European School on Magnetism, Cluj 2015

From Basic Magnetic Concepts To Spin Currents
(Introduction)

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Spin-polarised current
Pure spin current
Spin waves
The discovery of Giant Magnetoresistance


- Ultra High Vaccum deposition techniques, Thin films / atomic empilements

- Spin dependent conduction

\[ \alpha = \frac{\rho_{\uparrow}}{\rho_{\downarrow}} \neq 1 \]

- Antiferromagnetic coupling -> anti-parallel state
Band structure: ferromagnetism and transport

Density of states

Magnetic order

Spin dependent conductivity

\[ \sigma = \sigma_\uparrow + \sigma_\downarrow \]
\[ \rho = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \]

Asymétrie
\[ \alpha = \frac{\rho_\downarrow}{\rho_\uparrow} \]

Polarisation
\[ \rho_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \]

2 current model:
\[ j = j_\uparrow^F + j_\downarrow^F \]

Competition between:
exchange, magneto-static,
magneto-cristalline, external field
Modeling

\[ R(P) = \frac{2R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow} \]

\[ R(AP) = \frac{R_\uparrow + R_\downarrow}{2} \]

2 CSR then CPP-GMR model Valet & Fert, PRB 93'
Spin injection at F/ NM interface

Magnetization manipulation by spin current


J. Grollier, APL 78 (2001)
O. Boule, Nat. Phys. (2007)
M. Klaeui, PRL 95 (2005)

Spin transfer torque

J. Slonczewski
JMMM 1996
L. Berger
PRB 1996

Magnetization reversal
(electrical commutation)

Precessional regime
(HF emission)

Domain wall displacement
(memories)

J. Grollier, APL 78 (2001)
O. Boule, Nat. Phys. (2007)
M. Klaeui, PRL 95 (2005)
Charge to Spin current conversion

at Ferromagnetic | Non-magnetic interfaces

Lead to GMR effect and spin transfer Torque

by Spin Orbit Coupling:
- Spin Hall Effect
- Rashba-Edelstein Effect

Localized Spin-Orbit interaction

By charge current injection
Spin pumping
Heat gradient,...
Spin Orbit effects in
Ferro-Magnetic / Non-Magnetic tri-layers

Pt/Co/Al$_2$O$_3$, Ta/CoFeB/MgO, Pt(t)/Co(/Ni)/P(t)....

Efficient systems to propagate DW or to switch magnetization with in plane currents

(and for skyrmions)

Spintec, Cornell, Tohoku, IBM, Kyoto, ... very active field of research

SOT + DMI

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Ferro-Magnetic / Non-Magnetic tri-layers

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SOT + DMI

The nature of DW revealed by (NV center) scanning nanomagnetometry, T. Hingant, L. V. et al, Nat. Commun. 2015
Spin Orbit effects in
Ferro-Magnetic / Non-Magnetic bi-layers

Spin Hall effect

How to efficiently transfer spins from NM to FM?

What is the source of the SOT
Spin Orbit effects in
Ferro-Magnetic / Non-Magnetic bi-layers

Rashba effect?
Spin momentum lock-in at Rashba interfaces
and Topological Insulator

Rashba-Edelstein effect
Spin Orbit effects in
Ferro-Magnetic / Non-Magnetic bi-layers

Spin currents in presence of Domain walls

Interplay between spin current and DWs walls, Spin Orbit Torque?
Spin current induced by

Spin Pumping

Spin Orbit Coupling

Thermal Spin Injection

Spin waves

Johnson, Silsbee 1985, Jedema 2001

Spin Hall and Rashba effects

Silsbee, Monod 1979, Tserkovnyak, Bauer 2002

Saitoh 2006

A.Slachter et al. Nat. Phys. 2010

Kajiwara et al. Nature Phys. 2010
Spin transport in Lateral Spin Valves

Non local measurements, separating charge and spin currents

\[ j^N_C = j^N_\uparrow + j^N_\downarrow \quad \text{and} \quad j^N_S = j^N_\uparrow - j^N_\downarrow \]

Lateral spin transport in Metals, S.-C.s or carbon based hybrid structures:

- to access material parameters,
- to find optimum spin injection/detection conditions,
- to exploit spin currents...

\[ \Delta V \]

\[ \mu_n \]

\[ j^N_\uparrow \]

\[ j^N_\downarrow \]

\[ \mu^\uparrow_n \quad j^N_\uparrow \quad \mu^\downarrow_n \quad j^N_\downarrow \]

\[ X = 0 \quad X = L \]

\[ j^N_C = j^N_\uparrow + j^N_\downarrow = 0 \]

\[ j^N_S = j^N_\uparrow - j^N_\downarrow \neq 0 \]
Nonlocal spin valve measurement

Charge neutral point shifts upward.
Nonlocal spin valve measurement

Detector in antiparallel

Charge neutral point shifts downward.
Probes configurations and expected results

**NL**

![Diagram of NL configuration]

- $\Delta R_s \sim 2 \times R_s (NL)$

**GMR**

![Diagram of GMR configuration]

- $\Delta V/I$ vs $H [T]$
Non-Local results NiFe/Al

$\Delta \text{Rs(GMR)} \sim 2 \times \Delta \text{Rs(NL)}$

Sum of the spin accumulation at the two interfaces

P. Laczkowski et al, APEX 4, 063007 (2011)
NiFe/(Cu or Al) lateral spin valves

Py/Al

T=77K, L=150nm

Generally a few mΩ at low temperature

Yang et al. Nat. Phys. 2007: Py/Cu, 18.5 mΩ, T=10K

Py/Cu

T=300K

Py/Al, T=300K

fit: P=0.28, Lsf=343

Lsf, with P~45%

T=300K
Al ~450nm ~750nm
Cu ~300nm ~770nm

P. Laczkowski et al, APEX 4, 063007 (2011)
NiFe/(Au, Cu or Al) lateral spin valves

\[ R_F/R_N \approx 0.1 \text{ - } 0.2 \text{ with } \text{Al} \text{ & } \text{Cu} \]
\[ \approx 0.5 \text{ for NiFe/Au} \]

Balance between \( \frac{R_F}{R_N} \) & \( \sinh^{-1}(L_N/I_N^{sf}) \)

\[ \Delta V/I \approx 5.4 \text{ m\Omega} \]

\[ \Delta V/I \approx 18.5 \text{ m\Omega} \]

\[ \sinh^{-1}(L_N/I_N^{sf}) \]
Enhancement of the spin accumulation by lateral confinement

Coll. A. Fert, J.M. George, H. Jaffrès

Opened vs Confined Geometries

4-wires circuitry: Isf in NM, STT, SHE

Out of equilibrium of spin accumulation

- Spin sink experiment to measure Isf in NM

Side view

T. Kimura et al, PRB (2005)

- Insertion of a magnetic dot for STT

Yang et al, Nature Phys 2008

V/I (mΩ)

B (T)
Pure spin-current for spin Hall effect and magnetization switching

Spin Hall effect

Valenzuela et al, Nature 2006

Shadow evaporation for *in-vacuum* interface fabrication

Magnetization switching

Yang et al, Nature Phys 2008
Spin current induced by

- **FM/NM junction**
  - Johnson, Silsbee 1985, Jedema 2001

- **Spin Orbit Coupling**
  - Spin Hall and Rashba effects

- **Spin Pumping**
  - Silsbee, Monod 1979, Tserkovnyak, Bauer 2002
  - Saitoh 2006

- **Thermal Spin Injection**
  - A.Slachter et al. Nat. Phys. 2010

- **Spin waves**
  - Kajiwara *et al.* Nature Phys. 2010
Inverse spin Hall effect by ferromagnetic resonance and spin pumping

Saitoh APL 2006
Tserkovnyak PRL 2004
Silsbee, PRB 1979

Magnetization precession + Interfacial Electronic coupling + spin to charge conversion

in FM at FM/NM in NM

P = 200 mW

lorentzian voltage peak at resonance field

NiFe(15)/Pt(5)//
Ferromagnetic resonance (FMR)

FMR is a power technique:
- Magnetic anisotropies (angular dependence, frequency dependence)
- Magnetic transition (temperature dependence)
- Magnetic coupling
- ..etc

\[ \Rightarrow H_{\text{res}} \]
\[ \Rightarrow \Delta H_{\text{pp}} \]

Field (Oe)

\[ \frac{dX''}{dH} \text{ (a.u)} \]

P=200 mW
f= 9.6786 GHz
Enhancement of damping constant: Spin pumping effect

\( g_{\text{eff}} = \frac{4\pi M_s t_F}{g \mu_B} \left( \frac{\alpha_{FM/NM}}{\mu_B} - \alpha_{FM} \right) \)

Note: Not always \( \Delta \alpha \) is only due to SP
Spin pumping and ISHE: E. Saitoh et al. APL 2006

- Voltage ISHE: symmetrical Lorentzian peak at $H_{res}$
- Note: symmetrical contribution can also be due to other effects in the FM layer (AMR or PHE, AHE, IAHE or ISHE?)

Ando et al. 2008
Spin Pumping and spin to charge current conversion

- Spin-pumping – ISHE or IEE:
  - Pure spin currents
  - Easy lithography (if any)
  - Spin $\rightarrow$ Charge: Simple electrical detection (dc voltage measurement)

Also some difficulties exist...

Determining the spin current
  $\rightarrow$ Many variables

Ando, Saitoh (2009)

$$j_s = \frac{g_{\text{eff}}^4 \gamma^2 \hbar}{8 \pi \alpha^2} \frac{h_{\text{rf}}^2}{\left(4 \pi M_{\text{eff}} \gamma + (4 \pi M_{\text{eff}} \gamma)^2 + 4 \omega^2\right)} \left(\frac{2e}{\hbar}\right)$$

Spin Pumping and spin to charge current conversion

• Spin-pumping – ISHE or IEE:
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Determining the spin current
  → Many variables

\[ f(H_{\text{res}}) \rightarrow M_{\text{eff}} \]

\[ \Delta H(f) \rightarrow \alpha \]

\[ \Delta \alpha(t_N) = \frac{g \mu_B}{4\pi M_{\text{eff}} t_F} g_{\uparrow\downarrow} \rightarrow g_{\uparrow\downarrow} \]

From the ISHE voltage measurement:

\[ I_C = \frac{V_{\text{ISHE}}}{R} \]

\[ I_C = W \Theta_{\text{SHE}} \ell_{\text{sf}} \tanh\left(\frac{t_{NM}}{2\ell_{\text{sf}}}\right) j_s \]
The Spin Hall Angle and Spin Diffusion Length in Pt

• Platinum is widely studied, but results are scattered.

Values found in the literature are not consistent and spread on one order of magnitude.

• Platinum is widely studied, but results are scattered.

Values found in the literature are not consistent and spread on one order of magnitude.

There is a correlation with the spin diffusion length.

\[ I_C = -\theta_{\text{SHE}}\ell_{sf}WJ_S^{\text{eff}}\tanh\left(\frac{t_N}{2\ell_{sf}}\right) \]

must be disentangled.

Damping and $V_{\text{ISHE}}$ in Co/Pt and Co/Cu/Pt multilayers

- Lower charge production by inserting Cu

$\theta_{Pt} = 5 \pm 0.5 \%$

$l_{sf} = 3.4 \pm 0.4 \text{ nm}$

$\rho_{Pt} \sim 17 \times 10^{-8} \text{ } \Omega \cdot \text{m}$

$J_{eff} \sim 10^{-12} \text{ MA/m}^2$

$Geff \sim 40-80 \text{ nm}^2$

$\rightarrow$ Different length scale for $\alpha$ and $V_{\text{ISHE}}$

Co/Pt & Co/Cu/Pt: Spin memory loss (spin relaxation) at metallic interfaces


\[ I_C = -W \theta_{SHE}^N t_{sf}^N J_{S}^{\text{eff}} \tanh \left( \frac{t_N}{2\theta_{sf}^N} \right) R_{SML} \]

\[ \delta_{F/N} \text{ Spin flip parameter} \]

SML parameters for Co/Cu, Cu/Pt and Co/Pt

Spin memory loss

Back to the roots of GMR:

Bulk
\[ \rho^*, \beta, \text{lsf} \]
Resistivity, spin asymmetry, spin relaxation

Interface
\[ \text{A.R}^*, \gamma, \delta \]
Interface resistance, spin asymmetry, spin flip ratio

Spin memory loss is the analog for an interface of the \( t/\text{lsf} \) ratio for the bulk
Spin current induced by

**Spin Pumping**

**FM/NM junction**

Johnson, Silsbee 1985, Jedema 2001

**Spin Orbit Coupling**

Spin Hall and Rashba effects

**Thermal Spin Injection**

Silsbee, Monod 1979, Tserkovnyak, Bauer 2002

Saitoh 2006

**Spin waves**

A.Slachter et al. Nat. Phys. 2010

Kajiwara *et al.* Nature Phys. 2010
Spin Hall effects in metallic nanostructures

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from J. Inoue & H. Ohno
"Direct" spin Hall effect

Spin-orbit interaction

Trajectories of electrons are affected by the interaction between the electron-spin and orbital angular momentum.

- Origin of anomalous Hall effect (AHE)
- Nuisance that flips the spin direction leading to the spin decoherence.

Novel way for spin current generation & manipulation

Direct spin Hall effect (DSHE)

Un-polarized charge current

Transverse spin current

\[ \mathbf{J}_S \propto \mathbf{S} \times \mathbf{J}_c \]

“Direct” spin Hall effect

Spin-orbit interaction

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Novel way for spin current generation & manipulation

Direct spin Hall effect (DSHE)

Spin Hall effects: "the early days"

"Possibility of orientating electron spins with current".

A flux of spin:
\[ q_{\alpha \beta} = -b_s E_\alpha S_\beta - d_s \frac{\partial S_\beta}{\partial x_\alpha} + \beta_s n \epsilon_\alpha \beta_\gamma E_\gamma \]

drift – diffusion – transverse spin current
due to SO

Macroscopic samples from metallurgy
Mn impurities polarize the charge current


Cf also Bakun et al,
Polarized photo-current in SC
Spin Hall effect: recent observations in GaAs based SC

Detection: kerr rotation or polarized EL

Observation of the Spin Hall Effect in Semiconductors


Electrically induced electron-spin polarization near the edges of a semiconductor channel was detected and imaged with the use of Kerr rotation microscopy. The polarization is out-of-plane and has opposite sign for the two edges, consistent with the predictions of the spin Hall effect. Measurements of unstrained gallium arsenide and strained indium gallium arsenide samples reveal that strain modifies spin accumulation at zero magnetic field. A weak dependence on crystal orientation for the strained samples suggests that the mechanism is the extrinsic spin Hall effect.


Experimental Observation of the Spin-Hall Effect in a Two-Dimensional Spin-Orbit Coupled Semiconductor System

J. Wunderlich,1 B. Kaestner,1,2 J. Sinova,3 and T. Jungwirth1,4
1ESSI Cambridge Laboratory, Cavendish CHB, St John’s College, Cambridge, Cambridge, United Kingdom
2National Physical Laboratory, Teddington TW1 0SW, United Kingdom
3Department of Physics, Texas A & M University, College Station, Texas 77843-4242, USA
4Institute of Physics ASCR, Ovocný trh 5, 124 04 Prague 2, Czech Republic

School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom
(Received 16 November 2004; published 4 February 2005)

"Inverse" spin Hall effect in metallic systems

This technique is effective only for a nonmagnet with a long spin diffusion length. Such a nonmagnet exhibits small spin-orbit scattering. Small Spin Hall signal is expected.

Valenzuela & Tinkham

E. Saitoh et al,
a) Intrinsic deflection

Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

\[ \frac{d \langle \vec{r} \rangle}{dt} = \frac{\partial E}{\partial \vec{k}} + \frac{e}{\hbar} E \times b_n \]

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry’s phase curvature.

b) Side jump

The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

c) Skew scattering

Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.

Nagaosa et al, Rev. Mod. Phys. 10'
Exploitation of the spin Hall effect

LETTERS

Transmission of electrical signals by spin-wave interconversion in a magnetic insulator


Y₃Fe₅O₁₂

M = Pt

M/Y₃Fe₅O₁₂

STT

DT

SC

Y₃Fe₅O₁₂

Pt (o)

Pt (i)

H

J

J₃
Spin Hall/Orbit Effects: nowadays

Techniques and Analyses improvements:

New materials!

CuIr: Y. Niimi et al., PRL 106, 126601 (2011)
CuBi: Y. Niimi et al., PRL 109, 156602 (2012)
Pt/Co/AL₂O₃: M. Miron, Nat. Mat. 9, 230 (2010) + Pt/(Co/Ni)/Pt
Beta Ta and W

Towards applications:

Spin Hall/Orbit effects are technologically relevant!

<table>
<thead>
<tr>
<th>material</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt</td>
<td>0.02−0.12</td>
</tr>
<tr>
<td>CuIr</td>
<td>0.021</td>
</tr>
<tr>
<td>CuBi</td>
<td>−0.25</td>
</tr>
<tr>
<td>Ta</td>
<td>−0.15</td>
</tr>
<tr>
<td>AuW</td>
<td>0.06−0.10</td>
</tr>
<tr>
<td>W</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

M. Miron et al., Nature 476, 189 (2012)
L. Liu et al., PRL, 109, 096602 (2012)

3D modeling SpinFlow:

Switching time $\ll 1$ ns, K. Garello et al

M. Cubukcu et al, APL 2014
Exploitation of the spin Hall effect

Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect

Luqiao Liu, Takahiro Moriyama, D. C. Ralph, and R. A. Buhrman
Cornell University, Ithaca, New York, 14853
(Received 12 October 2010; published 20 January 2011)
Second Harmonic Torque measurement

An AC current is used to excite the magnetization from its equilibrium position

Measurement of 2f components at various current and field direction
Allow to determine the corresponding effective fields

Problem: heat effects

Extrinsic Spin Hall Effect Induced by Iridium Impurities in Copper

Y. Niimi,1,* M. Morota,1 D. H. Wei,1 C. Deranlot,2 M. Basletic,3 A. Hamzic,3 A. Fert,2 and Y. Otani1,4

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2Unité Mixte de Physique CNRS/Thales, 91767 Palaiseau France associée à l’Université de Paris-Sud, 91405 Orsay, France
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(Received 12 January 2011; published 22 March 2011)
Spin Hall Effect Induced by Resonant Scattering on Impurities in Metals

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(Received 12 October 2010; published 15 April 2011)

The spin Hall effect is a promising way for transforming charge currents into spin currents in spintronic devices. Large values of the spin Hall angle, the characteristic parameter of the yield of this transformation, have been recently found in noble metals doped with nonmagnetic impurities. We show that this can be explained by resonant scattering off impurity states split by the spin-orbit interaction. By using as an example copper doped with 5d impurities we describe the general conditions and provide a guide for experimentalists for obtaining the largest effects.

DOI: 10.1103/PhysRevLett.106.157208

PACS numbers: 85.75.-d, 73.50.Jt, 75.76.+j

Cu matrix with 2% imp.
Spin Hall/Orbit effects

Spin to charge conversion at Rashba interfaces

- High SOC observed at Ag/Bi interface (Ast, PRL 2006), and more generally, Bi(111) with Cu, Si,… also Pb, W…

- Thin Bi films = metallic surface & insulating bulk -> 2D e⁻ gaz (PRL 2013)

Rashba effect at interfaces or surfaces of materials

\[ \hat{H}_{\text{SO}} = \alpha_R \mathbf{\sigma} \cdot (\mathbf{k}_\parallel \times \mathbf{e}_z), \quad \alpha_R \sim \frac{\partial V}{\partial z} \]

\text{Bi/Ag(111): } \alpha_R = 3.05 \text{ eVÅ}^\circ

<table>
<thead>
<tr>
<th>Material</th>
<th>( E_R ) (meV)</th>
<th>( \hat{k}_0 ) (Å(^{-1}))</th>
<th>( \alpha_R ) (eVÅ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs/InAlAs heterostructure</td>
<td>&lt;1</td>
<td>0.028</td>
<td>0.07</td>
</tr>
<tr>
<td>Ag(111) surface state</td>
<td>&lt;0.2</td>
<td>0.004</td>
<td>0.03</td>
</tr>
<tr>
<td>Au(111) surface state</td>
<td>2.1</td>
<td>0.012</td>
<td>0.33</td>
</tr>
<tr>
<td>Bi(111) surface state</td>
<td>( \sim 14 )</td>
<td>( \sim 0.05 )</td>
<td>( \sim 0.56 )</td>
</tr>
<tr>
<td>Bi/Ag(111) surface alloy</td>
<td>200</td>
<td>0.13</td>
<td>3.05</td>
</tr>
</tbody>
</table>

Ast et al. PRL 2007
Current-induced spin accumulation in the presence of Rashba coupling (Edelstein-Rashba effect)

Edelstein-Rashba effect

deficit of spin down electrons + excess of spin up electrons

= spin up accumulation

Courtesy of A. Fert
Generation of charge current by spin injection in the presence of Rashba coupling (Edelstein-Rashba effect)

Spin current injection

Charge current or voltage if open circuit (Inverse Edelstein-Rashba effect)

Courtesy of A. Fert
Spin to charge current conversion in Ag/Bi multilayers

\[ H_R = \alpha_R (k \times \hat{z}) \sigma \]
FMR linewidth and charge current production at resonance

\[ I_c = \frac{aV}{R_s l} \]
FMR linewidth and charge current production at resonance

![Graph showing FMR linewidth and charge current production at resonance](image)
Analyzing spin to charge current conversion

\[ \theta_{SHE} = \frac{J_C}{J_S} \]

For SHE in a 0.4 nm thick Ag/Bi interfacial alloy layer:

\[ \Theta_{SHE} \approx 2J_C^*/(J_S t_1) = 1.5 \text{ (150\%)}!! \]

Sign is reversed by stacking order (cf Viret’s group)!
Spin current induced by

FM/NM junction

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Johnson, Silsbee 1985, Jedema 2001

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Saitoh 2006

A.Slachter et al. Nat. Phys. 2010

Kajiwara et al. Nature Phys. 2010
MR and current induced magnetic switching rely on how spin currents flow in magnetic nanostructures.

Various ways to produce spin currents, including SOC (spin-orbittronics).

Many challenges: STT, SOT, SOC, DMI (skyrmions), Interfaces (Rashba, TI).

Thank you!