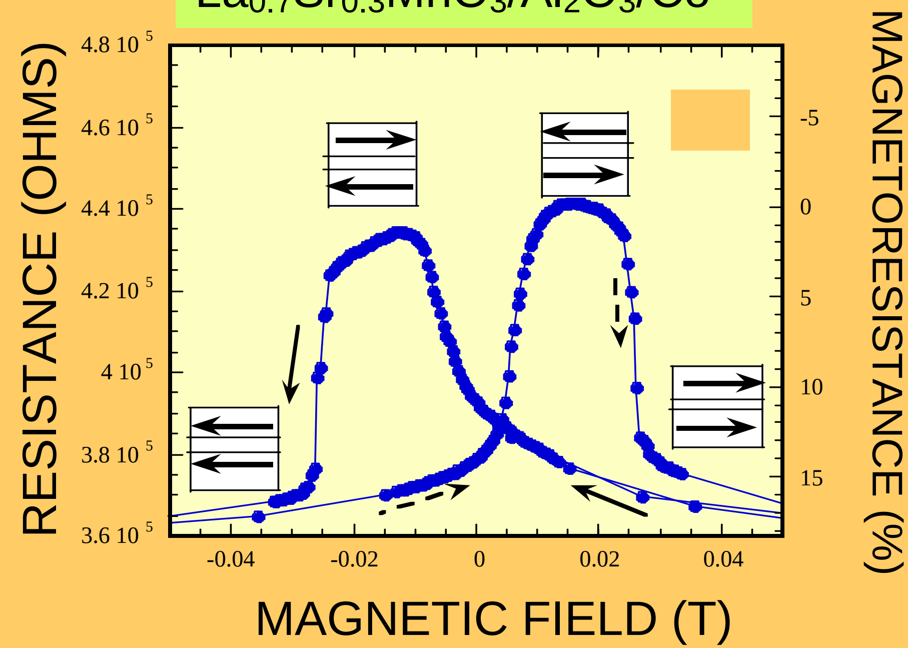
TEM IMAGE BY J.L. MAURICE

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

$R_P < R_{AP}$

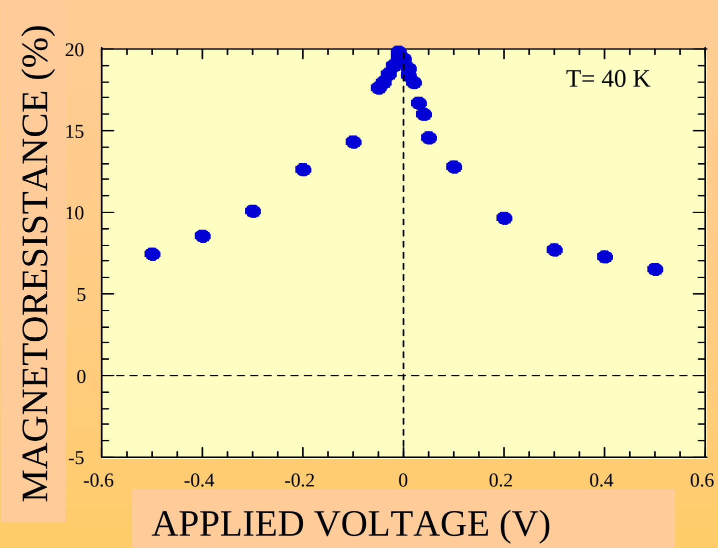
P(Co) IS POSITIVE

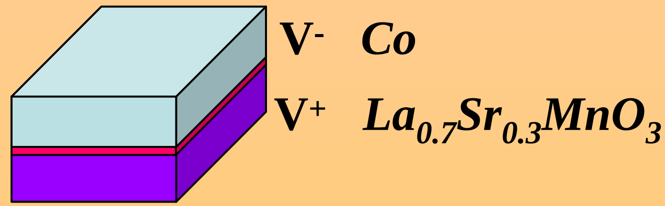
$$\mathrm{TMR} \propto P_{(LSMO)}P_{(Co)} / [1 + P_{(LSMO)}P_{(Co)}]; \quad \text{with } P_{(LSMO)} > 0$$

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

TMR: understanding the TMR effect

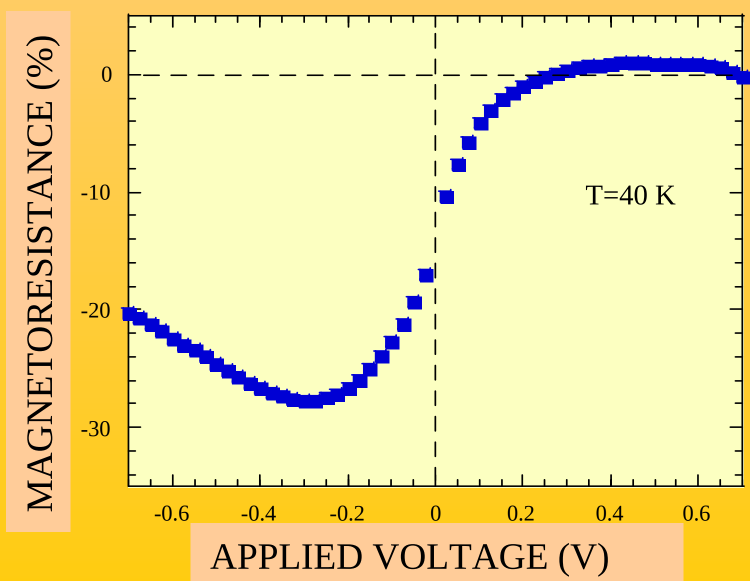
DEPENDENCE OF THE TUNNEL MAGNETORESISTANCE WITH VOLTAGE



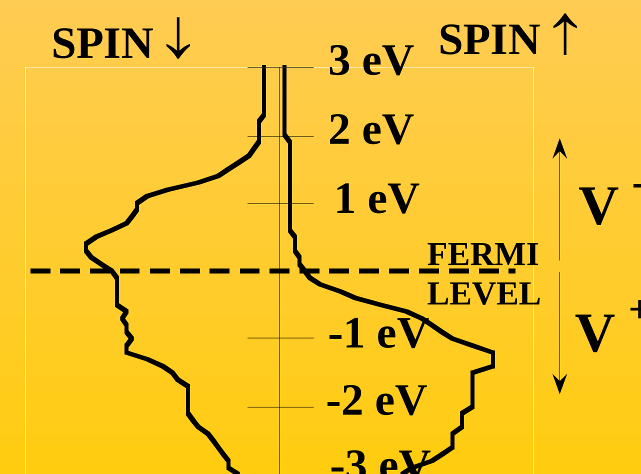


I= Al_2O_3: CURRENT BY "s-type" ELECTRONS

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

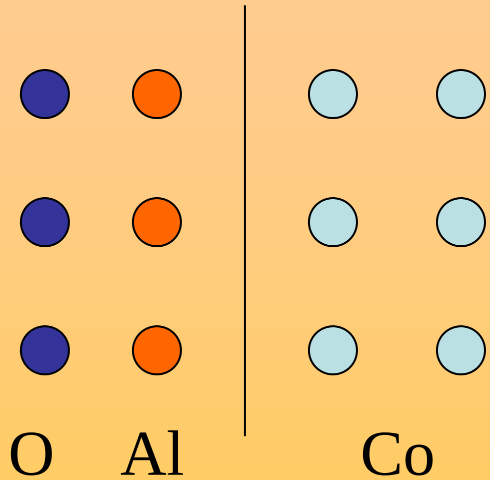


Co "d" electrons



TMR: understanding the TMR effect

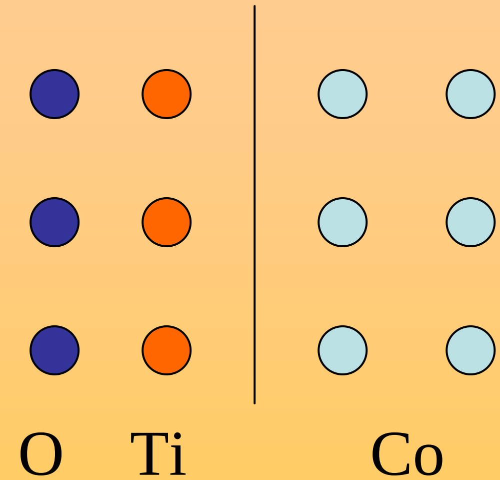
Al_2O_3/Co INTERFACE



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., Nanoletters, in press.)

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

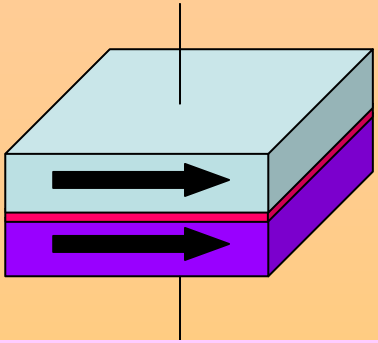
-BAND STRUCTURE OF THE INSULATOR

-BONDING AND MATCHING EFFECTS AT THE INTERFACE FERROMAGNET-INSULATOR+ RESONANT STATES +TRANSMISSION OF THE TUNNELLING ELECTRONS

⇒ COMPARISON BETWEEN THEORY AND EXPERIMENT REQUIRES FULL EPITAXIAL TUNNEL JUNCTIONS (the most successful steps in this direction have been given on the Fe/MgO/Fe system, as we will see later)

CSIC

TMR: application in Magnetic Random Access Memories (MRAM)

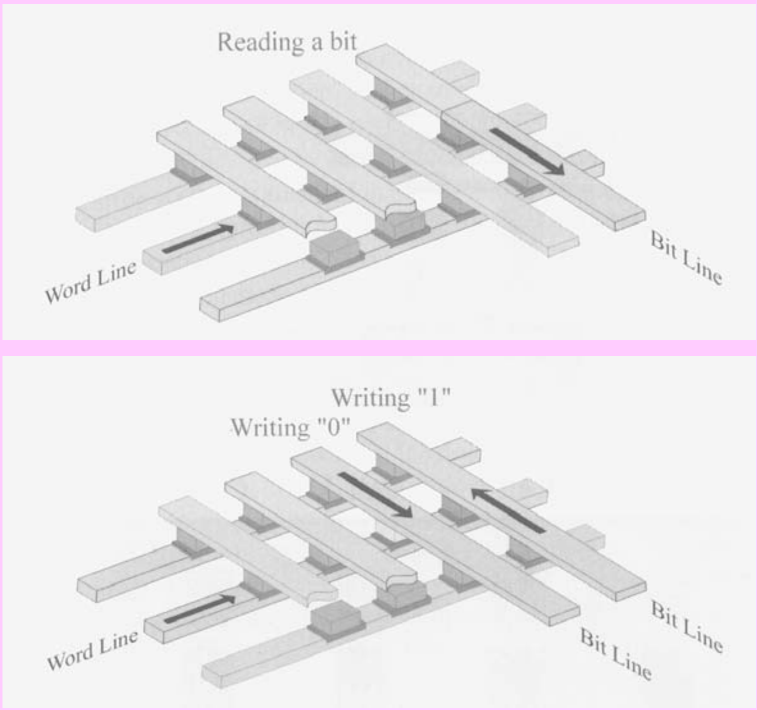


-The "universal" memory should have the speed of "SRAM", the density of "DRAM" and non volatility as "FLASH". The MRAM is supposed to attain all these features

ADVANTAGES OF MRAM:

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

APPLICATIONS IN MEMORIES FOR: ***MOBILE PHONES, DIGITAL CAMERAS, LAPTOP COMPUTERS, INTELLIGENT CARDS,...***

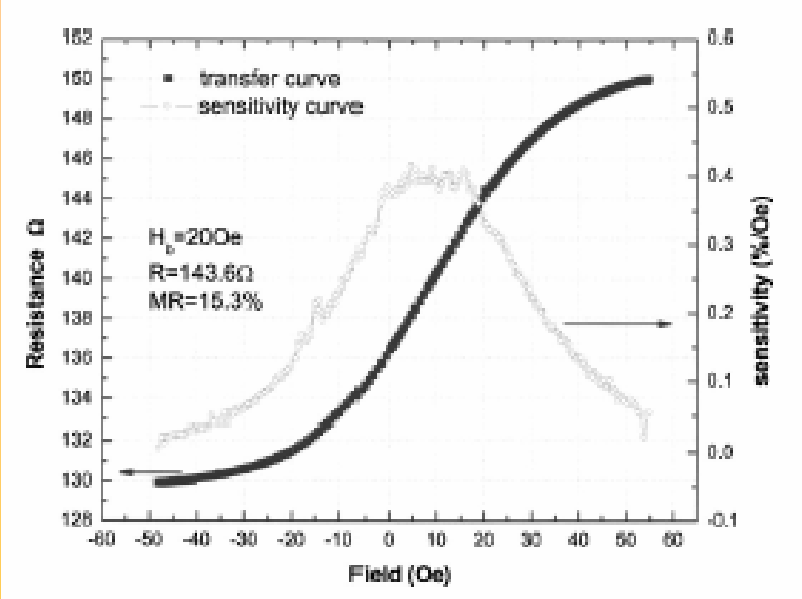


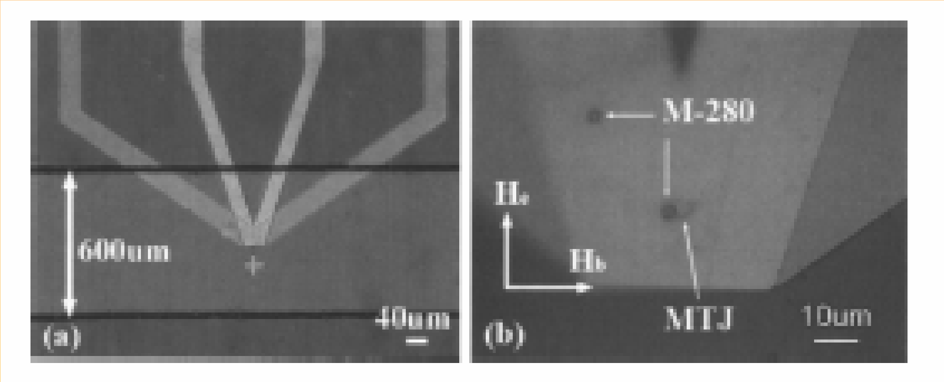
****COMPANIES PRESENTLY WORKING ON FIRST-GENERATION MRAM PROTOTYPES:ANELVA, CYPRESS, DESPATCH, FREESCALE (=MOTOROLA SEMICONDUCTOR), IBM, INFINEON, MICROMEM, NVE, SPINTRON, HONEYWELL***

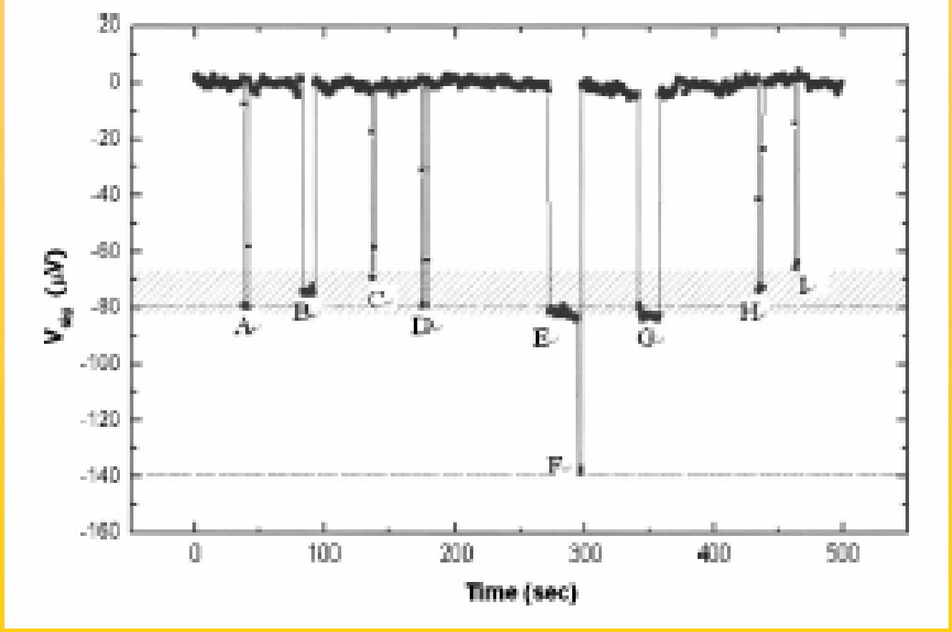
For a review on the history of memories, see Parkin in "Spin dependent transport in Magnetic Nanostructures", edited by Maekawa and Shinjo, Taylor and Francis

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

TMR: detection of biological hybridization by means of microfluidics and magnetic tunnel junction sensors





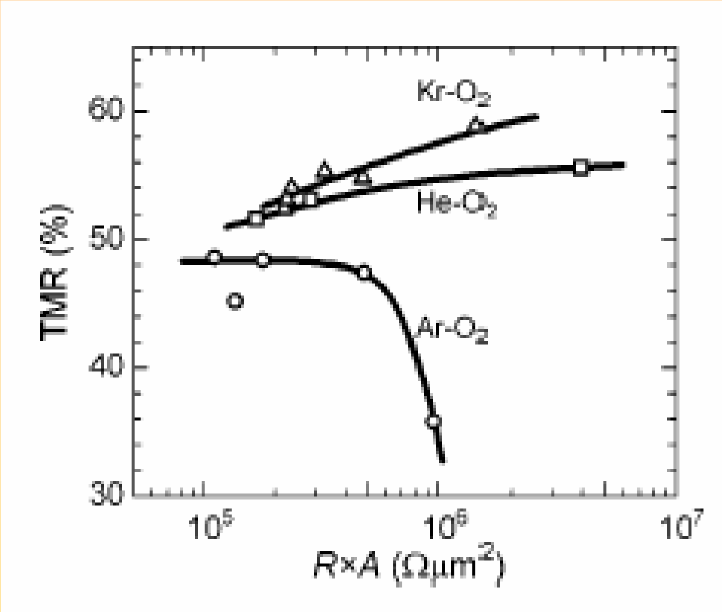


*A.C. External magnetic field and lock-in detection
*Wheastone bridge configuration

W. Shen et al., Appl. Phys. Lett. 86 (2005) 253901

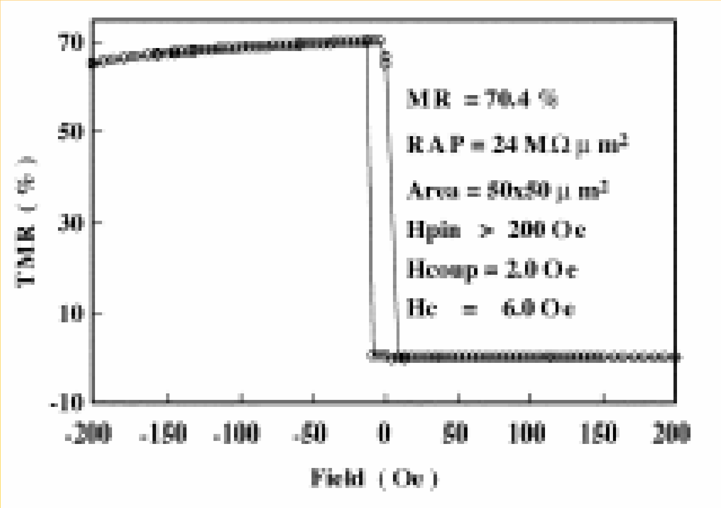
TMR: MR limitation (~70%) in Al_2O_3-based magnetic tunnel junctions

Optimization of the Al plasma-oxidation



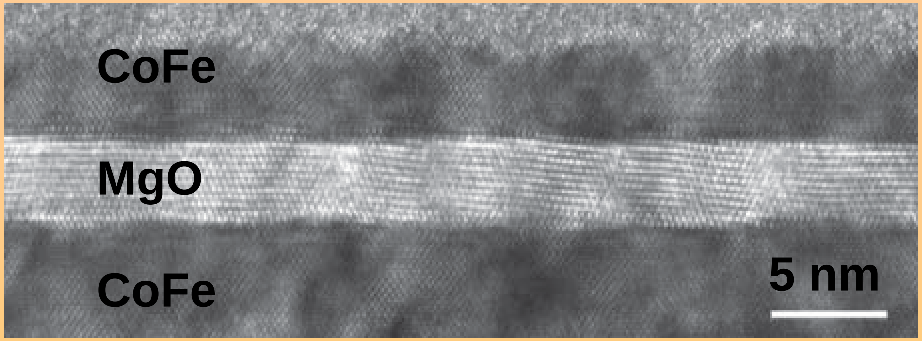
Tsunoda et al., Appl. Phys. Lett. 17 (2002) 3135

Use of CoFeB electrodes

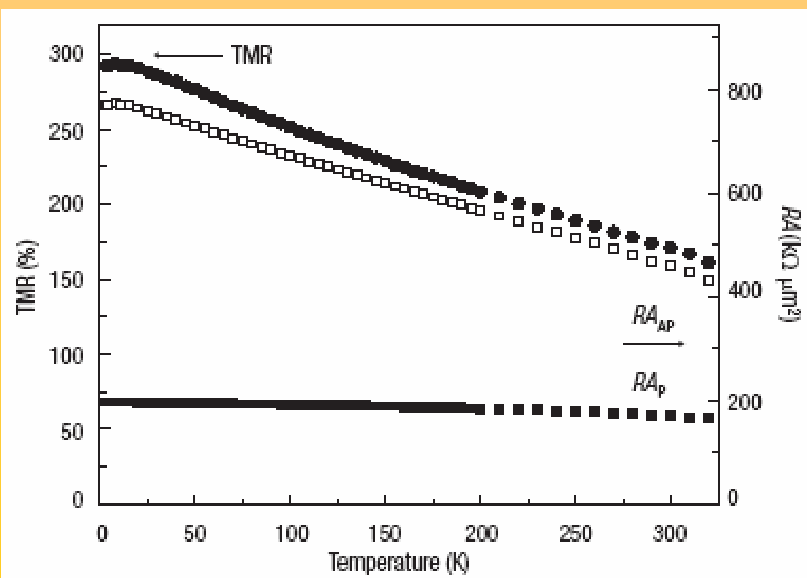


Wang et al., IEEE Trans. Magn. 40 (2004) 2269

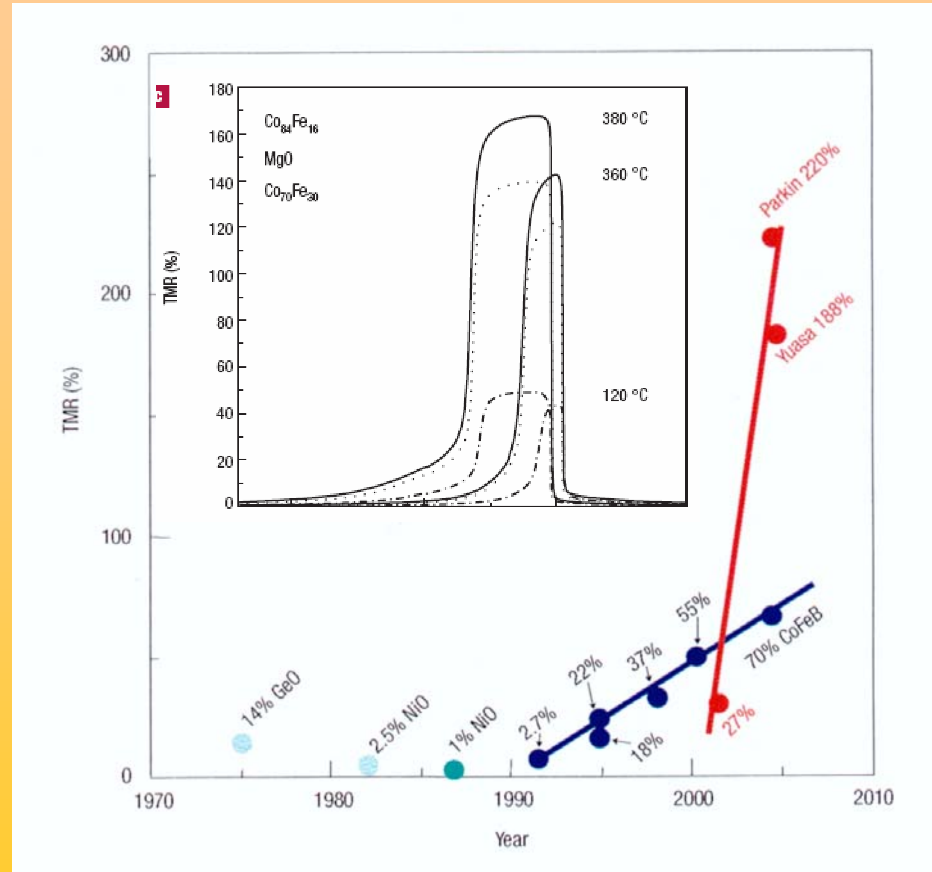
TMR: MgO-based sputtered magnetic tunnel junctions



MR> 150% at room temperature

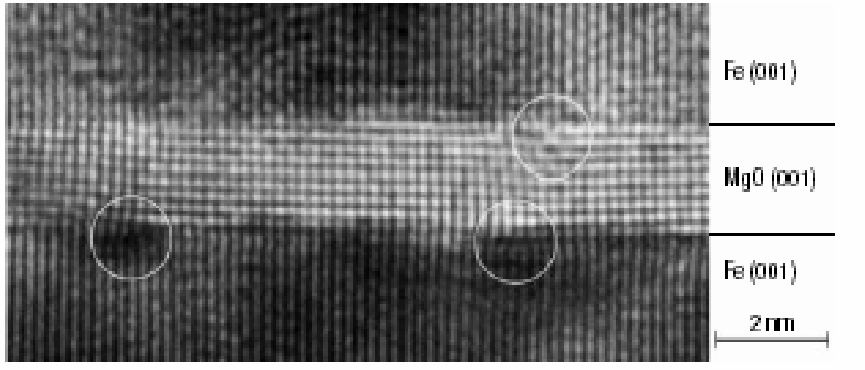


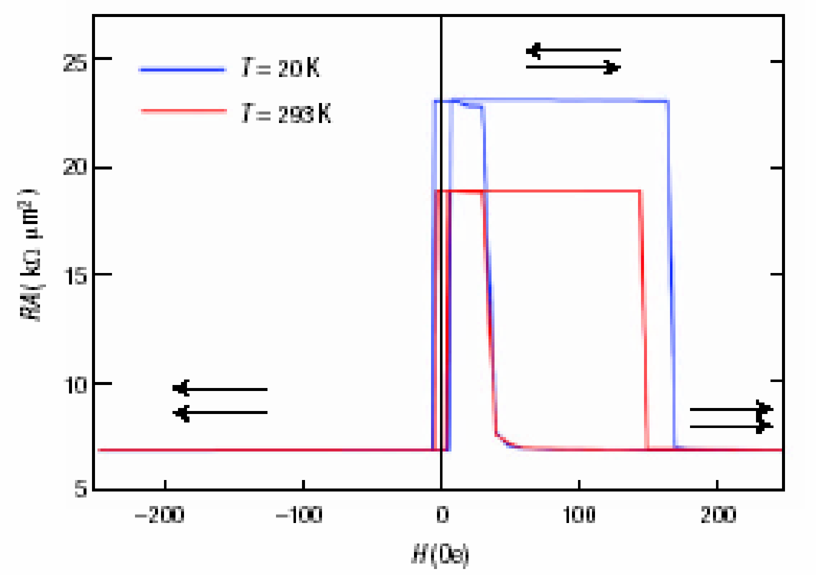
S.S.P. Parkin et al., Nature materials 3 (2004) 862

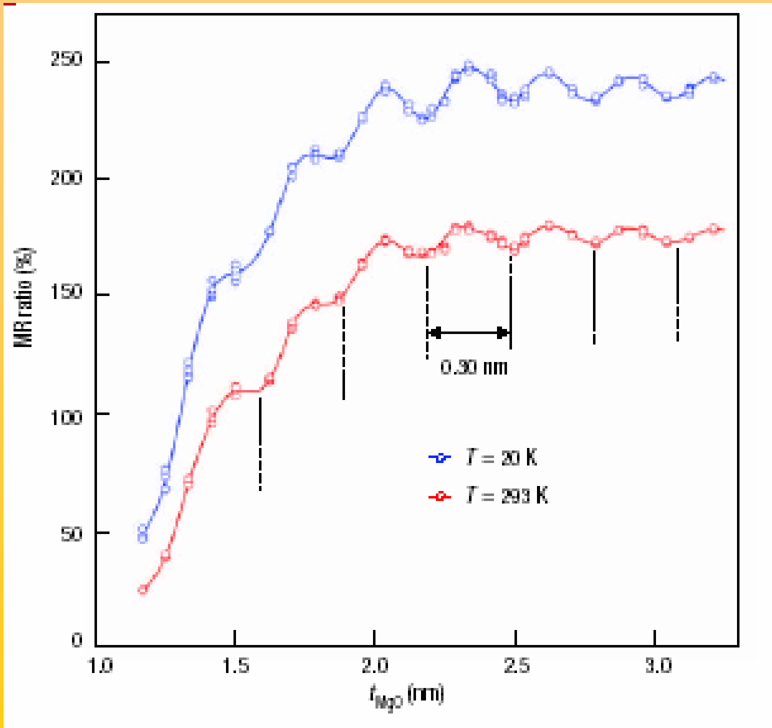


[Previous experimental papers on this system: Bowen et al., Appl. Phys. Lett. 79 (2001) 1655; Faure-Vincent et al., Appl. Phys. Lett. 82 (2003) 4507]

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







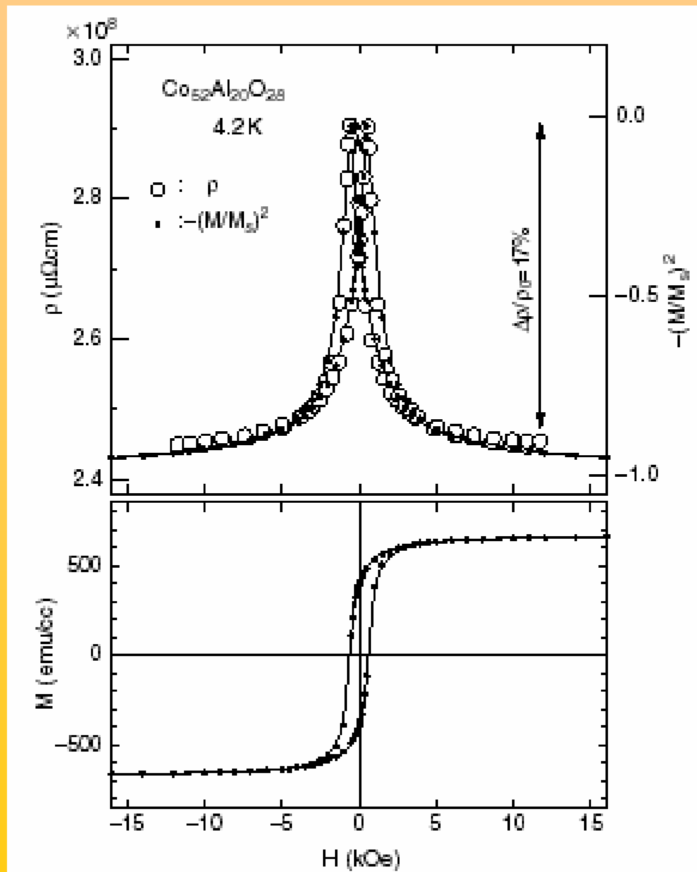
⇒ *OSCILLATIONS IN THE TMR HAVE BEEN RELATED TO THE COHERENT SPIN-POLARISED TUNNELLING*

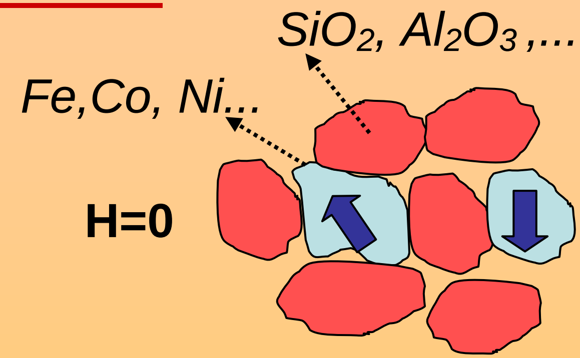
[Theoretical papers on this system: Butler et al., Phys. Rev. B 63 (2001) 054416; Mathon et al., Phys. Rev. B 63 (2001) 220403R]

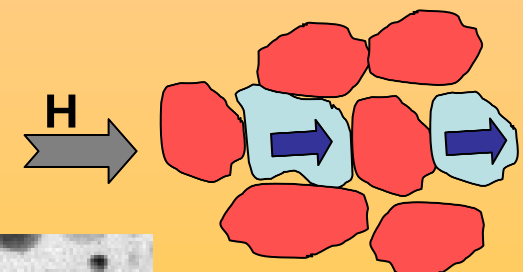
Yuasa et al., Nature materials 3 (2004) 868

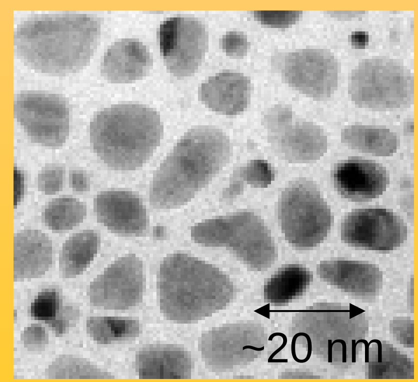
TUNNEL MR (TMR) IN GRANULAR MATERIALS

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







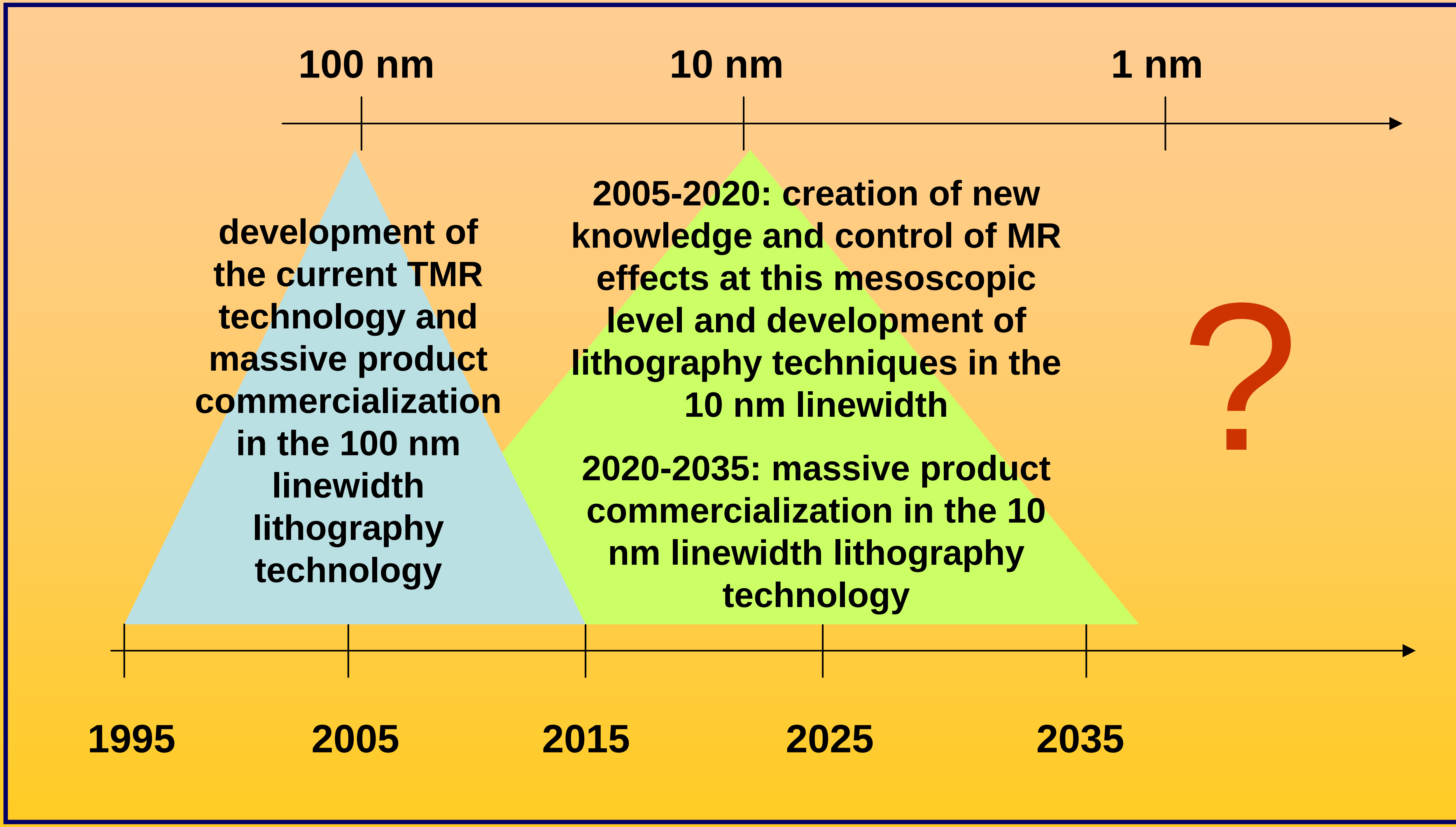


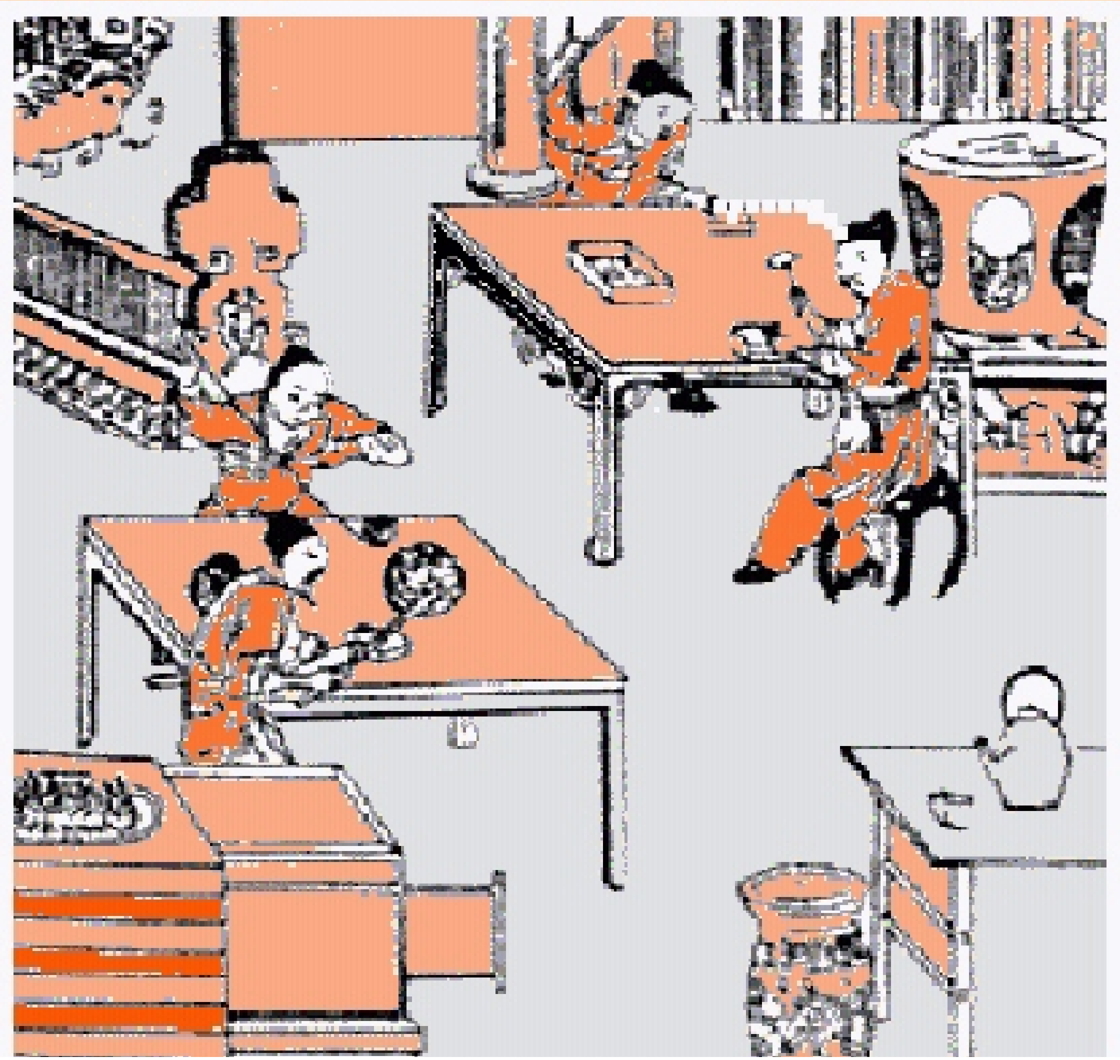
Co in Zr_2O_3 matrix

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

PERSPECTIVES

PERSPECTIVES: APPROACHING THE NANOWORLD





TAPESTRY WORK DATING BACK TO 1637 THAT SHOWS THE FIRST FACTORY IN CHINA PRODUCING MAGNETS FOR MAGNETIC NEEDLES IN COMPASSES