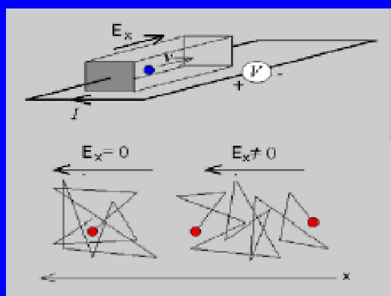
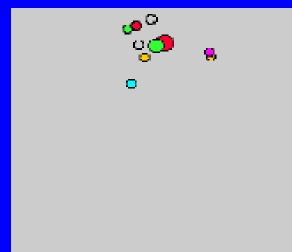
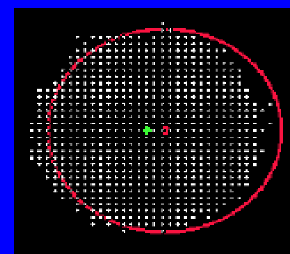
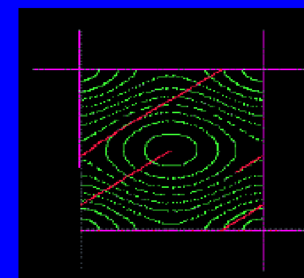
# Transport Phenomena in Solids

## Motions of electrons and transport phenomena



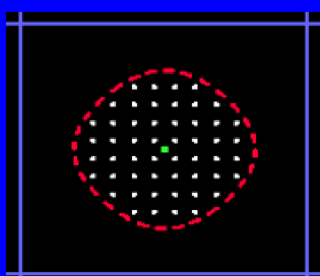



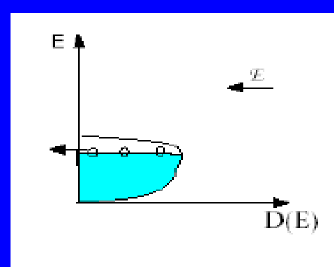


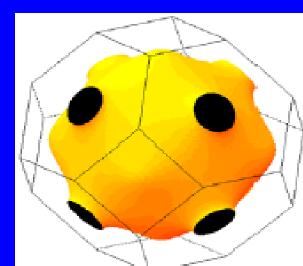


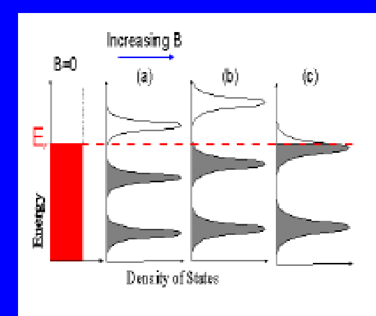
$$\sigma = \frac{ne^2\tau}{m}$$

$$\left(\frac{1}{m^*}\right)_{ij} = \frac{1}{\hbar^2}\sum_j \frac{\partial^2 E(\vec{k})}{\partial k_i \partial k_j}$$








Some pictures are taken from the UvA-VU Master Course: Advanced Solid State Physics by Anne de Visser (University of Amsterdam), Solid State Course by Mark Jarrel (Cincinnati University), from Ibach and Lüth, from Ashcroft and Mermin and from several sources on the web.

# GIANT MAGNETORESISTANCE

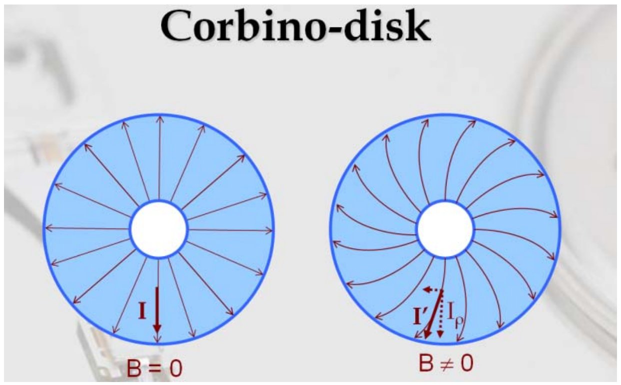
**Magnetoresistance** is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it.

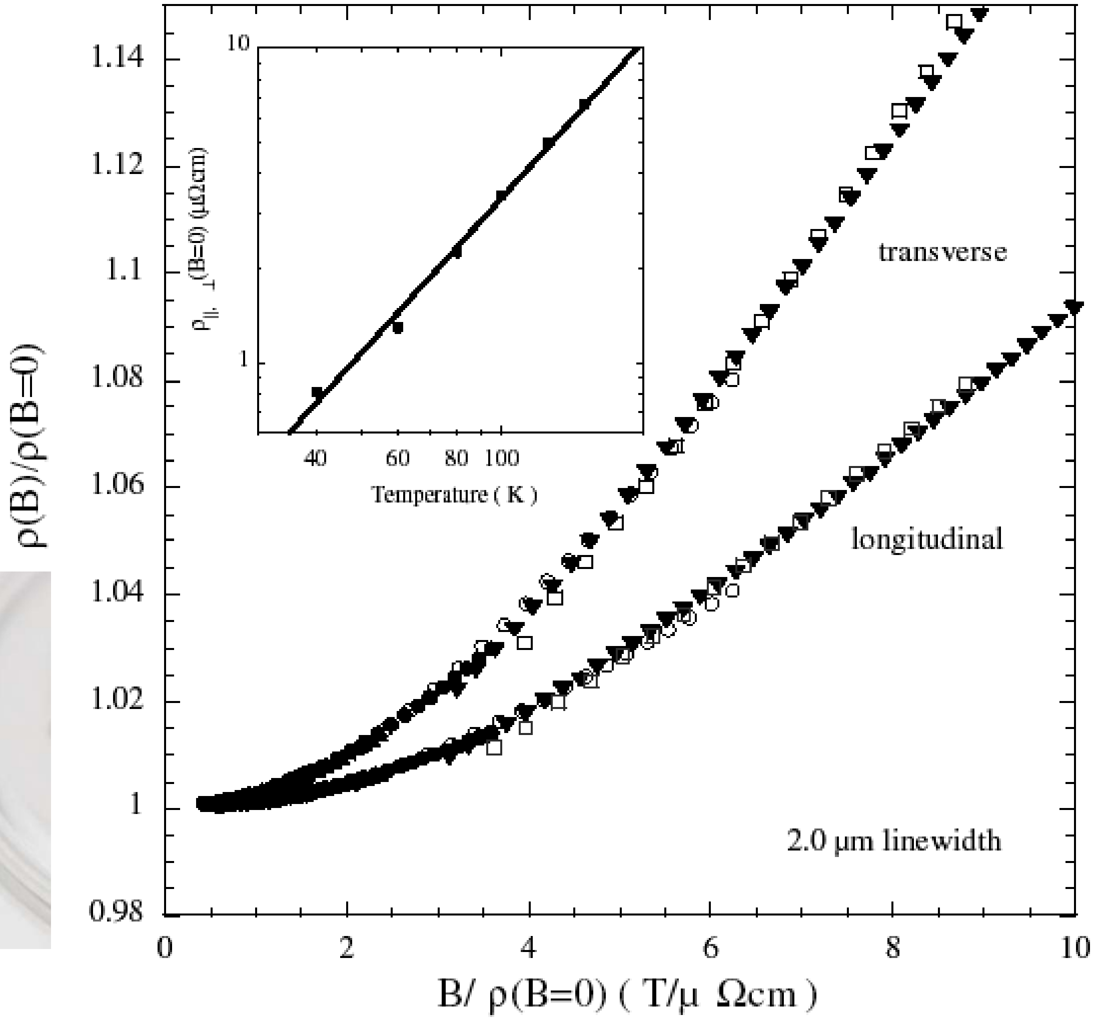
$$MR = (\rho(H) - \rho(0)) / \rho(0)$$

The level of magnetoresistance shown by a material is usually expressed in terms of the **percentage change in resistance** from the highest to the lowest resistance and is usually of the order of **a few percent**. The main application for MR sensors is in the read heads of hard disk drives.

# Ordinary Magnetoresistance

Lorentz force acting on trajectory of electron;longitudinal magnetoresistance (MR).



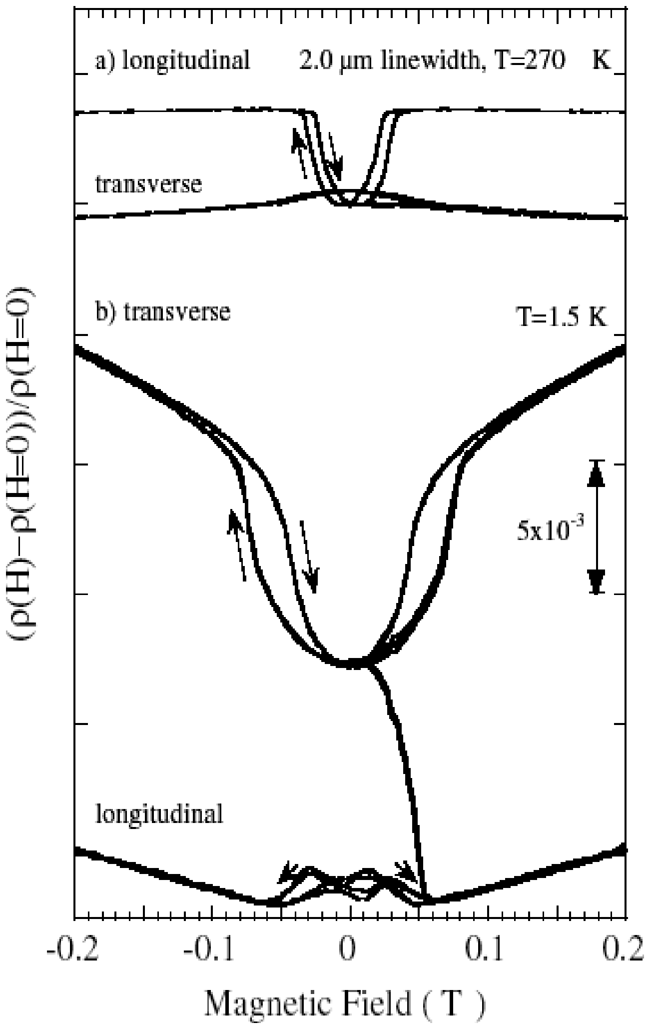




A.D. Kent *et al* J. Phys. Cond. Mat. ***13***, R461 (2001)

**Figure 10.** Scaling plot of transverse and longitudinal MR above magnetic saturation for a 2 $\mu$m wire in the form $\rho(B)/\rho(B=0)$ versus $B/\rho(B=0)$ at temperatures of (open squares) 1.5 K, (open triangles down) 40 K, (open circles) 60 K, (solid circles) 80 K, (solid triangles up) 100 K, (solid diamonds) 125 K, and (open diamonds) 150 K. The inset shows the scaling parameters $\rho_{\parallel}(B=0)$ and $\rho_{\perp}(B=0)$ as a function of temperature on a log-log plot, and overlap on the scale shown in the plot.

# Anisotropic MR Role of spin-orbit coupling on electron scattering

The magnetoresistance can be longitudinal or transverse, depending on whether the magnetic field is applied in a direction parallel to or perpendicular to the direction of the electrical current, respectively.




A.D. Kent *et al*
J. Phys. Cond. Mat. ***13***, R461 (2001)

**Figure 9.** (a) MR data at 270 K of a 2 $\mu$m wire in the transverse and longitudinal field geometries ($\rho_\perp(H=0$, 270 K$)=$ 14.7 $\mu\Omega$cm). (b) MR at 1.5 K again in the transverse and longitudinal field geometries ($\rho_\perp(H=0$, 1.5 K$)=0.74$ $\mu\Omega$cm).

Now the anisotropy in magnetoresistance is defined as

$$\frac{\Delta\rho}{\rho_{//}} = (\rho_{//} - \rho_{\perp})/\rho_{//}$$

ferromagnetic anisotropy of resistivity → FAR

- The largest value of FAR at room temperature so far reported in the literature is 6.5% for the $Ni_{70}Co_{30}$ alloy.
- exceeds 10% at the liquid nitrogen temperature of 77K.

# Domain walls

Since the early experiments on iron whiskers [1], it was recognized that walls between domains in ferromagnets are a source of electrical resistance in addition to that present in the domains. By applying magnetic fields to saturate magnetization, and thereby erase domains in an otherwise multidomain ferromagnet, the resistance of iron was found to drop significantly. Cabrera and Falicov


[1] See G. R. Taylor, A. Isin, and R. V. Coleman, Phys. Rev. **165**, 621 (1968), and references therein.

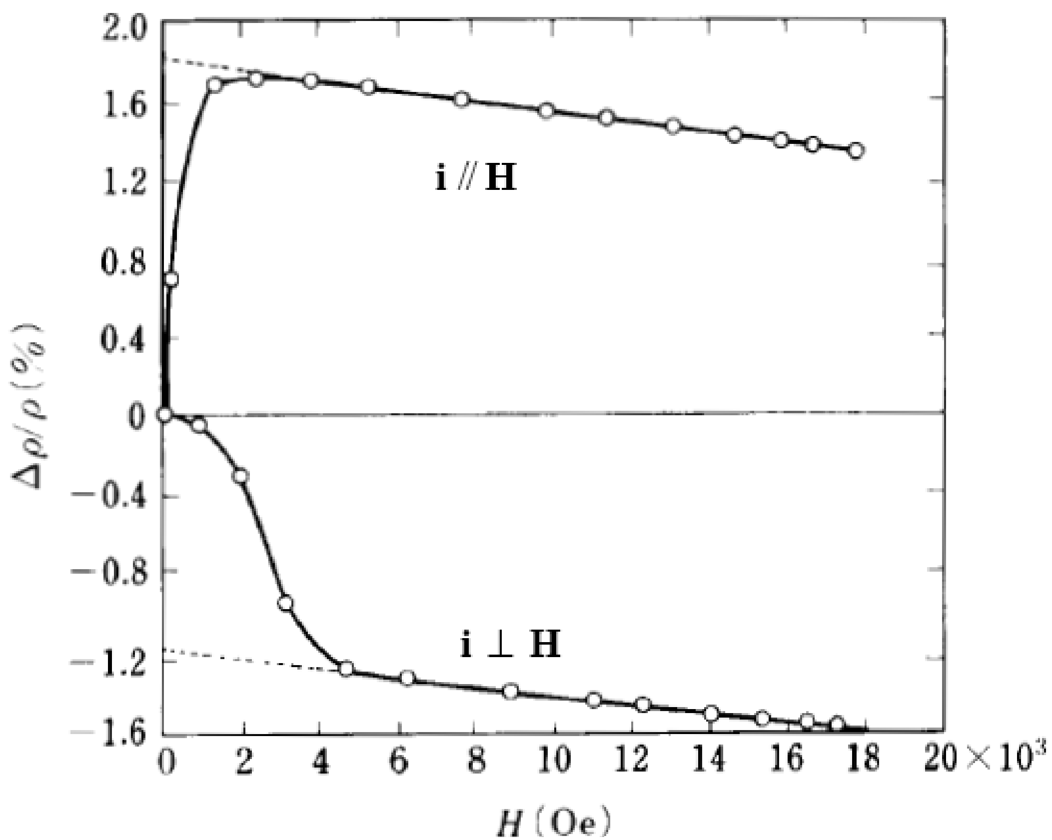
[2] G. G. Cabrera and L. M. Falicov, Phys. Status Solidi (b) **61**, 539 (1974); *ibid* **62**, 217 (1974).

[3] R. V. Coleman, R. C. Morris, and D. J. Sellmyer, Phys. Rev. B **8**, 317 (1973).

[4] L. Berger, J. Appl. Phys. **49**, 2156 (1978).

Fe–Co and Fe–Ni ferromagnetic alloys are used as magnetic field sensors because they possess a large magnetoresistance.

The magnetoresistance can be longitudinal or transverse, depending on whether the magnetic field is applied in a direction parallel to or perpendicular to the direction of the electrical current, respectively.

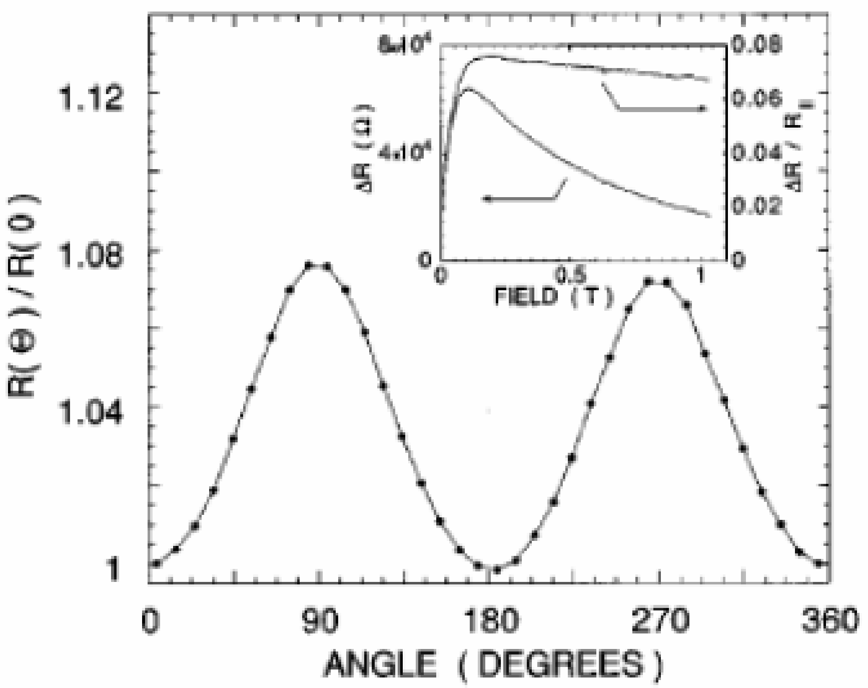



Longitudinal and transverse magnetoresistance of pure Ni.
[E. Englert, *Ann. Phys.* **14** (1932) 589]

An initial large change in resistivity is accompanied by growth of magnetic domains parallel to the direction of the magnetic field. Once it is saturated, the resistivity changes more or less linearly with increasing magnetic field.

**AMR** The Anisotropic magnetoresistance measures the change in resistance for the current pass through a ferromagnetic media, when magnetization change from parallel to perpendicular to the current.

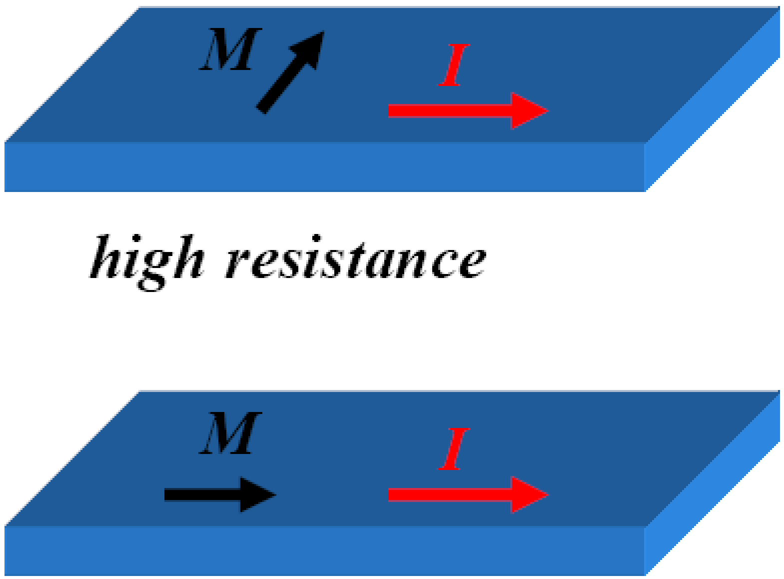
$La_{1-x}Ca_xMnO_\delta$




T=160 K ; B= 0.5 T

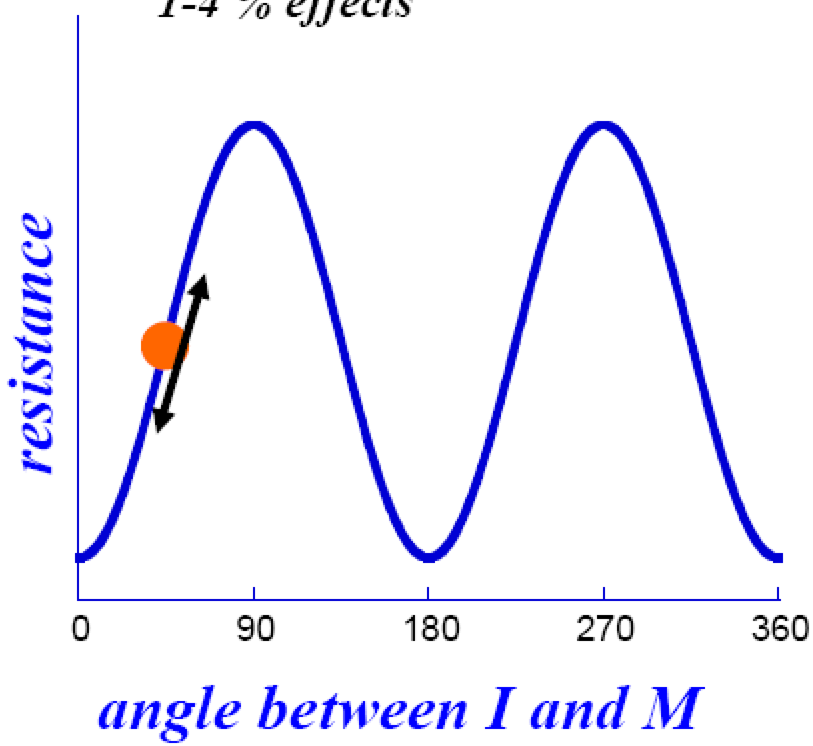
Eckstein, Appl. Phy. Let. 69 1312 1996

# Anisotropic Magneto-resistance (AMR)




*high resistance*

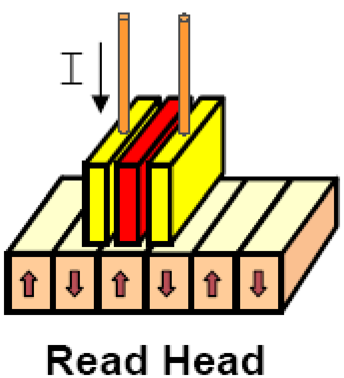
*low resistance*

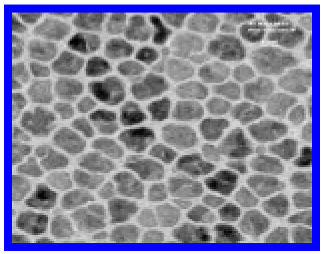



***Bulk property of magnetic materials***

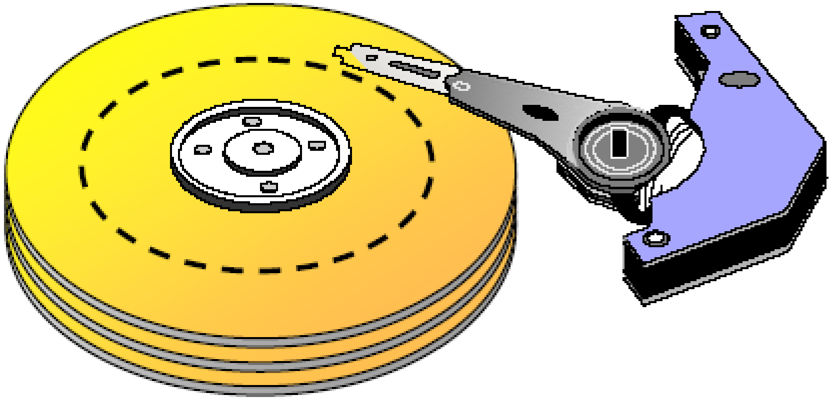
$$R = R_0 + \Delta R \cos^2\theta_{i,M}$$

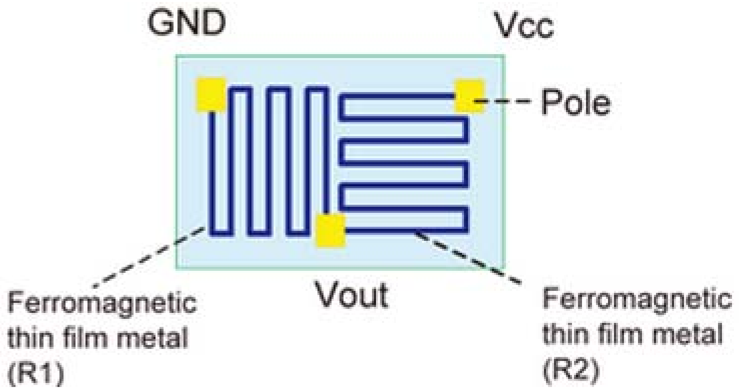
- Anisotropic Magnetoresistance – Reported in 1857 by British physicist Lord Kelvin.
- When a current is passed through a magnetic conductor, resistance changes based on the relative angle between the current and the conductor’s magnetization.
- Resistance increases when current is perpendicular to magnetization and decreases when current is parallel to magnetization.
- Cause: electron spin-orbit coupling
- Used as the basis of hard drive reading before GMR was discovered.



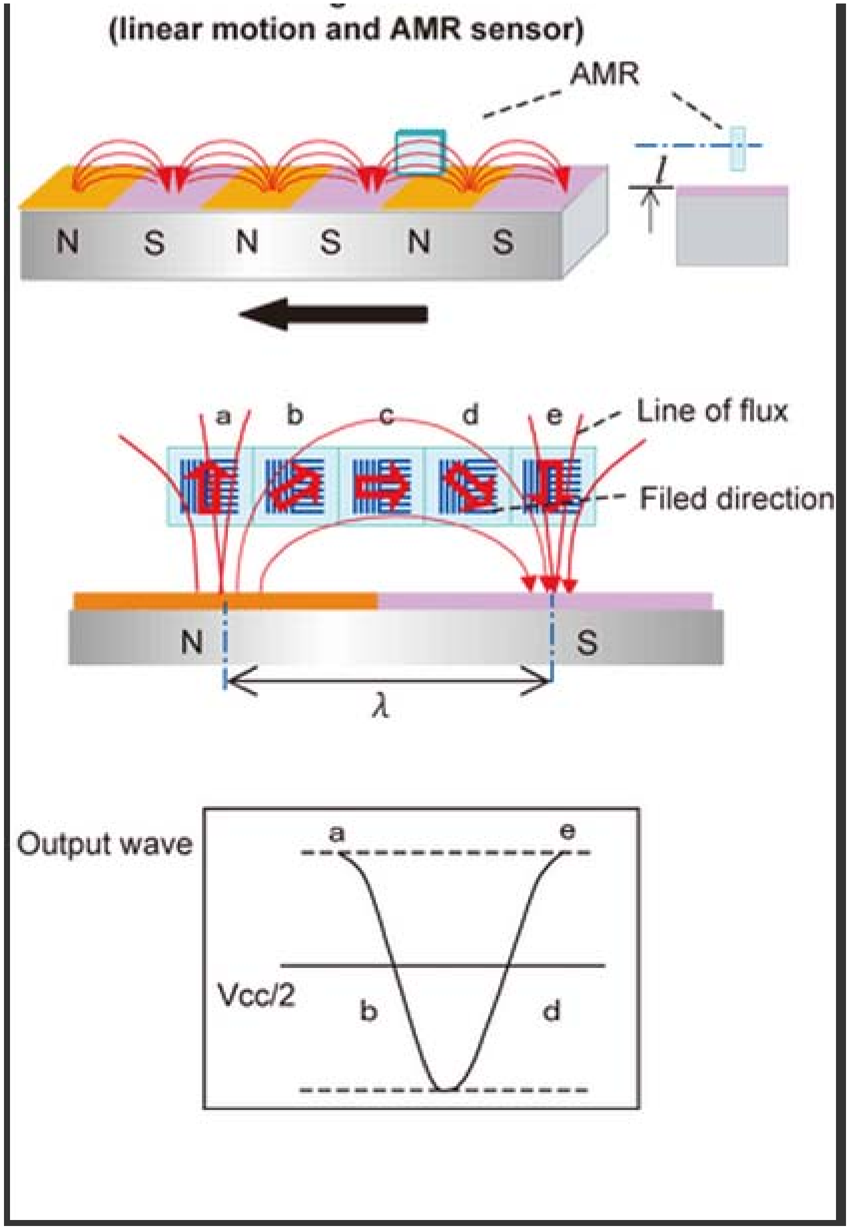



Disk

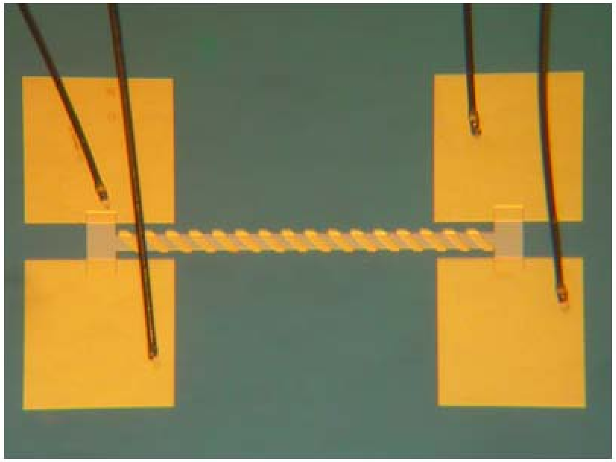





http://www.hkd.co.jp/english/amr_tec_amr/



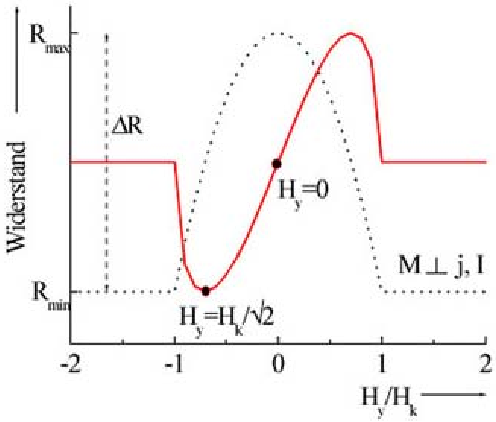
One of the most widely deployed magnetic field sensor is the AMR sensor. AMR stands for anisotropic magnetoresistance. In contrast to GMR sensors („giant magnetoresistance"), which require complex multilayer systems, the AMR sensor is characterized by its simplicity. It consists of a thin permalloy layer and metal stripes (so-called barber poles) which cause a linearization of the sensor characteristics. The spontaneous magnetization lies in the easy axis direction which is fixed by shape anisotropy. A magnetic field along the heavy axis (perpendicularly to the easy axis) provides a rotation of the magnetization in the permalloy strip and thus a change of its resistance.



AMR Sensor

Barber's pole

http://www.emg.tu-bs.de/forschung/mag_sens/amr_e.html

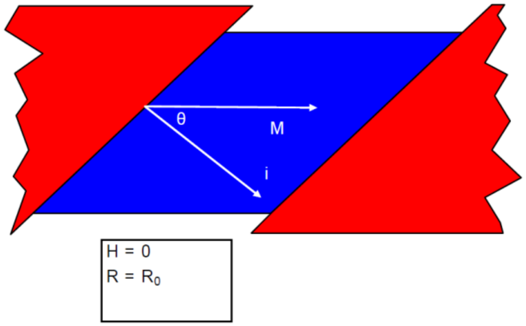



**Ideal characteristics of an AMR sensor with (red line) and without (dotted line) barber poles**

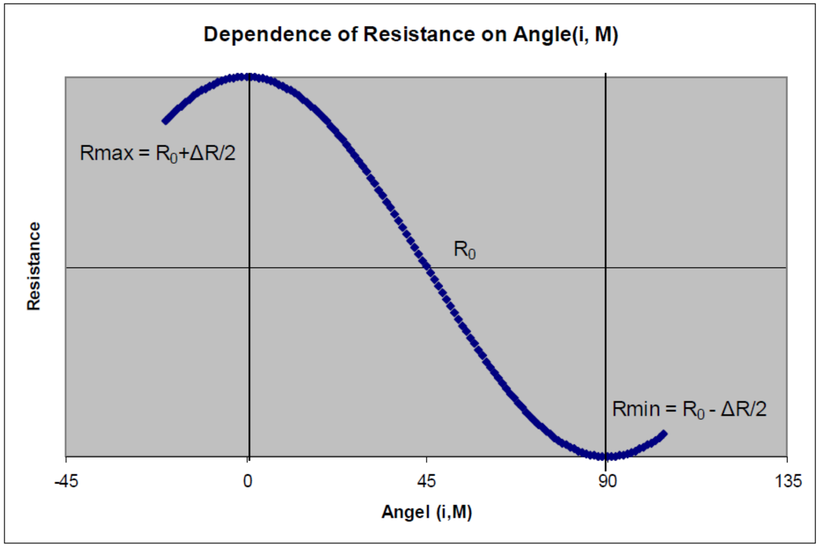
$$\boxed{R = R_0 + \Delta R \cos^2\theta_{i,M}}$$

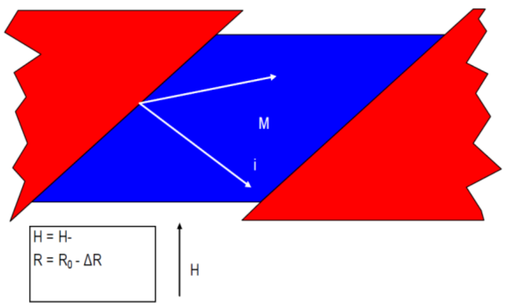
$$R = R_0 + \Delta R \cos^2\theta_{i,M}$$

The purpose of the barber-pole is to create a current vector (i) at 45º to the direction of the easy axis magnetization (M).



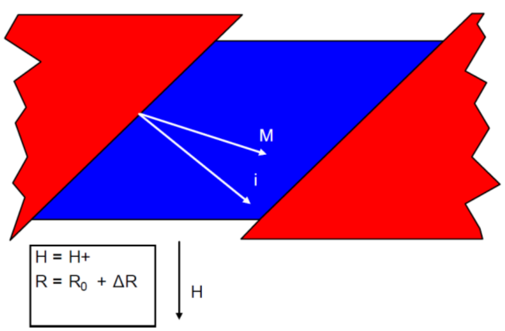

In the absence of an external field, R is $R_0$




A positive magnetic field H rotates M and decreases R.

http://www.resistorguide.com/magneto-resistor/

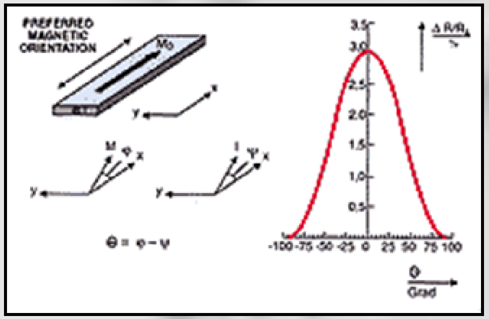



A negative magnetic field H decreases the angle between M and i and increases R.

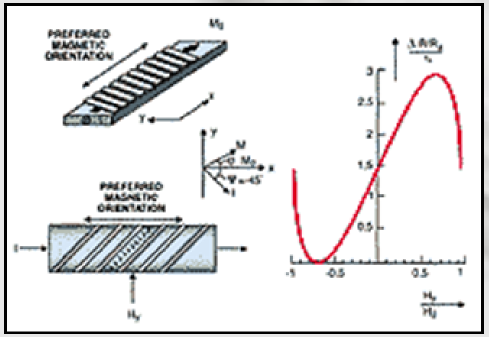
## ▽ Barber's pole:

←

(2a)




(2b)




## ▽ The sensor:

- permalloy base ($Fe_{20}Ni_{80}$)
- Au-Al strips

$\Rightarrow$ current flows in 45° $\rightarrow$ R(B) linear near 0



(2 a,b) Dr. Andreas P. Friedrich, Helmuth Lemme, "The Universal Current Sensor" , Sensors weekly (May 1, 2000)

## Giant Magnetoresistance (GMR).

# The Nobel Prize in Physics 2007

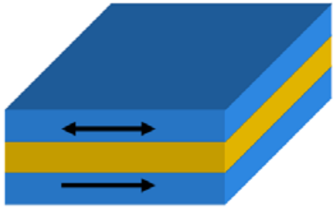
Albert Fert, Unité Mixte de Physique CNRS/THALES, Université Paris-Sud, Orsay, France

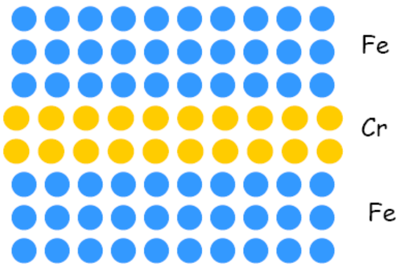
Peter Grünberg
Forschungszentrum Jülich, Germany

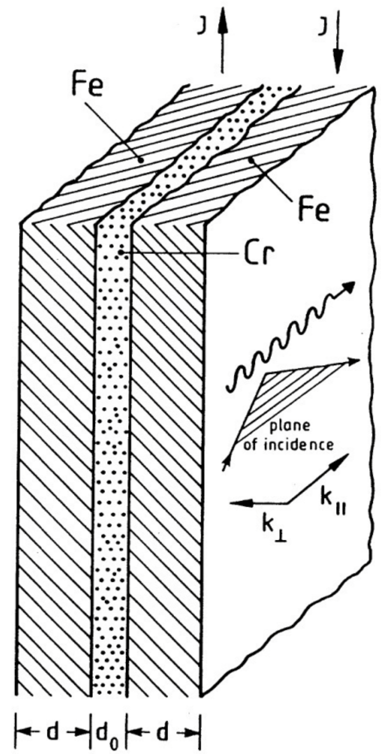
**That year's physics prize was awarded for the technology that is used to read data on hard disks. It is thanks to this technology that it has been possible to miniaturize hard disks so radically in recent years. Sensitive read-out heads are needed to be able to read data from the compact hard disks used in laptops and some music players, for instance.**

# Giant Magnetoresistance (GMR).

- System:
  - a thin layer of nonmagnetic material sandwiched between two layers of magnetic material.
- Right: a Fe-Cr-Fe trilayer






This effect has been observed in magnetic multilayers, e.g. Fe/Cr, where the alternate ferromagnetic layers couple anti-parallel to each other. Under the influence of a magnetic field the relative orientation of the magnetization of the layers changes and the electrical resistance decreases to a minimum when the magnetisation directions of the layers are parallel. This effect gives rise to resistance changes of 50-80%, and the effect has been termed **giant magnetoresistance (GMR).**

http://physicscentral.com/explore/action/magnetoresistance.cfm

Scientific Background on the Nobel Prize in Physics 2007

The Discovery of Giant Magnetoresistance

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

https://www.kva.se/globalassets/priser/nobel/2007/sciback_fy_en_07.pdf

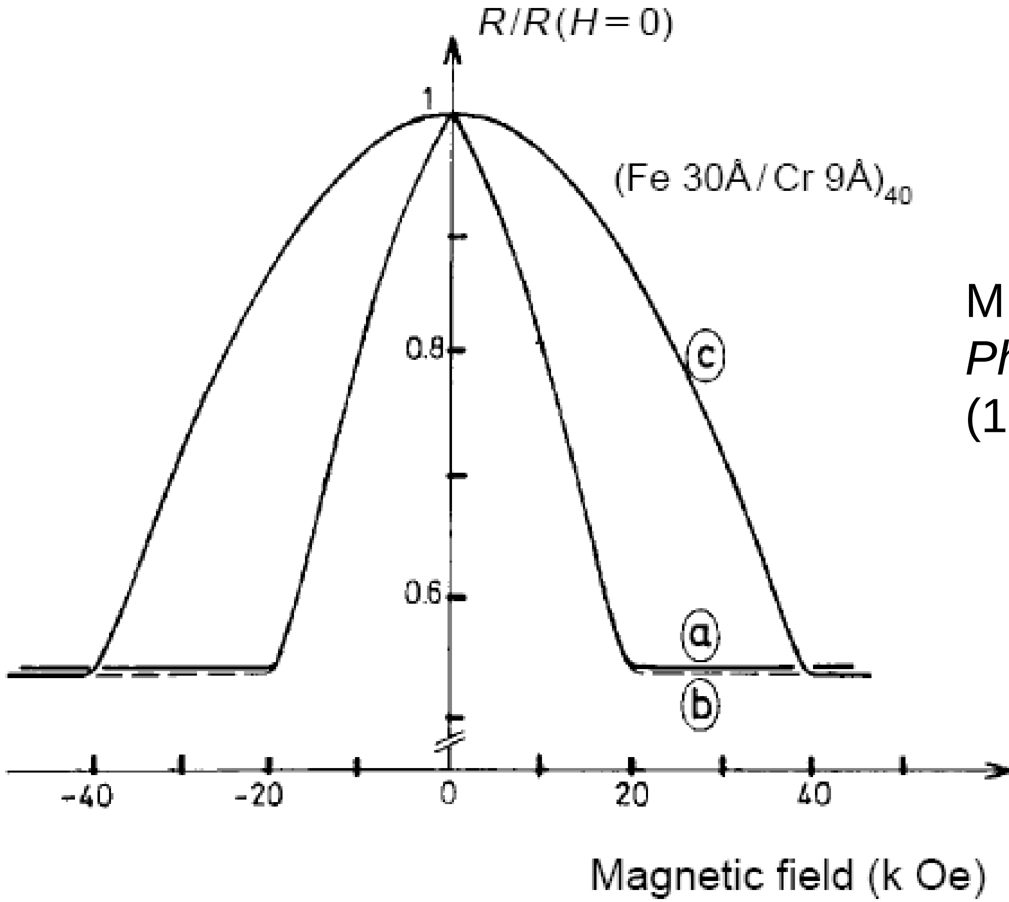
- Discovered independently by Professor Albert Fert of Université Paris-Sud in France and Professor Peter Grünberg of Forschungszentrum in Jülich, Germany.

- Both groups submitted papers to *Physical Review* in the summer of 1988.

# Science of GMR

## Giant magnetoresistance

Mizutani

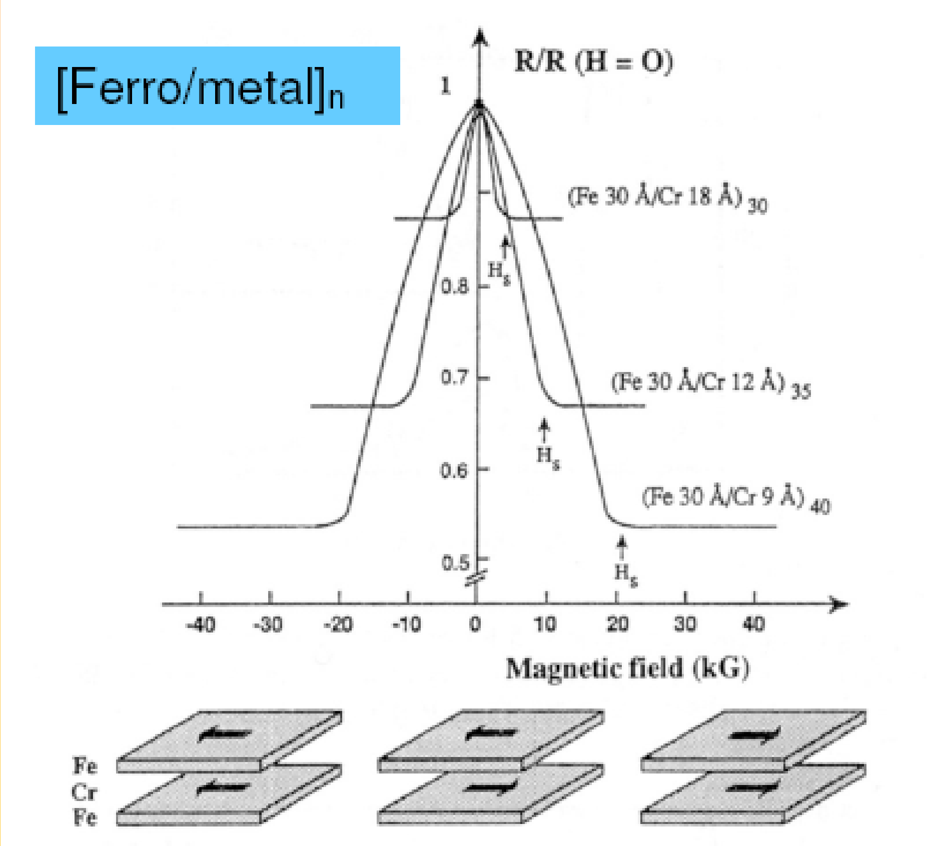



M. N. Baibich, et al.
*Phys. Rev. Lett.* **61** (1988) 2472

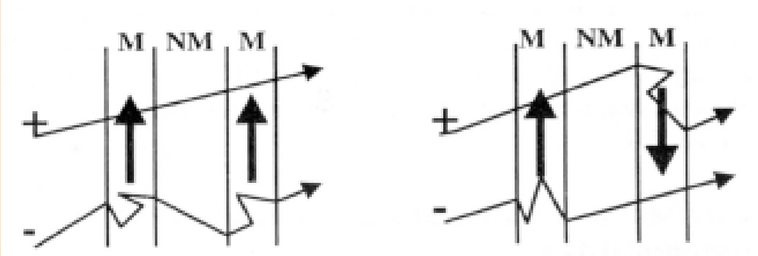
Mizutani

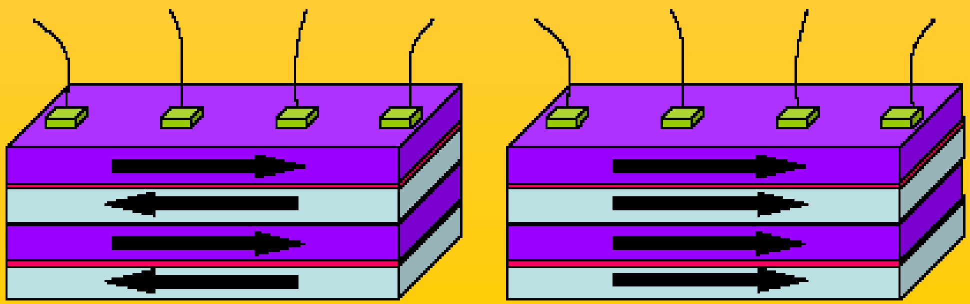
Figure 13.27. Magnetoresistance of [Fe 30 Å/Cr 9 Å]$_{40}$ superlattice at 4.2 K. The current is along [110] and the magnetic field is in the layer plane ⓐ parallel to the current direction, ⓑ perpendicular to the current and ⓒ perpendicular to the layer

The Fe/Cr multilayered film consists of alternate stacks of the ferromagnetic Fe and non-magnetic Cr layers.




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



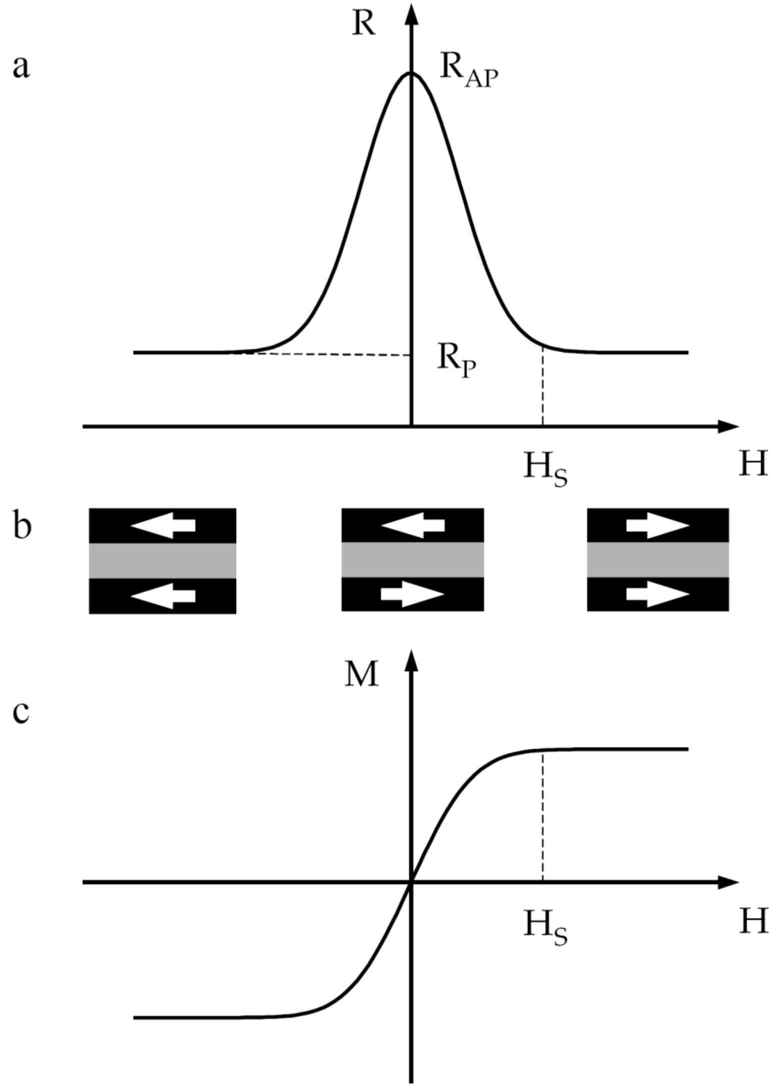



-The GMR effect was first observed in $[Fe/Cr]_n$ magnetic multilayers with layer thicknesses comparable to the mean free path.

-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%

E.Y. Tsymbal and D.G. Pettifor




Schematic representation of the GMR effect. (a): Change in the resistance of the magnetic multilayer as a function of applied magnetic field. (b): The magnetization configurations (indicated by the arrows) of the multilayer (trilayer) at various magnetic fields: the magnetizations are aligned antiparallel at zero field; the magnetizations are aligned parallel when the external magnetic field $H$ is larger than the saturation field $H_S$. (c): The magnetization curve for the multilayer.

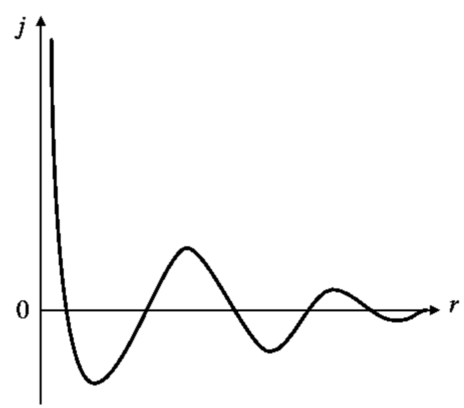
The change in the resistance of the multilayer arises when the applied field aligns the magnetic moments of the successive ferromagnetic layers

In the absence of the magnetic field the magnetizations of the ferromagnetic layers are antiparallel. Applying the magnetic field, which aligns the magnetic moments and saturates the magnetization of the multilayer, leads to a drop in the electrical resistance of the multilayer.

The interlayer exchange coupling is mediated by the itinerant electrons in the metallic spacer layer and is an analogue of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction between localized magnetic moments in a non-magnetic host metal. The interlayer exchange coupling oscillates between ferromagnetic and antiferromagnetic as a function of the thickness of the nonmagnetic layer. By choosing an appropriate thickness of the non-magnetic layer it is, therefore, possible to create an antiparallel configuration of the ferromagnetic layers and then reorient (align) the moments by an applied magnetic field.

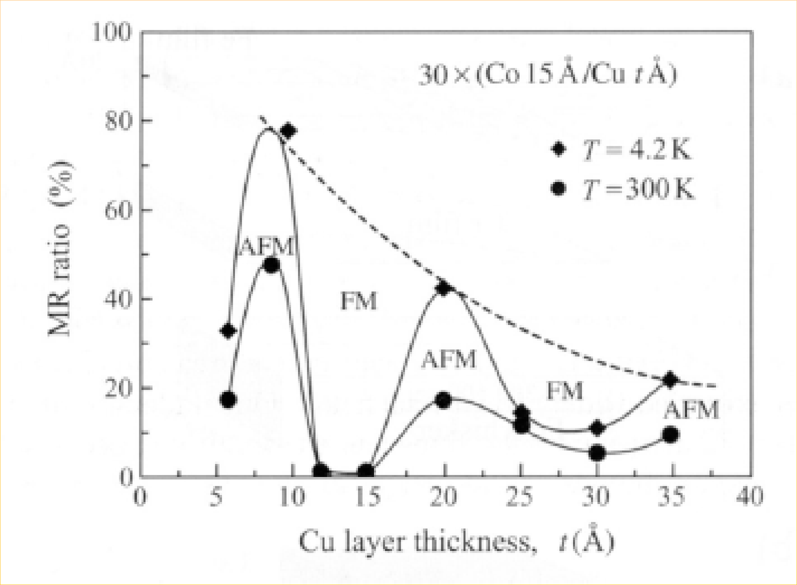
$$j\left(\boldsymbol{R}_l - \boldsymbol{R}_{l'}\right) = 9\pi \left(\frac{j^2}{\epsilon_F}\right) F\left(2k_F|\boldsymbol{R}_l - \boldsymbol{R}_{l'}|\right)$$

$$F(x) = \frac{x\cos x - \sin x}{x^4}$$

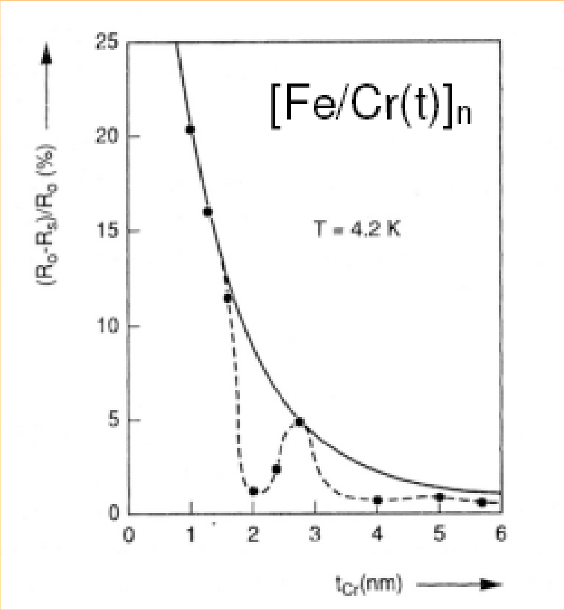


## GIANT MR (GMR): some facts

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



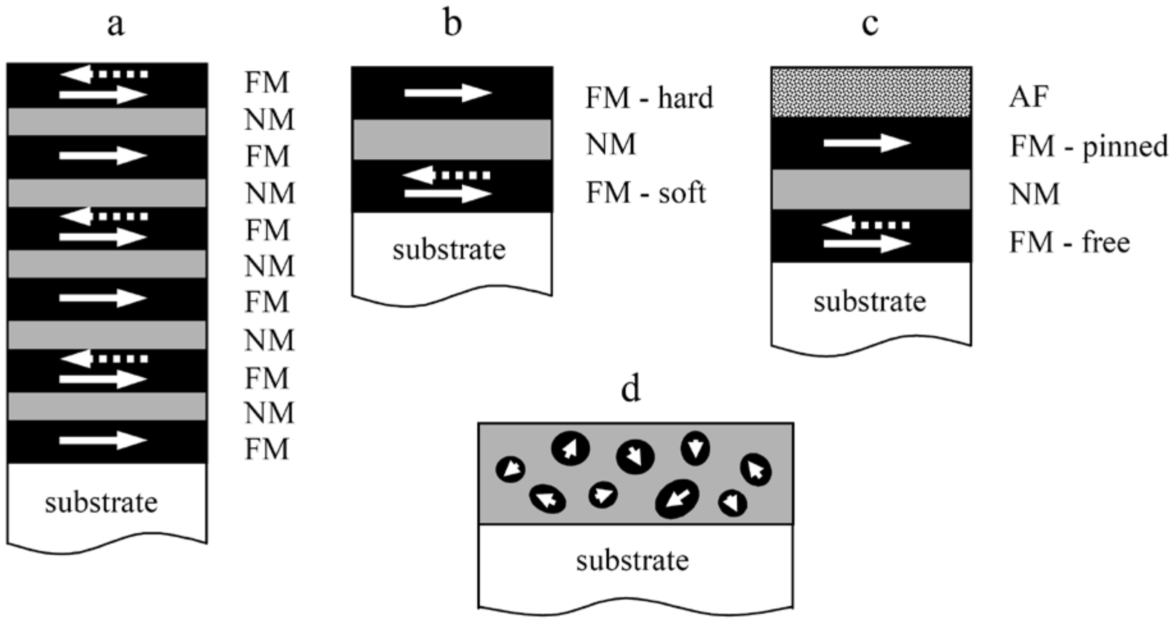

*Mosca et al., J. Magn. Magn. Mater. 94 (1991) 1*




*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*

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf




Various structures in which GMR can be observed: magnetic multilayer (a), pseudo spin valve (b), spin valve (c) and granular thin film (d). Note that the layer thickness is of the order of a few nanometers, whereas the lateral dimensions can vary from micrometers to centimetres. In the magnetic multilayer (a) the ferromagnetic layers (FM) are separated by nonmagnetic (NM) spacer layers. Due to antiferromagnetic interlayer exchange coupling they are aligned antiparallel at zero magnetic field as is indicated by the dashed and solid arrows. At the saturation field the magnetic moments are aligned parallel (the solid arrows). In the pseudo spin valve (b) the GMR structure combines hard and soft magnetic layers. Due to different coercivities, the switching of the ferromagnetic layers occurs at different magnetic fields providing a change in the relative orientation of the magnetizations. In the spin valve (c) the top ferromagnetic layer is pinned by the attached antiferromagnetic (AF) layer. The bottom ferromagnetic layer is free to rotate by the applied magnetic field. In the granular material (d) magnetic precipitates are embedded in the non-magnetic metallic material. In the absence of the field the magnetic moments of the granules are randomly oriented. The magnetic field aligns the moments in a certain direction.

E.Y. Tsymbal and D.G. Pettifor, *published in Solid State Physics, ed. by H. Ehrenreich and F. Spaepen, Vol. 56 (Academic Press, 2001) pp.113-237*

# Engineering MR Materials

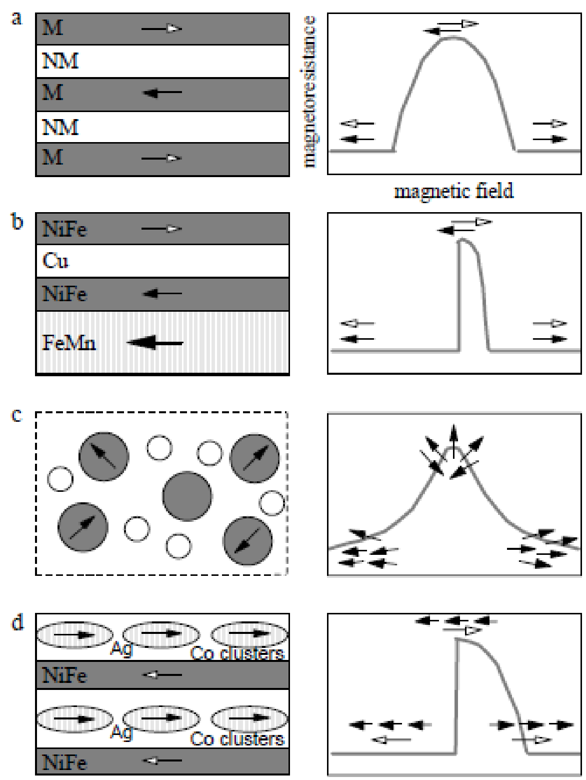
Various GMR nanostructures (left) and their magnetoresistance behaviour (right – note that all the hotizontal scales are different).
(a) antiferromagnetically coupled multilayer;
(b) spin – valve structure;
(c) granular alloy;
(d) hybrid nanostructure including clusters and layers. See text for details.

antiferromagnetically coupled multilayers

spin valve structure

granular material

hybrid cluster/layer

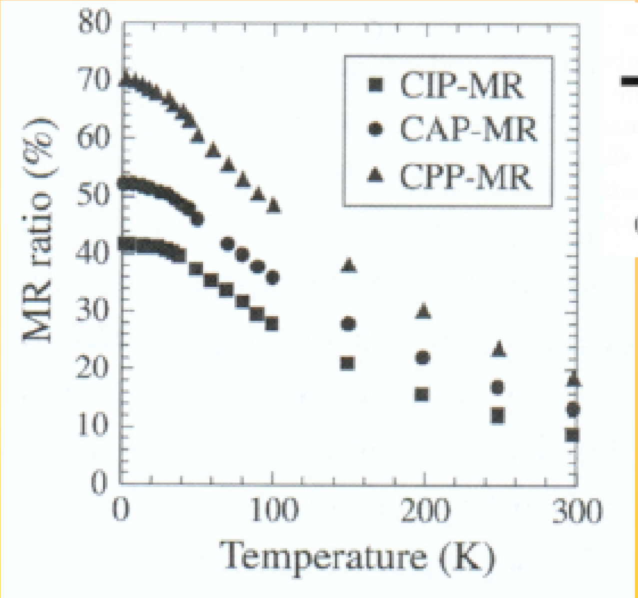


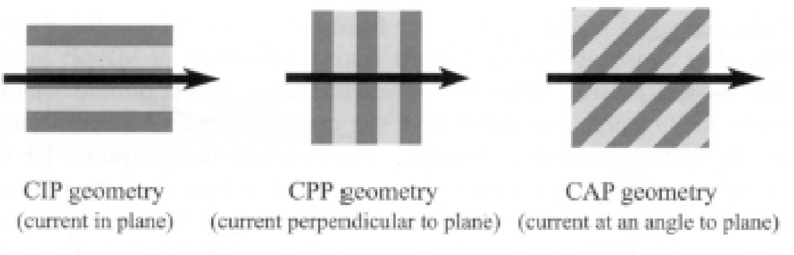

Barthélémy et al., Physics World Nov. 1994

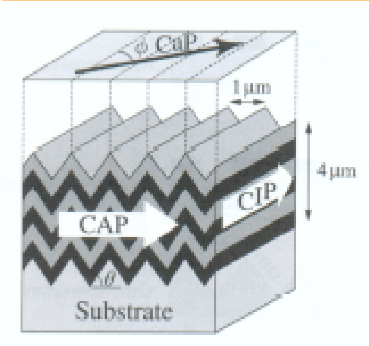
**Figure 2 :** Nanostructures for GMR. From top to bottom : - multilayers make use of an antiferromagnetic coupling among the layers, - spin valve bi-layer structures have one layer pinned magnetically; - granular materials; - hybrids. (after Physics World, Nov. 1994 p. 34)

## 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



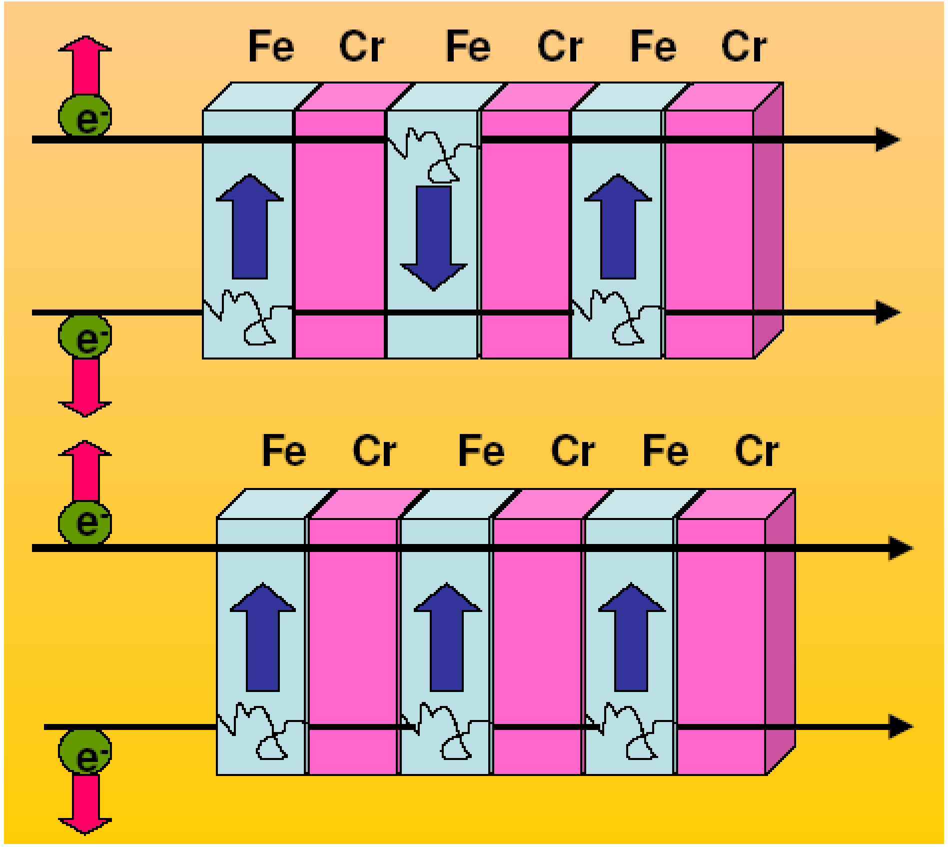

*Ono et al., Phys. Rev. B 55 (1997) 14457*

*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*

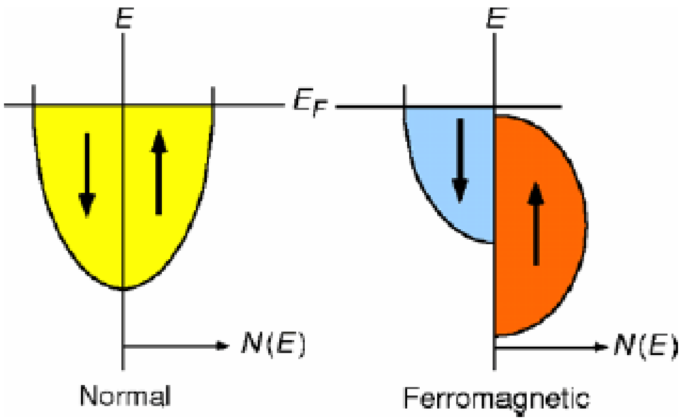
## GIANT MR (GMR): simple picture

- 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.




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

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



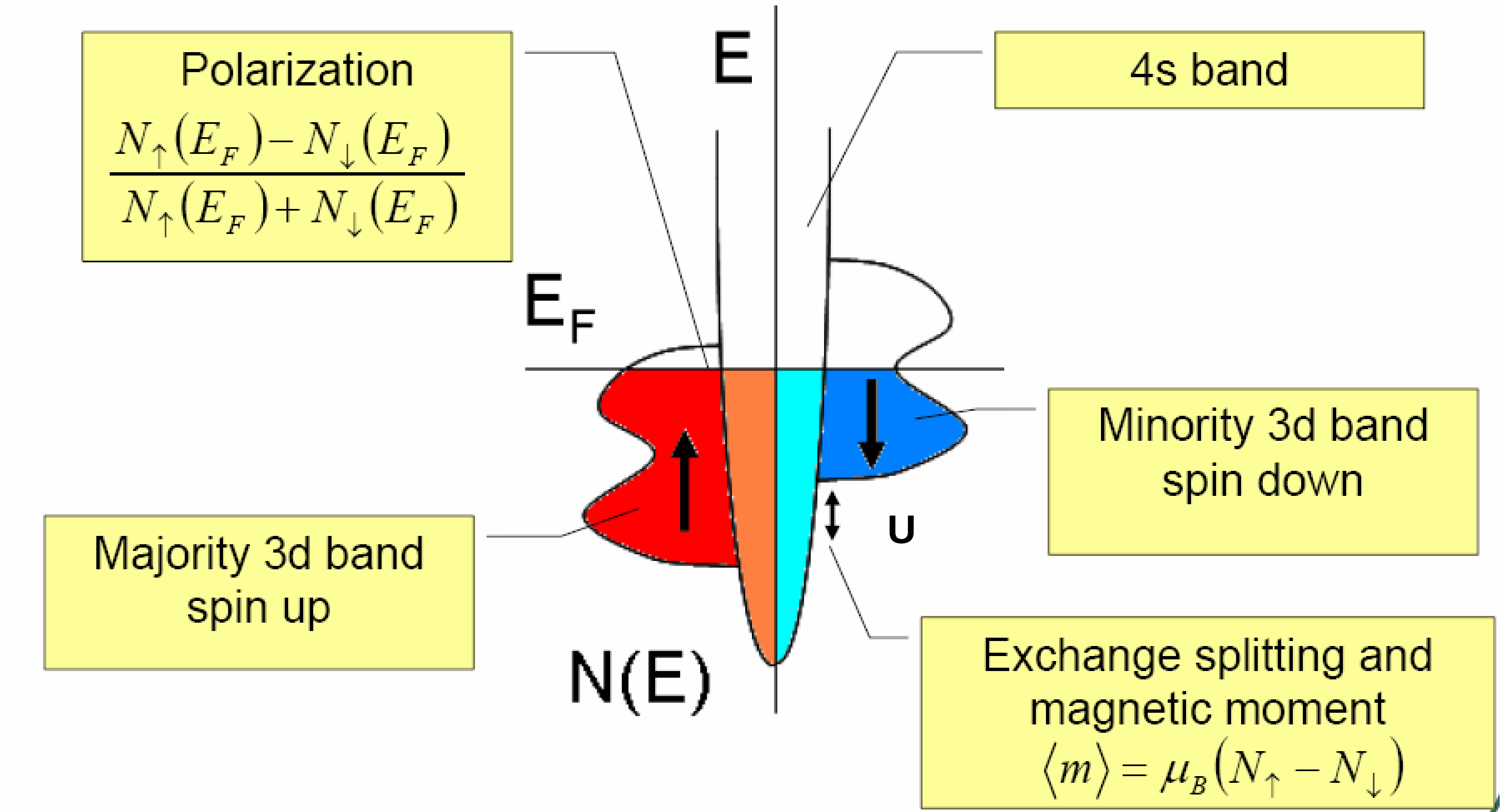

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

# Mott Model

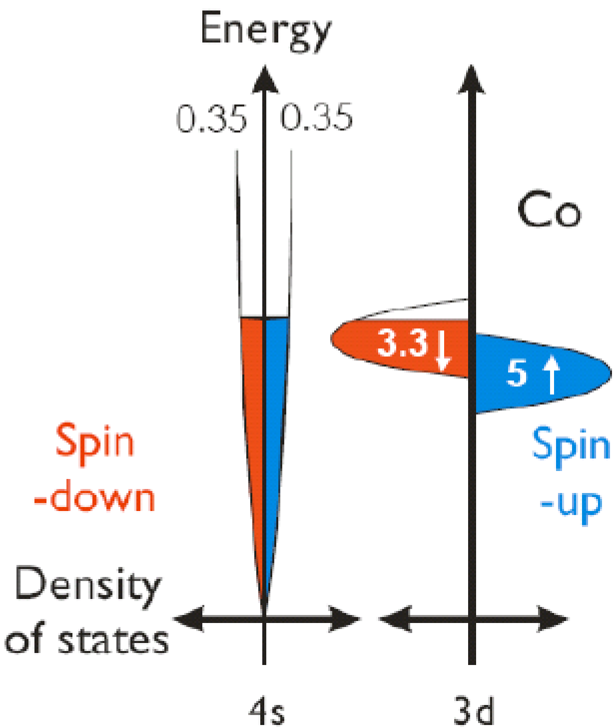
- The electrical conductivity in metals can be described in terms of two largely independent conducting channels, corresponding to the up-spin and down-spin electrons, and electrical conduction occurs in parallel for the two channels.
- In ferromagnetic metals the scattering rates of the up-spin and down-spin electrons are different.

❖ (We will assume that the scattering is strong for electrons with spin antiparallel to the magnetization direction and weak for electrons with spin parallel to the magnetization direction.)

# Band magnetism



# Transport: Two current model




$\sigma = \sigma_{\Uparrow} + \sigma_{\Downarrow}$

$\sigma_{\Uparrow} >> \sigma_{\Downarrow}$

- in all ferro and ferri-magnetic systems current is carried independently in two spin-channels

- conductivity in two channels can be very different

→can be described by spin-dependent mean free paths or scattering times

→**current is spin-polarized**

→**manipulate flow of spin polarized current → useful sensors and memories**

Neville Mott (1934)

Fert and Campbell, J. Phys. Metal Phys. **6**, 849 (1976).

The 3d band in the Fe layer is split into spin-up and spin-down sub-bands due to the exchange energy *U.*

$$\uparrow \quad (\varepsilon_{\mathrm{Fe}} - U) \text{ and } (\varepsilon_{\mathrm{Fe}} + U) \quad \downarrow$$

$$\boxed{\varepsilon_{\mathrm{Fe}} < \varepsilon_{\mathrm{Cr}}}$$

See Mizutani

$\varepsilon_{\mathrm{Fe}}$ is the mean energy of the Fe-3d band in the absence of *U.*

The detailed calculations show that

$$\varepsilon_{\mathrm{Fe}} + U\,(\downarrow) \approx \varepsilon_{\mathrm{Cr}}$$

spin-up and spin-down electrons to

experience different average potentials

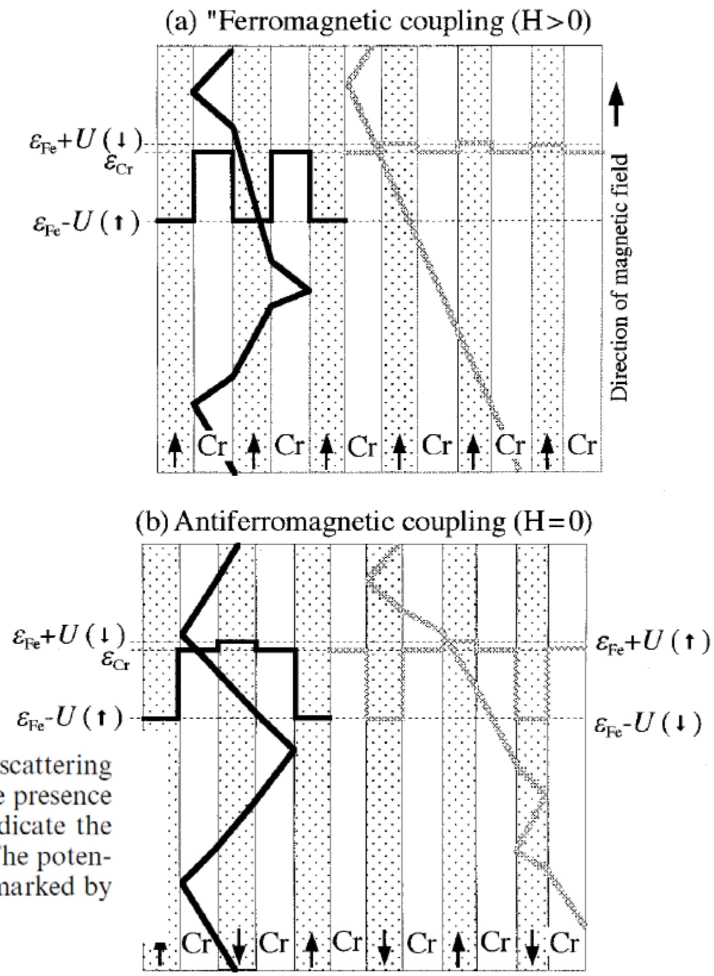
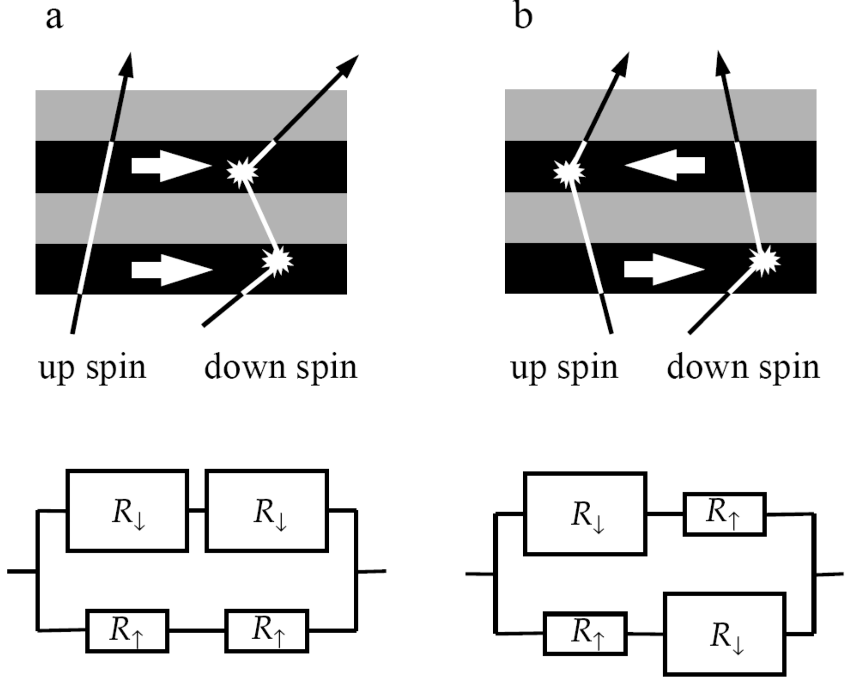



Figure 13.28. GMR mechanism in Fe/Cr multilayered film. The electron scattering path of spin-up (solid line) and spin-down (hatched line) electrons (a) in the presence and (b) in the absence of a magnetic field. The horizontal dotted lines indicate the average potentials $\varepsilon_{\mathrm{Fe}} \pm U$ and $\varepsilon_{\mathrm{Cr}}$ associated with Fe-3d and Cr-3d states. The potentials experienced by spin-up and spin-down electrons across the layers are marked by solid and hatched lines, respectively.




Schematic illustration of electron transport in a multilayer for parallel (a) and antiparallel (b) magnetizations of the successive ferromagnetic layers. The magnetization directions are indicated by the arrows. The solid lines are individual electron trajectories within the two spin channels. It is assumed that the mean free path is much longer than the layer thicknesses and the net electric current flows in the plane of the layers. Bottom panels show the resistor network within the two-current series resistor model. For the parallel-aligned multilayer (a), the up-spin electrons pass through the structure almost without scattering, whereas the down-spin electrons are scattered strongly within both ferromagnetic layers. Since conduction occurs in parallel for the two spin channels, the total resistivity of the multilayer is low. For the antiparallel-aligned multilayer (b), both the up-spin and down-spin electrons are scattered strongly within one of the ferromagnetic layers, and the total resistivity of the multilayer is high.

E.Y. Tsymbal and D.G. Pettifor, *published in Solid State Physics, ed. by H. Ehrenreich and F. Spaepen, Vol. 56 (Academic Press, 2001) pp.113-237*

$$\sigma = \sigma_{\uparrow} + \sigma_{\downarrow}$$

$$\boxed{\sigma_{Drude} = \frac{e^2}{\pi\hbar}\frac{k_F^2}{6\pi}\lambda}$$

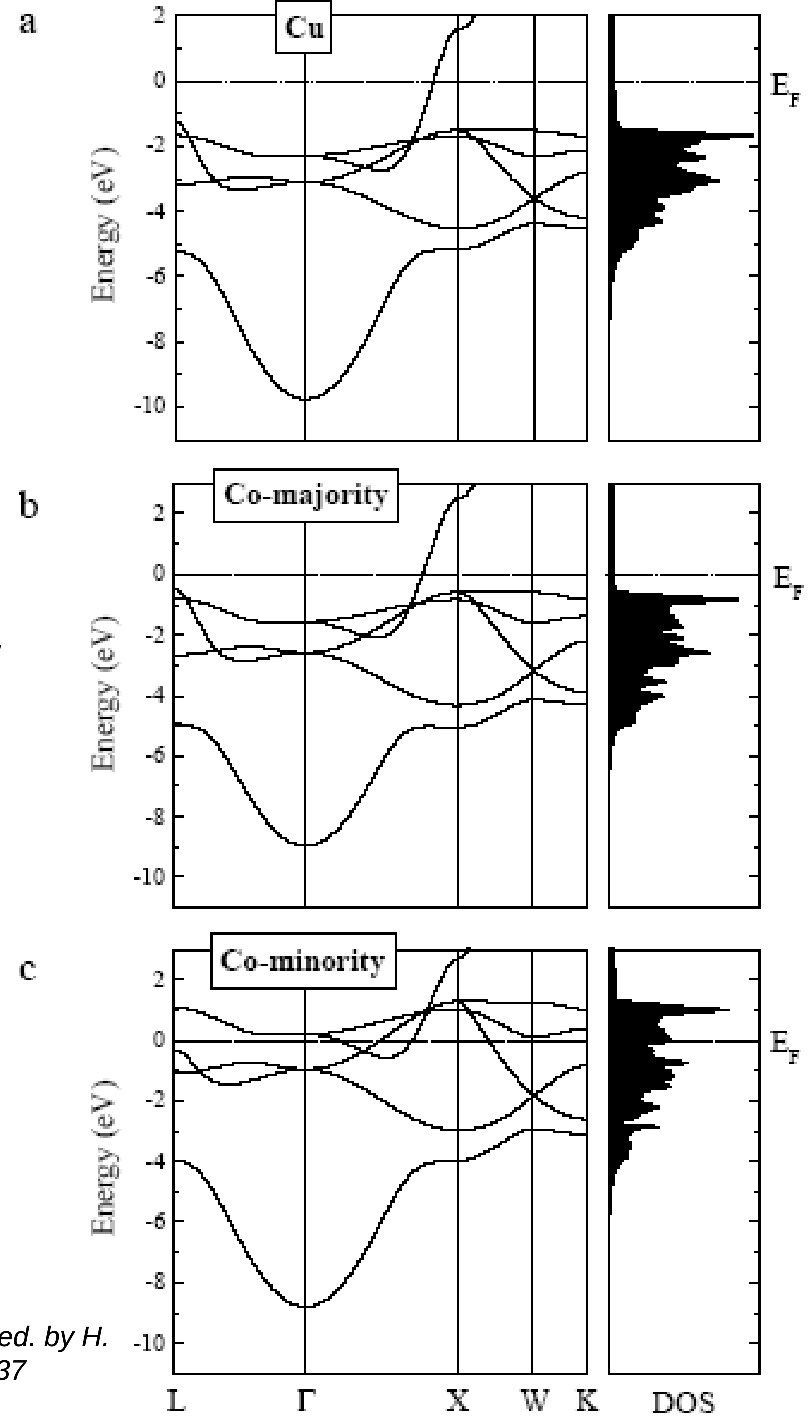
$$\lambda = v_F \tau$$

$$\tau^{-1} = \frac{2\pi}{\hbar}\left\langle V_{scat}{}^2 \right\rangle n(E_F)$$

are in general spin-dependent,

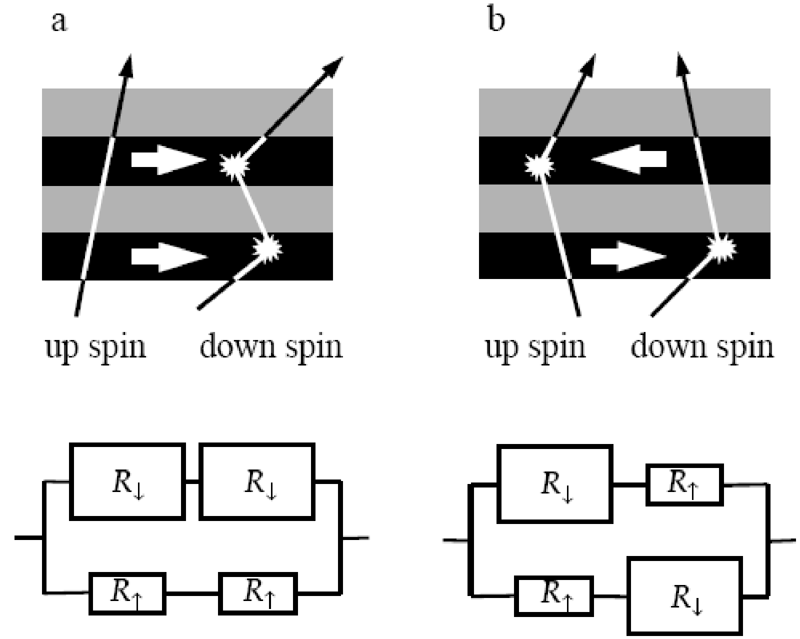
In ferromagnetic metals these quantities are different for the up- and down-spin electrons.

“Electronic band structures (left panels) and the density of states (right panels) of Cu (a) and fcc Co for the majority-spin (b) and minority-spin (c) electrons. The band structure of non-magnetic Cu is same for the up-spin and down-spin electrons. It is characterized by the fully occupied *d* bands and the presence of a dispersive *sp* band at the Fermi energy, which result in high conductivity of Cu. The electronic structure of ferromagnetic Co is different for the two spin orientations and is characterized by the exchange-split *d* bands. The Fermi level lies within the *sp* band for the majority-spin electrons, which leads to high conductivity of majority-spin channel. The Fermi level lies, however, within the *d* band for the minority-spin electrons resulting in low conductivity of the minority-spin channel. In the latter case the *sp* electrons are strongly hybridized with the *d* electrons, which diminishes their contribution to conduction”.(Mott)




from E.Y. Tsymbal and D.G. Pettifor, *published in Solid State Physics, ed. by H. Ehrenreich and F. Spaepen, Vol. 56 (Academic Press, 2001) pp.113-237*

$$R_{\uparrow,\downarrow} = \rho_{NM} d_{NM} + \rho_{\uparrow,\downarrow} d_{FM}$$




$$R_P = N\frac{2R_{\uparrow}R_{\downarrow}}{R_{\uparrow}+R_{\downarrow}} \qquad R_{AP} = N\frac{R_{\uparrow}+R_{\downarrow}}{2}$$

$$\boxed{\frac{\Delta R}{R} = \frac{R_{AP}-R_P}{R_P} = \frac{(R_{\downarrow}-R_{\uparrow})^2}{4R_{\downarrow}R_{\uparrow}}}$$

the resistance of the spacer layer is small as compared to the resistance of the ferromagnetic layers.

$$\frac{\Delta R}{R} = \frac{(\rho_{\downarrow}-\rho_{\uparrow})^2}{4\rho_{\downarrow}\rho_{\uparrow}} = \frac{(\alpha-1)^2}{4\alpha}$$

E.Y. Tsymbal and D.G. Pettifor, *published in Solid State Physics, ed. by H. Ehrenreich and F. Spaepen, Vol. 56 (Academic Press, 2001) pp.113-237*

the spin asymmetry parameter is defined by $\alpha = \rho_{\downarrow}/\rho_{\uparrow}$

Large asymmetry, i.e. $\alpha >> 1$ or $\alpha << 1$

requirement for obtaining high values of GMR.

an estimate of GMR in Co/Cu and Fe/Cr multilayers

$\alpha \approx 7$ for Co and $\alpha \approx 3$ for Fe.

For the Co/Cu multilayer this leads to a GMR value of 130%, which is very close to the best published experimental result of 120%.

for Fe/Cr gives a GMR of 30%, far below the highest ever observed value of 220%

the above model is too simplified

the properties of the FM/NM interface which were ignored in this estimate.

The finite resistance of the spacer layer may also be taken into account,

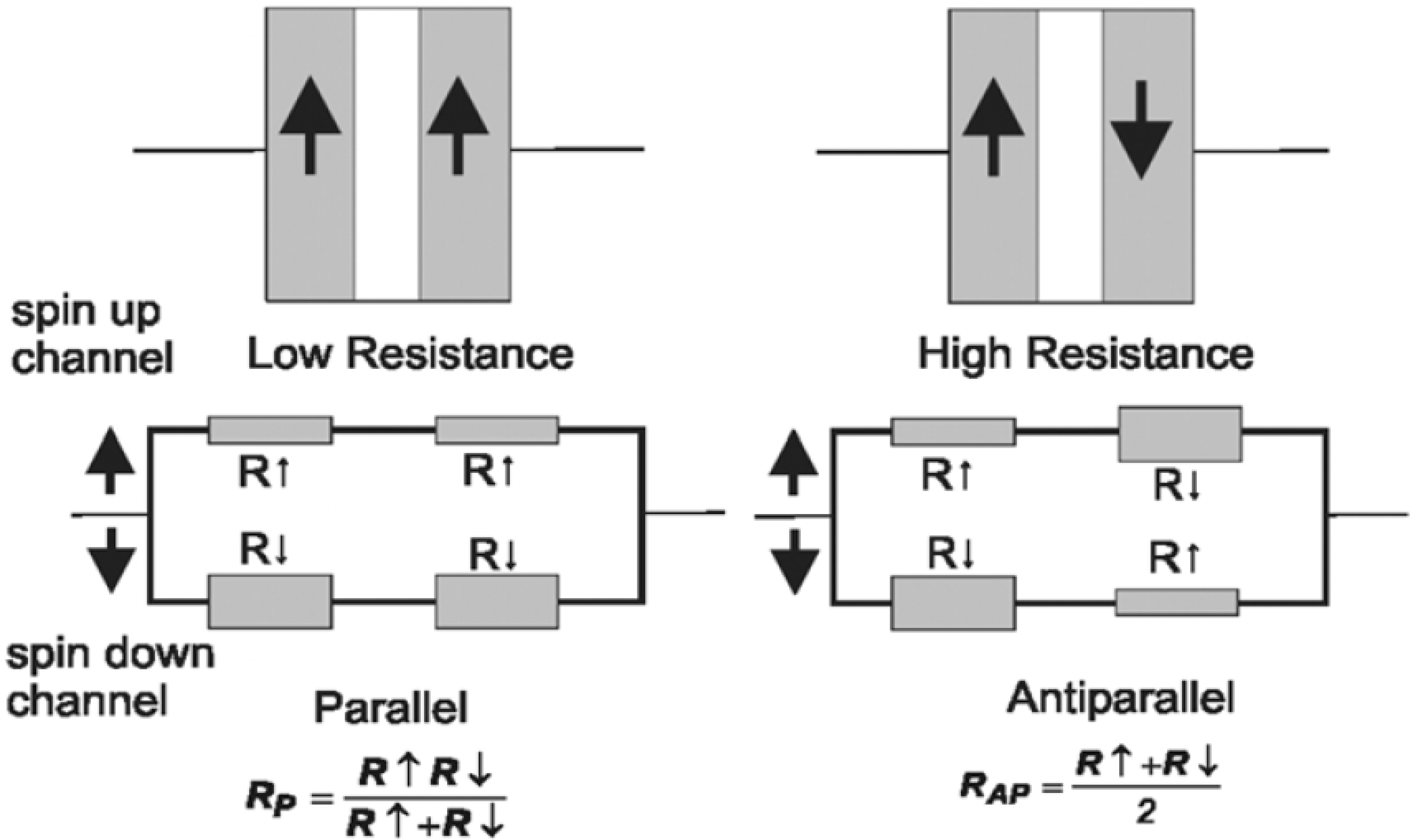
$$\frac{\Delta R}{R} = \frac{(\alpha - 1)^2}{4(\alpha + p d_{NM} / d_{FM})(1 + p d_{NM} / d_{FM})}$$

where $p = \rho_{NM} / \rho_{\uparrow}$

in order to obtain higher GMR, it is important to have a low resistivity of the non-magnetic spacer layer.

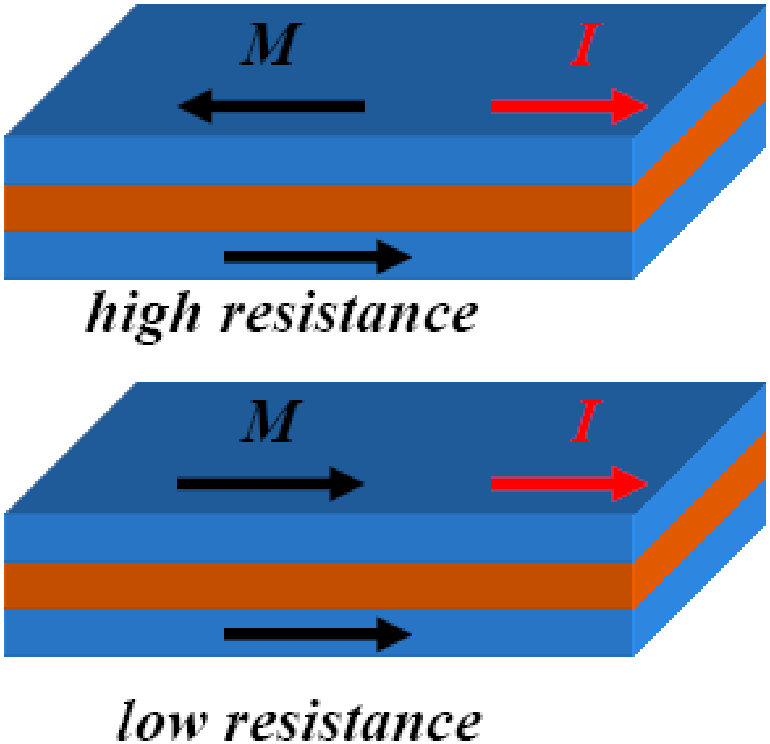
suggests that the resistance of the parallel configuration is always smaller than the resistance of the antiparallel configuration. In most cases this statement is correct.

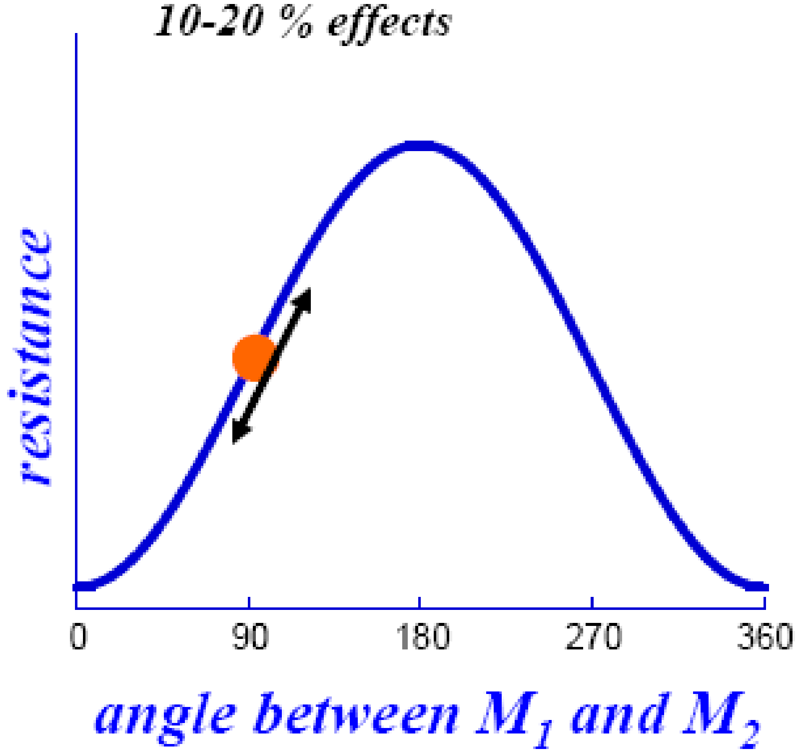
E.Y. Tsymbal and D.G. Pettifor
***Solid State Physics, ed. by H. Ehrenreich and F. Spaepen, Vol. 56 (Academic Press, 2001) pp.113-237***




E.Y. Tsymbal and D.G. Pettifor

# Giant Magneto-resistance (GMR)



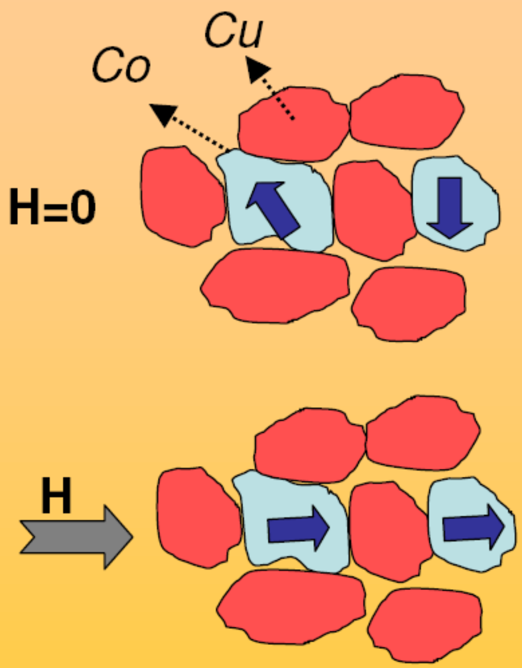

***Interface property of magnetic materials***

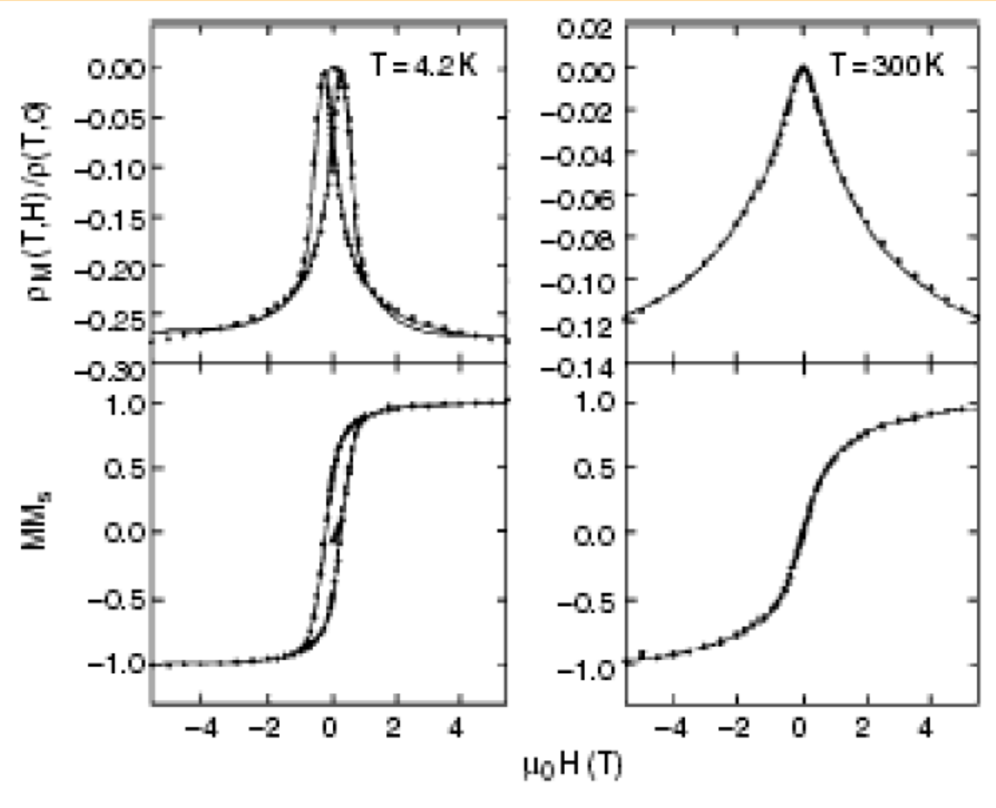
*Baibich et al. Phys. Rev. Lett.* ***61*** *2472 (1988)*

*Binasch et al. Phys. Rev. B 39, 4828 (1989); P. Grunberg, U.S. patent # 4,949,039*

# 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.

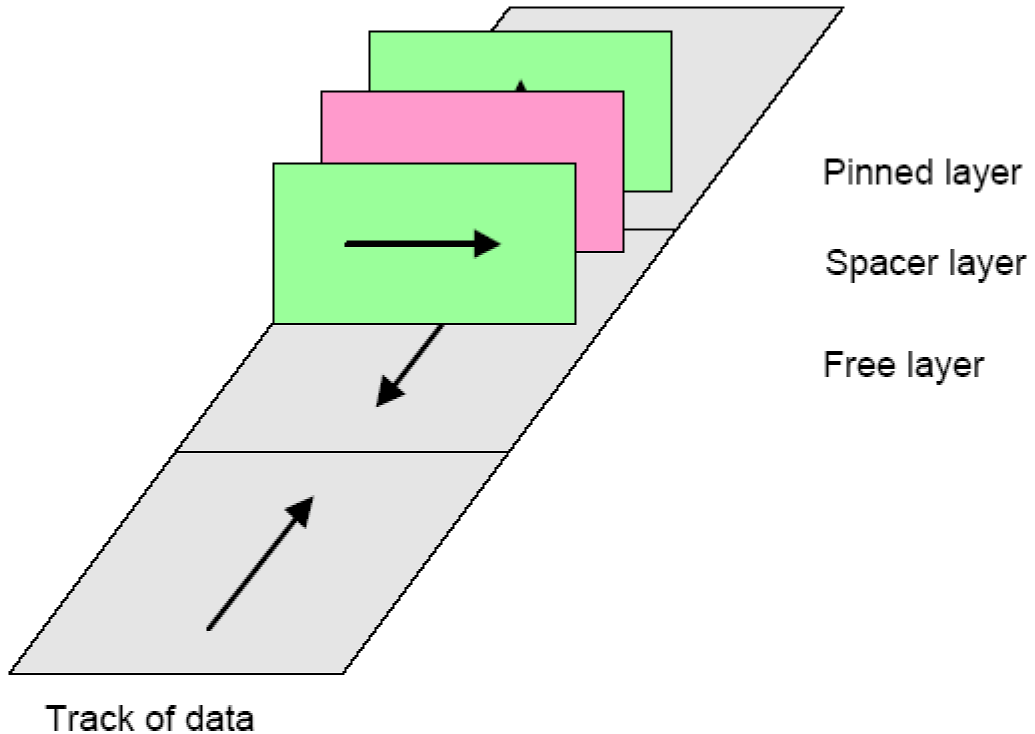


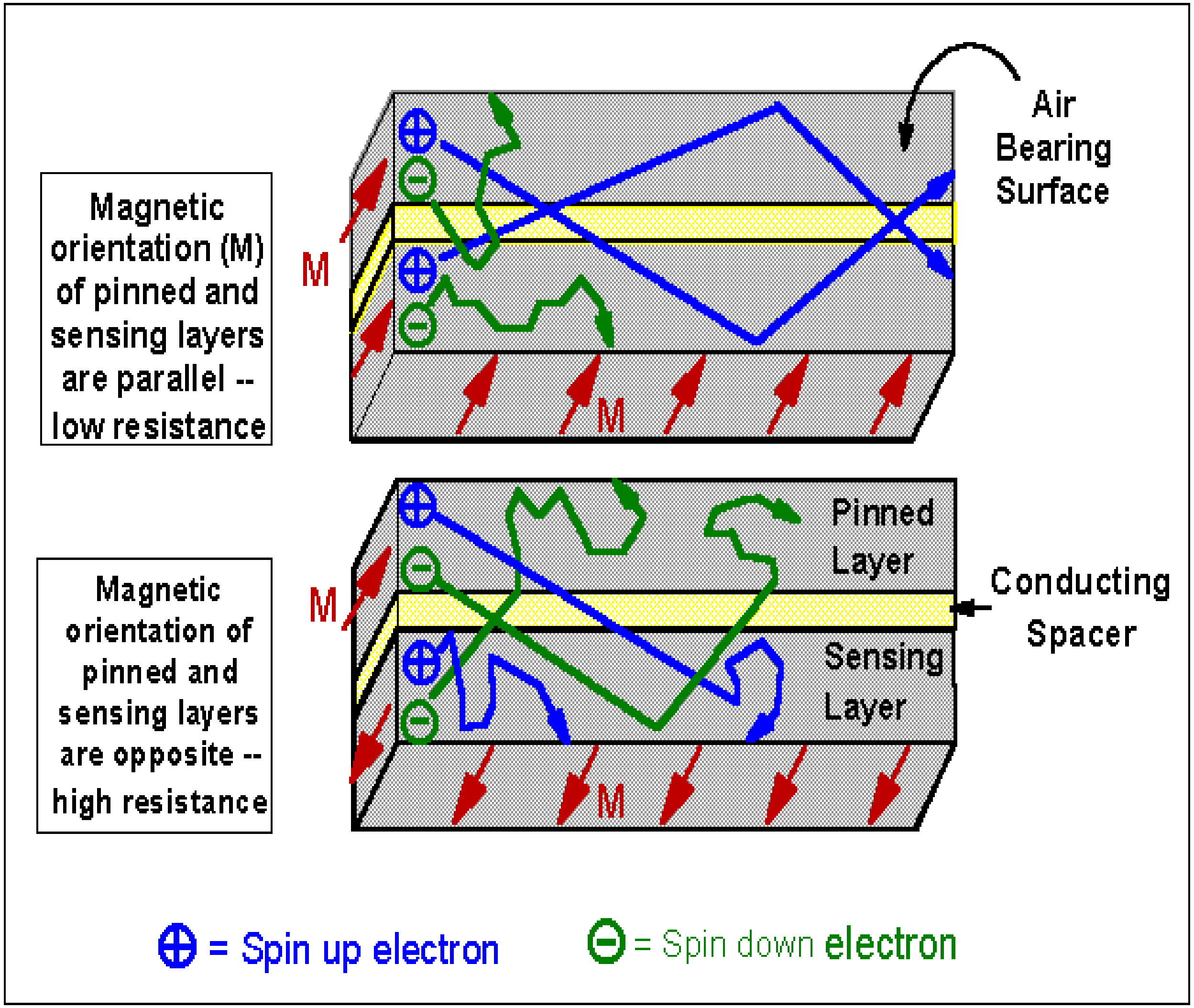




Berkowitz et al., Phys. Rev. Lett. 68 (1992) 3745; Xiao et al., Phys. Rev. Lett. 68 (1992) 3749; Wang and Xiao, Phys. Rev. B 50 (1994) 3423; Batlle and Labarta, J. Phys. D: Appl. Phys. 35 (2002) R15

http://magnetism.eu/esm/2005-constanta/slides/deteresa-slides.pdf

# GMR sensors

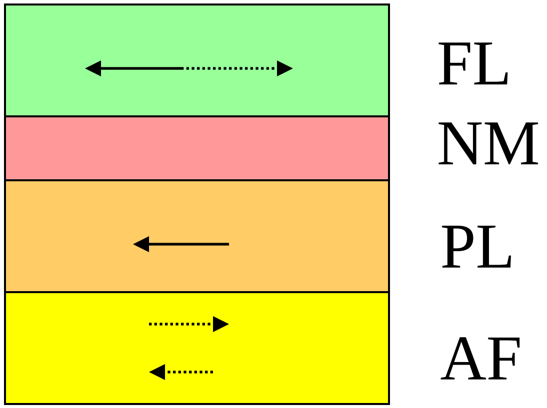




Magnetic orientation (M) of pinned and sensing layers are parallel -- low resistance
M
M
Air Bearing Surface
Magnetic orientation of pinned and sensing layers are opposite -- high resistance
M
M
Pinned Layer
Conducting Spacer
Sensing Layer
= Spin up electron
= Spin down electron

# Single-Spin-Valve

The FL is unusually composed of soft magnetic materials so that can change the magnetic direction with an application of a small magnetic field.  The NM layer is a separate layer to eliminate the magnetic coupling between the FL and PL and to realize free magnetic rotation in the FL.The AF magnetically couples with  the PL across the interface and cause the exchange bias effect on the PL.



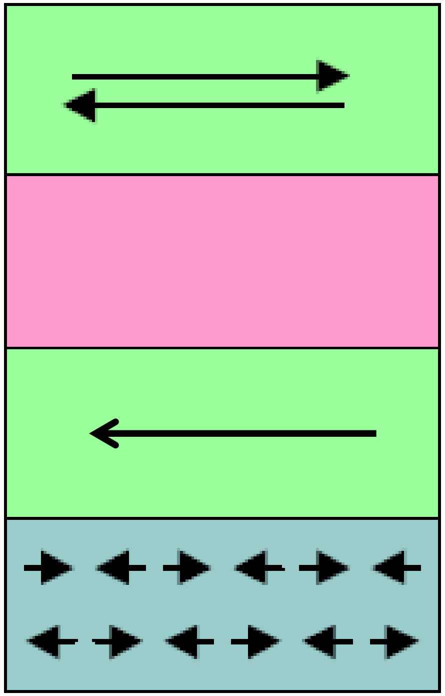

Structure of single spin-valve film

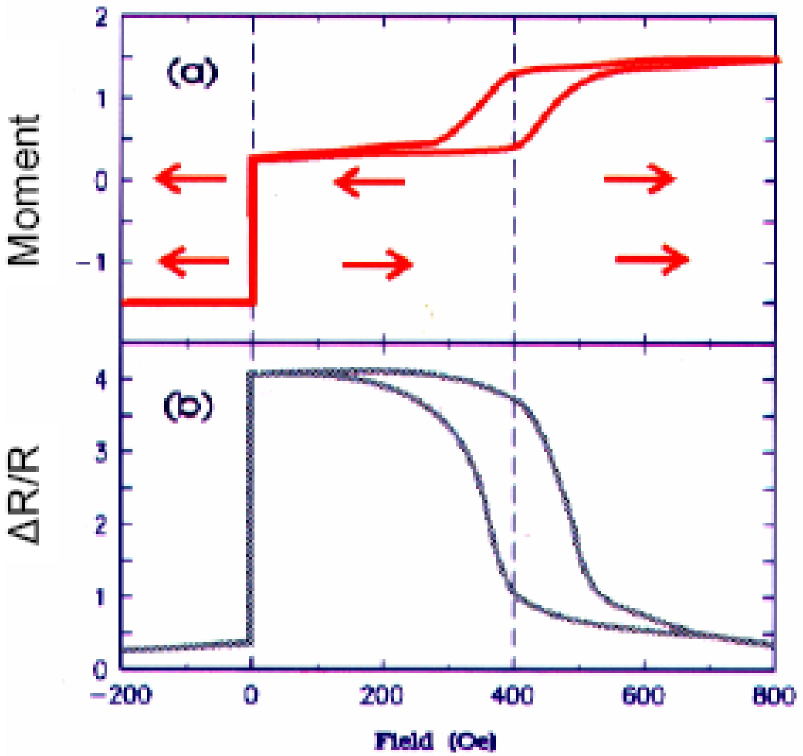
The prototype of the single spin valve film is $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$.

PtMn-based spin valves show excellent thermal stability of he MR properties owing to high $T_N > 350^{o}C$ and widely used for read heads

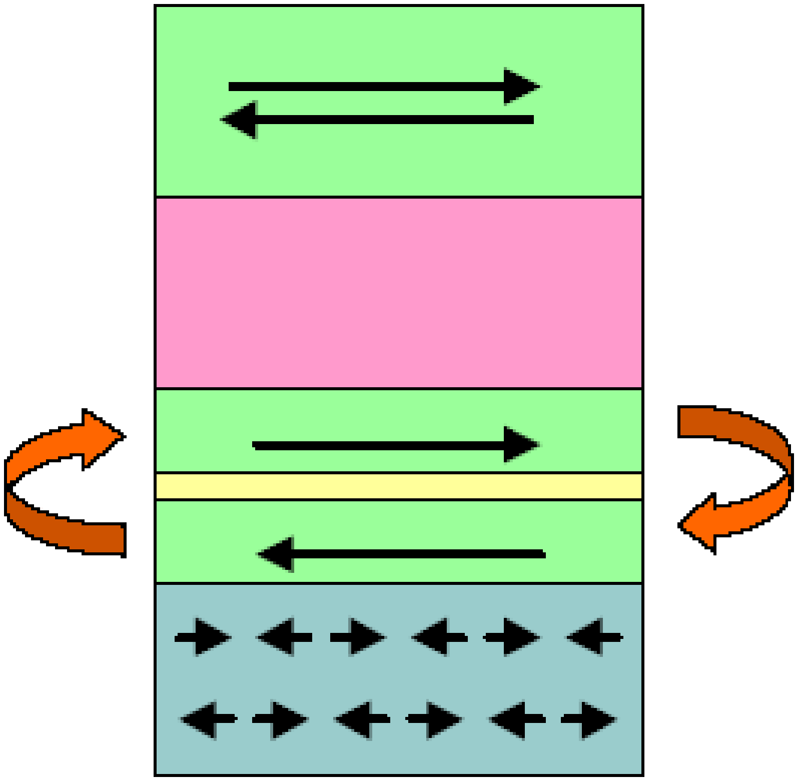
# GMR sensors

➢The reference ferromagnetic layer magnetization is pinned by an antiferromagnetic layer and does not rotate in small magnetic fields



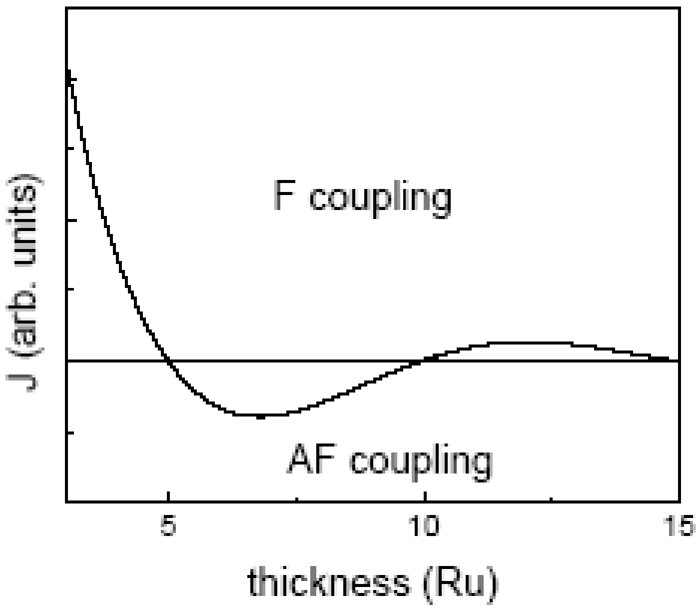


# GMR sensors

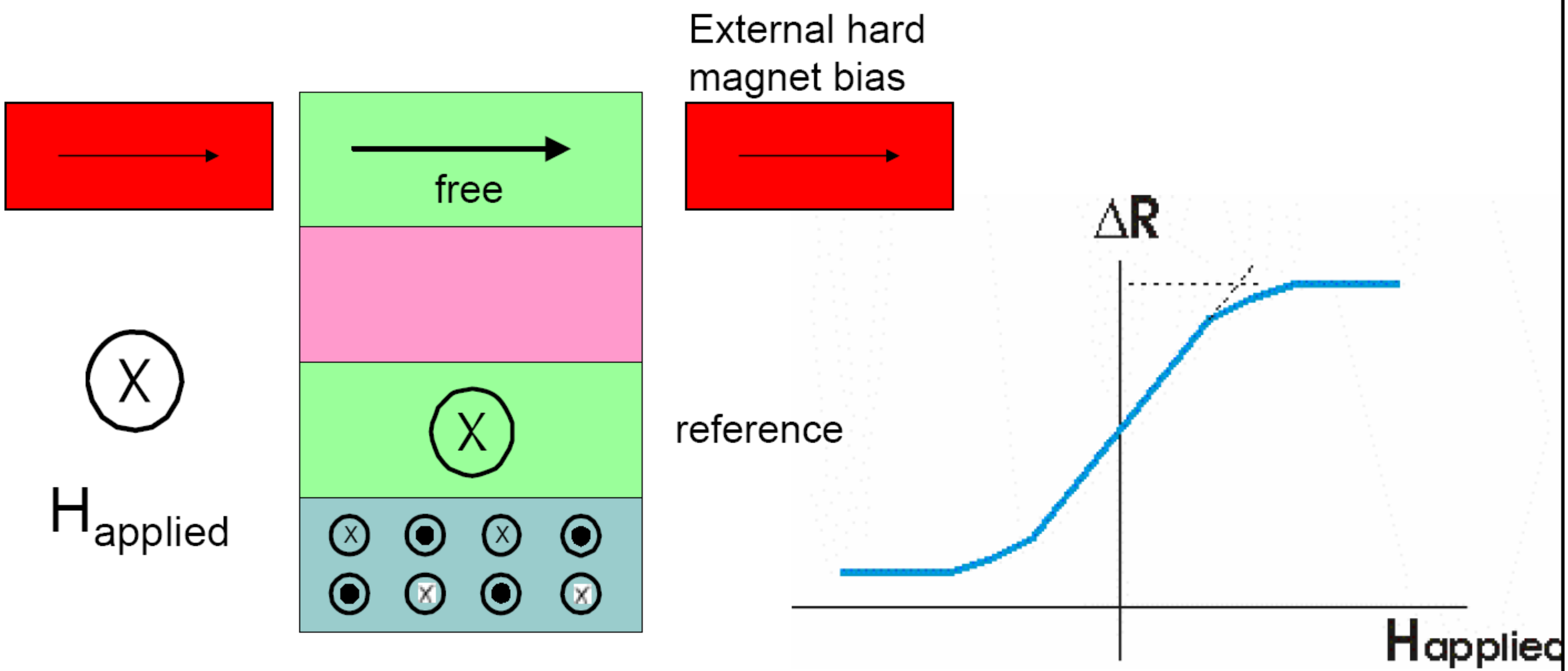


Pinned layer is AP pinned to obtain flux closure to minimize magneto-static coupling to free layer

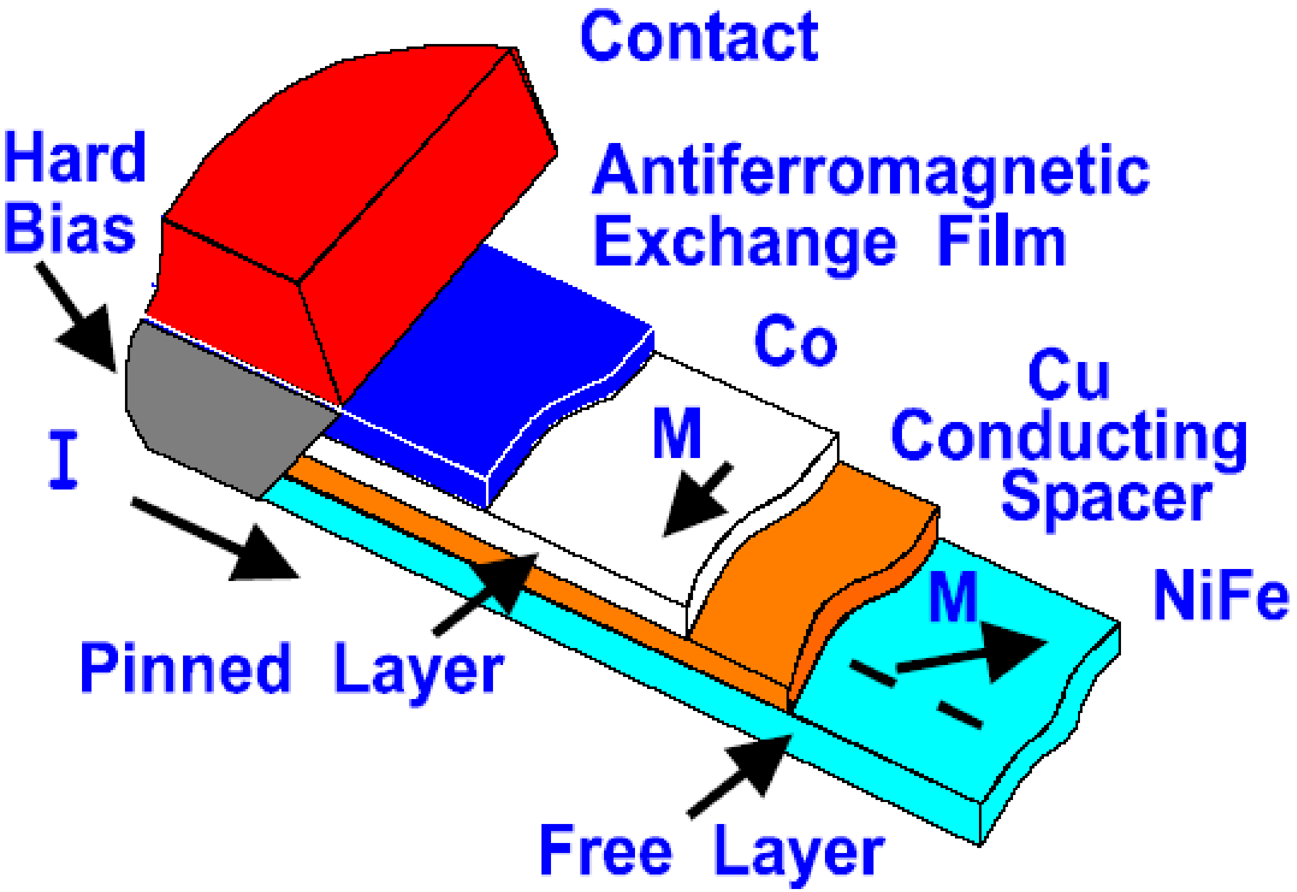
Utilize AP coupling property of Ru, Ir…



# GMR sensors

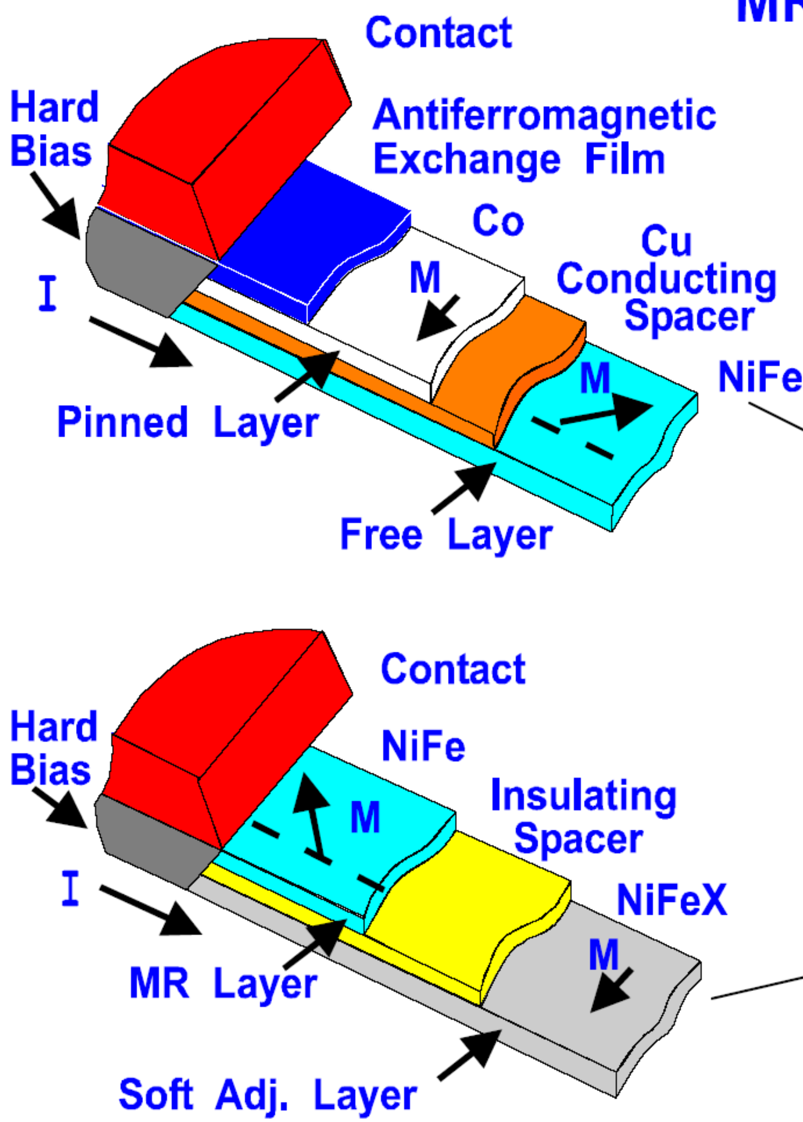

External hard
magnet bias
free
reference
Happlied
ΔR
Happlied

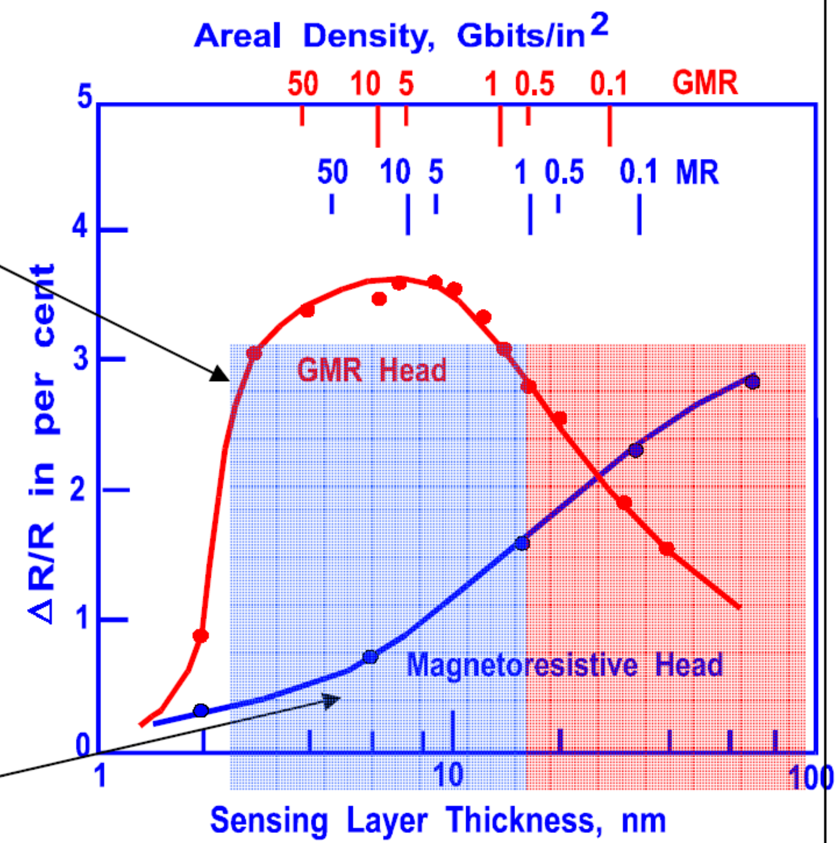
# GMR sensor




http://www.pcguide.com/ref/hdd/op/heads/techGMR-c.html
http://www.chem.wisc.edu/courses/801/Spring00/Ch1_3.html

# MR and GMR/Spin Valve Head Characteristics

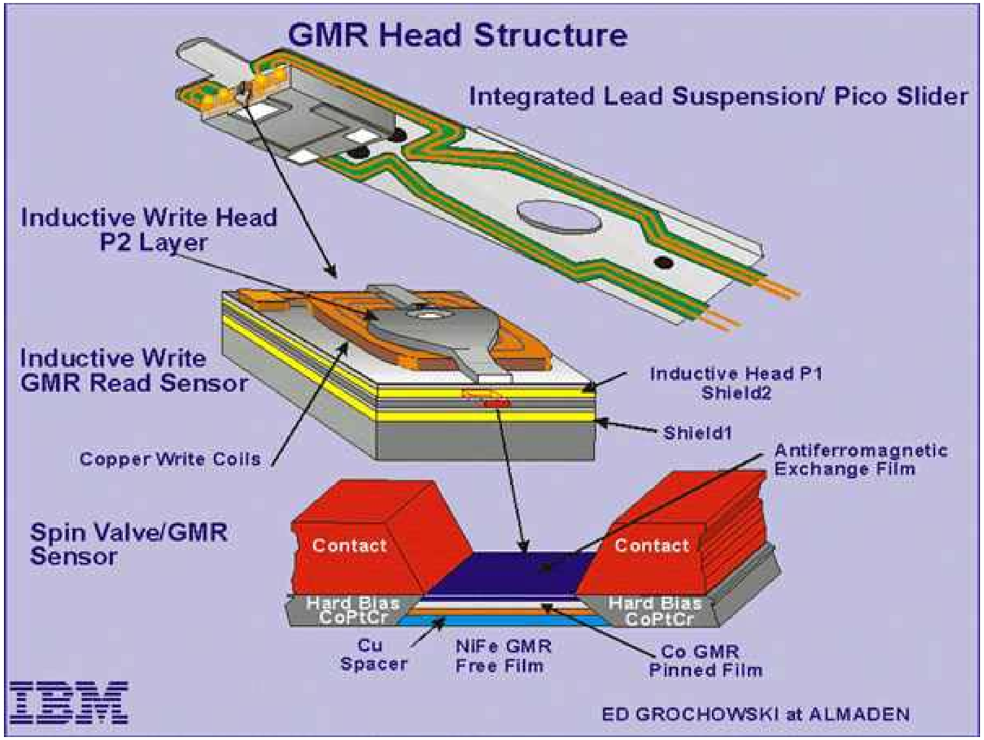


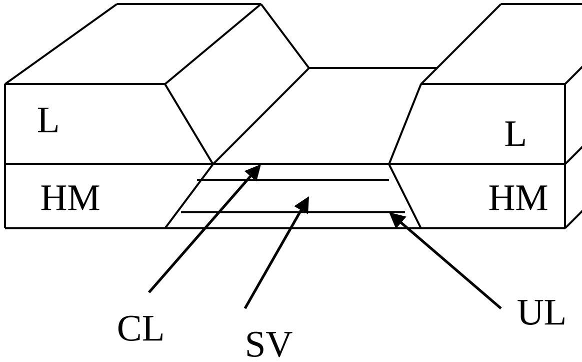

Spin dependent scattering in a single alloy

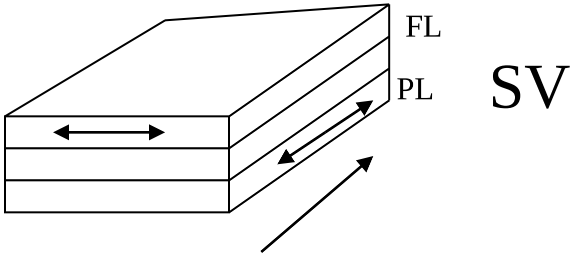
Grochowski/Gurney

# GMR Read head Structure



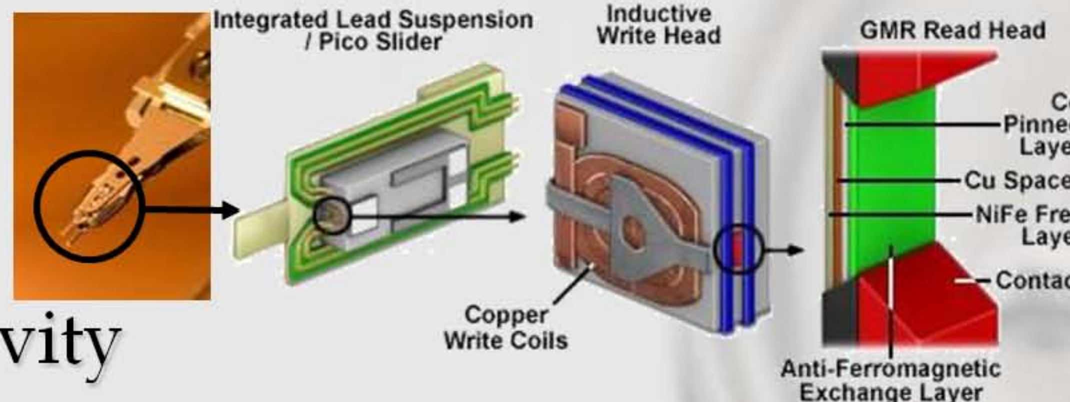

The MR element in a shield gap is composed of a spin-valve film (SV), with a cap layer(CL), and under layer(UL) leads (L) and hard magnets(HM).



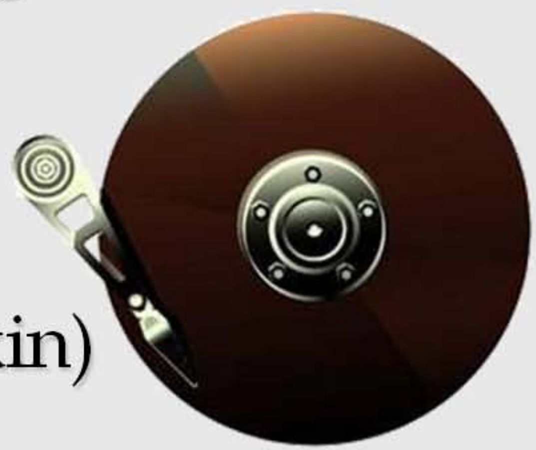



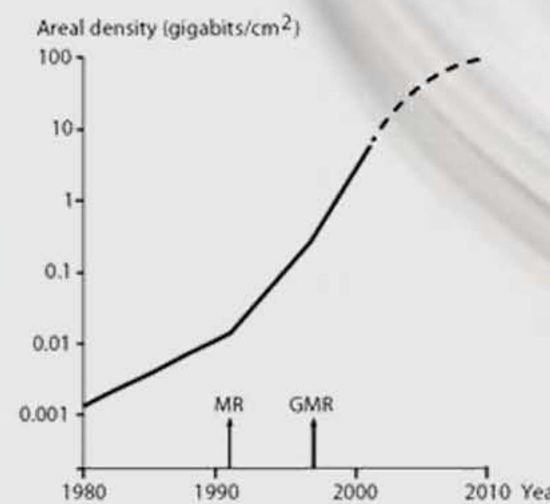

The easy axis of the FL makes a right angle against that of PL. The direction of the signal field is parallel to the easy axis of PL. and perpendicular to that of FL.

# Application – HDD read heads



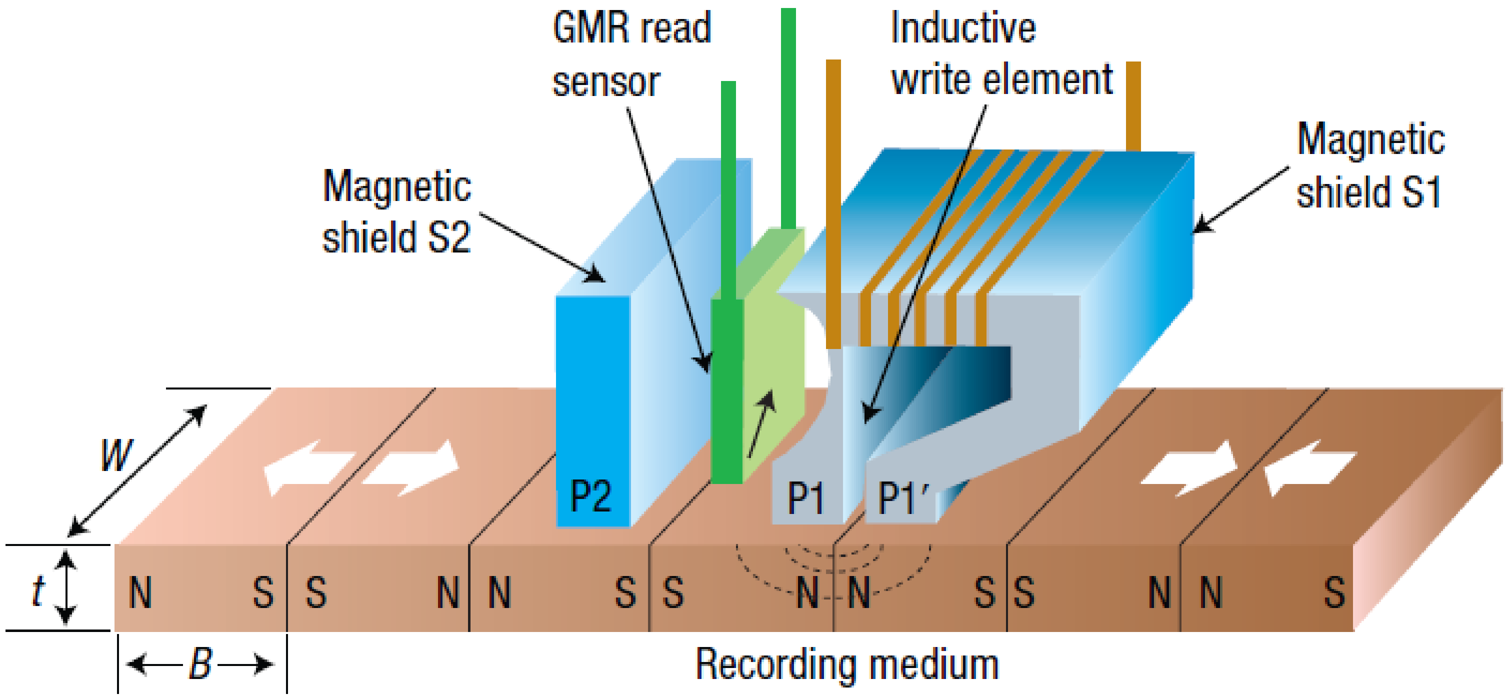

- ▽ Construction
  - layers with differing coercivity
  - \+ AFM layer (Bruce Gurney)
  - *R* measuring
- ▽ Efficiency
  - 1991. MR
  - 1997. GMR (Stuart Parkin)








Magnet Academy, (http://www.magnet.fsu.edu/education/tutorials/magnetacademy/gmr/), IBM Research, (http://www.research.ibm.com/research/gmr.html)




Magnetoresistive head for hard-disk recording. Schematic structure of the magnetoresistive head introduced by IBM in 1991.

Claude Chappert, Albert Fert, and Frederic Nguyen Van Dau. The emergence of spin electronics in data storage. *Nat Mater*, 6(11):813–823, 11 2007/11//print.

# Giant MR Heads

- ✓ Works on the same general principles of MR heads
- ✓ But uses some what different design that makes them superior in several ways
- ✓ The name “Giant” is not due to the size, but due to the superior technology
- ✓ By December 1997, IBM introduced their first hard disk with GMR heads
- ✓ They are more sensitive
- ✓ GMR are used in latest technology drives which capacities up to 75 GB