European School on Magnetism, Cluj 2015

From Basic Magnetic Concepts To Spin Currents (Introduction)

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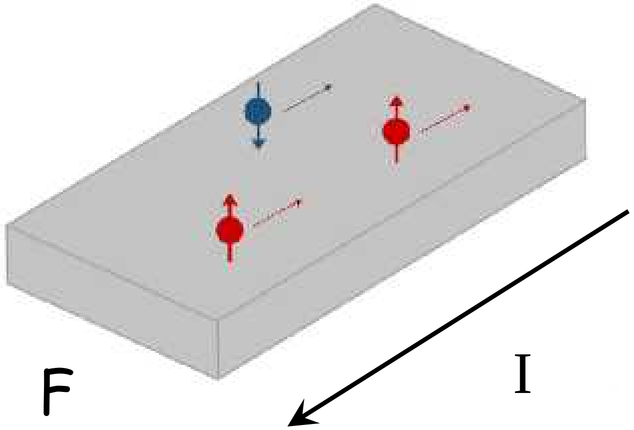
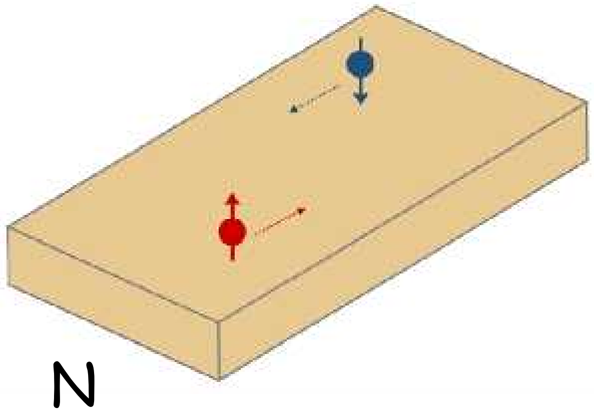
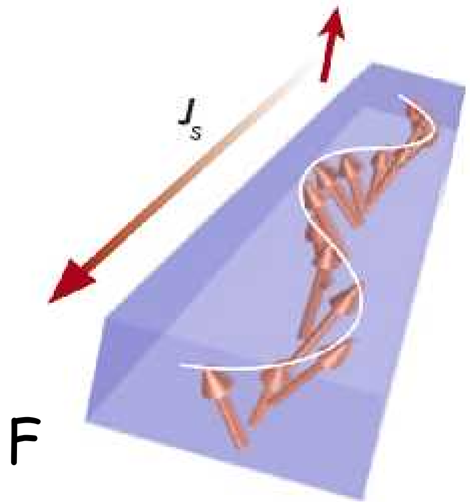


Spin-polarised current



Pure spin current

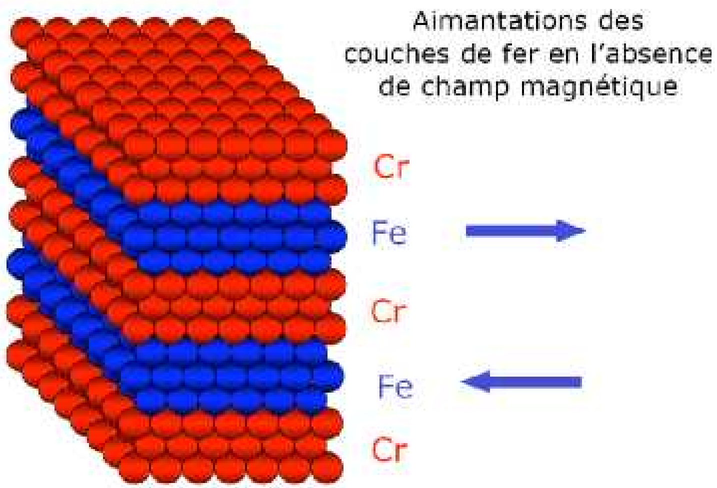


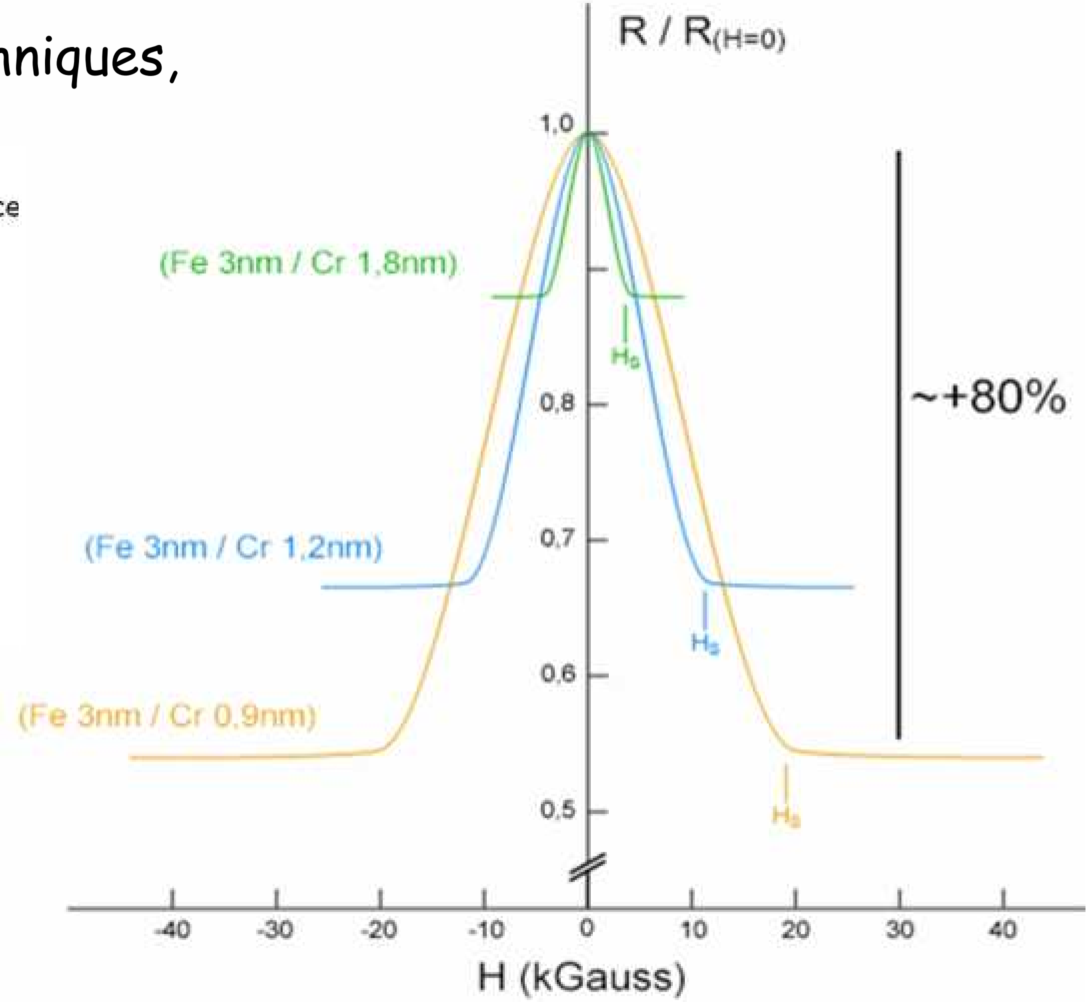
Spin waves

The discovery of Giant Magnetoresistance

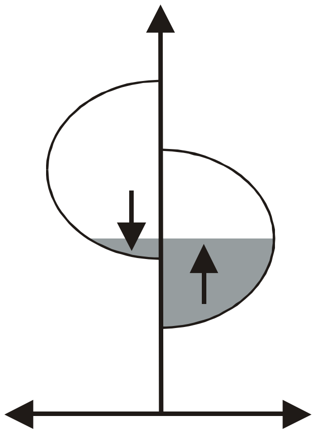
M. N. Baibich et al., Phys. Rev. Lett. **61**, 2472 (1988), A. Fert, P. Grunberg Nobel prize 2007

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



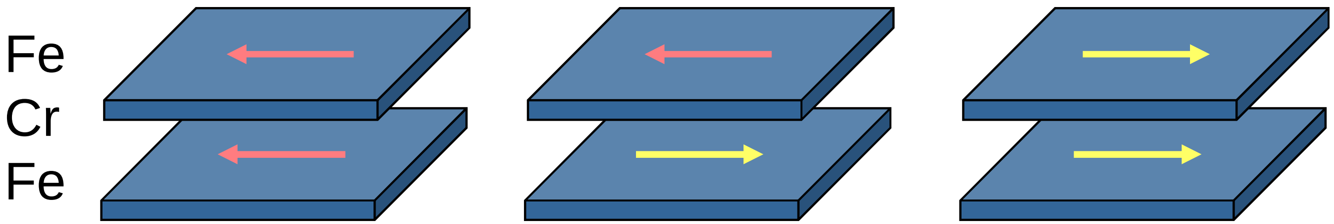


⊕ Spin dependent conduction



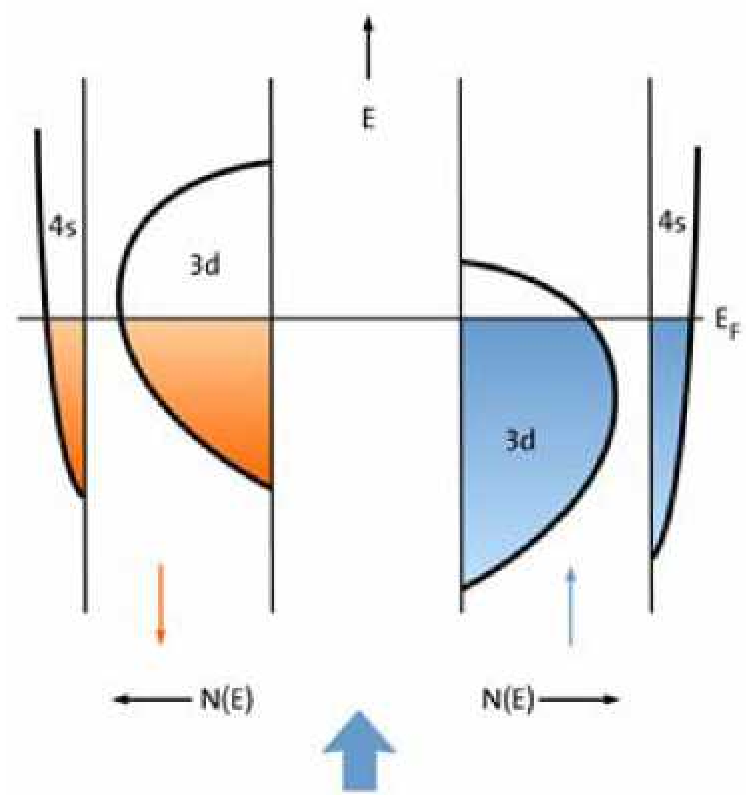
$$\sim = \frac{\circ_{\uparrow}}{\circ_{\downarrow}} \neq 1$$

⊕ Antiferromagnetc coupling -> anti-parallel state

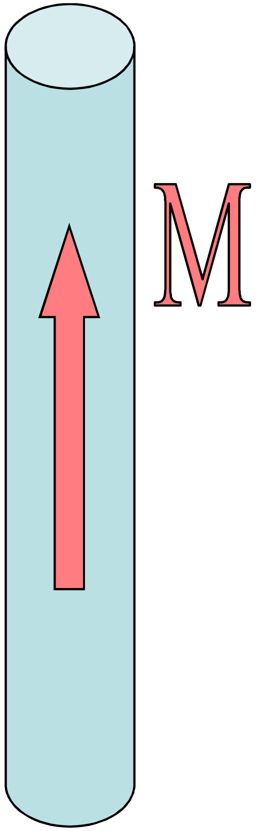


Band structure : ferromagnetism and transport

Density of states



Magnetic order



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

Spin dependent conductivity

$$\sigma = \sigma_\uparrow + \sigma_\downarrow$$

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

Asymétrie

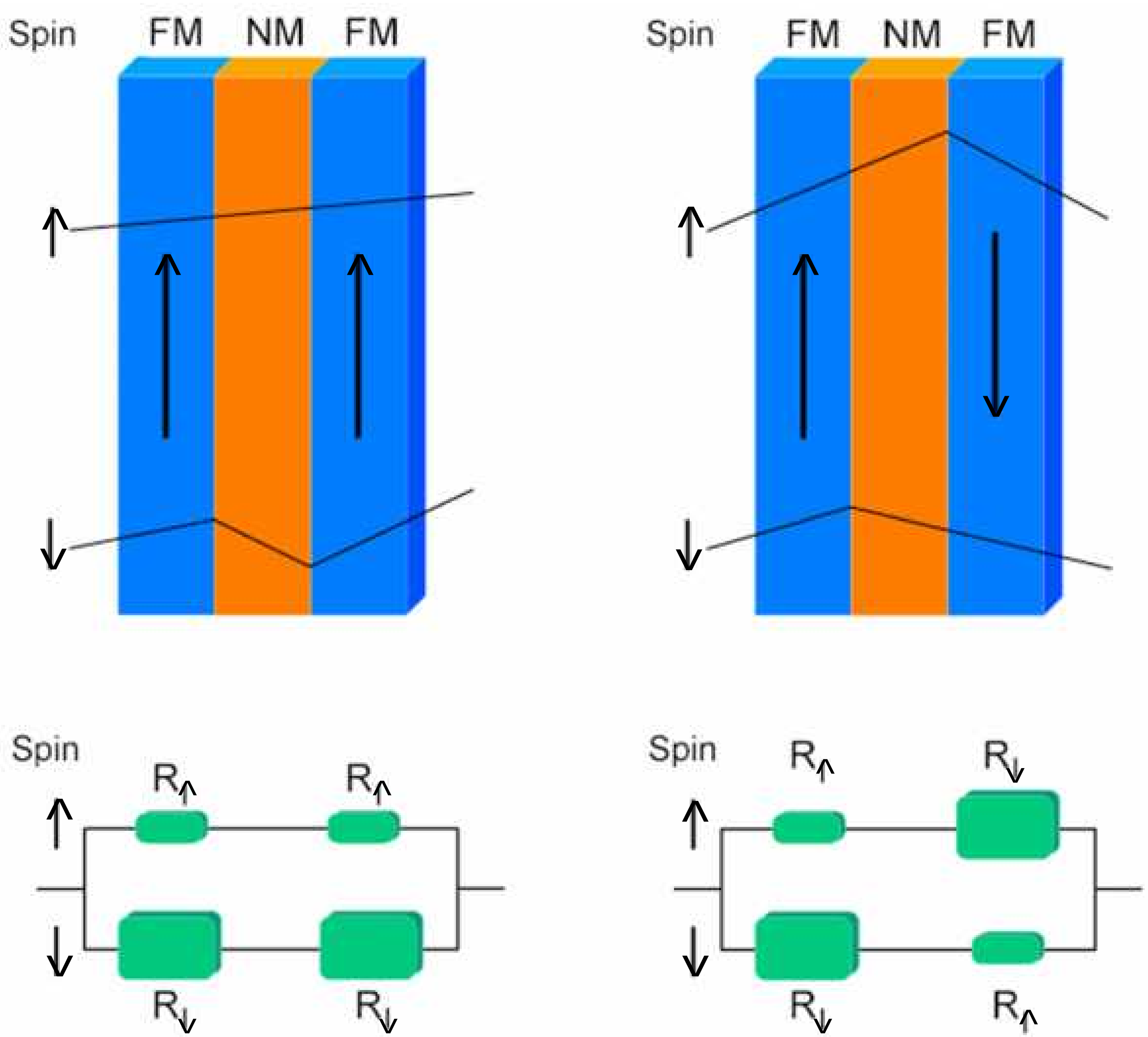
$$\alpha = \frac{\rho_\downarrow}{\rho_\uparrow}$$

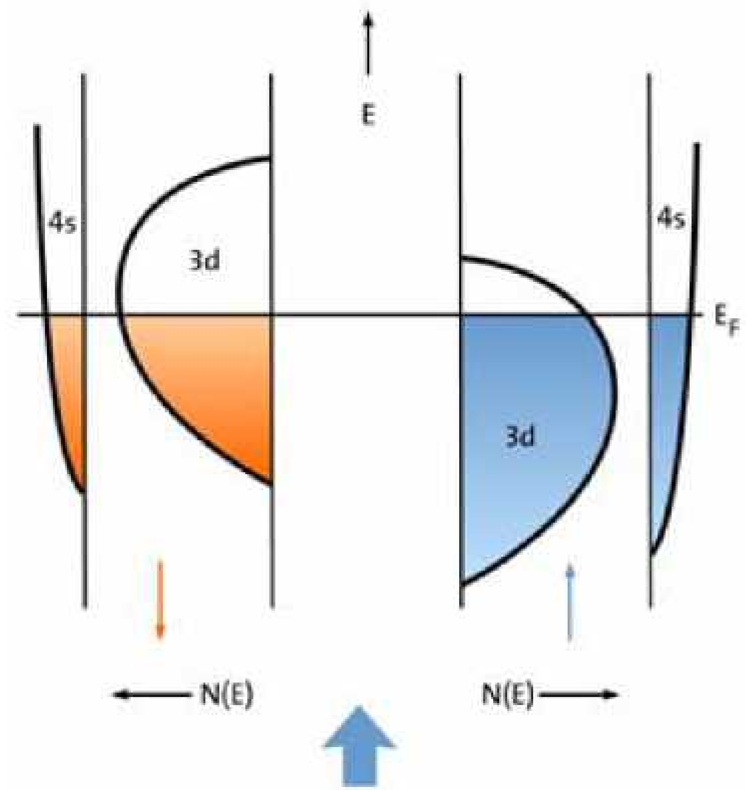
Polarisation

$$p_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

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

Modeling





$$\sim = \frac{\circ_\uparrow}{\circ_\downarrow} \neq 1$$

$$\ell_{sf}$$

$$R(P) = \frac{2R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow} \qquad R(AP) = \frac{R_\uparrow + R_\downarrow}{2}$$

2 CSRM then CPP-GMR model Valet & Fert, PRB 93'

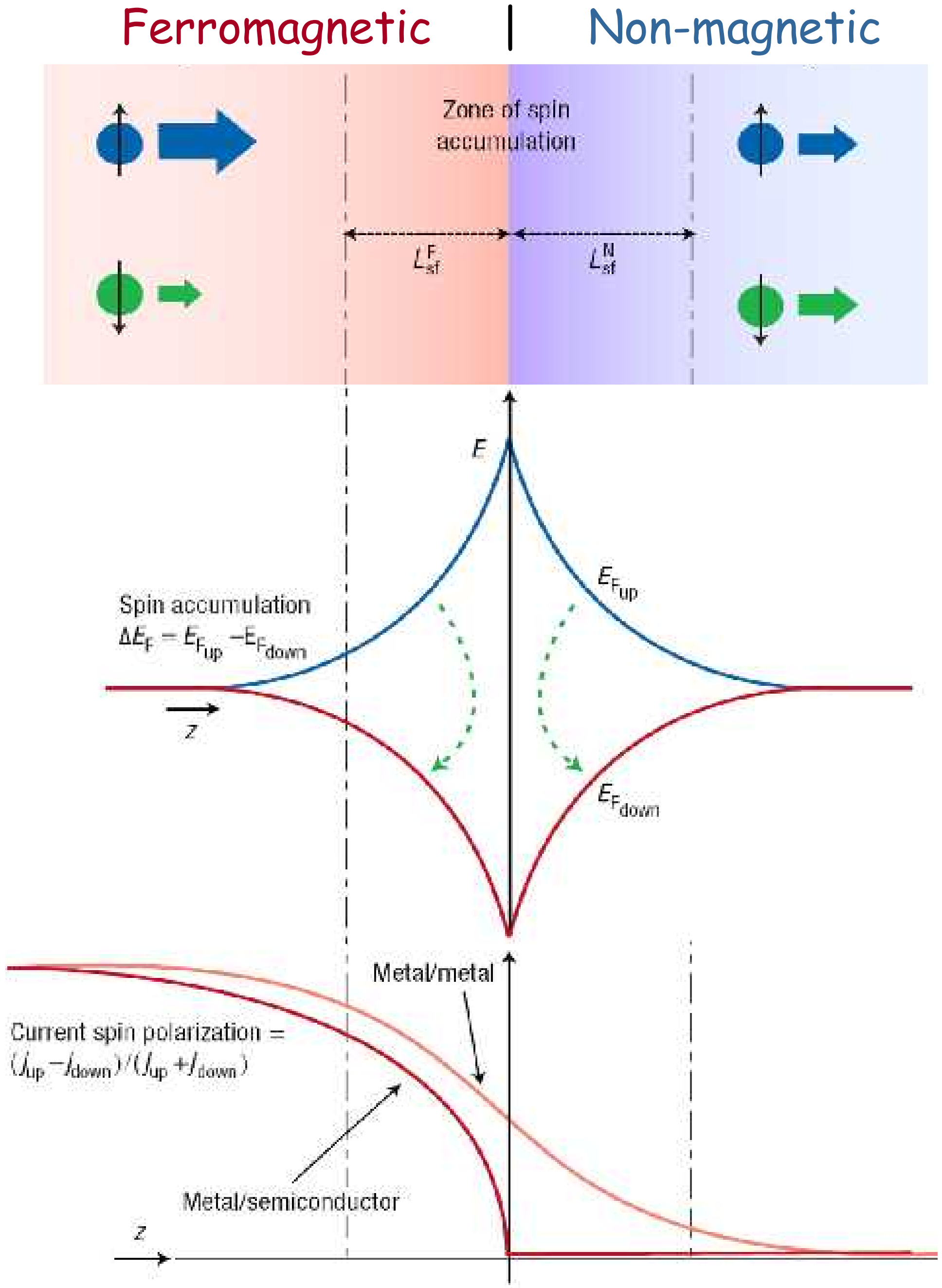
Spin injection at F/ NM interface

Spin dependent current density

$$j_{\uparrow}^{F} \neq j_{\downarrow}^{F}$$

Electrochemical potential

Current polarisation



$$j_{\uparrow}^{N} = j_{\downarrow}^{N}$$

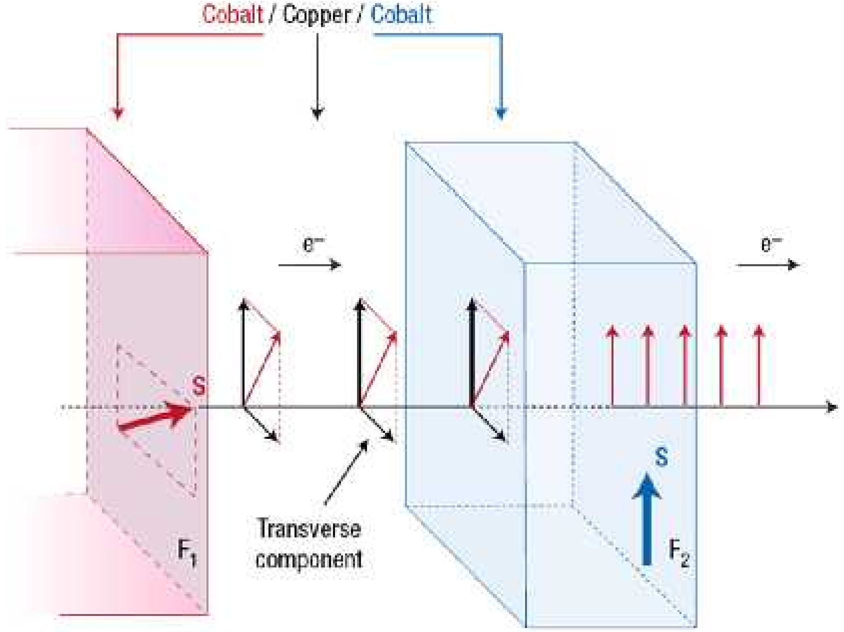
Characteristic length

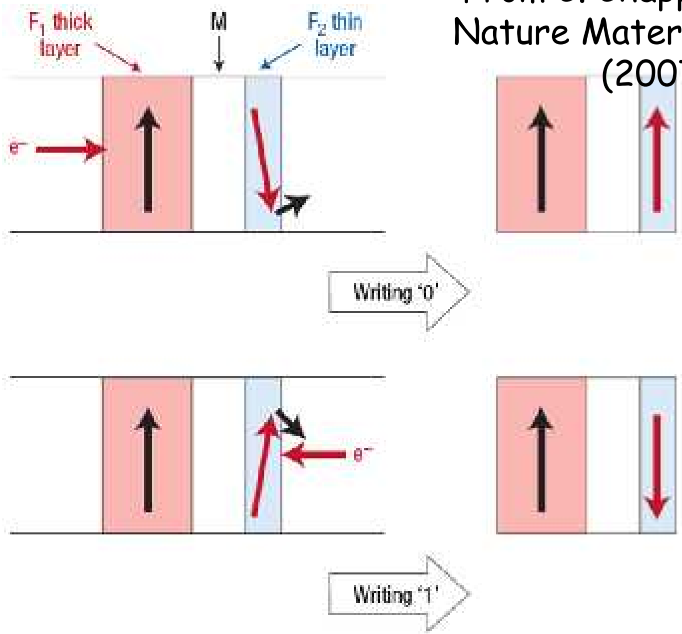
$$\ell_{sf}^{N(F)}$$

Spin diffusion length

From C. Chappert, A. Fert, and F. Van Dau, Nature Materials **6**, 813 (2007)

Magnetization manipulation by spin current





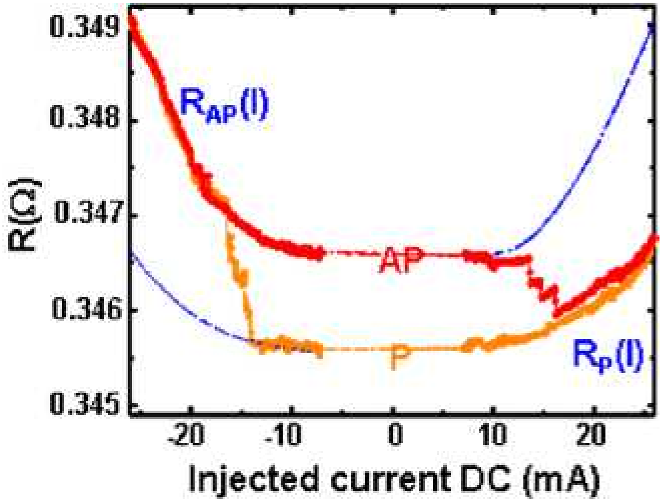
From C. Chappert, et al, Nature Materials **6**, 813 (2007)

Spin transfer torque

J. Slonczewski JMMM 1996

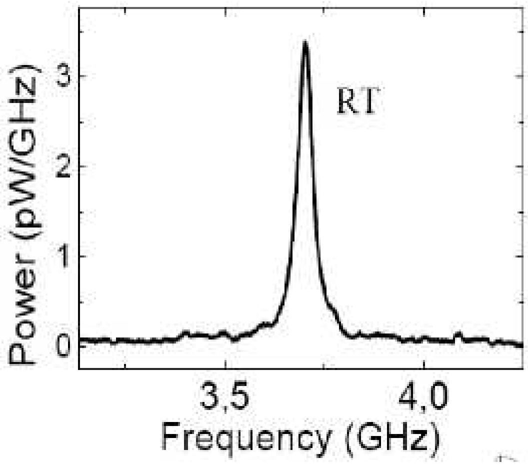
L. Berger PRB 1996

Magnetization reversal
(electrical commutation)



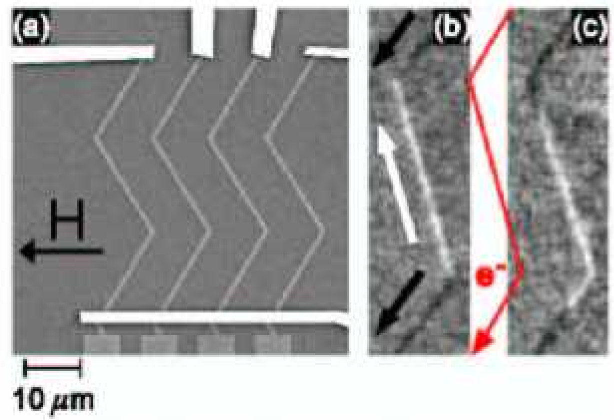
J. Grollier, APL 78 (2001)

Precessional regime
(HF emission)



O. Boule, Nat. Phys. (2007)

Domain wall displacement
(memories)

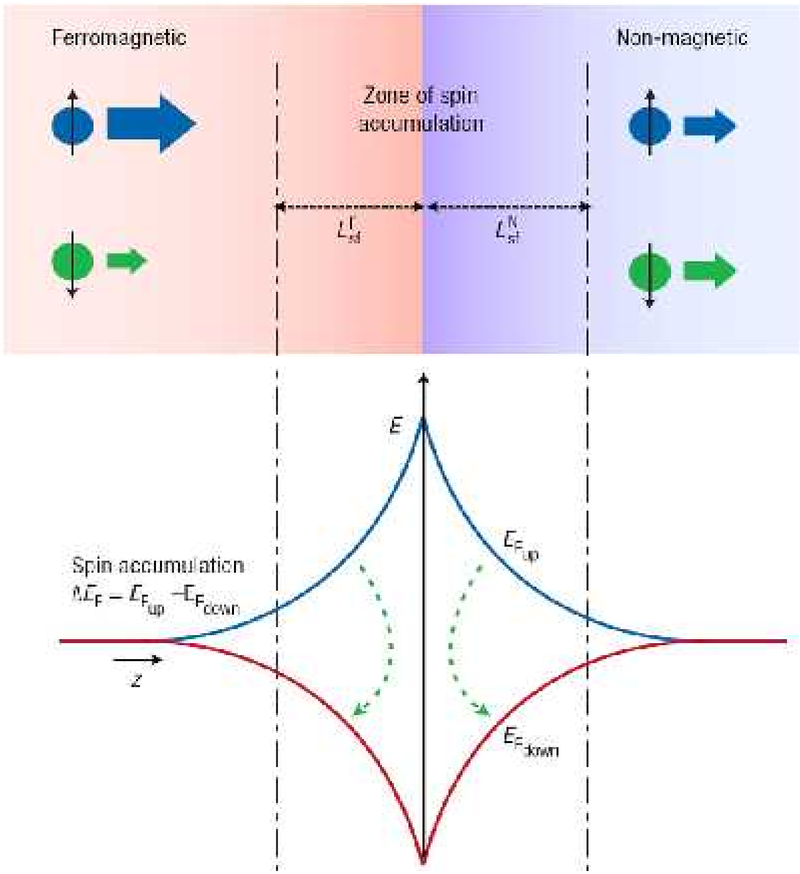


M. Klaeui, PRL 95 (2005)

Charge to Spin current conversion

at Ferromagnetic | Non-magnetic interfaces

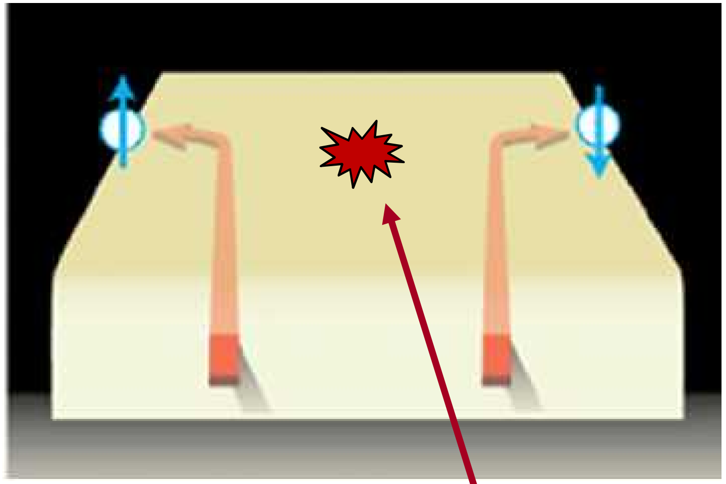
Lead to GMR effect and spin transfert Torque



By charge current injection
Spin pumping
Heat gradient,…

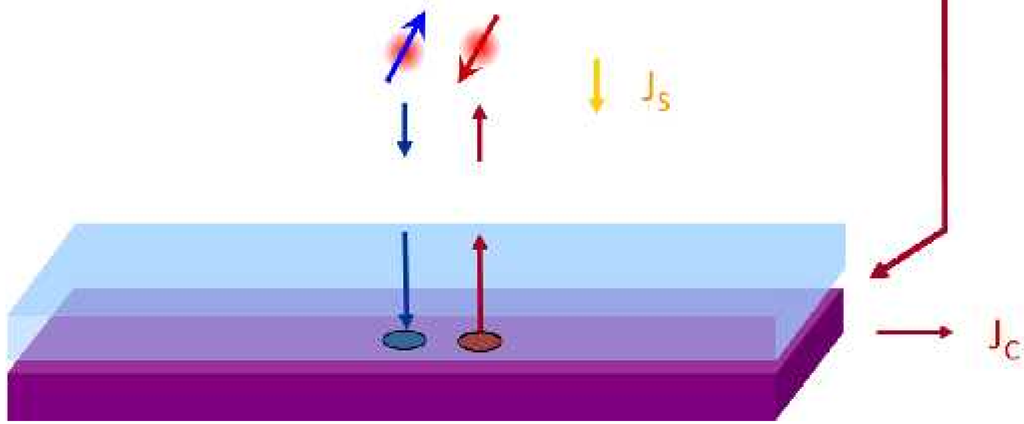
by Spin Orbit Coupling:

- Spin Hall Effect



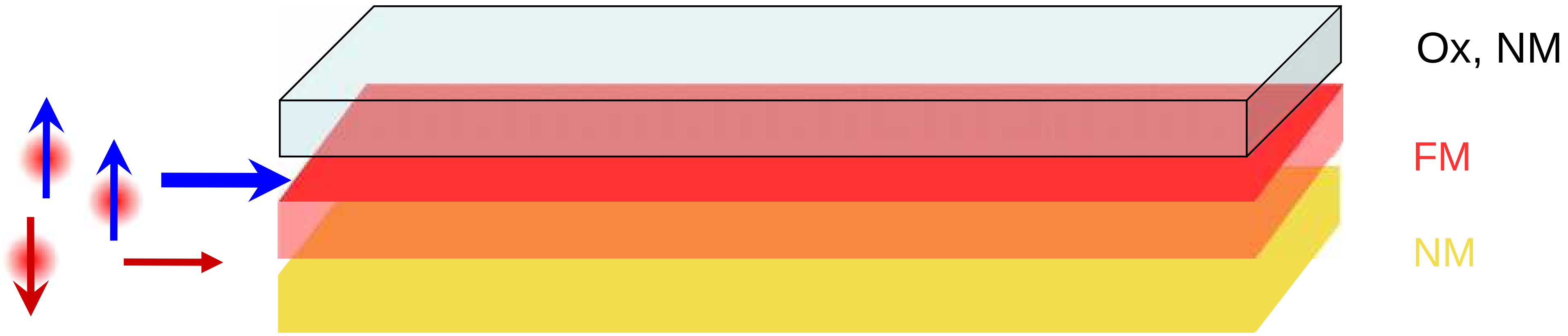
Localized Spin-Orbit interaction

- Rashba-Edelstein Effect



Spin Orbit effects in

Ferro-Magnetic / Non-Magnetic tri-layers



$Pt/Co/Al_2O_3$, 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)

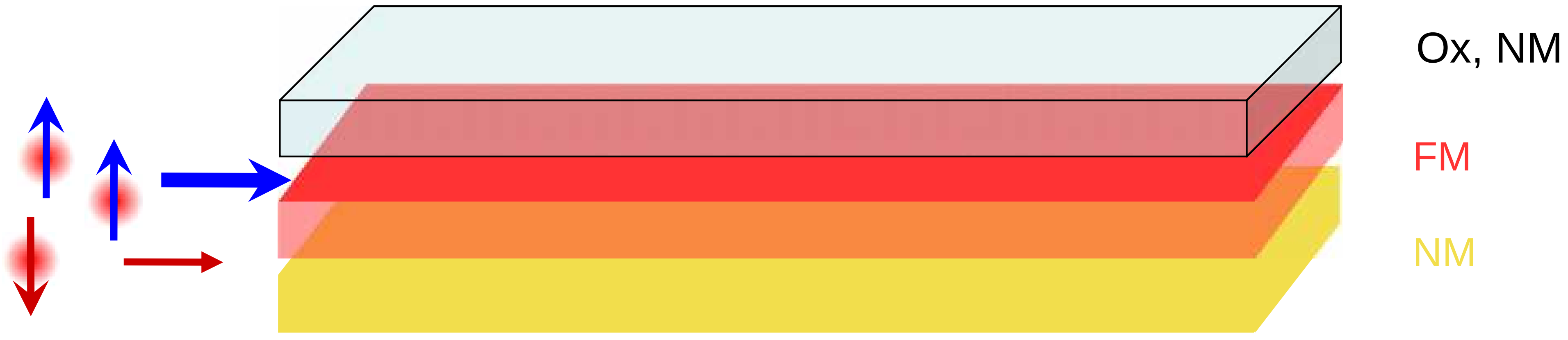
Spintec, Cornell, Tohoku, IBM, Kyoto,… very active field of research

SOT + DMI

Miron et al Nature 2011, Liu et al Science 2012, Emori et al Nat. Mat., Ryu et al Nat. Nano. 2013,…

Spin Orbit effects in

Ferro-Magnetic / Non-Magnetic tri-layers



Pt/Co/Al_2O_3, Ta/CoFeB/MgO, Pt(t)/Co(/Ni)/P(t)….

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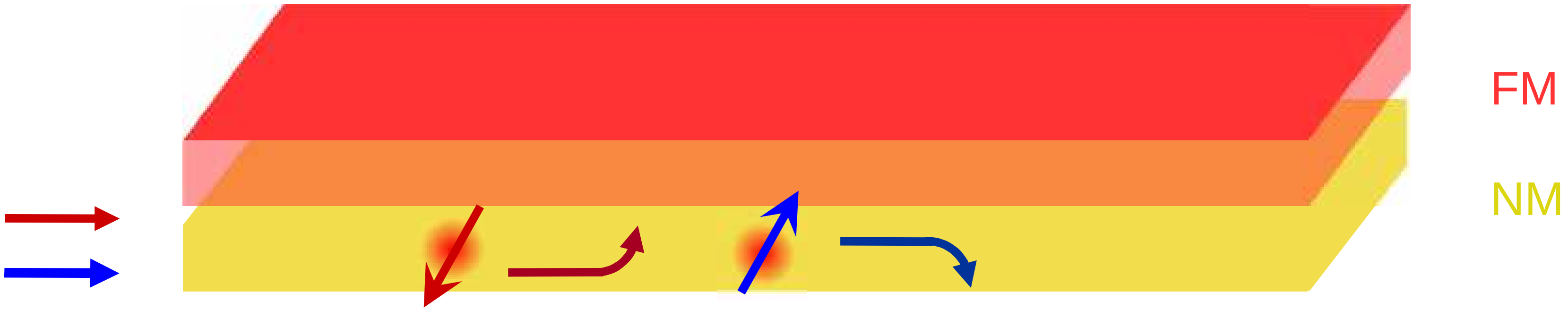
SOT + DMI

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



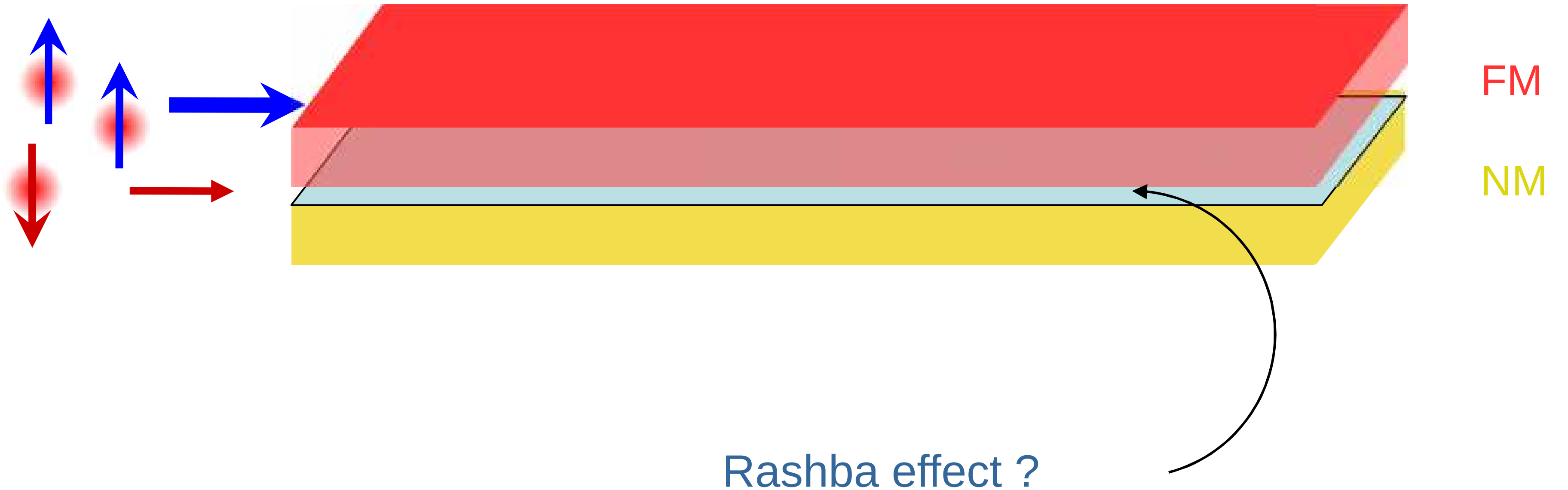
Spin Hall effect

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

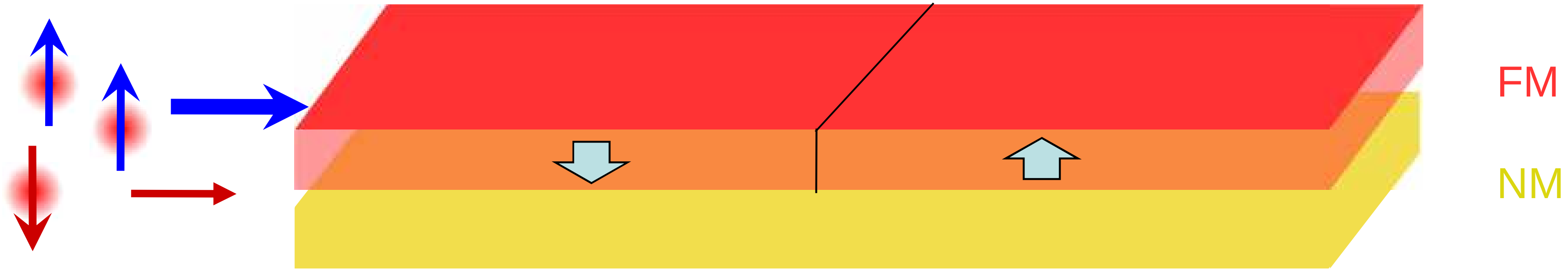


Rashba effect ?
Spin momentum lock-in at Rashba interfaces
and Topological Insulator

Rashba-Edelstein effect

Spin Orbit effects in

Ferro-Magnetic / Non-Magnetic bi-layers

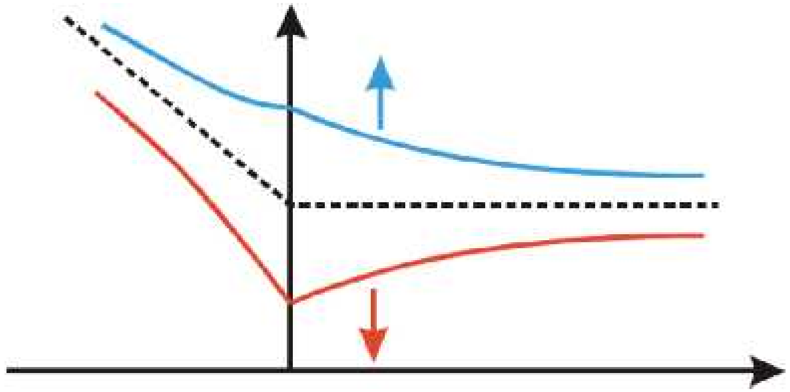


Spin currents in presence of Domain walls

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

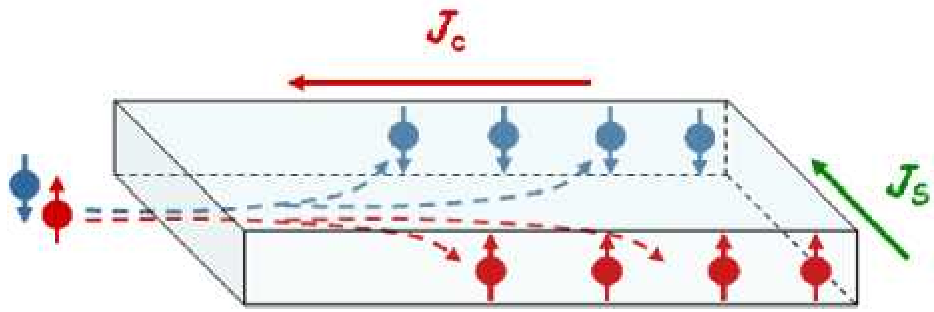
Spin current induced by

FM/NM junction



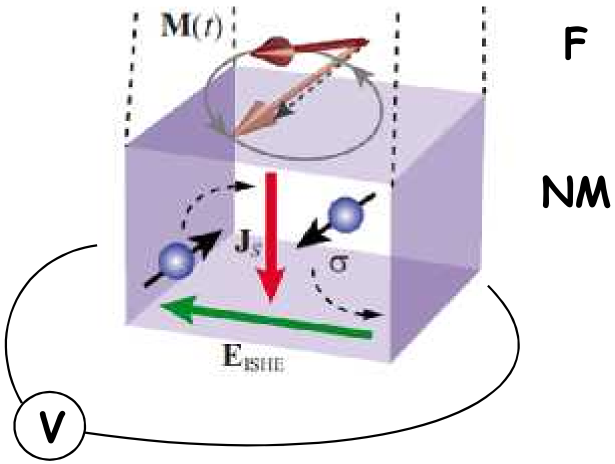
Johnson, Silsbee 1985, Jedema 2001

Spin Orbit Coupling



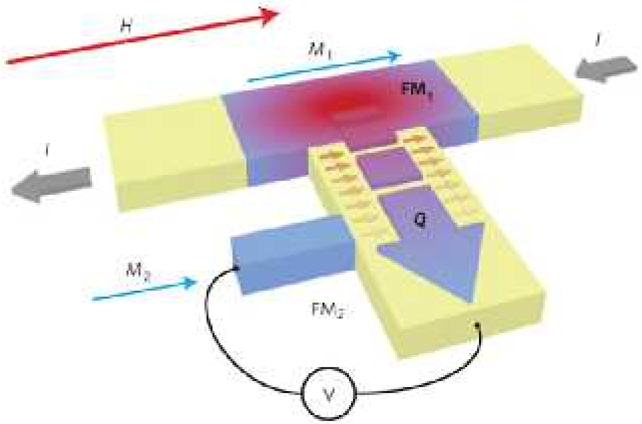
Spin Hall and Rashba effects

Spin Pumping



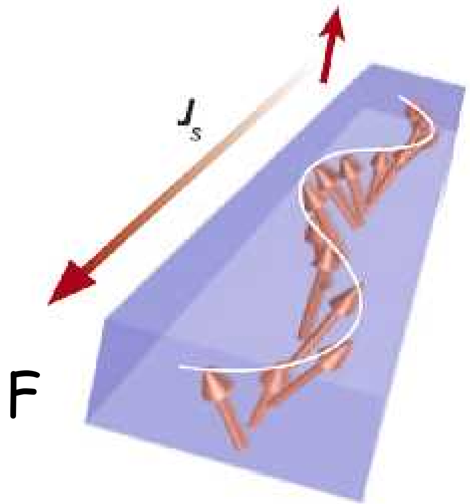
Silsbee, Monod 1979, Tserkovnyak, Bauer 2002
Saitoh 2006

Thermal Spin Injection



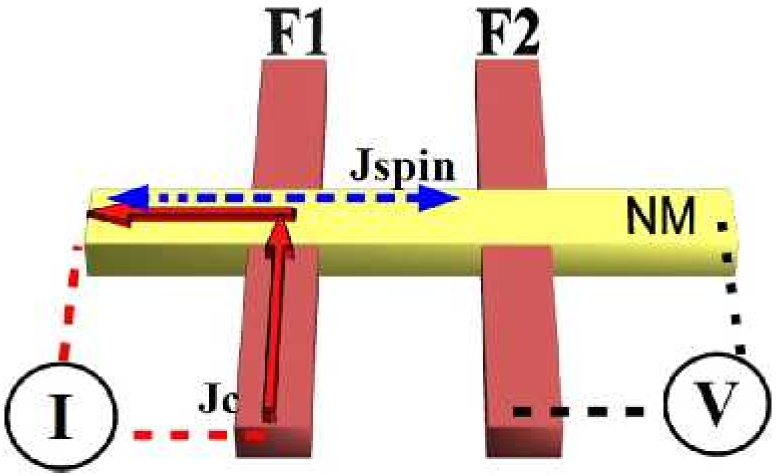
A.Slachter et al. Nat. Phys. 2010

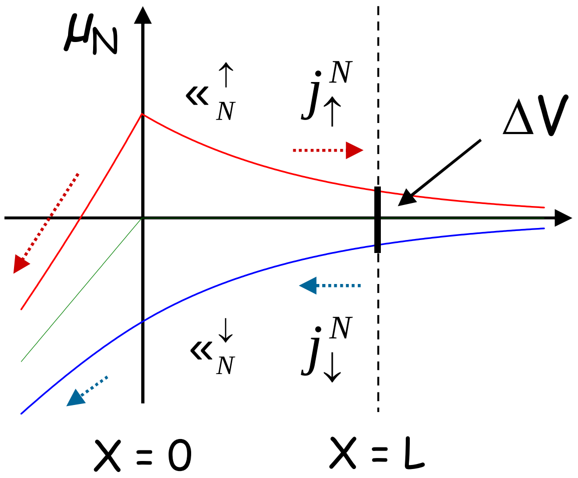
Spin waves



Kajiwara *et al*. Nature Phys. 2010

Spin transport in Lateral Spin Valves





~~Charge current~~ $j_C^N = j_\uparrow^N + j_\downarrow^N = 0$

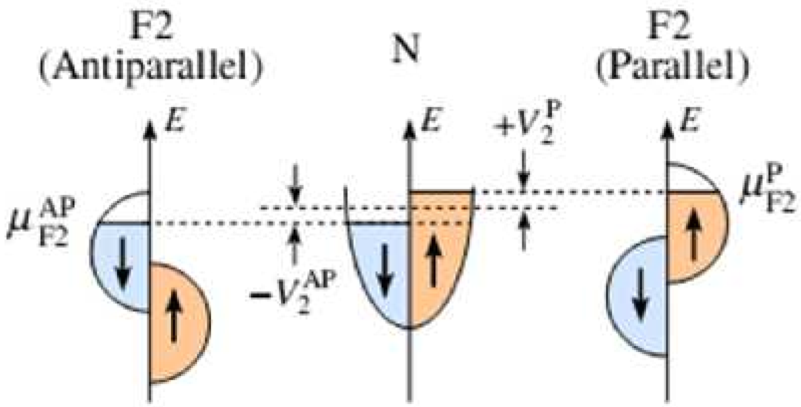
Spin current $j_S^N = j_\uparrow^N - j_\downarrow^N \neq 0$

Non local measurements,
separating charge and spin currents

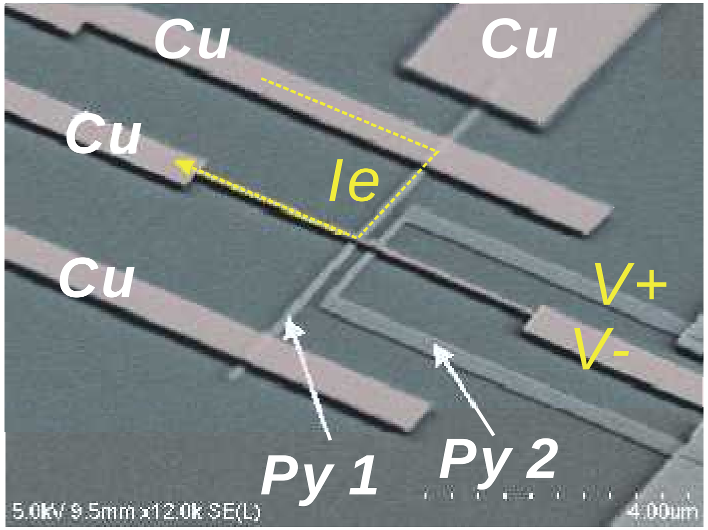
$$j_C^N = j_\uparrow^N + j_\downarrow^N \qquad j_S^N = j_\uparrow^N - j_\downarrow^N$$

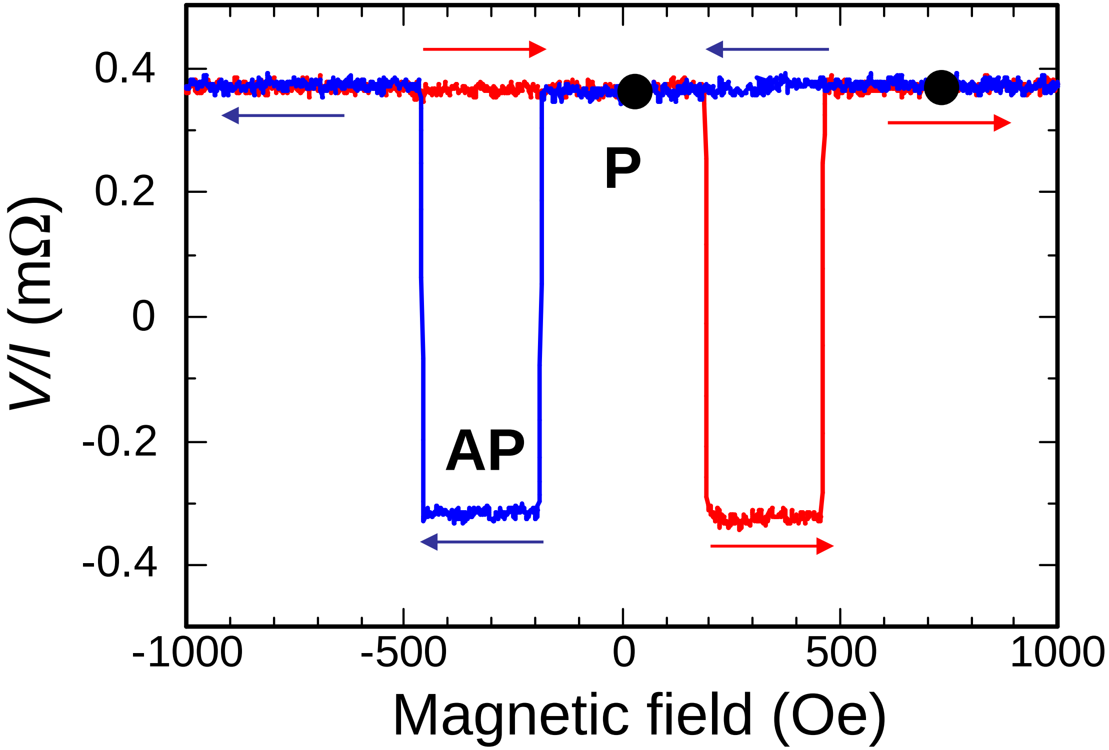
Lateral spin transport in Metals, S.-C.s or carbon based hybrid structures:

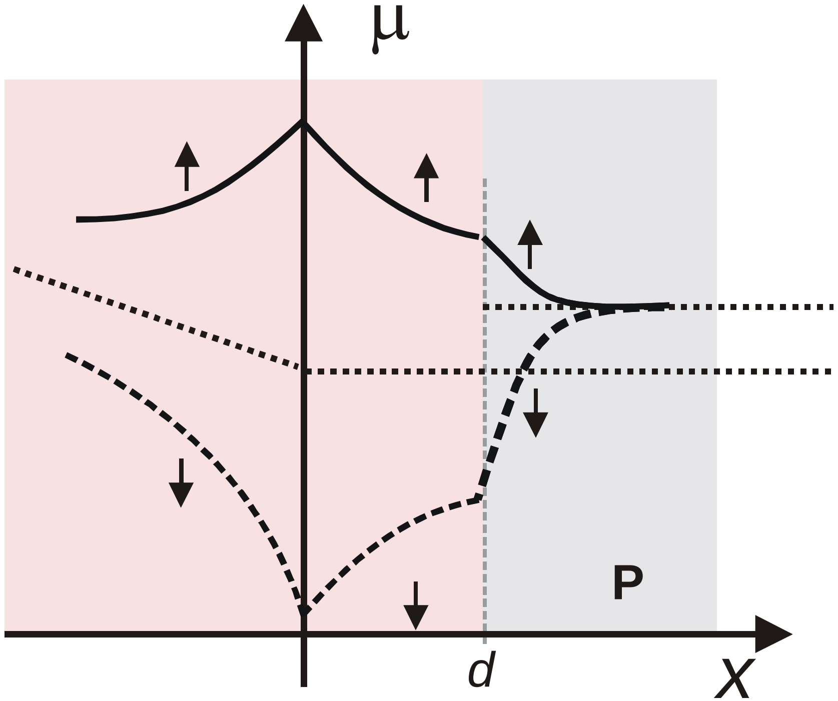
-to access material parameters,
-to find optimum spin injection/detection conditions,
-to exploit spin currents…



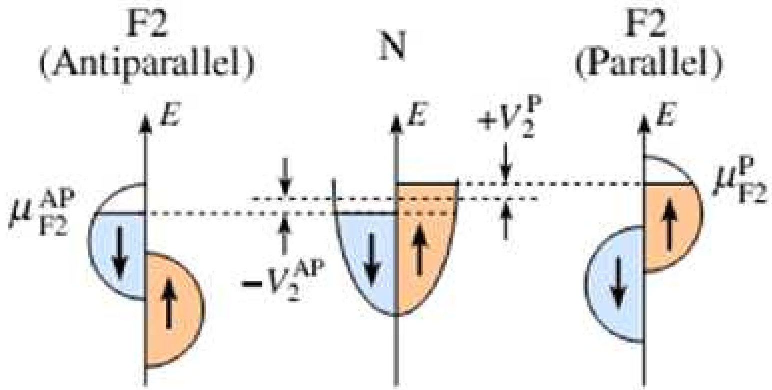
Nonlocal spin valve measurement





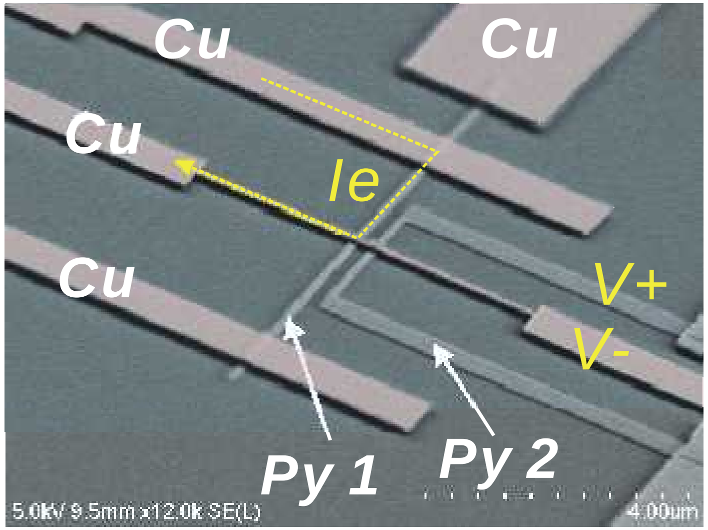


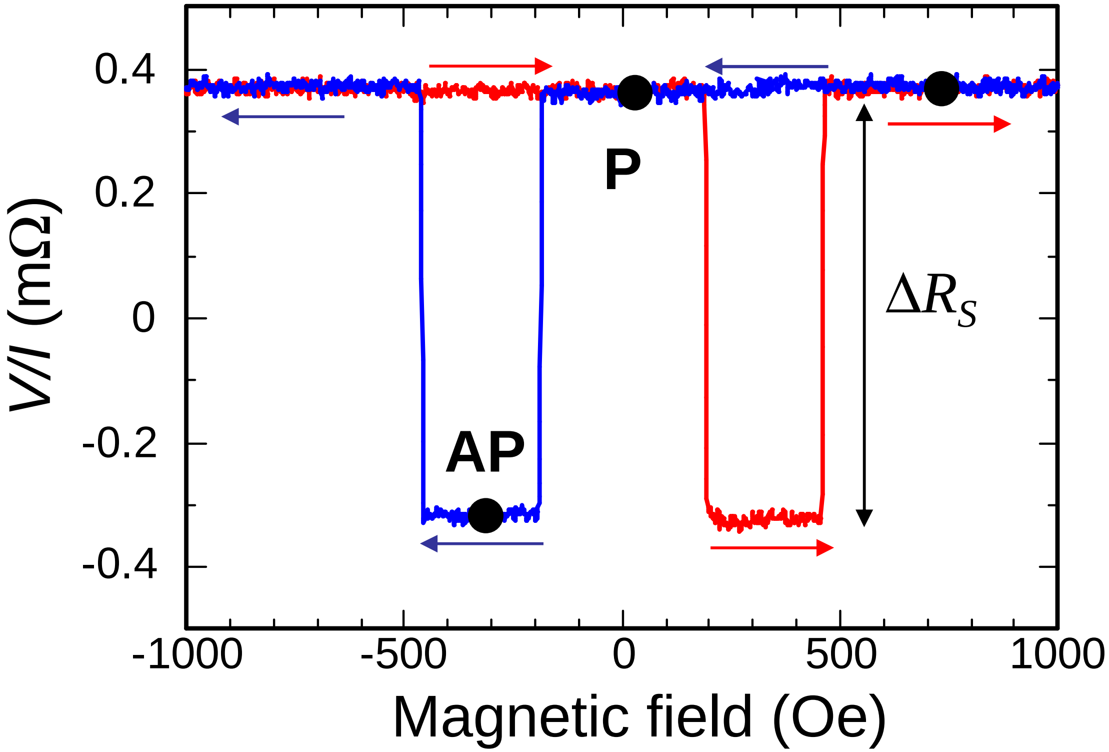
Detector in parallel

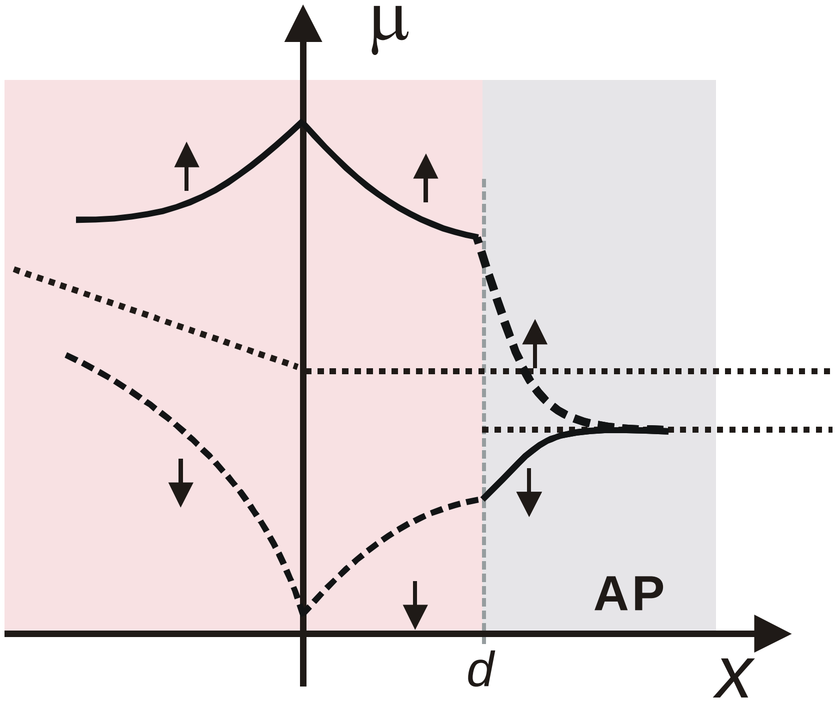


Charge neutral point shifts upward.

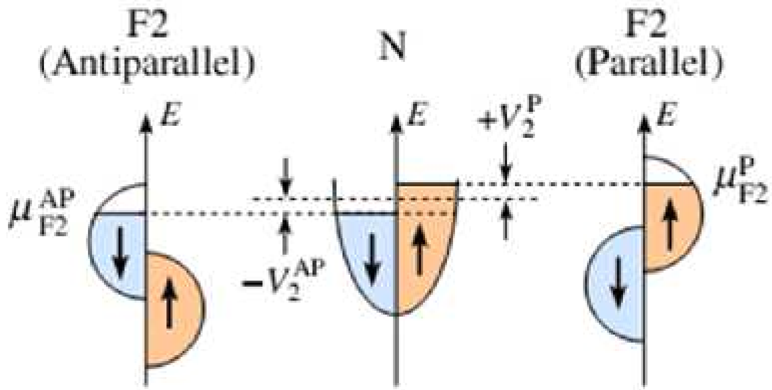
Nonlocal spin valve measurement





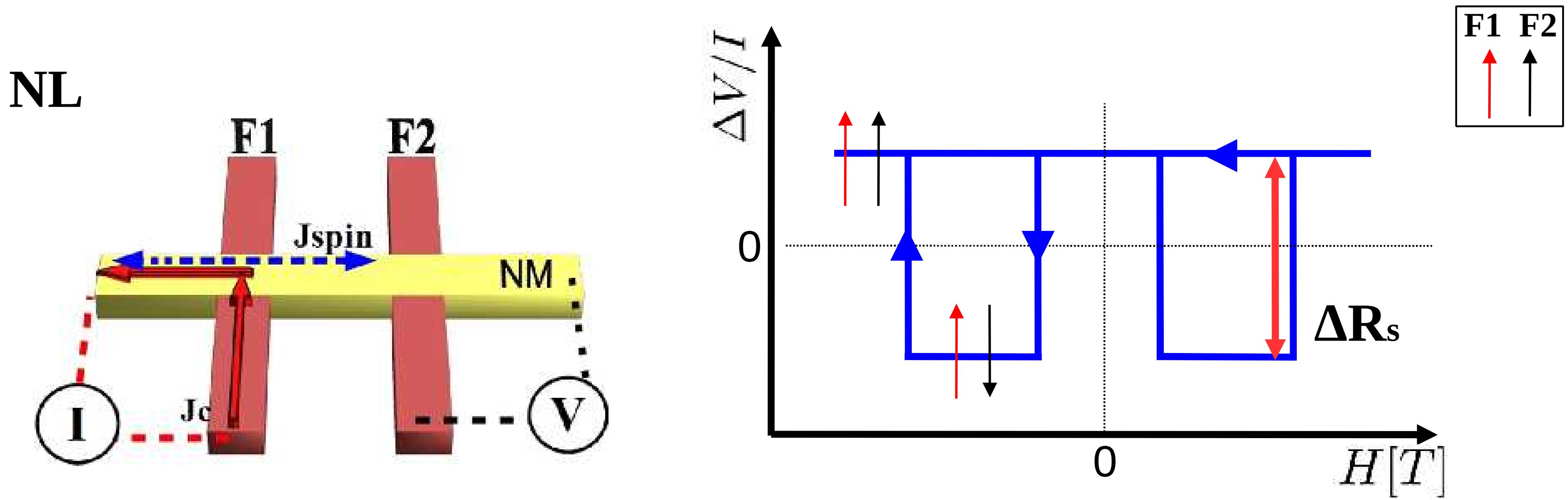


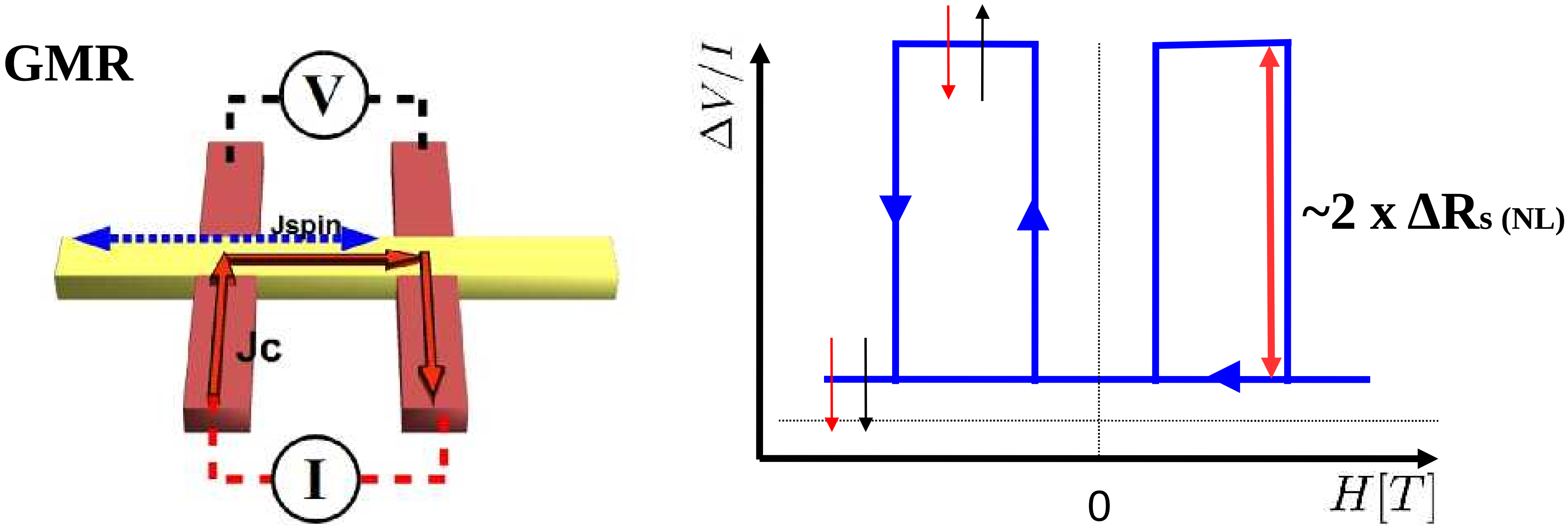
Detector in antiparallel



Charge neutral point shifts downward.

Probes configurations and expected results

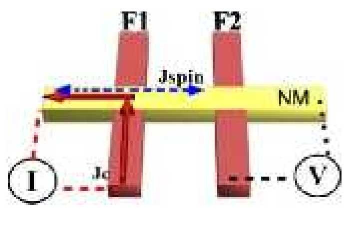




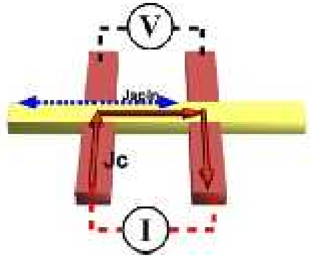
Non-Local results **NiFe/Al**

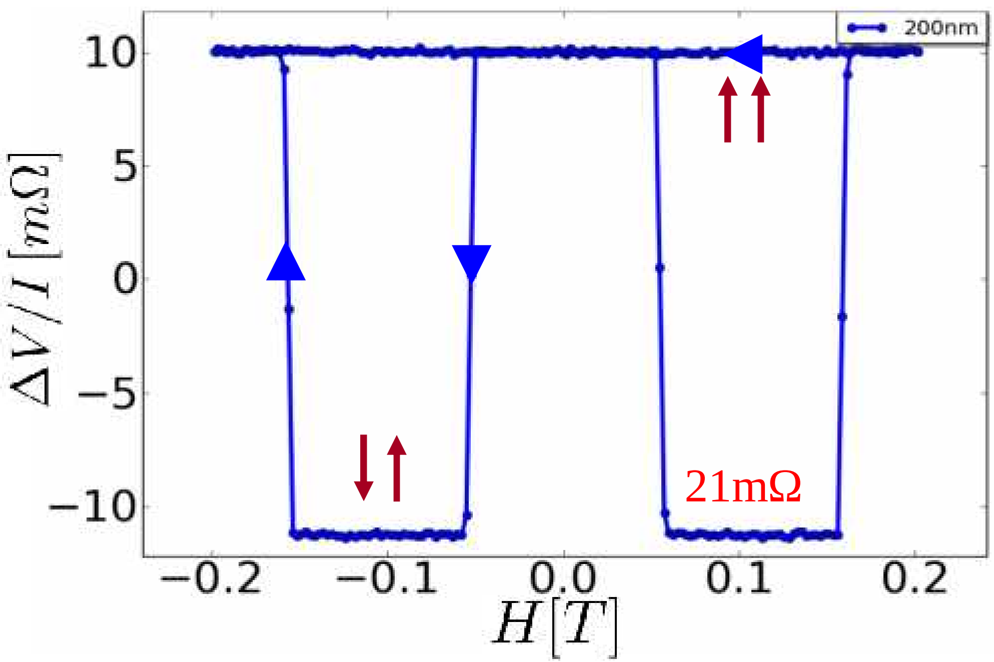
T=77K, L=200nm

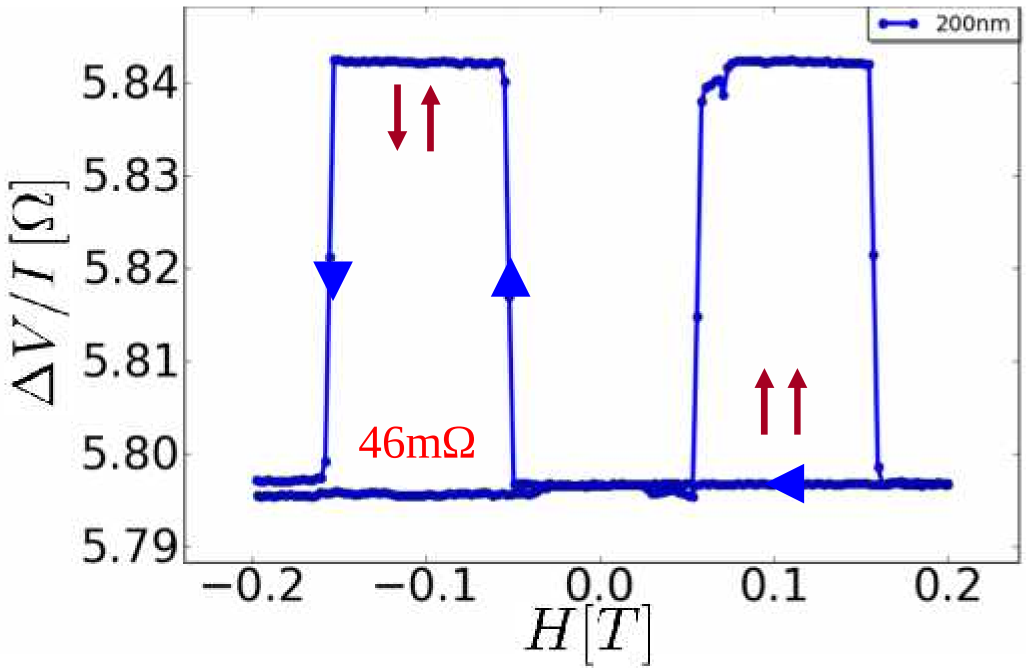
NL



GMR







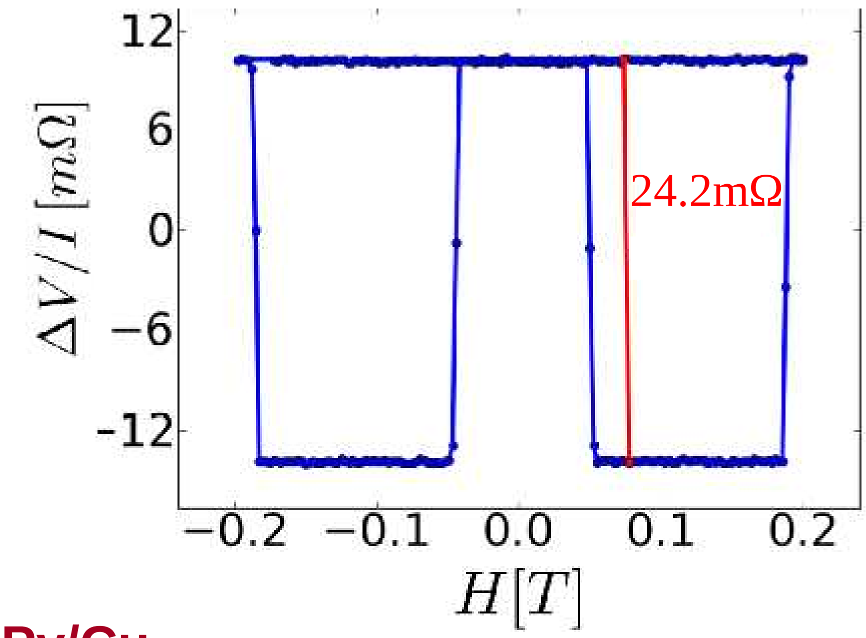
ΔRs(GMR) ~ 2 x ΔRs(NL)

Sum of the spin accumulation at the two interfaces

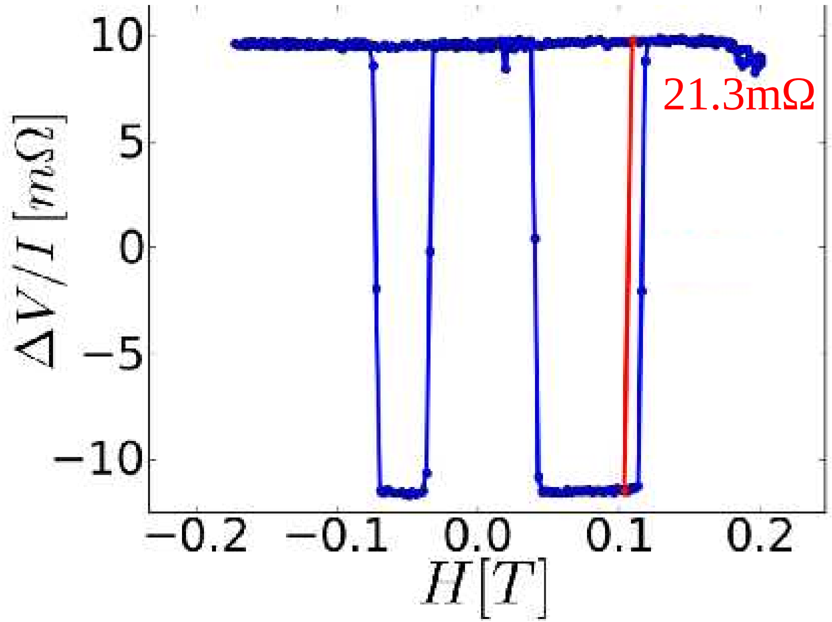
P. Laczkowski et al, *APEX* **4**, 063007 (2011)

NiFe/(Cu or Al) lateral spin valves

Py/Al T=77K, L=150nm



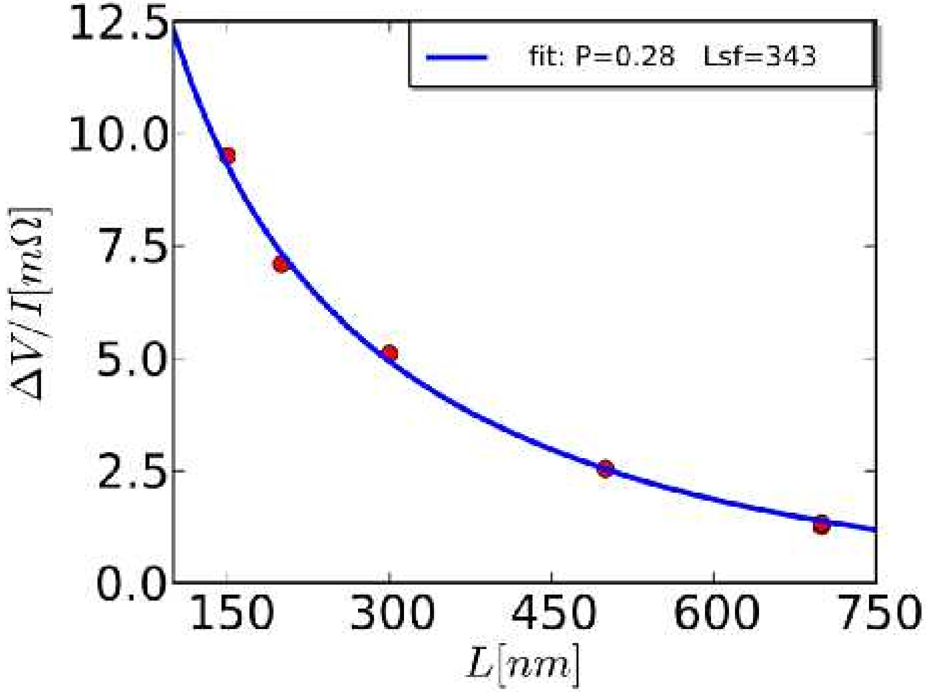
Py/Cu



Generally a few mΩ at low temperature

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

Py/Al, T=300K

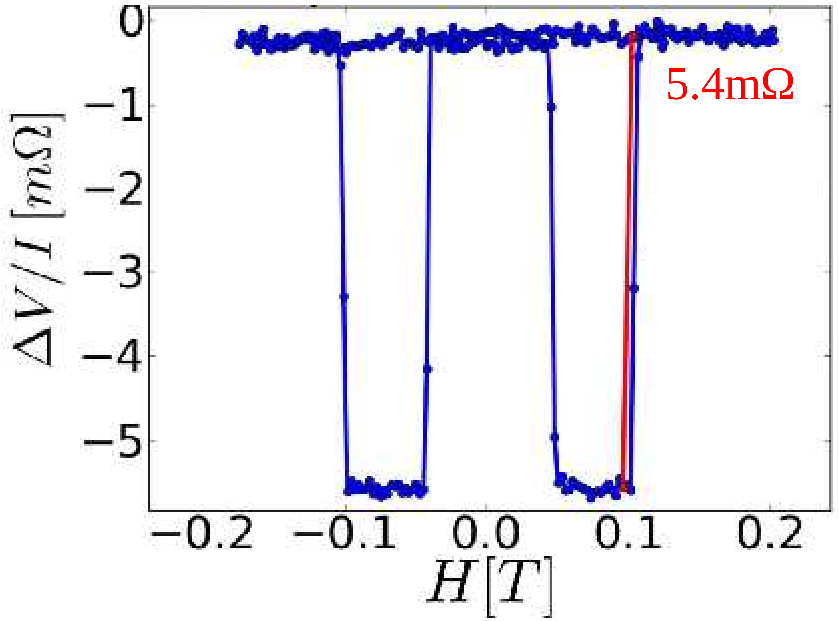


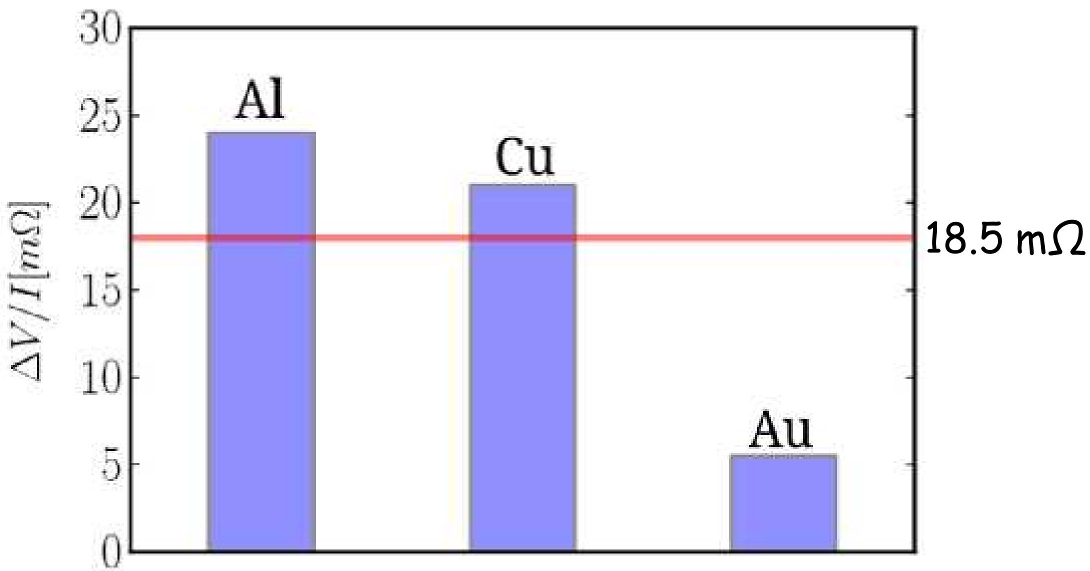
L_{sf}, with P~45%	T=300K	T=77K
Al	~450nm	~750nm
Cu	~300nm	~770nm

P. Laczkowski et al, APEX **4**, 063007 (2011)

NiFe/(Au, Cu or Al) lateral spin valves

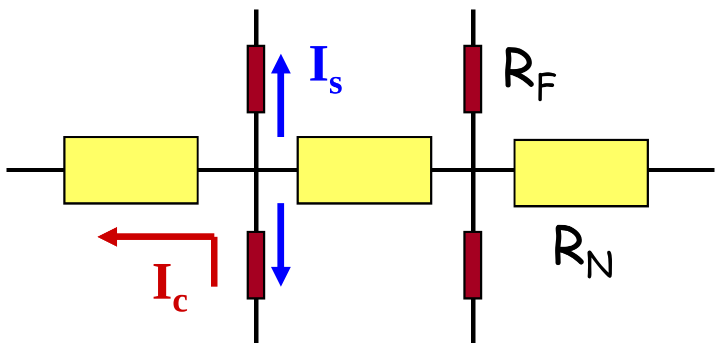
T=77K, L=150nm

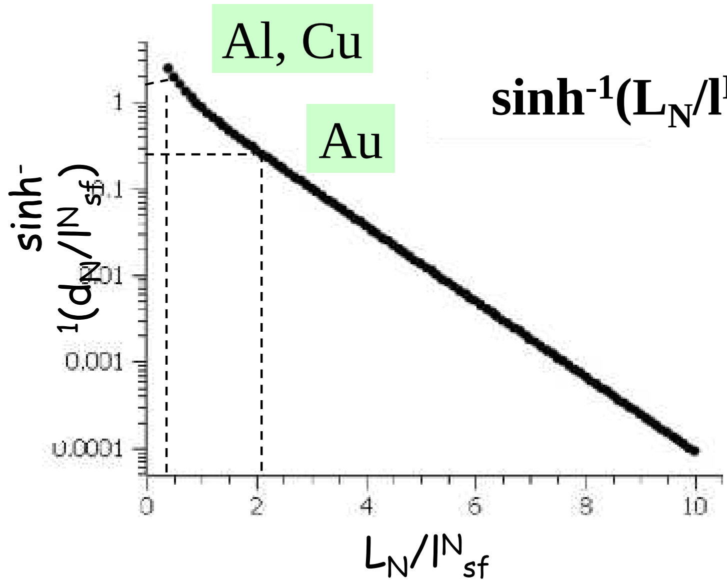




R_F/R_N ~ 0.1 - 0.2 with Al & Cu
~ 0.5 for NiFe/Au

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

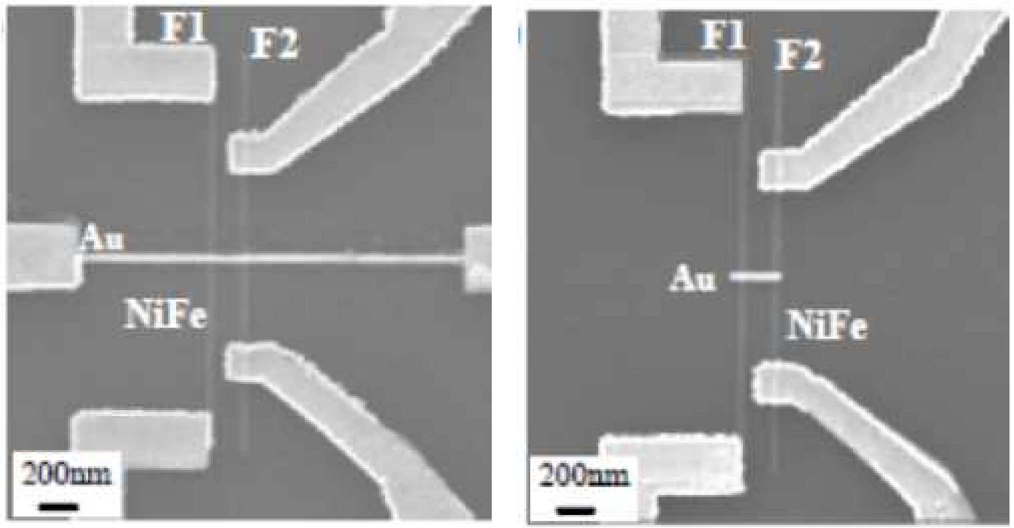


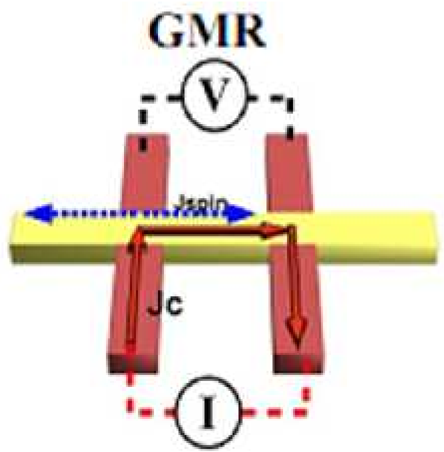


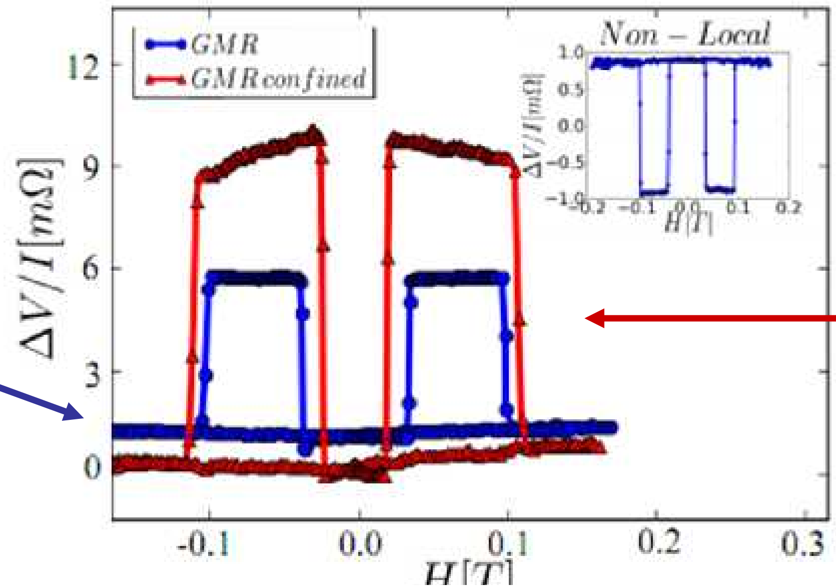
Enhancement of the spin accumulation by lateral confinement

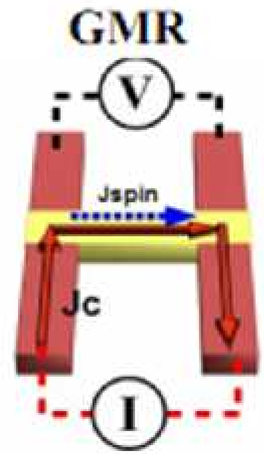
Coll. A. Fert, J.M. George, H. Jaffrès

Opened vs Confined Geometries



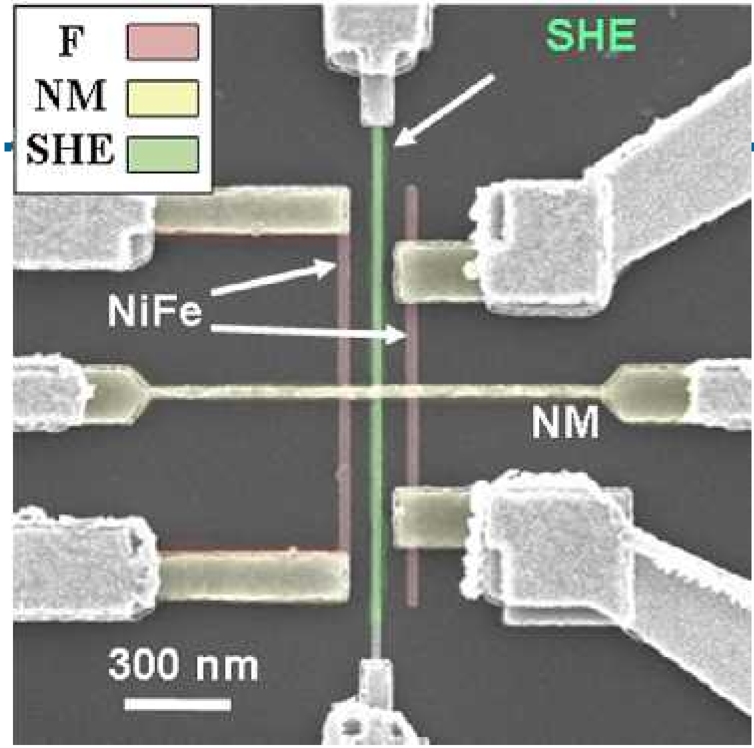






P. Laczkowski, Phys. Rev. B **85**, 220404**(R)** (2012)

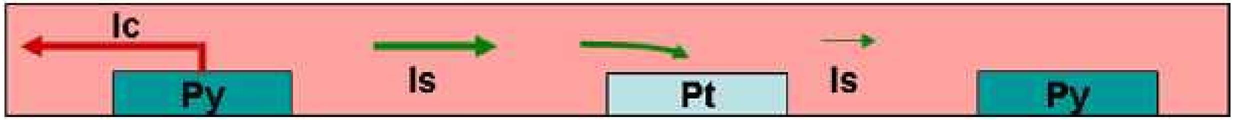
4-wires circuitry : lsf in NM, STT, SHE



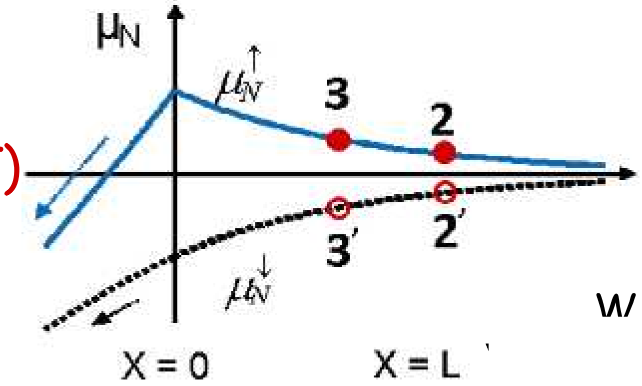
Out of equilibrium of spin accumulation

➢ Spin sink experiment to measure lsf in NM

Side view

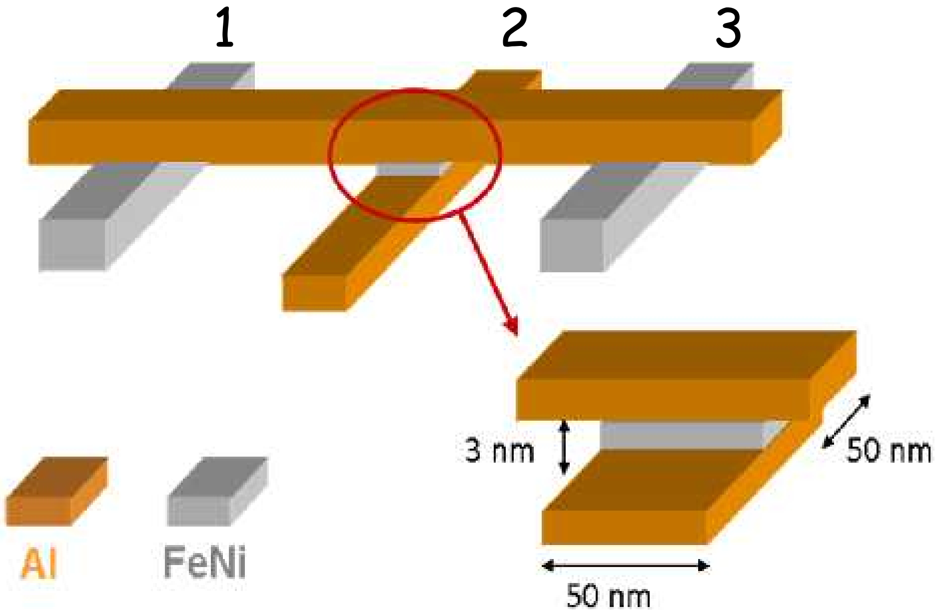


T. Kimura *et al*, PRB (2005)

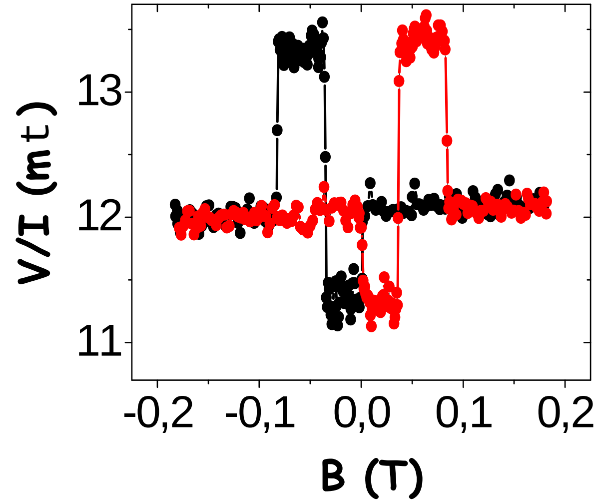


➢ Insertion of a magnetic dot for STT)

Yang et al, Nature Phys 2008

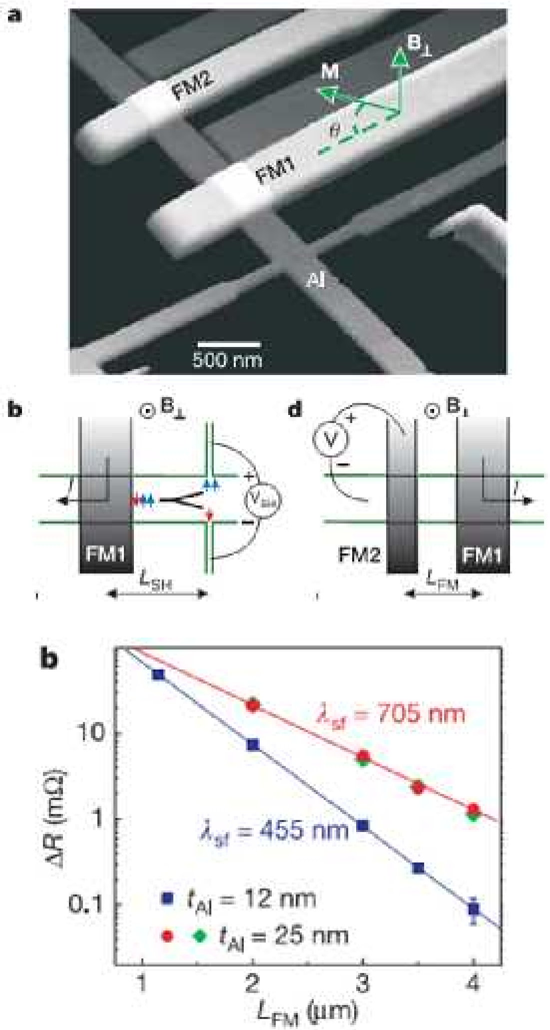


W/ F. Savero Torres



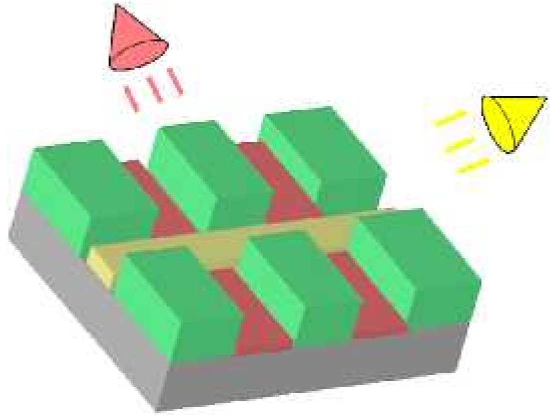
Pure spin-current for spin Hall effect and magnetization swithcing

Spin Hall effect

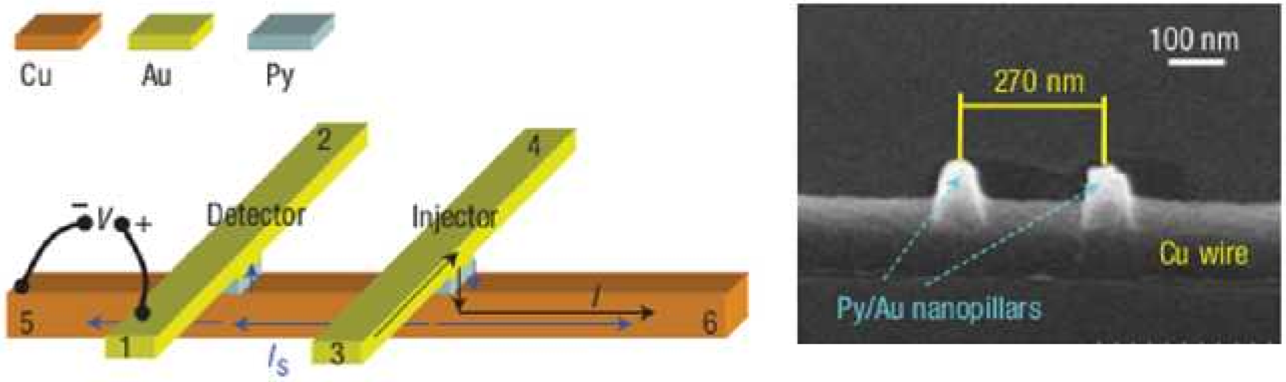


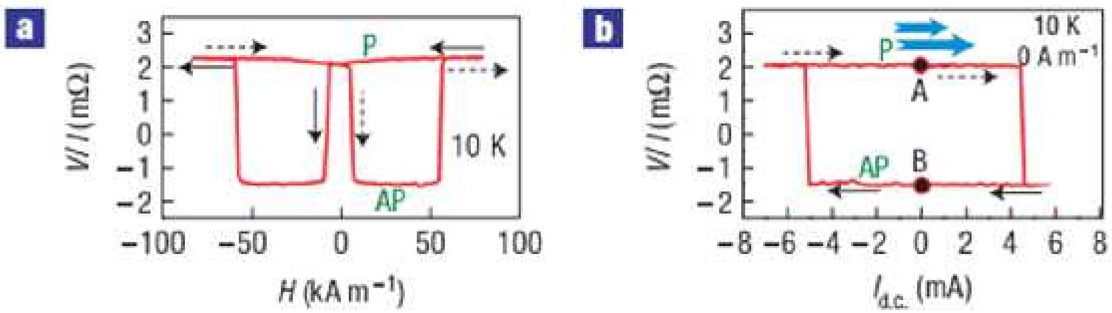
Valenzuela et al, Nature 2006

Shadow evaporation for *in-vacuum* interface fabrication



Magnetization switching

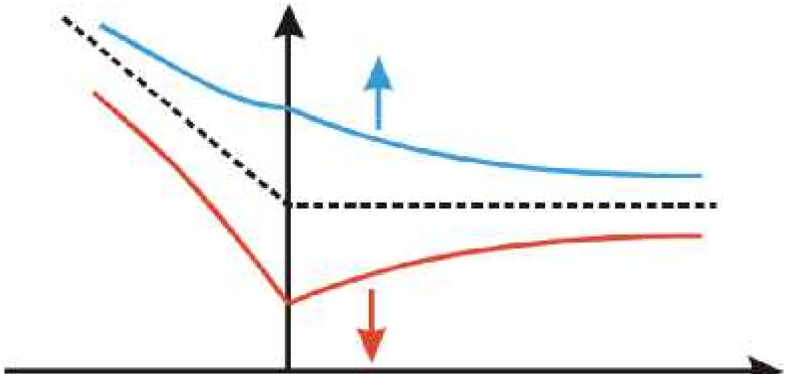




Yang et al, Nature Phys 2008

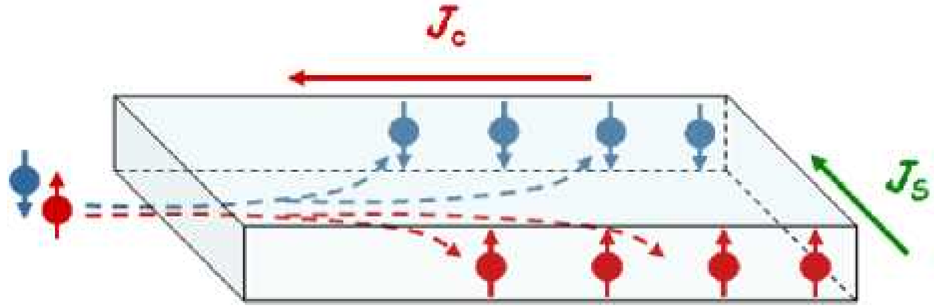
Spin current induced by

FM/NM junction



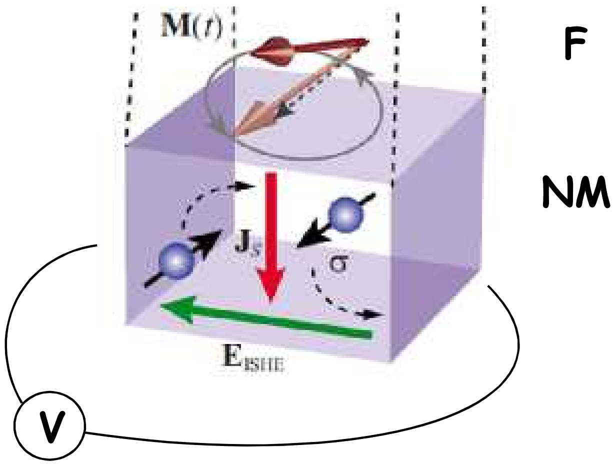
Johnson, Silsbee 1985, Jedema 2001

Spin Orbit Coupling



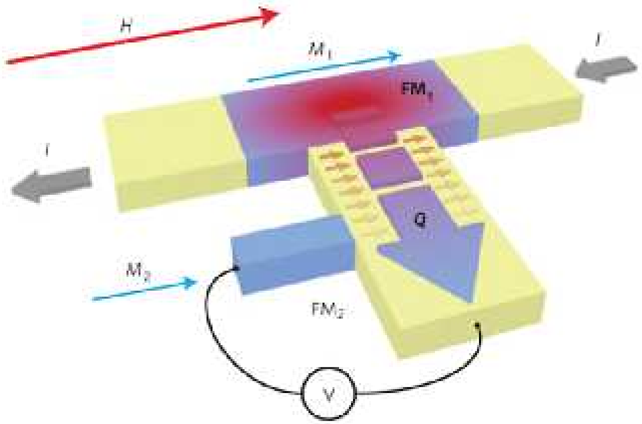
Spin Hall and Rashba effects

Spin Pumping



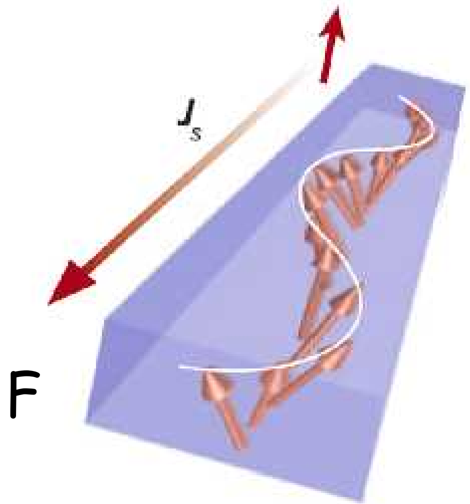
Silsbee, Monod 1979, Tserkovnyak, Bauer 2002
Saitoh 2006

Thermal Spin Injection



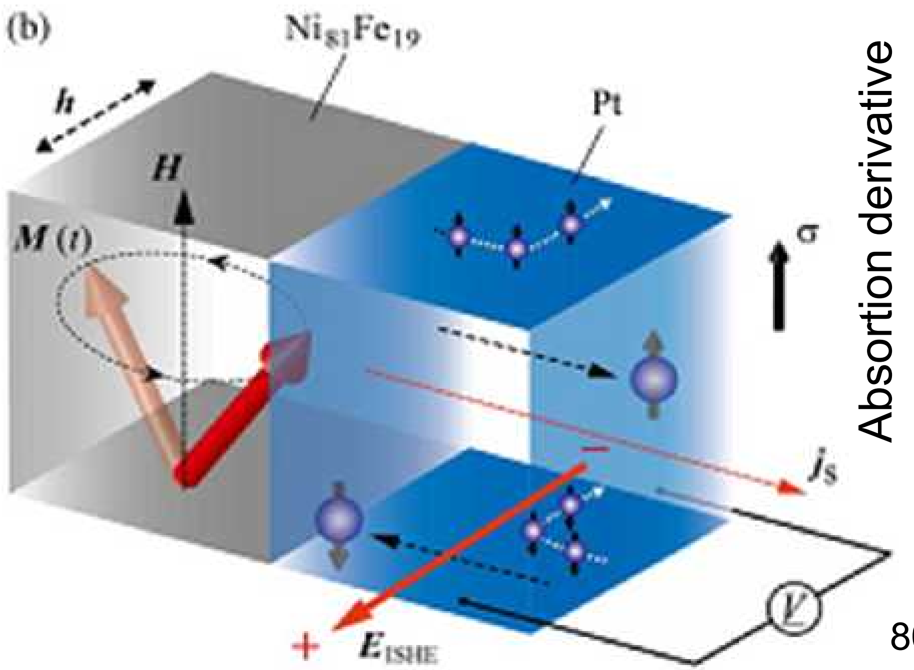
A.Slachter et al. Nat. Phys. 2010

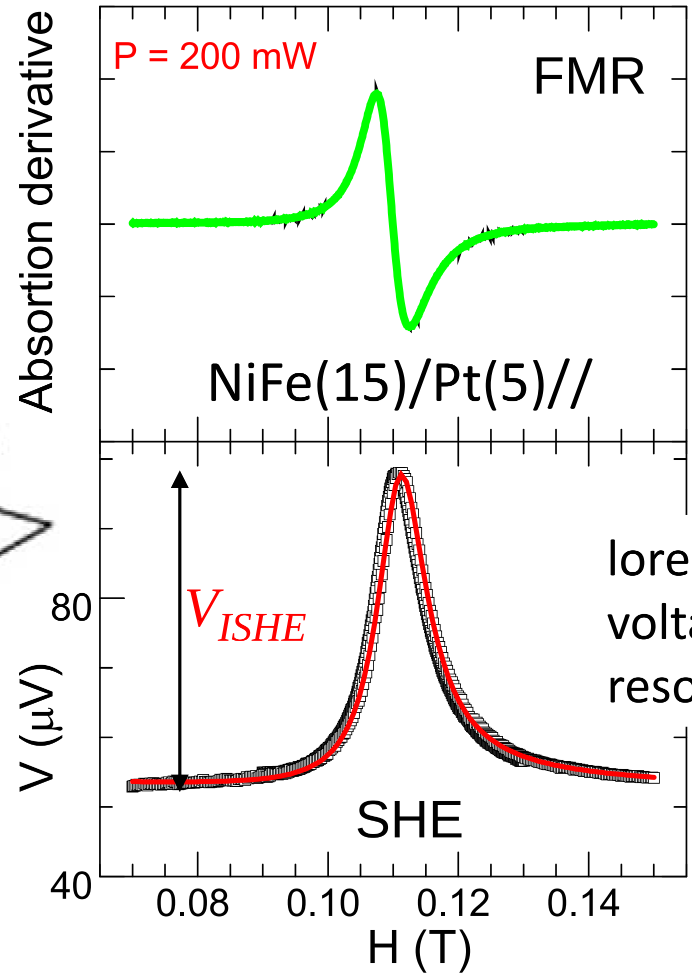
Spin waves



Kajiwara *et al*. Nature Phys. 2010

Inverse spin Hall effect by ferromagnetic resonance and spin pumping





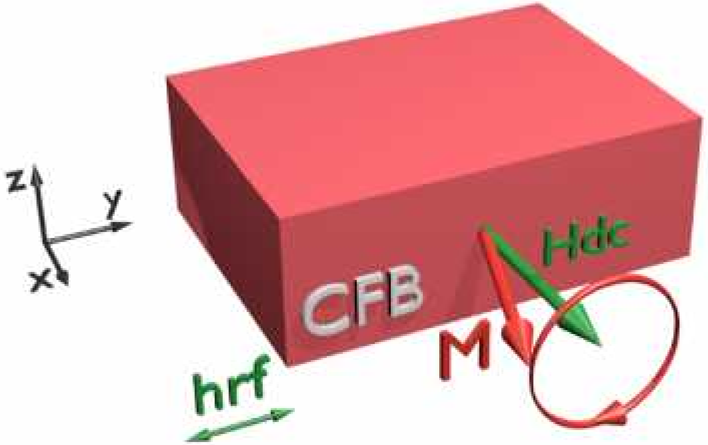
lorentziane voltage peak at resonance field

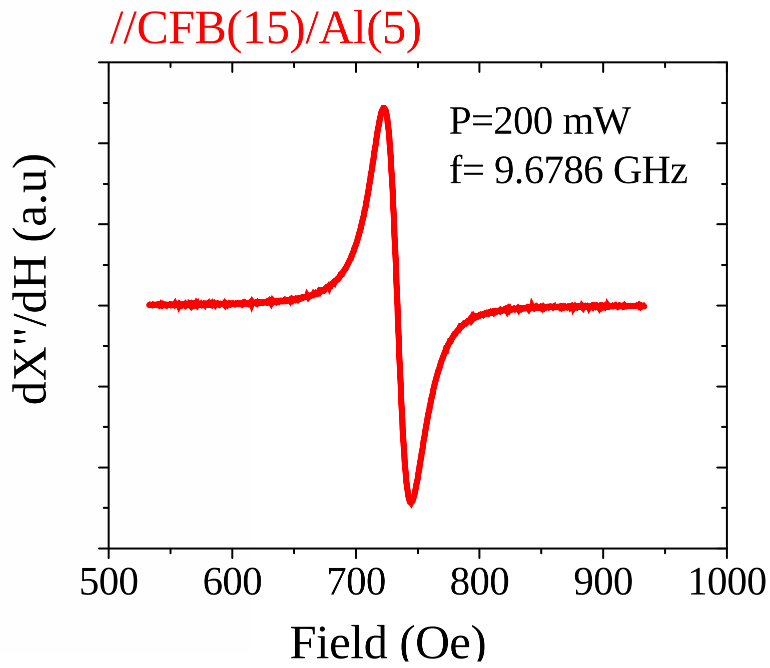
Saitoh APL 2006
Tserkovnyak PRL 2004
Silsbee, PRB 1979

Magnetization precession + Interfacial Electronic coupling + spin to charge conversion

in FM — at FM/NM — in NM

Ferromagnetic resonance (FMR)





➔ H_{res}

➔ ΔH_{pp}

FMR is a power technique:

- Magnetic anisotropies (angular dependence, frequency dependence)
- Magnetic transition (temperature dependence)
- Magnetic coupling
- ..etc

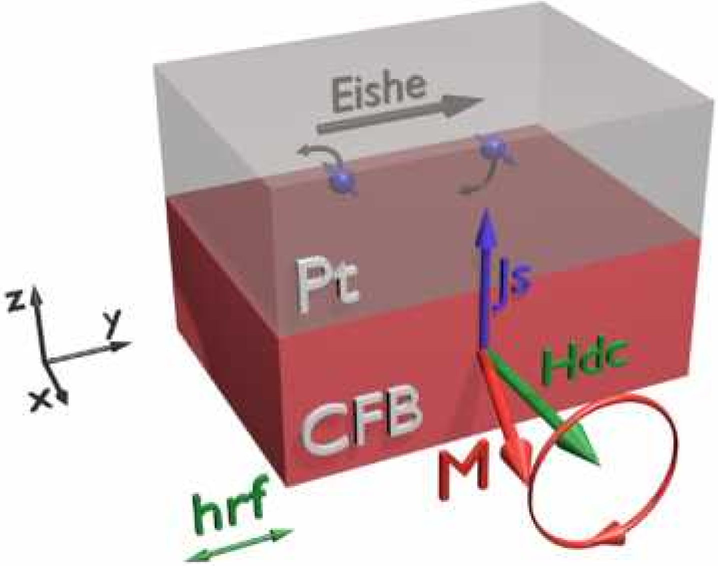
Enhancement of damping constant:

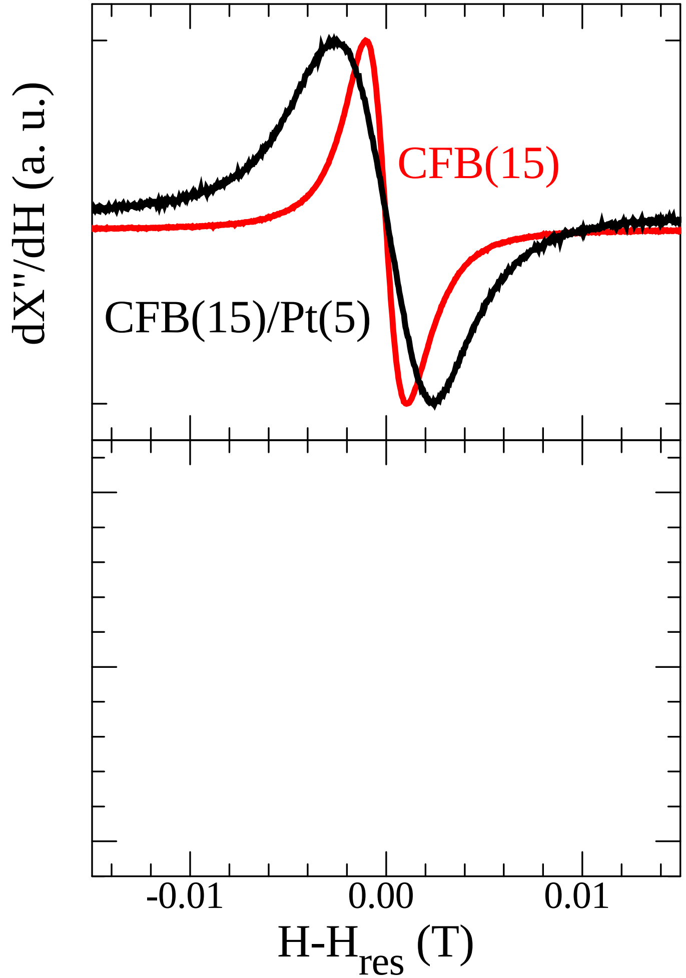
Spin pumping effect

Tserkovnyak et al. 2002

➔Spin mixing conductivity

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



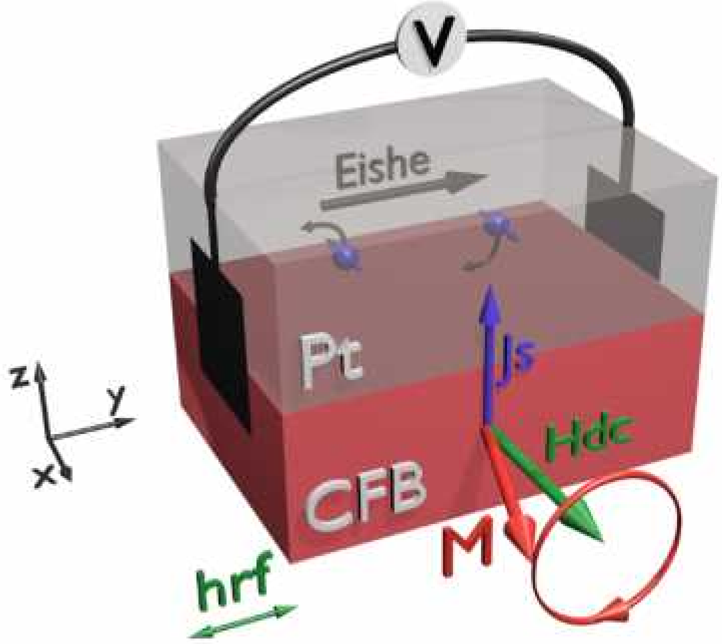


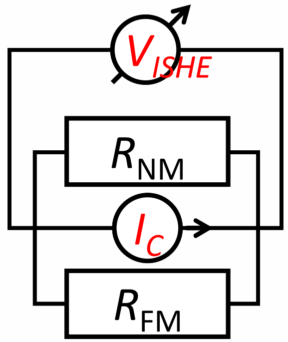
Note: Not always Δα is only due to SP

Spin pumping and ISHE: E. Saitoh *et* al. APL 2006

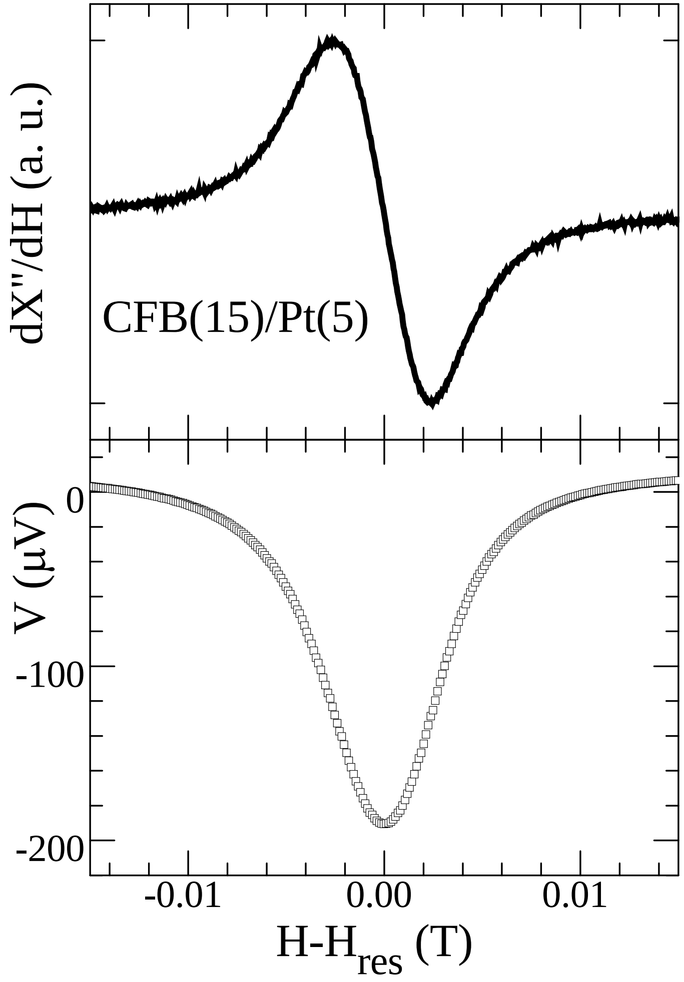
➔Voltage ISHE: symmetrical Lorentzian peak at H_{res}

➔ 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 – ISHE or IEE:
  - Pure spin currents
  - Easy lithography (if any)
  - Spin → Charge: Simple electrical detection (dc voltage measurement)

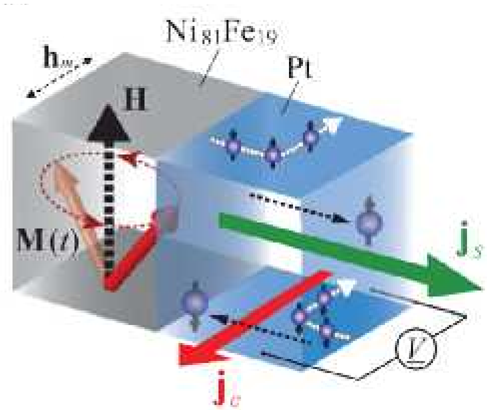
Also some difficulties exist…

Ando, Saitoh (2009)

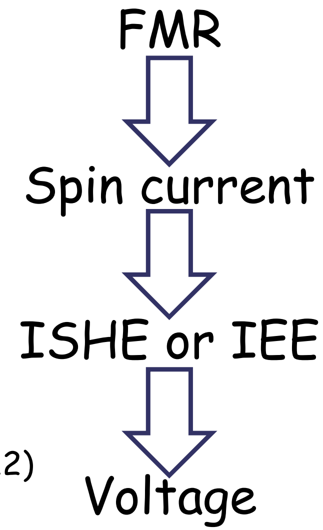
Determining the spin current

→ Many variables

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



H. Nakayama *et al*, *Phys. Rev. B* 85, 144408 (2012)



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$$f(H_{\text{res}}) \to M_{\text{eff}}$$

$$\Delta H(f) \to \alpha$$

$$\Delta\alpha(t_N) = \frac{g\mu_B}{4\pi M_{\text{eff}} t_F} g_{\text{eff}}^{\uparrow\downarrow} \to g_{\text{eff}}^{\uparrow\downarrow}$$

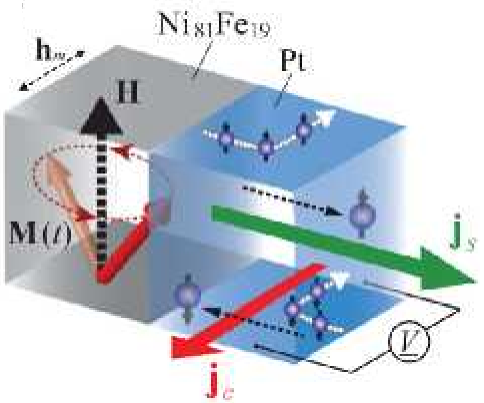
From the ISHE voltage measurement:

$$I_C = \frac{V_{\text{ISHE}}}{R}$$

$$I_C = W \bar{\;}_{\text{SHE}} \ell_{\text{sf}} \tanh\left(\frac{t_{\text{NM}}}{2\ell_{\text{sf}}}\right) j_S$$

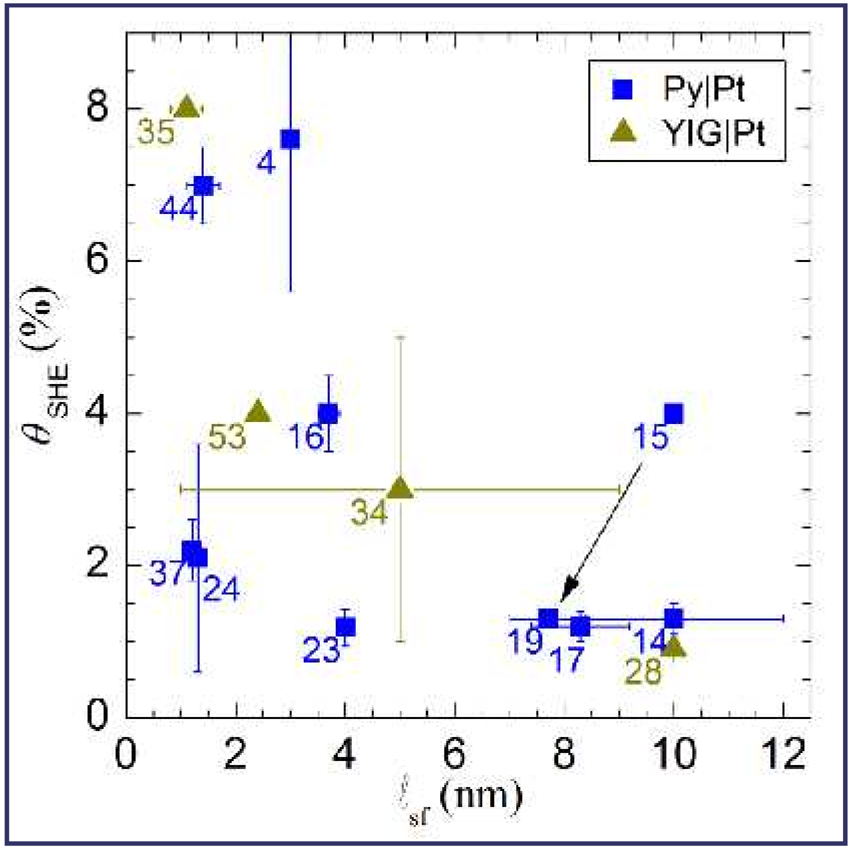
The Spin Hall Angle and Spin Diffusion Length in Pt

•Platinum is widely studied, but results are scattered



H. Nakayama *et al*, *Phys. Rev. B* 85, 144408 (2012)

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



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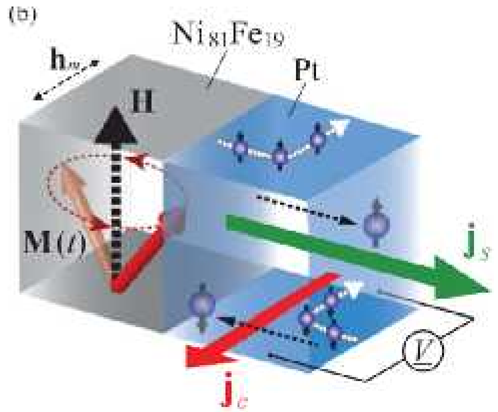


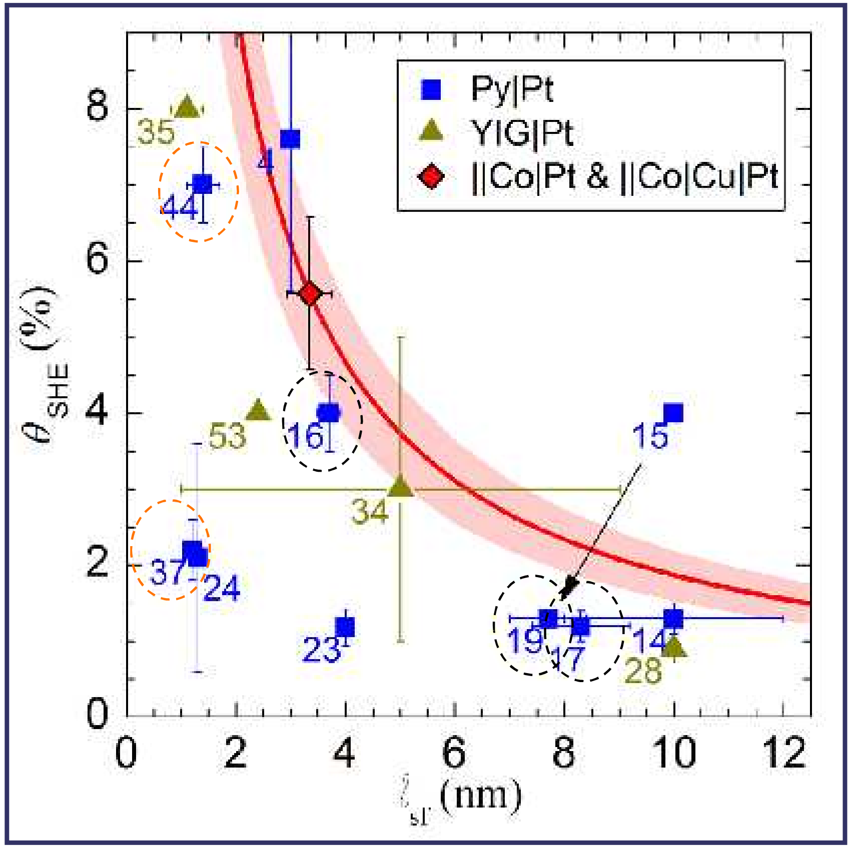
H. Nakayama *et al*, *Phys. Rev. B* 85, 144408 (2012)

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

There is a correlation with the spin diffusion length.

$$I_C = -\theta_{SHE}\ell_{sf} W J_S^{eff} \tanh\left(\frac{t_N}{2\ell_{sf}}\right)$$

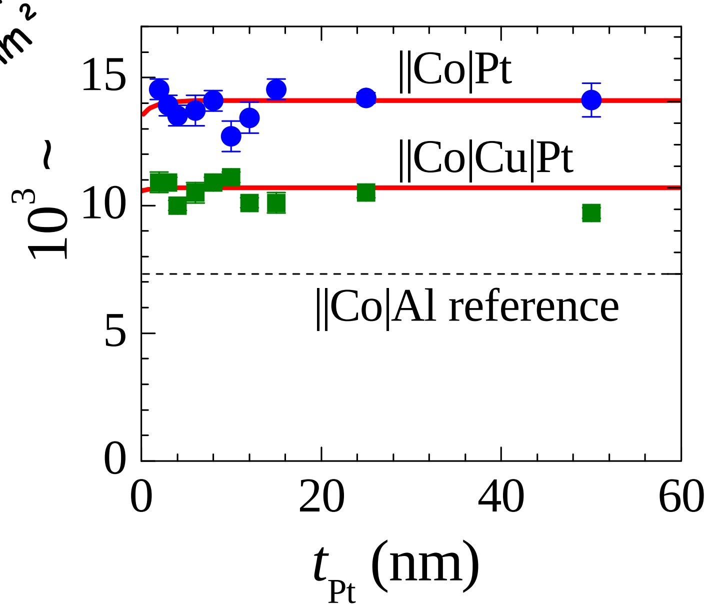
must be disentangled



J.-C. Rojas-Sánchez *et al*, *Phys. Rev. Lett.* 112, 106602 (2014)

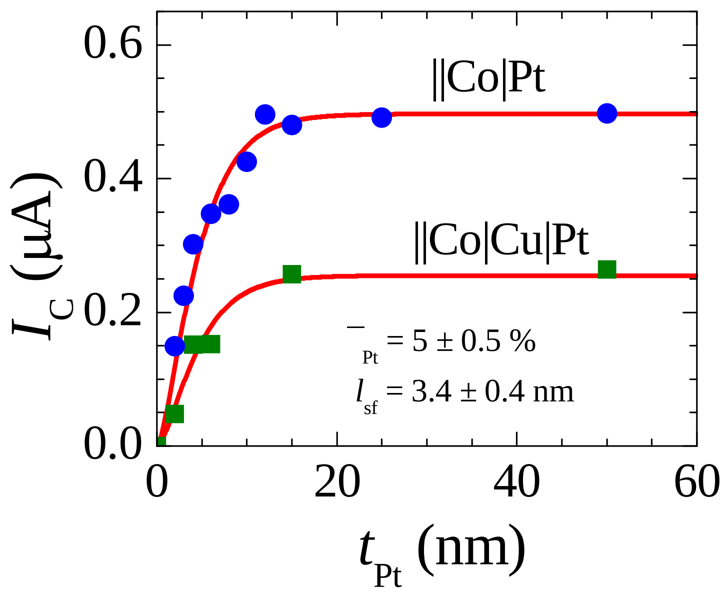
J_s^{eff} ~10-12 MA/m²
Geff ~40-80 nm⁻²

Damping constant



Charge current

ρ_{Pt} ~ 17 10^{-8} Ω.m



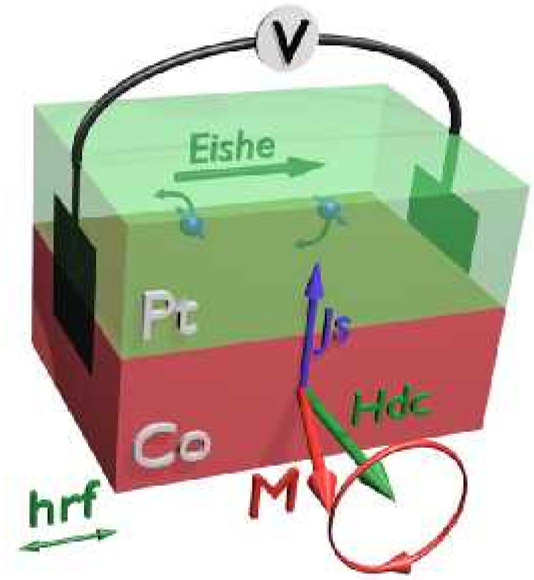
➔ Different length scale for α and V_{ISHE}

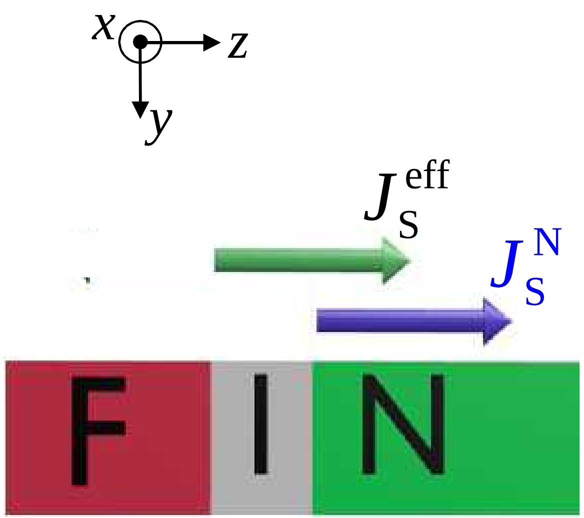
➔ Lower charge production by inserting Cu

J.-C. Rojas-Sánchez *et al*, *Phys. Rev. Lett.* 112, 106602 (2014)

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

See J. Bass and W. Pratt, J. Phys.: Condens. Matter 2007





¢ $_{F/N}$ Spin flip parameter

$$I_C = -W\theta_{SHE}^{N}\ell_{sf}^{N}J_S^{eff}\tanh\left[\frac{t_N}{2\ell_{sf}^{N}}\right]\boxed{R_{SML}}$$

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

J.-C. Rojas-Sánchez *et al*, *Phys. Rev. Lett.* 112, 106602 (2014)

Spin memory loss

Back to the roots of GMR:

Bulk	ρ^*,	β,	lsf

Resistivity, spin asymmetry, spin relaxation

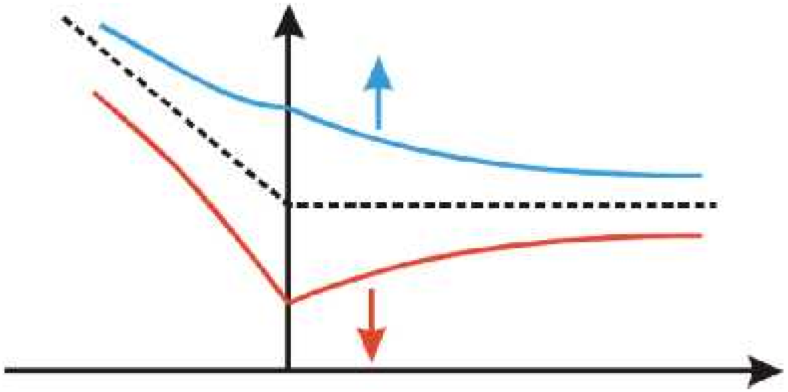
Interface	A.R*,	γ,	δ

Interface resistance, spin asymmetry, spin flip ratio

Spin memory loss is the analog for an interface of the t/lsf ratio for the bulk

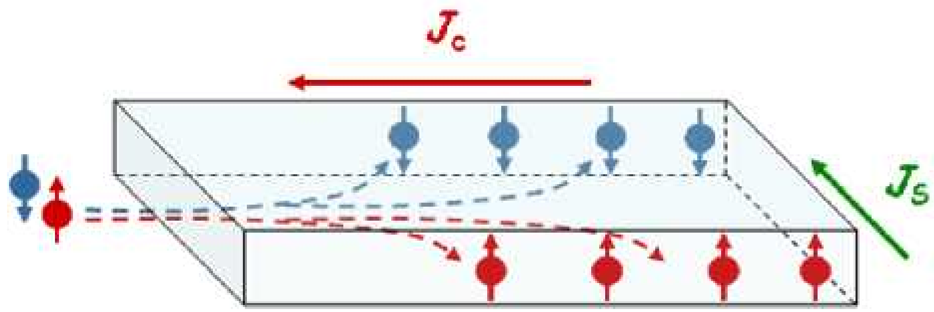
Spin current induced by

FM/NM junction



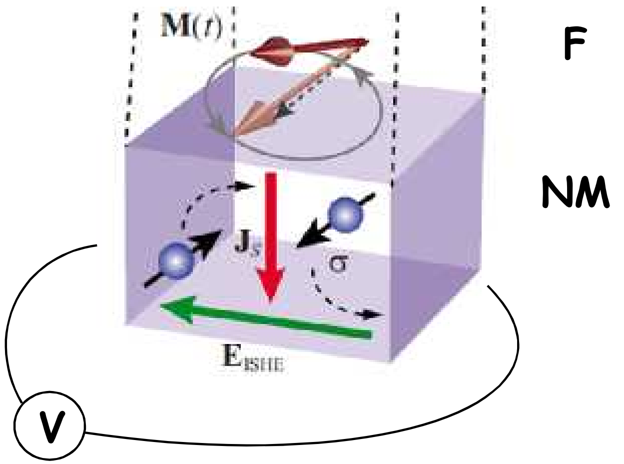
Johnson, Silsbee 1985, Jedema 2001

Spin Orbit Coupling

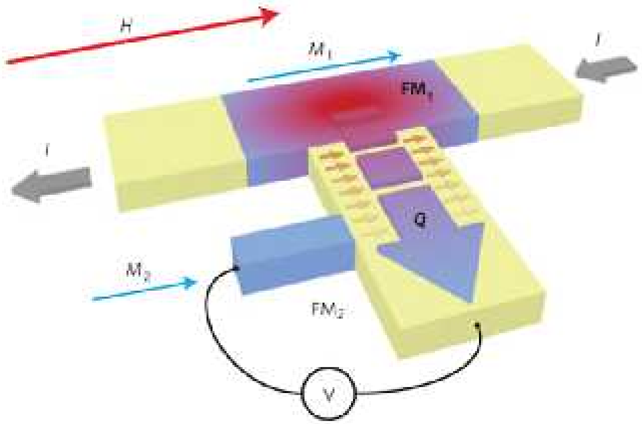


Spin Hall and Rashba effects

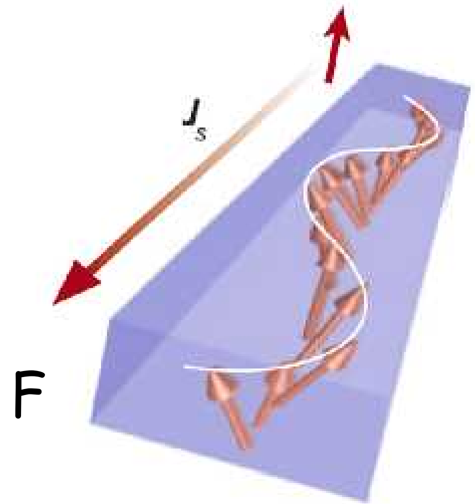
Spin Pumping



Thermal Spin Injection



Spin waves



Silsbee, Monod 1979, Tserkovnyak, Bauer 2002
Saitoh 2006

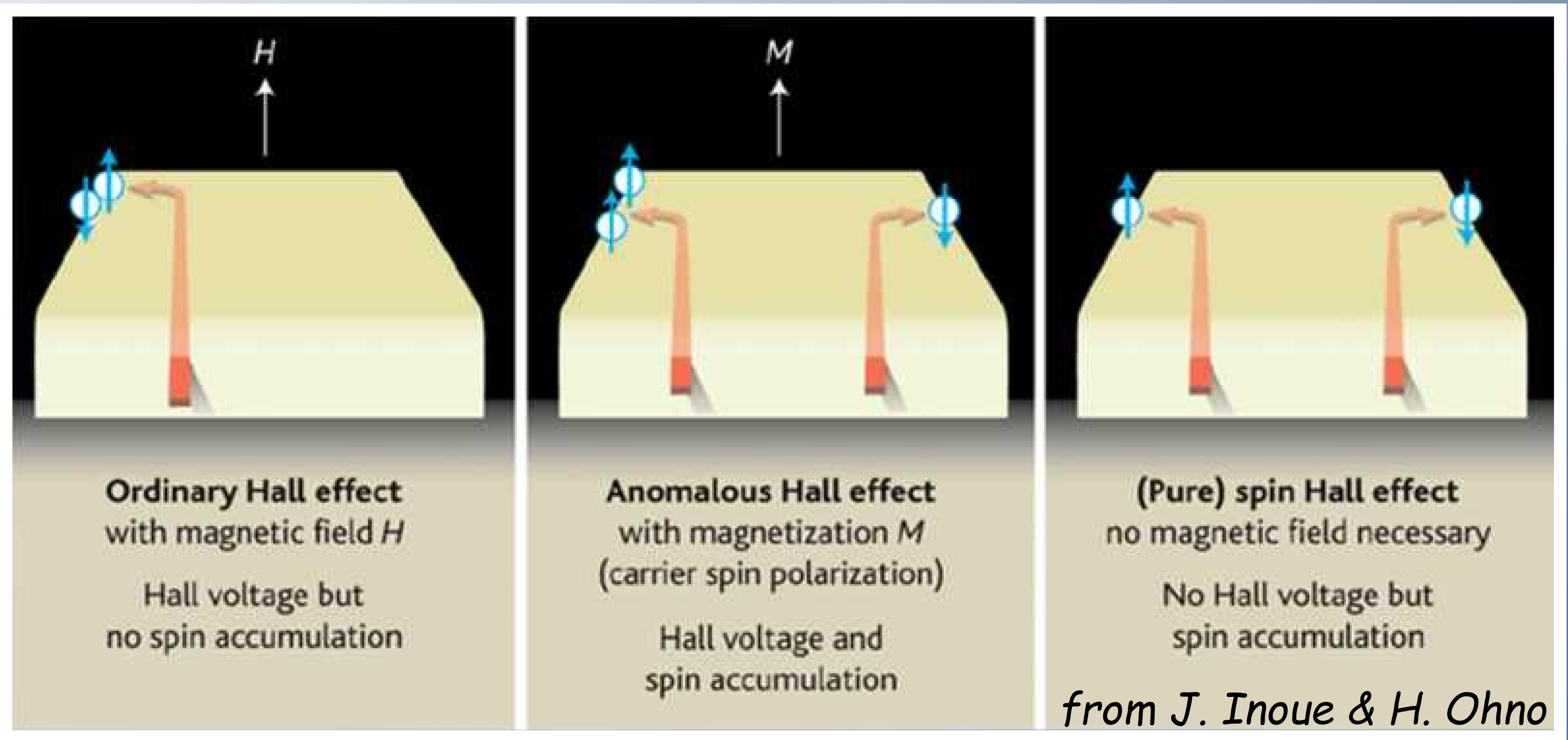
A.Slachter et al. Nat. Phys. 2010

Kajiwara *et al*. Nature Phys. 2010

Spin Hall effects in metallic nanostructures

Laurent Vila

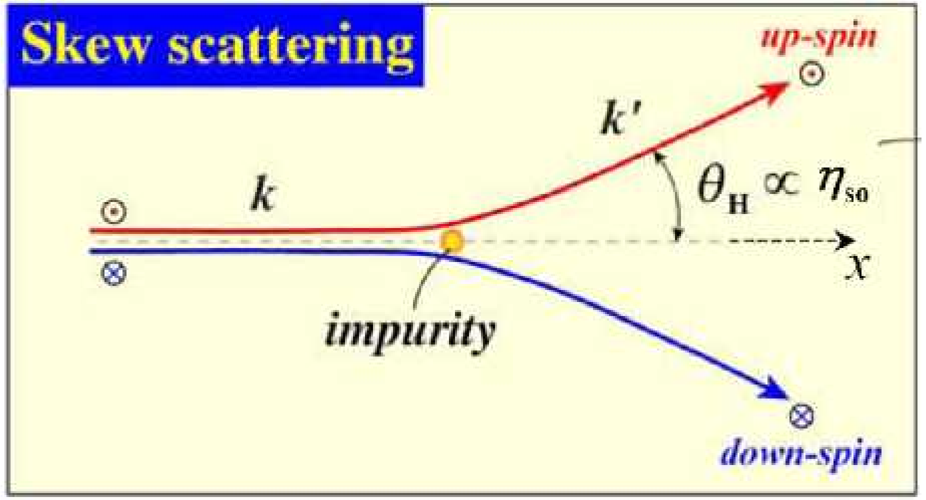
Laboratory of Nanostructure and Magnetism
Institute for Nanoscience and Cryogenics , CEA, Grenoble, France



"Direct" spin Hall effect

Spin-orbit interaction

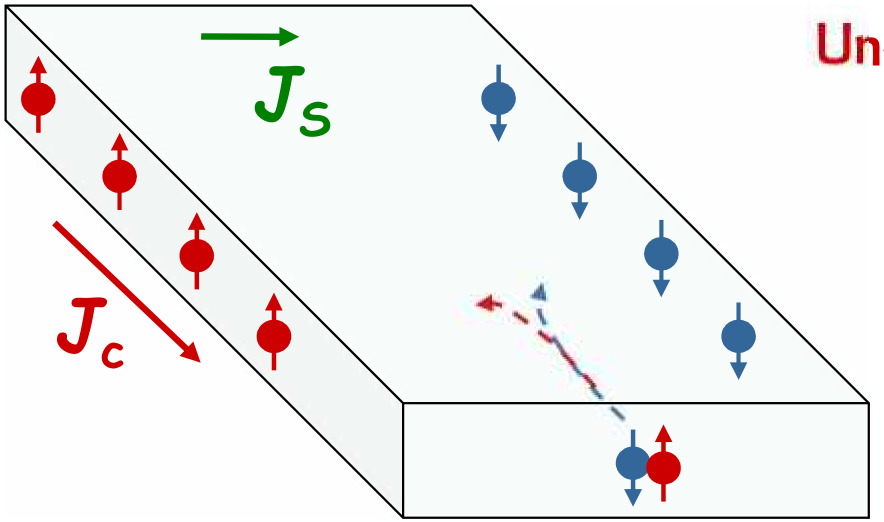
Trajectories of electrons are affected by the interaction between the electron-spin and orbital angular momentum.



- 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

$$J_s \propto S \times J_c$$

Opt. Detect°

Y. K. Kato *et al.* Science **306**, 1910 (2004).
J. Wunderlich *et al.* Phys. Rev. Lett. **94** (2005)

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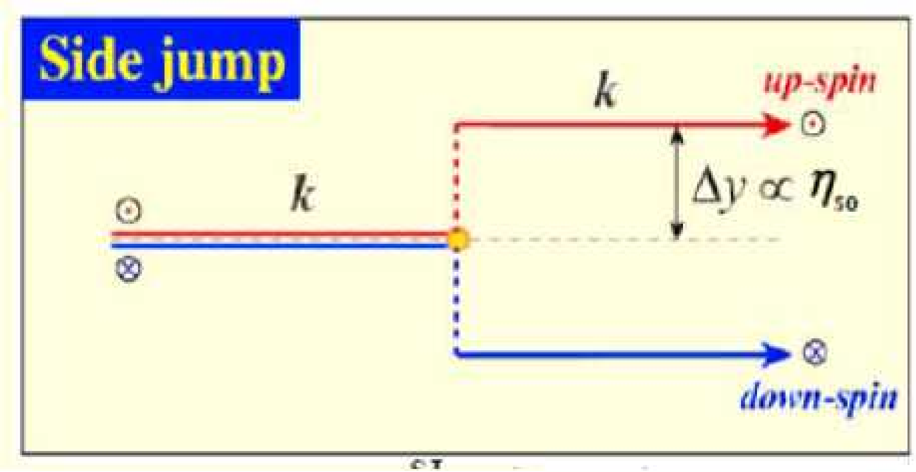

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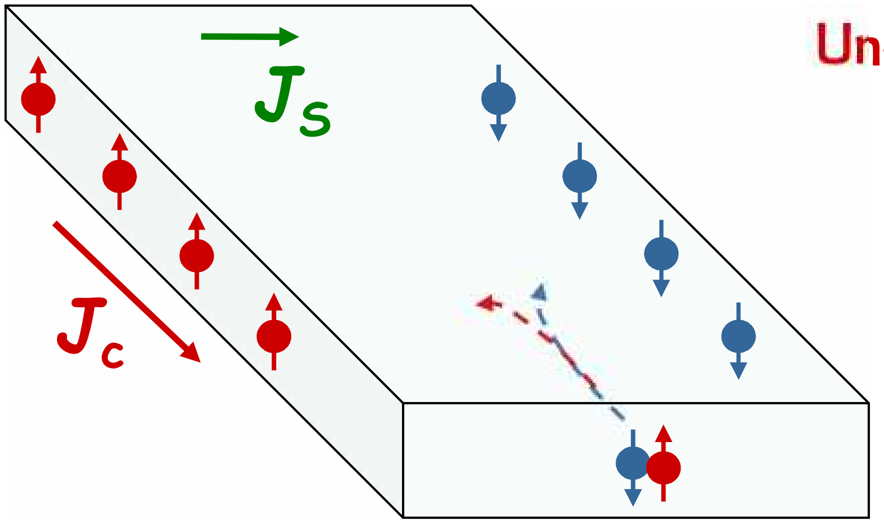

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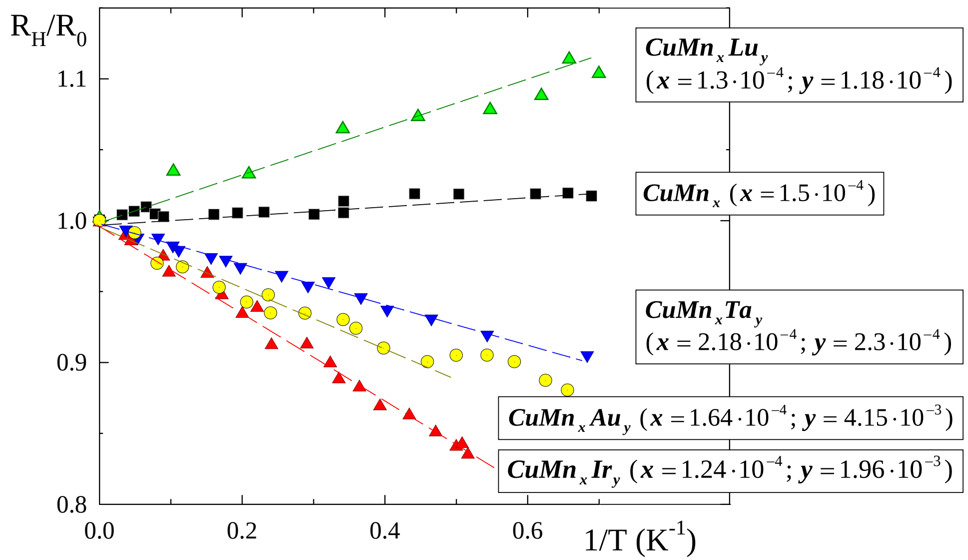
Y. K. Kato *et al.* Science **306**, 1910 (2004).
J. Wunderlich *et al.* Phys. Rev. Lett. **94** (2005).

Spin Hall effects : "the early days"

"Possibility of orientating electron spins with current".
M. I. Dyakonov and V. I. Perel, *Sov. Phys. JETP Lett.* **13**, 467 (1971).

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

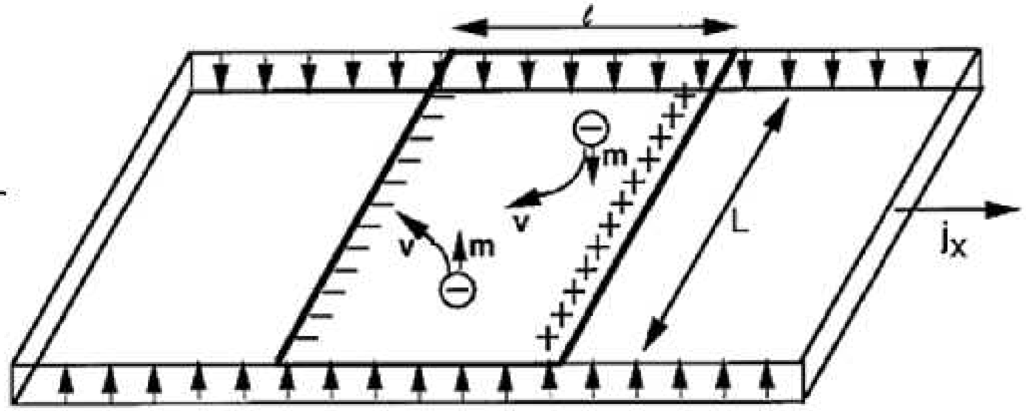
Fert et al, J. Magn. Magn. Mat. **24**, 231 (1981)

Cf also Bakun et al,
Sov. Phys. JETP Lett. **40**, 1293 (1984)
Polarized photo-current in SC

VOLUME 83, NUMBER 9 PHYSICAL REVIEW LETTERS

Spin Hall Effect

J. E. Hirsch



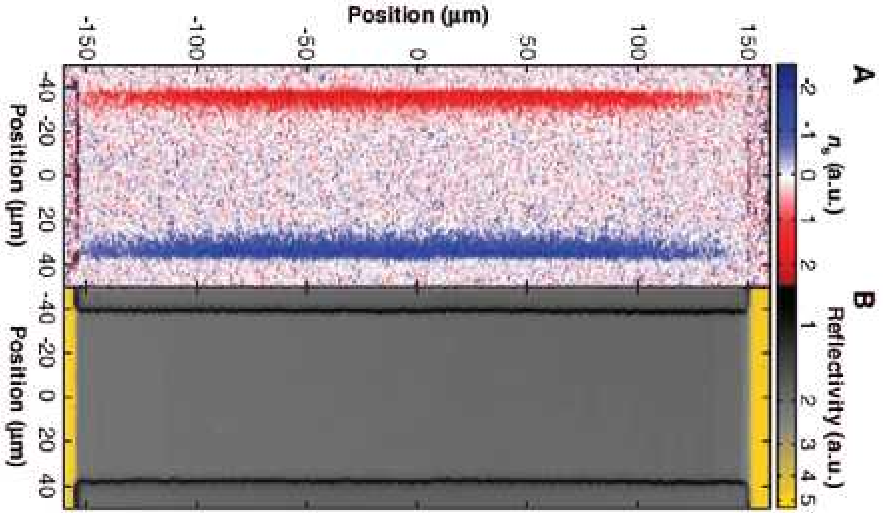
Spin Hall effect : recent observations in GaAs based SC

Detection : kerr rotation or polarized EL

Observation of the Spin Hall Effect in Semiconductors

Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom*

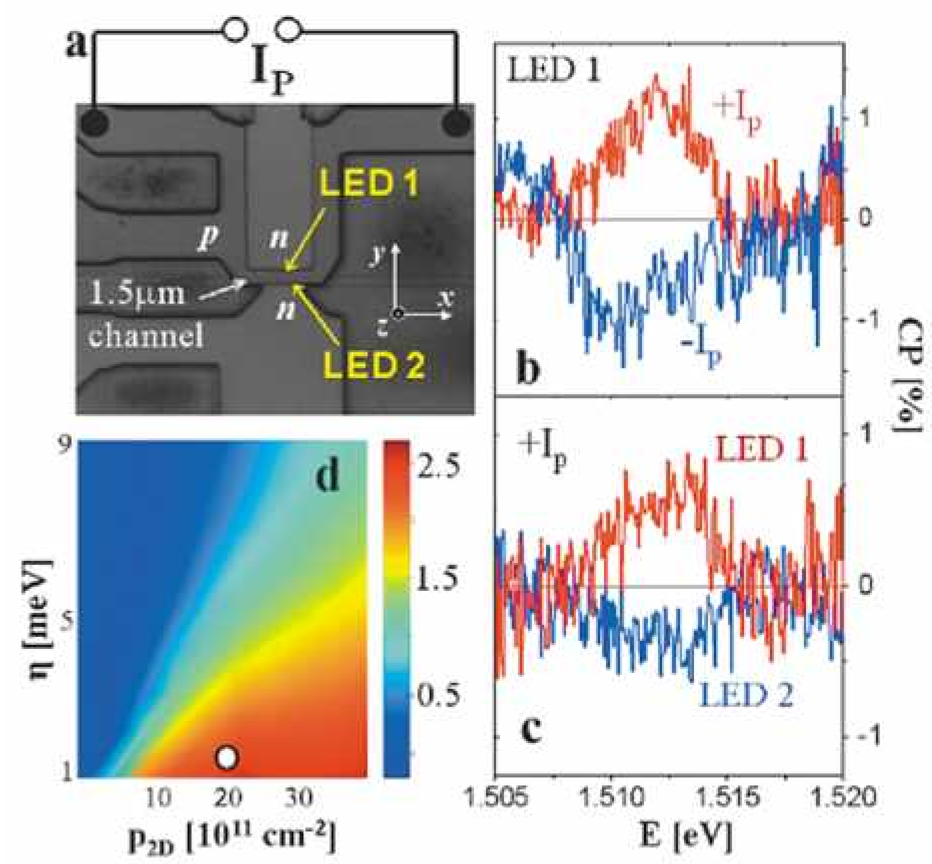
Electrically induced electron-spin polarization near the edges of a semiconductor channel was detected and imaged with the use of Kerr rotation microscopy. The polarization is out-of-plane and has opposite sign for the two edges, consistent with the predictions of the spin Hall effect. Measurements of 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.



PRL 94, 047204 (2005) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2005

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. Jungwirth[4,5]
[1]Hitachi Cambridge Laboratory, Cambridge CB3 0HE, United Kingdom
[2]National Physical Laboratory, Teddington TW11 0LW, United Kingdom
[3]Department of Physics, Texas A&M University, College Station, Texas 77843-4242, USA
[4]Institute of Physics ASCR, Cukrovarnická 10, 162 53 Praha 6, Czech Republic
[5]School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom
(Received 16 November 2004; published 4 February 2005)

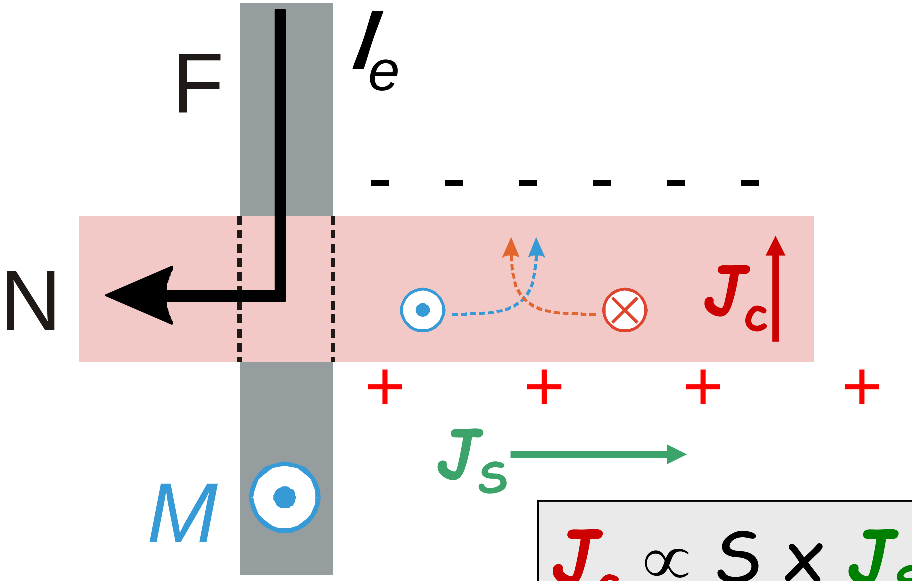


Y. K. Kato *et al.* Science **306**, 1910 (2004).

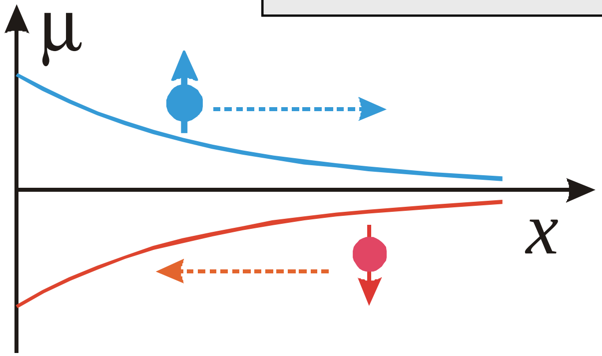
J. Wunderlich *et al.* Phys. Rev. Lett. **94** (2005)

“Inverse” spin Hall effect in metallic systems

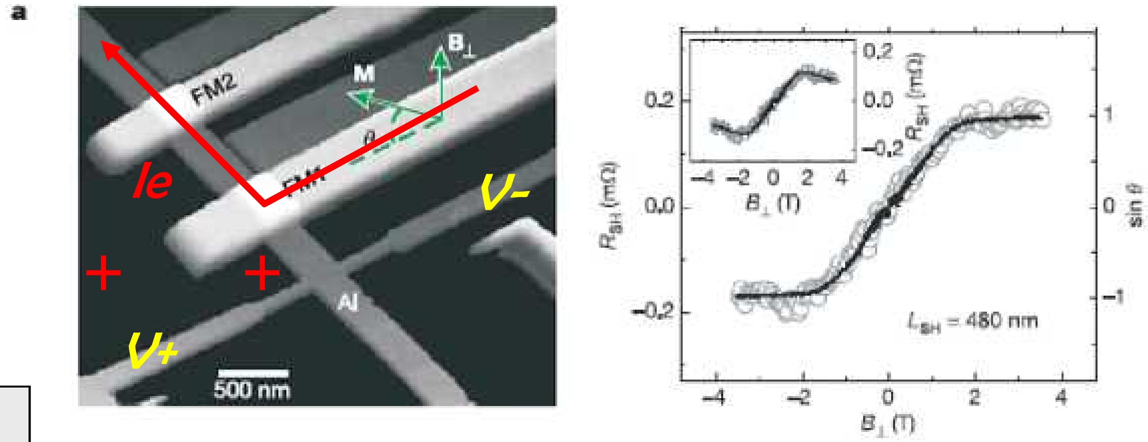
Non-local spin Hall device



$$J_c \propto S \times J_s$$



Observation of Inverse SHE of Al wire at 4 K.



Valenzuela & Tinkham
Nature **442**, 176 (2006)

Electrical detection

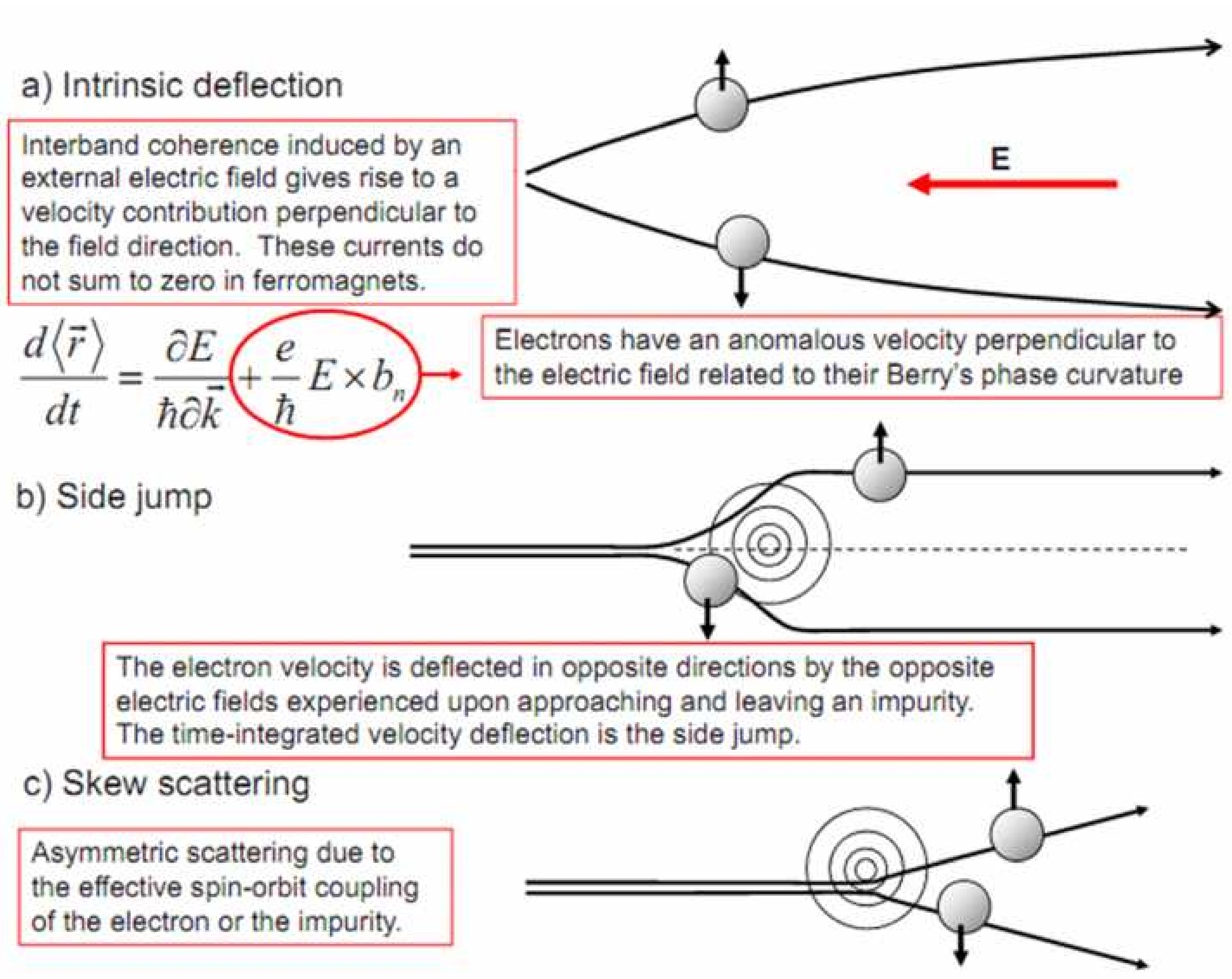
E. Saitoh et al,
Appl. Phys. Lett. **88**, 182509 (2006)

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.

Microscopic origin



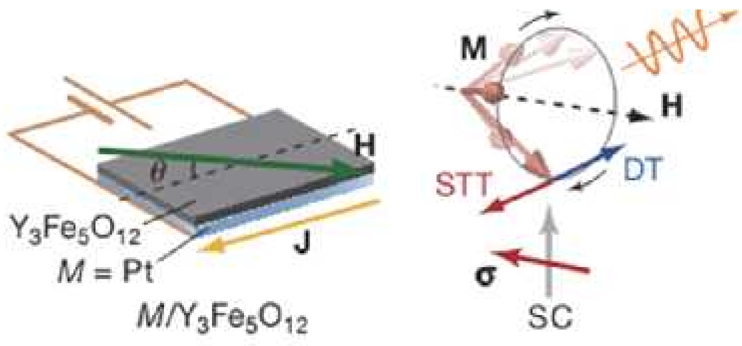
Nagaosa et al, Rev. Mod. Phys. 10'

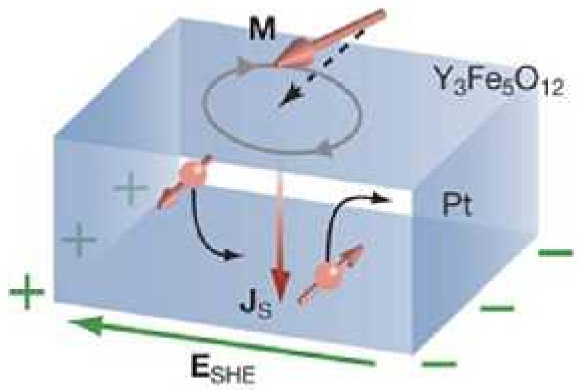
Exploitation of the spin Hall effect

LETTERS

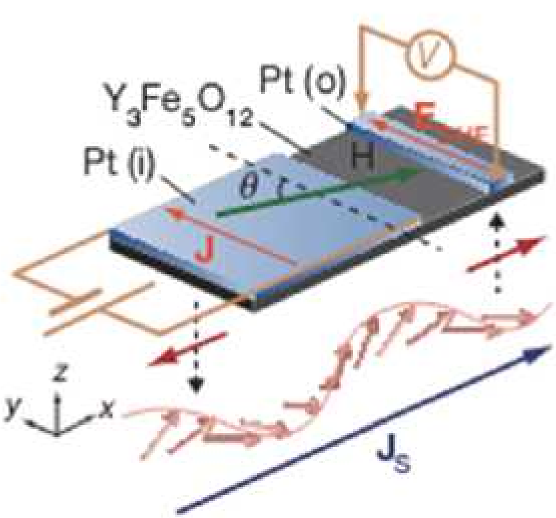
Transmission of electrical signals by spin-wave interconversion in a magnetic insulator

Y. Kajiwara[1,2], K. Harii[1], S. Takahashi[1,3], J. Ohe[1,3], K. Uchida[1], M. Mizuguchi[1], H. Umezawa[5], H. Kawai[5], K. Ando[1,2], K. Takanashi[1], S. Maekawa[1,3] & E. Saitoh[1,2,4]





a



Spin Hall/Orbit Effects : nowadays

Techniques and Analyses improvements:

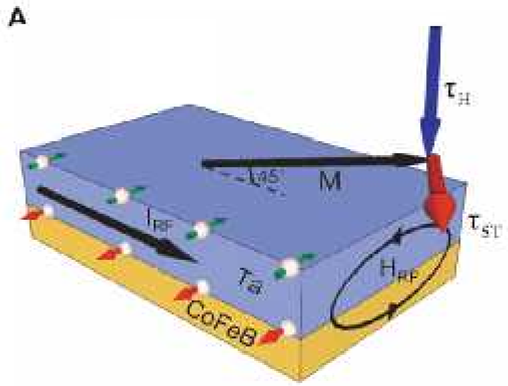
New materials !

CuIr: Y. Niimi *et al.*, PRL. 106, 126601 (2011)
Highly resistive Ta: L. Liu *et al.*, Science 336, 555 (2012)
CuBi: Y. Niimi *et al.*, PRL 109, 156602 (2012)
Pt/Co/AL$_2$O$_3$: M. Miron, Nat. Mat. 9, 230 (2010) + Pt/(Co/Ni)/Pt
Beta Ta and W

Spin Hall Angles: Js/Jc

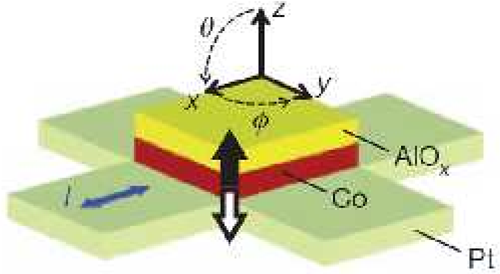
material	α
Pt	0.02 – 0.12
CuIr	0.021
CuBi	−0.25
Ta	-- 0.15
AuW	0.06 – 0.10
W	*-0.3*

Towards applications:



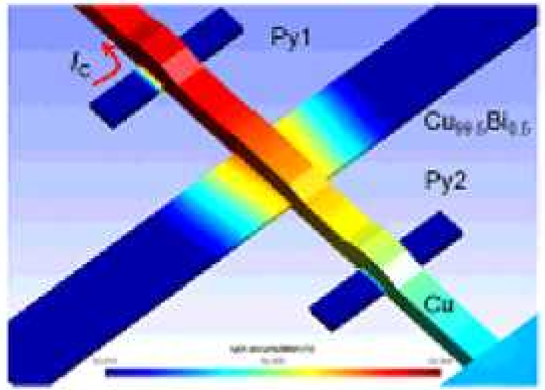
L. Liu *et al.*, Science 336, 555 (2012)

M. Miron *et al.*, Nature 476, 189 (2012)



L. Liu *et al.*, PRL, 109, 096602 (2012)

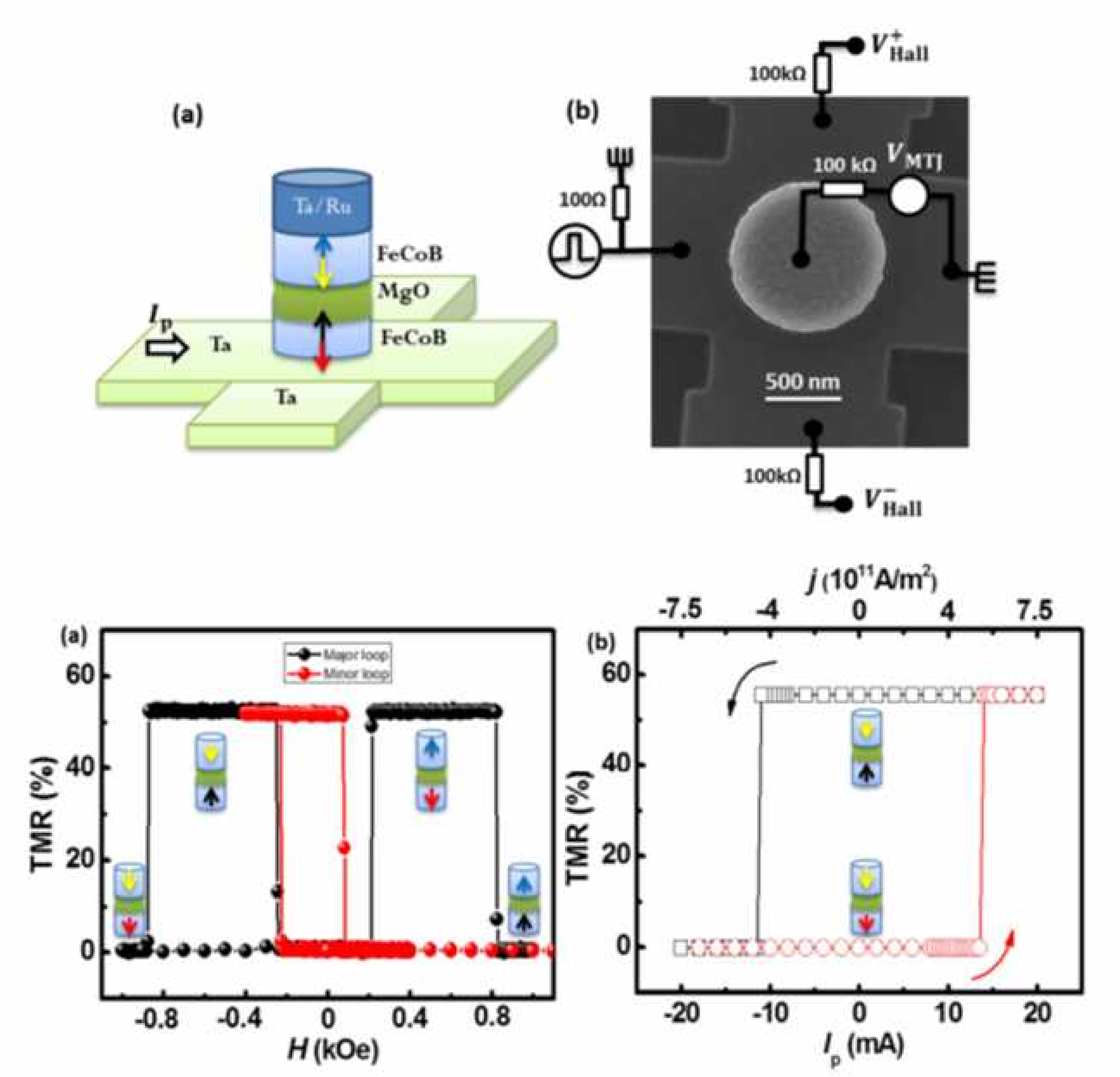
3D modeling SpinFlow:



Spin Hall/Orbit effects are technologically relevant !

Magnetization switching by Spin Orbit Torque

Switching time << 1 ns, K. Garello et al



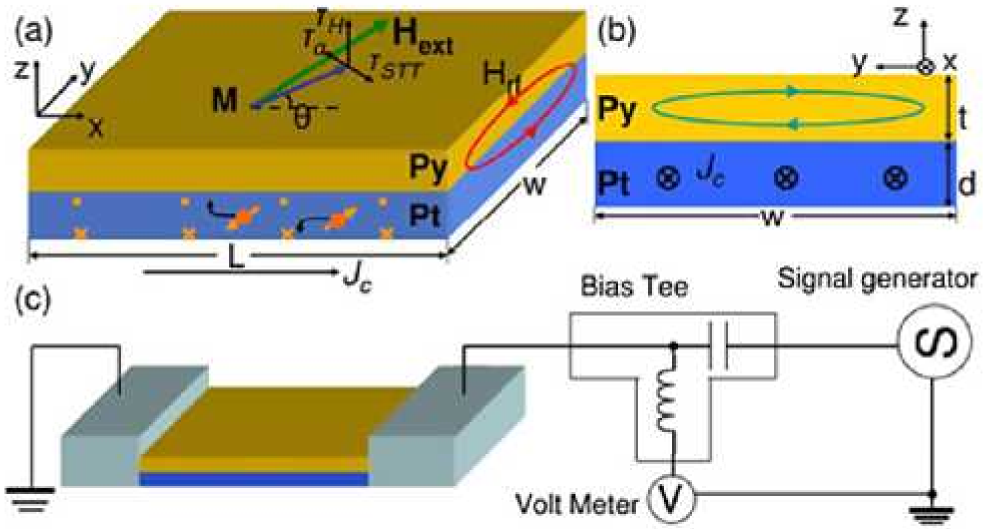
M. Cubukcu et al, APL 2014

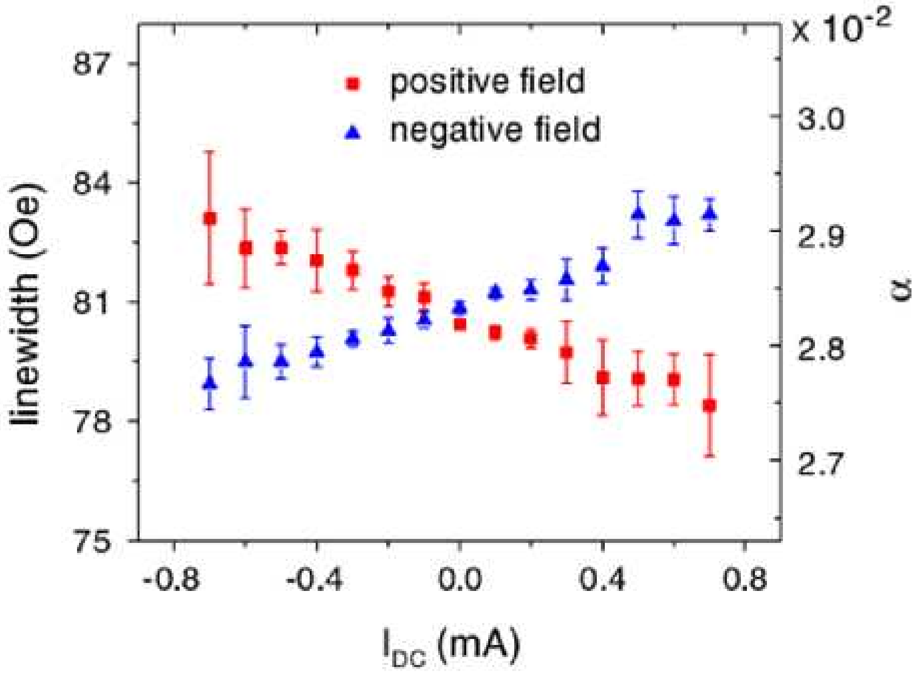
Exploitation of the spin Hall effect

PRL 106, 036601 (2011) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2011

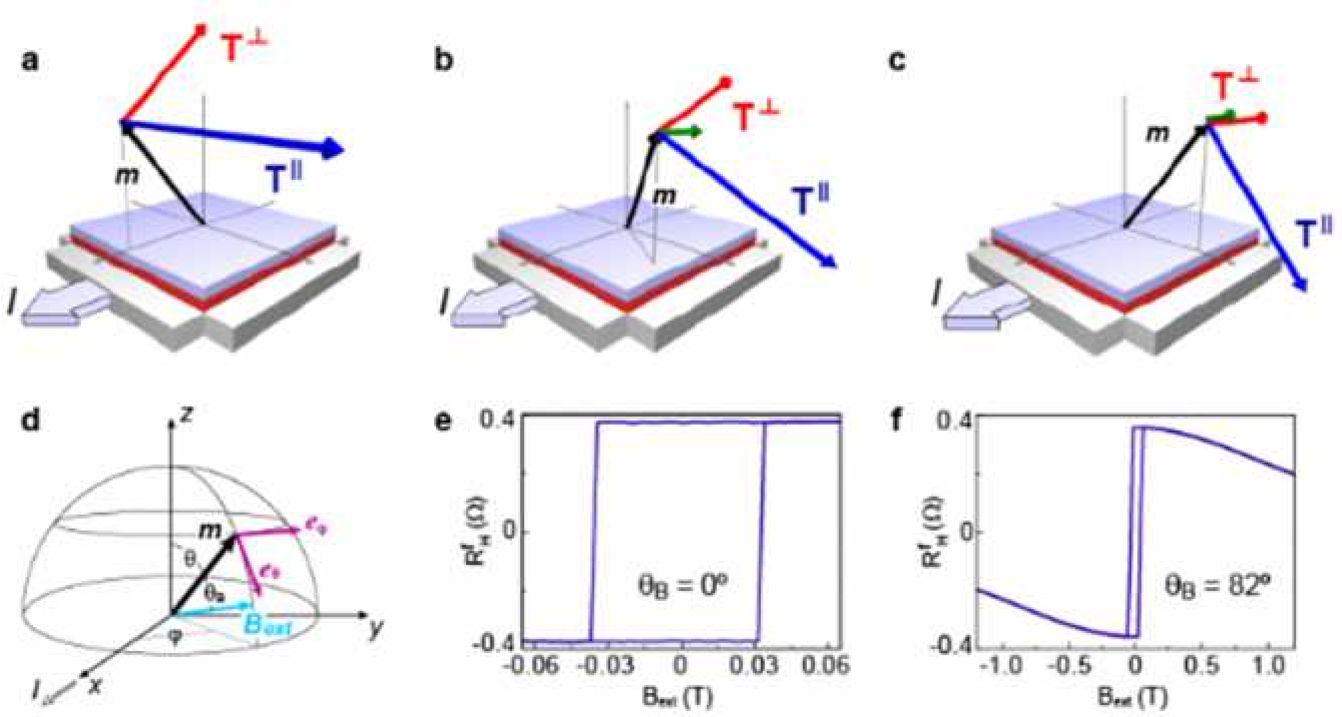
Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect

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)



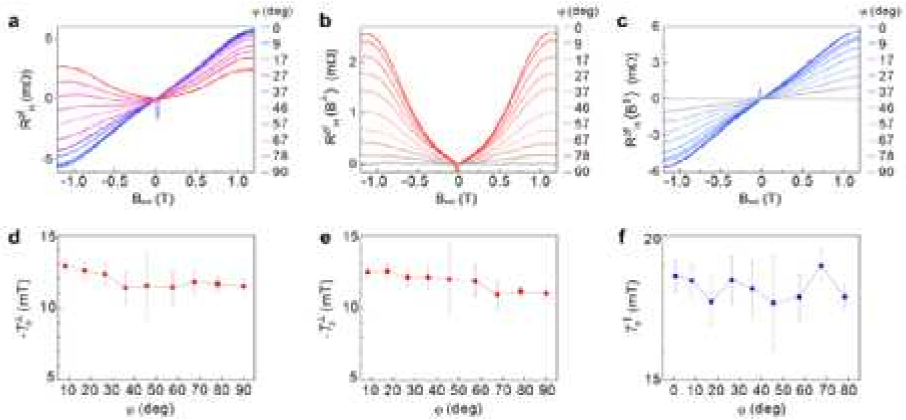


Second Harmonic Torque measurement



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

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

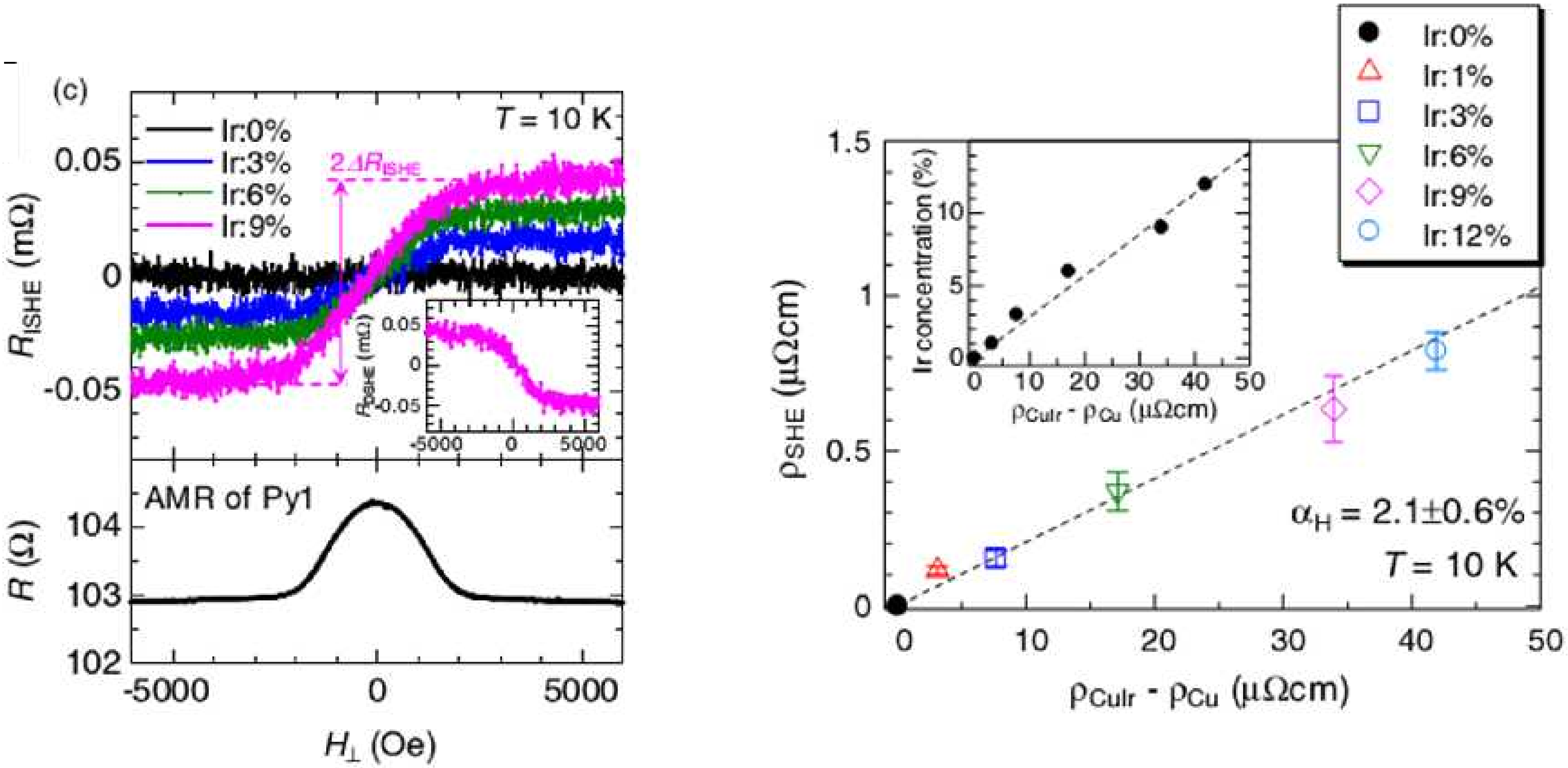


Problem: heat effects

Symmetry and magnitude of spin-orbit torques in ferromagnetic heterostructures, K. Garello et al Nat. Nano 2013

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. Otani[1,4]
[1]*Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa, Chiba 277-8581, Japan*
[2]*Unité Mixte de Physique CNRS/Thales, 91767 Palaiseau France associée à l'Université de Paris-Sud, 91405 Orsay, France*
[3]*Department of Physics, Faculty of Science, University of Zagreb, P.O. Box 331, HR-10002 Zagreb, Croatia*
[4]*RIKEN-ASI, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
(Received 12 January 2011; published 22 March 2011)



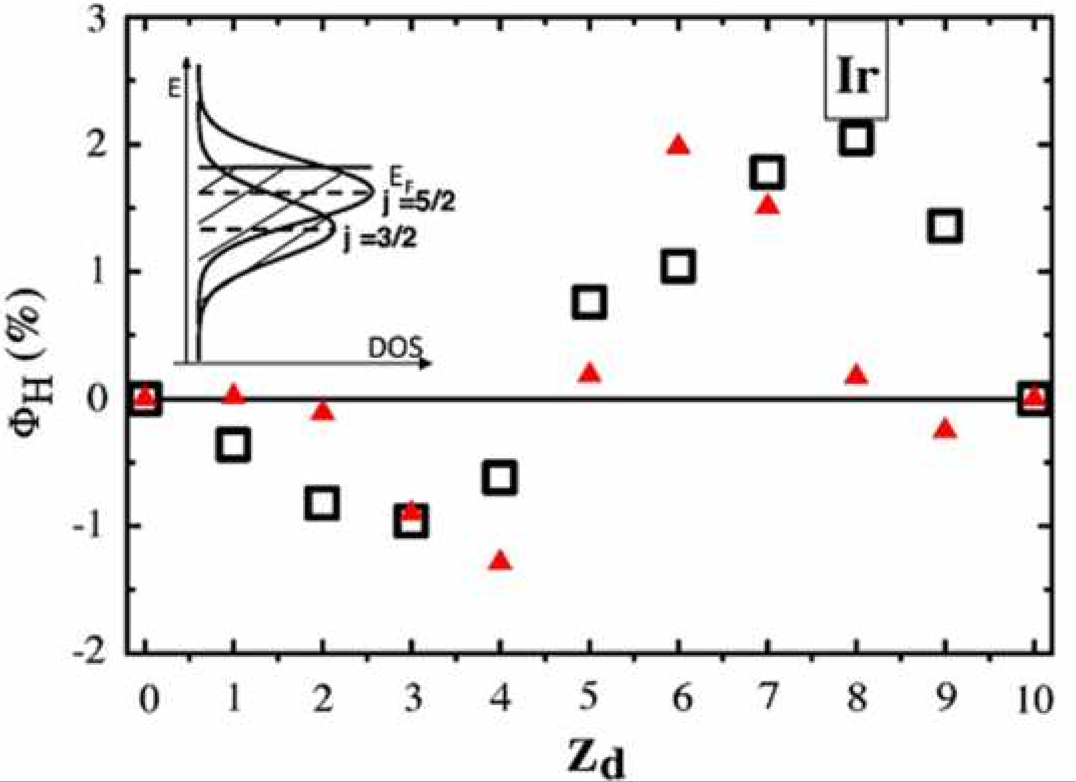
Spin Hall Effect Induced by Resonant Scattering on Impurities in Metals

Albert Fert
Unité Mixte de Physique CNRS/Thales, 91767, Palaiseau, France and Université Paris-Sud, 91405, Orsay, France

Peter M. Levy
Department of Physics, New York University, 4 Washington Place, New York, New York 10003, USA
(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 5*d* impurities we describe the general conditions and provide a guide for experimentalists for obtaining the largest effects.

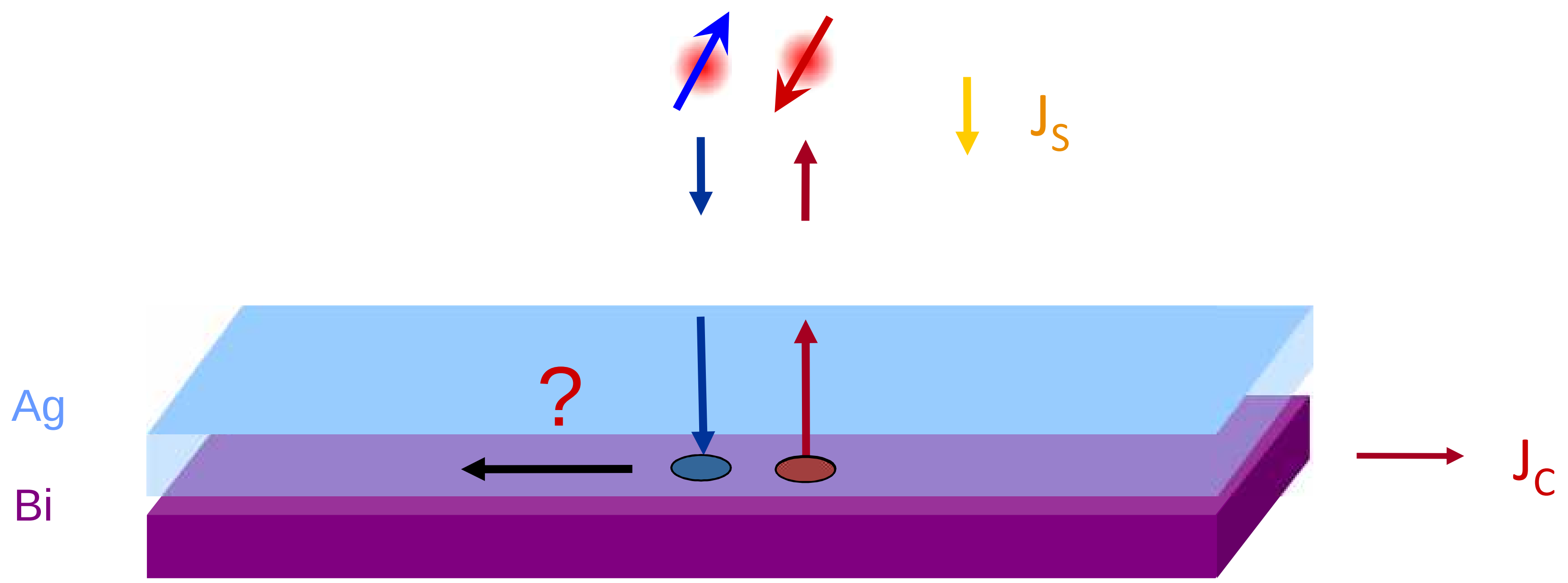
DOI: 10.1103/PhysRevLett.106.157208 PACS numbers: 85.75.−d, 73.50.Jt, 75.76.+j



Cu matrix
with 2% imp.

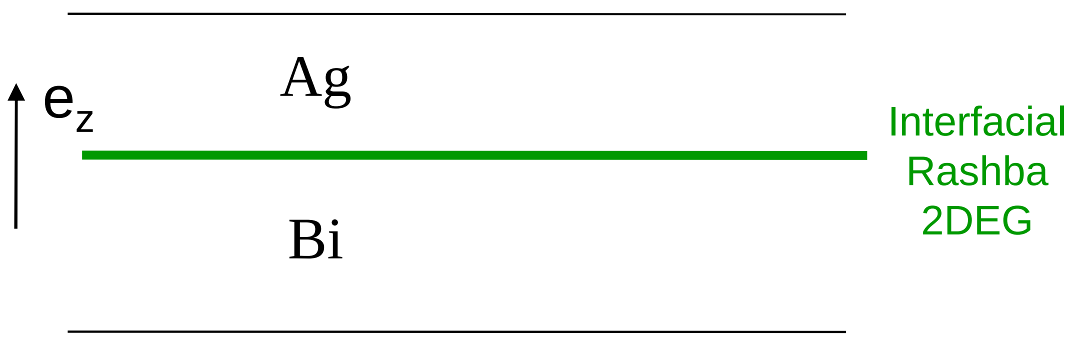
Spin to charge conversion at Rashba interfaces

- 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)



J.C. Rojas Sanchez, et al,
Nat. Commun. 4:2944 doi: 10.1038/ncomms3944 (2013)

Rashba effect at interfaces or surfaces of materials

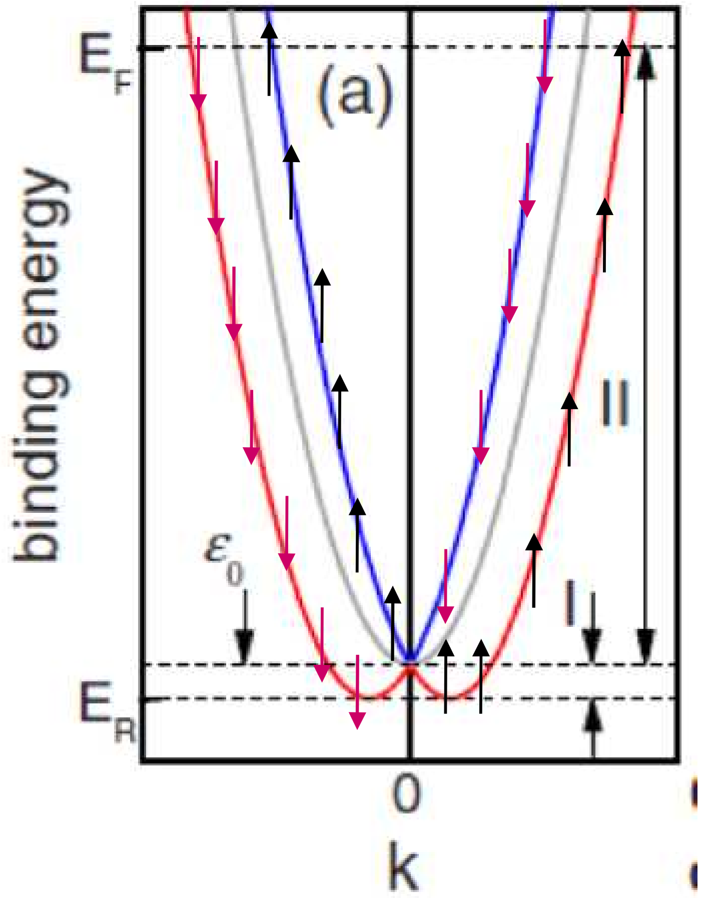


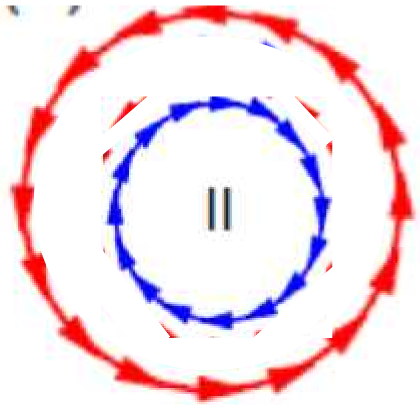
$$\hat{H}_{SO} = \alpha_R \boldsymbol{\sigma} \cdot (\boldsymbol{k}_{\parallel} \times \mathbf{e}_z), \quad \alpha_R \sim \frac{\partial V}{\partial z}$$

$$\text{Bi/Ag(111): } \alpha_R = 3.05 \text{ eV}\mathring{A}$$

Material	E_R (meV)	k_0 ($\mathring{A}^{-1}$)	α_R (eV $\mathring{A}$)
InGaAs/InAlAs heterostructure	<1	0.028	0.07
Ag(111) surface state	<0.2	0.004	0.03
Au(111) surface state	2.1	0.012	0.33
Bi(111) surface state	~14	~0.05	~0.56
Bi/Ag(111) surface alloy	200	0.13	3.05

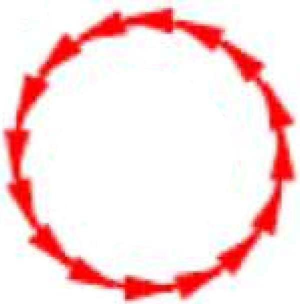
Ast et al. PRL 2007

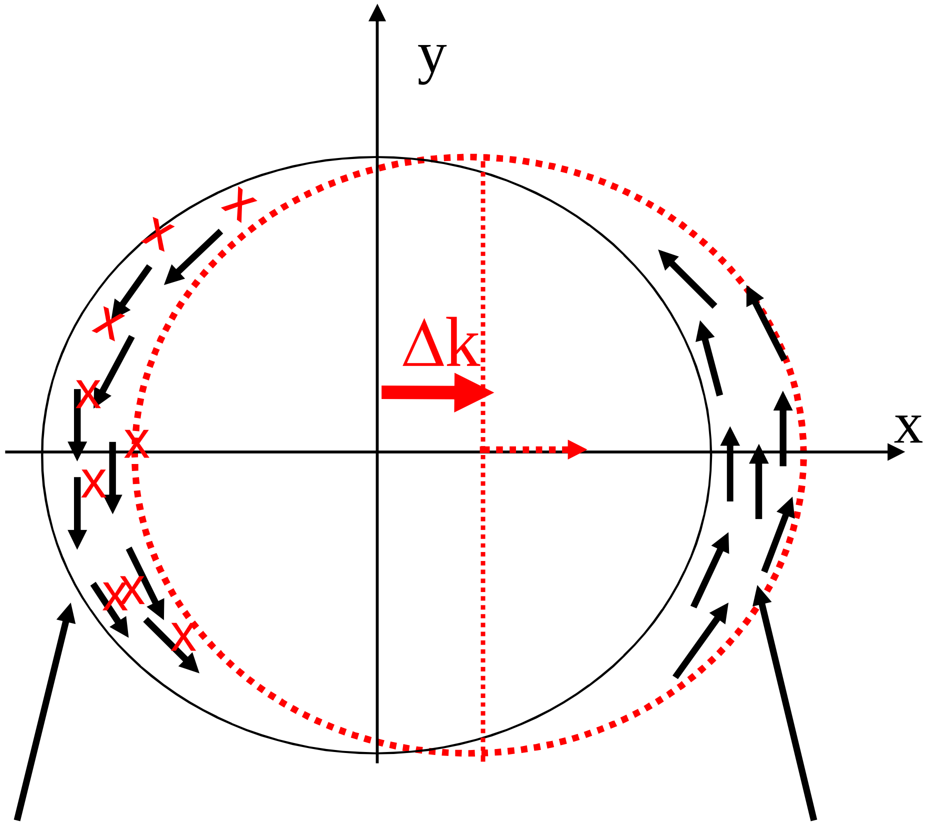




Fermi contours

Current-induced spin accumulation in the presence of Rashba coupling (Edelstein-Rashba effect)





deficit of spin ↓ electrons + excess of spin ↑electrons

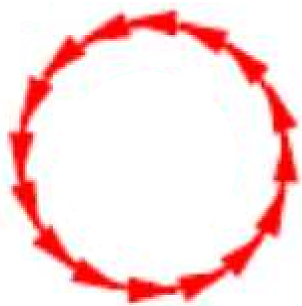
= spin ↑ accumulation

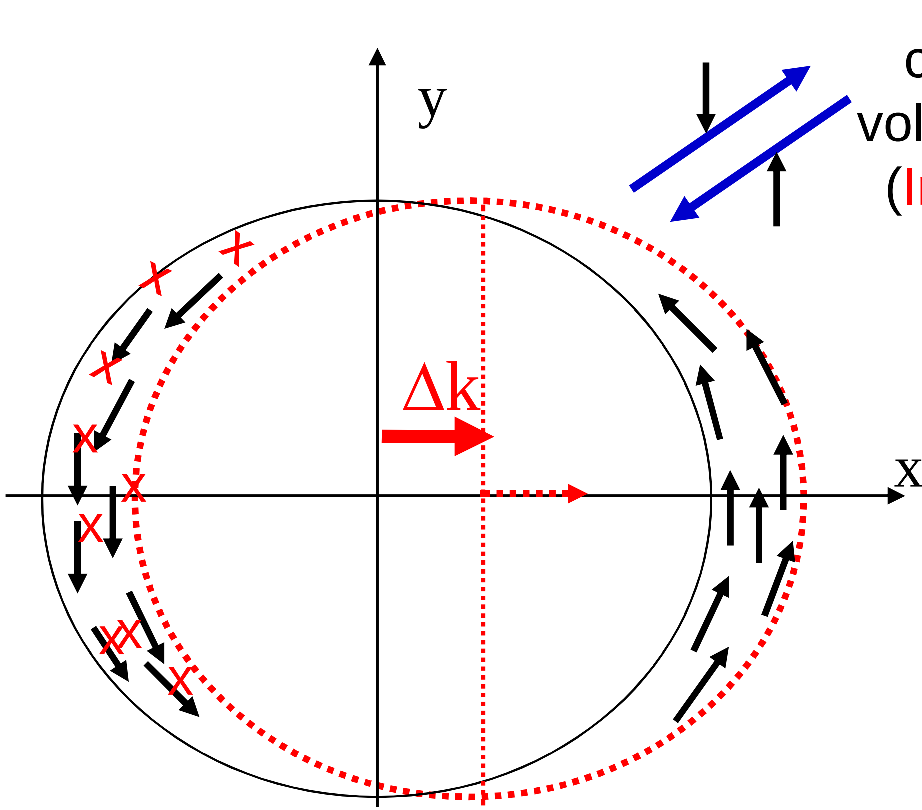
Edelstein-Rashba effect

Courtesy of A. Fert

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

Spin current injection



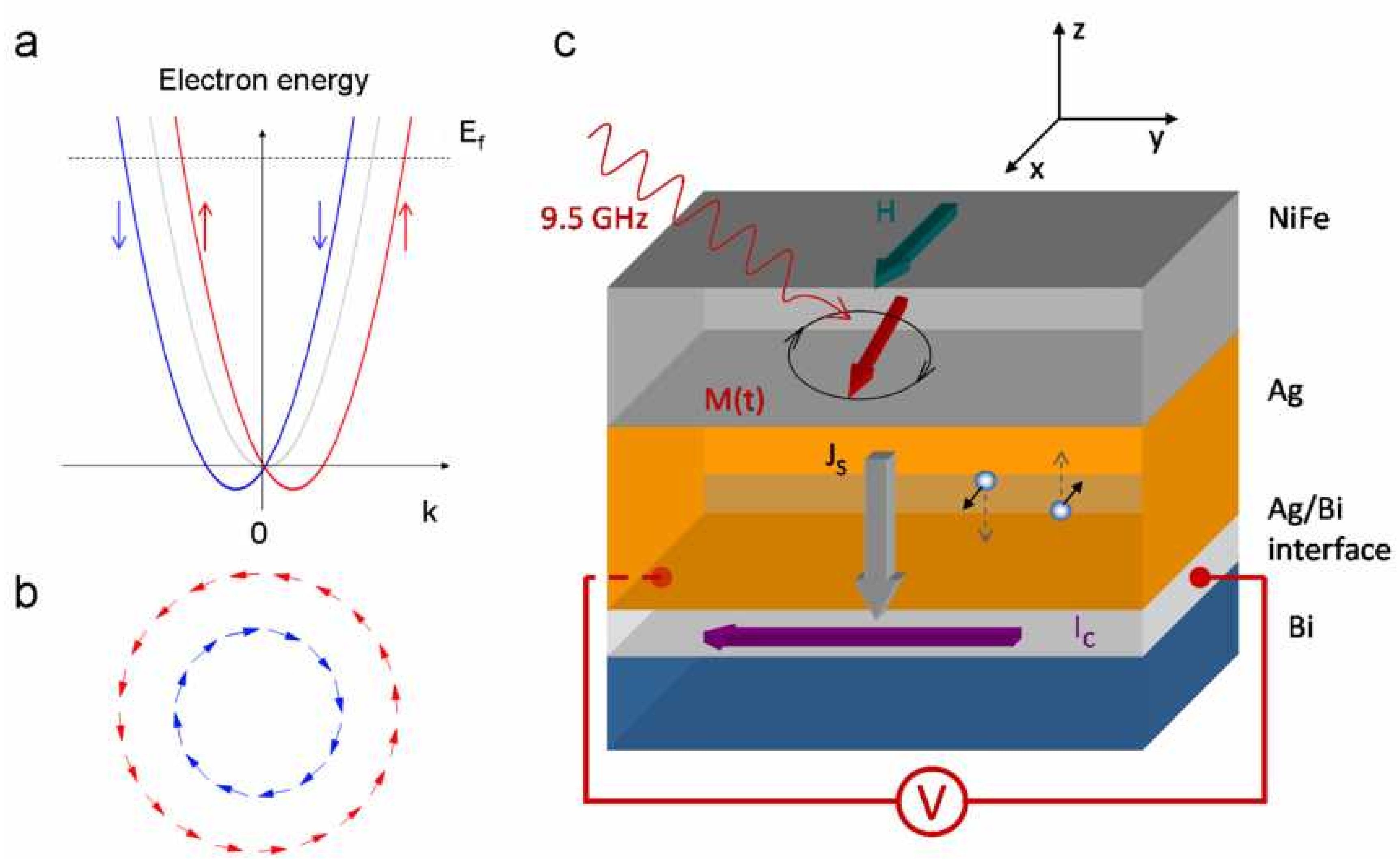


charge current or voltage if open circuit (Inverse Edelstein-Rashba effect)

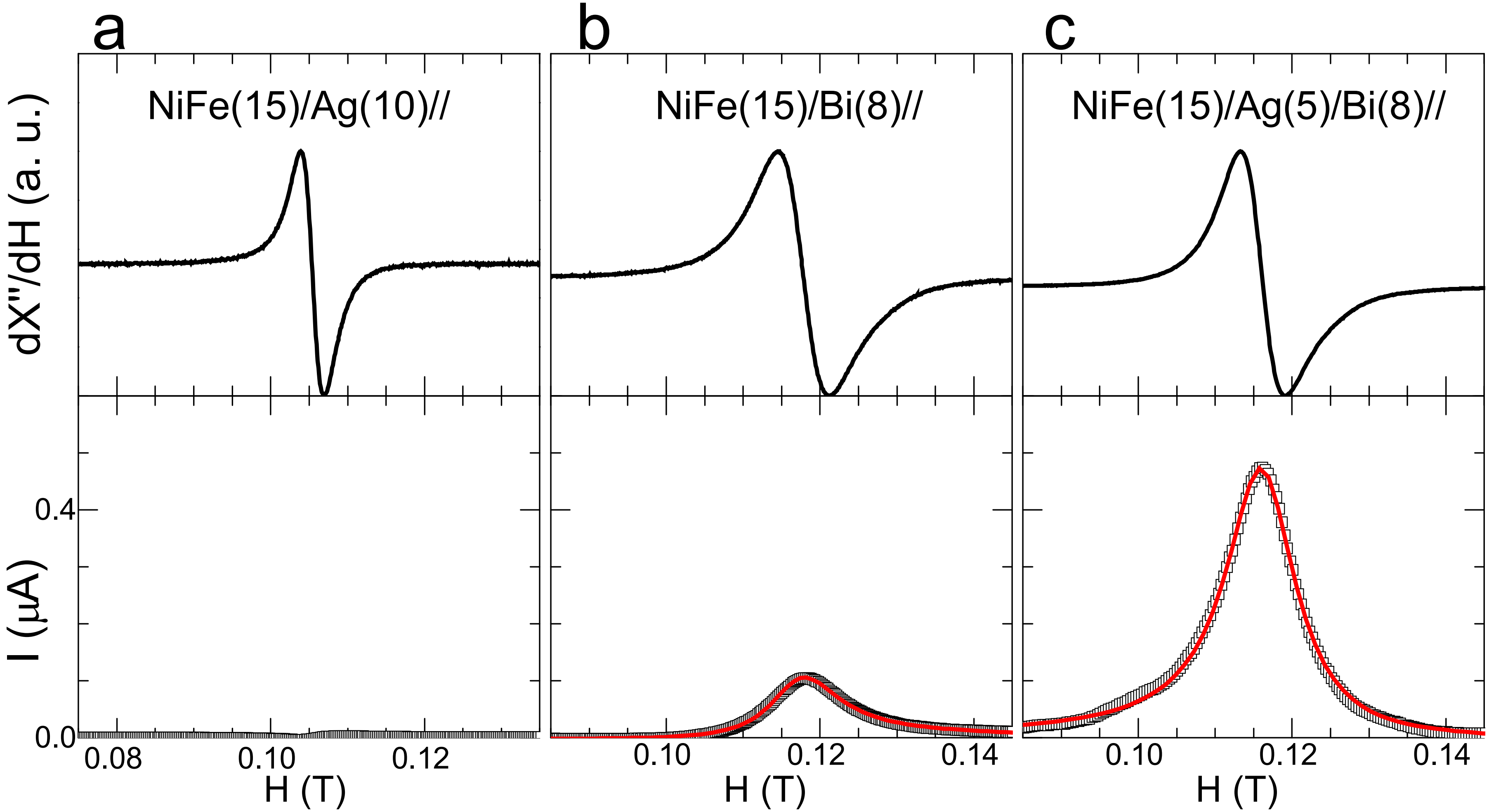
Courtesy of A. Fert

Spin to charge current conversion in Ag/Bi multilayers

$$H_R = \sim_R (k \times \hat{z}).\pm$$

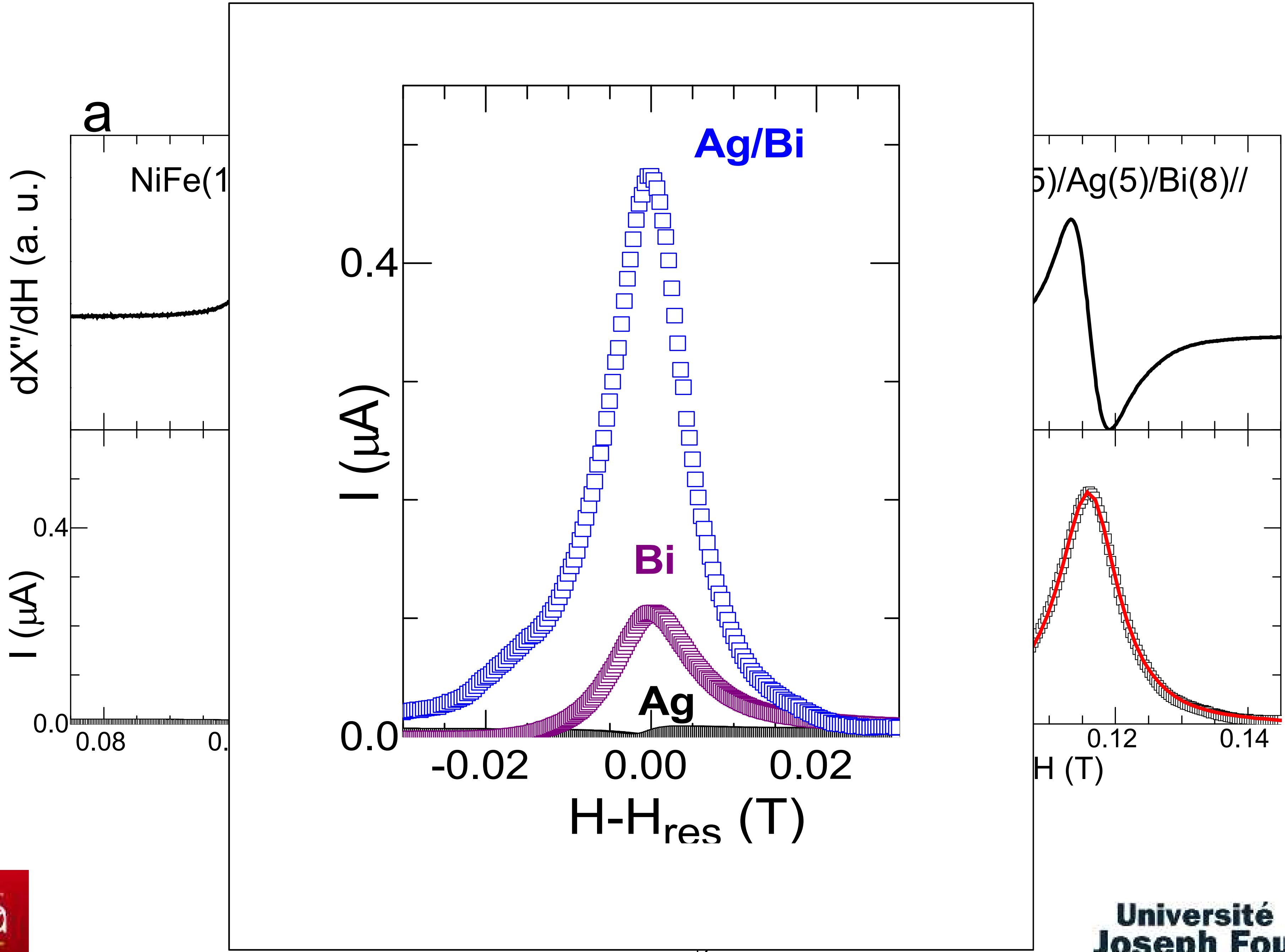


FMR linewidth and charge current production at resonance



$$I_C = \frac{aV}{R_S l}$$

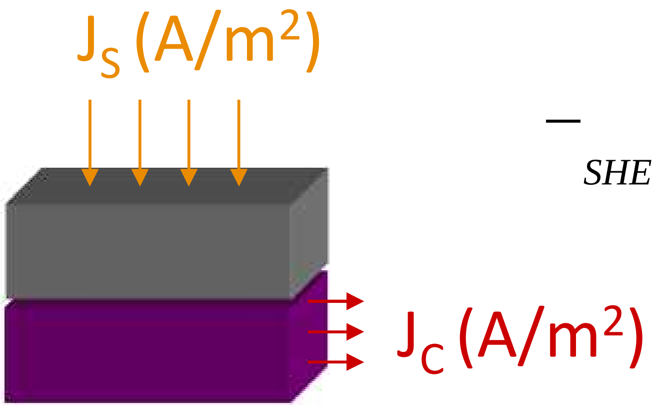
FMR linewidth and charge current production at resonance



Analyzing spin to charge current conversion

J.C. Rojas Sanchez et al, Nat. Commun. (2013)

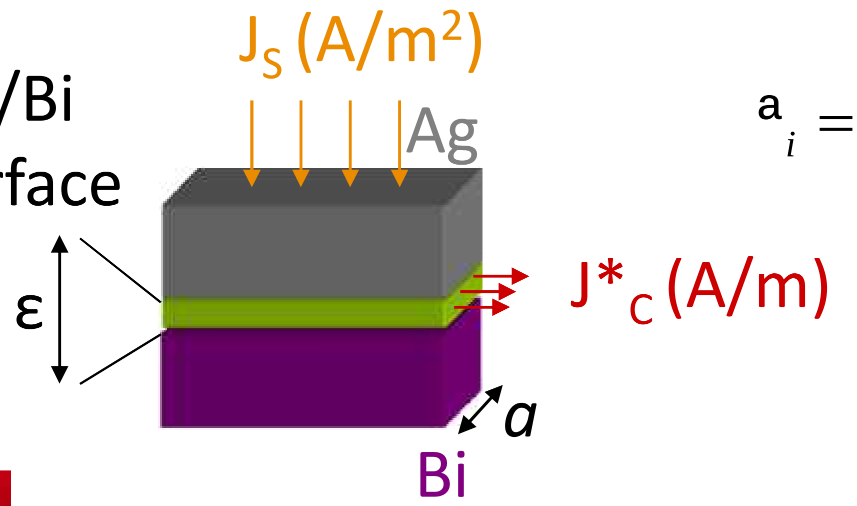
ISHE
in Bi



$$-_{SHE} = \frac{J_C}{J_S}$$

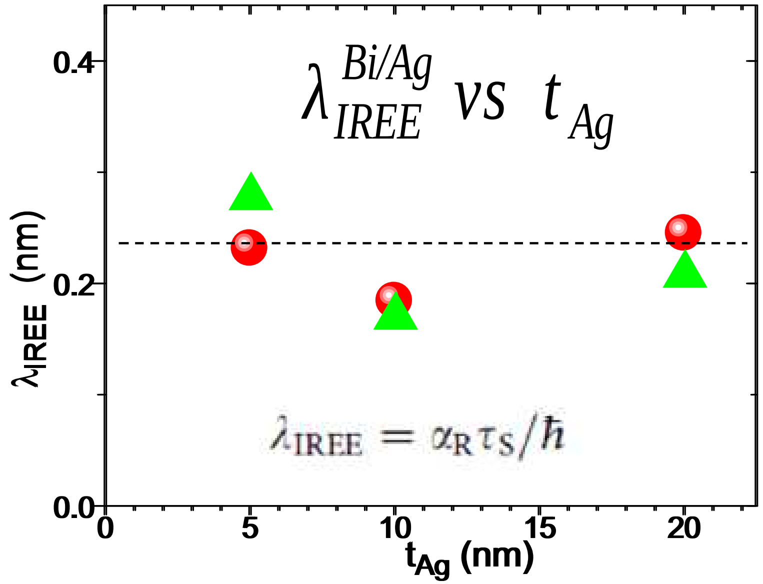
$g_{eff}^{\uparrow\downarrow} \sim 2\ 10^{19}\ m^{-2}$ $J_s \sim 5 - 6\ MA\ m^{-2}$

Ag/Bi
interface



$$a_i = \frac{J^*_C}{J_S}$$

Inverse Rashba Edelstein length



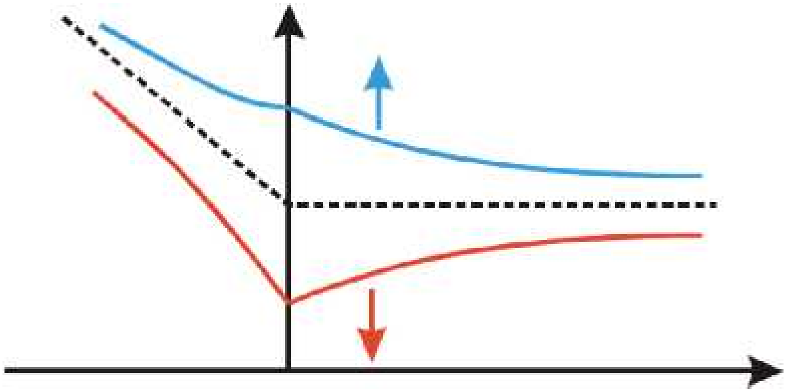
For SHE in a 0.4 nm thick Ag/Bi interfacial alloy layer:

$$\Theta_{SHE} \approx 2J_C^* / (J_s t_I) = 1.5\ (150\%)!!$$

Sign is reversed by stacking order (cf Viret's group) !

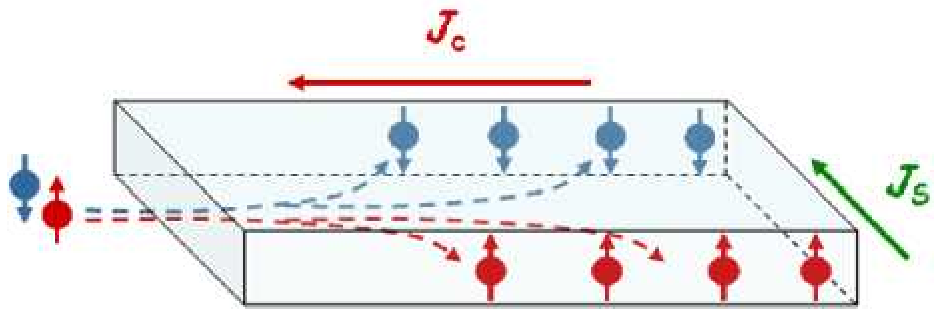
Spin current induced by

FM/NM junction



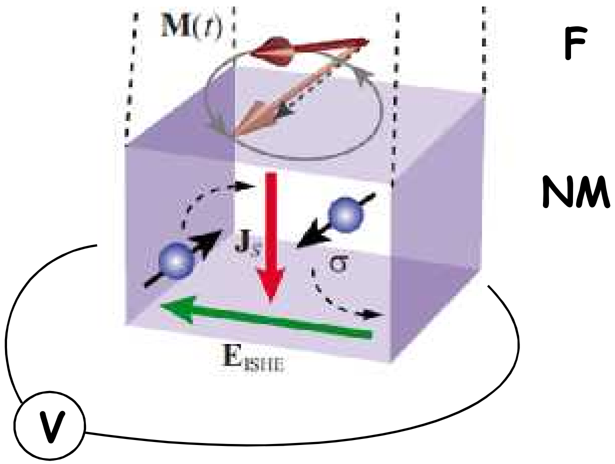
Johnson, Silsbee 1985, Jedema 2001

Spin Orbit Coupling



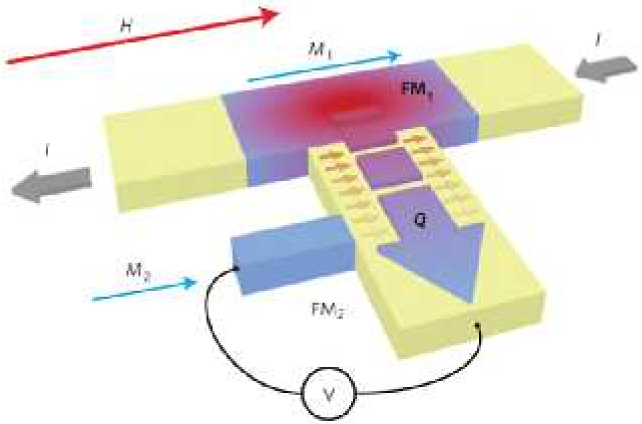
Spin Hall and Rashba effects

Spin Pumping



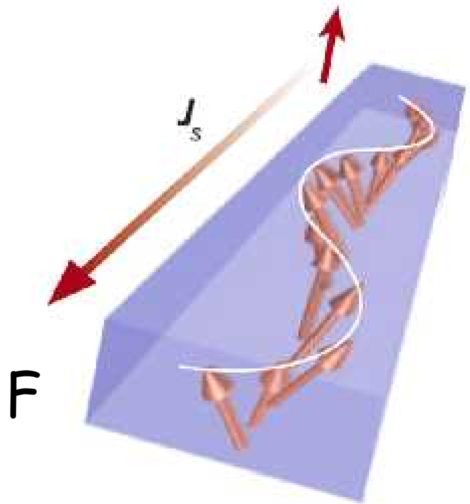
Silsbee, Monod 1979, Tserkovnyak, Bauer 2002
Saitoh 2006

Thermal Spin Injection



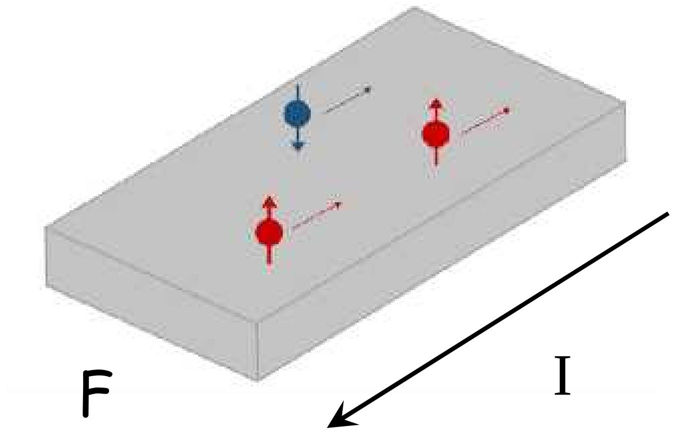
A.Slachter et al. Nat. Phys. 2010

Spin waves

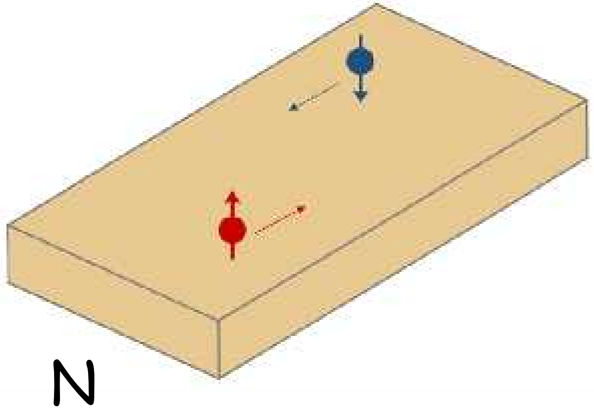


Kajiwara *et al*. Nature Phys. 2010

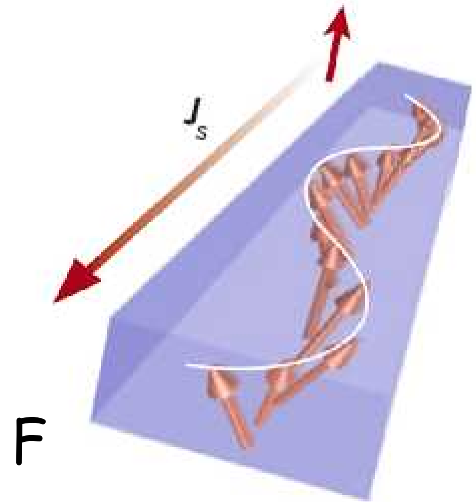
Conclusion



Spin-polarised current



Pure spin current



Spin waves

MR and current induced magnetic switching rely on how spin currents fow in magnetic nanostructures

Various way to produce spin currents, including SOC (spin-orbitronics)

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

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Thank you !