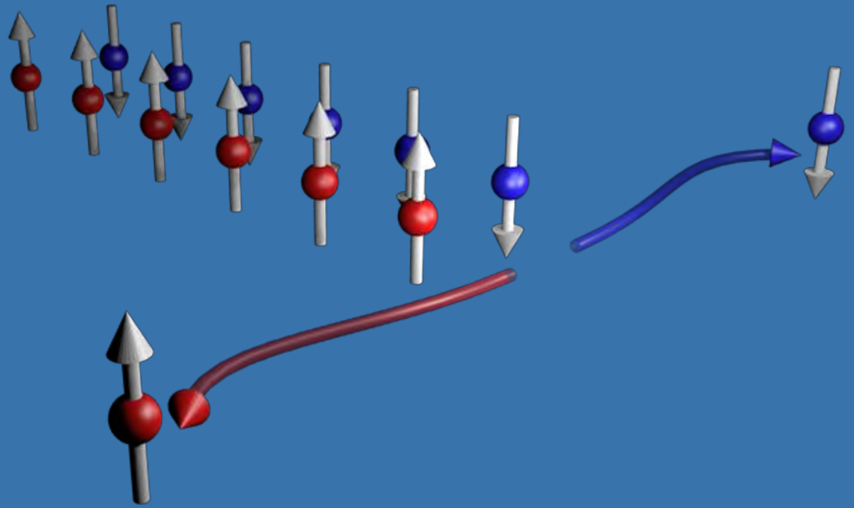
Spin Hall effect

European School of Magnetism
York, September 3rd 2024



Fèlix Casanova
Nanodevices group, CIC nanoGUNE
San Sebastian, Basque Country

OUTLINE

1. Introduction to spintronics
- Introduction
- Pure spin currents

2. Introduction to spin Hall effect
- Origin
- Discovery and relation with anomalous Hall effect
- Mechanisms (intrinsic, skew-scattering, side-jump)

3. Techniques to quantify SHE
- Optical
- Non-local transport
- FMR-based
- (Tables of quantification)

4. Related spin-orbit effects
- Edelstein effect in Rashba systems
- Spin-momentum locking in Topological Insulators

5. Applications
- Spin-orbit torques
- Spin-orbit logic

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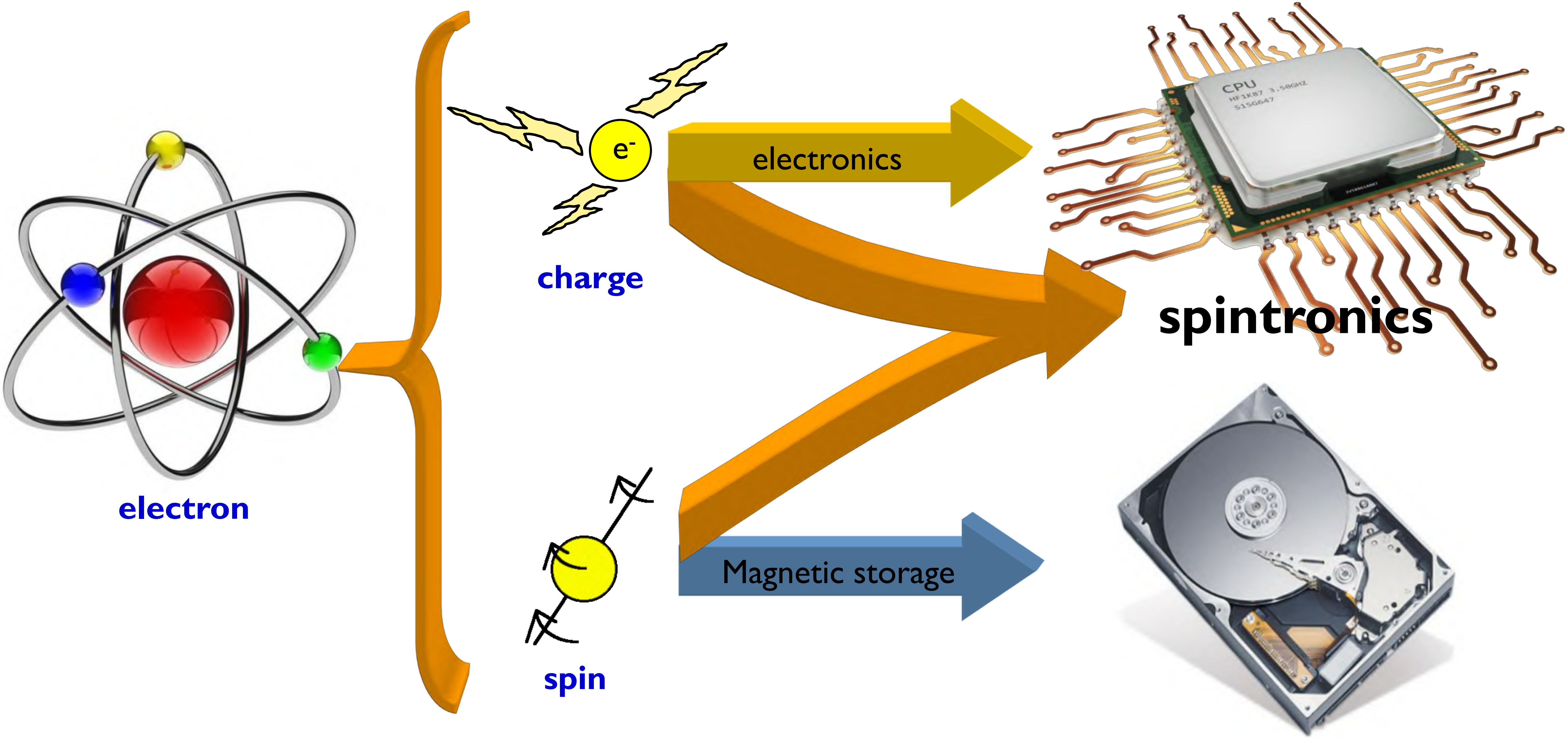
INTRODUCTION: SPINTRONICS



electron

e-

charge

spin

electronics

Magnetic storage

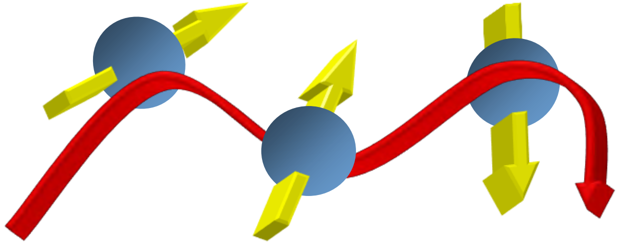
spintronics

INTRODUCTION: SPINTRONICS

Spintronics' paradox:

Best non-volatile information storage

But spin information is highly volatile when transfered!



We need to improve the transport and make manipulation real!!!

f.casanova@nanogune.eu

INTRODUCTION: PURE SPIN CURRENTS

Charge vs. Spin Currents

Charge

$$\overrightarrow{j_e} = \frac{d}{dt}(q\vec{r})$$

$$\overrightarrow{j_e} = q\vec{v}$$

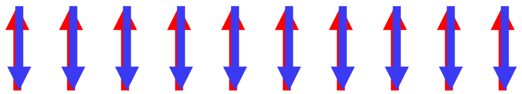
Spin

$$\overrightarrow{j_s} = \frac{d}{dt}(\sigma\vec{r})$$

$$\overrightarrow{j_s} = \sigma\vec{v} + \frac{d\sigma}{dt}\vec{r}$$

Moving Spins

Spin Dynamics

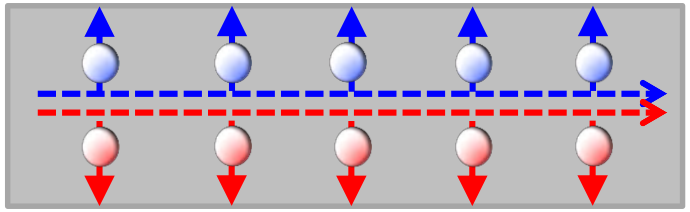


No Need for Moving Spin:
Potential for Low Power Dissipation!

J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006)

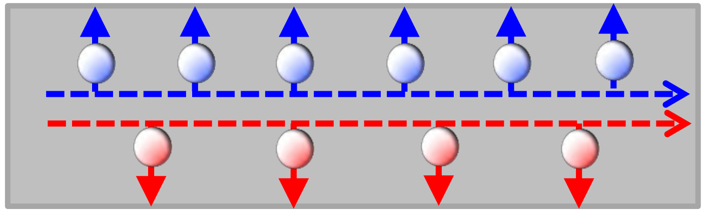
INTRODUCTION: PURE SPIN CURRENTS

$Ic=I_{\uparrow}+I_{\downarrow}$, $Is=I_{\uparrow}-I_{\downarrow}$



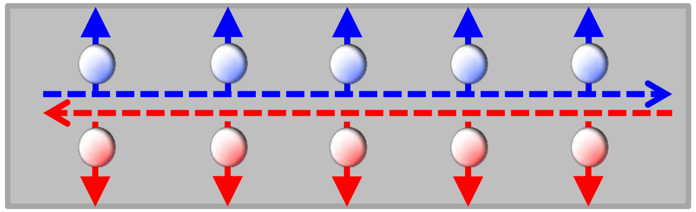
Charge current

$Ic\neq0$, $Is=0$



Spin-polarized current

$Ic\neq0$, $Is\neq0$

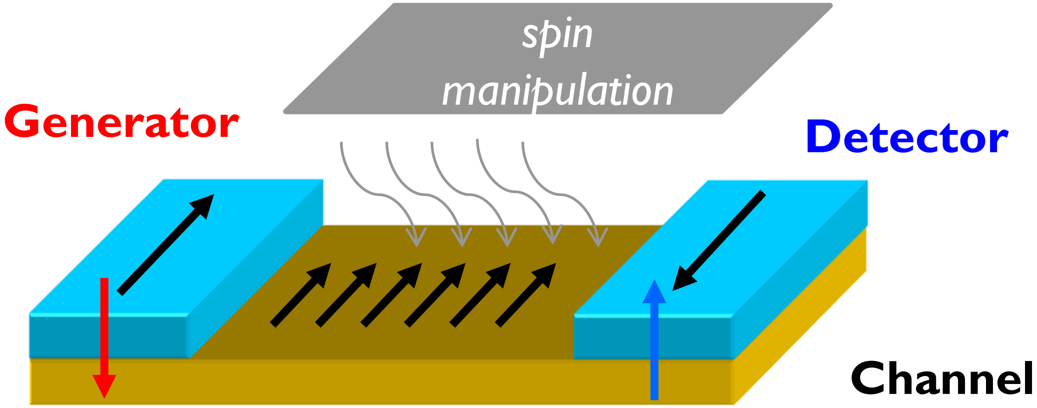


Pure spin current

$Ic=0$, $Is\neq0$

INTRODUCTION: PURE SPIN CURRENTS

- **New generation of spintronic devices: PURE SPIN CURRENTS**



- Spin generation (electrical spin injection, spin pumping, spin Hall effect…)
- Spin transport (non-magnetic material)
- Spin manipulation (electric field, magnetic field…)
- Spin detection (reciprocal of generation)

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INTRODUCTION: PURE SPIN CURRENTS

Can we generate pure spin currents in non-magnetic materials?

SPIN CURRENTS

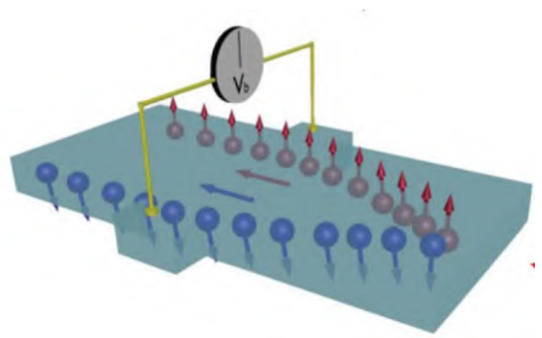
Electrical spin injection

Spin Hall effect

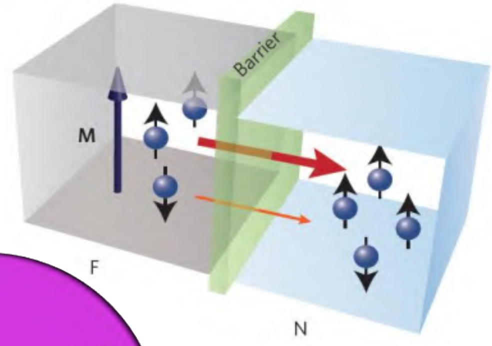
Spin pumping

Spin Seebeck effect

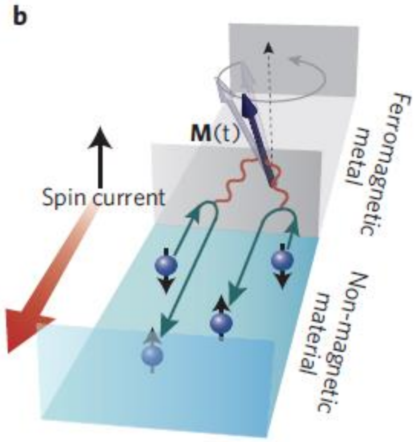
Photonic control



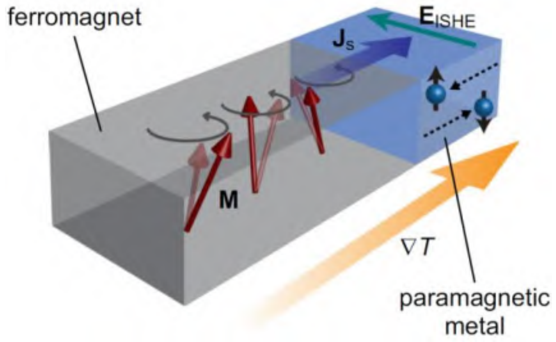
J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015)



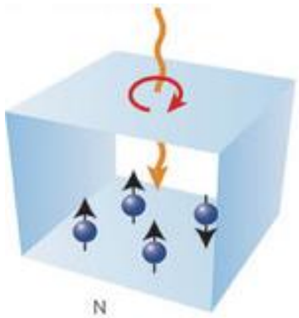
S. O. Valenzuela, Int. J. Mod. Phys. B. **23**, 2413 (2009)



K. Ando *et al.*, Nature Mater. **10**, 655 (2011)

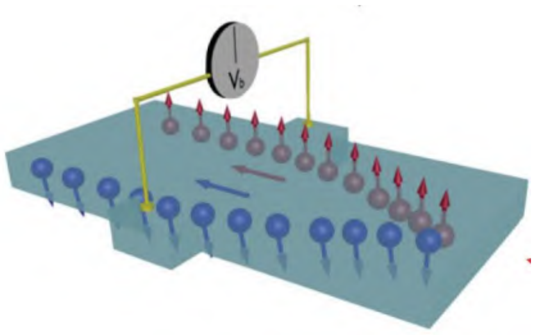


K. Uchida *et al.*, J. Phys.:Condens. Matter **26**, 343202 (2014)



I. Zutic and H. Dery, Nature Mater. **10**, 647 (2011)

INTRODUCTION: PURE SPIN CURRENTS



Electrical spin injection

Spin Hall effect

SPIN CURRENTS

Spin pumping

Spin Seebeck effect

Photonic control

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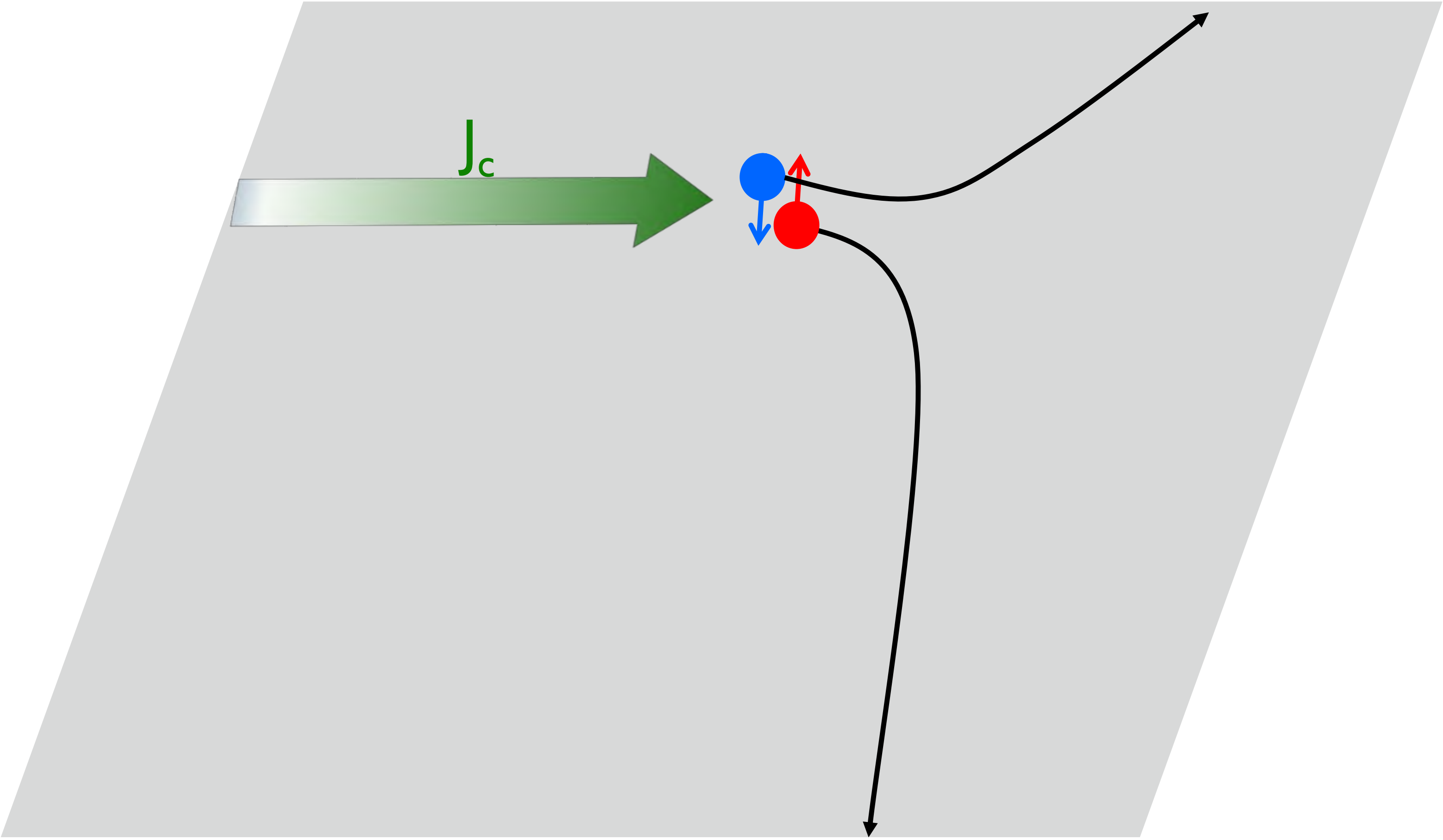
SPIN HALL EFFECT: ORIGIN

Spin-orbit coupling:

SPIN HALL EFFECT: ORIGIN

SPIN HALL EFFECT: ORIGIN

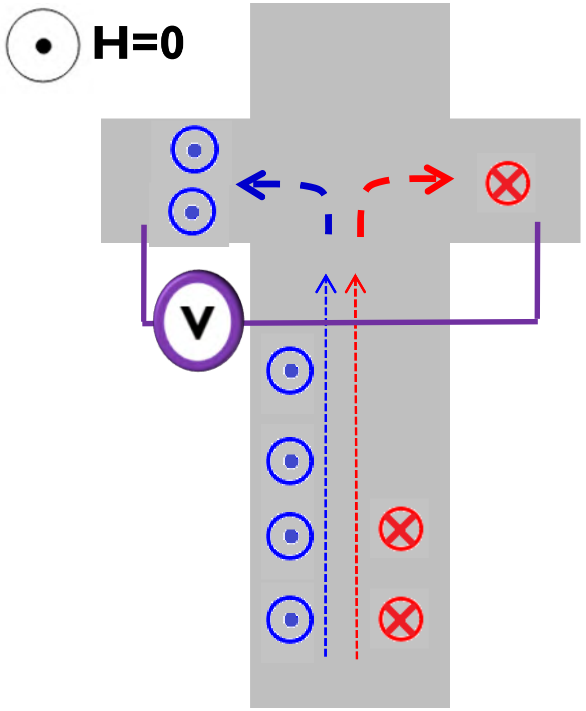
Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction



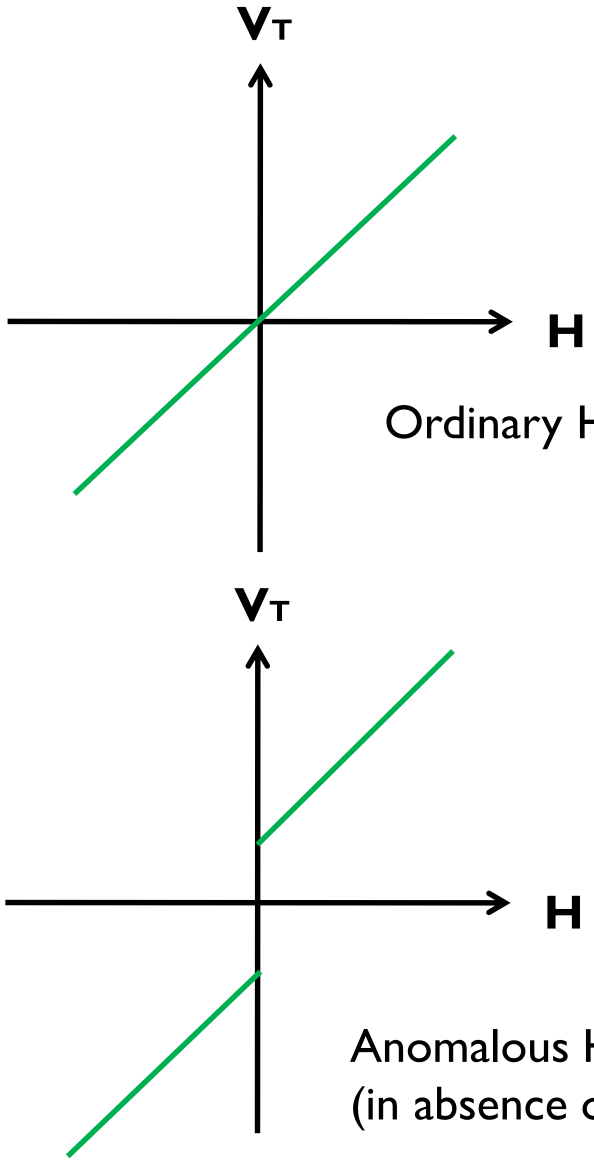
N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)

SPIN HALL EFFECT: DISCOVERY

ANOMALOUS
HALL EFFECT
in a **FM** material



✓ Spin-orbit coupling



Ordinary Hall effect (1879)

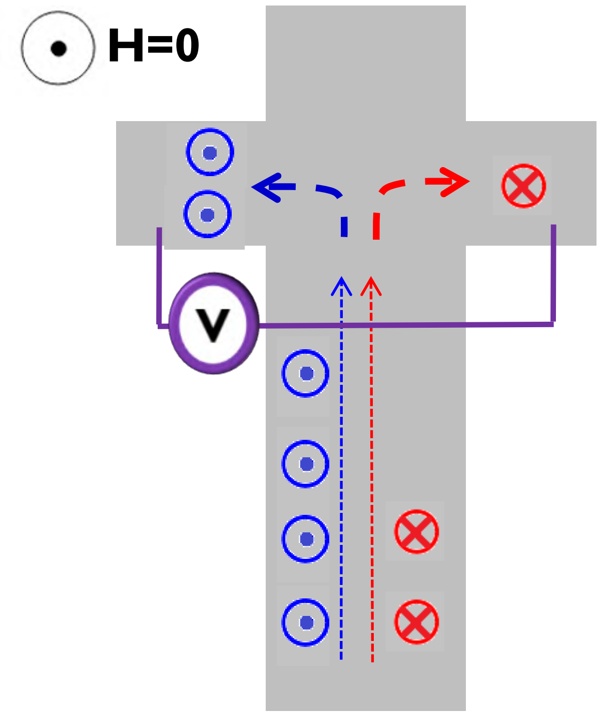
Anomalous Hall effect (1881)
(in absence of magnetic field)

E. H. Hall, Phil. Mag. **12**, 157 (1881)
R. Karplus & J.M. Luttinger, Phys. Rev. **95**, 1154 (1954)

SPIN HALL EFFECT: DISCOVERY

ANOMALOUS HALL EFFECT

in a **FM** material

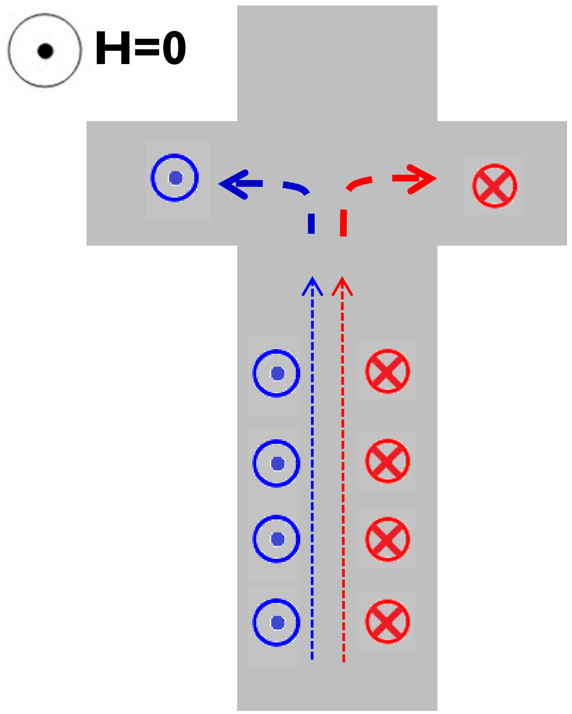


✓ Spin-orbit coupling

E. H. Hall, Phil. Mag. **12**, 157 (1881)
R. Karplus & J.M. Luttinger, Phys. Rev. **95**, 1154 (1954)

SPIN HALL EFFECT

in a **NM** material



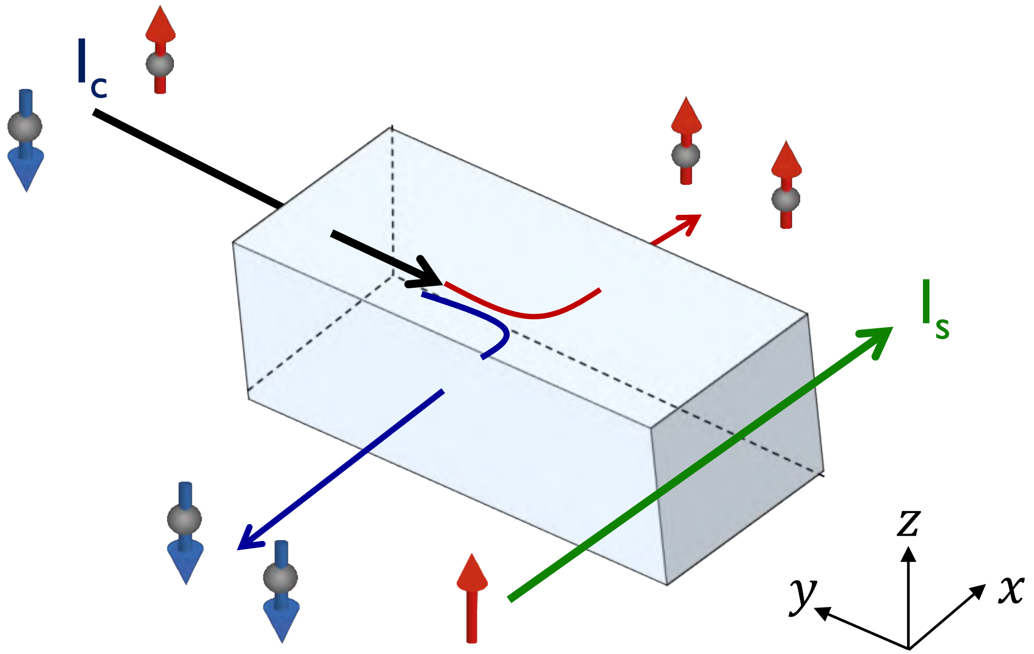
✓ Spin-orbit coupling

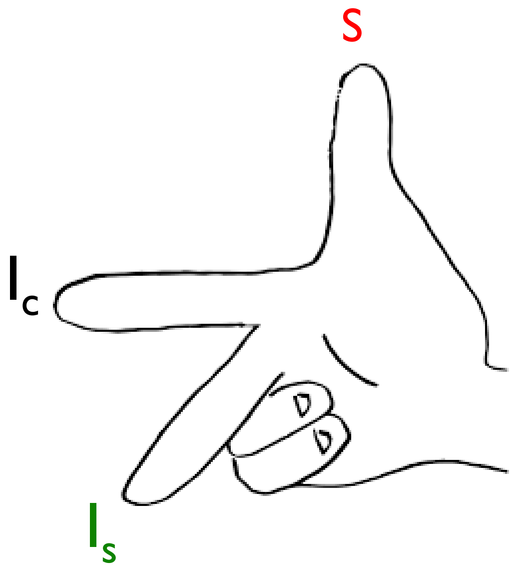
M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971)
J. E. Hirsch, Phys. Rev. Lett. **83**, 1834 (1999)
Y. K. Kato *et al.*, Science **306**, 1910 (2004)

SPIN HALL EFFECT: spin-to-charge current conversion

✓ Strong spin-orbit coupling materials

Direct effect **(SHE)**



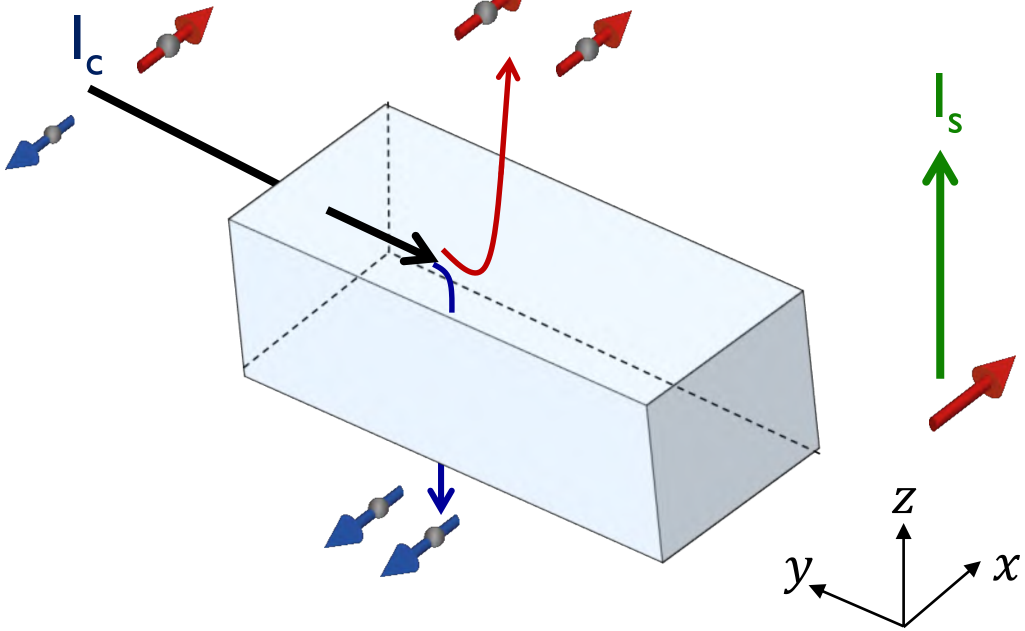


$$\boxed{\vec{j_s} = \left(\frac{\hbar}{e}\right) \theta_{SH}\, \vec{j_c} \times \vec{s}}$$

SPIN HALL EFFECT: spin-to-charge current conversion

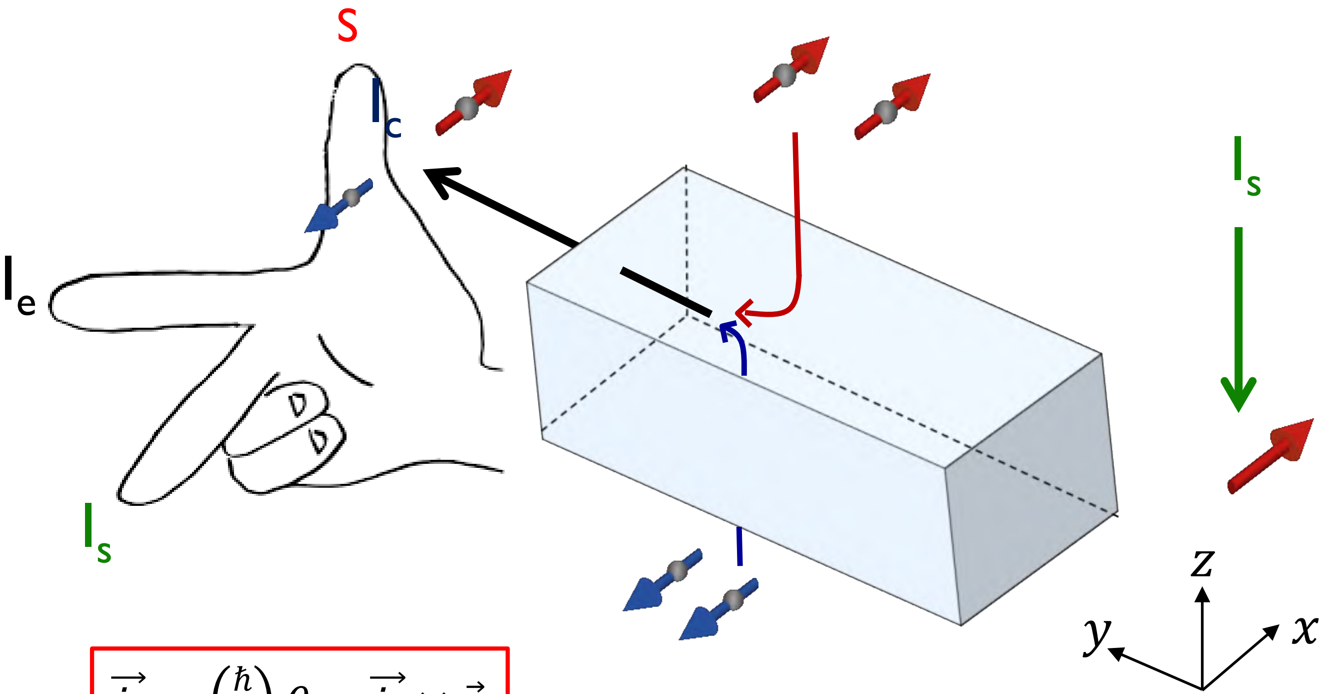
✓ Strong spin orbit coupling materials

Direct effect **(SHE)**



Spin current generation

Inverse effect **(ISHE)**



$$\boxed{\overrightarrow{j_s} = \left(\frac{\hbar}{e}\right) \theta_{SH}\, \overrightarrow{j_c} \times \vec{s}}$$

Spin current detection

SPIN HALL EFFECT: MECHANISMS

$$\boxed{\vec{j_s} = \left(\frac{\hbar}{e}\right)\theta_{SH}\,\vec{j_c} \times \vec{s}}$$

Spin Hall effect

$$\sigma_{SH} \approx -\frac{\rho_{SH}}{\rho_{xx}^2} \longrightarrow$$

Spin Hall conductivity
Given in conductivity units ($\Omega^{-1}m^{-1}$).
But a factor (ħ/e) or (ħ/2e) is implicit, depending on the definition.

$$\theta_{SH} = \frac{\sigma_{SH}}{\sigma_{xx}} = -\frac{\rho_{SH}}{\rho_{xx}} \longrightarrow$$

Spin Hall angle
Given without units (usually in %).
But it will be a factor 2 larger if the (ħ/2e) definition for σ_{SH} is used.

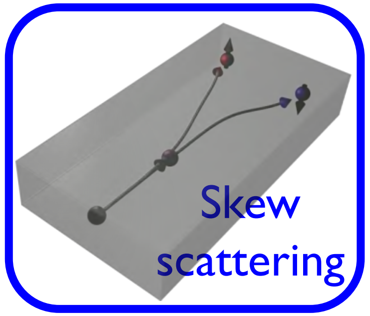
Relation between transverse conductivity and resistivity

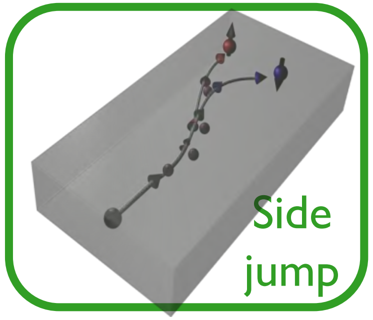
$$\sigma_{xy} = -\frac{\rho_{xy}}{\rho_{xx}^2 + \rho_{xy}^2} \approx -\frac{\rho_{xy}}{\rho_{xx}^2}$$

Phenomenological equation AHE

$$-\rho_{AH} = \sigma_{AH}^{int}\rho_{xx}^2 + \alpha_{AH}^{skew}\rho_{xx0} + \beta_{AH}^{side}\rho_{xx0}^2$$

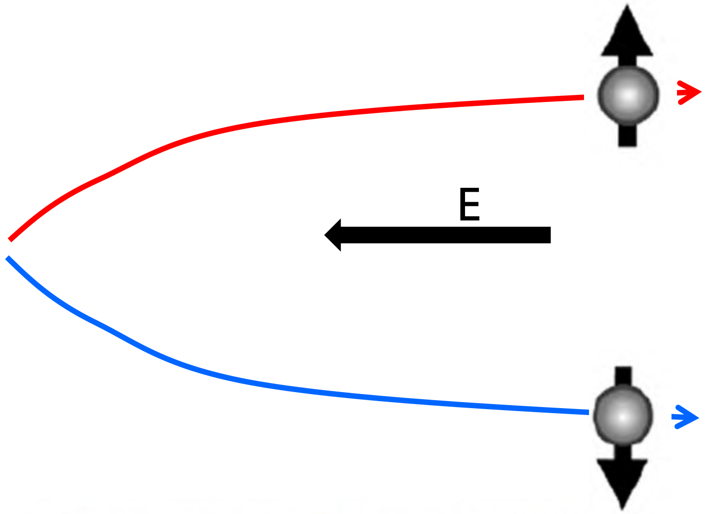
Y. Tian *et al.*, Phys. Rev. Lett. **103**, 087206 (2009)
D. Hou *et al.*, Phys. Rev. Lett. **114**, 217203 (2015)





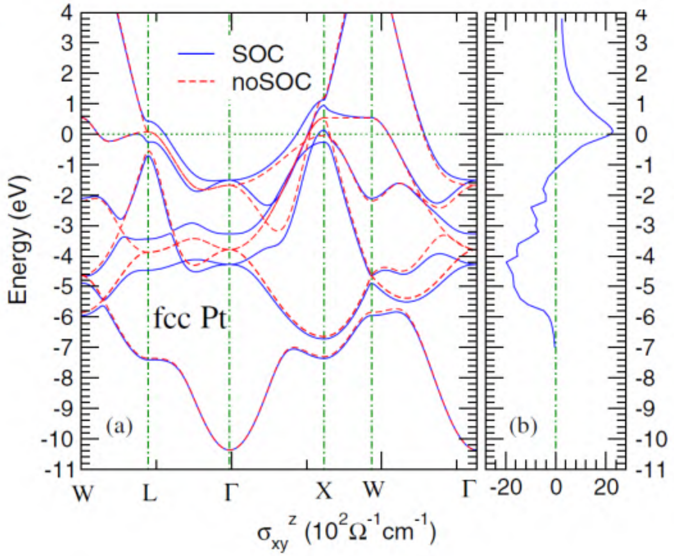
SPIN HALL EFFECT: MECHANISMS

INTRINSIC MECHANISM

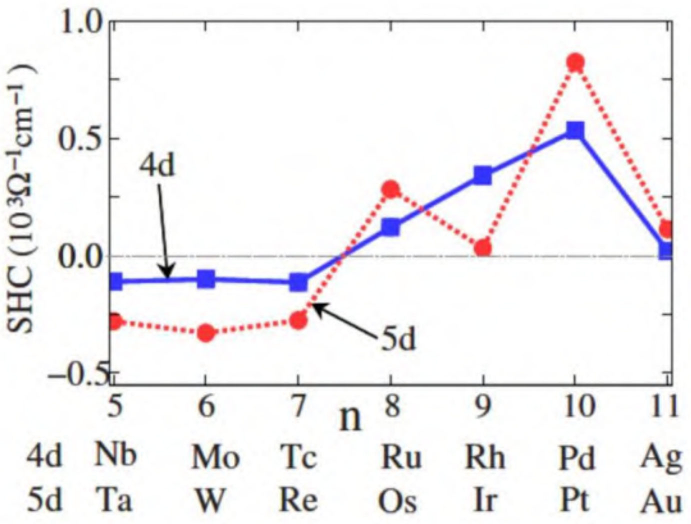


- Electrons deflect to the right or to the left as they are accelerated by an electric field ONLY because of the spin-orbit coupling (SOC) in the periodic potential (band structure)
- Electrons have an "anomalous" velocity perpendicular to the electric field related to their Berry phase curvature which is nonzero when they have SOC
- σ_{SH} is independent of scattering time (τ^0) $\quad \sigma_{SH}^{int} = cnt.$

$$-\rho_{SH} = \sigma_{SH}^{int}\,\rho_{xx}^{2}$$



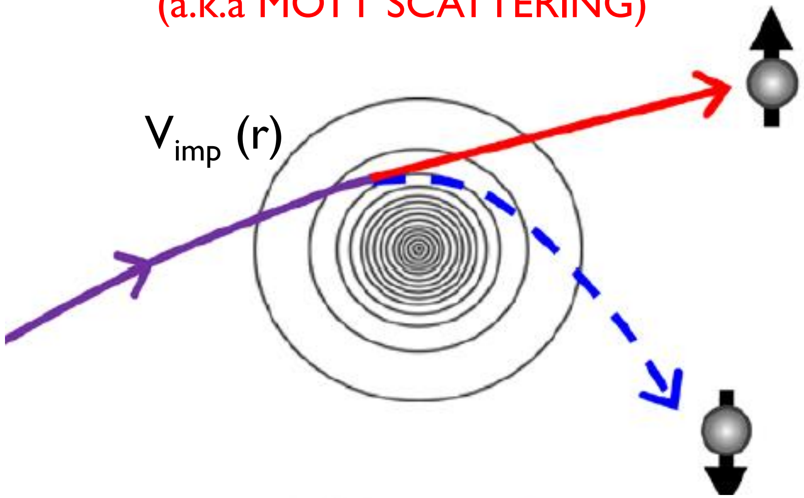
G.Y. Guo *et al.*, Phys. Rev. Lett. **100**, 096401 (2008)



T. Tanaka *et al.*, Phys. Rev. B **77**, 165117 (2008)

SPIN HALL EFFECT: MECHANISMS

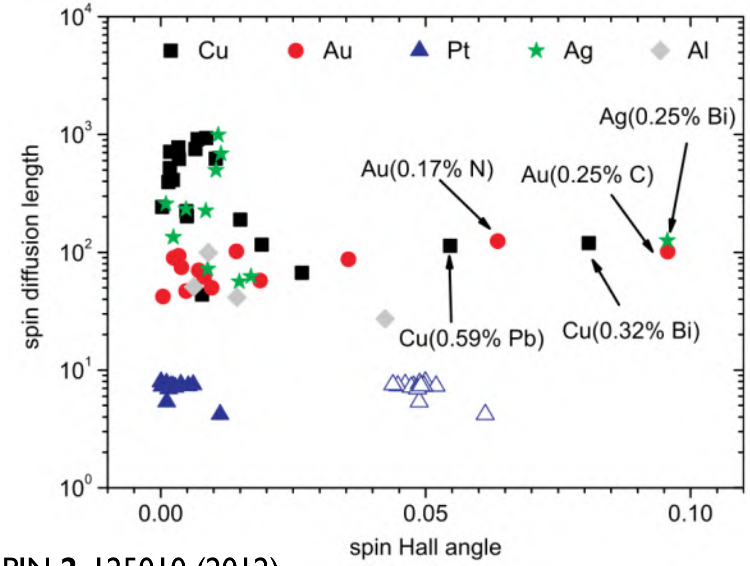
SKEW SCATTERING
(a.k.a MOTT SCATTERING)



- Asymmetric scattering due to the SOC of the electron or the impurity.
- Magnitude depends on the contrast between the SOC of the impurity and the host. Thus both heavy element impurities in light element hosts (e.g., Pb or Bi in Cu) or light element impurities in heavy element hosts (e.g., C or N in Au) can results in large spin Hall conductivities
- σ_{SH} is proportional to scattering time (τ^1) $\sigma_{SH} \propto \sigma_{xx}$

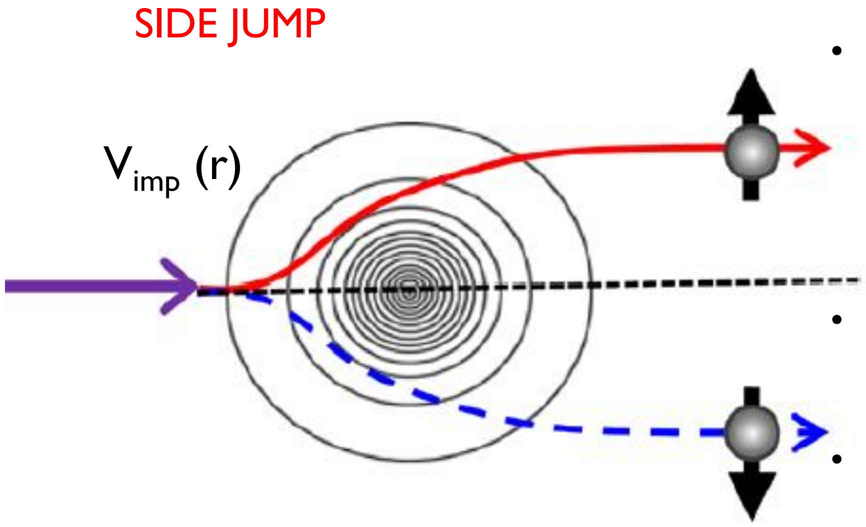
$$-\rho_{SH} = \alpha_{SH}^{skew} \boxed{\rho_{xx0}}$$

Residual resistivity accounts for scattering time due to impurities, but not other scattering sources (phonons).



M. Gradhand *et al.*, SPIN **2**, 125010 (2012)

SPIN HALL EFFECT: MECHANISMS



- Electrons deflect first to one side due to the field created by the impurity and deflect back when they leave the impurity since the field is opposite, resulting in a side step. They however come out in a different band so this gives rise to an anomalous velocity.

- Most obscure mechanism. Sometimes defined as any contribution that is not intrinsic and skew scattering.

- σ_{SH} is independent of scattering time (τ^0) $\beta_{SH}^{side} = cnt.$

$$-\rho_{SH} = \beta_{SH}^{side}\,\boxed{\rho_{xx0}^2}$$

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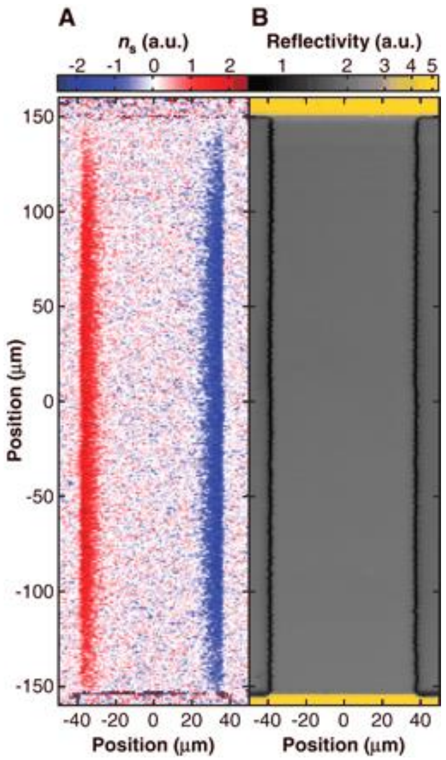
TECHNIQUES: optical detection

In semiconductors

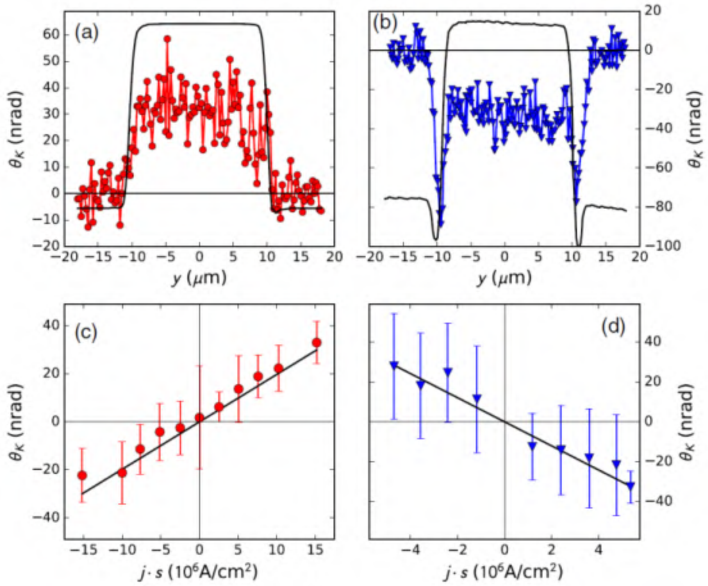


- First observation of SHE
- Spatially resolved MOKE
- GaAs

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

In metals

Pt W

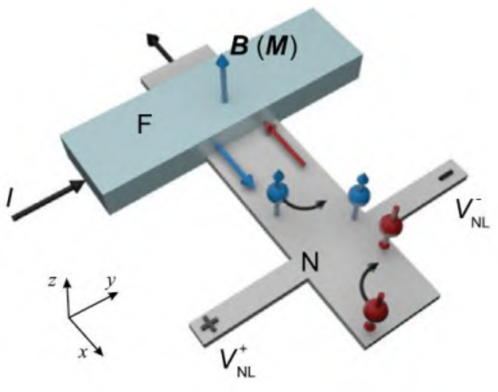


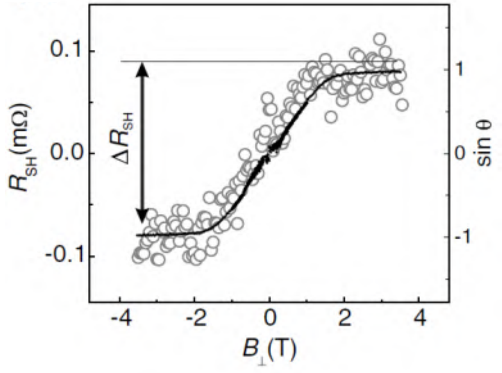
- Opposite signal in Pt and W
- Extremely small signal
- Sensitivity of 5×10^{-9} rad achieved with current-modulation technique

C. Stamm *et al.*, Phys. Rev. Lett. **119**, 087203 (2017)

TECHNIQUES: non-local transport

Lateral spin valve with Hall bar



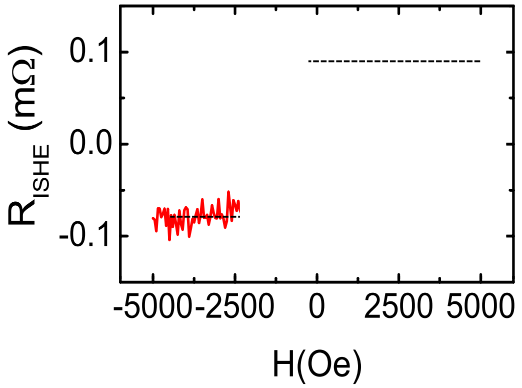


$$\Delta R_{SH} = \frac{\alpha_J}{t_N}\frac{\sigma_{SH}}{\sigma_{xx}^2} exp(-L/\lambda_N)$$

- First observation of SHE in a metal (Al)
- Only possible for materials with long λ_N

S.O.Valenzuela *et al.*, Nature **442**, 176 (2006)

Lateral spin valve with spin absorption



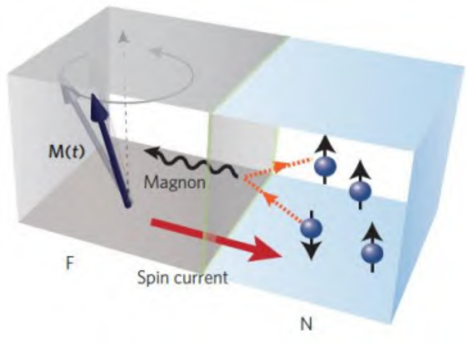
$$\theta_{SH} = \frac{w_{SOM} t_{SOM}}{x\,\rho_{SOM}\lambda_{SOM}}\frac{1-e^{-2t_{SOM}/\lambda_{SOM}}}{(1-e^{-t_{SOM}/\lambda_{SOM}})^2}\frac{I}{I_s(z=0)}\Delta R_{SH}$$

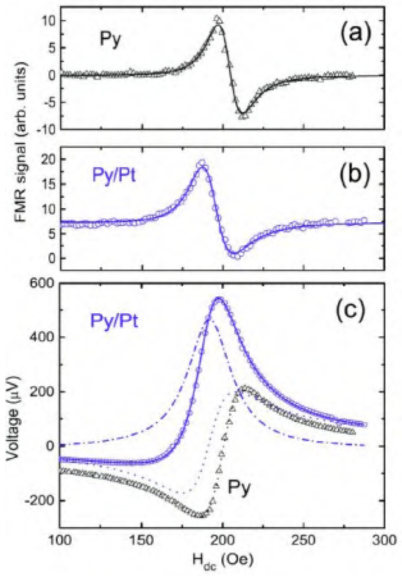
- Observation of SHE in heavy metals with short λ_N

M. Morota *et al.*, Phys. Rev. B **83**, 174405 (2011)
P. Laczkowski *et al.*, Phys. Rev. B **96**, 140405 (R) (2017)
E. Sagasta *et al.*, Phys. Rev. B **94**, 060412(R) (2016)

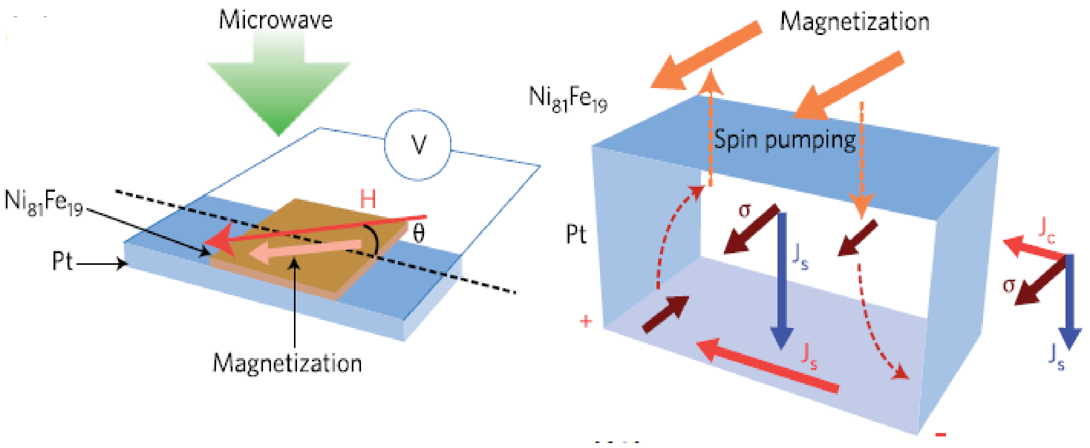
TECHNIQUES: FMR-based

Spin Pumping





- Microwaves (GHz) induce ferromagnetic resonance (FMR) in the FM
- Exchange coupling at FM/NM interface
- A DC spin current injected at the NM, free from conductivity mismatch

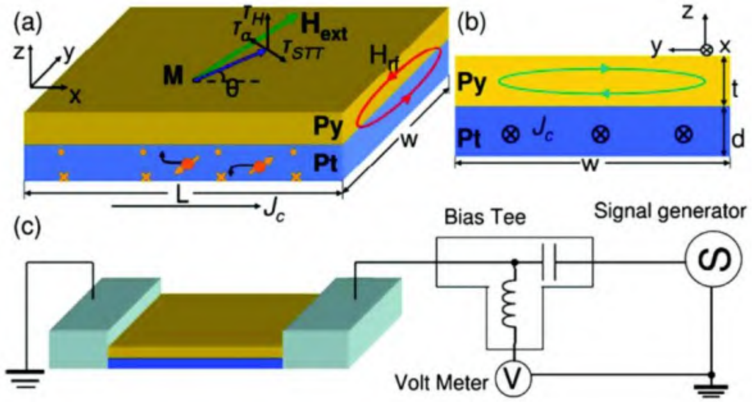


- ISHE gives rise to transverse DC voltage
- Easy to measure (no nanofab. required)
- Microwave cavity (fixed freq.) or coplanar waveguide (variable freq.) used
- Proper modeling to quantify (spurious effects like AMR or current shunting need to be considered)

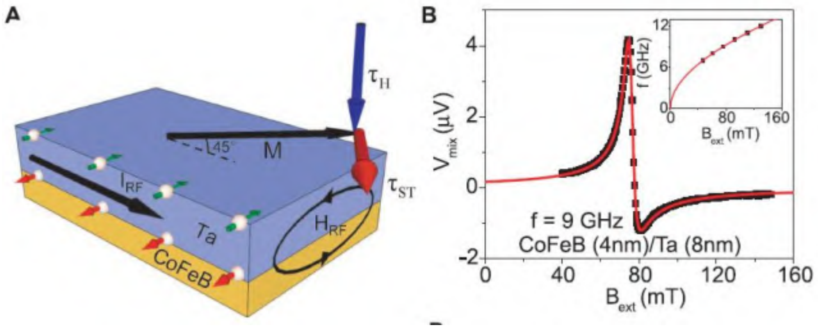
Y. Tserkovnyak *et al.*, Phys. Rev. Lett. **88**, 117601 (2002)
E. Saitoh *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)
O. Mosendz *et al.*, Phys. Rev. B **82**, 214403 (2010)

TECHNIQUES: FMR-based

Spin torque-FMR



- Microwave frequency (r.f.) charge current through FM/NM bilayer
- r.f. spin current is generated in the NM by SHE and will result in an oscillating STT in the adjacent FM, inducing magnetization precession which leads to an oscillatory AMR
- From the mixing of this oscillating AMR and the r.f. charge current, a measurable DC voltage signal (V_{mix}) is generated across the sample due to the spin-torque diode effect

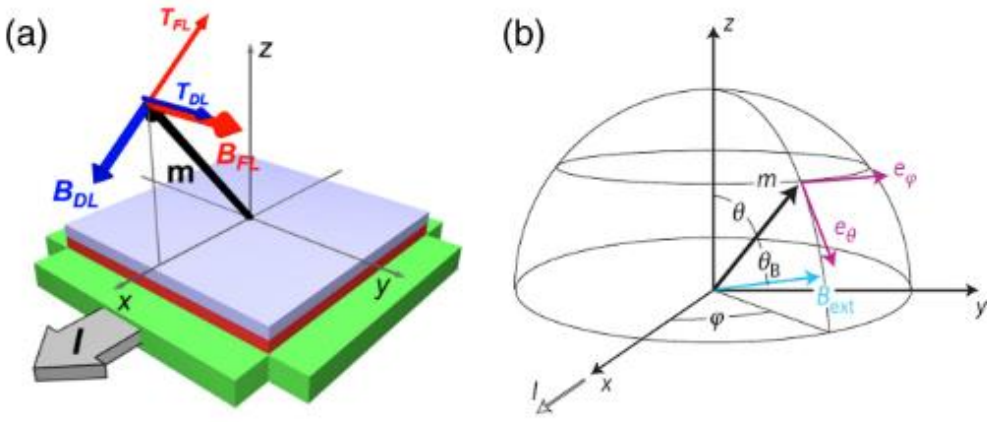


- V_{mix} is a combination of symmetric (torque from SHE) and antisymmetric Lorentzian (torque from Oersted field)
- Detailed analysis of V_{mix} enables quantification of θ_{SH}

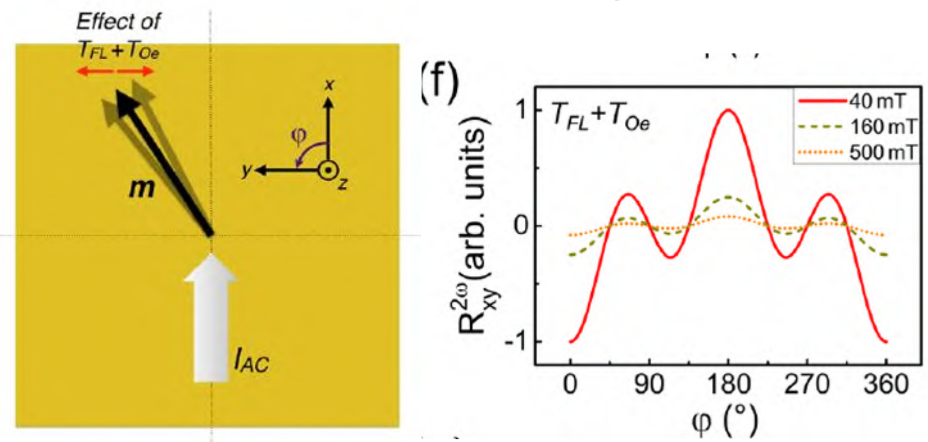
L. Liu *et al.*, Phys. Rev. Lett. **106**, 036601 (2011)
L. Liu *et al.*, Science **336**, 555 (2012)

TECHNIQUES: Harmonic Hall voltage

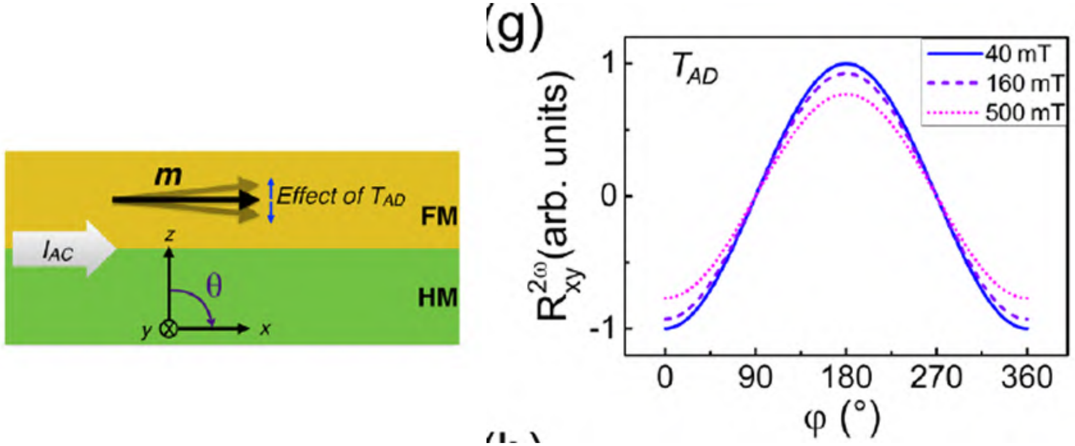
- All-electrical method to characterize spin-orbit torque in FM/NM bilayers
- Based on the second harmonic changes of the Hall voltage induced by small oscillations of the magnetization due to the injection of an a.c. current.
- Two type of torques: field-like torque and damping-like torque



Field-like torque



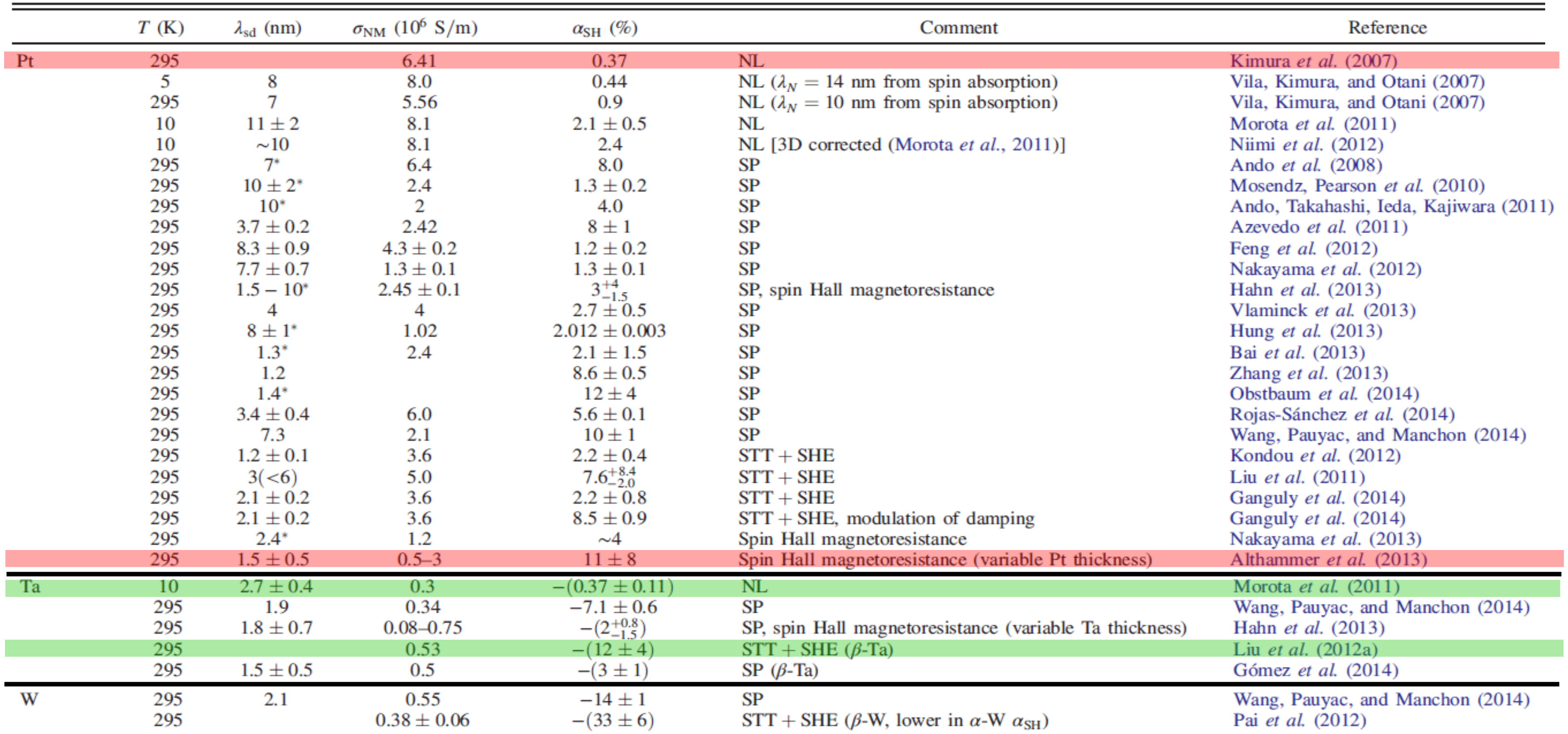
Damping-like torque



- $\mathbf{m_x \times m_y}$ through the planar Hall effect (PHE)
- $\mathbf{m_z}$ through the anomalous Hall effect (AHE)

K. Garello *et al.*, Nature Nanotech. **8**, 587 (2013)
C. O. Avci *et al.*, Phys. Rev. B **90**, 587 (2014)

TECHNIQUES: Quantification in pure metals



	T (K)	λ_{sd} (nm)	σ_{NM} (10^6 S/m)	α_{SH} (%)	Comment	Reference
Pt	295		6.41	0.37	NL	Kimura *et al.* (2007)
	5	8	8.0	0.44	NL ($\lambda_N = 14$ nm from spin absorption)	Vila, Kimura, and Otani (2007)
	295	7	5.56	0.9	NL ($\lambda_N = 10$ nm from spin absorption)	Vila, Kimura, and Otani (2007)
	10	11 ± 2	8.1	2.1 ± 0.5	NL	Morota *et al.* (2011)
	10	~10	8.1	2.4	NL [3D corrected (Morota *et al.*, 2011)]	Niimi *et al.* (2012)
	295	7^*	6.4	8.0	SP	Ando *et al.* (2008)
	295	$10 \pm 2^*$	2.4	1.3 ± 0.2	SP	Mosendz, Pearson *et al.* (2010)
	295	10^*	2	4.0	SP	Ando, Takahashi, Ieda, Kajiwara (2011)
	295	3.7 ± 0.2	2.42	8 ± 1	SP	Azevedo *et al.* (2011)
	295	8.3 ± 0.9	4.3 ± 0.2	1.2 ± 0.2	SP	Feng *et al.* (2012)
	295	7.7 ± 0.7	1.3 ± 0.1	1.3 ± 0.1	SP	Nakayama *et al.* (2012)
	295	$1.5 - 10^*$	2.45 ± 0.1	$3^{+4}_{-1.5}$	SP, spin Hall magnetoresistance	Hahn *et al.* (2013)
	295	4	4	2.7 ± 0.5	SP	Vlaminck *et al.* (2013)
	295	$8 \pm 1^*$	1.02	2.012 ± 0.003	SP	Hung *et al.* (2013)
	295	1.3^*	2.4	2.1 ± 1.5	SP	Bai *et al.* (2013)
	295	1.2		8.6 ± 0.5	SP	Zhang *et al.* (2013)
	295	1.4^*		12 ± 4	SP	Obstbaum *et al.* (2014)
	295	3.4 ± 0.4	6.0	5.6 ± 0.1	SP	Rojas-Sánchez *et al.* (2014)
	295	7.3	2.1	10 ± 1	SP	Wang, Pauyac, and Manchon (2014)
	295	1.2 ± 0.1	3.6	2.2 ± 0.4	STT + SHE	Kondou *et al.* (2012)
	295	3(<6)	5.0	$7.6^{+8.4}_{-2.0}$	STT + SHE	Liu *et al.* (2011)
	295	2.1 ± 0.2	3.6	2.2 ± 0.8	STT + SHE	Ganguly *et al.* (2014)
	295	2.1 ± 0.2	3.6	8.5 ± 0.9	STT + SHE, modulation of damping	Ganguly *et al.* (2014)
	295	2.4^*	1.2	~4	Spin Hall magnetoresistance	Nakayama *et al.* (2013)
	295	1.5 ± 0.5	0.5–3	11 ± 8	Spin Hall magnetoresistance (variable Pt thickness)	Althammer *et al.* (2013)
Ta	10	2.7 ± 0.4	0.3	$-(0.37 \pm 0.11)$	NL	Morota *et al.* (2011)
	295	1.9	0.34	-7.1 ± 0.6	SP	Wang, Pauyac, and Manchon (2014)
	295	1.8 ± 0.7	0.08–0.75	$-(2^{+0.8}_{-1.5})$	SP, spin Hall magnetoresistance (variable Ta thickness)	Hahn *et al.* (2013)
	295		0.53	$-(12 \pm 4)$	STT + SHE (β-Ta)	Liu *et al.* (2012a)
	295	1.5 ± 0.5	0.5	$-(3 \pm 1)$	SP (β-Ta)	Gómez *et al.* (2014)
W	295	2.1	0.55	-14 ± 1	SP	Wang, Pauyac, and Manchon (2014)
	295		0.38 ± 0.06	$-(33 \pm 6)$	STT + SHE (β-W, lower in α-W α_{SH})	Pai *et al.* (2012)

- Large dispersion of θ_{SH} values with different techniques (and also with the same techniques!)
- Different longitudinal resistivities can also give different θ_{SH} values
- WARNING: Mixed definitions of spin Hall angle [(ħ/e) and (ħ/2e)]!
- Values for other materials (Al, Au, Pd, Mo...) can be found in:

J. Sinova *et al.*, Rev. Mod. Phys. **87**, 1213 (2015)

TECHNIQUES: Quantification in alloys

Light

Heavy

HOST	IMP	Optimum %imp	θ_{SH} (%)	Mechanism	Technique	Ref.
Cu	Ir	Indep of % (0-12) (dilute regime)	2.1	Skew scattering	LSV	[1]
Cu	Bi	< 1 (dilute regime)	-24	Skew scattering	LSV	[2]
Cu	Pb	0.5 (the only studied)	-13	Skew scattering	LSV	[3]
Cu	Pt	28	5.4	Skew s./ side j.	ST-FMR(6nm films)	[4]
Ag	Bi	Indep of % (0-3)	-2.3	Skew scattering	LSV	[3]
Au	Ta	10 (max studied)	50	Side jump	SP-FMR	[5]
Au	W	~15	15	Intrinsic	LSV& SP-FMR	[5]
Au	Pt	50	20-30	Intrinsic	SP-FMR	[6]

[1] Y. Niimi *et al.*, Phys. Rev. Lett. **106**, 126601 (2011)
[2] Y. Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012)
[3] Y. Niimi *et al.*, Phys. Rev. B **89**, 054401 (2014)
[4] R. Ramaswamy *et al.*, Phys. Rev. Appl. **8**, 024034 (2017)
[5] P. Laczkowski *et al.*, Phys. Rev. B **96**, 140405 (R) (2017)
[6] M. Obstbaum *et al.*, Phys. Rev. Lett **117**, 167204 (2016)

OUTLINE

1. Introduction to spintronics
   - Introduction
   - Pure spin currents
2. Introduction to spin Hall effect
   - Origin
   - Discovery and relation with anomalous Hall effect
   - Mechanisms (intrinsic, skew-scattering, side-jump)
3. Techniques to quantify SHE
   - Optical
   - Non-local transport
   - FMR-based
   - (Tables of quantification)
4. Related spin-orbit effects
   - Edelstein effect in Rashba systems
   - Spin-momentum locking in Topological Insulators
5. Applications
   - Spin-orbit torques
   - Spin-orbit logic

RELATED EFFECTS: Edelstein effect

Spin Hall effect (3D)

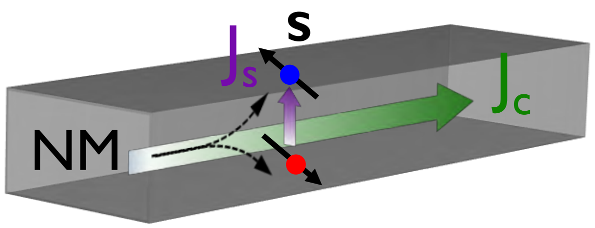
Edelstein effect / inverse spin galvanic effect (2D)

Bulk metals with strong SOC

Rashba interface

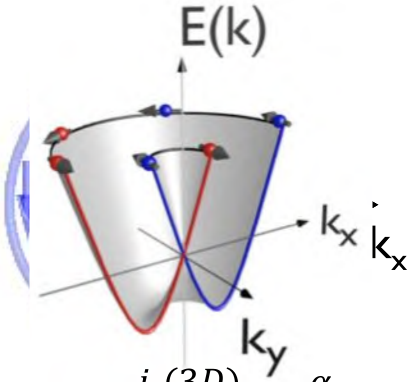
Topological insulator

Direct Effect

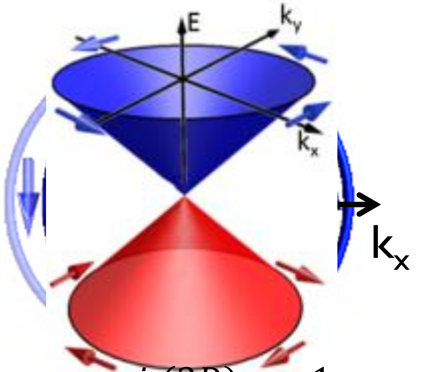


$$\boxed{\vec{j_s} \propto \theta_{SH}\, \vec{j_c} \times \vec{s}}$$

$$\theta_{SH} = \frac{j_s\ (3D)}{j_c(3D)}$$

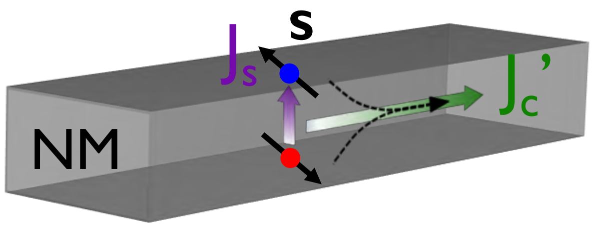


$$q_{EE} = \frac{j_s(3D)}{j_c(2D)} = \frac{\alpha_R}{\hbar v_F^2 \tau}$$



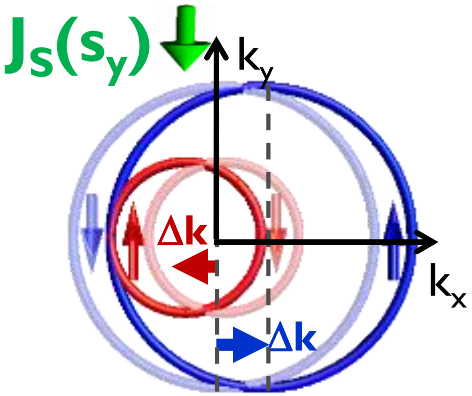
$$q_{EE} = \frac{j_s(3D)}{j_c(2D)} = \frac{1}{v_F \tau}$$

Inverse Effect

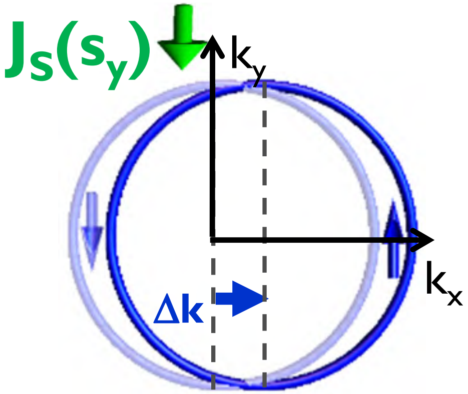


$$\boxed{\vec{j_c} \propto \theta_{ISH}\, \vec{j_s} \times \vec{s}}$$

$$\theta_{ISH} = \frac{j_c\ (3D)}{j_s(3D)}$$



$$\lambda_{IEE} = \frac{j_c(2D)}{j_s(3D)} = \alpha_R \frac{\tau}{\hbar}$$

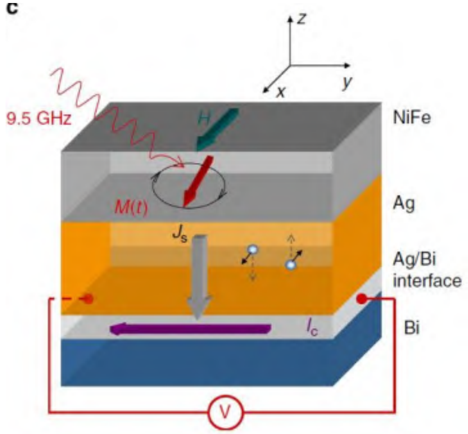


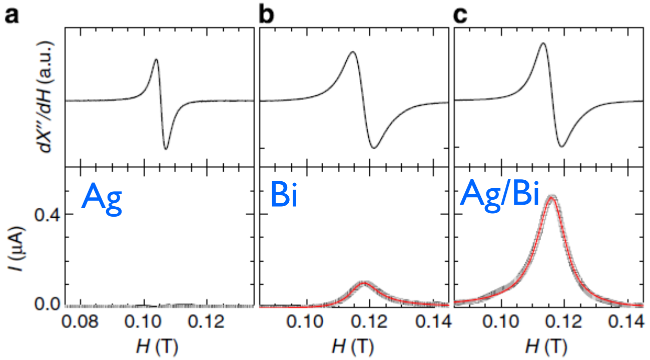
$$\lambda_{IEE} = \frac{j_c(2D)}{j_s(3D)} = v_F \tau$$

K. Kondou *et al.*, Nature Phys. **12**, 1027 (2016)
J. C. Rojas-Sanchez *et al.*, PRL **116**, 096602 (2016)

RELATED EFFECTS: Edelstein effect

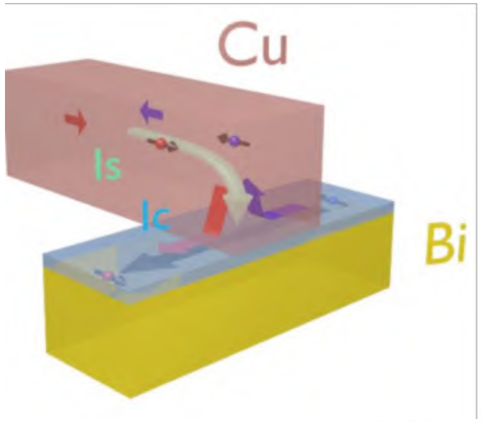
Rashba interfaces

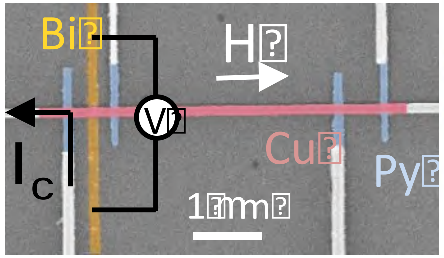


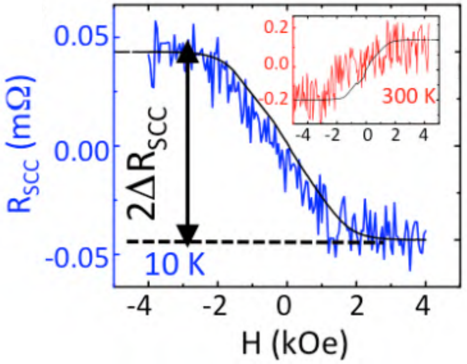


- Bi/Ag interface
- Spin pumping
- Measures inverse Edelstein effect
- λ_{IEE} ~ 0.2-0.3 nm (RT)

J. C. Rojas-Sanchez *et al.*, Nature Comms. **4**, 2944 (2013)





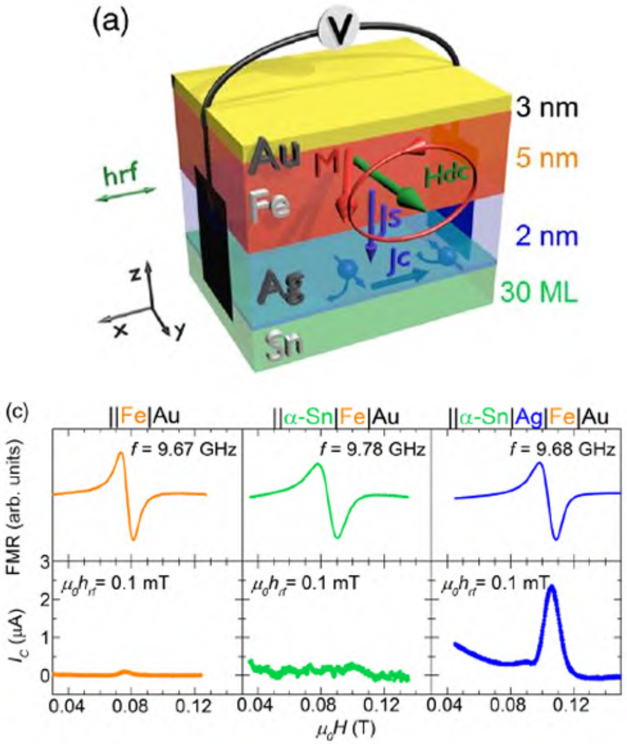


- Bi/Cu interface
- Spin absorption
- Measures inverse Edelstein effect
- λ_{IEE} ~ 0.01 nm (RT)

M. Isasa et al., Phys. Rev. B **93**, 014420 (2016)

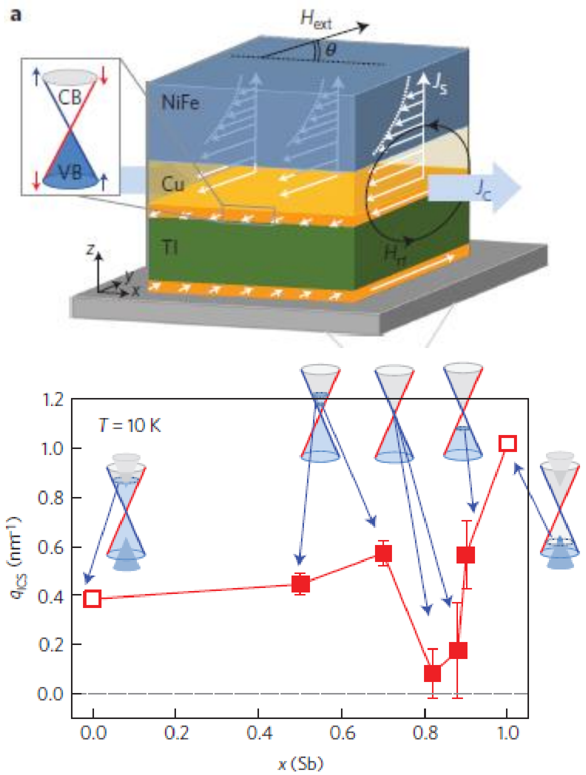
RELATED EFFECTS: Edelstein effect

Topological insulators



- α-Sn
- Spin pumping
- Measures inverse effect
- λ_{IEE} ~ 2.1 nm (RT)

J. C. Rojas-Sanchez *et al.*, PRL **116**, 096602 (2016)



- $(Bi_{1-x}Sb_x)_2Te_3$
- Spin torque - FMR
- Measures direct effect
- q_{EE} ~ 0.4-0.6 nm^{-1} (RT)

K. Kondou *et al.*, Nature Phys. **12**, 1027 (2016)

RELATED EFFECTS: Edelstein effect

Simple comparison:

$$\boxed{\theta_{SH} \approx \frac{\lambda_{IEE}}{t_{int}} \approx q_{EE} \times t_{int}}$$

Pt: θ_{SH} ~ 2-20%

Bi/Ag: $\theta_{SH} \sim \lambda_{IEE}/t_{int}$ ~ 50-75% (t_{int}=0.4 nm)

α-Sn: $\theta_{SH} \sim \lambda_{IEE}/t_{int}$ ~ 210% (t_{int}=1 nm)

$(Bi_{1-x}Sb_x)_2Te_3$: $\theta_{SH} \sim q_{EE} \times t_{int}$ ~ 40-60% (t_{int}=1 nm)

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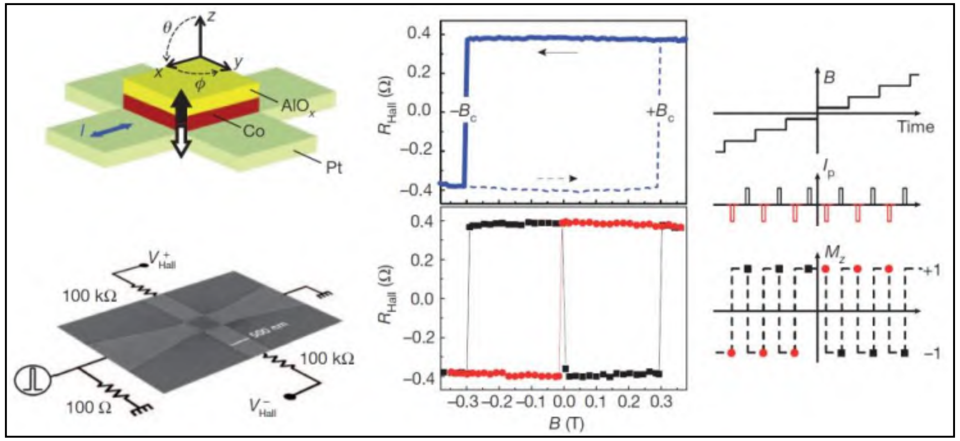
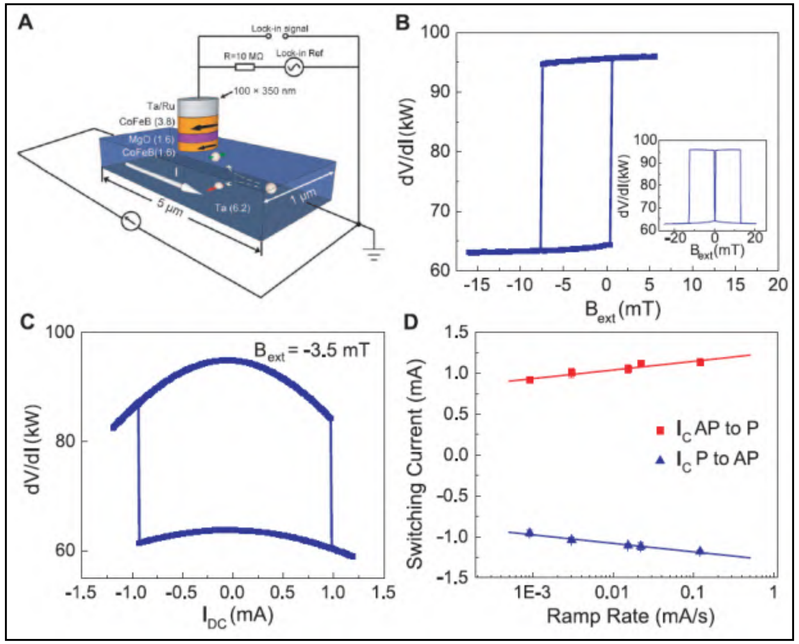
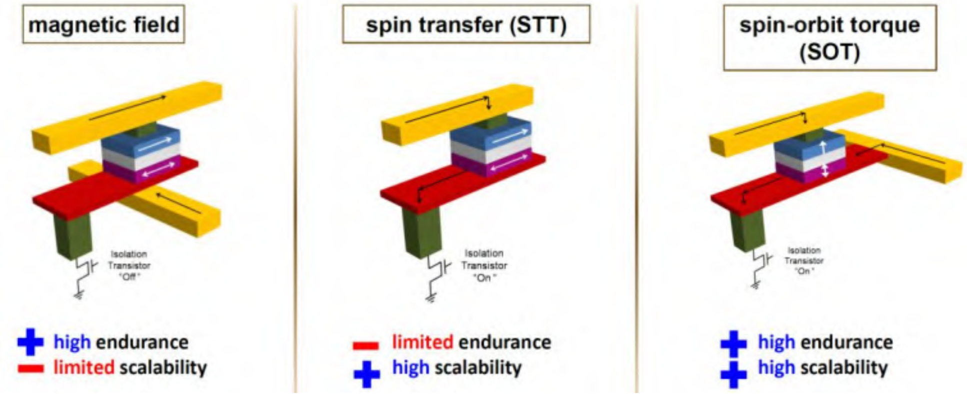
APPLICATIONS: SPIN-ORBIT TORQUE

Magnetization switching





- Magnetization switching with transverse spin current
- Originated by SHE and/or Edelstein effect
- Ultrafast switching (< 200 ps), deterministic
- MRAM based on SOT for writing



magnetic field

➕ high endurance
➖ limited scalability

spin transfer (STT)

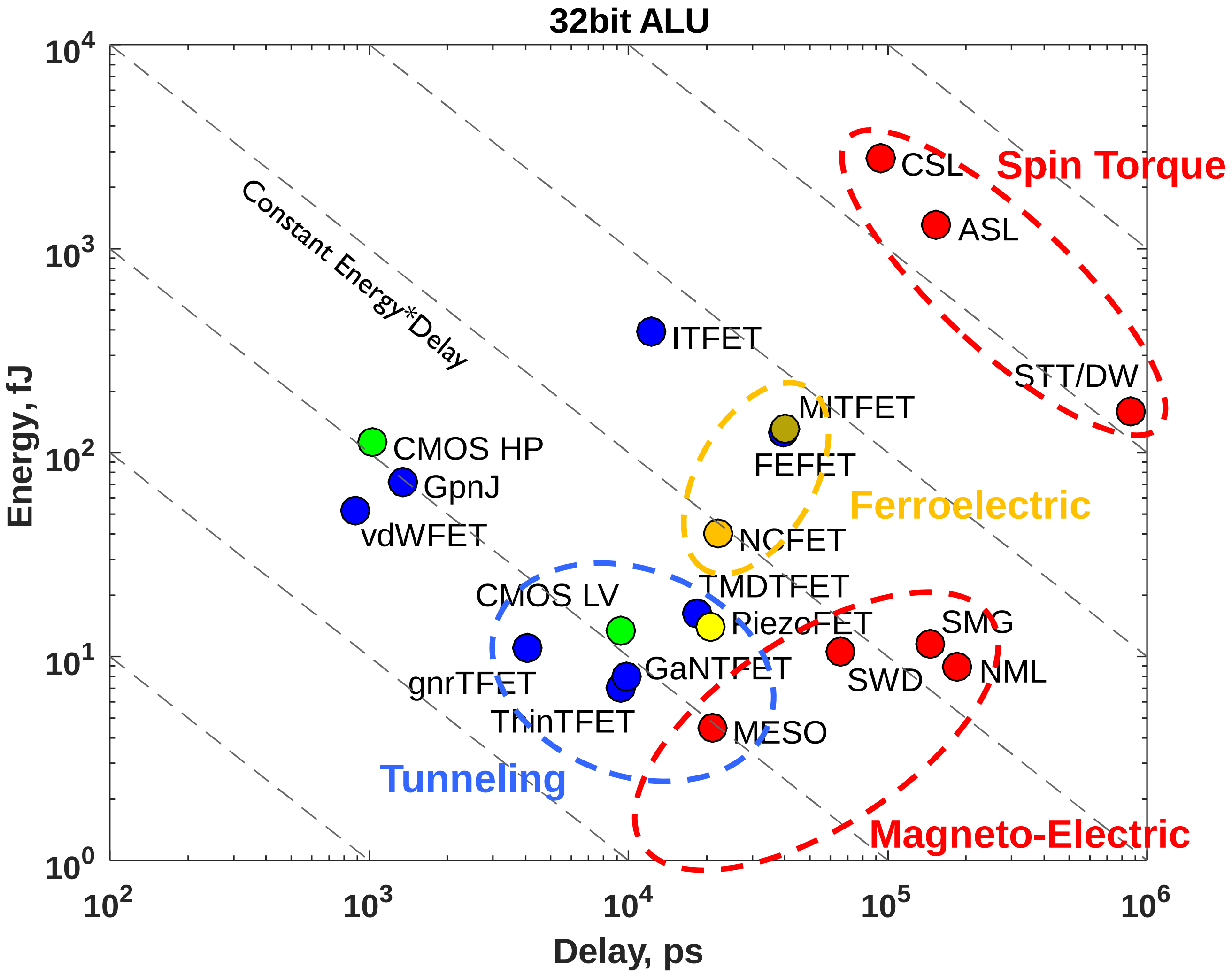
➖ limited endurance
➕ high scalability

spin-orbit torque (SOT)

➕ high endurance
➕ high scalability

I. M. Miron *et al.*, Nature **476**, 189 (2011)
L. Liu *et al.*, Science **336**, 555 (2012)

APPLICATIONS: SPIN-ORBIT LOGIC



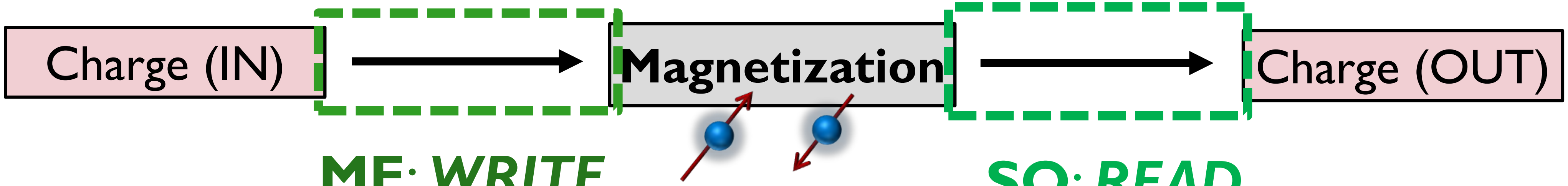
● CMOS Ref
● Electronic
● Spintronic
● Ferroelectric
● Orbitronic
● Straintronic

MESO logic: slower, but **lower energy** while enabling:

- ✓ **higher density (per functionality)**
- ✓ **voltage scalability**
- ✓ **non-volatile logic-in-memory**
- ✓ **compatibility with traditional and future architectures**

D. E. Nikonov and I. A. Young, *IEEE J. Explor. Comput. Devices and Circuits* **1**, 3-11 (2015)
S. Manipatruni et al., Nature **565**, 35 (2019)

APPLICATIONS: SPIN-ORBIT LOGIC



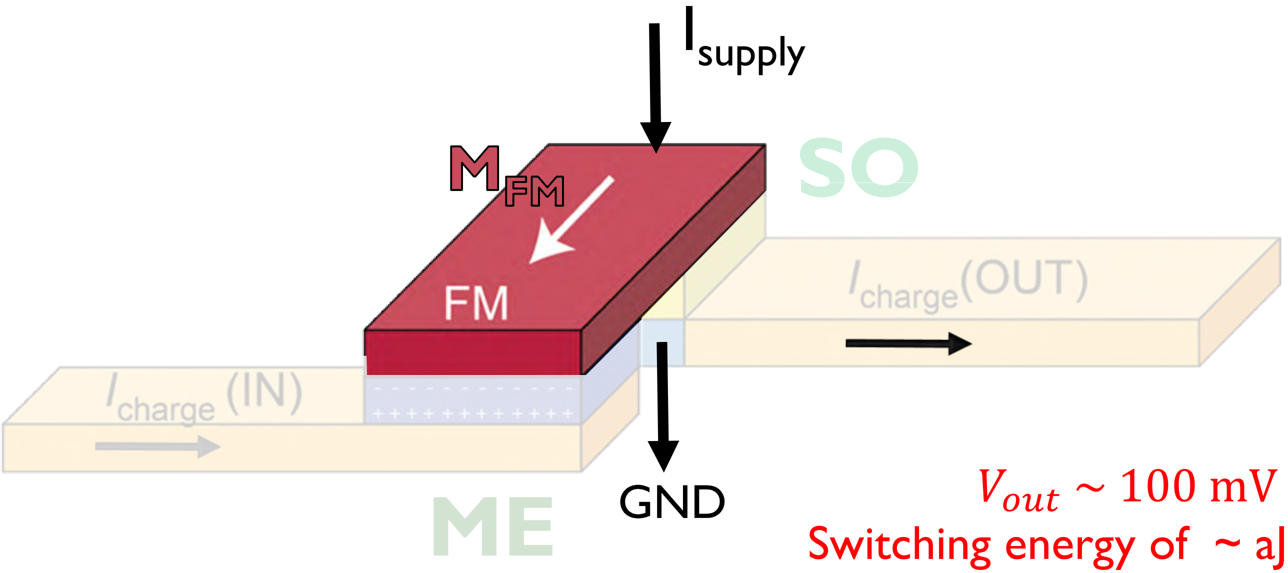
Charge (IN) → **Magnetization** → Charge (OUT)

ME; ***WRITE***

Magneto-electric effect

SO; ***READ***

Spin-orbit effect



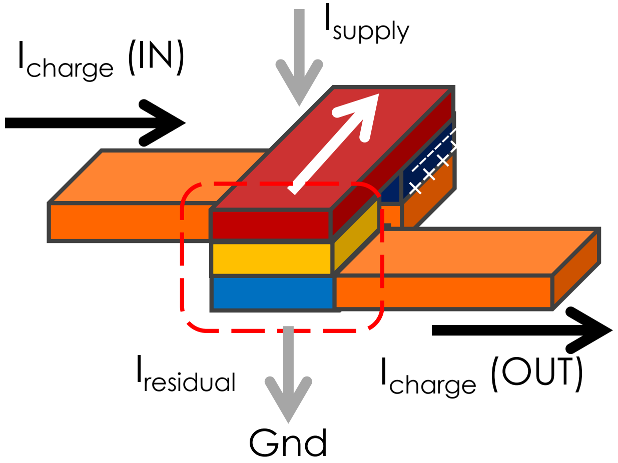
- 🟥 Magnet
- 🟦 Multiferroic oxide
- 🟦 Spin-orbit material
- 🟨 Spin channel
- 🟧 Interconnect

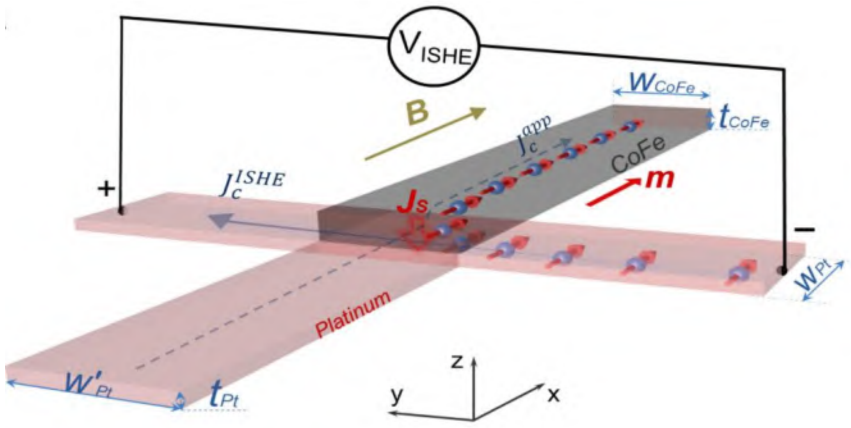
$V_{out} \sim 100$ mV

Switching energy of ~ aJ/bit !

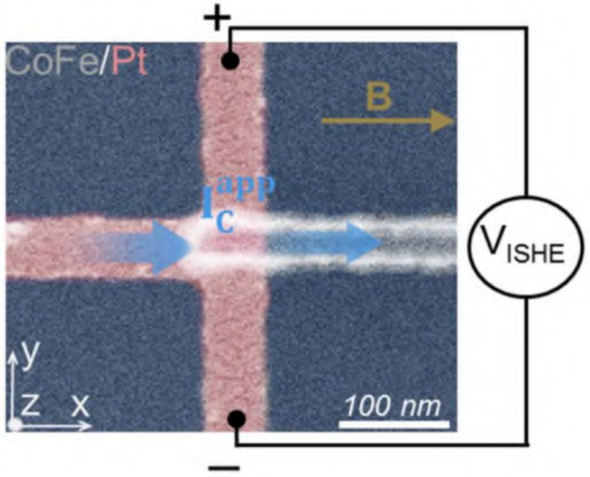
S. Manipatruni *et al.*, Nature **565**, 35-42 (2019)

APPLICATIONS: SPIN-ORBIT LOGIC





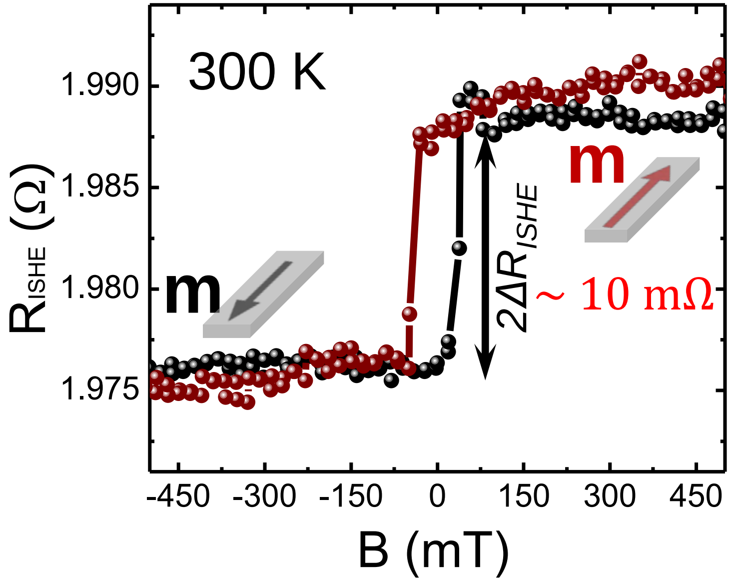
$$\vec{j_c} \propto \vec{j_s} \times \vec{s}$$



$$R_{ISHE} = \frac{V_{ISHE}}{I_C^{app}}$$

$V_{out} \sim 100\ \mathrm{mV}$

$\Delta R_{ISHE} \sim 1\ \mathrm{k\Omega}$



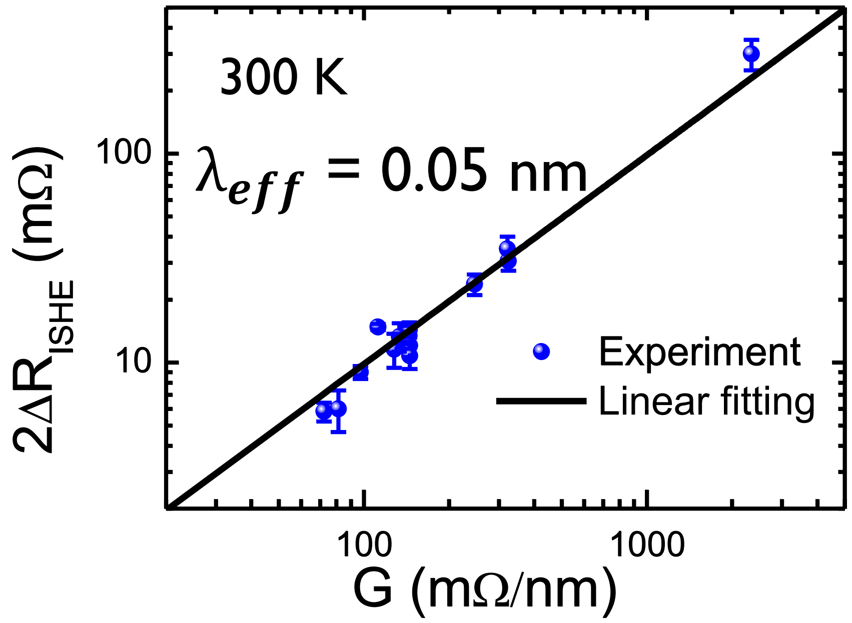
V.T. Pham *et al.*, Nature Electron. **3**, 309 (2020)

APPLICATIONS: SPIN-ORBIT LOGIC

Favorable downscaling for the spin Hall signal

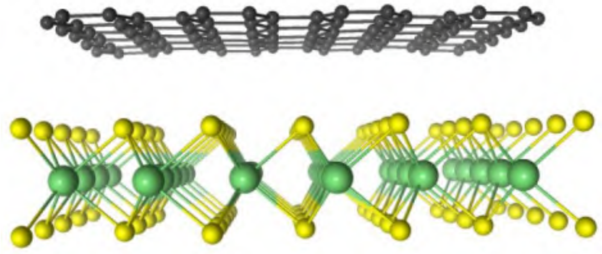
$$\Delta R_{(I)SHE} = \frac{1}{\left(\frac{t_{CoFe}}{\rho_{CoFe}} + \frac{t_{Pt}}{\rho_{Pt}}\right) w_{Pt}} \times \frac{P_{CoFe}\theta_{SH}\lambda_{Pt}}{1 + \frac{\lambda_{Pt}\rho_{Pt}}{\lambda_{CoFe}\rho^{*}_{CoFe}}} = G \times \lambda_{eff}$$

Geometrical factor Efficiency factor



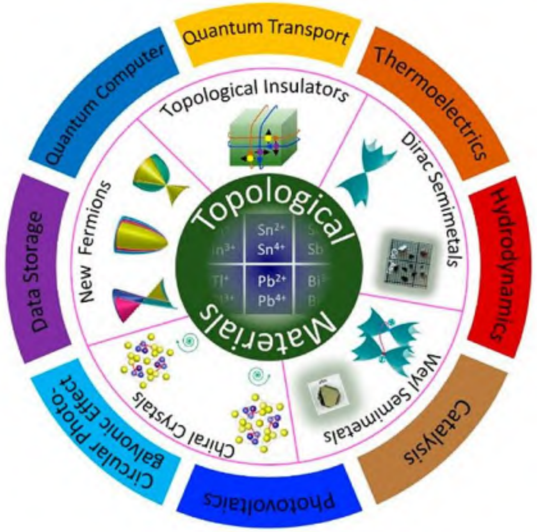
V. T. Pham *et al.*, Nature Electron. **3**, 309 (2020)

New materials with larger efficiency factor



2D materials and heterostructures

Review: J. F. Sierra *et al.*, Nature Nanotech. **16**, 858 (2021)

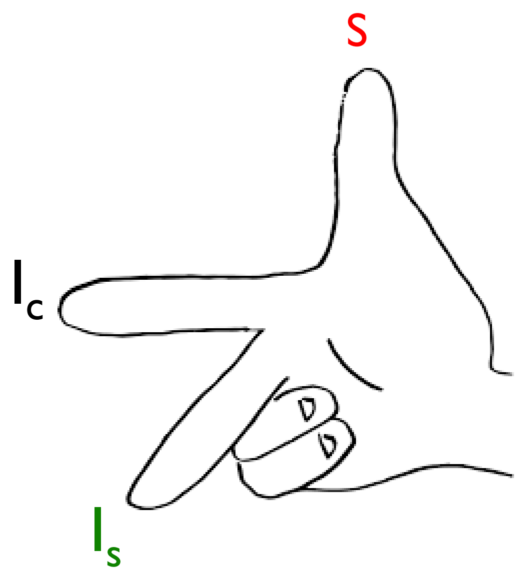


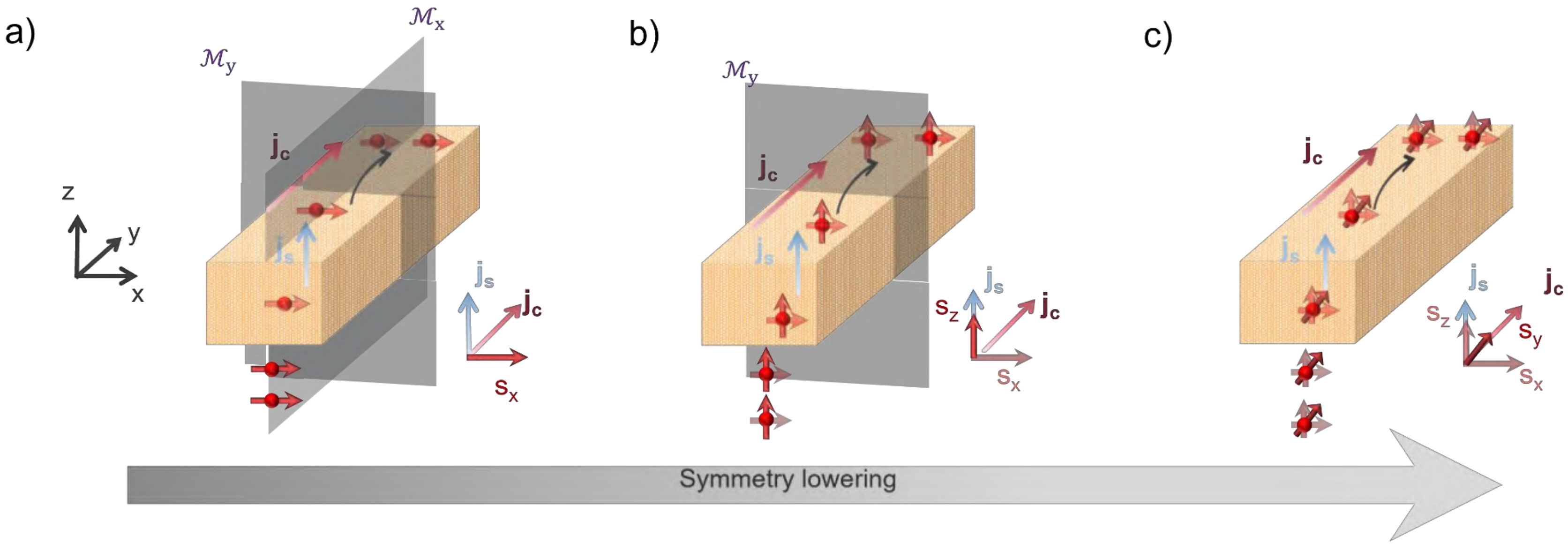
Topological materials

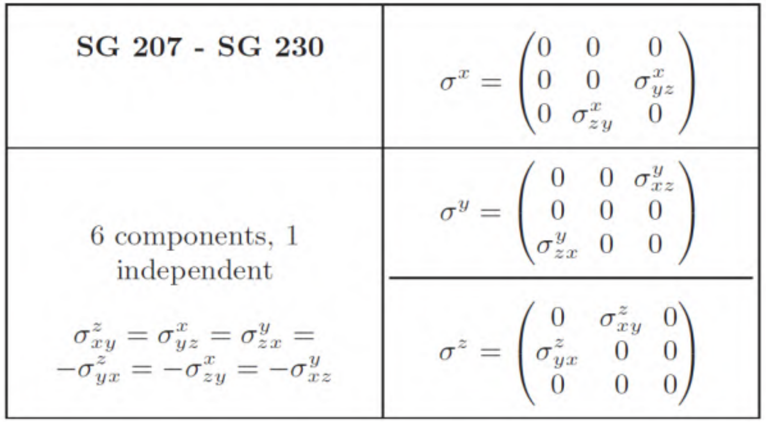
Review: Q. L. He *et al.*, Nature Mater. **21**, 15 (2022)

THE END

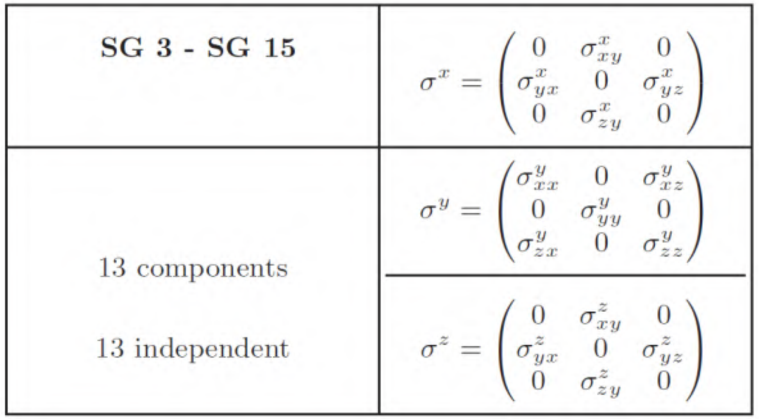
SPIN HALL EFFECT: Low symmetry



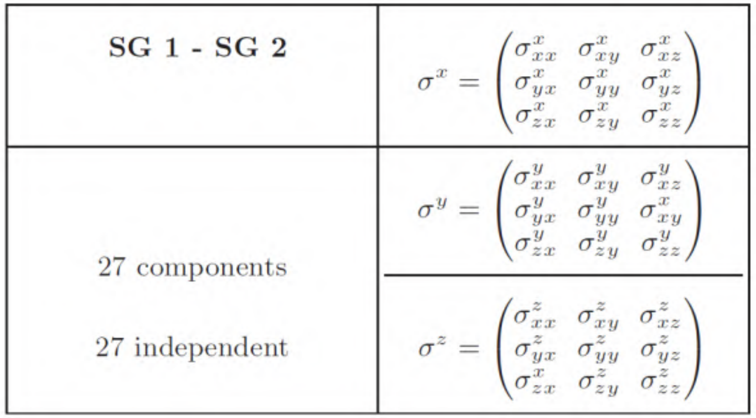




SG 207 - SG 230	$\sigma^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & 0 \end{pmatrix}$
6 components, 1 independent $\sigma^z_{xy} = \sigma^x_{yz} = \sigma^y_{zx} = -\sigma^z_{yx} = -\sigma^x_{zy} = -\sigma^y_{xz}$	$\sigma^y = \begin{pmatrix} 0 & 0 & \sigma^y_{xz} \\ 0 & 0 & 0 \\ \sigma^y_{zx} & 0 & 0 \end{pmatrix}$ $\sigma^z = \begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ \sigma^z_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$



SG 3 - SG 15	$\sigma^x = \begin{pmatrix} 0 & \sigma^x_{xy} & 0 \\ \sigma^x_{yx} & 0 & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & 0 \end{pmatrix}$
13 components 13 independent	$\sigma^y = \begin{pmatrix} \sigma^y_{xx} & 0 & \sigma^y_{xz} \\ 0 & \sigma^y_{yy} & 0 \\ \sigma^y_{zx} & 0 & \sigma^y_{zz} \end{pmatrix}$ $\sigma^z = \begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ \sigma^z_{yx} & 0 & \sigma^z_{yz} \\ 0 & \sigma^z_{zy} & 0 \end{pmatrix}$

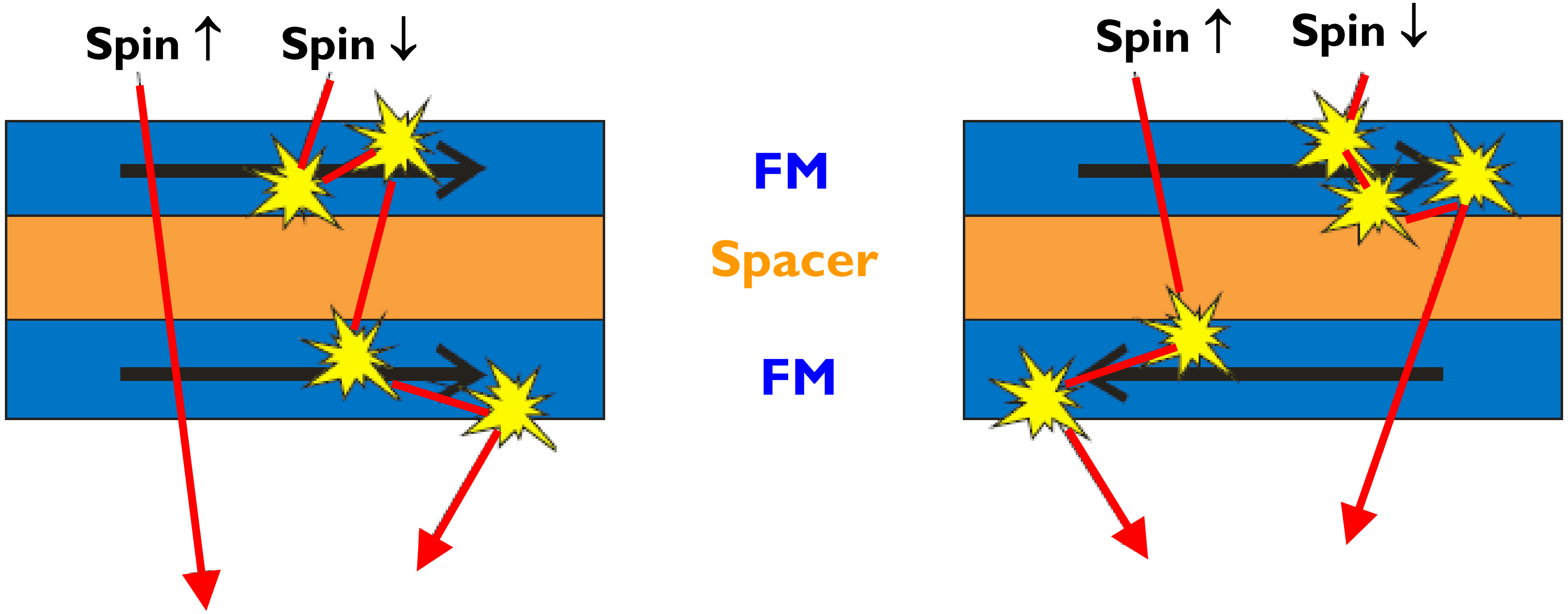


SG 1 - SG 2	$\sigma^x = \begin{pmatrix} \sigma^x_{xx} & \sigma^x_{xy} & \sigma^x_{xz} \\ \sigma^x_{yx} & \sigma^x_{yy} & \sigma^x_{yz} \\ \sigma^x_{zx} & \sigma^x_{zy} & \sigma^x_{zz} \end{pmatrix}$
27 components 27 independent	$\sigma^y = \begin{pmatrix} \sigma^y_{xx} & \sigma^y_{xy} & \sigma^y_{xz} \\ \sigma^y_{yx} & \sigma^y_{yy} & \sigma^x_{xy} \\ \sigma^y_{zx} & \sigma^y_{zy} & \sigma^y_{zz} \end{pmatrix}$ $\sigma^z = \begin{pmatrix} \sigma^z_{xx} & \sigma^z_{xy} & \sigma^z_{xz} \\ \sigma^z_{yx} & \sigma^z_{yy} & \sigma^z_{yz} \\ \sigma^z_{zx} & \sigma^z_{zy} & \sigma^z_{zz} \end{pmatrix}$

CK Safeer *et al.*, Nano Lett. **19**, 8758 (2019)
A. Roy *et al.*, arXiv:2110.09242 (2021)

INTRODUCTION: SPINTRONICS

- BASIC spintronic devices use two ferromagnets (**FM**) in a polarizer/analyzer arrangement: **spin valves**



Parallel magnetization: Low resistance

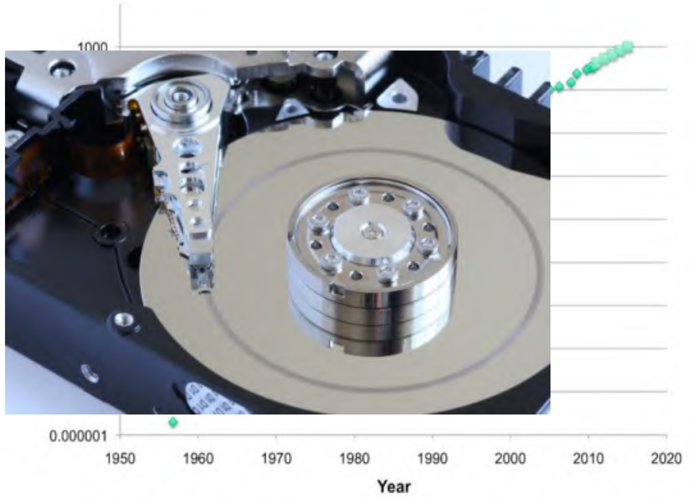
Antiparallel magnetization: High resistance

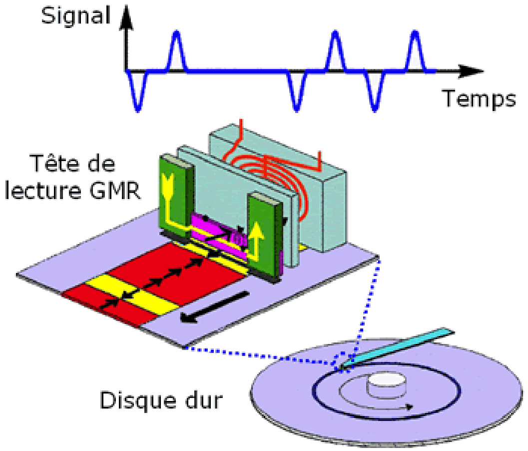
- Terminology depends on **spacer**:
  - <u>Metal</u>: giant magnetoresistance (GMR)
  - <u>Insulator</u>: tunnelling magnetoresistance (TMR)
  - <u>Domain wall</u>: domain wall magnetorresistance (DWMR)

INTRODUCTION: SPINTRONICS

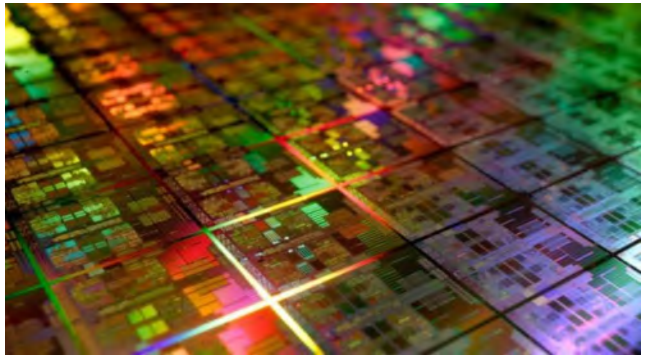
- **SPIN VALVES** in a vertical structure – two-terminal devices

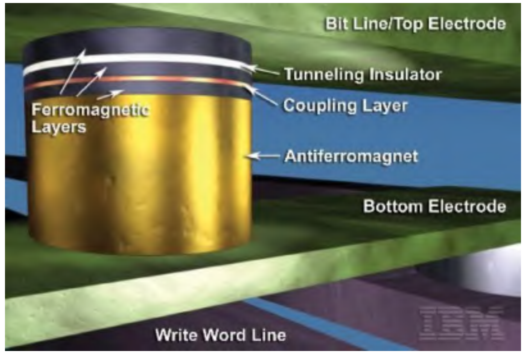
Magnetoresisitive read head
Basic phenomena: 1988
Market: IBM 1997





Magnetic RAM
4 Mbit chip
Revisited: 1995
Market: Freescale 2006





f.casanova@nanogune.eu

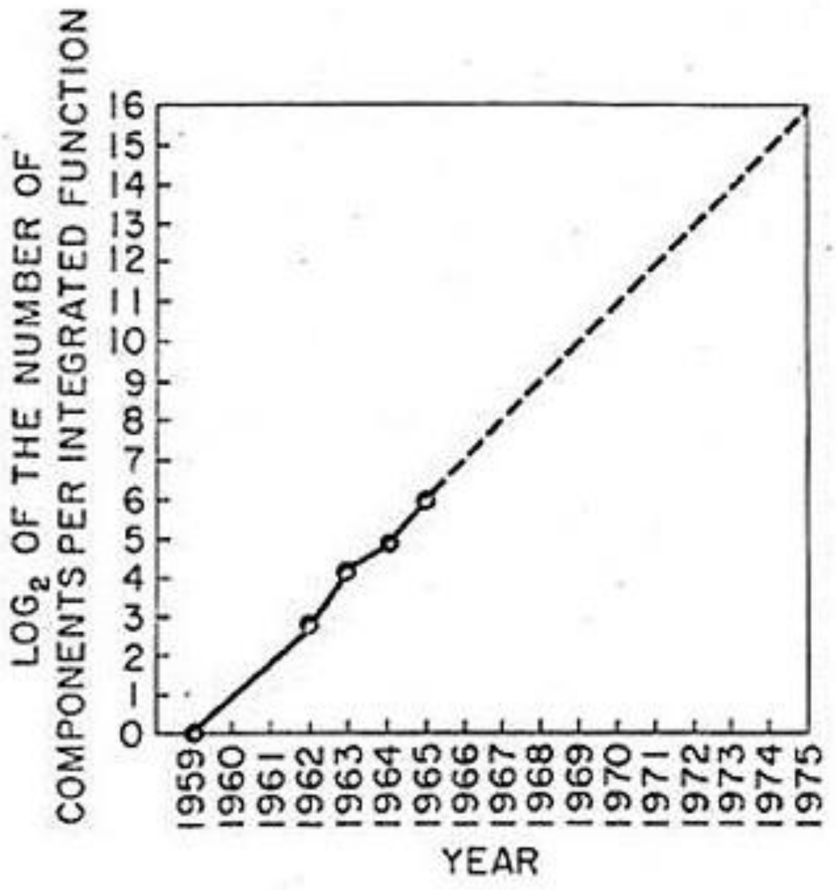
INTRODUCTION: SPINTRONICS

How do we move from here?

Towards second generation of spintronic devices

INTRODUCTION: MOORE’S LAW

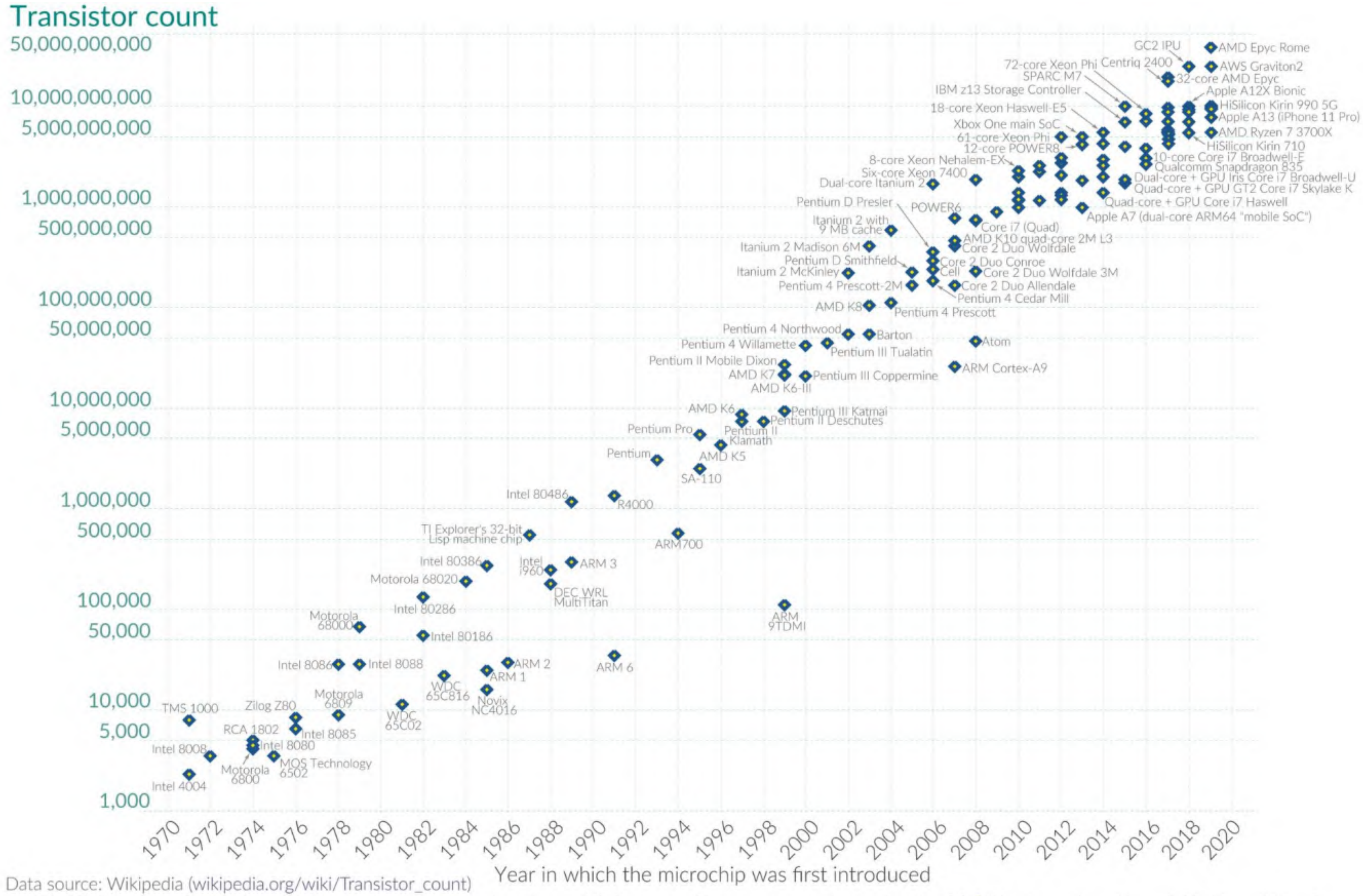
Moore’s law



Gordon Moore (1968)

INTRODUCTION: MOORE'S LAW

Moore's law

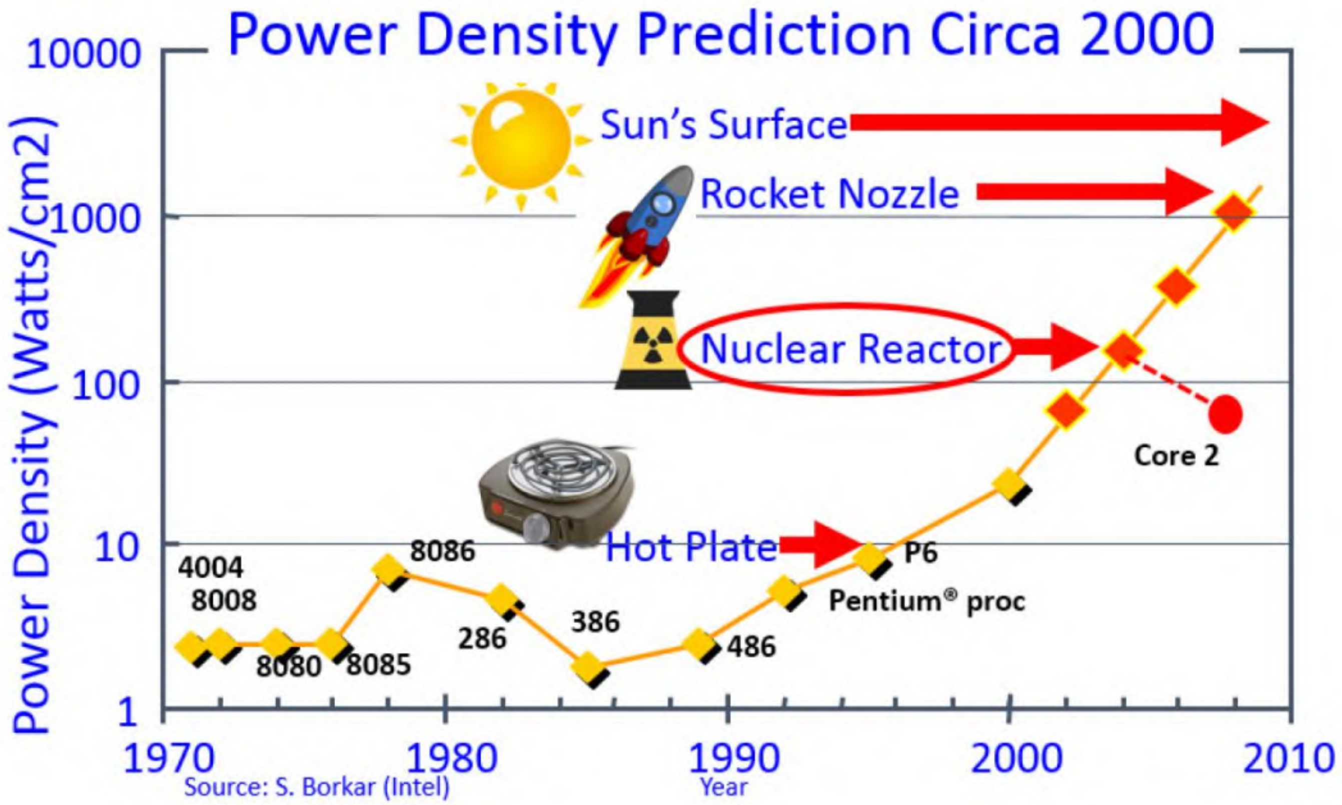


Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

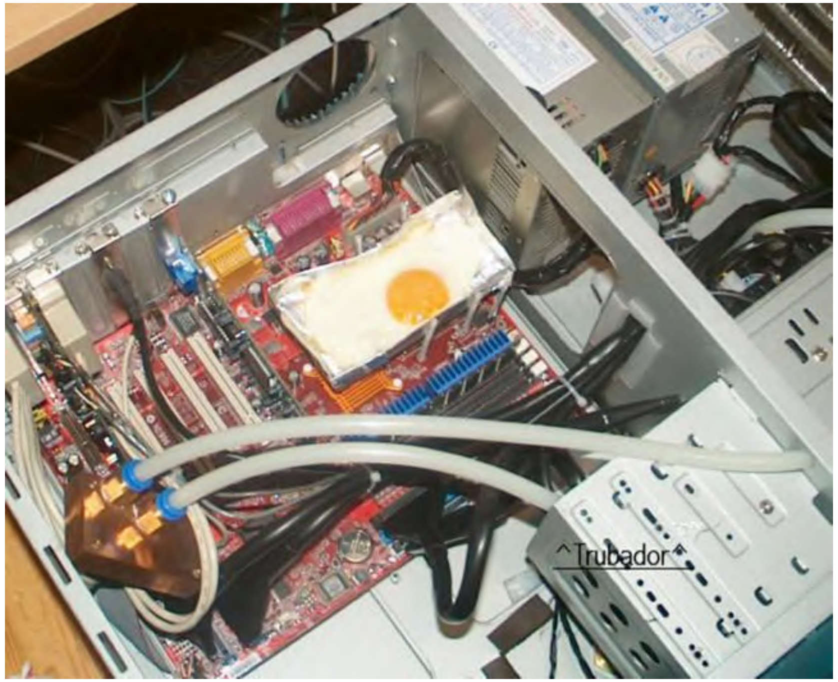
Gordon Moore (2020)

INTRODUCTION: MOORE'S LAW

What about power?

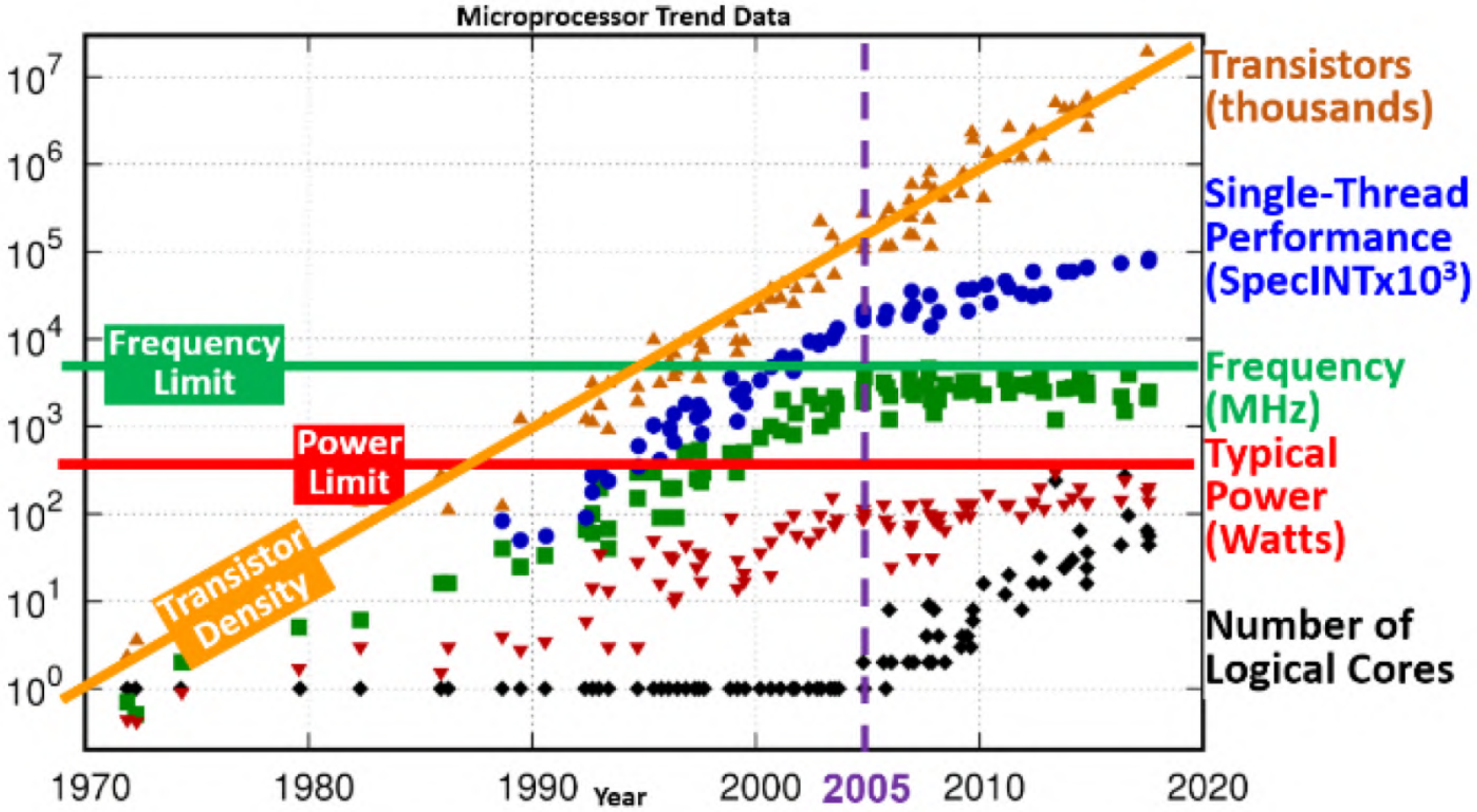


Source: S. Borkar (Intel)



INTRODUCTION: MOORE'S LAW

Other parameters also relevant for the future trend



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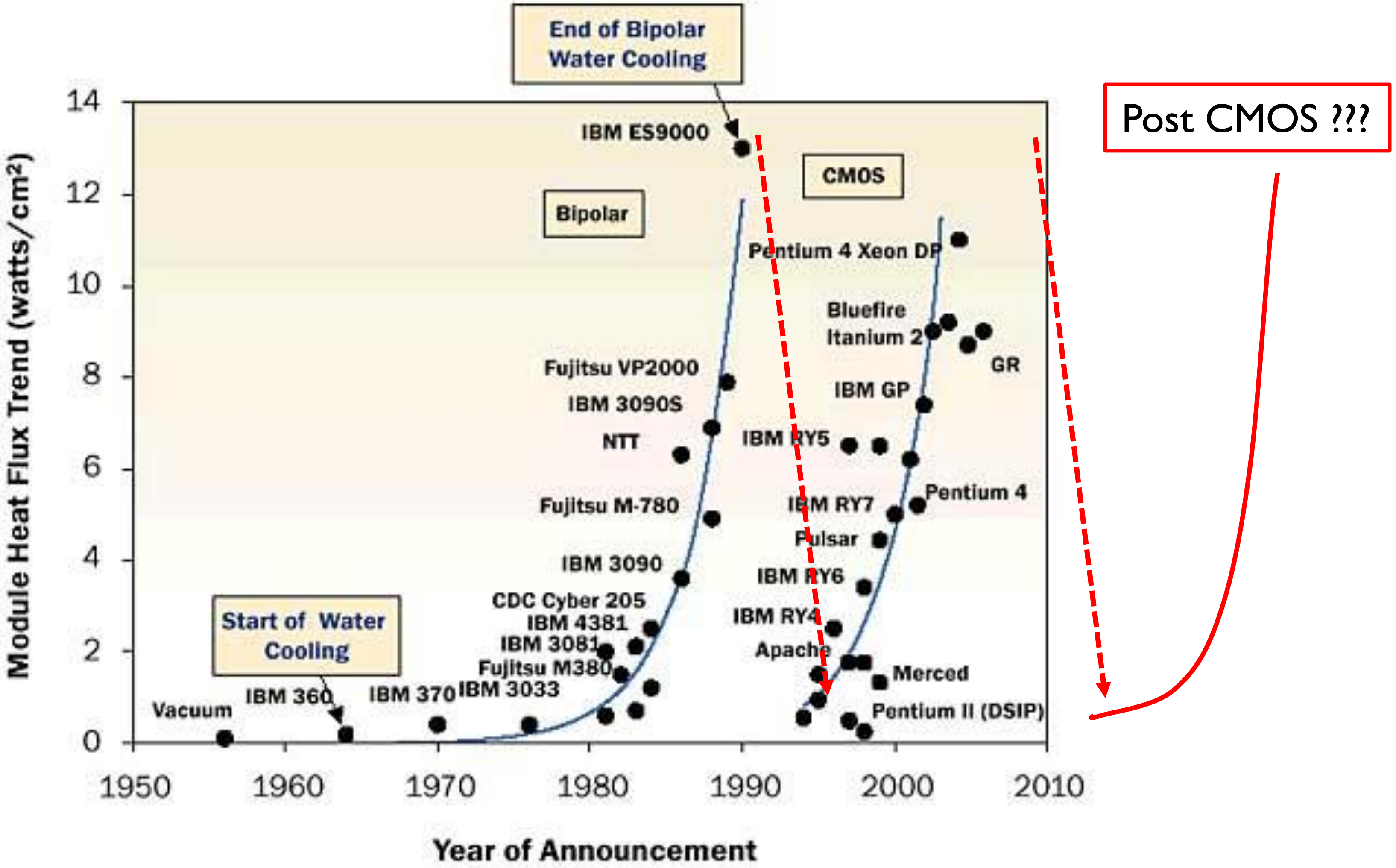
INTRODUCTION: MOORE'S LAW



Semiconductor industry faced this situation before with bipolar transistors

Courtesy of Ian Young (Research Components, Intel)

OUTLINE

1. Introduction to spintronics
- Introduction
- Pure spin currents

2. Introduction to spin Hall effect
- Origin
- Discovery and relation with anomalous Hall effect
- Mechanisms (intrinsic, skew-scattering, side-jump)

3. Techniques to quantify SHE
- Optical
- Non-local transport
- FMR-based
- (Tables of quantification)

4. Novel spin-dependent phenomena
- Spin Hall Magnetoresistance
- Spin Seebeck effect

5. Related spin-orbit effects
- Edelstein effect in Rashba systems
- Spin-momentum locking in Topological Insulators

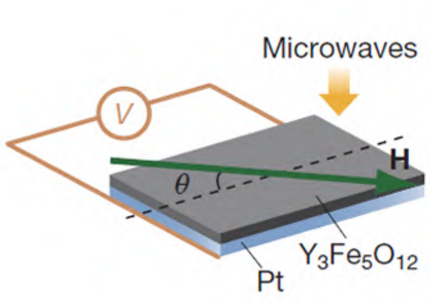
6. Applications
- Spin-orbit torques
- Spin-orbit logic

NOVEL SPIN-DEPENDENT PHENOMENA

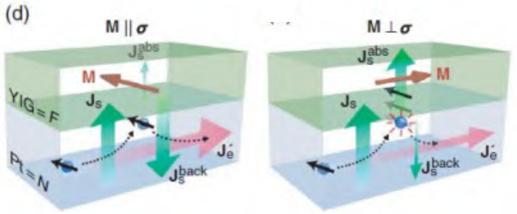
Spin pumping

Spin Hall magneto-resistance

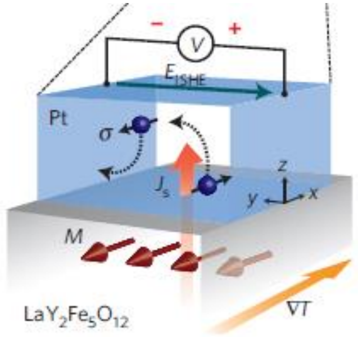
Spin Seebeck effect



Kajiwara *et al.*,
Nature **464**, 262 (2010)



Nakayama *et al.*,
Phys. Rev. Lett. **110**, 206601 (2013)



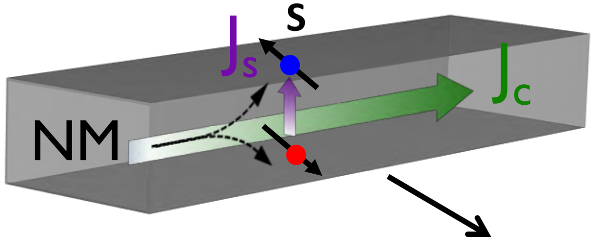
Uchida *et al.*,
Nature Mater. **9**, 894 (2010)

Spin-mixing interface conductance $G_{\uparrow\downarrow}$

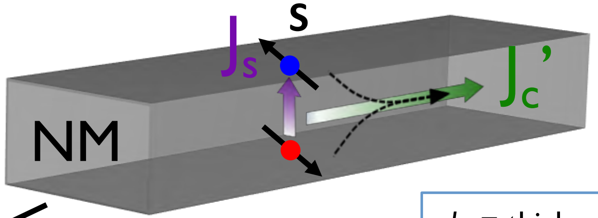
M. Weiler *et al.*, Phys. Rev. Lett. **111**, 176601 (2013)

Spin Hall Magnetoresistance (SMR)

Spin Hall effect (SHE)

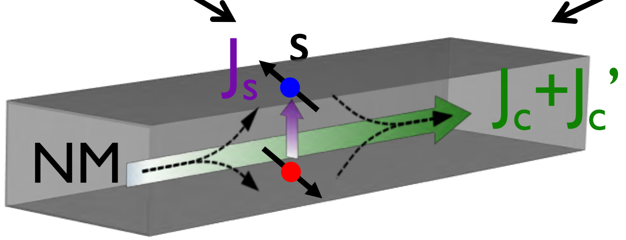


Inverse spin Hall effect (ISHE)

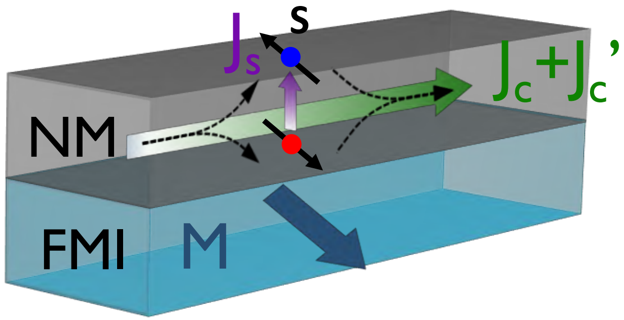


d_N = thickness of the **NM** layer
θ_{SH} = spin Hall angle
λ_N = spin-diffusion length

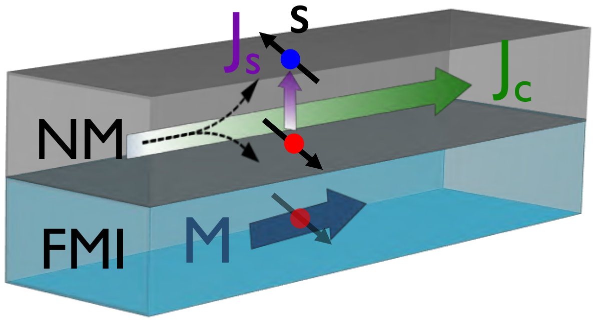
NM: non-magnetic metal with strong spin-orbit coupling
FMI: ferromagnetic insulator



$$\Delta\rho_0 = 2\theta_{SH}^2\rho_N - \frac{2\theta_{SH}^2\lambda_N\rho_N}{d_N}\tanh\left(\frac{d_N}{2\lambda_N}\right)$$



M || s: low resistance state

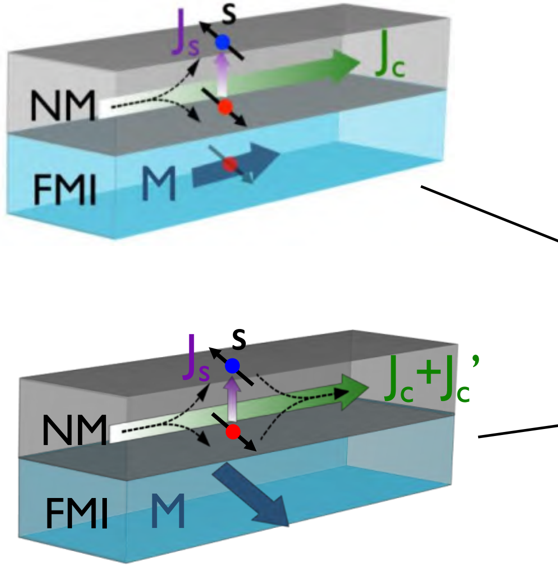


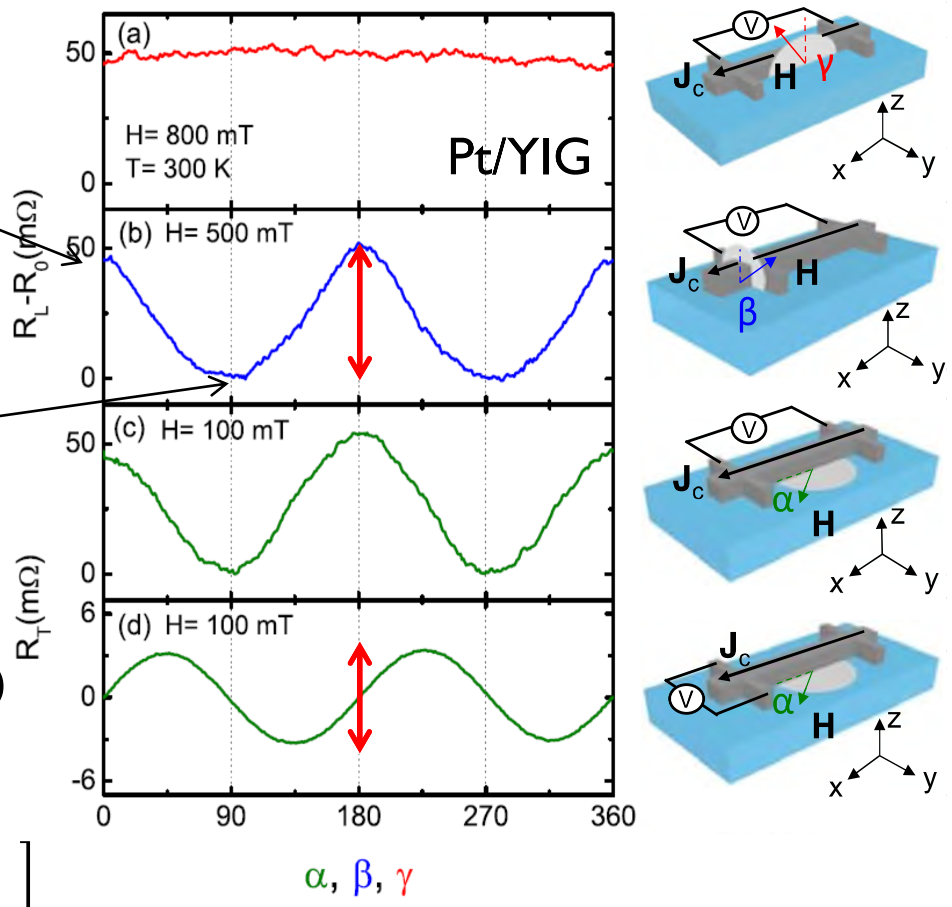
M ⊥ s: high resistance state

H. Nakayama *et al.*, Phys. Rev. Lett. **110**, 206601 (2013)
C. Hahn *et al.*, Phys. Rev. B **87**, 174417 (2013)
N. Vlietstra *et al.*, Phys. Rev. B **87**, 184421 (2013)

M. Isasa *et al.*, APL **105**, 142402 (2014)
M. Isasa *et al.*, Phys. Rev. Appl. **6**, 034007 (2016)
S. Vélez *et al.*, Phys. Rev. B **94**, 174405 (2016)

Spin Hall Magnetoresistance (SMR)





$$\rho_L = \rho_0 + \Delta\rho_0 + \boxed{\Delta\rho_1}(1 - m_y^2)$$

$$\rho_T = \boxed{\Delta\rho_1} m_x m_y + \Delta\rho_2 m_z$$

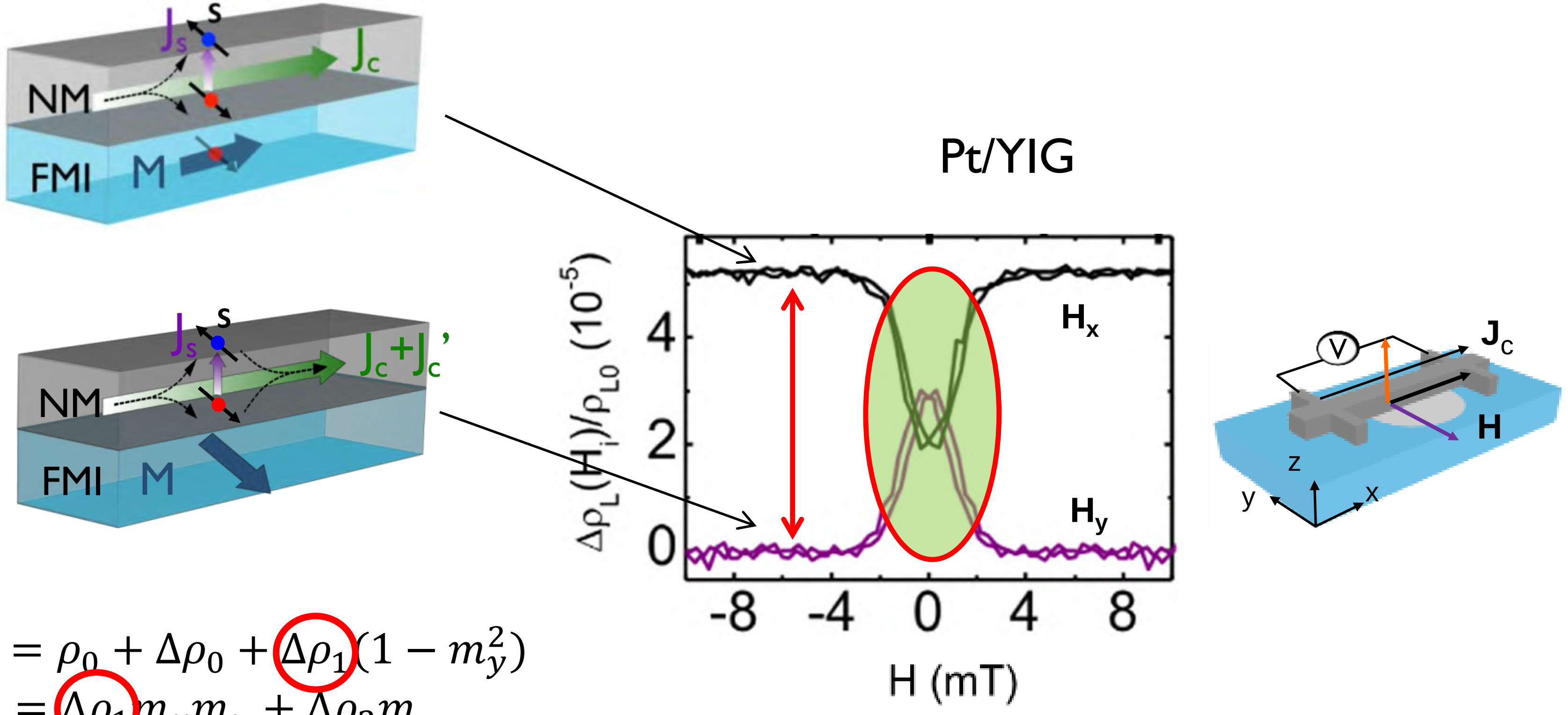
$$\frac{\Delta\rho_1}{\rho_N} = \frac{2\theta_{SH}^2\lambda_N}{d_N} Re\left[\frac{\lambda_N G_{\uparrow\downarrow}\tanh^2\left(\frac{d_N}{2\lambda_N}\right)}{1 + 2\rho_N\lambda_N G_{\uparrow\downarrow}\coth\left(\frac{d_N}{\lambda_N}\right)}\right]$$

$G_{\uparrow\downarrow}$ = spin-mixing conductance

- Effective tool to characterize θ_{SH}, λ_N and $G_{\uparrow\downarrow}$

Y.-T. Chen et al., Phys. Rev. B **87**, 144411 (2013)

Spin Hall Magnetoresistance (SMR)



$$\rho_L = \rho_0 + \Delta\rho_0 + \boxed{\Delta\rho_1}(1 - m_y^2)$$

$$\rho_T = \boxed{\Delta\rho_1} m_x m_y + \Delta\rho_2 m_z$$

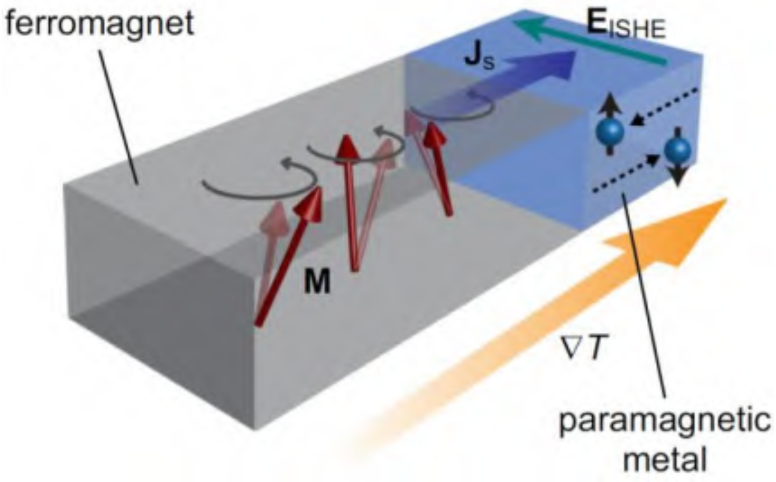
$$\frac{\Delta\rho_1}{\rho_N} = \frac{2\theta_{SH}^2 \lambda_N}{d_N} Re\left[\frac{\lambda_N G_{\uparrow\downarrow} \tanh^2\left(\frac{d_N}{2\lambda_N}\right)}{1 + 2\rho_N \lambda_N G_{\uparrow\downarrow} \coth\left(\frac{d_N}{\lambda_N}\right)}\right]$$

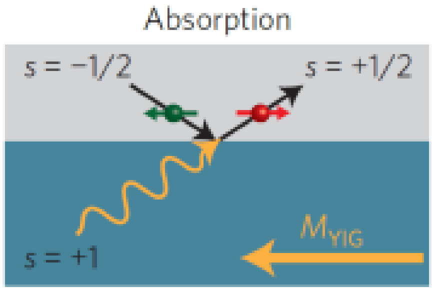
$G_{\uparrow\downarrow}$ = spin-mixing conductance

- Effective tool to characterize θ_{SH}, λ_N and $G_{\uparrow\downarrow}$
- Effective tool to **probe surface magnetization**

Y.-T. Chen et al., Phys. Rev. B **87**, 144411 (2013)

Spin Seebeck effect

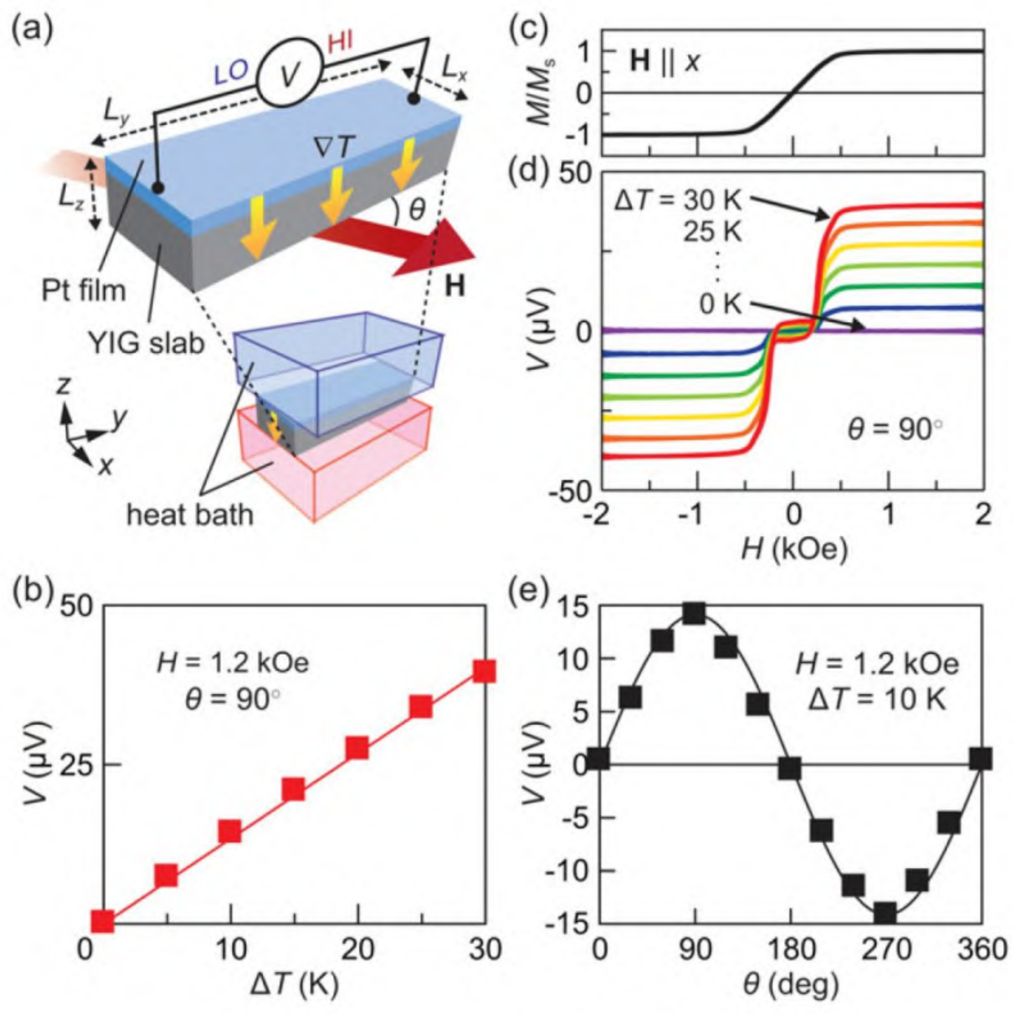




- Temperature gradient induces magnon current
- Magnon accumulation at the FM side generates spin accumulation at the NM side
- Exchange coupling at the NM/FM ($G_{\uparrow\downarrow}$)
- When FM is metallic, anomalous Nernst effect can give similar signal (controversy)

K. Uchida *et al.*, J. Phys.:Condens. Matter **26**, 343202 (2014)

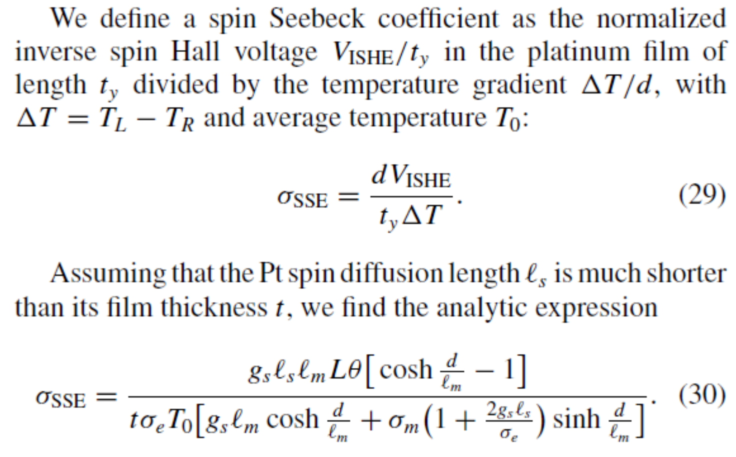
Spin Seebeck effect



$$\boxed{V_y = S_{SSE}\frac{L_y \Delta T}{L_z}}$$

S_{SSE} coefficient depends on $\theta_{SH}$and $G_{\uparrow\downarrow}$

Complex modeling of S_{SSE}:



We define a spin Seebeck coefficient as the normalized inverse spin Hall voltage V_{ISHE}/t_y in the platinum film of length t_y divided by the temperature gradient $\Delta T/d$, with $\Delta T = T_L - T_R$ and average temperature T_0:

$$\sigma_{\mathrm{SSE}} = \frac{d V_{\mathrm{ISHE}}}{t_y \Delta T}. \tag{29}$$

Assuming that the Pt spin diffusion length ℓ_s is much shorter than its film thickness t, we find the analytic expression

$$\sigma_{\mathrm{SSE}} = \frac{g_s \ell_s \ell_m L\theta\left[\cosh\frac{d}{\ell_m} - 1\right]}{t\sigma_e T_0\left[g_s \ell_m \cosh\frac{d}{\ell_m} + \sigma_m\left(1 + \frac{2g_s\ell_s}{\sigma_e}\right)\sinh\frac{d}{\ell_m}\right]}. \tag{30}$$

K. Uchida *et al.*, J. Phys.:Condens. Matter **26**, 343202 (2014)

L. Cornelissen *et al.*, Phys. Rev. B **94**, 014412 (2016)