Magnetism and Electron Transport in nano structures

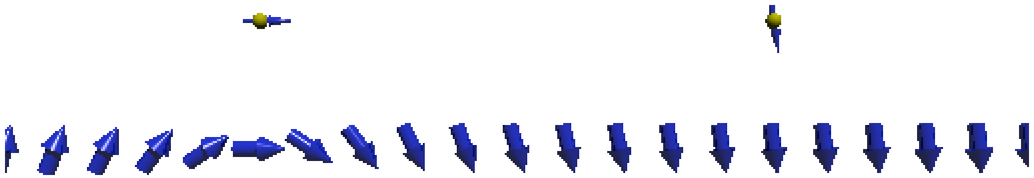


Figure courtesy of
Dr. J. Ohe

多々良源

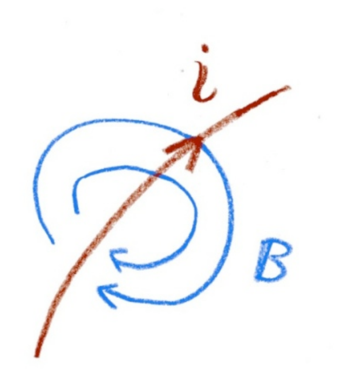
Gen Tatara

首都大学東京　大学院理工学研究科

Tokyo Metropolitan Univ. and PRESTO JST

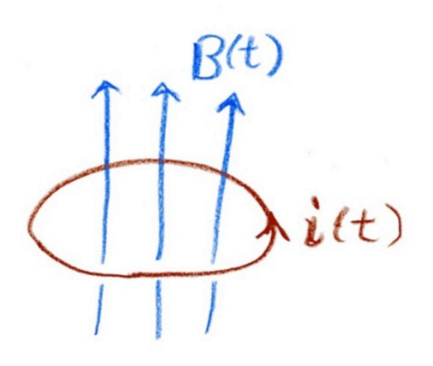
Hiroshi Kohno(Osaka), Junya Shibata(Kanagawa)
Junichiro Ohe(Hamburg), Akihito Takeuchi (TMU)

Magnetism and electric current



Current⇒Magnetic field

Ampere (~1820)

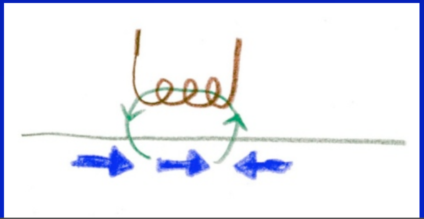


Magnetic field ⇒Current

Faraday (~1830)

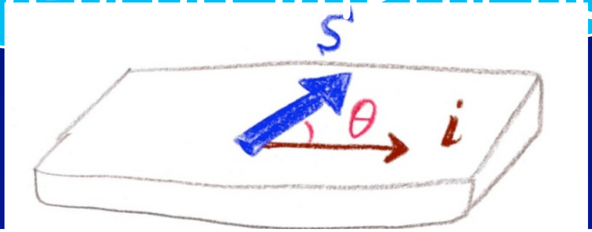
Ampere law:

write in mechanism of all magnetic devices



Beyond Maxwell equation

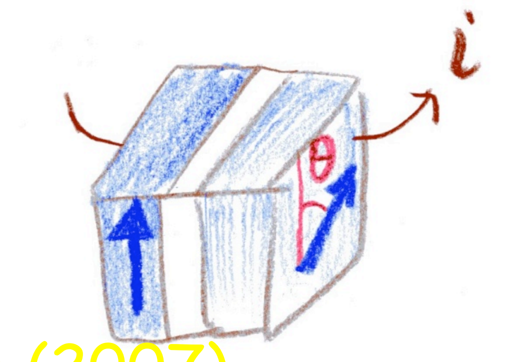
- Read out mechanism (20 cent.)
  - Spin-orbit interaction

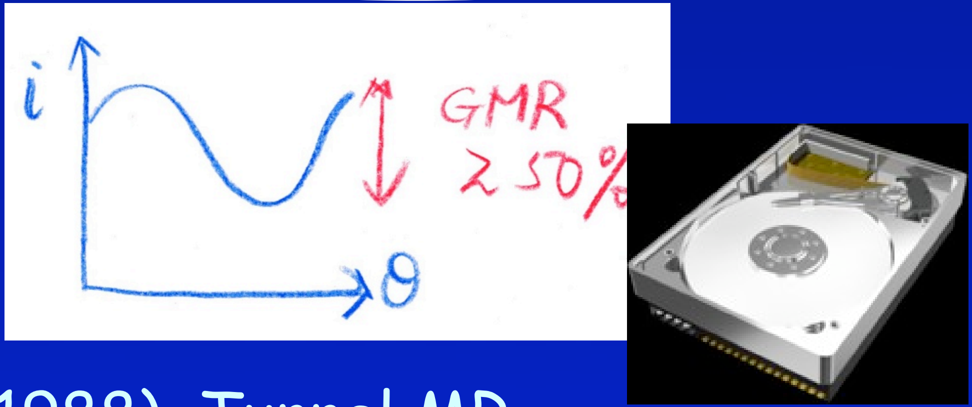


$$\rho(\theta) = \rho_0 + \delta\rho \sin^2\theta$$

AMR : Anisotropic MagnetoResistance

- Nanostructure and exchange interaction





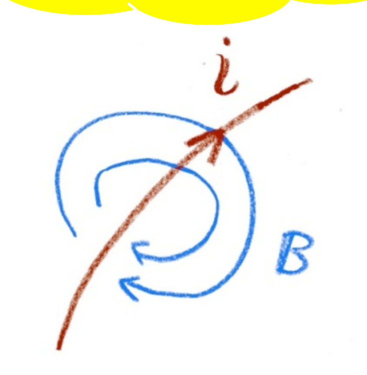
Nobel prize (2007)

GMR : Giant MR (1988), Tunnel MR

19 cent. 20 cent.~

Maxwell equation

current
⇓
magnetism

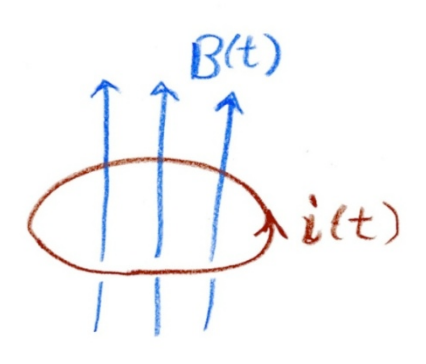


Ampere

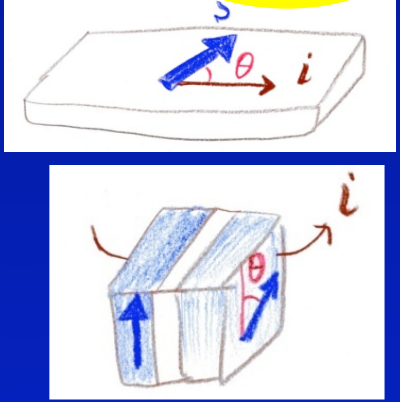
Material
and structure

Spin-orbit
Exchange interaction

magnetism
⇓
current



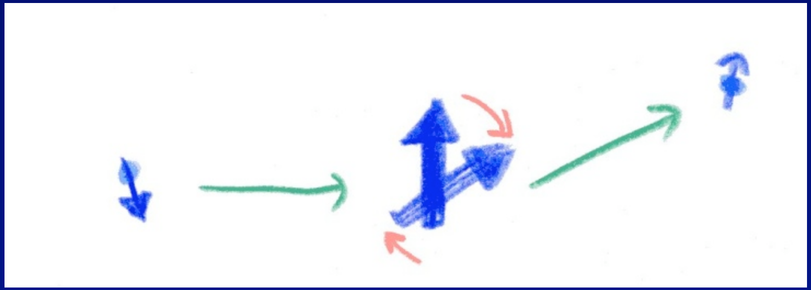
Faraday



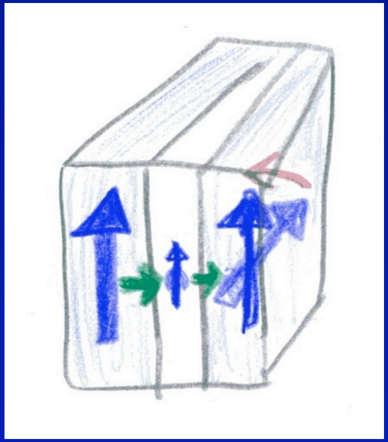
AMR, GMR('88),
TMR

- sd Exchange interaction

$$J\int dx\, \vec{S}(x)\times c^{+}\vec{\sigma}c(x)$$



Transfer of spin between local spin and conduction electron



Magnetization flip by spin polaralized current

Slonczewski, Berger '96

Spin transfer effect

Without magnetic field

19 cent.

20 cent.~

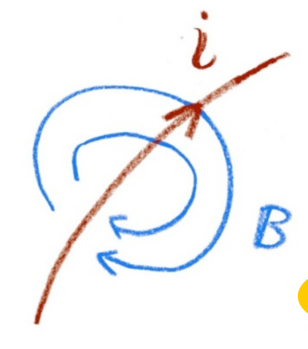
21 cent.~(??)

Maxwell equation

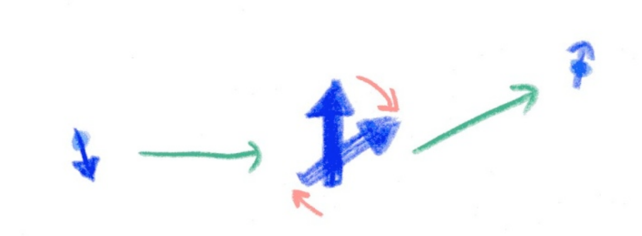
current

⇓

magnetism



Ampere



Spin transfer

Berger, Slonczewski

1978-, '96

Material

and structure

Spin-orbit

Exchange interaction

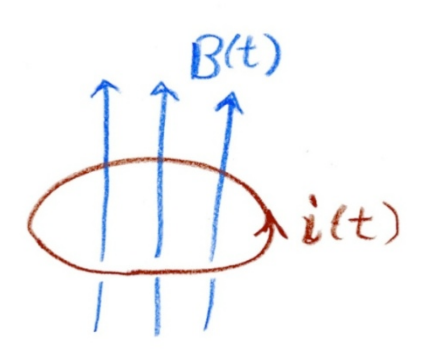
Efficient in

Nano scale

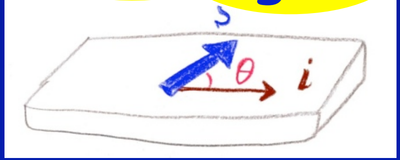
magnetism

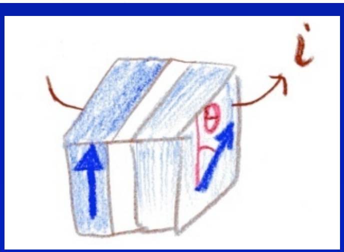
⇓

current



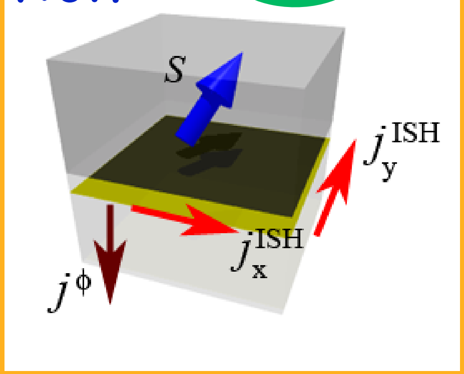
Faraday





AMR, GMR('88),

TMR



Inverse spin Hall

Saitoh,Miyajima'06

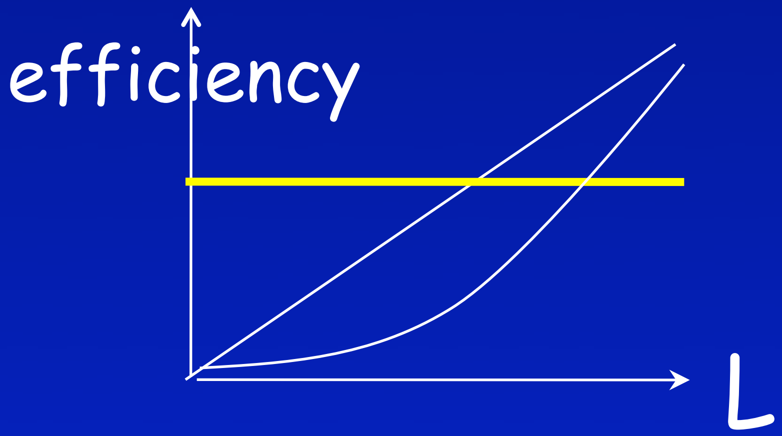
Why useful ?

- Effects survives in nano scale

⇔Ampere, Faraday

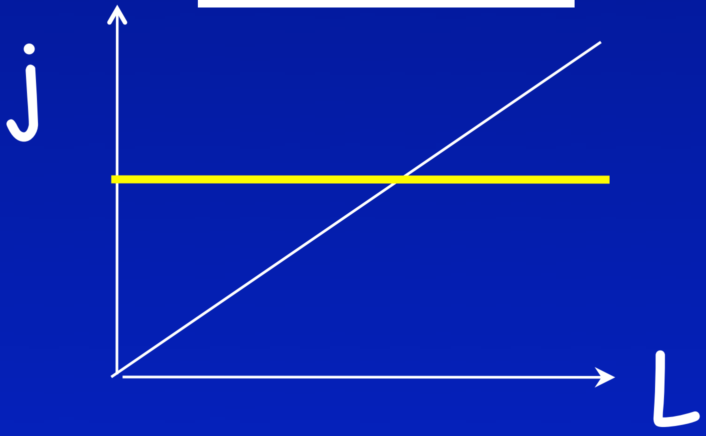
- Ampere field

$$B \propto I \propto L^2 j$$



- Faraday

$$j \propto \frac{S}{L}\dot{M} \propto L$$

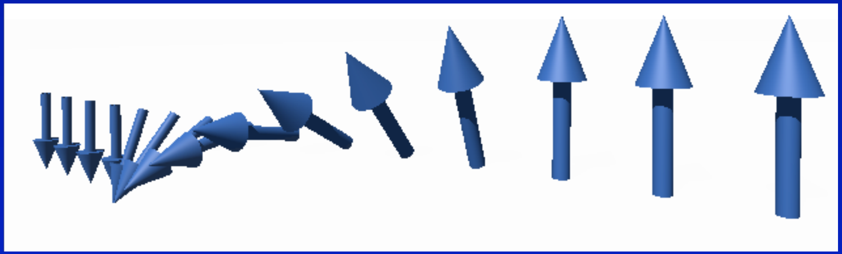


- Spin transfer and inverse spin Hall: remains finite for L→0

PART 1 :
Current-driven magnetization switching

- behavior of domain wall under current

- Does it moves by current?
- What is the threshold current?
- How fast?



Model

sd model of ferromangets

Rigid wall : $K >> K_\perp$

- Magnetization (local spin)
- Conduction electron

+Exchange interaction

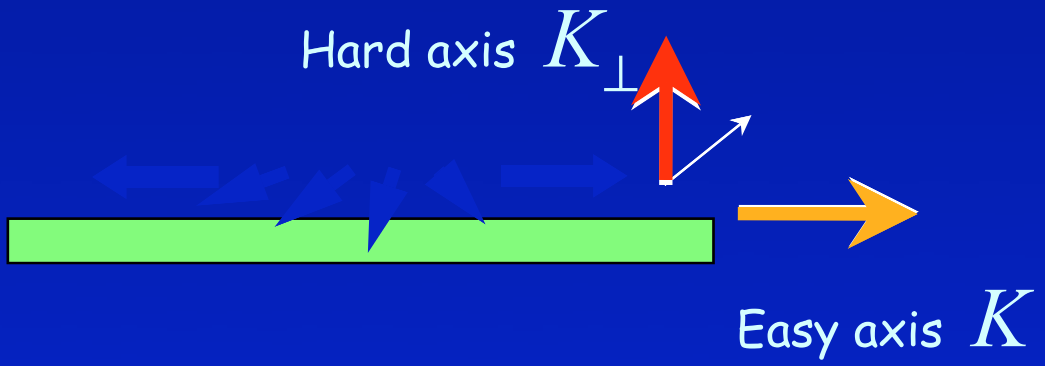
Rigidity of DW

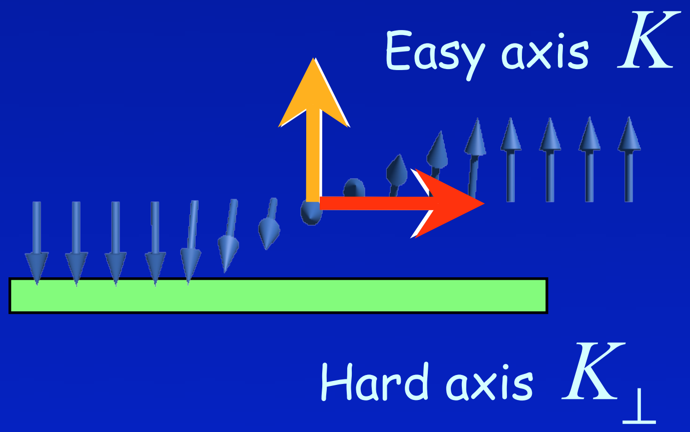
Out of plane
Energy
(dynamics)

$$L = \int dx \left(-\hbar S\dot{\phi}(1-\cos\theta) - \tfrac{1}{2}\left(J(\nabla S)^2 \boxed{- KS_z^2} \boxed{+ K_\perp S_y^2} \right)\right)$$

$$+ \sum_k c_k^+ \left(i\hbar\partial_t - \varepsilon_k\right) c_k + H_{sf} + \Delta \int dx\, \vec{S}(x) \times c^+ \vec{\sigma} c(x)$$

- Local spin part





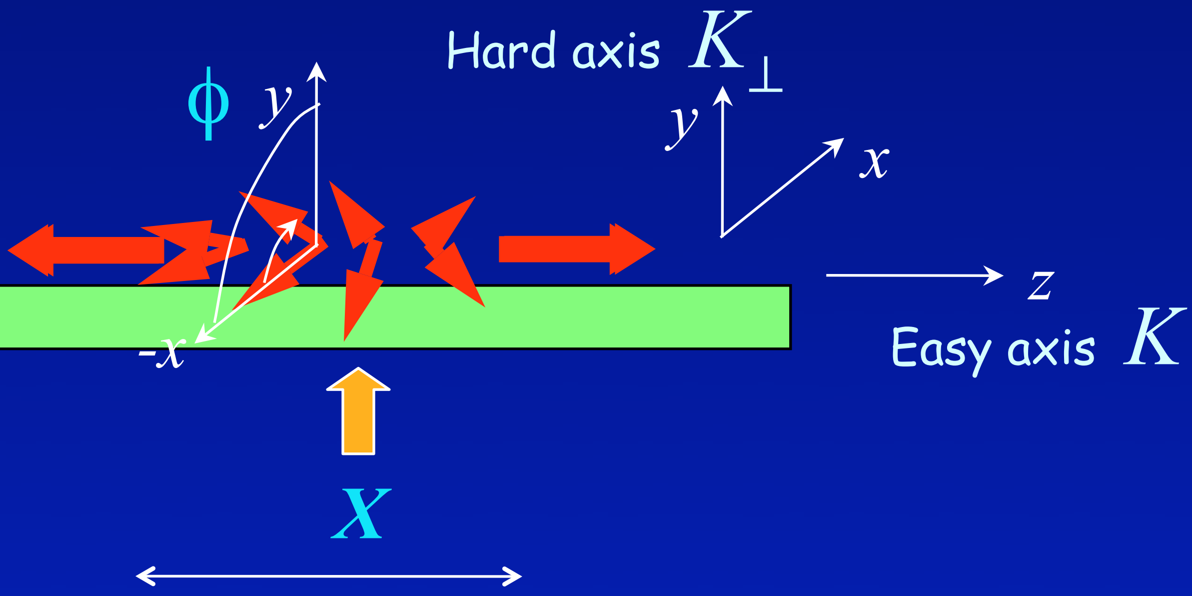
Perpendicular easy axis

Description of DW

Slonczewski ('72)
Berger ('78-93)
Braun & Loss ('96)
Takagi & GT ('96)

- Rigid 1D wall $K >> K_\perp$

Low energy dynamics of DW is described by X and ϕ



λ : wall thickness

Other deformations are high-energy mode

Model   sd model of ferromangets

- Magnetization (local spin)
- Conduction electron

+Exchange interaction

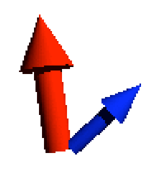
Close to adiabatic limit

$$\frac{v_F}{\lambda}\frac{\hbar}{\Delta} \ll 1$$

$$L = \int dx \left(-\hbar S\dot{\phi}(1-\cos\theta) - \tfrac{1}{2}\left(J(\nabla S)^2 - K S_z^{\ 2} + K_\perp S_y^{\ 2} \right)\right)$$

$$+ \sum_k c_k^{\ +}\left(i\hbar\partial_t - \varepsilon_k \right) c_k + H_s + \Delta\int dx\, \vec{S}(x) \times c^{+}\vec{\sigma}c(x)$$

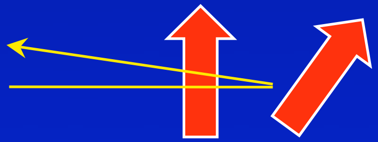
- Exchange interaction
  - torque



$$\tau = \int dx\, \vec{\mathbf{S}}(x) \times \vec{s}(x)$$

Berger '92

  - force



$$F = \int dx\, \nabla\vec{\mathbf{S}}(x) \times \vec{s}(x)$$

Berger '84

- Equation of motion of DW under current

$\frac{\delta}{\delta X}$

$$\frac{\hbar SN}{\lambda}\left(\dot{\phi}+\alpha\frac{\dot{X}}{\lambda}\right)=-\Delta\int d^{3}x\nabla\vec{S}\times\vec{\sigma}$$

Force

$\frac{\delta}{\delta\phi}$

$$\frac{\hbar SN}{\lambda}\left(\dot{X}-\alpha\lambda\dot{\phi}\right)=-\frac{NS^{2}K_{\perp}}{2}\sin 2\phi-\Delta\int d^{3}x(\vec{S}\times\vec{\sigma})$$

Torque

Coupled non-linear equation of X and ϕ

σ : electron spin density in the presence of DW

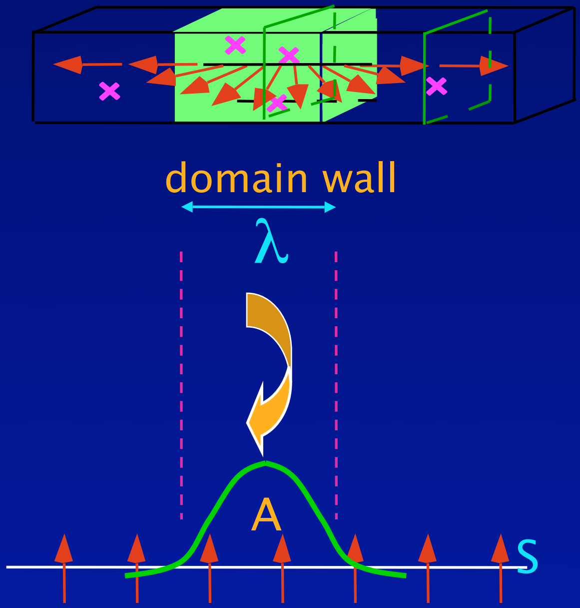
effect of electric current

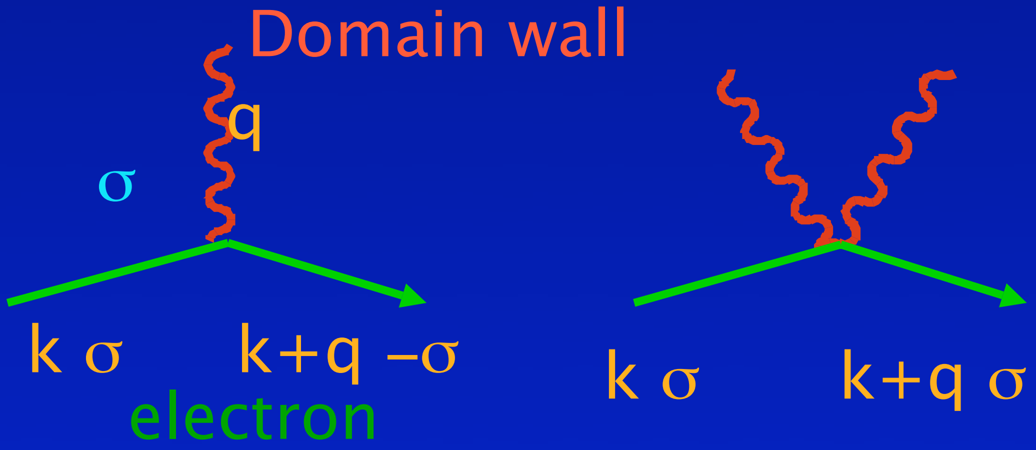
α : Gilbert damping (friction)

Domain wall

- Described by SU(2) gauge field

$$\partial_\mu \vec{S} = (\vec{A}_\mu \times \vec{S})$$





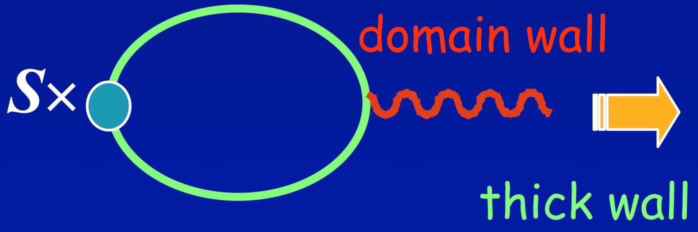
•Force and torque due to electron

$$\frac{\hbar SN}{\lambda}\left(\dot{\phi}+\alpha\frac{\dot{X}}{\lambda}\right)=-\Delta\int d^3x\nabla\vec{S}\times\vec{\sigma}$$

$$\frac{\hbar SN}{\lambda}\left(\dot{X}-\alpha\lambda\dot{\phi}\right)=-\frac{NS^2K_\perp}{2}\sin 2\phi-\boxed{\Delta\int d^3x(\vec{S}\times\vec{\sigma})}$$

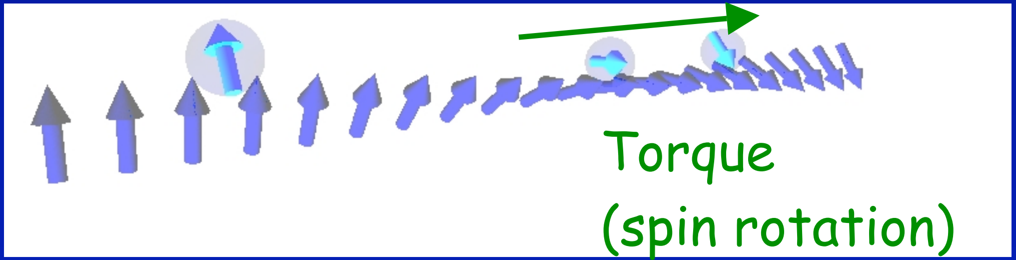
Under electron flow ➡ Keldish Green function (electron) $G^<$

•Torque $\boxed{\int d^3x\,\boldsymbol{S}\times\boldsymbol{\sigma}=}$



$\boxed{\propto\ j_s}$

Spin current

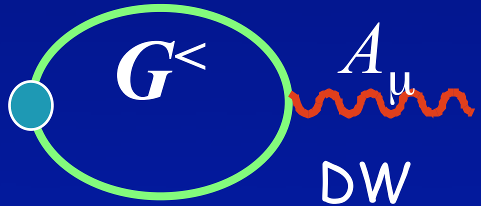


•Non-adiabatic correction (finite DW width)

$$\frac{\hbar SN}{\lambda}\left(\dot{\phi}+\alpha\frac{\dot{X}}{\lambda}\right)=\boxed{-\Delta\int d^3x\nabla\vec{S}\times\vec{\sigma}}$$

$$\frac{\hbar SN}{\lambda}\left(\dot{X}-\alpha\lambda\dot{\phi}\right)=-\frac{NS^2K_\perp}{2}\sin 2\phi-\Delta\int d^3x(\vec{S}\times\vec{\sigma})$$

•force $\boxed{\int d^3x\nabla \boldsymbol{S}\cdot\boldsymbol{\sigma}=}$ $\nabla \boldsymbol{S}\cdot$



$= \boxed{eN\rho_w j}$

ρ_w: DW resistivity

Dominates for thin wall

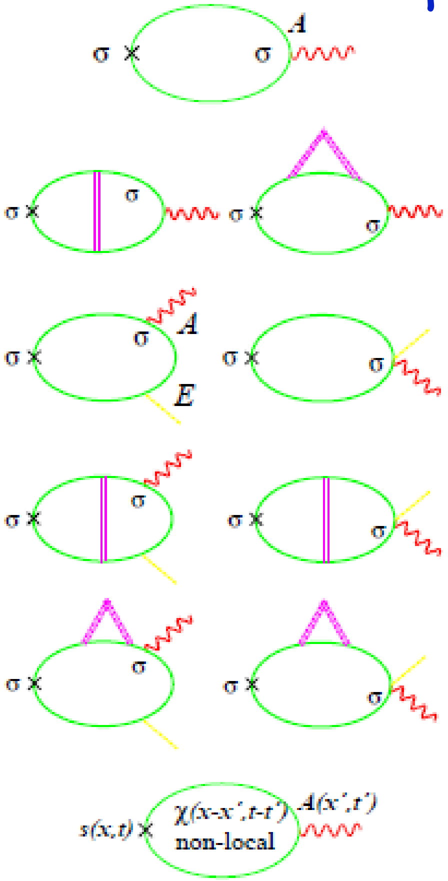
Electron spin density and torques: results

$$J\vec{s}\times\vec{n}$$

n: local spin

- Local torque

Torque from electron



$\tau \propto \dot{n}$	spin renormalization
$\frac{1}{\tau_{\mathrm{sf}}} n \times \dot{n}$	Gilbert damping α
$(j_{\mathrm{s}} \cdot \nabla) n$	Spin transfer torque
$\frac{1}{\tau_{\mathrm{sf}}}[n \times (j \cdot \nabla) n]$	β-term
τ_{nl}	momentum transfer force

$$\boxed{\alpha_{sf}\dot{\vec{S}} + Pj\times\nabla\vec{S} + \beta_{sf}(\vec{S}\times j\times\nabla\vec{S}) + \cdots}$$

P: spin polarization

Domain wall dynamics under current

- Equation of motion of transverse wall

$$\dot{X} - \alpha\lambda\dot{\phi}_0 = \frac{K_\perp \lambda}{2\hbar} S \sin 2\phi_0 + \frac{a^3}{2S} P \frac{j}{e}$$

$$\dot{\phi}_0 + \alpha\frac{\dot{X}}{\lambda} = \beta j + f_{\text{pin}}$$

Berger '84
GT & Kohno '04

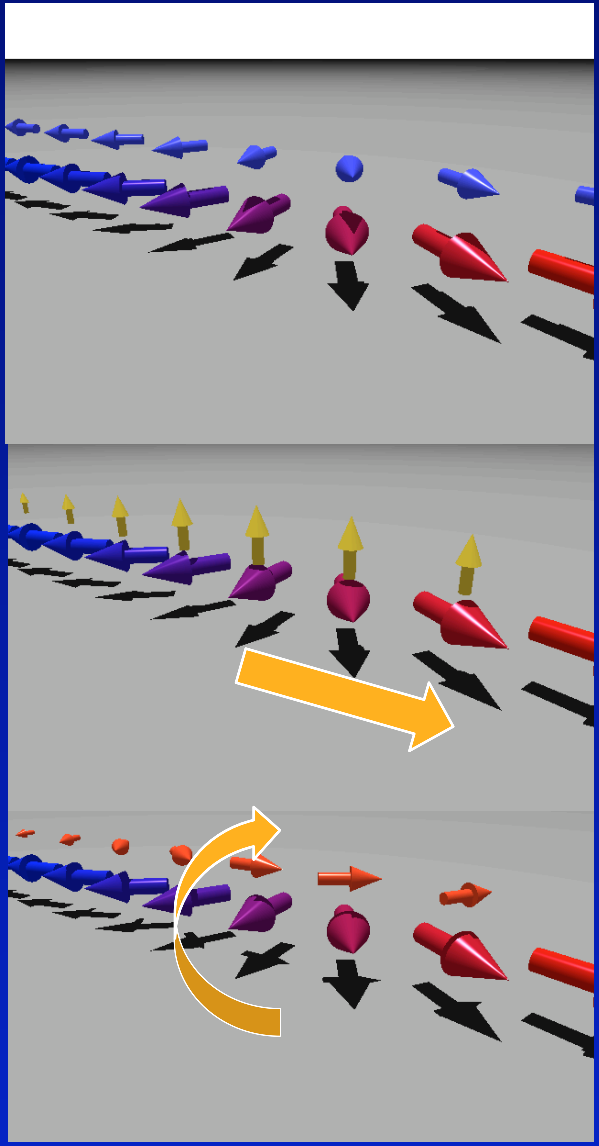
- $\beta = \left(\frac{ena^3}{2\hbar S} R_{\text{w}} A + P\beta_{\text{sf}}\right)$

  λ: domain wall thickness

Non-adiabaticity
spin relaxation, reflection

Domain wall dynamics under current

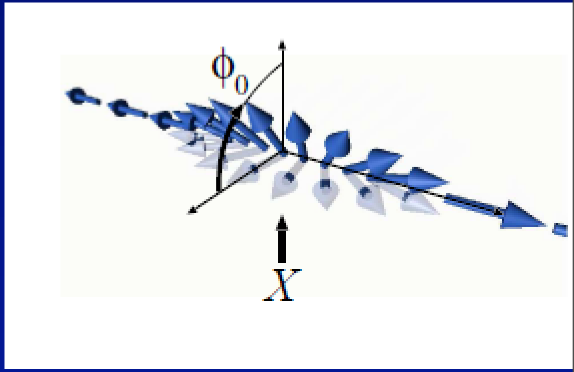
Spin polarization of conduction electron



Adiabatic component

σ

S



Spin transfer

Translation

$$\dot{X} \propto j_s$$

Spin relaxation
Non-adiabaticity

Tilting

$$\dot{\phi} \propto j_s$$

Domain wall dynamics under current

- Equation of motion of transverse wall

$$\dot{X} - \alpha\lambda\dot{\phi}_0 = \frac{K_\perp \lambda}{2\hbar} S \sin 2\phi_0 + \frac{a^3}{2S} P \frac{j}{e}$$

$$\dot{\phi}_0 + \alpha \frac{\dot{X}}{\lambda} = \beta j + f_{\mathrm{pin}}$$

Berger '84
GT & Kohno '04

- $\beta = \left(\frac{ena^3}{2\hbar S} R_{\mathrm{w}} A + P \beta_{\mathrm{sf}} \right)$

  λ: domain wall thickness

Non-adiabaticity
spin relaxation, reflection

Domain wall dynamics under current

- Equation of motion of transverse wall

$$\dot{X} - \alpha\lambda\dot{\phi}_0 = \frac{K_\perp \lambda}{2\hbar} S \sin 2\phi_0 + \frac{a^3}{2S} P \frac{j}{e}$$

$$\dot{\phi}_0 + \alpha \frac{\dot{X}}{\lambda} = \beta j + f_{\mathrm{pin}}$$

Berger '84
GT & Kohno '04

- $\beta = \left(\frac{ena^3}{2\hbar S} R_{\mathrm{w}} A + P\beta_{\mathrm{sf}} \right)$

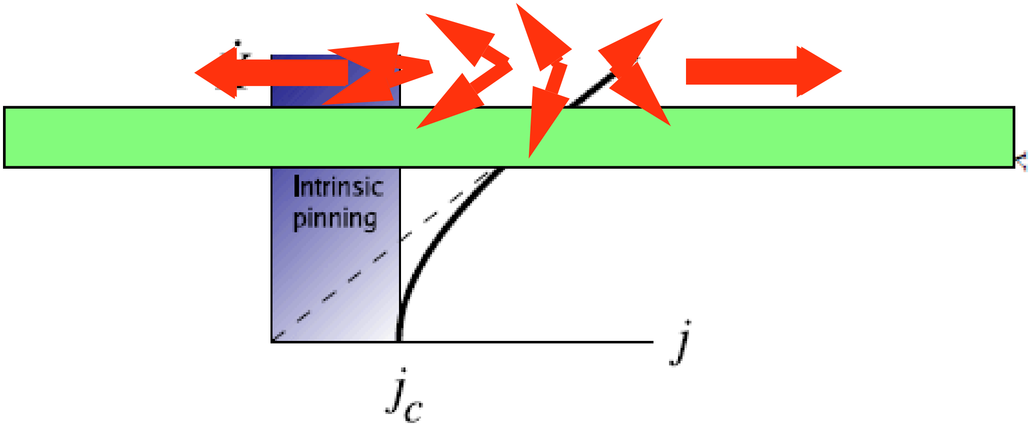
  λ: domain wall thickness

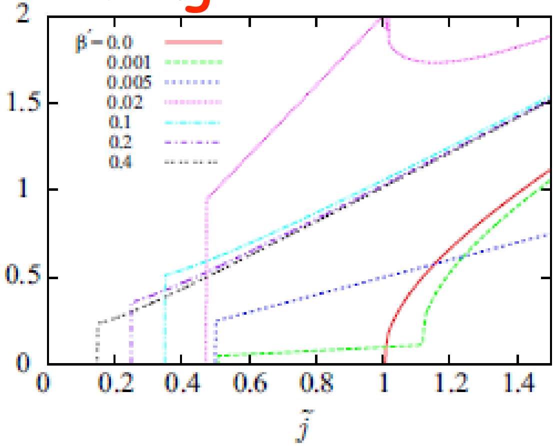
Non-adiabaticity
Spin relaxation (spin-orbit)

- Threshold currents

●$\beta \lesssim \alpha$ Intrinsic pinning **Thick wall**

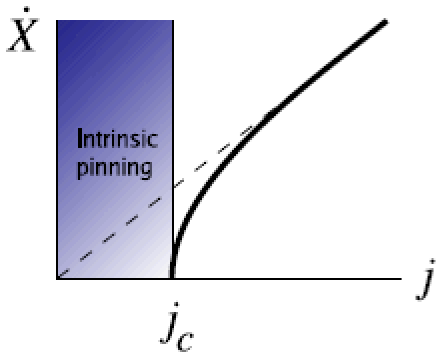
●$\beta \gtrsim \alpha$ Extrinsic pinning **Thin wall or Strong S-O**





Domain wall dynamics under current

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



$$j_c \approx K_\perp$$

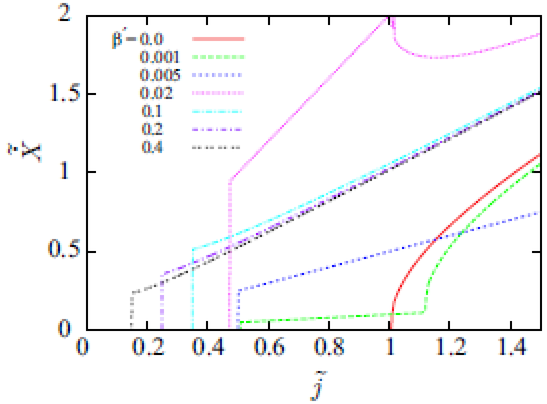
Anisotropy energy

$K_\perp$:sample geometry

$$v = P \frac{a^3}{2eS} j$$

Angular mom. conservation

- $\beta \gtrsim \alpha$ Extrinsic pinning



$$j_c \approx \sqrt{K_\perp V_0}$$

V_0: extrinsic pinning

$$j_c \approx V_0 / \beta$$

V_0:sample quality

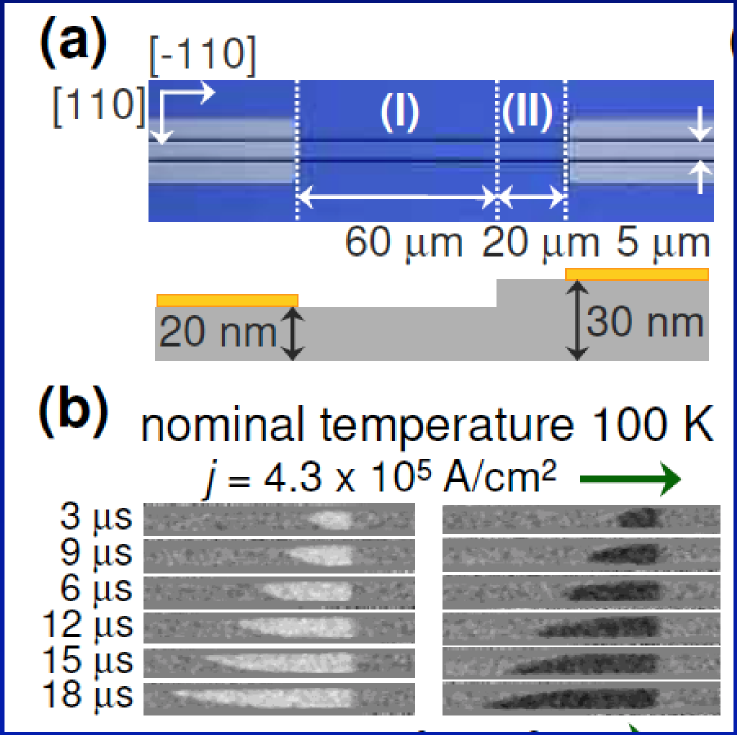
β:wall thickness, spin-orbit

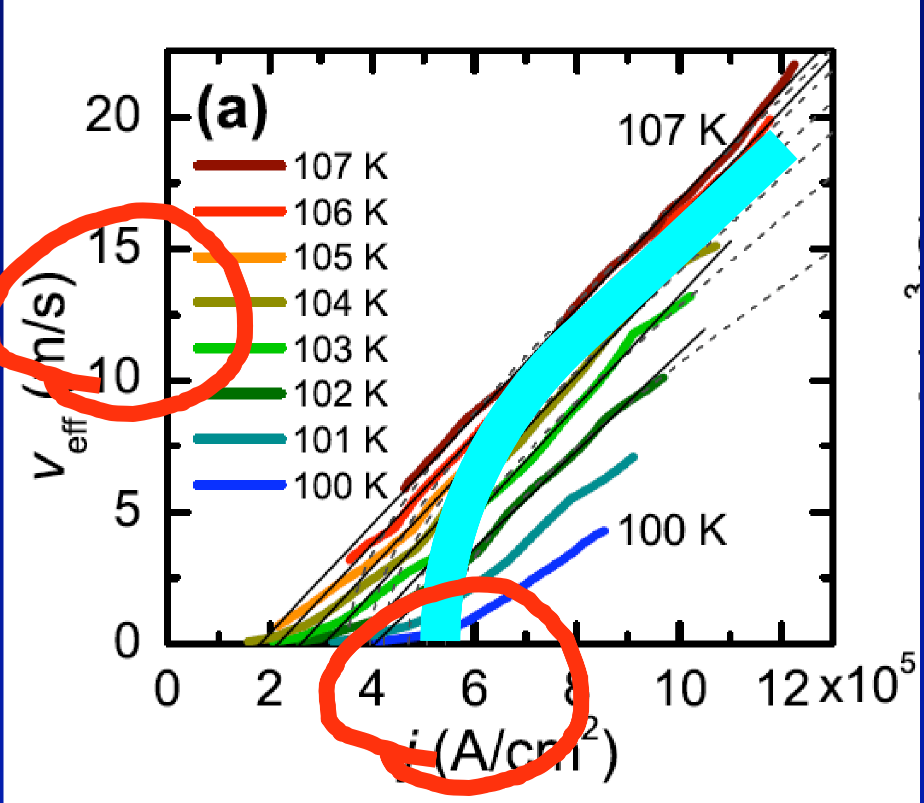
$$v = (\beta / \alpha) j$$

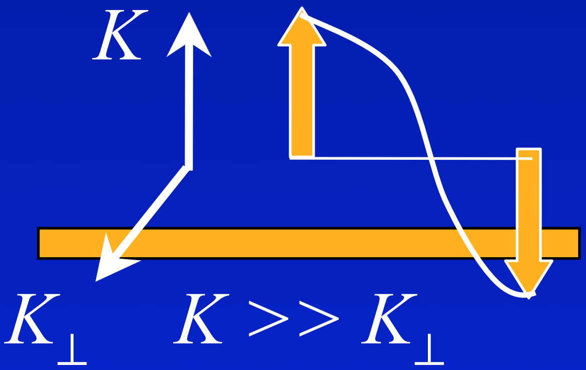
Small j

Experiment rigid DW

GaMnAs Yamanouchi, Chiba, Matsukura, Dietl & Ohno, PRL (2006)







$K >> K_\perp$

Intrinsic pinning GT & Kohno ('04)

Spin transfer Small β

T-dependence (creep): Ieda, Maekawa

Behavior of threshold (metals)

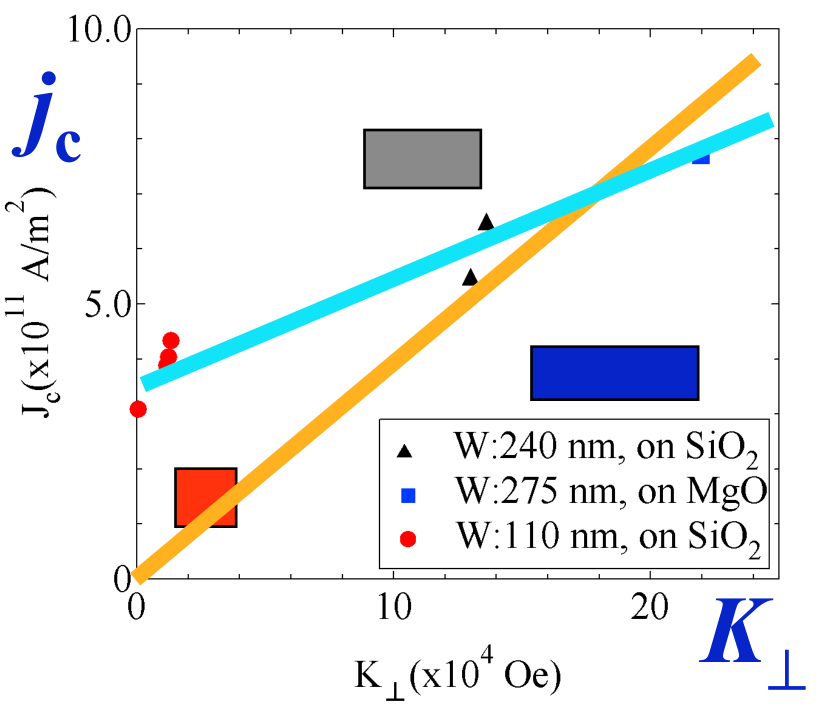
$j_c \propto K_\perp \lambda$ If intrinsic pinning

- Yamaguchi, Ono

  J_c depends

  on sample geometry ($K_\perp$)

  (but weakly)

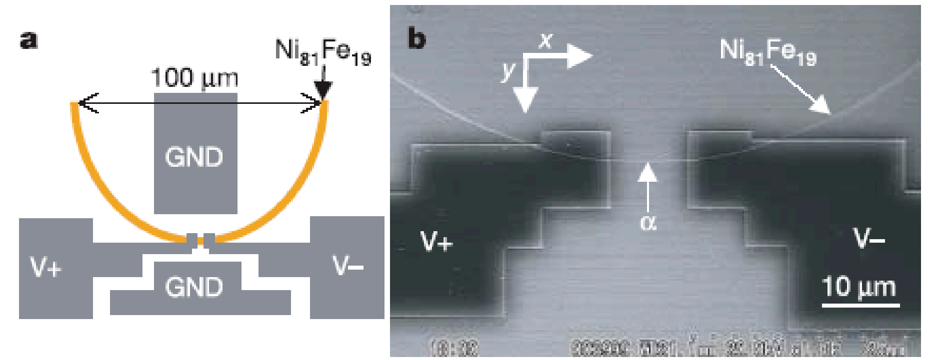


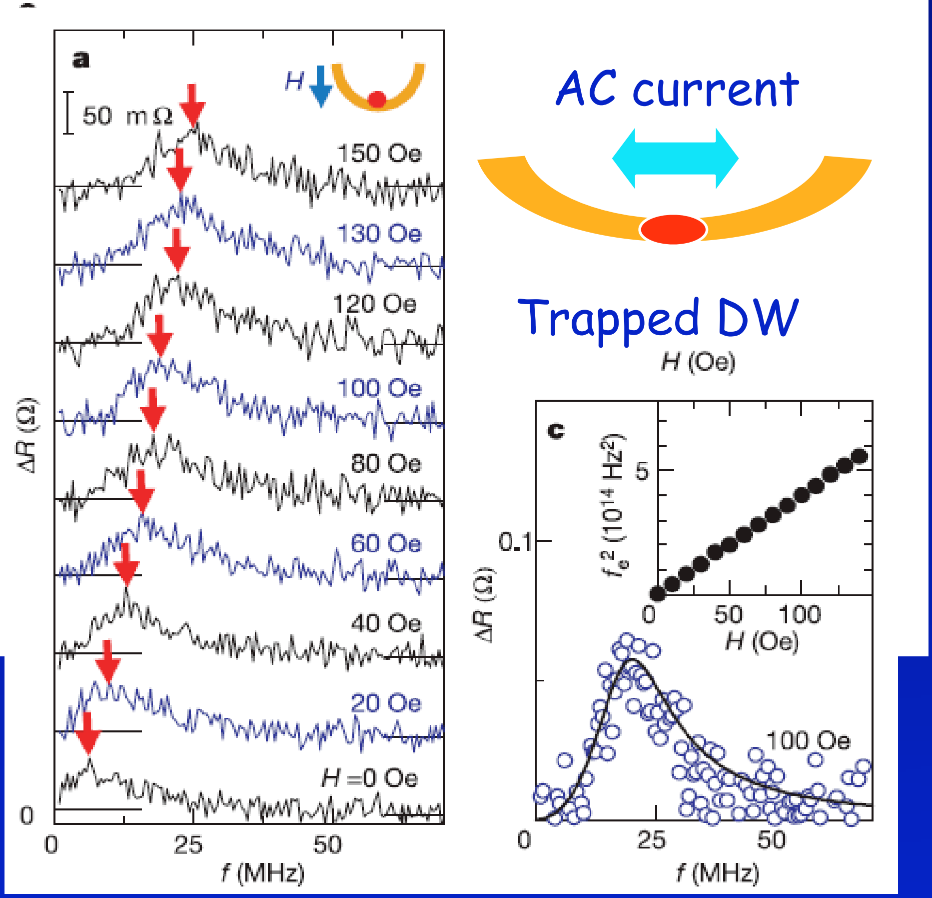
- Origin of threshold ?
  - Deformation, creep?
  - Heating?

•Manipulation by AC current

•E. Saitoh et al, Nature 432, 203 (2004)

Small current, small deformation





DW motion by use of resonance

- Low-current operation

$j \approx 10^{10} [\mathrm{A/m^2}]$

Resonance at 20MHz

- Force dominates
- Determination of DW character

$m = 6.6 \times 10^{-23}$ kg

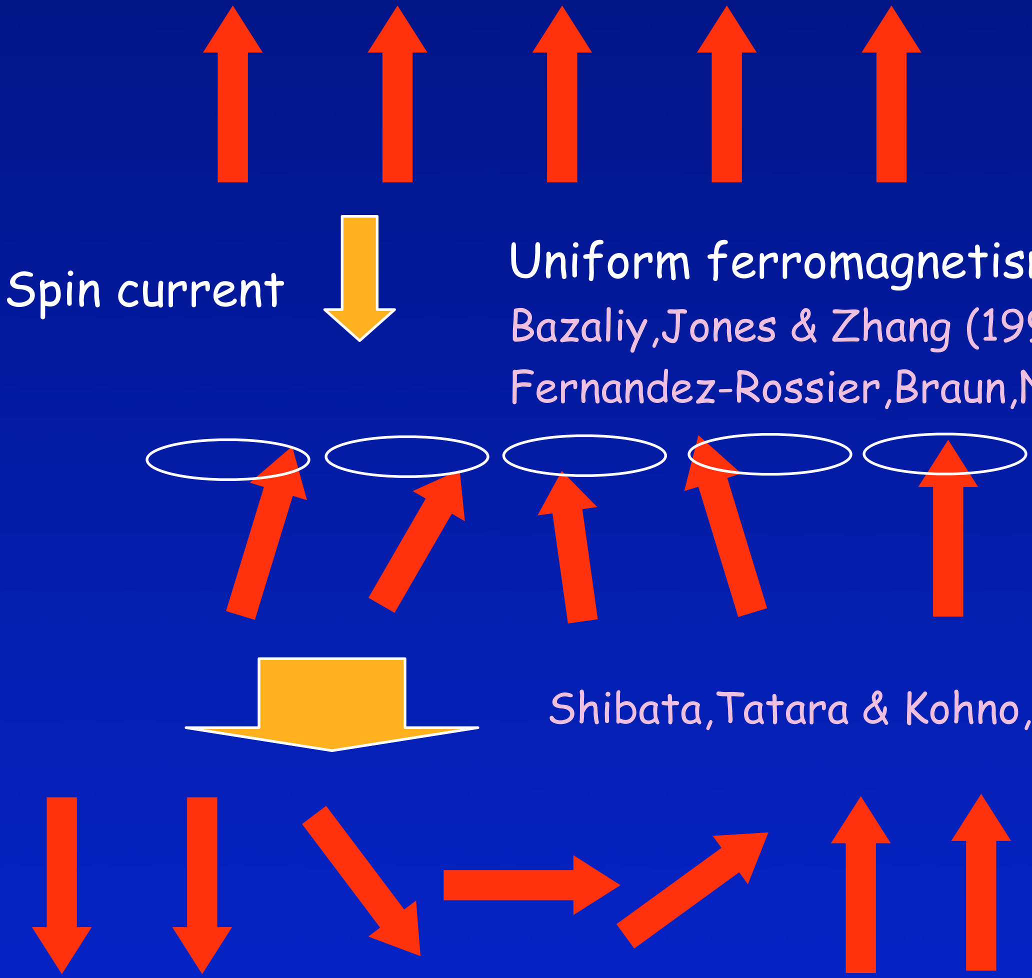
$\tau = 10^{-8}$ s ($\alpha = 0.01$)

$R_w = 10^{-4}\ \Omega$

- Thomas, Parkin et al, Nature (2006)

•Domain wall nucleation by spin current

Spin current favors spin Berry phase inhomegenuity



Spin current

Uniform ferromagnetism unstable

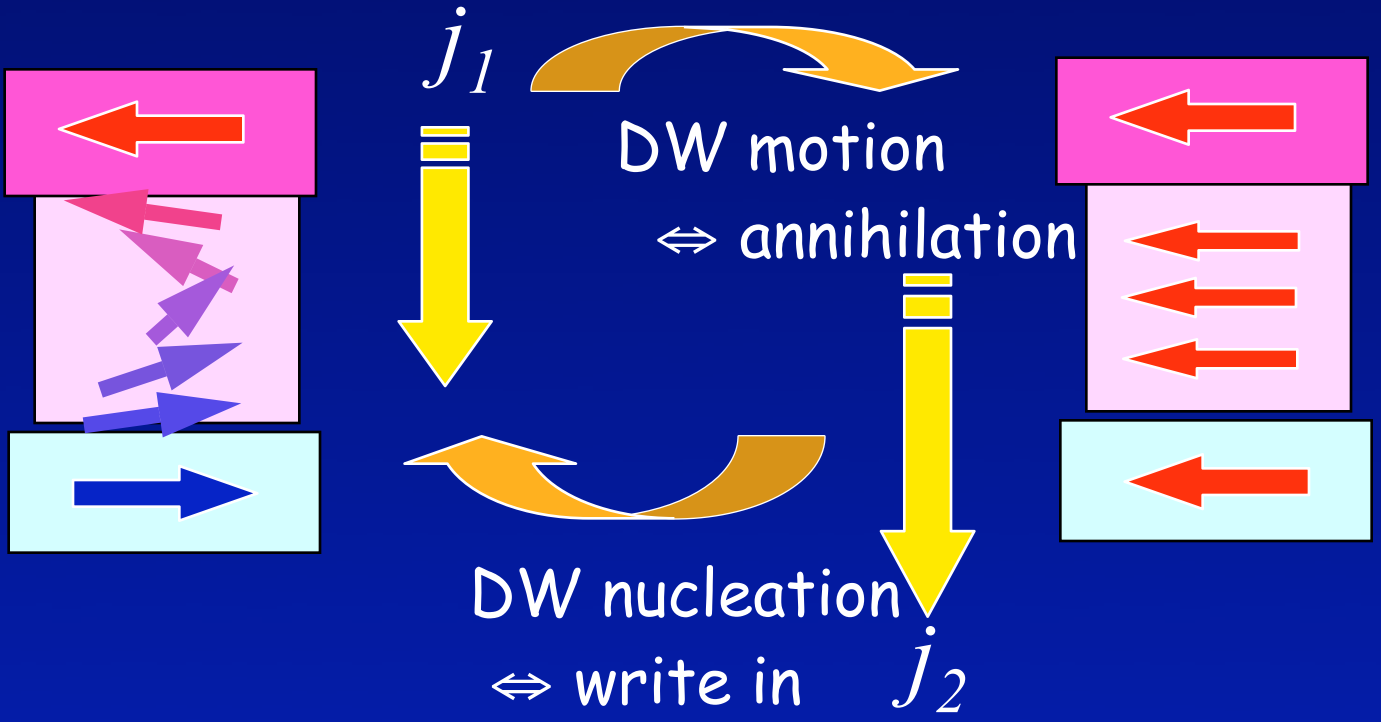
Bazaliy,Jones & Zhang (1998)

Fernandez-Rossier,Braun,Nunez &MacDonald (2004)

Shibata,Tatara & Kohno, Phys. Rev. Lett. (2005)

DW nucleation

- DW devices operated by Current



j_1

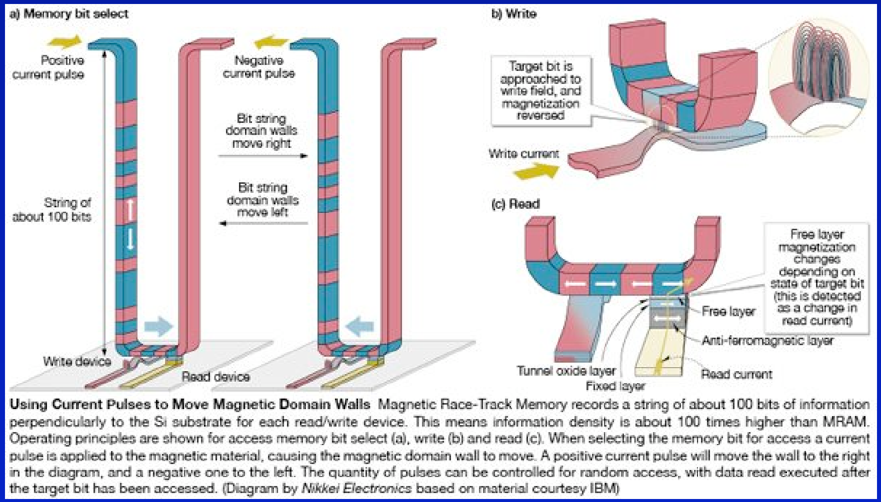
DW motion

⇔ annihilation

DW nucleation

⇔ write in

j_2



Using Current Pulses to Move Magnetic Domain Walls Magnetic Race-Track Memory records a string of about 100 bits of information perpendicularly to the Si substrate for each read/write device. This means information density is about 100 times higher than MRAM. Operating principles are shown for access memory bit select (a), write (b) and read (c). When selecting the memory bit for access a current pulse is applied to the magnetic material, causing the magnetic domain wall to move. A positive current pulse will move the wall to the right in the diagram, and a negative one to the left. The quantity of pulses can be controlled for random access, with data read executed after the target bit has been accessed. (Diagram by *Nikkei Electronics* based on material courtesy IBM)

DW racetrack memory (MRAM)

S. Parkin (IBM)

Current-driven domain wall motion

- Aim
  - Low current operation
  - Fast motion

By factor of 10-100

$j_c = 10^{10}$ A/m^2

$v = 100$ m/s

Theory

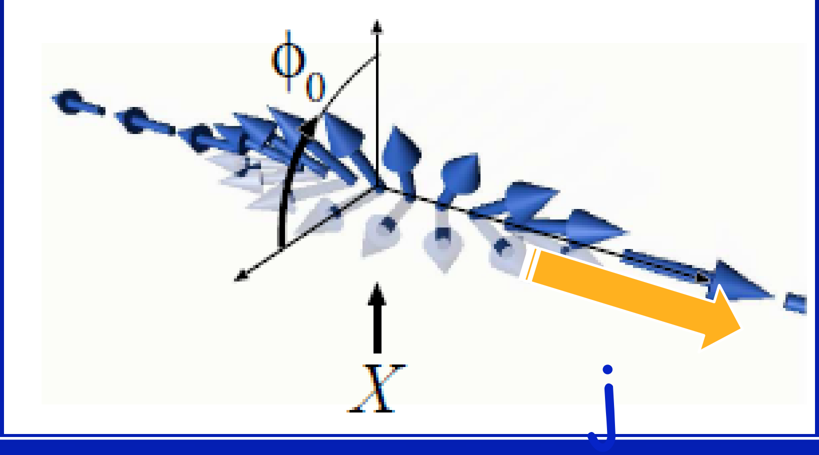
- Material (spin-orbit)
- Shape (anisotropy)
- Surface (reduce extrinsic pinning)

PART 2 :

Current from Magnetization dynamics
Inverse (reciprocal) spin Hall effect

Saitoh, Miyajima '06

Part 1: Current ⇒Spin current ⇒Magnetization dynamics



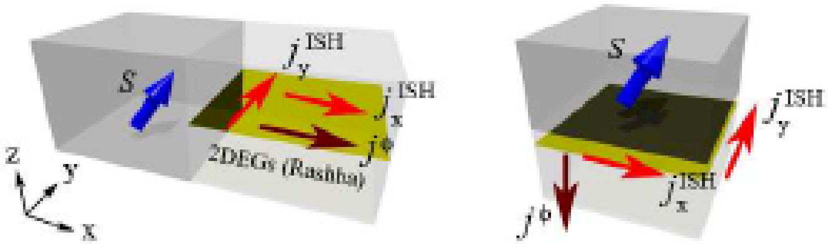
Magnetization dynamics(⇒spin current)⇒Electric current?

Yes. Exchange + Spin-orbit interactions

Spin Battery

Current pumping by magnetization dynamics

- Rashba spin-orbit α
- Exchange coupling J_{ex} to magnetization $M(x,t)$



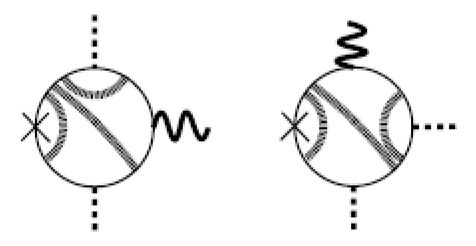
- Naive result:

$$j_\mu \sim \mathrm{tr}[k_\mu \alpha (k \times \sigma)_z J_{\mathrm{ex}} (M \cdot \sigma)] \propto \alpha J_{\mathrm{ex}} \epsilon_{\mu\nu z} k^2 M^\nu$$

- Saitoh Miyajima et al '06 experiment
- Stern'92, Barnes Maekawa '07, Duine '07
  Voltage from spin Berry phase (fictitious flux)
- Ohe, Takeuchi & GT '07 perturbative

Electric current

Ohe, Takeuchi, GT



- Rashba spin-orbit α
- Exchange J

$$j_\mu^{(\mathrm{ISH})}(\boldsymbol{x},t) = -\frac{4}{\pi} em\alpha {J_{\mathrm{ex}}}^2 \tau^2 \epsilon_{\mu\eta z} \int \frac{d^2x_1}{a^2} D(\boldsymbol{x}-\boldsymbol{x}_1)(\boldsymbol{S}_{\boldsymbol{x}} \times \dot{\boldsymbol{S}}_{\boldsymbol{x}_1})_\eta$$

$$j_\mu^{\phi}(\boldsymbol{x},t) = \frac{4}{\pi^2} e\alpha {J_{\mathrm{ex}}}^2 \tau^3 \frac{\partial}{\partial x_\mu} \epsilon_{\nu\eta z} \int \frac{d^2x_1}{a^2} \int \frac{d^2x_2}{a^2} D(\boldsymbol{x}-\boldsymbol{x}_1) \frac{\partial}{\partial x_{1\nu}} D^{(2)}(\boldsymbol{x}_1-\boldsymbol{x}_2)(\boldsymbol{S}_{\boldsymbol{x}_1} \times \dot{\boldsymbol{S}}_{\boldsymbol{x}_2})_\eta .$$

$$j_\mu^{(\mathrm{ISH})} \sim -j_0 \epsilon_{\mu\eta z} \left\langle \boldsymbol{S} \times \dot{\boldsymbol{S}} \right\rangle_\eta ,$$

$$D(q) \propto 1/(Dq^2)$$

$$j_0 \propto \alpha J^2$$

$$j_\mu^{(\mathrm{ISH})} = \gamma_{\mathrm{ISH}} \epsilon_{\mu\nu z} (\nabla \cdot {j_{\mathrm{s}}}^{(2)\nu}),$$

- Spin damping (spin current) ⇒charge current

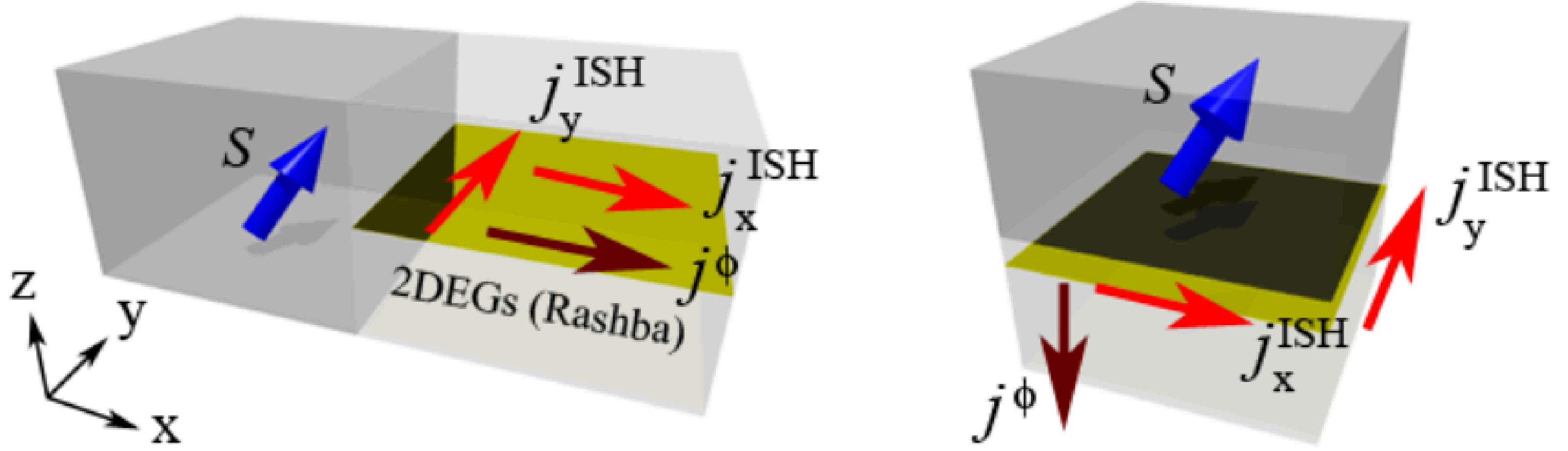
Conversion of magnetic energy into electric one

Pumped current

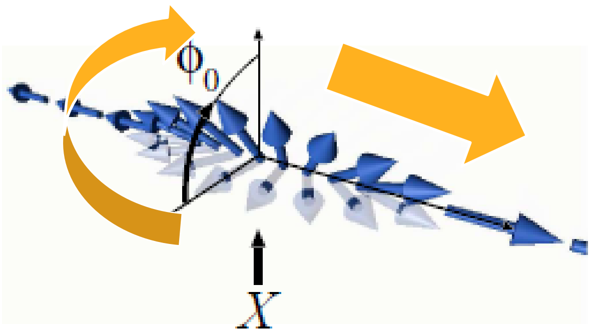
Ohe, Takeuchi, GT

$$j_\mu^{(\mathrm{ISH})} \sim -j_0 \epsilon_{\mu\eta z} \left\langle \boldsymbol{S} \times \dot{\boldsymbol{S}} \right\rangle_\eta ,$$

$$j_0 \propto \alpha J^2$$



Pumping of charge current by spin dynamics

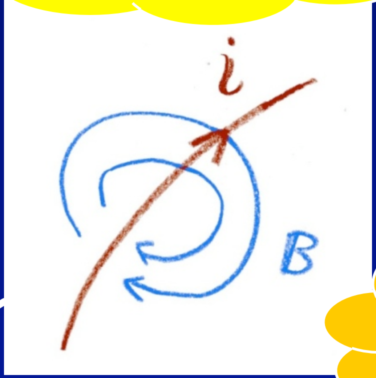


$$j \propto \alpha J^2 \dot{X}, \alpha J^2 \dot{\phi}$$

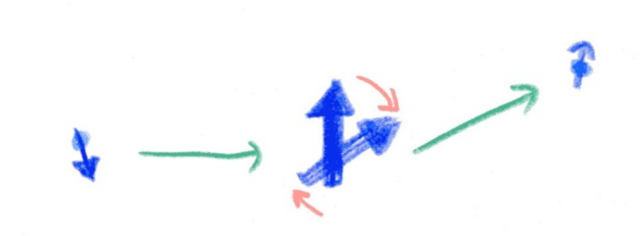
19 cent. | 20 cent.~ | 21 cent.~(??)

current
⇓
magnetism

Maxwell equation



Ampere



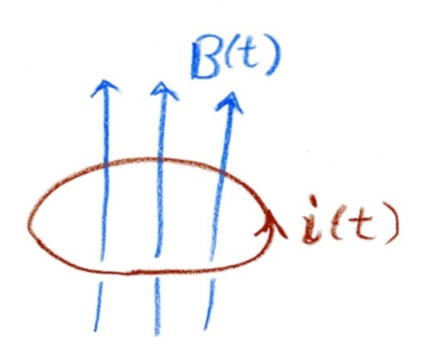
Spin transfer
Berger, Slonczewski
1978-, '96

Material
and structure

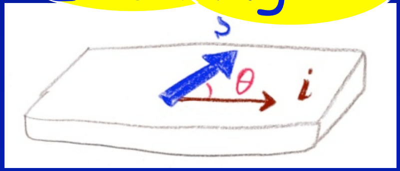
Spin-orbit
Exchange interaction

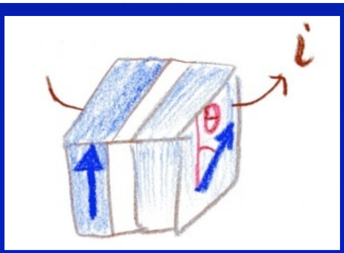
Efficient in
Nano scale

magnetism
⇓
current

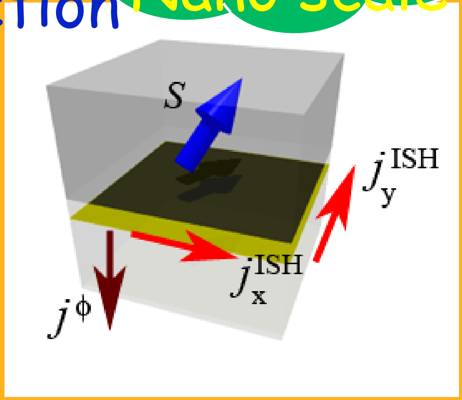


Faraday





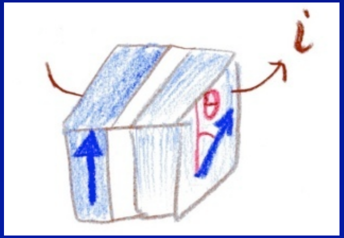
AMR, GMR('88),
TMR

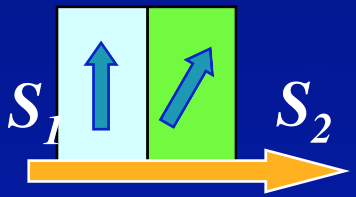


Inverse spin Hall
Saitoh,Miyajima'06

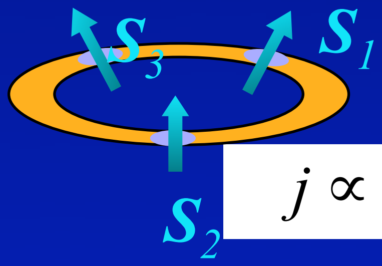
スピン依存伝導：相互作用で分類

	輸送現象デバイス	電流による磁化運動	磁化から電流生成
交換相互作用	GMR, TMR	スピン移行トルク	スピン流、電流
スピン軌道相互作用	AMR 異常ホール スピンホール	直交したトルク 別の運動モード	ダイレクトな電流 スピン電池





$(S_1 \times S_2) \cdot \sigma$



$$j \propto S_1 \times (S_2 \times S_3)$$

$$j_\mu^{(\mathrm{ISH})} \sim -j_0 \epsilon_{\mu\eta z} \left\langle \boldsymbol{S} \times \dot{\boldsymbol{S}} \right\rangle_\eta ,$$

Local spin under current

Modified Landau-Lifshitz-Gilbert eq.

$$\dot{\vec{n}} = \frac{g\mu_B}{\hbar}\vec{B}_{\rm eff}\times\vec{n} + (\alpha_0+\alpha_{\rm sf})\vec{n}\times\dot{\vec{n}} - \frac{s}{2S}\dot{\vec{n}}$$

$$\boxed{-\frac{a^3}{2e}(\vec{j}_{\rm s}\cdot\nabla)\vec{n} \quad -\beta_{\rm sf}\frac{a^3}{e}[\vec{n}\times(\vec{j}_{\rm s}\cdot\nabla)\vec{n}]}$$

$$+\vec{\tau}_{\rm nl} \quad (O(\nabla^2\vec{n}))$$

(Spin-polaraized) current j

pushes and twists spin structure

Berger, Slonczewski, Zhang&Li, Thiaville et al....

Kohno GT Shibata

Summary

Current-driven domain wall dynamics

- For Low Jc and high wall speed
  ~1/10 ~10
- Origin of Jc
- Spin relaxation, non-adiabaticity
- Role of deformation on Jc

Pumping of charge current by spin dynamics

Spin-orbit interaction