Spintronics and Nanomagnetics

ECS 521/641

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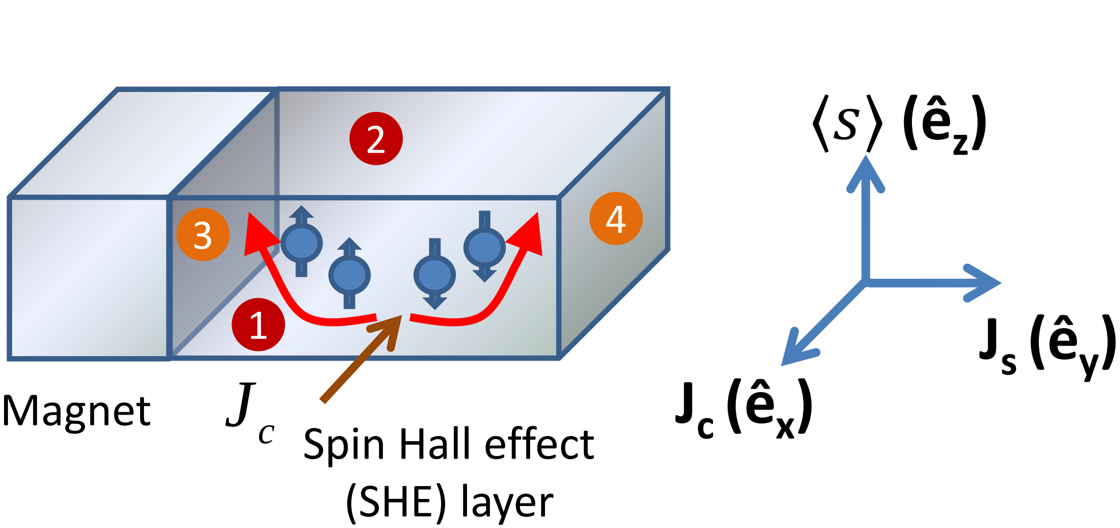
Spin-transfer-torque

Reciprocity: Spin-transfer-torque (Direct SHE) and Spin pumping (Inverse SHE)



- **Charge current generates spin current via direct SHE and**
- **Spin current exerts spin-transfer-torque on magnet**

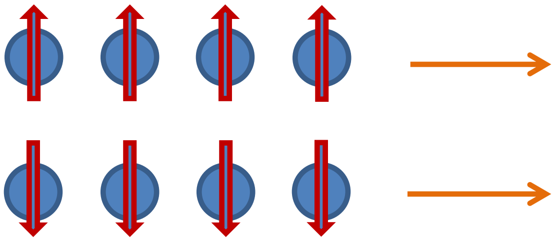
- **Precessing magnet injects pure spin current and**
- **Spin current generates charge current via inverse SHE**

$$J_s = \theta_{SH} \langle s \rangle \times J_c$$

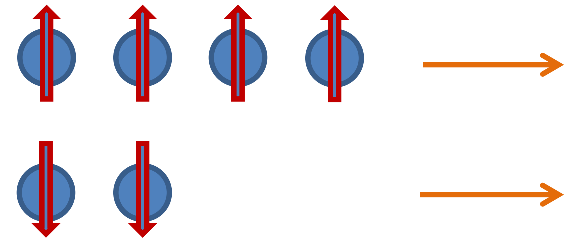
Onsager's reciprocity

$$J_c = \theta_{SH} J_s \times \langle s \rangle$$

Charge current versus Spin current

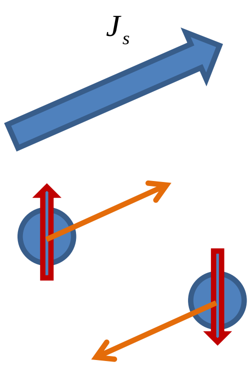


Charge current



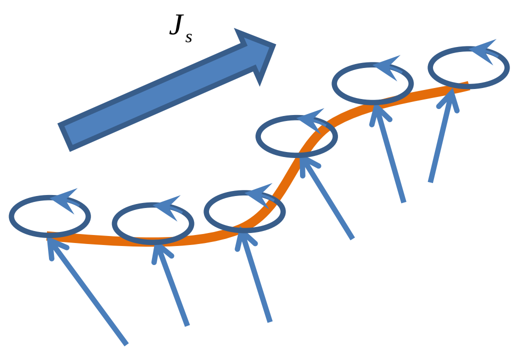
Spin-polarized spin current

Charge → Spin
Spin-orbit coupling
Pt, Ta, W, CuBi



Pure spin current

(Ferri)magnetic
insulators
YIG ($Y_3Fe_5O_{12}$)



Spin-wave spin current

Prediction of spin-transfer-torque (1996)

2013 Oliver E. Buckley Condensed Matter Physics Prize Recipient

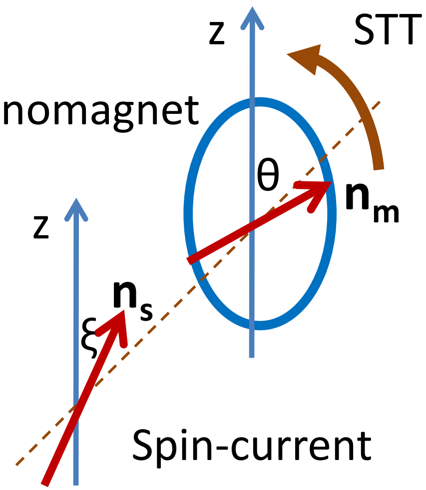
John Slonczewski
IBM Research Staff Emeritus

Luc Berger
Carnegie Mellon University Emeritus

"*For predicting **spin-transfer torque** and opening the field of current-induced control over magnetic nanostructures.*"

- J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996)
- L. Berger, Phys. Rev. B **54**, 9353 (1996)

Spin-transfer-torque (STT)



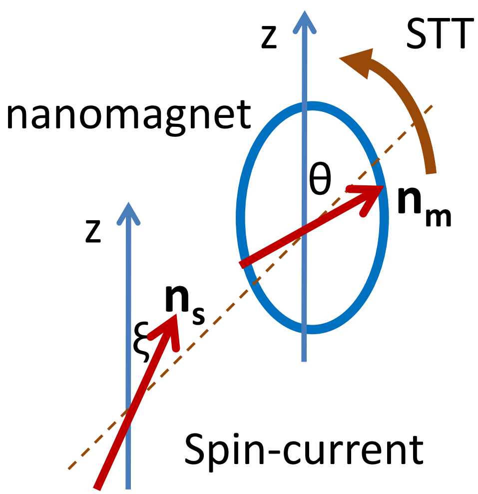
A spin-polarized current transfers its spin angular momentum to the magnetic body

1996

Spin-transfer-torque (STT)

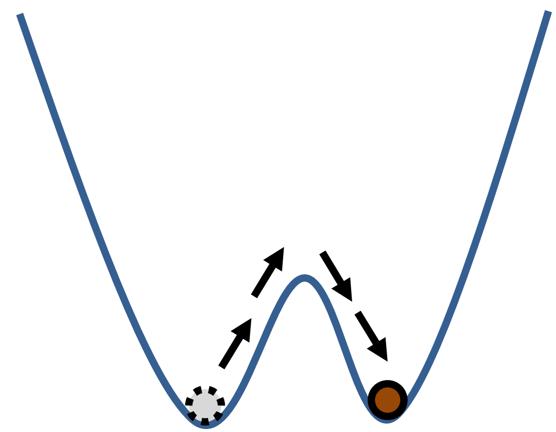
A magnetic body absorbs the angular-momentum from the spin current only in the direction **perpendicular** to $\boldsymbol{M}$

STT can rotate the magnetization axis of the nanomagnet



Spin-polarized spin current

Ohmic I^2R dissipation



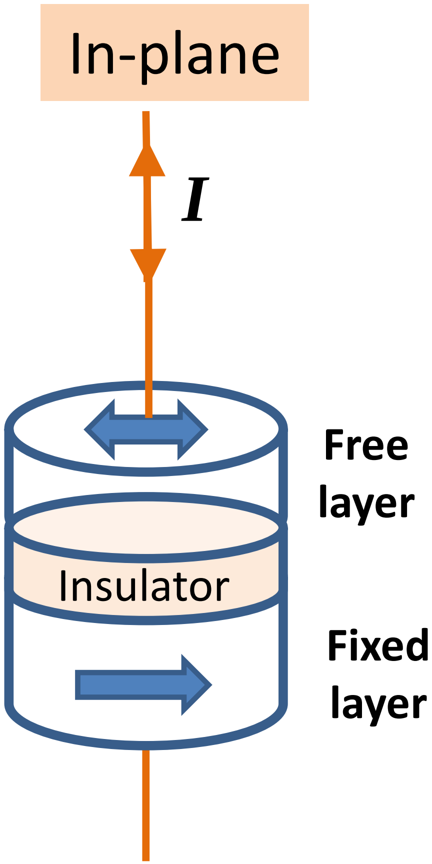
$$\boldsymbol{STT} = \boldsymbol{s}\ \mathbf{n}_\mathrm{m} \times (\mathbf{n}_\mathrm{s} \times \mathbf{n}_\mathrm{m}) = \boldsymbol{s}\, sin(\xi - \theta)\,\hat{\mathbf{e}}_\theta$$

$$\boldsymbol{s} = (\hbar / 2e)\eta \boldsymbol{I} \qquad \eta = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow}$$

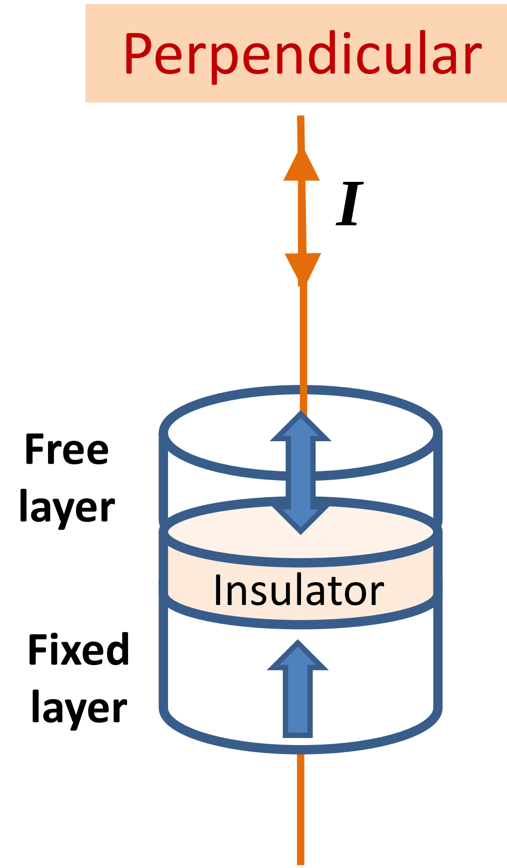
Spin polarization

- Current density: 10^7 A/cm^2
- **Huge energy dissipation 10^6-10^8 kT (~1 pJ)**

Switching nanomagnets with STT



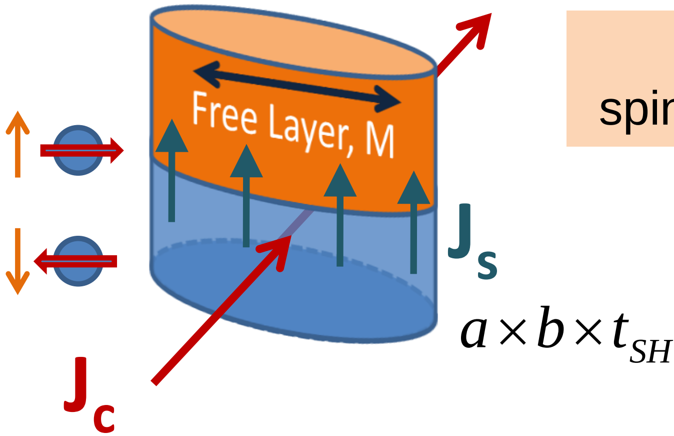
$$\boldsymbol{s} = (\hbar / 2e)\eta \boldsymbol{I}$$



20-30 nm (circular cross-section)

- Current: ~10 μA
- **Energy dissipation: ~1 fJ**

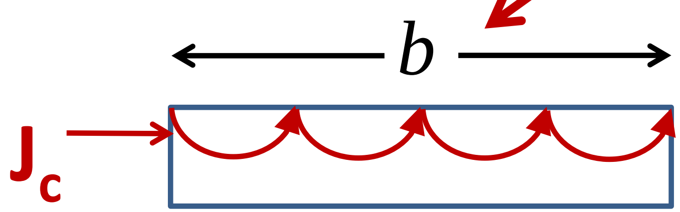
Spin-orbit-torque (SOT)



Spin-Hall Material

Pure
spin current

$$\frac{I_s}{I_c} = \frac{\mathbf{J_s}}{\mathbf{J_c}}\frac{\mathbf{A_s}}{\mathbf{A_c}} = \Theta_{SH}\frac{b}{t_{SH}}$$



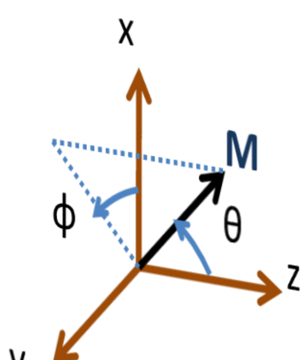
$$A = \frac{\pi}{4}ab$$

Charge → Spin
Spin-orbit coupling
Pt, Ta, W, CuBi

$$E = I_c^2 RT = \left(\frac{t_{SH} I_s}{\Theta_{SH} b}\right)^2 \left(\rho \frac{2}{\pi}\frac{b}{a t_{SH}}\right) T = \frac{1}{2}\left(\frac{\rho}{\Theta_{SH}^2}\right)\left(\frac{t_{SH}}{A}\right) I_s^2 T$$

Material parameters

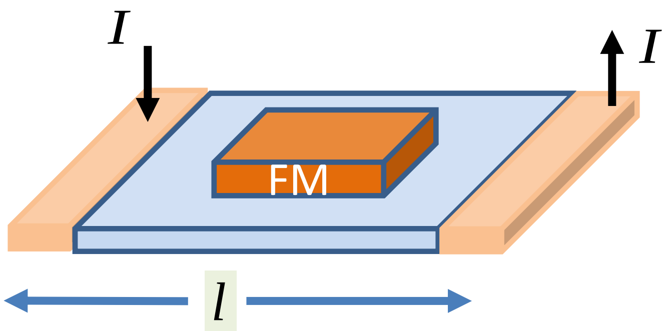
Dimension



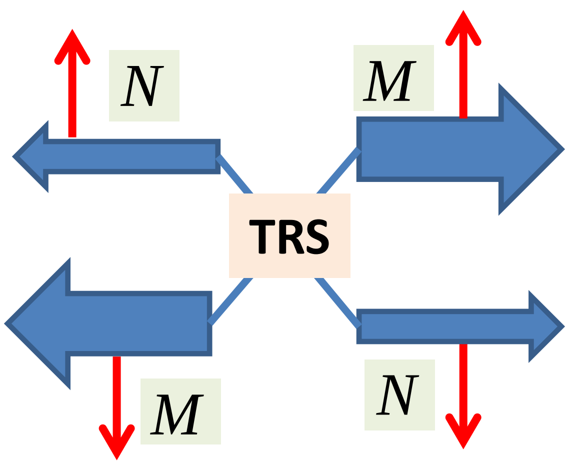
- **Energy dissipation: ~0.1 fJ**

Roy, K., J. Phys. D: Appl. Phys. (Fast Track Communication) **47,** 422001 (2014)

Surface spin-orbit-torque (SOT)

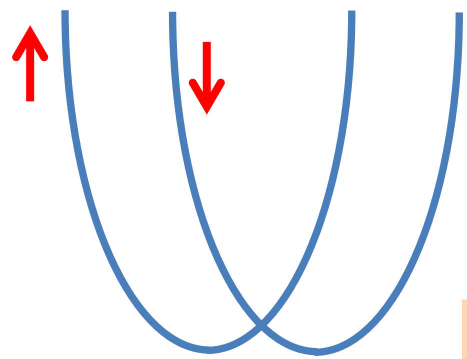


2D channel with
Spin-orbit coupling (SOC)



FM: Broken
Time Reversal symmetry (TRS)

Rashba
INTERFACE



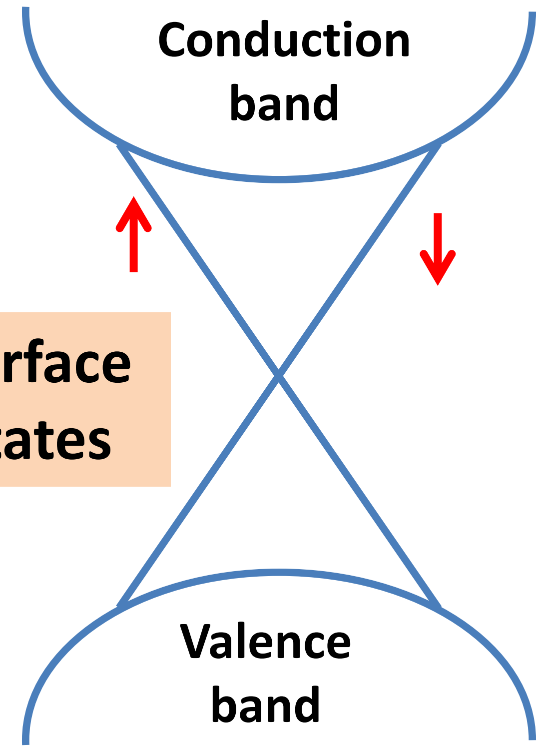
$$G_B = \frac{e^2}{h}\left(M + N\right)$$

$$p_0 = \frac{M - N}{M + N}$$

$$G = G_B \frac{\lambda_{SS}}{l}$$

G_B: **Ballistic conductance**

Topological Insulators
SURFACE

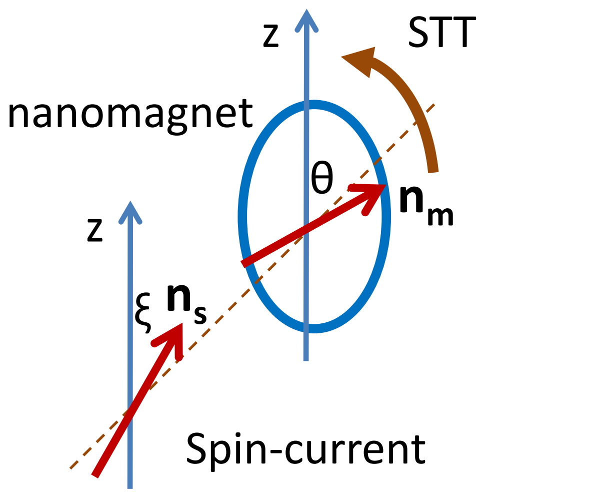


Surface states

$p_0 = 1$ **ideally**
BUT Bulk conduction

Spin-transfer-torque on nanomagnets

Spin-transfer-torque (STT)



A magnetic body absorbs the angular-momentum from the spin current only in the direction **perpendicular** to $\boldsymbol{M}$

$$\frac{d\boldsymbol{M}}{dt} = -|\gamma| \underbrace{\boldsymbol{M} \times \boldsymbol{H_{eff}}}_{\textbf{precession}} + \frac{\alpha}{M} \underbrace{\boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}}_{\textbf{damping}}$$

LLG Equation

$$\boldsymbol{H_{eff}} = -\frac{1}{M}\nabla E$$

$$M = \mu_0 M_s \Omega$$

E : Potential energy

M : Magnetization

Ω : Volume

A spin-polarized current transfers its spin angular momentum to the magnetic body

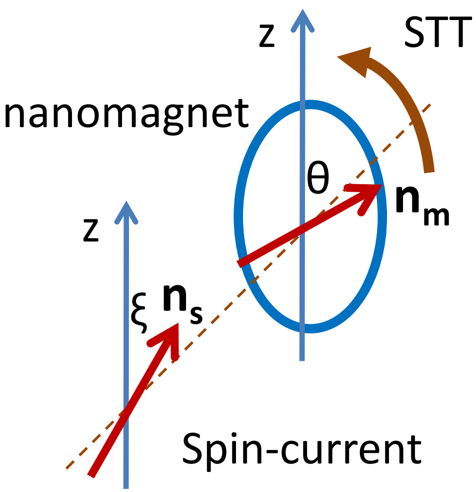
$$\boldsymbol{STT} = \boldsymbol{s}\ \mathbf{n}_m \times (\mathbf{n}_s \times \mathbf{n}_m) = \boldsymbol{s}\, sin(\xi - \theta)\, \hat{\mathbf{e}}_\theta$$

$$\boldsymbol{s} = (\hbar / 2e)\eta \boldsymbol{I} \qquad \eta = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow}$$

Spin polarization

STT as $\boldsymbol{\nabla} E$?

Spin-transfer-torque (STT)



STT cannot be expressed as $\boldsymbol{\nabla} E$

$$\frac{d\boldsymbol{M}}{dt} = -|\gamma| \underbrace{\boldsymbol{M} \times \boldsymbol{H_{eff}}}_{\text{precession}} + \frac{\alpha}{M} \underbrace{\boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}}_{\text{damping}}$$

LLG Equation

A spin-polarized current transfers its spin angular momentum to the magnetic body

$$\boldsymbol{STT} = \boldsymbol{s}\ \mathbf{n_m} \times (\mathbf{n_s} \times \mathbf{n_m}) = \boldsymbol{s}\, sin(\xi - \theta)\, \hat{\mathbf{e}}_\theta$$

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Spin polarization

$$\boldsymbol{H_{eff}} = -\frac{1}{M} \nabla E$$

$$M = \mu_0 M_s \Omega$$

E : Potential energy

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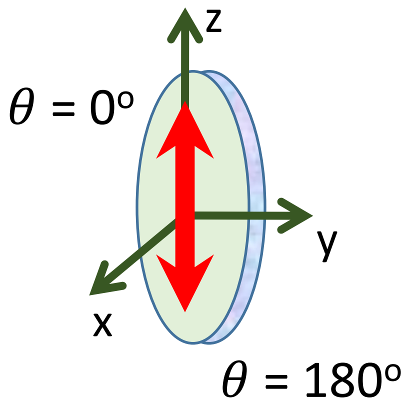
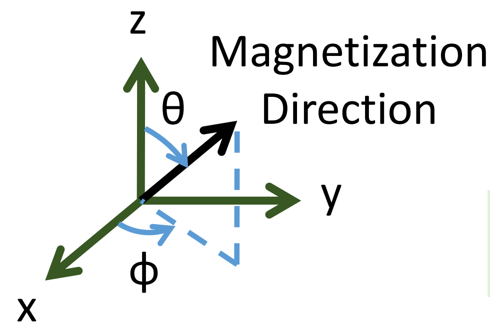
Ω : Volume

3D potential landscape of a nanomagnet

Easy axis:
θ = 180°, 0°

Hard axis:
θ = 90°





Magnet's plane: ϕ = ± 90°

M_s *in* A/m

Potential energy

$$E_{shape}(\theta,\phi) = \frac{1}{2}\mu_0 M_s [H_k \;+\; H_d\, cos^2\phi]\,\Omega \sin^2\theta$$

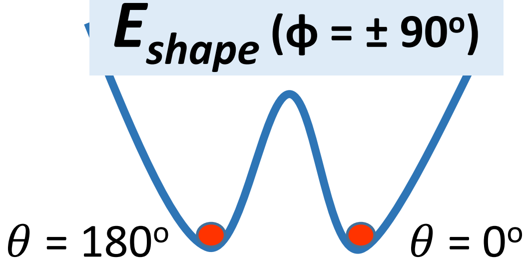
$$H_k = (N_{d-yy} - N_{d-zz})M_s$$

$$H_d = (N_{d-xx} - N_{d-yy})M_s$$

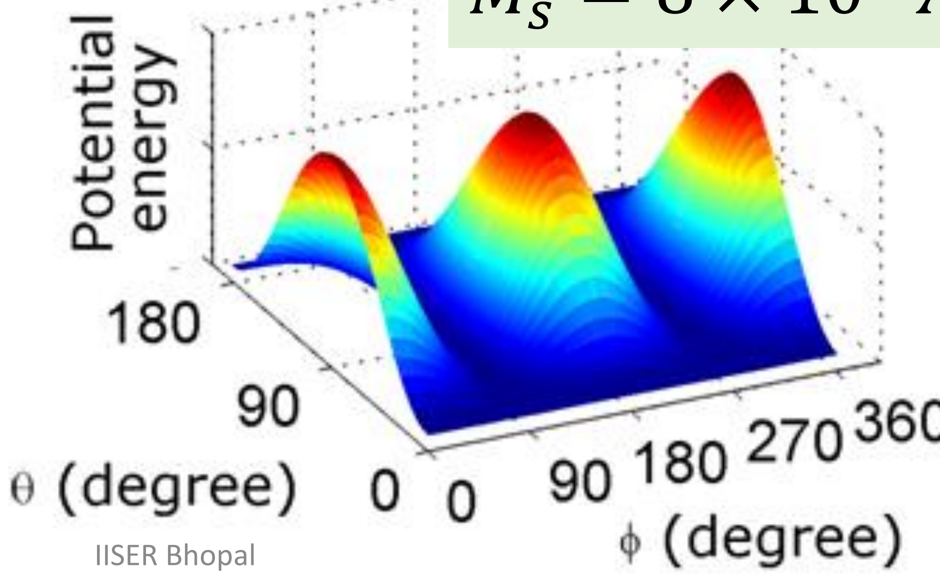
$$M_s = 8 \times 10^5\ A/m$$

E

$\boldsymbol{E_{shape}}$ **(ϕ = ± 90°)**



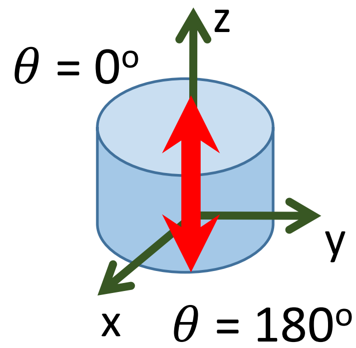
In-plane (**ϕ = ± 90°**) energy barrier: 30 - 80 kT (T=300 K)

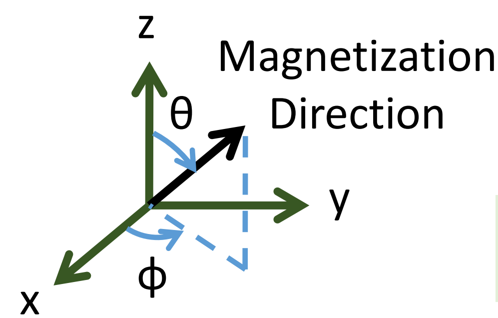


Perpendicular anisotropy

Easy axis:
θ = 180º, 0º

Hard axis:
θ = 90º





Magnet's plane: ϕ = ± 90º

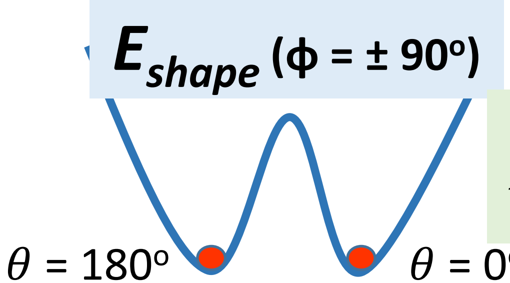
M_s *in A/m*

Potential energy

$$E_{shape}(\theta,\phi) = \frac{1}{2}\mu_0 M_s^2\, \Omega\, N_d(\theta,\phi)$$

$$N_d(\theta,\phi) = N_{d-xx}\sin^2\theta\cos^2\phi + N_{d-yy}\sin^2\theta\sin^2\phi + N_{d-zz}\cos^2\theta$$

$$N_{d-xx} + N_{d-yy} + N_{d-zz} = 1$$



$$E_{shape}(\theta,\phi) = \frac{1}{2}\mu_0 M_s[H_k + H_d\, cos^2\phi]\Omega\sin^2\theta$$

$$H_k = (N_{d-yy} - N_{d-zz})M_s$$

In-plane (**ϕ = ± 90º**) energy barrier: 30 - 80 kT (T=300 K)

Circular cross-section

$$H_d = (N_{d-xx} - N_{d-yy})M_s \quad = 0$$

LLG: Including $\boldsymbol{H_{shape}}$ and $\boldsymbol{H_M}$

$$\frac{d\boldsymbol{m}}{dt} = -|\gamma|\boldsymbol{m} \times \boldsymbol{H_{eff}} + \alpha\left(\boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt}\right)$$

$$\frac{d\boldsymbol{m}}{dt} = \frac{d\theta}{dt}\hat{e}_\theta + sin\theta\frac{d\phi}{dt}\hat{e}_\phi \qquad \boldsymbol{m} = \frac{\boldsymbol{M}}{M} = \hat{e}_r$$

$$\alpha\left(\boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt}\right) = \alpha\frac{d\theta}{dt}\hat{e}_\phi - \alpha\, sin\theta\frac{d\phi}{dt}\hat{e}_\theta$$

$$M = \mu_0 M_s \Omega$$

$$\boldsymbol{H_M} = -\frac{1}{M}\nabla E_M$$

$$\boldsymbol{H_{eff}} = \boldsymbol{H_{shape}} + \boldsymbol{H_M}$$

$$\nabla E_M = \frac{\partial E_M}{\partial\theta}\hat{e}_\theta + \frac{1}{sin\theta}\frac{dE_M}{d\phi}\hat{e}_\phi$$

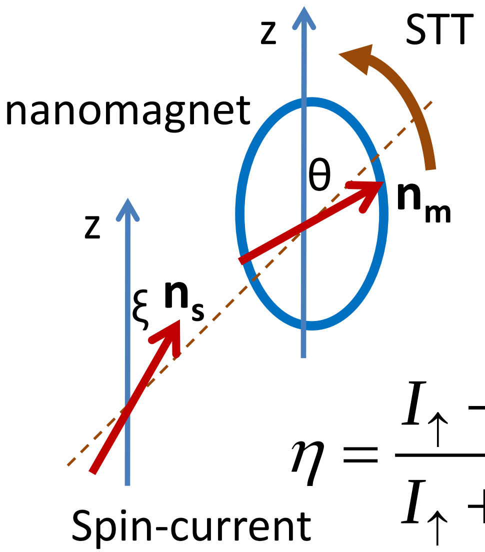
$$E_M = -\boldsymbol{M} \cdot \boldsymbol{H_M}$$
$$= -MH_M(sin\theta\, cos\phi\, sin\theta_m cos\phi_m$$
$$+ sin\theta\, sin\phi\, sin\theta_m\, sin\phi_m$$
$$+ cos\theta\, cos\theta_m)$$

Determine $\frac{d\theta}{dt}$ and $\frac{d\phi}{dt}$

LLG: How to include STT?

Use spherical coordinates

$$\frac{d\boldsymbol{m}}{dt} - \alpha\left(\boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt}\right) = -\frac{|\gamma|}{M}\boldsymbol{M} \times \boldsymbol{H}_{\boldsymbol{eff}} = -\frac{|\gamma|}{M}\boldsymbol{T}_{\boldsymbol{STT}}$$



$$\eta = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow}$$

$$\boldsymbol{STT} = \boldsymbol{s}\ \mathbf{n}_\mathbf{m} \times (\mathbf{n}_\mathbf{s} \times \mathbf{n}_\mathbf{m}) = \boldsymbol{s}\sin(\xi - \theta)\hat{\mathbf{e}}_\theta$$

$$\boldsymbol{s} = (\hbar / 2e)\eta \boldsymbol{I}$$

$$\boldsymbol{n}_{\boldsymbol{s}} = sin\xi\hat{\boldsymbol{e}}_{\boldsymbol{y}} + cos\xi\hat{\boldsymbol{e}}_{\boldsymbol{z}}$$

$$\boldsymbol{n}_{\boldsymbol{s}} \times \boldsymbol{n}_{\boldsymbol{m}} = (cos\theta sin\xi - sin\theta sin\phi cos\xi)\hat{\boldsymbol{e}}_{\boldsymbol{x}} + sin\theta cos\phi cos\xi\hat{\boldsymbol{e}}_{\boldsymbol{y}} - sin\theta cos\phi sin\xi\hat{\boldsymbol{e}}_{\boldsymbol{z}}$$

Cartesian coordinates

$$\boldsymbol{n}_{\boldsymbol{m}} \times (\boldsymbol{n}_{\boldsymbol{s}} \times \boldsymbol{n}_{\boldsymbol{m}}) = -sin\theta cos\phi(sin\theta sin\phi sin\xi + cos\theta cos\xi)\hat{\boldsymbol{e}}_{\boldsymbol{x}} + [cos\theta(cos\theta sin\xi - sin\theta sin\phi cos\xi) + sin^2\theta cos^2\phi sin\xi]\hat{\boldsymbol{e}}_{\boldsymbol{y}} - [sin\theta(sin\theta cos\xi - cos\theta sin\phi sin\xi)]\hat{\boldsymbol{e}}_{\boldsymbol{z}}$$

Use STT to switch magnetization

J. Sun, Phys. Rev. B **62**, 570 (2000)