Introduction to (Electron) Transport
ESM-Cargese 2017

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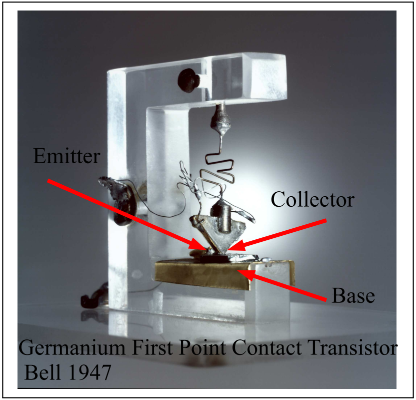
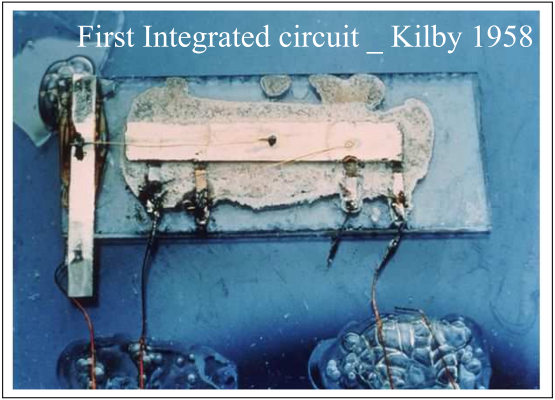
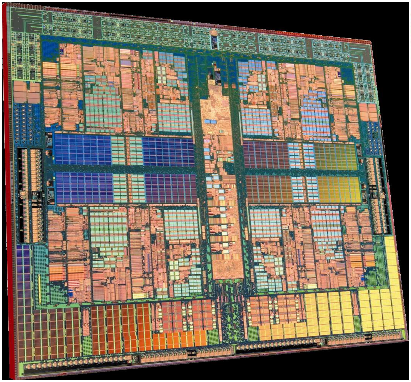
Electronics

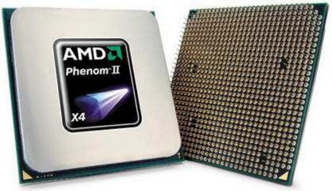


Modern electronics was created in 1947 when the transistor was invented in Bell laboratories by Bardeen, Shockley and Brattain (Nobel prize 1955).



With the possibility to integrate components on a single chip (Kilby 1958, also Nobel winner in 2000), it allows to densify circuits : integrated circuits (IC).





45 nm transistors
800 million transistors
3.5 Ghz
125 Watt

Recent microprocessors contain more than a billion transistors, transistor channel length decreasing from 45 nm to 32 nm to 22 nm, now(2014) 14 nm technology, next is 10 nm ... 5 nm ?

Spintronics

Semiconductor based electronics does not take the electron spin into account (only x2 in calculations).

When the spin of the electron is explicitly taken into account, it becomes an extra degree of freedom

Charge transport + spin = magnetic electronics =spintronics

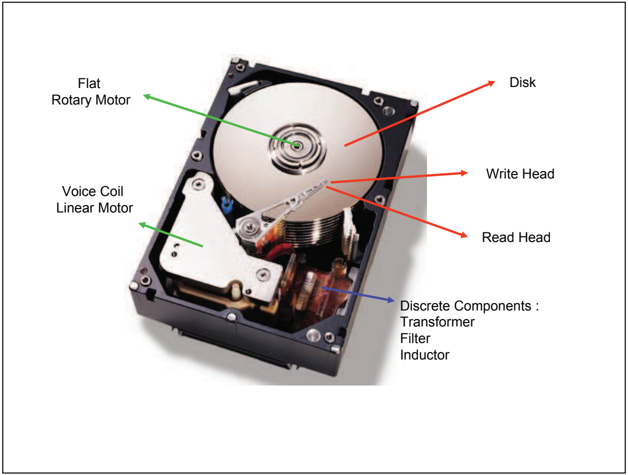
New structures, New physics effects, Giant MagnetoResistance (Nobel prize 2007)

Physics Nobel 2007

Albert Fert (Orsay) + Peter Grünberg (Jülich)
Giant Magnetoresistance (discovery 1987-1988)

The famous application

Spin electronics (spintronics) at the nanoscale has allowed a revolution in recording consumer electronics (Hard Disk Drive).



Outline

Introduction to electron transport

Part 1 : Electron transport and spin transport

Part 2 : What happens at the nanoscale ?

Outline

Introduction to electron transport

Part 1 : Electron transport and spin transport

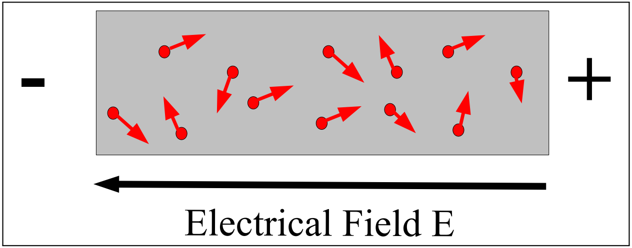
Part 2 : What happens at the nanoscale ?

Outline Part 1

- Ohm's law (classical)
- Boltzmann equation (semi-classical)
- Temperature dependence
- Field dependence

Drude's model

In a conducting material (silicon, copper) :



Carrier charge : q (Coulomb)

Carrier density : n ($/m^3$)

Current density : $\vec{j} = qn\vec{v}$ (A/m^2)

Applying an electric field : $\vec{E}$ (Volt/m)

No collisions $\rightarrow$ constant acceleration !

The carriers are accelerated between collisions

which redistribute the momenta

Drude's model

Average time between Collisions : τ (s)
Momentum acquired during τ is $qE\tau$
Average momentum of carriers $p = qE\tau$
classical mechanics $\vec{p} = m\vec{v} = q\vec{E}\tau$
So the drift velocity $\vec{v} = \frac{q\vec{E}\tau}{m}$
The current $\vec{j} = qn\vec{v} = \frac{q^2 n\tau}{m}\vec{E}$

The current is proportional to the applied electric field

$\vec{j} = \sigma\vec{E}$ Ohm's law

Conductivity

$$\vec{j} = \sigma \vec{E}$$

σ is the conductivity (in Siemens per meter (S/m))

Its inverse $\rho = 1/\sigma$ is the resistivity in Ohm.meter($\Omega.m$)

$$\sigma = \frac{q^2 n \tau}{m}$$

High conductivity means :
large density of carriers
long collision time
small carrier mass
it does not depend on the sign of the charge

Mobility

$$\vec{j} = \sigma \vec{E} = q.n.\vec{v}$$

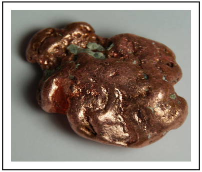
One defines the mobility μ : $\vec{v} = \mu \vec{E}$

$$\mu = \frac{\sigma}{nq} = \frac{q\tau}{m} (\mathrm{m}^2/\mathrm{Vs})$$

Example : Numbers for Cu

Copper :

Example : Numbers for Cu



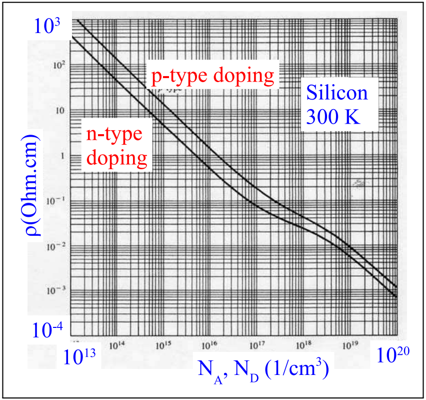
Assuming one conduction electron per atom
Density of carriers : 8.47 10^{28} $/m^3$

electron charge : -1.6 10^{-19} C
electron mass : 9.11 10^{-31} kg

resistivity at 300 K : 1.7 $\mu\Omega.cm$

mobility at 300 K : 43 cm^2/Vs
collision time = 2.4 10^{-14} s
drift velocity (E=1 V/mm)= 4.3 m/s

Density of carriers



In semiconductors, since $\rho \propto 1/n$ (assuming τ is constant),
doping allows n and ρ to span 7 orders of magnitude
low carrier density can be modified by an electrical field
Field effect transistor MOSFET, p-n junction (diode),
Ohm's law does not hold anymore

Improving the classical image

The classical image of the carriers is rapidly unable to explain transport phenomena :

- gap, bands (insulators / semiconductors / metals)
- - (effective) mass different from electron mass (high mobility semicond., heavy fermions)
- - spin ...

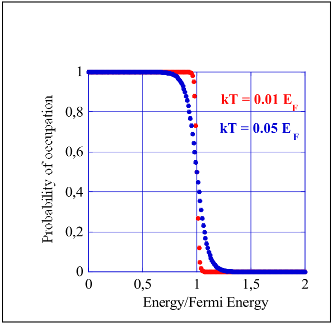
Electron is a fermion and there are correlation effects (not free electrons). It is more correct to use quantum mechanics in these solid state materials (and it becomes a bit more complicated !)

Lets add some QM (but not too much).

Fermi-Dirac statistics

Electrons are fermions so they follow Pauli principle and abide by the Fermi-Dirac statistics

$$f(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}}$$



E_F =2-5 eV and kT=25 meV at 300 K

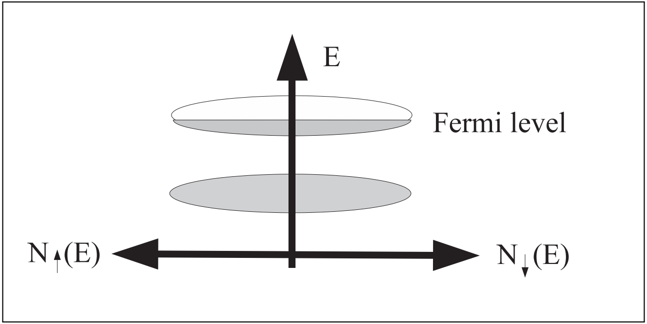
so kT is 1% E_F

Only electrons in the energy range E_F-kT, E_F+kT participate to transport.

(Out of equilibrium (non thermal) transport is possible in extreme cases : one talks about hot electron injection)

Band structure

Electron transport happens in a more or less periodic atomic lattice

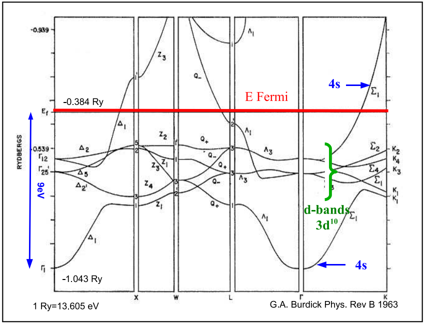


Such a band structure leads to a first definition of metals and insulators

Metals have a finite density of states at the Fermi level

For insulators, the Fermi energy is in a band gap,

so no carriers at 0 Kelvin



Cu band structure. Cu=[Ar]$3d^{10}4s^{1}$

The effect of interactions can be represented by free electrons with an effective mass.

$$E = E_0 + \frac{\hbar^2 k^2}{2m^*} \text{ i.e. } m^* = \frac{\hbar^2}{\frac{\partial^2 E}{\partial k^2}}$$

4s electrons are light (free, delocalised),
3d electrons are heavier (more localised)

Electron velocity

The classical electron has a velocity $\frac{mv^2}{2} = \frac{3}{2}kT$
for Cu it gives v=1.1 10^5 m/s
Since the kinetic energy is not anymore kT but E_F,

$$E = \frac{\hbar^2 k^2}{2m} = E_F$$

a quantum electron has a velocity $v_F = \frac{\hbar k_F}{m} = 10^6$ m/s
The distance between scattering events is the mean free path λ
For Cu at 300 K : $v_F = 10^6$ m/s and $\tau = 2\ 10^{-14}$s gives $\lambda =$20 nm

Boltzmann Equation

Electrons should be treated as interacting particles :
- not the free electron mass but an effective mass

Density should be taken from band structure calculations

Carriers could be holes

Drude $\rightarrow$ Semi-classical model

Boltzmann Equation

How to proceed when an electric field is applied ?
Considering $f(\vec{r}, \vec{v}, t)$ to be the distribution of electrons
$=$ probability to find one electron at $\vec{r}$ with velocity $\vec{v}$ at time t

$f(\vec{r}, \vec{v}, t) = f_0 + g(\vec{r}, \vec{v}, t)$
with $f_0(\vec{r}, \vec{v})$ the stationary distribution (no $\vec{E}$)
Without collisions : $f(\vec{r} + \vec{v}dt, \vec{v} + \frac{\vec{F}}{m}dt, t + dt) = f(\vec{r}, \vec{v}, t)$
i.e. df=0
i.e. $\frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} + \frac{\vec{F}}{m}\frac{\partial f}{\partial \vec{v}} = 0$
With collisions : $\frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} + \frac{\vec{F}}{m}\frac{\partial f}{\partial \vec{v}} = (\frac{\partial f}{\partial t})_{coll}$

Boltzmann Equation

$\frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} + \frac{\vec{F}}{m}\frac{\partial f}{\partial \vec{v}} = (\frac{\partial f}{\partial t})_{coll}$
Relaxation time approximation : $(\frac{\partial f}{\partial t})_{coll} = -\frac{g}{\tau}$
τ is the relaxation time

If the electrical field goes to zero, the distribution comes back to equilibrium with characteristic time τ.

Looking for σ
Applying an electric field along x

$$j_x = \sigma E_x = q \int v_x f(v) dv = q \int v_x g(v) dv$$

Using $\frac{-g}{\tau} = \frac{q\vec{E}}{m}\frac{\partial f}{\partial \vec{v}}$ one gets

$$\sigma = \frac{-q^2}{4\pi^3} \int v\tau \frac{\partial f}{\partial E} d^3k$$

$$\sigma = \frac{q^2}{12\pi^3 \hbar} < \lambda > S_F$$

$< \lambda >$ is the average mean free path on the Fermi surface

Back to Drude

Free electron band : $E = \frac{\hbar^2 k^2}{2m}$
Fermi surface is a sphere

$$S_F = 4\pi k_F^2$$

Density of states in k-space $= \frac{2V}{(2\pi)^3}$

$$N = \frac{4\pi k_F^3}{3} \cdot \frac{2V}{(2\pi)^3}$$

$$k_F = (3n\pi^2)^{1/3}$$

$\sigma = \frac{e^2 n\tau}{m}$ it is Drude's result

Mean free path

$\lambda = v\tau$

To be compared to characteristic lenghtscales

$\rightarrow$:

- $\lambda \approx$ lattice parameter a : electron localisation (insulation character)
  $\rightarrow$ hopping transport (thermally activated)

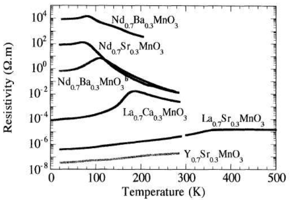


FIG. 2. Temperature dependence of the resistivity of $(A^{3+}_{1-x}B^{2+}_{x})MnO_3$ thin films (^{b} denotes a polycrystalline ceramic).

Coey et al. PRL 1995

Mean free path

$\lambda = v\tau$
To be compared to characteristic lenghtscales

$\rightarrow$:

- $\lambda \approx$ lattice parameter a : electron localisation (insulation character)
- $a < \lambda <$ sample size : diffusive regime
- $\lambda >$ sample size : ballistic behaviour (full quantum treatment required, including contacts)

λ can be limited by the sample surface contribution : Fuchs Sondheimer correction for finite size.
g(r,v) depends on z (non uniform)
Thin films resistivity is larger than bulk resistivity

Relaxation time

Several microscopic scattering events may happen in a conductor :
Assuming the scattering rates are independent and using Drude's
$\sigma = \frac{q^2 n\tau}{m}$ one gets :
Matthiesen rule : $\frac{1}{\tau} = \sum \frac{1}{\tau_i}$

One adds the resistivities due to the different scattering mechanisms :

$\rho = \rho_1 + \rho_2 + \rho_3$

Relaxation time

Microscopic relaxation mechanisms

In a periodic potential, a plane wave is a solution : the conductivity is infinite

But the sample is never periodic (=mathematically periodic)

Temperature-independent scattering :

defects, impurities, surface-interface

Temperature-dependent scattering :

lattice excitations (phonons)

magnetic excitations (spin waves = magnons)

electron-electron collisions

Scaterring can be elastic (E conserved) or inelastic

The relaxation time for wavevector $\vec{k}$ is different from the relaxation time for spin

$\rightarrow$ spin-flip and non spin-flip relaxation times

Mean free path : localisation limit

Ioffe-Regel limit (shortest mean free path for a metal)

$$< \lambda >= a$$

with α electron per site and $1/a^3$ density of sites

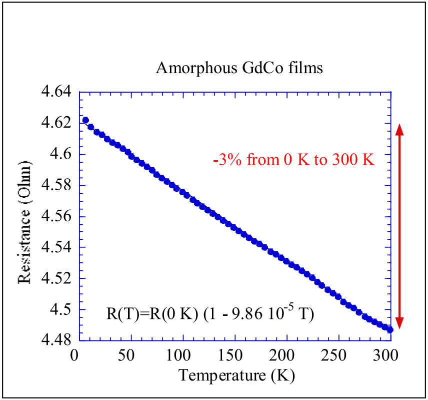
$$\sigma = \frac{e^2 < \lambda >}{12\pi^3\hbar} S_F$$

and $S_F = 4\pi k_F^2$ with $n = \frac{\alpha}{a^3} = \frac{k_F^3}{3\pi^2}$

$$\sigma = 0.33 \frac{\alpha^{2/3} e^2}{\hbar a}$$

This gives a maximum resistivity for a metal : 100-300 $\mu\Omega.cm$

Conductivity : Amorphous Film



Temperature-dependence of an amorphous film

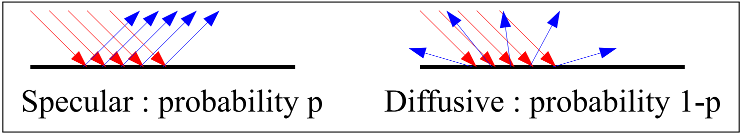
Amorphous = Maximum atomic disorder

Finite size effect

The Fuchs-Sondheimer model takes into account the z dependence of the electron distribution in a thin film (thickness t).

$$-\frac{g}{\tau} = \frac{\hbar k_z}{m} \cdot \frac{\partial g}{\partial z} + \frac{q\vec{E}}{m} \frac{\partial g}{\partial \vec{v}}$$

Depending on the boundary conditions at the film interfaces :



specular reflexion at the interfaces : $g(v_z > 0) = g(v_z < 0)$ at the interface

diffusive interfaces $g(z=0)=g(z=t)=0$

$$\rho = \rho_{bulk}(1 + \frac{3\lambda}{8t})$$

Fuchs-Sondheimer approximation (diffusive + $\lambda \ll$ thickness)

Impurities contribution

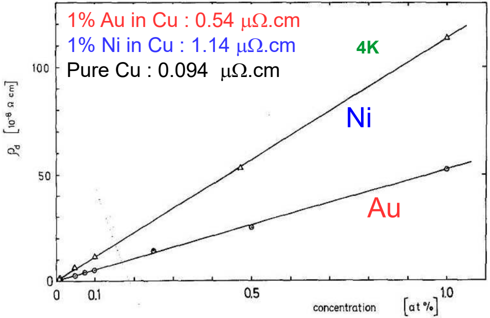


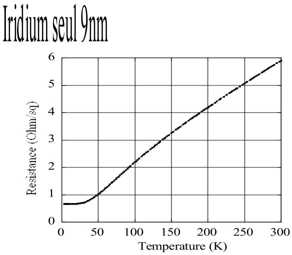
Fig. 3. Residual resistivity vs nominal composition in *Cu*Au and *Cu*Ni alloys.

Lengeler et al. J. Low Temp 1970

The residual resistivity ratio RRR can be used to measure the purity of a sample

$$RRR = \frac{\rho(300K)}{\rho(4.2K)}$$

Temperature independent defect contribution



Ir layer (9 nm thick) on Sapphire

Rsq (300K) = 5.91 Ohm/sq
Rsq (3K) = 0.67 Ohm/sq
RRR = 8.8

Quality control of thin films
Ordered / disordered alloys
Mixed interface (multilayers)
Annealing effect

Crystallographic contribution

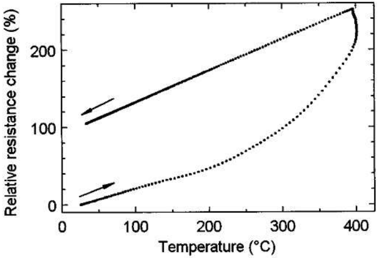


FIG. 1. Relative resistance change vs temperature of NiFe/Cu/NiFe trilayers during a thermal cycle at 4 K/min and isothermal annealing at 400 °C for 2 h in N_2/H_2(5 vol %) gas mixture. The irreversible resistance change originates mainly from interdiffusion.

Appl. Phys. Lett., Vol. 77, No. 3, 17 July 2000

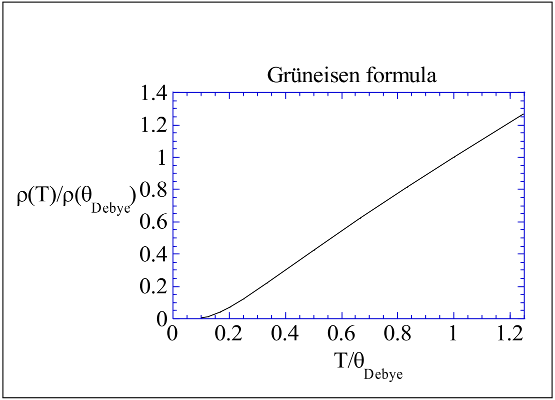
Annealing effect

Intermixing at the NiFe/Cu interfaces

Phonon Contribution

Static defects (impurities, crystallographic) do not depend on T
Lattice vibrations (phonons)do
The number of phonons in a mode varies as $n(\hbar\omega) = \frac{1}{e^{\frac{\hbar\omega}{kT}} - 1}$
The density of modes $D(\omega) = \frac{V\omega^2}{2\pi^2 c_s^3}$ (Debye model)
The total number of phonons /m^3 is $< n >= \frac{3}{2\pi^2 c_s^3} \int_0^{\omega_D} \frac{\omega^2}{e^{\frac{\hbar\omega}{kT}} - 1}$
When T$\ll \theta_D$, $< n > \propto T^3$
When T$\gg \theta_D$, $< n > \propto T$

Phonon Contribution



R(T) is linear at high temperature and $\propto T^3$ at low temperature

$\rightarrow$ metallic resistance can be used as temperature sensor

(platinum Pt_{100} and Pt_{1000})

Magnetic contribution

For magnetic materials, magnetic excitations also cause scattering spin waves are similar to lattice vibrations but :
E=$\hbar\omega = Dq^2$ for spin waves and E=$\hbar\omega = Aq$ for phonons
Example : At the Curie temperature, ferromagnetic order disappears.
The magnetic susceptibility diverges at Tc, magnetic fluctuations diverge.

VOLUME 24, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1970

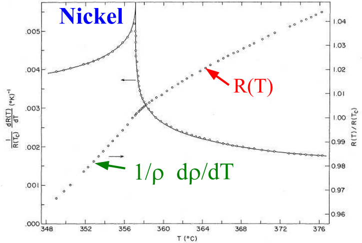
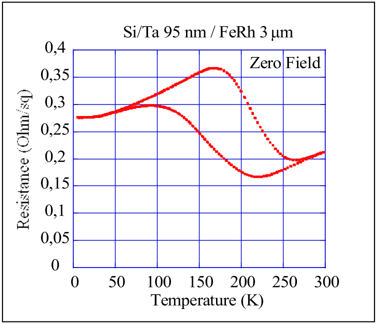


FIG. 1. Electrical resistivity $R(T)$ of nickel and dR/dT versus temperature in the region of the Curie point T_c. The solid lines represent fits of Eq. (1) to the data as discussed in text. For the sake of clarity only a small fraction of the data points is shown.

Phase transition



$Fe_{50}Rh_{50}$ antiferromagnetic to ferromagnetic transition can be evidenced on the R(T) curve

AF period is twice the F period in real space, half in k-space. An half-filled band may split.

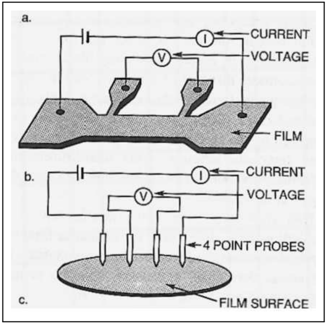
(For measurement : No need to apply some magnetic field to study a magnetic transition)

electron - electron

Material	Cu	Ni	Au	Pt
Resistivity 300 K ($10^{-8}\Omega.m$)	1.7	7	2.2	10

Ni $3d^9 4s^1$ = Cu minus 1 electron
Pt $5d^9 6s^1$,Au $5d^{10} 4s^1$

How to measure a Resistance ?



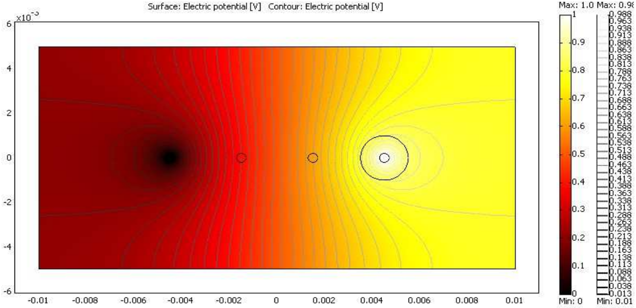
4 wire measurement of resistance

$$R = \rho \frac{length}{width.thickness}$$

2 wire measurement includes the cable resistance and the contact resistance

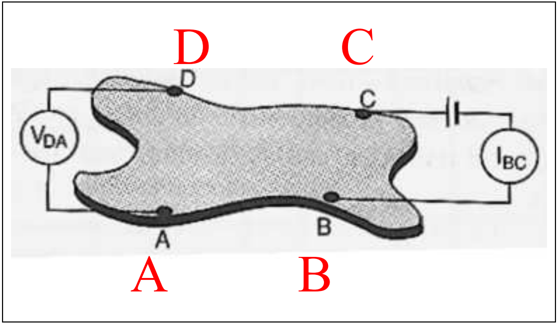
Resistance measurement

1:2 aspect ratio Sample
0.3 separation between contacts



Calculated Resistance is 15% larger than the simple formula R=ρl/s

Van der Pauw protocol



if the resistivity is homogeneous
if the sample is simply connex
if the 4 contacts are small and on the edge

$$e^{-\frac{\pi R_1}{R_\square}} + e^{-\frac{\pi R_2}{R_\square}} = 1$$

$R_\square = \frac{\rho}{thickness}$ is the resistance per square or sheet resistance
Similar trick for Hall effect (spinning current protocol).

Introduction to electron transport

Part 1 : Electron transport and spin transport - Magn. field effects

Part 2 : What happens at the nanoscale ?

Cyclotron

Electron trajectories under an applied magnetic field will become helicoïdal
classical Lorentz force : $\vec{f} = q\vec{E} + q\vec{v} \wedge \vec{B}$
longer trajectories to go from A to B $\rightarrow$ increased resistivity
Metals obey Kohler's scaling :

$$\frac{\Delta\rho}{\rho} = f(\omega_c \tau)$$

and $\omega_c = \frac{qB}{m}$ (cyclotron pulsation) so $\frac{\Delta\rho}{\rho} = f(\frac{B}{\rho_0})$
ρ_0 is the resistivity at B=0
large effect when the resistivity is small (single crystal at low T)
cyclotron magnetoresistance

Kohler scaling

It is most often a B^2 law and $\frac{\delta\rho}{\rho} = 0.1\%$ in 1 Tesla at usual metals at room temperature

Metal Normal Magnetoresistance

The cyclotron MR and thermometry : Pt sensor

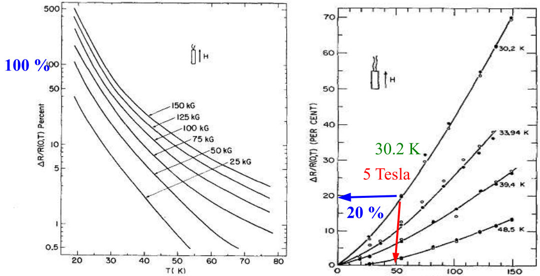


FIG. 13. Temperature dependence of $\Delta R/R(O,T)$ for $20<T<80$ K of No. 2742 and 2743 platinum thermometers. Parallel configuration.

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 42, NUMBER 1 JANUARY 1971

Low Temperature Thermometry in High Magnetic Fields.
II. Germanium and Platinum Resistors

L. J. NEURINGER, A. J. PERLMAN, L. G. RUBIN, AND Y. SHAPIRA

At low temp, magnetoresistance has to be taken into account

Ferromagnetic metals

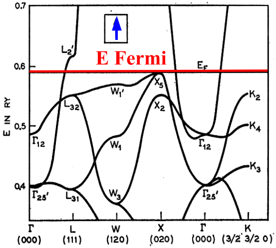


FIG. 6. The ↑ spin band structure of Ni in model (c).

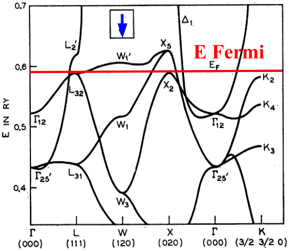


FIG. 7. The ↓ spin band structure of Ni in model (c).

J.C. Phillips Phys. Rev. B 1964

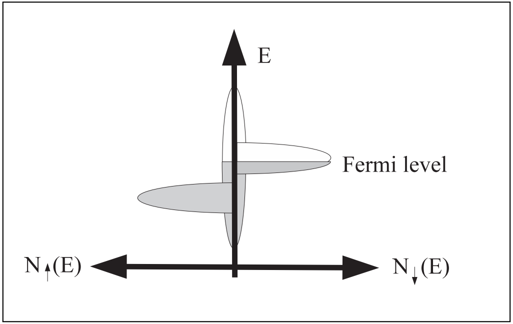
PHYSICAL REVIEW VOLUME 133, NUMBER 4A 17 FEBRUARY 1964

Fermi Surface of Ferromagnetic Nickel*

J. C. PHILLIPS†
Department of Physics and Institute for the Study of Metals, University of Chicago, Chicago, Illinois

Magnetic conductors

In a ferromagnetic metal



density of state, effective mass, mean free path ...

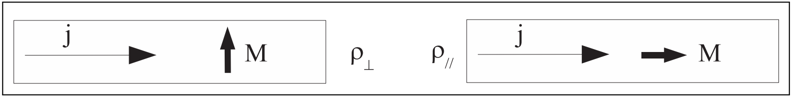
become spin-dependent

$3d^{\uparrow}$, $3d^{\downarrow}$ (heavy), $4s^{\uparrow}$ $4s^{\downarrow}$ (light)electrons

s-d scattering

Magnetoresistance

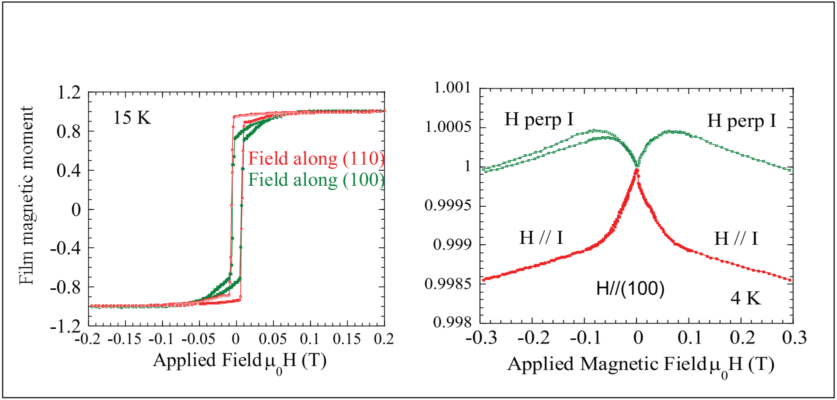
Anisotropic Magnetoresistance (volume effect)



Phenomelogical angle dependence :

$$\rho = \rho_{\perp} + (\rho_{//} - \rho_{\perp}) cos^2(\boldsymbol{k}, \boldsymbol{M}) \quad (1)$$

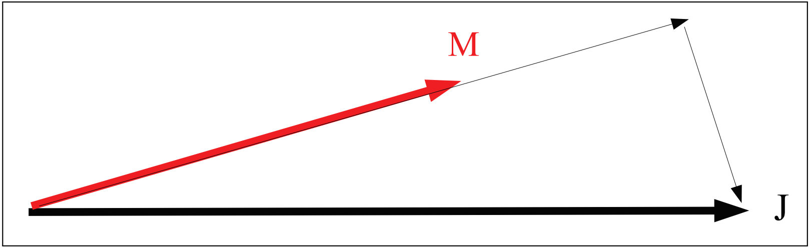
Value : a few percents in FeNi



example of AMR (LaSrMnO manganite epitaxial film)

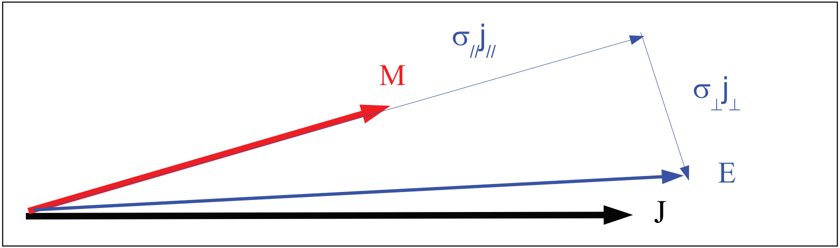
Anisotropic Magnetoresistance

Planar Hall effect = AMR



Anisotropic Magnetoresistance

Planar Hall effect = AMR



There is a transverse E-field ⇒ similar to Hall

Physical Origin :

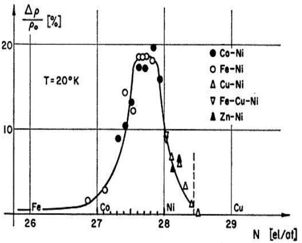


FIG. 1. The ferromagnetic anisotropy of resistivity $\Delta\rho/\rho_0 = (\rho_{\|}-\rho_{\perp})/\rho_0$ in polycrystalline fcc nickel alloys at low temperature.

[4] L. Berger, Physica **30**, 1141 (1964); Phys. Rev. **138**, A1083 (1965).

Measurements

PHYSICAL REVIEW B **68**, 012402 (2003)

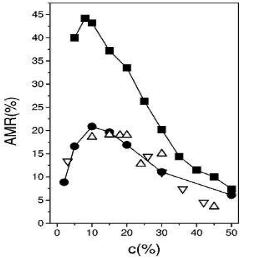


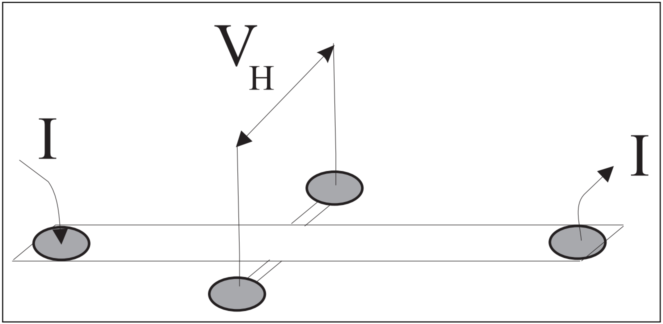
FIG. 3. Calculated and experimental AMR ratios of $Ni_{1-c}Fe_c$ alloys. Full circles: present work, full squares: calculations of Ref. 8, up-triangles: experiment (Ref. 3), down triangles: experiment (Refs. 5 and 6). The solid lines serve as a guide for eyes.

Ab-initio Calculations

$$\frac{\Delta\rho}{\rho} = \left(\frac{\lambda_{spin-orbit}\hbar^2}{\Delta E}\right)^2$$

Spin-orbit interaction $\lambda_{SO}\vec{L}\vec{S}$ mixes 3d up and down states, nearly (ΔE degenerate at E_F.

Bulk effect



$$\vec{f} = q\vec{E} + q\vec{v} \wedge \vec{B}$$

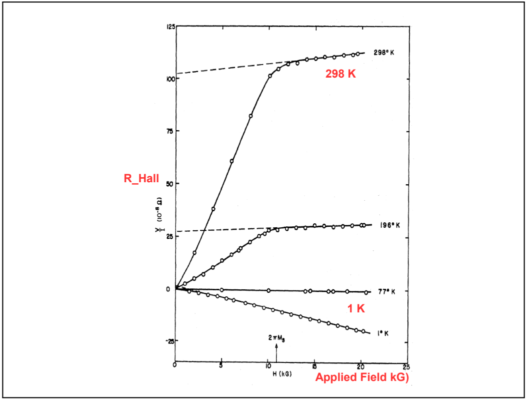
Normal(ordinary) Hall effect $V_H = R_H I B_z$

$R_H = \frac{1}{n.q}$

If you know n : magnetic field sensor

If you know B_z : doping characterisation

In a ferromagnetic sample, a new contribution to Hall effect appears



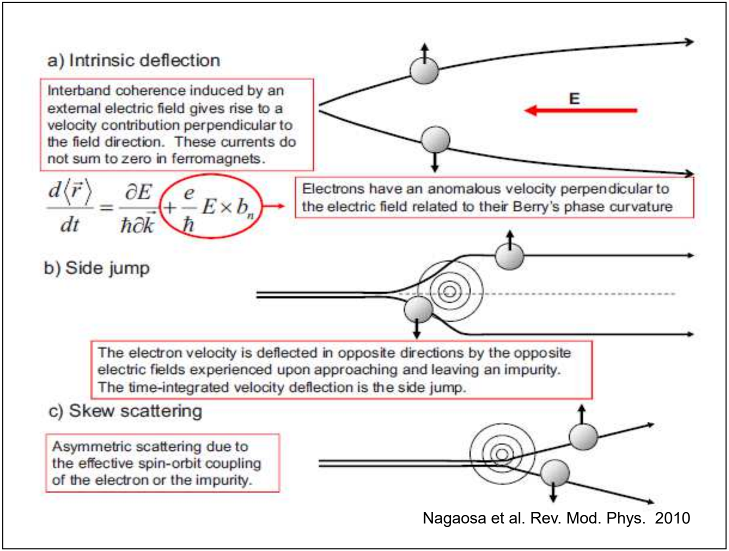
Strange temperature-dependence
Dheer, P.R. (1967)
Review : Nagaosa et al. Rev. Mod. Phys. 2010

Field-effect : EHE

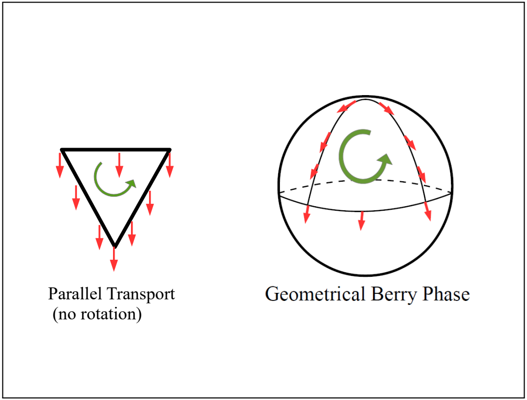
Extraordinary Hall effect $V_H = R_e I M_z$
Also called Anomalous Hall effect

Due to spin-orbit coupling, scattering of carriers on magnetic moments is not left-right symmetric

EHE : mechanisms



$$R_e = \alpha_{skew}\rho + \beta_{side,Berry}\rho^2$$



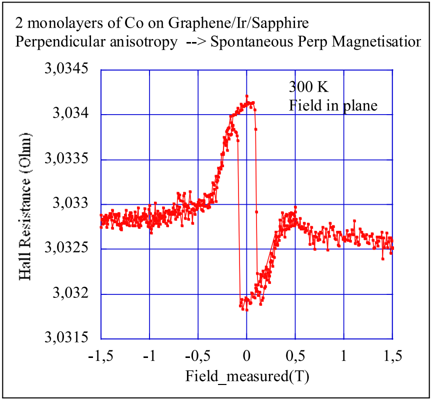
Usual Dynamical Phase $e^{\frac{-iEt}{\hbar}}$

Geometrical Phase : $\gamma_n(C) = i \int_C < n(R)|\nabla_R n(R) > .dR$

M. Berry, Proc. R. Soc. Lond. A392,(1984)

EHE : magnetometry

EHE can be used as a magnetometry tool



2 monolayers of Cobalt

Field-effect : EHE

4158 Appl. Phys. Lett., Vol. 80, No. 22, 3 June 2002

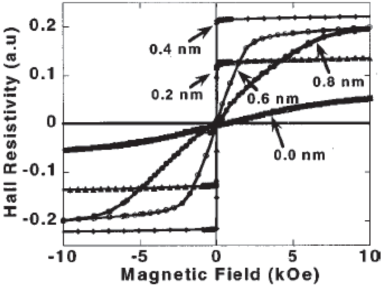


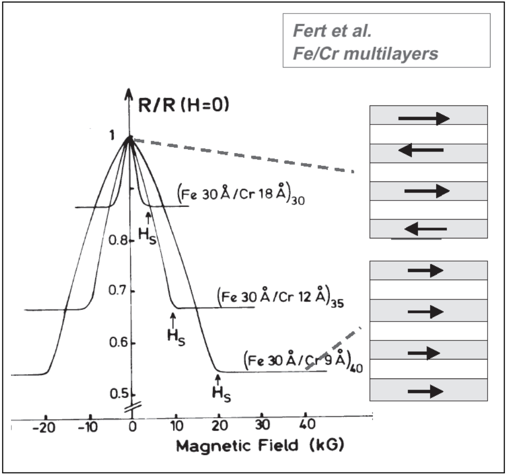
FIG. 1. Extraordinary Hall effect as a function of applied field for a series of samples of the composition Pt 3 nm/$Co_{90}Fe_{10}$ 0.6 nm/Al t_{Al} with $0<t_{Al}<1.2$ nm. Samples were naturally oxidized in air for 24 h.

Introduction to electron transport

Part 1 : Electron transport and spin transport

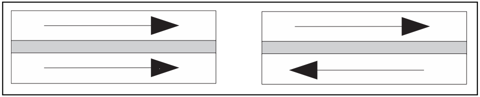
Part 2 : What happens at the nanoscale ?

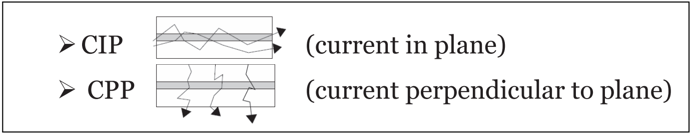
Giant Magnetoresistance



Magnetoresistance : GMR

Giant magnetoresistance





lengthscales :

current-in-plane : mean free path

current-perpendicular to plane : spin diffusion length

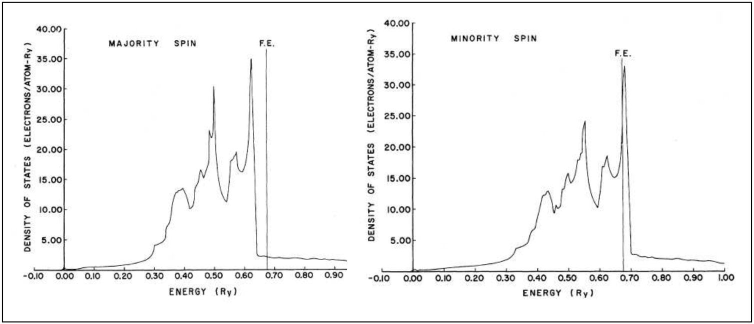
Two-current model

Mott 1930

If spin flip can be neglected, the total current is the sum of the current carried by $\uparrow$ and $\downarrow$

The material is equivalent to 2 resistors in parallel

$$\frac{1}{\rho} = \frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow}$$



The 4s electrons are lighter than the 3d ones

The 4s electrons are mainly responsible for carrying the charge current

In a strong ferromagnet like Ni, at E_F there are $4s_\uparrow$ and $4s_\downarrow$ electrons and only $3d_\downarrow$ ones.

No possibility for $4s_\uparrow$-$3d_\uparrow$scattering

Mean free path $\lambda_\uparrow$ is longer than mean free path $\lambda_\downarrow$

Mean free path $\lambda_\uparrow$ is longer than mean free path $\lambda_\downarrow$
Example : Cobalt : $\lambda_\uparrow$=10 nm and $\lambda_\downarrow$=1 nm
Introducing $\alpha = \frac{\rho_\uparrow}{\rho_\downarrow}$ the bulk resistivity assymetry

GMR multilayers

Vocabulary

Magnetisation $\uparrow$ / magnetisation $\downarrow$

Defines the quantification axis

In quantum mechanics the magnetic moment is opposite to the angular momentum

orbital angular momentum : $\vec{\sigma}_l = \vec{r} \wedge \vec{p}$ (or $L = \frac{\hbar}{i} \wedge \vec{\nabla}$)

and magnetic (orbital) moment $\vec{\mu}_{orb} = -\frac{e}{2m}\vec{\sigma}_l$

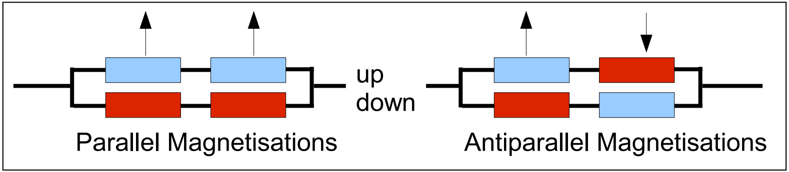
Spin$\uparrow$ / spin$\downarrow$ carriers

in transport, spin$\uparrow$ is (wrongly) said to be parallel to magnetic moment $\uparrow$

GMR multilayers

Majority/minority carriers
In a magnetic multilayer, the magnetisation may vary (antiparallel configuration)
A spin $\uparrow$ electron may be majority carrier in one layer and minority carrier in the next one.

GMR Resistor model



$$\rho_{parallel} = \frac{2\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \text{ and } \rho_{antiparallel} = \frac{\rho_\uparrow + \rho_\downarrow}{2}$$

GMR current-in-plane

2-current-model applied to the multilayer
spin-dependent Boltzmann eq. (similar to Fuchs-Sondheimer treatment (thickness dependence))

$$-\frac{g\uparrow}{\tau\uparrow} = \frac{\hbar k_z\uparrow}{m\uparrow}.\frac{\partial g\uparrow}{\partial z} + \frac{q\vec{E}}{m\uparrow}\frac{\partial g\uparrow}{\partial\vec{v}\uparrow}$$

$$-\frac{g\downarrow}{\tau\downarrow} = \frac{\hbar k_z\downarrow}{m\downarrow}.\frac{\partial g\downarrow}{\partial z} + \frac{q\vec{E}}{m\downarrow}\frac{\partial g\downarrow}{\partial\vec{v}\downarrow}$$

The boundaries conditions are :
Spin dependent reflection/transmission/diffusion at each interface

A lot of material parameters required to calculate cip-GMR : systematic study as a function of all thicknesses

or use litterature values (same crystallinity, texture, interface roughness ...)

GMR perpendicular-to-plane

ingredients for Valet-Fert model (1993)
Spin-dependent electrochemical potential $\mu_\uparrow$
Spin-dependent currents $\vec{j}\uparrow = \sigma\uparrow \frac{\partial\mu\uparrow}{\partial z}$
In a bulk : $\mu = \mu\uparrow = \mu\downarrow = E_F + q.Potential$
Far from the spacer : Polarised charge current
Need for spin-flip near the spacer region

spin diffusion length

In a non magnetic metal most scattering events do not flip the spin of the electrons

Scattering on a magnetic impurities or absorption/emission of a magnetic excitation (magnon) can flip the spin.

Spin-flip scattering is an inelastic event
$\Rightarrow$ vanishingly small at low temperature, not common at higher T (1 event out of 1000 in a non magnetic metal), 5 nm in a ferromagnetic metal

spin diffusion length

$$D\frac{\partial^2 \Delta\mu_i}{\partial x^2} = \frac{\Delta\mu_i}{\tau sf}$$

at the interface between 2 conductors, the spin polarisation of the current cannot change discontinuously.

$$l_{sf} = \sqrt{\frac{v_F \tau_{sf} \lambda}{3}}$$

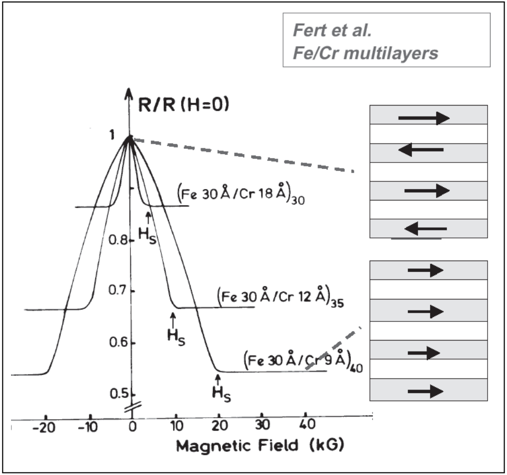
(proof : $l_{sf} = \sqrt{\frac{N}{3}}\lambda$ random walk and $\tau_{sf} = N.\tau$)

Close to the interface (lenghtscale l_{sf}), an out-of-equilibrium spin population exists :

spin accumulation effect

spin injection from a ferromagnetic electrode to a semiconductor (Datta-Das transistor)

Magnetoresistance : GMR



How to use this Giant Magnetoresistance effect :

Room temperature, smaller fields

Magnetoresistance : oscillating GMR

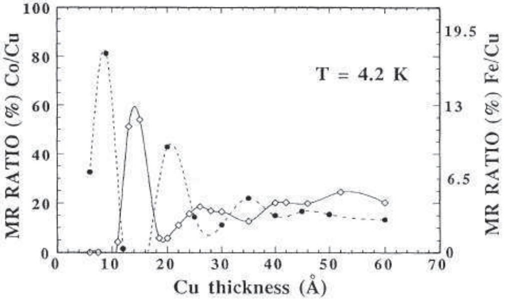


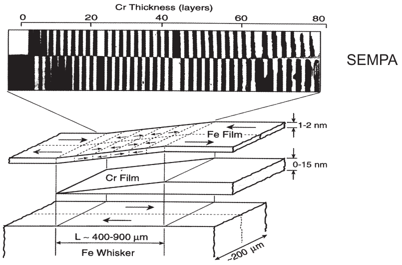
FIG. 3. Variation of the MR ratio as a function of the thickness of copper t_{Cu} for 60×(15-Å Fe/t_{Cu} Cu) (open symbols) and 30×(15-Å Co/t_{Cu} Cu) (black dots) multilayers. The solid and the dashed lines are guides for the eye. Notice the different vertical scale for Fe/Cu and Co/Cu.

F. Petroff et al., Phys. Rev. B 44, 5355 (1991)

Interlayer coupling : RKKY

$$J = \frac{cos(2.k_F.r)}{r^3}$$

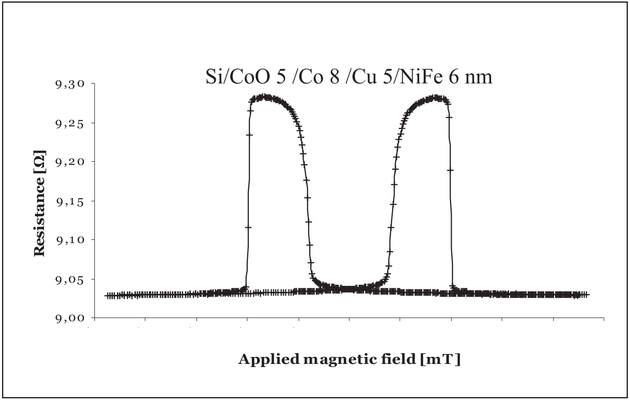
oscillating coupling through a metallic spacer. lengthscale k_F
finite, discrete thickness effect, period becomes a few monolayers.



J. Unguris et al., PRL 67(1991)140

Use also to create artifical antiferromagnet : Co/Ru/Co
Now, difference in coercive fields or exchange bias is prefered to pin one of the layer and keep the other one free.

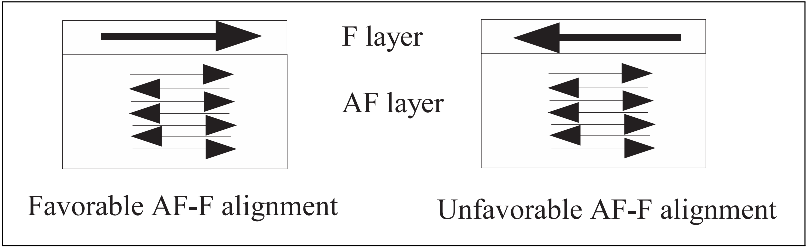
Magnetoresistance : GMR



GMR junction using a soft material (FeNi) and a harder one (Cobalt)

Interface effect

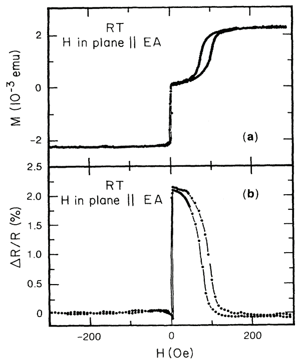
Exchange bias



It increases the coercive field (coercivity enhancement)

It biases the ferromagnetic layer if the system has been cooled under field

Magnetoresistance : Spin Valve



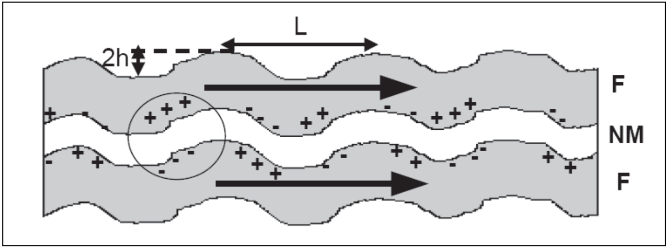
Spin Valve
10 Oe response

Si/NiFe 15 /Cu 2.6/
NiFe 15/FeMn 10/Ag 2 nm

B. Dieny et al. PRB 43(1991)

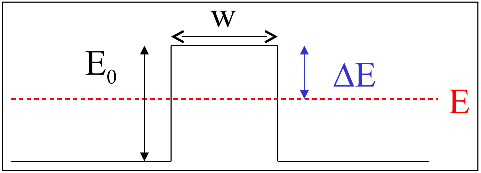
Pinning of one layer using a FeMn antiferromagnetic layer (exchange bias)

Interlayer coupling : Orange peel



Coupling may still exit in “uncoupled” system

orange peel=magnetostatic, pinholes



A thin insulating layer (Al_2O_3, MgO) is inserted between 2 metallic electrodes

Classical transport can not happen if the electron energy is smaller than the barrier height.

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} \mid \psi > + V(x) \mid \psi >= E \mid \psi > \text{ Schroedinger 1D}$$

Quantum mechanics allows for propagation of an evanescent wave inside the barrier. If the barrier is thin enough, the probability to tunnel through the barrier is non zero.

Magnetic Tunnel Resistance

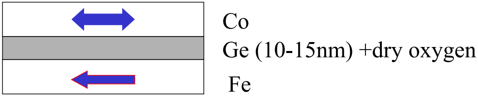
Volume 54A, number 3 PHYSICS LETTERS 8 September 1975

TUNNELING BETWEEN FERROMAGNETIC FILMS

M. JULLIERE
Institut National des Sciences Appliquées, 35031 Rennes Cedex, France

Received 25 June 1975

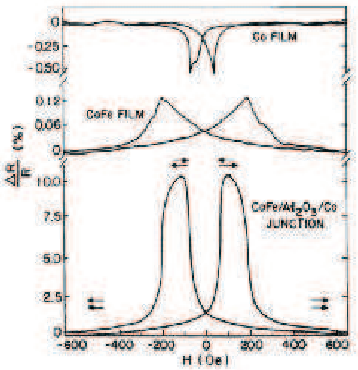
Fe-Ge-Co junctions conductance G(V) is studied when mean magnetizations of the two ferromagnetic film are parallel or antiparallel. Conductance measurement, in these two cases, is related to the spin polarizations of the conduction electrons.



When electrodes are ferromagnetic, tunnneling probabilities depend on the spin-dependent density of states at E_F

So on the relative magnetic configuration : parallel /antiparallel

Magnetoresistance : TMR



$\Delta R/R=(R_a-R_p)/R_a=2\ P_1\ P_2/(1+P_1\ P_2)$

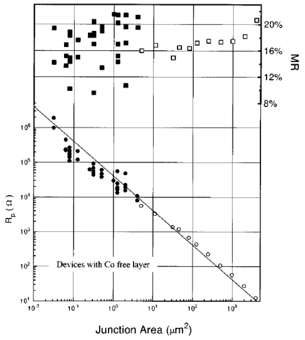
P_{Co} = 34% P_{CoFe} = 48%

Resistance of CoFe/Al_2O_3/Co junction (295 K)
1.6 nm Al_2O_3 (1.9 eV barrier). 0.2x0.3 mm size

Moodera et al. PRL,74(16), 3273 (1995)

$$TMR(Julliere) = \frac{R_{antiparallel} - R_{parallel}}{R_{parallel}} = \frac{2P_1P_2}{1-P_1P_2} \qquad (2)$$

Magnetoresistance : Barrier quality



Gallagher et al. JAP 1997

Junction resistance should scale as $\frac{1}{S}$

Difficult to obtain since any thickness fluctuation, pinhole will short-circuit the barrier

One uses the Area Resistance $RA = R_{junction}.S$

It depends mainly on the barrier (thickness,height)

Magnetoresistance : Barrier quality

NiFe(100 Å)/CoFe(20 Å)/Al_2O_3/CoFe(40 Å)/MnRh(170 Å)

Appl. Phys. Lett., Vol. 73, No. 22, 30 November 1998

Sousa et al. (Lisbon)

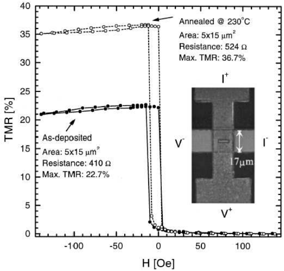


FIG. 1. Tunneling magnetoresistance vs field for an as-deposited spin tunnel junction, and for the same junction after consecutive anneals up to 230 °C. In the inset, the four-probe measuring scheme is illustrated using an optical microscope picture of the junction.

Barrier (Simmons ' fit)
0.87 to 0.77 nm wide
1.8 eV to 2.5 eV

Annealing can repair (improve) the barrier quality

Magnetoresistance : Barrier quality

RBS measurement of Al and O distributions

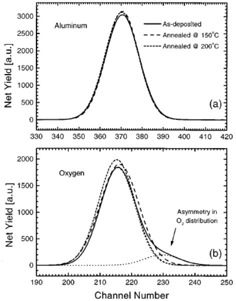
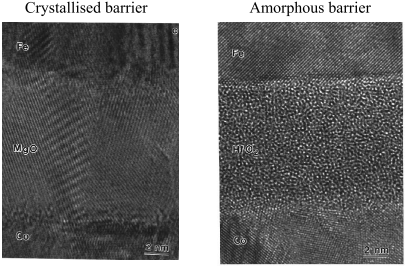


FIG. 5. Gaussian curve fits to the aluminum (a) and oxygen (b) peaks obtained by Rutherford backscattering analysis, for as-deposited junctions, and for junctions annealed at 150 and 200 °C.

Sousa et al. APL 98

For example, Oxygen diffusion out of the barrier is cured

Magnetoresistance : Barrier quality



Smith et al. JAP,83 ,5154 (1998)

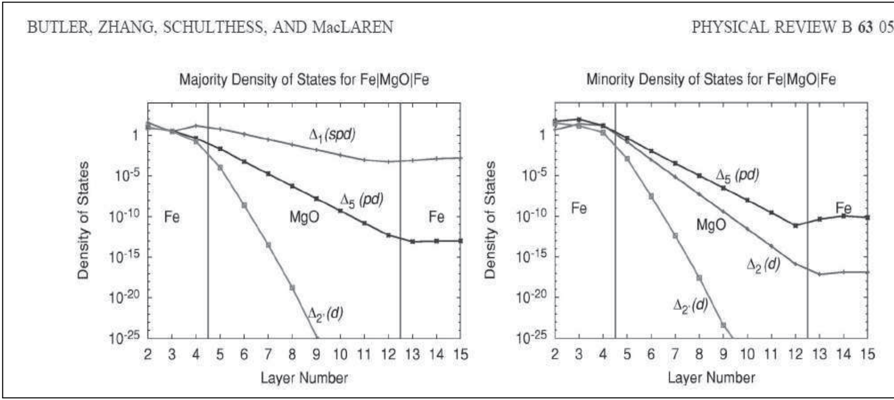
FIG. 3. High-resolution, cross-sectional electron micrograph of a [50 nm Co/10 nm HfO_2/50 nm Fe] junction showing abrupt, smooth interfaces and amorphous oxide structure.

The barrier can be amorphous (Al2O3) but a crystalline barrier (MgO) will bring new effects

selective tunnelling according to symmetry of the wavefunction

$\rightarrow$ spin filtering

Magnetoresistance : TMR spin filtering



electron wavefunction's propagation through the tunnel barrier depends on symmetry

Magnetoresistance : Giant TMR

4508 Appl. Phys. Lett., Vol. 82, No. 25, 23 June 2003

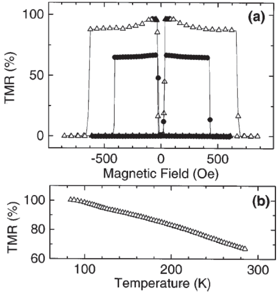


FIG. 1. (a) TMR of a 65×95 μm^2 large MgO (100)/Fe/MgO–2.5 nm/Fe/Co/Au junction at 80 K (-Δ-) and 293 K (-●-). The measurements are performed along the easy axis, the junction being biased at 10 mV. (b) Variation of TMR at 10 mV with temperature.

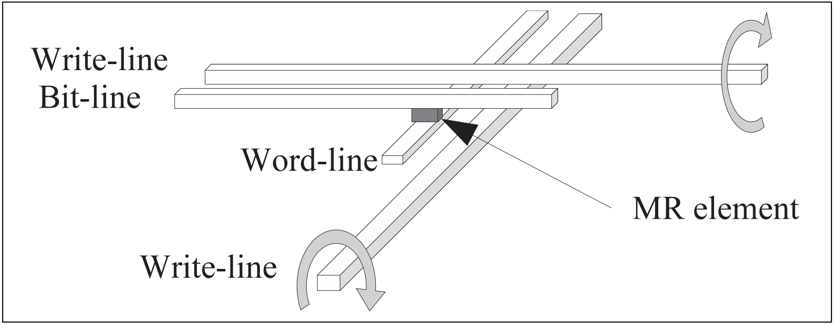
TMR ratio larger than 100 % can be achieved using epitaxial Fe/MgO/Fe (Nancy group)

MBE(epitaxial) or sputtering

thick barrier (2-3 nm)

Use as a memory element or sensor

Magnetic RAM memory, it is commercial (Freescale, Everspin ...)



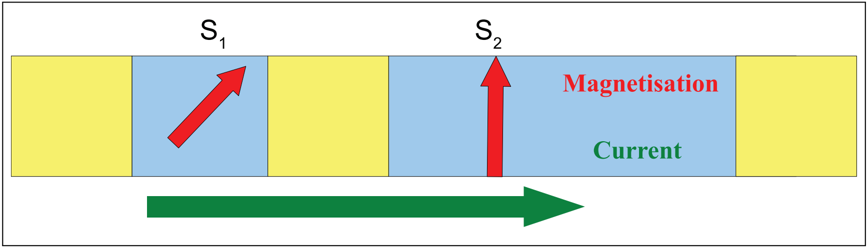
second generation : heat-assisted

⇒ reduces H_c, helps select cell

third generation : no more field lines : spin torque assisted what is Spin torque ?

GMR = effect of magnetic configuration on currents

Spin Torque = effect of currents on magnetic configuration



Spin torque

Appl. Phys. Lett. **88**, 232507 (2006)

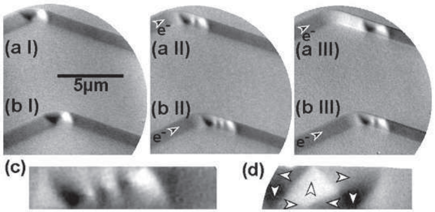


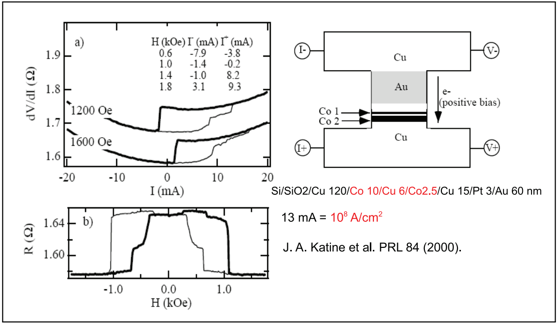
FIG. 4. XMCDPEEM images of two domain walls in adjacent lines after consecutive pulse injections with $j = 8.7 \times 10^{11}$ A/m^2. Top wall: (a I) vortex wall after remagnetization which transforms to a double vortex (a II) and back (a III) during consecutive injections. Bottom wall: (b I) a vortex wall that transforms to a triple vortex (b II) and back to a double vortex spin structure (b III). (c) High resolution image of the spin structure of a triple vortex wall. (d) High resolution spin structure of the double vortex wall with two vortices that have opposite sense of rotation.

Domain wall propagation without applied field

Magnetisation reversal of a nanoparticle

Spin torque oscillator (current-tunable GHz emission)

Spin torque



Magnetic reversal of a patterned electrode

GHz dynamics

Landau-Lifschitz-Gilbert equation

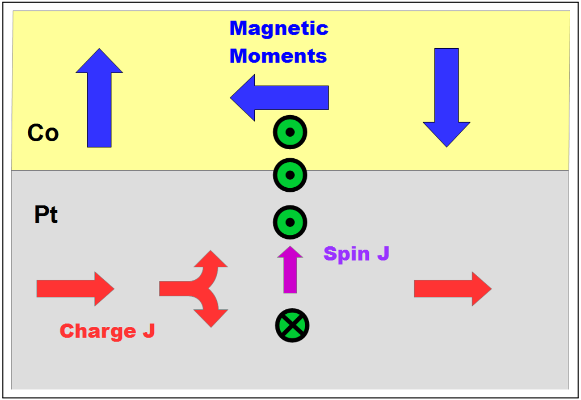
$$\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{M} \times \boldsymbol{H_{eff}} + \alpha \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{H_{eff}}) + SpinTorque \qquad (3)$$

γ the gyromagnetic ratio
α the damping constant
$\boldsymbol{H_{eff}}$ the effective field :

$$\boldsymbol{H_{eff}} = -\frac{1}{\mu_0} \frac{\partial E}{\partial \boldsymbol{M}}$$

The effective field includes contributions from the applied field (Zeeman energy), the demagnetizing field (shape anisotropy), magnetocrystalline and exchange energies.

The STT may induce an antidamping (STT oscillator)

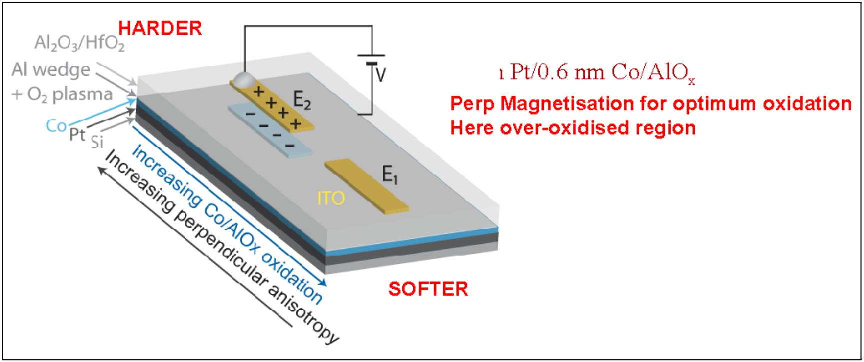


Side view

Spin current $J_s = \theta_{SHE} J_c$

Pt and Ta : Injection with Opposite Spin Signs

Voltage control of magnetisation reversal



Sputtering Pt/Co/AlOx

ALD dielectrics + ITO Sputtering (Institut Néel, see Bernand-Mantel et al.)