Room temperature chiral magnetic skyrmions in ultrathin Pt/Co/MgO nanostructures

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Outline

• Observation of chiral Néel domain walls by XMCD-PEEM in ultrathin Pt/Co/MgO films
• Large DMI in Pt/Co/MgO thin films
  → BLS spin wave spectroscopy measurements
  → Ab-initio calculations
• Room temperature chiral magnetic skyrmions in Pt/Co/MgO nanostructures
  → Experiments
  → Micromagnetic simulations and numerical models
**Magnetic skyrmion**

- **Nanometer scale**

- **Chiral** magnetic object driven by the Dzyaloshinskii-Moriya $H_{\text{DMI}} = -\mathbf{D}_{1,2}(\mathbf{u}).(\mathbf{S}_1 \times \mathbf{S}_2)$

- **Topologically protected**

  \[ S = \frac{1}{4\pi} \int_C \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) \]

  \[ \rightarrow |S|=1 \text{ for single skyrmion} \]
  \[ \rightarrow S=0 \text{ for FM states} \]


1\textsuperscript{a} A. Fert et al., Nat Nano 8, 152 (2013).

1\textsuperscript{b} Nagaosa, Nat.Nano, 8,899 (2013).
Non-volatile memory and logic applications

- Manipulation by current with low density\(^1,2,3,4\) (~10\(^6\) A/m\(^2\))
- Need for isolated skyrmions stable at room temperature and zero magnetic field with 10 of nms diameter
- chirality and \(|S| = 1\) needed for current induced motion

Experimental observations of chiral skyrmion structures

- B-20 bulk or thin film chiral magnet (MnSi$_3$, Fe$_{1-x}$Co$_x$Si$_4$, FeGe,...)

- Sputtered ultrathin FM/Heavy metal multilayers

  - Large DMI + large spin orbit torque
  - Tunable properties (K, DMI, A) by playing on materials
  - Fast sputtering deposition
  - Compatible with spintronics devices (MTJ)

- Ultrathin epitaxial film (Ir(111)/Fe(1ML), Ir(111)/FePd,...)

  - Interfacial DMI due to inversion asymmetry by the interface+ Heavy metal
  - Néel like skyrmion
  - Only stable at low temperature

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Samples and experiments

- **Samples**
  - Si/Ta/Pt(3 nm)/Co(1 nm)/Mg-ox(2nm)/Ta
  - annealed 1H30 @ 250°C
  - Perpendicularly magnetized ($H_{sat} = 200$ mT)

- **XMCD-PEEM magnetic microscopy**
  - High lateral spatial resolution (down to 25 nm)
  - Magnetic contrast proportional to the projection of $M$ on X ray beam direction
    - $\rightarrow$ contrast 3x larger for $M_{inplane}$ than $M_{out-of-plane}$
    - Imaging of the **internal structure** of DWs/skyrmion
  - Observation in a virgin demagnetized state at room temperature

Stöhr et al.
Chiral Néel Domain Wall

- Dark contrast for down/up DW (P to beam) and a bright contrast for up/down DW (AP to beam) → Left handed chiral Néel DW
- XMCD contrast well fitted assuming a chiral Néel DW profile with gaussian convolution → DW width ≈ 30±4 nm (π√A/K)
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Measurement of DMI from BLS spin wave spectroscopy

• DMI leads to a shift in frequency for spin waves with opposite k vector (\(\mathbf{k} \perp \mathbf{H}_{\text{in-plane}}\))
• Difference in frequency shifts between Stokes and anti-Stokes peaks in BLS measurements

\[ E_{DMI} = \pm 2D\hbar k_x \gamma/M_s \]
\[ \Delta f(k_x) = \frac{2\gamma k_x D}{\pi M_s} \]

Brillouin Light Scattering experiment

\[ H=0.7 \, \text{T} \]
\[ K_{SW}=4.1 \, \mu \text{m}^{-1} \]

M. Belmeguenai et al., LSPM, Université Paris 13 (PRB 91, 180405 (2014) and K. Di et al., PRL 114, 047201 (2015))
Measurement of DMI from BLS spin wave spectroscopy

\[ \Delta f(k) = \frac{2\gamma kD}{\pi M_s} \]

\[ D = \frac{D_s}{t} \rightarrow D_s = 2.17 \pm 0.14 \text{ pJ/m} \]

\[ D/D_c \sim 0.8 \quad D_c = \frac{4\sqrt{AK_{\text{eff}}}}{\pi} \]

\[ \rightarrow \text{Largest value reported so far in sputtered magnetic thin films} \]

\[ D = 2.05 \pm 0.3 \text{ mJ/m}^2 \]
Ab-initio calculations

\[
d = \frac{(E_{cw} - E_{ccw})}{12}
\]

- Calculations based on density functional theory
- DMI calculated from the difference between clockwise and counter clockwise spin spiral. (H. Yang, M. Chshiev et al., 115, 267210 (2015)

- Pt/Co 5 ML/MgO \(\rightarrow\) \(D=2.3\ \text{mJ/m}^2\) for 5 ML (\(\sim 1\ \text{nm}\)) close to the experimental value \(D=2.03\pm0.3\ \text{mJ/m}^2\)
- Pt/Co 5 ML/vacuum \(\rightarrow\) \(D=1.5\ \text{mJ/m}^2\)
Ab-initio calculations (2)

- Larger contribution of DMI at the Pt/Co interface
- Larger DMI in Pt/Co/MgO due to an additional contribution at the Co/MgO interface
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Zero field room temperature chiral Néel skyrmion

- Chiral Néel skyrmion stable room temperature at zero field in 420 nm square dots (S=1).
- Profile well fitted by two gaussian convoluted chiral Néel domain walls
  - Skyrmion diameter = $130 \pm 3$ nm
Micromagnetic simulation

$D=2.05 \text{ mJ/m}^2$, $M_s=1.4 \times 10^6 \text{ J/m}^3$, $A=27.5 \text{ pJ/m}$, $K_u=1.45 \times 10^6 \text{ J/m}^3$, $H=0$

Skyrmion diameter = 128 nm
DW width = 37 nm

- Micromagnetic simulation well reproduce experiments.
Skyrmion structure

- Skyrmion diameter (130 nm) large compared to the DW width (37 nm) \(\rightarrow\) skyrmion structure closer to two independant chiral Néel DWs
Application of a perpendicular magnetic field

- Skyrmion in a 630 nm diameter disk patterned in Pt/Co(1.1 nm)/MgO
- Larger skyrmion diameter (190 nm), which can be explained by the larger thickness
- Large decrease of the skyrmion diameter from 190 nm to 70 nm when applying a small Hz=4 mT opposite to the core
- Reversible contraction/expension of the skyrmion with H_z
Rotation of the beam direction

- Rotation of the black/white contrast when rotating the sample with respect to the X-ray beam direction
  - confirms the radial orientation of the DW in-plane spins of the skyrmion
Model

- Ansatz: \[ \theta(r) = \theta_{DW}(r - d/2) + \theta_{DW}(r + d/2) \]
  \[ \theta_{DW}(r) = 2 \arctan[\exp(r/\Delta)] \]

\[ E = E_\sigma + E_{mag} \]

- \( E_\sigma \) = exchange, DMI, anisotropy, internal stray field (~DW energy)

\[ E_{\sigma}[\theta(r)] = 2\pi t \int_{0}^{R} \left\{ A \left[ \left( \frac{d\theta}{dr} \right)^2 + \frac{\sin^2 \theta}{r^2} \right] - D \left[ \frac{d\theta}{dr} + \frac{\cos \theta \sin \theta}{r} \right] + (K_{eff} + E_{DW}^s) \sin^2 \theta \right\} rdr \]

  exchange  DMI  Anisotropy  DW demag energy


- \( E_{mag} \) = magnetostatic energy due to the dipolar interaction between the domains

\[ E_{mag}(d) = E_{mag0} - t(1 - N_{DW}) \frac{\mu_0 M_s^2}{2} \int_{0}^{R} \cos^2 \theta \cdot 2\pi r dr \] with \[ E_{mag0} = \frac{4\pi t}{R} \int_{0}^{\infty} [1 - \exp(-\beta x)] I^2(x) dx \]

\[ I(x) = \int_{0}^{1} dr' r' J_0(x r') \cos \theta(r') \]

**Force on the skyrmion DWs**

\[
F_\sigma = -\frac{\partial E_\sigma}{\partial d}
\]

\[
F_{\text{mag}} = -\frac{\partial E_{\text{mag}}}{\partial d}
\]

**Calculation for a 420 nm circular dot**

- **Force** \( F_\sigma \) due to DW energy (K, A, DMI)
  \rightarrow \ F_\sigma = 0 \text{ for } d = 20 \text{ nm} \ (\text{DW energy } (\sim d) \text{ vs curvature energy due to exchange } (\sim 1/d) )

- **Force** \( F_{\text{mag}} \) due to magnetostatic interaction between domains: expands the skyrmion
  \rightarrow \ F_{\text{mag}} + F_\sigma = 0 \text{ for larger } d = 90 \text{ nm}.

- Magnetostatic effect important when thickness \( t > l_w = \frac{\sigma}{\mu_0 M_s^2} \) \ (= E_{\text{mag}} > E_{\text{DW}}) \)

- \( \sigma = 4\sqrt{(AK)} - \pi D \) \rightarrow \ l_w \sim 1 \text{ nm} \sim t \ \rightarrow \text{Large effect of dipolar interaction due to lowered DW energy by DMI}
Influence of the nanostructure lateral dimensions

- No skyrmion observed at zero field for skyrmions with lateral dimension > 1 µm
- The magnetostatic interaction destabilizes the skyrmion for larger structure
Dependance of the skyrmion diameter on thickness and $H$:

- Skyrmion stable only within a narrow range of film thickness between 0.9 and 1.1 nm.
- Large dependance of the diameter on the film thickness
- skyrmion diameter can be tuned by small perpendicular magnetic field

Micromagnetic simulation
Conclusion

• Observation of isolated skyrmion and its internal chiral Néel structure at room temperature and zero external magnetic field in Pt/Co/MgO nanostructures

• A large DMI is measured using BLS experiments. Ab-initio calculations suggest an additional DMI contribution at the Co/MgO interface.

• Experimental results are substantiated by micromagnetic simulations

• The skyrmion size and stability is the result of balance between the DW energy modulated by DMI and the domain magnetostatic interaction