Spin Hall effect and Spin-Orbit Torques

An Overview

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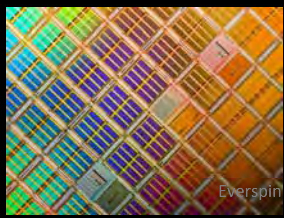
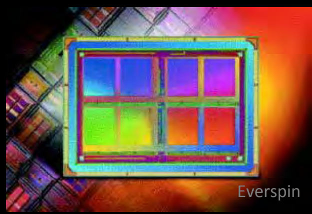
Barcelona





Universitat Autònoma de Barcelona

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An overview

Brief introduction

- Spintronics
- Spin-dependent Hall effects
- Spin Hall effect (SHE) and inverse spin Hall effect (iSHE)

Detection of the SHE and iSHE

Spin Hall effects in metals

- Electronic transport experiments
- Spin pumping

Spin orbit torques

- Measurements techniques
- Spin Hall effect torque
- Rashba spin-orbit torque

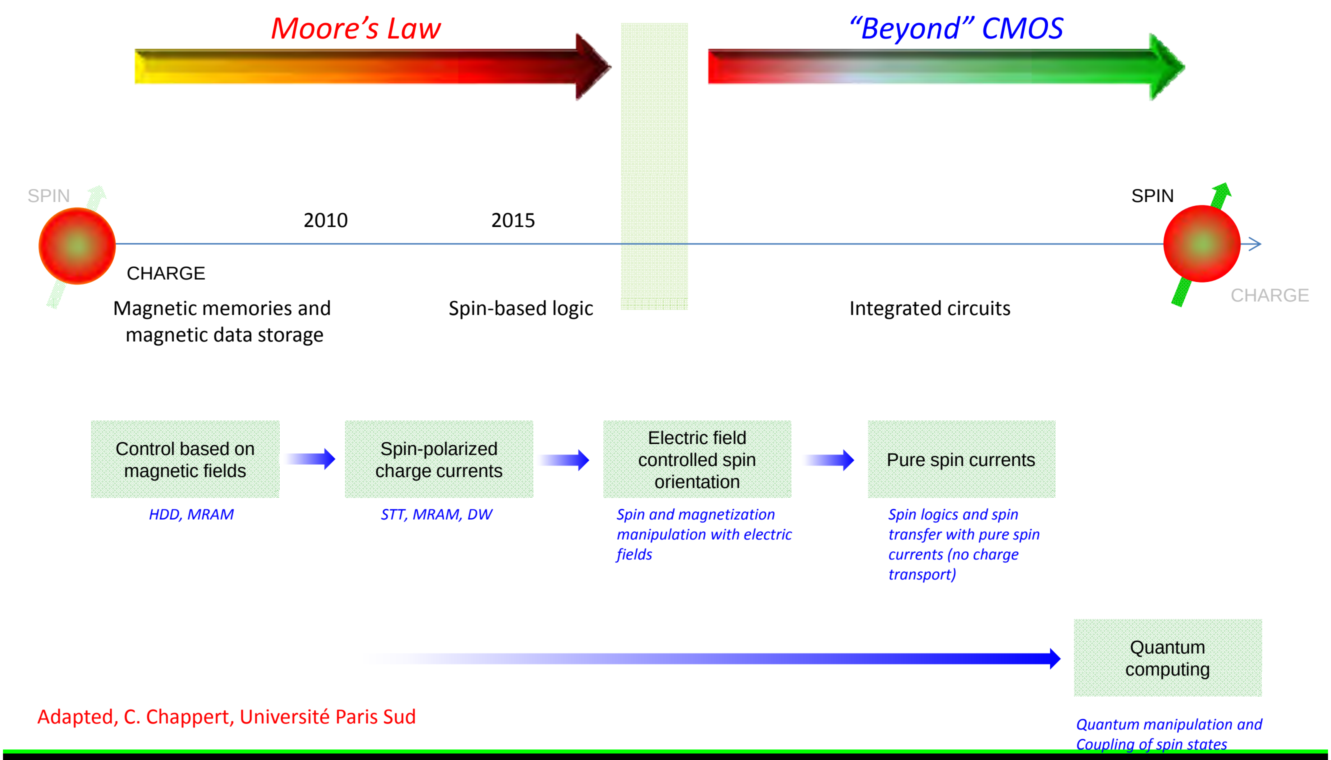
Spin-based electronics. Spintronics

- Conventional electronics uses charge of carriers
- Spin-based electronics incorporates spin of carriers (higher speed and lower dissipation)
- Fundamental elements for spintronic devices
  - Generate spins. Spin injection
  - Transport spins from the source
  - Manipulate spins/macrospin
  - Detect spins

For e review see, I. Zutic, J. Fabian and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004).

Spintronics

Fundamental physics and applications

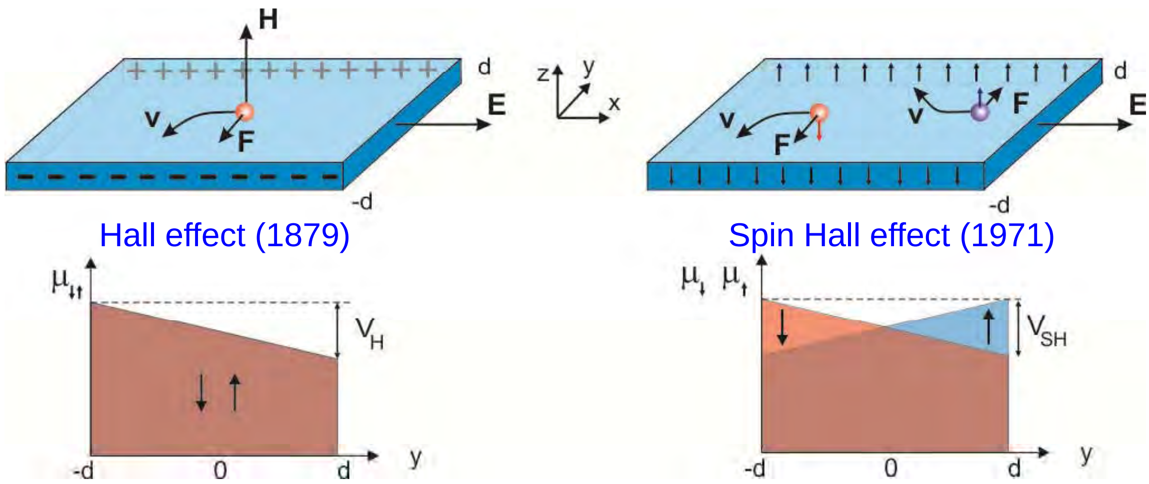


Adapted, C. Chappert, Université Paris Sud

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);

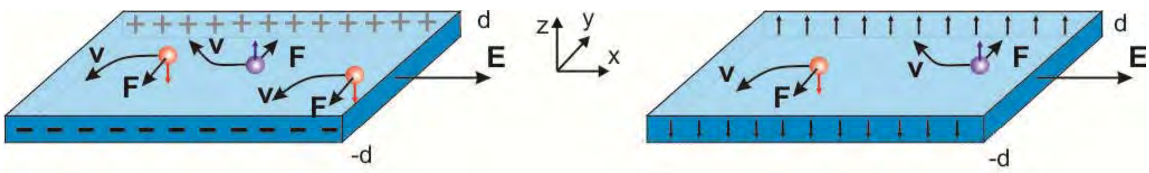
S. Zhang, PRL **85**, 393 (2000); S. Murakami, N. Nagaosa, S.C. & Zhang. Science **301**, 1348 (2003); J. Sinova, *et al.,* PRL **92**, 126603 (2004).

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)

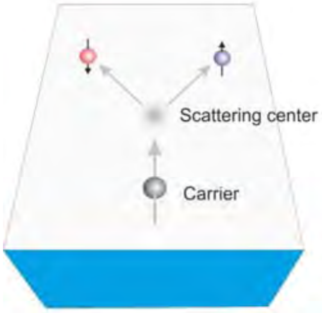
Novel Frontiers in Magnetism, Benasque 2014 *Sergio O. Valenzuela*, SOV@icrea.cat; www.icn.cat/pend

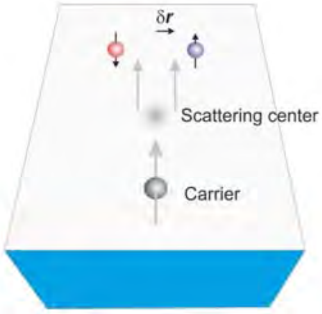
Spin Hall Effects

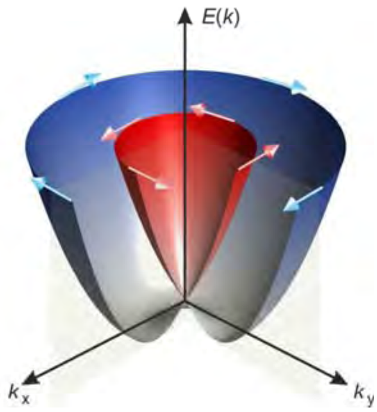
Pure spin currents

Extrinsic

Intrinsic







Skew Scattering

Side-Jump Scattering

Band Structure
E.g. Rashba

Smit, Physica 24, 39 (1958)

Berger, PRB 2, 4559 (1970)

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 vs. Inverse Spin Hall

Spin Hall

Charge Current

⇓

Transverse

Spin Imbalance

Spin Dependent Scattering

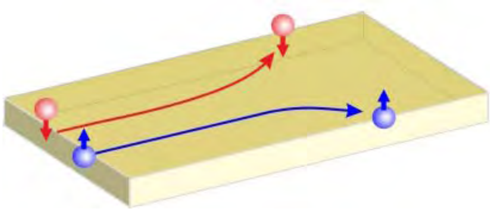
Inverse Spin Hall

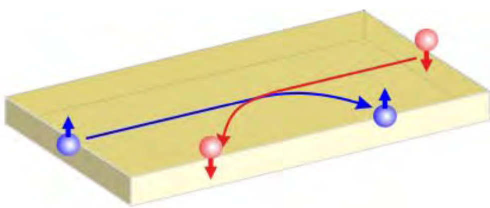
Spin Current

⇓

Transverse

Charge Imbalance





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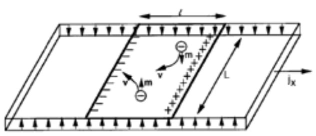
Measurements techniques
Spin Hall effect torque
Rashba spin-orbit torque

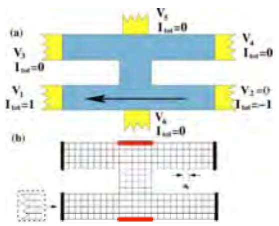
Spin Hall Effects

Observation

"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).





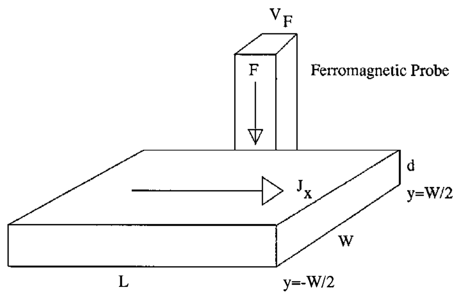
A current generates a spin imbalance trough the spin Hall effect in an Al strip

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).

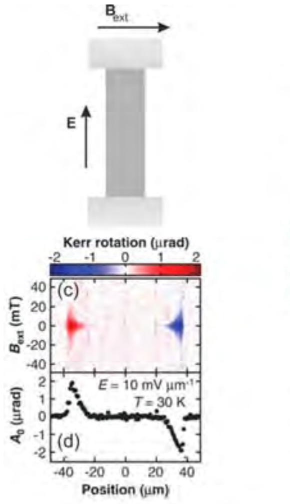


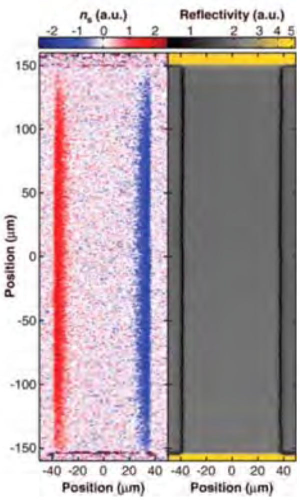
S.F. Zhang. PRL **85**, 393 (2000).

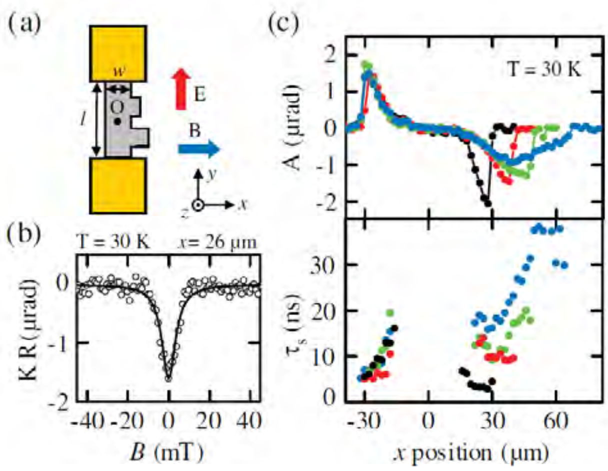
Spin Hall Effects
Observation

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

Direct observation in GaAs with optical detection







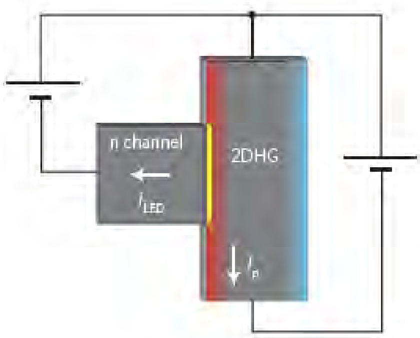
Change in polarization and intensity of light reflected from a magnetized surface (magnetic dependence of the permittivity tensor)

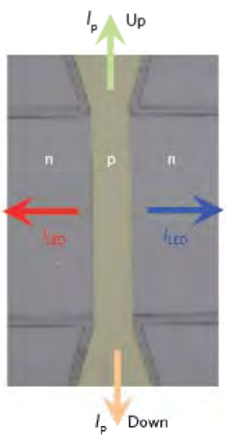
Y. K. Kato *et al.*, Science **306**, 1910 (2004)

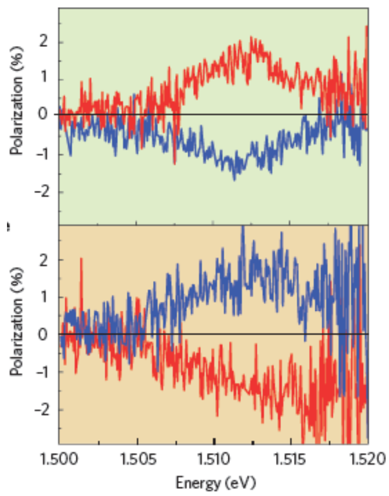
Sih *et al.*, PRL (2006)

Spin Hall Effects
Observation

Circularly polarized electroluminescence (2DEG)





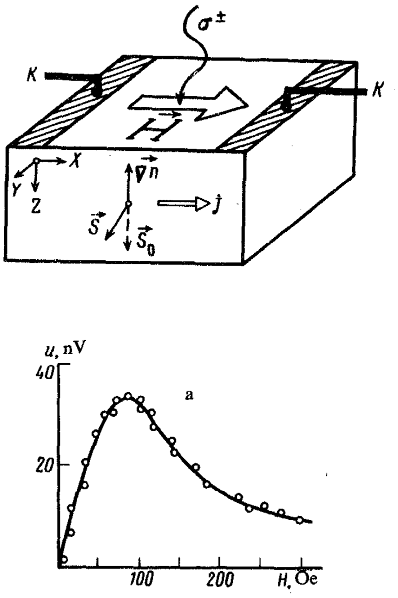


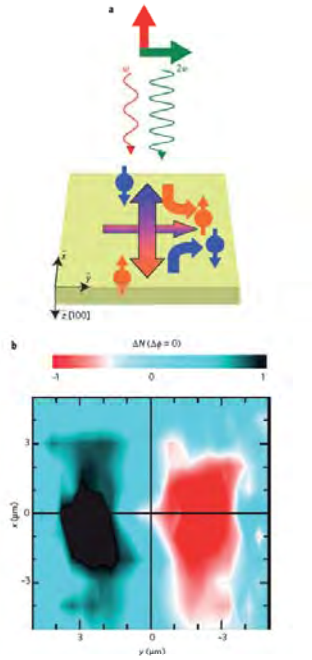
Wunderlich *et al.*, PRL (2005); Jungwirth et al, Nature Materials (2012)

Inverse Spin Hall Effect

Observation

Surface photocurrent by optical orientation in the surface of a semiconductor





A.A. Bakun *et al.*, Sov. Phys. JETP Lett. **40**, 1293 (1984).

Zhao H *et al.*, PRL (2006)

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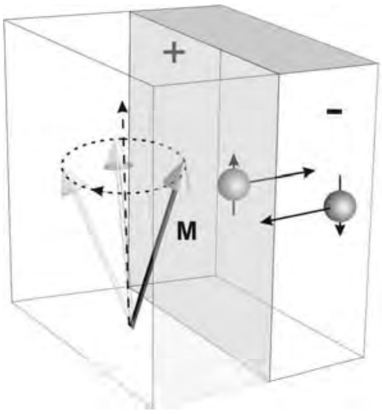
Inverse Spin Hall Effect

Observation in Metals

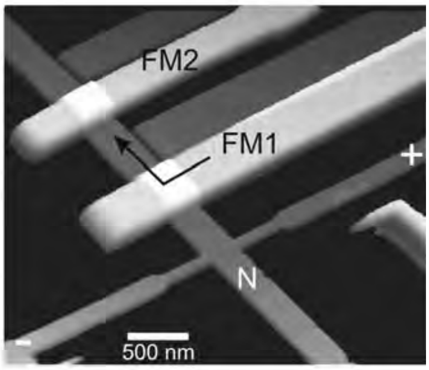
Inverse spin Hall effect as a spin current measurement detection mechanism

Spin current by spin pumping



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

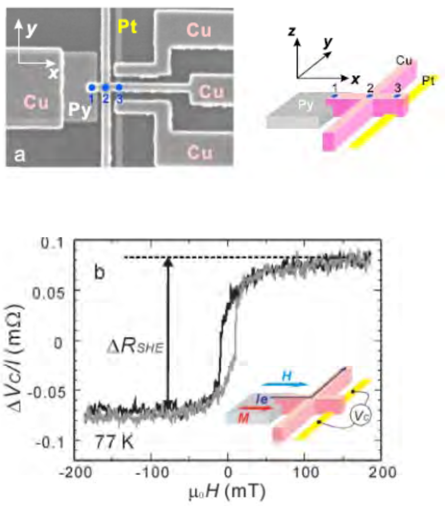
Spin current by electrical injection from FM



SOV *et al.* Nature (2006)

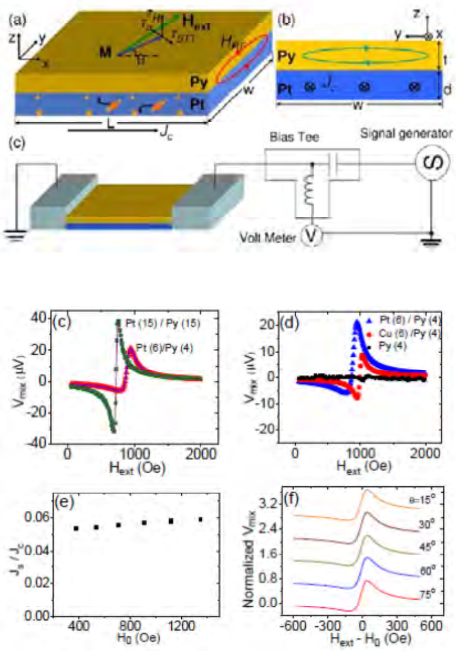
Spin Hall Effect

Observation in Metals



Spin Hall cross adapted for
materials with
short spin relaxation length

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

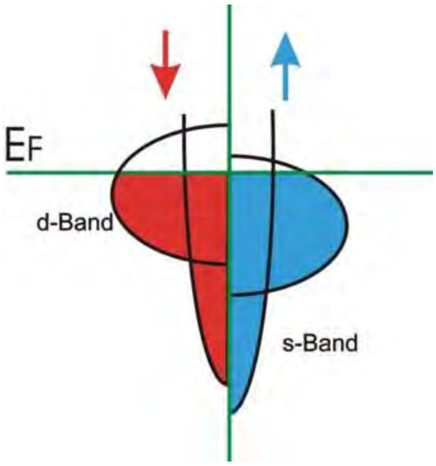


Liu *et al.*, PRL (2011)

Spintronics

Spin generation and spin injection

- Two spin channel model (Mott 1930)
  - Metallic ferromagnets. Spin-up and spin-down are two independent families of carriers



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

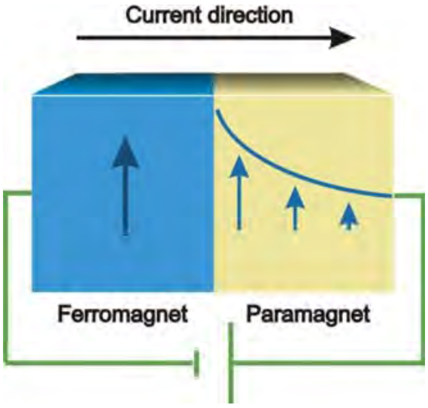
$$P = \frac{N_M - N_m}{N_M + N_m} \qquad -1 \leq P \leq 1$$

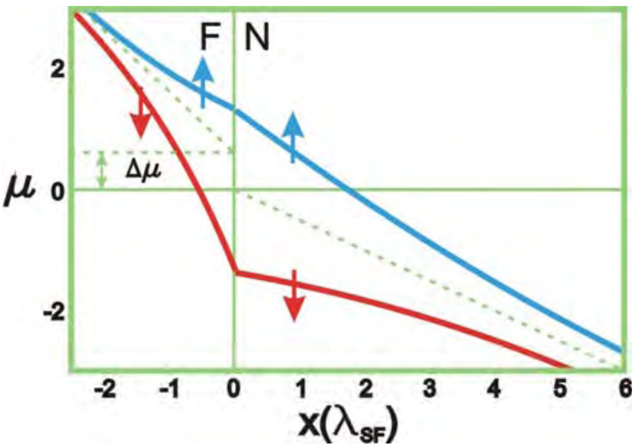
I.I. Mazin, PRL **83**, 1427-1430 (1999)

Spintronics

Spin generation and spin injection

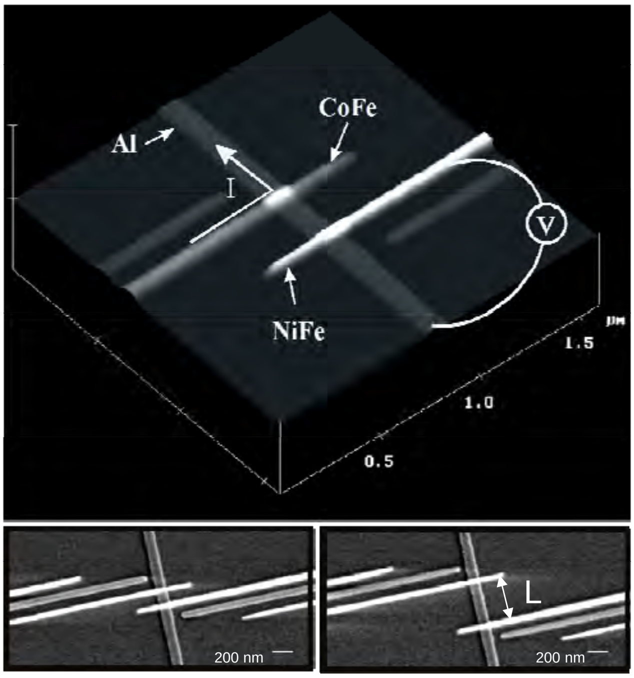
- Spin polarized current in a nonmagnetic metal
- Spin accumulation decays exponentially
- Characteristic length. Spin diffusion/relaxation length λ_{sf}





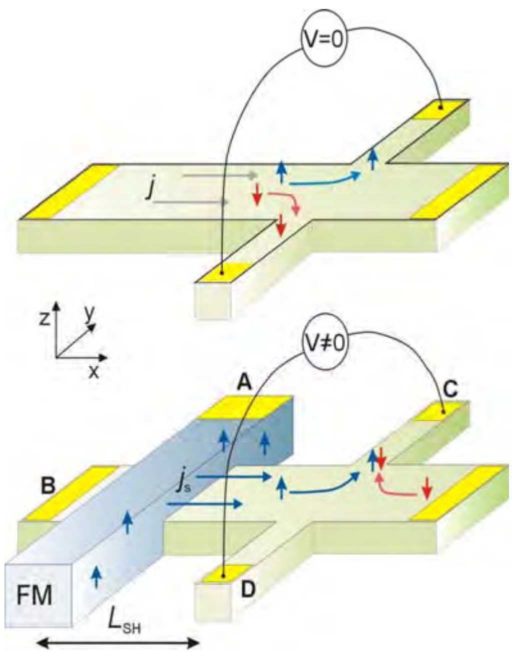
Johnson and Silsbee PRB **35**, 4959 (1987)
van Son et al., PRL **58**, 2271 (1987)

Measurement scheme



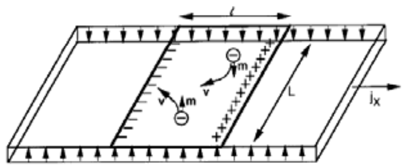
- Current *I* injected into Al strip from one of the ferromagnets (CoFe)
- Non-equilibrium spin density (spin accumulation)
- The detector (NiFe) samples the electrochemical potential of the spin populations
- *L* is varied to obtain the spin relaxation length

Spin Hall effect. Electronic detection



J.E. Hirsch. PRL **83**, 1834 (1999).

A.A. Bakun *et al.*, Sov. Phys. JETP Lett. **40**, 1293 (1984).



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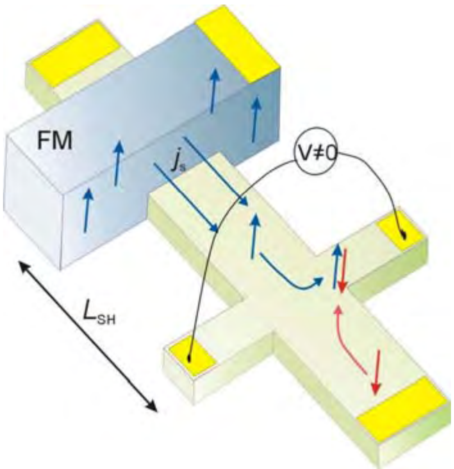
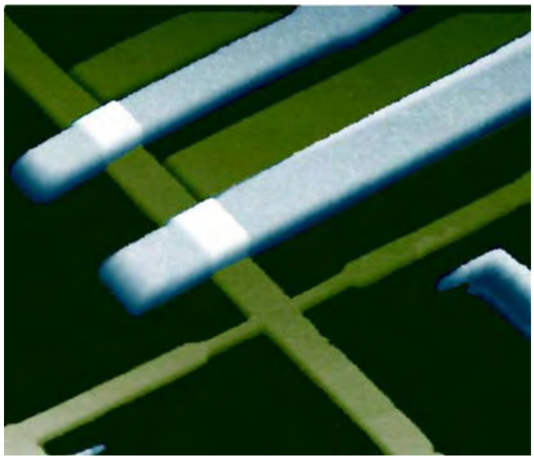
Second order effect

Spin Hall effect. Electronic detection





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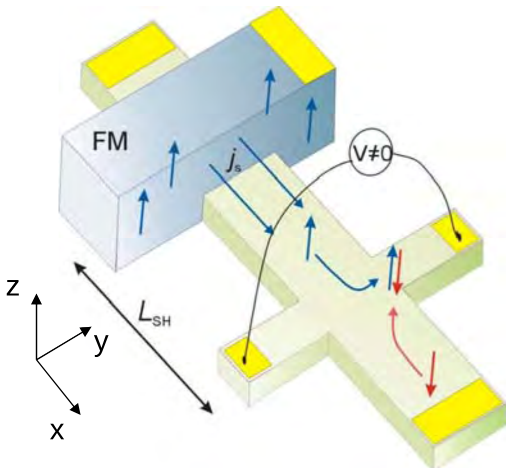


Diffusive system

$$\nabla^2 \delta\mu(\mathbf{r}) = \frac{\delta\mu(\mathbf{r})}{\lambda_{sf}^2}; \quad \delta\mu(\mathbf{r}) = \frac{\mu^{\uparrow}(\mathbf{r}) - \mu^{\downarrow}(\mathbf{r})}{2}$$

$$\mathbf{j}_c(\mathbf{r}) = \sigma_c \mathbf{E}(\mathbf{r}) + \frac{\sigma_{SH}}{\sigma_c}[\hat{\mathbf{z}} \times j_s]$$

Charge current in *y* direction is zero

$$V_{SH} \equiv V_{CD} = -E_y(x) w_N = w_N \frac{\sigma_{SH}}{\sigma_c^2} j_s(x)$$

and

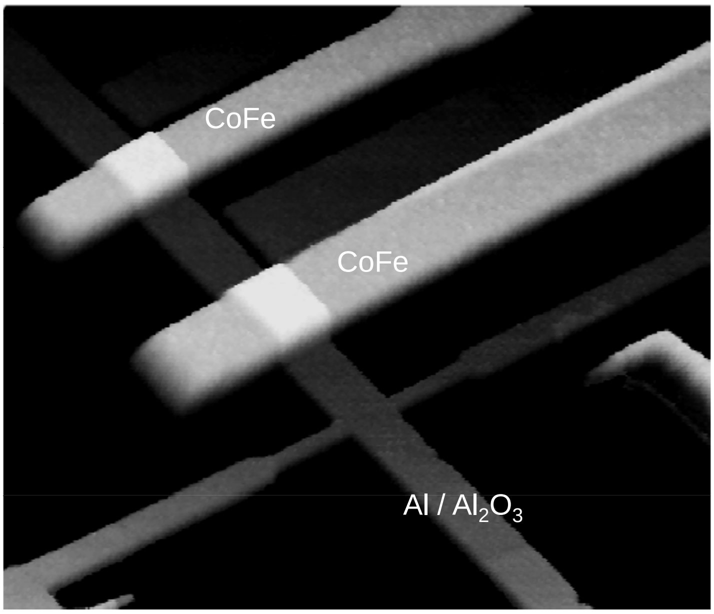
$$j_s(x) = \frac{1}{2} P \frac{I}{A_N} e^{-x/\lambda_{sf}}$$

$$R_{SH} = \frac{1}{2} \frac{P}{t_N} \frac{\sigma_{SH}}{\sigma_c^2} e^{-x/\lambda_{sf}}$$

Zhang, S. PRL **85**, 393 (2000); JAP **89**, 7564 (2001).

S. Takahashi *et al.*, Chapter 8 in *Concepts in spin electronics* (Oxford Univ. Press, 2006).

Sample layout



e-beam lithography

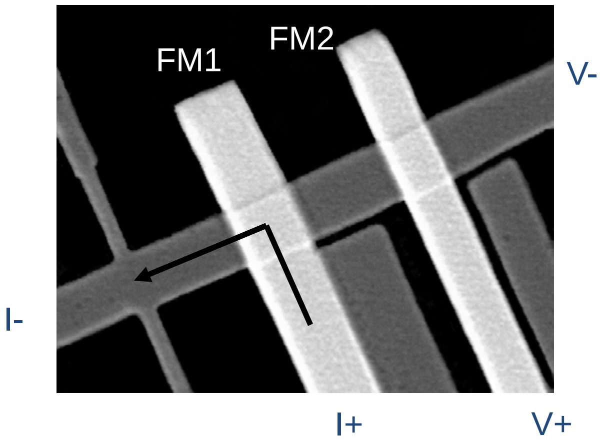
Shadow evaporation

Al Film
Al_2O_3 tunnel barrier
CoFe electrodes

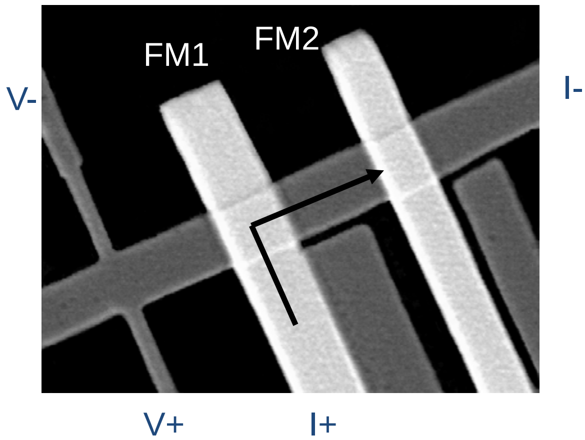
P ~ 30 %

Measurement schemes

Johnson-Silsbee



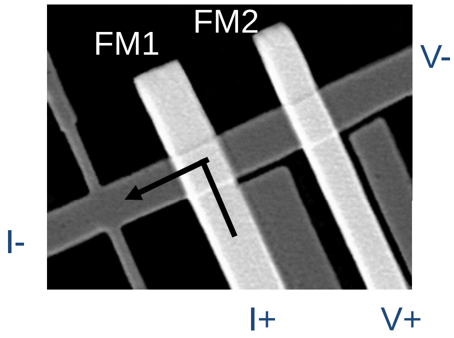
Spin Hall effect

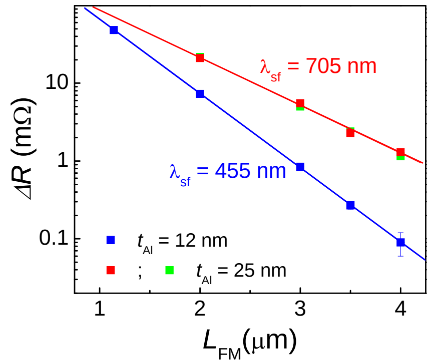


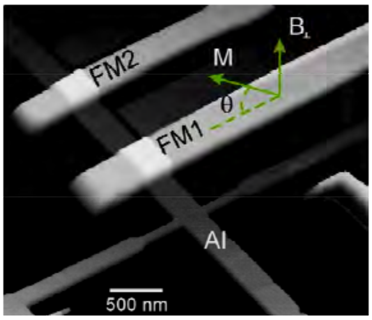
SOV and M. Tinkham, Nature **442**, 176 (2006)

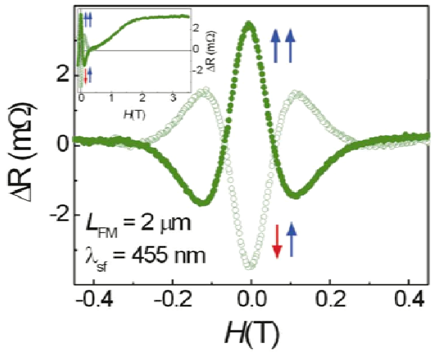
Nonlocal spin detection. Spin precession

Jonhson-Silsbee

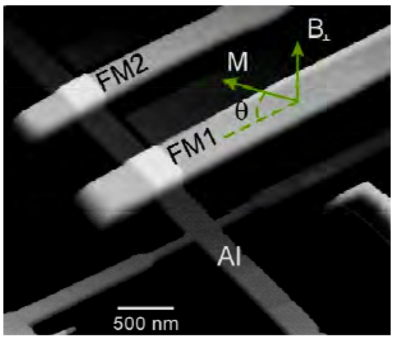








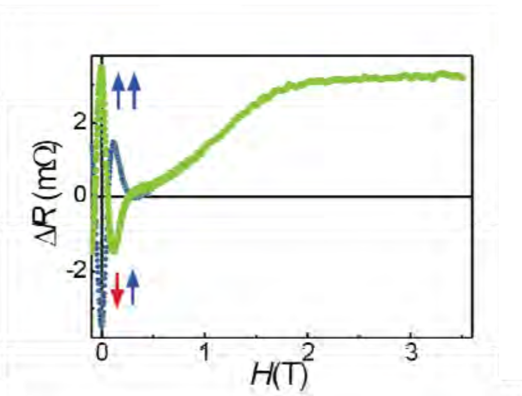
Jonhson-Silsbee

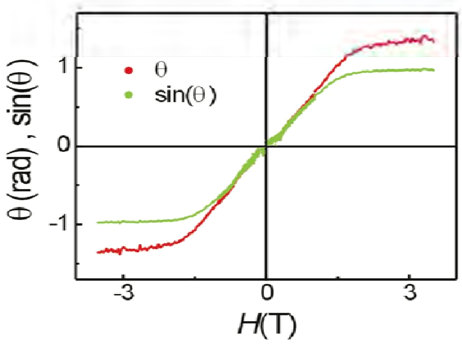


$$\frac{V_{\uparrow\uparrow}}{V_0} = +f(B_\perp)\cos^2\theta + \sin^2\theta$$

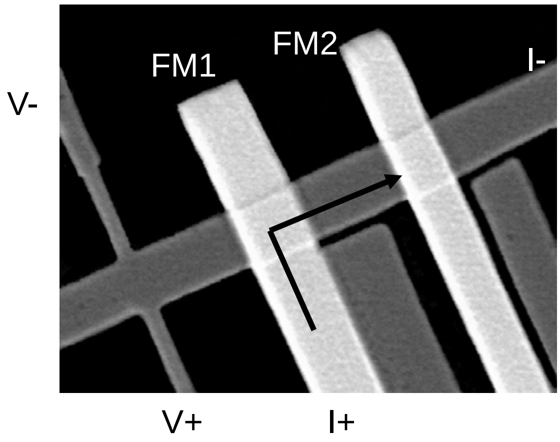
$$\frac{V_{\downarrow\uparrow}}{V_0} = -f(B_\perp)\cos^2\theta + \sin^2\theta$$

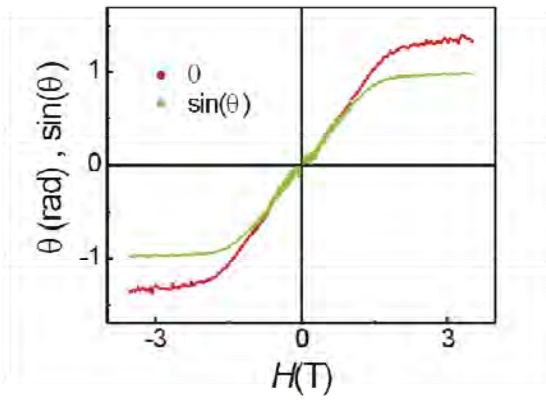
Jedema *et al.*, Nature **416**, 713 (2002)





Inverse Spin Hall effect





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

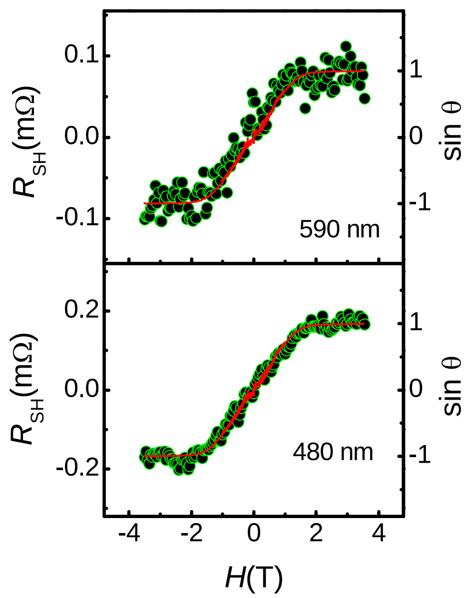
$\Delta R_{SH} = 2(P\ \sigma_{SH} / t_{Al}\ \sigma^2_c) \exp[-L_{SH}/\lambda_{sf}]$

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

SOV and M. Tinkham, Nature **442**, 176 (2006)

S. Takahashi *et al.*, Chapter 8 in *Concepts in spin electronics* (Oxford Univ. Press, 2006)

Inverse Spin Hall effect



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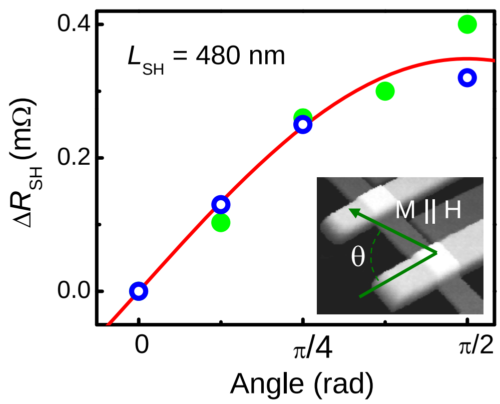

SOV and M. Tinkham, Nature **442**, 176 (2006), J. Appl. Phys. **101**, 09B103 (2007)

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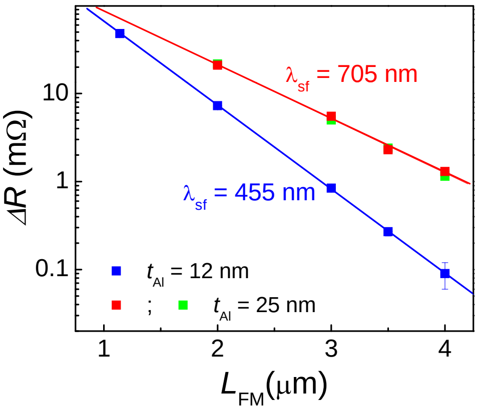
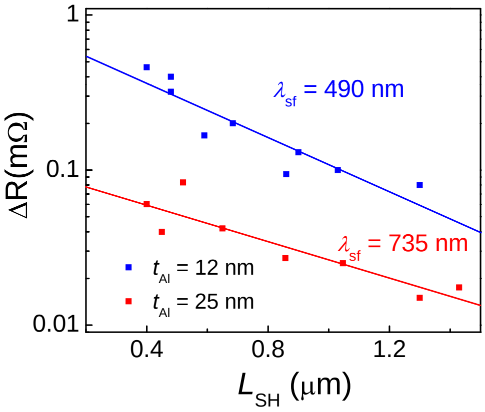
Inverse Spin Hall effect

Comparison with conventional nonlocal detection





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

P ~ 28 %

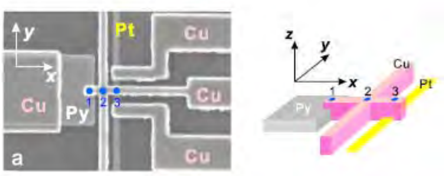
s_{SH} ~ 30 (wcm)$^{-1}$

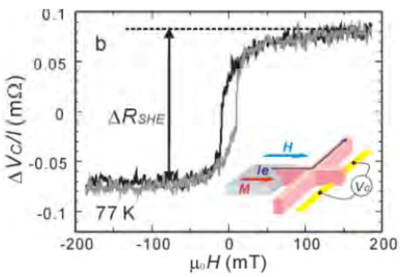
Predicted (extrinsic): s_{SH} ~ 10 (wcm)$^{-1}$

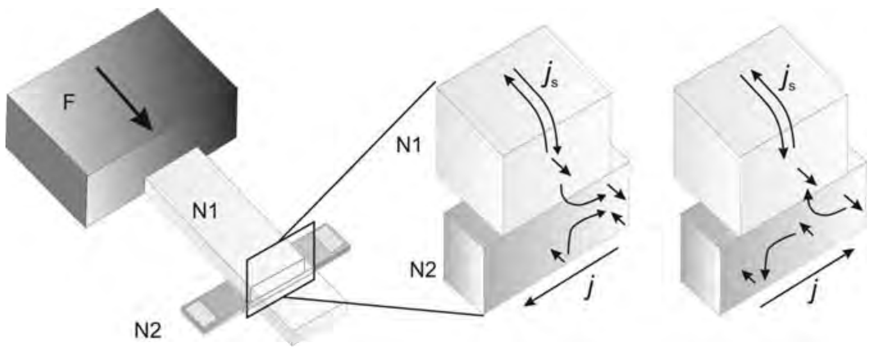
Zhang, PRL (2001); Shchelushkin & Brataas, PRB (2005)

Inverse and Direct Spin Hall effect

Spin Hall cross adapted for materials with short spin relaxation length



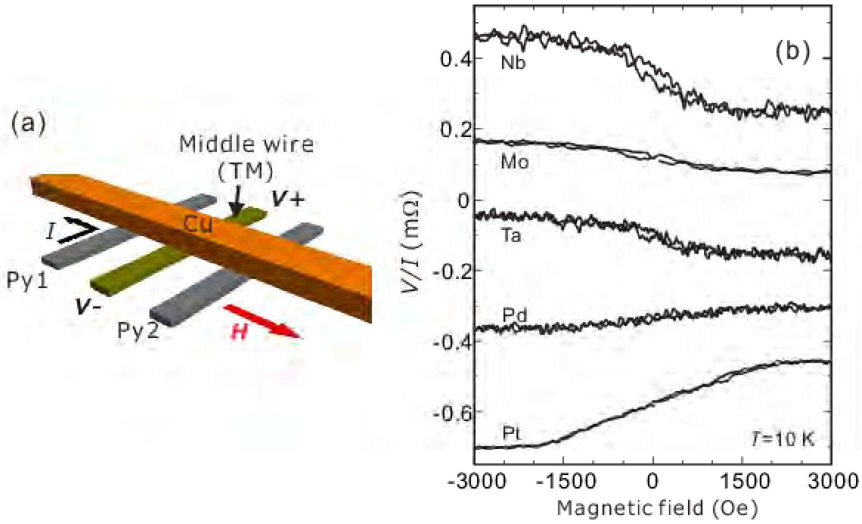




T. Kimura *et al.*, PRL (2007)

Inverse and Direct Spin Hall effect

Spin Hall cross adapted for materials with short spin relaxation length



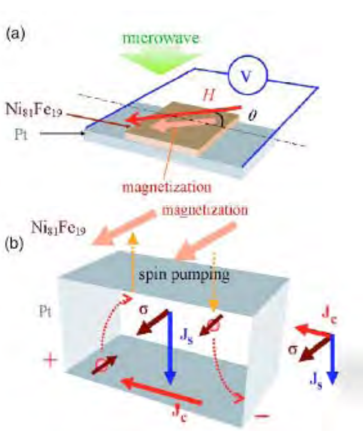
Morota et al *Phys. Rev. B*, **83**, 174405 (2011)

Inverse Spin Hall Effect

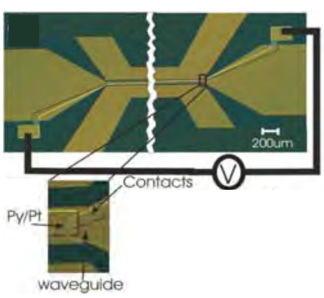
Observation in Metals

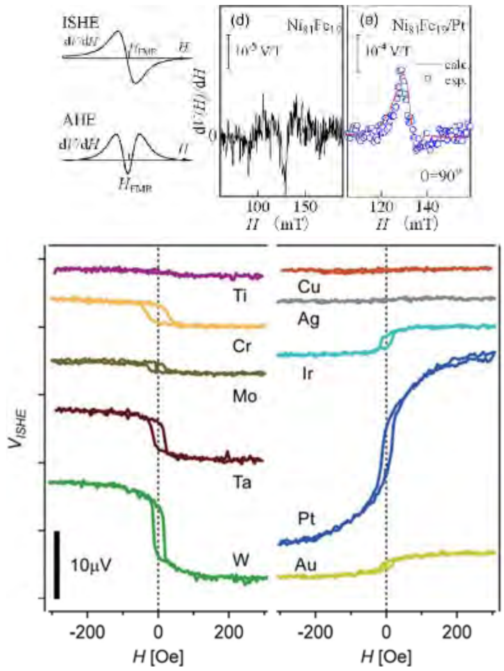
Inverse spin Hall effect as a spin current measurement detection mechanism

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 $(\Omega\text{cm})^{-1}$	$\bar{\eta}_{so}$	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)	$35 \pm 3^*$	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	2.8×10^4	0.34	$-(0.8 \pm 0.18)$	[53]
Mo (295K)	$35 \pm 3^*$	4.66×10^4	0.14	$-(0.05 \pm 0.01)$	[56]†
Nb (10K)	5.9 ± 0.3	1.1×10^4	0.14	$-(0.87 \pm 0.20)$	[53]
Pd (295K)	9^*	1.97×10^4	0.23	1.0	[68]†
Pd (10K)	13 ± 2	2.2×10^4	0.18	1.2 ± 0.4	[53]
Pd (295K)	$15 \pm 4^*$	4.0×10^4	0.28	0.64 ± 0.10	[56]†
Pt (295K)		6.41×10^4	0.74	0.37	[10]
Pt (5K)	14	8.0×10^4	0.61	0.44	[12]
Pt (295K)	10	5.56×10^4	0.58	0.9	[12]
Pt (10K)	11 ± 2	8.1×10^4	0.77	2.1 ± 0.5	[53]
Pt (295K)	7^*	6.4×10^4	0.97	8.0	[55]†
Pt (295K)	$3 - 6$	5.0×10^4	0.88-1.75	$7.6^{+8.4}_{-2.0}$	[57]†
Pt (295K)	$10 \pm 2^*$	2.4×10^4	0.25	1.3 ± 0.2	[56]†
Ta (10K)	2.7 ± 0.4	3.0×10^3	0.17	$-(0.37 \pm 0.11)$	[53]

Spin Current, Maekawa, SOV, Saitoh, Kimura Eds (Oxford University Press, 2012)

Spin Hall effect and Spin Orbit Torques

An overview

Brief introduction

- Spintronics
- Spin-dependent Hall effects
- Spin Hall effect (SHE) and inverse spin Hall effect (iSHE)

Detection of the SHE and iSHE

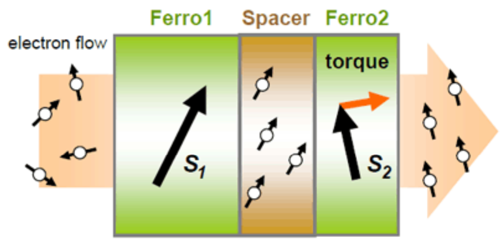
Spin Hall effects in metals

- Electronic transport experiments
- Spin pumping

Spin orbit torques

- Measurements techniques
- Spin Hall effect torque
- Rashba spin-orbit torque

Spin Torque



Two spin components of a wavefunction have different kinetic energies (k_{up} different from k_{down}).

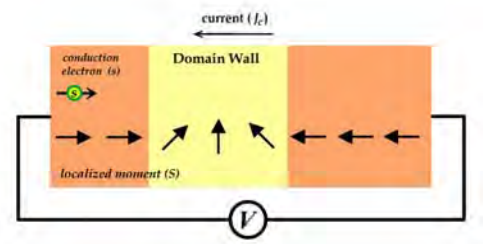
The spin precesses in the exchange field of the magnet.

Precession length is very short (a few atomic spacings) for typical exchange fields ~ ($k_{up} – k_{down}$).

Electrons take different paths (from all parts of Fermi surface), leading to classical dephasing.

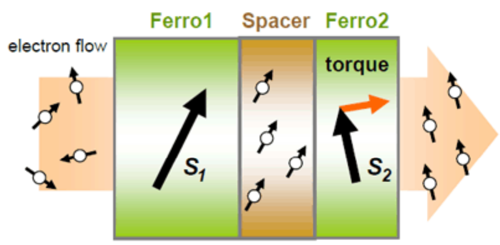
By conservation of angular momentum, a spin transfer torque acts on the material.

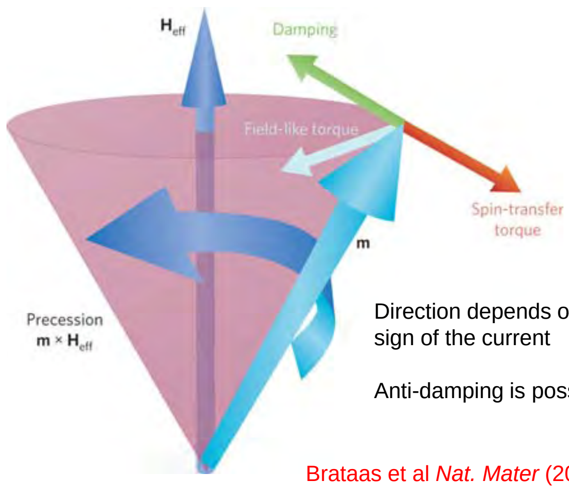
Torque = net flux of non-equilibrium spin current through the volume surface.



S. Maekawa (Tohoku and JAEA)

Spin Torque

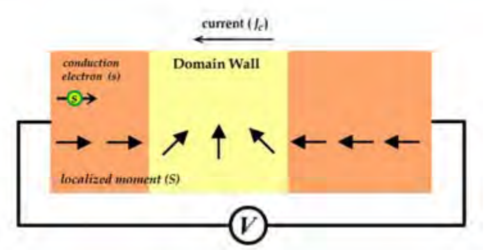




Direction depends on the sign of the current

Anti-damping is possible.

Brataas et al *Nat. Mater* (2012)

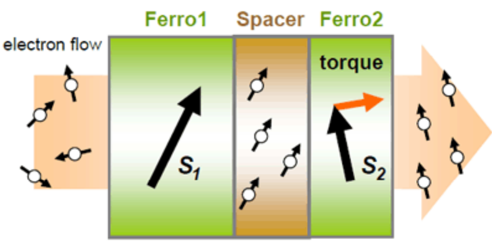


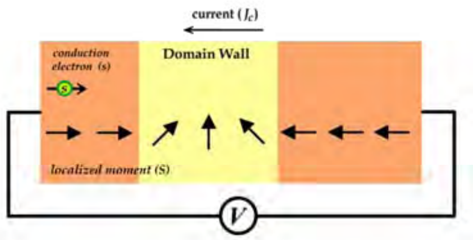
S. Maekawa (Tohoku and JAEA)

$$\dot{\mathbf{M}} = -\gamma_0' \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\lambda}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}})$$ Landau-Lifshitz

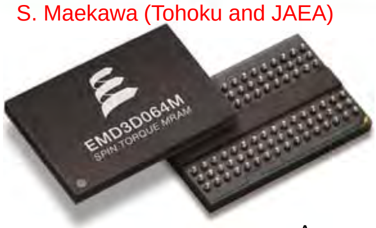
$$\dot{\mathbf{M}} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \dot{\mathbf{M}}$$ Gilbert

Spin Torque

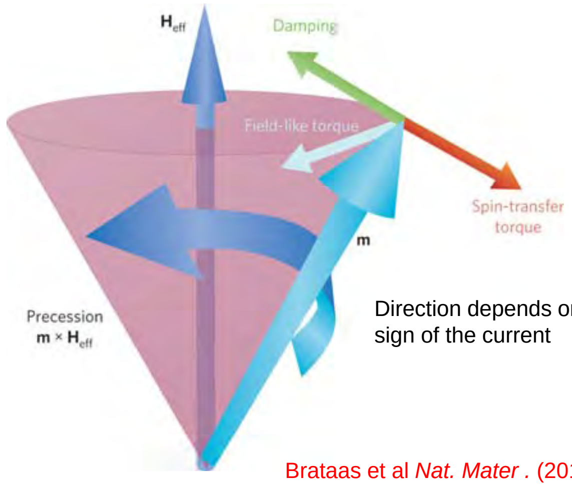




S. Maekawa (Tohoku and JAEA)



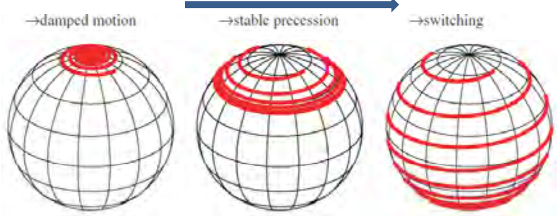
Announced 11/2012



Direction depends on the sign of the current

Brataas et al *Nat. Mater .* (2012)

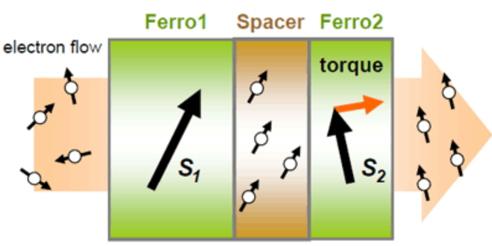
Increasing Current



Ralph and Stiles *JMMM* (2008)

Spin Hall Effects

Spin Orbit Torques



Spin Hall

Charge Current

⇓

Transverse

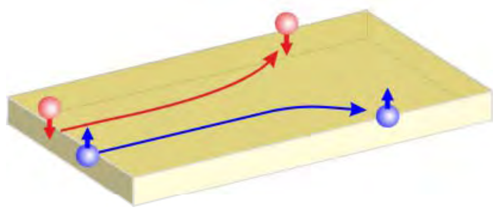
Spin Imbalance

Spin current generated by SHE can also result in spin torque

Current is not applied through a tunnel junction, which can be damaged by the high current densities

Separate the write and read lines

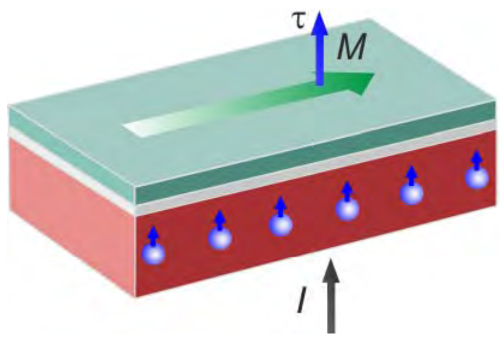
More efficient spin transfer



Spin torque by filtering or spin Hall effect

Efficiency

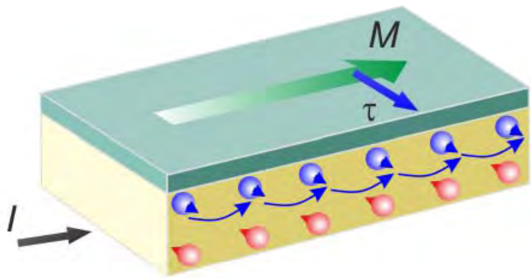
Spin transfer torque by spin filtering



Torque ~ J_s = J *Polarization

J = I / Transverse Area

Spin transfer torque by SHE



Torque ~ J_s = J * Θ_{SH}

J = I / Longitudinal Area

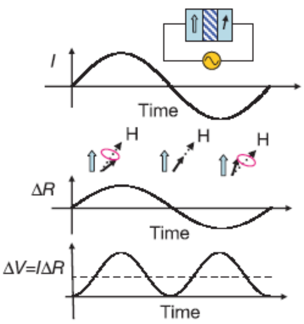
Spin Hall Effects

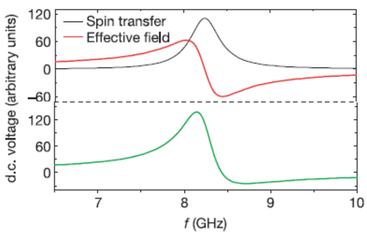
Spin Orbit Torques

Spin-torque FMR:

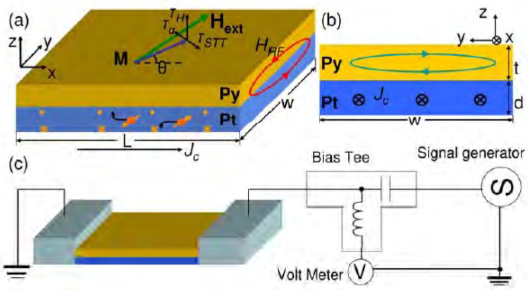
Resonant AC current excitation

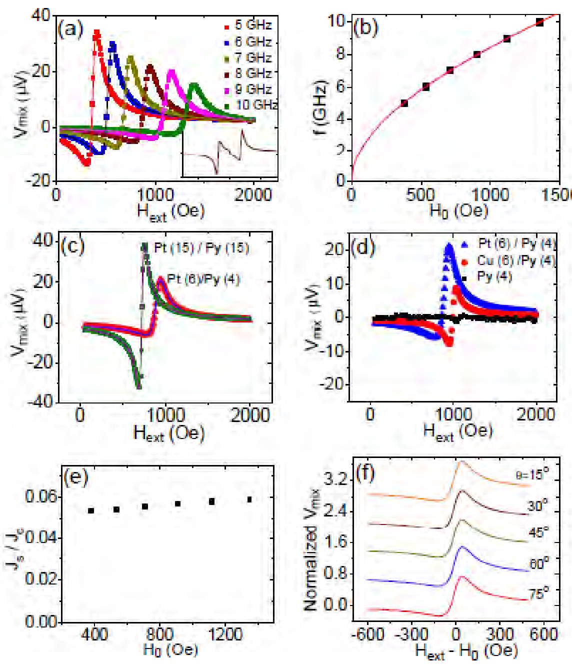
AMR readout





Tulapurkar et al Nature (2005)



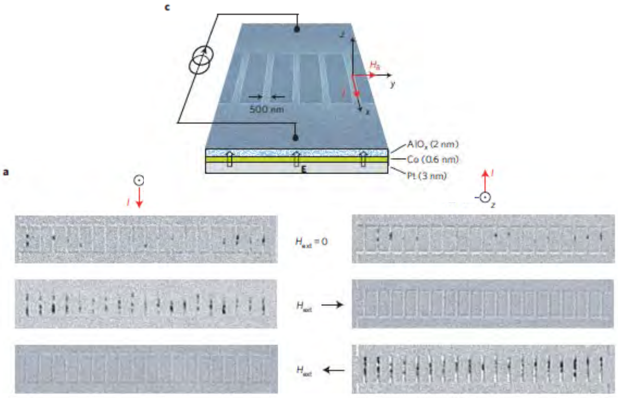


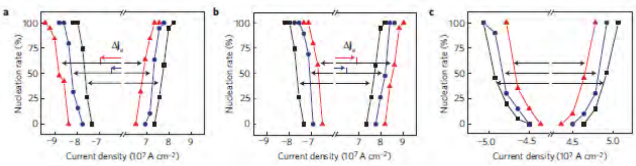
Liu *et al* PRL (2011)

Spin Orbit Torques

Spin Orbit Torques: Rashba vs Spin Hall effect

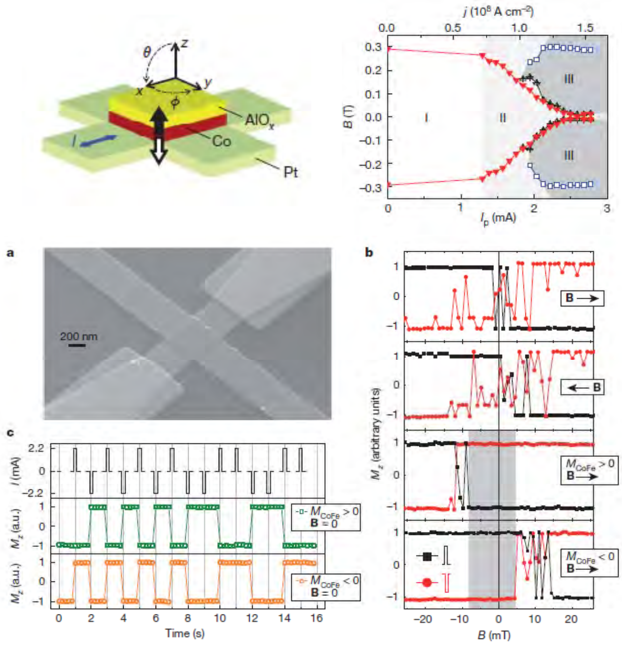
Nucleation of Domain Walls





Miron *et al* Nature Mater. (2010)

Magnetization Switching

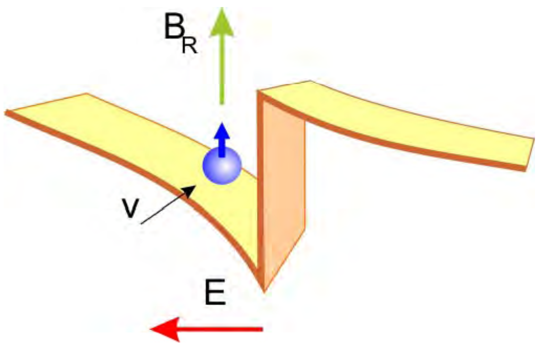


Miron *et al* Nature (2011)

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* is in fixed direction, can result in antidamping

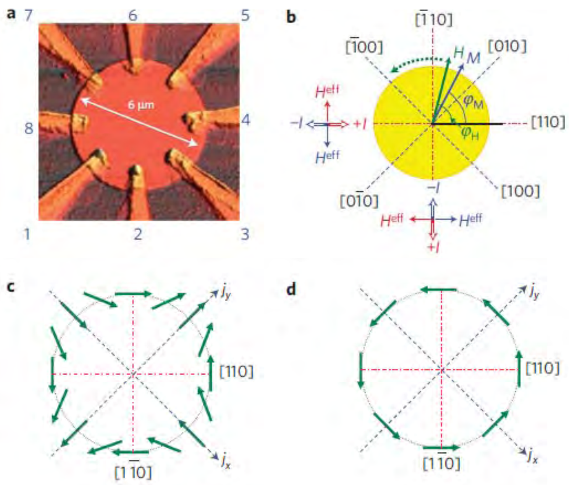
To manipulate the magnetization, Rashba field has to be similar to coercive field

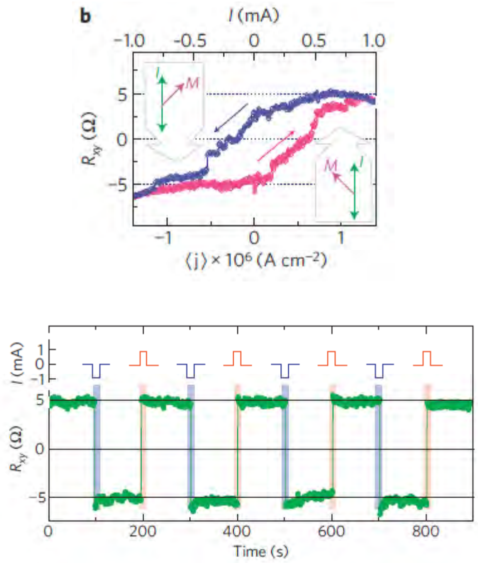
Spin Hall only requires that the torque compensates the damping

Spin Orbit Torques

Semiconductors

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

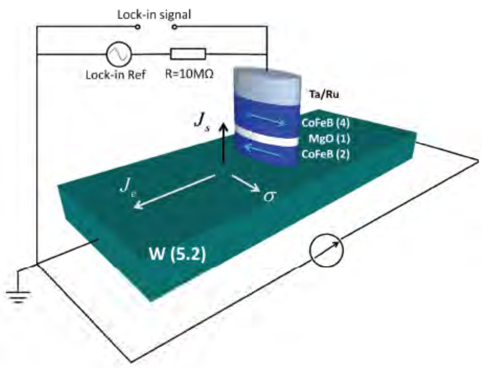
$\mathbf{\Omega}_\varepsilon = C\Delta\varepsilon(k_x, -k_y, 0)$ Strain

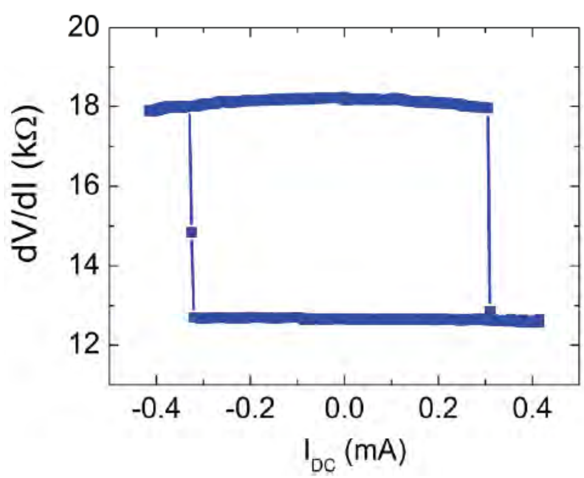
$\mathbf{\Omega}_R = \alpha_R(-k_y, k_x, 0)$ Rashba

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

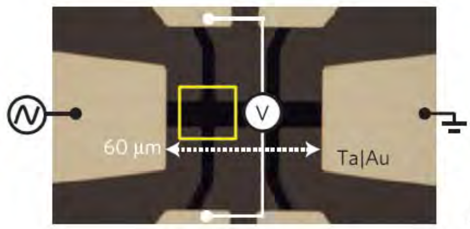
Liu *et al* Science (2012)

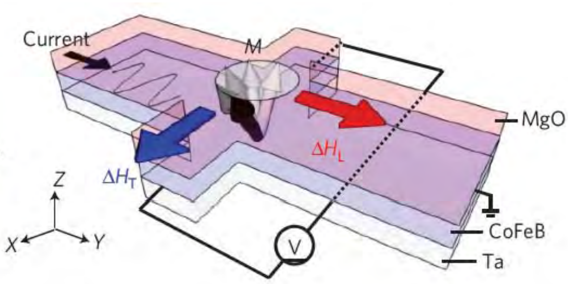
Spin Orbit Torques

Spin Orbit Torques: Rashba vs Spin Hall effect

However….

Study as a function of Ta thickness shows sign change in the effective field: competition of two effects



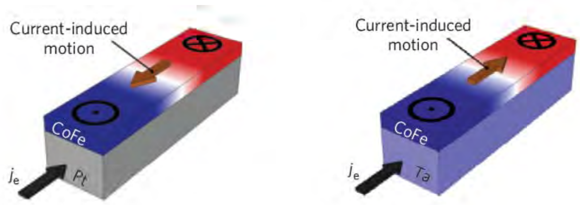


Kim *et al* Nat. Mat. (2012)

Garello *et al* Nat. Nanotechnol. (2013)

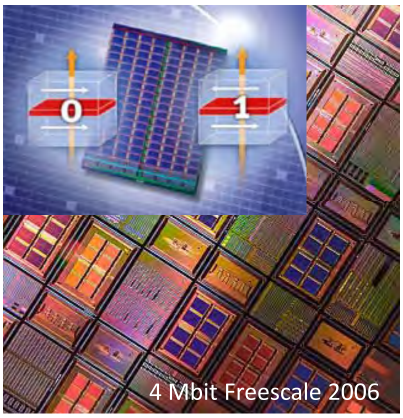
Also….

Nucleation and propagation of domain walls



Spin valves

Magnetic Access Random Memory (MRAM)



4 Mbit Freescale 2006

No need to constantly refresh the information through the periodic application of an electrical charge. Less leakage.

Start-up routines go faster

Reduced risk of data loss from unexpected power outages

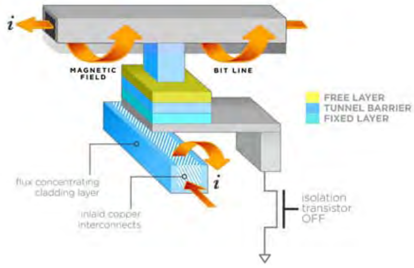
Reduced dissipation

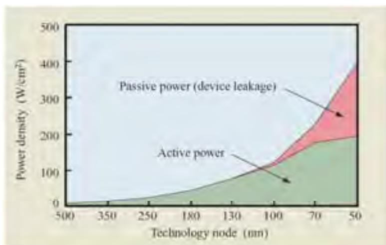
Fast writing/reading

Larger power requirement for writing

Larger memory cell size

16 Mbit



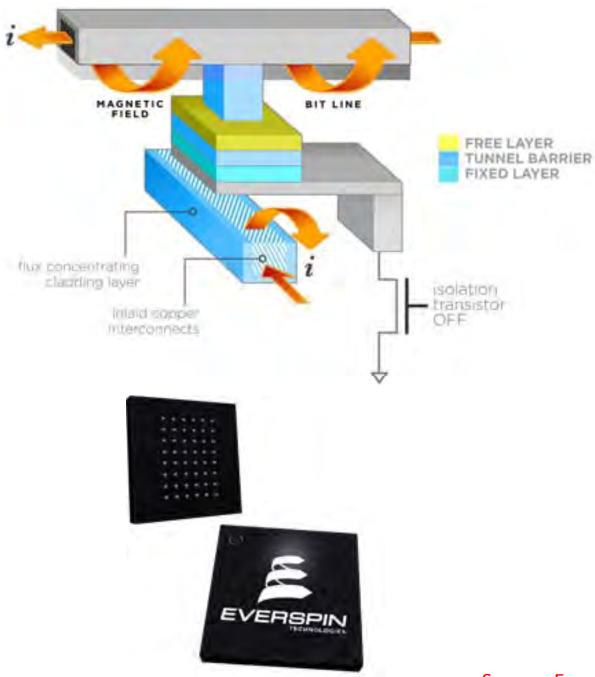


Industrial computing/automation (Siemens), aeronautics (Airbus),

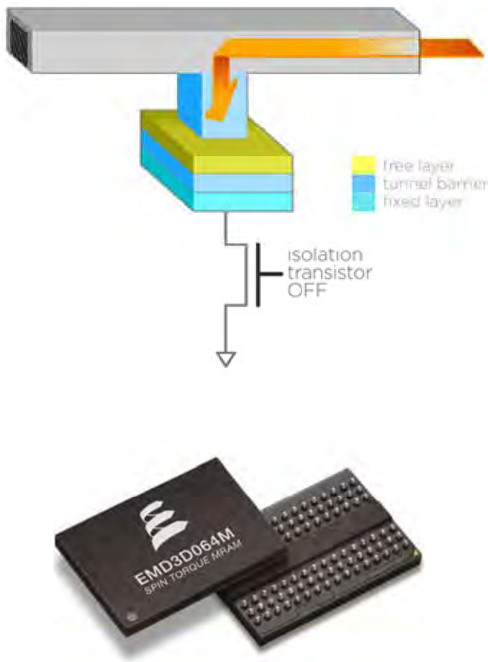
Spin valves

Magnetic Access Random Memory (MRAM) Current developments

Toggle RAM



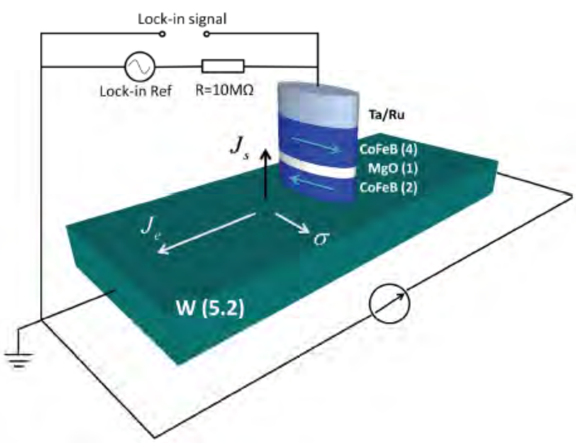
Spin Transfer Torque RAM (11/2012)



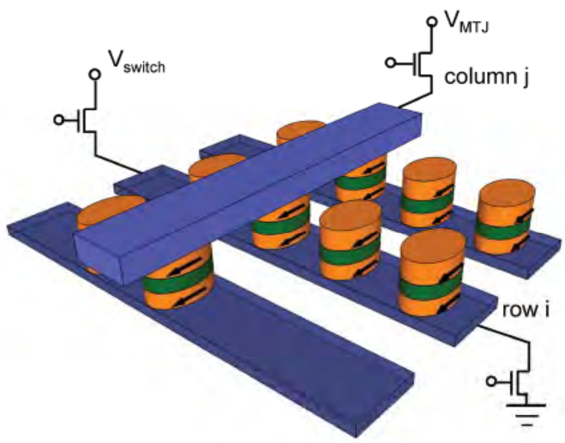
Source: Everspin

Spin Orbit Torques

Applications



Liu *et al* Science (2012)



D. C. Ralph, Cornell group

Crosspoint architecture

Combine spin filtering torque with spin orbit torque

Reduces number of transistors

Oscillators

Deminov et al. Nat Mater (2012); Liu et al., PRL (2012)

Summary

Several methods have been developed to characterized the spin Hall and inverse spin Hall effect

Quantitatively (sign) agreement is obtained, but results can differ by orders of magnitude

Spin Hall effects can be used as spin current sources or as spin current detectors

As spin source, spin Hall effect can be used in spin transfer torque devices, offering an example of spin-orbit torque

The torque symmetry can be field- or (anti)damping-like, historically associated with Rashba effect or spin Hall effect, respectively (Dzyaloshinskii-Moriya interaction, incomplete filtering,...)

Effective spin Hall angles (relationship between applied current and effective torque) can be very significant (about 0.3 in W), leading to magnetization switching

Combine spin filtering torque with spin orbit torque for applications