Shift of Magnetic Hysteresis Loop by Dzyaloshinskii Moriya Interaction in Laterally Asymmetric Microstructure

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- Introduction of DMI
- Measurement technique of DMI
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  - Asymmetric Domain Wall Motion
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- Asymmetric Hysteresis for Probing DMI
  (Static Measurement)

Han, CY et al. Nano Lett. 16, 4438 (2016)
DMI (Dzyaloshinskii-Moriya Interaction)

Most general expression for two sites exchange energy

\[ E_{ex} = \sum_{i \neq j} \tilde{S}_i^+ \tilde{A}_{ij} S_j \]

\[ \tilde{A}_{ij}^S = \frac{1}{2} (\tilde{A}_{ij} + \tilde{A}_{ij}^+) \]

\[ \tilde{A}_{ij}^A = \frac{1}{2} (\tilde{A}_{ij} - \tilde{A}_{ij}^+) \]

Antisymmetric exchange interaction (DMI)

\[ E_{ex}^A = \sum_{i \neq j} \tilde{S}_i^+ \tilde{A}_{ij}^A S_j = -\sum_{i \neq j} \tilde{D}_{ij} \cdot (\tilde{S}_i \times \tilde{S}_j) \]

- Dzyaloshinskii (1958): purely symmetry
- Moriya (1960): microscopic mechanism
What’s the role of DMI?

\[ E_{ex} = -\sum_{i\neq j} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

\[ E_{DMI} = -\sum_{i\neq j} D_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \]

- EC (exchange coupling) prefers aligned spins
- DMI prefers perpendicular spin configurations
  - They compete each other, spiral spin configuration!
- Domain walls (DW) with different chirality have different energies due to the DMI
  - Walker breakdown is suppressed
- Formation of \textit{Skyrmion} (small, stable, and easy to move)
Inversion Symmetry Breaking
Dzyaloshinskii-Moriya Interaction

\[ E_{DMI} = -\sum_{i \neq j} D_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \]
Skyrmion for future memory/logic devices

- Skyrmion is topologically stable and small object
- Easily moving with small field or current
- Broad ground state energy of skyrmions
Skyrmion-ics

a

![Graph showing the temperature dependence of the magnetic moment](image)

\[ T = 27.225 \text{ K} \]

\[ I (\text{10}^4 \text{ A m}^{-2}) \]

\[ J (\text{10}^4 \text{ A m}^{-2}) \]

b

![Diagram showing the movement of skyrmions](image)

\[ T = 0 \text{ ns} \]

\[ T = 2.8 \text{ ns} \]

\[ 1 \text{ MA cm}^{-2} \]

\[ 5 \text{ MA cm}^{-2} \]

\[ v = 55.7 \text{ m s}^{-1} \]

\[ v = 12.1 \text{ m s}^{-1} \]

\[ m = 1 \]

\[ m = 0 \]

\[ m = -1 \]

20 nm

20 nm

20 nm

c

![Diagram showing the movement of skyrmions](image)

\[ T = 0 \text{ ns} \]

\[ T = 2.8 \text{ ns} \]

\[ 1 \text{ MA cm}^{-2} \]

\[ 5 \text{ MA cm}^{-2} \]

\[ \text{Final position} \]

20 nm

d

![Diagram showing the movement of skyrmions](image)

\[ T = 0 \text{ ns} \]

\[ T = 1 \text{ ns} \]

\[ 57 \text{ nm} \]

\[ 20 \text{ nm} \]

\[ 5 \text{ MA cm}^{-2}, v = 57.3 \text{ m s}^{-1} \]

20 nm

20 nm

20 nm

20 nm

20 nm

20 nm

20 nm

20 nm
Topologically protected Skyrmion

- Topologically same objects, easily deformed

- Topologically different objects

(a) sphere

(b) torus

(c) 2-torus
Topologically Protected 1D Skyrmion

Two domain walls of opposite chirality

1D Skyrmion (360° domain wall)

Topologically Protected!!
DW motion & Walker Breakdown

After Walker breakdown, DW precesses & energy loss
DMI acts as effective field in DW

Eq. of motion of DW [S. Emori, Nat. Mat. 12, 611 (2013)]

\[
(1 + \alpha^2) \frac{dX}{dt} = \alpha \gamma_0 \lambda H_z + (1 + \alpha \beta) b_j - \frac{\gamma_0 \lambda H_K}{2} \sin(2\Phi) \\
+ \frac{\gamma_0 \lambda \pi}{2} [\alpha H_{SHE} - H_y] \cos(\Phi) + \frac{\gamma_0 \lambda \pi}{2} [H_{DMI} + H_x] \sin(\Phi)
\]

\[
(1 + \alpha^2) \lambda \frac{d\Phi}{dt} = \gamma_0 \lambda H_z + (\beta - \alpha) b_j - \frac{\alpha \gamma_0 \lambda H_K}{2} \sin(2\Phi) \\
+ \frac{\gamma_0 \lambda \pi}{2} [H_{SHE} + \alpha H_y] \cos(\Phi) - \frac{\alpha \gamma_0 \lambda \pi}{2} [H_{DMI} + H_x] \sin(\Phi)
\]

DMI prefers Neel wall
DW motion with DMI

- DMI plays crucial role in the DW dynamics
- DMI prefers Neel type DW
- Walker breakdown is suppressed
- High DW velocity

A. Thiaville et al. EPL 100, 57002 (2012)
How to measure DMI?

Imaging magnetic configuration

Asymmetric SW’s dispersion relation

Asymmetric magnetic DWM

M. Belmeguenai et al., PRB (2015)
K Di et al., PRL (2015)
H. S. Körner et al., PRB (2015)
Measurement methods of DMI

- BLS (Brillouin Light Scattering): Inha U. (DGIST) + TU/e, Singapore NU, NIST, etc.
- SPEELS (Spin polarized electron energy loss spectroscopy): J. Kirschner, Max-Planck
- FMR with antenna: Osaka, KIST
- DW motion: Seoul Nat. Univ., TU/e, Univ. of Leeds
- **New method: DGIST+ Inha + TU/e + Mainz**
  - Relatively simple, less sample limitation, quick & dirty method
Non-Reciprocal Spin Wave dispersion with DMI

\[
\frac{\omega}{\gamma \mu_0} = \sqrt{(H + M_s/4 + J k^2)(H + 3M_s/4 + J k^2) - \frac{e^{-4|k||d|} M_s^2}{16} (1 + 2e^{2|k||d|}) + pD^* k}
\]

\[
\Lambda_{\pm} = \frac{1}{\alpha \omega} \left( 2\gamma \mu_0 J |k_{\pm}| + \frac{\gamma \mu_0 M_s^2 de^{-4|k_{\pm}|d}(1 + e^{2|k_{\pm}|d})/8 \pm pD^*(\omega \mp \gamma \mu_0 pD^*|k_{\pm}|)}{H + M_s/2 + J k_{\pm}^2} \right).
\]

- DMI add extra linear term in SW dispersion relations
- Shift of SWD
- Different SW velocity for \( \pm k \)
Theory for spin waves with iDM interaction

\[ f_{DE} = f_0 \left( M_s, H_{ext}, K_U, A_{ex}, k_x \right) + p \frac{\gamma D}{\pi M_s} k_x \]

\[ \Delta f = \left| f_{DE} (+k_x) - f_{DE} (-k_x) \right| = \frac{2\gamma D}{\pi M_s} k_x \]

\[ f_0 + \frac{\gamma D}{\pi M_s} k_x \]

\[ f_0 - \frac{\gamma D}{\pi M_s} k_x \]

- \( f_0 \): saturated magnetization
- \( H_{ext} \): applied magnetic field
- \( K_U \): anisotropy energy
- \( A_{ex} \): exchange stiffness constant
- \( k_x \): wavenumber of spin waves
- \( \gamma \): gyromagnetic ratio
- \( D \): DM energy density
- \( p \): polarity of DM energy density
BLS schematic and spectrum

Sample structure

- AIOx cap 2 nm
- CoFeB (Co) wedge
- Pt 4 nm
- SiO2 substrate

Co48Fe32B20 Wedge shape
- 1.0 – 3.0nm

Co Wedge shape
- 1.0 – 2.0nm

Stokes intensity (a.u.)

Frequency (GHz)

$\Delta f = 1.99$ GHz

Strong Point of BLS!!!
Result of the Field dependence

\[ \Delta f = \frac{2\gamma D}{\pi M_s} k_x \]

- \( \gamma = 2.37 \times 10^5 \text{ m/(A s)} \)
- \( k_x = 0.0167 \times \text{nm}^{-1} \)
- \( M_s = 1100 \text{ kAm} \)
- \( D = 1.13 \text{ mJ/m}^2 \)

\( t_{Co} = 1.2 \text{ nm} \)

\( \Delta f = 2.18 \text{ GHz} \)
Result of SW Dispersion relations

\[ f_{DE} = f_0 + p \frac{\gamma D}{\pi M_s} k_x \]

\[ t_{Co}(\text{nm}) = \begin{cases} 1.70, & 1.60, \\ 1.50, & 1.35, \\ 1.25, & 1.20, \\ 1.15, & 1.10 \end{cases} \]

\[ f(\text{GHz}) \]

\[ k_x (\text{nm}^{-1}) \]
iDM energy density of Pt/Co/AlO$_x$

Field dependence ($D_H$)

Dispersion relation ($D_k$)

$D_f = \frac{\pi^2 \Delta D \cdot M_s}{k_s \cdot k_x}$

$D_{\text{max}} = 1.24 \text{ mJ/m}^2$

@ $t_{Co} = 1.0 \text{ nm}$
SPEELS (Spin polarized electron energy loss spectroscopy)

- $q \sim 1 \text{ nm}^{-1}$
- Zero-magnetic field
- High quality samples
Asymmetric magnetic domain-wall motion by the Dzyaloshinskii-Moriya interaction

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![Image](image.png)

**FIG. 2.** (Color online) Two-dimensional equi-speed contour map of \( V \) as a function of \( H_x \) and \( H_z \). The color corresponds to the magnitude of \( V \) with the scale on the right. The symbols with error bars show the measured positions \((H_x, H_z)\) on several equi-speed contours. The black solid lines show the best fit using Eq. (2). The purple line indicates the symmetric axis \( H_x = H_0 \) for inversion.
Non-reciprocity of Spin Waves

Propagating SW velocity for left ≠ right due to DMI in real space

FMR with antenna

- Complicate pattern, rather poor signal for thin FM
- Better frequency resolution
- Osaka, Korea Univ., KIST, etc.

D. S. Kim, JKPS (2015)

Magnetostatic Spin Wave in a Very Thin CoFeB Film Grown ... – Dongseok Kim et al.

Fig. 1. (Color online) (a) Schematics of the sample structure and antenna geometry. $d_{gap}$ is the distance between the two antennas. (b) The Fourier transform of the in-plane magnetic field underneath the antennas. The maxima is at $k = 1.2 \mu m^{-1}$. (c) A side view of the sample and the antennas. An antenna is composed of three lines, and a different current direction. Spin waves are induced by the antennas and have a wavelength of 5.2 $\mu m$.

Fig. 3. (Color online) (a) Comparison of $S_{21}$ (solid lines) and $S_{12}$ (colored open symbols) spectra for different distances between antennas. The asymmetry between $S_{12}$ and $S_{21}$ weakens and finally disappears for $d_{gap} > 10 \mu m$. 

Asymmetric Hysteresis for Probing Dzyaloshinskii–Moriya Interaction

D. Han, CY et al. Nano Lett. 16, 4438 (2016).
Asymmetric Nucleation due to DMI

FIG. 1. Kerr images showing the chiral nucleation of domains at one edge of the pad of the Pt/Co/AIOₓ microstructure, by application of an out-of-plane field pulse. (a)–(d) Magnetization is initially saturated ↑ and $B_z = 0$, +160, +215, and +260 mT, (e)–(f) magnetization is initially saturated ↑ and $B_z = -160$ and $-260$ mT, (g)–(h) magnetization is initially saturated ↓ and $B_z$ is +160 and +260 mT. The width of the pad is 70 µm. The dotted lines highlight the left and right edges of the pad and the arrows show the side of the sample where nucleation takes place.

FIG. 3 (color online). (a) Sketch of the micromagnetic configuration within a microstructure with the DMI in zero applied field (i), under an x field (ii), under an additional negative z field (iii), and after reversal, with a domain wall of magnetization parallel to the x field (iv). (b) Results of a 1D calculation showing the reversal field for $D/D_{c0} = 0$ (dashes) and 0.5 (lines). For $D \neq 0$ an easy and a hard branch develop, corresponding to the reversal at the two edges of the microstructure. Inset: complete asteroids.
Dzyaloshinskii-Moriya Interaction

\[ E_{DMI} = -\sum_{i \neq j} D_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \]
Chirality-induced asymmetric switching

Interfacial DMI + Boundary: Chiral tilting

Lower energy barrier

Higher energy barrier

Boundary condition at side edges

\[
\frac{\partial \mathbf{m}}{\partial n} = \frac{1}{\xi} (\hat{z} \times \hat{n}) \times \mathbf{m}
\]

where \( \xi = 2A/D \)

Edge dominant reversal in M-H loop

\[ M_z \text{-dependent switching} \]

Up-Down

Down-Up

Symmetric Hysteresis Loop
Breaking the Lateral Symmetry!!

\[ H_R - H_L \approx H_x [1 - \sin(\gamma)] \]

Asymmetric Hysteresis Loop
Measurement principle: asymmetric hysteresis

Ta/Pt/Co/Ir

Ta/AlOx/Co/Pt

Inverted sign?

TU/e

Kerr Microscope (EVICO)
MOKE Images Pt/Co/Ir

\[ \mu_0 H_x = 120 \text{mT} \]
Easy Determination of DMI Sign

Left-handed chirality

Right-handed chirality
Asymmetric Hysteresis Loops

Ta/Pt/Co/Ir

Ta/AlOx/Co/Pt

\[ H_R - H_L \sim H_x [1 - \sin(\gamma)] \]
Object asymmetry
\[ \sim H_x (1 - \sin \gamma) \]
A droplet model

domain wall energy ($\sigma_{DW}$)

$E_{b} = f(\sigma, H_{z})$

energy barrier ($E_{b}$)

$\sigma = f(D, H_{x}, \gamma)$

Zeeman energy

DW energy : DMI + in-plane field

$\Delta E = \pi R t \sigma_{DW}$

$-\pi R^{2} t \mu_{0} M_{s} \left( \sqrt{1 - \left( \frac{H_{in}}{(H_{K} + H_{z})} \right)^{2}} H_{z} \right)$

$\sigma_{DW} = \sigma_{0} \left( \sqrt{1 - \left( \frac{H_{in} \cos \varphi / H_{K}}{\sigma_{0}} \right)^{2}} \right)$

$\sigma_{0} = 4 \sqrt{A K_{eff}}$

$+ \left( H_{in} \cos \varphi / H_{K} + \frac{2D}{\sigma_{0}} \right) \left( \arccos \left( H_{in} \cos \varphi / H_{K} \right) \right)$

$E_{B} = \frac{\pi \left( \sigma_{DW} \right)^{2} t}{4 \mu_{0} M_{s} \sqrt{1 - \left( \frac{H_{in}}{(H_{K} + H_{z})} \right)^{2}} H_{z}}$

Arrhenius equation

$\tau = \tau_{0} \exp \left( -\frac{E_{B}}{k_{B} T} \right)$

$H_{C,L} = \frac{\pi t \left( \sigma_{DW} \right)^{2}}{4 \mu_{0} M_{s} p k_{B} T \sqrt{1 - \left( H_{in} / H_{K} \right)^{2}}}$,

$p = \frac{E_{B}}{k_{B} T}$

$H_{C,R} = \frac{\pi t \left( \sigma_{DW} \gamma \right)^{2}}{4 \mu_{0} M_{s} p k_{B} T \sqrt{1 - \left( H_{in} / H_{K} \right)^{2}}}$,
**Droplet Model + Angle-Resolved Data**

**A droplet model**

- **Energy barrier** $E_b = f(\sigma, H_z)$
- **Domain wall energy** $\sigma_{DW}$
- **Zeeman energy** $\sigma = f(D, H_x, \gamma)$

**Results**

- **Ta/Pt/Co/Ir**
  - $D = 1.69 \pm 0.03 \text{ mJ/m}^2$ (at $A = 10 \text{ pJ/m}$)
- **Ta/AlOx/Co/Pt**
  - $D = -1.43 \pm 0.06 \text{ mJ/m}^2$ (at $A = 10 \text{ pJ/m}$)

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S Pizzini et al., PRL (2014)
J. Vogel et al., Comptes Rendus Physique (2006)
BLS measurements

**Figure a:**
- Stokes and Anti-Stokes measurements for Pt/Co/Ir and AlOx/Co/Pt.
- BLS intensity (arb. Unit) vs. frequency (GHz).

**Figure b:**
- DMI energy density (mJ/m²) vs. $t^1$ (nm⁻¹).
- Data points and curves for different samples:
  - Ta/Pt/Co/Ir
  - Ta/AlOx/Co/Pt
  - Pt/Co/AlOx (Ref. S6)
  - Pt/Co/AlOx (Ref. S7)
  - Ta/Pt/Co/AlOx (Ref. S8)
  - Ta/Ir/Co/AlOx (Ref. S8)
Comparison with BLS

Asymmetric hysteresis

- Ta/Pt/Co/Ir : $1.69 \pm 0.03 \text{ mJ/m}^2$
- Ta/AlOx/Co/Pt : $-1.43 \pm 0.06 \text{ mJ/m}^2$

BLS measurement

- Ta/Pt/Co/Ir : $1.34 \pm 0.12 \text{ mJ/m}^2$
- Ta/AlOx/Co/Pt : $-1.00 \pm 0.05 \text{ mJ/m}^2$

- With the nominally same samples
- Most serious error came from DW width (energy)
Conclusions

- Asymmetric Hysteresis Loop measurement
  - Relatively easy, simple, & quick
  - In principle, it is applicable to any kind of MH-loop (static, AHE, MR, VSM, …)
  - Qualitatively and/or Quantitatively
Thank You

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