Magnetoresistance – Giant MagnetoResistance (GMR) and Tunnelling MagnetoResistance (TMR)
(http://www.almaden.ibm.com/st/ gives more information)

Reading heads in magnetic data storage media

Multibillion dollar industry!

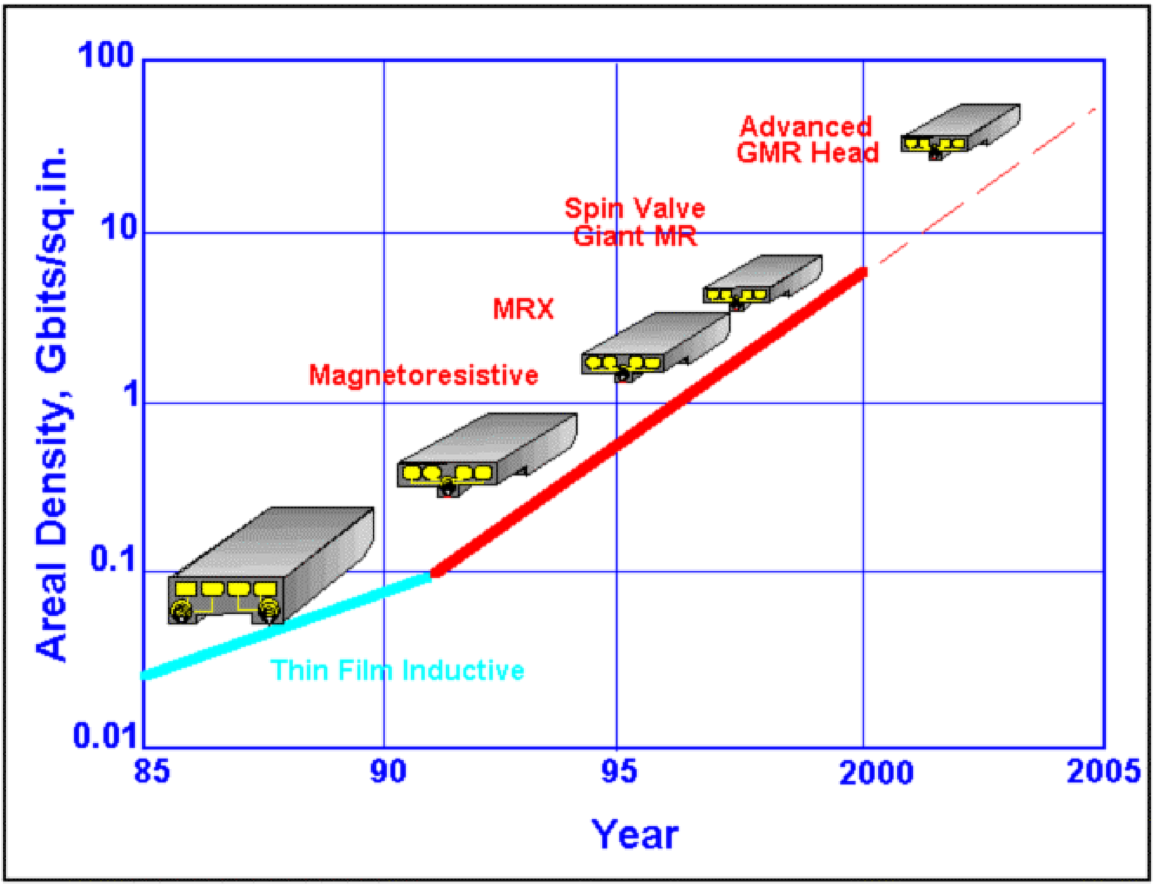


Figure 10. Magnetic head evolution

Future applications include ***spintronics*** *...*

Fundamentals of ferromagnets

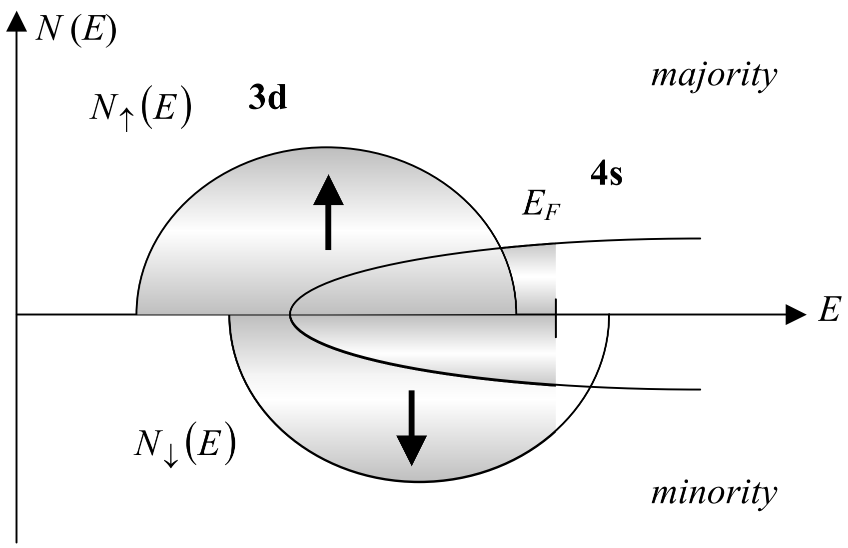
Pair-interaction between atomic magnetic moments J_{ij}

$$E_{ex} = -2\sum_{i,j} J_{ij}\, \underline{s}_i \cdot \underline{s}_j \quad , \; J_{ij} \text{ [J]}$$

with the magnetic moments given by the relation $\underline{m}_i = g\mu_B \underline{s}_i$.
Short-range interaction, often enough to consider nearest-neighbour (nn) interactions. For ferromagnetic 3d elements, the magnitude of the pair-interaction can be estimated from mean-field theory (z = number of nn's, $J_{ij} = J$ if nn-interaction, $J_{ij} = 0$ otherwise)

$$k_B T_c \approx \frac{zJ}{2} \text{ if } T_c \approx 1000\,\text{K}, \text{ this implies an energy} \sim 0.1 \text{ eV}$$

The *Density Of States* (DOS), $N(E)$, in a ferromagnet is split into majority and minority bands due to the exchange interaction.



- s- and d-electrons contribute to electrical conduction. The mobility of 3d electrons is smaller (flat energy bands ⇒ low velocity/high effective mass) than for 4s electrons.

- Since ↓-electrons have more empty states to scatter to, the resistivity will be higher for these electrons; two independent conduction electron channels.
- The resistivity of ↑-electrons (majority electrons) will be $\rho_{\uparrow} \approx \rho_{s\to s}$, while the resistivity of ↓-electrons (minority electrons) can be written as $\rho_{\downarrow} = \rho_{s\to s} + \rho_{s\to d}$, where $\rho_{s\to d} > \rho_{s\to s}$.

The essence of this is that in a ferromagnetic metal there exists *two current channels*, one that can conduct a current better than the other.

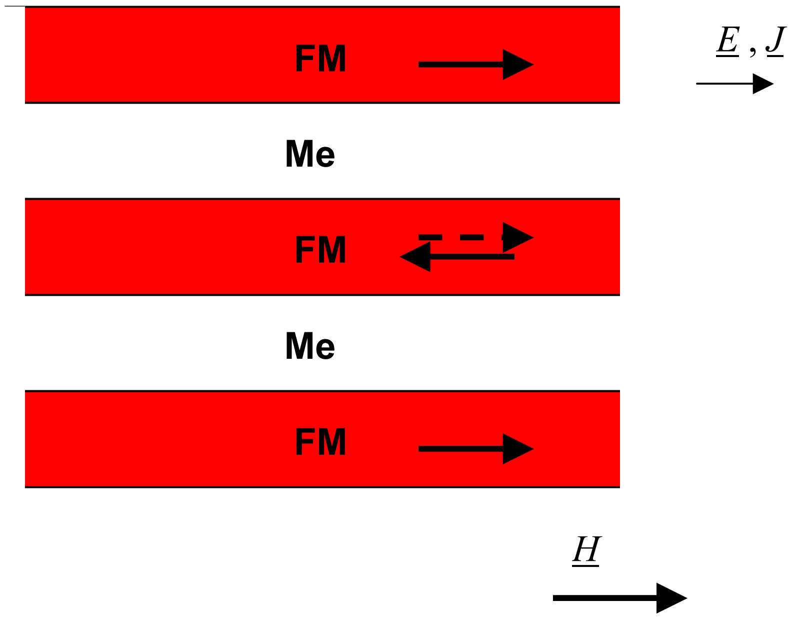
Giant MagnetoResistance (*GMR*)

Spin dependent scattering, two current channels, one for majority spins (often low resistivity) $\rho_{\uparrow}$ and one for minority spins (often high resistivity) $\rho_{\downarrow}$

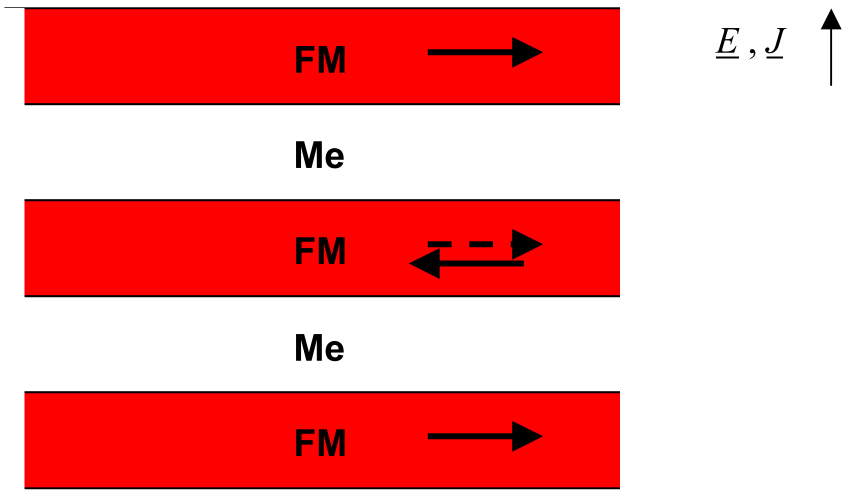
Systems/geometries displaying GMR

A *Multilayers*

CIP (Current In Plane) multilayers



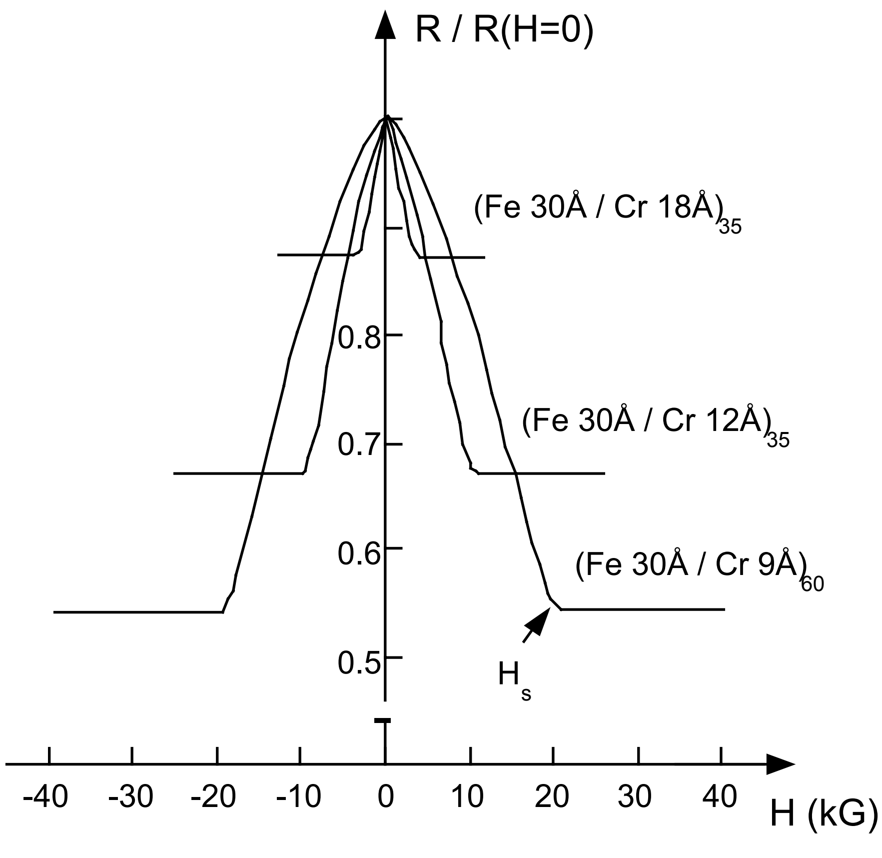
CPP (Current Perpendicular Plane) multilayers



(FM t_{FM} / Me t_{Me}) $_n$ multilayers

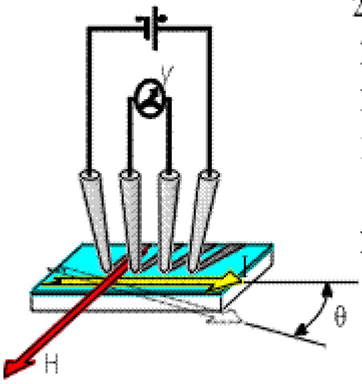
FM = Fe, Ni, Co or some 3d alloy, Me = Cu, Ag, V, Cr, $t_{FM\ (Me)}$ = layer thickness ≈ a few monolayers

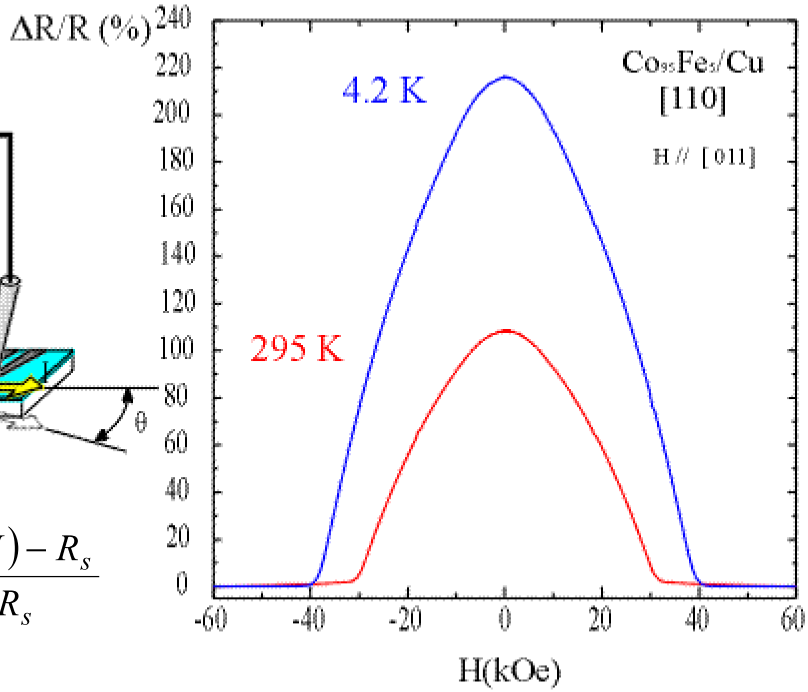
CIP geometry



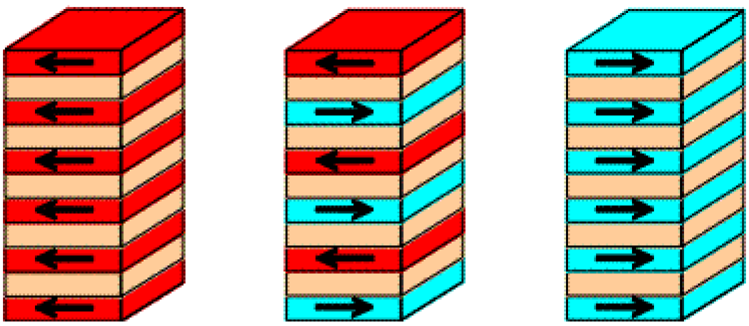
High resistance for antiferromagnetically (AF) coupled layers, low resistance for ferromagnetically (F) aligned layers. H_s corresponds to the field at which all layer magnetizations point along the field direction.

Giant Magnetoresistance





$$\frac{\Delta R}{R} = \frac{R(H) - R_s}{R_s}$$

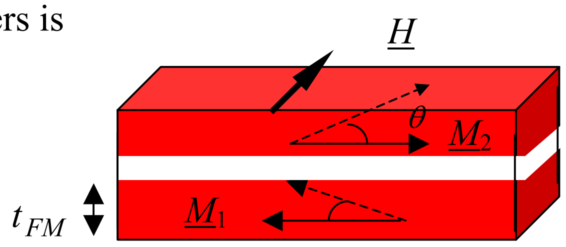


Magnetic coupling

Phenomenologically, the coupling between the magnetizations $\underline{M}_i$ in nearest-neighbor FM layers can be expressed as

$$E_{ex}/A = -J_1 \frac{\underline{M}_i}{|\underline{M}_i|} \cdot \frac{\underline{M}_{i+1}}{|\underline{M}_{i+1}|}$$

where J_1 is given in units of [J/m^2]. Adding a Zeeman term, the energy for two FM layers is



$$\begin{aligned} E/V &= -\frac{J_1}{t_{FM}} \frac{\underline{M}_1 \cdot \underline{M}_2}{|\underline{M}_1||\underline{M}_2|} - \mu_0 \underline{H} \cdot (\underline{M}_1 + \underline{M}_2) = \\ &= -\frac{J_1}{t_{FM}} \cos(\pi - 2\theta) - 2\mu_0 H M_s \cos\left(\frac{\pi}{2} - \theta\right) = \\ &= \frac{J_1}{t_{FM}} \cos(2\theta) - 2\mu_0 H M_s \sin(\theta) \end{aligned}$$

Minimizing with respect to θ and using $M = M_s \sin(\theta)$ one obtains

$$M = -\frac{\mu_0 H M_s^2 t_{FM}}{2J_1}; H_s = -\frac{2J_1}{\mu_0 M_s t_{FM}} \text{ or } J_1 = -\frac{\mu_0 M_s H_s t_{FM}}{2}$$

The microscopic origin of the AF coupling can be explained using the RKKY (Ruderman-Kittel-Kasuya-Yosida) model (P. Bruno and C. Chappert, Phys. Rev. B **46**, 261 (1992)), indirect type of interaction between two FM layers, FM1 polarizes the conduction electrons and the polarization propagates across the Me spacer layer and interacts with FM2. The RKKY interaction between two localized spins is

$$H_{ij} = -J(\underline{R}_{ij})\underline{S}_i \cdot \underline{S}_j$$

where the exchange integral is

$$J(\underline{R}_{ij}) \sim \int d^3\underline{q}\, \chi(\underline{q}) \exp(i\underline{q} \cdot \underline{R}_{ij})$$

where $\chi(\underline{q})$ is the $\underline{q}$-component of the carrier spin susceptibility of the Me spacer layer ($\underline{q}$ = scattering vector, connects two Fermi surface points).

For a *free-electron gas*, the RKKY exchange integral for two atomic magnetic moments, embedded in a non-magnetic host and being a distance *R* apart is

$$J(R) \propto \frac{1}{R^3} \cos(2k_F R)$$

The interaction decays as $1/R^3$ and oscillates with the period $\lambda = \pi/k_F$.

In a superlattice, the interlayer coupling is obtained by summing over all magnetic pairs *ij* (*i* and *j* referring to FM1 and FM2, respectively, the coupling energy per unit area for any magnetic moment in FM1 is

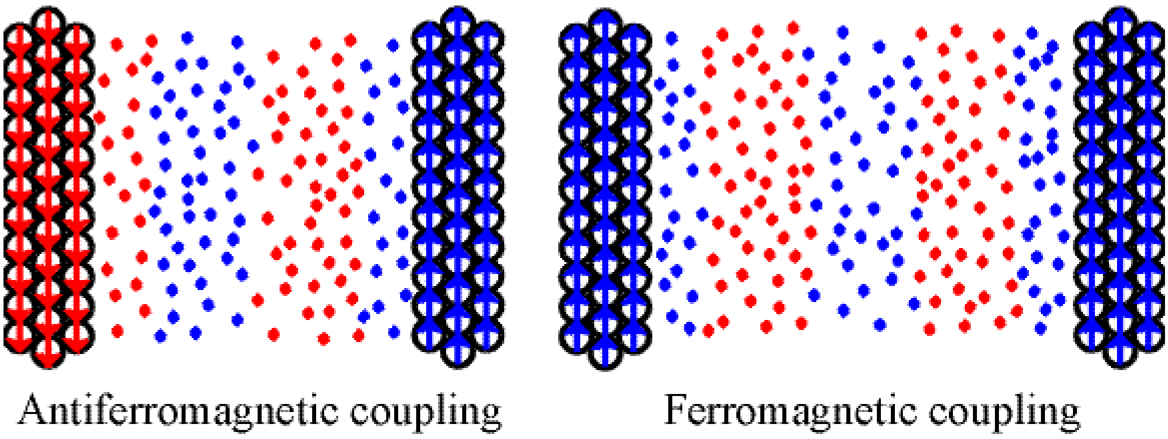
$$E_{ex}/A = -J_1 \cos(\theta_{12}) \propto -\sum_{j \in \mathrm{FM2}} J(\underline{R}_{oj}) \cos(\theta_{12}),$$

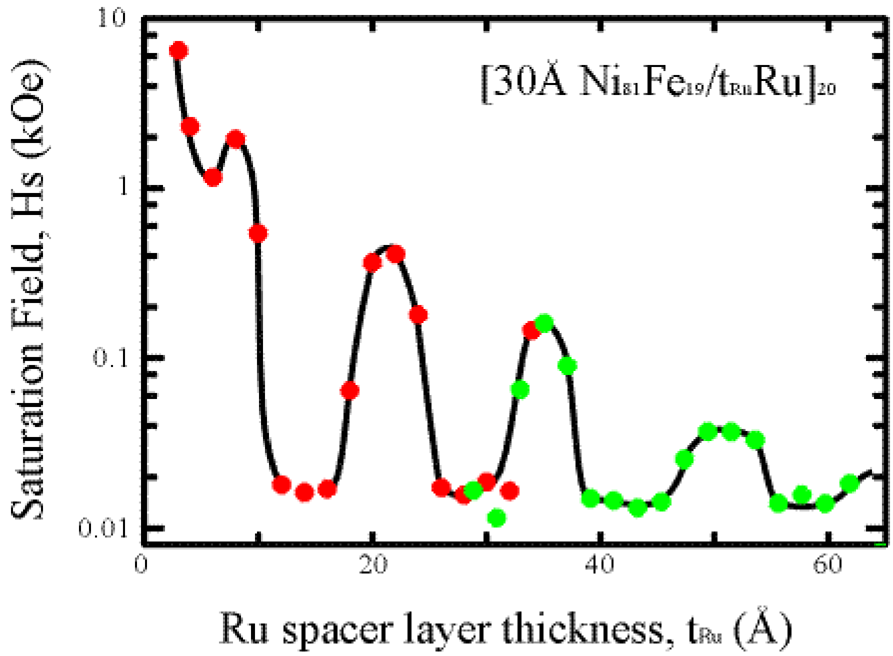
where θ_{12} is the angle between the magnetizations in FM1 and FM2. Summing all pair interactions one obtains

$$J_1(z) \propto \frac{1}{z^2} \sin(2k_F z)$$

Here the coupling strength decays with thickness of the *Me* layer as $1/z^2$.

Exchange Coupling via Transition Metals: Universal Oscillations



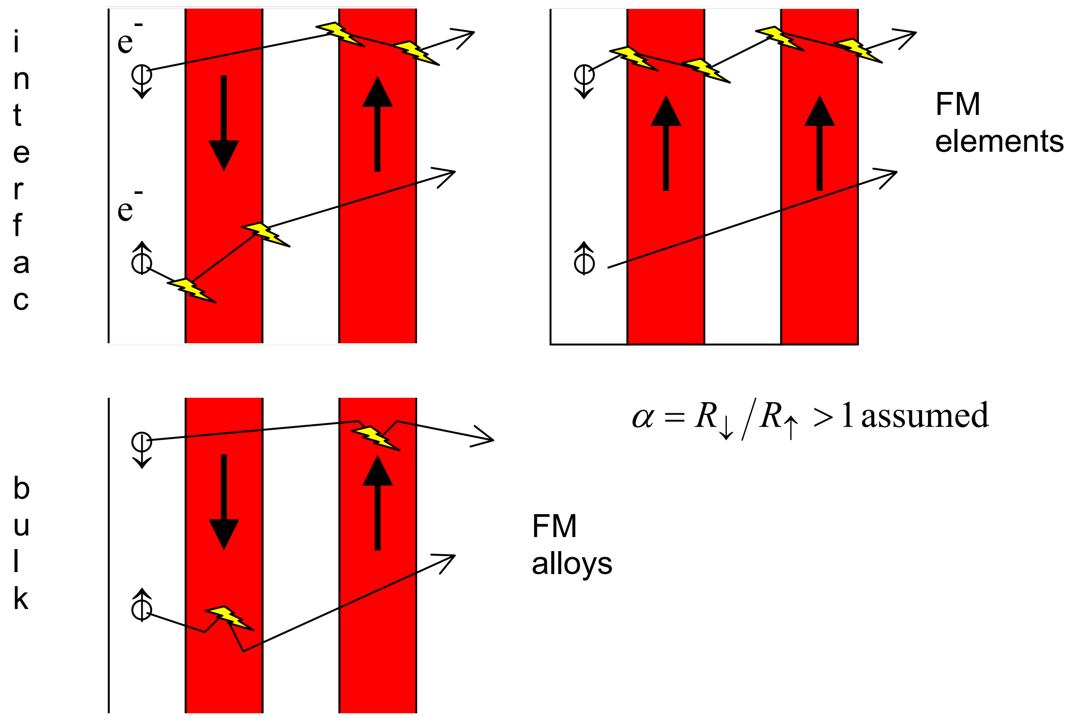


$J \sim 1/t_{Ru}^{1.8}$

- phase of oscillation varies with magnetic material
- oscillation period independent of magnetic material
- $J \sim M^2$

Mechanism of GMR

Two current channels with different resistivities, the difference is mainly explained by the electronic structure and a difference in the density of states for the majority and minority conduction electrons. In addition, we need to consider scattering centers, here we distinguish between bulk scattering and interface (FM/Me) scattering.



Scattering centers at interfaces may be surface roughness, regions of interdiffusion, spin dependent band offset (difference in energy between the bottom of the conduction band and the Fermi energy in adjacent layers), etc., while scattering in the bulk of a layer is due to impurity atoms.

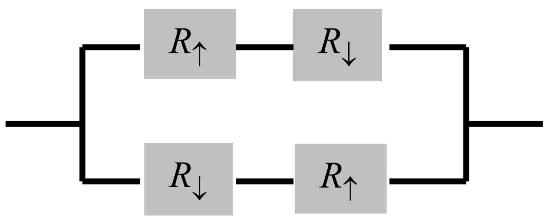
An important length scale in GMR materials is the spin diffusion length l_{sdl}. In GMR materials it is important that l_{sdl} >> the layer thickness. In 3d elements and at RT $l_{sdl} \approx 10^3 - 10^4$ Å. For the CIP geometry, another important length scale is the mean free path l_{mfp}, since the conduction electrons should be able to "sample" different FM layers. If l_{mfp} > layer thickness we are in the homogeneous limit, "alloy limit", while if l_{mfp} < layer thickness we are in the local limit. For 3d elements, l_{mfp} ~ 50 - 300 Å, while a permalloy layer, l_{mfp} for minority electrons is 10 - 20 Å.

In the *homogeneous* limit, the resistance of the different current channels can be described using simple resistor models. Similar results are expected for the CIP and CPP geometries in this limit.

AF configuration

$$R_+ = R_\downarrow + R_\uparrow + (2R_{Me}) \text{ and } R_- = R_\uparrow + R_\downarrow + (2R_{Me})$$

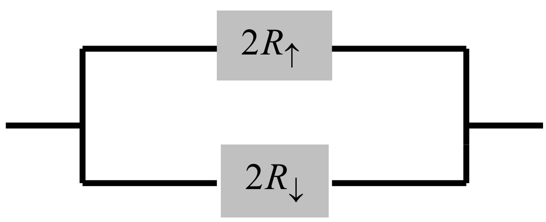
where R_+ (R_-) is the resistance for electrons with S=+1/2 (S=-1/2), while $R_\downarrow$ and $R_\uparrow$ are the resistances for the two conduction channels.



$$R_{AF} = \frac{R_\downarrow + R_\uparrow}{2}$$

F configuration

$$R_+ = 2R_\uparrow + (2R_{Me}) \text{ and } R_- = 2R_\downarrow + (2R_{Me})$$



$$R_F = \frac{2R_\downarrow R_\uparrow}{R_\downarrow + R_\uparrow}$$

The magnetoresistance thus is

$$\frac{\Delta R}{R_{AF}} = \frac{(R_{\downarrow} - R_{\uparrow})^2}{(R_{\downarrow} + R_{\uparrow})^2} = \frac{(\alpha - 1)^2}{(\alpha + 1)^2} \quad (*)$$

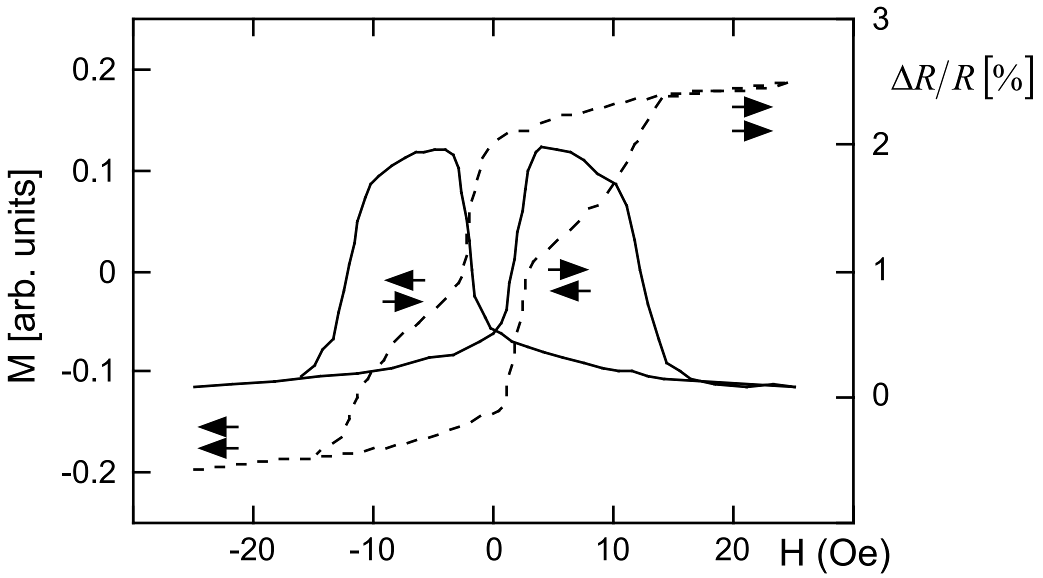
In the *local* limit, there is a difference between CIP and CPP geometries. For the CIP geometry, all layers will conduct in parallel and independently and there will be no difference between the AF and F configurations; i.e. there is no GMR effect. For the CPP geometry, we instead have a similar situation as for the homogeneous limit and a magnetoresistance given by (*).

B *Sandwich structures*

In the absence of AF coupling, there are (at least) two possible approaches to obtain different relative orientation of the magnetization in successive FM layers:

- Use two ferromagnetic materials exhibiting different coercivities, either as building block in a multilayer or as part of a sandwich structure.

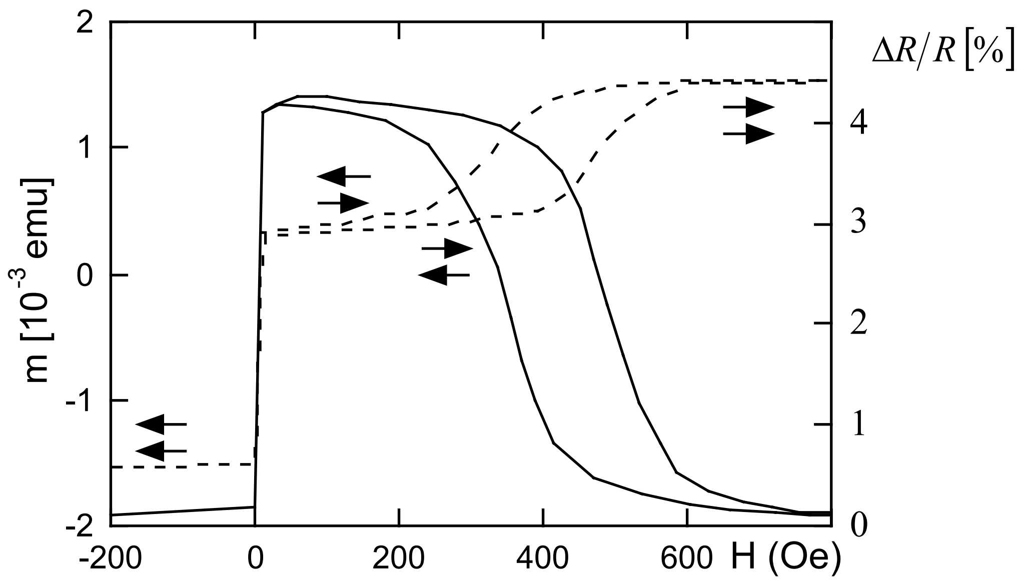
Si / 100 Å Ta / 40 Å $Ni_{80}Fe_{20}$ / 60 Å Cu / 40 Å $Ni_{80}Co_{20}$ / 50 Å Ta.



The coercivity of NiFe is 2 Oe, while NiCo has a coercivity of 12 Oe.

- Use two FM layers separated by a Me layer in a sandwhich structure, one FM layer will be constrained by coupling to a adjacent antiferromagnetic layer (exchange anisotropy).

Si / 50 Å / Ta 2 x (60 Å $Ni_{80}Fe_{20}$ / 22 Å Cu / 40 Å $Ni_{80}Fe_{20}$ / 70 Å FeMn) / 50 Å Ta).



Multilayered or sandwich structures in applications?

Multilayer

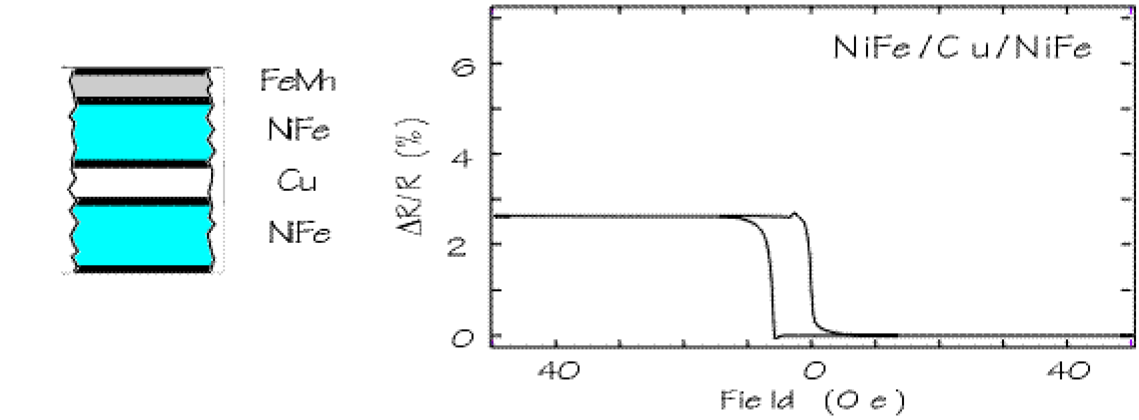
$$\left.\begin{aligned}\frac{\Delta R}{R_s} &\approx 100\% \\ H_s &\approx 10\,\text{kOe}\end{aligned}\right\}\frac{1}{H_s}\frac{\Delta R}{R_s} \approx 0.01\,\%/\text{Oe}$$

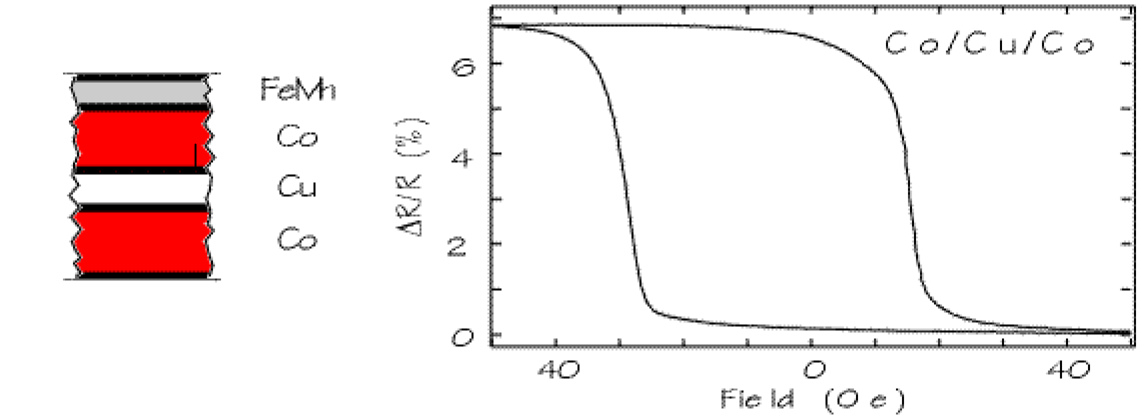
Sandwich

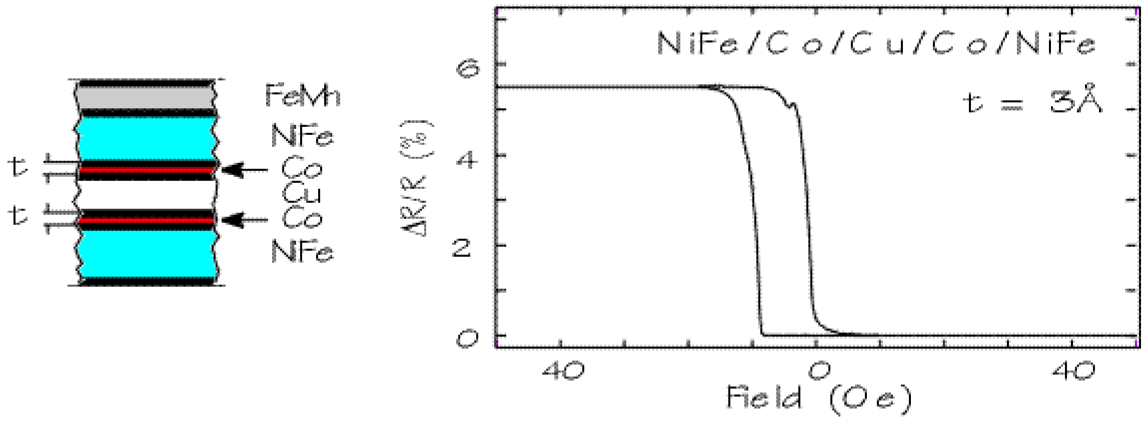
$$\left.\begin{aligned}\frac{\Delta R}{R_s} &\approx 2-5\% \\ H_s &\approx 5-10\,\text{Oe}\end{aligned}\right\}\frac{1}{H_s}\frac{\Delta R}{R_s} \approx 0.2-1\,\%/\text{Oe}$$

For a summary of experimental results, see eg. B. Dieny (J. Magn. Magn. Mater. **136**, 335-359 (1994)).

Effect of Interface Nano-layer on GMR







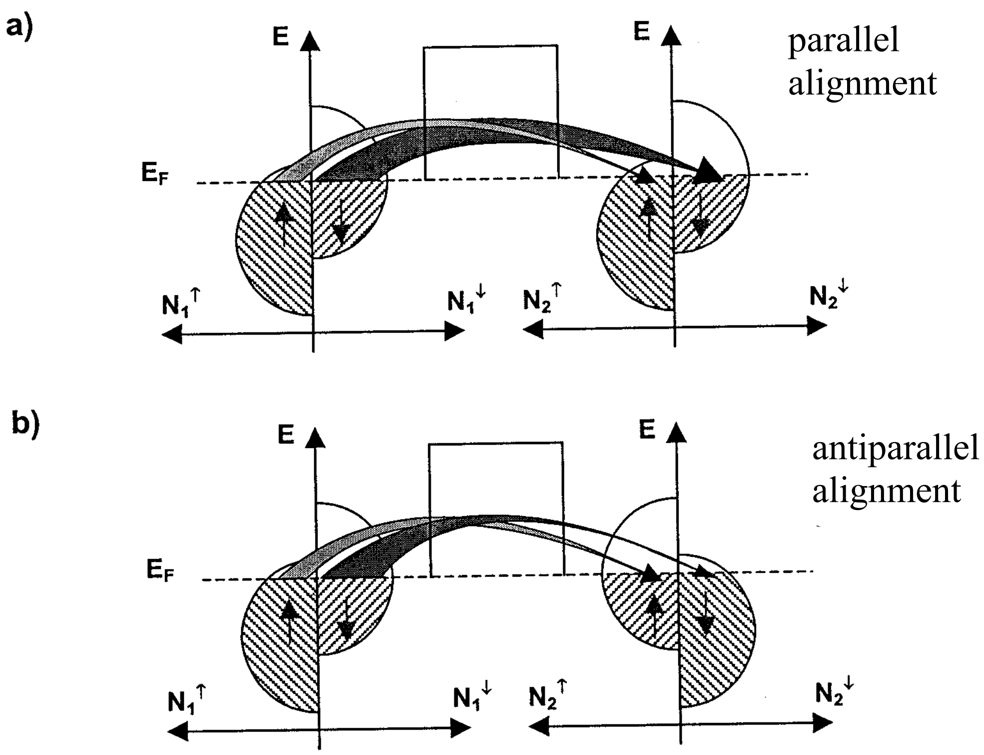
S.S.P. Parkin, Phys. Rev. Lett. 71, 1641 (1993)

Tunnelling MagnetoResistance (*TMR*)

Quantum mechanics dictates that an electron in a metallic electrode has a certain probability to tunnel through an (insulating) potential barrier to another metallic electrode.

Important parameters – thickness of barrier (d), hight of potential barrier (V_0) and density of states (DOS) in the metallic electrodes ($N(\varepsilon_F)$)

In ferromagnets like Fe, Ni and Co, or alloys of these, the DOS for spin-up and spin-down 3d electrons are exchange-split



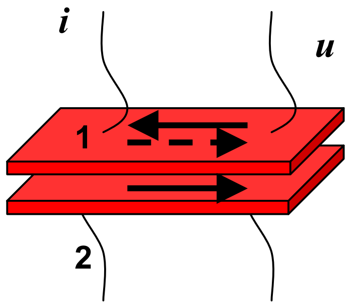
$\Rightarrow$ spin polarized transport

Important parameter – spin polarization ($N_\uparrow = N_\uparrow(E_F)$)

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Jullière´s model

- conservation of spin
- the conductance is proportional to products if the type $N_{\uparrow 1} N_{\uparrow 2}$



Relation between conductance and resistivity changes ($G_{\uparrow\uparrow}$ is the conductance in case of parallel magnetizations in the two FM electrodes)

$$\frac{\Delta G}{G_{\uparrow\downarrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{\frac{1}{R_{\uparrow\uparrow}} - \frac{1}{R_{\uparrow\downarrow}}}{\frac{1}{R_{\uparrow\downarrow}}} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{\Delta R}{R_{\uparrow\uparrow}}$$

Conductance when the magnetization in the two FM electrodes are parallel

$$G_{\uparrow\uparrow} \propto N_{\uparrow} N_{\uparrow} + N_{\downarrow} N_{\downarrow} = N_{\uparrow}^2 + N_{\downarrow}^2$$

and the correponding result when the magnetizations are in opposite directions

$$G_{\uparrow\downarrow} \propto 2 N_{\uparrow} N_{\downarrow}$$

Using the definition of spin polarization, we obtain

$$G_{\uparrow\uparrow} \propto \frac{1}{2}\left(1 + P^2\right)\left(N_{\uparrow} + N_{\downarrow}\right)^2 \text{ and}$$

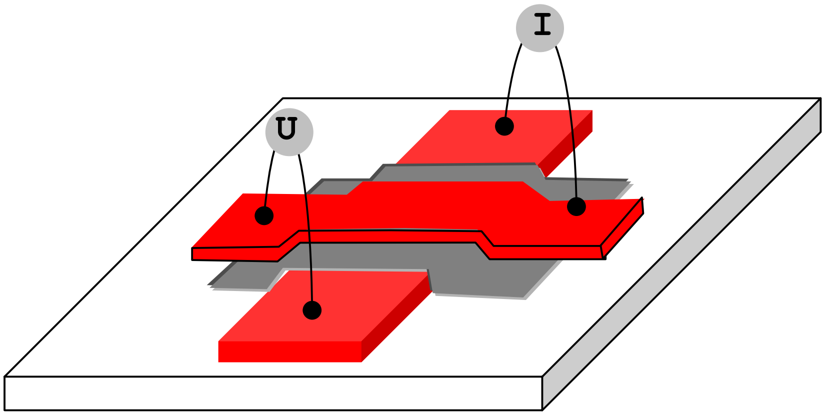
$$G_{\uparrow\downarrow} \propto \frac{1}{2}\left(1 - P^2\right)\left(N_{\uparrow} + N_{\downarrow}\right)^2$$

and

$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{2P^2}{1 - P^2}$$

$$\frac{\Delta R}{R_{\uparrow\downarrow}} = \frac{2P^2}{1 + P^2} \leq 1$$

Experimental geometry



Typical dimensions

FM electrodes 0.1 x 0.1 mm^2, for future applications smaller, thickness 100-200 Å

Oxide tunnel barrier 10-20 Å thick, barrier 2-3 eV

Materials

FM electrodes Co, Fe, Ni, NiFe, CoFe

Oxide tunnel barrier NiO, CoO, MgO, Al_2O_3

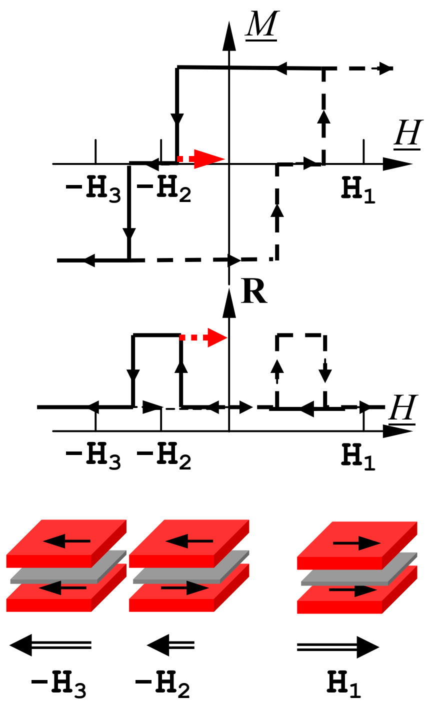
Junction resistance from < 100 Ω to tens of kΩ

Important

Sharp interfaces without interdiffusion, minimum of spin-flip scattering at interfaces

Measured spin polarizations
(Meservey and Tedrow, Phys. Rep. **238**, 173 (1994))

Material	Ni	Co	Fe	NiFe	CoFe
Polarization	+23%	+35%	+40%	+32%	~50%



$\Delta R / R_{\uparrow\uparrow}$ -results for "good" Co/Al_2O_3/NiFe junctions

20.2%	27.1%	27.3%
RT	77K	4.2K

Ferromagnetic materials with $P \sim 1$ would give even better results.

Use of magnetic tunnel junctions