Interfacial spin-orbit coupling and chirality

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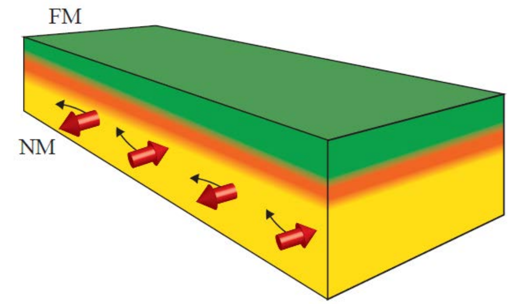
Contents

- Short review of recent experimental data
  - Spin Hall effect
  - Interfacial spin-orbit coupling
  - Dzyaloshinski-Moriya interaction ➔ Chiral magnetic structure
- Chirality in equilibrium
  - Interfacial spin-orbit coupling vs. DM interaction
- Chirality in nonequilibrium
  - Spin torque
  - Spin-dependent electromagnetic field (or spin motive force)
- Questions



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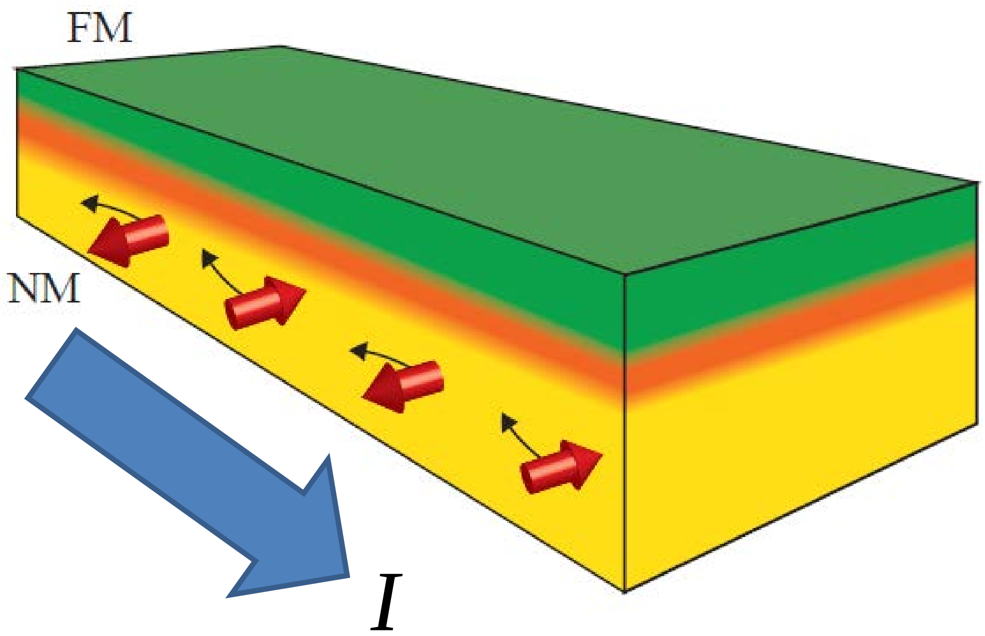
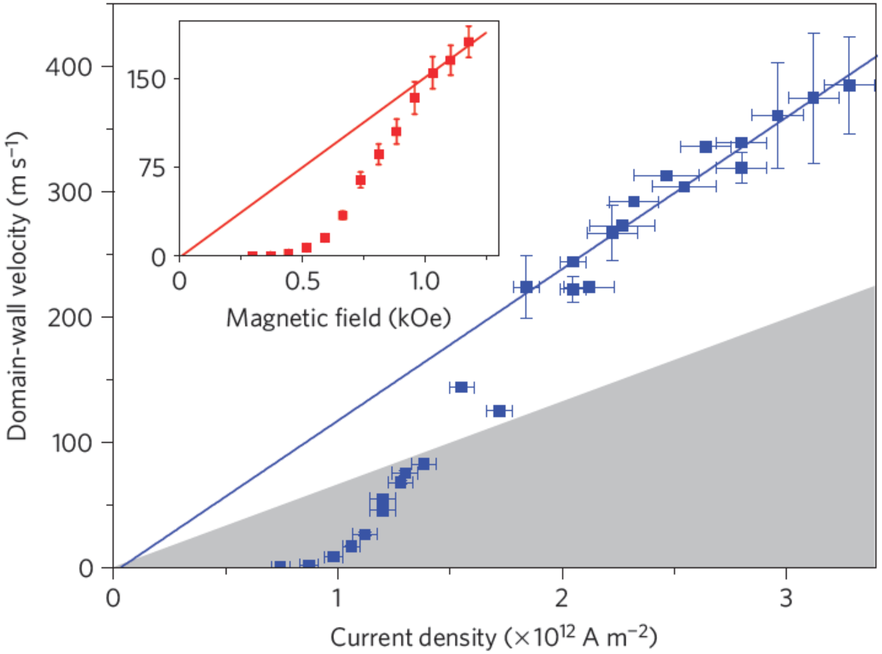
SHORT REVIEW OF RECENT EXPERIMENTS

Magnetic bilayer – Domain wall motion

NM/FM = Pt/Co, Pt/CoFeB, Ta/CoFeB, W/CoFeB, …





Miron et al., Nature Materials 10, 419 (2011)

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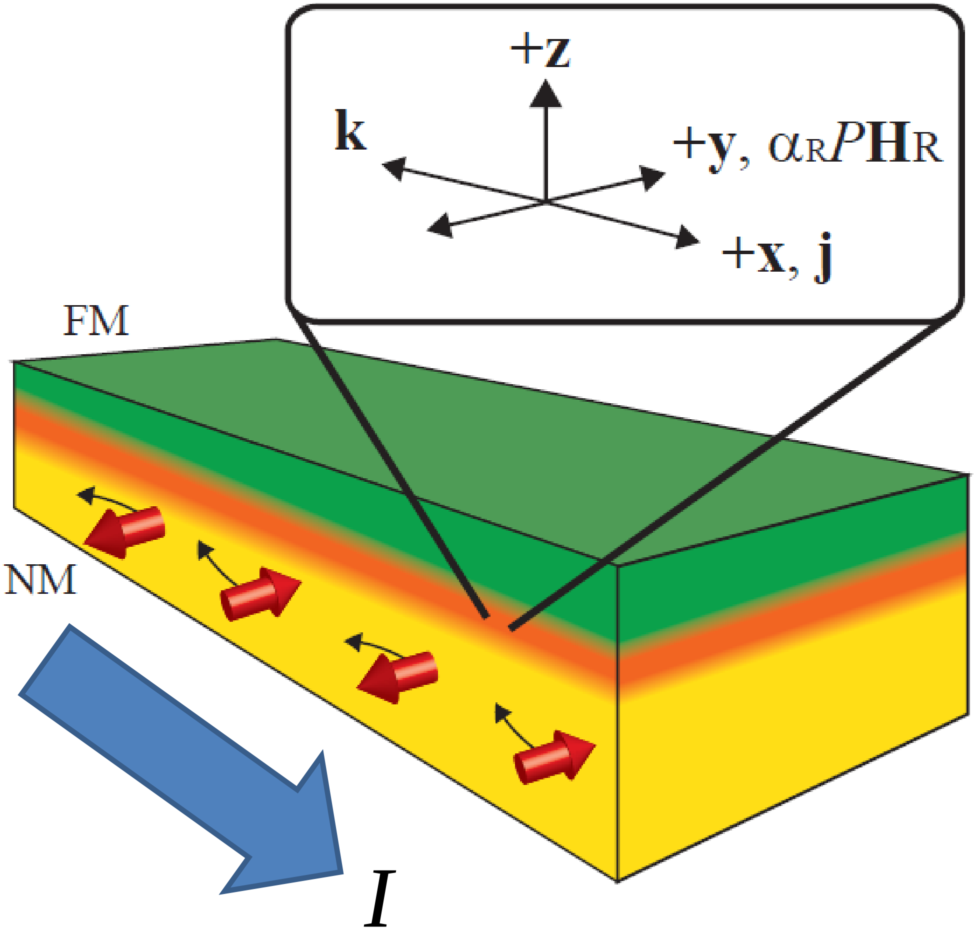
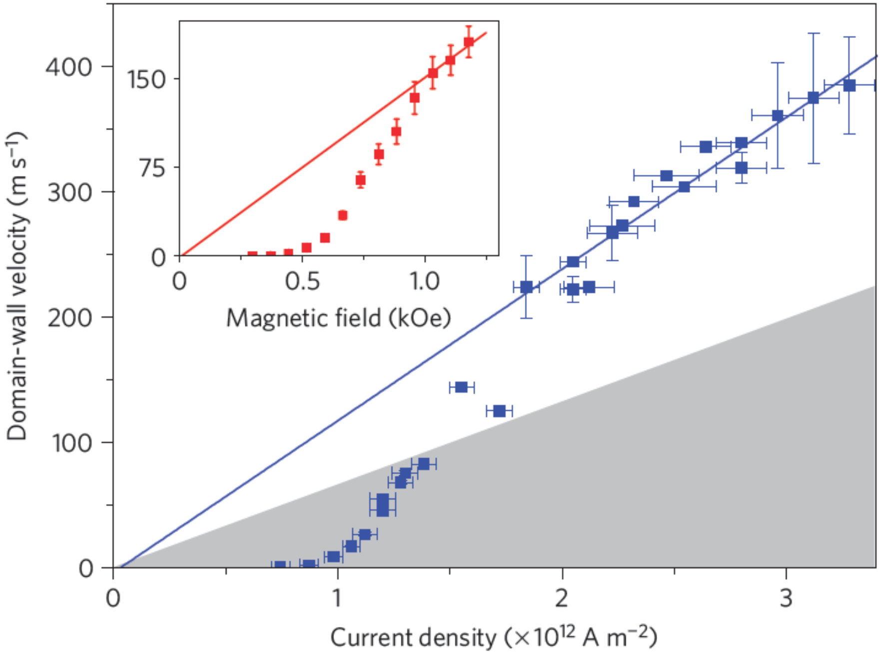
Magnetic bilayer – Domain wall motion

NM/FM = Pt/Co, Pt/CoFeB, Ta/CoFeB, W/CoFeB, …



Interface spin-orbit coupling?



Miron et al., Nature Materials 10, 419 (2011)

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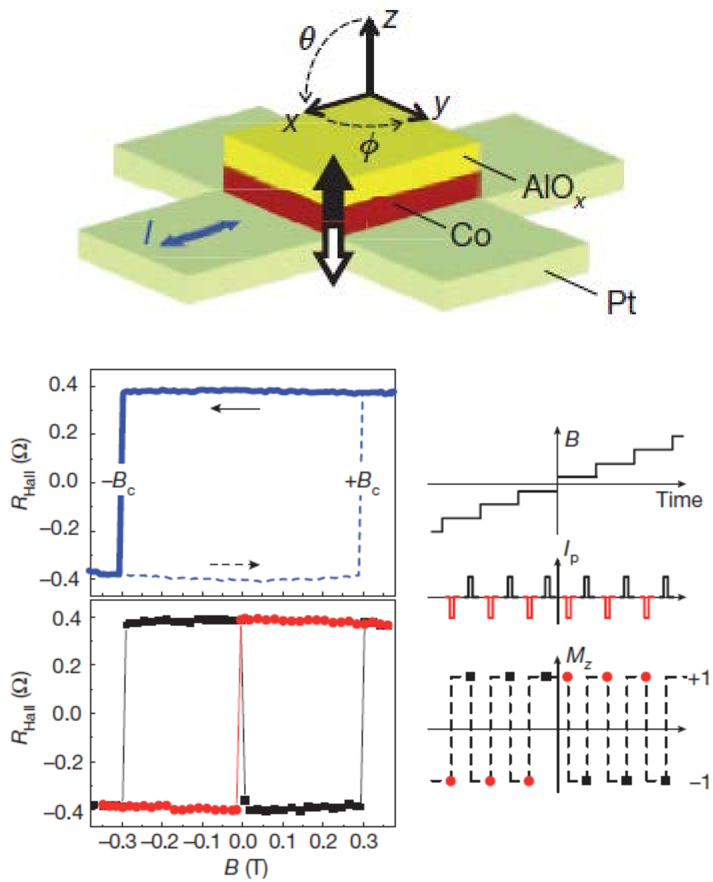
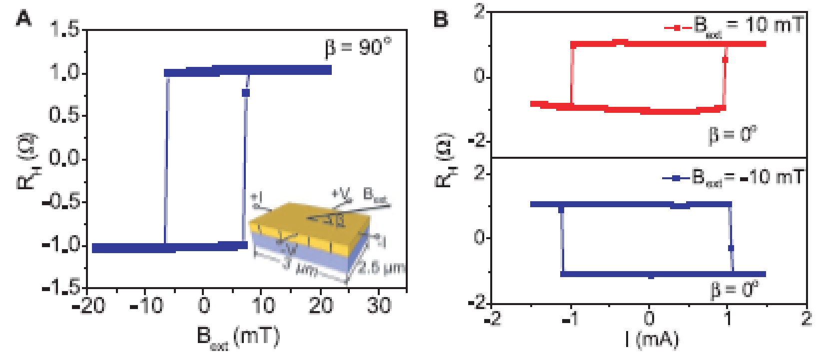
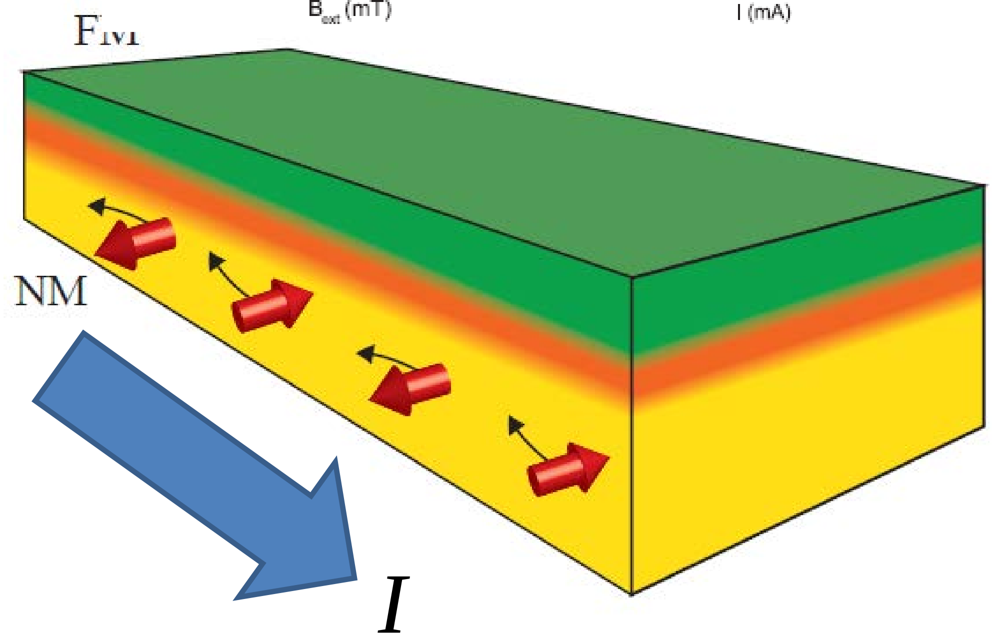
Magnetic bilayer – Magnetization switching

Miron et al., Nature 476, 189 (2011)



Liu et al., Science 336, 555 (2012)





Interface spin-orbit coupling?

Bulk spin Hall effect?

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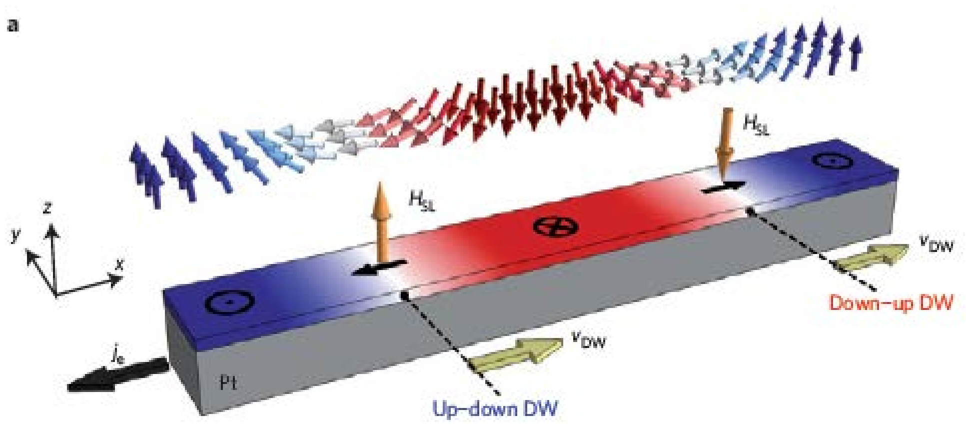
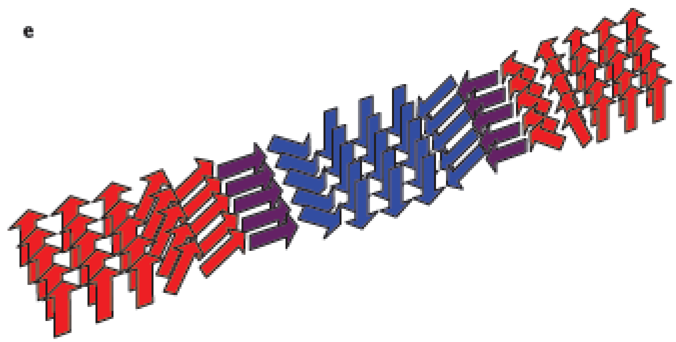
Magnetic bilayer – Domain wall motion

- Chirality ?

Emori et al., Nature Materials 12, 611 (2013)



Ryu et al., Nature Nanotechnology 8, 527 (2013)



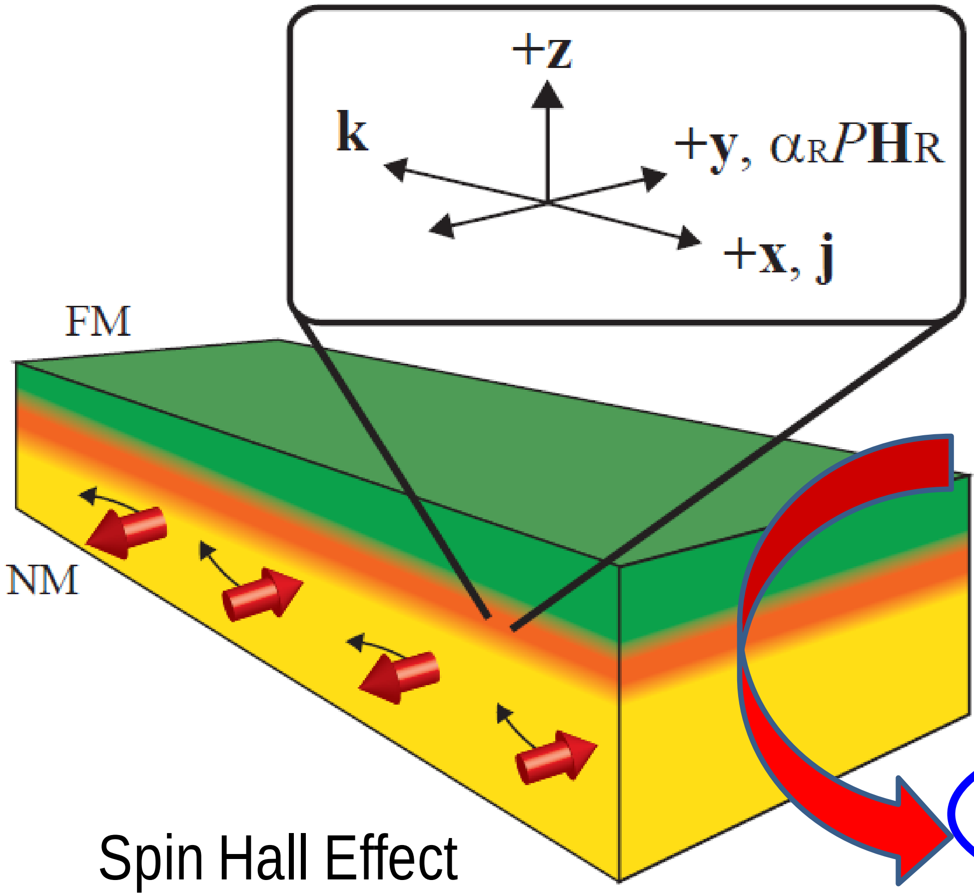
- Dzyaloshinskii-Moriya interaction

$$H_{\mathrm{DM}} = \sum_{ij} \mathbf{D}_{ij} \cdot \left(\mathbf{S}_i \times \mathbf{S}_j \right)$$

Dzyaloshinskii, Sov. Phys. JETP 5, 1259 (1957)
Moriya, Phys. Rev. 120, 91 (1960)

$$H_{\mathrm{DM}}^{\mathrm{1D}} = \int dx \left[D\hat{\mathbf{y}} \cdot \left(\hat{\mathbf{m}} \times \partial_x \hat{\mathbf{m}} \right) \right], \quad H_{\mathrm{DM}}^{\mathrm{2D}} = \int dxdy \left[D\hat{\mathbf{y}} \cdot \left(\hat{\mathbf{m}} \times \partial_x \hat{\mathbf{m}} \right) - D\hat{\mathbf{x}} \cdot \left(\hat{\mathbf{m}} \times \partial_y \hat{\mathbf{m}} \right) \right]$$

Magnetic bilayers



Spin Hall Effect

Liu et al., PRL 106, 036601 (2011);
Science 336, 555 (2012);
PRL 109, 096602 (2012)
Haazen et al., Nature Mater. (2013)

Interfacial spin-orbit coupling

Miron et al., Nature Materials 9, 230 (2010)
Nature Materials 10, 419 (2011)
Nature 476, 189 (2011)

Dzyaloshinskii-Moriya interaction

Thiaville et al., EPL 100, 57002 (2012)
Emori et al., Nature Mater. 12, 611 (2013)
Ryu et al., Nature Nanotech. 8, 527 (2013)

CHIRALITY IN EQUILIBRIUM

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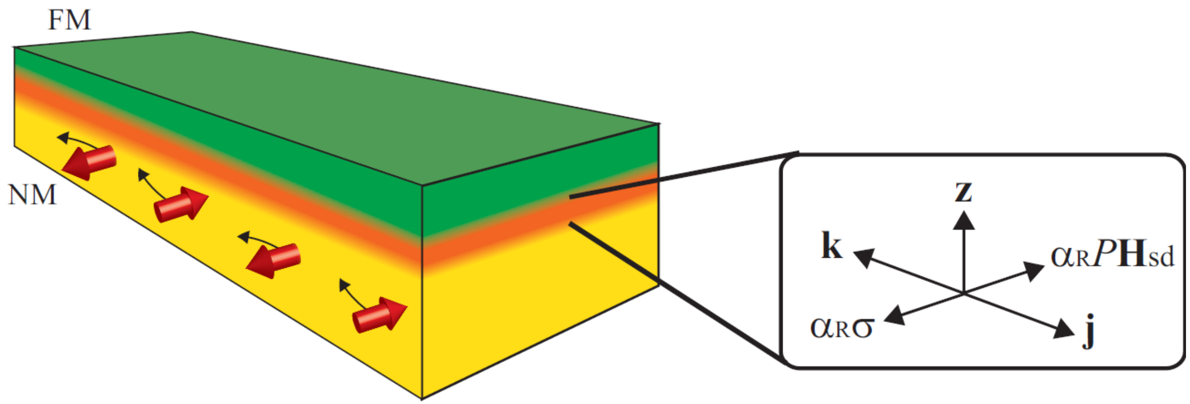
Naïve analysis

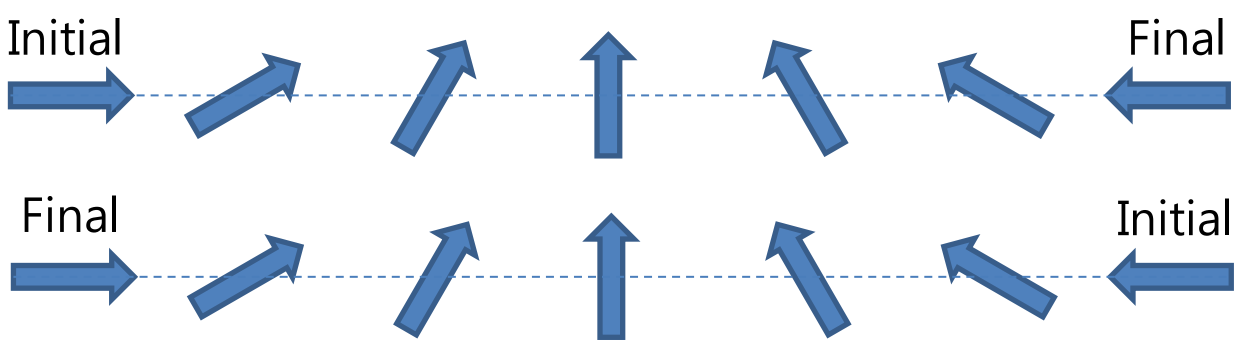


- Interfacial spin-orbit coupling & no exchange coupling

$$H_{\mathrm{R}} = \boldsymbol{\sigma} \cdot \left[\frac{\alpha_{\mathrm{R}}}{\hbar} (\mathbf{p} \times \hat{\mathbf{z}}) \right]$$

$k > 0 \rightarrow B_{\mathrm{eff}} \odot$

$k < 0 \rightarrow B_{\mathrm{eff}} \otimes$

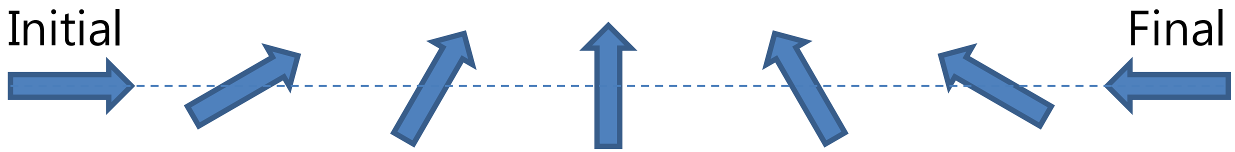


Naïve analysis

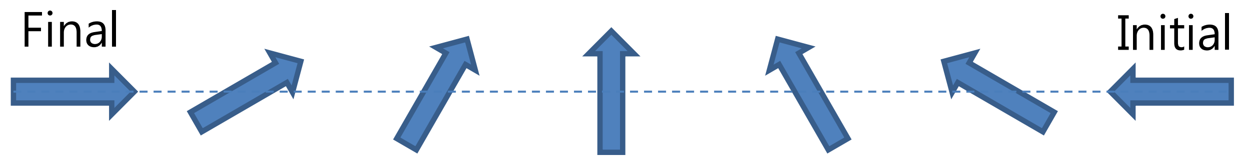
- Interfacial SOC & no exchange coupling

$$H_R = \boldsymbol{\sigma}\cdot\left[\frac{\alpha_R}{\hbar}(\mathbf{p}\times\hat{\mathbf{z}})\right]$$

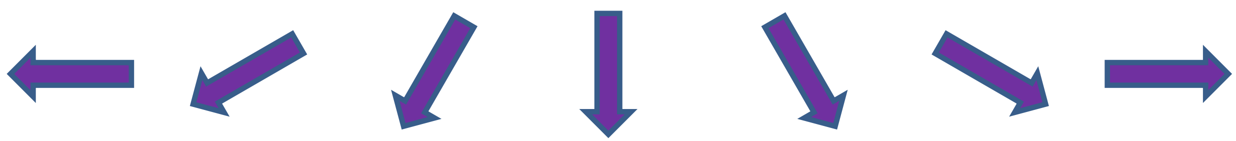
$k > 0 \Rightarrow B_{\text{eff}} \odot$



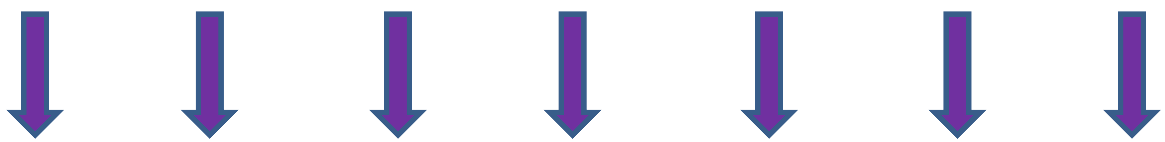
$k < 0 \Rightarrow B_{\text{eff}} \otimes$



- Let's turn on exchange coupling $H_{\text{exc}} = J\boldsymbol{\sigma}\cdot\mathbf{m}$
  - Case I

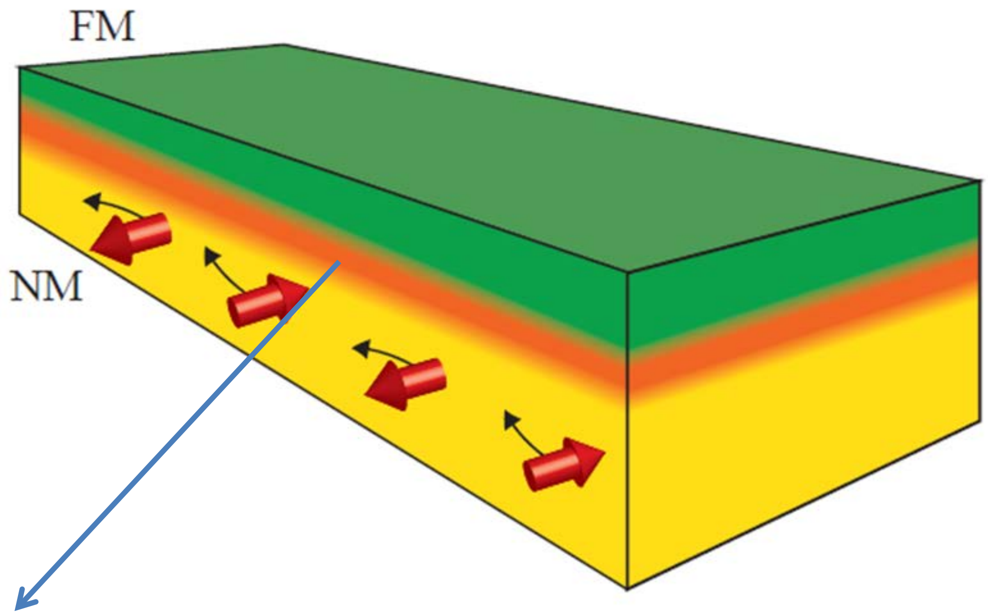


  - Case II



- ➔ Conduction electron energy lowered for chiral $\mathbf{m}$

Effecitive Hamiltonian for interface



- 2D Hamiltonian

$$H = H_{\mathrm{kin}} + H_{\mathrm{exc}} + H_{\mathrm{R}}$$

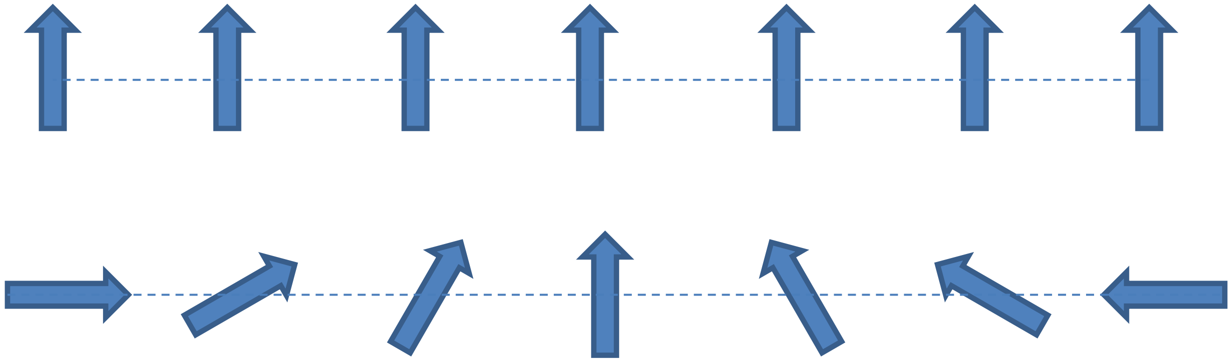
$$= \frac{\mathbf{p}^2}{2m_e} + J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}} + \frac{\alpha_{\mathrm{R}}}{\hbar}\boldsymbol{\sigma}\cdot\left(\mathbf{p}\times\hat{\mathbf{z}}\right)$$

Unitary transformation

- Unitary transformation

$$U = \exp\left[-ik_{\mathrm{R}}\boldsymbol{\sigma}\cdot\left(\mathbf{r}\times\hat{\mathbf{z}}\right)/2\right], \quad k_{\mathrm{R}} = \frac{2\alpha_{\mathrm{R}} m_e}{\hbar^2}$$

  – Spin rotation by angle $k_{\mathrm{R}}r$ around $\mathbf{r}\times\mathbf{z}$ direction



Unitary transformation

- Unitary transformation

$$U = \exp\left[-ik_{\mathrm{R}}\boldsymbol{\sigma}\cdot(\mathbf{r}\times\hat{\mathbf{z}})/2\right], \quad k_{\mathrm{R}} = \frac{2\alpha_{\mathrm{R}} m_e}{\hbar^2}$$

  – Spin rotation by angle $k_{\mathrm{R}} r$ around $\mathbf{r}\times\mathbf{z}$ direction

- Transformed Hamiltonian $U^{+}HU$

$$U^{\dagger}HU = \frac{\mathbf{p}^2}{2m_e} + J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}}' + (\text{higher order terms})$$

$$\hat{\mathbf{m}}' = R^{-1}\hat{\mathbf{m}}$$

$J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}}$ $\qquad$ $J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}}'$

before $\qquad$ after

  – 3×3 Rotation matrix $R(\mathbf{r})$
    - Same rotation as U when acting on classical vector $\mathbf{m}$

Equilibrium energy

- Ground state energy of filled Fermi sea vs. **m**
  - $k_{\mathrm{R}}=0$
    - Energy density $\varepsilon = A\left(\partial_x \hat{\mathbf{m}} \cdot \partial_x \hat{\mathbf{m}} + \partial_y \hat{\mathbf{m}} \cdot \partial_y \hat{\mathbf{m}}\right)$
  - $k_{\mathrm{R}}\neq 0$
    - Unitary transformation $H\left(k_{\mathrm{R}}, \{\hat{\mathbf{m}}\}\right) \Rightarrow H\left(k_{\mathrm{R}}=0, \{\hat{\mathbf{m}}'\}\right)$
    - Energy density $\varepsilon = A\left(\partial_x \hat{\mathbf{m}}' \cdot \partial_x \hat{\mathbf{m}}' + \partial_y \hat{\mathbf{m}}' \cdot \partial_y \hat{\mathbf{m}}'\right)$

$$\partial_x \hat{\mathbf{m}}' = \partial_x \left(R^{-1}\hat{\mathbf{m}}\right) = R^{-1}\left(\partial_x \hat{\mathbf{m}} + k_{\mathrm{R}} \hat{\mathbf{y}} \times \hat{\mathbf{m}}\right) = R^{-1}\tilde{\partial}_x \hat{\mathbf{m}}$$

$$\partial_y \hat{\mathbf{m}}' = \partial_y \left(R^{-1}\hat{\mathbf{m}}\right) = R^{-1}\left(\partial_y \hat{\mathbf{m}} - k_{\mathrm{R}} \hat{\mathbf{x}} \times \hat{\mathbf{m}}\right) = R^{-1}\tilde{\partial}_y \hat{\mathbf{m}}$$

Equilibrium energy

- Ground state energy of filled Fermi sea vs. $\mathbf{m}$
  - $k_{\mathrm{R}}=0$
    - Energy density $\varepsilon = A\left(\partial_x \hat{\mathbf{m}}\cdot\partial_x \hat{\mathbf{m}} + \partial_y \hat{\mathbf{m}}\cdot\partial_y \hat{\mathbf{m}}\right)$

$$\partial_u \hat{\mathbf{m}} \Rightarrow \tilde{\partial}_u \hat{\mathbf{m}} = \partial_u \hat{\mathbf{m}} + k_{\mathrm{R}}\left(\hat{\mathbf{z}}\times\hat{\mathbf{u}}\right)\times\hat{\mathbf{m}}$$

  - $k_{\mathrm{R}}\neq 0$
    - Unitary transformation $H\left(\alpha_{\mathrm{R}},\{\hat{\mathbf{m}}\}\right)\Rightarrow H\left(\alpha_{\mathrm{R}}=0,\{\hat{\mathbf{m}}'\}\right)$
    - Energy density $\varepsilon = A\left(\tilde{\partial}_x \hat{\mathbf{m}}\cdot\tilde{\partial}_x \hat{\mathbf{m}} + \tilde{\partial}_y \hat{\mathbf{m}}\cdot\tilde{\partial}_y \hat{\mathbf{m}}\right)$

$$\partial_x \hat{\mathbf{m}}' = \partial_x\left(R^{-1}\hat{\mathbf{m}}\right) = R^{-1}\left(\partial_x \hat{\mathbf{m}} + k_{\mathrm{R}}\hat{\mathbf{y}}\times\hat{\mathbf{m}}\right) = R^{-1}\tilde{\partial}_x \hat{\mathbf{m}}$$

$$\partial_y \hat{\mathbf{m}}' = \partial_y\left(R^{-1}\hat{\mathbf{m}}\right) = R^{-1}\left(\partial_y \hat{\mathbf{m}} - k_{\mathrm{R}}\hat{\mathbf{x}}\times\hat{\mathbf{m}}\right) = R^{-1}\tilde{\partial}_y \hat{\mathbf{m}}$$

Equilibrium energy

- Ground state energy of filled Fermi sea vs. $\mathbf{m}$
  - $k_R \neq 0$
    - Energy density

$$\varepsilon = A\left(\partial_x \hat{\mathbf{m}} \cdot \partial_x \hat{\mathbf{m}} + \partial_y \hat{\mathbf{m}} \cdot \partial_y \hat{\mathbf{m}}\right) + D\left[\hat{\mathbf{y}} \cdot \left(\hat{\mathbf{m}} \times \partial_x \hat{\mathbf{m}}\right) - \hat{\mathbf{x}} \cdot \left(\hat{\mathbf{m}} \times \partial_x \hat{\mathbf{m}}\right)\right]$$

Dzyaloshinskii-Moriya interaction

$$D = 2k_R A = 2\frac{2\alpha_R m_e}{\hbar^2} A$$

(*) Imamura, Bruno, and Utsumi, PRB 69, 121303 (2004)

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More realistic case ?

- Nonquadratic dispersion ?
- Tight-binding version of H

$$H_{\rm kin} = -\frac{\hbar^2}{2m_e a^2}\sum_{ln\sigma}\left[C^\dagger_{l+1,n,\sigma}C_{l,n,\sigma} + C^\dagger_{l,n+1,\sigma}C_{l,n,\sigma} + \text{h.c.}\right],$$

$$H_{\rm exc} = J\sum_{ln\sigma\sigma'}\left[C^\dagger_{l,n,\sigma}(\boldsymbol{\sigma})_{\sigma\sigma'}C_{l,n,\sigma'}\right]\cdot\hat{\mathbf{m}}_{l,n},$$

$$H_{\rm R} = \frac{\alpha_{\rm R}}{2a}\sum_{ln\sigma\sigma'}\left[iC^\dagger_{l,n+1,\sigma}(\sigma_x)_{\sigma\sigma'}C_{l,n,\sigma} - iC^\dagger_{l+1,n,\sigma}(\sigma_y)_{\sigma\sigma'}C_{l,n,\sigma} + \text{h.c.}\right]$$

  – Nonquadratic dispersion

$$D = 2k_{\rm R}A = 2\frac{2\alpha_{\rm R}m_e}{\hbar^2}A$$

CHIRALITY
IN NONEQUILIBRIUM

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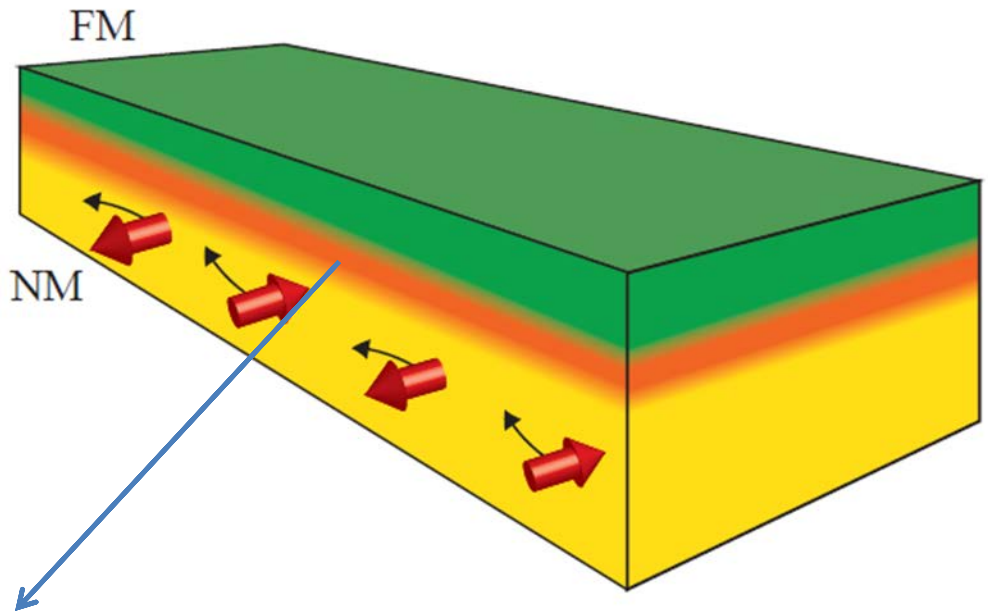
Effecitive Hamiltonian for interface



- 2D Hamiltonian

$$H = H_{\text{kin}} + H_{\text{exc}} + H_{\text{R}} + H_{\text{imp}}$$

$$= \frac{\mathbf{p}^2}{2m_e} + J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}} + \frac{\alpha_{\text{R}}}{\hbar}\boldsymbol{\sigma}\cdot(\mathbf{p}\times\hat{\mathbf{z}}) + H_{\text{imp}}$$

Unitary transformation

- Unitary transformation

$$U = \exp\left[-ik_{\mathrm{R}}\boldsymbol{\sigma}\cdot(\mathbf{r}\times\hat{\mathbf{z}})/2\right], \quad k_{\mathrm{R}} = \frac{2\alpha_{\mathrm{R}} m_e}{\hbar^2}$$

  – Spin rotation by angle $k_{\mathrm{R}} r$ around $\mathbf{r}\times\mathbf{z}$ direction

- Transformed Hamiltonian $U^{+}HU$

$$U^{\dagger}HU = \frac{\mathbf{p}^2}{2m_e} + J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}}' + H'_{\mathrm{imp}} + (\text{higher order terms})$$

$$\hat{\mathbf{m}}' = R^{-1}\hat{\mathbf{m}}$$

  – 3×3 Rotation matrix $R(\mathbf{r})$
    - Same rotation as U when acting on classical vector $\mathbf{m}$

Spin torque

k_R=0

$$\partial_x \hat{\mathbf{m}} = 0 \Rightarrow \mathbf{T}_{\mathrm{adia}} = \mathbf{T}_{\mathrm{non}} = 0$$

Adiabatic torque

$$\mathbf{T}_{\mathrm{adia}} = v_s \partial_x \hat{\mathbf{m}}$$

$$v_s = \frac{Pjg\mu_B}{2eM_s}$$

Nonadiabatic torque

$$\mathbf{T}_{\mathrm{non}} = -\beta v_s \hat{\mathbf{m}} \times \partial_x \hat{\mathbf{m}}$$

$$\partial_x \hat{\mathbf{m}} \Rightarrow \tilde{\partial}_x \hat{\mathbf{m}} = \partial_x \hat{\mathbf{m}} + k_R \hat{\mathbf{y}} \times \hat{\mathbf{m}}$$

$k_R \neq 0$

$$\tilde{\partial}_x \hat{\mathbf{m}} = 0 \Rightarrow \mathbf{T}_{\mathrm{adia}} + \mathbf{T}_{\mathrm{f}} = \mathbf{T}_{\mathrm{non}} + \mathbf{T}_{\mathrm{d}} = 0$$

$$\mathbf{T}_{\mathrm{adia}} \Rightarrow v_s \tilde{\partial}_x \hat{\mathbf{m}} \equiv \mathbf{T}_{\mathrm{adia}} + \mathbf{T}_{\mathrm{f}}$$

$$\mathbf{T}_{\mathrm{non}} \Rightarrow -\beta v_s \hat{\mathbf{m}} \times \tilde{\partial}_x \hat{\mathbf{m}} = \mathbf{T}_{\mathrm{non}} + \mathbf{T}_{\mathrm{d}}$$

$$\mathbf{T}_{\mathrm{f}} = k_R v_s \hat{\mathbf{y}} \times \hat{\mathbf{m}}$$

Field-like torque

$$\mathbf{T}_{\mathrm{d}} = -\beta k_R v_s \hat{\mathbf{m}} \times (\hat{\mathbf{y}} \times \hat{\mathbf{m}})$$

Damping-like torque (Slonczewski-like)

Manchon & Zhang, Obata & Tatara,
Matos-Abiague & Rodriguez-Suarez,
Hals, Brataas &Tserkovnyak

Wang & Manchon
Kim, Seo, Ryu, Lee, HWL
Pesin & MacDonald
van der Vijl & Duine

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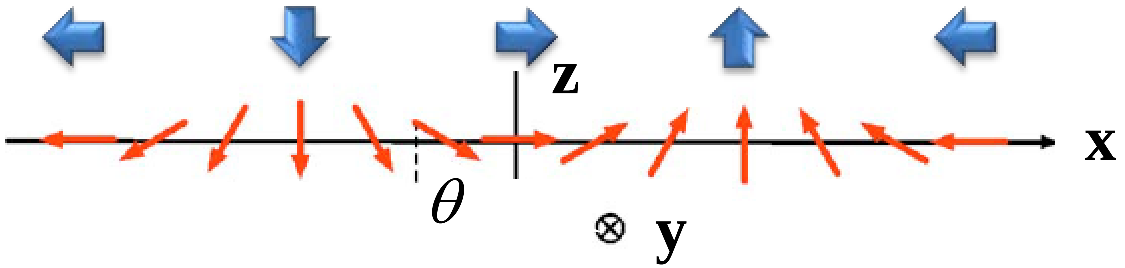
Chirality in spin torque

$$\tilde{\partial}_x \hat{\mathbf{m}} = \partial_x \hat{\mathbf{m}} + k_{\mathrm{R}} \hat{\mathbf{y}} \times \hat{\mathbf{m}}$$

$$\tilde{\partial}_x \hat{\mathbf{m}} = 0$$



$$\frac{d\theta}{dx} = k_{\mathrm{R}}$$

= precession rate of conduction electrons due to interfacial SOC

➔ No current-induced torque if magnetization precesses at the same rate as the conduction electrons would due to RSOC

Theory vs. Experiment

Theory

- DM interaction

$$D\left[\hat{\mathbf{y}}\cdot\left(\hat{\mathbf{m}}\times\partial_x\hat{\mathbf{m}}\right)-\hat{\mathbf{x}}\cdot\left(\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}}\right)\right]$$

$$D=2k_{\mathrm{R}}A$$

  - ➔ $k_{\mathrm{R}}=2.5\times10^{8}\ \mathrm{m}^{-1}$

- Field-like torque

$$\mathbf{T}_{\mathrm{f}}=-k_{\mathrm{R}}v_{\mathrm{s}}\hat{\mathbf{m}}\times\hat{\mathbf{y}}=-\gamma\hat{\mathbf{m}}\times\left(\frac{k_{\mathrm{R}}v_{\mathrm{s}}}{\gamma}\hat{\mathbf{y}}\right)$$

$$v_{\mathrm{s}}=\frac{Pjg\mu_{\mathrm{B}}}{2eM_{\mathrm{s}}}$$

  - 1.3 mT @ $j=10^{11}\ \mathrm{A/m^2}$

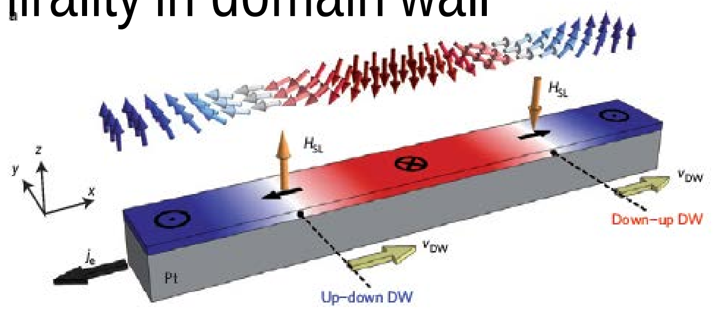
- Damping-like torque

$$\mathbf{T}_{\mathrm{d}}=-\beta k_{\mathrm{R}}v_{\mathrm{s}}\hat{\mathbf{m}}\times\left(\hat{\mathbf{y}}\times\hat{\mathbf{m}}\right)=-\gamma\hat{\mathbf{m}}\times\left(\frac{\beta k_{\mathrm{R}}v_{\mathrm{s}}}{\gamma}\hat{\mathbf{y}}\times\hat{\mathbf{m}}\right)$$

  - ➔ $\beta=4$

Experiment (Emori, Pt/CoFe(0.6nm)/MgO)

- Chirality in domain wall



  - ➔ DM interaction
    - D~0.5 mJ/m^2, A~10^{-11} J/m

- Field-like torque
  - Effective field along **y** direction
    - 2 mT @ $j=10^{11}\ \mathrm{A/m^2}$

- Damping-like torque
  - Effective field along **y**×**m** direction
    - 5 mT @ $j=10^{11}\ \mathrm{A/m^2}$

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Equilibrium vs. Nonequilibrium

$k_R=0$

Equilibrium (no current)

- Exchange energy $J\boldsymbol{\sigma}\cdot\hat{\mathbf{m}} \Rightarrow A(\partial_x\hat{\mathbf{m}}\cdot\partial_x\hat{\mathbf{m}})$
  - Reactive torque
    $$\mathbf{H}_{\mathrm{eff}} = -\frac{1}{M_s}\frac{\delta E[\hat{\mathbf{m}}]}{\delta\hat{\mathbf{m}}} \Rightarrow -\gamma\hat{\mathbf{m}}\times\mathbf{H}_{\mathrm{eff}}$$
  - Dissipative torque (Landau-Lifshitz)
    $$-\alpha\hat{\mathbf{m}}\times\left(\hat{\mathbf{m}}\times\gamma\mathbf{H}_{\mathrm{eff}}\right)$$

Nonequilibrium (finite current)

- Correction to equilibrium torques
  - Correction to reactive torque
    - ➔ Adiabatic torque $\mathbf{T}_{\mathrm{adia}} = v_s\partial_x\hat{\mathbf{m}}$
  - Correction to dissipative torque
    - ➔ Nonadiabatic torque
      $$\mathbf{T}_{\mathrm{non}} = -\beta v_s\hat{\mathbf{m}}\times\partial_x\hat{\mathbf{m}}$$

$k_R\neq0$

- DM interaction $D\left[\hat{\mathbf{y}}\cdot(\hat{\mathbf{m}}\times\partial_x\hat{\mathbf{m}})\right]$
  - Reactive torque
    $$\mathbf{H}_{\mathrm{eff}}^{\mathrm{DM}} = -\frac{1}{M_s}\frac{\delta E^{\mathrm{DM}}[\hat{\mathbf{m}}]}{\delta\hat{\mathbf{m}}} \Rightarrow -\gamma\hat{\mathbf{m}}\times\mathbf{H}_{\mathrm{eff}}^{\mathrm{DM}}$$
  - Dissipative torque
    $$-\alpha\hat{\mathbf{m}}\times\left(\hat{\mathbf{m}}\times\gamma\mathbf{H}_{\mathrm{eff}}^{\mathrm{DM}}\right)$$

- Correction to equilibrium torques
  - Correction to reactive torque
    - ➔ Field-like torque $\mathbf{T}_{\mathrm{f}} = -k_R v_s\hat{\mathbf{m}}\times\hat{\mathbf{y}}$
  - Correction to dissipative torque
    - ➔ Damping-like torque
      $$\mathbf{T}_{\mathrm{d}} = -\beta k_R v_s\hat{\mathbf{m}}\times\left(\hat{\mathbf{y}}\times\hat{\mathbf{m}}\right)$$

Xiao, Zangwill, Stiles

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Garate, Gilmore, Stiles, MacDonald

Spin-dependent electric field

Adiabatic electric field

$$\mathbf{E}^{\pm}_{\mathrm{adia}} = \pm \frac{\hbar}{2e} \sum_{i=x,y} \hat{\mathbf{e}}_i \left(\partial_i \hat{\mathbf{m}} \times \hat{\mathbf{m}} \cdot \partial_t \hat{\mathbf{m}} \right)$$

Berger, PRB 1986
Volovik, JPC 1987
Barnes & Maekawa, PRL 2007

Nonadiabatic electric field

$$\mathbf{E}^{\pm}_{\mathrm{non}} = \pm \beta \frac{\hbar}{2e} \sum_{i=x,y} \hat{\mathbf{e}}_i \left(\partial_i \hat{\mathbf{m}} \times \partial_t \hat{\mathbf{m}} \right)$$

Duine, PRB 2008, 2009
Tserkovnyak & Mecklenburg, PRB 2008

RSOC

$$\tilde{\mathbf{E}}^{\pm}_{\mathrm{adia}} = \pm \frac{\hbar}{2e} \sum_{i=x,y} \hat{\mathbf{e}}_i \left(\tilde{\partial}_i \hat{\mathbf{m}} \times \hat{\mathbf{m}} \cdot \partial_t \hat{\mathbf{m}} \right) = \mathbf{E}^{\pm}_{\mathrm{adia}} + \mathbf{E}^{\pm}_{\mathrm{f}}$$

$$\tilde{\mathbf{E}}^{\pm}_{\mathrm{non}} = \pm \beta \frac{\hbar}{2e} \sum_{i=x,y} \hat{\mathbf{e}}_i \left(\tilde{\partial}_i \hat{\mathbf{m}} \times \partial_t \hat{\mathbf{m}} \right) = \mathbf{E}^{\pm}_{\mathrm{non}} + \mathbf{E}^{\pm}_{\mathrm{d}}$$

"Field-like" electric field

$$\mathbf{E}^{\pm}_{\mathrm{f}} = \pm \frac{\hbar}{2e} \frac{2\alpha_{\mathrm{R}} m_e}{\hbar^2} \hat{\mathbf{z}} \times \partial_t \hat{\mathbf{m}}$$

Kim, Moon, Lee & HWL, PRL 2012

"Damping-like" electric field

$$\mathbf{E}^{\pm}_{\mathrm{d}} = \mp \beta \frac{\hbar}{2e} \frac{2\alpha_{\mathrm{R}} m_e}{\hbar^2} \hat{\mathbf{z}} \times \left(\hat{\mathbf{m}} \times \partial_t \hat{\mathbf{m}} \right)$$

Tatara, Nakabayashi & Lee, PRB 2013

Spin-dependent magnetic field

$$\mathbf{B}_{\pm} = \mp\hat{\mathbf{z}}\frac{\hbar}{2e}\left(\partial_x\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}}\right)\cdot\hat{\mathbf{m}}$$

Volovik, JPC 1987

RSOC

$$\tilde{\mathbf{B}}_{\pm} = \mp\hat{\mathbf{z}}\frac{\hbar}{2e}\left(\tilde{\partial}_x\hat{\mathbf{m}}\times\tilde{\partial}_y\hat{\mathbf{m}}\right)\cdot\hat{\mathbf{m}}$$

$$= \mp\hat{\mathbf{z}}\frac{\hbar}{2e}\left(\partial_x\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}}\right)\cdot\hat{\mathbf{m}} \pm \frac{\hbar}{2e}k_{\mathrm{R}}\nabla\times\left(\hat{\mathbf{z}}\times\hat{\mathbf{m}}\right) + O\left(k_{\mathrm{R}}^2\right)$$

Chiral magnet & skyrmion

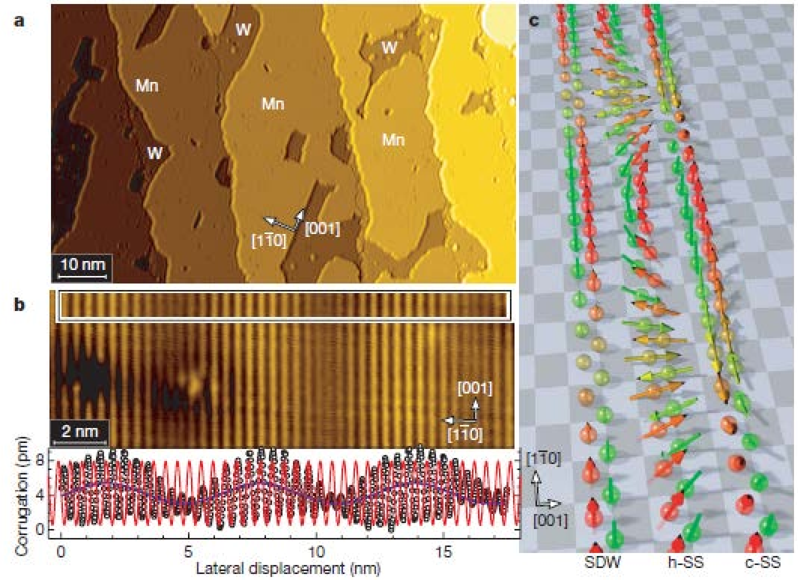
Single atomic layer of Mn on W

nature Vol 447 | 10 May 2007 | doi:10.1038/nature05802

LETTERS

Chiral magnetic order at surfaces driven by inversion asymmetry

M. Bode[1]†, M. Heide[2], K. von Bergmann[1], P. Ferriani[1], S. Heinze[1], G. Bihlmayer[2], A. Kubetzka[1], O. Pietzsch[1], S. Blügel[2] & R. Wiesendanger[1]

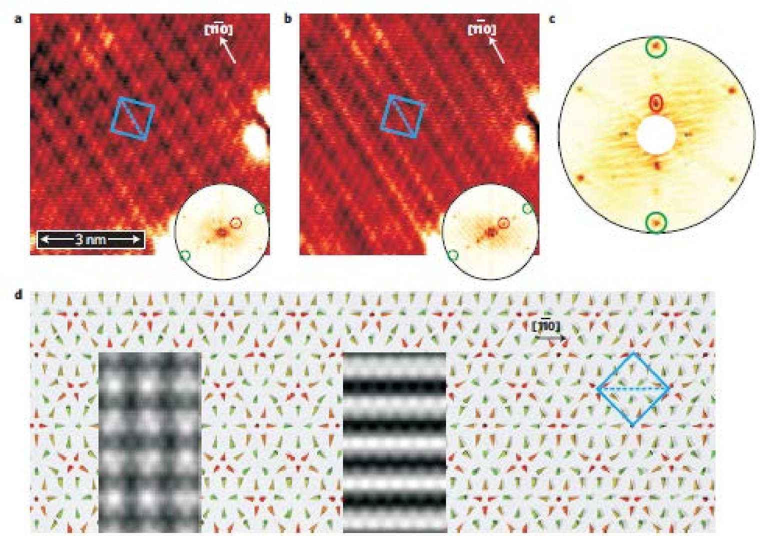


Single atomic layer of Fe on Ir

nature physics ARTICLES
PUBLISHED ONLINE: 31 JULY 2011 | DOI:10.1038/NPHYS2045

Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions

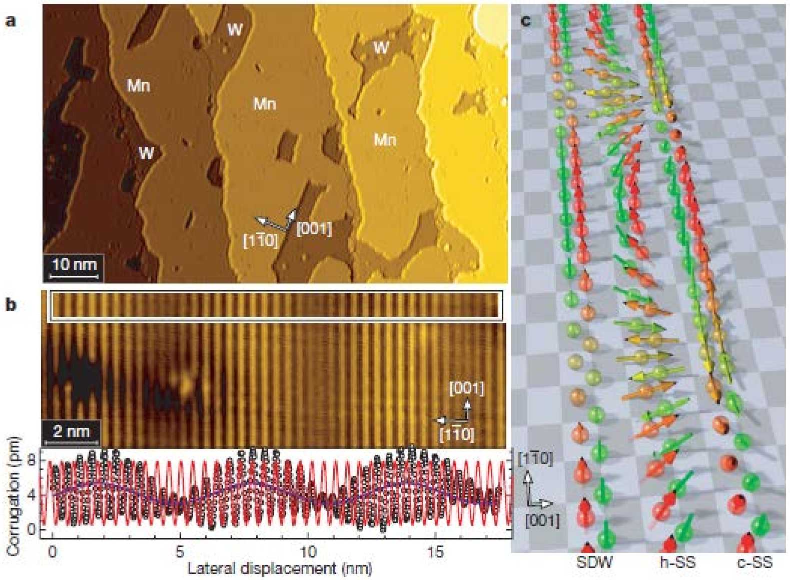
Stefan Heinze[1]*†, Kirsten von Bergmann[2]*†, Matthias Menzel[2]†, Jens Brede[2], André Kubetzka[2], Roland Wiesendanger[2], Gustav Bihlmayer[3]† and Stefan Blügel[3]



Chiral magnet & skyrmion

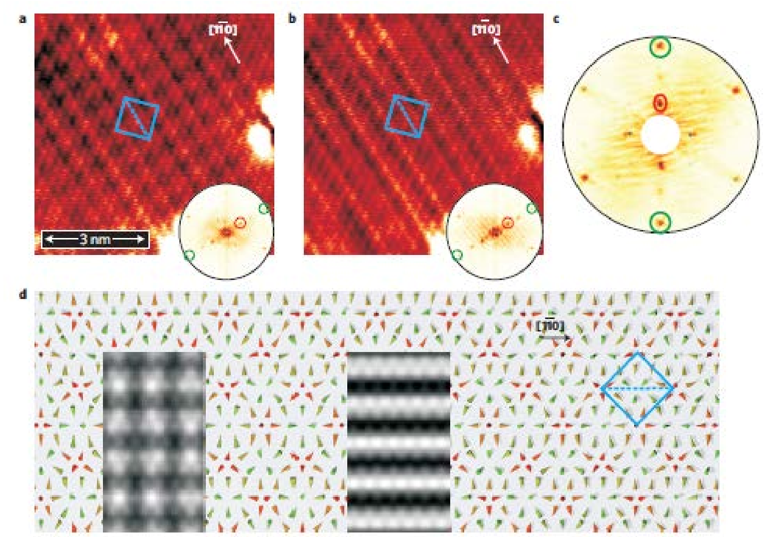
Single atomic layer of Mn on W

$$\tilde{\mathbf{B}}_\pm = \underbrace{\mp\hat{\mathbf{z}}\frac{\hbar}{2e}\left(\partial_x\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}}\right)\cdot\hat{\mathbf{m}}}_{0} \underbrace{\pm\frac{\hbar}{2e}k_{\mathrm{R}}\nabla\times\left(\hat{\mathbf{z}}\times\hat{\mathbf{m}}\right)}_{140\ \mathrm{T}}$$



Single atomic layer of Fe on Ir

$$\tilde{\mathbf{B}}_\pm = \underbrace{\mp\hat{\mathbf{z}}\frac{\hbar}{2e}\left(\partial_x\hat{\mathbf{m}}\times\partial_y\hat{\mathbf{m}}\right)\cdot\hat{\mathbf{m}}}_{10^4\ \mathrm{T}} \underbrace{\pm\frac{\hbar}{2e}k_{\mathrm{R}}\nabla\times\left(\hat{\mathbf{z}}\times\hat{\mathbf{m}}\right)}_{?\ \mathrm{T}}$$



Summary

- Interfacial spin-orbit coupling
  - ➔ Chirality in equilibrium energy
  - ➔ Chirality in nonequilibrium properties (spin torque, spin-dependent electromagnetic fields)
  - ➔ Chiral derivative
  - ➔ Chiral corrections can be important
    - Spin-orbit torque
    - Spin-dependent magnetic field in chiral magnet & skyrmion

THE END

POSTECH