Sources of Spin Currents

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http:// nanodevices.icn2.cat

ESM
Cluj, Romania, Sept 2, 2015

Spin Currents
An overview

Spin current introduction

Spin angular momentum current sources

- Ferromagnetic materials (electric and thermal driving)
- Optical orientation
- Spin-orbit effects
- Topological insulators
- Mechanical motion
- …..

Implementations

Nature of spin currents

Spin currents vs. charge currents
Basic concepts

Charge conservation law

Charge *q* in position $\vec{r}$

$$\vec{j}_c = \tfrac{d}{dt}(q\vec{r}) \longrightarrow \vec{j}_c = q\vec{v}$$

Spin currents vs. charge currents
Basic concepts

Charge conservation law

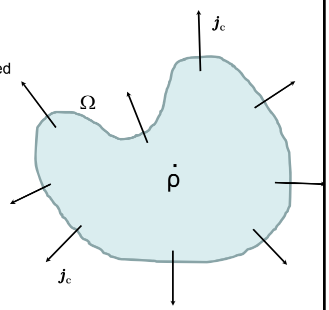
closed surface Ω
change in total ***charge*** enclosed

$$\iiint_V \dot{\rho}\, d\boldsymbol{r} = -\iint_\Omega \boldsymbol{j}_c \cdot d\boldsymbol{\Omega}$$

ρ: charge density
$\boldsymbol{j}_c$: charge current density

Gauss theorem

$$\dot{\rho} = -\mathrm{div}\,\boldsymbol{j}_c$$



Spin currents vs. charge currents
Basic concepts

Spin angular momentum conservation law

closed surface Ω
change in total ***spin*** enclosed

M: local magnetization
magnetic moment density

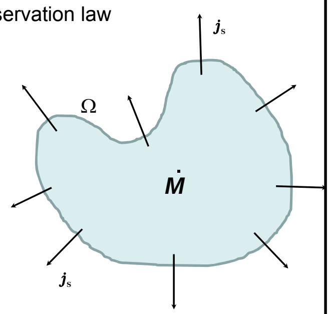
$\boldsymbol{j}_s$: spin current density

$$\frac{d\boldsymbol{M}}{dt} = -\mathrm{div}\,\boldsymbol{j}_s$$

Spin angular momentum is generally not conserved

$$\frac{d\boldsymbol{M}}{dt} = -\mathrm{div}\,\boldsymbol{j}_s + \boldsymbol{T}$$

T: non-conservation of angular momentum $\boldsymbol{T} = -(\boldsymbol{M} - \boldsymbol{M}_0)/\tau$



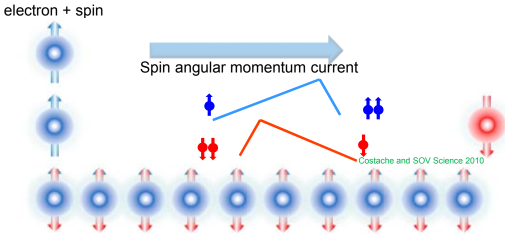
Spin currents vs. charge currents
Basic concepts

Spin angular momentum current (second-rank tensor)

Spin σ in position $\vec{r}$

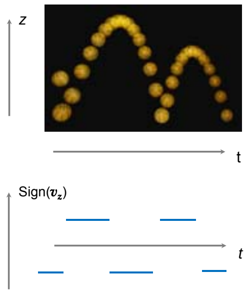
$$\vec{j}_s = \tfrac{d}{dt}(\sigma\vec{r}) \longrightarrow \vec{j}_s = \sigma\vec{v} + \dot{\sigma}\vec{r}$$

electron + spin

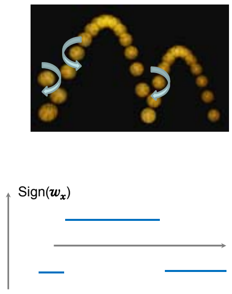


Spin currents vs. charge currents
Bouncing balls

Ball with no spin, velocity



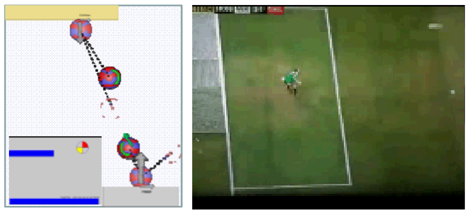
Ball spinning, angular momentum



Spin currents vs. charge currents
Bouncing balls

Interaction with the environment: nontrivial flow of angular momentum
In few cases spin currents can be defined in terms of a conservation law

Basics of spintronics, by G. Tatara (2009)



http://www2.eng.cam.ac.uk/~hemh/movies.htm

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Spin currents vs. charge currents
Bouncing balls

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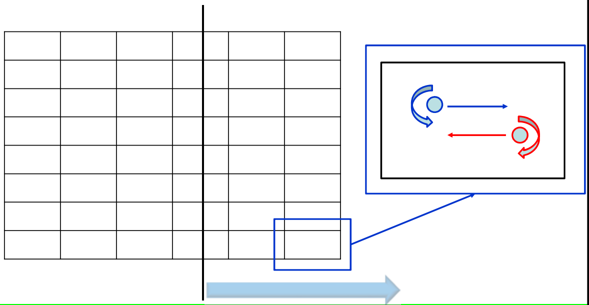

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Spin current generation
Angular momentum "reservoir/source"

(Spin) angular momentum Spin currents

Mechanical motion
Mechanical resonance
Non-uniform fluid flow

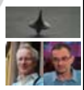
Magnetic materials
Metallic (carrier motion)
Insulator (tunneling filter, spin waves)
(Tedrow and Meservey 1971, Aronov 1976, Aronov and Pikus 1976)

Spin-orbit effects
Spin Hall and spin galvanic effects
(Dyakonov Perel 1971, Hirsch 1999, Murakami 2003, Sinova 2004, Ganichev 2003)

Nuclear spins
Overhauser/Feher effect
(Clark and Feher 1963)

Optical Orientation
(Kastler 1950, Lampel 1968, Meier Zakharchenya 1984)

Magnetization dynamics
Ferromagnetic resonance
Spin pumping



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Spin current generation
Magnetic materials

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Metallic (carrier motion)
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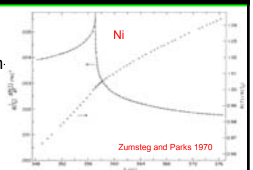
Magnetic Materials
Spin generation and spin injection

- Two spin channel model
  - Metallic ferromagnets. Spin-up and spin-down are two independent families of carriers (Mott 1936)



Nevill Francis Mott

- Unusual behaviour of the resistance of FM metals
  - Low T, magnon scattering becomes vanishingly small
  - Electrons of majority and minority spin (parallel or antiparallel to magnetization) do not mix in scattering processes
  - The conductivity can be expressed as the sum of two independent parts (see also Campbell 1967, Fert and Campbell 1968, Valet and Fert 1993)

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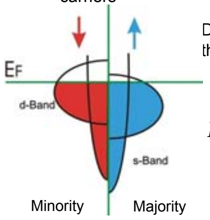
Magnetic Materials
Spin generation and spin injection

- Exchange splitting (Stoner 1938)
  - Different density of states at the Fermi level for spin up and down carriers
  - Different mobility for spin up and down carriers



Different m^*, v_F, k_F, $g(E_F)$, thus different conductivity σ

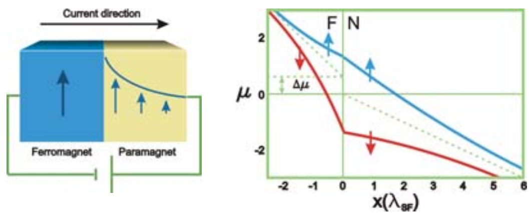
$$P = \frac{N_M - N_m}{N_M + N_m}$$

$-1 \leq P \leq 1$

Edmund Clifton Stoner

Magnetic Materials
Spin generation and spin injection

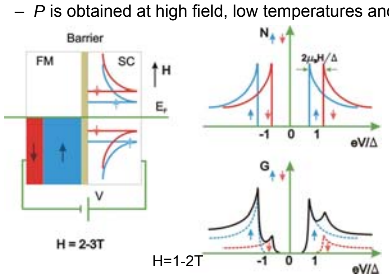
- Spin polarized current in a nonmagnetic metal
- Spin accumulation decays exponentially
- Characteristic length. Spin diffusion/relaxation length λ_{sf}



Johnson and Silsbee PRB **35**, 4959 (1987)
van Son et al., PRL **58**, 2271 (1987)

Spin current outside a ferromagnet
Meservey and Tedrow experiment

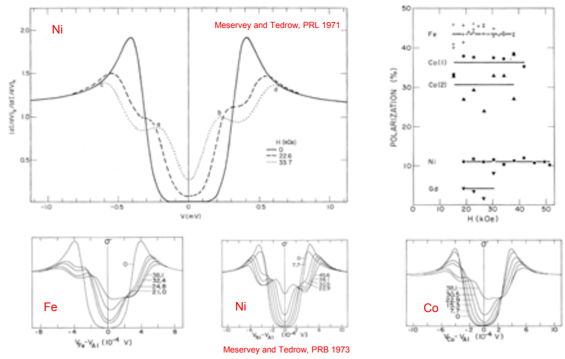
- Meservey-Tedrow technique. Superconductor with Zeeman split density of states as a spin detector
  - *P* is obtained at high field, low temperatures and zero bias



Partially polarized materials:
Fe, Co, Ni
(*P* ~ 25-45 %)

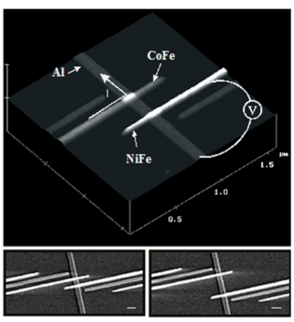
Meservey and Tedrow, PRL 1971, Review: Phys. Rep. **238**, 173 (1994)

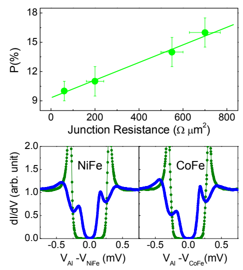
Spin current outside a ferromagnet
Meservey and Tedrow experiment



Meservey and Tedrow, PRB 1973

Spin current outside a ferromagnet
Meservey and Tedrow experiment



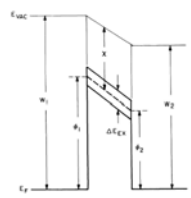


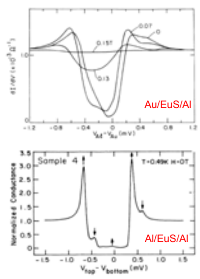
H= 0; 2T

SOV and M. Tinkham, APL **85**, 5914 (2004)

Solid-state spin filter
Spin tunnelling through a ferromagnetic insulator

The observation of internal field emission (Fowler-Nordheim tunneling} in magnetically ordered insulators is reported. A large magnetic field effect was observed and interpreted as a decrease in the barrier height due to spin ordering (Esaki *et al.* PRL 1967)

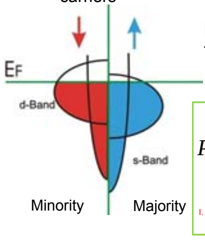




(Moodera *et al.* PRL 1988, PRB 1990)

Polarization
How is it defined?

- Spin splitting
  - Different density of states at the Fermi level for spin up and down carriers
  - Different mobility for spin up and down carriers



Different m^*, v_F, k_F, $g(E_F)$, thus different conductivity

$$P = \frac{N_M - N_m}{N_M + N_m} \quad -1 \le P \le 1$$

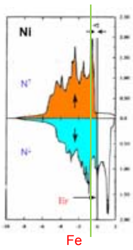
I. I. Mazin, PRL **83**, 1427-1430 (1999)

Edmund Clifton Stoner

Polarization
How is it defined?

$$P = \frac{N_M - N_m}{N_M + N_m}$$ Fraction of unpaired carriers: ratio of spin current to charge current. $$P = \frac{j_s/\mu_B}{j_c/e}$$

The polarization is not unequivocally defined for each ferromagnet, it depends on the experimental details and measurement method I. I. Mazin, PRL **83**, 1427-1430 (1999)

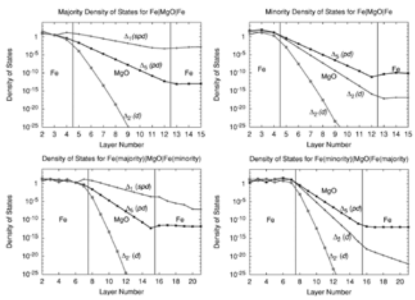


- From energy band calculations $P < 0$ for Ni and $P > 0$ for Fe
- Experimentally TMR > 0 for Ni-I-Fe and bias dependent
- Tunneling probability has to be taken into account (tunneling matrix)
- Current and tunneling mediated by free(s)-like electrons (s-electrons are more extended and move easily)
- Interface. Symmetry states

Stearns, J. Magn. Magn. Mat. **5**, 167 (1977)

Polarization
How is it defined?

Tunnelling conductance depends strongly on the symmetry of the Bloch states in the electrodes and of the evanescent states in the barrier layer Butler et al PRB (2000)



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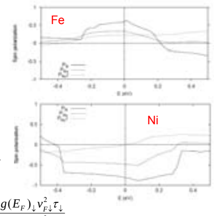
Photoemission experiments:
Density of states $P = \frac{g(E_F)_\uparrow - g(E_F)_\downarrow}{g(E_F)_\uparrow + g(E_F)_\downarrow}$

Tunnelling Transport
Matrix elements $P = \frac{g(E_F)_\uparrow |T_\uparrow|^2 - g(E_F)_\downarrow |T_\downarrow|^2}{g(E_F)_\uparrow |T_\uparrow|^2 + g(E_F)_\downarrow |T_\downarrow|^2}$

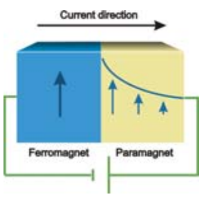
Ballistic transport
Weight with the Fermi velocity $P = \frac{g(E_F)_\uparrow v_{F\uparrow} - g(E_F)_\downarrow v_{F\downarrow}}{g(E_F)_\uparrow v_{F\uparrow} + g(E_F)_\downarrow v_{F\downarrow}}$

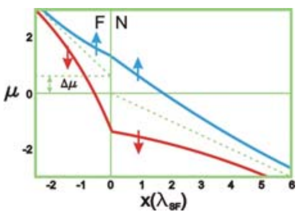
Diffusive transport
Weight with the Fermi velocity squared $P = \frac{g(E_F)_\uparrow v_{F\uparrow}^2 \tau_\uparrow - g(E_F)_\downarrow v_{F\downarrow}^2 \tau_\downarrow}{g(E_F)_\uparrow v_{F\uparrow}^2 \tau_\uparrow + g(E_F)_\downarrow v_{F\downarrow}^2 \tau_\downarrow}$



Spintronics
Spin generation and spin injection

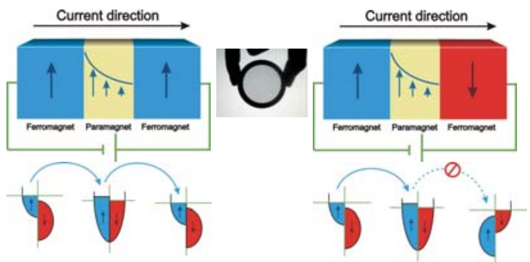
- Spin polarized current in a nonmagnetic metal
- Spin accumulation decays exponentially
- Characteristic length. Spin diffusion/relaxation length λ_{sf}





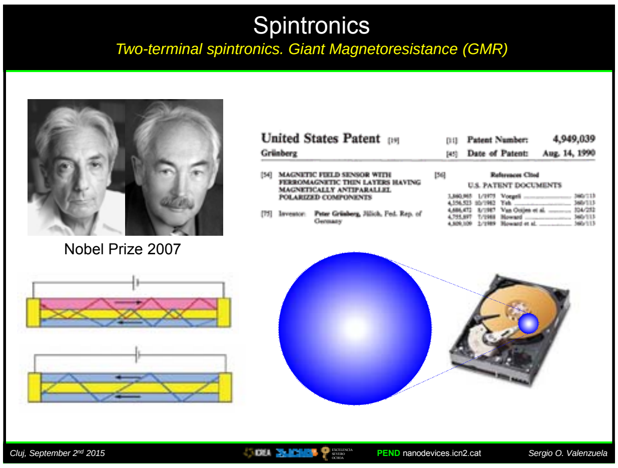
Johnson and Silsbee PRB **35**, 4959 (1987)
van Son et al., PRL **58**, 2271 (1987)

Spintronics
Two-terminal spintronics. Giant Magnetoresistance (GMR)



Parallel Magnetization, ↑↑
High conductance

Antiparallel Magnetization, ↑↓
Low conductance


Spintronics
Two-terminal spintronics. Giant Magnetoresistance (GMR)
Nobel Prize 2007
United States Patent
Grünberg
Patent Number: 4,949,039
Date of Patent: Aug. 14, 1990
MAGNETIC FIELD SENSOR WITH FERROMAGNETIC THIN LAYERS HAVING MAGNETICALLY ANTIPARALLEL POLARIZED COMPONENTS
Cluj, September 2nd 2015
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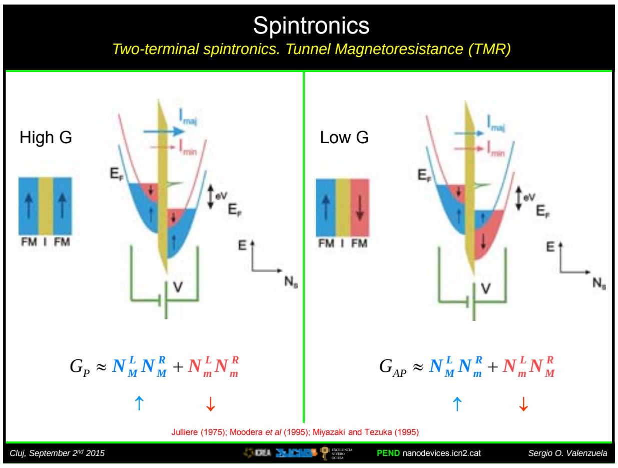
Spintronics
Two-terminal spintronics. Tunnel Magnetoresistance (TMR)
High G
Low G
FM I FM
I_{maj}
I_{min}
E_F
eV
E
N_s
V
$G_P \approx N_M^L N_M^R + N_m^L N_m^R$
$G_{AP} \approx N_M^L N_m^R + N_m^L N_M^R$
Julliere (1975); Moodera et al (1995); Miyazaki and Tezuka (1995)
Cluj, September 2nd 2015
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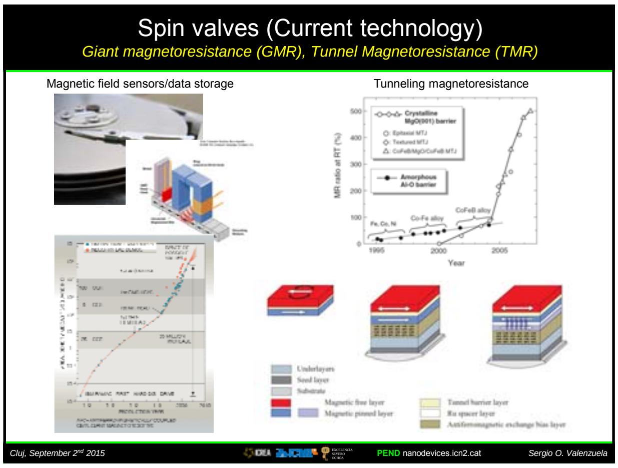
Spin valves (Current technology)
Giant magnetoresistance (GMR), Tunnel Magnetoresistance (TMR)
Magnetic field sensors/data storage
Tunneling magnetoresistance
MR ratio at RT (%)
Year
Crystalline MgO(001) barrier
Amorphous Al-O barrier
Fe, Co, Ni
Co-Fe alloy
CoFeB alloy
Underlayers
Seed layer
Substrate
Magnetic free layer
Magnetic pinned layer
Tunnel barrier layer
Ru spacer layer
Antiferromagnetic exchange bias layer
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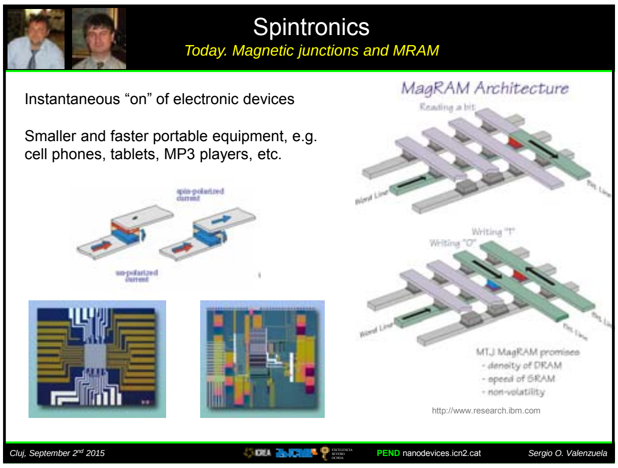
Spintronics
Today. Magnetic junctions and MRAM
Instantaneous “on” of electronic devices
Smaller and faster portable equipment, e.g. cell phones, tablets, MP3 players, etc.
spin-polarized current
un-polarized current
MagRAM Architecture
Reading a bit
Writing "1"
Writing "0"
MTJ MagRAM promises
- density of DRAM
- speed of SRAM
- non-volatility
http://www.research.ibm.com
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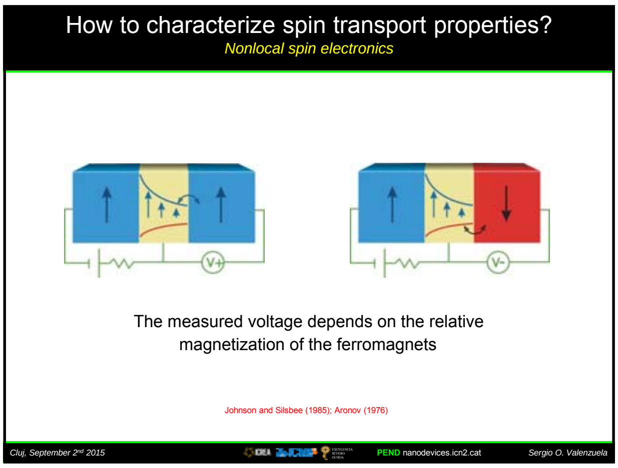
How to characterize spin transport properties?
Nonlocal spin electronics
V+
V-
The measured voltage depends on the relative magnetization of the ferromagnets
Johnson and Silsbee (1985); Aronov (1976)
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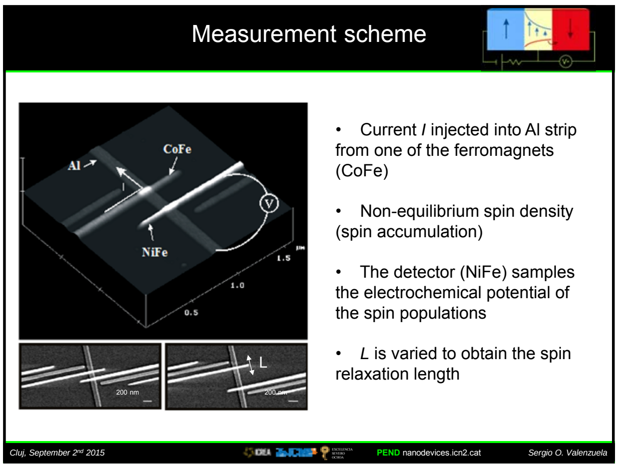
Measurement scheme
Al
CoFe
NiFe
I
V
L
200 nm
• Current I injected into Al strip from one of the ferromagnets (CoFe)
• Non-equilibrium spin density (spin accumulation)
• The detector (NiFe) samples the electrochemical potential of the spin populations
• L is varied to obtain the spin relaxation length
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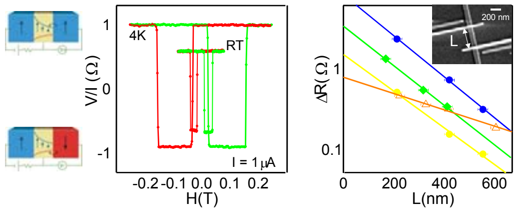
Spin relaxation, spin transfer through interfaces



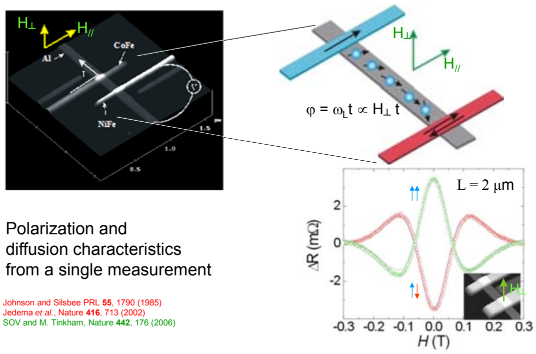
$$\frac{V_{\pm}}{I} = \pm\frac{1}{2} P_{CoFe} P_{NiFe} \frac{\lambda_{sf}}{\sigma_{Al} A} e^{-L/\lambda_{sf}}$$

SOV and M. Tinkham, APL **85**, 5914 (2004)
SOV, Int. J. Mod. Phys. B **23**, 2413 (2009)

4K: $P = (P_{NiFe}P_{CoFe})^{1/2}$ ~25%; λ_{sf} ~0.2-1 μm
Room T: P ~ 17%; λ_{sf} ~0.2-0.4 μm
Spin flip time

$$\left.\begin{aligned} \lambda_{sf} &= \sqrt{D\tau_{sf}} \\ \sigma &= e^2 N_{Al} D \end{aligned}\right\} \tau_{sf} \sim 50\text{ps at RT}$$

Spin precession



Polarization and diffusion characteristics from a single measurement

Johnson and Silsbee PRL **55**, 1790 (1985)
Jedema *et al.*, Nature **416**, 713 (2002)
SOV and M. Tinkham, Nature **442**, 176 (2006)

Nonlocal measurements in a wide range of materials

Spin transport in metals and through interfaces
- Johnson and Silsbee PRL **55**, 1790 (1985).
- Jedema et al., Nature (2001, 2002).
- T. Kimura, J. Hamrle, Y. Otani, K. Tsukagoshi and Y. Aoyagi, Appl. Phys. Lett. **85**, 3501 (2004).
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- D. Beckmann, H.B. Weber, and H.v. Löhneysen, Phys. Rev. Lett. **93**, 197003 (2004).
- M. Urech, J. Johansson, N. Poli, V. Korenivski, and D.B. Haviland, J. Appl. Phys. **99**, 08M513 (2006).

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- N. Tombros *et al.* Nature **448**, 571 (2007).

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- T. Kimura *et al.*, Nature Phys. **4**, 11 (2008).

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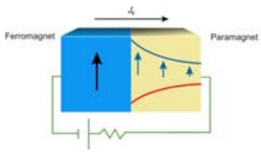
- S.O. Valenzuela, Int. J. Mod. Phys. B **23**, 2413 (2009).
- "*Spin Currents*" Oxford University Press (2012) Eds Maekawa, SOV, Saitoh and Kimura.

Spin currents and spin caloritronics

Thermal spin injection

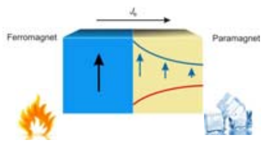


$$\begin{pmatrix} J_c \\ J_s \end{pmatrix} = \sigma \begin{pmatrix} 1 & P \\ P & 1 \end{pmatrix} \begin{pmatrix} \Delta\mu_c/e \\ \Delta\mu_s/e \end{pmatrix}$$

$$\begin{pmatrix} J_c \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & S \\ \Pi & \kappa/\sigma \end{pmatrix} \begin{pmatrix} \Delta V \\ -\Delta T \end{pmatrix}$$

$$S \propto T\left(\frac{\sigma'}{\sigma}\right) \quad \sigma' = \frac{\partial}{\partial E}\sigma\Big|_{E=E_F}$$

$\Pi = ST$ (Thomson relation)



$$\begin{pmatrix} J_c \\ J_s \\ J_Q \end{pmatrix} = \sigma \begin{pmatrix} 1 & P & S \\ P & 1 & P'S \\ ST & P'ST & \kappa/\sigma \end{pmatrix} \begin{pmatrix} \Delta\mu_c/e \\ \Delta\mu_s/e \\ -\Delta T \end{pmatrix}$$

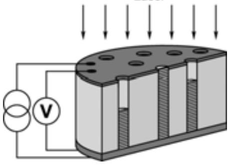
$$P = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad P' = \frac{\partial_\varepsilon\sigma^{\uparrow} - \partial_\varepsilon\sigma^{\downarrow}}{\partial_\varepsilon\sigma^{\uparrow} + \partial_\varepsilon\sigma^{\downarrow}}\Big|_{E_F}$$

M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987)

Spin-dependent thermoelectric effects in spin valves (2006)

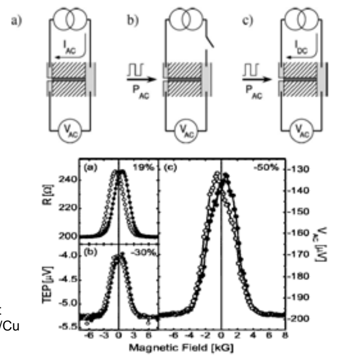
J. Shi, K. Pettit, *et al.* Phys. Rev. B (1996)
McCann, E. & Fal'ko, Appl. Phys. Lett. (2002).

thermoelectric power and thermal conductivity on granular and multilayer GMR systems

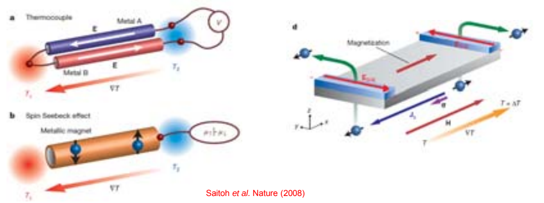


L. Gravier, S. Serrano-Guisan, *et al.*, Phys. Rev. B (2006)

Spin-dependent heat and charge transport perpendicular to the plane of magnetic Co/Cu multilayers. Peltier effect.



Spin Seebeck effect



Saitoh *et al.* Nature (2008)

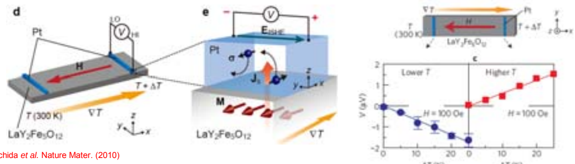
Original idea: two spin channels acting as the two distinct materials in a thermocouple. A temperature gradient should result in a spin voltage proportional to the temperature difference
Which can be detected by inverse spin Hall effect in Pt

Reviews: Bauer, MacDonald, Maekawa, Solid State Commun. (2010); Bauer in *Spin Current* (Oxford University Press, 2012)

Spin Seebeck effect

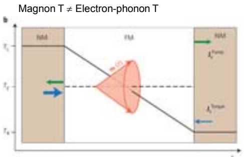
Basic mechanism

Spin Seebeck in insulators



Uchida *et al.* Nature Mater. (2010)

Magnon T ≠ Electron-phonon T



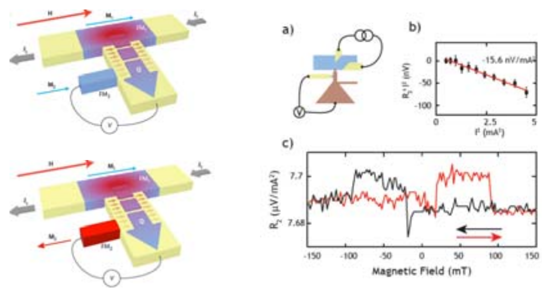
Spin pumping (SP) vs. Johnson-Nyquist noise

$$V_{ISHE} \propto J_S$$

$$J_S = J_S^{SP} - J_S^{J-N} = C(T_F^M - T_N^e)$$

Uchida *et al.* Nature Mater. (2010); Xiao *et al.*, Phys. Rev. B (2010); Bauer *et al.* Nature Mater. (2012)

Spin-dependent Seebeck effect



Slachter *et al.* Nature Phys. (2010)

Nonlocal measurements in a wide range of materials

Spin transport in metals and through interfaces

- Johnson and Silsbee PRL **55**, 1790 (1985).
- Jedema et al., Nature (2001, 2002).
- T. Kimura, J. Hamrle, Y. Otani, K. Tsukagoshi and Y. Aoyagi, Appl. Phys. Lett. **85**, 3501 (2004).
- SOV and M. Tinkham, Appl. Phys. Lett. **85**, 5914 (2004); Phys. Rev. Lett. (2005).
- Y. Ji, A. Hoffmann, J.S. Jiang, S.D. Bader, Appl. Phys. Lett. **85**, 6218 (2004).
- S. Garzon, I. Zutic, and R.A. Webb, Phys. Rev. Lett. **94**, 176601 (2005).
- SOV and M. Tinkham, Nature **442**, 176 (2006).
- Y. Ji, A. Hoffmann, J.E. Pearson, and S.D. Bader, Appl. Phys. Lett. **88**, 052509 (2006).
- R. Godfrey and M. Johnson, Phys. Rev. Lett. **96**, 136601 (2006).
- J.H. Ku, J. Chang, K. Kim, and J. Eom, Appl. Phys. Lett. **88**, 172510 (2006).
- N. Poli, M. Urech, V. Korenivski, and D.B. Haviland, J. Appl. Phys. **99**, 08H701 (2006).
- G. Bridoux, M. V. Costache, J. Van de Vondel, I. Neumann and SOV, Appl. Phys. Lett. (2011).

Zero dimensional structures

- M. Zaffalon, and B.J. van Wees, Phys. Rev. Lett. **91**, 186601 (2003).

Superconductors

- D. Beckmann, H.B. Weber, and H.v. Löhneysen, Phys. Rev. Lett. **93**, 197003 (2004).
- M. Urech, J. Johansson, N. Poli, V. Korenivski, and D.B. Haviland, J. Appl. Phys. **99**, 08M513 (2006).

Semiconductors

- X. Lou *et al.* ,Nat. Phys. **3**, 197 (2007); G. Salis *et al.*, Phys. Rev. B **81**, 205323 (2010), *ibid* **80**, 115332 (2009) .

Nanotubes/Graphene

- N. Tombros, S.J. van der Molen, and B.J. van Wees, Phys. Rev. B **73**, 233403 (2006).
- N. Tombros *et al.* Nature **448**, 571 (2007).

Spin torque by pure spin currents

- T. Kimura *et al.*, Nature Phys. **4**, 11 (2008).

Review

- S.O. Valenzuela, Int. J. Mod. Phys. B **23**, 2413 (2009).
- "*Spin Currents*" Oxford University Press (2012) Eds Maekawa, SOV, Saitoh and Kimura.

Spin current generation

Optical orientation

(Spin) angular momentum
Spin currents

Mechanical motion
Mechanical resonance
Non-uniform fluid flow

Magnetic materials
Metallic (carrier motion)
Insulator (tunneling filter, spin waves)
(Tedrow and Meservey 1971, Aronov 1976, Aronov and Pikus 1976)

Spin-orbit effects
Spin Hall and spin galvanic effects
(Dyakonov Perel 1971, Hirsch 1999, Murakami 2003, Sinova 2004, Ganichev 2003)

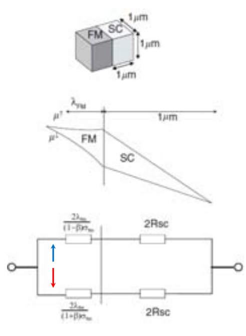
Nuclear spins
Overhauser/Feher effect
(Clark and Feher 1963)

Optical Orientation
(Kastler 1950, Lampel 1968, Meier Zakharchenya 1984)

Magnetization dynamics
Ferromagnetic resonance
Spin pumping

Conductance mismatch

Fundamental obstacle spin injection into a semiconductor



Schmidt et al 2000, 2005

The difference in electrochemical potential between spin-up and spin-down collapses within the spin relaxation length

The resistance contributing to the splitting of the potentials

$$R_{fm}^{\uparrow\downarrow} = \frac{2\lambda}{\sigma_{fm}(1 \pm \beta)}$$

Here β is the spin polarization (*P*) of the ferromagnet

Solutions:
1- add a high resistance in spin channels with a strong spin asymmetry
2- Use semiconducting FMs

Optical orientation/pumping

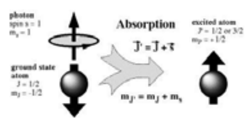
Spin injection by optical methods

Conservation of angular momentum

Photons of right or left polarized light have a projection of the angular momentum on the direction of their propagation (helicity) equal to +1 or −1, respectively (in units of ℏ)

Electron orbital momentum is oriented by light and through spin-orbit interaction electron spins become polarized

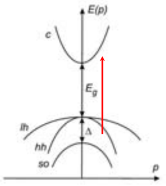
For the simple case of an atom/molecule



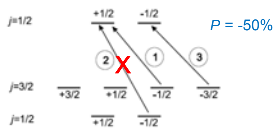
Optical orientation/pumping
Spin injection by optical methods

Circularly polarized photon absorbed in a semiconductor

Angular momentum distributed between the photo-excited electron and hole according to the selection rules determined by the band structure



Band structure of GaAs



Selection rules for interband transitions in GaAs

$E_g < \hbar\omega < E_g + \Delta$

average electron spin equal to (−1/2)(3/4) + (+1/2)(1/4) = −1/4
average hole spin equal to +5/4, with a sum +1

Optical orientation/pumping
Spin injection by optical methods

Circularly polarized photon absorbed in a semiconductor

Angular momentum distributed between the photo-excited electron and hole according to the selection rules determined by the band structure

First report in Si

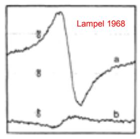
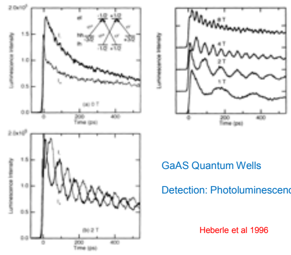


FIG. 1. Curve *a*: Signal proportional to the Si^{29} magnetization obtained in $H_0 = 1$ G after 21 h of irradiation with circularly polarized light at 77°K. Curve *b*: Signal proportional to the equilibrium Si^{29} magnetization in $H_0 = 6$ kG at 300 °K.



GaAS Quantum Wells

Detection: Photoluminescence

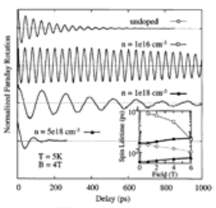
Heberle et al 1996

Optical orientation/pumping
Spin injection by optical methods

Circularly polarized photon absorbed in a semiconductor

Angular momentum distributed between the photo-excited electron and hole according to the selection rules determined by the band structure

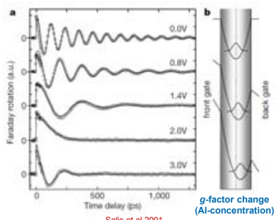
Dependence on doping concentration



Kikkawa and Awschalom 1998

Detection: Faraday Rotation

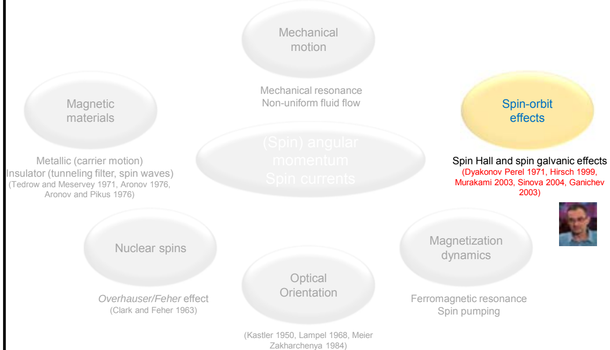
Electrical control of spin precession



g-factor change (Al-concentration)

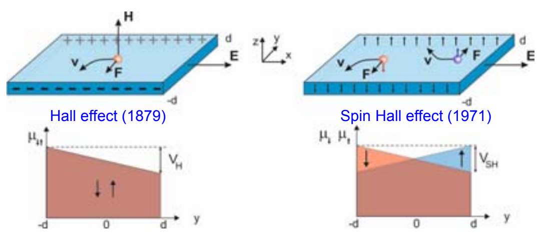
Salis et al 2001

Spin current generation
Spin Hall effects



Spin Hall Effects
Pure spin currents

The spin Hall effect has the symmetry of the conventional Hall effect

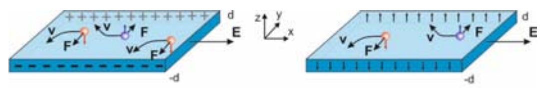


M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971); J.E. Hirsch, PRL **83**, 1834 (1999);
S. Zhang, PRL **85**, 393 (2000); S. Murakami, N. Nagaosa, S.C. & Zhang. Science **301**, 1348 (2003); J. Sinova, *et al.*, PRL **92**, 126603 (2004).

Spin Hall Effects
Pure spin currents

Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction

N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)



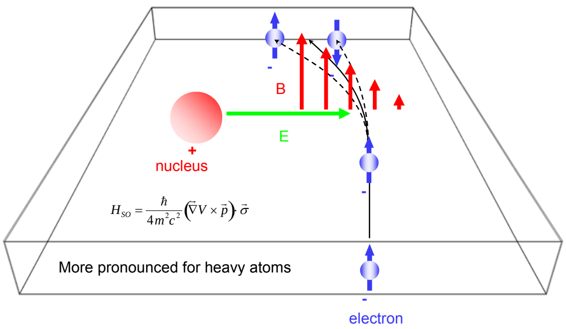
Anomalous Hall effect (1881)

Spin Hall effect

E.H. Hall, Phil . Mag. 12, 157 (1881)

M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971); J.E. Hirsch, PRL **83**, 1834 (1999)

Spin Hall Effects. Skew Scattering Case.
Pure spin currents

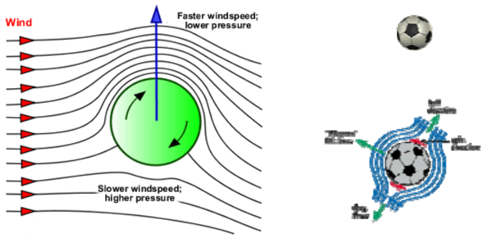


Axel Hoffmann, Argonne National Laboratory, US.

Spin Hall Effect Analogue
Magnus effect

Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction

N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)



Spin Hall Effects
Pure spin currents

Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction

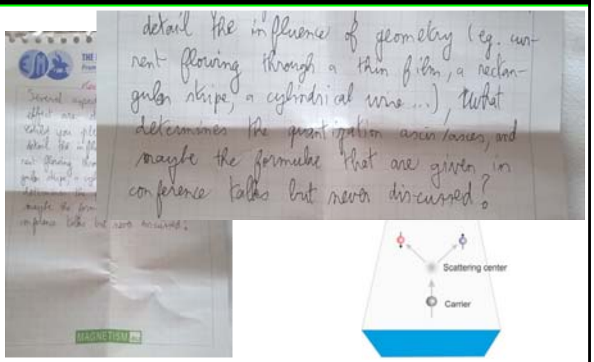
N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)

Spin Hall Effects
Pure spin currents

Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction

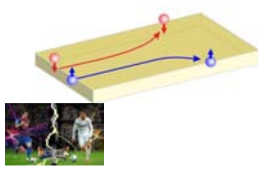
N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)

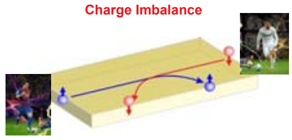
Spin Hall Effects
Question on quantization axis



Spin Hall vs. Inverse Spin Hall

Spin Hall		Inverse Spin Hall
Charge Current		Spin Current
⇓	Spin Dependent Scattering	⇓
Transverse Spin Imbalance		Transverse Charge Imbalance

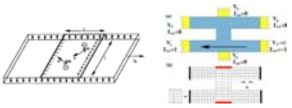




Spin Hall Effects
Observation and Measurement

"The orientation of the electrons in the spin layer can be detected by paramagnetic resonance, by the nuclear magnetization resulting from the Overhauser effect, and by the change produced in the surface impedance by the gyrotropy of the spin layer. In semiconductors the orientation can lead to circular polarization of the luminescence excited by the unpolarised light"

M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971); J.E. Hirsch, PRL **83**, 1834 (1999).

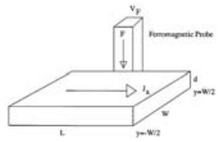


A current generates a spin imbalance trough the spin Hall effect in an Al strip

The spin imbalance drives a spin current which generates a voltage in a second Al strip

Second order effect

J.E. Hirsch. PRL **83**, 1834 (1999). Hankiewicz et al PRB (2004)
A.A. Bakun *et al.*, Sov. Phys. JETP Lett. **40**, 1293 (1984).

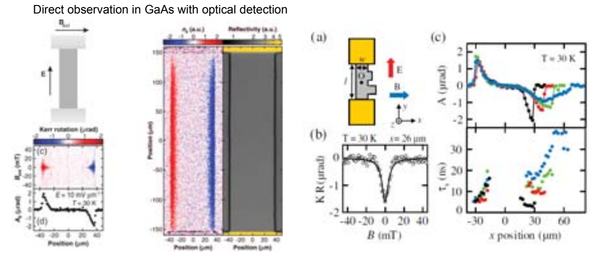


S.F. Zhang. PRL **85**, 393 (2000).

Spin Hall Effects
Observation: Kato et al and Wunderlich et al (2004)

Magneto-optical Kerr microscopy (semiconductors both bulk and 2DEG)

Direct observation in GaAs with optical detection



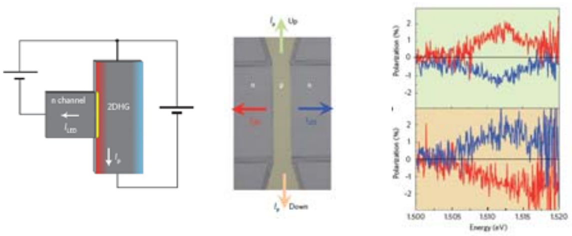
Change in polarization and intensity of light reflected from a magnetized surface (magnetic dependence of the permittivity tensor)

Y. K. Kato *et al.*, Science **306**, 1910 (2004)

Sih *et al.*, PRL (2006)

Spin Hall Effects
Observation

Circularly polarized electroluminescence (2DEG)

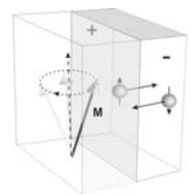


Wunderlich *et al.*, PRL (2005); Jungwirth et al, Nature Materials (2012)

Inverse Spin Hall Effect
Observation in Metals

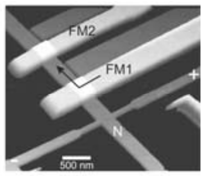
Inverse spin Hall effect as a spin current measurement detection mechanism

Spin current by spin pumping



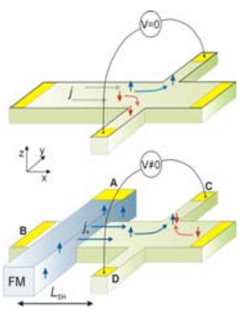
E. Saitoh *et al.*, APL (2006)

Spin current by electrical injection from FM

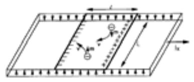


SOV *et al.* Nature (2006)

Spin Hall effect. Electronic detection



J.E. Hirsch. PRL **83**, 1834 (1999).
A.A. Bakun *et al.*, Sov. Phys. JETP Lett. **40**, 1293 (1984).



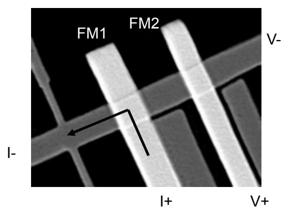
A current generates a spin imbalance trough the spin Hall effect in an Al strip

The spin imbalance drives a spin current which generates a voltage in a second Al strip

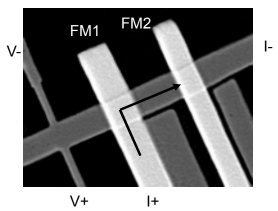
Second order effect

Measurement schemes

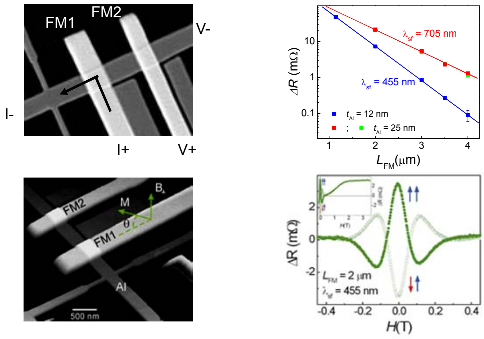
Johnson-Silsbee



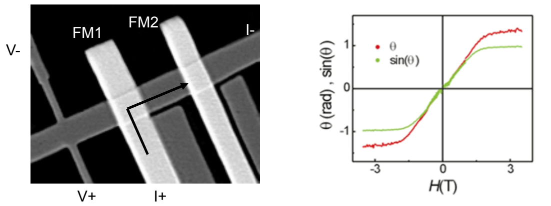
Spin Hall effect



Nonlocal spin detection. Spin precession
Jonhson-Silsbee



Inverse Spin Hall effect

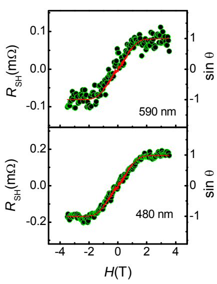


$V/I = R_{SH} = (1/2)\,\Delta R_{SH} \sin\theta$

$\Delta R_{SH} = 2(P\,\sigma_{SH} / t_{Al}\,\sigma_c^2)\exp[-L_{SH}/\lambda_{sf}]$

Zhang, S. PRL **85**, 393 (2000)
S. Takahashi *et al.*, Chapter 8 in *Concepts in spin electronics* (Oxford Univ. Press, 2006)

Inverse Spin Hall effect



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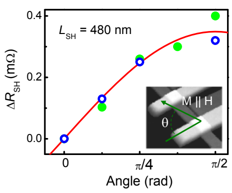
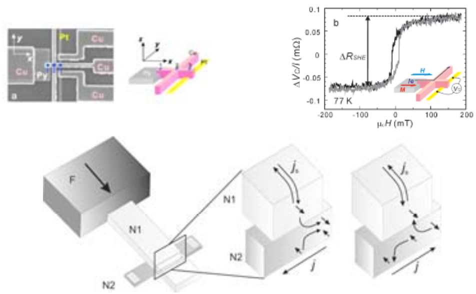


SOV and M. Tinkham, Nature **442**, 176 (2006), J. Appl. Phys. **101**, 09B103 (2007)

Inverse and Direct Spin Hall effect

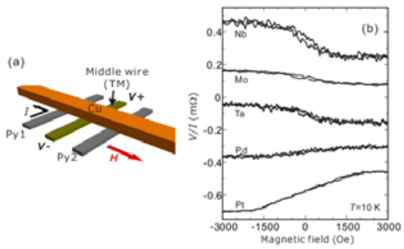
Spin Hall cross adapted for materials with short spin relaxation length



T. Kimura *et al.*, Vila *et al* PRL (2007)

Inverse and Direct Spin Hall effect

Spin Hall cross adapted for materials with short spin relaxation length

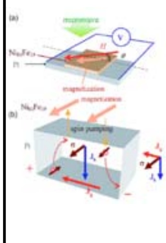


Morota et al *Phys. Rev. B*, **83**, 174405 (2011)

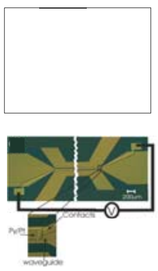
Inverse Spin Hall Effect
Observation in Metals

Inverse spin Hall effect as a spin current measurement detection mechanism

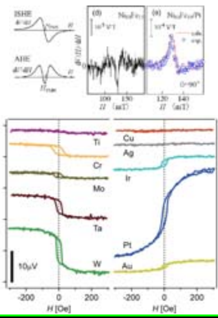
Spin current by spin pumping



E. Saitoh *et al.*, APL (2006)



Mosendz *et al.*, PRL and PRB (2010)



Inverse Spin Hall Effect

Observation in Metals

Spin Hall angle comparison

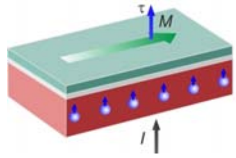
	λ_N (nm)	σ_N $(\Omega cm)^{-1}$	η_{sc}	α_{SH} (%)	Ref.
Al (4.2K)	455 ± 15	1.05 ×10^5	0.0079	0.032 ± 0.006	[9, 11]
Al (4.2K)	705 ± 30	1.70 ×10^5	0.0083	0.016 ± 0.004	[9, 11]
Au (295K)	86 ± 10	3.70 ×10^5	0.3	11.3	[49]
Au (295K)	35 ± 3*	2.52 ×10^5	0.52	0.35 ± 0.03	[56]†
CuIr (10K)	5 – 30			2.1 ± 0.6	[61]
Mo (10K)	10	3.03 ×10^4	0.32	−0.20	[69]
Mo (10K)	10	6.67 ×10^3	0.07	−0.075	[69]
Mo (10K)	8.6 ± 1.3	2.8 ×10^6	0.34	−(0.8 ± 0.18)	[53]
Mo (295K)	35 ± 3*	4.66 ×10^4	0.14	−(0.05 ± 0.01)	[56]†
Nb (10K)	5.9 ± 0.3	1.1 ×10^6	0.14	−(0.87 ± 0.20)	[53]
Pd (295K)	9*	1.97 ×10^4	0.23	1.0	[68]†
Pd (10K)	13 ± 2	2.2 ×10^6	0.18	1.2 ± 0.4	[53]
Pd (295K)	15 ± 4*	4.0 ×10^6	0.28	0.64 ± 0.10	[56]†
Pt (295K)		6.41 ×10^4	0.74	0.37	[10]
Pt (5K)	14	8.0 ×10^6	0.61	0.44	[12]
Pt (295K)	10	5.56 ×10^4	0.58	0.9	[12]
Pt (10K)	11 ± 2	8.1 ×10^6	0.77	2.1 ± 0.5	[53]
Pt (295K)	7*	6.4 ×10^6	0.97	8.0	[55]†
Pt (295K)	3 – 6	5.0 ×10^6	0.88-1.75	$7.6^{+8.4}_{-2.0}$	[57]†
Pt (295K)	10 ± 2*	2.4 ×10^6	0.25	1.3 ± 0.2	[56]†
Ta (10K)	2.7 ± 0.4	3.0 ×10^5	0.17	−(0.37 ± 0.11)	[53]

Spin Current, Maekawa, SOV, Saitoh, Kimura Eds (Oxford University Press, 2012); Siniva, SOV, Wunderlich, Back, Jungwirth, arXiv:1411.3249

Spin torque by filtering or spin Hall effect

Efficiency

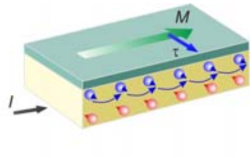
Spin transfer torque by spin filtering



Torque ~ J_s = J *Polarization

J = I / Transverse Area

Spin transfer torque by SHE



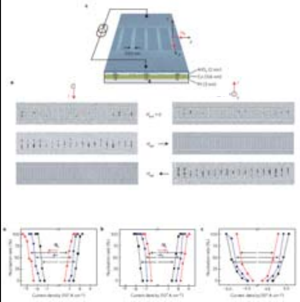
Torque ~ J_s = J * Θ_{SH}

J = I / Longitudinal Area

Spin Orbit Torques

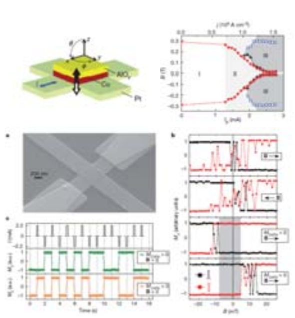
Spin Orbit Torques: Rashba vs Spin Hall effect

Nucleation of Domain Walls



Miron *et al* Nature Mater. (2010)

Magnetization Switching

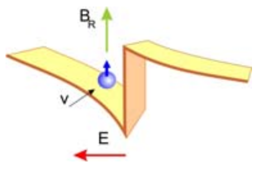


Miron *et al* Nature (2011)

Spin Orbit Torques

Spin Orbit Torques: Rashba vs Spin Hall effect

For example: Pt/Co - AlOx



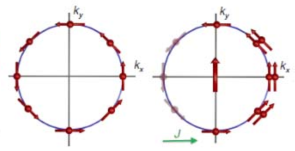
$$H_R = \alpha_r \mathbf{s} \cdot (\hat{\mathbf{z}} \times \mathbf{p})$$

Rashba field: *Effective field* has a fixed direction, no anti-damping

Spin Hall: *Spin torque* can result in antidamping

To manipulate the magnetization, Rashba field has to be similar to coercive field

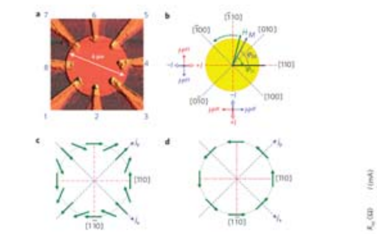
Spin Hall only requires that the torque compensates the damping

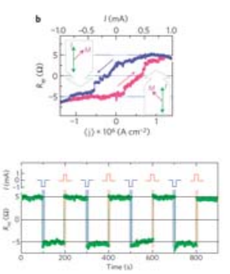


Spin Orbit Torques

Spin Orbit Torques

Ferromagnetic Semiconductor with Zinc-Blende symmetry Ga,Mn)As





$\mathcal{H}_{so} = (\hbar/2)\hat{\sigma} \cdot \mathbf{\Omega}(\mathbf{k})$

$\mathbf{\Omega}_D \propto k^3$ Zinc-blende (GaAs) Dresselhaus term

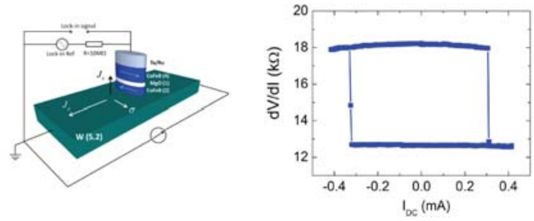
$\mathbf{\Omega}_\varepsilon = C\Delta\varepsilon(k_x, -k_y, 0)$ Strain

$\mathbf{\Omega}_R = \alpha_R(-k_y, k_x, 0)$ Rashba

Chernyshov *et al* Nature Phys. (2009)

Spin Orbit Torques

Spin Orbit Torques: Rashba vs Spin Hall effect



Results consistent with SHE

Spin Hall angle of W is found to be about 0.3, in Ta 0.15.

Switching currents are predicted below 50 uA

Liu *et al* Science (2012)