SNU

Ferrimagnetic Spintronics

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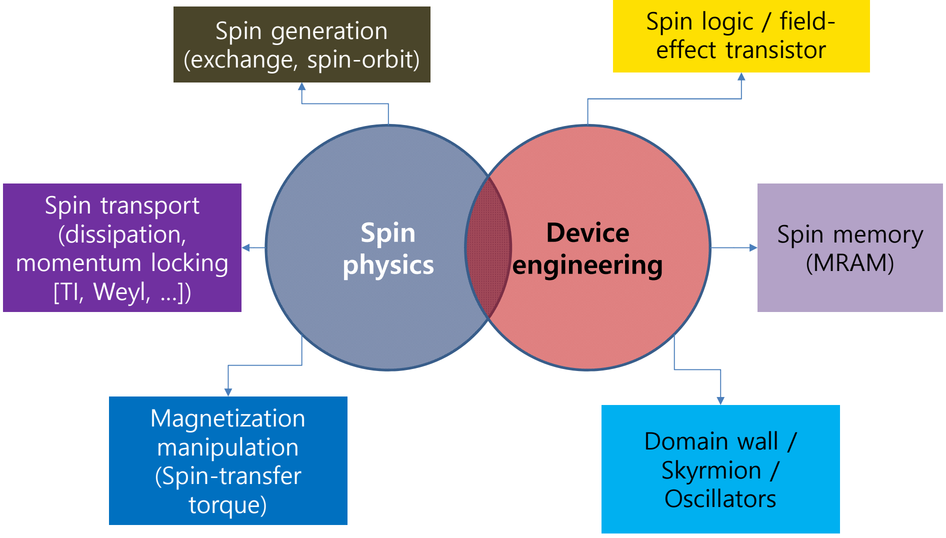
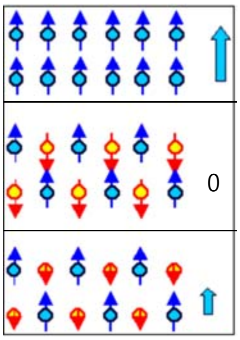
Outline

- Introduction
  - Ferrimagnets for antiferromagnetic spintronics study
- Dynamics of antiferromagnetic spin textures in ferrimagnets
  - Field- or current-driven ferrimagnetic domain wall (DW) motion
  - Vanishing skyrmion Hall effect
- (if time is allowed) Spin coherence length in ferrimagnets
- Summary

Spintronics (= Spin + Electronics)



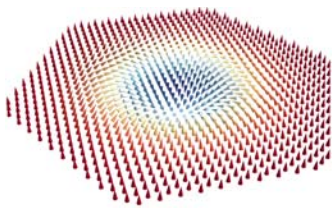
Magnet



- Ferromagnet
- Antiferromagnet
- Ferrimagnet

- Magnetic domain wall (DW)

- Magnetic skyrmion



Ferromagnetic spintronics

- Ferromagnet = A core material for spintronics research
- Spin(-polarized) current generation through exchange splitting
- Spin current detectors
- Spin-transfer torque (STT) or spin-orbit torque (SOT) switching
  ➔ nonvolatile memory and logic applications
- STT- or SOT-driven domain wall/skyrmion motion

- Physics (spin transport & magnetization dynamics) well understood
- Switching current for MRAM applications ➔ NOT sufficiently low
- **Domain wall speed for SRAM replacement ➔ NOT sufficiently high**
- **Skyrmion Hall effect ➔ information loss**

➔ Antiferromagnets would help to resolve these issues

A review cluster for antiferromagnetic spintronics

nature physics

« Previous Issue | Volume 14 | Next Issue »

Volume 14 Issue 3, March 2018

Comment

Comment | 02 March 2018
The multiple directions of antiferromagnetic spintronics
New developments in spintronics based on antiferromagnetic materials show promise for improved fundamental understanding and applications in technology.
T. Jungwirth, J. Sinova [...] & C. Felser

Perspectives

Perspective | 02 March 2018
Antiferromagnetic spin textures and dynamics
As part of a Focus on antiferromagnetic spintronics, this Perspective looks at the complex and often faster dynamics of antiferromagnetic spin textures.
O. Gomonay, V. Baltz [...] & Y. Tserkovnyak
Focus: Antiferromagnetic spintronics

Perspective | 02 March 2018
Synthetic antiferromagnetic spintronics
As part of a Focus on antiferromagnetic spintronics, this Perspective examines the opportunities afforded by synthetic, as opposed to crystalline, antiferromagnets.
R. A. Duine, Kyung-Jin Lee [...] & M. D. Stiles
Focus: Antiferromagnetic spintronics

Review Articles

Review Article | 02 March 2018
Spin transport and spin torque in antiferromagnetic devices
As part of a focus on antiferromagnetic spintronics, this Review considers the role of spin transport and spin torque in potential antiferromagnetic memory devices.
J. Železný, P. Wadley [...] & H. Ohno
Focus: Antiferromagnetic spintronics

Review Article | 02 March 2018
Antiferromagnetic opto-spintronics
An overview of how electromagnetic radiation can be used for probing and modification of the magnetic order in antiferromagnets, and possible future research directions.
P. Němec, M. Fiebig [...] & A. V. Kimel
Focus: Antiferromagnetic spintronics

Review Article | 02 March 2018
Topological antiferromagnetic spintronics
Topological states of various kinds may find application in spintronic devices. The authors review recent progress in this area.

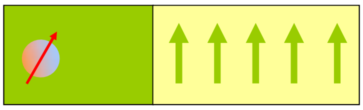
Why antiferromagnets?

$$\frac{d\boldsymbol{S}}{dt} = \frac{1}{i\hbar}[\boldsymbol{S}, \mathcal{H}] \Rightarrow \frac{d\mathbf{S}}{dt} = -\gamma \mathbf{S}\times\mathbf{H}$$

For ferromagnets, **S** precesses around **H**

For antiferromagnets, $\mathbf{S}_{net} = \mathbf{S}_1 + \mathbf{S}_2 = 0$ ➔ $\frac{dS}{dt}$??

$$\frac{\partial \mathbf{s}}{\partial x} = \frac{1}{v_x}\frac{\partial \mathbf{s}}{\partial t} \propto -\mathbf{s}\times\hat{\mathbf{m}} \Rightarrow \mathbf{s} \propto (\cos kx, \sin kx, 0)$$



For antiferromagnets, $\mathbf{S}_{net} = \mathbf{S}_1 + \mathbf{S}_2 = 0$ ➔ $\frac{dS}{dx}$??

Rare-earth (RE)–transition metal (TM) Ferrimagnet

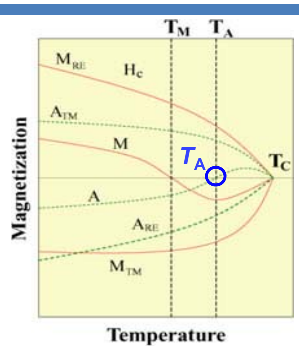
$\boldsymbol{S}$ = Angular momentum

$\boldsymbol{M}$ = Magnetic moment

γ= Gyromagnetic ratio

$$\boldsymbol{S} = -\frac{\boldsymbol{M}}{\gamma} = -\frac{\hbar}{g_L \mu_B}\boldsymbol{M}$$

- Lande-g factor (g_L)
  - ➔ 2.2 for Co, 2.0 for Gd



For RE-TM ferrimagnets, T_M ($\mathbf{M}_{tot}$ = 0 but $\mathbf{S}_{tot} \neq 0$) is different from $\mathbf{T_A}$ ($\mathbf{S}_{tot}$ = 0 but $\mathbf{M}_{tot} \neq 0$)

T_M: Magnetic moment compensation point

T_A: Angular moment compensation point ➔ Magnetization dynamics is antiferromagnetic at $\mathbf{T_A}$ + finite Zeeman coupling

Collaborators

- **Field-driven ferrimagnetic domain wall motion**
  - T. Ono (Kyoto Univ.), Kab-Jin Kim (currently at KAIST), Se Kwon Kim (currently at Missouri Univ.)
- **Vanishing skyrmion Hall effect**
  - T. Ono (Kyoto Univ.), Duck-Ho Kim (currently at KIST), Se Kwon Kim (currently at Missouri Univ.), Sug-Bong Choe (SNU)
- **Spin-transfer torques for ferrimagnetic domain walls**
  - T. Ono (Kyoto Univ.), Duck-Ho Kim (currently at KIST), Se Kwon Kim (currently at Missouri Univ.)
- **Long spin coherence length in ferrimagnets**
  - H. Yang (National Univ. of Singapore)

Field-driven antiferromagnetic domain wall motion in the vicinity of T_A

AF-DW motion by spin-orbit torque

Shiino et al. PRL 117, 087203 (2016)

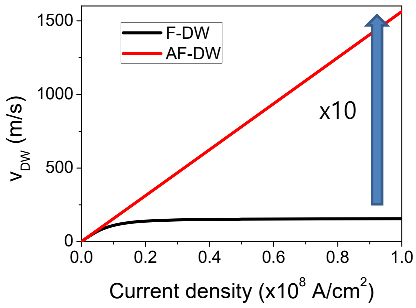
$$v_{DW} = v_{AF} = -\pi\gamma\lambda B_D/2\alpha,$$

Shiino et al. PRL '16

$$v_F = \frac{\gamma\pi D}{2m_s\sqrt{1+(\alpha D/B_D m_s\lambda)^2}}.$$

Thiaville et al. EPL '12

- α : damping constant
- λ : DW width
- D : DMI
- M_S : Saturation magnetization
- B_D : Damping-like SOT ~ J



- AF-DW can be 10 times faster than F-DW for the same parameters
- No DW tilting in AF-DW

Antiferromagnet vs Ferrimagnet

$$\frac{dS}{dt} = \frac{1}{i\hbar}[S, \mathcal{H}] \xrightarrow{\mathbf{M}=\gamma\mathbf{S}} \frac{d\mathbf{M}}{dt} = -\gamma\,\mathbf{M}\times\mathbf{B}$$

Time evolution of the state of a magnet is governed by the commutation relation of the angular momentum **S**, not of the magnetic moment **M**.

At T_A ($\mathbf{S}_{tot}$ = 0 but $\mathbf{M}_{tot} \neq 0$), the spin dynamics of ferrimagnets is antiferromagnetic , but a magnetic field works

[NOTE] Exchange coupling has no Lande "g"-factor. Only Zeeman coupling has "g" ➔ Field-driven AF spin dynamics !

Field-driven ferrimagnetic DW motion: Theory

Equations of Motion with two collective coordinates:

DW position X and DW angle ϕ

$$M\ddot{X} + G\dot{\phi} + \frac{M}{\tau}\dot{X} = F$$

$$I\ddot{\phi} - G\dot{X} + \frac{I}{\tau}\dot{\phi} = -\kappa \sin\phi \cos\phi$$

M : Mass

I : the moment of inertia

G : Gyrotropic coeff

τ : relaxation time

F : Force (external field)

κ : DW hard-axis anisotropy

- G = $2(S_1 - S_2)$ x Area
- At T = T_A ➔ $S_1 - S_2 = \delta_s = 0$ ➔ G = 0

  ➔ X and ϕ are decoupled

Field-driven ferrimagnetic DW motion: Theory (2)

In the precessional regime

DW speed $$v_{DW} = \frac{\alpha s}{(\alpha s)^2 + {\delta_s}^2}(M_1 - M_2)\lambda H$$

Walker breakdown field $$H_{WB} = \frac{K_d \alpha s}{2\delta_s (M_1 - M_2)\lambda}$$

- At T = T_M ➔ $M_1 - M_2 = 0$

  ➔ $v_{DW1} = v_{DW2} = 0$

& DW motion changes its direction at T_M

- **At T = T_A ➔ $\delta_s = 0$ & $M_1 - M_2 \neq 0$**

  ➔ v_{DW} = maximum & $H_{WB} \to \infty$

$\alpha S = \alpha_1 S_1 + \alpha_2 S_2$

α : damping constant

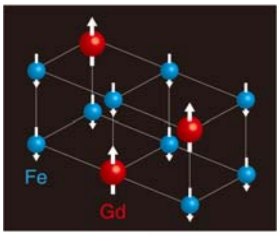
λ : DW width

H : external field

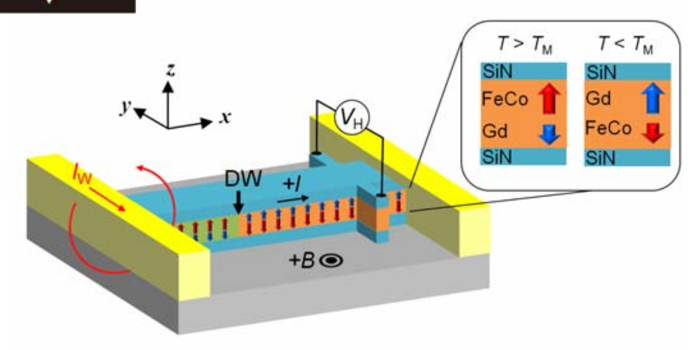
K_d : DW hard-axis anisotropy

Field-driven DW Experiment: FeCoGd

Kim et al., Nat. Mater. 16, 1187 (2017)

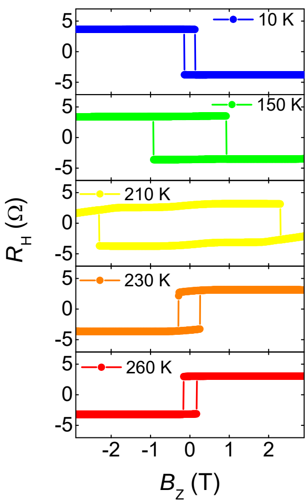


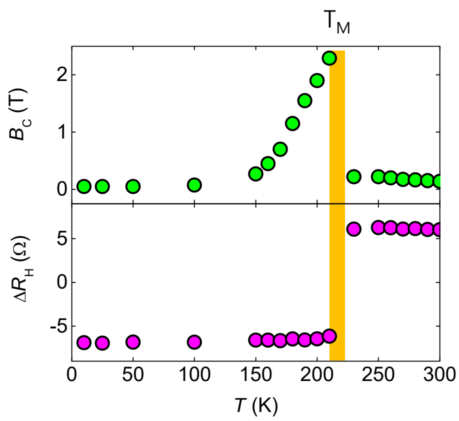
Done by T. Ono's group



Determination of T_M

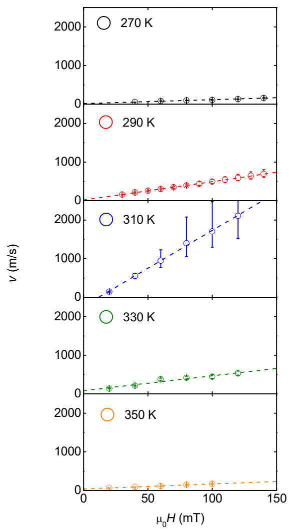
T_M : Magnetization compensation temperature

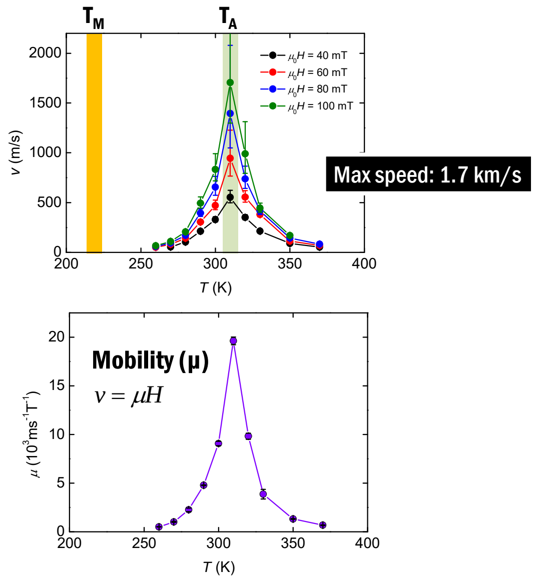




T_M is found to be 220 K

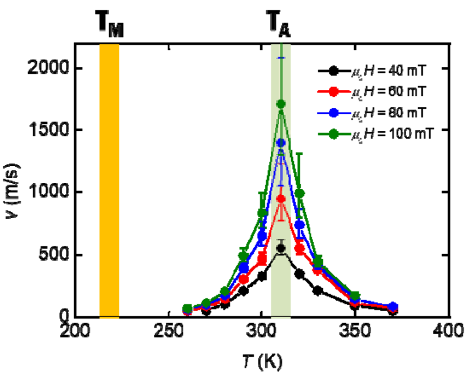
DW velocity: Experiment



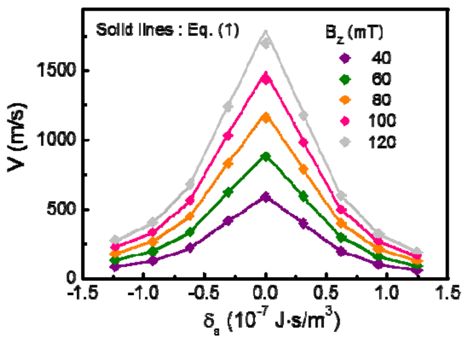


DW velocity: Modeling

Experiment



Theory/Modeling

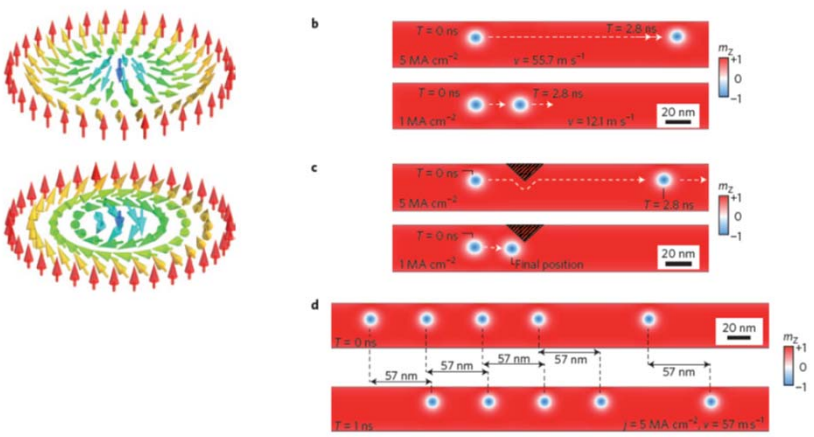


- Solid lines : $$v_{DW} = \frac{\alpha s}{(\alpha s)^2 + {\delta_s}^2}(M_1 - M_2)\lambda H$$
- Simulation index 5 = T_A (δ_s = 0)

Vanishing skyrmion Hall effect of RE-TM ferrimagnet at T_A

Magnetic Skyrmions

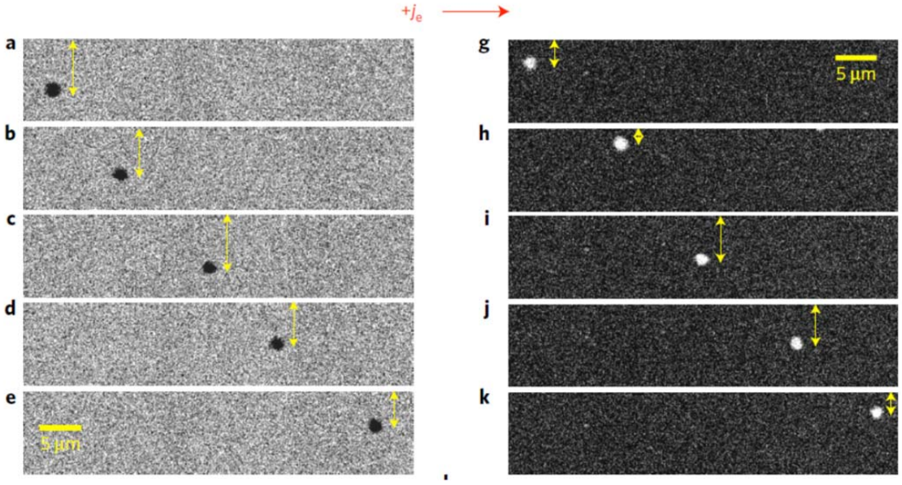
A. Fert et al., "Skyrmions on the track", **Nat. Nano.** (2013)



- **Skyrmions: small (~ 10 nm), fast, move at low current, defect-insensitive**

Skyrmion Hall effect

W. Jiang et al., Nat. Phys. (2017); K. Litzius et al., Nat. Phys. (2017)



- **Transverse deflection of skyrmion ~ the Hall effect**

Charge Hall effect vs Skyrmion Hall effect

Charge Hall effect

Elementary charge — External magnetic field

Lorentz force: $Q\dot{\boldsymbol{R}} \times \boldsymbol{B}$

Topological charge — Fictitious magnetic field

$Q \equiv \int dxdy \boldsymbol{n} \cdot (\partial_x \boldsymbol{n} \times \partial_y \boldsymbol{n})/4\pi$

$\boldsymbol{B} = -4\pi s_{net} \hat{\boldsymbol{z}}$

Net spin density

Skyrmion Hall effect

Vanishing skyrmion Hall effect for antiferromagnet (s_{net} = δ_s = 0)

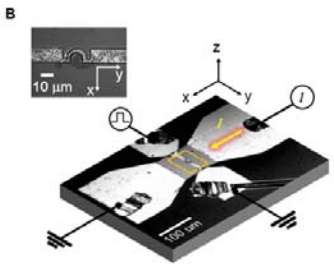
Barker & Tretiakov, PRL **116**, 147203; Zhang, Zhou, & Ezawa, NCOMM **7**, 10293 (16)

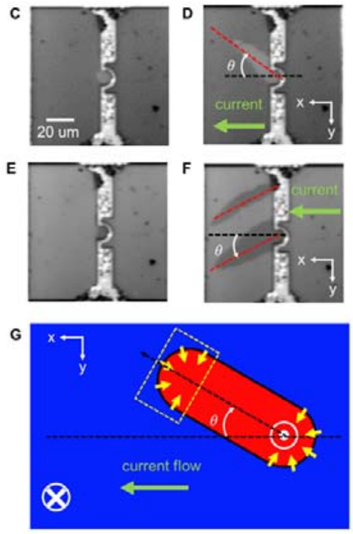
Current-driven bubble elongation in GdFeCo/Pt

Hirata et al., Nat. Nanotechnol. 14, 232 (2019)

DMI field = 63 mT >> DW hard-axis anisotropy field = 0.9 mT

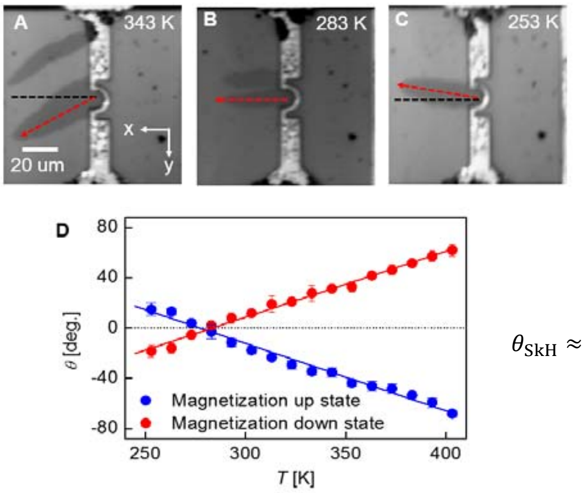
➔ Well-defined topological charge Q





Bubble elongation ~ half skyrmion motion

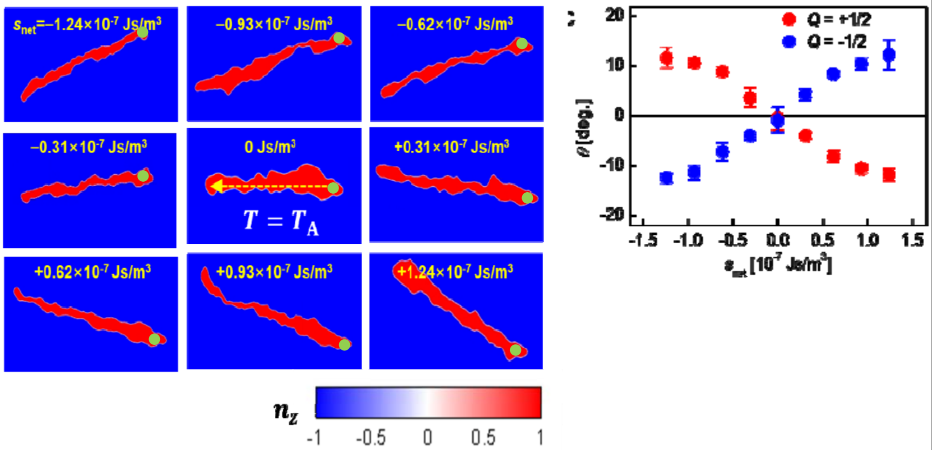
Elongation angle vs temperature (Experiment)



$$\theta_{\mathrm{SkH}} \approx \tan^{-1}\left(\frac{2s_{\mathrm{net}}Q\lambda}{\alpha s_{\mathrm{total}}r}\right),$$

Elongation angle ≈ 0 at T_A ➔ Vanishing skyrmion Hall effect for s_{net} = 0

Elongation angle vs temperature (Modeling)

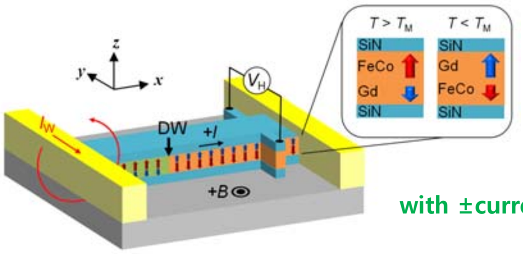


Elongation angle ≈ 0 at T_A ➔ Consistent with experiment & theory

STT-driven antiferromagnetic domain wall motion in the vicinity of T_A

Field-driven DW motion assisted by ±current J

T. Okuno et al. arXiv:1903.03251



with ±current injection

$$v_H = \frac{v(H,+J)+v(H,-J)}{2} = \frac{\alpha s(M_1 - M_2)}{\delta_s^2 + (\alpha s)^2}\lambda H$$

➔ Equivalent with the previous work

$$v_{STT} = \frac{v(H,+J)-v(H,-J)}{2} = -\frac{\delta_s}{\delta_s^2+(\alpha s)^2}PJ - \frac{\alpha\beta s}{\delta_s^2+(\alpha s)^2}PJ$$

$v_{A\text{-}STT}$: adiabatic STT $v_{N\text{-}STT}$: non-adiabatic STT

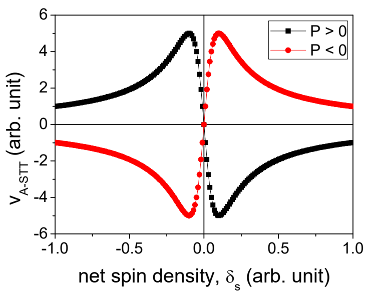
P = spin polarization, α = damping, β = non-adiabaticity

Expected v_{STT} as a function of temperature (or δ_s)

Assuming the signs of P and β do not change at T_A (i.e., spin transport is dominated by TM elements)

Adiabatic STT

$$v_{A-STT} = -\frac{\delta_s}{\delta_s^2+(\alpha s)^2}PJ$$

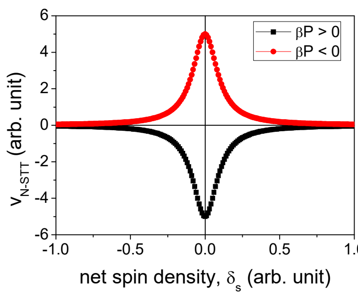


Anti-symmetric & $v_{A\text{-}STT}$ = 0 @ T_A

➔ No DW tilting ➔ No adiabatic contribution

Non-adiabatic STT

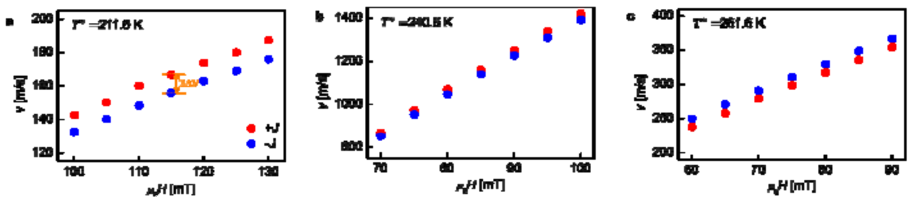
$$v_{N-STT} = -\frac{\alpha\beta s}{\delta_s^2+(\alpha s)^2}PJ$$



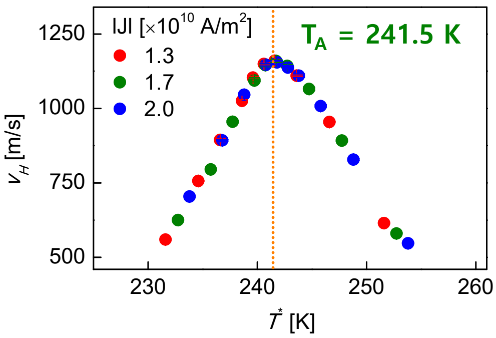
Symmetric & $|v_{N\text{-}STT}|$ = max @ T_A

➔ Equivalent with a magnetic field

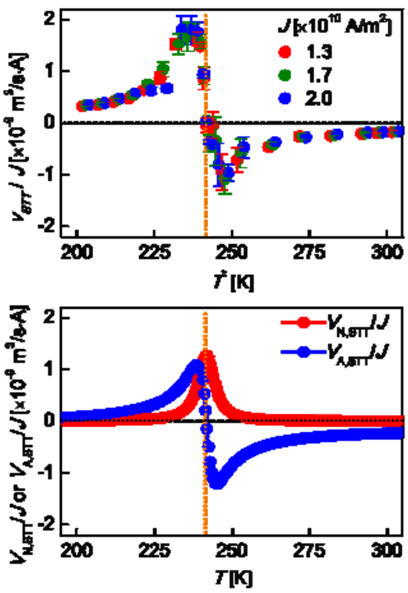
Field-driven DW motion assisted by ±current J

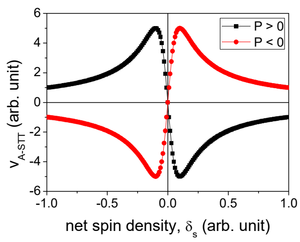


$$v_H = \frac{v(H,+J)+v(H,-J)}{2}$$
$$= \frac{\alpha s(M_1 - M_2)}{\delta_s^2 + (\alpha s)^2}\lambda H$$

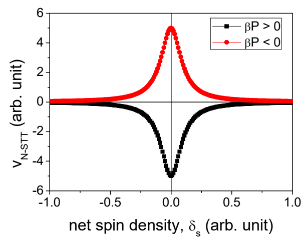


Field-driven DW motion assisted by ±current J



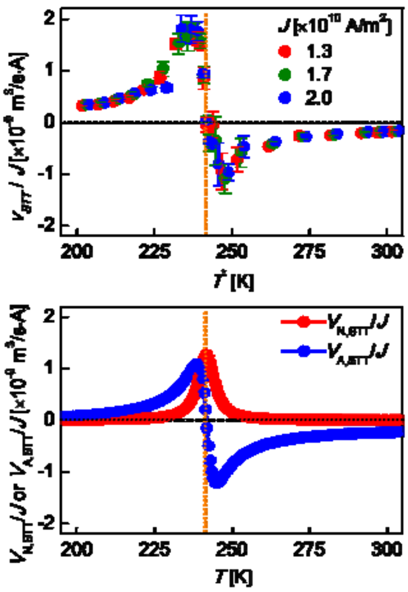


P > 0



βP < 0 ➔ β < 0

Fitting results



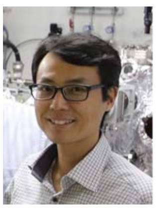
Fitting Parameters

$$\alpha = 0.00317 \pm 0.00009$$
$$\beta = -0.529 \pm 0.016$$
$$P = 0.092 \pm 0.001$$

- Small damping ➔ also observed in another set of experiment (**PRL 122, 127203 (2019)**)
- Negative β ➔ Garate et al. PRB 79, 104416 (2009); β can be negative in systems with both holelike and electronlike carriers.
- Large |β| & small P ➔ possibly due to antiferromagnetic coupling

Long spin coherence length and bulk-like spin-orbit torque in ferrimagnetic multilayers

Collaborators



Hyunsoo Yang
Nat'l Univ. of Singapore

Hiroyuki Awano
Toyota Tech. Inst., Japan

Surface-torque characteristic of ferromagnets

- Eherenfest's theorem in quantum mechanics

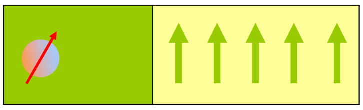
$$\langle \dot{x} \rangle = \frac{1}{i\hbar}\left[x, \hat{H}\right]$$

- Dynamics of non-equilibrium spin density **s**

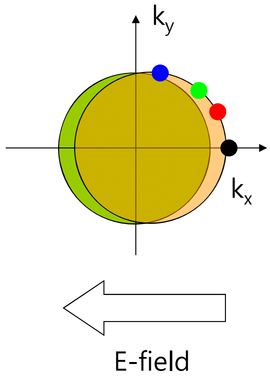
$$\hat{H} \equiv \hat{H}_{ex} = -J_{ex}\mathbf{s}\cdot\mathbf{S} \Rightarrow \frac{\partial \mathbf{s}}{\partial t} = -\gamma\,\mathbf{s}\times\mathbf{H}_{ex}$$

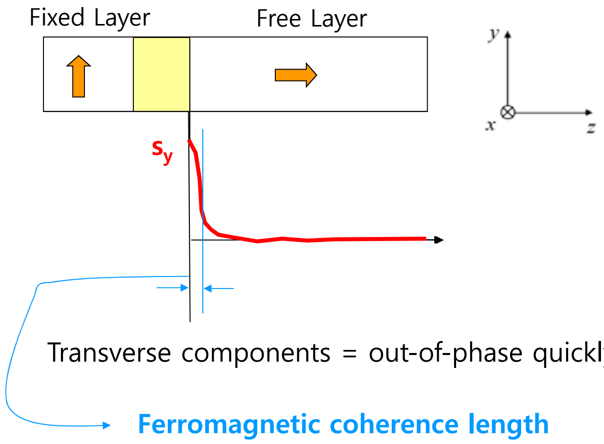
- Spin precession in real space

$$\frac{\partial \mathbf{s}}{\partial x} = \frac{1}{v_x}\frac{\partial \mathbf{s}}{\partial t} \propto -\mathbf{s}\times\hat{\mathbf{m}} \Rightarrow \mathbf{s} \propto (\cos kx, \sin kx, 0)$$



Surface-torque characteristic of ferromagnets





Transverse components = out-of-phase quickly

Ferromagnetic coherence length

$$\lambda_c = \frac{\pi}{k_F^{\uparrow} - k_F^{\downarrow}} \sim \frac{1}{J_{ex}}$$

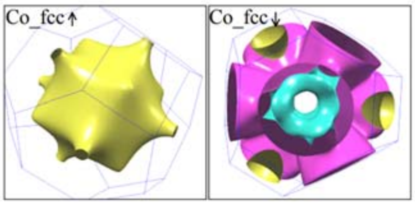
Waintal et al. PRB 2000; Stiles PRB 2002

Ferromagnetic coherence length λ_c in ferromagnets

Free electron model ➔ Spherical Fermi surface

$$\lambda_c = \frac{\pi}{k_F^{\uparrow} - k_F^{\downarrow}}$$

Ab initio calculations ➔ Much more complicated Fermi surface



http://www.phys.ufl.edu/fermisurface

$$\lambda_c < \frac{\pi}{k_F^{\uparrow} - k_F^{\downarrow}} << 1\,nm$$

- Spin torque = Surface torque

➔ STT efficiency ~ $1/t_F$

$1/t_F$-dependence is problematic

Switching current

$$I_{SW}^{STT} = \alpha \frac{4e}{\hbar} \frac{K_{eff} A_F t_F}{\eta_{STT}}$$

$$I_{SW}^{SOT} \approx \frac{2e}{\hbar} \frac{K_{eff} A_H t_F}{\theta_{SH}}$$

Thermal stability factor

$$\Delta = \frac{E_B}{k_B T} = \frac{K_{eff} A_F t_F}{k_B T}$$

Trade-off between the switching current and retention time.

Why is STT or SOT correlated to the FL thickness?

➔ Because the STT or SOT for FM is **a surface torque**.

STT magnitude

$$a_J = \frac{\hbar}{2} \frac{1}{M_S t_F} \eta_{STT} \frac{J}{e}$$

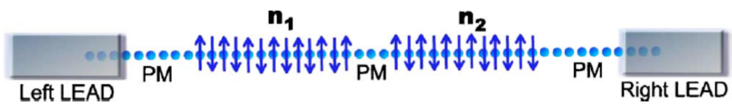
SOT magnitude

$$c_J = \frac{\hbar}{2} \frac{1}{M_S t_F} \theta_{SH} \frac{J}{e}$$

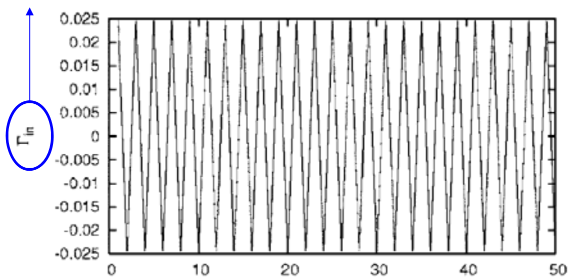
How to avoid $1/t_F$-dependence of STT?

Antiferromagnets

[Nunez, Duine, Haney, & MacDonald, PRB 73, 214426 (2006)]



Slonczewski's STT



Staggered STT

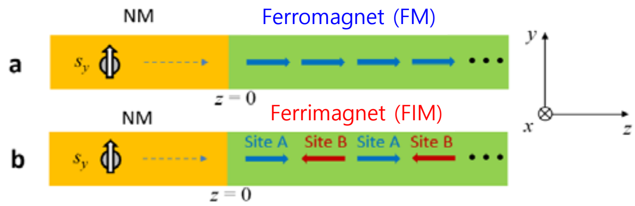
$$\propto \Delta \hat{\mathbf{M}}_i \times \mathbf{s}_i = (-1)^i \Delta \hat{\mathbf{z}} \times \mathbf{s}_i$$

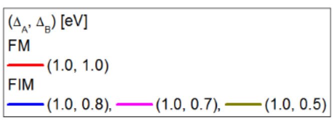
➔ Non-equilibrium spin density $\mathbf{s}_i$ is **UNIFORM**

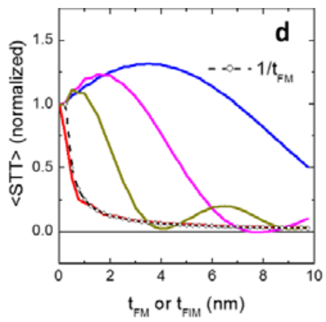
Calculation of non-equilibrium spin density s

Yu et al. Nat. Mater. 18, 29 (2019)

- Tight-binding calculation



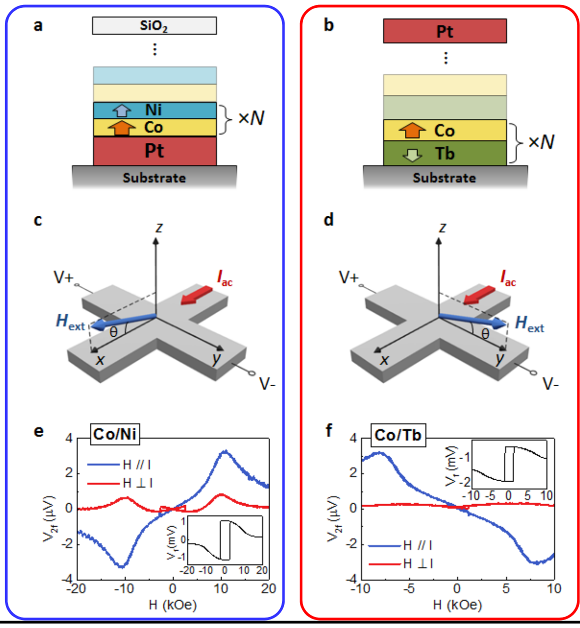




- FM ➔ well-known $1/t_{FM}$-dependence ➔ surface-torque
- FIM ➔ much longer spin coherence length ➔ bulk-torque

Bulk SOT in ferrimagnetic multilayers: Experiment

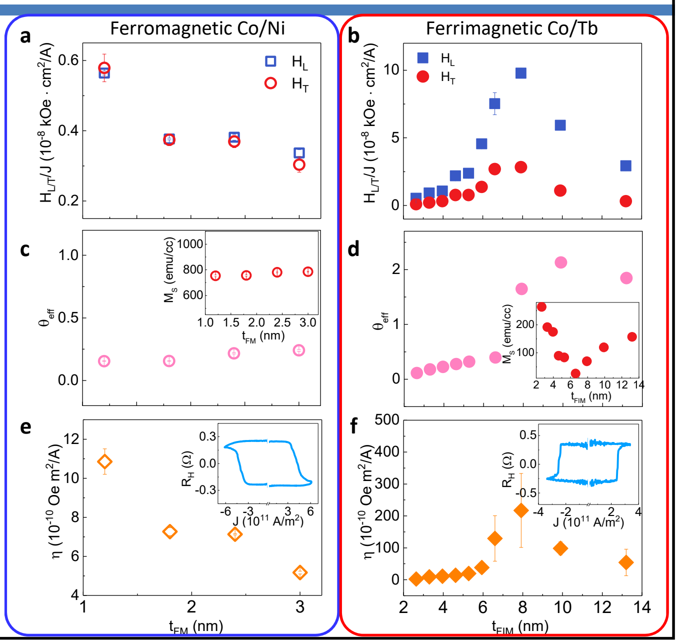
$[Co/Ni]_N$ FM multilayer



$[Co/Tb]_N$ FIM multilayer

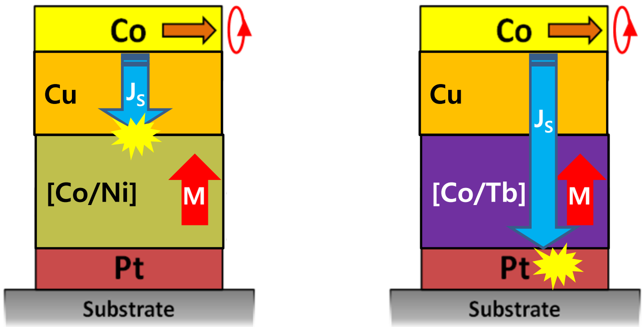
Bulk SOT in ferrimagnetic multilayers: Experiment

- $H_{L/T}$
- Spin-Orbit effective field
- θ_{eff}
- effective spin Hall angle
- η
- switching efficiency = (depining field)/(switching current density)



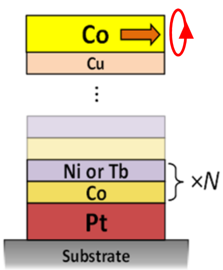
Long spin coherence length: Spin pumping

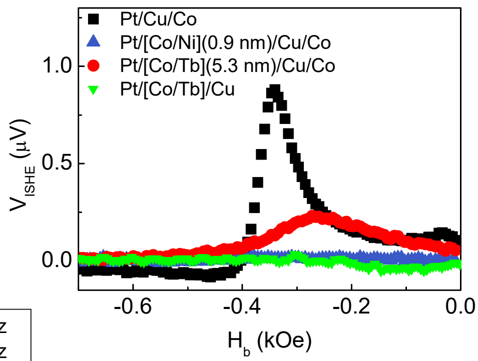
STT ← Onsager Reciprocity → Spin pumping

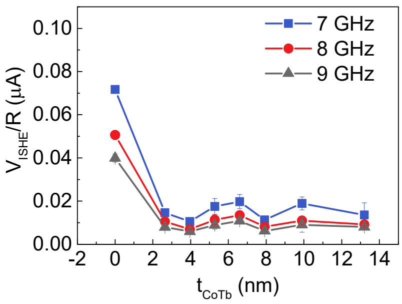


- [Co/Ni]: Spin current $\mathbf{J_S}$ is blocked at Cu/[Co/Ni] interface and does not reach Pt → No inverse spin Hall signal
- [Co/Tb]: Spin current $\mathbf{J_S}$ passes through [Co/Tb] layer and reach Pt layer → Finite inverse spin Hall signal

Long spin coherence length: Spin pumping







FIM → Very long spin coherence length

Summary

Antiferromagnetic spin dynamics at the angular momentum compensation temperature T_A of an antiferromagnetically coupled ferrimagnet

1. Field-driven DW motion ➔ maximum DW speed at T_A [Nat. Mater. 16, 1187 (2017)]
2. Skyrmion Hall effect ➔ Vanishes at T_A [Nat. Nanotechnol. 14, 232 (2019)]
3. STT for ferrimagnetic domain walls
4. Long spin coherent length and bulk-like spin-orbit torque characteristic [Nat. Mater. 18, 29 (2019)]