The origin, the development and the future of spintronics

Influence of spin on conduction

Magnetic nanostructures

Spin up electron

Spin down electron

Spintronics

GMR, TMR, etc...

Magnetic switching

and microwave
generation by spin
transfer, spintronics
with semiconductors,
molecular spintronics,
etc

Memory (M-RAM)

Read heads, sensors, etc.
Spin dependent conduction in ferromagnetic metals

Fert et al, PRL 21, 1190, 1968
Loegel-Gautier, JPCS 32, 1971
Dorlejin et al, ibid F7, 23, 1977

\[ \alpha \approx 0.3 \]
\[ \alpha \approx 20 \]

\[ \beta = \frac{\rho_\downarrow - \rho_\uparrow}{\rho_\downarrow + \rho_\uparrow} = \frac{\alpha - 1}{\alpha + 1} \]
Mixing impurities A and B with opposite or similar spin asymmetries: the pre-concept of GMR

**Example: Ni + impurities A and B** *(Fert-Campbell, 1968, 1971)*

1st case 

\[ \alpha_A > 1, \quad \alpha_B < 1 \]

High mobility channel \( \rho_{AB} \gg \rho_A + \rho_B \)

2nd case 

\[ \alpha_A \text{ and } \alpha_B > 1 \]

\[ \rho_{AB} \approx \rho_A + \rho_B \]

J. de Physique 32, 1971
Molecular Beam Epitaxy
(growth of metallic multilayers)
• Magnetic multilayers
Magnetic multilayers

Magnetizations of Fe layers at zero field in Fe/Cr multilayers

Fe
Cr
Fe
Cr
Fe

P. Grünberg, 1986 → antiferromagnetic interlayer coupling
Magnetic multilayers

Magnetizations of Fe layers in an applied field in Fe/Cr multilayers

P. Grünberg, 1986 → antiferromagnetic interlayer coupling
• Giant Magnetoresistance (GMR)
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

Orsay

Resistence ratio

\[ \frac{R}{R(H=0)} \]

(Fe 3nm/Cr 1.8 nm)
(Fe 3nm/Cr 1.2 nm)
(Fe 3nm/Cr 0.9 nm)

Magnetic field (kGauss)

Current

AP (AntiParallel)  P (Parallel)

Jülich

\[ V = RI \]

MR=1.5%
Giant Magnetoresistance (GMR)
(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)

- **Resistance ratio**
  \[
  \frac{R}{R(H=0)}
  \]

- **Magnetic field (kGauss)**

- **Resistance ratio**
  \[
  \sim + 80\%
  \]

- **Current**
  - AP (AntiParallel)
  - P (Parallel)

- **Condition for GMR:**
  layer thickness \( \approx \) nm

- **Anti-parallel magnetizations** (zero field, high resistance)
  - Fe
  - Cr
  - Fe

- **Parallel magnetizations** (appl. field, low resist.)
  - Fe
  - Cr
  - Fe

- **net current**
The Magnetic Recording System

Read head of hard disc drive

Magnetic fields generated by the media

1997 (before GMR): 1 Gbit/in², 2007: GMR heads ~ 300 Gbit/in²
Arrays of GMR biochips for analysis of biomolecules (example: antigens are trapped by antibodies and also decorated by other antibodies labelled by magnetic nanoparticles which are detected by a GMR sensor)

9 μm (Philips), 1μm (Santa Barbara)

→ Probe arrays for analysis of thousands of different targets in parallel
- Magnetic Tunnel Junctions, Tunneling Magnetoresistance (TMR)

\[ \text{ferromagnetic electrodes} \quad \approx 0.1 \mu m \quad \text{tunneling barrier (insulator)} \]

\begin{align*}
\text{Low resistance state} & \quad \text{High resistance state} \\
\text{Moodera et al, 1995, Miyasaki et al, 1995, CoFe/Al}_2\text{O}_3/\text{Co, MR } \approx 30-40\% \\
\text{Jullière, 1975, low T, hardly reproducible}
\end{align*}

Applications: - read heads of Hard Disc Drive

- M-RAM (Magnetic Random Access Memory)

MRAM: density/speed of DRAM/SRAM + nonvolatility + low energy consumption
Epitaxial magnetic tunnel junctions (MgO, etc)

First examples on Fe/MgO/Fe(001):
  CNRS/Thales (Bowen, AF et al, APL 2001)
  Nancy (Faure-Vincent et al, APL 2003)
  Tsukuba (Yuasa et al, Nature Mat. 2005)
  IBM (Parkin et al, Nature Mat. 2005) .. etc

Yuasa et al, Fe/MgO/Fe
Nature Mat. 2005
$\Delta R/R = (R_{AP} - R_P)/R_P \approx 200\%$ at RT

CoFeB/MgO/CoFeB,
$\Delta R/R \approx 500\%$ at RT in several laboratories in 2006-2007

Clearer picture of the physics of TMR:
what is inside the word « spin polarization »?
FIG. 2. Tunneling density of states on each atomic layer at $k_{\parallel} = 0$ for the Co/MgO/Co tunnel junction. Top panel: parallel spin alignment, bottom panel: antiparallel spin alignment.
MgO, ZnSe (Mavropoulos et al, PRL 2000), etc

→ $\Delta_1$ symmetry (sp) slowly decaying

→ tunneling of Co majority spin electrons

SrTiO$_3$ and other d-bonded insulators (Velev et al, PRL 95, 2005; Bowen et al, PR B 2006)

→ $\Delta_5$ symmetry (d) slowly decaying

→ tunneling of Co minority spin electrons

in agreement with the negative polarization of Co found in TMR with SrTiO$_3$, TiO$_2$ and Ce$_{1-x}$La$_x$O$_2$ barriers (de Teresa, A.F. et al, Science 1999)
Beyond MgO

\[ \Delta_1 \] symmetry (sp) slowly decaying

→ tunneling of Co majority spin electrons

\[ \Delta_5 \] symmetry (d) slowly decaying

→ tunneling of Co minority spin electrons

SrTiO\(_3\) and other d-bonded insulators (Velev et al, PRL 95, 2005; Bowen et al, PR B 2006)

in agreement with the negative polarization of Co found in TMR with SrTiO\(_3\), TiO\(_2\) and Ce\(_{1-x}\)La\(_x\)O\(_2\) barriers (de Teresa, A.F. et al, Science 1999)

Physical basis of « spin polarization » (SP)

Tunneling: SP of the DOS for the symmetry selected by the barrier

Electrical conduction: SP depends on scatterers, impurities, ..
Spin Transfer
(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules
Introduction:

Spin accumulation and spin currents

Spin Transfer
(magnetic switching, microwave generation)

Spintronics with semiconductors

Spintronics with molecules

Introduction:
spin accumulation and spin currents
Co/Cu: Current in Plane (CIP)-GMR
(Mosca, AF et al, JMMM 1991)

Co/Cu: Current \perp \text{to Plane} (CPP) GMR
(L. Piraux, AF et al, APL 1994, JMMM 1999)

CIP-GMR
scaling length = mean free path

CPP-GMR
scaling length = spin diffusion length >> mean free path
spin accumulation theory,
(Valet-Fert, PR B 1993)
Spin injection/extraction at a NM/FM interface (beyond ballistic range)

Spin accumulation

\[ \Delta \mu = E_{F\uparrow} - E_{F\downarrow} \]

Spin current

\[ = J_{\uparrow} - J_{\downarrow} \]

\[ I_{\text{NM}}^{\text{sf}} = \text{spin diffusion length in NM} \]

\[ I_{\text{FM}}^{\text{sf}} = \text{spin diffusion length in FM} \]

\[ E_{F\uparrow} - E_{F\downarrow} \sim \exp(-z / I_{\text{sf}}^{\text{NM}}) \text{ in NM} \]

\[ E_{F\uparrow} - E_{F\downarrow} \sim \exp(z / I_{\text{sf}}^{\text{FM}}) \text{ in FM} \]

(illustration in the simplest case = flat band, low current, no interface resistance, single polarity)

(example: 0.5 \( \mu \)m in Cu, >10\( \mu \)m in carbon nanotube)
Spin injection/extraction at a Semiconductor/FM interface

Spin accumulation
$$\Delta \mu = E_{F\uparrow} - E_{F\downarrow}$$

Spin current
$$= J_{\uparrow} - J_{\downarrow}$$

1) situation without interface resistance (« conductivity mismatch »)
(Schmidt et al, PR B 2000)

If similar spin splitting on both sides but much larger density of states in F metal

much larger spin accumulation density and much more spin flips on magnetic metal side

almost complete depolarization of the current before it enters the SC
Spin injection/extraction at a Semiconductor/FM interface

\[ \Delta \mu = E_{F\uparrow} - E_{F\downarrow} \]

Current Spin Polarization
\[ (J_{\uparrow} - J_{\downarrow}) / (J_{\uparrow} + J_{\downarrow}) \]

Spin dependent drop of the electro-chemical potential

Discontinuity increases the spin accumulation in NM

Re-balanced spin relaxations in F and NM

Extension of the spin-polarized current into the semiconductor

Rasbhal, PR B 2000
A.F-Jaffrès, PR B 2001
Spin transfer

(\text{J. Slonczewski, JMMM 1996, L. Berger, PR B 1996})

Ex: Cobalt/Copper/ Cobalt
Spin transfer


The transverse component of the spin current is absorbed and transferred to the total spin of the layer.

\[
\frac{\text{torque}}{\hbar} = \left( \frac{d \mathbf{S}}{dt} \right)_i = \text{absorbed transverse spin current} \\
\propto j M x (M x M_0)
\]
Experiments on pillars

Metallic pillar ≈ 50x150 nm²

a) First regime (low H): irreversible switching (CIMS)

b) Second regime (high H): steady precession (microwave generation)

E-beam lithography + etching
Regime of irreversible magnetic switching

First experiments on pillars:
Cornell (Katine et al, PRL 2000)
CNRS/Thales (Grollier et al, APL 2001)
IBM (Sun et al, APL 2002)

Py/Cu/Py 50nmX150nm (Boule, AF et al)

GaMnAs/InGaAs/GaMnAs tunnel junction \( (\text{MR}=150\%) \)
(Elsen, AF et al, PR B 2006)

typical switching current \( \approx 10^7 \text{A/cm}^2 \)
switching time can be as short as 0.1 ns (Chappert et al)
Regime of steady precession (microwave frequency range)

CNRS/Thales, Py/Cu/PY (Grollier et al)
(Py = permalloy)

Increasing current
Co/Cu/Py (« wavy » angular variation calculated by Barnas, AF et al, PR B 2005)

Free Py: fast spin relaxation
Fixed Co: slower spin relaxation

Py (8nm, free)
Cu (8nm)
Co (8nm, fixed)
IrMn (15nm)

or CoO or Cu

100x170nm²

Py/Cu/Py (standard)

dV/dI (Ω)

Negative I (mA)

Power (pW/GHz)
Frequency (GHz)

Boulle, AF et al, Nature Phys. 2007 oscillations at H=0

H ≈ 0 (2 Oe)

9.5 mA
9 mA
8.5 mA
8 mA
7.5 mA
7 mA
6.5 mA
6 mA
Switching of reprogrammable devices (example: MRAM)

1) By external magnetic field
   (present generation of MRAM, nonlocal, risk of "cross-talk" limits integration)

2) "Electronic" reversal by spin transfer from current
   (for the next generation of MRAM, with already promising demonstrations by several companies)
Spin Transfer Oscillators (STO) (communications, microwave pilot)

Advantages:

- **direct oscillation in the microwave range** (5-40 GHz)

- **agility**: control of frequency by dc current amplitude (frequency modulation, fast switching)

- high quality factor

- small size ($\approx 0.1\mu m$) (on-chip integration)

- oscillations without applied field

- Needed improvements

  - increase of power by synchronization of $\frac{f}{f - \text{eff}} \approx 18000$
Experiments of STO synchronization by electrical connection
(B. Georges, AF et al, CNRS/Thales and LPN-CNRS, preliminary results)
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Spintronics with semiconductors and molecules
Spintronics with semiconductors

Magnetic metal/semiconductor hybrid structures

Example: spin injection from Fe into LED (Mostnyi et al, PR. B 68, 2003)

Ferromagnetic semiconductors (FS)

GaMnAs ($T_c \rightarrow 170K$) and R.T. FS

Electrical control of ferromagnetism

TMR, TAMR, spin transfer (GaMnAs)

Field-induced metal/insulator transition
Spintronics with semiconductors

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Spin Field Effect Transistor

Semiconductor channel between spin-polarized source and drain transforming spin information into large (?) and tunable (by gate voltage) electrical signal
Semiconductor channel:

« Measured effects of the order of **0.1-1%** have been reported for the change in voltage or resistance (between P and AP)…. »,

from the review article « *Electrical Spin Injection and Transport in Semiconductors* » by *BT Jonker* and *ME Flatté* in *Nanomagnetism* (ed.: *DL Mills and JAC Bland*, *Elsevier 2006*)
Nonmagnetic lateral channel between spin-polarized source and drain

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Carbon nanotubes:

\[ \frac{\Delta R}{R} \approx 60\text{-}70\%, \quad V_{AP} - V_P \approx 60 \text{ mV} \]

LSMO = La\textsubscript{2/3}Sr\textsubscript{1/3}O\textsubscript{3}
Nonmagnetic lateral channel between spin-polarized source and drain

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Two interface spin transport problem (diffusive regime)

AF and Jaffrès
PR B 2001
+cond-mat
0612495, +
IEEE Tr.El.Dev.
54,5,921,2007

Condition for spin injection

\[ \text{dwell time } \tau_n < \text{spin lifetime } \tau_{sf} \]

\[ \tau_n = \frac{2L}{v t_r} \propto \frac{L r_b^*}{v} \]

\[ \Delta R = \frac{\gamma^2}{(1-\gamma^2)} \]

\[ \frac{R}{R^P} = \frac{1+\tau_n/\tau_{sf}}{1+\tau_{sf}/\tau_{sf}} \]

Interface resistance \( r_b^* \)
in most experiments

\[ \tau_n \gg \tau_{sf} \]

\[ \gamma = \text{spin asymmetry of the interface resistance} \]

\[ r_b^* = \text{unit area interface resist. } \propto 1/\text{trans.co eff } t^*_r \]

\[ r_N = \rho_N l_{sf}^N \]
Nanotubes (also graphene, other molecules):

small spin–orbit → spin lifetime \( \tau_{sf} \) is long \((\approx 50\text{ns})\)

high velocity \( v \) → \( \tau_n = \frac{2L}{v\tau_r} \) is short \((< \tau_{sf})\)

Semiconductor:

\( \tau_{sf} \) can be long \((\text{for } n \approx 10^{17} \text{ el/cm}^3)\)

but \( v \) is small → \( \tau_n = \frac{2L}{v\tau_r} \) is long \((>> \tau_{sf})\)

Transport between SP source and drain: \( \tau_n \) = dwell time, \( \tau_{sf} \) = spin lifetime, \( \gamma \) = injection SP:

: the contrast between P(on) and AP(off), \( \frac{\Delta R}{R^P} = \frac{\gamma^2 / (1 - \gamma^2)}{1 + \tau_n / \tau_{sf}} \), is large if \( \tau_n < \tau_{sf} \)
Transport between SP source and drain: \( \tau_n \) = dwell time, \( \tau_{sf} \) = spin lifetime, \( \gamma \) = injection SP.

The contrast between P (on) and AP (off), \( \frac{\Delta R}{R^P} = \frac{\gamma^2}{1 - \tau_n/\tau_{sf}} \), is large if \( \tau_n < \tau_{sf} \).

Nanotubes (also graphene, other molecules):

- Small spin–orbit \( \rightarrow \) spin lifetime \( \tau_{sf} \) is long (\( \approx 50\text{ns} \))

- High velocity \( v \rightarrow \tau_n = \frac{2L}{vt_r} \) is short (\( < \tau_{sf} \))

Semiconductor

- \( \tau_{sf} \) can be long (for \( n \approx 10^{17} \text{el/cm}^3 \))

- But \( v \) is small \( \rightarrow \tau_n = \frac{2L}{vt_r} \) is long (\( >> \tau_{sf} \))

Solution for semiconductors:

- Shorter L ?, larger transmission
  
  \( t_r ? \)
Nanotubes (also graphene, other molecules):

- Small spin–orbit → spin lifetime $\tau_{sf}$ is long ($\approx 50\text{ns}$)
- High velocity $v$ → $\tau_n = \frac{2L}{vt_r}$ is short ($< \tau_{sf}$)

Semiconductor:

- $\tau_{sf}$ can be long (for $n \approx 10^{17} \text{ el/cm}^3$)
- But $v$ is small → $\tau_n = \frac{2L}{vt_r}$ is long ($>> \tau_{sf}$)

Solution for semiconductors:

- Shorter $L$ ?, larger transmission $t_r$ ?

Potential of molecular spintronics (nanotubes, graphene and others)
Transport between SP source and drain: $\tau_n = $ dwell time, $\tau_{sf} = $ spin lifetime, $\gamma = $ injection SP

: the contrast between P(on) and AP(off), 
\[ \frac{\Delta R}{R^P} = \frac{\gamma^2}{1 + \tau_n / \tau_{sf}}, \]
is large if $\tau_n < \tau_{sf}$

Nanotubes (also graphene, other molecules):

small spin–orbit $\rightarrow$ spin lifetime $\tau_{sf}$ is long ($\approx 50$ns)

high velocity $\nu$ $\rightarrow$ $\tau_n = \frac{2L}{\nu t_r}$ is short ($< \tau_{sf}$)

Semiconductor

$s$: $\tau_{sf}$ can be long (for $n \approx 10^{17}$ el/cm$^3$)

but $\nu$ is small $\rightarrow$ $\tau_n = \frac{2L}{\nu t_r}$ is long ($>> \tau_{sf}$)

Solution for semiconductors:

shorter L $\Rightarrow$, larger transmission $t_r$ $\Rightarrow$

Potential of molecular spintronics (nanotubes, graphene and others)

Next challenge for molecules:

spin control by gate
Summary

Already important applications of GMR/TMR (HDD, MRAM..) and now promising new fields
- Spin transfer for magnetic switching and microwave generation
- Spintronics with semiconductors, molecules or nanoparticles
Acknowledgements to


Université Paris-Sud and Unité Mixte de Physique CNRS-Thales, Orsay, France

P. M. Levy, New York University, A. Hamzic, Zagreb University

B. Lépine, A. Guivarch and G. Jezequel

Unité PALMS, Université de Rennes, Rennes, France

G. Faini, R. Giraud, A. Lemaître: CNRS-LPN, Marcoussis, France

L. Hueso, N. Mathur, Cambridge

J. Barnas, M. Gimtra, I. Weymann, Poznan University