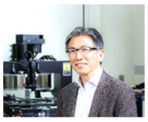


Transport and spintronics

YoshiChika Otani

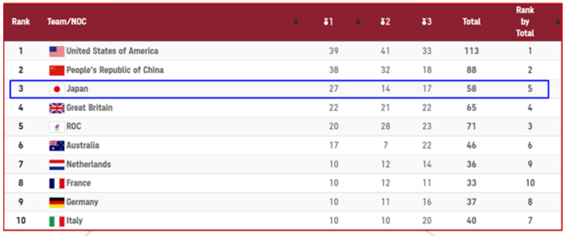
ISSP, the University of Tokyo
Center for Emergent Matter Science, RIKEN

Tokyo Olympic games

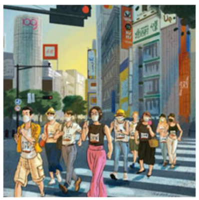

Gymnastic warming up


Sprinters

Tokyo Olympic Medal Count 2021



Rank	Team/NOC	1	2	3	Total	Rank by Total
1	United States of America	39	41	33	113	1
2	People's Republic of China	38	32	18	88	2
3	Japan	27	14	17	58	5
4	Great Britain	22	21	22	65	4
5	ROC	20	28	23	71	3
6	Australia	17	7	22	46	6
7	Netherlands	10	12	14	36	9
8	France	10	12	11	33	10
9	Germany	10	11	16	37	8
10	Italy	10	10	20	40	7


Power walking


Baton relay


Hurdler


Long jumper

From Instagram Adrian Hogan: "Daily Olympics in Tokyo"

Self Introduction

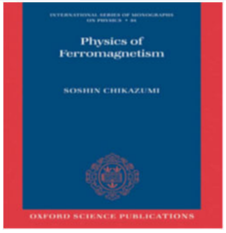
Graduate course（1984～1989)

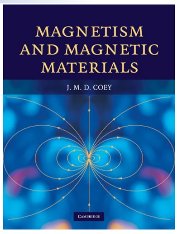
Supervised by Prof. Chikazumi and Prof. Miyajima
Physics of Ferromagnetism
Magnetic anisotropy in $Nd_2Fe_{14}B$ Intermetallic compounds

Post-doc period（1989～1993）

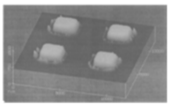
1. (1989～1991) Ireland Trinity college Prof. Michael Coey
   Magnetic anisotropy in $Sm_2Fe_{17}N_{3\text{-}\delta}$ Intermetallic compounds (Nitromag)
2. (1991～1993) France Grenoble Laboratoire Louis Néel
   Prof. Dominique Givord
   Prof. Bernard Pannetier

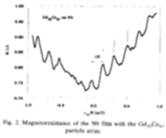
Magnetization reversal process in micron dots array of ferromagnets
Interaction between ferromagnetic dots and superconductive Niobium film





Magnetostatic interactions between magnetic arrays and superconducting thin films





JMMM 126 622 (1993).

Work（1993～Present）

1. (1993～95) Assistant Prof. for Prof. Hideki Miyajima in Phys. Dept. at Keio Univ.
2. (1995～2002) Associate Prof. in Materials Science Dept. for Prof. Kazuaki Fukamichi
3. (2002～Present) **Team leader of Quantum Nano-Magnetism Research Team**
   at **RIKEN FRS** Director Akira Tonomura ⇒ **RIKEN CEMS** Director Yoshinori Tokura
4. (2004～Present) **Professor at ISSP University of Tokyo**
   Nano-magnetism and Spintronics

Outline of my lecture

1. Introduction
2. Basics of electrical transport
   i. Free electrons motion in a crystal
   ii. Transport in ferromagnets
   iii. Two currents model for ferromagnets
3. Spin currents and spin dynamics
   i. Spin current
   ii. Spin dynamics
   iii. Interaction of spin currents and spin dynamics
4. Spin conversion phenomena
   i. Spin Hall effect in metals
   ii. Edelstein effect (Rashba Interface & TI surface state)
   iii. Magnetic spin Hall effect
5. New directions in spintronics
   i. Antiferromagnetic spintronics
   ii. Strong coupling

} 1_{st} Part (1–3)

} 2_{nd} Part (4–5)

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1_{st} Part

4. Spin conversion phenomena
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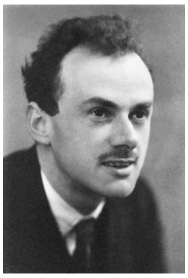
2_{nd} Part

Important attitude

Paul Adrien Maurice DIRAC



“I understand what an equation means if I have a way of figuring out the characteristics of its solution without actually solving it.”

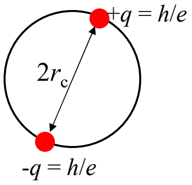
Dimension analysis

- **Bohr magneton μ_B**

$$\mu_B = \frac{\mu_0 e\hbar}{2m_e} = \left[\frac{1}{\varepsilon_0 c^2}\right]\cdot\left[\frac{e^2}{4\pi m_e}\right]\cdot\left[\frac{h}{e}\right] = \left[\frac{e^2}{4\pi\varepsilon_0 c^2 m_e}\right]\cdot q_m$$

= 2×classical electron radius [m]×monopole [Wb]

= 1.16541×10^{-29} [Wb • m]



- **Different expression of**

Energy $\quad \mu_B H = \dfrac{\mu_B}{\mu_0}B \quad \therefore \dfrac{\mu_B}{\mu_0} = 9.272\times10^{-24}\left[\dfrac{\mathrm{J}}{\mathrm{T}}\right]$

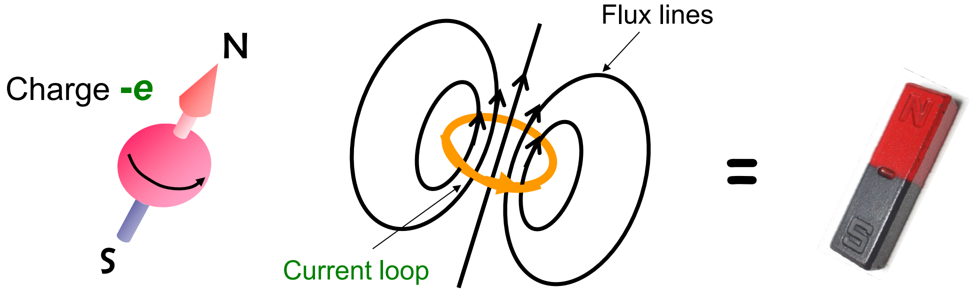
Temperature $\quad \dfrac{\mu_B}{\mu_0}B = kT \quad \therefore \dfrac{\mu_B}{\mu_0} = 0.671710\left[\dfrac{\mathrm{K}}{\mathrm{T}}\right]$

Mole (Avogadro numbers)

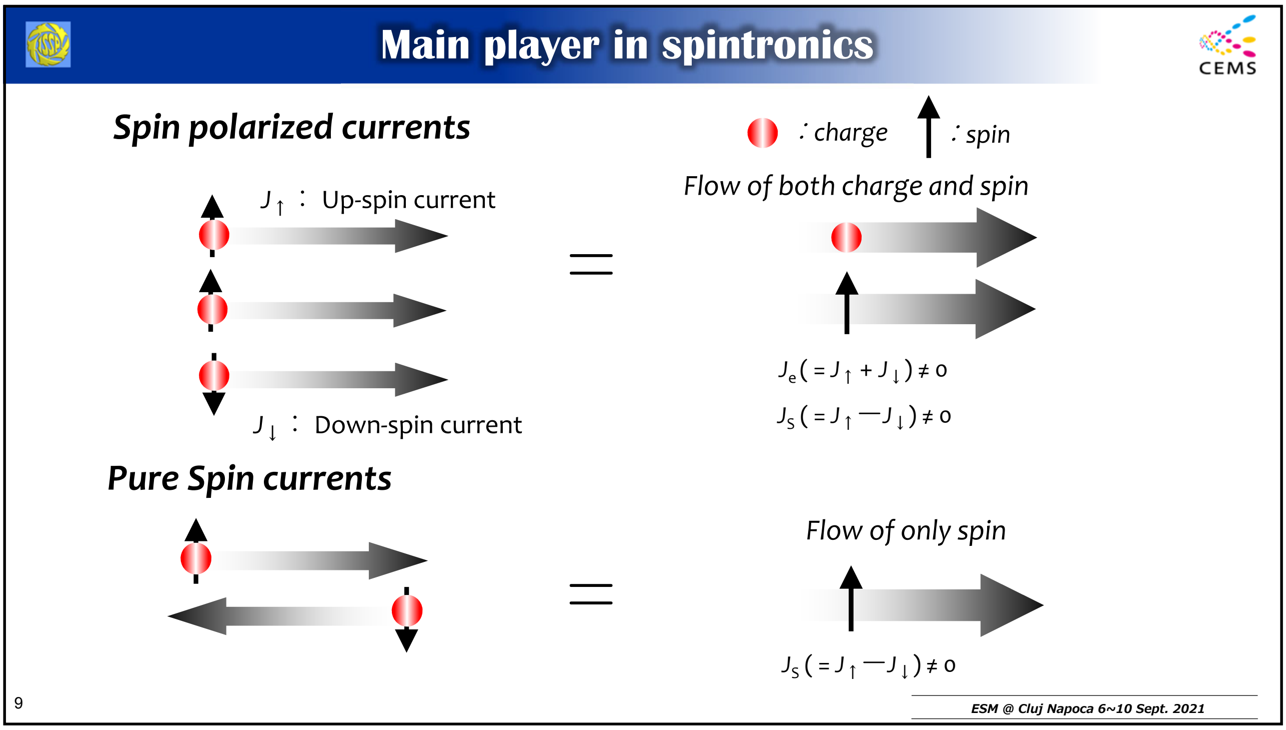
$$M_B = N_A\mu_B = 5.584939\left[\frac{\mathrm{J}}{\mathrm{T\cdot mol}}\right]$$

Electron spins

Spin angular momentum



Rotating electron is equivalent to the electric current loop.
Thus, an electron spin can be regarded as an atomic magnet!
Population of up and down spins are equal in non-magnets.



Main player in spintronics

CEMS

Spin polarized currents

: charge : spin

Flow of both charge and spin

$J_\uparrow$: Up-spin current

=

$J_\downarrow$: Down-spin current

$J_e(=J_\uparrow+J_\downarrow)\neq 0$

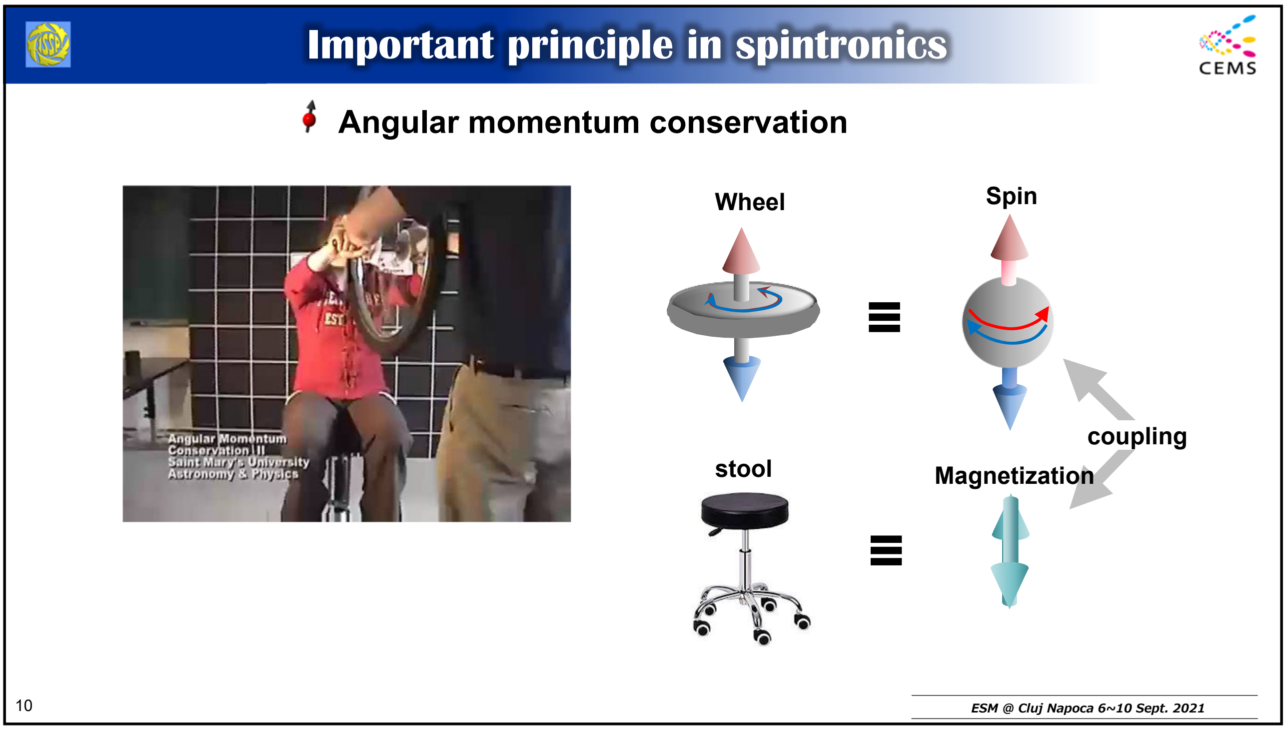
$J_S(=J_\uparrow - J_\downarrow)\neq 0$

Pure Spin currents

=

Flow of only spin

$J_S(=J_\uparrow - J_\downarrow)\neq 0$



Important principle in spintronics

CEMS

Angular momentum conservation

Angular Momentum Conservation II
Saint Mary's University
Astronomy & Physics

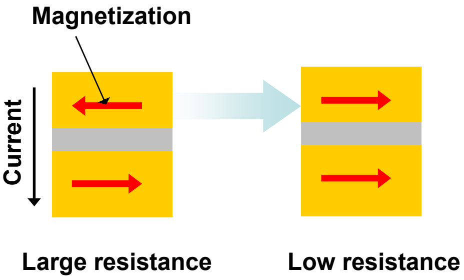
Wheel ≡ **Spin**

stool ≡ **Magnetization**

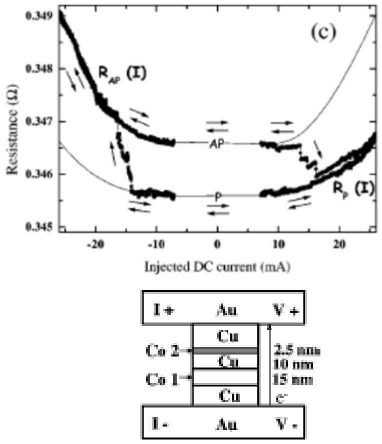
coupling

Spin injection induced magnetization reversal

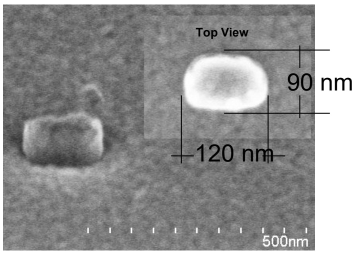
Grollier, Fert *et al.* (2001)



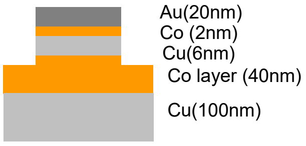
CPP-GMR signal



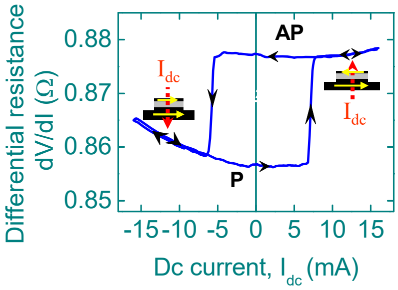
Spin injection induced magnetization reversal



SEM image of a metallic pillar .



Yang *et al*. JAP 97(2005)064304.

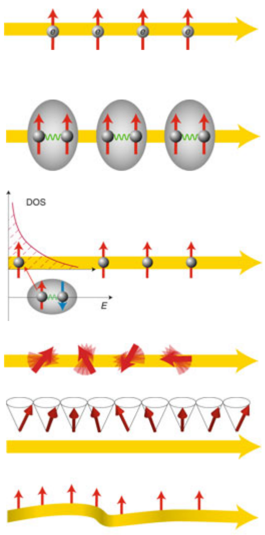


DC current induced magnetic switching in a pillar structure with a size of 120 nm × 90 nm, indicated by the jumps of the differential resistance.

Various spin currents

Wei Han et al. Nature Mater. 2019

Electron (hole) ($S = 1/2$)	Metals, semiconductors, topological insulators and etc
Spin-triplet pair ($S = 1$)	Spin Currents
Quasiparticle ($S = 1/2$)	SCs
Spinon ($S = 1/2$)	Quantum spin liquids
Magnon ($S = 1$)	Magnetic insulators
Electron-hole pair or magnon ($S = 1$)	Spin superfluids



Quiz 1

1. Researchers in our institute succeeded in generating a very strong magnetic fields of 1200 T (https://www.youtube.com/watch?v=ikeqxOoW9pA).

   How many degrees in Kelvin is this 1200T magnetic field?

A: ~7 K

B: ~328 K

[✓ C: ~720 K]

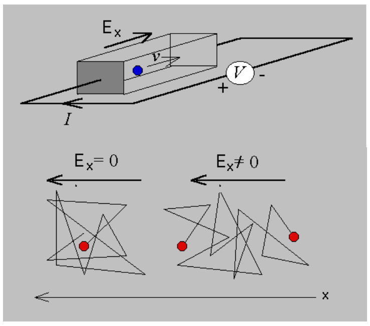
2. Basics of electrical transport

From Instagram Adrian Hogan: “Daily Olympics in Tokyo”

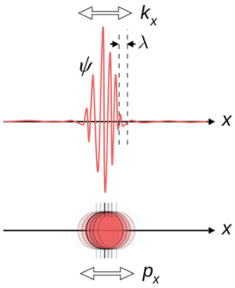
Basics of electrical transport

Wave-particle duality

Particle view



Wave view



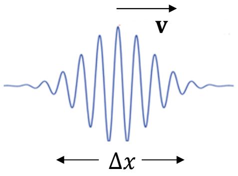
$$j = \rho v = \frac{1}{2i}(\psi^* \nabla \psi - \psi \nabla \psi^*) = \rho \left(k_0 + \frac{4t(x - k_0 t)}{1 + 4t^2} \right).$$

Basics of electrical transport

i. Free electrons motion in a crystal

Velocity $v = \frac{\hbar k}{m} \Leftarrow \frac{1}{\hbar}\frac{d\varepsilon}{dk}$ $[\because \varepsilon = (\hbar k)^2/2m]$

Group velocity of wave packet $\boxed{\mathbf{v} = \frac{1}{\hbar}\mathrm{grad}_k \varepsilon(\mathbf{k})}$



When an external force **F** is applied to the **electron wave packet**, and the energy increases by Δε during Δt, Δε is caused by Δ**k** due to the energy conservation law;

$$\Delta\varepsilon = (\mathbf{F}\cdot\mathbf{v})\Delta t \quad = \mathrm{grad}_k \varepsilon(\mathbf{k})\cdot\Delta\mathbf{k} \quad = \hbar(\mathbf{v}\cdot\Delta\mathbf{k})$$

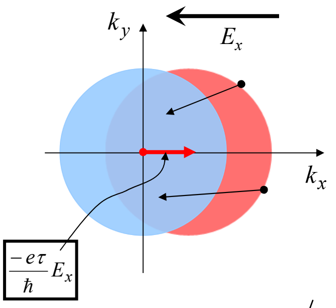
$\boxed{\frac{d\mathbf{k}}{dt} = \frac{\mathbf{F}}{\hbar}}$ Considering $\mathbf{p} = \hbar\mathbf{k}$ ➡ $m\frac{d\mathbf{v}}{dt} = \mathbf{F}$

When Lorentz force acts, $\boxed{\frac{d\mathbf{k}}{dt} = \frac{e}{\hbar}(\mathbf{E} + \mathbf{v}\times\mathbf{B})}$

Basics of electrical transport

Drude Model

When $B = 0$ $\boxed{\hbar\frac{d\mathbf{k}}{dt} = m\frac{d\mathbf{v}}{dt} = -e\mathbf{E}}$



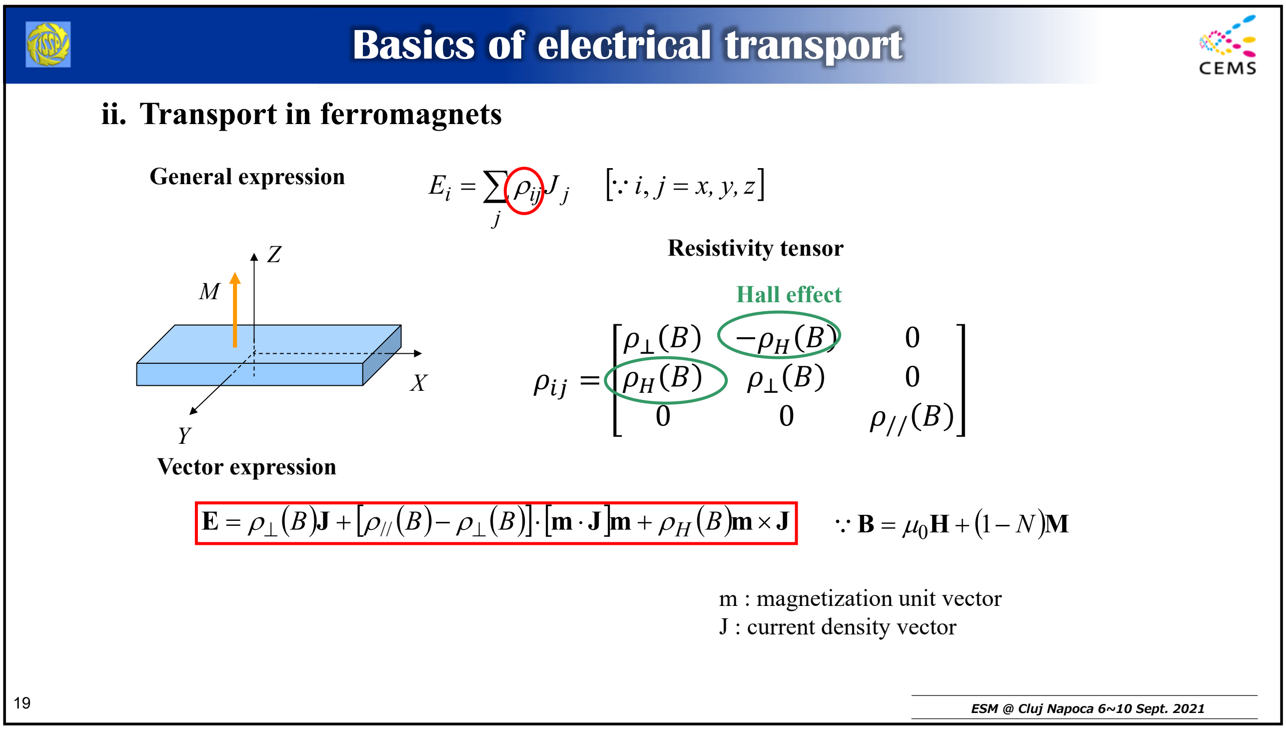
$$\frac{d}{dt}\langle v_x\rangle = -\frac{eE_x}{m} - \frac{1}{\tau}\langle v_x\rangle$$

$<v_x>$: mean drift velocity
τ : relaxation time

Stationary state $\frac{d}{dt}\langle v_x\rangle = 0$

$$\langle v_x\rangle = -\frac{e\tau}{m}E_x = -\underset{\text{mobility}}{\mu}E_x$$

For n electrons, $J_x = -ne\langle v_x\rangle = -ne\mu E_x = \sigma E_x$ Ohm's law



Basics of electrical transport

ii. Transport in ferromagnets

General expression

$$E_i = \sum_j \rho_{ij} J_j \quad [\because i, j = x, y, z]$$

Resistivity tensor

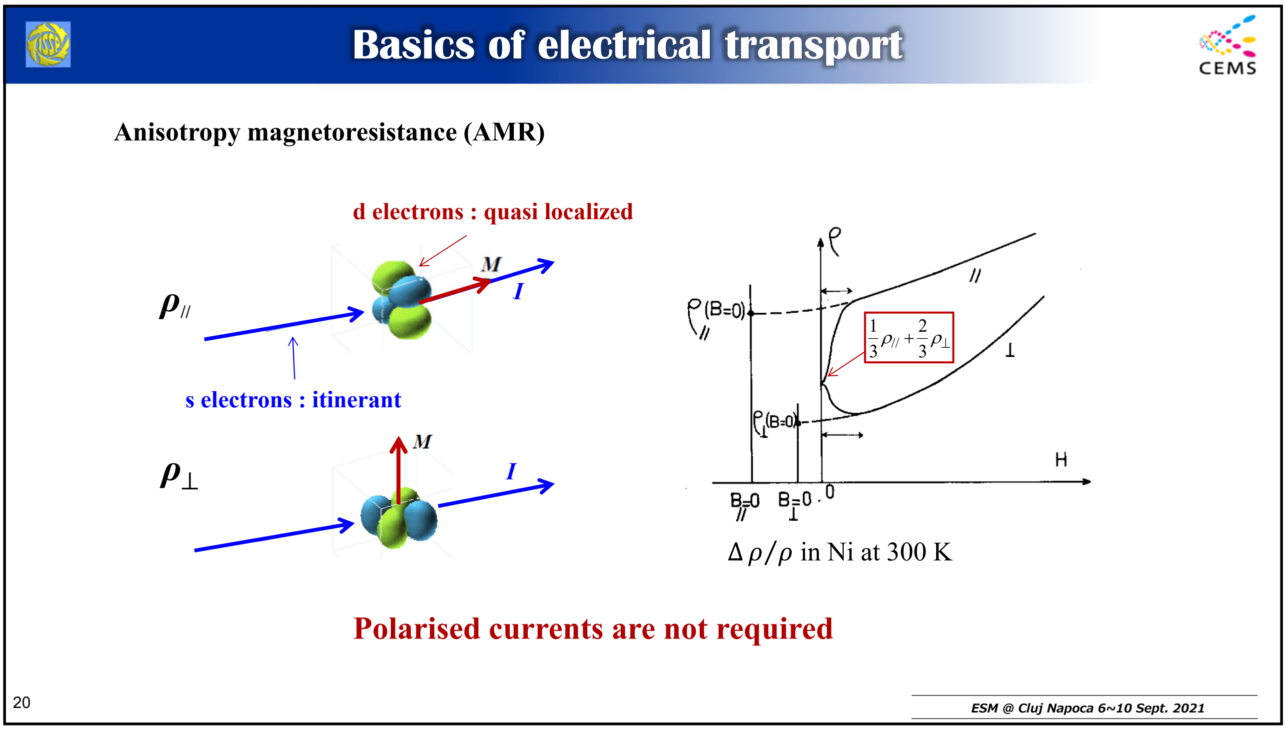
Hall effect

$$\rho_{ij} = \begin{bmatrix} \rho_\perp(B) & -\rho_H(B) & 0 \\ \rho_H(B) & \rho_\perp(B) & 0 \\ 0 & 0 & \rho_{//}(B) \end{bmatrix}$$

Vector expression

$$\boxed{\mathbf{E} = \rho_\perp(B)\mathbf{J} + [\rho_{//}(B) - \rho_\perp(B)] \cdot [\mathbf{m} \cdot \mathbf{J}]\mathbf{m} + \rho_H(B)\mathbf{m} \times \mathbf{J}} \qquad \because \mathbf{B} = \mu_0\mathbf{H} + (1-N)\mathbf{M}$$

m : magnetization unit vector
J : current density vector



Basics of electrical transport

Anisotropy magnetoresistance (AMR)

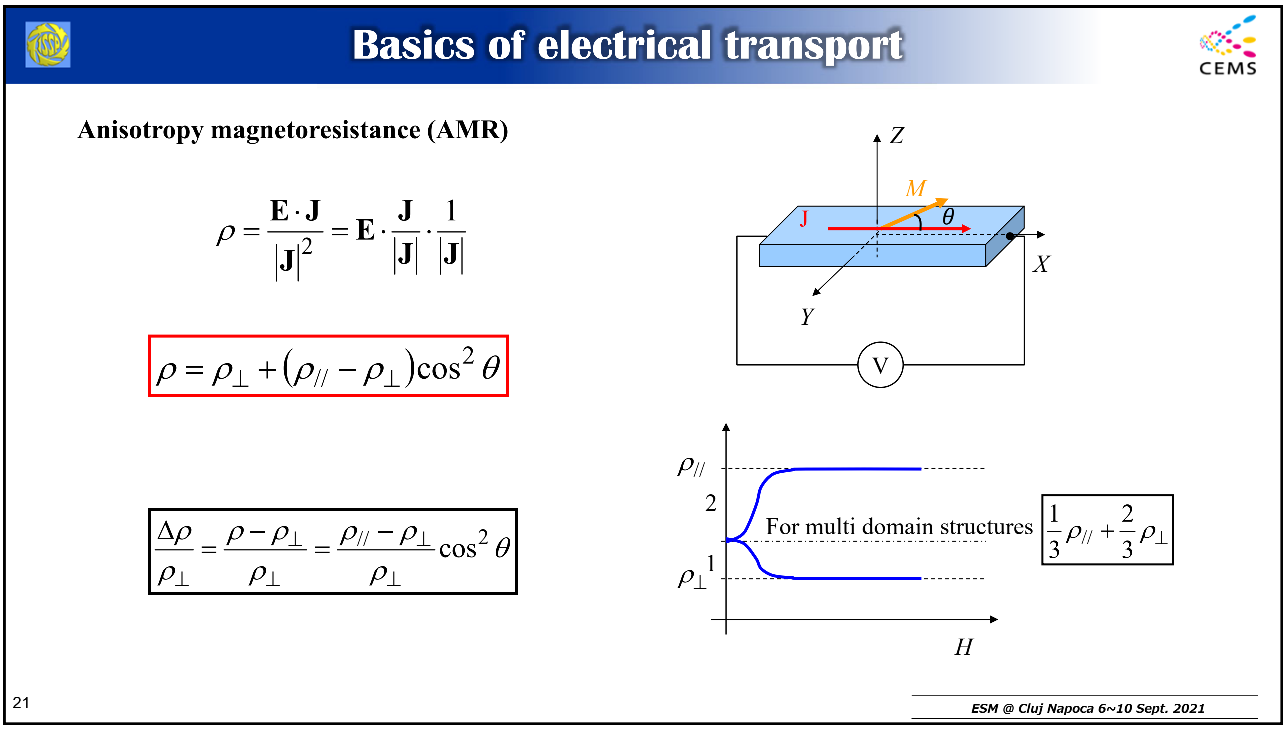
d electrons : quasi localized

s electrons : itinerant

$$\boxed{\frac{1}{3}\rho_{//} + \frac{2}{3}\rho_\perp}$$

$\Delta\rho/\rho$ in Ni at 300 K

Polarised currents are not required



Basics of electrical transport

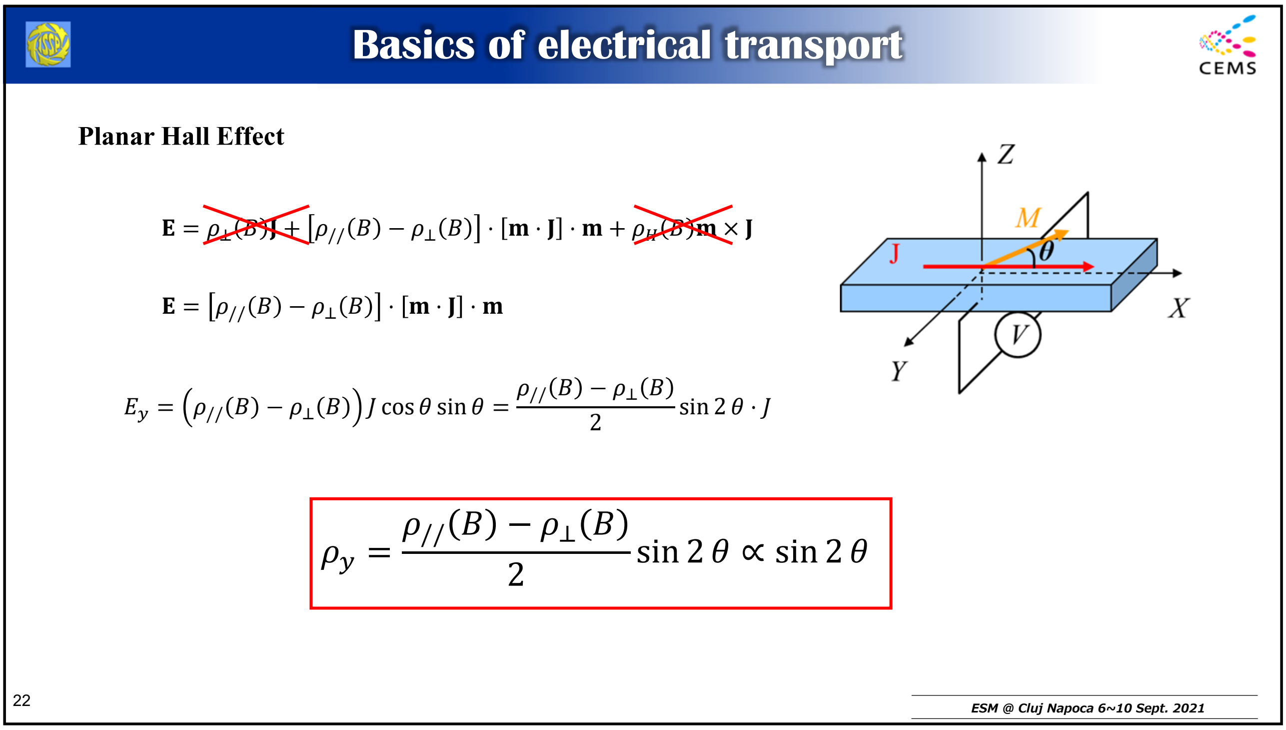
Anisotropy magnetoresistance (AMR)

$$\rho = \frac{\mathbf{E}\cdot\mathbf{J}}{|\mathbf{J}|^2} = \mathbf{E}\cdot\frac{\mathbf{J}}{|\mathbf{J}|}\cdot\frac{1}{|\mathbf{J}|}$$

$$\boxed{\rho = \rho_\perp + (\rho_{//} - \rho_\perp)\cos^2\theta}$$

$$\boxed{\frac{\Delta\rho}{\rho_\perp} = \frac{\rho - \rho_\perp}{\rho_\perp} = \frac{\rho_{//} - \rho_\perp}{\rho_\perp}\cos^2\theta}$$

For multi domain structures $\boxed{\frac{1}{3}\rho_{//} + \frac{2}{3}\rho_\perp}$



Basics of electrical transport

Planar Hall Effect

$$\mathbf{E} = \xcancel{\rho_\perp(B)\mathbf{J}} + [\rho_{//}(B) - \rho_\perp(B)]\cdot[\mathbf{m}\cdot\mathbf{J}]\cdot\mathbf{m} + \xcancel{\rho_H(B)\mathbf{m}} \times \mathbf{J}$$

$$\mathbf{E} = [\rho_{//}(B) - \rho_\perp(B)]\cdot[\mathbf{m}\cdot\mathbf{J}]\cdot\mathbf{m}$$

$$E_y = \left(\rho_{//}(B) - \rho_\perp(B)\right)J\cos\theta\sin\theta = \frac{\rho_{//}(B) - \rho_\perp(B)}{2}\sin 2\,\theta\cdot J$$

$$\boxed{\rho_y = \frac{\rho_{//}(B) - \rho_\perp(B)}{2}\sin 2\,\theta \propto \sin 2\,\theta}$$

Basics of electrical transport

Spin scattering asymmetry α

$\alpha = \frac{\rho_{\downarrow}}{\rho_{\uparrow}}$ degree of spin dependent scattering

=1 no sin dependent scattering

>1 or < 1 spin dependent scattering

AMR $$\frac{\Delta\rho}{\rho_0} = \frac{\rho - \rho_{\perp}}{\frac{1}{3}\rho_{//} + \frac{2}{3}\rho_{\perp}} \cong \frac{\rho_{//} - \rho_{\perp}}{\rho_{\perp}} \cong \frac{\rho_{//} - \rho_{\perp}}{\rho_{//}} \qquad \rho_{//(\perp)} = \frac{\rho^{\uparrow}_{//(\perp)}\rho^{\downarrow}_{//(\perp)}}{\rho^{\uparrow}_{//(\perp)} + \rho^{\downarrow}_{//(\perp)}}$$

ρ_0: resistivity at the demagnetized state $\quad \rho^{\uparrow}_{//} = \rho^{\uparrow}_{\perp} + \gamma\rho^{\downarrow}_{\perp} \quad \rho^{\downarrow}_{//} = \rho^{\downarrow}_{\perp} - \gamma\rho^{\uparrow}_{\perp}$

Impurity	Ti	V	Cr	Mn	Fe	Co
ρ_0 (μΩcm/%)	2.9	4.5	5.0	0.61	0.35	0.145
$\alpha = \frac{\rho_0^{\downarrow}}{\rho_0^{\uparrow}}$	4	0.55	0.45	15	20	20
$\rho_0^{\uparrow}$	3.6	12.7	16.1	0.65	0.37	0.15
$\rho_0^{\downarrow}$	14.5	7.0	7.2	9.8	7.4	4.6

Fert and Campbell, J. Phys. F (1976)

$$\boxed{\frac{\Delta\rho}{\rho_0} = (1+\alpha\gamma)(1-\gamma) - 1 \cong \gamma(\alpha - 1) \qquad \left[\because \alpha \equiv \frac{\rho^{\downarrow}_{\perp}}{\rho^{\uparrow}_{\perp}}, \quad \gamma \equiv \left(\frac{\lambda}{J_{ex}}\right)^2\right]}$$

λ: spin-orbit interaction, J_{ex}: exchange interaction

$\gamma = (\lambda/J_{\mathrm{ex}})^2 \sim 0.01$ for Fe, Co, and Ni

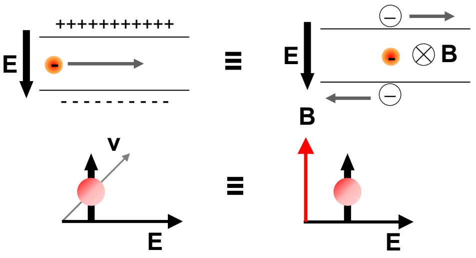
---

Spin Orbit Interaction

- **Relativistic effect ⇒ coordinate transformations ⇒ Lorentz transformation**

Effect of E on the moving charged particle

$$\boxed{\mathbf{B} = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}(-\mathbf{v} \times \mathbf{E})}$$



Zeeman interaction

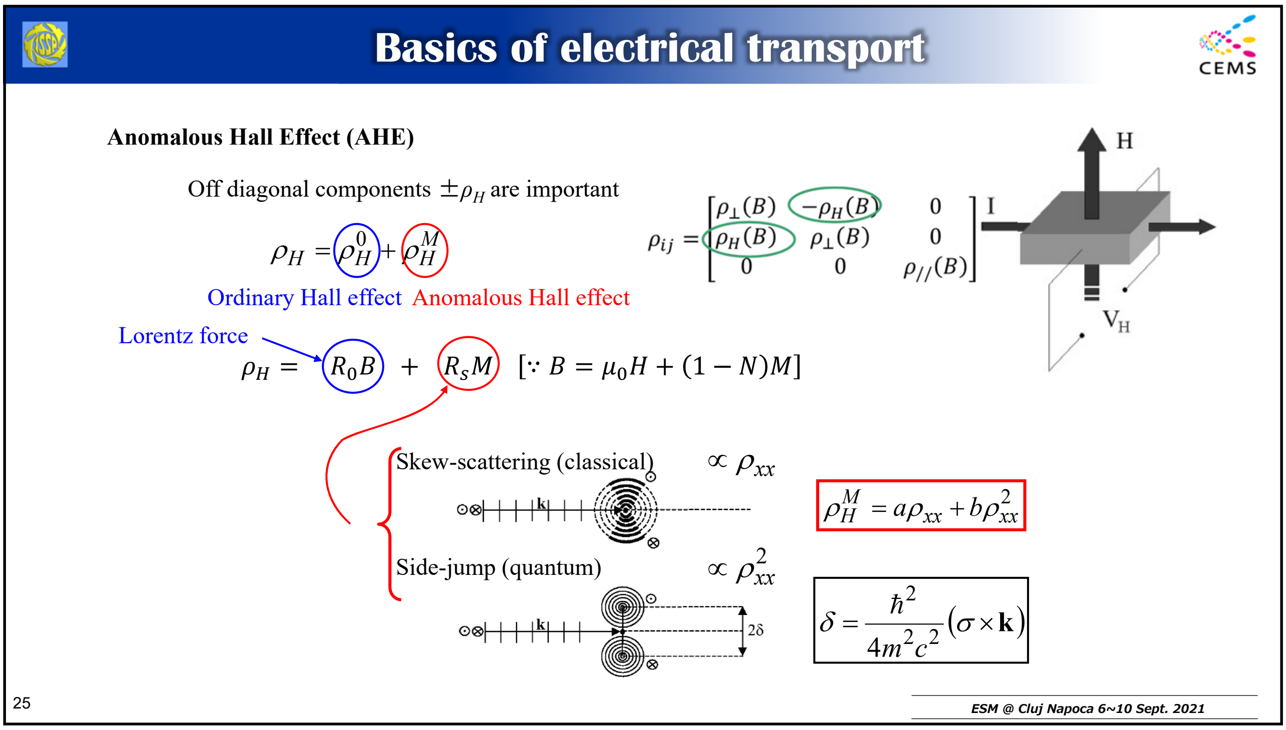
Zeeman energy $-\mathbf{s} \cdot \mathbf{B}$ is given

$$\boxed{H_{\mathrm{SO}} \approx -\mathbf{s} \cdot \mathbf{B} \propto \mathbf{s} \cdot (\mathbf{p} \times \nabla V(\mathbf{r}))}$$

$$\boxed{H_{\mathrm{SO}} \approx \frac{1}{r}\frac{\partial V(\mathbf{r})}{\partial r}(\mathbf{r} \times \mathbf{p}) \cdot \mathbf{s}}$$

Central force field

$$\nabla V(\mathbf{r}) = \frac{\partial V(\mathbf{r})}{\partial r}\frac{1}{r}\mathbf{r}$$



Basics of electrical transport

Anomalous Hall Effect (AHE)

Off diagonal components $\pm\rho_H$ are important

$$\rho_H = \rho_H^0 + \rho_H^M$$

Ordinary Hall effect Anomalous Hall effect

$$\rho_{ij} = \begin{bmatrix}\rho_\perp(B) & -\rho_H(B) & 0\\ \rho_H(B) & \rho_\perp(B) & 0\\ 0 & 0 & \rho_{//}(B)\end{bmatrix}$$

Lorentz force

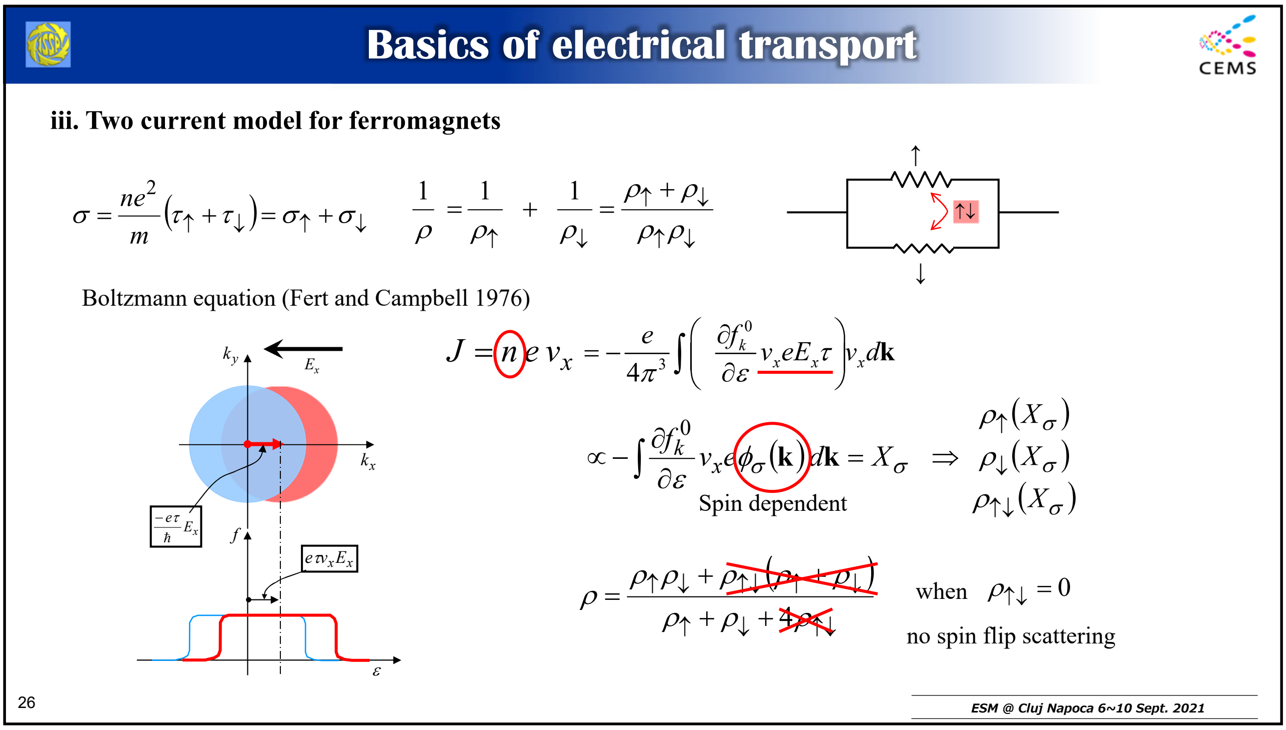
$$\rho_H = R_0 B + R_s M \quad [\because B = \mu_0 H + (1-N)M]$$

Skew-scattering (classical) $\propto \rho_{xx}$

Side-jump (quantum) $\propto \rho_{xx}^2$

$$\boxed{\rho_H^M = a\rho_{xx} + b\rho_{xx}^2}$$

$$\boxed{\delta = \frac{\hbar^2}{4m^2c^2}(\sigma\times\mathbf{k})}$$



Basics of electrical transport

iii. Two current model for ferromagnets

$$\sigma = \frac{ne^2}{m}(\tau_\uparrow + \tau_\downarrow) = \sigma_\uparrow + \sigma_\downarrow \qquad \frac{1}{\rho} = \frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow} = \frac{\rho_\uparrow + \rho_\downarrow}{\rho_\uparrow\rho_\downarrow}$$

Boltzmann equation (Fert and Campbell 1976)

$$J = n e v_x = -\frac{e}{4\pi^3}\int\left(\frac{\partial f_k^0}{\partial\varepsilon}\underline{v_x e E_x \tau}\right) v_x d\mathbf{k}$$

$$\propto -\int \frac{\partial f_k^0}{\partial\varepsilon} v_x e\phi_\sigma(\mathbf{k}) d\mathbf{k} = X_\sigma \Rightarrow \begin{matrix}\rho_\uparrow(X_\sigma)\\ \rho_\downarrow(X_\sigma)\\ \rho_{\uparrow\downarrow}(X_\sigma)\end{matrix}$$

Spin dependent

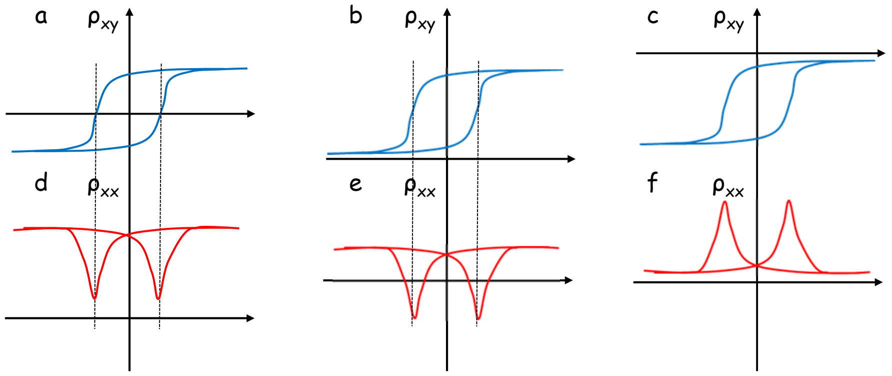
$$\rho = \frac{\rho_\uparrow\rho_\downarrow + \cancel{\rho_{\uparrow\downarrow}(\rho_\uparrow + \rho_\downarrow)}}{\rho_\uparrow + \rho_\downarrow + \cancel{4\rho_{\uparrow\downarrow}}}$$

when $\rho_{\uparrow\downarrow} = 0$

no spin flip scattering

Quiz 2

2. Please select typical AHE and AMR curves for ferromagnetic metals from 6 choices below;



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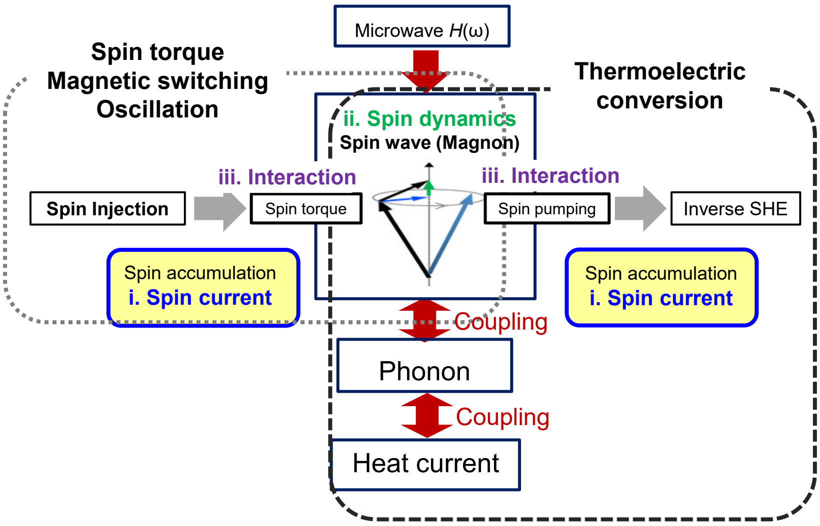
3. Spin currents and spin dynamics

From Instagram Adrian Hogan: “Daily Olympics in Tokyo”

Spin currents and spin dynamics



Microwave $H(\omega)$

Spin torque
Magnetic switching
Oscillation

Thermoelectric conversion

ii. Spin dynamics
Spin wave (Magnon)

iii. Interaction

iii. Interaction

Spin Injection → Spin torque

Spin pumping → Inverse SHE

Spin accumulation
i. Spin current

Spin accumulation
i. Spin current

Coupling

Phonon

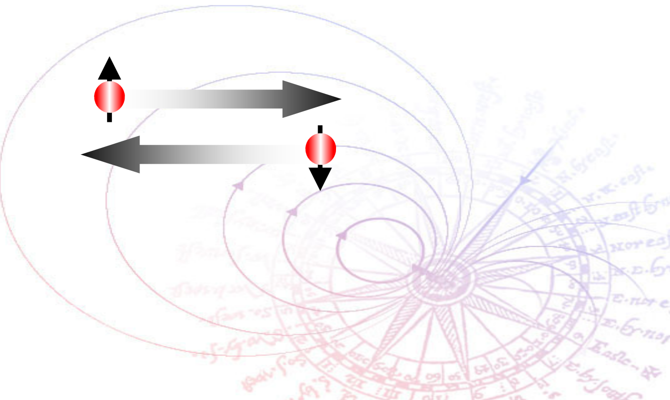
Coupling

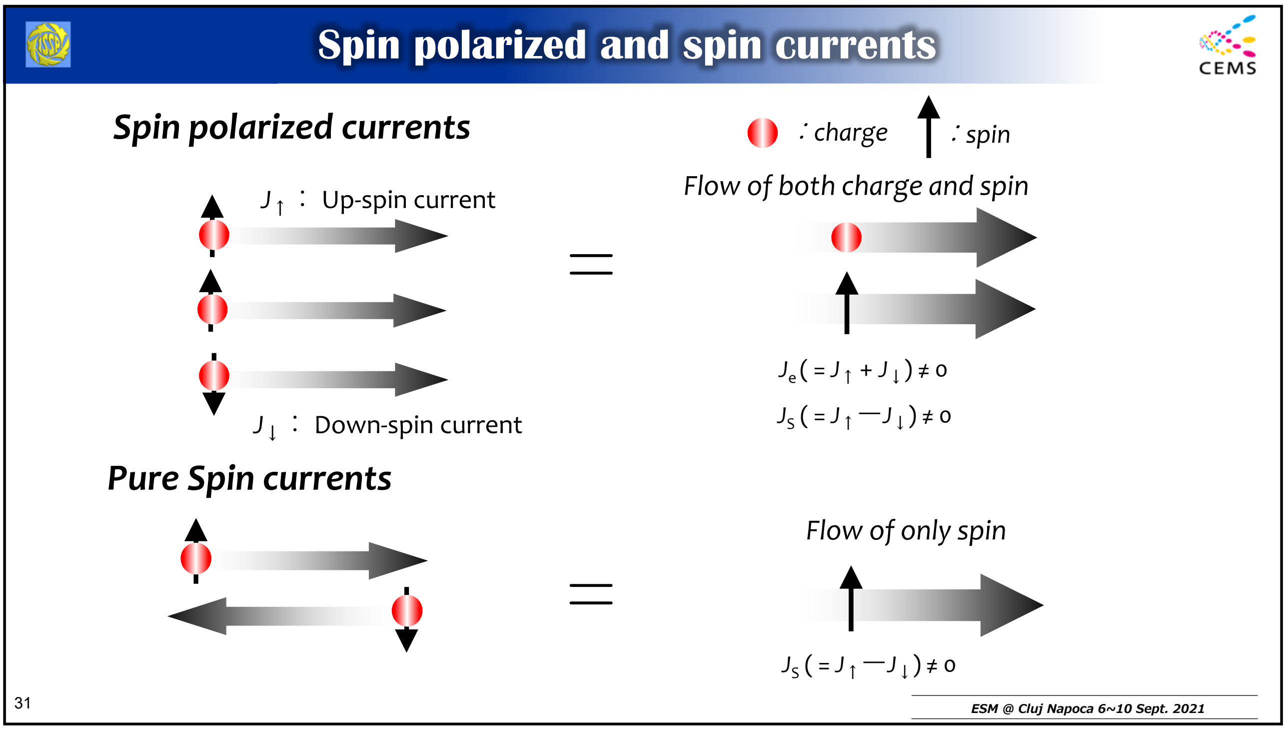
Heat current

---

i. Spin current

－Flow of spin angular momentum－





Spin polarized and spin currents

Spin polarized currents

● *: charge* ↑ *: spin*

Flow of both charge and spin

$J_\uparrow$: Up-spin current

=

$J_\downarrow$: Down-spin current

$J_e (= J_\uparrow + J_\downarrow) \neq 0$

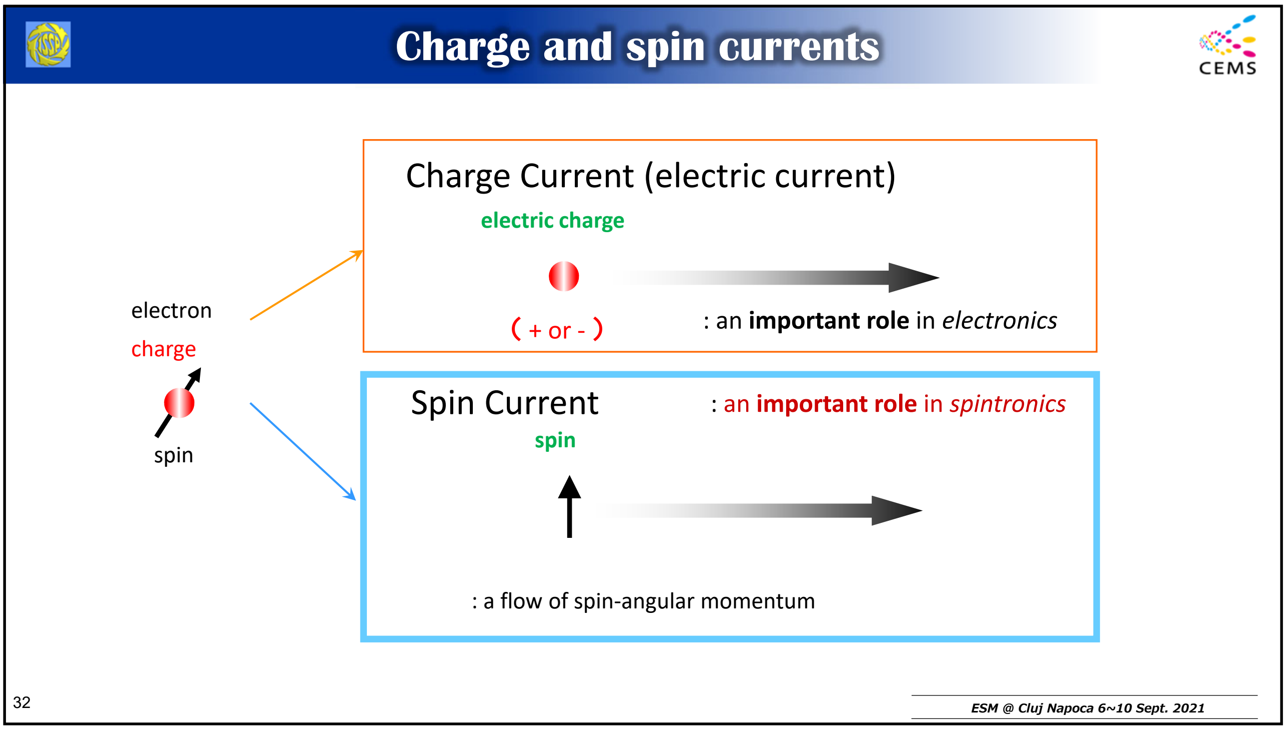
$J_S (= J_\uparrow - J_\downarrow) \neq 0$

Pure Spin currents

Flow of only spin

=

$J_S (= J_\uparrow - J_\downarrow) \neq 0$



Charge and spin currents

electron

charge

spin

Charge Current (electric current)

electric charge

(+ or -)

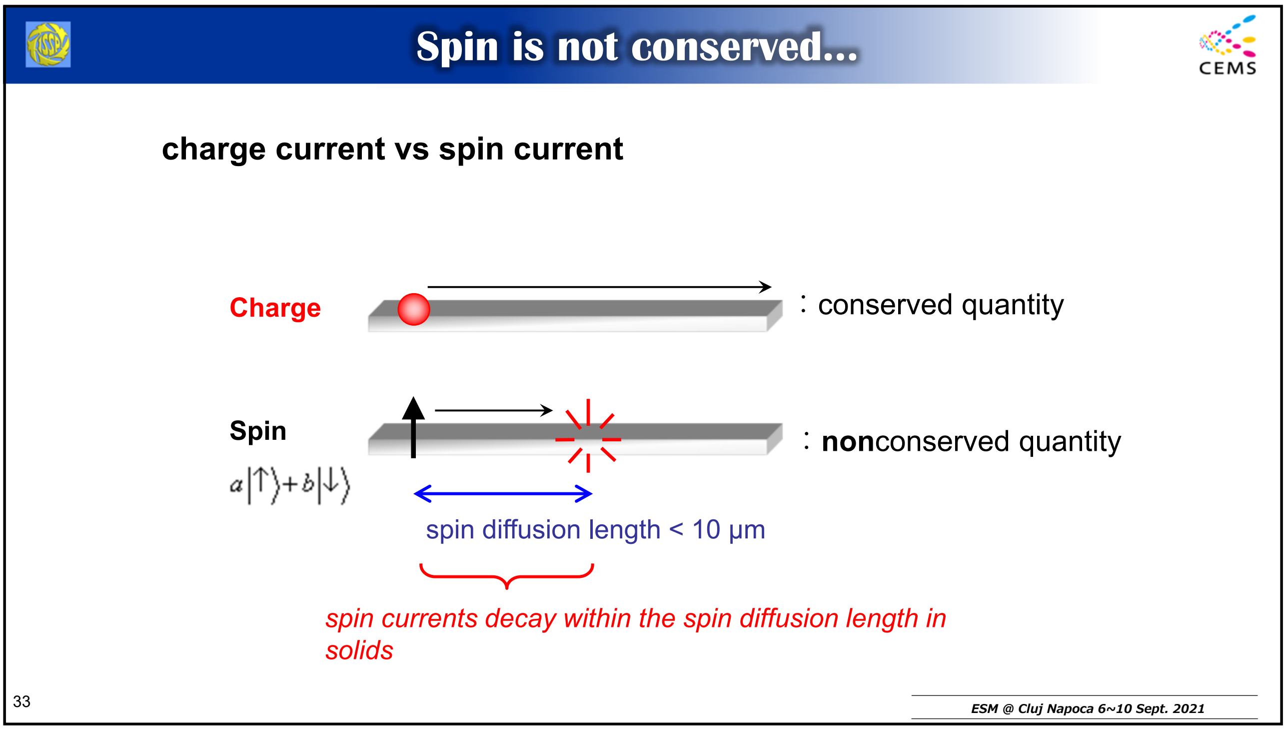
: an **important role** in *electronics*

Spin Current

: an **important role** in *spintronics*

spin

: a flow of spin-angular momentum



Spin is not conserved...

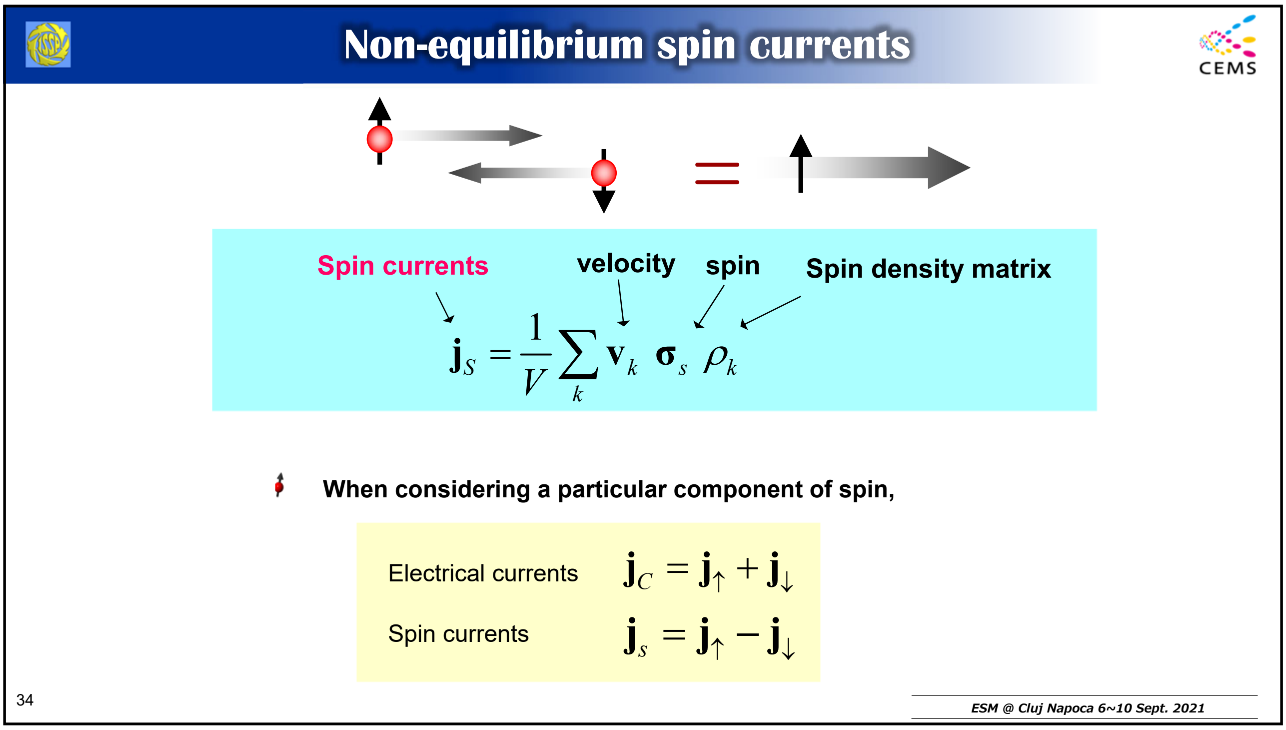
charge current vs spin current

Charge : conserved quantity

Spin $a|\uparrow\rangle + b|\downarrow\rangle$: **non**conserved quantity

spin diffusion length < 10 μm

spin currents decay within the spin diffusion length in solids



Non-equilibrium spin currents

$=$

Spin currents **velocity** **spin** **Spin density matrix**

$$\mathbf{j}_S = \frac{1}{V}\sum_k \mathbf{v}_k \, \boldsymbol{\sigma}_s \, \rho_k$$

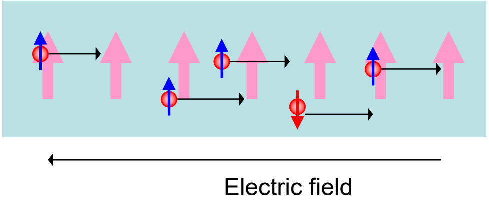
- **When considering a particular component of spin,**

Electrical currents $\mathbf{j}_C = \mathbf{j}_\uparrow + \mathbf{j}_\downarrow$

Spin currents $\mathbf{j}_s = \mathbf{j}_\uparrow - \mathbf{j}_\downarrow$

Non equilibrium spin currents

- Electrical currents in a ferromagnet



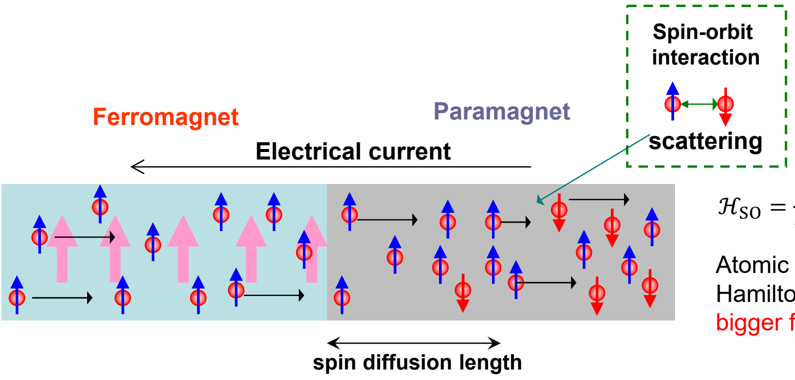
$$\sigma_\uparrow \neq \sigma_\downarrow$$

$$\mathbf{j}_S = \mathbf{j}_\uparrow - \mathbf{j}_\downarrow = p\mathbf{j}_c \qquad \neq 0$$

Spin polarization $p = \dfrac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$

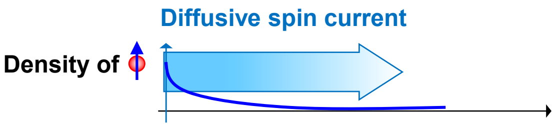
$$\mathbf{j}_C = \mathbf{j}_\uparrow + \mathbf{j}_\downarrow \qquad \neq 0$$

Electrical currents across the F/N interface



$$\mathcal{H}_{SO} = \frac{\mu_0}{4\pi}\cdot\frac{Ze^2}{2m^2}\cdot\frac{\hbar}{r^3}(\hbar\mathbf{l}\cdot\mathbf{s})$$

Atomic Spin-Orbit (SO) Hamiltonian shows SOI is bigger for heavier elements.



Spin-orbit interaction in various materials

$$\left.\begin{aligned}\lambda_N &= \sqrt{D\tau_{sf}}\\ \rho_N &= \frac{m}{ne^2\tau}\end{aligned}\right\}\rho_N\lambda_N = \frac{\sqrt{3}\pi}{2k_F^2}\frac{h}{e^2}\sqrt{\frac{\tau_{sf}}{\tau}} = \left(\frac{3\sqrt{3}\pi}{4}\frac{R_K}{k_F^2}\right)\frac{1}{\eta_{SO}} \qquad \because \frac{\tau}{\tau_{sf}} = \frac{4}{9}\eta_{SO}^2$$

$R_K = h/e^2 \approx 25.8\,\mathrm{k\Omega}$ $\quad k_F = 1.36\times10^8\ \mathrm{cm^{-1}}$ (for Cu), $1.75\times10^8\ \mathrm{cm^{-1}}$ (for Al)

S. Takahashi & S. Maekawa Physica C 437-438, 309-313 (2006)

	λ_N [nm]	ρ_N [mΩcm]	$\rho_N\lambda_N$ [$\times10^{-10}\,\Omega\mathrm{cm}^2$]	τ/τ_{sf} [$\times10^{-3}$]	η_{SO}
Cu* (4.2 K)	1000	1.43	1.4	0.71	0.04
Cu** (4.2 K)	546	3.44	1.9	0.41	0.03
Cu*** (4.2 K)	1500	1.00	1.5	0.62	0.04
Al* (4.2 K)	1200	1.25	1.5	0.22	0.02
Pt (77K)	10	12.8	0.26	9.10	0.14

* Jedema *et al.*PRB 67 (2003) ** Garzon *et al.*PRL 94 (2005) *** Kimura *et al.*PRB 72 (2005)

Diffusive electrical currents

Consider σ(=↑or↓)

conductivity E field Diffusion const Density change

$$J_\sigma = J_\sigma^{drift} + J_\sigma^{diffuse} = \sigma_\sigma E + eD_\sigma\nabla\delta n_\sigma$$

Einstein's relation

$$\sigma = N(E_F)e^2D$$

Electrical potential

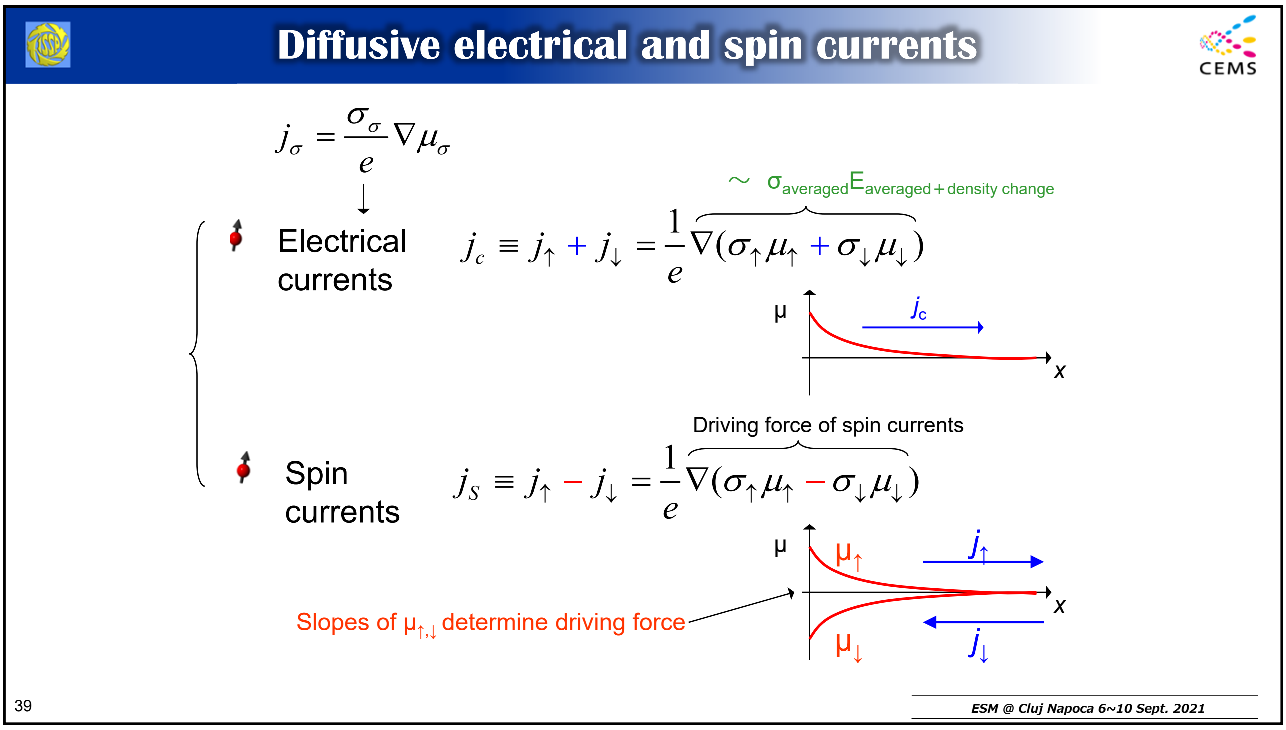
$$j_\sigma = \frac{\sigma_\sigma}{e}\left[e\nabla\phi + \frac{\nabla\delta n_\sigma}{N_\sigma(E_F)}\right]$$

$=\mu_C$: Chemical potential

$$=\nabla\mu$$

$$j_\sigma = \frac{\sigma_\sigma}{e}\nabla\mu_\sigma$$

Electrochemical potential : $\mu = \phi + \mu_C$



Diffusive electrical and spin currents

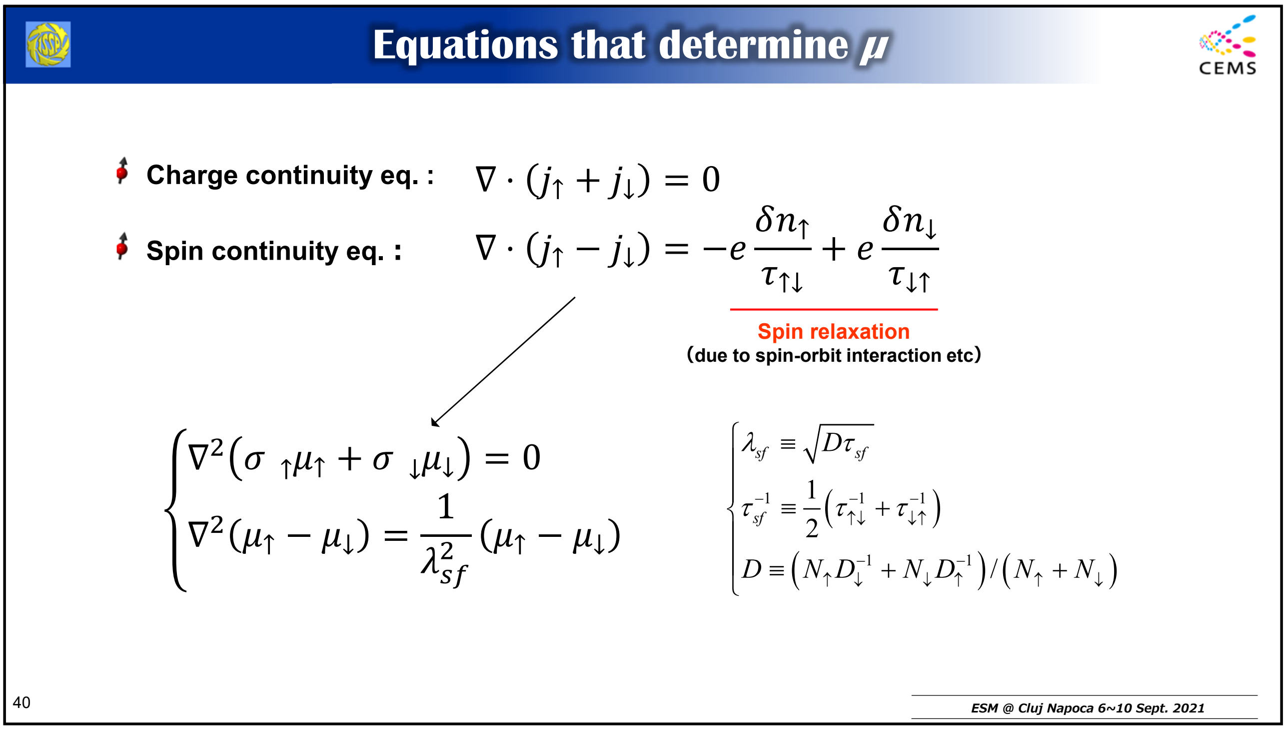
$$j_\sigma = \frac{\sigma_\sigma}{e}\nabla\mu_\sigma$$

$$\downarrow$$

- Electrical currents $$j_c \equiv j_\uparrow + j_\downarrow = \frac{1}{e}\nabla\overbrace{(\sigma_\uparrow\mu_\uparrow + \sigma_\downarrow\mu_\downarrow)}^{\sim\ \sigma_{\text{averaged}}E_{\text{averaged}+\text{density change}}}$$

- Spin currents $$j_S \equiv j_\uparrow - j_\downarrow = \frac{1}{e}\nabla\overbrace{(\sigma_\uparrow\mu_\uparrow - \sigma_\downarrow\mu_\downarrow)}^{\text{Driving force of spin currents}}$$

Slopes of $\mu_{\uparrow,\downarrow}$ determine driving force



Equations that determine μ

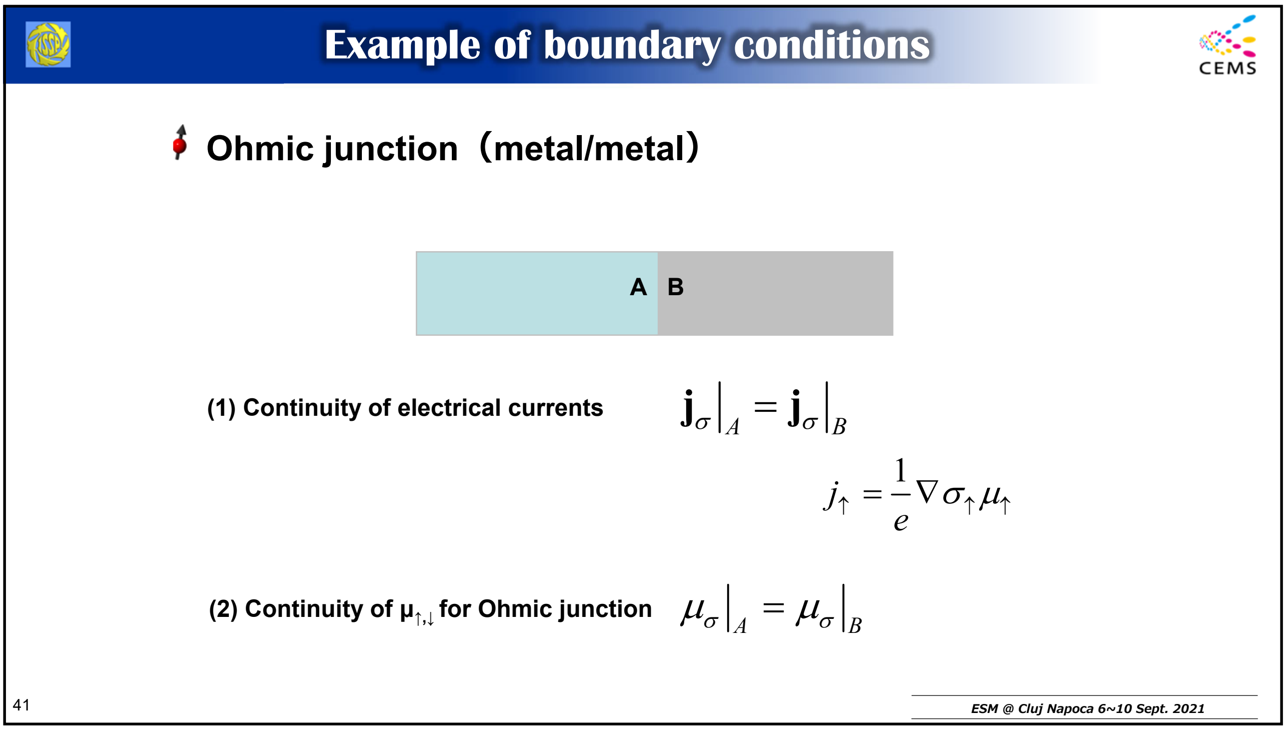
- **Charge continuity eq. :** $\nabla\cdot(j_\uparrow + j_\downarrow) = 0$
- **Spin continuity eq. :** $\nabla\cdot(j_\uparrow - j_\downarrow) = -e\dfrac{\delta n_\uparrow}{\tau_{\uparrow\downarrow}} + e\dfrac{\delta n_\downarrow}{\tau_{\downarrow\uparrow}}$

Spin relaxation

(due to spin-orbit interaction etc)

$$\begin{cases}\nabla^2(\sigma_\uparrow\mu_\uparrow + \sigma_\downarrow\mu_\downarrow) = 0\\ \nabla^2(\mu_\uparrow - \mu_\downarrow) = \dfrac{1}{\lambda_{sf}^2}(\mu_\uparrow - \mu_\downarrow)\end{cases}$$

$$\begin{cases}\lambda_{sf} \equiv \sqrt{D\tau_{sf}}\\ \tau_{sf}^{-1} \equiv \dfrac{1}{2}\left(\tau_{\uparrow\downarrow}^{-1} + \tau_{\downarrow\uparrow}^{-1}\right)\\ D \equiv \left(N_\uparrow D_\downarrow^{-1} + N_\downarrow D_\uparrow^{-1}\right)/\left(N_\uparrow + N_\downarrow\right)\end{cases}$$



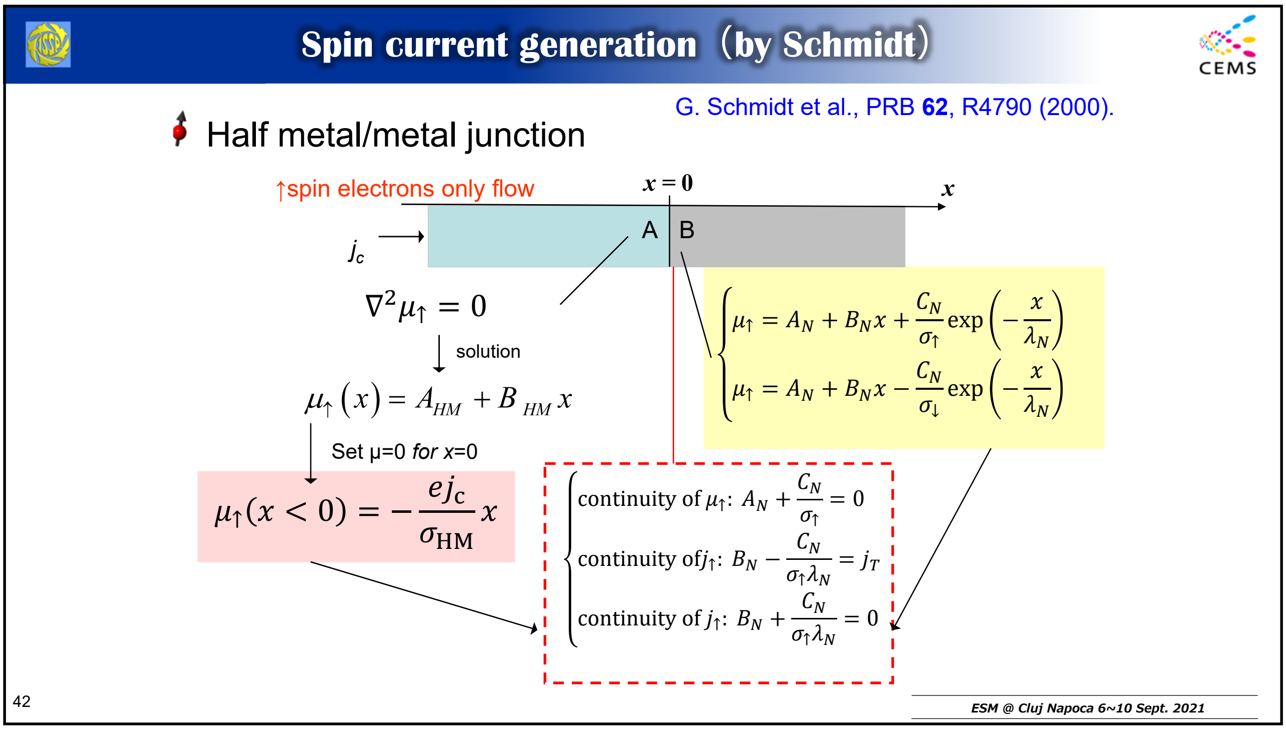
Example of boundary conditions

- Ohmic junction（metal/metal）

(1) Continuity of electrical currents $\mathbf{j}_\sigma\big|_A = \mathbf{j}_\sigma\big|_B$

$$j_\uparrow = \frac{1}{e}\nabla\sigma_\uparrow\mu_\uparrow$$

(2) Continuity of $\mu_{\uparrow,\downarrow}$ for Ohmic junction $\mu_\sigma\big|_A = \mu_\sigma\big|_B$



Spin current generation（by Schmidt）

G. Schmidt et al., PRB **62**, R4790 (2000).

- Half metal/metal junction

$$\nabla^2\mu_\uparrow = 0$$

solution

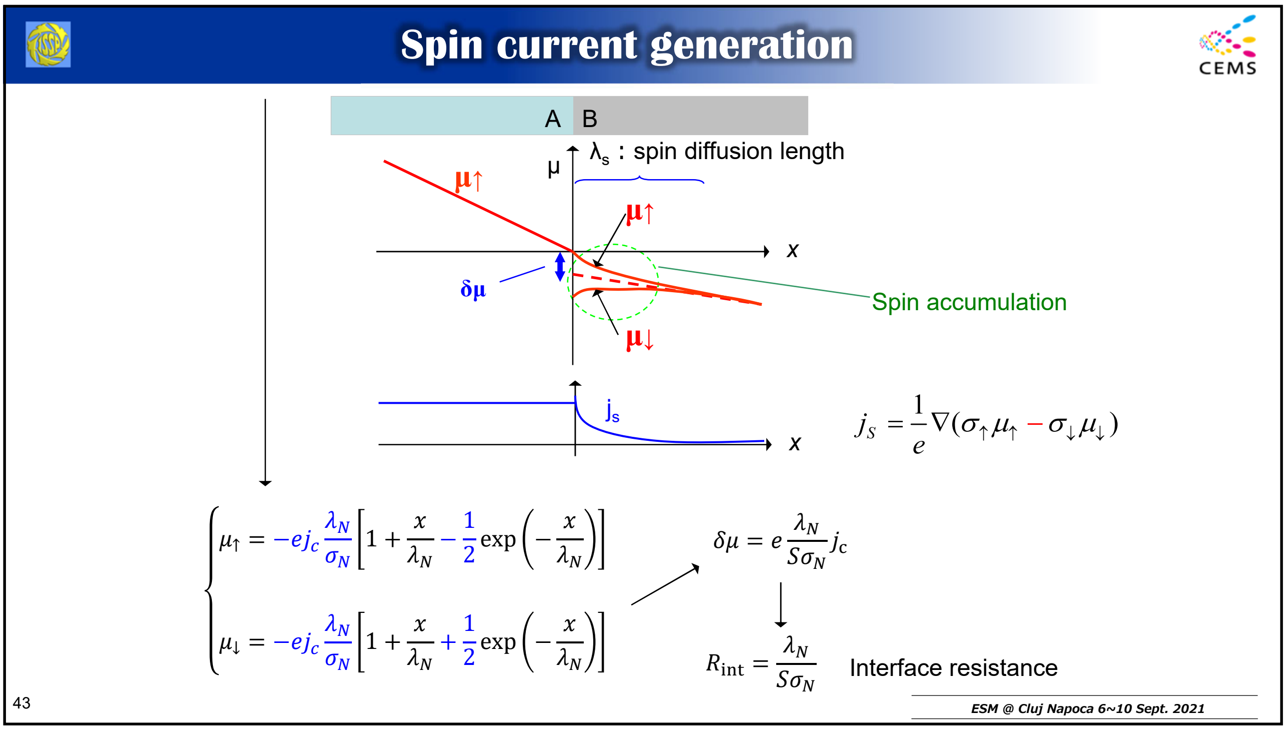
$$\mu_\uparrow(x) = A_{HM} + B_{HM}\,x$$

Set μ=0 *for x*=0

$$\mu_\uparrow(x < 0) = -\frac{ej_c}{\sigma_{\text{HM}}}x$$

$$\begin{cases}\mu_\uparrow = A_N + B_N x + \dfrac{C_N}{\sigma_\uparrow}\exp\left(-\dfrac{x}{\lambda_N}\right)\\ \mu_\uparrow = A_N + B_N x - \dfrac{C_N}{\sigma_\downarrow}\exp\left(-\dfrac{x}{\lambda_N}\right)\end{cases}$$

$$\begin{cases}\text{continuity of } \mu_\uparrow\text{: } A_N + \dfrac{C_N}{\sigma_\uparrow} = 0\\ \text{continuity of} j_\uparrow\text{: } B_N - \dfrac{C_N}{\sigma_\uparrow\lambda_N} = j_T\\ \text{continuity of } j_\uparrow\text{: } B_N + \dfrac{C_N}{\sigma_\uparrow\lambda_N} = 0\end{cases}$$



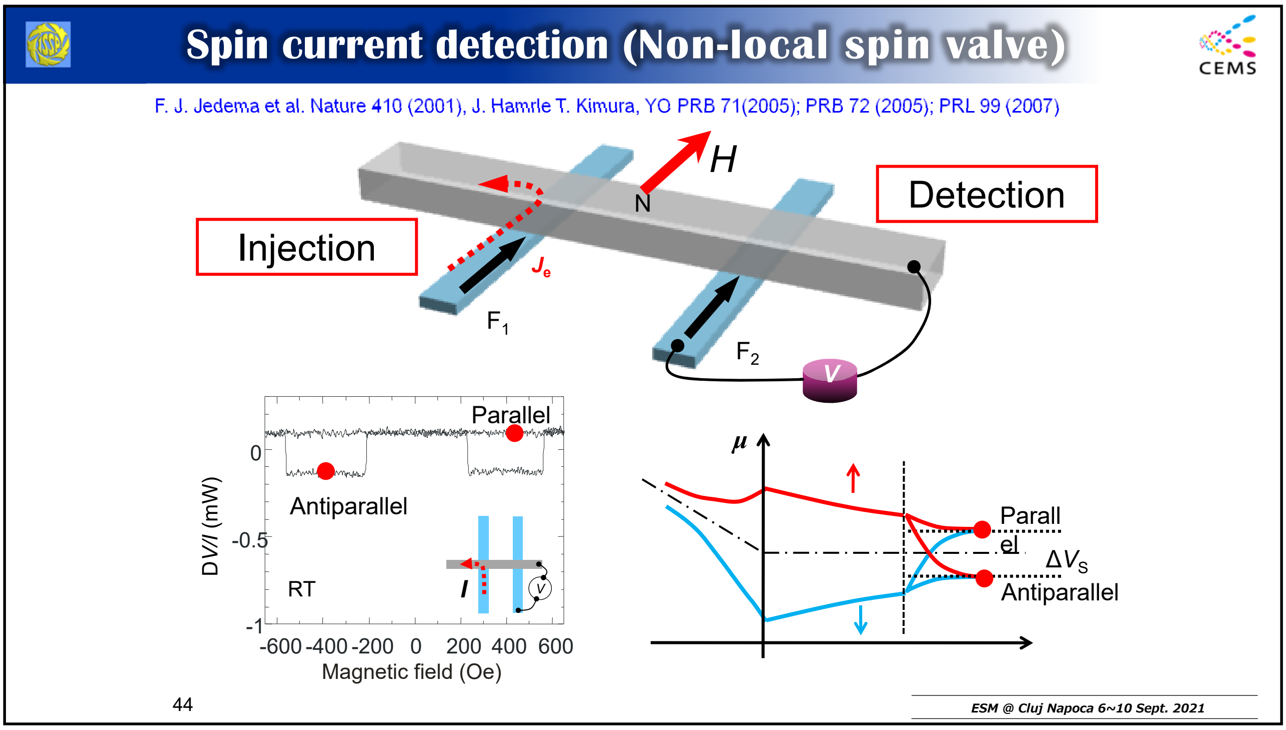
Spin current generation

$$j_S = \frac{1}{e}\nabla(\sigma_\uparrow\mu_\uparrow - \sigma_\downarrow\mu_\downarrow)$$

$$\begin{cases} \mu_\uparrow = -ej_c\dfrac{\lambda_N}{\sigma_N}\left[1+\dfrac{x}{\lambda_N}-\dfrac{1}{2}\exp\left(-\dfrac{x}{\lambda_N}\right)\right] \\ \mu_\downarrow = -ej_c\dfrac{\lambda_N}{\sigma_N}\left[1+\dfrac{x}{\lambda_N}+\dfrac{1}{2}\exp\left(-\dfrac{x}{\lambda_N}\right)\right] \end{cases}$$

$$\delta\mu = e\frac{\lambda_N}{S\sigma_N}j_c$$

$$R_{\text{int}} = \frac{\lambda_N}{S\sigma_N}$$ Interface resistance



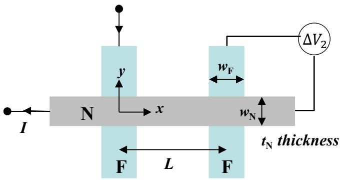
Spin current detection (Non-local spin valve)

F. J. Jedema et al. Nature 410 (2001), J. Hamrle T. Kimura, YO PRB 71(2005); PRB 72 (2005); PRL 99 (2007)

Spin current detection (ohmic junction)

- NLSV structures (no interface resistance)

Takahashi & Maekawa, PRB **67**, 052409 (2003).
Hamrle *et al.*, PRB **71**, 094402 (2005).



$$\Delta R_S = \frac{\Delta V_2}{I} = \frac{4{p_F}^2 R_N e^{-L/\lambda_N}}{\left(\frac{R_N}{R_F}+2\right)^2 - \left(\frac{R_N}{R_F}\right)^2 e^{-2L/\lambda_N}} = \frac{4{p_F}^2 {Q_F}^2 R_N e^{-L/\lambda_N}}{(1+2Q_F)^2 - e^{-2L/\lambda_N}}$$

$$Q_F = \frac{R_F}{R_N}$$

$$\sigma_N{}^{\uparrow} = \sigma_N{}^{\downarrow} = \frac{1}{2}\sigma_N \quad \sigma_F{}^{\uparrow} = \frac{(1+p_F)}{2}\sigma_F \quad R_N = \frac{\lambda_N}{\sigma_N A_N} = \frac{\lambda_N}{\sigma_N w_N t_N}$$

N wire cross sectional area

Polarization

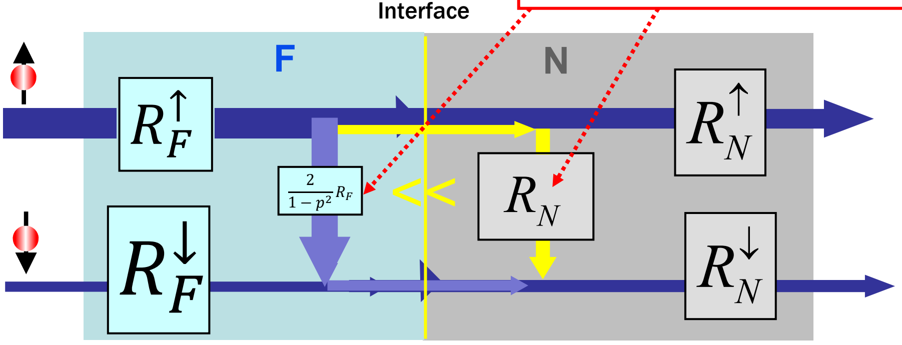
$$p_F = \frac{\sigma_F{}^{\uparrow} - \sigma_F{}^{\downarrow}}{\sigma_F{}^{\uparrow} + \sigma_F{}^{\downarrow}} \quad \sigma_F{}^{\downarrow} = \frac{(1-p_F)}{2}\sigma_F \quad R_F = \frac{\lambda_F}{(1-{p_F}^2)\sigma_F A_J} = \frac{\lambda_F}{(1-{p_F}^2)\sigma_F w_N w_F}$$

F/N junction area

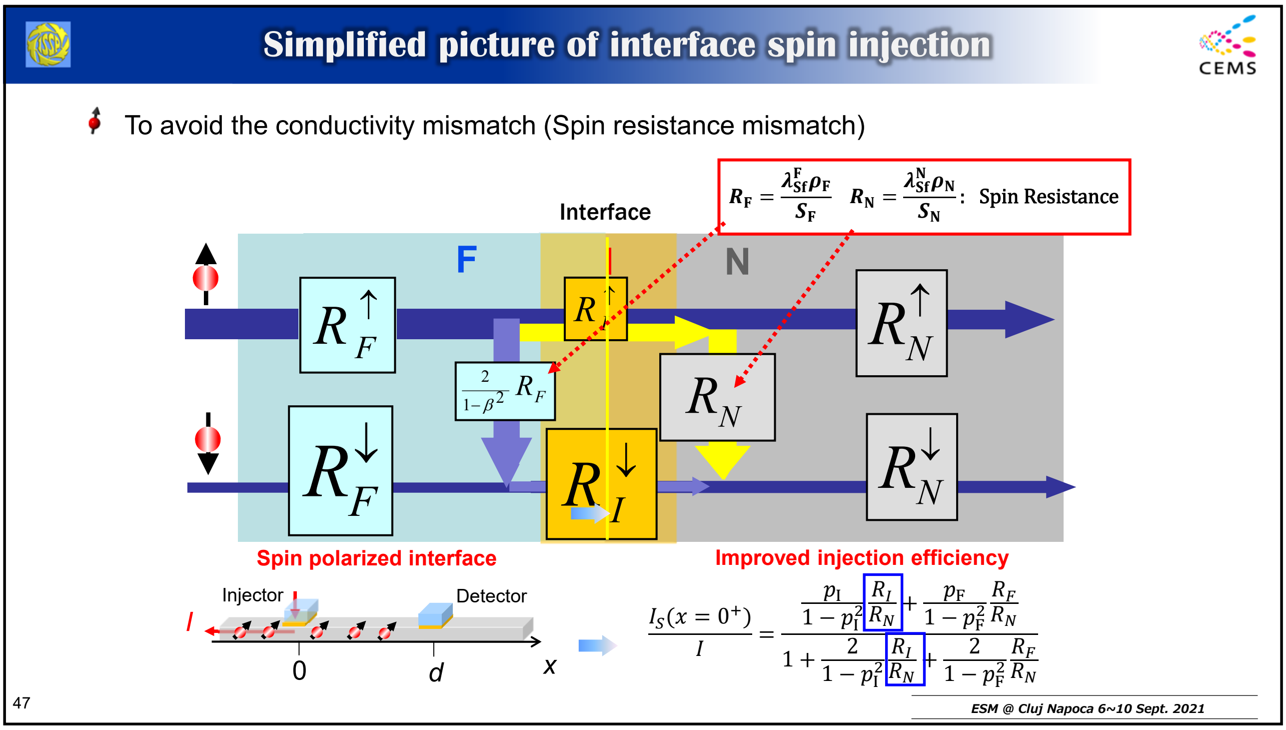
Simplified view of interface spin injection

- Conductivity mismatch (Spin resistance mismatch)

$$\boldsymbol{R_F} = \frac{\lambda_{Sf}^F \rho_F}{S_F},\ \boldsymbol{R_N} = \frac{\lambda_{Sf}^N \rho_N}{S_N}:\ \text{Spin Resistance}$$



E. I. Rashba, Phys. Rev. B **62**, R16267(R)



Simplified picture of interface spin injection

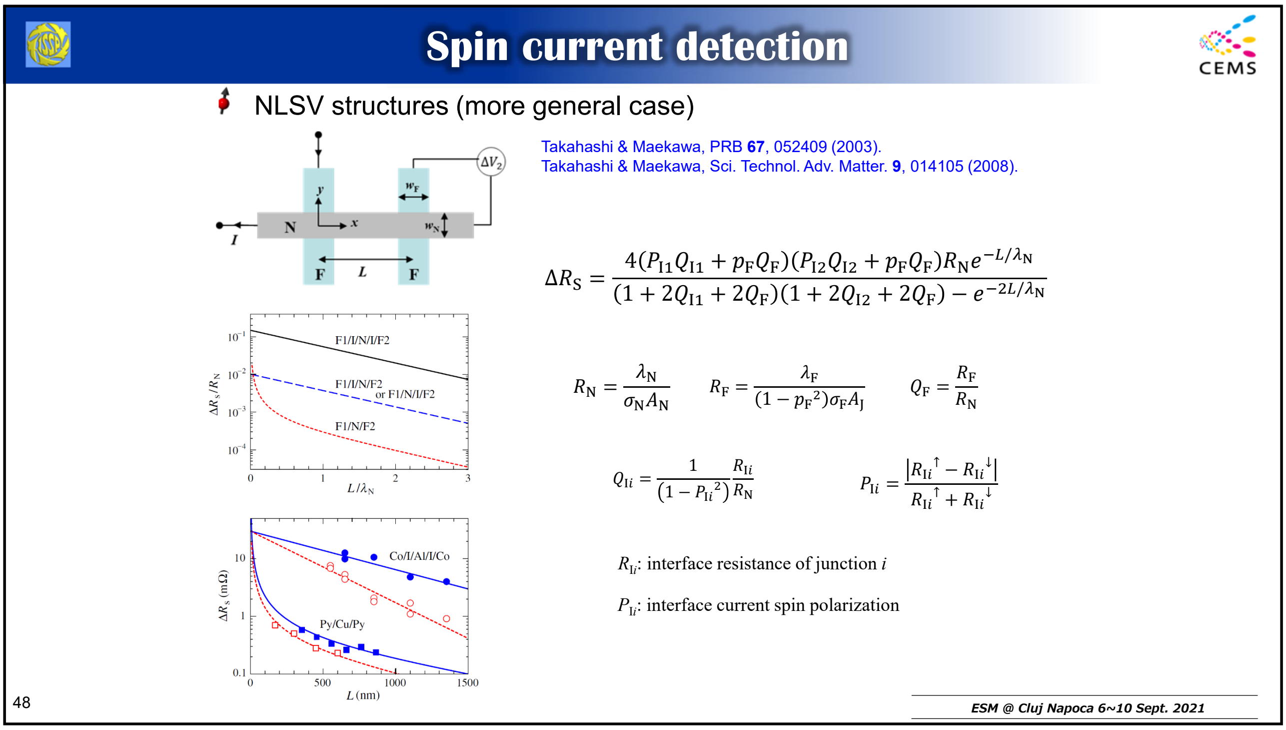
- To avoid the conductivity mismatch (Spin resistance mismatch)

$$\boldsymbol{R_{\mathrm{F}} = \frac{\lambda_{\mathrm{Sf}}^{\mathrm{F}}\rho_{\mathrm{F}}}{S_{\mathrm{F}}}} \quad \boldsymbol{R_{\mathrm{N}} = \frac{\lambda_{\mathrm{Sf}}^{\mathrm{N}}\rho_{\mathrm{N}}}{S_{\mathrm{N}}}}\text{: Spin Resistance}$$

Spin polarized interface

Improved injection efficiency

$$\frac{I_S(x=0^+)}{I} = \frac{\frac{p_{\mathrm{I}}}{1-p_{\mathrm{I}}^2}\boxed{\frac{R_I}{R_N}} + \frac{p_{\mathrm{F}}}{1-p_{\mathrm{F}}^2}\frac{R_F}{R_N}}{1+\frac{2}{1-p_{\mathrm{I}}^2}\boxed{\frac{R_I}{R_N}} + \frac{2}{1-p_{\mathrm{F}}^2}\frac{R_F}{R_N}}$$



Spin current detection

- NLSV structures (more general case)

Takahashi & Maekawa, PRB **67**, 052409 (2003).
Takahashi & Maekawa, Sci. Technol. Adv. Matter. **9**, 014105 (2008).

$$\Delta R_{\mathrm{S}} = \frac{4(P_{\mathrm{I}1}Q_{\mathrm{I}1}+p_{\mathrm{F}}Q_{\mathrm{F}})(P_{\mathrm{I}2}Q_{\mathrm{I}2}+p_{\mathrm{F}}Q_{\mathrm{F}})R_{\mathrm{N}}e^{-L/\lambda_{\mathrm{N}}}}{(1+2Q_{\mathrm{I}1}+2Q_{\mathrm{F}})(1+2Q_{\mathrm{I}2}+2Q_{\mathrm{F}})-e^{-2L/\lambda_{\mathrm{N}}}}$$

$$R_{\mathrm{N}} = \frac{\lambda_{\mathrm{N}}}{\sigma_{\mathrm{N}}A_{\mathrm{N}}} \qquad R_{\mathrm{F}} = \frac{\lambda_{\mathrm{F}}}{(1-p_{\mathrm{F}}{}^2)\sigma_{\mathrm{F}}A_{\mathrm{J}}} \qquad Q_{\mathrm{F}} = \frac{R_{\mathrm{F}}}{R_{\mathrm{N}}}$$

$$Q_{\mathrm{I}i} = \frac{1}{(1-P_{\mathrm{I}i}{}^2)}\frac{R_{\mathrm{I}i}}{R_{\mathrm{N}}} \qquad P_{\mathrm{I}i} = \frac{|R_{\mathrm{I}i}{}^{\uparrow}-R_{\mathrm{I}i}{}^{\downarrow}|}{R_{\mathrm{I}i}{}^{\uparrow}+R_{\mathrm{I}i}{}^{\downarrow}}$$

$R_{\mathrm{I}i}$: interface resistance of junction i

$P_{\mathrm{I}i}$: interface current spin polarization

Quiz 3

3. Which approach below is adequate to increase spin injection efficiency? Choose correct ones from the following (possibilities of multiple correct approaches) ; correct answers are marked in red.

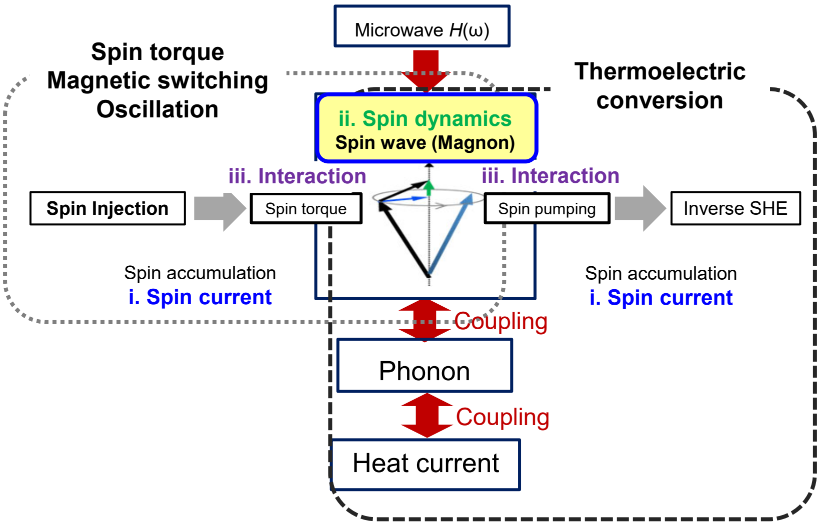
a. Reduce the junction size or make a point contact.

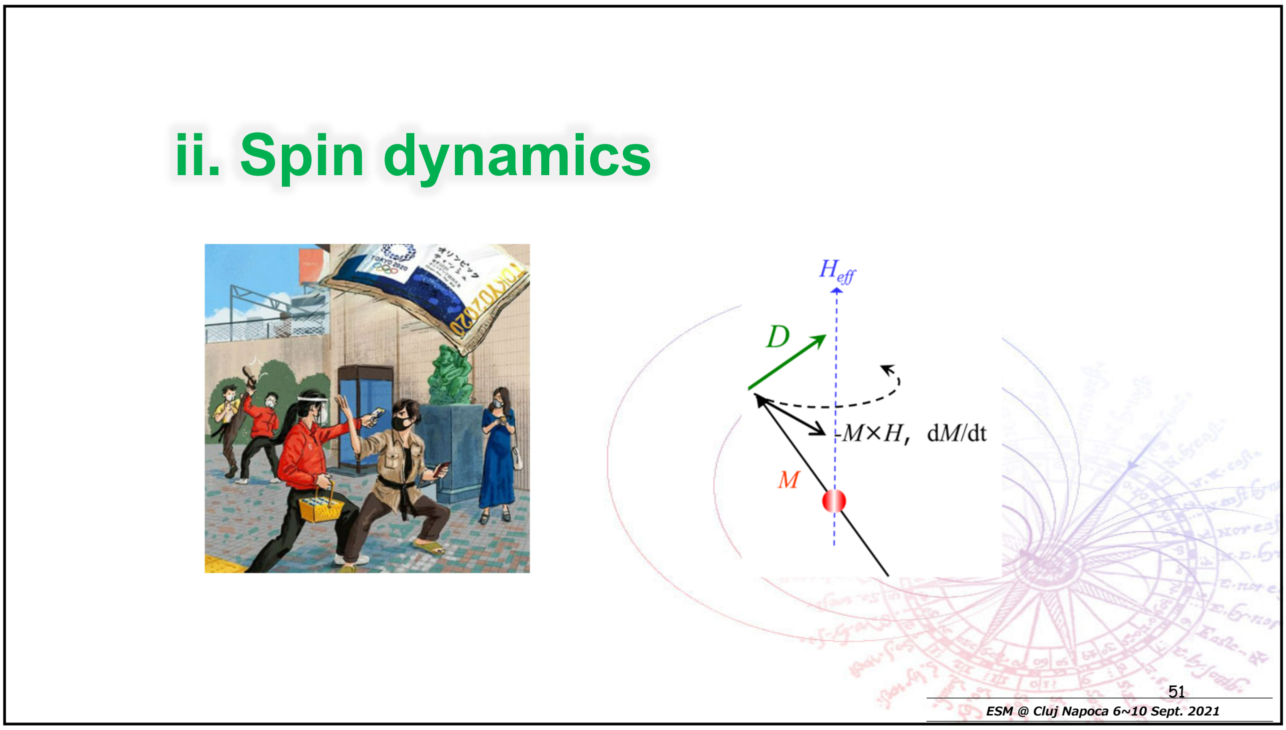
b. Introduce a resistive interface layer with its resistance matching the resistance of the paramagnetic layer.

c. Introduce a resistive interface layer with its resistance matching the spin resistance of the paramagnetic layer.

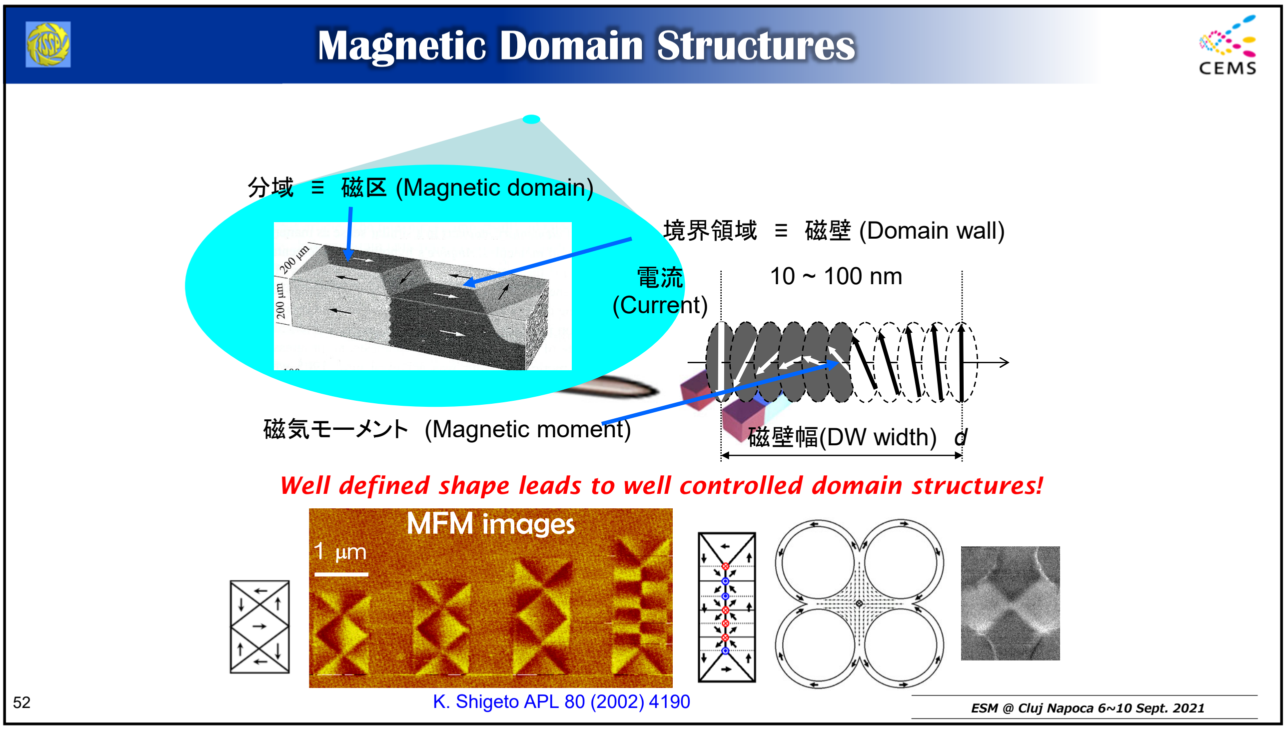
d. Introduce a tunnel barrier interface with a very high resistance.

Spin currents and spin dynamics





ii. Spin dynamics

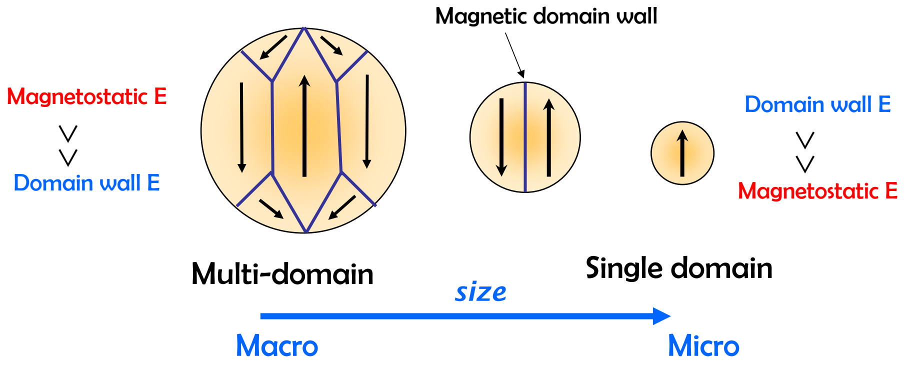


Magnetic Domain Structures

Well defined shape leads to well controlled domain structures!

K. Shigeto APL 80 (2002) 4190

Size Dependent Magnetic Domain



Magnetic domain wall

Magnetostatic E
>
>
Domain wall E

Domain wall E
>
>
Magnetostatic E

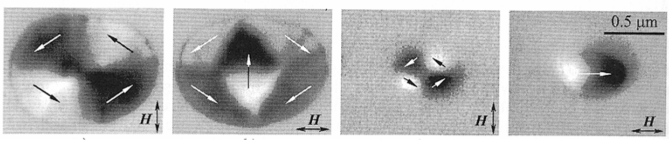
Multi-domain

Single domain

size

Macro

Micro



Magnetic free energy

- **Free energy of the system given by Magnetization**

$$\mathbf{M} = \mathbf{M}(r) = M_s \cdot \mathbf{m}(r)$$

$$\mathbf{m}(r) = \left(m_x(r), m_y(r), m_z(r)\right) \qquad \because |\mathbf{m}(r)| = 1$$

$$E = \int \left[\underbrace{A(\nabla \mathbf{m})^2}_{\text{Exchange}} + \underbrace{K \cdot f(\mathbf{m})}_{\text{Anisotropy}} - \underbrace{\frac{1}{2\mu_0} M_s^2 \mathbf{m}(r) \cdot \mathbf{h}_D(r)}_{\text{Magnetostatic}} - \underbrace{M_s H_{ext} \mathbf{m}(r) \cdot \mathbf{h}_{ext}}_{\text{Magnetic potential}} \right] dV$$

$$= A \int \left[(\nabla \mathbf{m})^2 + \frac{1}{\xi_K^2} \cdot f(\mathbf{m}) - \frac{1}{\xi_M^2} \mathbf{m}(r) \cdot \mathbf{h}_D(r) - \frac{1}{\xi_H^2} \mathbf{m}(r) \cdot \mathbf{h}_{ext} \right] dV$$

Characteristic length [m]

$$\boxed{\xi_K = \sqrt{\frac{A}{K}}} \qquad \boxed{\xi_M = \sqrt{\frac{2\mu_0 A}{M_s^2}}} \qquad \boxed{\xi_H = \sqrt{\frac{A}{M_s H_{ext}}}}$$

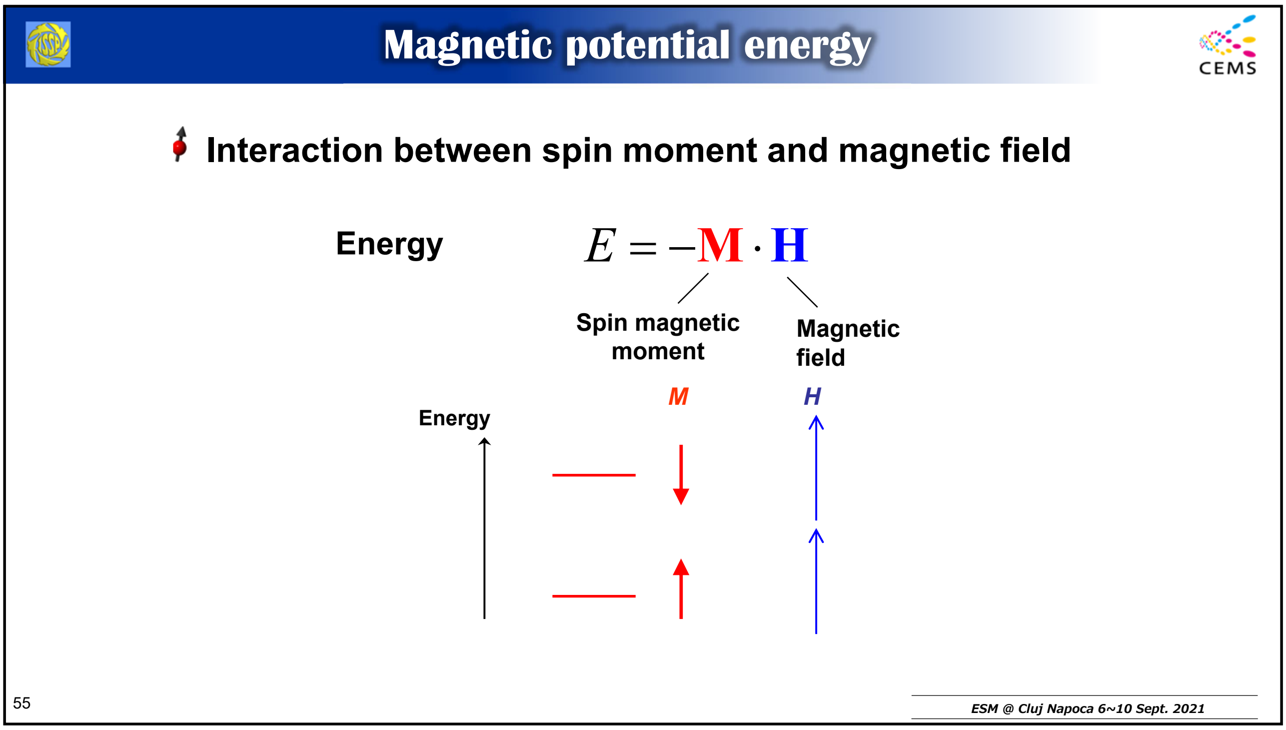
Anisotropy | Magnetostatic | Magnetic potential

Typical value for Fe
A = 8×10^{-12} [J/m],
K = 5×10^{5} [J/m^3],
M_s = 2.15 [T]

⇒ ξ_K ~ 4 nm

⇒ ξ_M ~ 3.6 nm

⇒ ξ_H ~ 2.2 nm



Magnetic potential energy

- Interaction between spin moment and magnetic field

Energy $E = -\mathbf{M} \cdot \mathbf{H}$

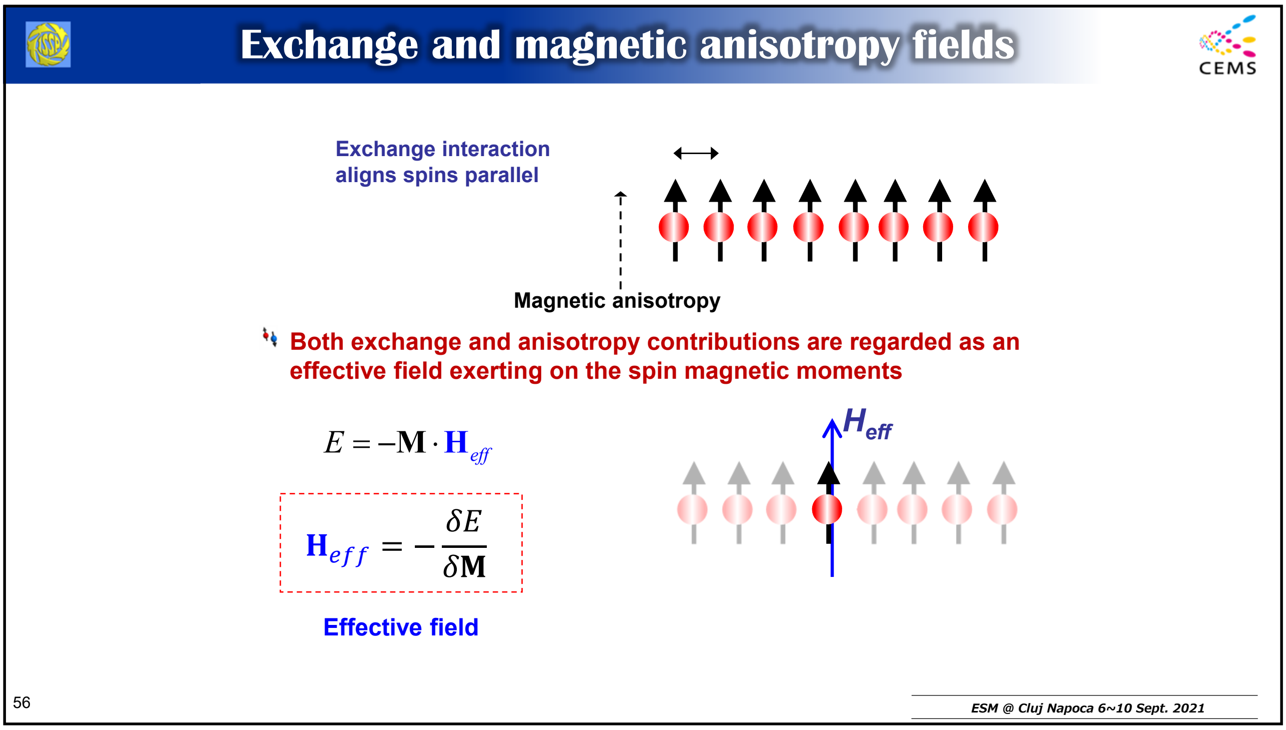
Spin magnetic moment

Magnetic field

Energy

M

H



Exchange and magnetic anisotropy fields

Exchange interaction
aligns spins parallel

Magnetic anisotropy

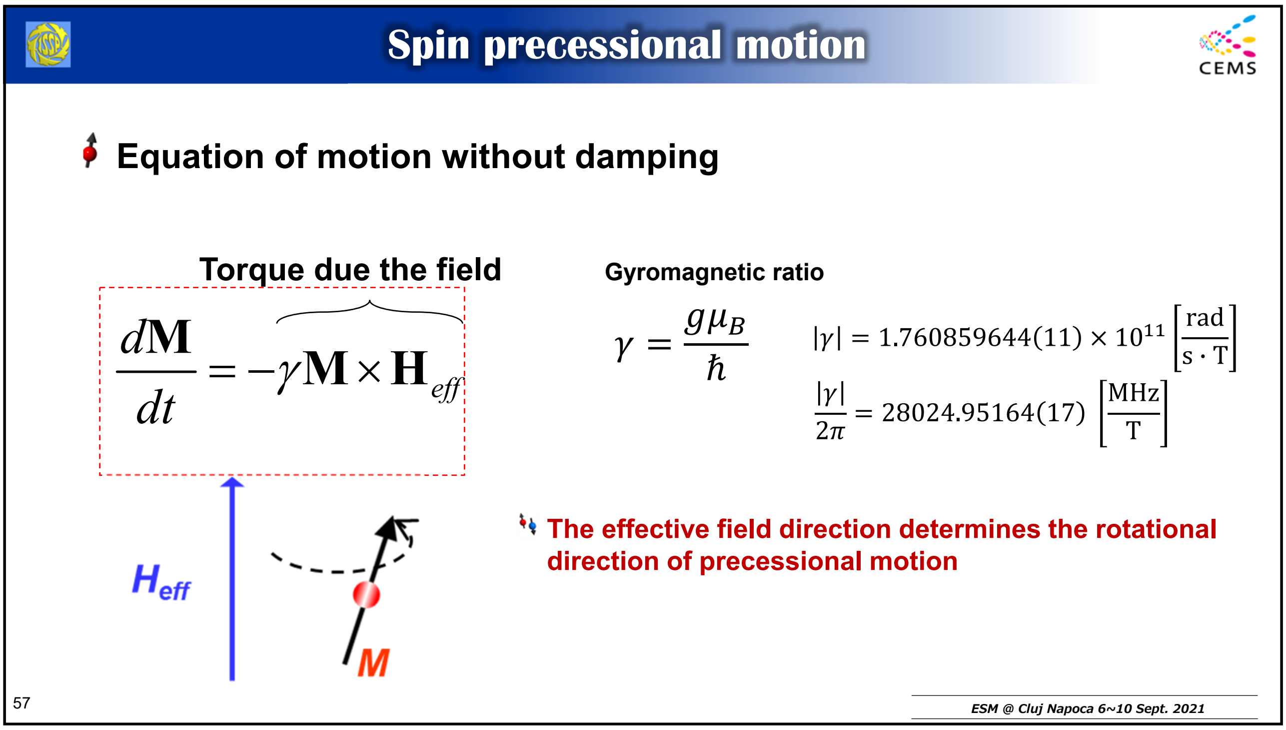
- Both exchange and anisotropy contributions are regarded as an effective field exerting on the spin magnetic moments

$E = -\mathbf{M} \cdot \mathbf{H}_{eff}$

$$\boxed{\mathbf{H}_{eff} = -\frac{\delta E}{\delta \mathbf{M}}}$$

Effective field

H_{eff}



Spin precessional motion

- Equation of motion without damping

$$\frac{d\mathbf{M}}{dt} = -\overbrace{\gamma\mathbf{M}\times\mathbf{H}_{eff}}^{\text{Torque due the field}}$$

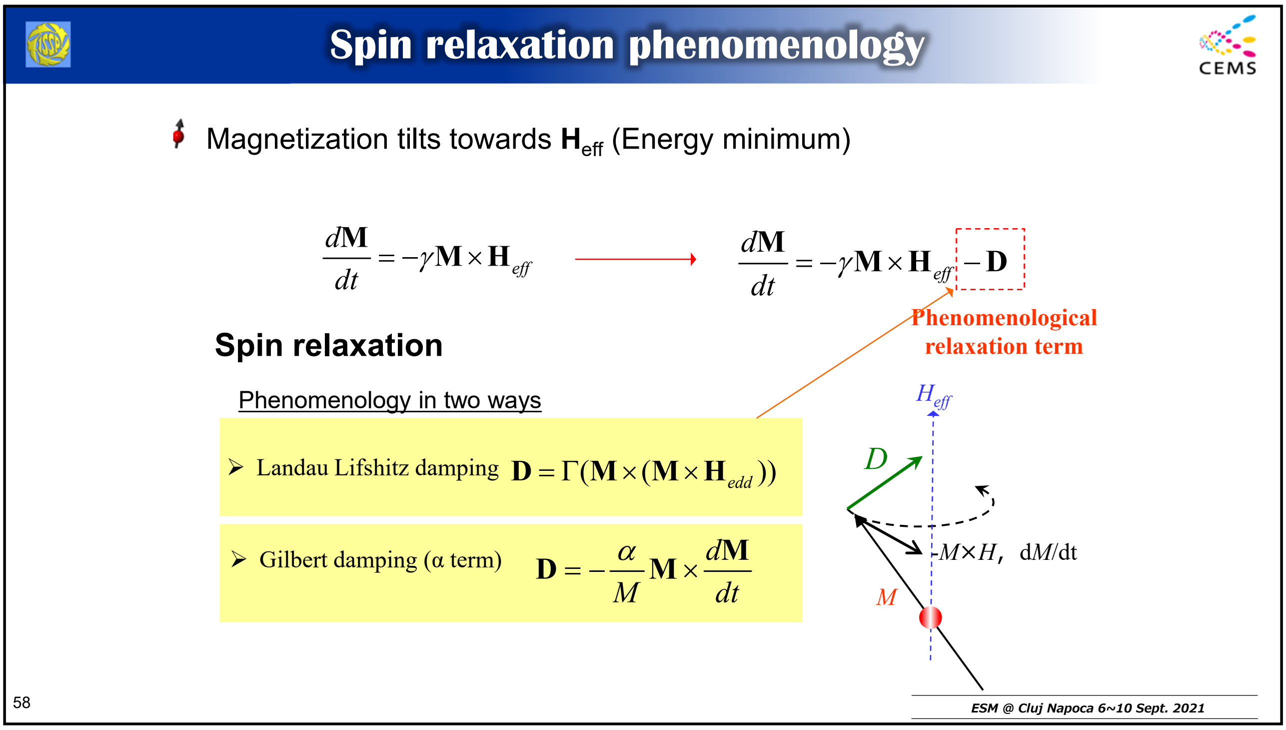
Gyromagnetic ratio

$$\gamma = \frac{g\mu_B}{\hbar}$$

$$|\gamma| = 1.760859644(11)\times 10^{11}\left[\frac{\text{rad}}{\text{s}\cdot\text{T}}\right]$$

$$\frac{|\gamma|}{2\pi} = 28024.95164(17)\left[\frac{\text{MHz}}{\text{T}}\right]$$

- The effective field direction determines the rotational direction of precessional motion



Spin relaxation phenomenology

- Magnetization tilts towards $\mathbf{H}_{eff}$ (Energy minimum)

$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{H}_{eff} \longrightarrow \frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{H}_{eff}\boxed{-\mathbf{D}}$$

Phenomenological relaxation term

Spin relaxation

Phenomenology in two ways

- Landau Lifshitz damping $\mathbf{D} = \Gamma(\mathbf{M}\times(\mathbf{M}\times\mathbf{H}_{edd}))$
- Gilbert damping (α term) $\mathbf{D} = -\frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt}$

Phenomenology of damping

CEMS

Two expressions

Gilbert damping term

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M}\mathbf{M} \times \frac{d\mathbf{M}}{dt}$$

***Substitute dM/dt* recursively**

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} + \frac{\alpha}{M}\mathbf{M} \times \left(-\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M}\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right)$$

$$= -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha\gamma}{M}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}) - \alpha^2 \frac{d\mathbf{M}}{dt}$$

$$(1+\alpha^2)\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha\gamma}{M}\mathbf{M} \times (\mathbf{M} \times \mathbf{H})$$

α<<1 approximation

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha\gamma}{M}\mathbf{M} \times (\mathbf{M} \times \mathbf{H})$$

Landau Lifshitz damping term

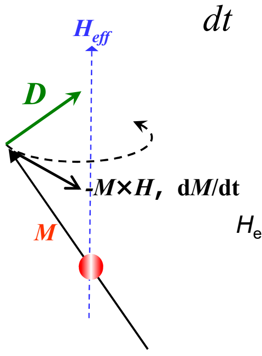
Microscopic origin of damping :
Interaction with conduction electrons, magnetoelastic interaction, eddy current…

Most popular equation of motion

CEMS

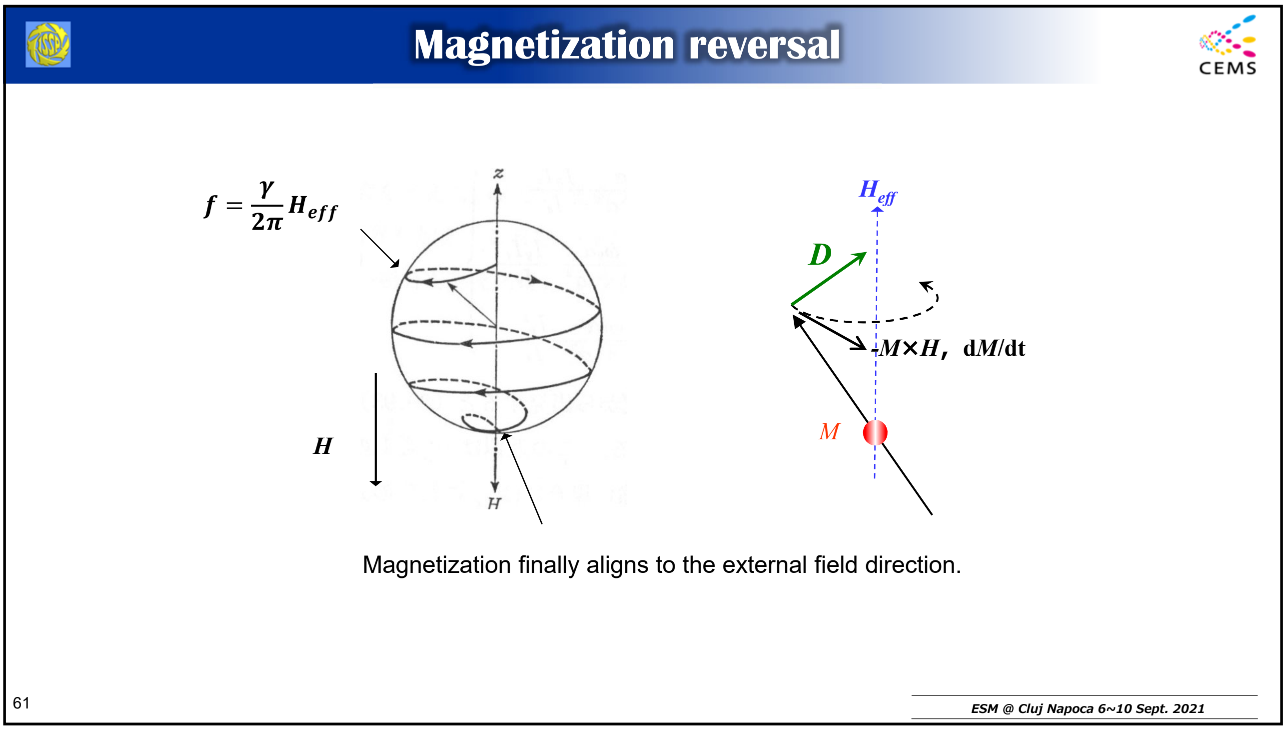
- LLG (Landau Lifshitz Gilbert) equation

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \underbrace{\frac{\alpha}{M}\mathbf{M} \times \frac{d\mathbf{M}}{dt}}_{\text{Gilbert damping (α term)}}$$



H_{eff} sum of external, anisotropy, and demagnetizing fields

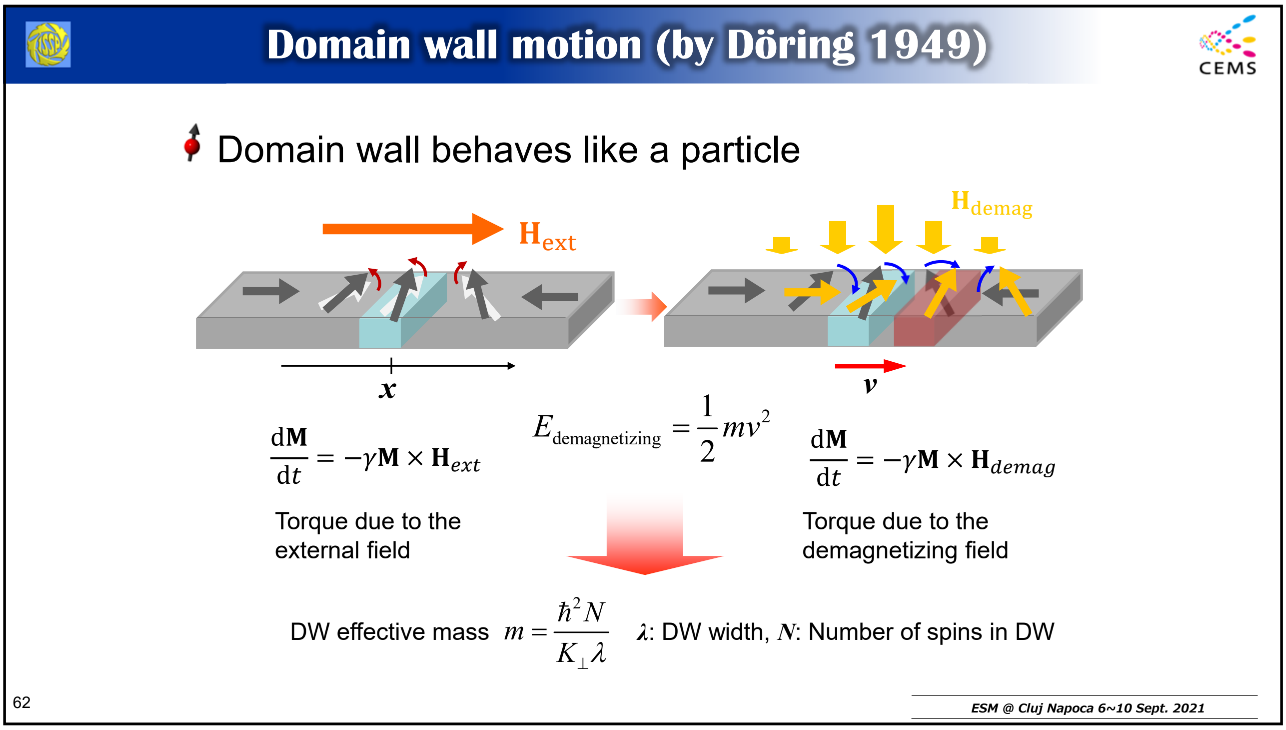
Micromagnetic basic equation



Magnetization reversal

$$f = \frac{\gamma}{2\pi} H_{eff}$$

Magnetization finally aligns to the external field direction.



Domain wall motion (by Döring 1949)

- Domain wall behaves like a particle

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{ext}$$

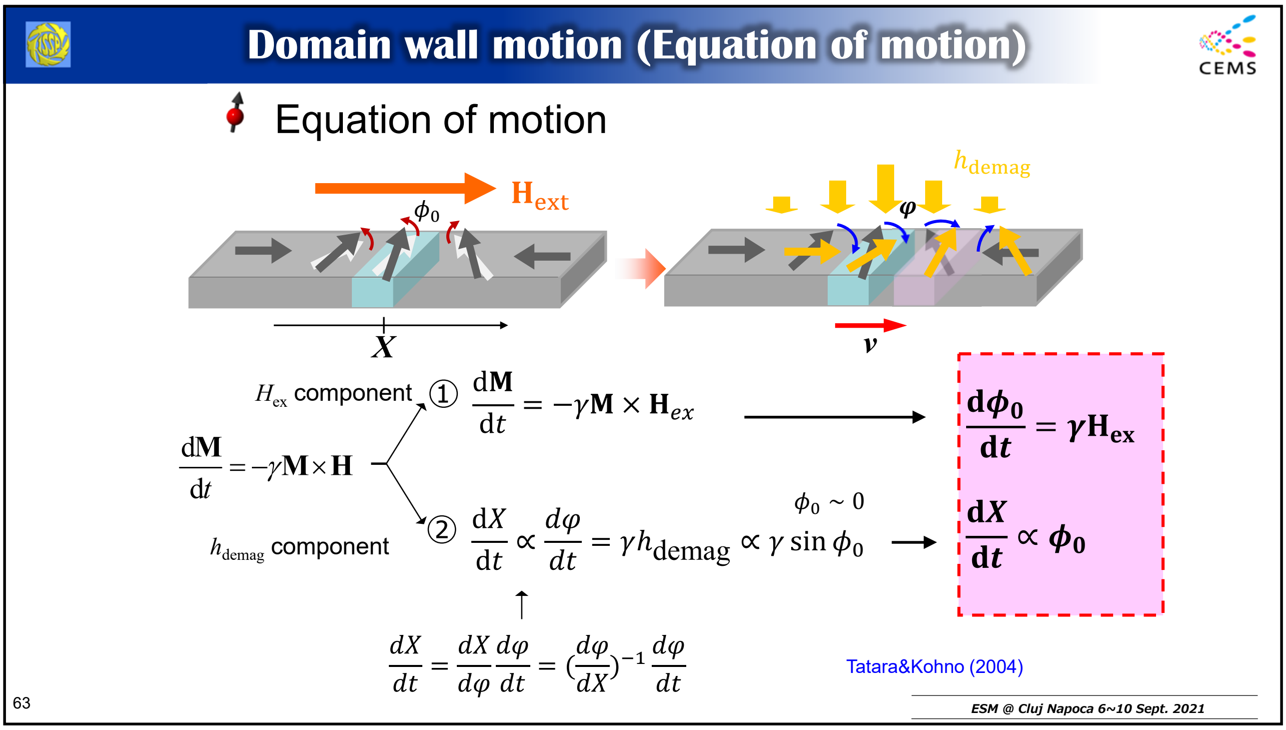
Torque due to the external field

$$E_{\text{demagnetizing}} = \frac{1}{2} m v^2$$

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{demag}$$

Torque due to the demagnetizing field

DW effective mass $m = \dfrac{\hbar^2 N}{K_{\perp} \lambda}$ λ: DW width, N: Number of spins in DW



Domain wall motion (Equation of motion)

Equation of motion

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M}\times\mathbf{H}$$

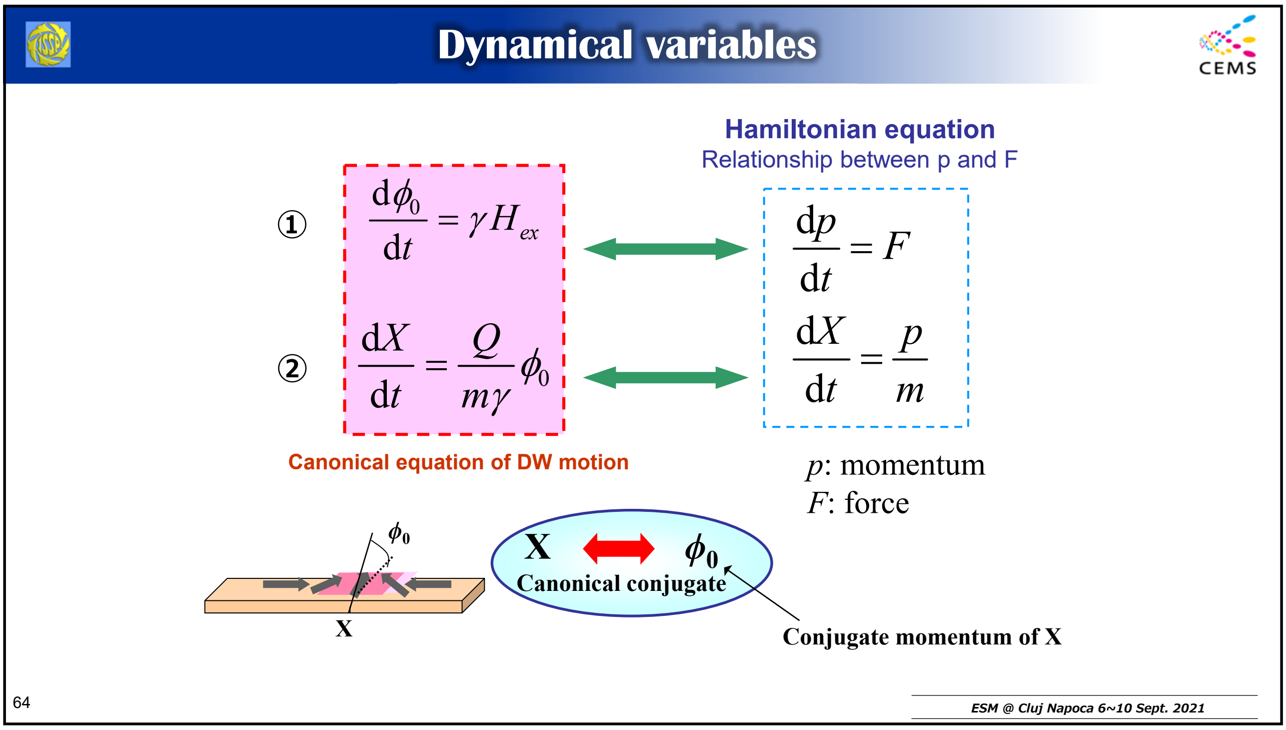
$H_{\rm ex}$ component ① $\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M}\times\mathbf{H}_{ex}$ $\longrightarrow$ $\frac{d\phi_0}{dt} = \gamma H_{\rm ex}$

$h_{\rm demag}$ component ② $\frac{dX}{dt} \propto \frac{d\varphi}{dt} = \gamma h_{\rm demag} \propto \gamma \sin\phi_0 \xrightarrow{\phi_0 \sim 0} \frac{dX}{dt} \propto \phi_0$

$\uparrow$

$$\frac{dX}{dt} = \frac{dX}{d\varphi}\frac{d\varphi}{dt} = \left(\frac{d\varphi}{dX}\right)^{-1}\frac{d\varphi}{dt}$$

Tatara&Kohno (2004)



Dynamical variables

Hamiltonian equation
Relationship between p and F

① $\frac{d\phi_0}{dt} = \gamma H_{ex}$ ⟷ $\frac{dp}{dt} = F$

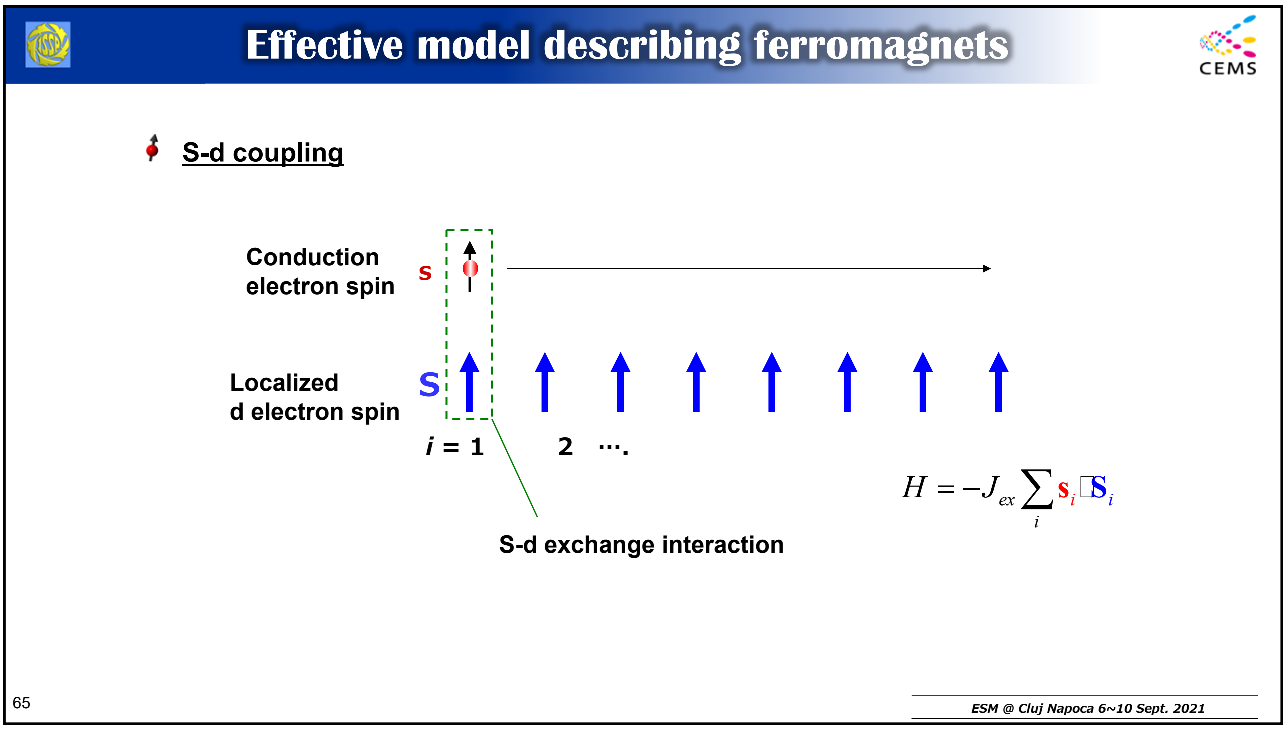
② $\frac{dX}{dt} = \frac{Q}{m\gamma}\phi_0$ ⟷ $\frac{dX}{dt} = \frac{p}{m}$

Canonical equation of DW motion

p: momentum
F: force

X ⟷ ϕ_0
Canonical conjugate

Conjugate momentum of X

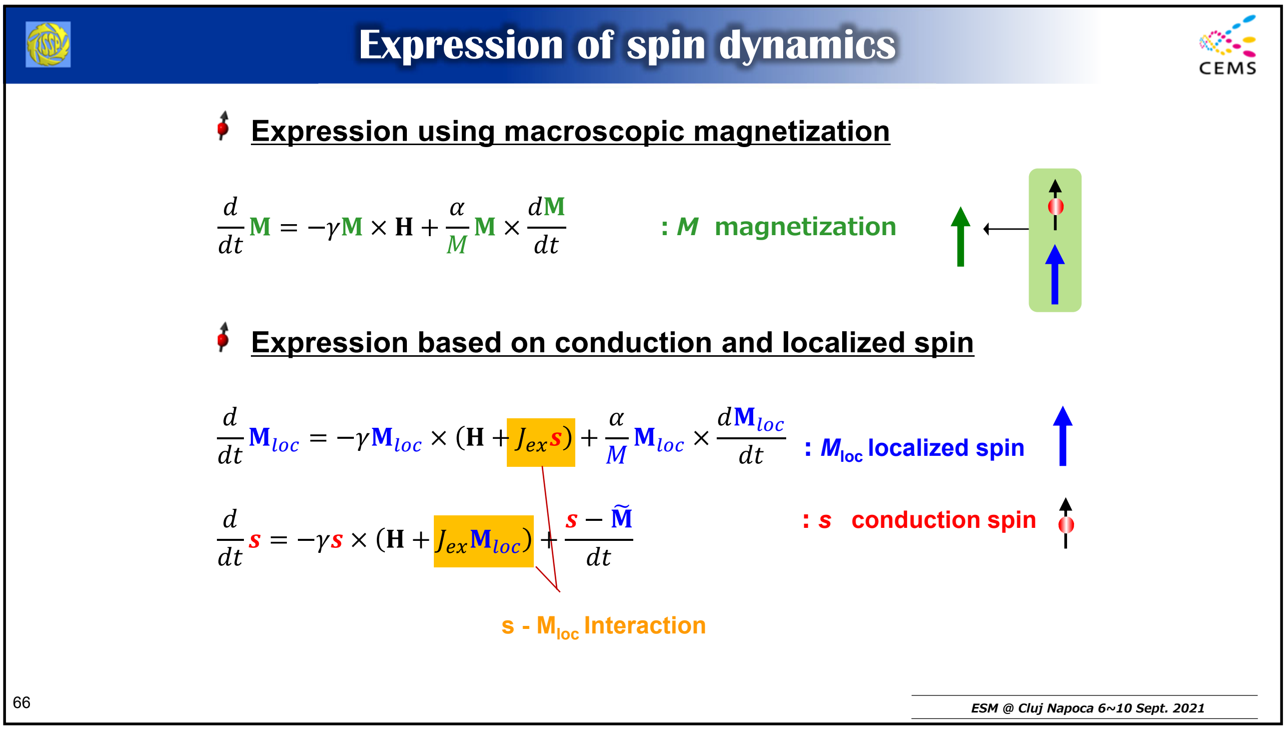


Effective model describing ferromagnets

S-d coupling

$$H = -J_{ex}\sum_i \mathbf{s}_i \cdot \mathbf{S}_i$$

S-d exchange interaction



Expression of spin dynamics

Expression using macroscopic magnetization

$$\frac{d}{dt}\mathbf{M} = -\gamma\mathbf{M}\times\mathbf{H} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt}$$

: *M* magnetization

Expression based on conduction and localized spin

$$\frac{d}{dt}\mathbf{M}_{loc} = -\gamma\mathbf{M}_{loc}\times(\mathbf{H}+J_{ex}\boldsymbol{s}) + \frac{\alpha}{M}\mathbf{M}_{loc}\times\frac{d\mathbf{M}_{loc}}{dt}$$

: M_{loc} localized spin

$$\frac{d}{dt}\boldsymbol{s} = -\gamma\boldsymbol{s}\times(\mathbf{H}+J_{ex}\mathbf{M}_{loc}) + \frac{\boldsymbol{s}-\widetilde{\mathbf{M}}}{dt}$$

: *s* conduction spin

s - M_{loc} Interaction

Quiz 4

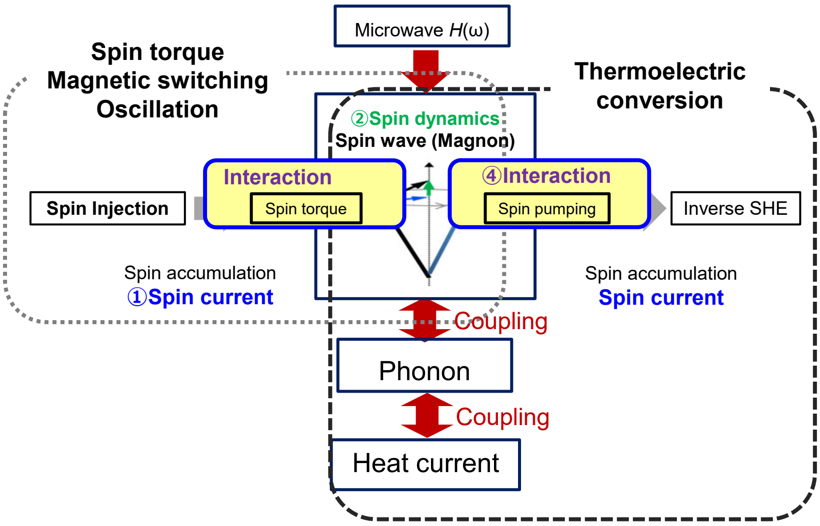
4. Select correct descriptions in the following? (possibilities of multiple correct ones) ; correct answers are marked in red.

   a. The rotational direction of magnetic precessional motion is determined by the gravity.

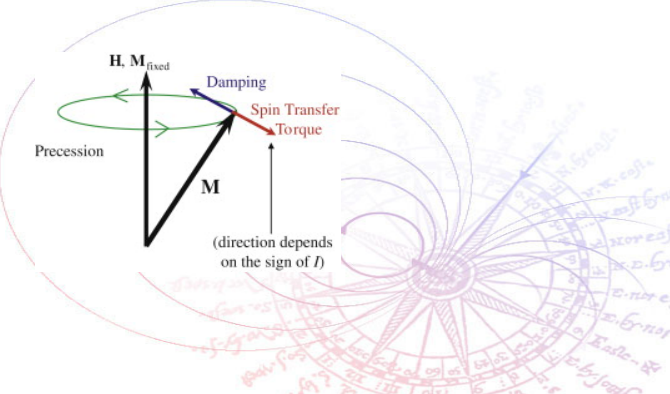
   b. The demagnetizing energy of the ferromagnetic DW provides its kinetic energy.

   c. Precession means rectifying the movement.

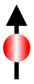
Spin currents and spin dynamics



iii. Interaction between spin currents and spin dynamics

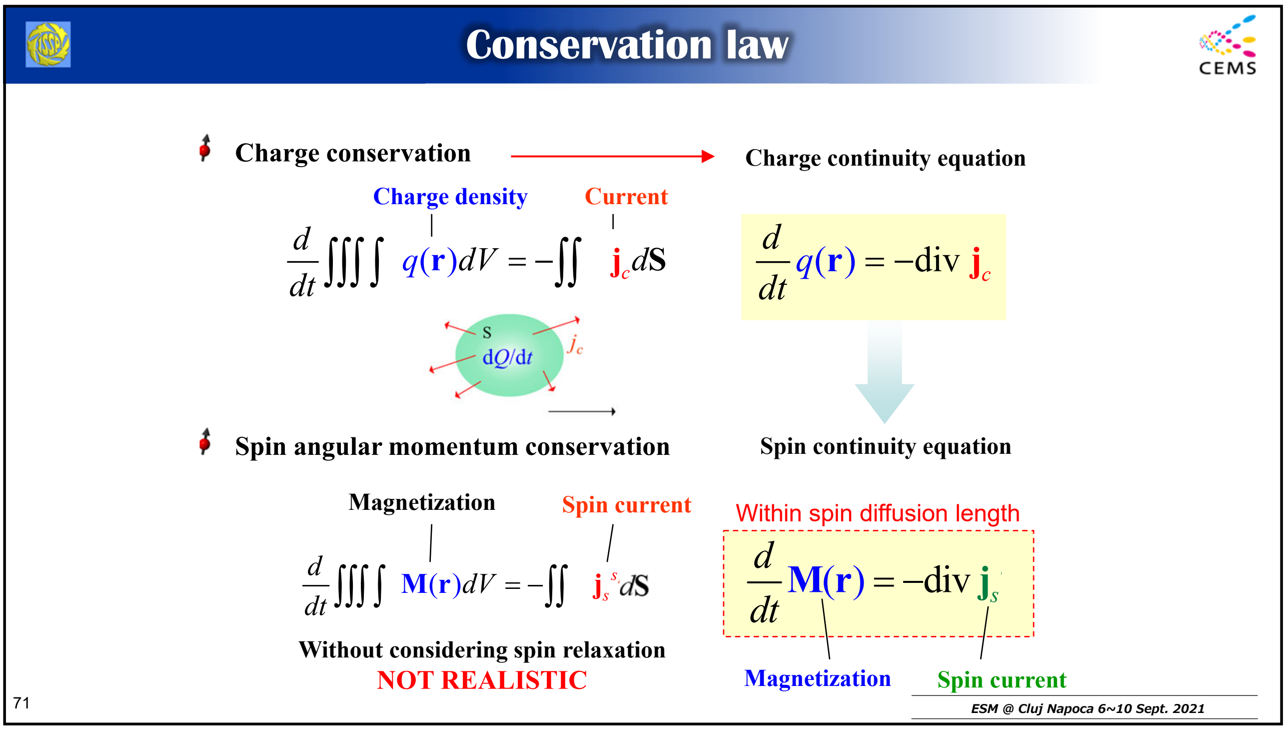


Spin angular momentum



Spin angular momentum $\frac{\hbar}{2}$

Spin magnetic moment $-\frac{g\mu_B S}{\hbar} = -\frac{g\mu_B}{2}$



Conservation law

- Charge conservation → Charge continuity equation

Charge density Current

$$\frac{d}{dt}\iiint q(\mathbf{r})dV = -\iint \mathbf{j}_c d\mathbf{S}$$

$$\boxed{\frac{d}{dt}q(\mathbf{r}) = -\mathrm{div}\ \mathbf{j}_c}$$

- Spin angular momentum conservation

Spin continuity equation

Magnetization Spin current

$$\frac{d}{dt}\iiint \mathbf{M}(\mathbf{r})dV = -\iint \mathbf{j}_s^{\,s} d\mathbf{S}$$

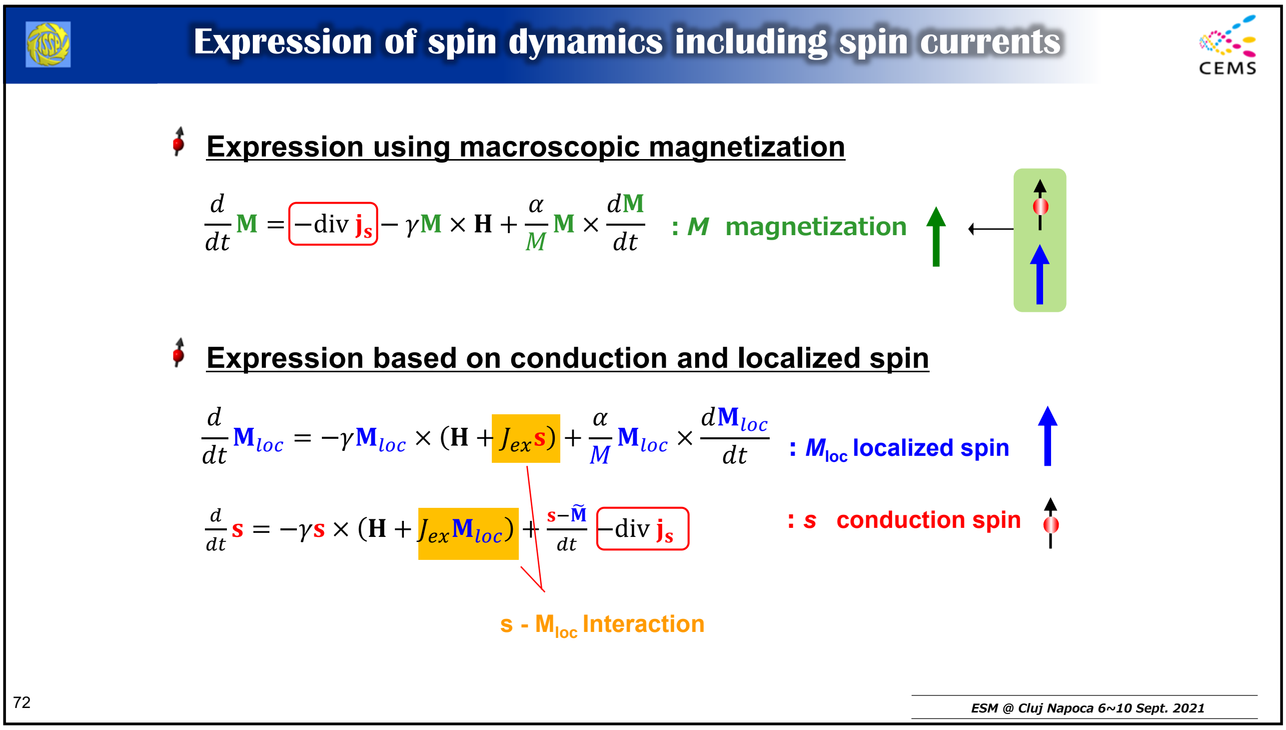
Without considering spin relaxation

NOT REALISTIC

Within spin diffusion length

$$\boxed{\frac{d}{dt}\mathbf{M}(\mathbf{r}) = -\mathrm{div}\ \mathbf{j}_s}$$

Magnetization Spin current



Expression of spin dynamics including spin currents

- **Expression using macroscopic magnetization**

$$\frac{d}{dt}\mathbf{M} = \boxed{-\mathrm{div}\ \mathbf{j}_s} - \gamma\mathbf{M}\times\mathbf{H} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt}$$

: *M* magnetization

- **Expression based on conduction and localized spin**

$$\frac{d}{dt}\mathbf{M}_{loc} = -\gamma\mathbf{M}_{loc}\times(\mathbf{H} + J_{ex}\mathbf{s}) + \frac{\alpha}{M}\mathbf{M}_{loc}\times\frac{d\mathbf{M}_{loc}}{dt}$$

: M_{loc} localized spin

$$\frac{d}{dt}\mathbf{s} = -\gamma\mathbf{s}\times(\mathbf{H} + J_{ex}\mathbf{M}_{loc}) + \frac{\mathbf{s}-\tilde{\mathbf{M}}}{dt}\boxed{-\mathrm{div}\ \mathbf{j}_s}$$

: *s* conduction spin

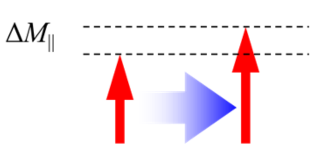
s - M_{loc} Interaction

Dynamical spin injection and spin torque

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

Parallel component
Spin accumulation

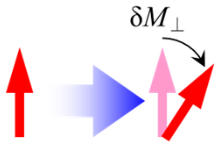
$$\frac{d}{dt}\mathbf{M}_{\parallel} = -\mathrm{div}\,\mathbf{j}_s\Big|_{\parallel\mathbf{M}}$$



$$\Delta M = g\mu_B N(\delta n_{\uparrow} - \delta n_{\downarrow})$$
$$= g\mu_B N(\varepsilon_F)(\mu_{\uparrow} - \mu_{\downarrow})$$

Perpendicular component
Spin torque

$$\frac{d}{dt}\mathbf{M}_{\perp} = -\mathrm{div}\,\mathbf{j}_s\Big|_{\perp\mathbf{M}}$$



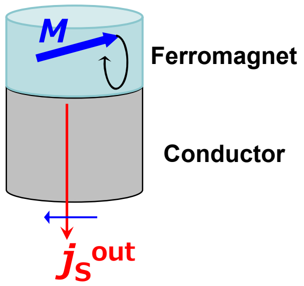
Spin pumping

***When M* is precessing**

$$\frac{d}{dt}\mathbf{M}(\mathbf{r}) = -\delta\mathbf{j}_S{}^{out} - \gamma\mathbf{M}\times\mathbf{H} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt}$$

Spin current pumped into conductor

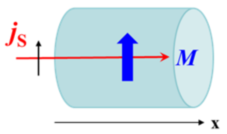
$$\delta\mathbf{j}_S{}^{out} = \gamma\mathbf{M}\times\mathbf{H} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt} - \frac{d}{dt}\mathbf{M}(\mathbf{r})$$



J_s with spin polarization parallel to the external field can modulate relaxation

Spin currents and spin torque in ferromagnets

$$\frac{d}{dt}\mathbf{M}(\mathbf{r}) = -\gamma\mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt} - \delta\mathbf{j}_S$$



$\mathbf{j}_s \,//\, \mathbf{m}$

$$\frac{d}{dt}\mathbf{m}(\mathbf{r}) = -\gamma\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff} + \alpha\mathbf{m}(\mathbf{r})\times\boxed{\frac{d\mathbf{m}(\mathbf{r})}{dt}} - u\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x}$$

Spin current velocity

$$u = \frac{g\mu_B p}{2eM_S}j_C$$

p**:spin polarization**

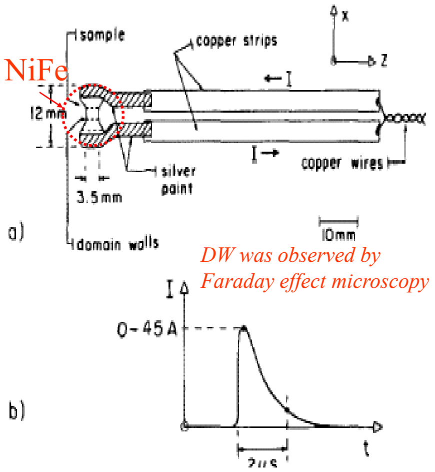
***Substitute dm/dt* recursively**

$$(1+\alpha^2)\frac{d}{dt}\mathbf{m}(\mathbf{r}) = \underbrace{-\gamma\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff}}_{\text{Torque by } H_{\text{eff}}} \underbrace{-\alpha\mathbf{m}(\mathbf{r})\times(\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff})}_{\text{Damping towards } H_{\text{eff}}} \underbrace{-u\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x}}_{\text{Torque by spin current}} \underbrace{-u\alpha\mathbf{m}(\mathbf{r})\times\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x}}_{\text{Damping torque by spin current}}$$

Non uniform magnetization distribution such as DW causes these two terms

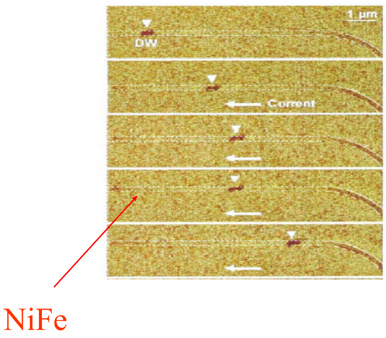
Current driven DW motion (Experiments)

Freitas & Berger, JAP (1984).

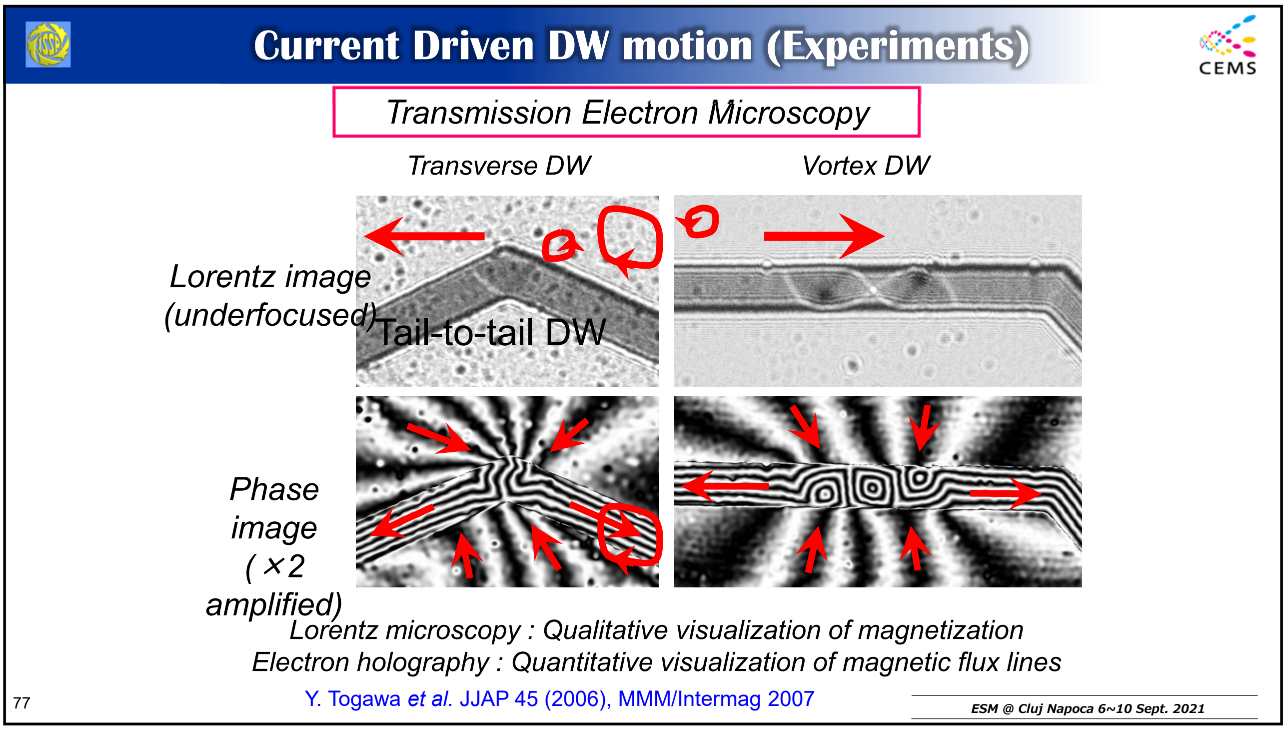


DW was observed by Faraday effect microscopy

Yamaguchi、Ono *etal.*, PRL (2004).



Yamanouchi *et al.*, Nature (2004).
Saitoh *et al.*, Nature (2004).



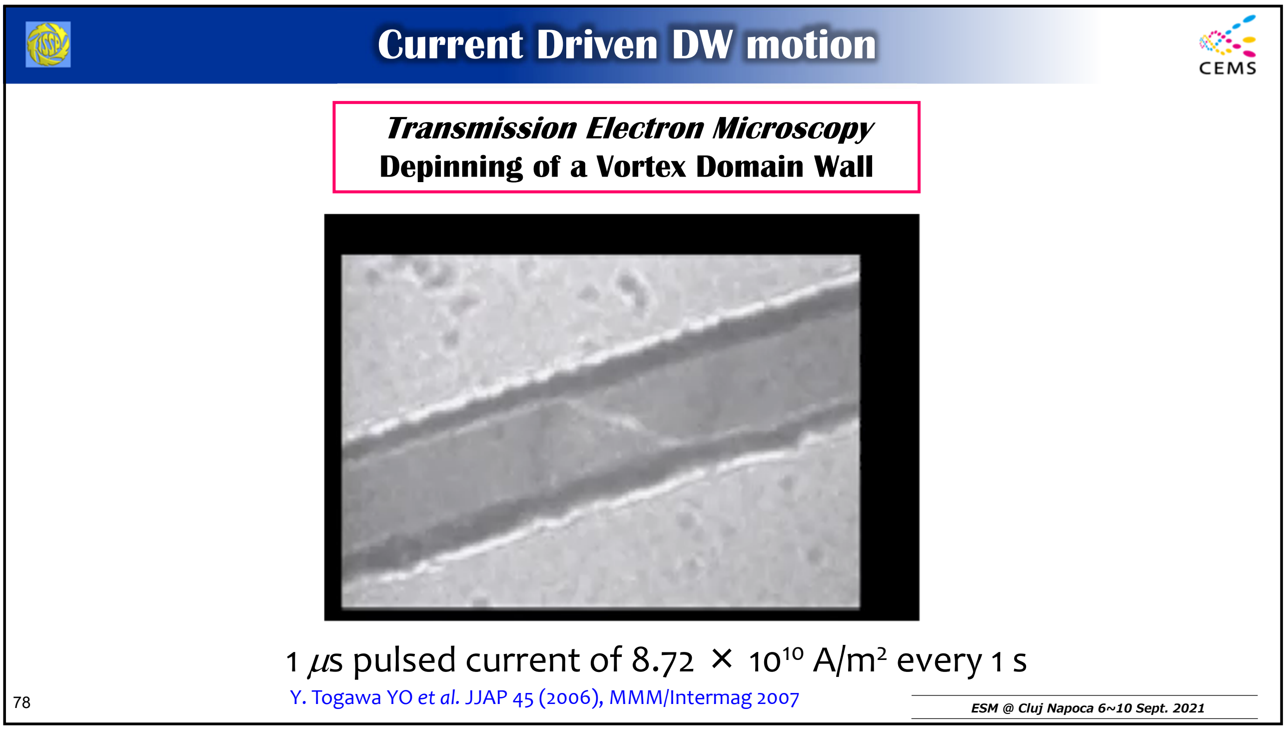
Current Driven DW motion (Experiments)

Transmission Electron Microscopy

Lorentz microscopy : Qualitative visualization of magnetization

Electron holography : Quantitative visualization of magnetic flux lines

Y. Togawa *et al.* JJAP 45 (2006), MMM/Intermag 2007



Current Driven DW motion

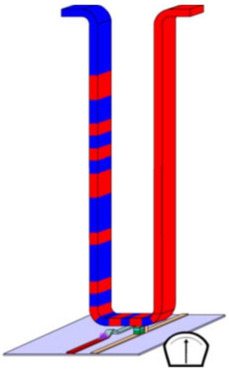
Transmission Electron Microscopy

Depinning of a Vortex Domain Wall

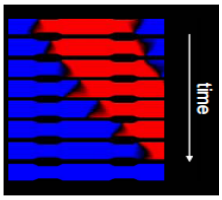
1 μs pulsed current of 8.72 × 10^{10} A/m^2 every 1 s

Y. Togawa YO *et al.* JJAP 45 (2006), MMM/Intermag 2007

Racetrack memory

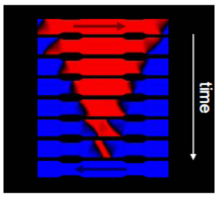


Current-driven dynamics



H = 0, I > 0

Field-driven dynamics



H = -200 Oe

→Current pulses move domains along “racetrack” shift register
→TMR sensor to read bit pattern
→Special current pulse-driven element to re-write a bit

Parkin, US patents 6834005, 6898132, 6920062

Courtesy of Dr. S.S.P. Parkin

β (non-adiabatic) term contribution

$$(1+\alpha^2)\frac{d}{dt}\mathbf{m}(\mathbf{r}) = -\gamma\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff} - \alpha\mathbf{m}(\mathbf{r})\times(\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff}) - u\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x} \underbrace{- u\alpha\mathbf{m}(\mathbf{r})\times\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x}}_{\text{Damping torque}}$$

Magnetic moment tilts out of the easy plane, decelerates domain wall motion

$$\frac{d}{dt}\mathbf{M}(\mathbf{r}) = -\gamma\mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M}\mathbf{M}\times\frac{d\mathbf{M}}{dt} + \boxed{\beta u\mathbf{M}\times\mathrm{div}\mathbf{M}} - \mathrm{div}\,\mathbf{j}_S$$

Non-adiabatic torque

$$(1+\alpha^2)\frac{d}{dt}\mathbf{m}(\mathbf{r}) = -\gamma\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff} - \alpha\mathbf{m}(\mathbf{r})\times(\mathbf{m}(\mathbf{r})\times\mathbf{H}_{eff}) - u(1+\alpha\beta)\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x} \underbrace{+ u(\beta-\alpha)\mathbf{m}(\mathbf{r})\times\frac{\partial\mathbf{m}(\mathbf{r})}{\partial x}}_{\beta\text{ term suppresses damping torque}}$$

S. Zhang & Z. Li PRL 93 (2004)

Quiz 5

5. Select correct descriptions in the following? (possibilities of multiple correct ones) ; correct answers are marked in red.

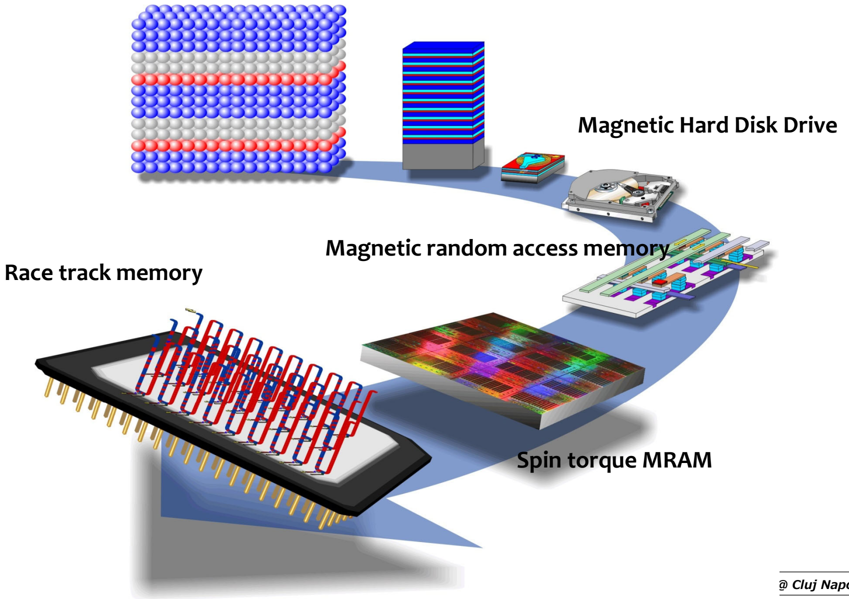
   a. The electronic charge is not conserved quantity. Therefore, the continuity equation holds.

   b. The spin accumulation is conserved quantity. Therefore, the continuity equation holds.

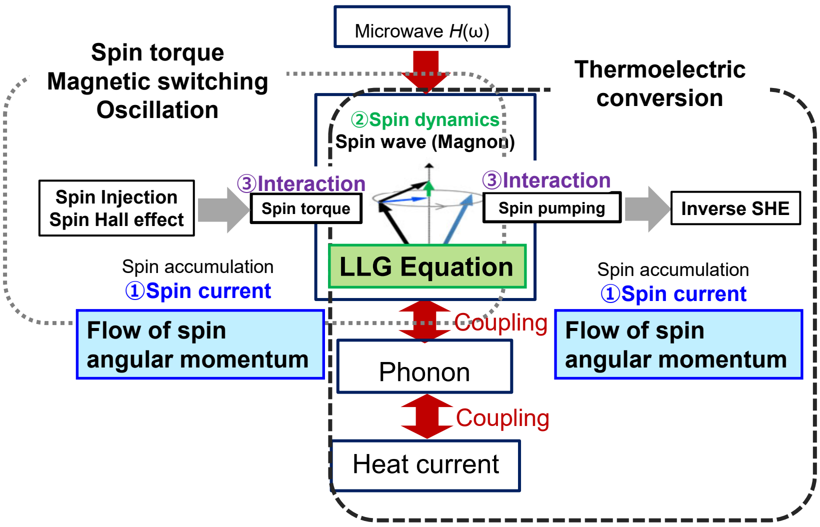
   c. Magnetization dynamics generates the spin current whose polarization component parallel to the effective field causes spin torque and the perpendicular component causes spin accumulation.

   d. Spin torque can shift DW without changing its size unlike magnetic field.

World trend of memory devices



Summary



Microwave $H(\omega)$

Spin torque
Magnetic switching
Oscillation

Thermoelectric conversion

②**Spin dynamics**
Spin wave (Magnon)

Spin Injection
Spin Hall effect

③**Interaction**
Spin torque

③**Interaction**
Spin pumping

Inverse SHE

LLG Equation

Spin accumulation
①**Spin current**

Flow of spin angular momentum

Spin accumulation
①**Spin current**

Flow of spin angular momentum

Coupling

Phonon

Coupling

Heat current

Outline of my lecture

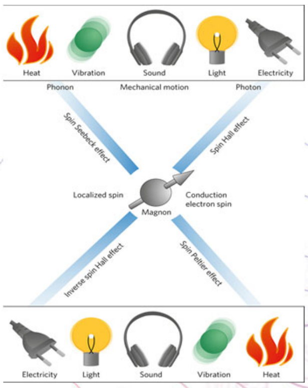
1. Introduction
2. Basics of electrical transport
   - i. Free electrons motion in a crystal
   - ii. Transport in ferromagnets
   - iii. Two currents model for ferromagnets
3. Spin currents and spin dynamics
   - i. Spin current
   - ii. Spin dynamics
   - iii. Interaction of spin currents and spin dynamics

1_{st} Part

4. Spin conversion phenomena
   - i. Spin Hall effect in metals
   - ii. Edelstein effect (Rashba Interface & TI surface state)
   - iii. Magnetic spin Hall effect
5. New directions in spintronics
   - i. Antiferromagnetic spintronics
   - ii. Strong coupling

2_{nd} Part

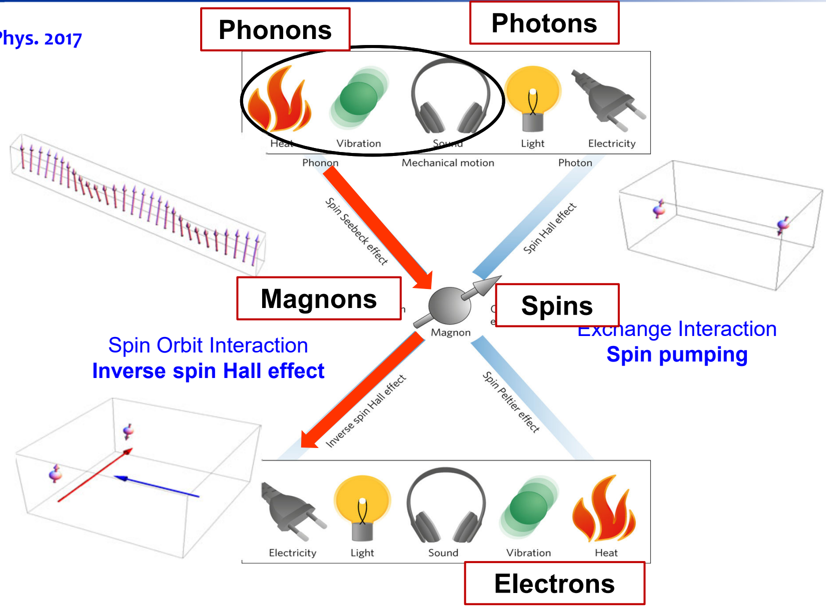
4. Spin conversion phenomena



From Instagram Adehogan: Go Fun The World “Daily Olympics in Tokyo”

Spin Conversion - Versatile functionality -

YO et al. Nature Phys. 2017



Phonons

Photons

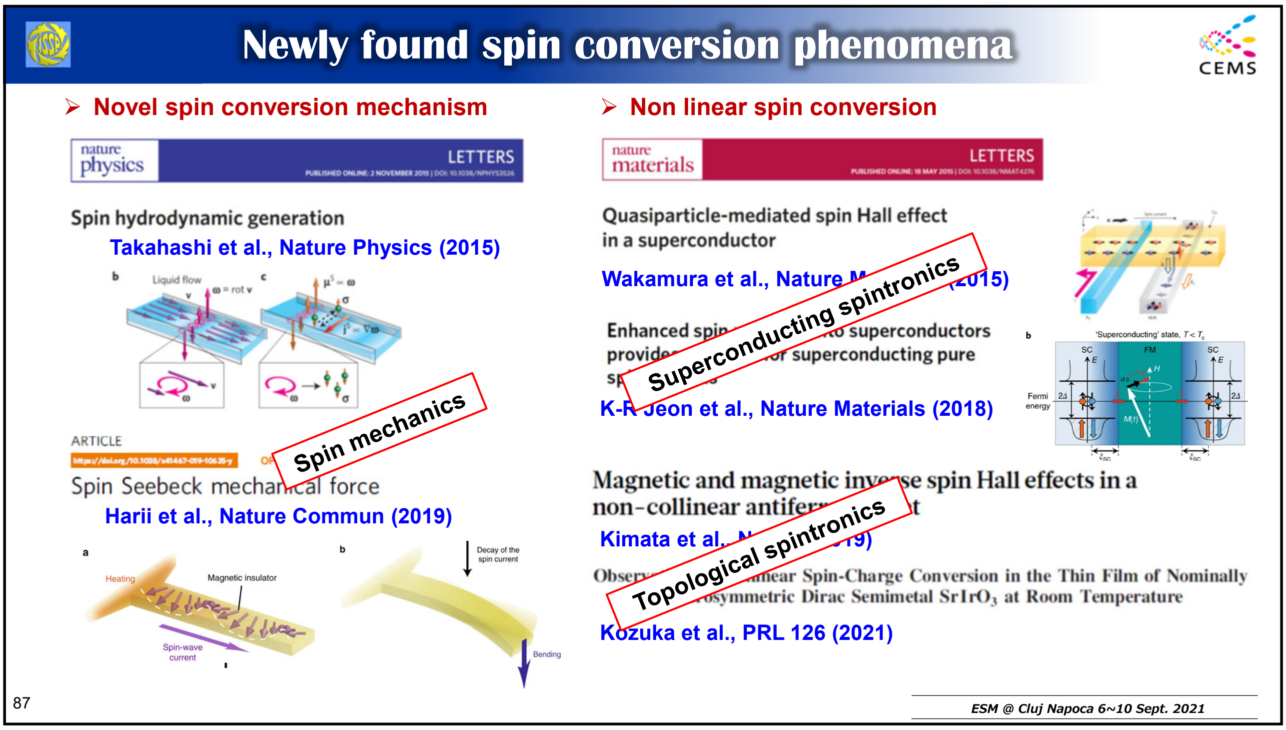
Magnons

Spins

Spin Orbit Interaction
Inverse spin Hall effect

Exchange Interaction
Spin pumping

Electrons



Newly found spin conversion phenomena

- Novel spin conversion mechanism

nature physics LETTERS
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3526

Spin hydrodynamic generation

Takahashi et al., Nature Physics (2015)

ARTICLE
https://doi.org/10.1038/s41467-019-10625-y

Spin Seebeck mechanical force

Harii et al., Nature Commun (2019)

- Non linear spin conversion

nature materials LETTERS
PUBLISHED ONLINE: 18 MAY 2015 | DOI: 10.1038/NMAT4276

Quasiparticle-mediated spin Hall effect in a superconductor

Wakamura et al., Nature M (2015)

Enhanced spin superconductors provide superconducting pure sp

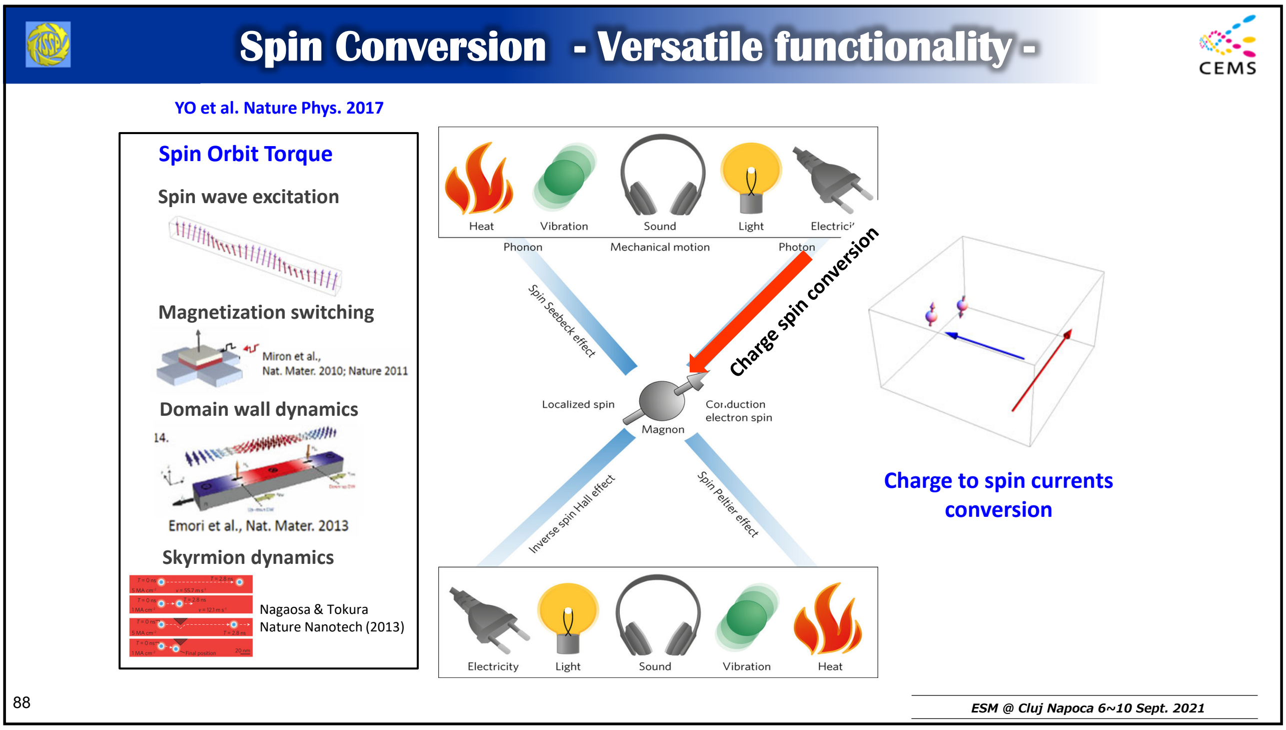
K-R Jeon et al., Nature Materials (2018)

Magnetic and magnetic inverse spin Hall effects in a non-collinear antiferr t

Kimata et al., N 19)

Obser near Spin-Charge Conversion in the Thin Film of Nominally osymmetric Dirac Semimetal $SrIrO_3$ at Room Temperature

Kozuka et al., PRL 126 (2021)



Spin Conversion - Versatile functionality -

YO et al. Nature Phys. 2017

Spin Orbit Torque

Spin wave excitation

Magnetization switching

Miron et al.,
Nat. Mater. 2010; Nature 2011

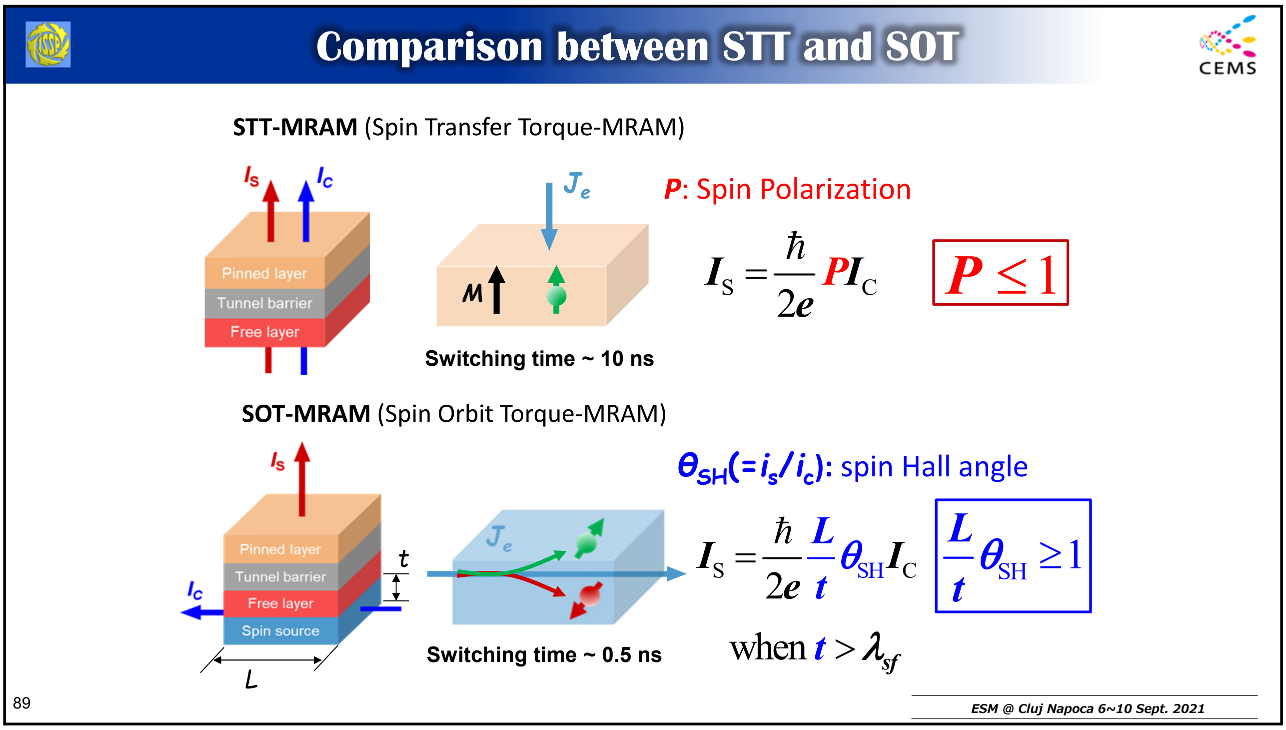
Domain wall dynamics

Emori et al., Nat. Mater. 2013

Skyrmion dynamics

Nagaosa & Tokura
Nature Nanotech (2013)

Charge to spin currents conversion



Comparison between STT and SOT

STT-MRAM (Spin Transfer Torque-MRAM)

P: Spin Polarization

$$I_S = \frac{\hbar}{2e} P I_C$$

$$\boxed{P \le 1}$$

Switching time ~ 10 ns

SOT-MRAM (Spin Orbit Torque-MRAM)

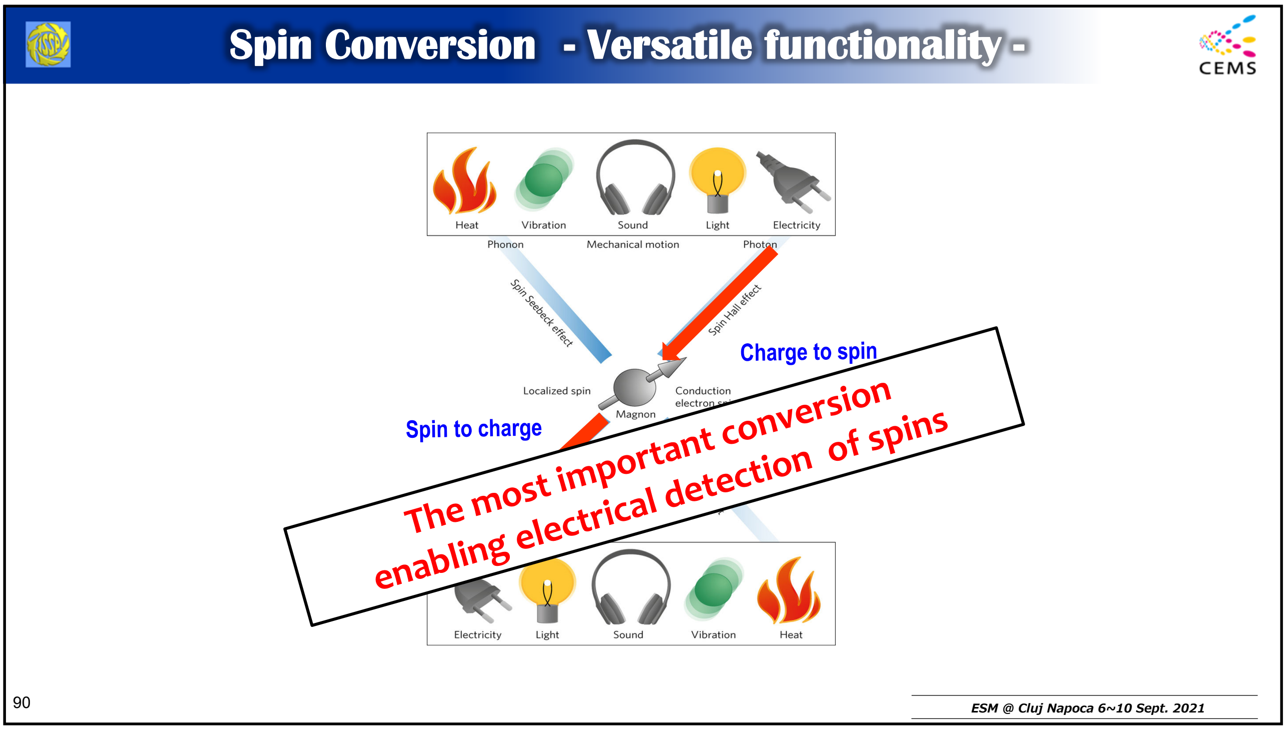
$\theta_{SH}(=i_s/i_c)$: spin Hall angle

$$I_S = \frac{\hbar}{2e} \frac{L}{t} \theta_{SH} I_C$$

$$\boxed{\frac{L}{t} \theta_{SH} \ge 1}$$

when $t > \lambda_{sf}$

Switching time ~ 0.5 ns



Spin Conversion - Versatile functionality -

Charge to spin

Spin to charge

The most important conversion enabling electrical detection of spins

Quiz 6

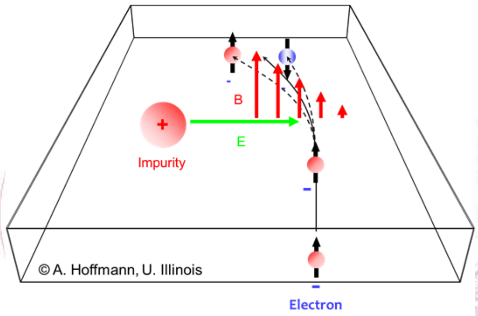
4. Select correct descriptions in the following? (possibilities of multiple correct ones) ;

   a. Spin charge interconversion effects provide much more effective means to generate spin currents than electrical spin polarized current injection.

   b. Spin conversion effects are useless because of small efficiency; only valuable for spintronics researchers.

---

i. Spin Hall effect in metals



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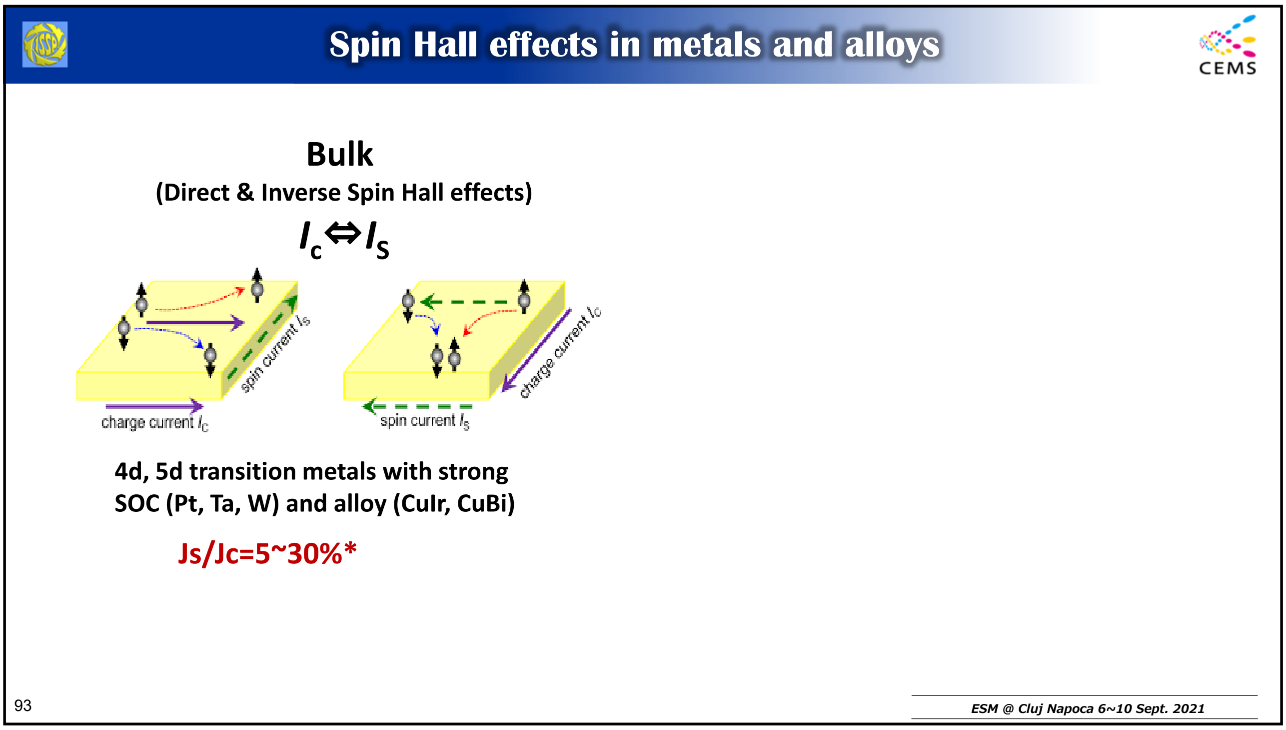


Spin Hall effects in metals and alloys

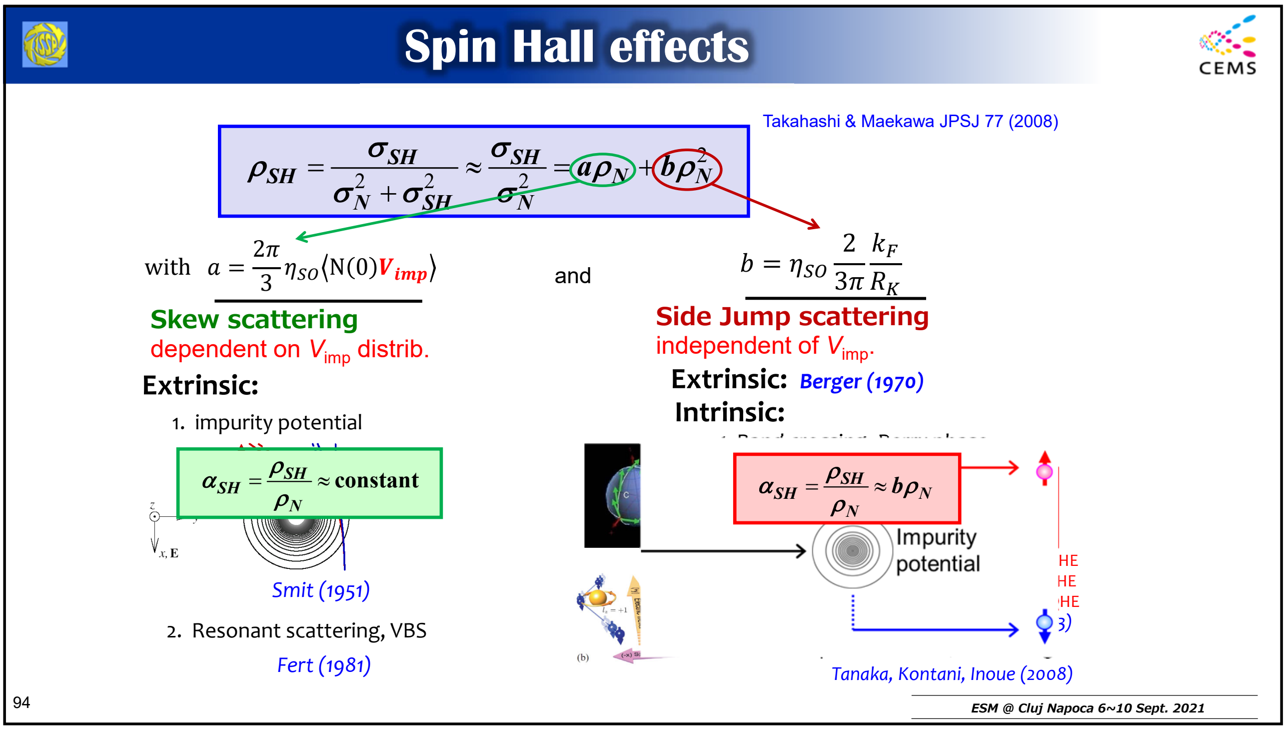
Bulk

(Direct & Inverse Spin Hall effects)

$I_c \Leftrightarrow I_S$

4d, 5d transition metals with strong SOC (Pt, Ta, W) and alloy (CuIr, CuBi)

Js/Jc=5~30%*



Spin Hall effects

Takahashi & Maekawa JPSJ 77 (2008)

$$\rho_{SH} = \frac{\sigma_{SH}}{\sigma_N^2 + \sigma_{SH}^2} \approx \frac{\sigma_{SH}}{\sigma_N^2} = a\rho_N + b\rho_N^2$$

with $a = \frac{2\pi}{3}\eta_{SO}\langle \mathrm{N}(0) V_{imp} \rangle$ and $b = \eta_{SO}\frac{2}{3\pi}\frac{k_F}{R_K}$

Skew scattering

dependent on V_{imp} distrib.

Extrinsic:

1. impurity potential

$$\alpha_{SH} = \frac{\rho_{SH}}{\rho_N} \approx \textbf{constant}$$

Smit (1951)

2. Resonant scattering, VBS

Fert (1981)

Side Jump scattering

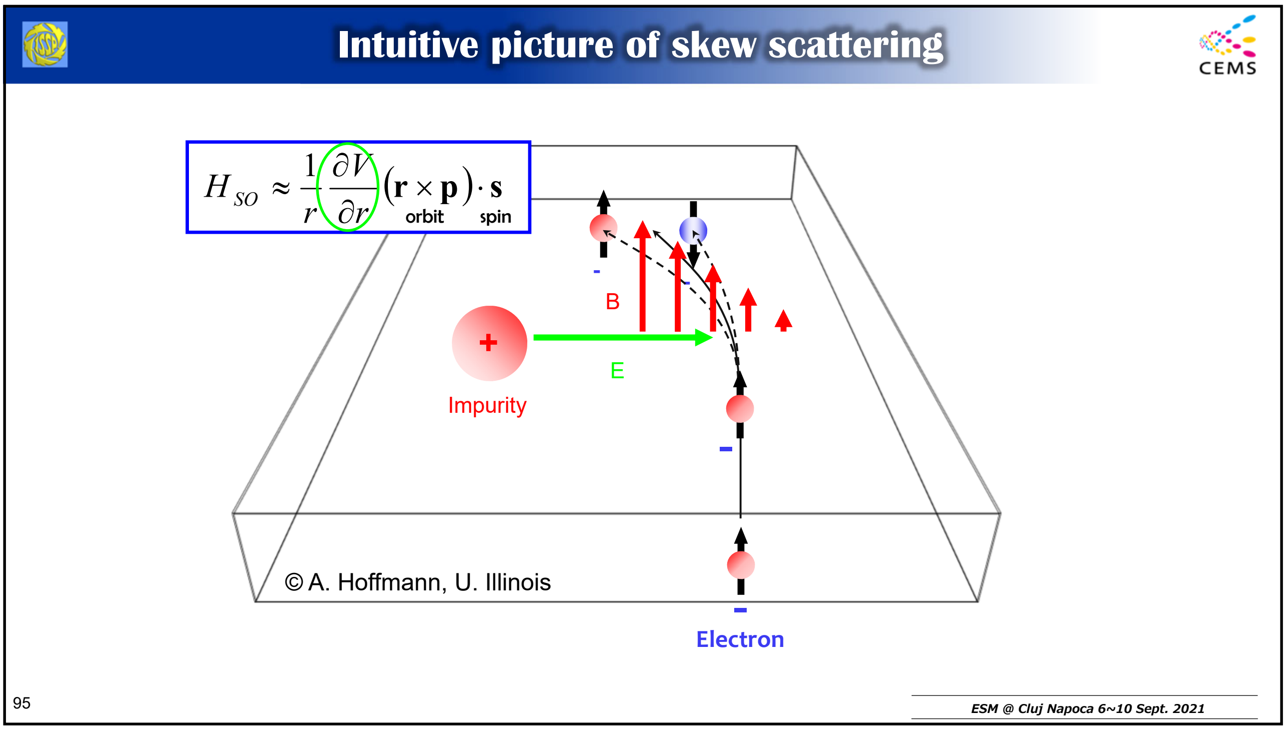
independent of V_{imp}.

Extrinsic: Berger (1970)

Intrinsic:

$$\alpha_{SH} = \frac{\rho_{SH}}{\rho_N} \approx b\rho_N$$

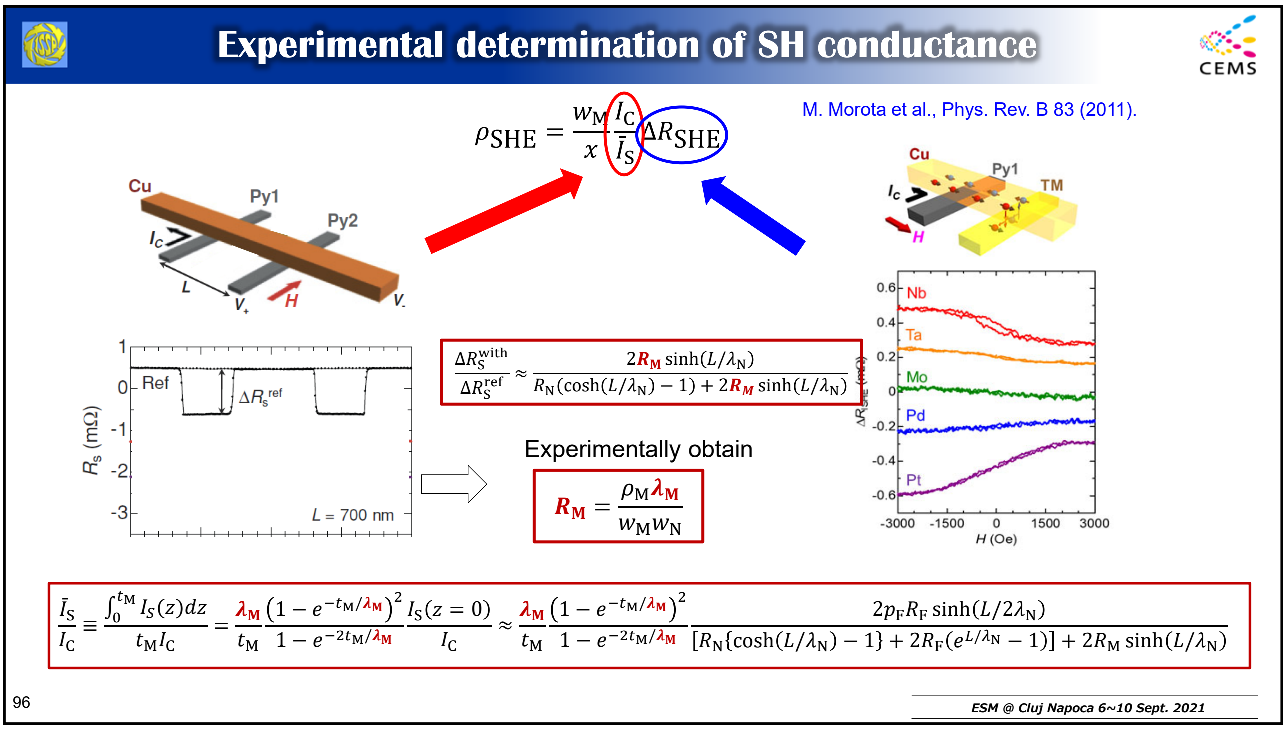
Tanaka, Kontani, Inoue (2008)



Intuitive picture of skew scattering

$$H_{SO} \approx \frac{1}{r}\frac{\partial V}{\partial r}\underset{\text{orbit}}{(\mathbf{r}\times\mathbf{p})}\cdot\underset{\text{spin}}{\mathbf{s}}$$

© A. Hoffmann, U. Illinois



Experimental determination of SH conductance

$$\rho_{\text{SHE}} = \frac{w_{\text{M}}}{x}\frac{I_{\text{C}}}{\bar{I}_{\text{S}}}\Delta R_{\text{SHE}}$$

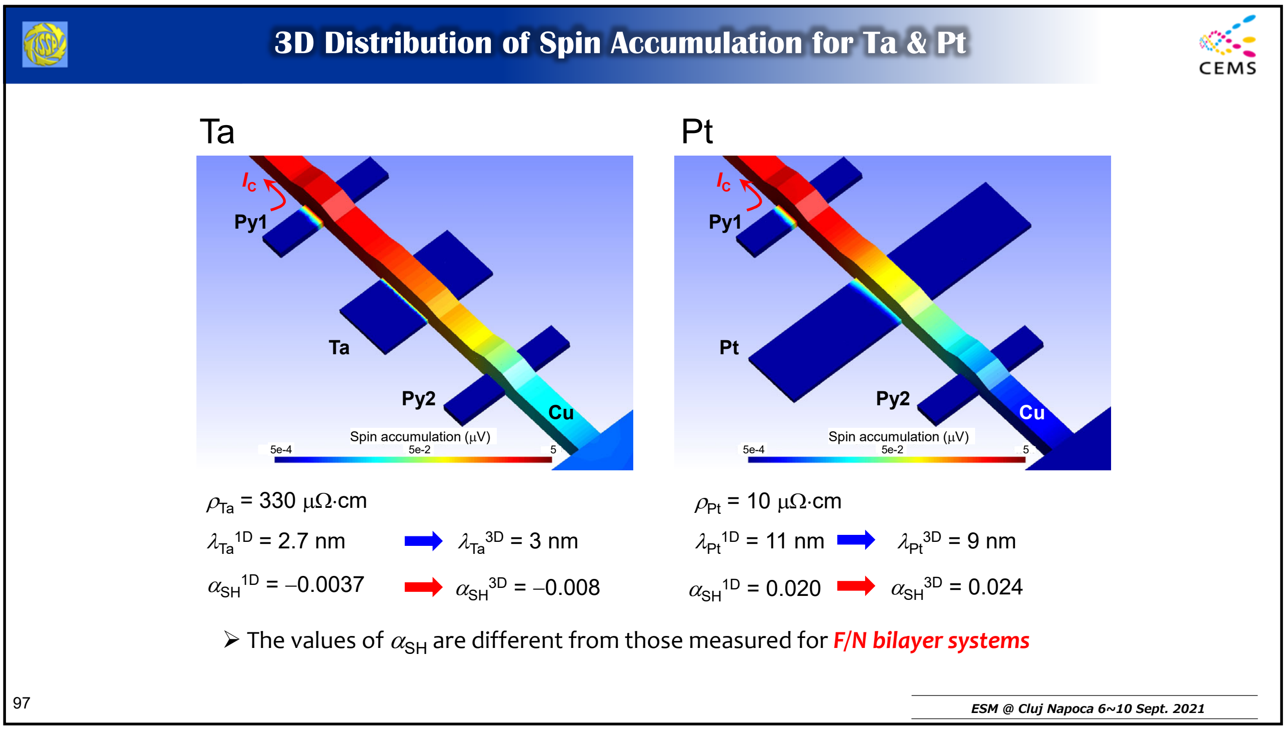
M. Morota et al., Phys. Rev. B 83 (2011).

$$\frac{\Delta R_{\text{S}}^{\text{with}}}{\Delta R_{\text{S}}^{\text{ref}}} \approx \frac{2\boldsymbol{R}_{\mathbf{M}}\sinh(L/\lambda_{\text{N}})}{R_{\text{N}}(\cosh(L/\lambda_{\text{N}})-1)+2\boldsymbol{R}_{\boldsymbol{M}}\sinh(L/\lambda_{\text{N}})}$$

Experimentally obtain

$$\boldsymbol{R}_{\mathbf{M}} = \frac{\rho_{\text{M}}\boldsymbol{\lambda}_{\mathbf{M}}}{w_{\text{M}}w_{\text{N}}}$$

$$\frac{\bar{I}_{\text{S}}}{I_{\text{C}}} \equiv \frac{\int_0^{t_{\text{M}}} I_S(z)dz}{t_{\text{M}}I_{\text{C}}} = \frac{\boldsymbol{\lambda}_{\mathbf{M}}}{t_{\text{M}}}\frac{\left(1-e^{-t_{\text{M}}/\boldsymbol{\lambda}_{\mathbf{M}}}\right)^2}{1-e^{-2t_{\text{M}}/\boldsymbol{\lambda}_{\mathbf{M}}}}\frac{I_{\text{S}}(z=0)}{I_{\text{C}}} \approx \frac{\boldsymbol{\lambda}_{\mathbf{M}}}{t_{\text{M}}}\frac{\left(1-e^{-t_{\text{M}}/\boldsymbol{\lambda}_{\mathbf{M}}}\right)^2}{1-e^{-2t_{\text{M}}/\boldsymbol{\lambda}_{\mathbf{M}}}}\frac{2p_{\text{F}}R_{\text{F}}\sinh(L/2\lambda_{\text{N}})}{[R_{\text{N}}\{\cosh(L/\lambda_{\text{N}})-1\}+2R_{\text{F}}(e^{L/\lambda_{\text{N}}}-1)]+2R_{\text{M}}\sinh(L/\lambda_{\text{N}})}$$



3D Distribution of Spin Accumulation for Ta & Pt

ρ_{Ta} = 330 μΩ·cm

λ_{Ta}^{1D} = 2.7 nm ➡ λ_{Ta}^{3D} = 3 nm

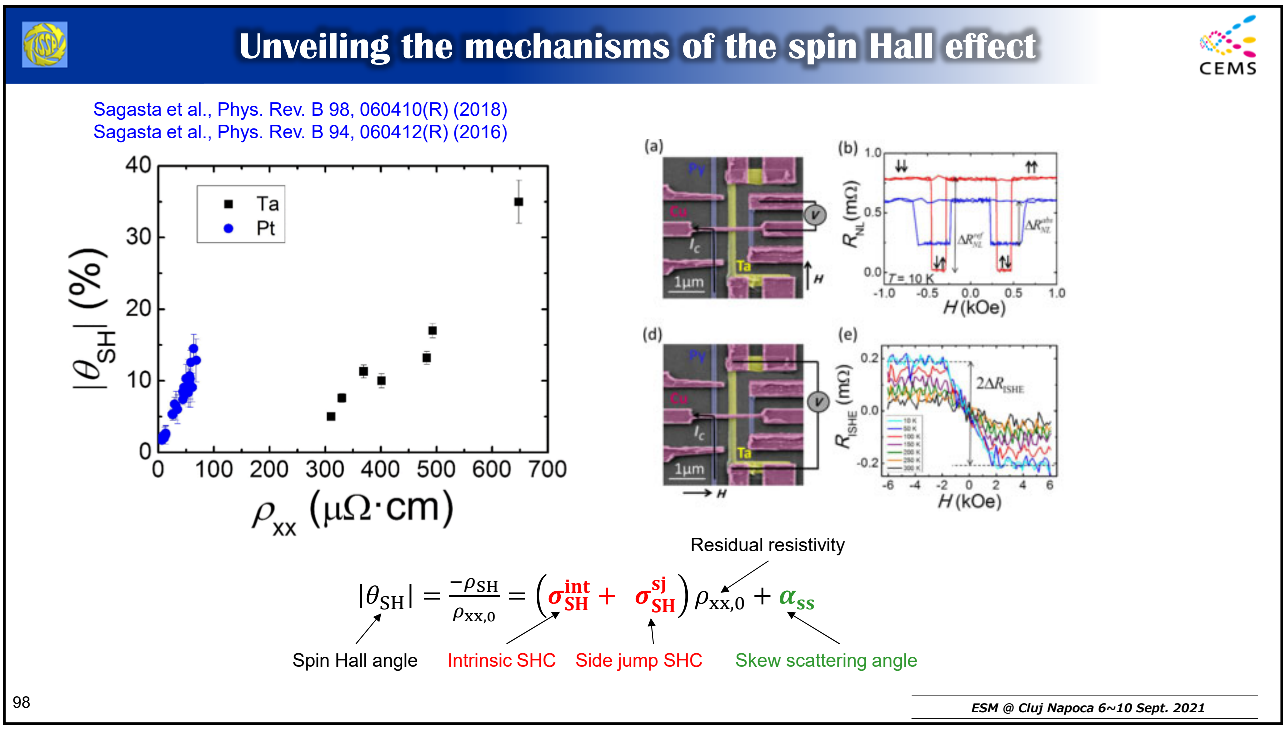
α_{SH}^{1D} = –0.0037 ➡ α_{SH}^{3D} = –0.008

ρ_{Pt} = 10 μΩ·cm

λ_{Pt}^{1D} = 11 nm ➡ λ_{Pt}^{3D} = 9 nm

α_{SH}^{1D} = 0.020 ➡ α_{SH}^{3D} = 0.024

- The values of α_{SH} are different from those measured for ***F/N bilayer systems***



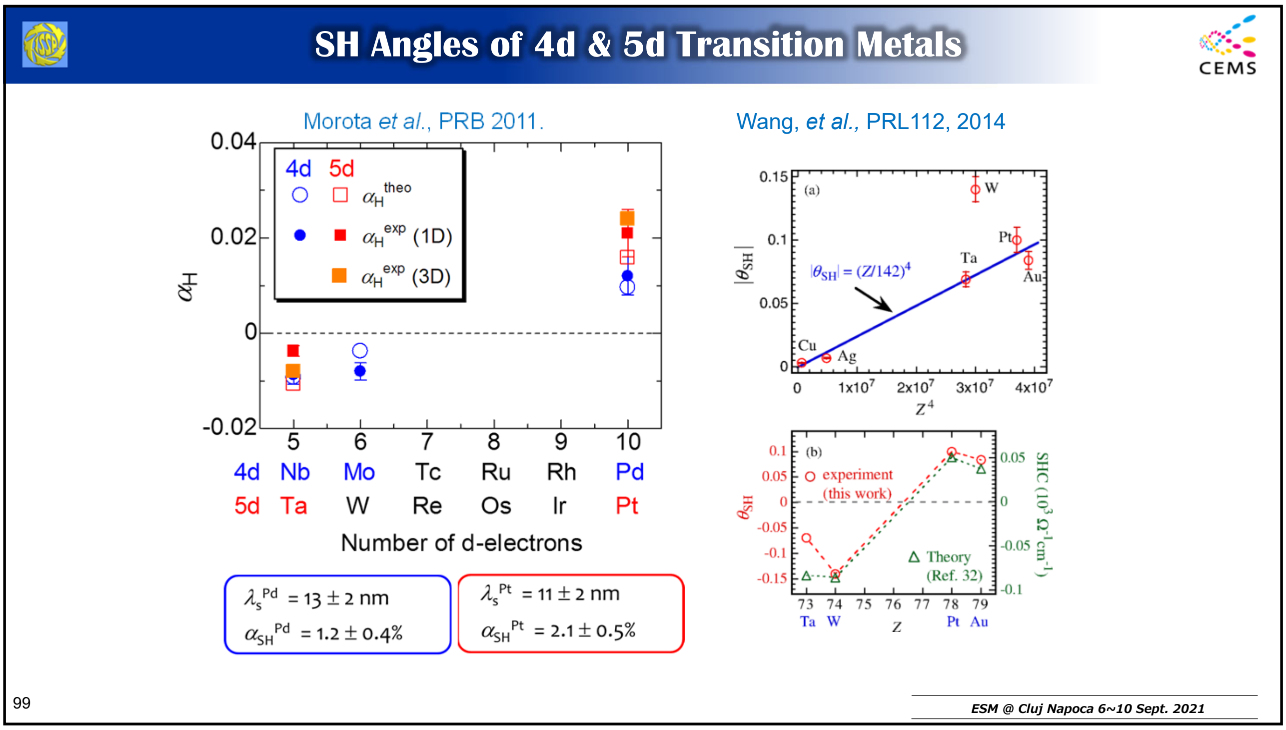
Unveiling the mechanisms of the spin Hall effect

Sagasta et al., Phys. Rev. B 98, 060410(R) (2018)
Sagasta et al., Phys. Rev. B 94, 060412(R) (2016)

Residual resistivity

$$|\theta_{SH}| = \frac{-\rho_{SH}}{\rho_{xx,0}} = \left(\sigma_{SH}^{int} + \sigma_{SH}^{sj}\right)\rho_{xx,0} + \alpha_{ss}$$

Spin Hall angle Intrinsic SHC Side jump SHC Skew scattering angle



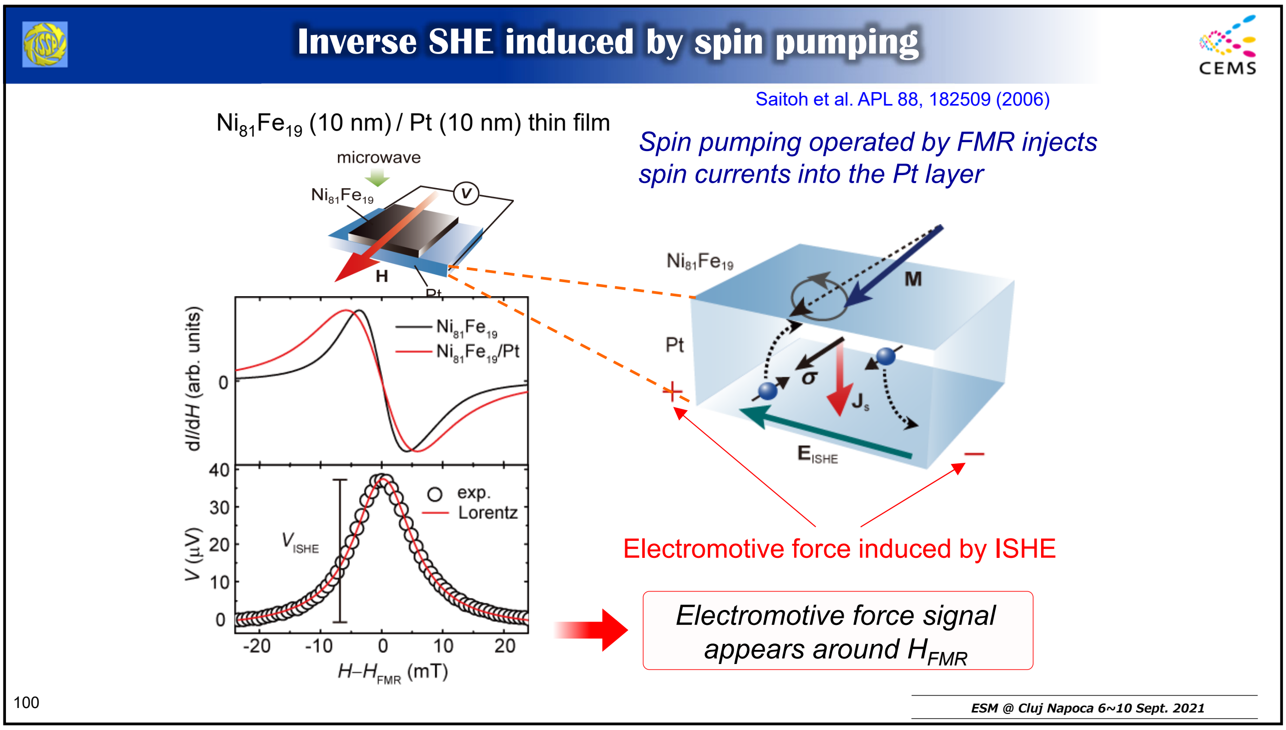
SH Angles of 4d & 5d Transition Metals

Morota *et al.*, PRB 2011.

λ_s^{Pd} = 13 ± 2 nm
α_{SH}^{Pd} = 1.2 ± 0.4%

λ_s^{Pt} = 11 ± 2 nm
α_{SH}^{Pt} = 2.1 ± 0.5%

Wang, *et al.*, PRL112, 2014



Inverse SHE induced by spin pumping

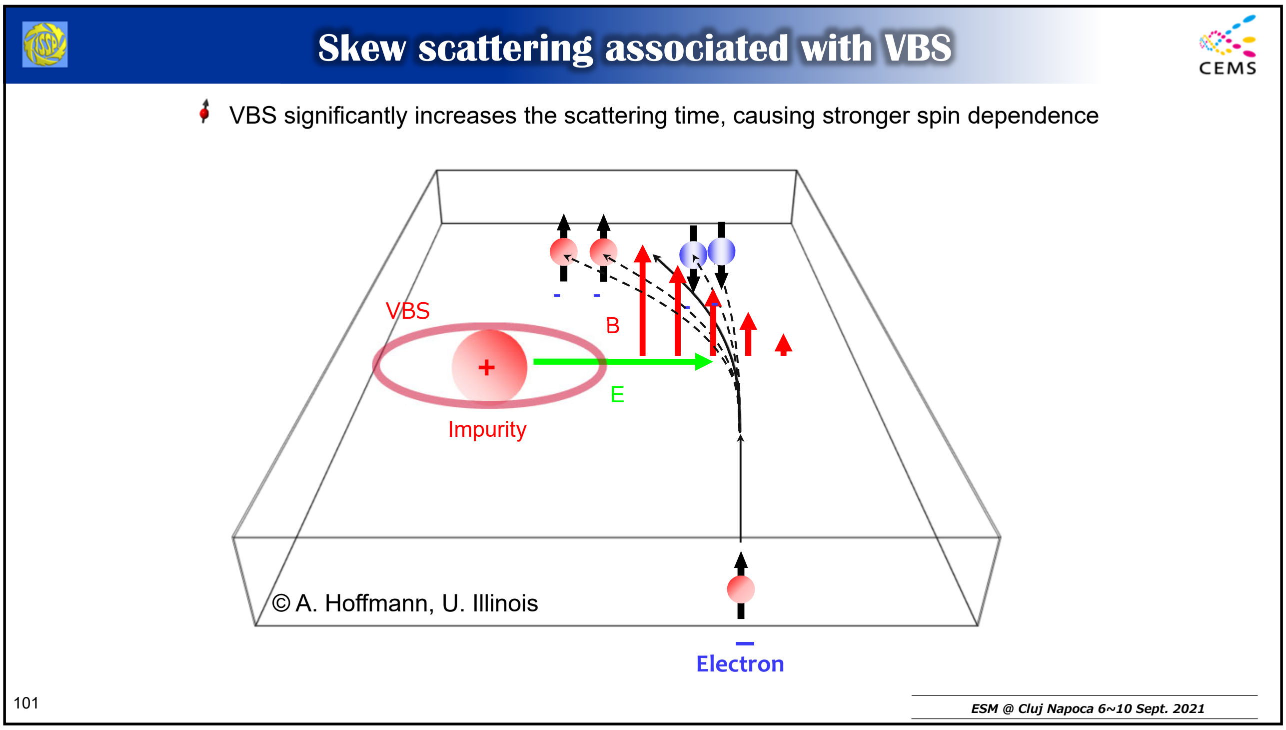
Saitoh et al. APL 88, 182509 (2006)

$Ni_{81}Fe_{19}$ (10 nm) / Pt (10 nm) thin film

Spin pumping operated by FMR injects spin currents into the Pt layer

Electromotive force induced by ISHE

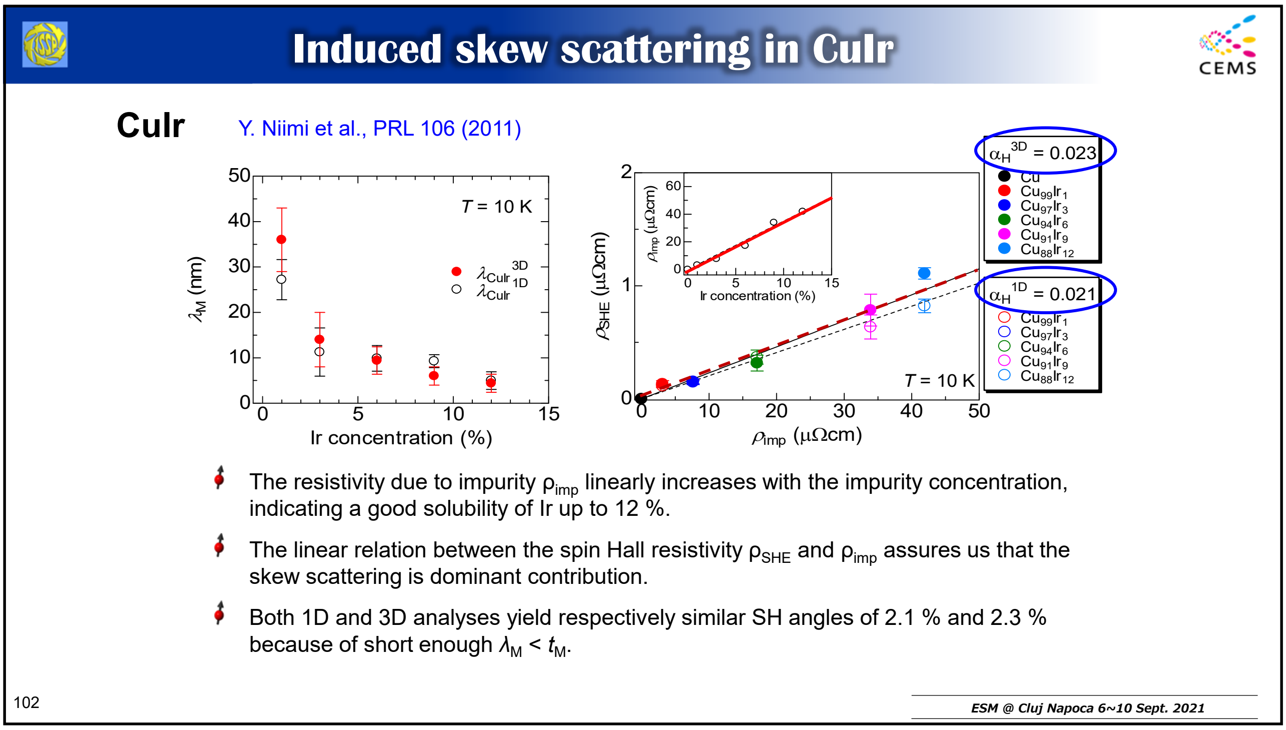
Electromotive force signal appears around H_{FMR}



Skew scattering associated with VBS

- VBS significantly increases the scattering time, causing stronger spin dependence

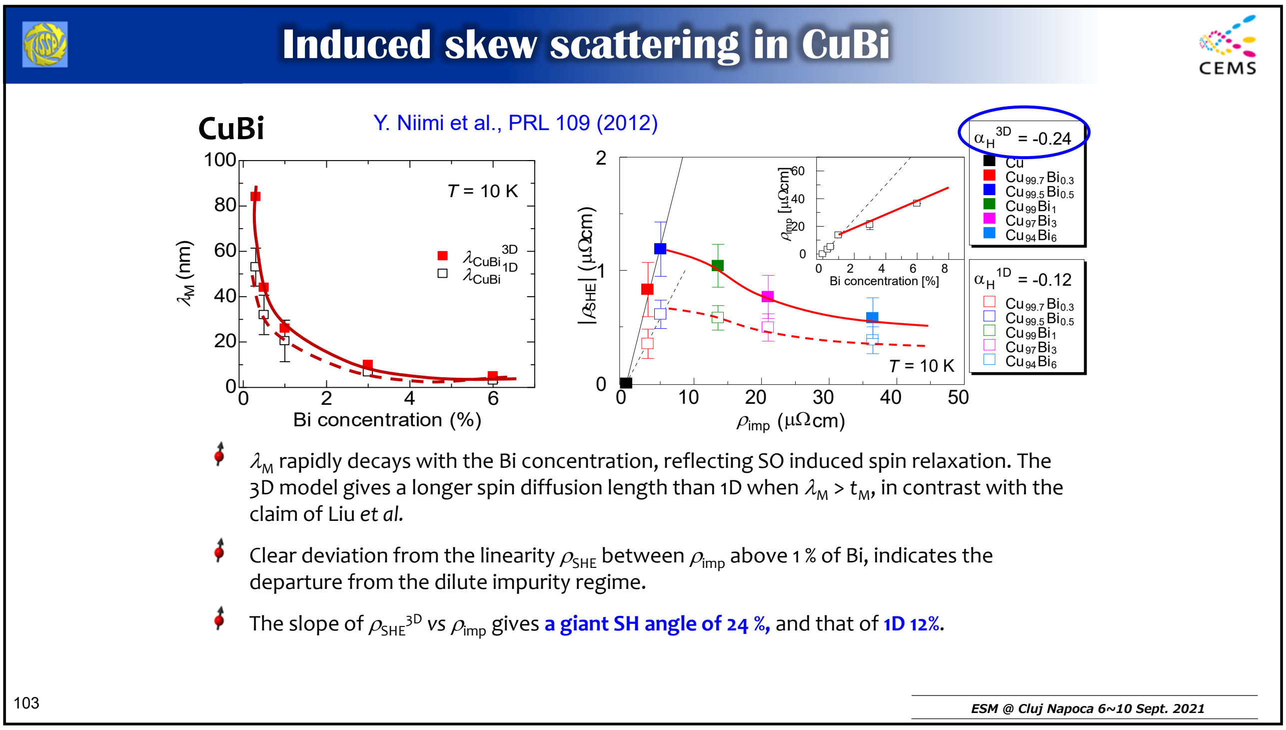
---



Induced skew scattering in CuIr

CuIr Y. Niimi et al., PRL 106 (2011)

- The resistivity due to impurity ρ_{imp} linearly increases with the impurity concentration, indicating a good solubility of Ir up to 12 %.
- The linear relation between the spin Hall resistivity ρ_{SHE} and ρ_{imp} assures us that the skew scattering is dominant contribution.
- Both 1D and 3D analyses yield respectively similar SH angles of 2.1 % and 2.3 % because of short enough $\lambda_M < t_M$.

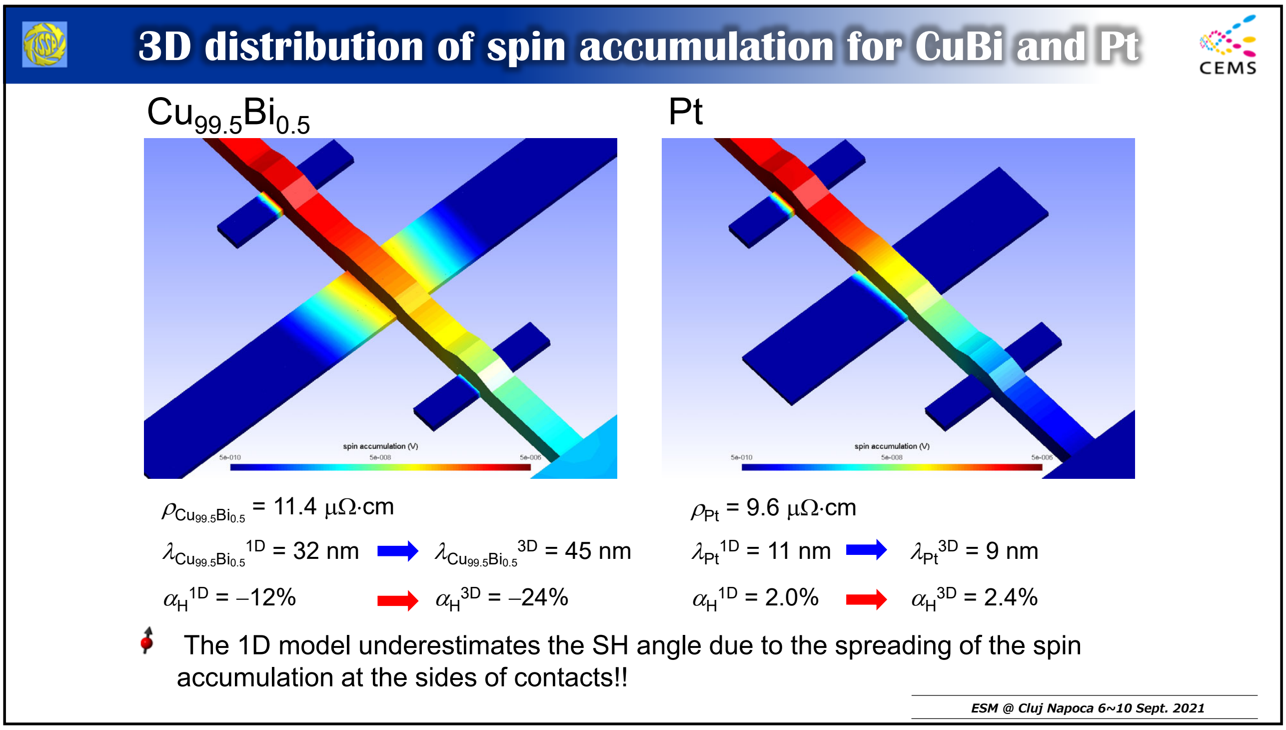


Induced skew scattering in CuBi

CuBi

Y. Niimi et al., PRL 109 (2012)

- λ_M rapidly decays with the Bi concentration, reflecting SO induced spin relaxation. The 3D model gives a longer spin diffusion length than 1D when $\lambda_M > t_M$, in contrast with the claim of Liu *et al.*
- Clear deviation from the linearity ρ_{SHE} between ρ_{imp} above 1 % of Bi, indicates the departure from the dilute impurity regime.
- The slope of ρ_{SHE}^{3D} *vs* ρ_{imp} gives **a giant SH angle of 24 %,** and that of **1D 12%**.



3D distribution of spin accumulation for CuBi and Pt

$\rho_{Cu_{99.5}Bi_{0.5}}$ = 11.4 μΩ·cm

$\lambda_{Cu_{99.5}Bi_{0.5}}^{1D}$ = 32 nm → $\lambda_{Cu_{99.5}Bi_{0.5}}^{3D}$ = 45 nm

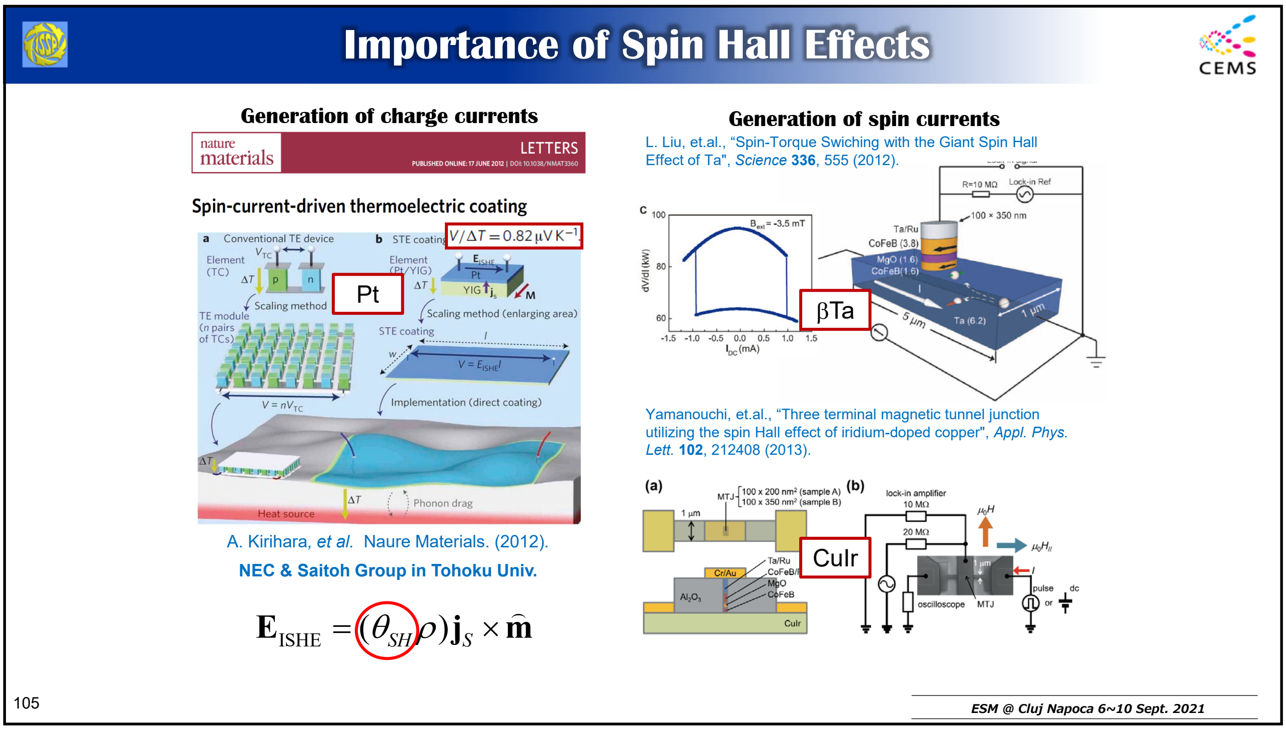
α_H^{1D} = –12% → α_H^{3D} = –24%

ρ_{Pt} = 9.6 μΩ·cm

λ_{Pt}^{1D} = 11 nm → λ_{Pt}^{3D} = 9 nm

α_H^{1D} = 2.0% → α_H^{3D} = 2.4%

- The 1D model underestimates the SH angle due to the spreading of the spin accumulation at the sides of contacts!!



Importance of Spin Hall Effects

Generation of charge currents

Spin-current-driven thermoelectric coating

A. Kirihara, *et al.* Naure Materials. (2012).

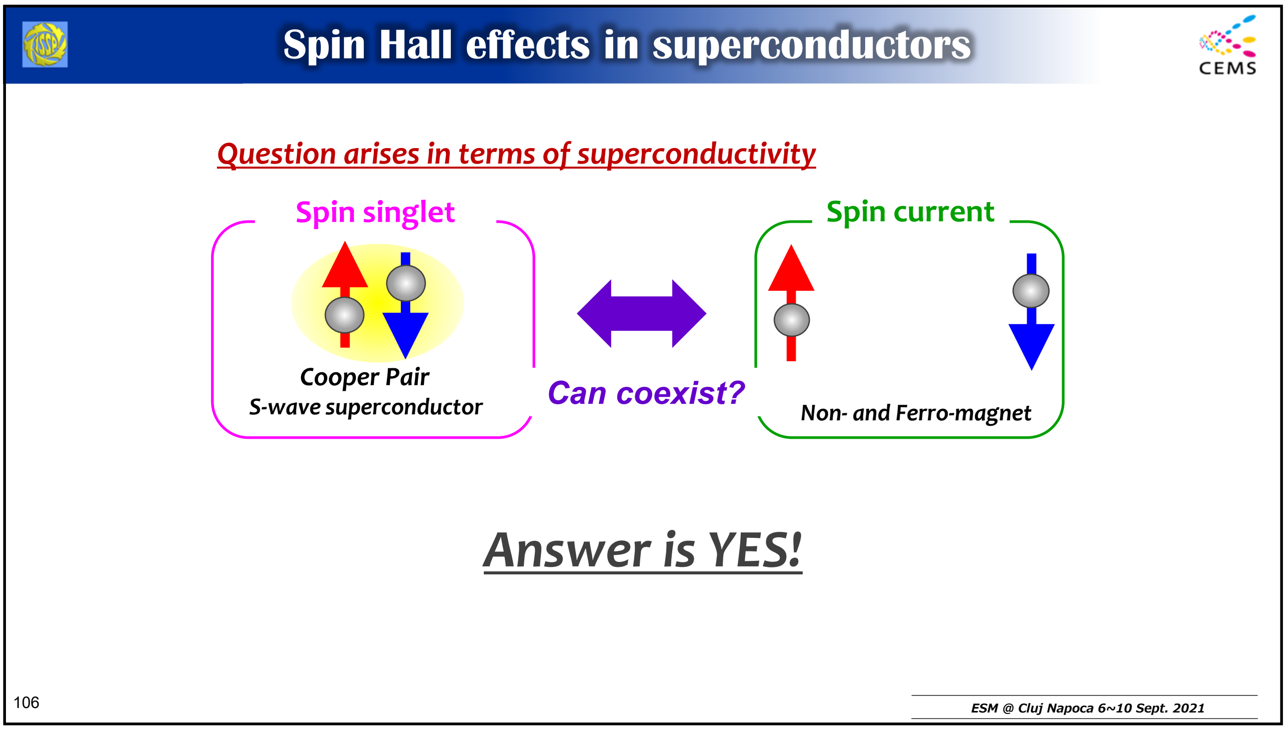
NEC & Saitoh Group in Tohoku Univ.

$$\mathbf{E}_{\mathrm{ISHE}} = (\theta_{SH}\rho)\mathbf{j}_S \times \hat{\mathbf{m}}$$

Generation of spin currents

L. Liu, et.al., "Spin-Torque Swiching with the Giant Spin Hall Effect of Ta", *Science* **336**, 555 (2012).

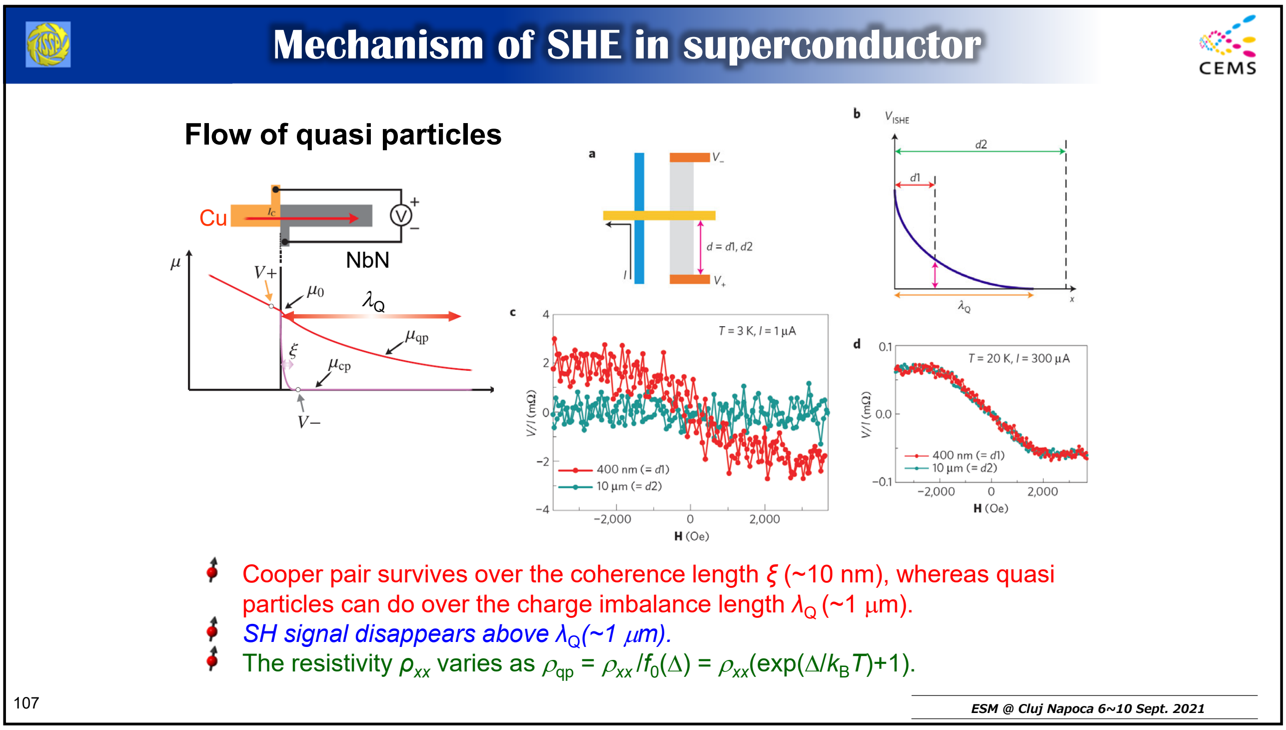
Yamanouchi, et.al., "Three terminal magnetic tunnel junction utilizing the spin Hall effect of iridium-doped copper", *Appl. Phys. Lett.* **102**, 212408 (2013).



Spin Hall effects in superconductors

Question arises in terms of superconductivity

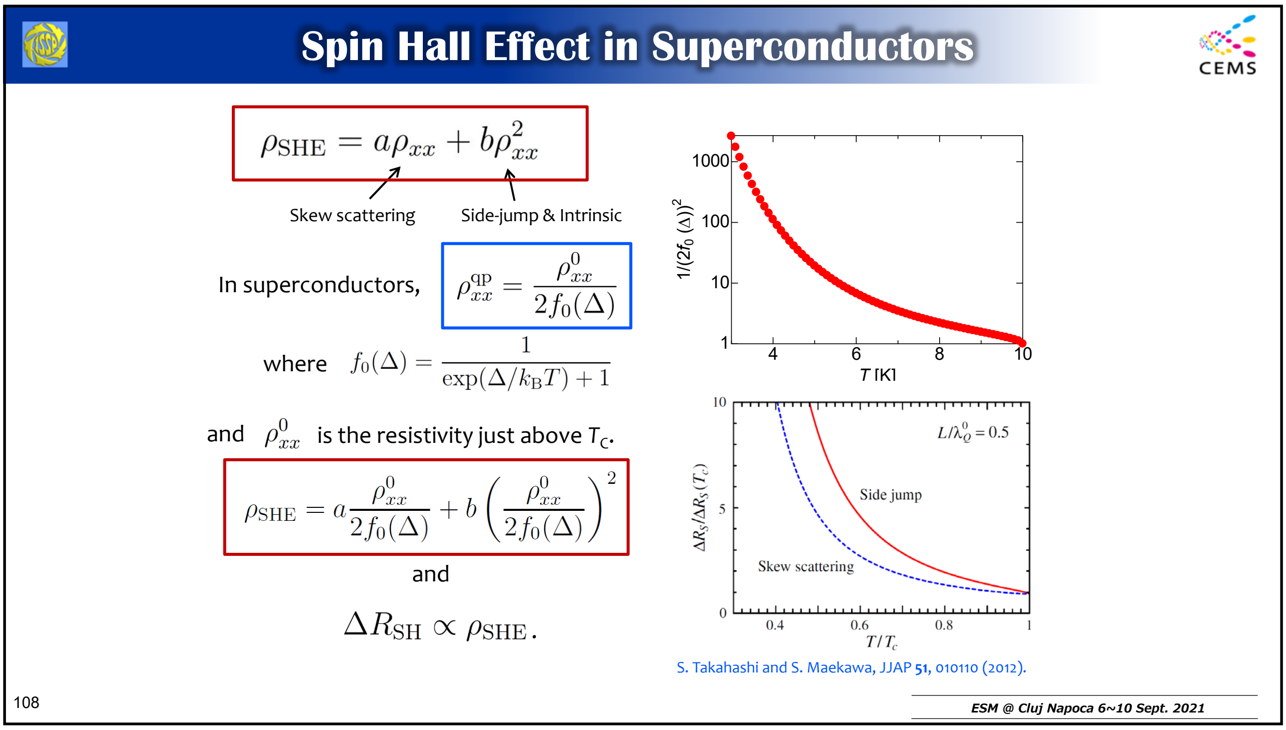
Answer is YES!



Mechanism of SHE in superconductor

Flow of quasi particles

- Cooper pair survives over the coherence length ξ (~10 nm), whereas quasi particles can do over the charge imbalance length λ_Q (~1 μm).
- *SH signal disappears above λ_Q(~1 μm).*
- The resistivity ρ_{xx} varies as $\rho_{qp} = \rho_{xx}/f_0(\Delta) = \rho_{xx}(\exp(\Delta/k_BT)+1)$.



Spin Hall Effect in Superconductors

$$\boxed{\rho_{\rm SHE} = a\rho_{xx} + b\rho_{xx}^2}$$

Skew scattering

Side-jump & Intrinsic

In superconductors, $\boxed{\rho_{xx}^{\rm qp} = \dfrac{\rho_{xx}^0}{2f_0(\Delta)}}$

where $f_0(\Delta) = \dfrac{1}{\exp(\Delta/k_{\rm B}T)+1}$

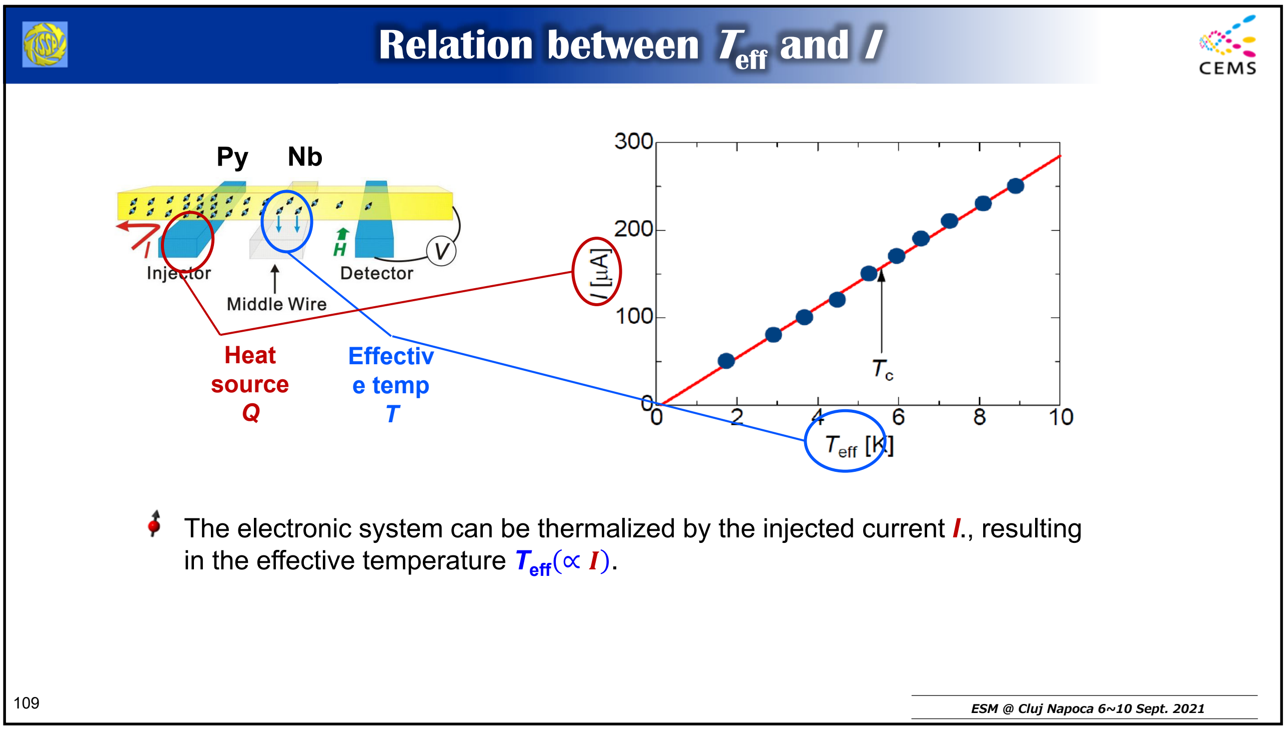
and ρ_{xx}^0 is the resistivity just above T_c.

$$\boxed{\rho_{\rm SHE} = a\frac{\rho_{xx}^0}{2f_0(\Delta)} + b\left(\frac{\rho_{xx}^0}{2f_0(\Delta)}\right)^2}$$

and

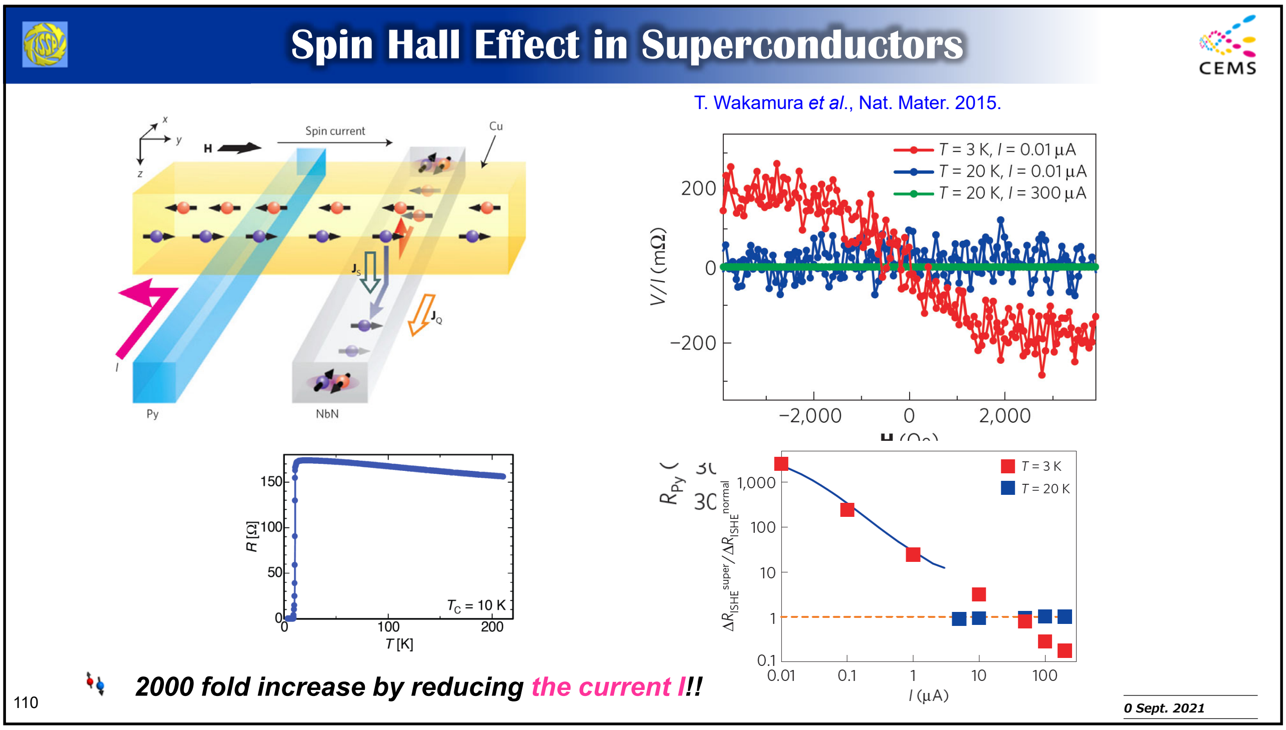
$$\Delta R_{\rm SH} \propto \rho_{\rm SHE}.$$

S. Takahashi and S. Maekawa, JJAP **51**, 010110 (2012).



Relation between T_{eff} and I

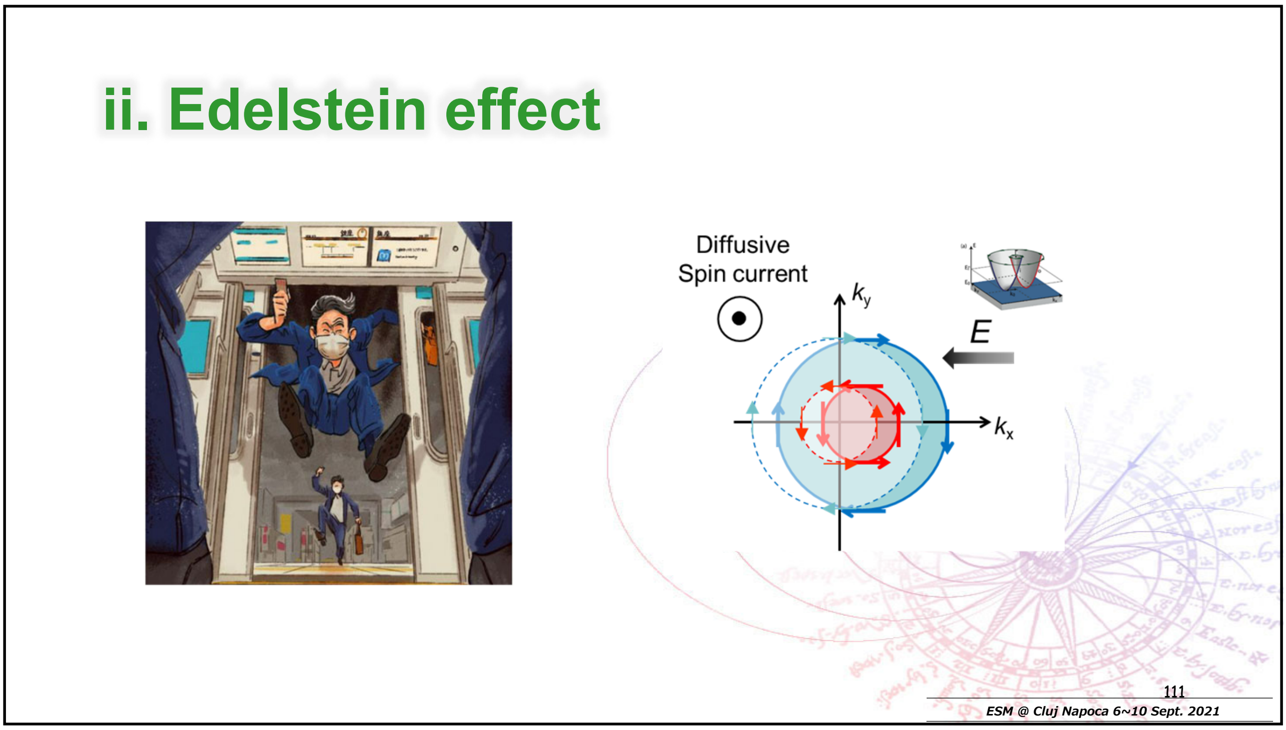
- The electronic system can be thermalized by the injected current ***I***., resulting in the effective temperature $T_{\text{eff}}(\propto I)$.



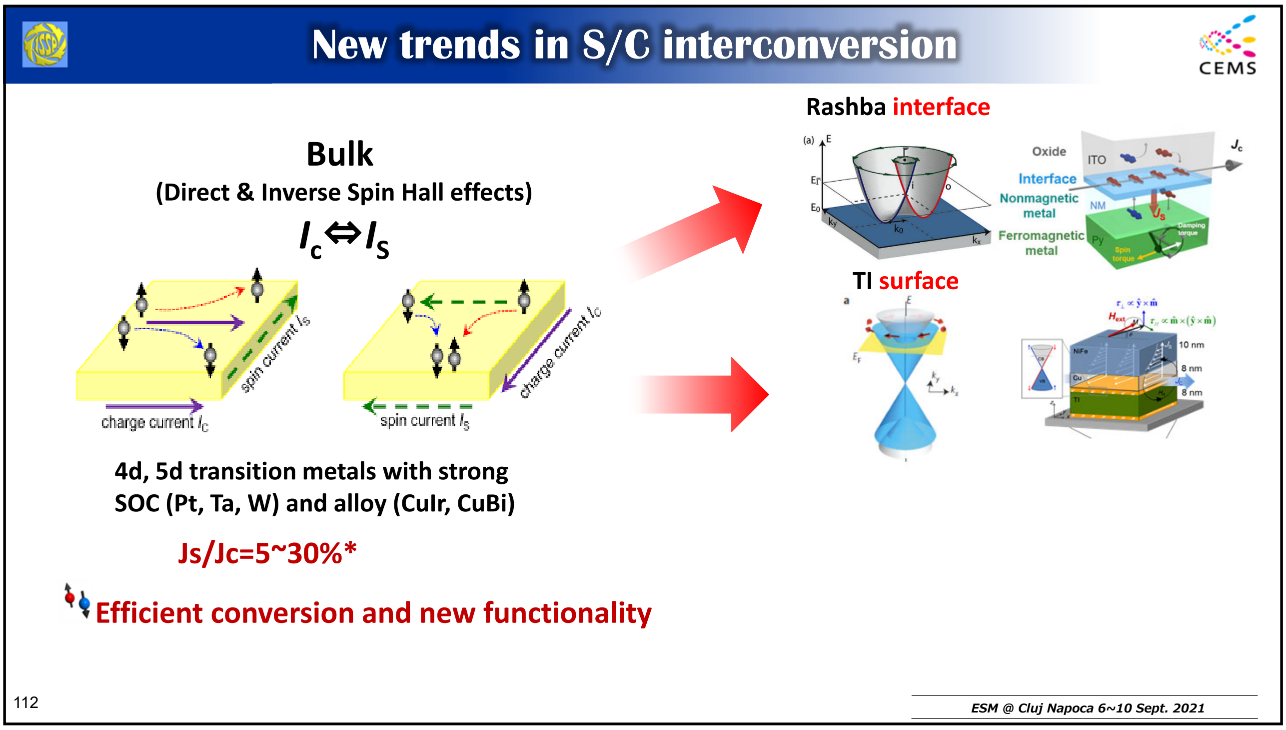
Spin Hall Effect in Superconductors

T. Wakamura *et al*., Nat. Mater. 2015.

2000 fold increase by reducing the current I!!



ii. Edelstein effect



New trends in S/C interconversion

Bulk

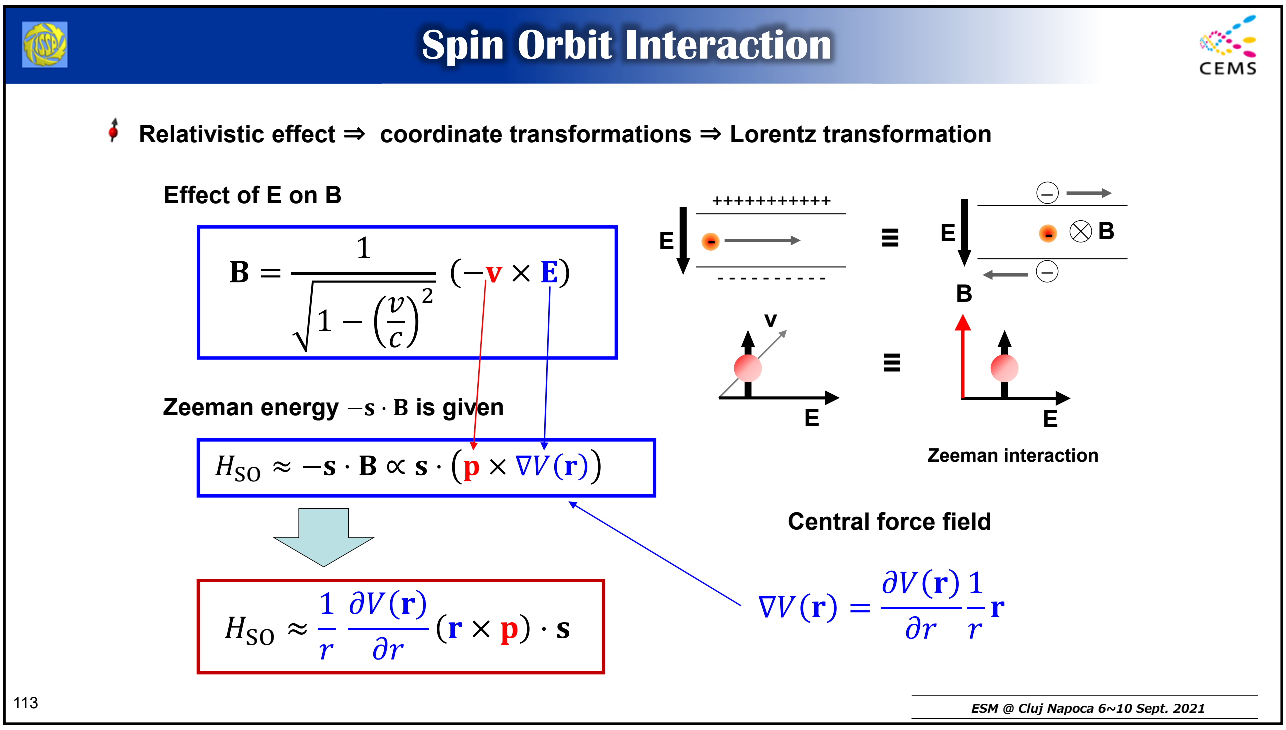
(Direct & Inverse Spin Hall effects)

$I_c \Leftrightarrow I_S$

4d, 5d transition metals with strong SOC (Pt, Ta, W) and alloy (CuIr, CuBi)

Js/Jc=5~30%*

Efficient conversion and new functionality



Spin Orbit Interaction

- Relativistic effect ⇒ coordinate transformations ⇒ Lorentz transformation

Effect of E on B

$$\mathbf{B} = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}(-\mathbf{v}\times\mathbf{E})$$

Zeeman energy $-\mathbf{s}\cdot\mathbf{B}$ is given

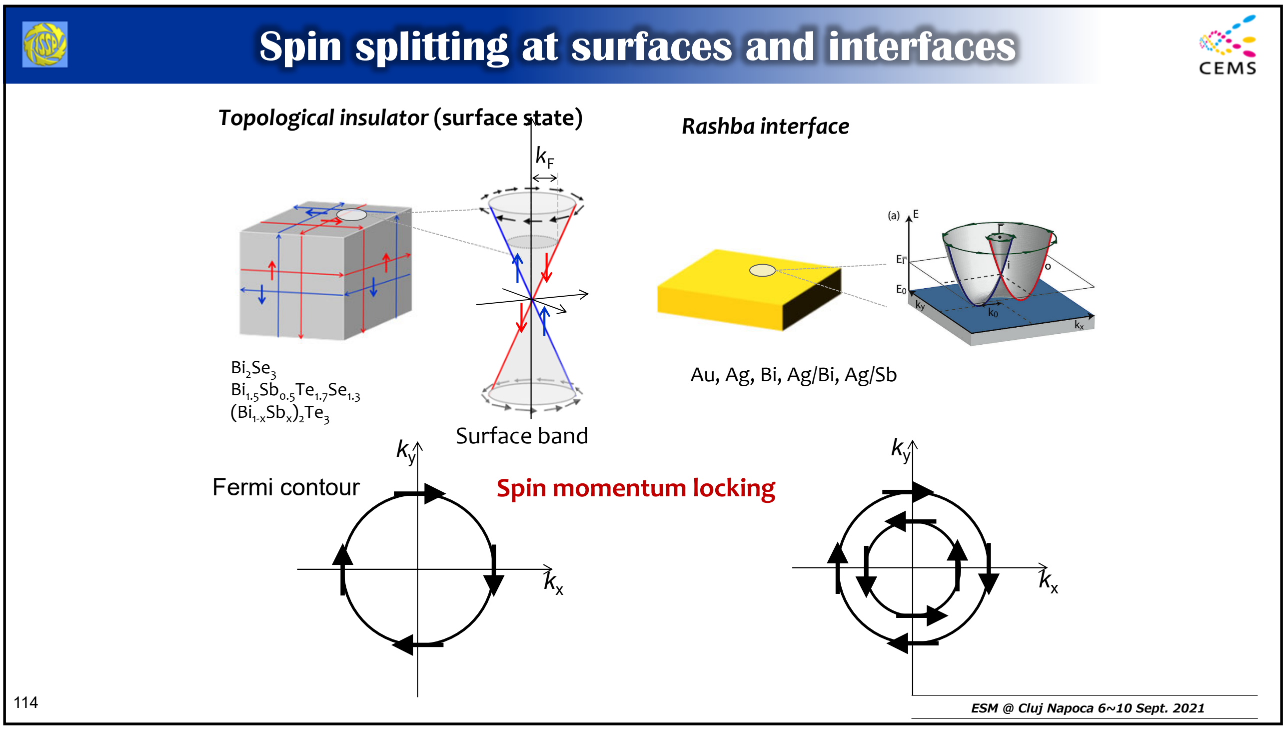
$$H_{SO} \approx -\mathbf{s}\cdot\mathbf{B} \propto \mathbf{s}\cdot\left(\mathbf{p}\times\nabla V(\mathbf{r})\right)$$

$$H_{SO} \approx \frac{1}{r}\frac{\partial V(\mathbf{r})}{\partial r}(\mathbf{r}\times\mathbf{p})\cdot\mathbf{s}$$

Zeeman interaction

Central force field

$$\nabla V(\mathbf{r}) = \frac{\partial V(\mathbf{r})}{\partial r}\frac{1}{r}\mathbf{r}$$



Spin splitting at surfaces and interfaces

Topological insulator (surface state)

Rashba interface

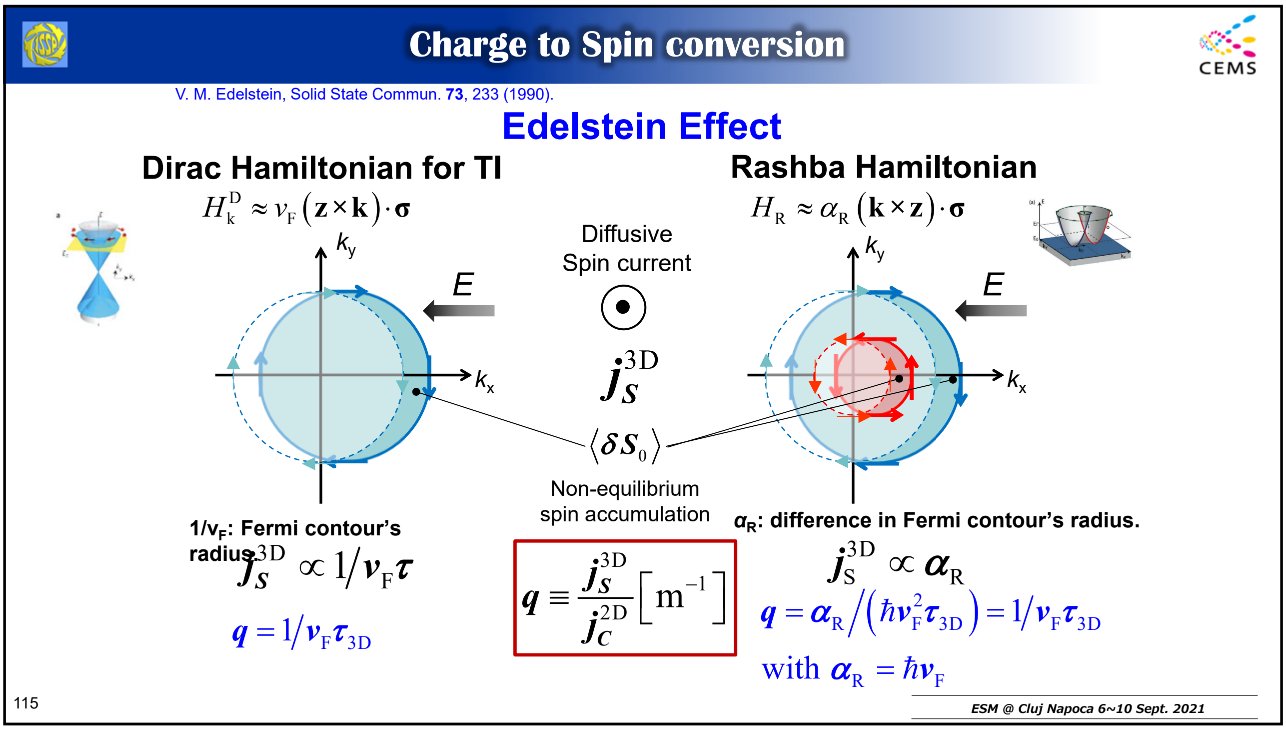
Bi_2Se_3
$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$
$(Bi_{1-x}Sb_x)_2Te_3$

Surface band

Au, Ag, Bi, Ag/Bi, Ag/Sb

Fermi contour

Spin momentum locking



Charge to Spin conversion

V. M. Edelstein, Solid State Commun. **73**, 233 (1990).

Edelstein Effect

Dirac Hamiltonian for TI

$$H_k^D \approx v_F(\mathbf{z}\times\mathbf{k})\cdot\boldsymbol{\sigma}$$

Rashba Hamiltonian

$$H_R \approx \alpha_R(\mathbf{k}\times\mathbf{z})\cdot\boldsymbol{\sigma}$$

Diffusive
Spin current

j_S^{3D}

$\langle \delta S_0 \rangle$

Non-equilibrium
spin accumulation

$1/v_F$: Fermi contour's radius

$$j_S^{3D} \propto 1/v_F\tau$$

$$q = 1/v_F\tau_{3D}$$

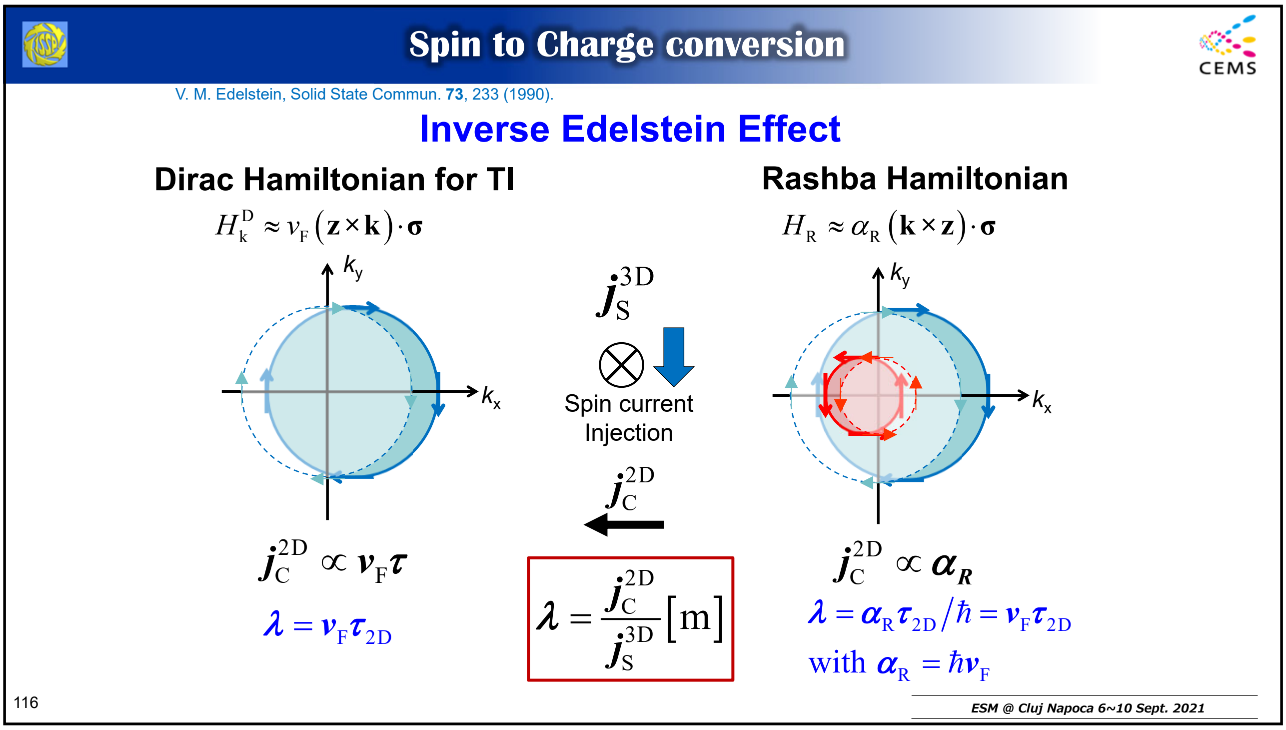
$$\boxed{q \equiv \frac{j_S^{3D}}{j_C^{2D}}\left[\mathrm{m}^{-1}\right]}$$

α_R: difference in Fermi contour's radius.

$$j_S^{3D} \propto \alpha_R$$

$$q = \alpha_R/\left(\hbar v_F^2\tau_{3D}\right) = 1/v_F\tau_{3D}$$

with $\alpha_R = \hbar v_F$



Spin to Charge conversion

V. M. Edelstein, Solid State Commun. **73**, 233 (1990).

Inverse Edelstein Effect

Dirac Hamiltonian for TI

$$H_k^D \approx v_F(\mathbf{z}\times\mathbf{k})\cdot\boldsymbol{\sigma}$$

Rashba Hamiltonian

$$H_R \approx \alpha_R(\mathbf{k}\times\mathbf{z})\cdot\boldsymbol{\sigma}$$

j_S^{3D}

Spin current
Injection

j_C^{2D}

$$j_C^{2D} \propto v_F\tau$$

$$\lambda = v_F\tau_{2D}$$

$$\boxed{\lambda = \frac{j_C^{2D}}{j_S^{3D}}[\mathrm{m}]}$$

$$j_C^{2D} \propto \alpha_R$$

$$\lambda = \alpha_R\tau_{2D}/\hbar = v_F\tau_{2D}$$

with $\alpha_R = \hbar v_F$

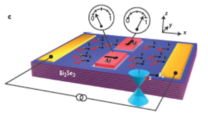
ii.1 Edelstein effect at TI surfaces

Recent studies on charge-to-spin conversion in TI

CEMS

2014~

Spin momentum locking

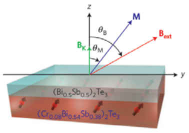


Spin valve

Bi_2Se_3

C. H. Li *et. al*, Natnano, (2014).

Magnetization switching

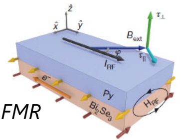


$(Bi_{0.5}Sb_{0.5})_2Te_3$

Y.Fan *et. al*, Nature materials (2014).

θ_{SH}=14000~42500 %

Conversion efficiency



ST-FMR

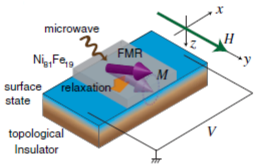
Bi_2Se_3

A. R. Mellnik *et. al*, Nature(2014).

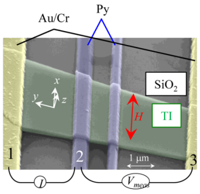
θ_{SH}=100~150%

Current

S-C current



C-S current

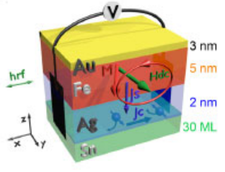


$Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$

Y. Shiomi *et. al*, Phys. Rev. Let. (2014).

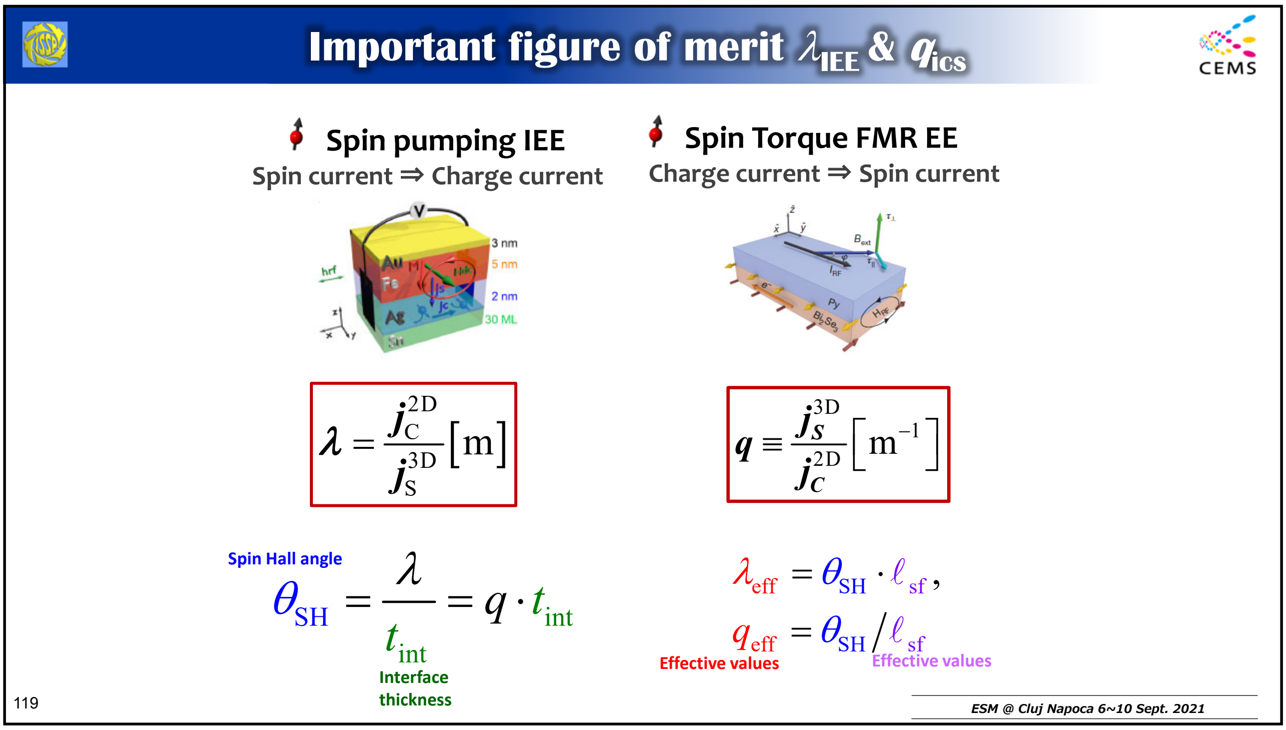
Y. Ando *et. al*, NanoLett.(2014).

S-C current



α-Sn

J.-C. Rojas-Sanchez *et. al*, Phys. Rev. Lett.(2016).



Important figure of merit λ_{IEE} & q_{ics}

Spin pumping IEE

Spin current ⇒ Charge current

Spin Torque FMR EE

Charge current ⇒ Spin current

$$\boxed{\lambda = \frac{\dot{j}_C^{2D}}{\dot{j}_S^{3D}}[\mathrm{m}]}$$

$$\boxed{q \equiv \frac{\dot{j}_S^{3D}}{\dot{j}_C^{2D}}\left[\mathrm{m}^{-1}\right]}$$

Spin Hall angle

$$\theta_{SH} = \frac{\lambda}{t_{int}} = q \cdot t_{int}$$

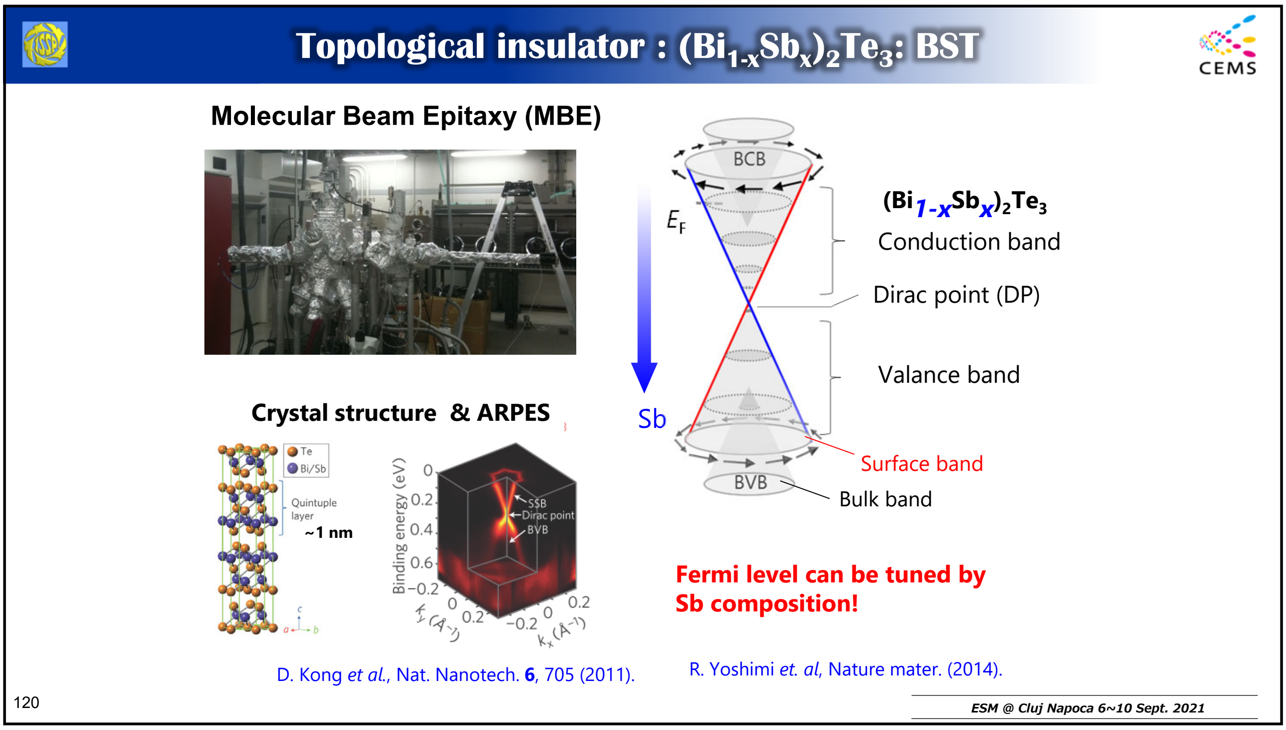
Interface thickness

$$\lambda_{eff} = \theta_{SH} \cdot \ell_{sf},$$

$$q_{eff} = \theta_{SH} / \ell_{sf}$$

Effective values

Effective values



Topological insulator : $(Bi_{1-x}Sb_x)_2Te_3$: BST

Molecular Beam Epitaxy (MBE)

Crystal structure & ARPES

D. Kong *et al.*, Nat. Nanotech. **6**, 705 (2011).

$(Bi_{1-x}Sb_x)_2Te_3$

Conduction band

Dirac point (DP)

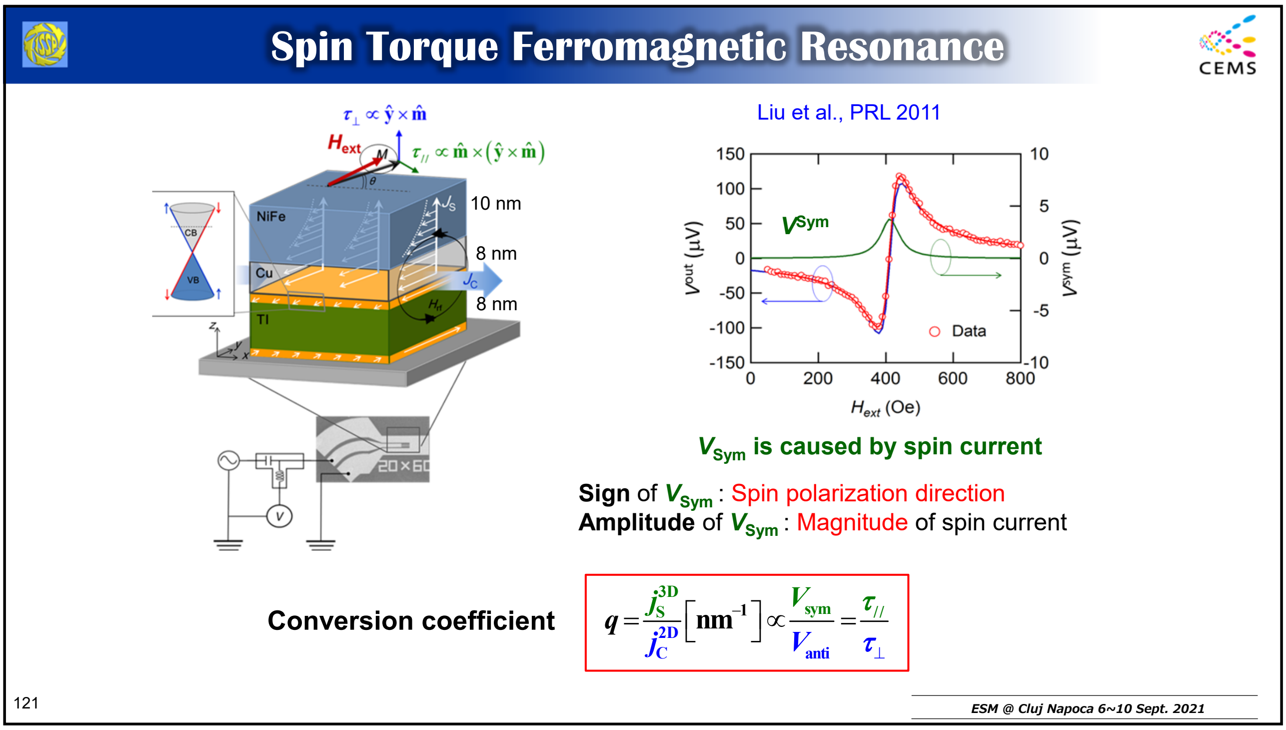
Valance band

Surface band

Bulk band

Fermi level can be tuned by Sb composition!

R. Yoshimi *et. al*, Nature mater. (2014).



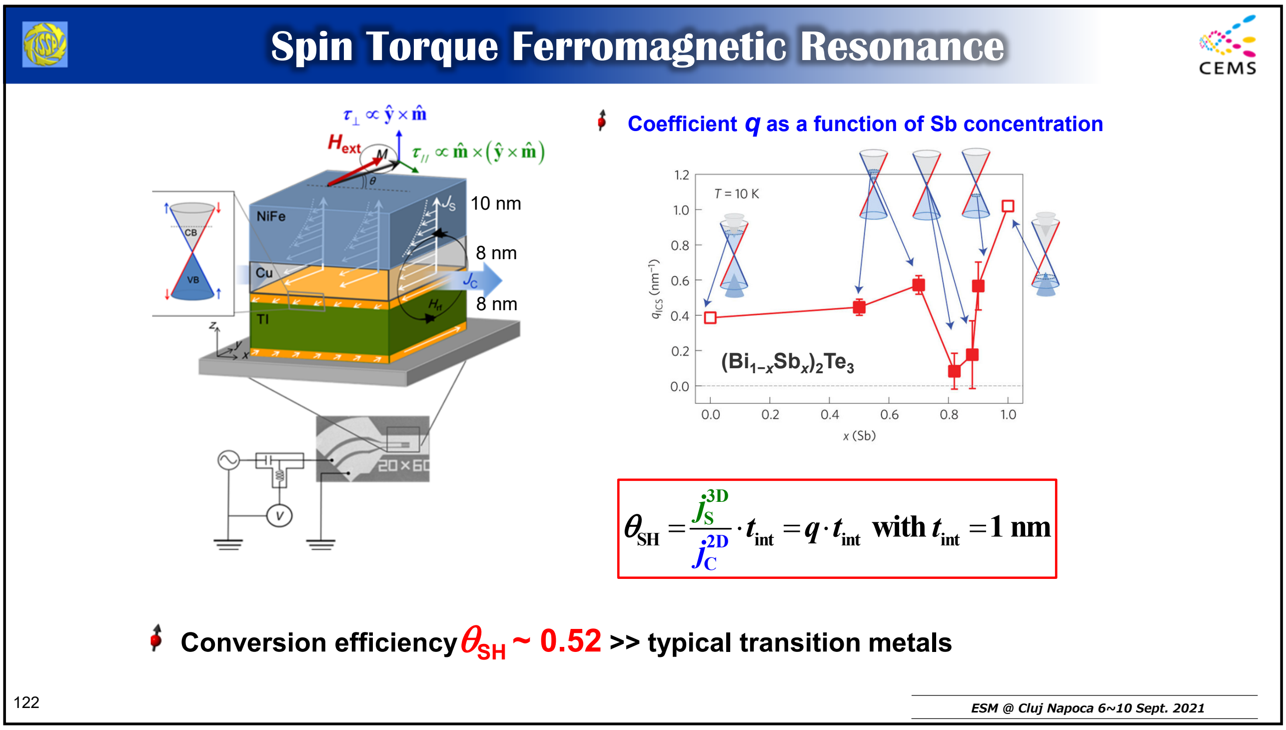
Spin Torque Ferromagnetic Resonance

V_{Sym} is caused by spin current

Sign of V_{Sym} : Spin polarization direction
Amplitude of V_{Sym} : Magnitude of spin current

Conversion coefficient

$$q = \frac{j_S^{3D}}{j_C^{2D}}\left[\mathrm{nm}^{-1}\right] \propto \frac{V_{sym}}{V_{anti}} = \frac{\tau_{//}}{\tau_\perp}$$

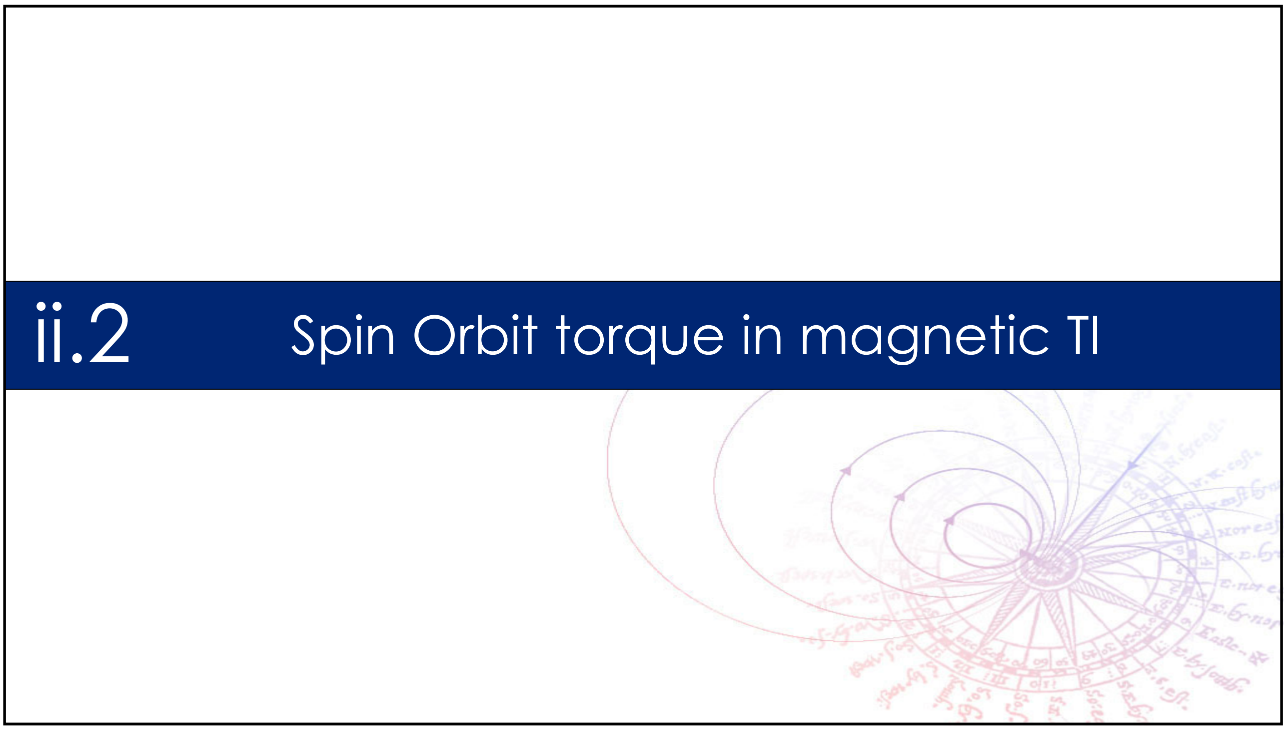


Spin Torque Ferromagnetic Resonance

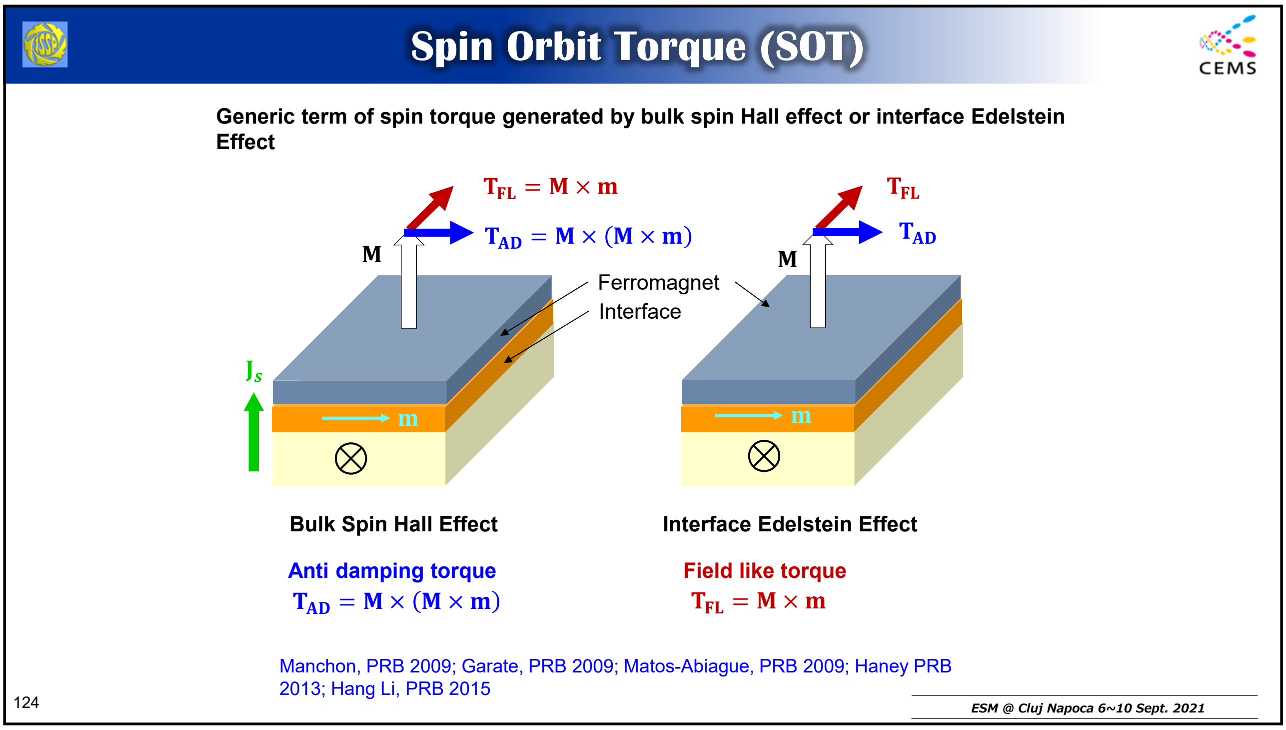
- **Coefficient *q* as a function of Sb concentration**

$$\theta_{SH} = \frac{j_S^{3D}}{j_C^{2D}}\cdot t_{int} = q\cdot t_{int} \ \text{with}\ t_{int} = 1\ \mathrm{nm}$$

- **Conversion efficiency θ_{SH} ~ 0.52 >> typical transition metals**



ii.2 Spin Orbit torque in magnetic TI



Spin Orbit Torque (SOT)

Generic term of spin torque generated by bulk spin Hall effect or interface Edelstein Effect

Bulk Spin Hall Effect

Anti damping torque

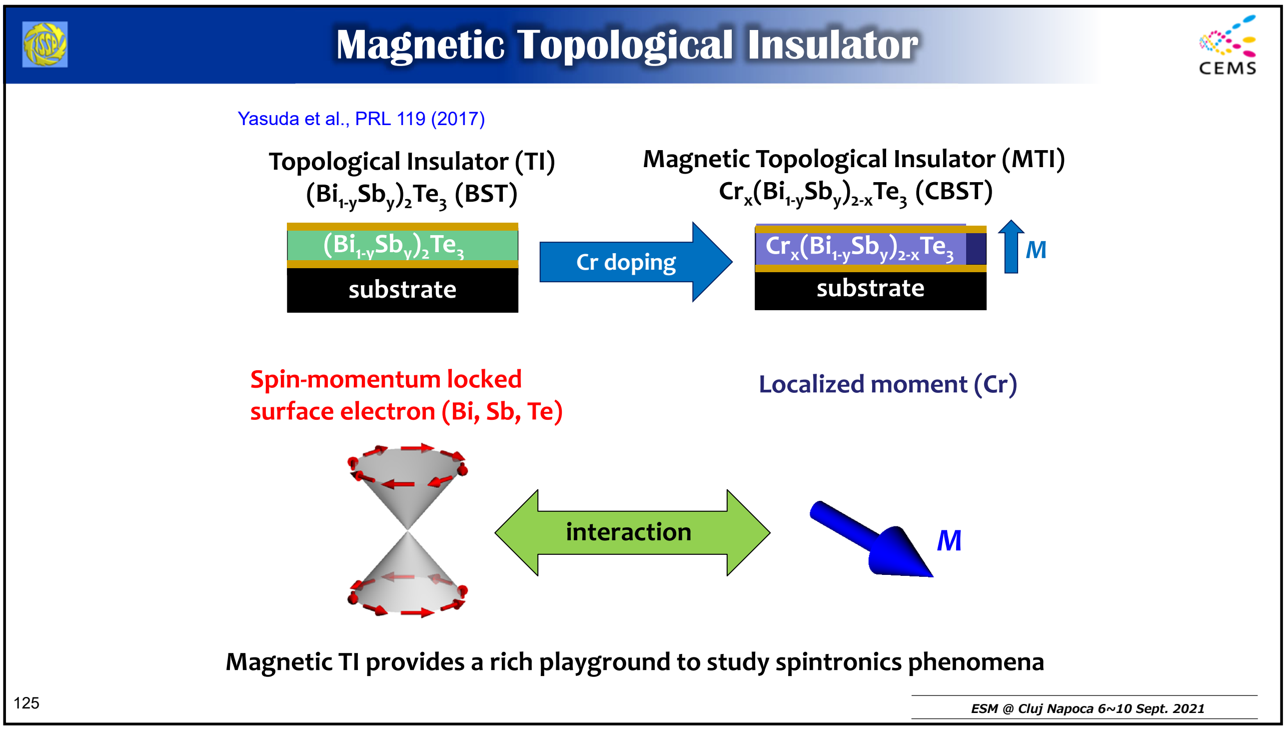
$\mathbf{T}_{\mathrm{AD}} = \mathbf{M} \times (\mathbf{M} \times \mathbf{m})$

Interface Edelstein Effect

Field like torque

$\mathbf{T}_{\mathrm{FL}} = \mathbf{M} \times \mathbf{m}$

Manchon, PRB 2009; Garate, PRB 2009; Matos-Abiague, PRB 2009; Haney PRB 2013; Hang Li, PRB 2015



Magnetic Topological Insulator

Yasuda et al., PRL 119 (2017)

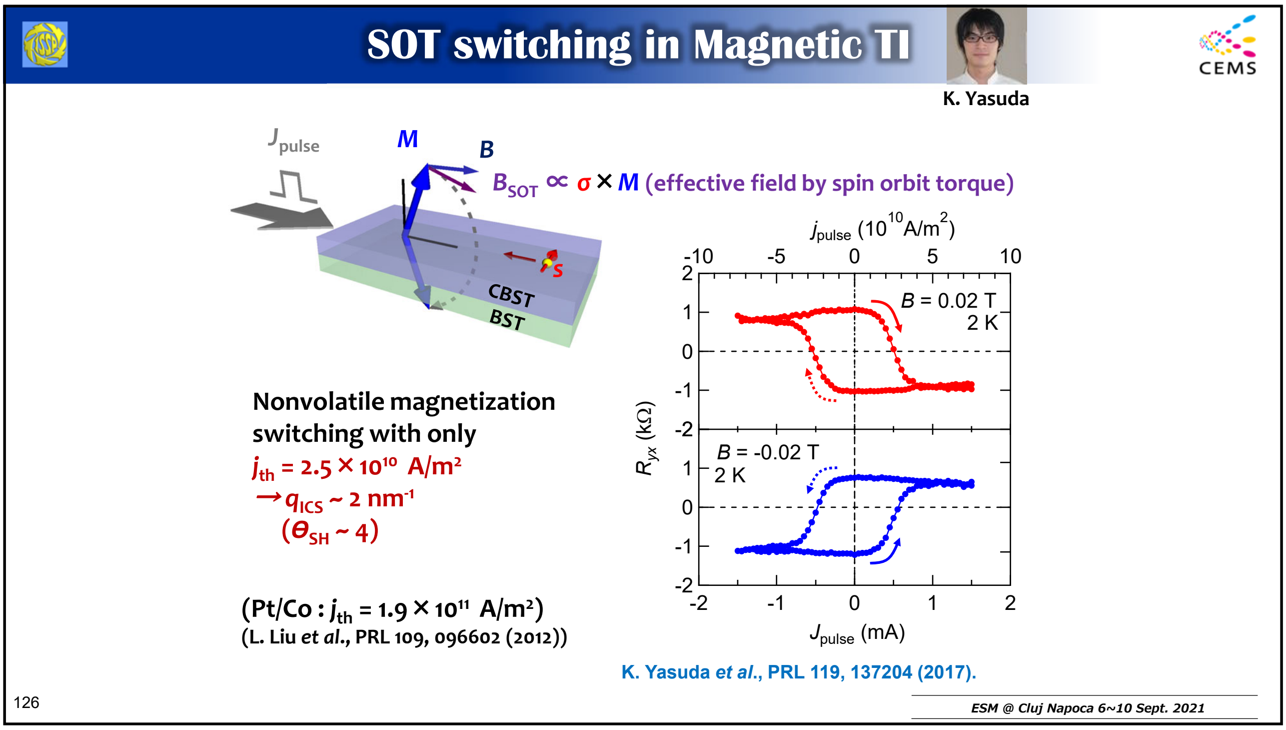
Topological Insulator (TI)
$(Bi_{1-y}Sb_y)_2Te_3$ (BST)

Magnetic Topological Insulator (MTI)
$Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$ (CBST)

Spin-momentum locked surface electron (Bi, Sb, Te)

Localized moment (Cr)

Magnetic TI provides a rich playground to study spintronics phenomena



SOT switching in Magnetic TI

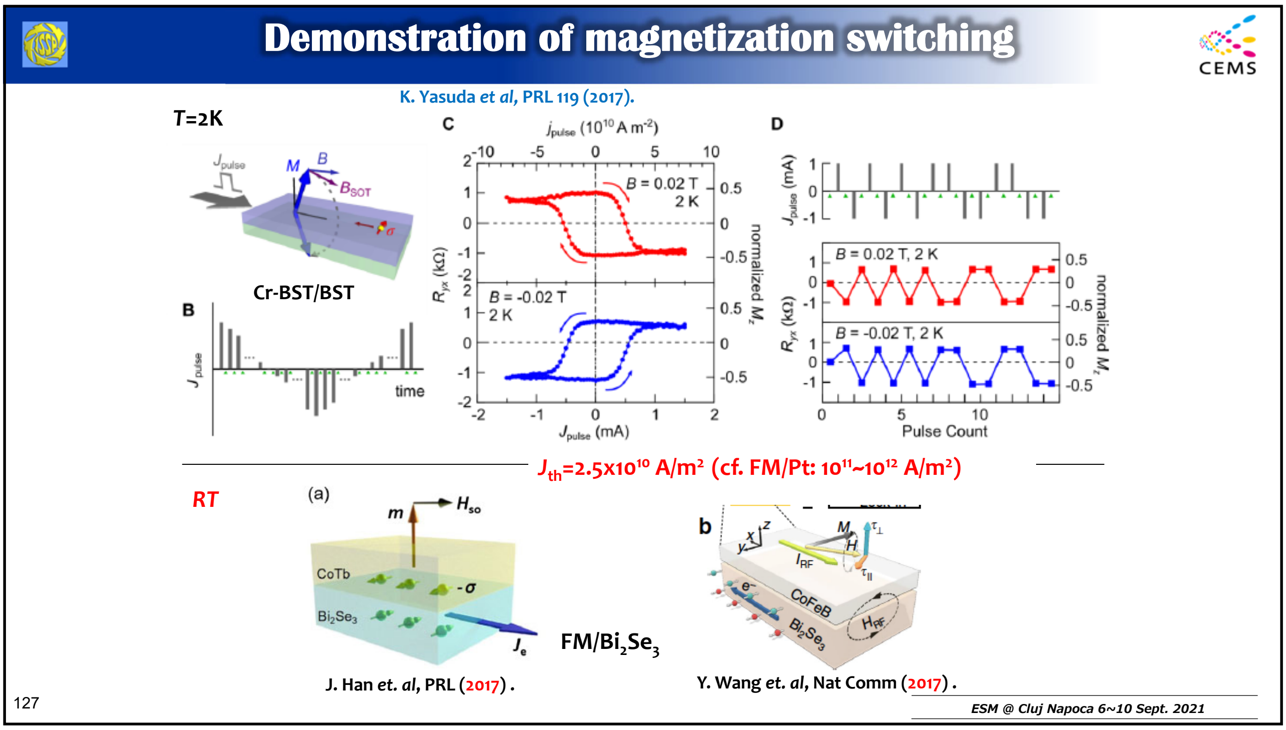
K. Yasuda

$B_{SOT} \propto \sigma \times M$ (effective field by spin orbit torque)

Nonvolatile magnetization switching only
$j_{th} = 2.5 \times 10^{10}$ A/m^2
→ $q_{ICS} \sim 2$ nm^{-1}
$(\theta_{SH} \sim 4)$

(Pt/Co : $j_{th} = 1.9 \times 10^{11}$ A/m^2)
(L. Liu *et al.*, PRL 109, 096602 (2012))

K. Yasuda *et al.*, PRL 119, 137204 (2017).



Demonstration of magnetization switching

K. Yasuda *et al*, PRL 119 (2017).

T=2K

Cr-BST/BST

J_{th}=2.5x10^{10} A/m^2 (cf. FM/Pt: 10^{11}~10^{12} A/m^2)

RT

FM/Bi_2Se_3

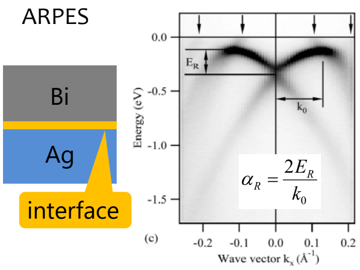
J. Han *et. al*, PRL (2017) .

Y. Wang *et. al*, Nat Comm (2017) .

ii.3 Rashba effect at interfaces

Spin-Charge conversion at Metal/Metal interface

Bi/Ag(111) interface

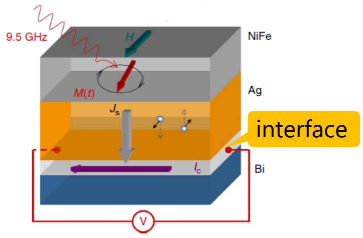


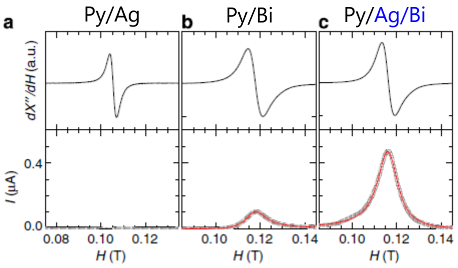
G. R. Ast Phys. Rev. Lett. 98, 186807 (2007).

Material	E_R (meV)	k_0 (Å^{-1})	α_R (eV Å)	Reference
InGaAs/InAlAs heterostructure	<1	0.028	0.07	[4]
Ag(111) surface state	<0.2	0.004	0.03	[5,6]
Au(111) surface state	2.1	0.012	0.33	[6,7]
Bi(111) surface state	~14	~0.05	~0.56	[8]
Bi/Ag(111) surface alloy	200	0.13	3.05	This work

Spin-to-charge current conversion

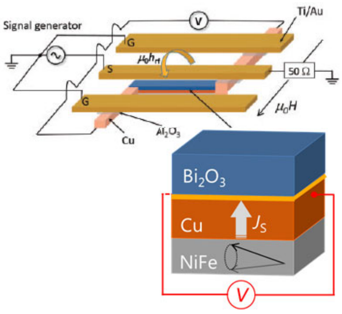
J.C. Rojas Sánchez *et al*, Nat. Commun. 4, 2944 (2013).





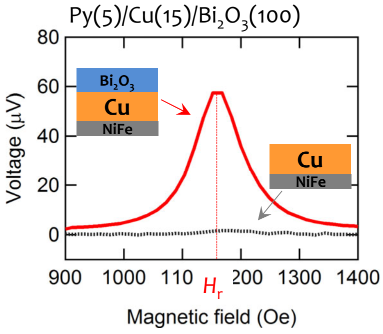
Spin-Charge conversion at metal/oxide interface

Spin pumping method

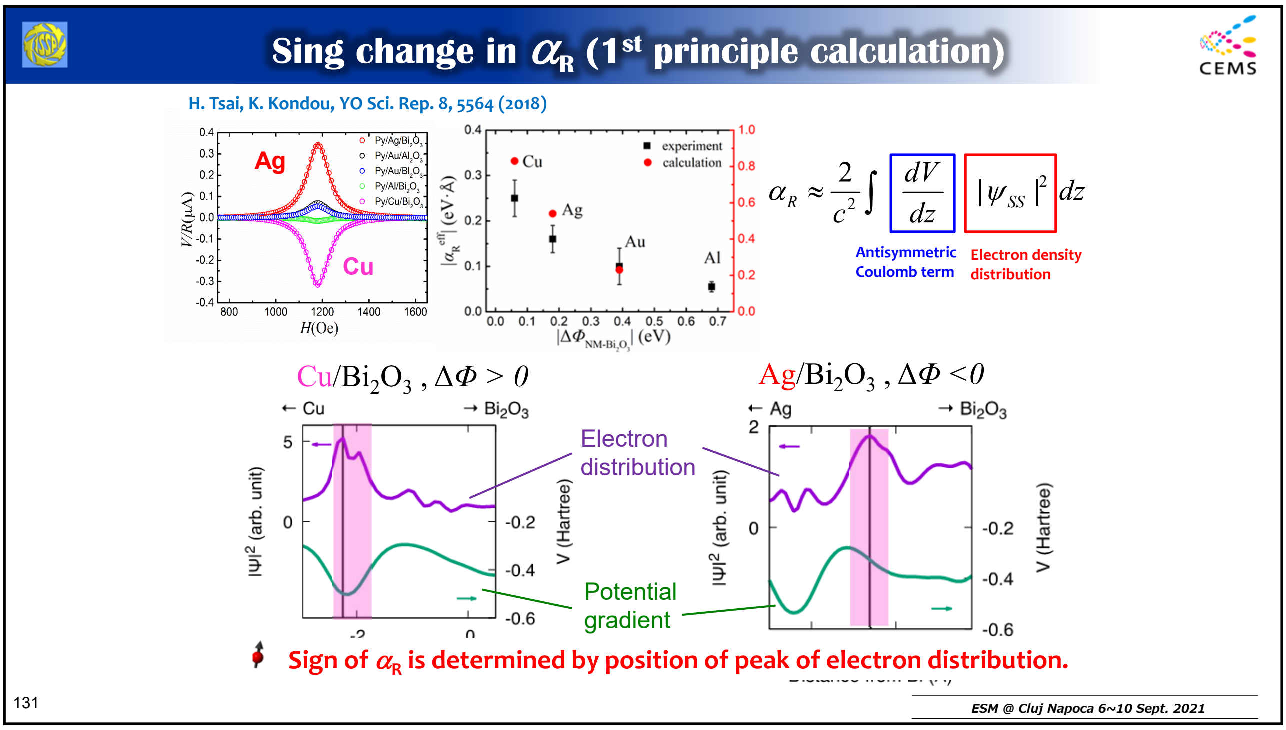


//NiFe(5nm)/Cu/Bi_2O_3(100nm)

Detected dc voltage due to S/C conversion



- Observation of spin-to-charge current conversion in Cu/Bi_2O_3 interface. S. Karube, K. Kondou, YO APEX **9**, 0.33001 (2016).
- Clear material dependence show that charge density distribution across the interface is important for strong Rashba splitting. H. Tsai, K. Kondou, YO Sci. Rep. (2018) in press.



Sing change in α_R (1^{st} principle calculation)

H. Tsai, K. Kondou, YO Sci. Rep. 8, 5564 (2018)

$$\alpha_R \approx \frac{2}{c^2}\int \boxed{\frac{dV}{dz}}\ \boxed{|\psi_{SS}|^2}\, dz$$

Antisymmetric Coulomb term

Electron density distribution

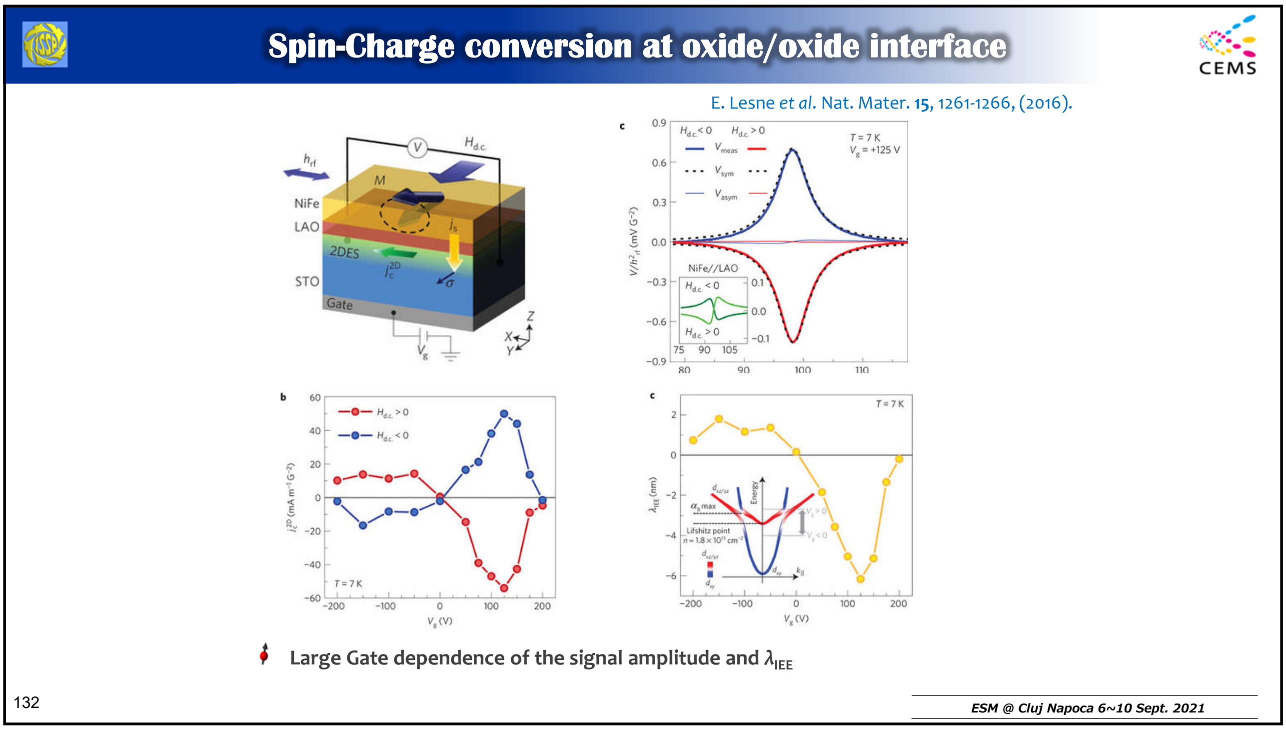
Cu/Bi_2O_3 , $\Delta\Phi > 0$

Ag/Bi_2O_3 , $\Delta\Phi < 0$

Electron distribution

Potential gradient

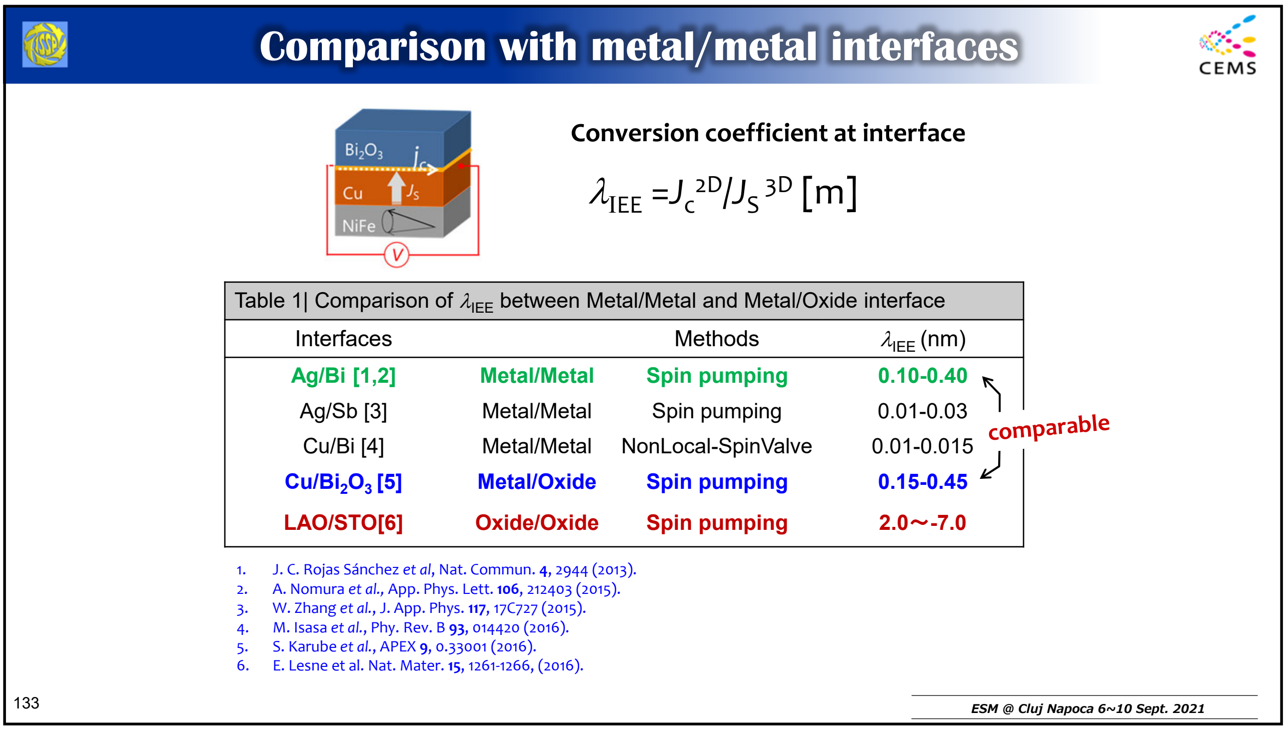
Sign of α_R is determined by position of peak of electron distribution.



Spin-Charge conversion at oxide/oxide interface

E. Lesne *et al.* Nat. Mater. **15**, 1261-1266, (2016).

Large Gate dependence of the signal amplitude and λ_{IEE}



Comparison with metal/metal interfaces

Conversion coefficient at interface

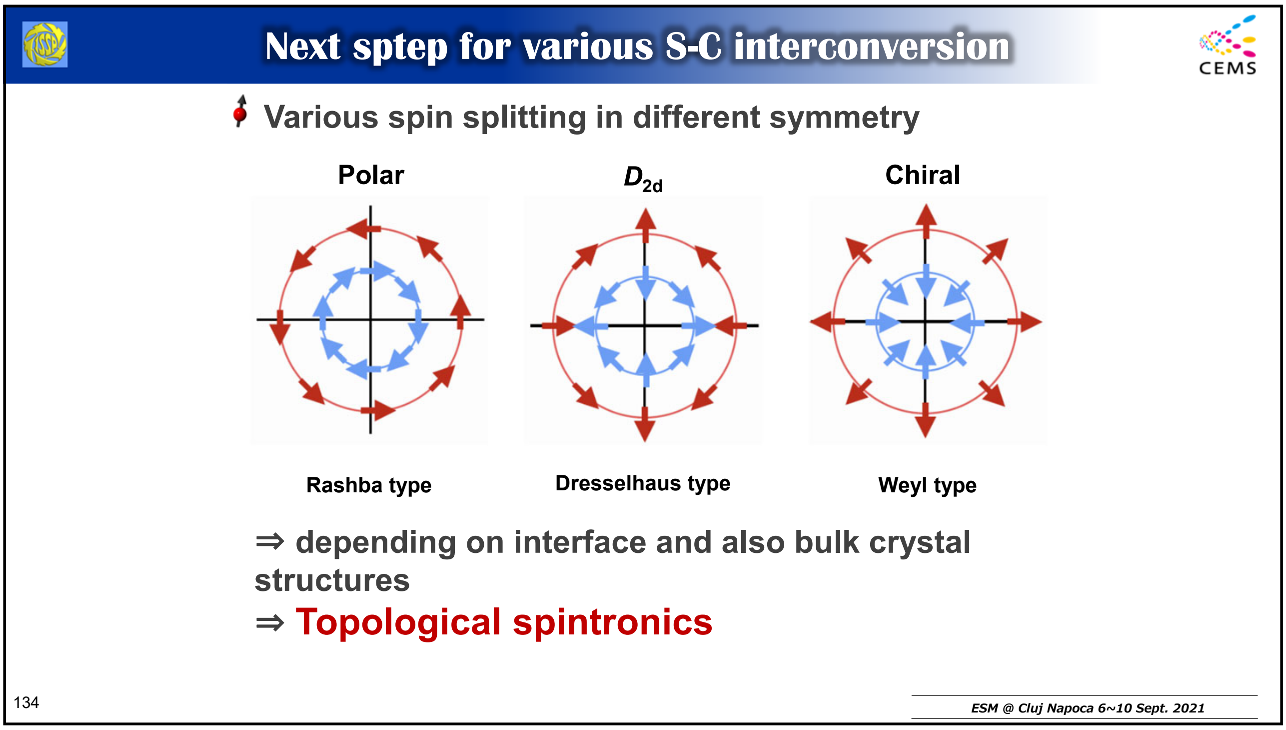
$$\lambda_{\mathrm{IEE}} = J_c^{2D}/J_S^{3D}\ [\mathrm{m}]$$

Table 1| Comparison of λ_{IEE} between Metal/Metal and Metal/Oxide interface

Interfaces		Methods	λ_{IEE} (nm)
Ag/Bi [1,2]	**Metal/Metal**	**Spin pumping**	**0.10-0.40**
Ag/Sb [3]	Metal/Metal	Spin pumping	0.01-0.03
Cu/Bi [4]	Metal/Metal	NonLocal-SpinValve	0.01-0.015
Cu/Bi$_2$O$_3$ [5]	**Metal/Oxide**	**Spin pumping**	**0.15-0.45**
LAO/STO[6]	**Oxide/Oxide**	**Spin pumping**	**2.0～-7.0**

comparable

1. J. C. Rojas Sánchez *et al*, Nat. Commun. **4**, 2944 (2013).
2. A. Nomura *et al.*, App. Phys. Lett. **106**, 212403 (2015).
3. W. Zhang *et al.*, J. App. Phys. **117**, 17C727 (2015).
4. M. Isasa *et al.*, Phy. Rev. B **93**, 014420 (2016).
5. S. Karube *et al.*, APEX **9**, 0.33001 (2016).
6. E. Lesne et al. Nat. Mater. **15**, 1261-1266, (2016).



Next sptep for various S-C interconversion

Various spin splitting in different symmetry

⇒ depending on interface and also bulk crystal structures

⇒ Topological spintronics

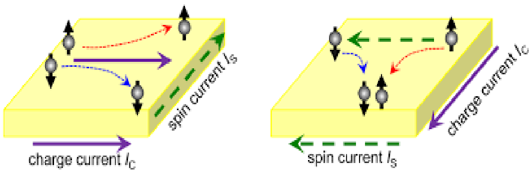
iii. Magnetic spin Hall effect

New trends in S/C interconversion

Bulk

(Direct & Inverse Spin Hall effects)

$I_c \Leftrightarrow I_s$

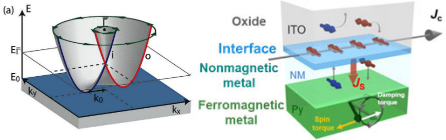


4d, 5d transition metals with strong SOC (Pt, Ta, W) and alloy (CuIr, CuBi)

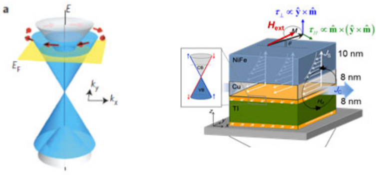
Js/Jc=5~30%*

Efficient conversion and new functionality

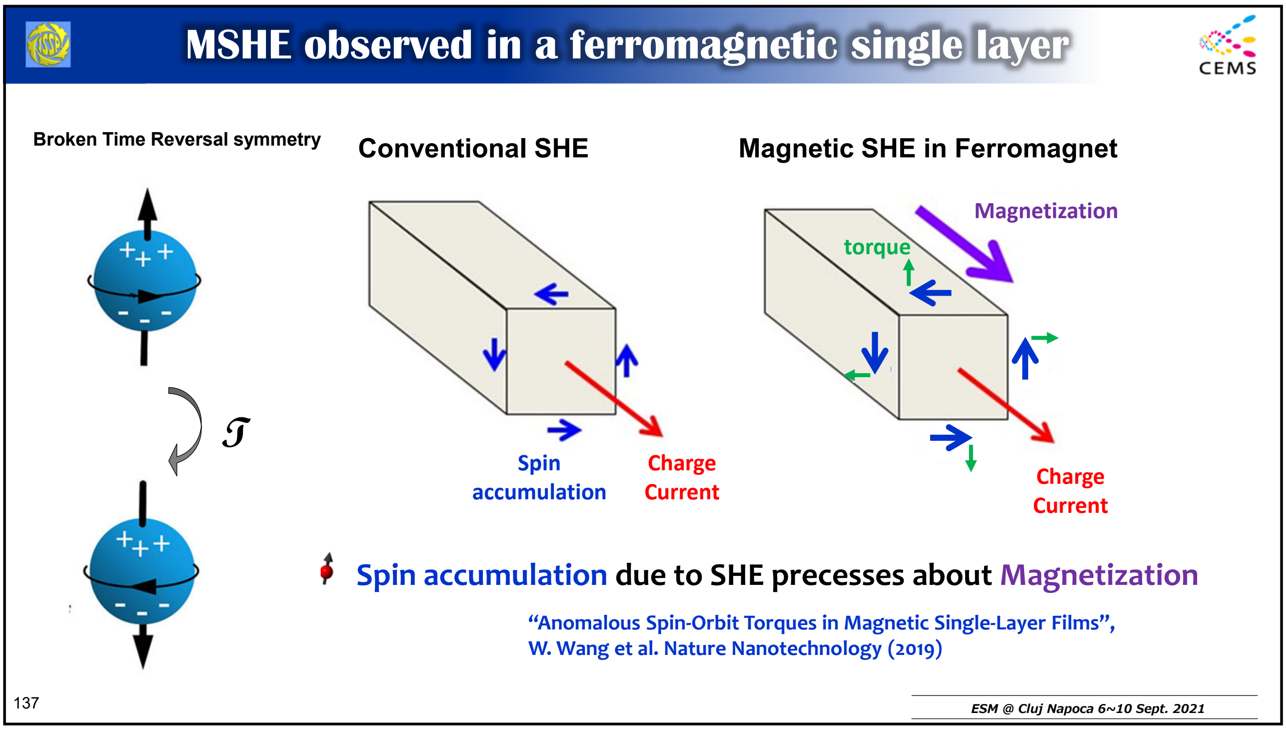
Rashba interface



TI surface



Novel type SHE in the system with Broken TRS



MSHE observed in a ferromagnetic single layer

Broken Time Reversal symmetry

$\mathcal{T}$

Conventional SHE

Spin accumulation

Charge Current

Magnetic SHE in Ferromagnet

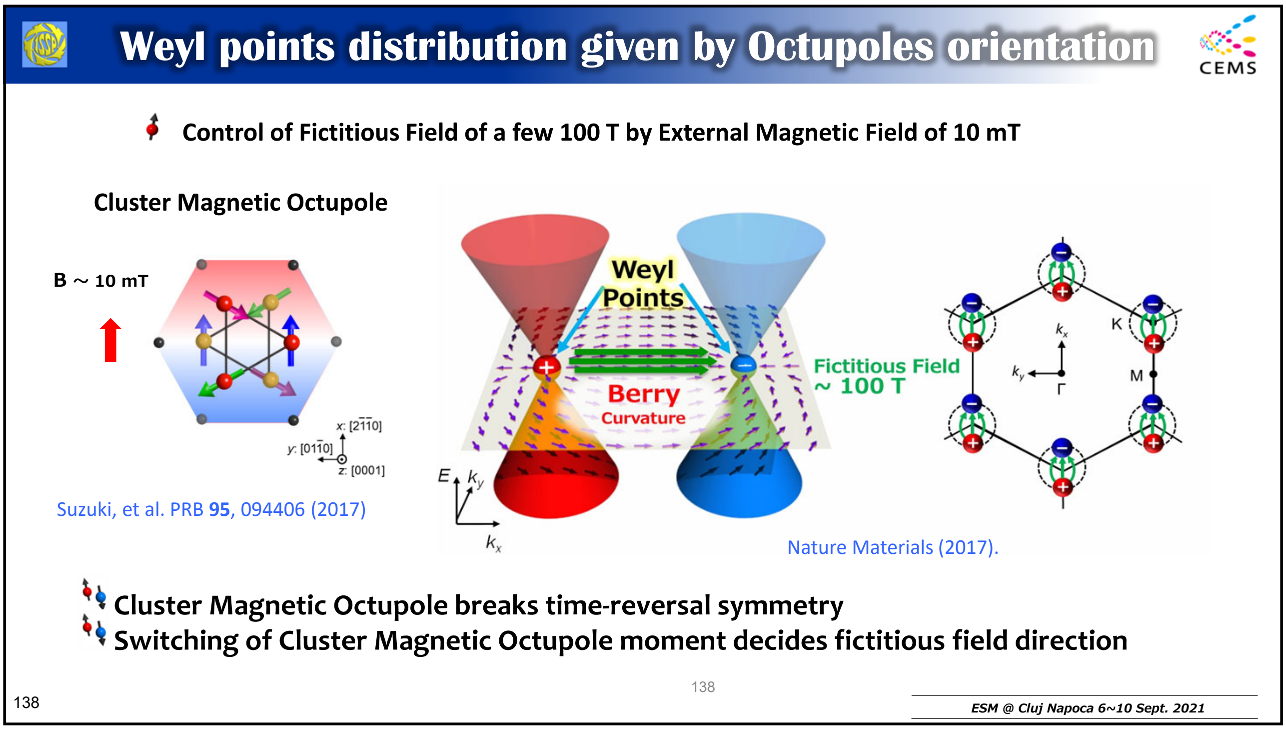
Magnetization

torque

Charge Current

Spin accumulation due to SHE precesses about Magnetization

"Anomalous Spin-Orbit Torques in Magnetic Single-Layer Films",
W. Wang et al. Nature Nanotechnology (2019)



Weyl points distribution given by Octupoles orientation

Control of Fictitious Field of a few 100 T by External Magnetic Field of 10 mT

Cluster Magnetic Octupole

B ~ 10 mT

x: [2$\bar{1}\bar{1}$0]
y: [01$\bar{1}$0]
z: [0001]

Suzuki, et al. PRB **95**, 094406 (2017)

Weyl Points

Berry Curvature

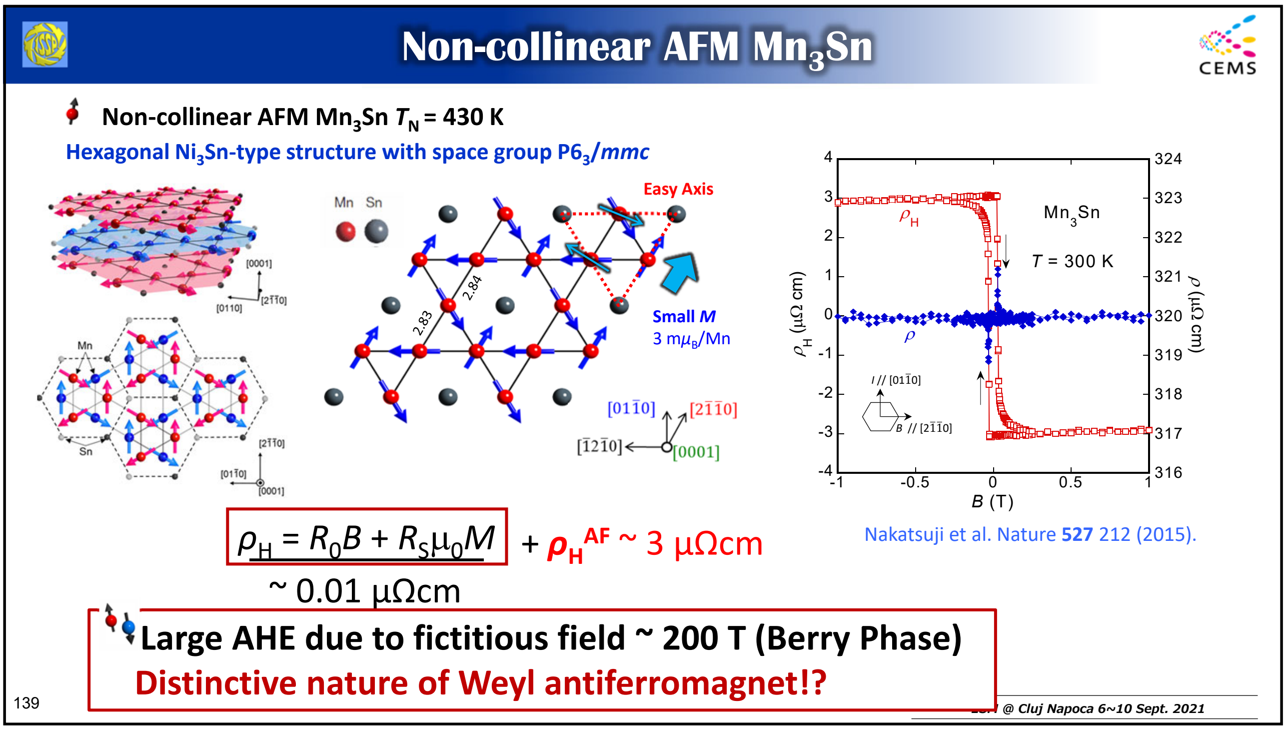
Fictitious Field ~ 100 T

E, k_y, k_x

K, M, Γ

Nature Materials (2017).

- Cluster Magnetic Octupole breaks time-reversal symmetry
- Switching of Cluster Magnetic Octupole moment decides fictitious field direction



Non-collinear AFM Mn_3Sn

- Non-collinear AFM Mn_3Sn T_N = 430 K

Hexagonal Ni_3Sn-type structure with space group $P6_3/mmc$

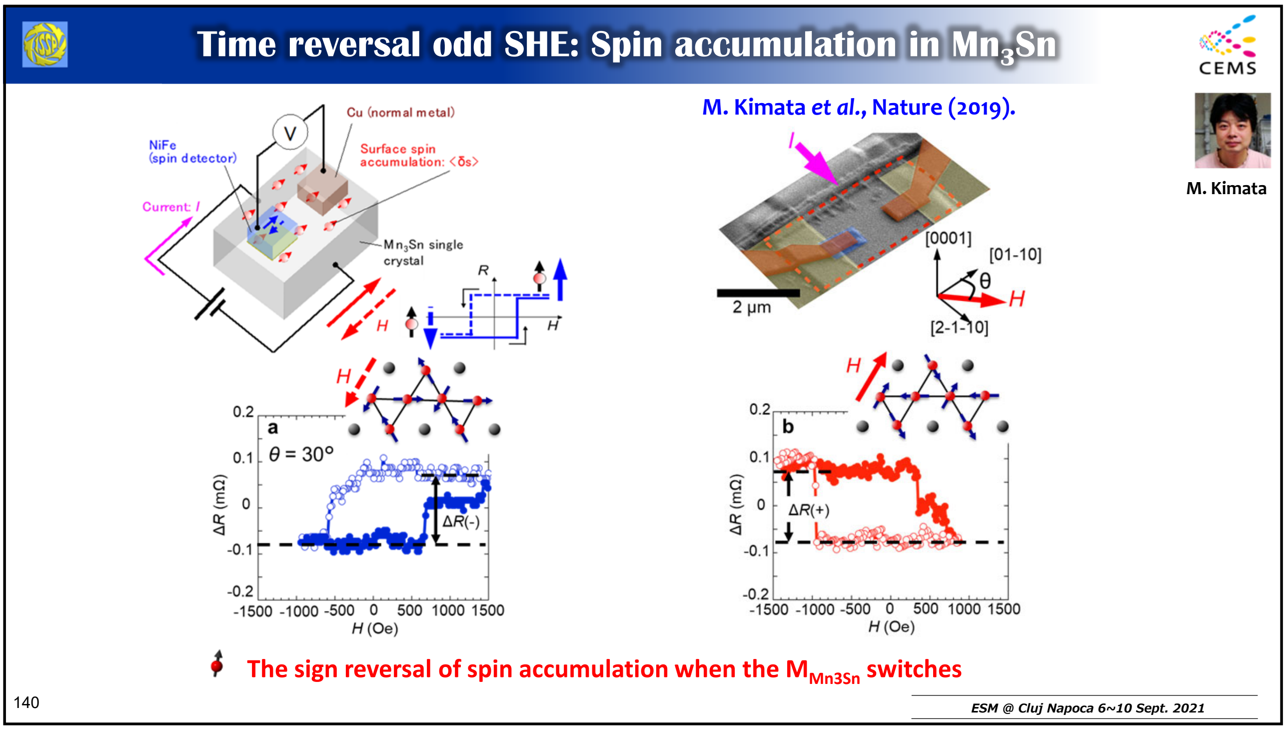
Nakatsuji et al. Nature **527** 212 (2015).

$$\boxed{\rho_H = R_0 B + R_S \mu_0 M} + \rho_H^{AF} \sim 3\ \mu\Omega\text{cm}$$

~ 0.01 μΩcm

Large AHE due to fictitious field ~ 200 T (Berry Phase)

Distinctive nature of Weyl antiferromagnet!?



Time reversal odd SHE: Spin accumulation in Mn_3Sn

M. Kimata *et al.*, Nature (2019).

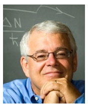
M. Kimata

- The sign reversal of spin accumulation when the M_{Mn3Sn} switches

Magnetic SHE different from Conventional SHE

- Unlike the spin-current language, SHE occurs as a linear response of spin density **s** to an electric field **E**; $(\chi = \partial s/\partial E)$

H. Chen

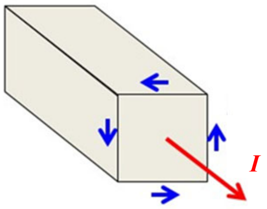


A. MacDonald

Conventional SHE

Intraband contribution

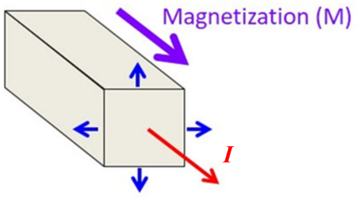
$$\langle s^{\alpha}\rangle_d = -\frac{e\hbar}{2}\tau E_{\beta}\sum_n \int [d\mathbf{k}]\frac{\partial f_n}{\partial \epsilon_n} v^{\beta}_{nn}\sigma^{\alpha}_{nn}$$



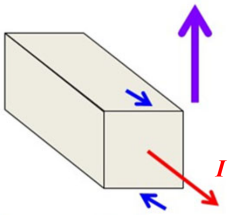
Magnetic SHE

Interband contribution

$$\langle s^{\alpha}\rangle_{od} = -\frac{e\hbar}{2}E_{\beta}\sum_{m\neq n}\int [d\mathbf{k}](f_m - f_n)\mathrm{Im}\left[\frac{v^{\beta}_{mn}\sigma^{\alpha}_{nm}}{(\epsilon_m - \epsilon_n)^2}\right]$$



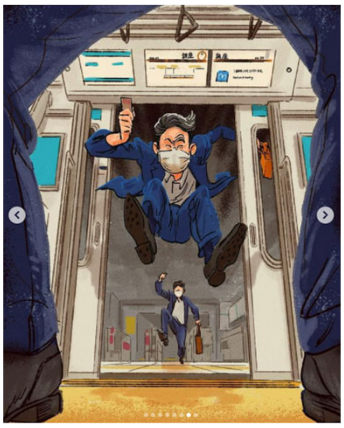
M parallel to current



M perpendicular to current

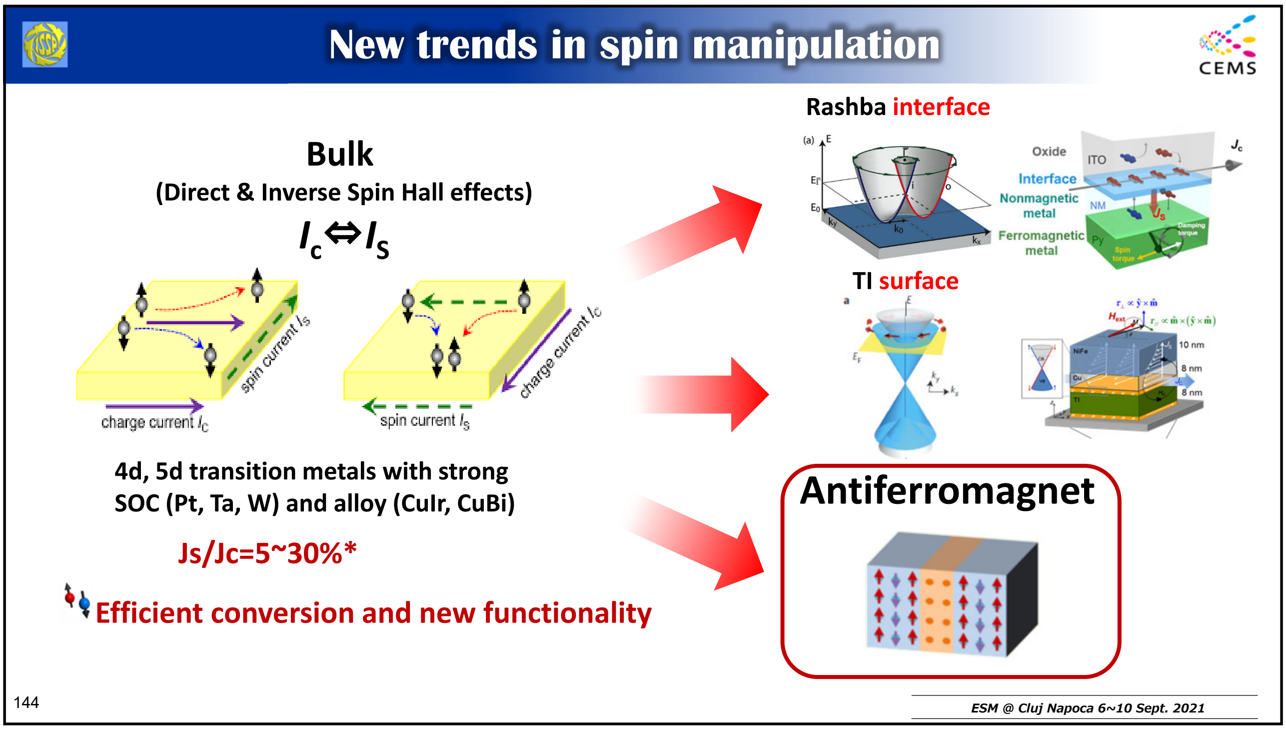
---

5. New directions in spintronics



From Instagram Adehogan: Go Fun The World "Daily Olympics in Tokyo"

i. Antiferromagnetic spintronics



New trends in spin manipulation

Bulk

(Direct & Inverse Spin Hall effects)

$I_c \Leftrightarrow I_S$

4d, 5d transition metals with strong SOC (Pt, Ta, W) and alloy (CuIr, CuBi)

Js/Jc=5~30%*

Efficient conversion and new functionality

Rashba interface

TI surface

Antiferromagnet

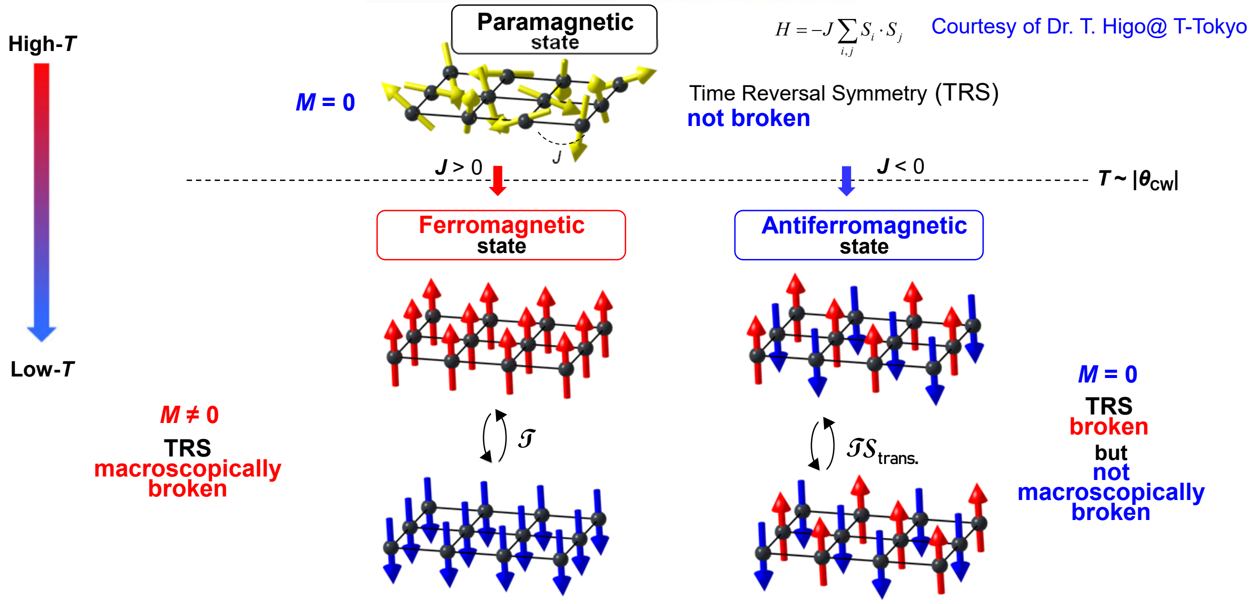
Antiferromagnetic spintronics

Comparison between F and AF

	Ferromagnet	Antiferromagnet
Stray field	～ 1 T	Nearly zero → good for miniaturization
Resonance frequency	～ GHz	～THz → high speed operation
RT semiconductor	Challenge	Available → variety of material choice
Coupling with magnetic fields	Direct	**Indirect** → Difficult to control

---

Magnetic phases

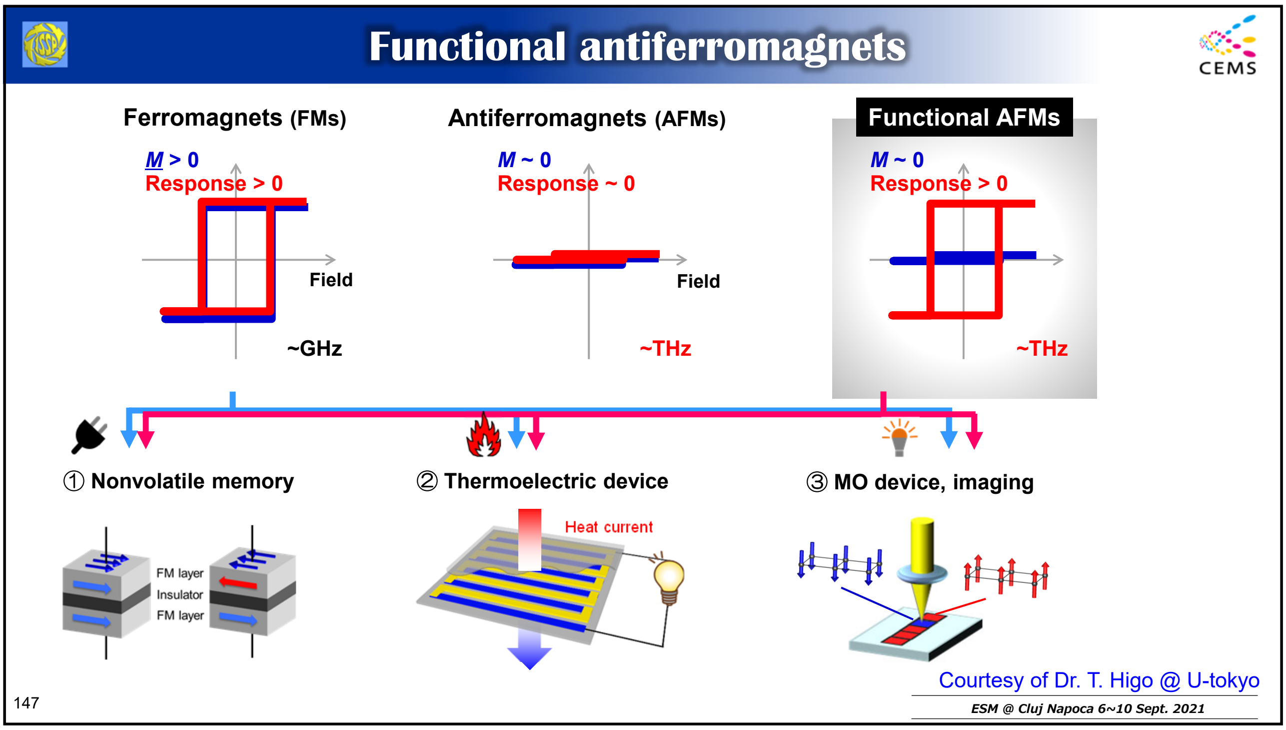


$H = -J\sum_{i,j} S_i \cdot S_j$ Courtesy of Dr. T. Higo@ T-Tokyo

Time Reversal Symmetry (TRS) **not broken**

$M \neq 0$
TRS
macroscopically broken

$M = 0$
TRS
broken
but
not macroscopically broken



Functional antiferromagnets

Ferromagnets (FMs)

Antiferromagnets (AFMs)

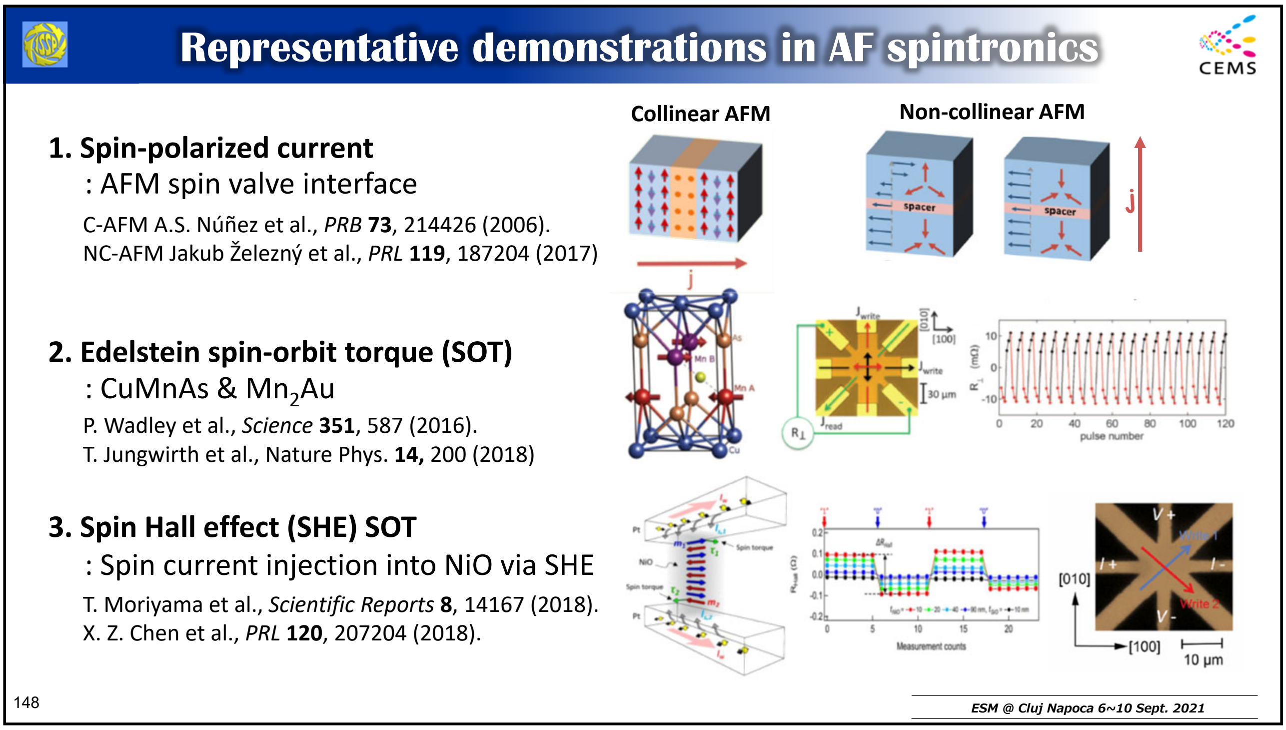
Functional AFMs

① Nonvolatile memory

② Thermoelectric device

③ MO device, imaging

Courtesy of Dr. T. Higo @ U-tokyo



Representative demonstrations in AF spintronics

1. Spin-polarized current

: AFM spin valve interface

C-AFM A.S. Núñez et al., *PRB* **73**, 214426 (2006).
NC-AFM Jakub Železný et al., *PRL* **119**, 187204 (2017)

2. Edelstein spin-orbit torque (SOT)

: CuMnAs & Mn_2Au

P. Wadley et al., *Science* **351**, 587 (2016).
T. Jungwirth et al., Nature Phys. **14,** 200 (2018)

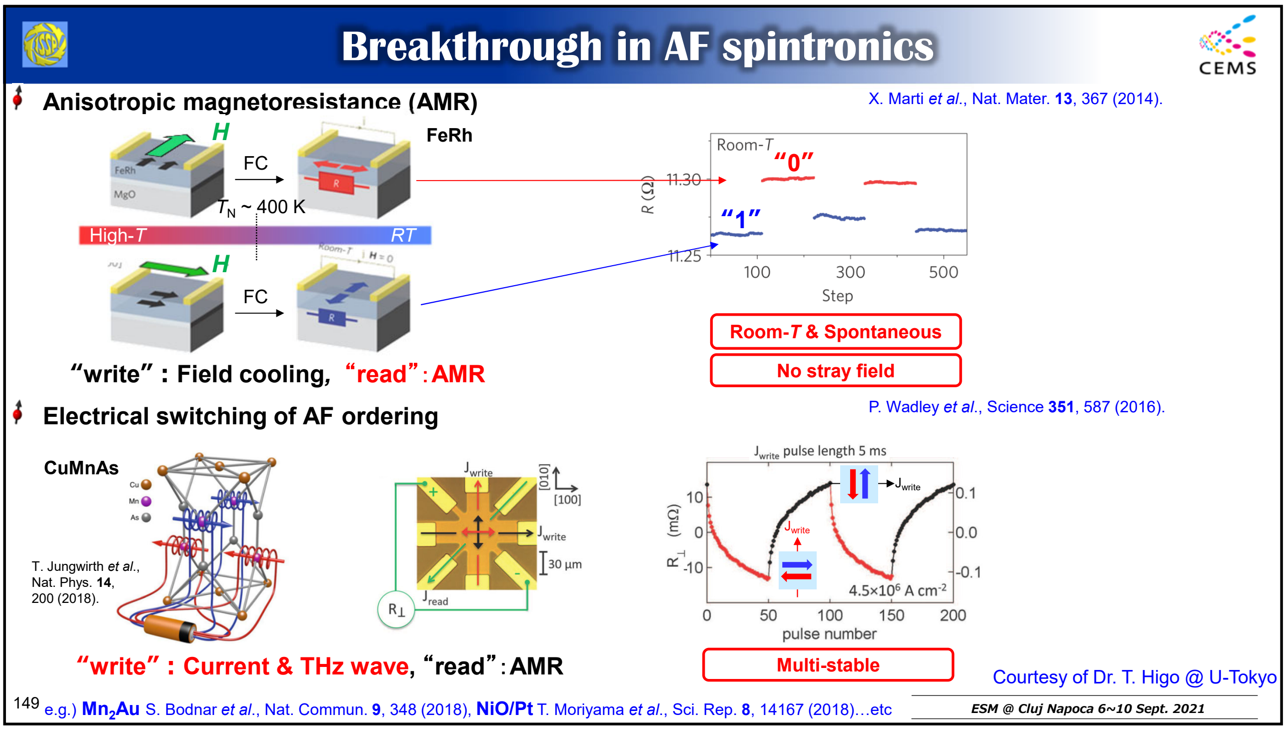
3. Spin Hall effect (SHE) SOT

: Spin current injection into NiO via SHE

T. Moriyama et al., *Scientific Reports* **8**, 14167 (2018).
X. Z. Chen et al., *PRL* **120**, 207204 (2018).

Collinear AFM

Non-collinear AFM



Breakthrough in AF spintronics

- **Anisotropic magnetoresistance (AMR)**

X. Marti *et al.*, Nat. Mater. **13**, 367 (2014).

Room-*T* & Spontaneous

No stray field

"write" : Field cooling, "read" : AMR

- **Electrical switching of AF ordering**

P. Wadley *et al.*, Science **351**, 587 (2016).

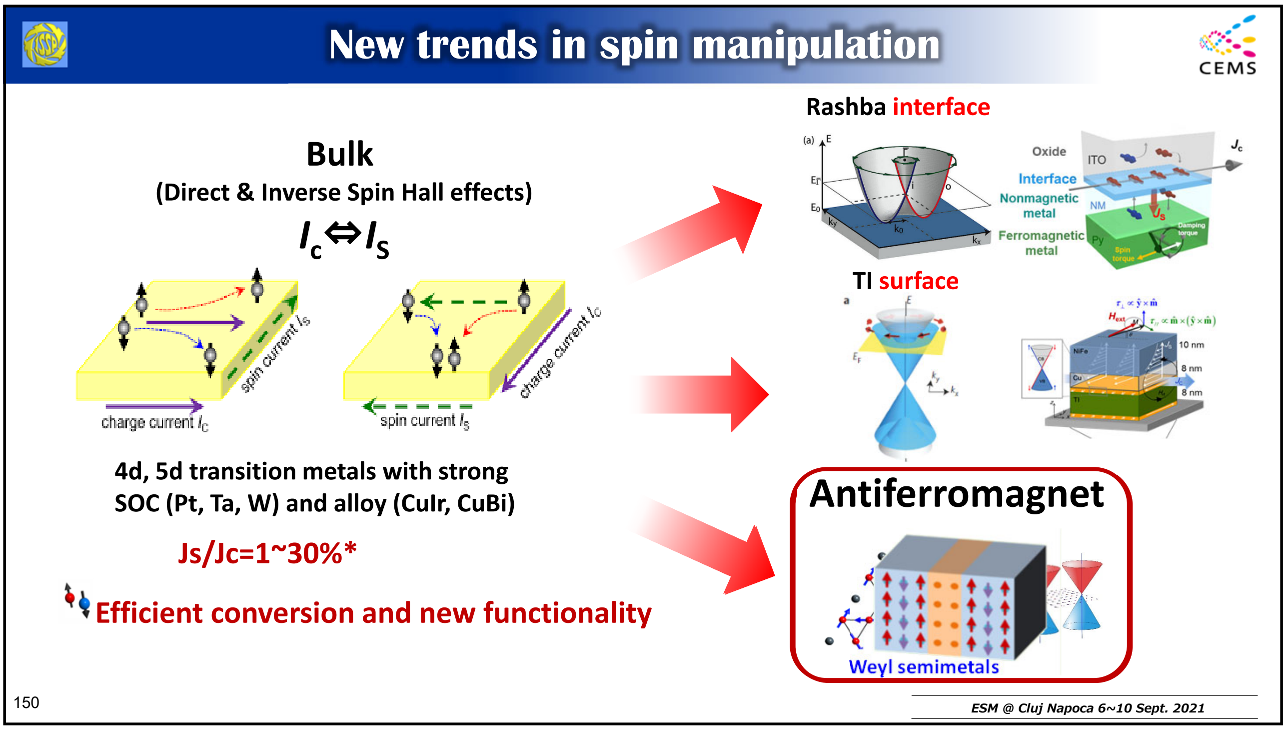
T. Jungwirth *et al.*, Nat. Phys. **14**, 200 (2018).

"write" : Current & THz wave, "read" : AMR

Multi-stable

Courtesy of Dr. T. Higo @ U-Tokyo

e.g.) **Mn_2Au** S. Bodnar *et al.*, Nat. Commun. **9**, 348 (2018), **NiO/Pt** T. Moriyama *et al.*, Sci. Rep. **8**, 14167 (2018)…etc



New trends in spin manipulation

Bulk

(Direct & Inverse Spin Hall effects)

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4d, 5d transition metals with strong SOC (Pt, Ta, W) and alloy (CuIr, CuBi)

Js/Jc=1~30%*

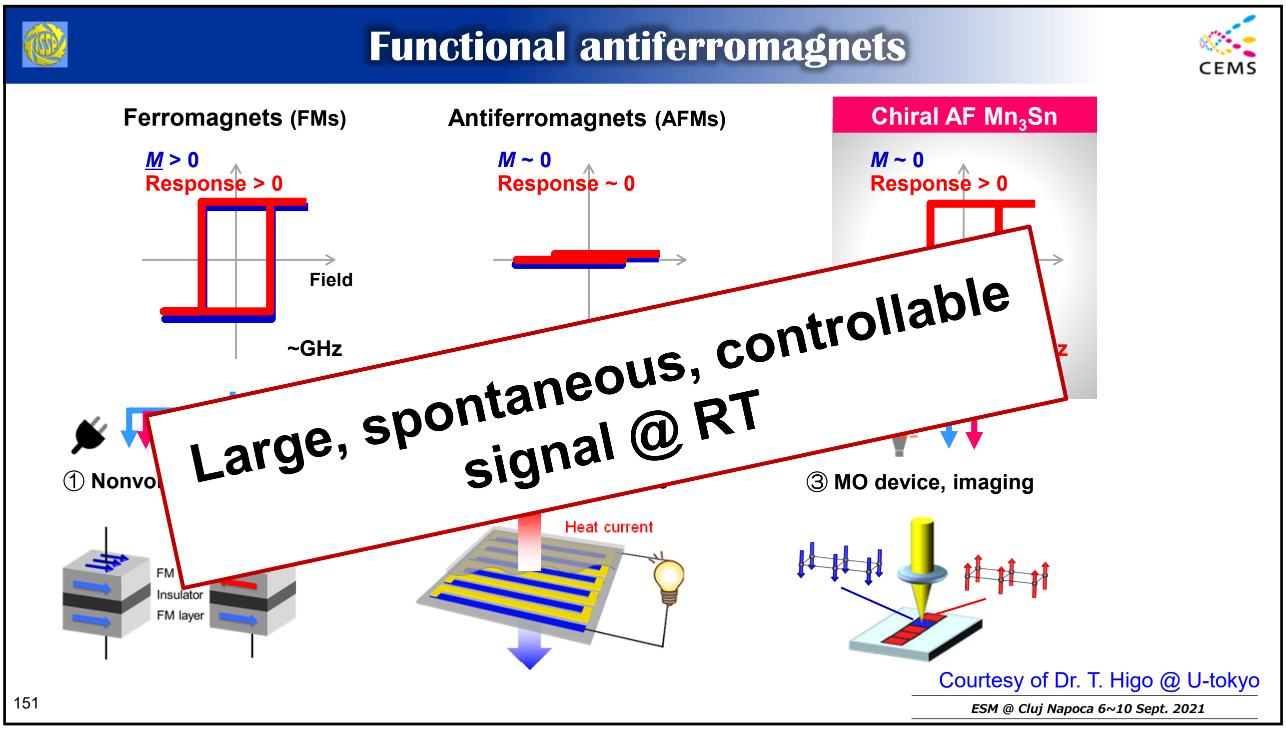
Efficient conversion and new functionality

Rashba interface

TI surface

Antiferromagnet

Weyl semimetals



Functional antiferromagnets

Ferromagnets (FMs)

M > 0
Response > 0

Antiferromagnets (AFMs)

M ~ 0
Response ~ 0

Chiral AF Mn_3Sn

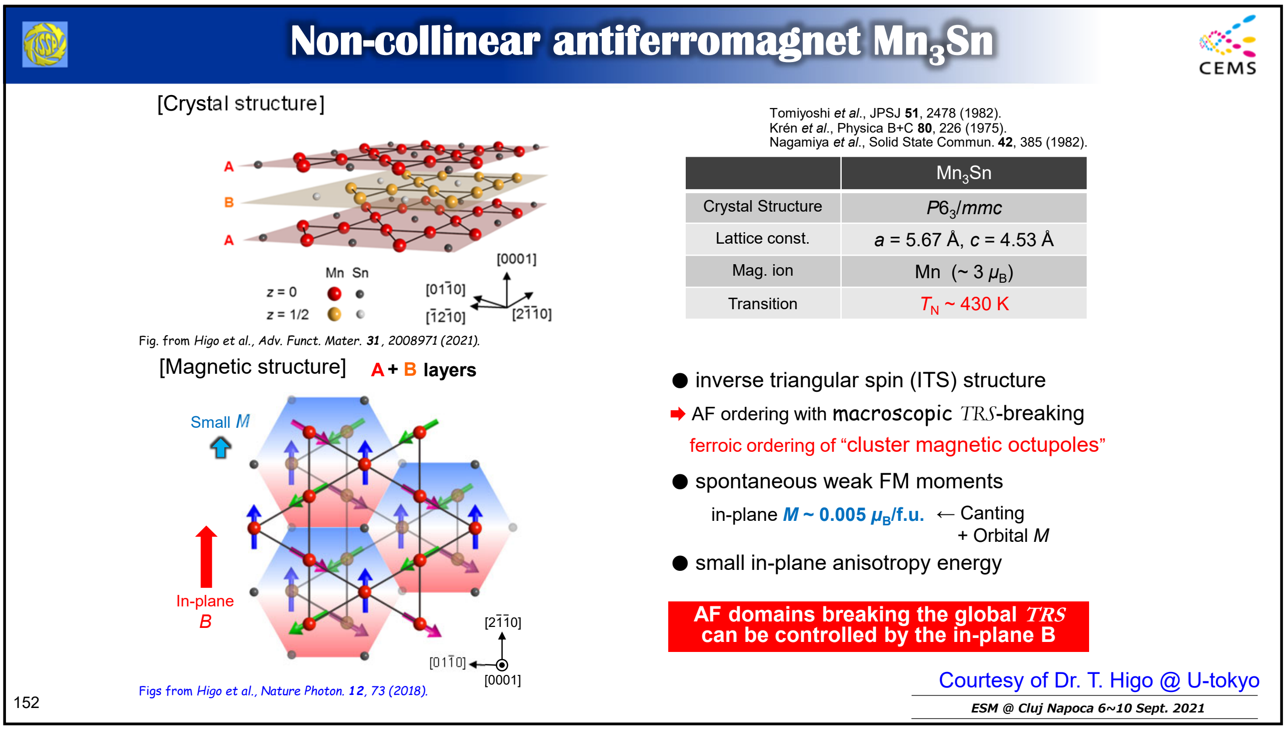
M ~ 0
Response > 0

① Nonvo

③ MO device, imaging

Large, spontaneous, controllable signal @ RT

Courtesy of Dr. T. Higo @ U-tokyo



Non-collinear antiferromagnet Mn_3Sn

[Crystal structure]

Fig. from Higo et al., Adv. Funct. Mater. 31, 2008971 (2021).

Tomiyoshi et al., JPSJ 51, 2478 (1982).
Krén et al., Physica B+C 80, 226 (1975).
Nagamiya et al., Solid State Commun. 42, 385 (1982).

	Mn_3Sn
Crystal Structure	$P6_3/mmc$
Lattice const.	a = 5.67 Å, c = 4.53 Å
Mag. ion	Mn (~ 3 μ_B)
Transition	T_N ~ 430 K

[Magnetic structure] **A + B layers**

Figs from Higo et al., Nature Photon. 12, 73 (2018).

- inverse triangular spin (ITS) structure

➡ AF ordering with macroscopic TRS-breaking
ferroic ordering of "cluster magnetic octupoles"

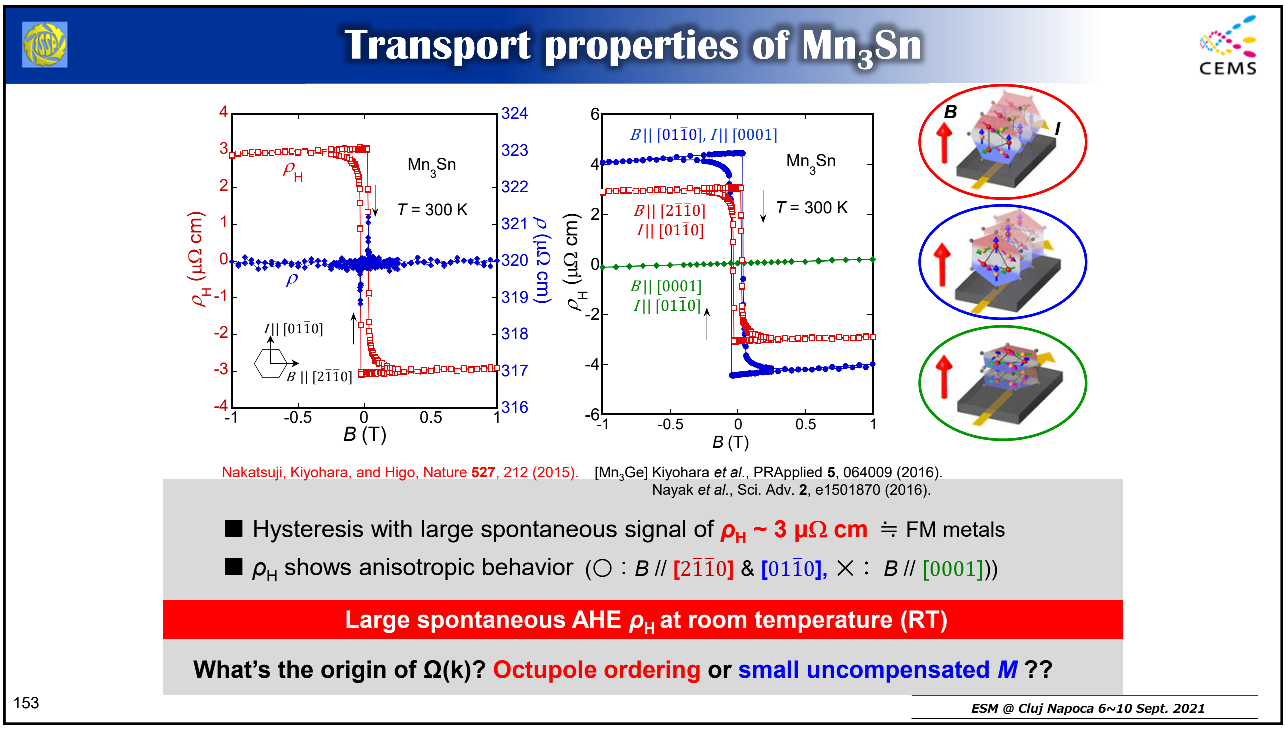
- spontaneous weak FM moments

in-plane M ~ 0.005 μ_B/f.u. ← Canting
+ Orbital M

- small in-plane anisotropy energy

AF domains breaking the global TRS can be controlled by the in-plane B

Courtesy of Dr. T. Higo @ U-tokyo



Transport properties of Mn_3Sn

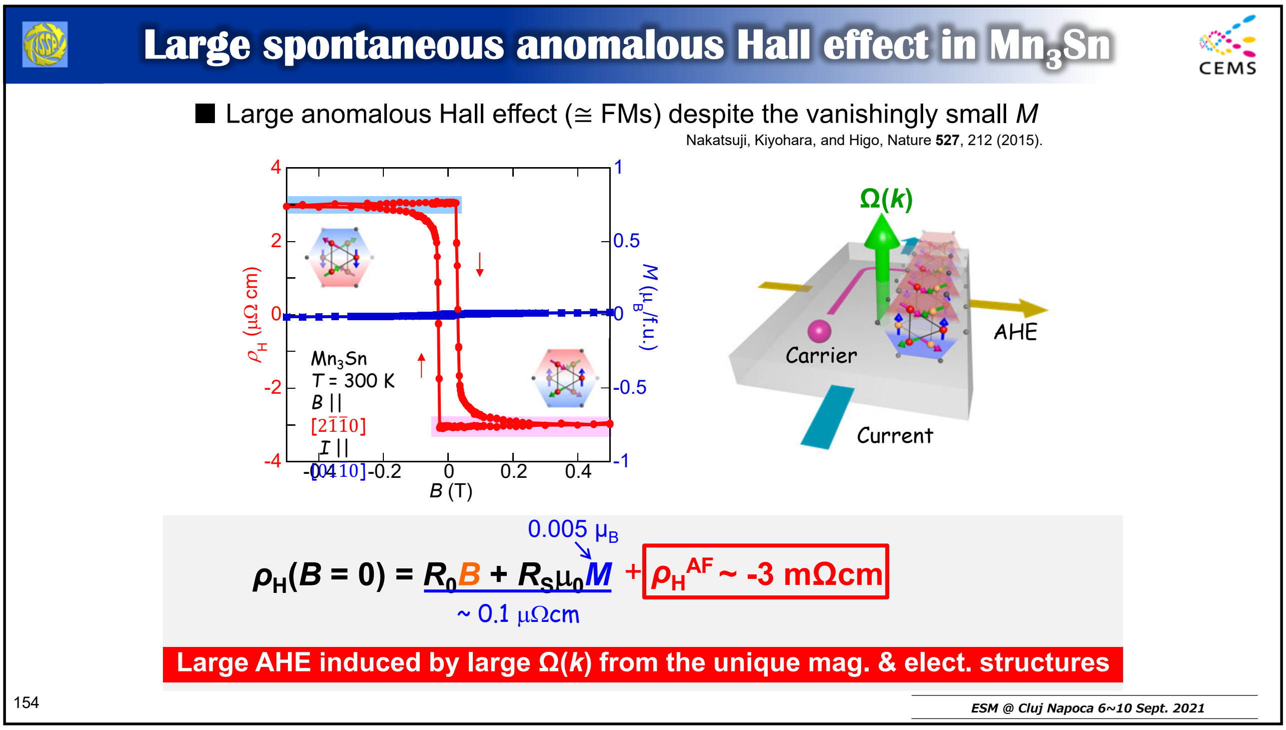
Nakatsuji, Kiyohara, and Higo, Nature **527**, 212 (2015).

[Mn_3Ge] Kiyohara *et al.*, PRApplied **5**, 064009 (2016).
Nayak *et al.*, Sci. Adv. **2**, e1501870 (2016).

- Hysteresis with large spontaneous signal of **ρ_H ~ 3 μΩ cm** ≒ FM metals
- ρ_H shows anisotropic behavior (○ : *B* // **[2$\bar{1}\bar{1}$0]** & **[01$\bar{1}$0]**, × : *B* // [0001]))

Large spontaneous AHE ρ_H at room temperature (RT)

What's the origin of Ω(k)? Octupole ordering or small uncompensated *M* ??



Large spontaneous anomalous Hall effect in Mn_3Sn

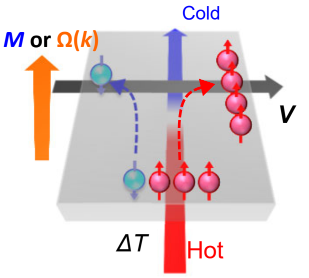
- Large anomalous Hall effect (≅ FMs) despite the vanishingly small *M*

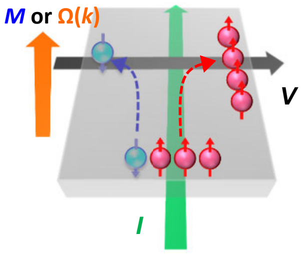
Nakatsuji, Kiyohara, and Higo, Nature **527**, 212 (2015).

$$\rho_H(B = 0) = \underbrace{R_0 B + R_S \mu_0 \overset{0.005\ \mu_B}{M}}_{\sim 0.1\ \mu\Omega cm} + \boxed{\rho_H^{AF} \sim -3\ m\Omega cm}$$

Large AHE induced by large Ω(*k*) from the unique mag. & elect. structures

Anomalous Nernst effect





Anomalous Nernst effect (ANE)	**Anomalous Hall effect (AHE)**
Nernst conductivity	Hall conductivity
$\alpha_{xy} = -\frac{e}{T\hbar}\int \frac{dk}{(2\pi)^3}\Omega_n(k)\{(\varepsilon_{nk}-\mu)f_{nk}+\cdots\}$	$\sigma_{xy} = -\frac{e^2}{\hbar}\int \frac{dk}{(2\pi)^3}\Omega_n(k)f_{nk}$
Nernst coefficient	Hall resistivity
$S_{xy} = \rho_{xx}(\alpha_{xy} - S_{yy}\sigma_{xy})$	$\rho_{xy} = -\sigma_{xy} \times \rho_{xx}\rho_{yy}$
$S_{xy} = Q_0 B + Q_S \mu_0 M + S_{xy}^{AF}$	$\rho_H = R_0 B + R_S \mu_0 M + \rho_H^{AF}$

Berry phase

- Time dependent Schrödinger equation that governs the wave function

$$\hat{\mathcal{H}}|\psi\rangle = i\hbar\frac{d}{dt}|\psi\rangle \qquad \hat{\mathcal{H}} = \hat{\mathcal{H}}(\mathbf{k}(t))$$: Energy operator

- The wave function for an eigenstate

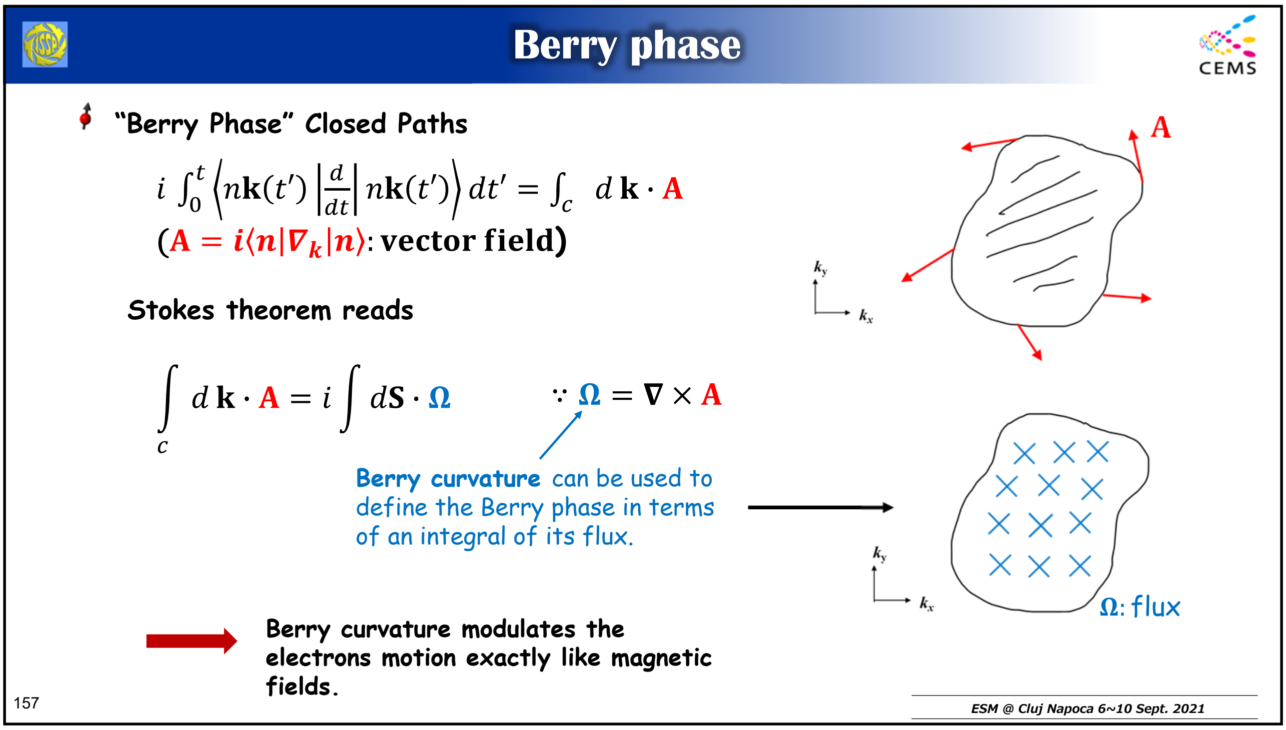
$$|\psi\rangle = e^{-i\phi(t)}|n\rangle$$ for an eigenstate

Phase

$$\phi(t) = \frac{1}{\hbar}\int_0^t E_n\mathbf{k}(t')dt' - i\int_0^t \left\langle n\mathbf{k}(t')\left|\frac{d}{dt}\right|n\mathbf{k}(t')\right\rangle dt'$$

Conventional
Dynamical phase

Berry phase: which depends on the time derivative of the wave function. It is important in the case of time dependent adiabatic transport.



Berry phase

- "Berry Phase" Closed Paths

$$i\int_0^t \left\langle n\mathbf{k}(t')\left|\frac{d}{dt}\right|n\mathbf{k}(t')\right\rangle dt' = \int_C d\,\mathbf{k}\cdot\mathbf{A}$$

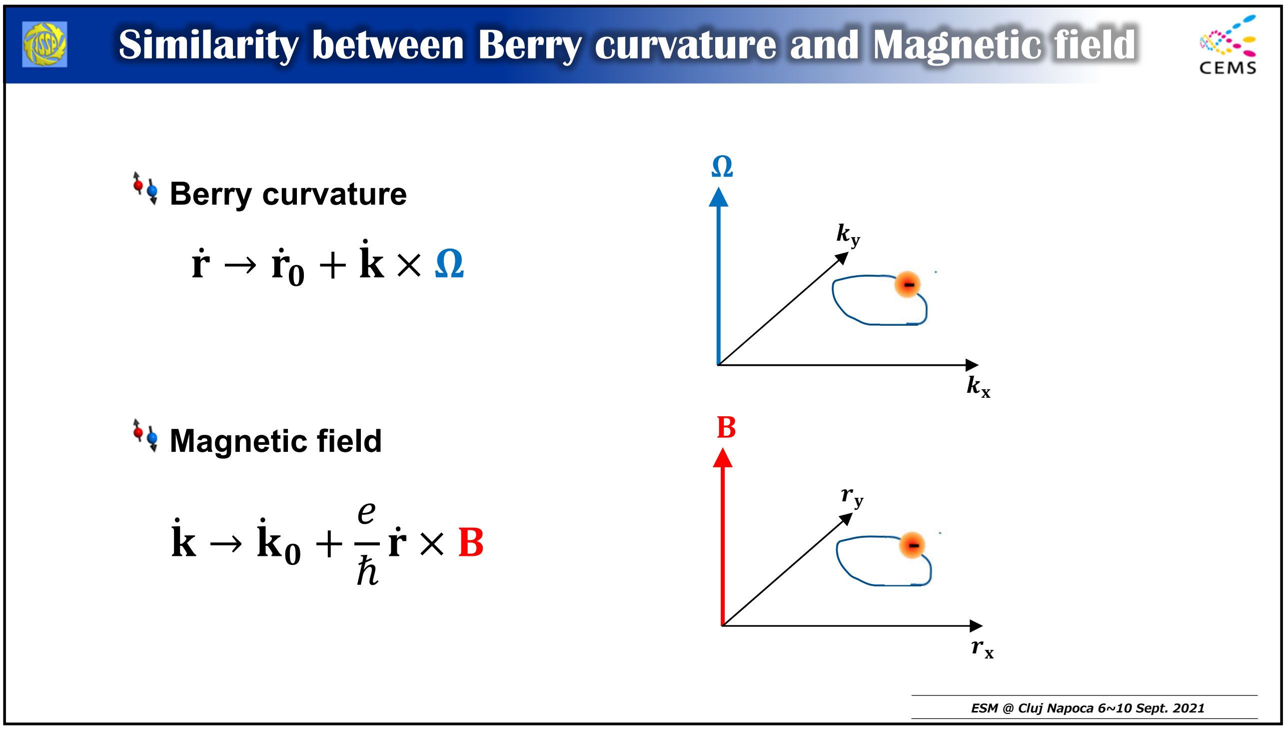
$(\mathbf{A} = i\langle n|\nabla_k|n\rangle$: vector field)

Stokes theorem reads

$$\int_C d\,\mathbf{k}\cdot\mathbf{A} = i\int d\mathbf{S}\cdot\mathbf{\Omega} \qquad \because\ \mathbf{\Omega} = \nabla\times\mathbf{A}$$

Berry curvature can be used to define the Berry phase in terms of an integral of its flux.

Berry curvature modulates the electrons motion exactly like magnetic fields.



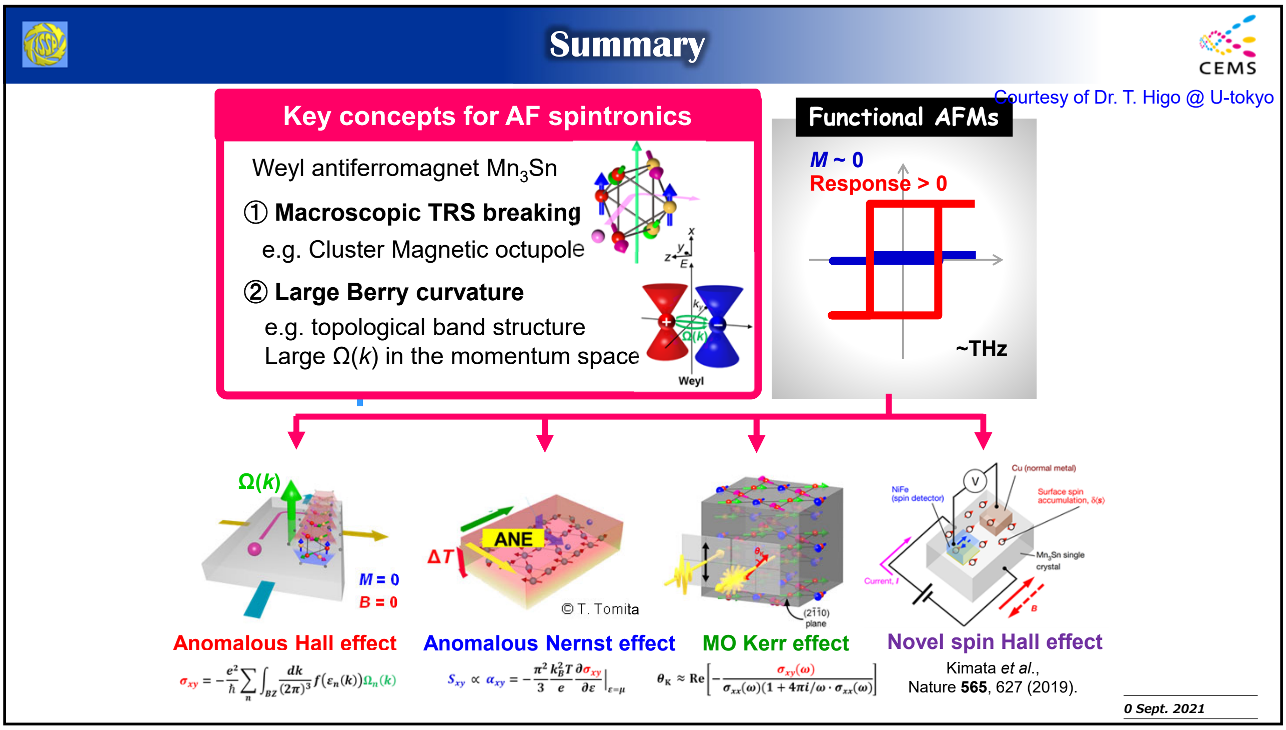
Similarity between Berry curvature and Magnetic field

- Berry curvature

$$\dot{\mathbf{r}} \rightarrow \dot{\mathbf{r}}_0 + \dot{\mathbf{k}}\times\mathbf{\Omega}$$

- Magnetic field

$$\dot{\mathbf{k}} \rightarrow \dot{\mathbf{k}}_0 + \frac{e}{\hbar}\dot{\mathbf{r}}\times\mathbf{B}$$



Summary

Courtesy of Dr. T. Higo @ U-tokyo

Key concepts for AF spintronics

Weyl antiferromagnet Mn_3Sn

① **Macroscopic TRS breaking**

e.g. Cluster Magnetic octupole

② **Large Berry curvature**

e.g. topological band structure

Large $\Omega(k)$ in the momentum space

Functional AFMs

$M \sim 0$

Response > 0

~THz

Anomalous Hall effect

$$\sigma_{xy} = -\frac{e^2}{\hbar}\sum_n \int_{BZ} \frac{dk}{(2\pi)^3} f(\varepsilon_n(k))\Omega_n(k)$$

Anomalous Nernst effect

$$S_{xy} \propto \alpha_{xy} = -\frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial\sigma_{xy}}{\partial\varepsilon}\Big|_{\varepsilon=\mu}$$

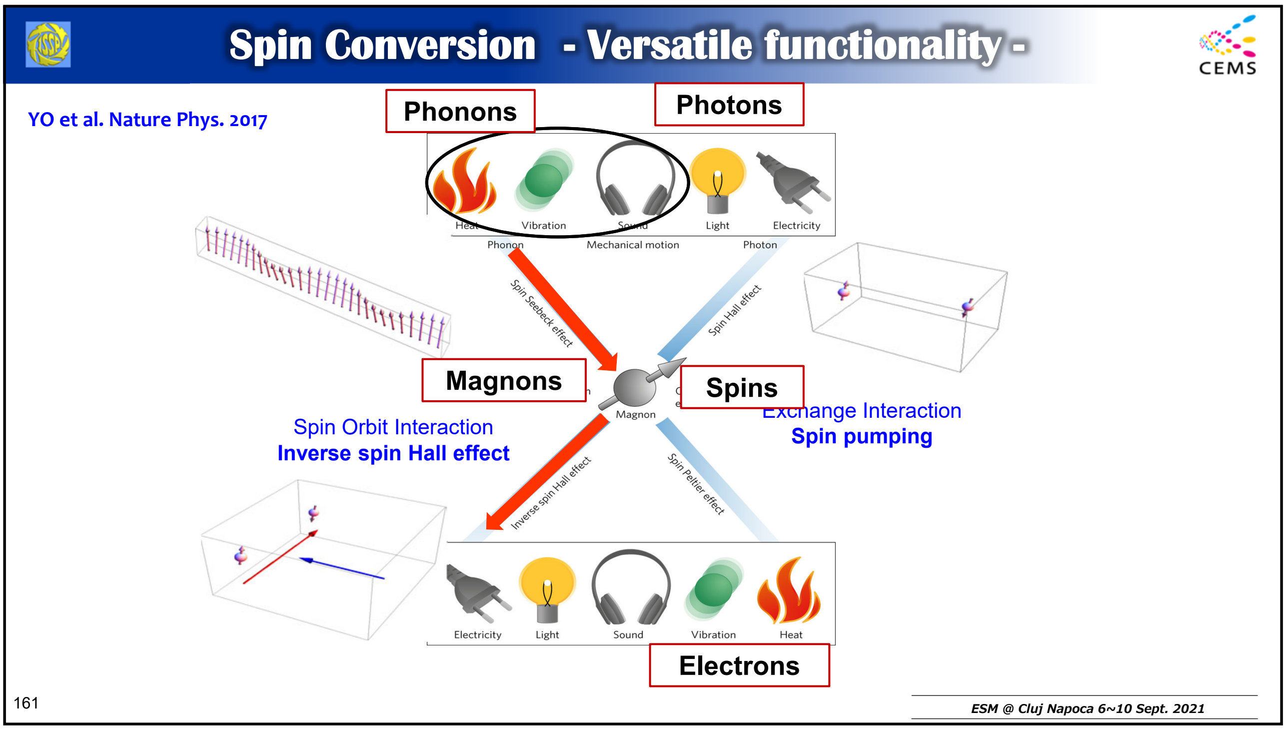
MO Kerr effect

$$\theta_K \approx \mathrm{Re}\left[-\frac{\sigma_{xy}(\omega)}{\sigma_{xx}(\omega)(1+4\pi i/\omega\cdot\sigma_{xx}(\omega))}\right]$$

Novel spin Hall effect

Kimata *et al.*,
Nature **565**, 627 (2019).

ii. Strong coupling



Spin Conversion - Versatile functionality -

YO et al. Nature Phys. 2017

Phonons

Photons

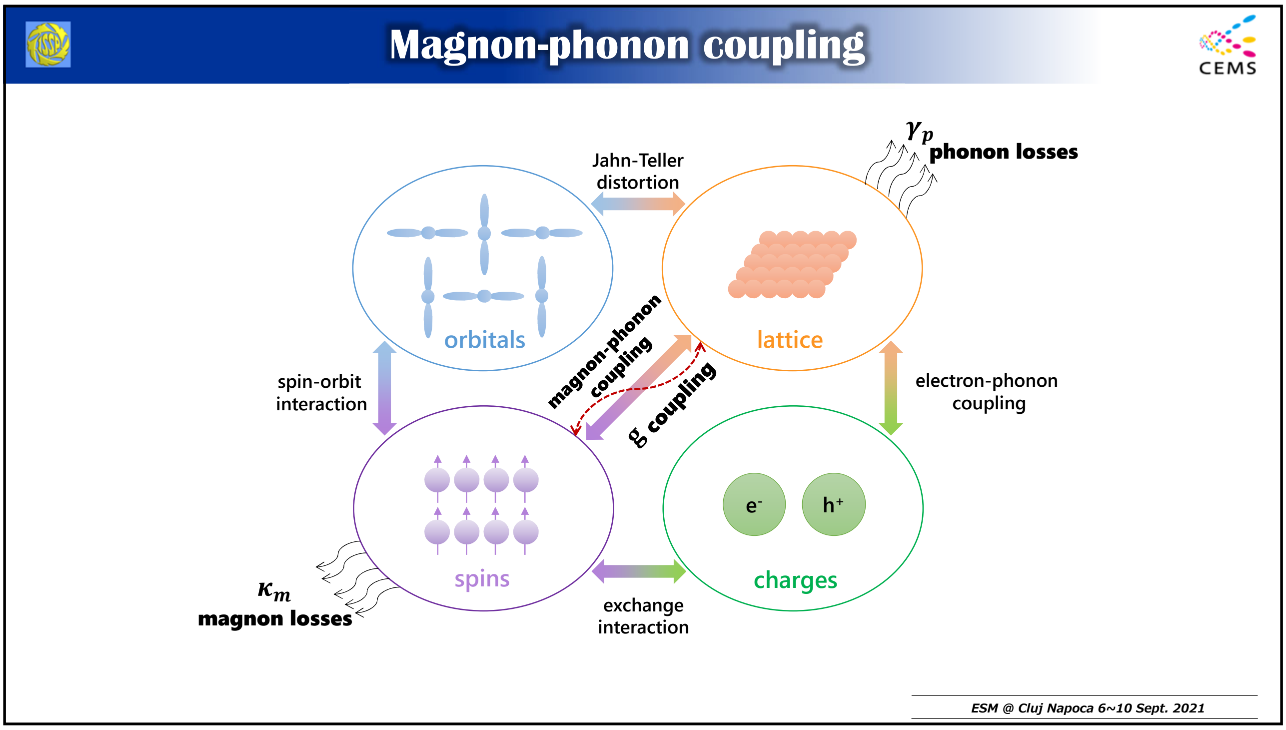
Magnons

Spins

Electrons

Spin Orbit Interaction
Inverse spin Hall effect

Exchange Interaction
Spin pumping

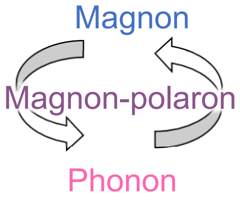


Magnon-phonon coupling

Magnon-phonon coupling

- **Two dispersion curves of magnon and phonon make level crossing, resulting in a hybridized state magnetic polaron**

Quantized spin waves, excitation state of spin structure.

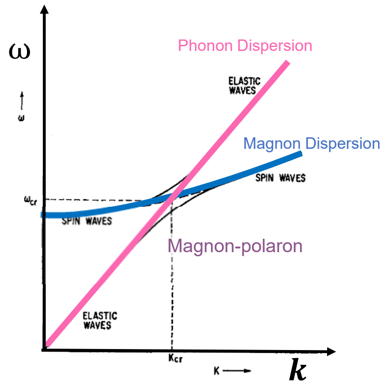


Magnon

Magnon-polaron

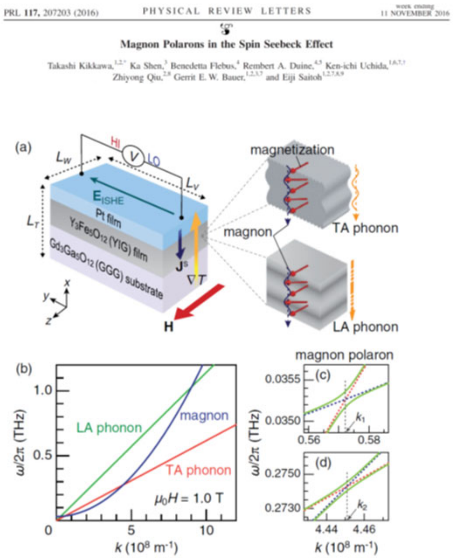
Phonon

Quantized elastic waves, excitation state of lattice.



J. R. Eshbach, Journal of Applied Physics **34**, 1298 (**1963**);

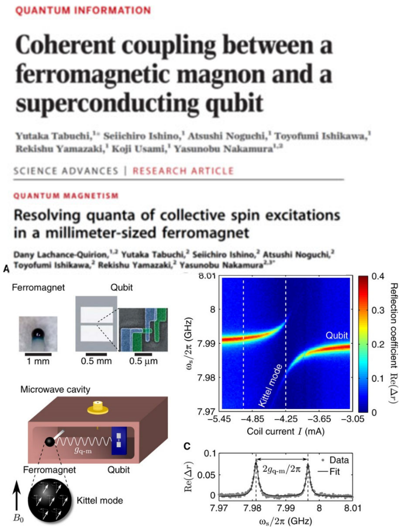
Novel type of coupling



PRL **117,** 207203 (2016) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2016

Magnon Polarons in the Spin Seebeck Effect

Takashi Kikkawa,[1,2,*] Ka Shen,[3] Benedetta Flebus,[4] Rembert A. Duine,[4,5] Ken-ichi Uchida,[1,6,7,†] Zhiyong Qiu,[2,8] Gerrit E. W. Bauer,[1,2,3,7] and Eiji Saitoh[1,2,7,8,9]



QUANTUM INFORMATION

Coherent coupling between a ferromagnetic magnon and a superconducting qubit

Yutaka Tabuchi,[1*] Seiichiro Ishino,[1] Atsushi Noguchi,[1] Toyofumi Ishikawa,[1] Rekishu Yamazaki,[1] Koji Usami,[1] Yasunobu Nakamura[1,2]

SCIENCE ADVANCES | RESEARCH ARTICLE

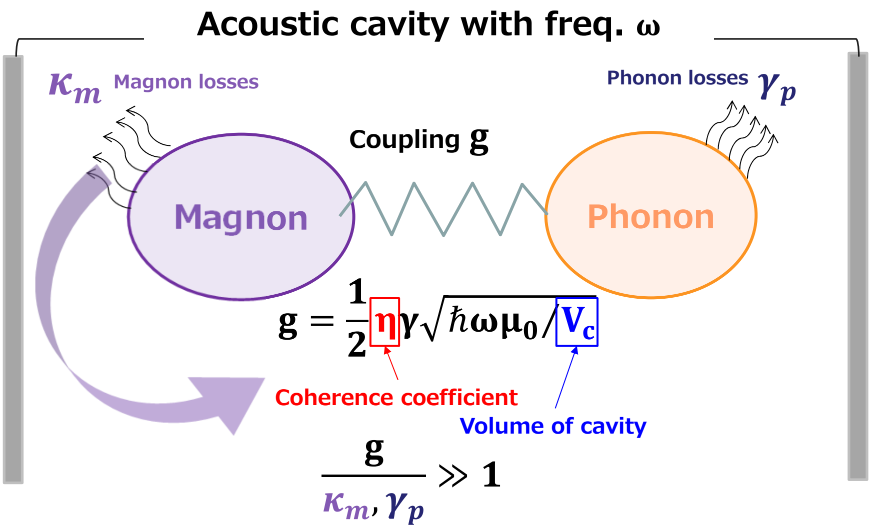
QUANTUM MAGNETISM

Resolving quanta of collective spin excitations in a millimeter-sized ferromagnet

Dany Lachance-Quirion,[1,2] Yutaka Tabuchi,[2] Seiichiro Ishino,[2] Atsushi Noguchi,[2] Toyofumi Ishikawa,[2] Rekishu Yamazaki,[2] Yasunobu Nakamura[2,3*]

Y. Tabuchi *et al.*, Science **349,** 405 (2015)
D. Lachance-Quirion *et al.*, Sci. Adv. **3,** e1603150 (2017)

Spin cavitronics



$$g = \frac{1}{2}\boxed{\eta}\gamma\sqrt{\hbar\omega\mu_0/\boxed{V_c}}$$

$$\frac{g}{\kappa_m, \gamma_p} \gg 1$$

Summary

1. Introduction
2. Basics of electrical transport
    i. Free electrons motion in a crystal
    ii. Transport in ferromagnets
    iii. Two currents model for ferromagnets
3. Spin currents and spin dynamics
    i. Spin current
    ii. Spin dynamics
    iii. Interaction of spin currents and spin dynamics

1_{st} Part

4. Spin conversion phenomena
    i. Spin Hall effect in metals
    ii. Edelstein effect (Rashba Interface & TI surface state)
    iii. Magnetic spin Hall effect
5. New directions in spintronics
    i. Antiferromagnetic spintronics
    ii. Strong coupling

2_{nd} Part

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Prof. T. Higo @ U-Tokyo for sharing his materials about non-collinear AFMs

All group members @ ISSP U-Tokyo and CEMS RIKEN

Thank you
for your kind attention