From Charge Currents to Spin Currents — ESM Brno 2019

Laurent Ranno
laurent.ranno@neel.cnrs.fr

Institut Néel - Université Grenoble-Alpes

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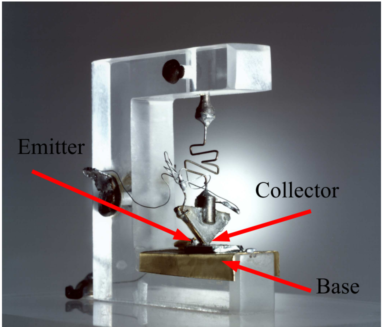
THE EUROPEAN SCHOOL ON MAGNETISM

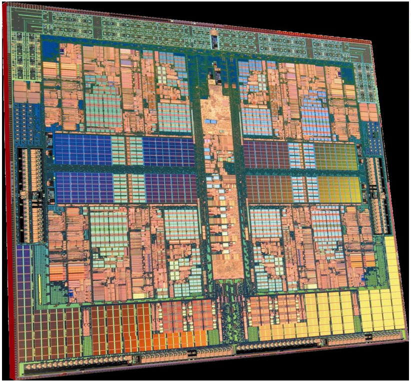
Electronics

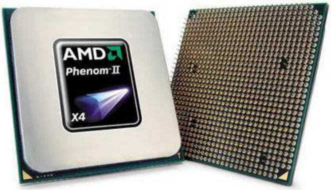


Germanium First Point Contact Transistor
Bell 1947

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

Electronics





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 14 nm / 10 nm technology, next is 7 nm ... 3 nm limit ?

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

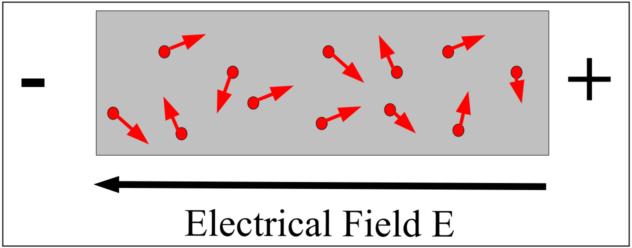
Spin transport without charge transport = Spin currents

Outline

- Classical transport
- Magnetotransport
- Spin currents

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

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

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 : $\vec{v} = \mu\vec{E}$

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

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

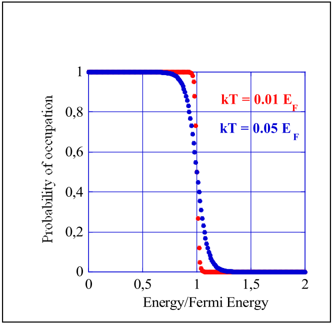
Electron is a fermion and there are correlation effects (not free electrons). It is more correct to use quantum mechanics in these solid state materials (and it becomes a bit more complicated !)

Fermi-Dirac statistics

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

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

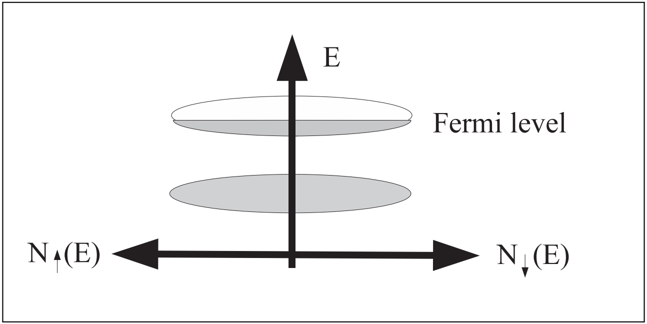
Fermi-Dirac statistics



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



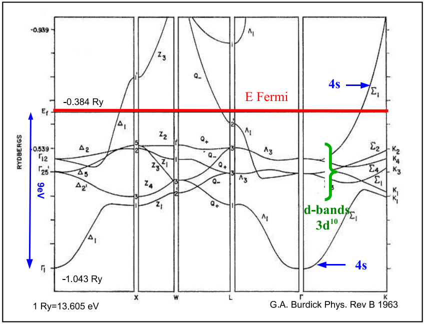
Such a band structure leads to a first definition of metals and insulators

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

Effective mass



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

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

$E = E_0 + \frac{\hbar^2 k^2}{2m^*}$ 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

$$\sigma = \frac{q^2 n(E_F)\tau}{m^*}$$

Mean free path

$\lambda = v\tau$

According to the value $\rightarrow$:

$\lambda \approx$ lattice parameter a : electron localisation (insulation character)

$\rightarrow$ hopping transport (thermally activated)

$a < \lambda <$ 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.

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 one gets :
Matthiesen rule : $\frac{1}{\tau} = \sum \frac{1}{\tau_i}$

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

Temperature-independent scattering :

defects,impurities

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

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. Magnetic fluctuations diverge.

VOLUME 24, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1970

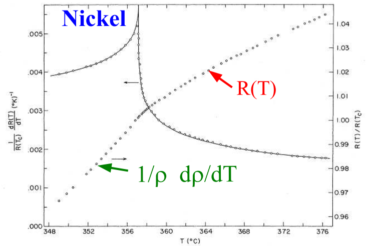
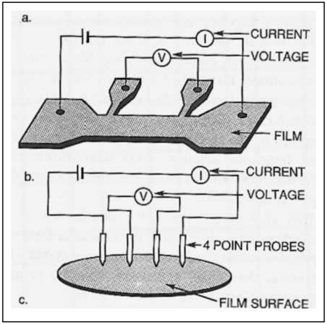


FIG. 1. Electrical resistivity $R(T)$ of nickel and dR/dT versus temperature in the region of the Curie point T_c. The solid lines represent fits of Eq. (1) to the data as discussed in text. For the sake of clarity only a small fraction of the data points is shown.

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

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



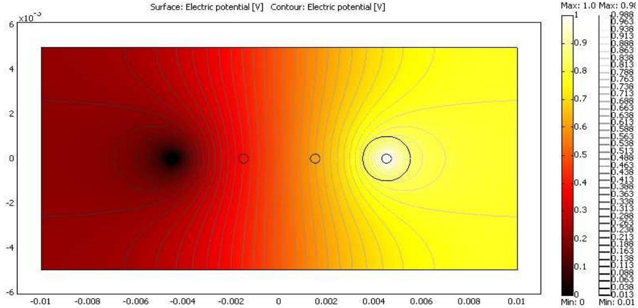
4 wire measurement of resistance

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

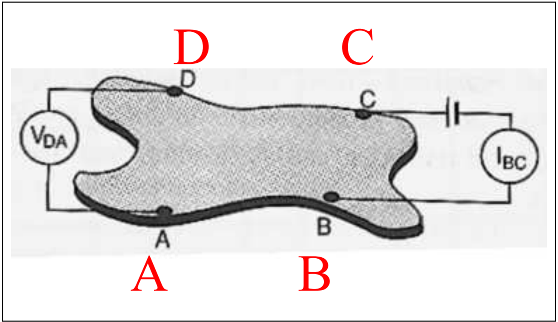
2 wire measurement includes the cable resistance and the contact resistance

Resistance measurement

1:2 aspect ratio Sample
0.3 separation between contacts



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



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

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

$R_\square = \frac{\rho}{thickness}$ $R_\square$ is the resistance per square or sheet resistance

Magneto-transport

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

The cyclotron MR and thermometry : Pt sensor

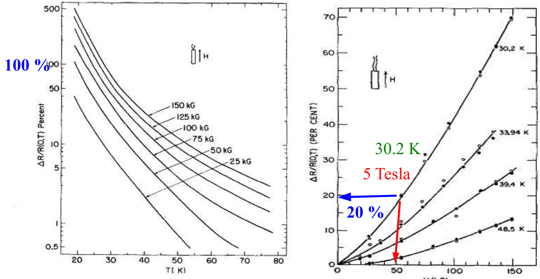


FIG. 13. Temperature dependence of $\Delta R/R(O,T)$ for $20<T<80$ K of No. 2742 and 2743 platinum thermometers. Parallel configuration.

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

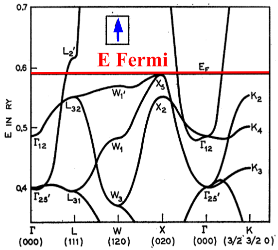


FIG. 6. The ↑ spin band structure of Ni in model (c).

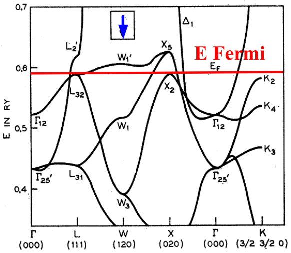


FIG. 7. The ↓ spin band structure of Ni in model (c).

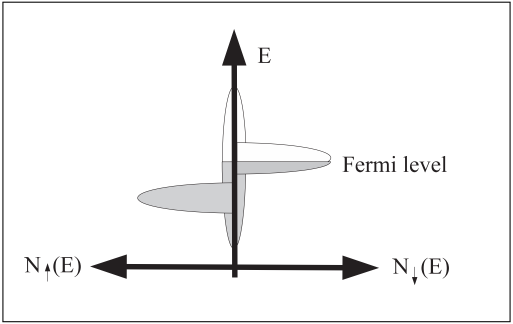
J.C. Phillips Phys. Rev. B 1964

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

In a ferromagnetic metal



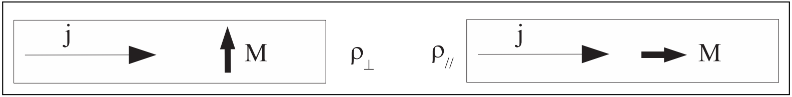
density of state, effective mass, mean free path ...

become spin-dependent

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

s-d scattering

Anisotropic Magnetoresistance (volume effect)

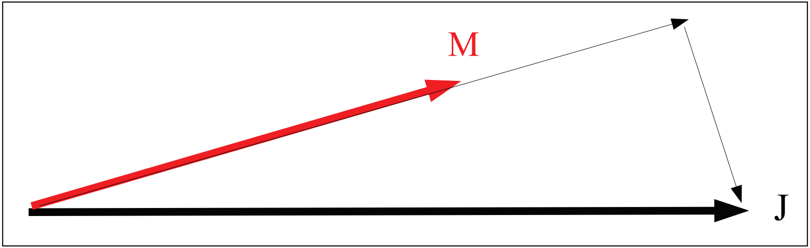


$$\rho = \rho_\perp + (\rho_{//} - \rho_\perp) cos^2(\boldsymbol{k}, \boldsymbol{M}) \qquad (1)$$

Value : a few percents in FeNi

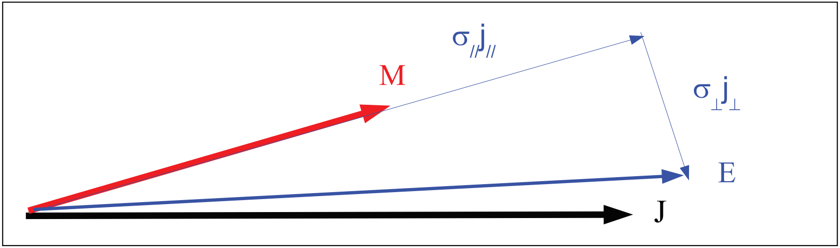
Anisotropic Magnetoresistance

Planar Hall effect = AMR



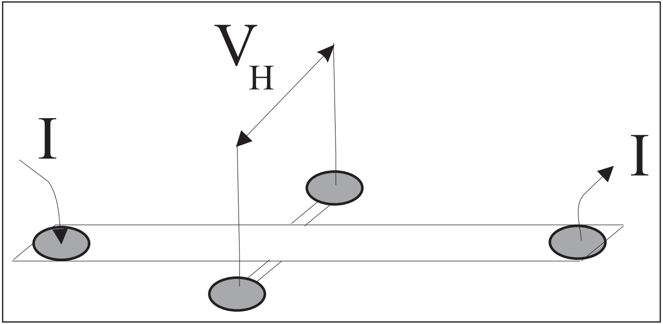
Anisotropic Magnetoresistance

Planar Hall effect = AMR



There is a transverse E-field ⇒ similar to Hall

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

Field-effect : EHE

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

Extraordinary Hall effect $V_H = R_e I M_z$

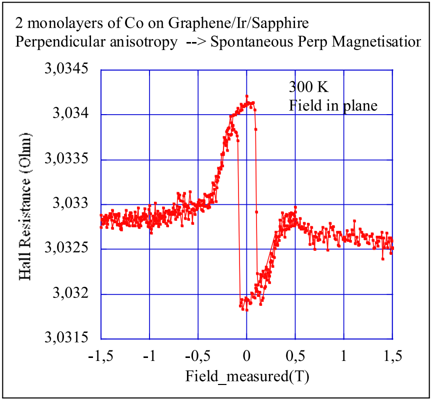
due to spin-orbit coupling, scattering of carriers on magnetic moments is not left-right symmetric

Usually, R_e increases with ρ (diffusive) : $R_e = \alpha\rho^1 + \beta\rho^2$)

(intrinsic(Fermi Surface), skew scattering, side-jump mechanisms)

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

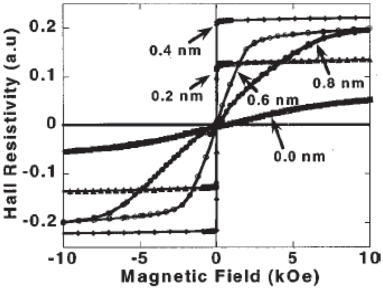
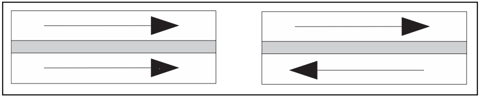
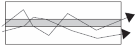
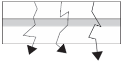


FIG. 1. Extraordinary Hall effect as a function of applied field for a series of samples of the composition Pt 3 nm/$Co_{90}Fe_{10}$ 0.6 nm/Al t_{Al} with $0 < t_{Al} < 1.2$ nm. Samples were naturally oxidized in air for 24 h.

Giant magnetoresistance



- CIP  (current in plane)
- CPP  (current perpendicular to plane)

lengthscales :

current-in-plane : mean free path

current-perpendicular to plane : spin diffusion length

Two-current model

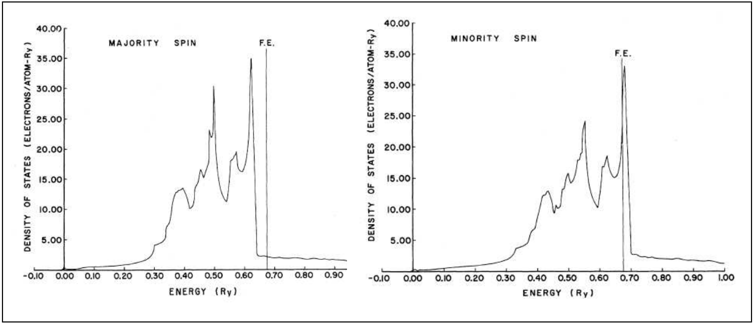
Mott 1930

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

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

Two-current model



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 $\lambda_\downarrow$

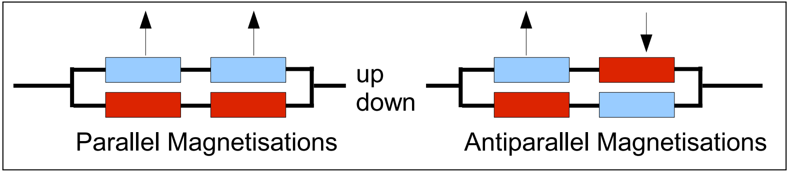
Mean free path $\lambda_\uparrow$ is longer than mean free path $\lambda_\downarrow$
Example : Cobalt : $\lambda_\uparrow$=10 nm and $\lambda_\downarrow$=1 nm
Introducing $\alpha = \frac{\rho_\uparrow}{\rho_\downarrow}$ the bulk resistivity assymetry

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



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

Improvements : Boltzmann equation (spin-dependent) with Spin dependent reflection/transmission/diffusion at each interface

GMR perpendicular-to-plane

Ingredients for Valet-Fert model (PRB 1993)

Spin-dependent electrochemical potential $\mu_\uparrow$
Spin-dependent currents $\vec{j}_\uparrow = \frac{-\sigma_\uparrow \partial \mu_\uparrow}{e \partial z}$
In a bulk : $\mu = \mu_\uparrow = \mu_\downarrow = E_F + q.Potential$
Charge and Spin currents can be defined

$$\vec{j}_\uparrow + \vec{j}_\downarrow = \vec{j}(\text{charge current})$$

$$\vec{j}_\uparrow - \vec{j}_\downarrow = \vec{j}(\text{spin current})$$

Interface ferromagnetic - non magnetic metal : Need for spin-flip

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
⇒ 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.

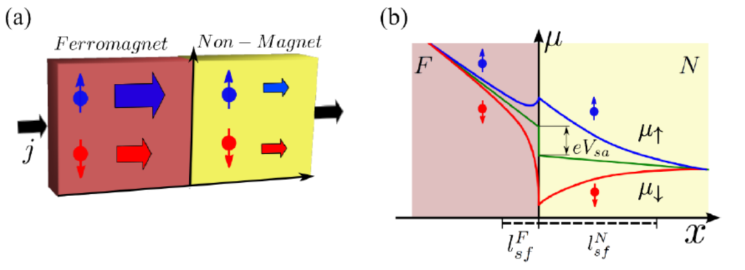
$$l_{sf} = \sqrt{\frac{v_F \tau_{sf} \lambda}{3}}$$

($l_{sf} = \sqrt{\frac{N}{3}}\lambda$ 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 metal or a semiconductor (Conductivity Mismatch Problem)



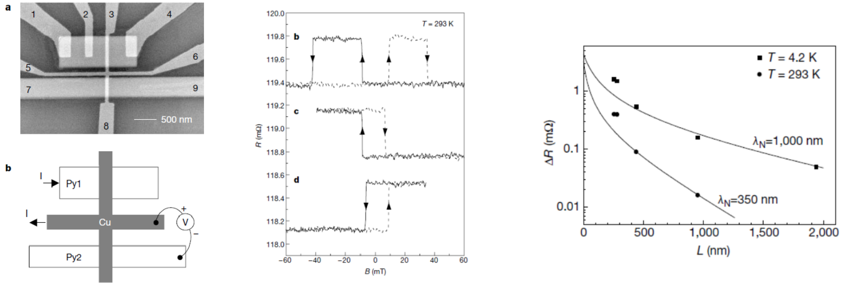
Thesis Laczkowski, UGA 2012

Spin current is injected

Relaxation happens on a spin diffusion length

Spin Current Generation

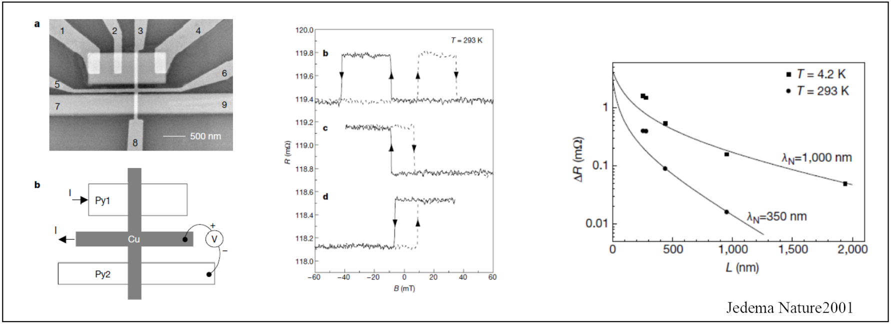
- spin accumulation without charge current
- Spin Hall effect
- Spin pumping
- Rashba-Edelstein mechanism
- Temperature gradient (Spin Seebeck geometry)



Jedema Nature2001

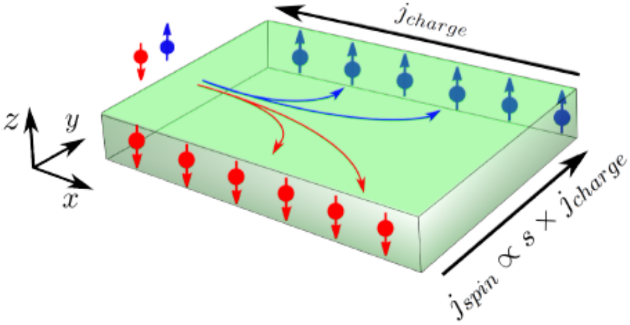
Spin ↑ Current is injected into Copper

Non local Spin Valve : Spin current detection



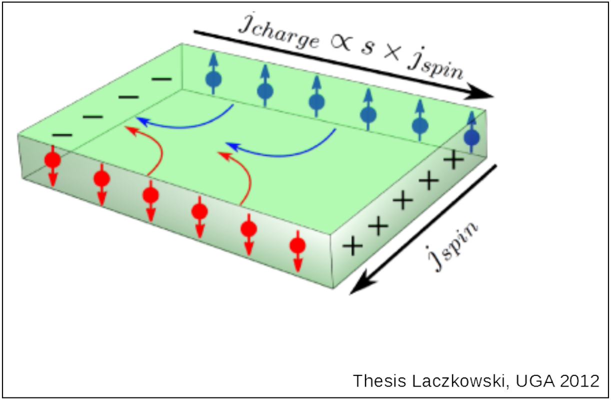
Py Fermi level aligns on the ↑ or ↓ chemical potential in Cu.
MR-like signal

Spin Hall Effect

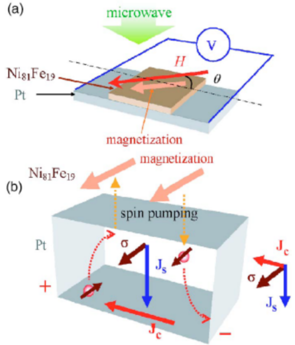


Charge current, Spin current, Spin are perp.
Large Effect in large spin-orbit heavy metals (Pt)

Inverse Spin Hall Effect



A charge current is generated by a flow of spins.

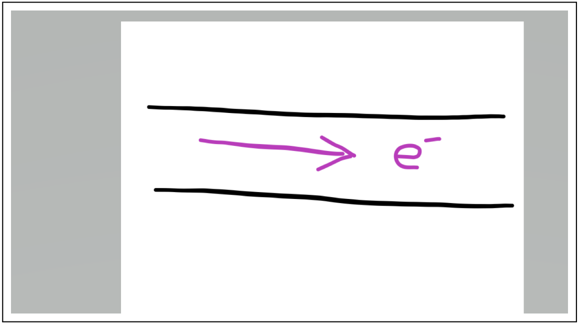


Permalloy (10 nm)
Platinum (7nm)

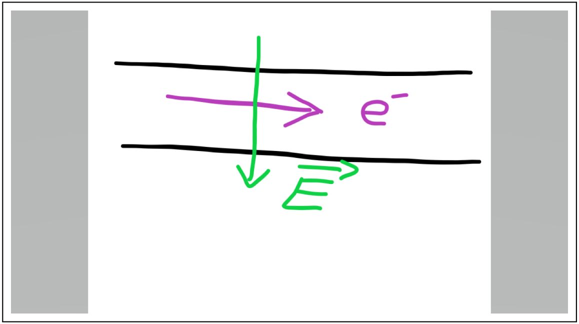
Saitoh, APL2006

Spin pumping in Permalloy, detection in Pt

Generating a Spin Polarisation

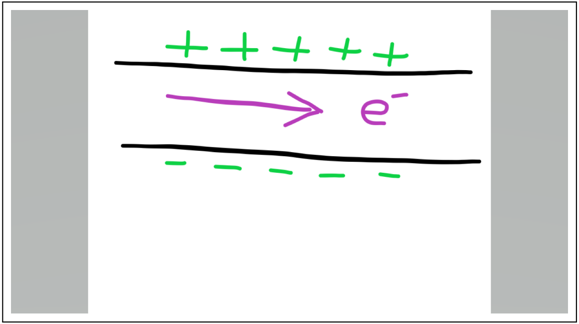


Conduction electron with moment $\vec{k}$ in an ultrathin film with Electric field at interface.



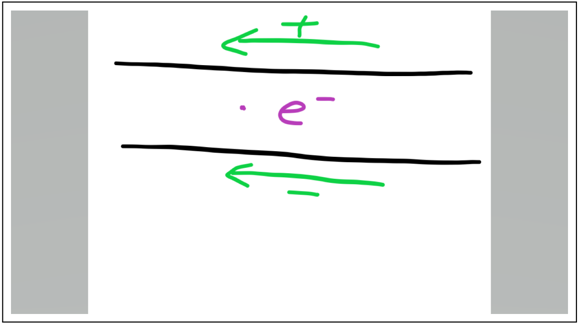
Electric Field at one interface

Rashba at Interface



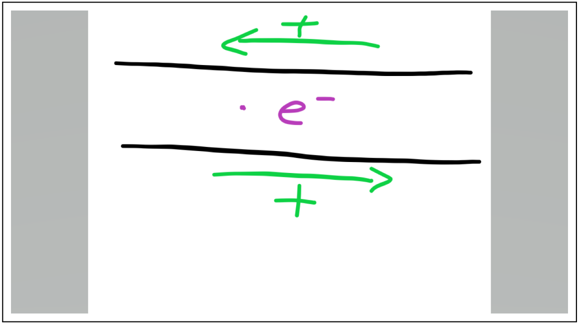
As if both interfaces are charged

Rashba at Interface

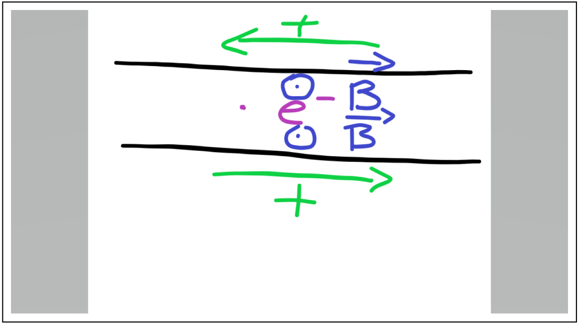


In the frame of the electron, it is at rest.
The interface charges are moving.

Rashba at Interface

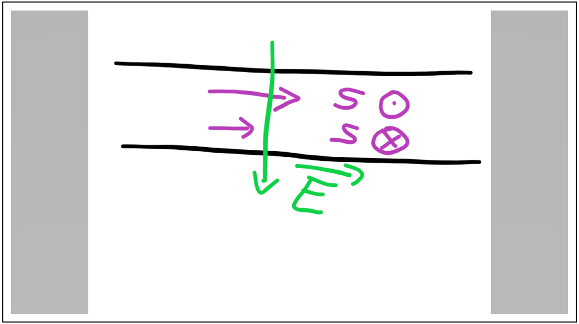


As if 2 currents at the interfaces



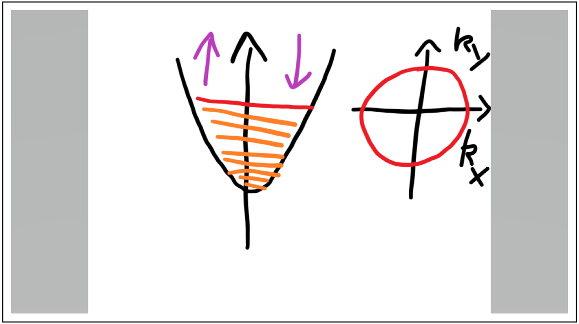
These currents create an in-plane effective magnetic field

Rashba at Interface

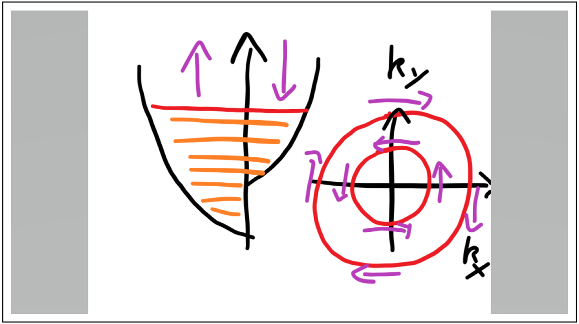


The transverse spin degeneracy is lifted
The original current is spin polarised

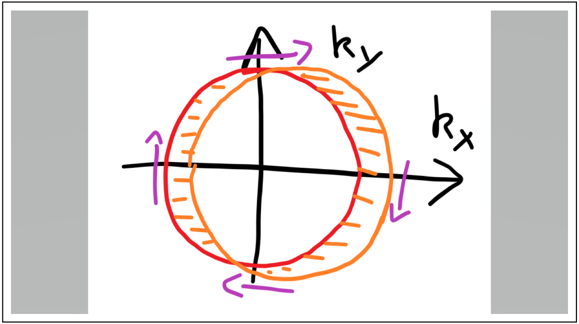
Rashba at Interface



Without magnetic field the current is not polarised in-plane

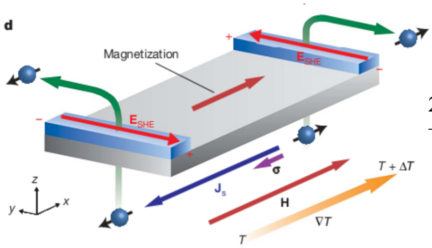


With Rashba field, the current becomes spin-polarised.
The spin polarisation is transverse to $\vec{k}$.



Rashba-Edelstein mechanism : converts a charge current into a spin current

Spin Seebeck



20 nm-thick Py on sapphire + Pt bar at one end

Uchida et al. Nature 2008 : proposal for a Spin Seebeck effect

Temperature gradient + Magnetisation are collinear

Diffusion of spin (ISHE detection)

Biblio

Book :
Spin Current (editors S. Maekawa, S.O. Valenzuela, E. Saitoh and T. Kimura) (Oxford Science Publications, OUP)
(edition 2 , 2017)