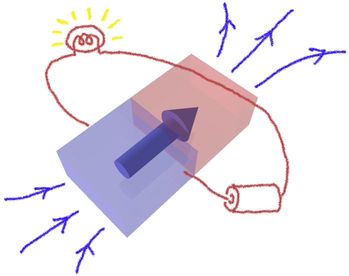
Electron transport and magnetization dynamics in metallic ferromagnets

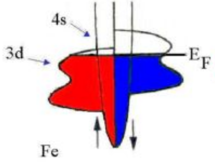
Gen TATARA

RIKEN Center for Emergent Matter Science (CEMS)

YKIS Kyoto 2014/12/04

Ferromagnetic metal





- Magnetization $\boldsymbol{M}(=\frac{g\mu_B}{a^3}\boldsymbol{S})$ (Localizied spin $\boldsymbol{S}$) d electron
- Finite electric conductivity Itinerant s electron

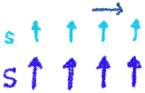
- sd interaction
  Between conduction electron spin $\boldsymbol{s}$ and localized spin

$$H_{\rm sd} = -J_{\rm sd}\boldsymbol{S}\cdot\boldsymbol{s}$$

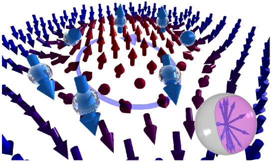
Strong $\Rightarrow$ Electron spin follows $\boldsymbol{S}$ perfectly Adiabatic limit

Ferromagnetic metal under electric current

- Uniform magnetization ⇒ No new feature



- Non uniform magnetization ⇒ Non-trivial transport



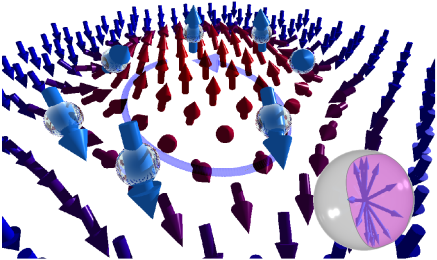
- Today's subjects
  - Rotation of conduction electron spin

    Spin Berry's phase ⇒ Spin electromagnetic field
  - Rotation of magnetization

    Spin-transfer torque ⇒ Magnetization dynamics

Spin electromagnetic field

Volovik'87, Stern'92, Barnes&Maekawa'07



Adiabatic limit

- Electron spin rotation

$\Rightarrow$ Phase $e^{i\varphi}$

$$\varphi = \int_C d\boldsymbol{r} \cdot \boldsymbol{A}_{\rm s}$$

- Spin magnetic field

$$\varphi = \int_S d\boldsymbol{S} \cdot \boldsymbol{B}_{\rm s}$$

- Spin electric field (dynamics)

$$\dot{\varphi} = -\int_C d\boldsymbol{r} \cdot \boldsymbol{E}_{\rm s}$$

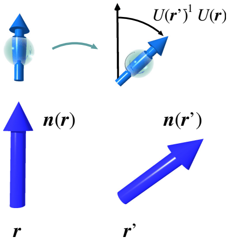
- Faraday's law is satisfied

$$\nabla \times \boldsymbol{E}_{\rm s} = -\frac{\partial \boldsymbol{B}_{\rm s}}{\partial t}$$

Electromagnetic field coupled to spin

Phase induced by localized spin

- Strong *sd* exchange interaction



- Electron spin $\parallel$ localized spin
- Electron wave function

$$|\theta\phi\rangle = \cos\frac{\theta}{2}|\uparrow\rangle + e^{i\phi}\sin\frac{\theta}{2}|\downarrow\rangle$$

- Overlap

$$\langle\theta'\phi'|\theta\phi\rangle = 1 + \frac{i}{2}(1-\cos\theta)\delta\phi \equiv e^{i\varphi}$$

- Effective vector potential $\quad \varphi = d\boldsymbol{r}\cdot\boldsymbol{A}_{\mathrm{s}}$

$$\boxed{\boldsymbol{A}_{\mathrm{s}} = \frac{1}{2}(1-\cos\theta)\partial\phi}$$

Phase induced by localized spin

- Effective vector potential   induced by *sd* interaction

$$\boldsymbol{A}_{\rm s} = \tfrac{1}{2}(1 - \cos\theta)\partial\phi$$

- Gauge interaction

$$\boxed{H_A = \int d^3r \boldsymbol{A}_{\rm s} \cdot \boldsymbol{j}_{\rm s}}$$

$\boldsymbol{j}_{\rm s}(= P\boldsymbol{j})$: Spin current ($P$: Spin polarization)

- Two effects
  - Current-induced torque on magnetization   Spin-transfer torque

$$\boldsymbol{B}_{\rm eff} = \frac{\delta H_A}{\delta \boldsymbol{S}} = \boldsymbol{S} \times (\boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S} \Rightarrow \boxed{\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S}}$$

  - Spin motive force on electron   Effective electromagnetic fields

$$\boldsymbol{E}_{\rm s} = -\nabla A_{{\rm s},0} + \partial_t \boldsymbol{A}_{\rm s} = -\frac{1}{2}\boldsymbol{n} \cdot (\dot{\boldsymbol{n}} \times \nabla_i \boldsymbol{n})$$

$$\boldsymbol{B}_{\rm s} = \nabla \times \boldsymbol{A}_{\rm s} = \frac{1}{4}\sum_{jk}\epsilon_{ijk}\boldsymbol{n} \cdot (\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$

Magnetization dynamics under current-induced torque

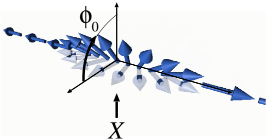
$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S}$$

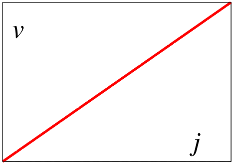
- Spin-transfer torque ⇒ Sliding of magnetization structure

$$(\partial_t - \boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S} = 0$$

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S}$$



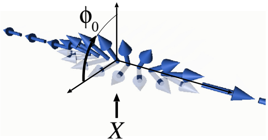


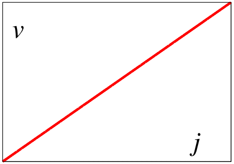
- Spin-transfer torque ⇒ Sliding of magnetization structure

$$(\partial_t - \boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S} = 0$$

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\mathrm{s}} \cdot \nabla)\boldsymbol{S} + \alpha(\boldsymbol{S} \times \dot{\boldsymbol{S}})$$





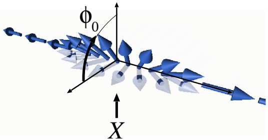
- Spin-transfer torque ⇒ Sliding of magnetization structure

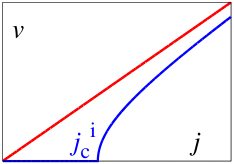
$$(\partial_t - \boldsymbol{j}_{\mathrm{s}} \cdot \nabla)\boldsymbol{S} = 0$$

- Damping (friction) Transverse torque ⇒ Screw motion

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S} + \alpha(\boldsymbol{S} \times \dot{\boldsymbol{S}}) + K_\perp(\boldsymbol{S} \times \boldsymbol{e}_y)$$





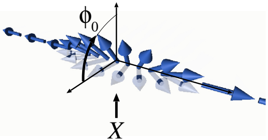
- Spin-transfer torque ⇒ Sliding of magnetization structure

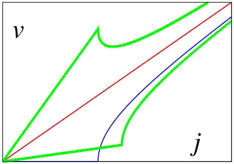
$$(\partial_t - \boldsymbol{j}_{\rm s} \cdot \nabla)\boldsymbol{S} = 0$$

- Damping (friction) Transverse torque ⇒ Screw motion
- Anisotropy energy $K_\perp (S_y)^2$ ⇒ Intrinsic pinning

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_s \cdot \nabla)\boldsymbol{S} + \alpha(\boldsymbol{S} \times \dot{\boldsymbol{S}}) + K_\perp(\boldsymbol{S} \times \boldsymbol{e}_y) + \beta[\boldsymbol{S} \times (\boldsymbol{j}_s \cdot \nabla)\boldsymbol{S}]$$





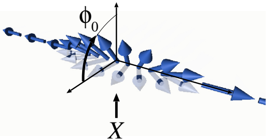
- Spin-transfer torque ⇒ Sliding of magnetization structure

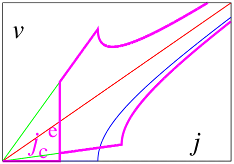
$$(\partial_t - \boldsymbol{j}_s \cdot \nabla)\boldsymbol{S} = 0$$

- Damping (friction) Transverse torque ⇒ Screw motion
- Anisotropy energy $K_\perp (S_y)^2$ ⇒ Intrinsic pinning
- Spin-orbit, spin relaxation of electron ⇒ Transverse torque β

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S} + \alpha(\boldsymbol{S}\times\dot{\boldsymbol{S}}) + K_\perp(\boldsymbol{S}\times\boldsymbol{e}_y) + \beta[\boldsymbol{S}\times(\boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S}] + \boldsymbol{\tau}_{\rm pin}$$





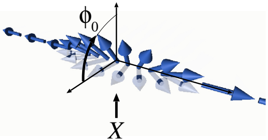
- Spin-transfer torque $\Rightarrow$ Sliding of magnetization structure

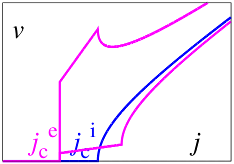
$$(\partial_t - \boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S} = 0$$

- Damping (friction)   Transverse torque $\Rightarrow$ Screw motion
- Anisotropy energy $K_\perp(S_y)^2 \Rightarrow$ Intrinsic pinning
- Spin-orbit, spin relaxation of electron $\Rightarrow$ Transverse torque β
- (Extrinsic) Pinning

Magnetization dynamics under current-induced torque

$$\dot{\boldsymbol{S}} = (\boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S} + \alpha(\boldsymbol{S}\times\dot{\boldsymbol{S}}) + K_\perp(\boldsymbol{S}\times\boldsymbol{e}_y) + \beta[\boldsymbol{S}\times(\boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S}] + \boldsymbol{\tau}_{\rm pin}$$



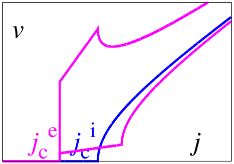


- Spin-transfer torque ⇒ Sliding of magnetization structure

$$(\partial_t - \boldsymbol{j}_{\rm s}\cdot\nabla)\boldsymbol{S} = 0$$

- Damping (friction) Transverse torque ⇒ Screw motion
- Anisotropy energy $K_\perp(S_y)^2$ ⇒ Intrinsic pinning
- Spin-orbit, spin relaxation of electron ⇒ Transverse torque β
- (Extrinsic) Pinning

Domain wall dynamics under current

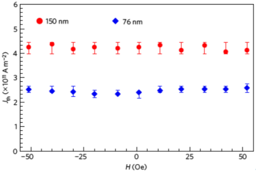


- $\beta \lesssim \alpha$ Intrinsic pinning
  - Threshold current

$$j_c = \frac{eS^2}{\hbar a^3 P} K_\perp \lambda$$

  - Stable operation

Insensitive to defects, external field

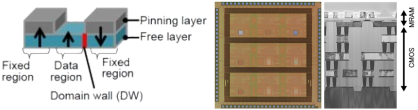


Koyama'11

- $\beta \gtrsim \alpha$ Extrinsic pinning
  - Threshold current

$$j_c \propto \frac{V_{\rm pin}}{\beta}$$

  - Strong spin-orbit interaction for low j_c large β

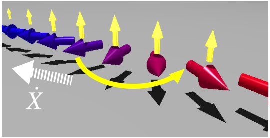


Domain wall MRAM (NEC)

Current-induced torque

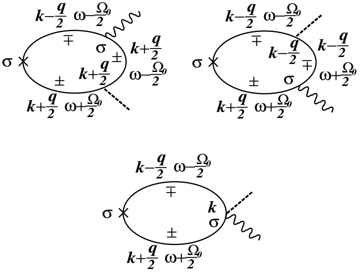
- Non-equilibrium conduction electron spin polarization $\delta \boldsymbol{s}$

$$\boldsymbol{\tau} = J_{sd} \delta \boldsymbol{s} \times \boldsymbol{S}$$



$$\boldsymbol{E}, \boldsymbol{j} \Rightarrow \delta \boldsymbol{s} \Rightarrow \boldsymbol{\tau}$$

- Calculation of non-equilibrium spin density



Thermally-induced torque

$$\nabla T \Rightarrow \delta \boldsymbol{s} \Rightarrow \boldsymbol{\tau}$$

- Luttinger's 'gravitaional potential' Ψ
- Equilibrium torque needs to be carefully subtracted
  Kohno,Hatami,Bauer'14

$$H_T = \int d^3 r \mathcal{E} \Psi$$

$\mathcal{E}$: Energy density

$$\nabla \Psi \sim \frac{\nabla T}{T}$$

- Vector potential formulation of thermal effect (?)

$$H_T = \int d^3 r \boldsymbol{A}_T \cdot \boldsymbol{j}_{\mathcal{E}}$$

$\boldsymbol{j}_{\mathcal{E}}$: Energy current

$$\dot{\boldsymbol{A}}_T \sim \frac{\nabla T}{T}$$

$$\dot{\mathcal{S}} = -\int d^3 r \frac{1}{T} \nabla \cdot \boldsymbol{j}_{\mathcal{E}}$$

Entropy change

Recent topics : Interface effects

- Rashba spin-orbit interaction   Inversion symmetry broken

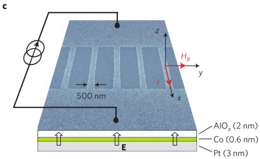
$$\boxed{H_{\rm R} = i\boldsymbol{E}_{\rm R} \cdot (\nabla \times \boldsymbol{\sigma})}$$

$\boldsymbol{E}_{\rm R}$: Rashba field

  - Large force on domain wall $\Rightarrow$ Efficient motion

Obata&GT'08,Manchon&Zhang'09

- Experiment   *Miron'10,'11*
  - Pt/Co/ALO layer   no inversion symmetry
  - $v = 400$ m/s   100 times larger
  - $j_c = 10^{12}$ A/m^2 same order
  - Rashba turned out not to be dominant



Recent topics : Interface effects

- Rashba spin-orbit interaction   Inversion symmetry broken

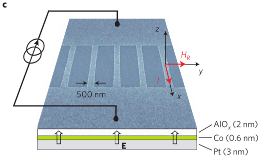
$$H_{\mathrm{R}} = i\boldsymbol{E}_{\mathrm{R}} \cdot (\nabla \times \boldsymbol{\sigma})$$

$\boldsymbol{E}_{\mathrm{R}}$: Rashba field

  - Large force on domain wall ⇒ Efficient motion

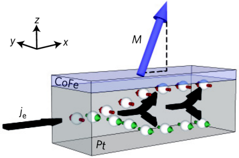
Obata&GT'08,Manchon&Zhang'09

- Experiment   *Miron'10,'11*
  - Pt/Co/ALO layer   no inversion symmetry
  - $v = 400$ m/s   100 times larger
  - $j_{\mathrm{c}} = 10^{12}$ A/m^2 same order
  - Rashba turned out not to be dominant



- Spin Hall torque   *Emori'13*

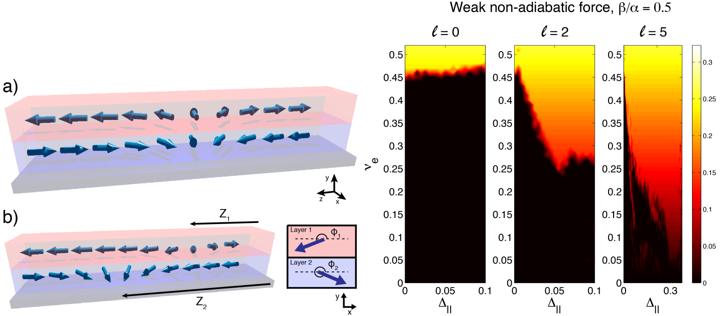
Spin Hall effect in heavy metal (Pt) layer
⇒ Large torque $v > 100$ m/s



Recent topics : Interface effects

- Synthetic antiferromagnetic system   Coupled two domain walls

Saarikoski, Kohno, Marrows, GT'14

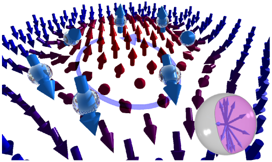


- Interlayer coupling removes random extrinsic pinning

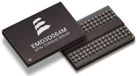
Two walls help each other to depin

Fast wall motion at low current by artificial structures

Electron transport in ferromagnetic metal



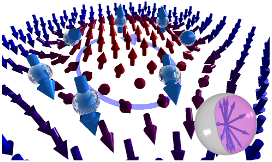
- Rotation of magnetization
  Spin-transfer torque ⇒ Current-induced magnetization dynamics



Magnetic memory (MRAM)

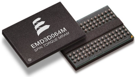
- Rotation of conduction electron spin
  Spin Berry's phase ⇒ Spin electromagnetic field

Electron transport in ferromagnetic metal



- Rotation of magnetization

  Spin-transfer torque $\Rightarrow$ Current-induced magnetization dynamics

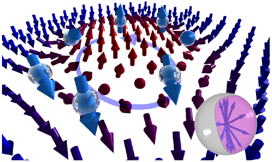


Magnetic memory (MRAM)

- Rotation of conduction electron spin

  Spin Berry's phase $\Rightarrow$ Spin electromagnetic field

Spin electromagnetic field



- Effective vector potential

$$\boldsymbol{A}_{\mathrm{s}} = \tfrac{1}{2}(1 - \cos\theta)\partial\phi$$

- Effective electromagnetic fields

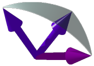
$$\boldsymbol{E}_{\mathrm{s}} = -\nabla A^{z}_{\mathrm{s},0} + \partial_t \boldsymbol{A}^{z}_{\mathrm{s}} = -\frac{1}{2}\boldsymbol{n}\cdot(\dot{\boldsymbol{n}} \times \nabla_i \boldsymbol{n})$$

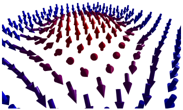
$$\boldsymbol{B}_{\mathrm{s}} = \nabla \times \boldsymbol{A}^{z}_{\mathrm{s}} = \frac{1}{4}\sum_{jk}\epsilon_{ijk}\boldsymbol{n}\cdot(\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$

Spin electromagnetic field

- Spin magnetic field

$$\boldsymbol{B}_{\mathrm{s},i} = \frac{\hbar}{4e}\sum_{jk}\epsilon_{ijk}\boldsymbol{n}\cdot(\nabla_j\boldsymbol{n}\times\nabla_k\boldsymbol{n})$$

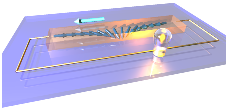




- Chirality (non-coplanarity)
- Frustrated magnets, Magnetic skyrmion
  $\sim$ 0.8 T for 30 nm size

- Spin electric field

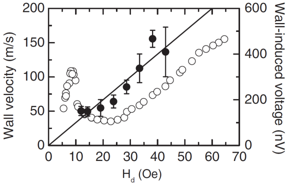
$$\boldsymbol{E}_{\mathrm{s},i} = -\frac{\hbar}{2e}\boldsymbol{n}\cdot(\dot{\boldsymbol{n}}\times\nabla_i\boldsymbol{n})$$

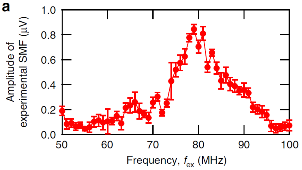


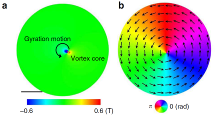
- Non-coplanarity in space-time
- Moving structures $E_\mathrm{s} \propto v$
  Domain wall, vortex, skyrmion
  $\sim$ 0.1 V/m for 10 nm DW @ $v = 4$ m/s

Current generation from magnetization dynamics

- $\boldsymbol{E}_\mathrm{s}$ from motion of domain wall, vortex $\quad V \sim \mu\mathrm{V},\ \boldsymbol{E}_\mathrm{s} \propto \boldsymbol{v}$

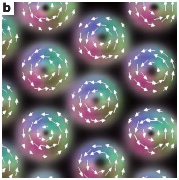


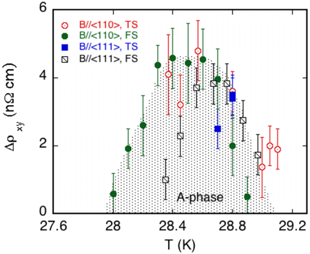


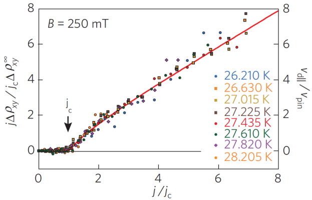


Domain wall *Yang'09* Vortex *Tanabe'12*

- Skyrmion lattice $\quad \rho_{xy} \sim 4\mathrm{n}\Omega\mathrm{cm} \propto \boldsymbol{B}_\mathrm{s}$







Topological Hall effect $\boldsymbol{B}_\mathrm{s}$ Voltage $\boldsymbol{E}_\mathrm{s} \propto \boldsymbol{v}$

Yu'10 *Lee'09, Neubauer'09* *Schulz'12*

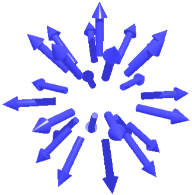
Monopole in adiabatic spin Berry's phase

$$\boldsymbol{E}_{\rm s} = -\frac{\hbar}{2e}\left[\boldsymbol{n}\cdot(\dot{\boldsymbol{n}} \times \nabla_i \boldsymbol{n})\right]$$
$$\boldsymbol{B}_{\rm s} = \frac{\hbar}{4e}\epsilon_{ijk}\boldsymbol{n}\cdot(\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$

- Satisfy Maxwell's equations with monopole

$$\boldsymbol{\nabla} \times \boldsymbol{E}_{\rm s} + \partial_t \boldsymbol{B}_{\rm s} = \boldsymbol{j}_{\rm m}$$
$$\boldsymbol{\nabla} \cdot \boldsymbol{B}_{\rm s} = \rho_{\rm m}$$

$$\boldsymbol{j}_{\rm m} = \frac{\hbar}{4e}\sum_{jk}\dot{\boldsymbol{n}}\cdot(\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$
$$\rho_{\rm m} = \frac{\hbar}{4e}\sum_{ijk}\nabla_i \boldsymbol{n}\cdot(\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$



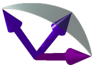
Topological monopole (Hedgehog)

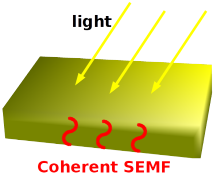
Coupling to electromagnetic fields

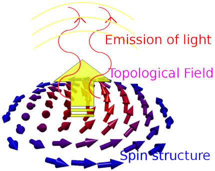
Effective interaction Hamiltonian *Kawaguchi,GT'14*

$$H_{\rm int} = \frac{e^2}{m}\int {\rm d}^3 r \left(2s_{\rm e}\tau \boldsymbol{E}\cdot\boldsymbol{A}_{\rm s} + 2s_{\rm e}\tau^2 \boldsymbol{E}\cdot\boldsymbol{E}_{\rm s} + b\boldsymbol{B}\cdot\boldsymbol{B}_{\rm s}\right)$$

τ: Electron elastic lifetime

- $\boldsymbol{A}_{\rm s}$ is physical field   Large *sd* splitting
- First term : Spin-transfer effect
- $B \Rightarrow B_{\rm s}$: Frustration 



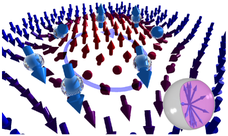


Electromagnetic excitation of spin electromagnetic fields (?)

Current generation from magnetization dynamics

- Spin Berry's phase

  Gradient of spin $\nabla \boldsymbol{S} \Rightarrow$ Effective gauge field, $\boldsymbol{E}_{\mathrm{s}}$, $\boldsymbol{B}_{\mathrm{s}}$



- Spin-orbit interaction

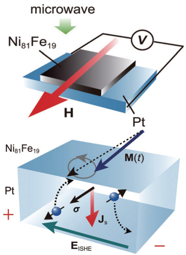
$$\boxed{H_{\mathrm{so}} = \boldsymbol{\lambda} \cdot (\boldsymbol{p} \times \boldsymbol{\sigma})}$$

  - Directly couples spin and electron motion
  - Current generation ?
  - Modification of spin Berry's phase ?

    Kim'12,Takeuchi'12,Nakabayashi'14,Takashima,Fujimoto'14

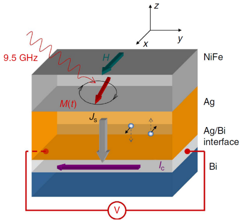
Charge current pumped by magnetization

- Spin pumping + Inverse spin Hall *Saitoh'06*



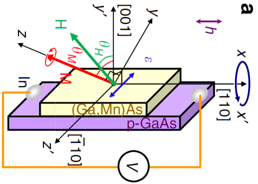
- Ferro/Pt
- Spin-orbit in heavy metal
- $\dot{\boldsymbol{M}} \Rightarrow \boldsymbol{j}_\mathrm{s} \Rightarrow \boldsymbol{j}$
- 4μV @ mW microwave

- Spin pumping + Inverse Edelstein *Sanchez'13*



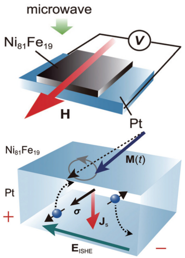
- Ferro/Ag/Bi
- Rashba spin-orbit at Ag/Bi interface
- $\dot{\boldsymbol{M}} \Rightarrow \boldsymbol{j}_\mathrm{s} \Rightarrow \boldsymbol{s} \Rightarrow \boldsymbol{j}$

- (Ga,Mn)As *Chen'13*



- Uniform ferromagnet
- Strong spin-orbit
- $\dot{\boldsymbol{M}} \Rightarrow \boldsymbol{j}$

Spin pumping and inverse spin Hall effects



- Spin pumping

$$j_\mathrm{s} = g_{\updownarrow} \tanh \frac{d}{2\lambda_s} \langle \boldsymbol{S} \times \dot{\boldsymbol{S}} \rangle$$

$g_{\upharpoonleft\downharpoonright}$: Mixing conductance   Spin flip at interface

- Inverse spin Hall

$$V = \rho_\mathrm{n} \theta_\mathrm{SHE} j_\mathrm{s}$$

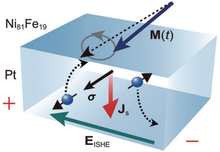
θ_SHE : Spin Hall angle   Spin-orbit interaction

- $V = \theta_\mathrm{SHE} \rho_\mathrm{n} g_{\updownarrow} \tanh \frac{d}{2\lambda_s} \langle \boldsymbol{S} \times \dot{\boldsymbol{S}} \rangle$

- Useful but incomplete description
  - Two phenomenological parameters $\theta_\mathrm{SHE}, g_{\updownarrow}$
  - Spin current is not defined uniquely   Not conserved current
  - $j \neq \theta_\mathrm{SHE} j_\mathrm{s}$ in a simple theoretical model   *Takeuchi,GT'10*

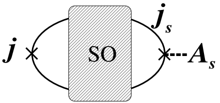
Spin pumping and inverse spin Hall effects

- Relation between observables



- $\dot{\boldsymbol{M}} \Rightarrow \boldsymbol{j}$
- Calculate current and motive force

- Feynman diagram

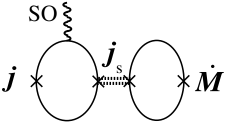


$$H_A = \int d\boldsymbol{r}\, \boldsymbol{j}_{\rm s} \cdot \boldsymbol{A}_{\rm s}$$

$\boldsymbol{j}_{\rm s}$: Spin current

$\boldsymbol{A}_{\rm s} \sim \dot{\boldsymbol{M}}, \nabla \boldsymbol{M}$: Spin gauge field

- Conventional picture

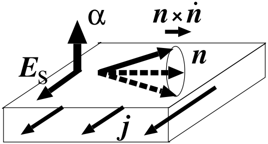


Different effect

Simple view of charge pumping

Takeuchi'12, GT PRB'13, Nakabayashi New J Phys'14

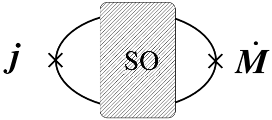
- Model



- *sd* interaction **n**: Magnetization
- Rashba & Random Spin-orbit interaction

$$H = \left(-\frac{\hbar^2}{2m}\nabla^2 - \epsilon_F\right) + \Delta_{\rm sd}\left(\boldsymbol{n}\cdot\boldsymbol{\sigma}\right) + \boldsymbol{\alpha}_{\rm R}\cdot\left(\boldsymbol{p}\times\boldsymbol{\sigma}\right) + \text{spin relaxation}$$

- Diagram calculation



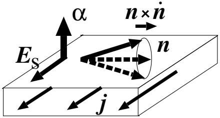
- Force $\boldsymbol{F} \equiv \frac{m}{en}\left\langle \frac{d\boldsymbol{j}}{dt}\right\rangle$
- Pumped current $\boldsymbol{j}$ with Hall contribution

Rashba-induced spin electromagnetic field

GT'13, Nakabayashi&GT, New J Phys.'14

- Result

$$\boldsymbol{j} = \frac{1}{\mu_s}\nabla \times \boldsymbol{B}_{\mathrm{R}} + \sigma_s \boldsymbol{E}_{\mathrm{R}}$$
$$\boldsymbol{F} = q_s \boldsymbol{E}_{\mathrm{R}} + q_s(\boldsymbol{v} \times \boldsymbol{B}_{\mathrm{R}})$$



Linear order in α_{R}

- Rashba-induced spin electromagnetic field

$$\boldsymbol{E}_{\mathrm{R}} = -\frac{m}{e\hbar}[\boldsymbol{\alpha}_{\mathrm{R}} \times (\dot{\boldsymbol{n}} + \beta_{\mathrm{R}}(\boldsymbol{n} \times \dot{\boldsymbol{n}}))]$$
$$\boldsymbol{B}_{\mathrm{R}} = \frac{m}{e\hbar}[\boldsymbol{\nabla} \times (\boldsymbol{\alpha}_{\mathrm{R}} \times \boldsymbol{n})]$$

β_{R} : spin relaxation rate

- $\boldsymbol{E}_{\mathrm{R}}$ & $\boldsymbol{B}_{\mathrm{R}}$: Effective spin electromagnetic fields
  $\boldsymbol{E}_{\mathrm{R}} \sim 2\mathrm{kV/m}$, $\boldsymbol{B}_{\mathrm{R}} \sim 0.2\mathrm{kT}$ Not charge electromagnetic fields
- Arise from Rashba interaction and spin dynamics
  Generalized spin Berry's phase

Effective spin electromagnetic field

- 'Maxwell's equations'

$$\begin{aligned} \boldsymbol{\nabla} \times \boldsymbol{E}_{\rm R} + \dot{\boldsymbol{B}}_{\rm R} &= \boldsymbol{j}_{\rm m} \\ \boldsymbol{\nabla} \cdot \boldsymbol{B}_{\rm R} &= 0 \\ \boldsymbol{\nabla} \cdot \boldsymbol{E}_{\rm R} &= -\frac{\rho_{\rm s}}{\epsilon_{\rm s}} \\ \boldsymbol{\nabla} \times \boldsymbol{B}_{\rm R} - \epsilon_{\rm s}\mu_{\rm s}\dot{\boldsymbol{E}}_{\rm R} &= \mu_{\rm s}\boldsymbol{j} \end{aligned}$$

- $\boldsymbol{j}_{\rm m} = \beta_{\rm R}\nabla \times (\boldsymbol{\alpha}_{\rm R} \times (\boldsymbol{n} \times \dot{\boldsymbol{n}}))$ Monopole current

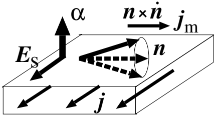
Monopole induced by magnetization dynamics and spin relaxation

$j_{\rm m}$ is not spin current

Effective spin electromagnetic field

- Current pumping by magnetization dynamics in Rashba system

$$\nabla \times \boldsymbol{E}_{\rm R} = \boldsymbol{j}_{\rm m}$$
$$\boldsymbol{j}_{\rm m} = \beta_{\rm R} \nabla \times (\boldsymbol{\alpha}_{\rm R} \times (\boldsymbol{n} \times \dot{\boldsymbol{n}}))$$



  - $\dot{\boldsymbol{M}} \to$ Monopole current $\boldsymbol{j}_{\rm m} \Rightarrow \boldsymbol{j}$
  - Effective electromagnetic fields satisfying Maxwell's eq. + monopole
  - Spin current is not necessary

Electromagnetic description of spintronics

Spintronics without spin current (?!)

Acknowledgements

Tokyo Metropolitan Univ. Akihito Takeuchi (→ Aoyama-gakuin),
Noriyuki Nakabayashi, Hideo Kawaguchi

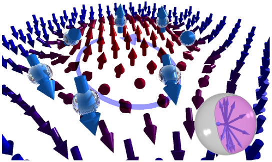
RIKEN Henri Saarikoski

Nagoya Univ. Hiroshi Kohno

Leeds Univ. Christopher H. Marrows

Grants Kakenhi 科研費 KAKENHI
Japan Society for the Promotion of Science and The Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan

Summary



- *sd* exchange interaction in ferromagnetic metals
- Effective vector potential for spin
  - Current-induced torque, Spin dynamics
  - Spin Berry's phase
- Spin-orbit effects
  - Novel driving mechanism of magnetization structures
    - Spin relaxation torque (β)
    - Rashba spin-orbit interaction   Interface, Multilayers
  - Modification of spin Berry's phase   Spin electromagnetic field
    - Spin-charge conversion
    - current generation by spin relaxation monopole $\nabla \times \boldsymbol{E}_{\rm R} = \boldsymbol{j}_{\rm m}$

References

- *Nakabayashi, GT, New J Phys,* **16***,015016(2014).*
- *Tatara, Nakabayashi, K.-J. Lee, Phys. Rev. B87,054403(2013).*
- *Takeuchi,Tatara, J. Phys. Soc. Jpn. 81,033705(2012).*
- *Kawaguchi, GT, J. Phys. Soc. Jpn.* **83***, 074710 (2014).*
- *Tatara, Takeuchi, Nakabayashi, Taguchi, J. Korean Phys. Soc. 61, 1331 (2012).*
- *GT, Kohno, Shibata, Phys. Rep. 468, 213 (2008)*
- 数理科学7月号(2014)

Post doc positions :   gen.tatara@riken.jp