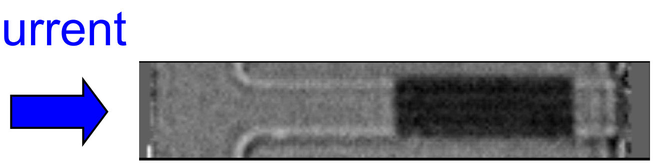
# Spin orbit torques and current induced domain wall motion in magnetic heterostructures

**Masamitsu Hayashi**

*National Institute for Materials Science*

# Introduction

- Sub|**underlayer A**|1 CoFeB|2 MgO|1 Ta (nm)

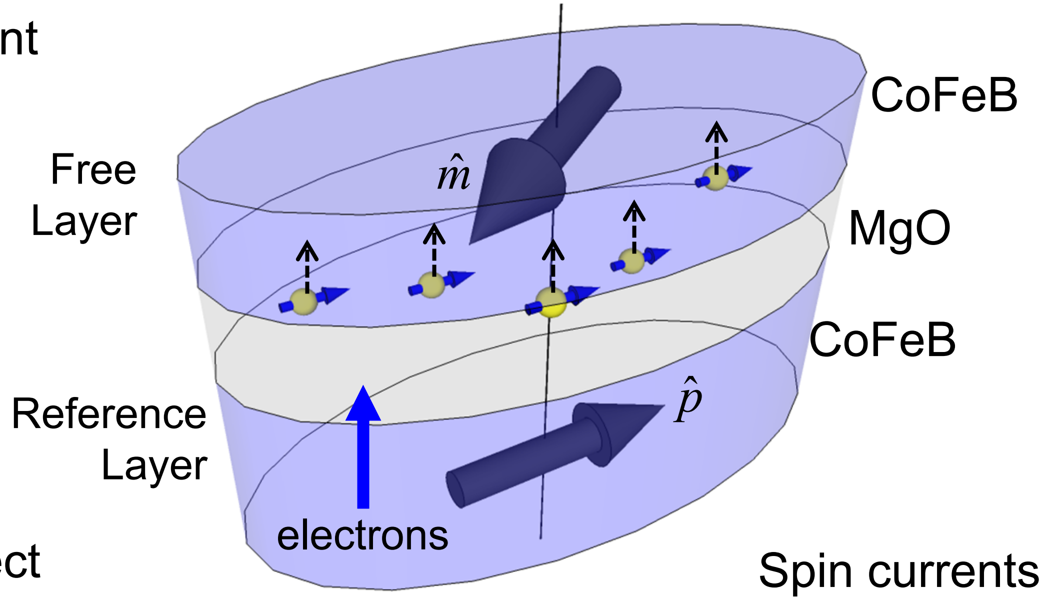


- Sub|**underlayer B**|1 CoFeB|2 MgO|1 Ta (nm)

- Domain wall moves in opposite direction depending on the underlayer material

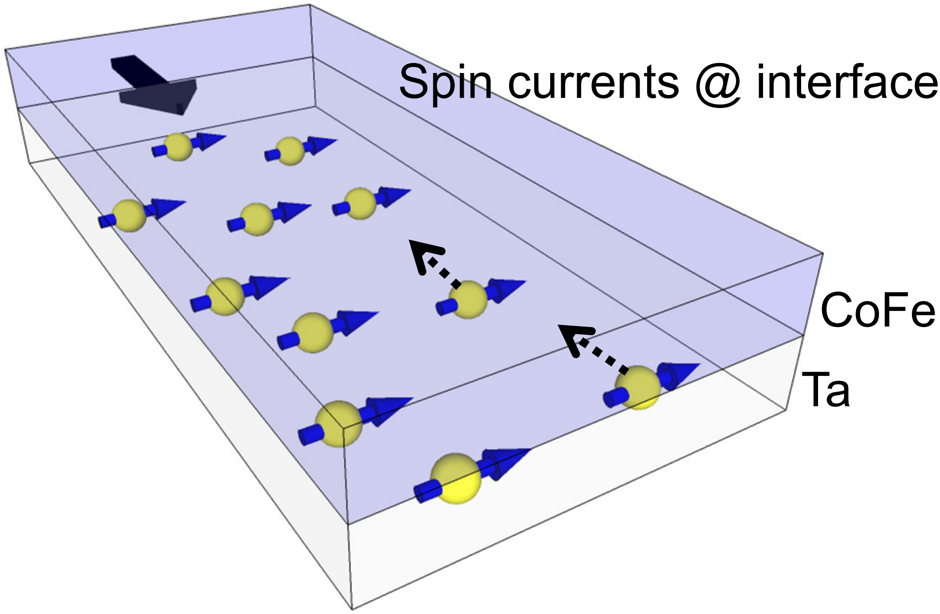
# Spin current generation

- Spin polarized current



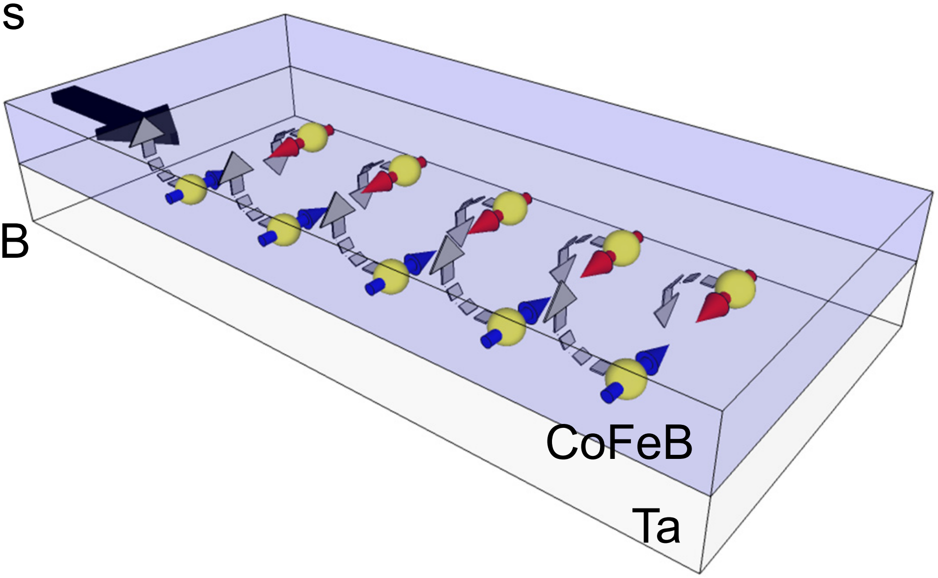
- Rashba-Edelstein effect

Spin currents @ interfaces



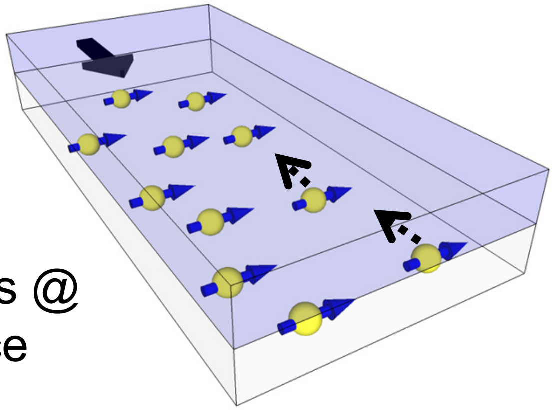
Spin currents @ bulk

- Spin Hall effect



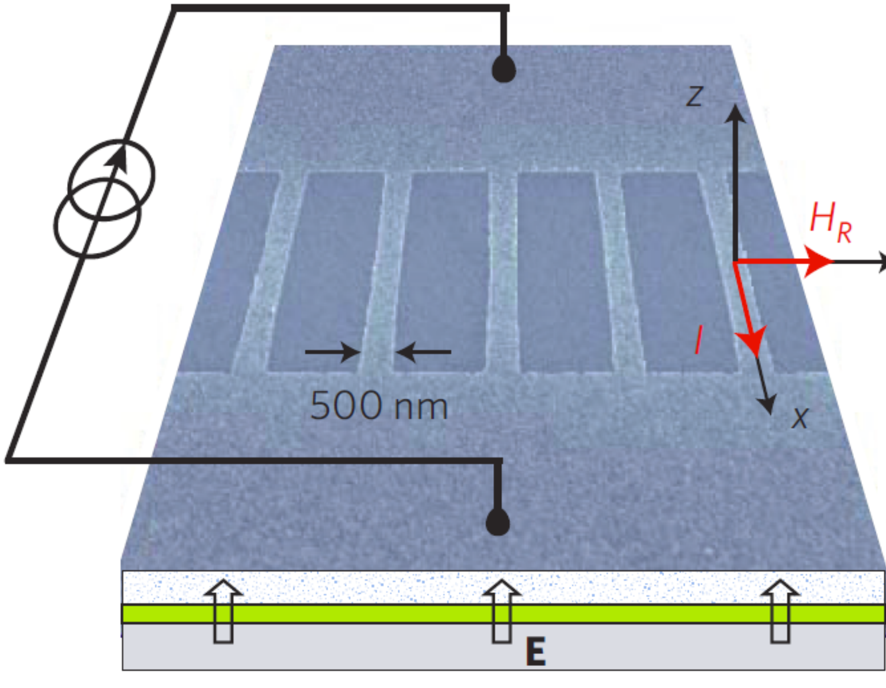
# Current induced domain nucleation

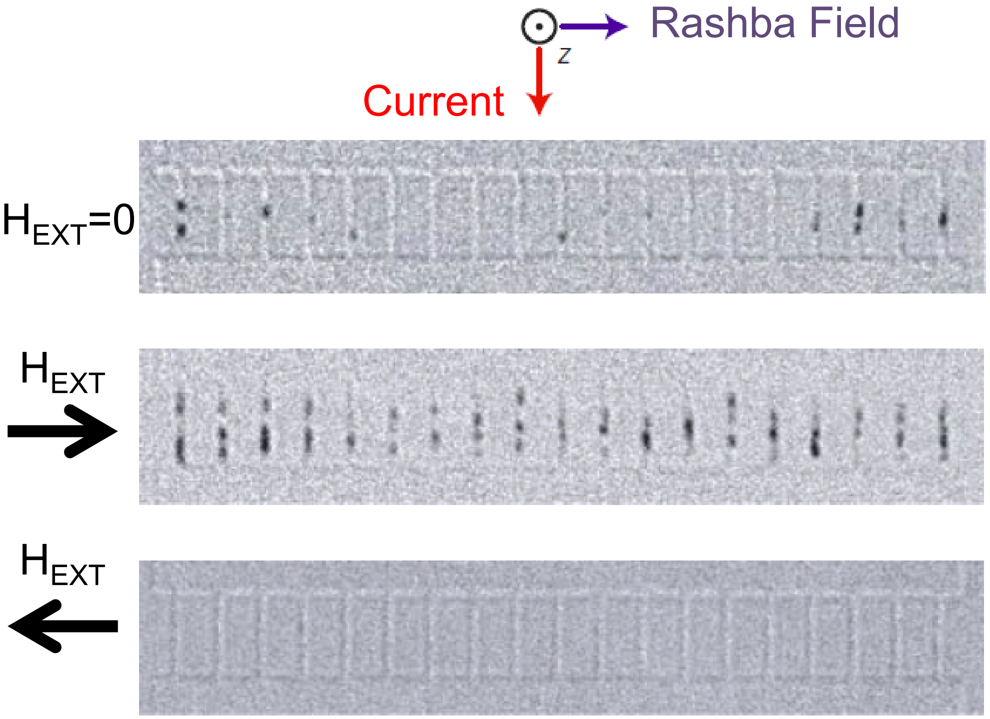
- Rashba-Edelstein effect

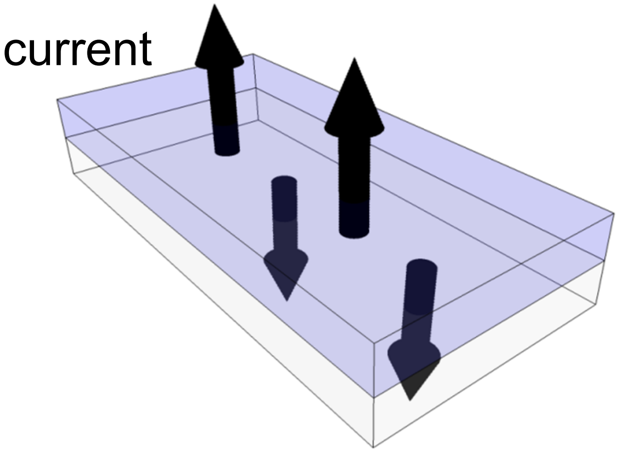


Spin currents @ interface

*Miron et al., Nature Mater.* ***9****, 230 (2010)*





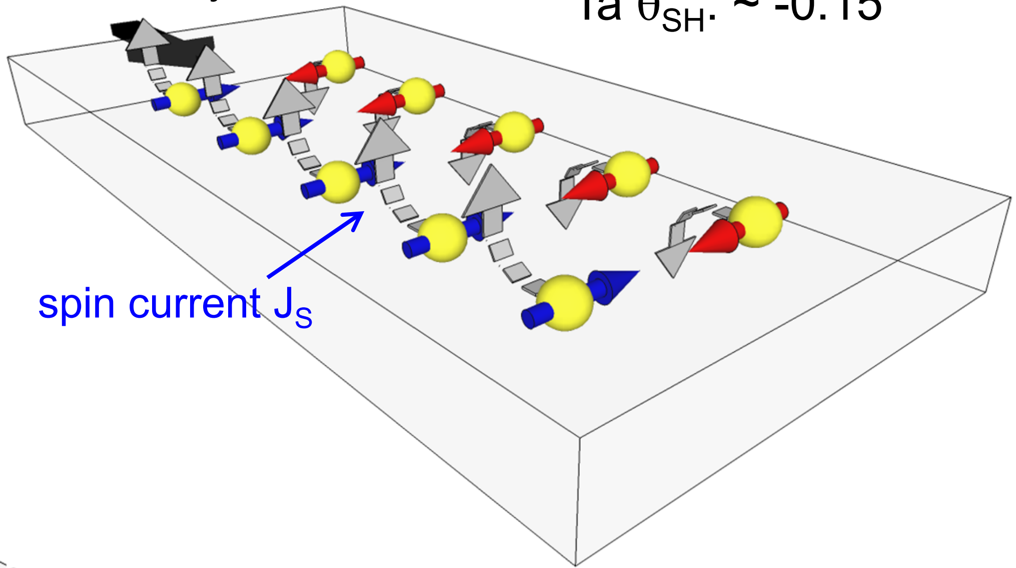


# Material dependent spin Hall effect

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

"Negative" spin Hall angle

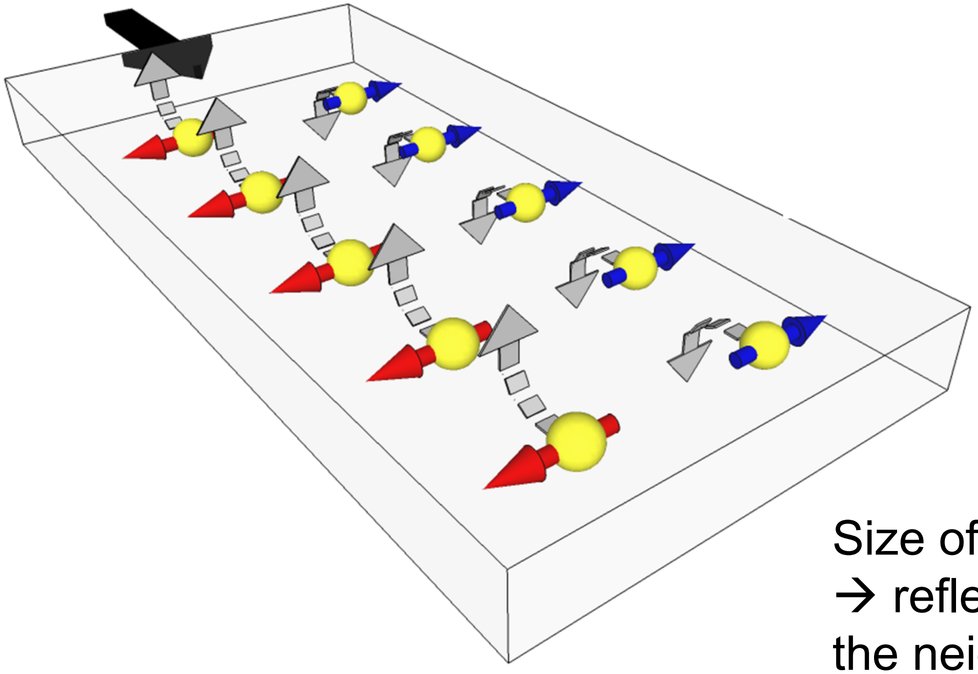
Ta $\theta_{SH}$: ~ -0.15



*Liu et al., PRL* ***109****,* 096602 *(2012)*

"Positive" spin Hall angle

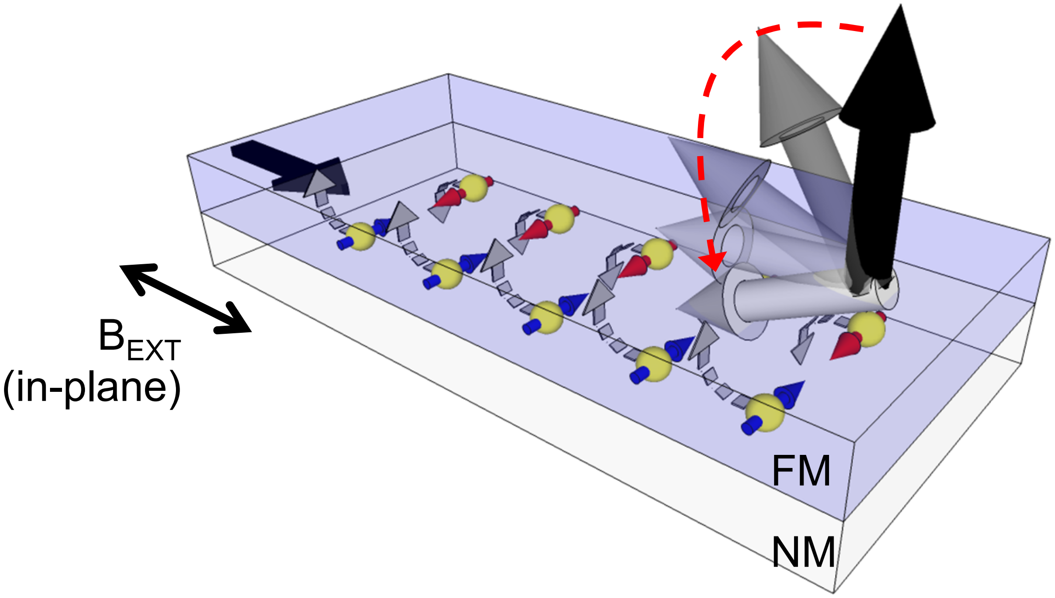
Pt $\theta_{SH}$: ~0.07

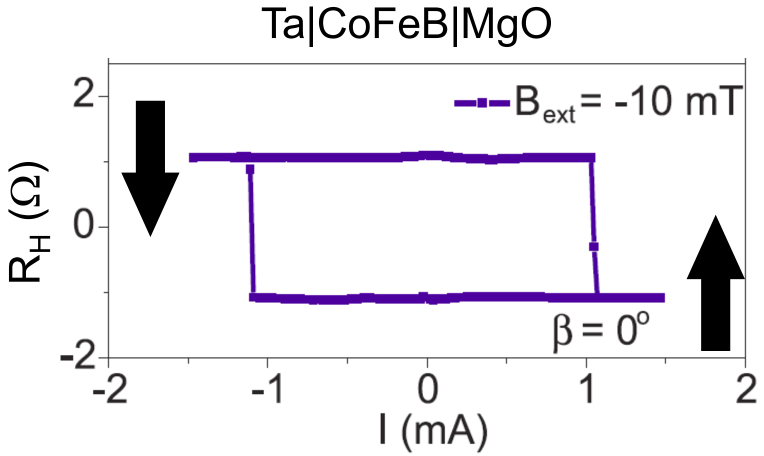


$$\theta_{SH} \sim \frac{J_S}{J}$$

Size of $\theta_{SH}$
→ reflects the amount of spin current entering the neighboring layer

# Switching of perpendicular magnets





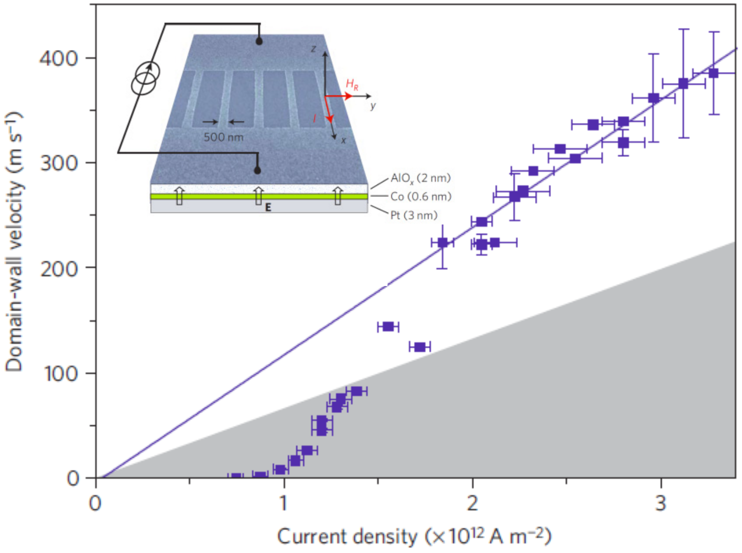
*Liu et al., Science* ***336****, 555 (2012)*  *Miron et al., Nature* ***476****, 189 (2011)*

- In-plane current and in-plane field can set the magnetization direction perpendicular to plane

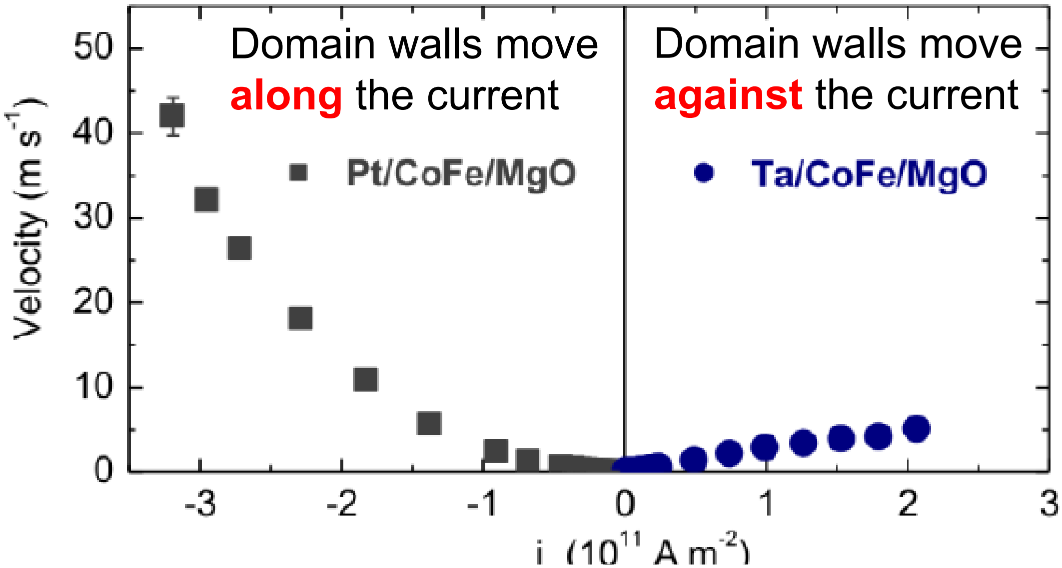
# Current driven motion of domain walls

- Domain wall moves against spin transfer torque (moves along the current)

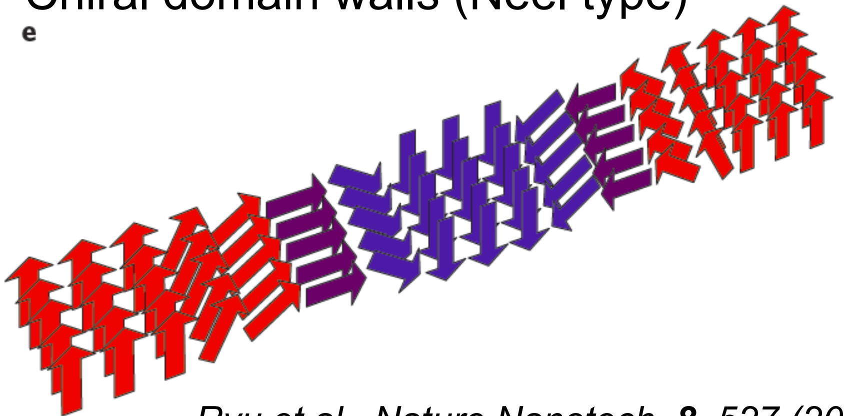
*Miron et al., Nature Mater.* ***10****, 419 (2011)*



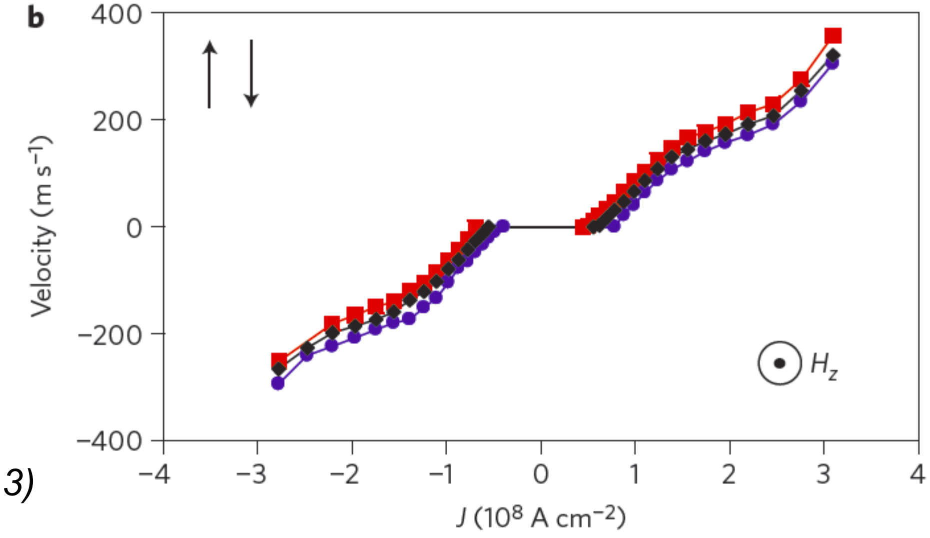
*Emori et al., Nature Mater.* ***12****, 611 (2013)*



- Chiral domain walls (Neel type)

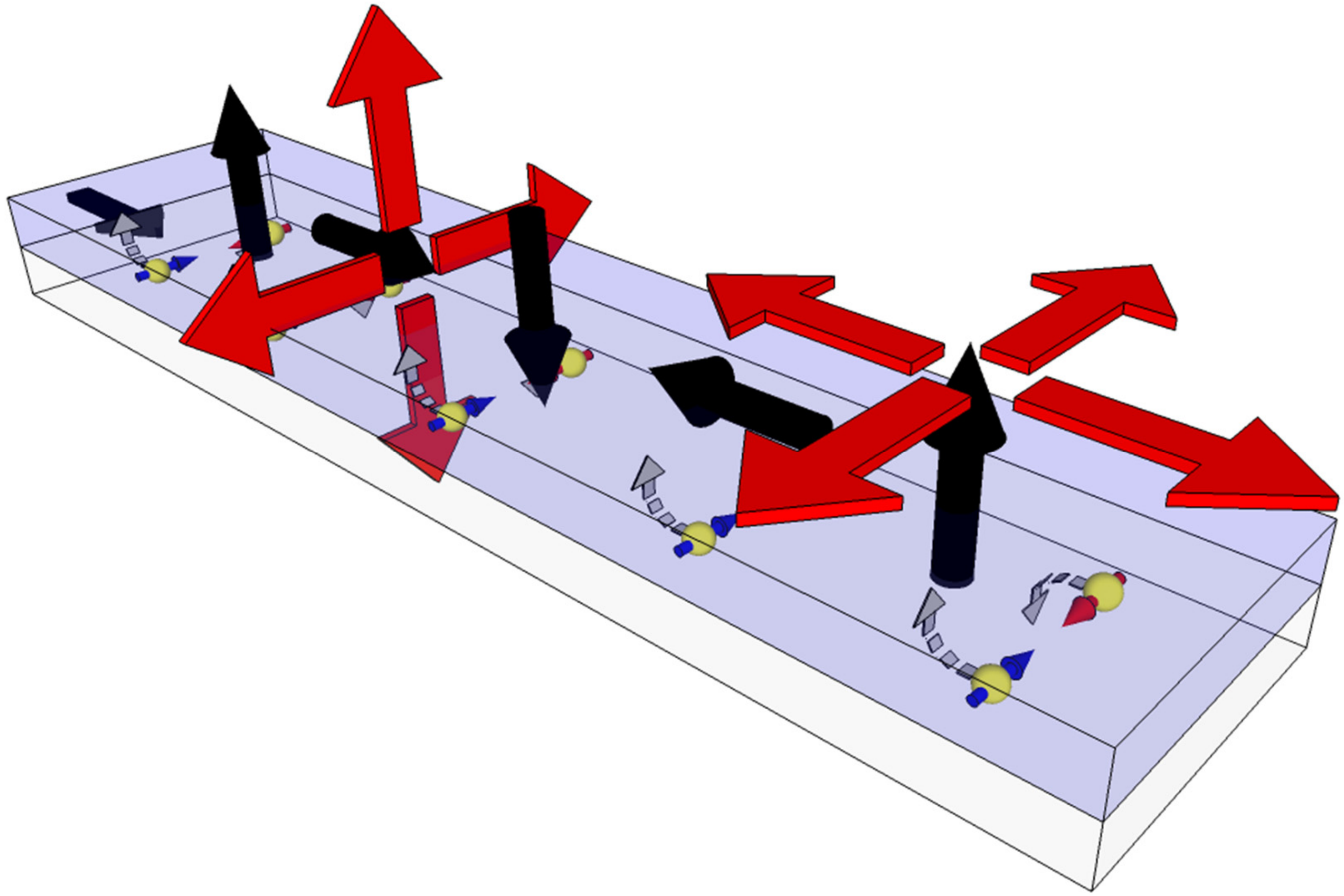


*Ryu et al., Nature Nanotech.* ***8****, 527 (2013)*



# Action on the magnetic moments

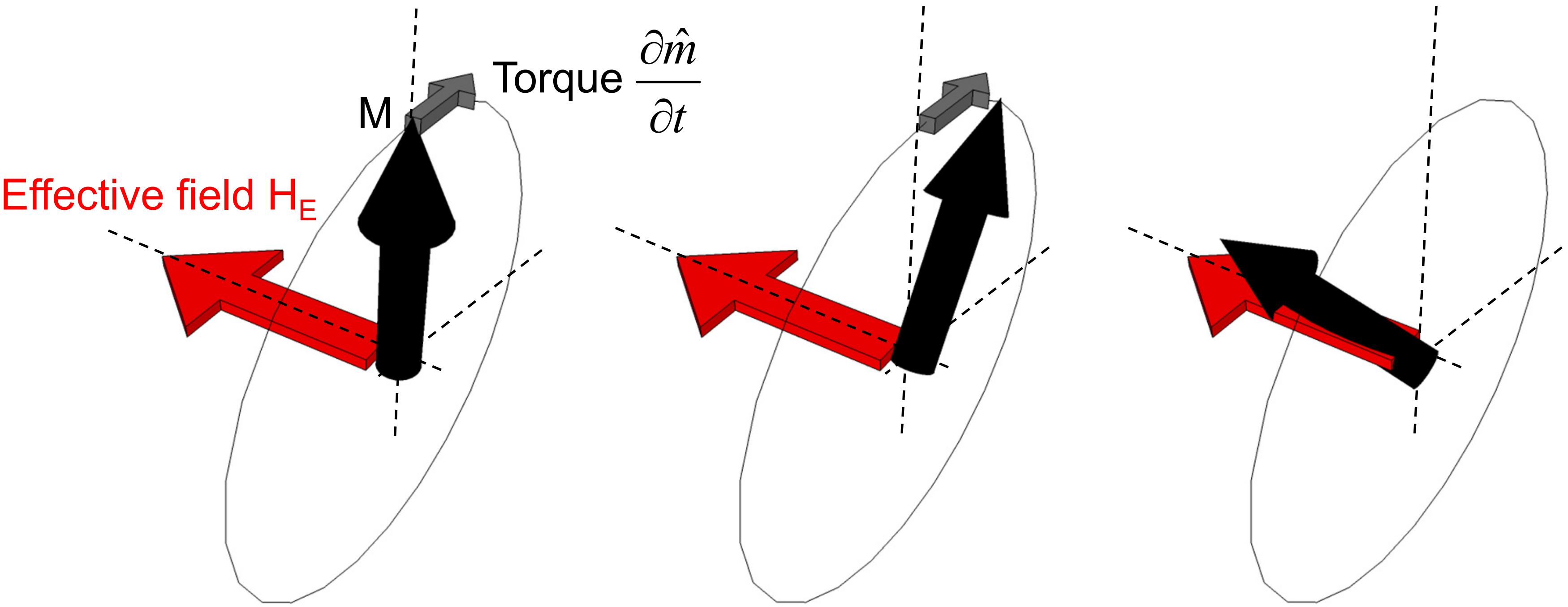
- Each moment will experience an effective (or the "equivalent") field



- Direction of the effective field gives information on how the moments will react to current/field

# The effective field and torque

$$\frac{\partial \hat{m}}{\partial t} = -\gamma \hat{m} \times \left(\vec{H}_E\right) + \alpha \hat{m} \times \frac{\partial \hat{m}}{\partial t}$$



Larmor precession

Magnetic damping

- Magnetization eventually points along the "effective field" direction

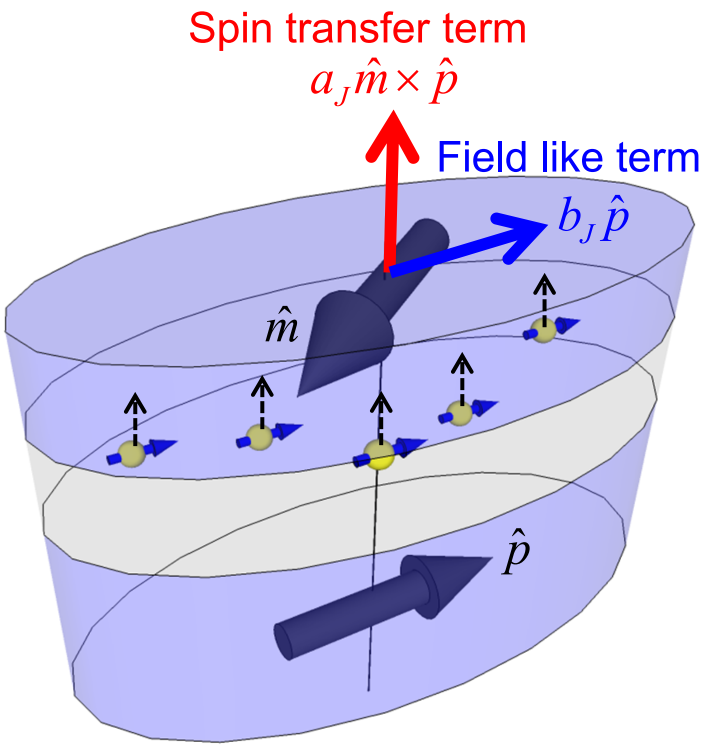
# Spin transfer torque in MTJs

- Spin transfer torque

*Zhang et al., PRL 88, 236601 (2002)*

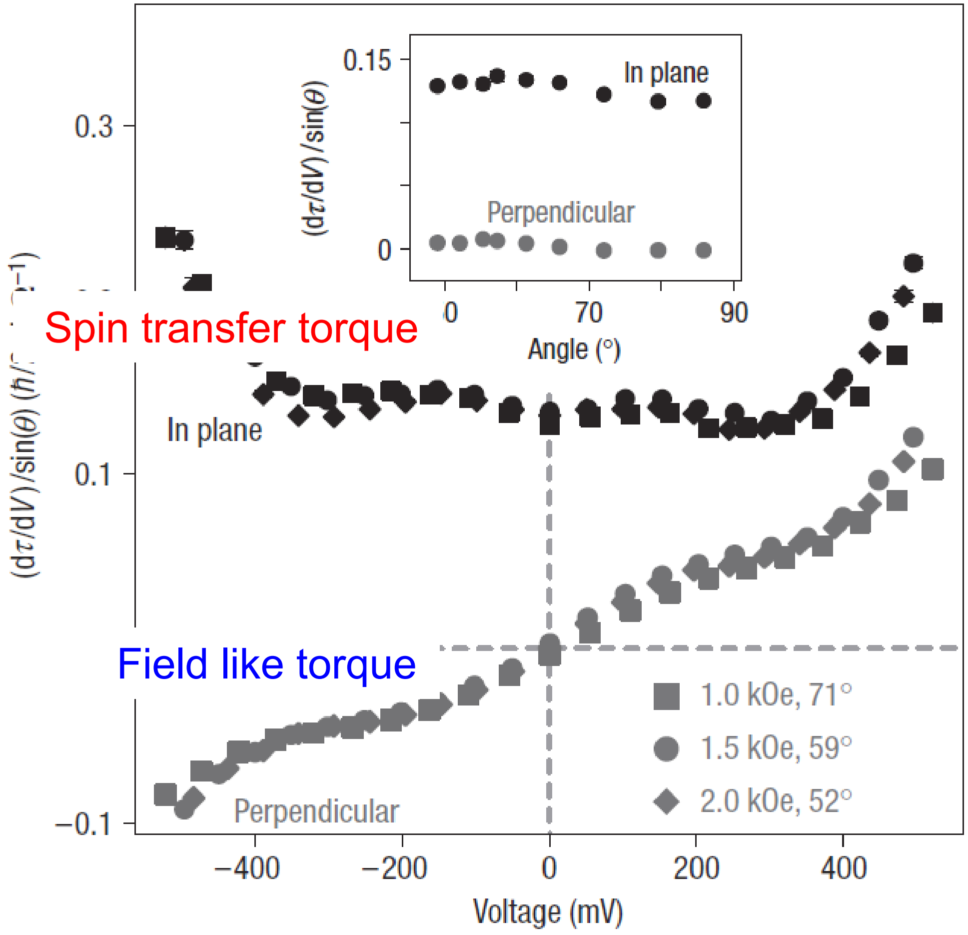
$$\frac{\partial \hat{m}}{\partial t} = -\gamma \hat{m}\times\left(\vec{H}_E\right) + \alpha \hat{m}\times\frac{\partial \hat{m}}{\partial t} \underline{- a_J \hat{m}\times\left(\hat{m}\times\hat{p}\right)} \underline{- \gamma b_J \hat{m}\times\hat{p}}$$

Spin transfer term Field like term



*Kubota et al., Nature Phys. (2008)*
*Oh et al., Nature Phys. (2009)*

*Sankey et al., Nature Phys. (2008)*



Spin transfer torque

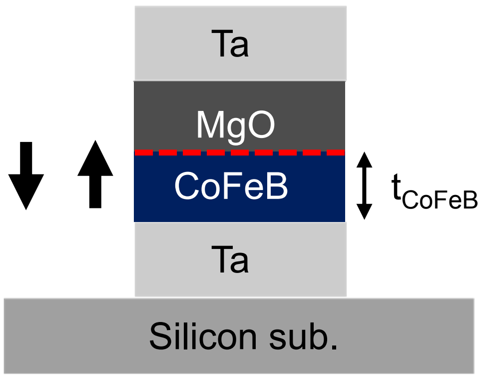
Field like torque

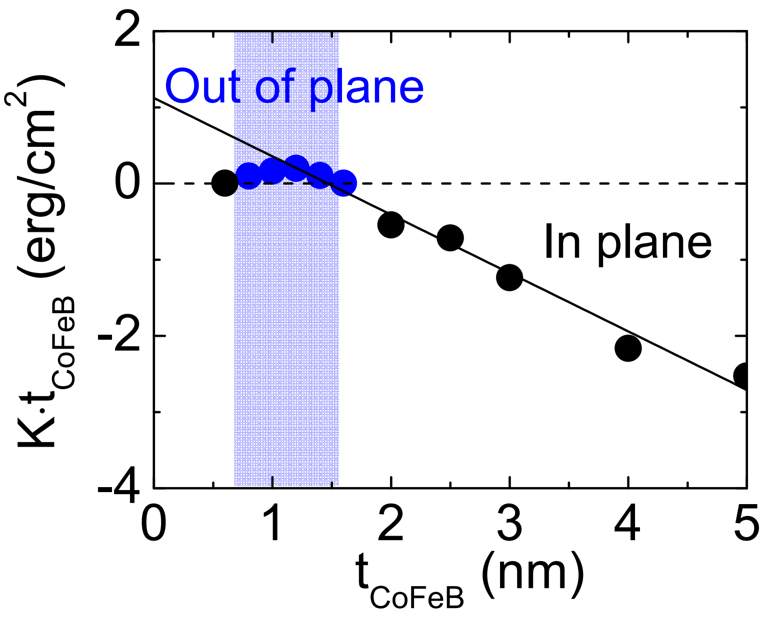
# Perpendicular magnetic anisotropy in CoFeB|MgO

- CoFeB|MgO interface provides the perpendicular magnetic anisotropy

*Ikeda et al., Nature Mater. (2010)*

- Film stack: Sub|Ta|CoFeB|MgO|Ta

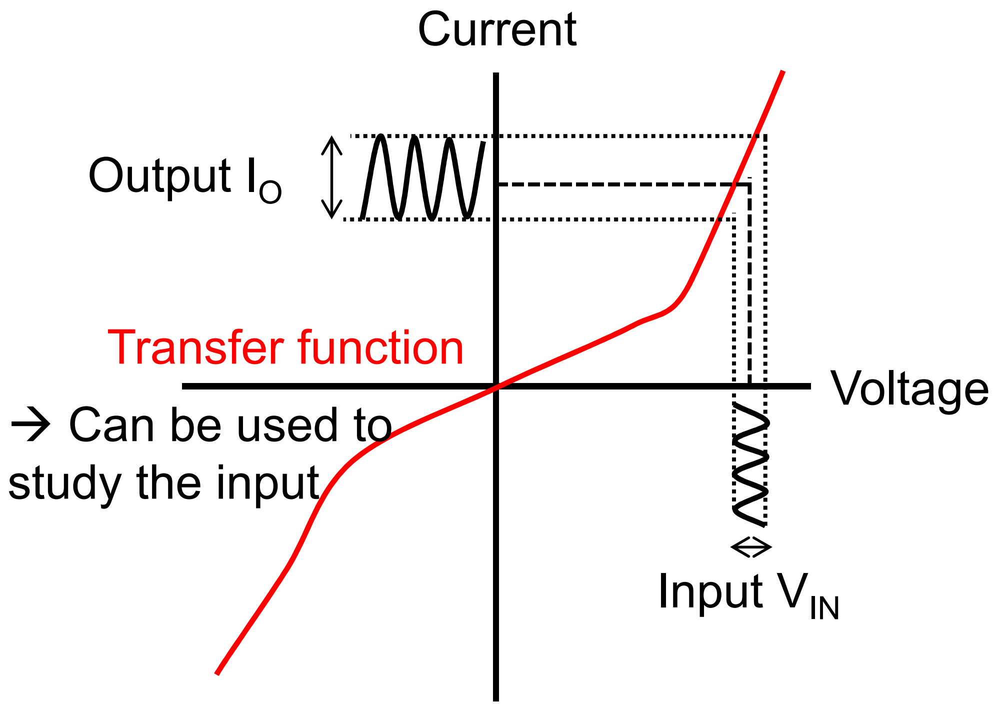




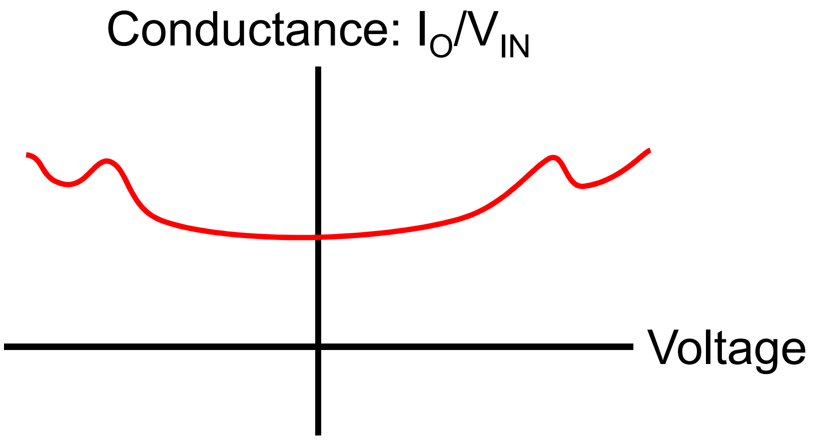
- Magnetic moments point along the film normal when the CoFeB thickness is ~1 nm

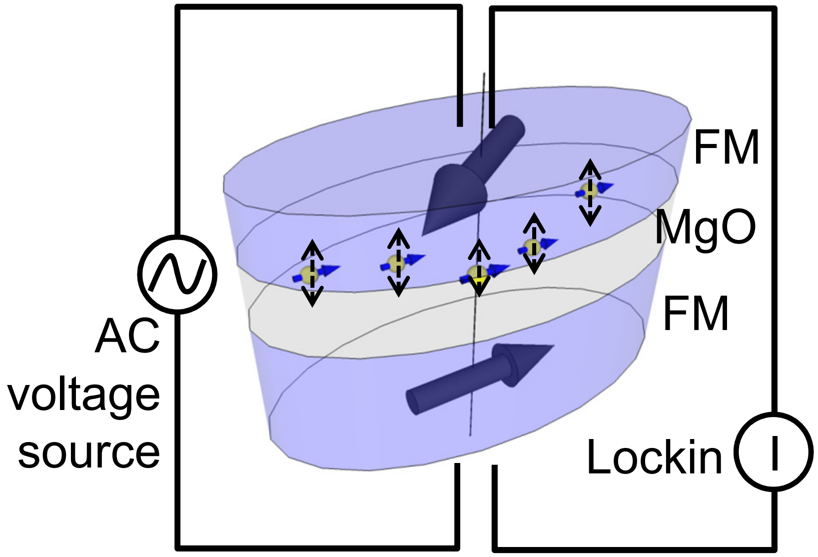
# Transfer function: AC lock-in technique

- Tunnel conductance measurements in MTJs



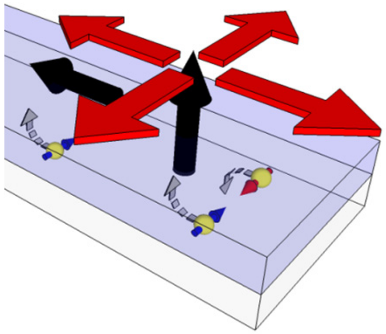
→ Can be used to study the input

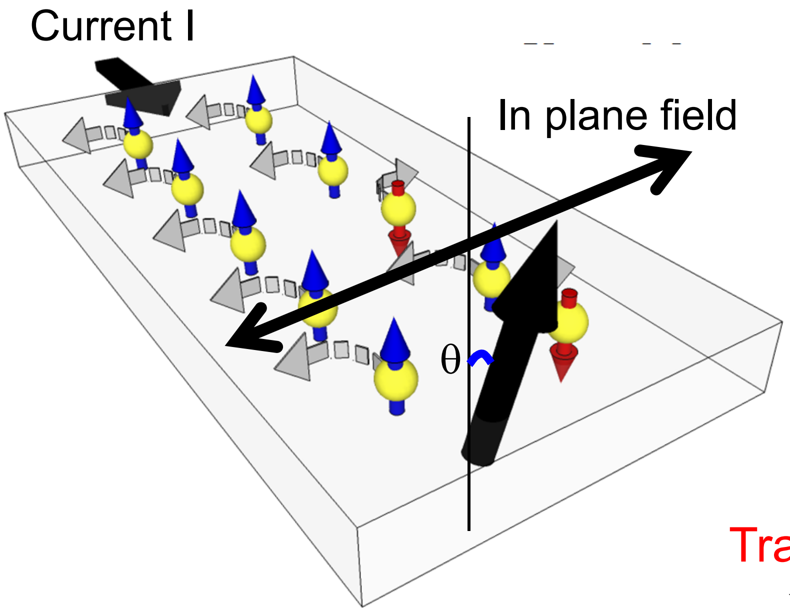


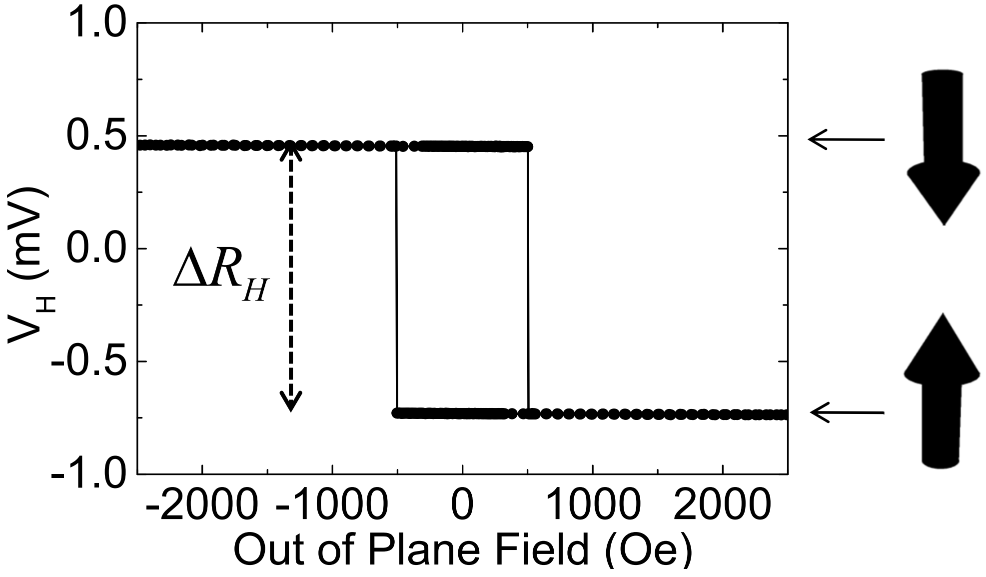


# Effective field measurements

- Anomalous Hall effect (in the ferromagnet)

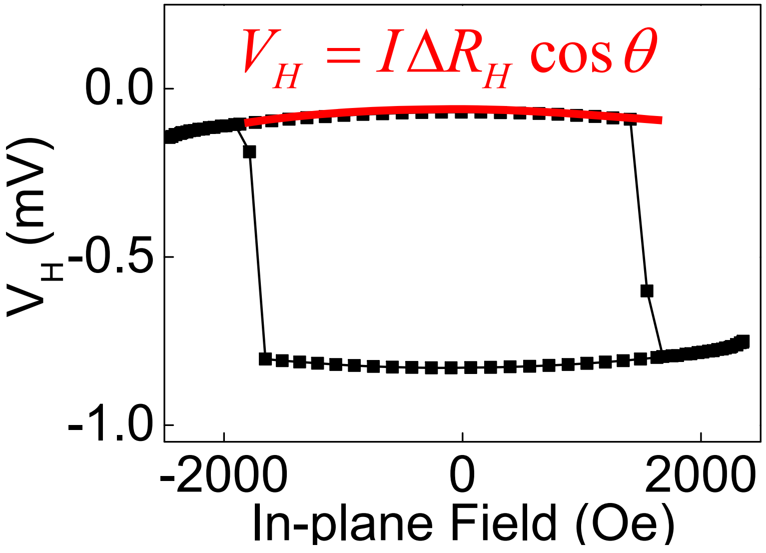




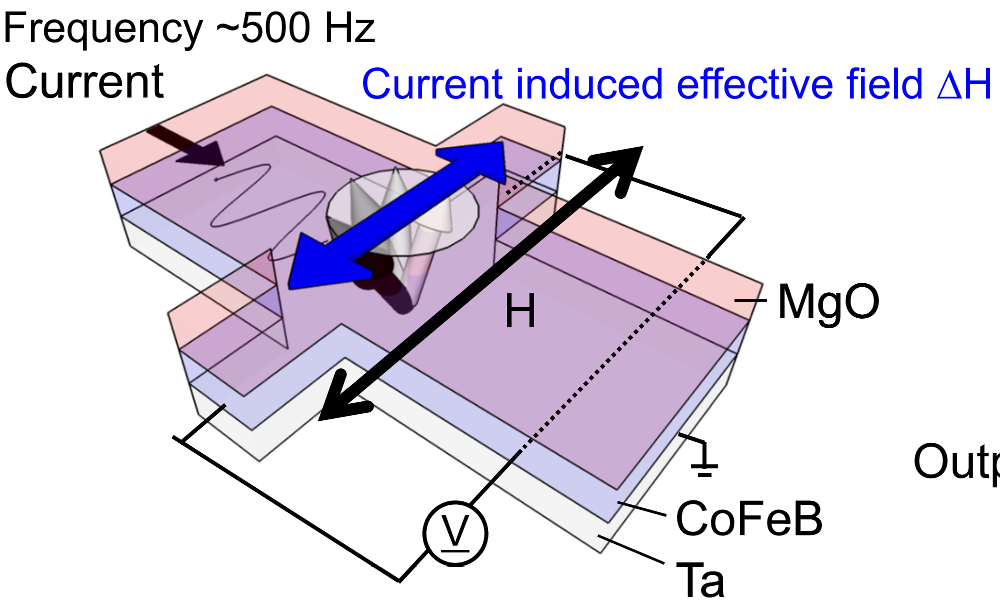


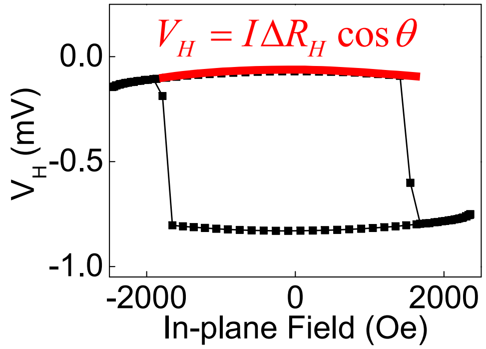
**Transfer function**

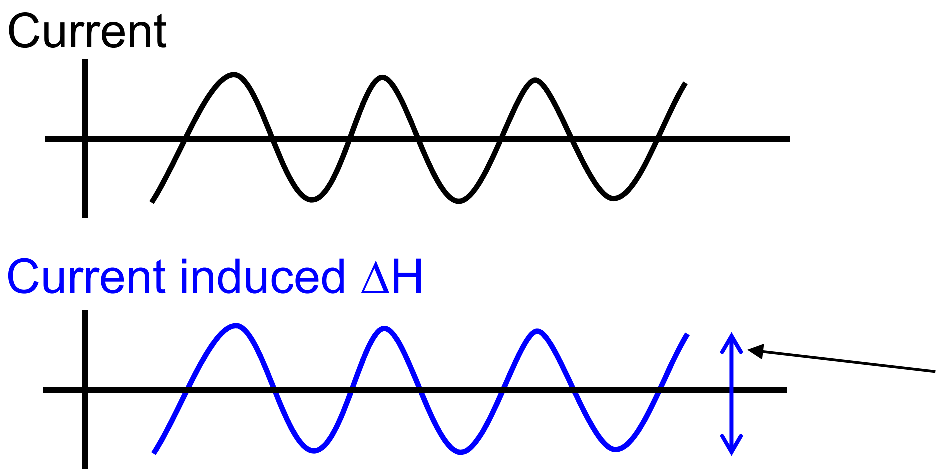
→ Relates $V_H$ and H

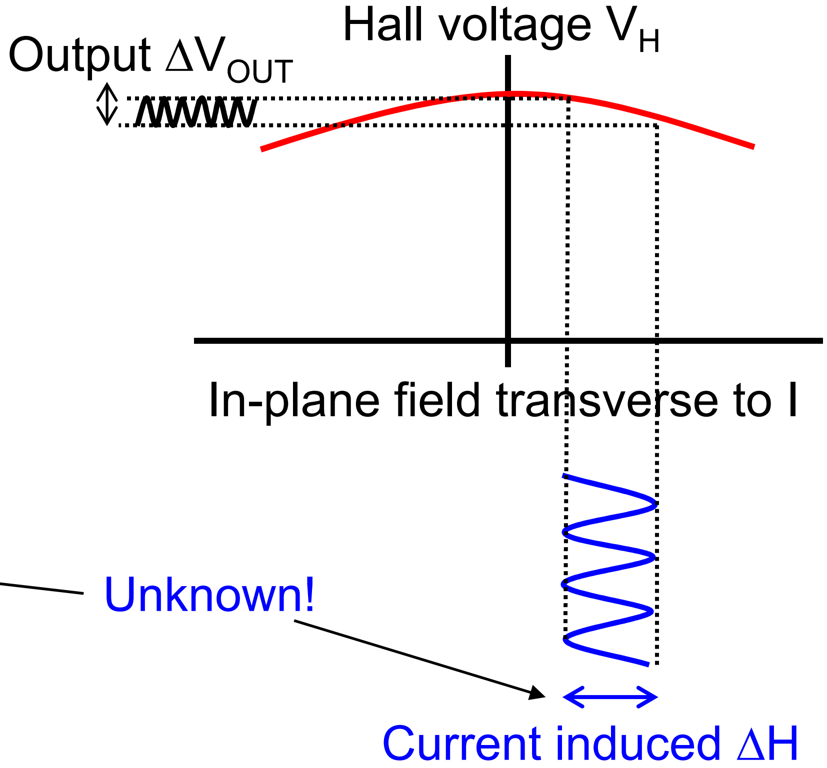


# Effective field measurements



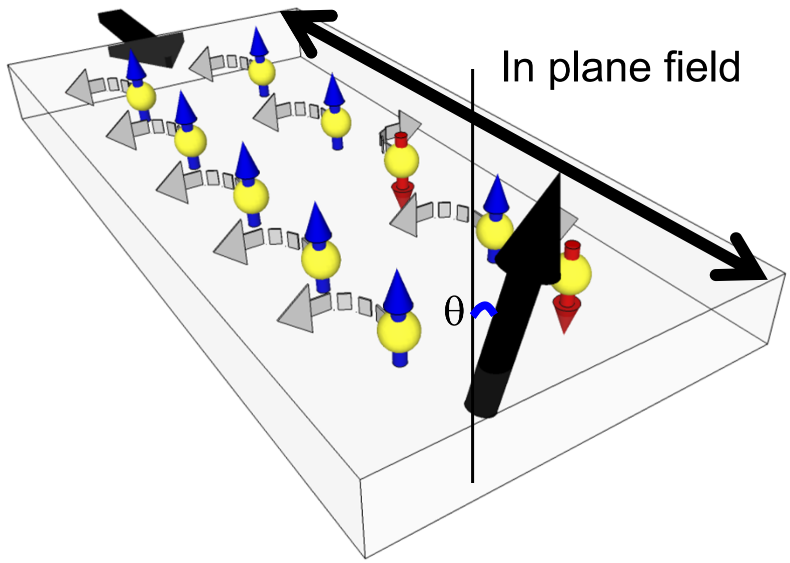


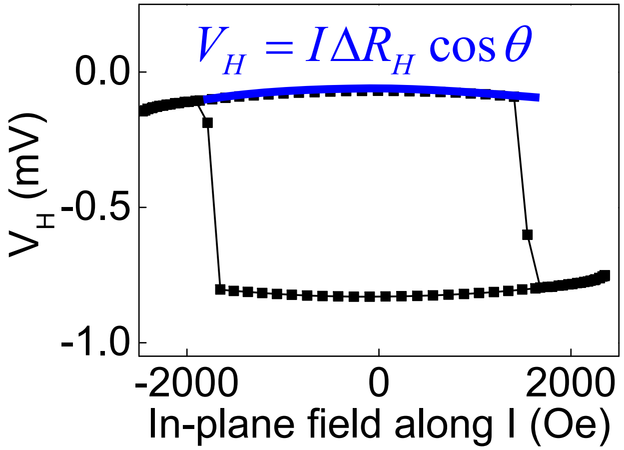


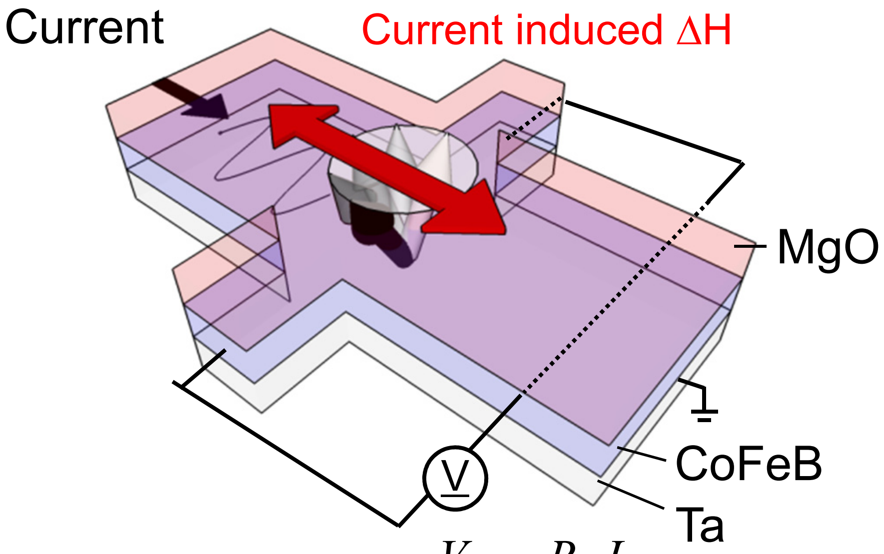


- Measuring $\Delta V_{OUT}$ gives information on the current induced effective field $\Delta H$

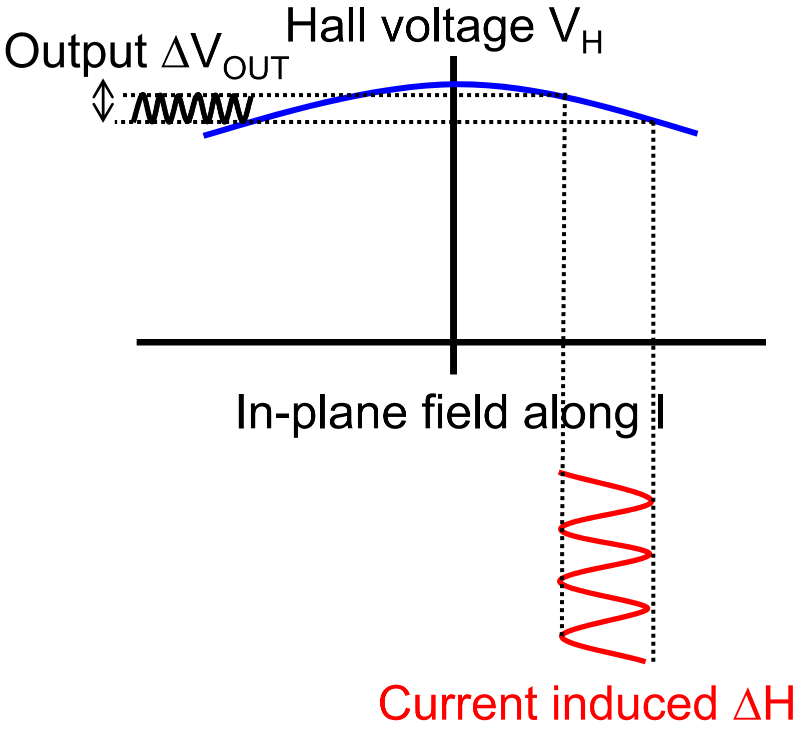
# Effective field measurements







$$V_H = R_H I$$

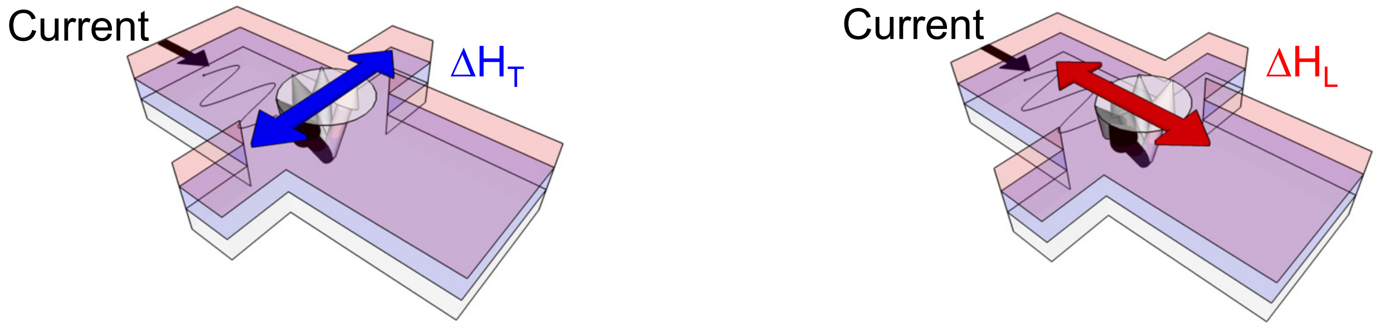


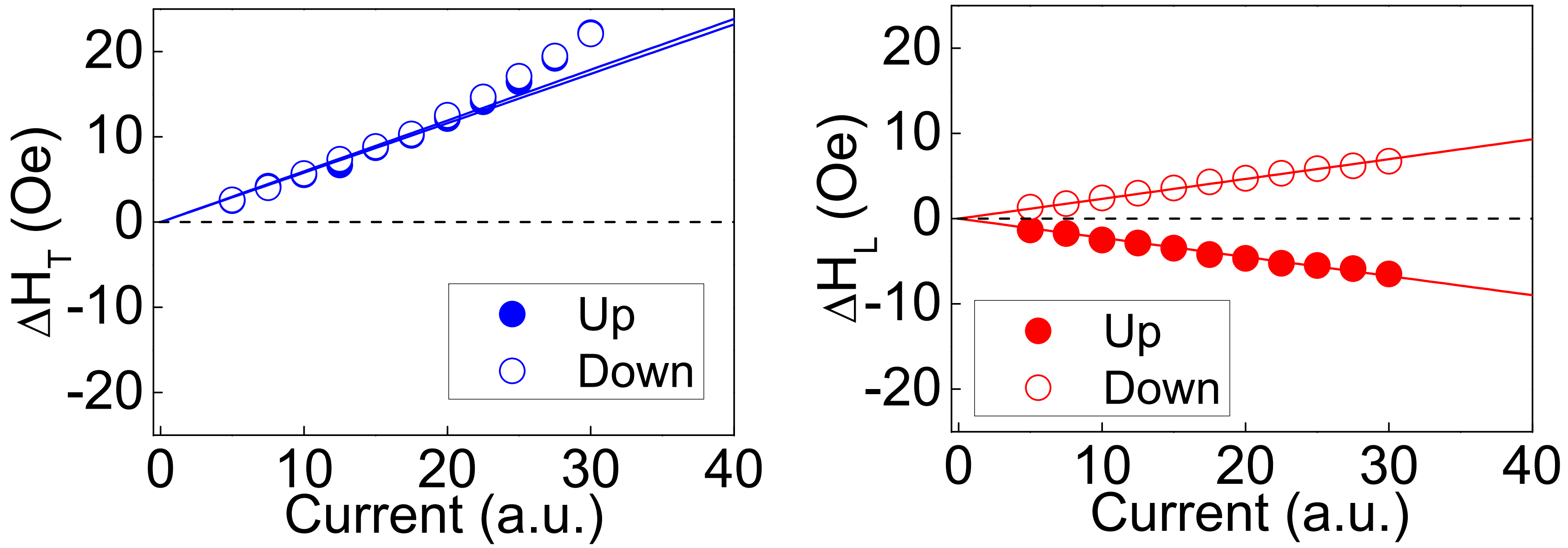
- Allows measurements of the Effective field along both field directions

# Current induced effective fields

- 1.3 Ta | 1 CoFeB | 2 MgO | 1 Ta

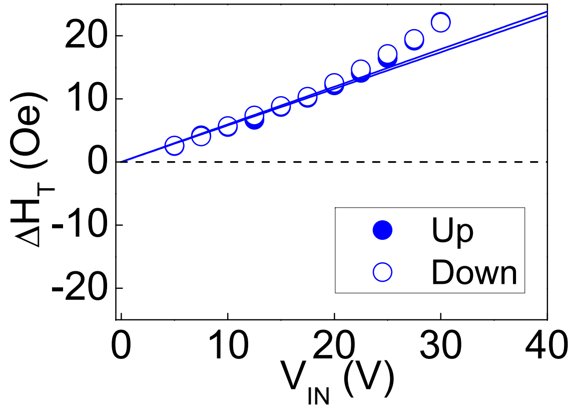
*J. Kim et al., Nature Mater. 12, 240 (2013)*

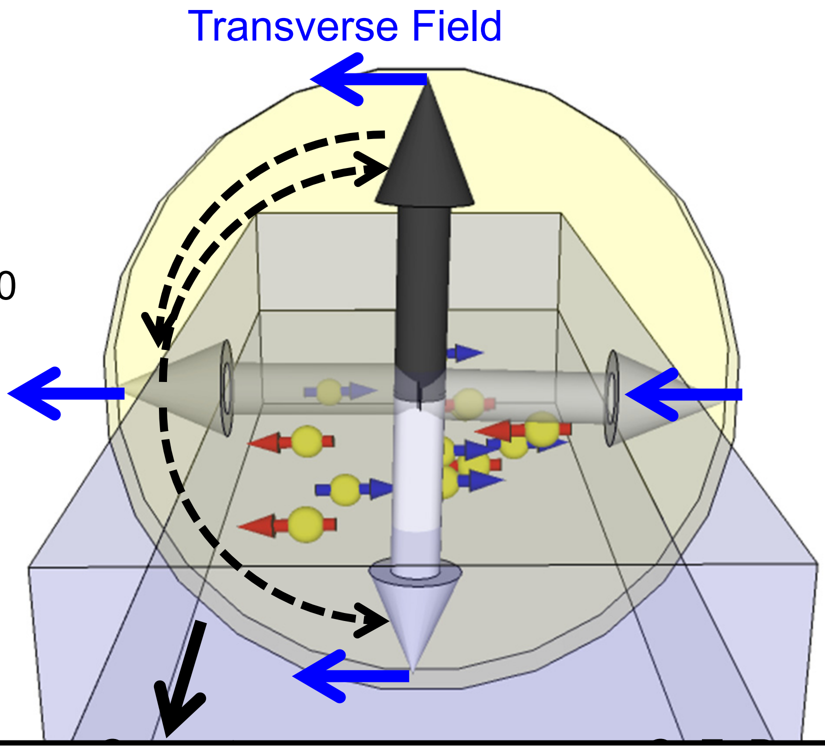


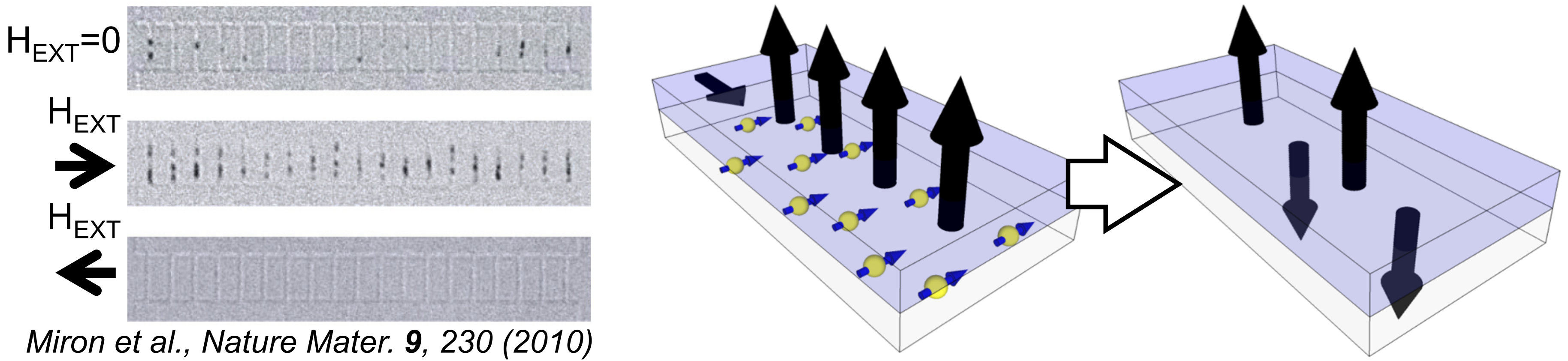


- Effective field scales with current
- It depends on the magnetization direction for the field along the current flow

# The Transverse effective field

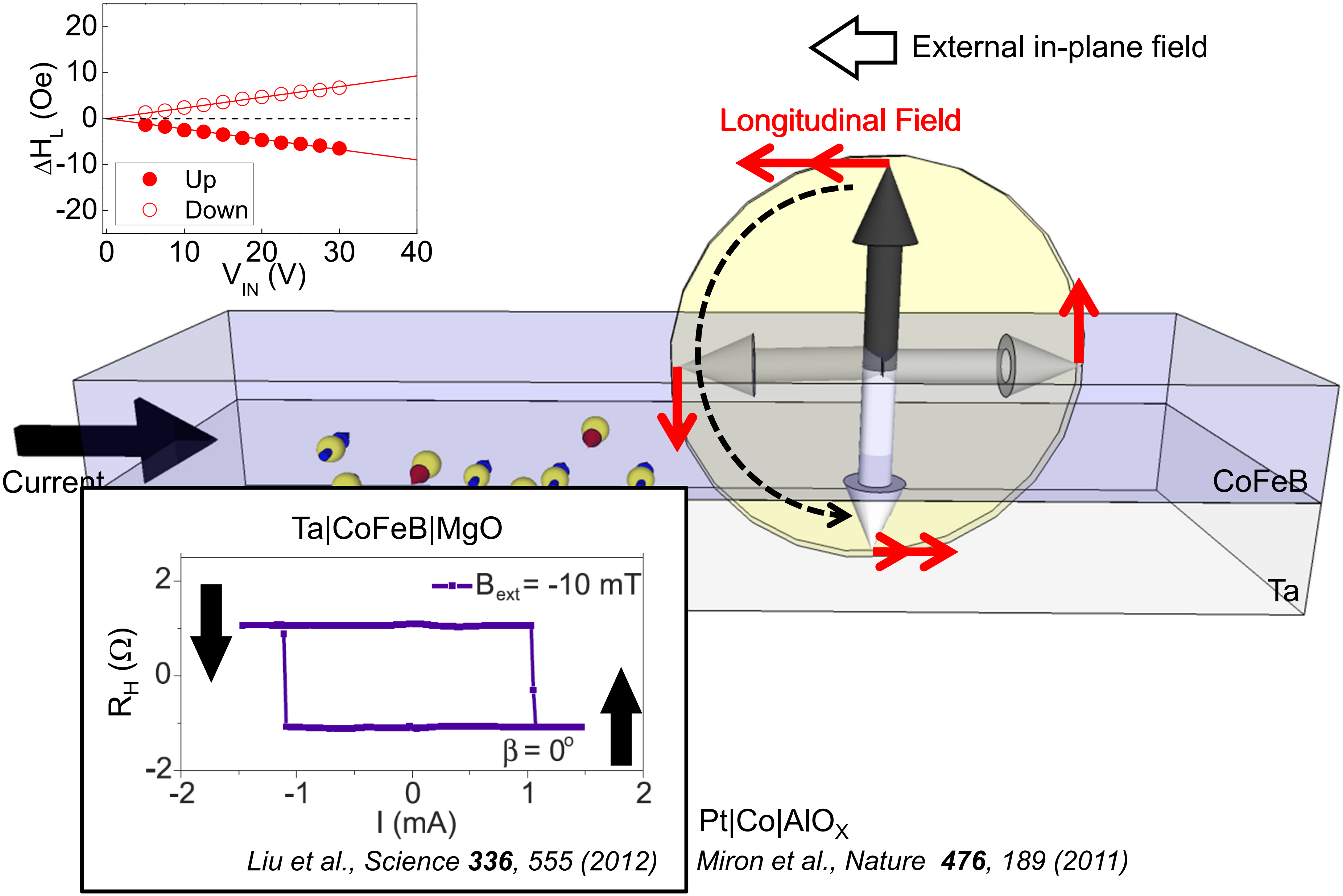






*Miron et al., Nature Mater.* ***9****, 230 (2010)*

# The Longitudinal Field



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

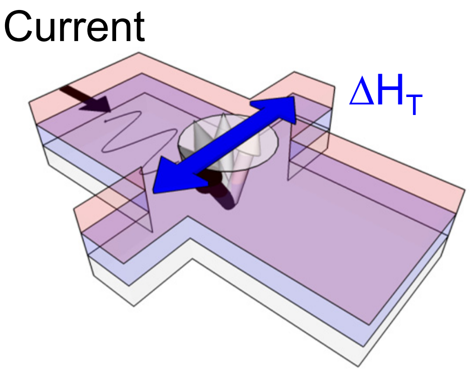
Pt|Co|AlO$_X$

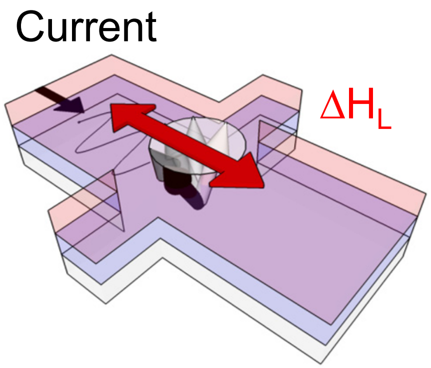
*Miron et al., Nature* ***476****, 189 (2011)*

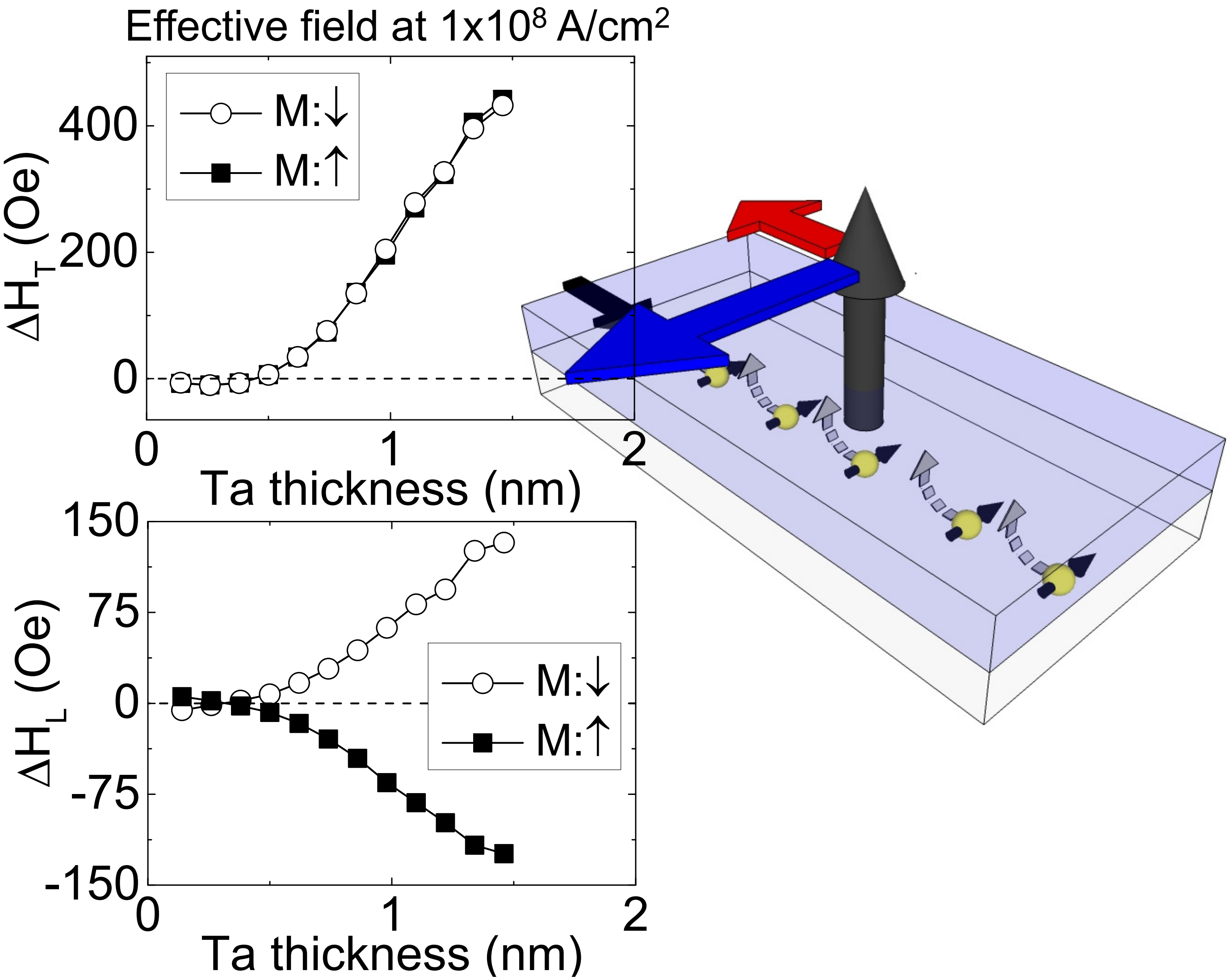
# Current induced effective fields

- $d_{Ta}$ Ta | 1 CoFeB | 2 MgO | 1 Ta

*J. Kim et al., Nature Mater. 12, 240 (2013)*







- Transverse field 2-3 times larger than the longitudinal field

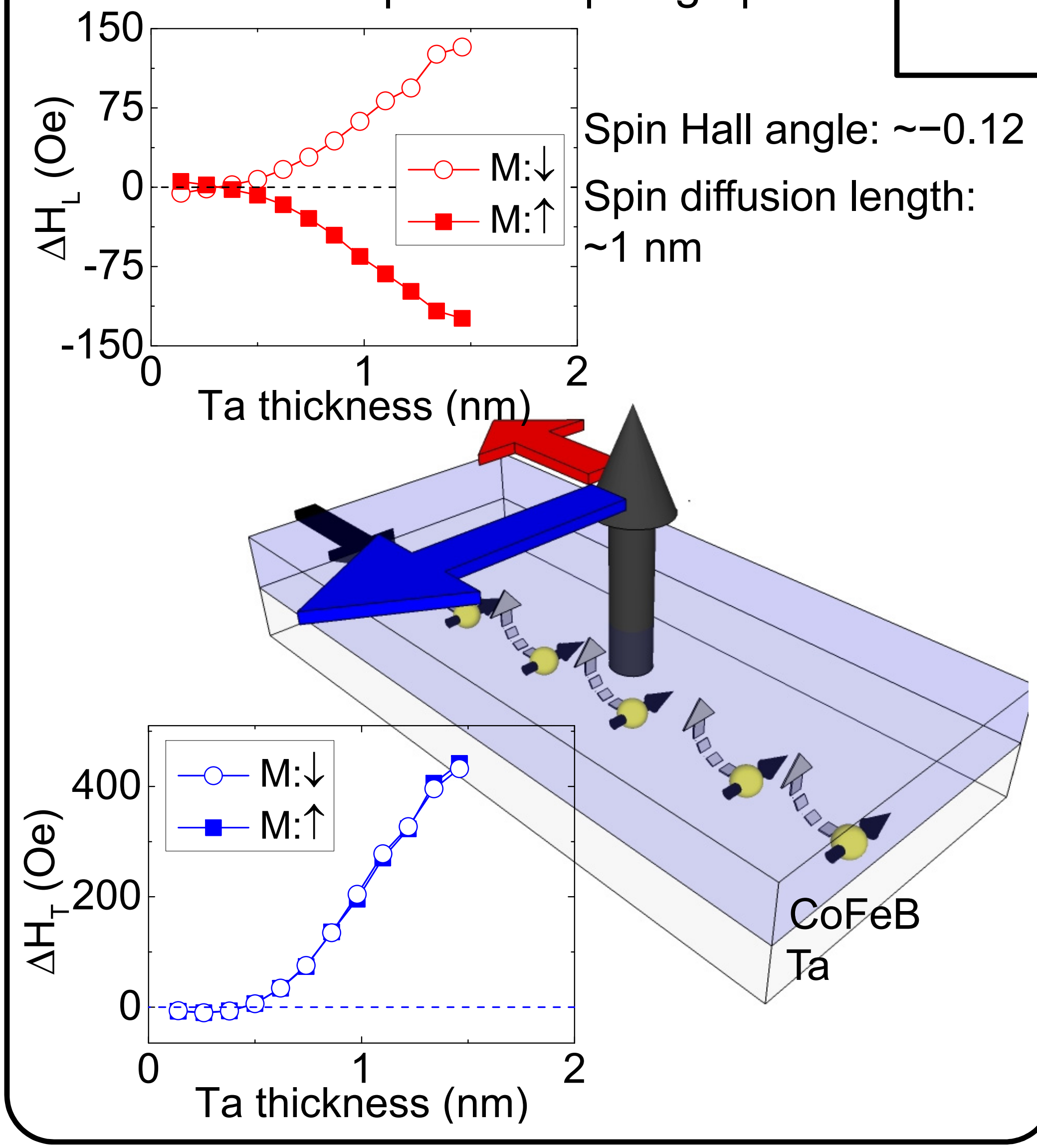
# Spin transfer torques

$$\Delta H_L = \frac{\hbar}{2eM_S t_{FM}} J_S \left(\hat{m}\times\hat{p}\right)$$

$$J_S = J\theta_{SH} = J_S(\infty)\left(1-\mathrm{sech}\left(\frac{d}{\lambda_{SD}}\right)\right)$$

*Liu et al. PRL* ***109****, 096602 (2012)*

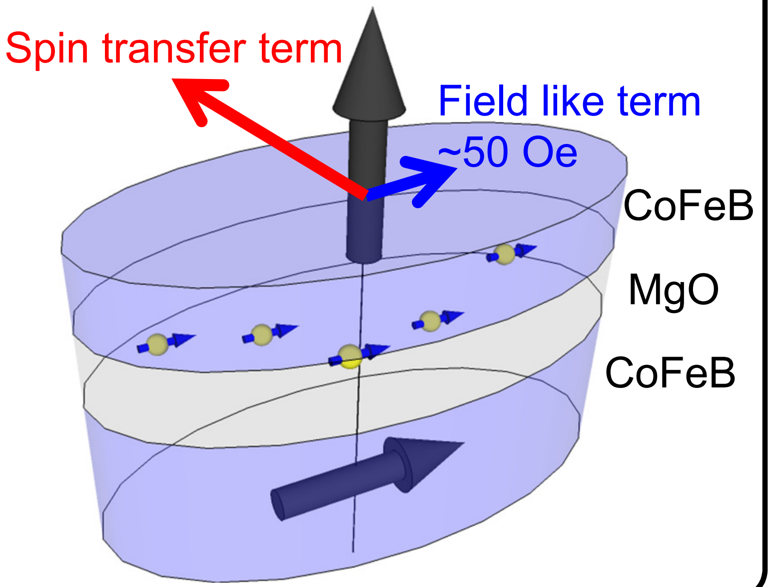
- d Ta|1 CoFeB|2 MgO|1 Ta



Spin Hall angle: ~−0.12

Spin diffusion length: ~1 nm

- Conventional MTJ

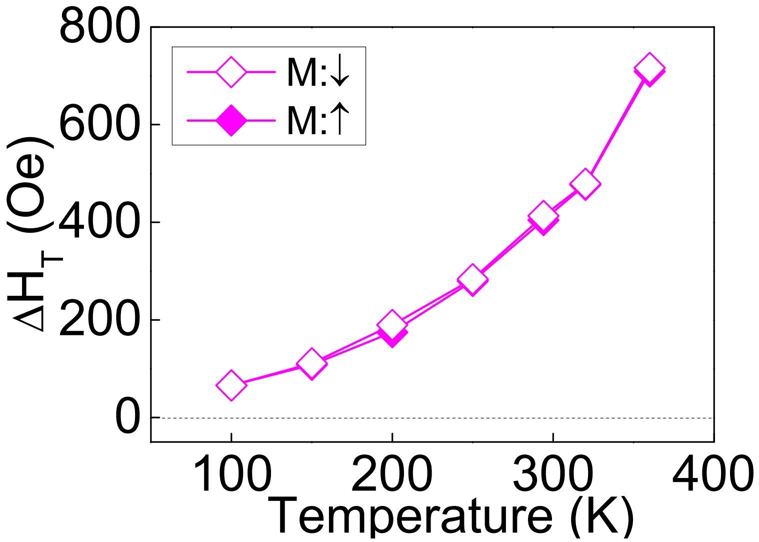


# Temperature dependence of the effective field

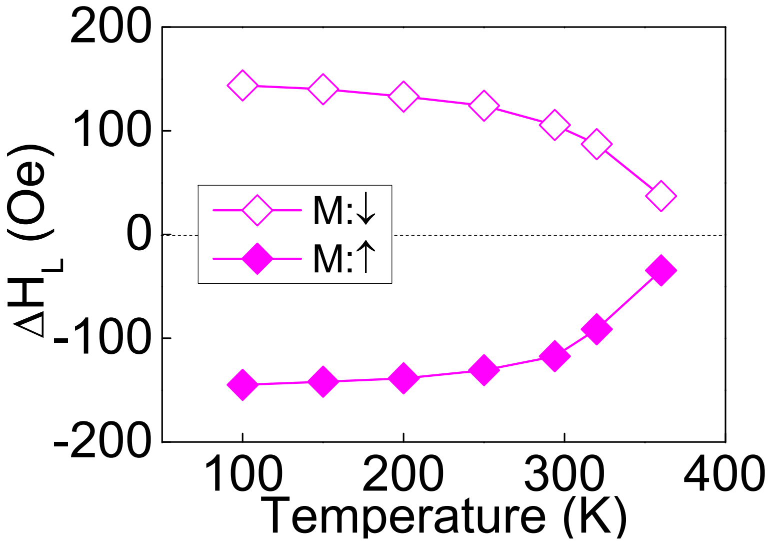
- 1.3 Ta | 1 CoFeB | 2 MgO | 1 Ta

Effective fields @ 1x$10^8$ A/$cm^2$

Transverse Field (field-like)



Longitudinal Field (spin transfer)



- Different temperature dependence for the transverse and longitudinal fields

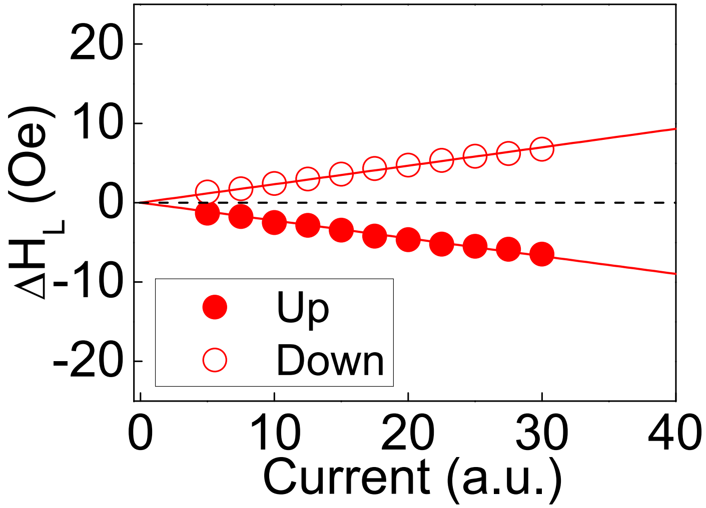
$$\vec{j}_s^{(\mathrm{F})} = \frac{\mu_s^0}{e}\hat{m} \times (\hat{m} \times \hat{y})\,\sigma\,\mathrm{Re}\,\frac{G_{\uparrow\downarrow}}{\sigma + 2\lambda G_{\uparrow\downarrow}\coth\frac{d_N}{\lambda}} + \frac{\mu_s^0}{e}(\hat{m} \times \hat{y})\,\sigma\,\mathrm{Im}\,\frac{G_{\uparrow\downarrow}}{\sigma + 2\lambda G_{\uparrow\downarrow}\coth\frac{d_N}{\lambda}}$$

*Chen et al., PRB **87**, 144411 (2013)*

→ Large imaginary part of the mixing conductance

# The Longitudinal effective field

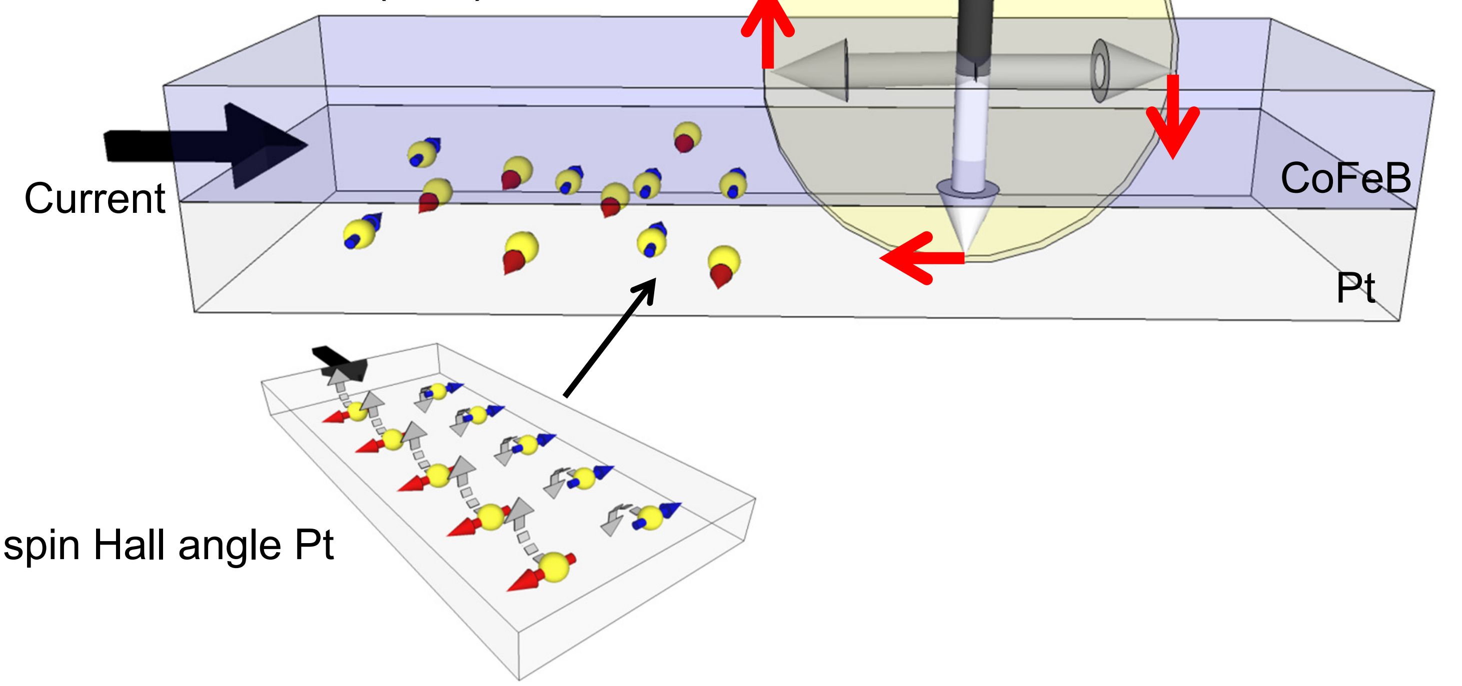
- Longitudinal (along the current flow) effective field



The effective field $\Delta H_L$ (~torque) direction

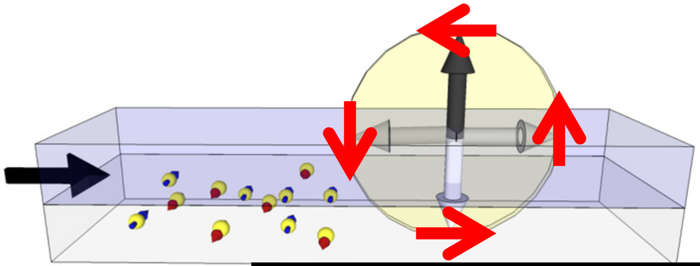
depends on the magnetization direction

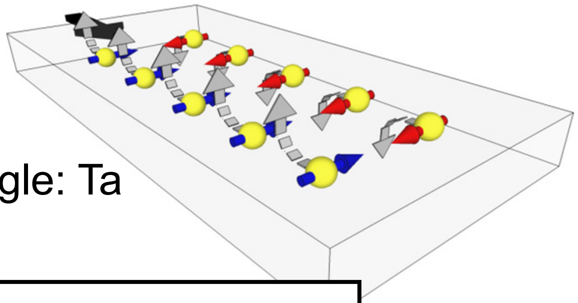
→ Typical characteristics of spin transfer torque



"Positive" spin Hall angle Pt

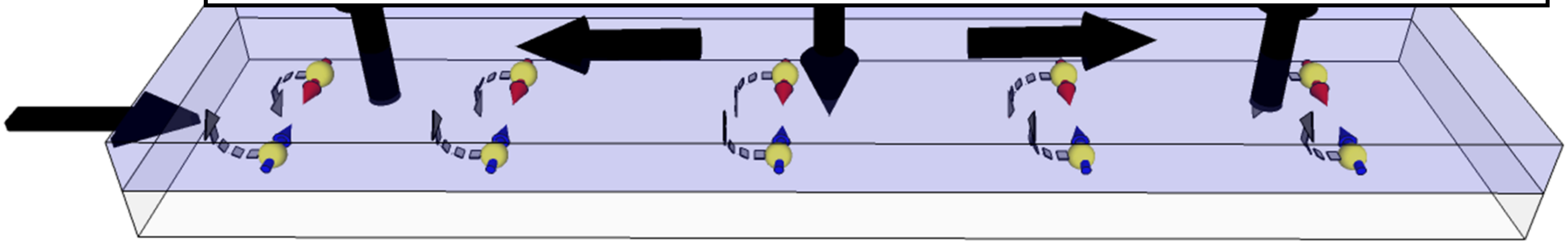
# Domain wall motion with spin Hall spin torque

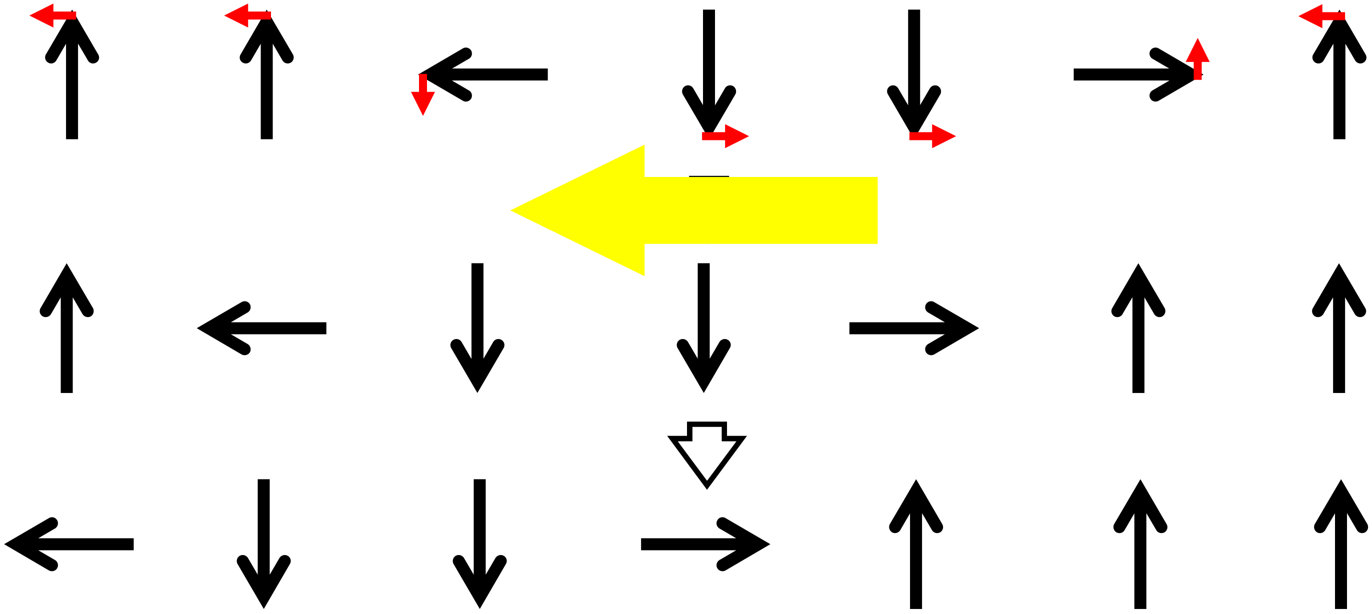




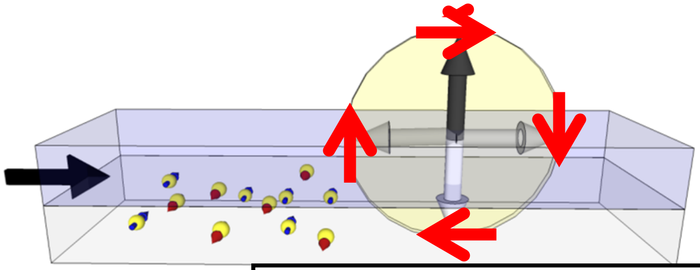
"Negative" spin Hall angle: Ta

Domain wall moves **against** the current flow

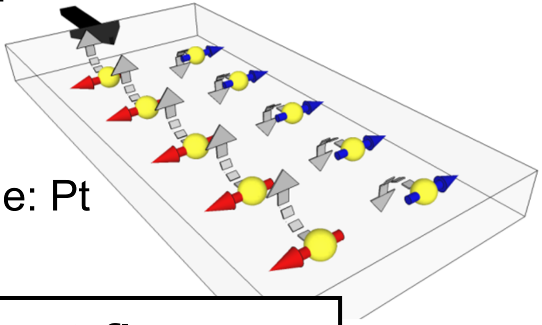




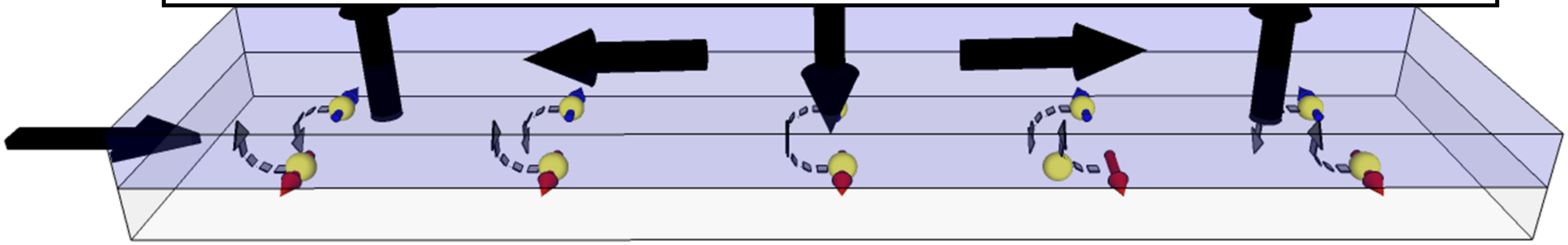
# Domain wall motion with spin Hall spin torque

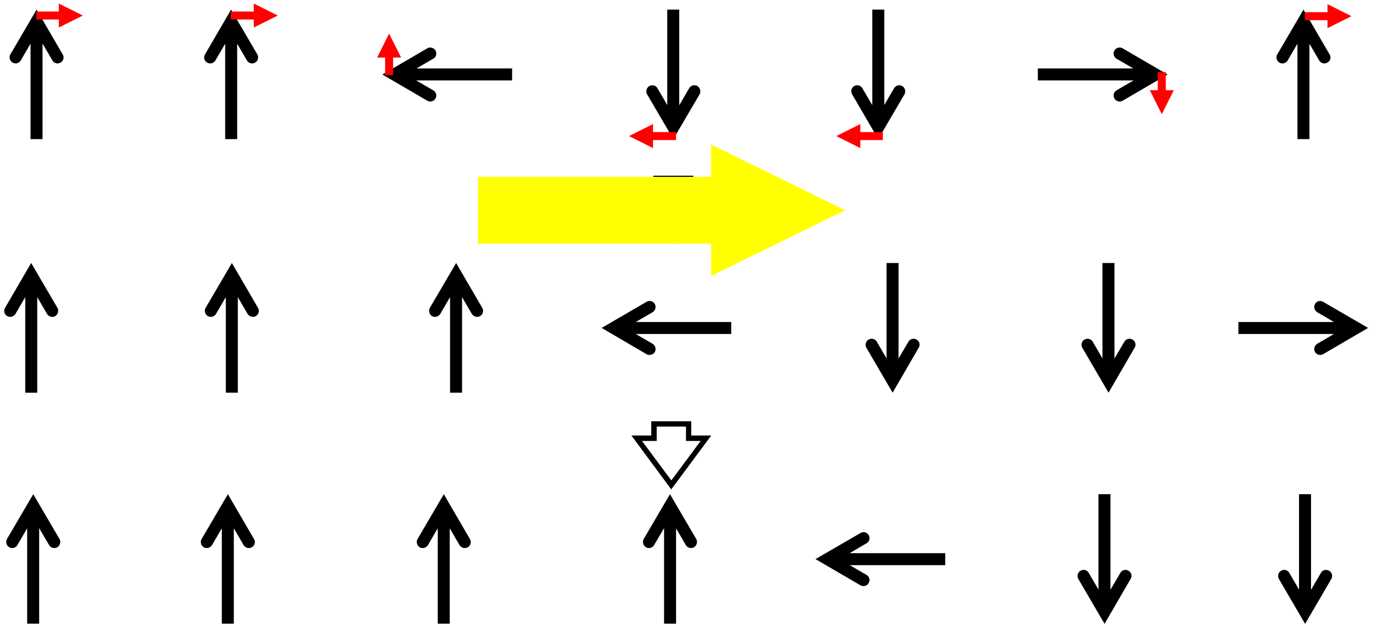


"Positive" spin Hall angle: Pt

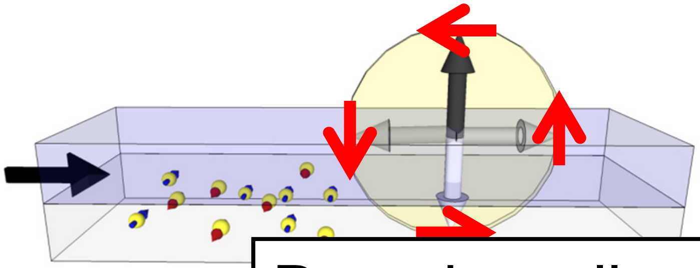


Domain wall moves **along** the current flow

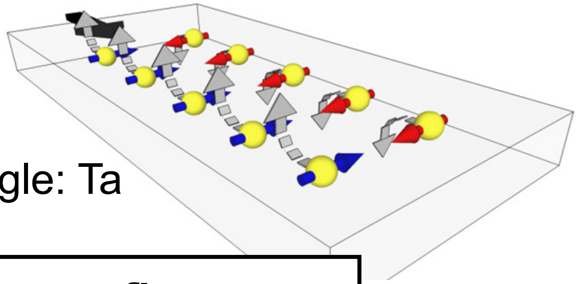




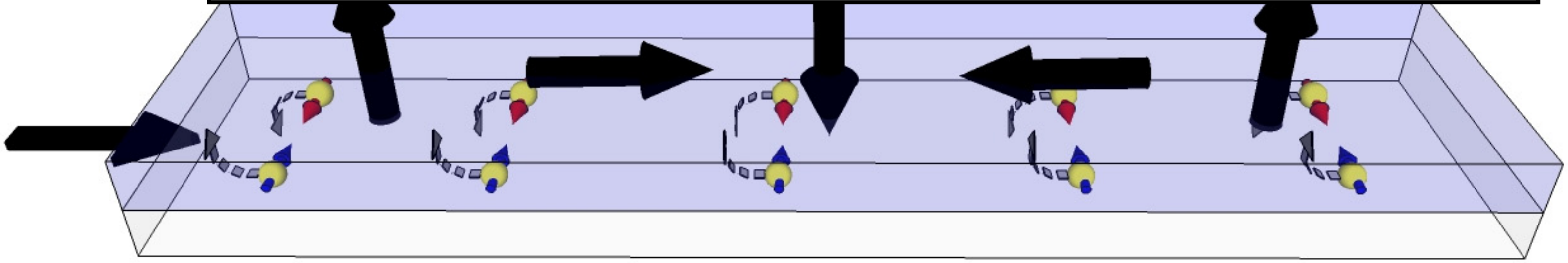
# Domain wall with spin Hall torque: chirality effect

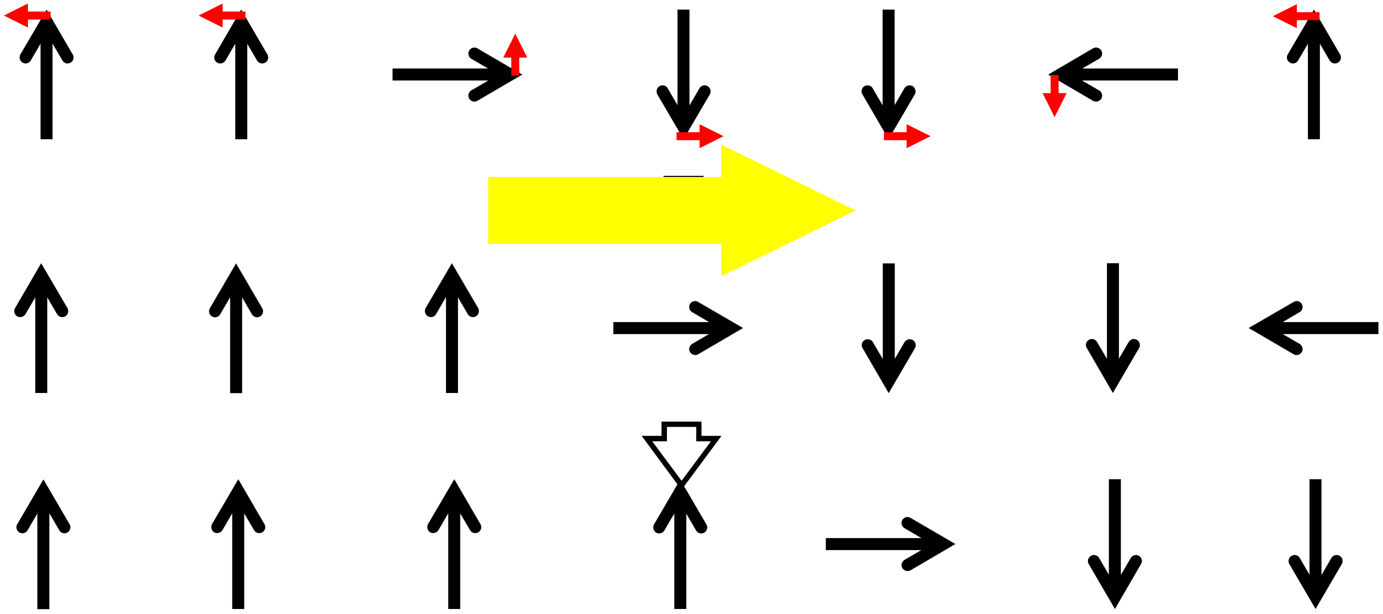


"Negative" spin Hall angle: Ta



Domain wall moves **along** the current flow

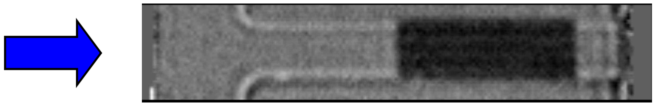




# Domain wall motion in Ta(N)|CoFeB|MgO

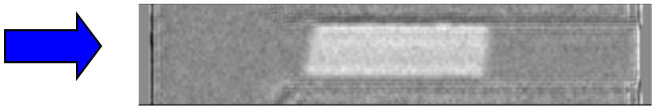
- Sub|**Ta**|1 CoFeB|2 MgO|1 Ta (nm)

Current



- Sub|**TaN**|1 CoFeB|2 MgO|1 Ta (nm)

Current



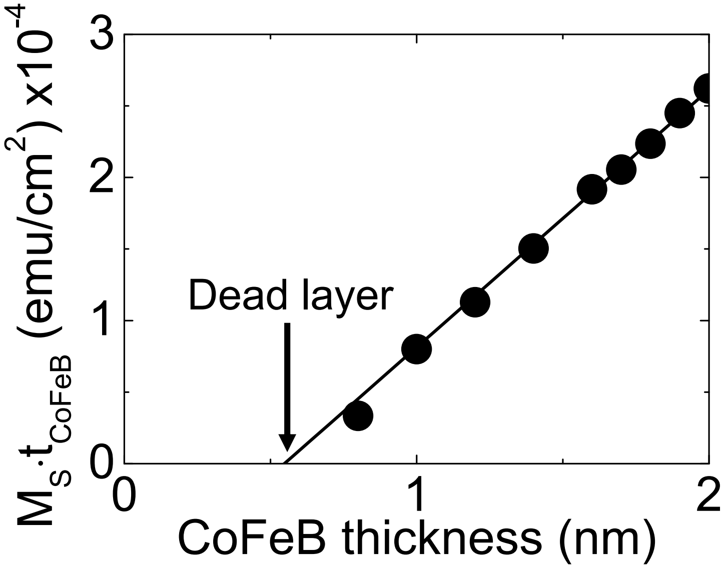
(a) Sign difference in the spin Hall angle

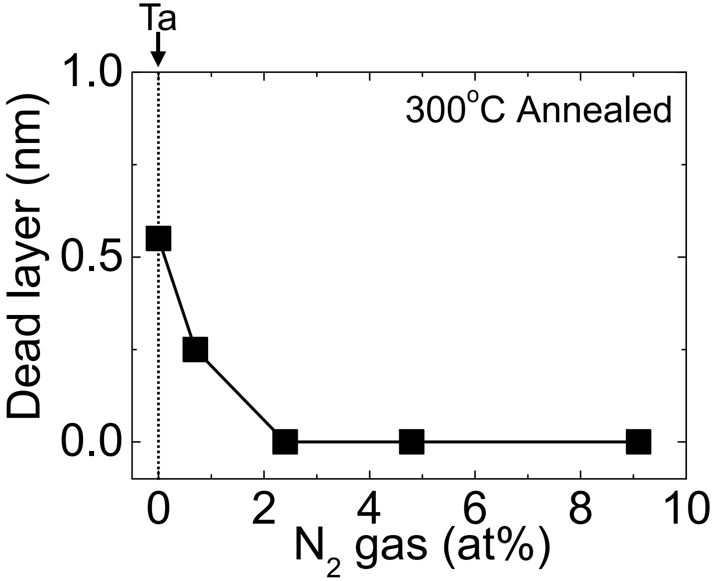
(b) Difference in the chirality of the domain wall spiral

# Ta|CoFeB|MgO heterostructures

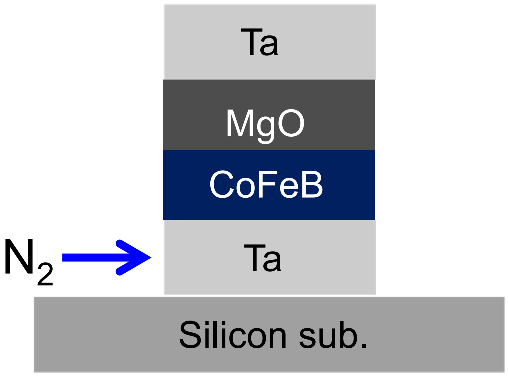
*Sinha et al., Appl. Phys. Lett. 102, 242405 (2013)*

- Sub|1 Ta|**t CoFeB**|2 MgO|1 Ta (nm)





- Use TaN as the underlayer: good diffusion barrier
  → Sputter Ta in Ar+$N_2$ gas atmosphere

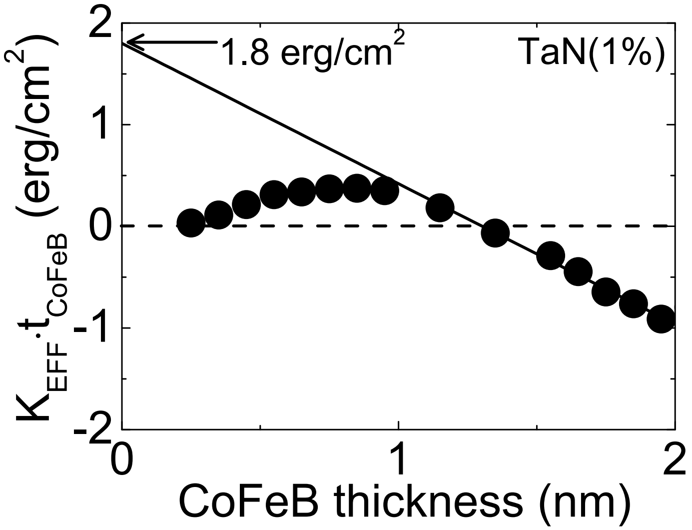


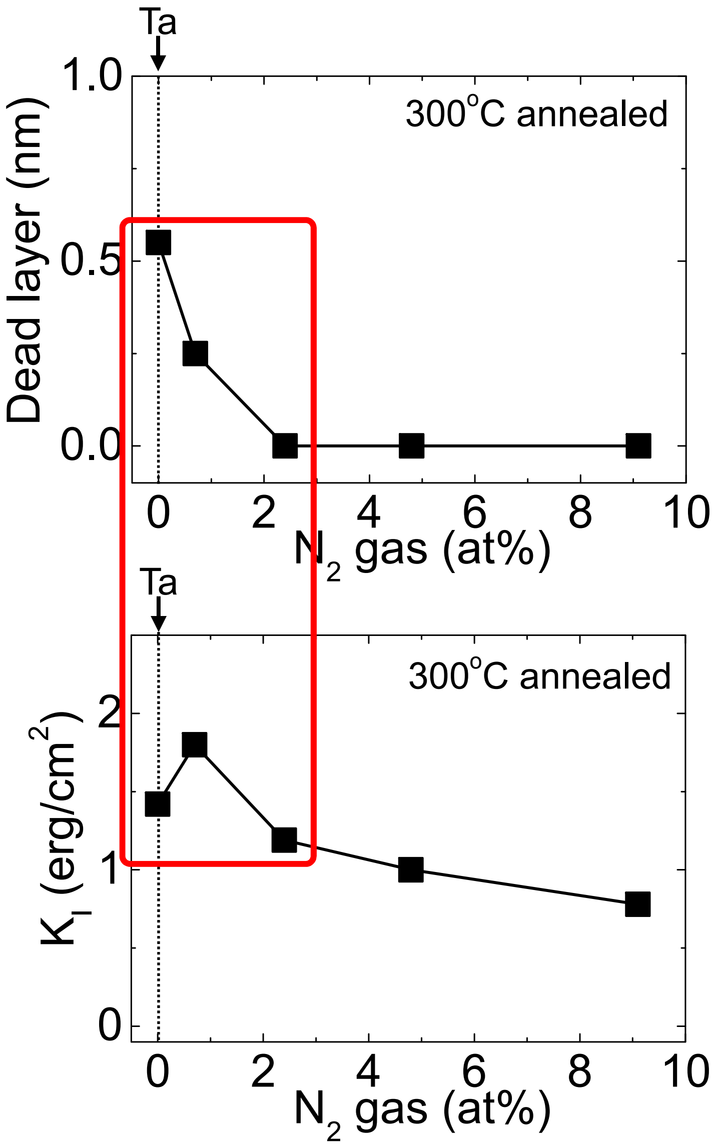
- Dead layer thickness reduces with increasing $N_2$ concentration

# Ta|CoFeB|MgO heterostructures

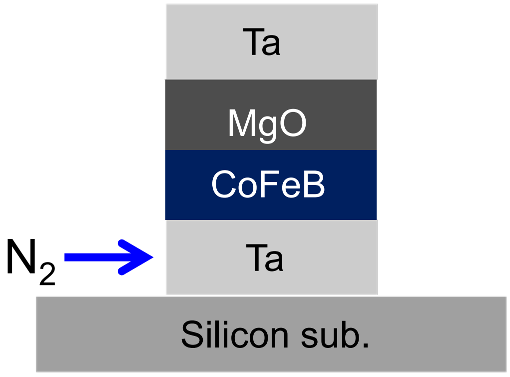
*Sinha et al., Appl. Phys. Lett. 102, 242405 (2013)*

- Sub|1 Ta|**t CoFeB**|2 MgO|1 Ta (nm)





- Use TaN as the underlayer: good diffusion barrier
  - → Sputter Ta in Ar+$N_2$ gas atmosphere

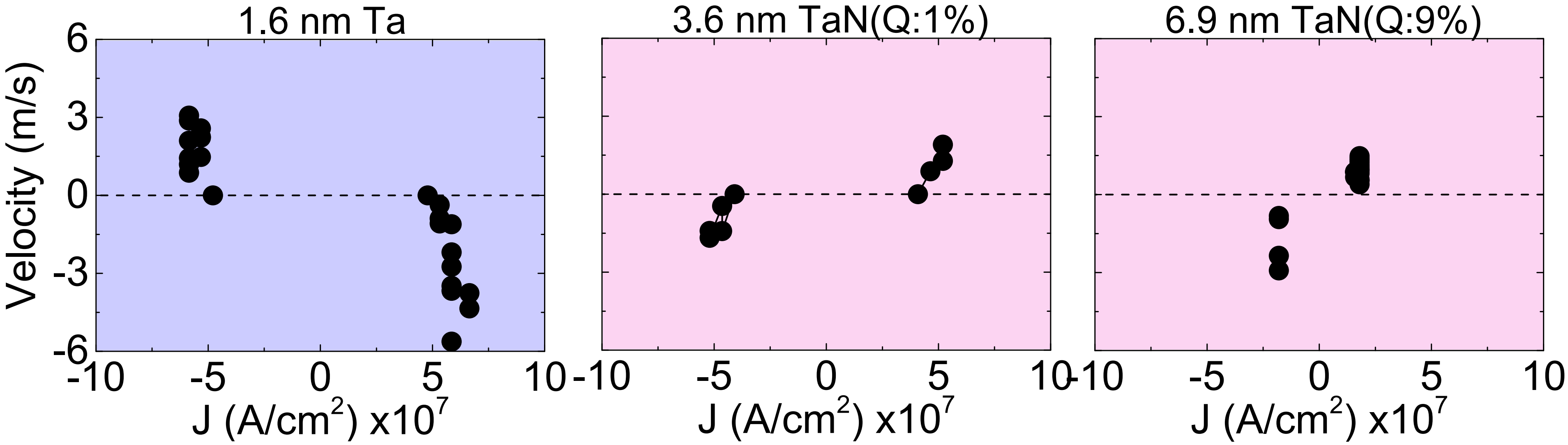


- Interface perpendicular magnetic anisotropy takes a maximum at $N_2$ gas ~1 at%

# Current driven domain wall motion

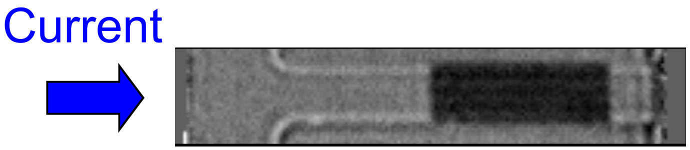
*Torrejon et al., arXiv:1308.1751*

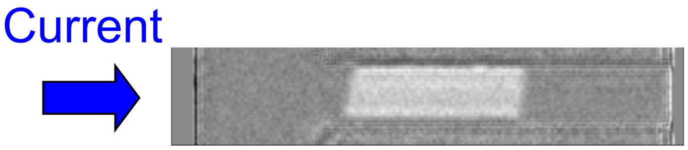
- Sub|**d underlayer**|1 CoFeB|2 MgO|1 Ta (nm)



**1.6 Ta**|1 CoFeB|2 MgO|1 Ta

**3.6 TaN(Q~1%)**|1 CoFeB|2 MgO|1 Ta



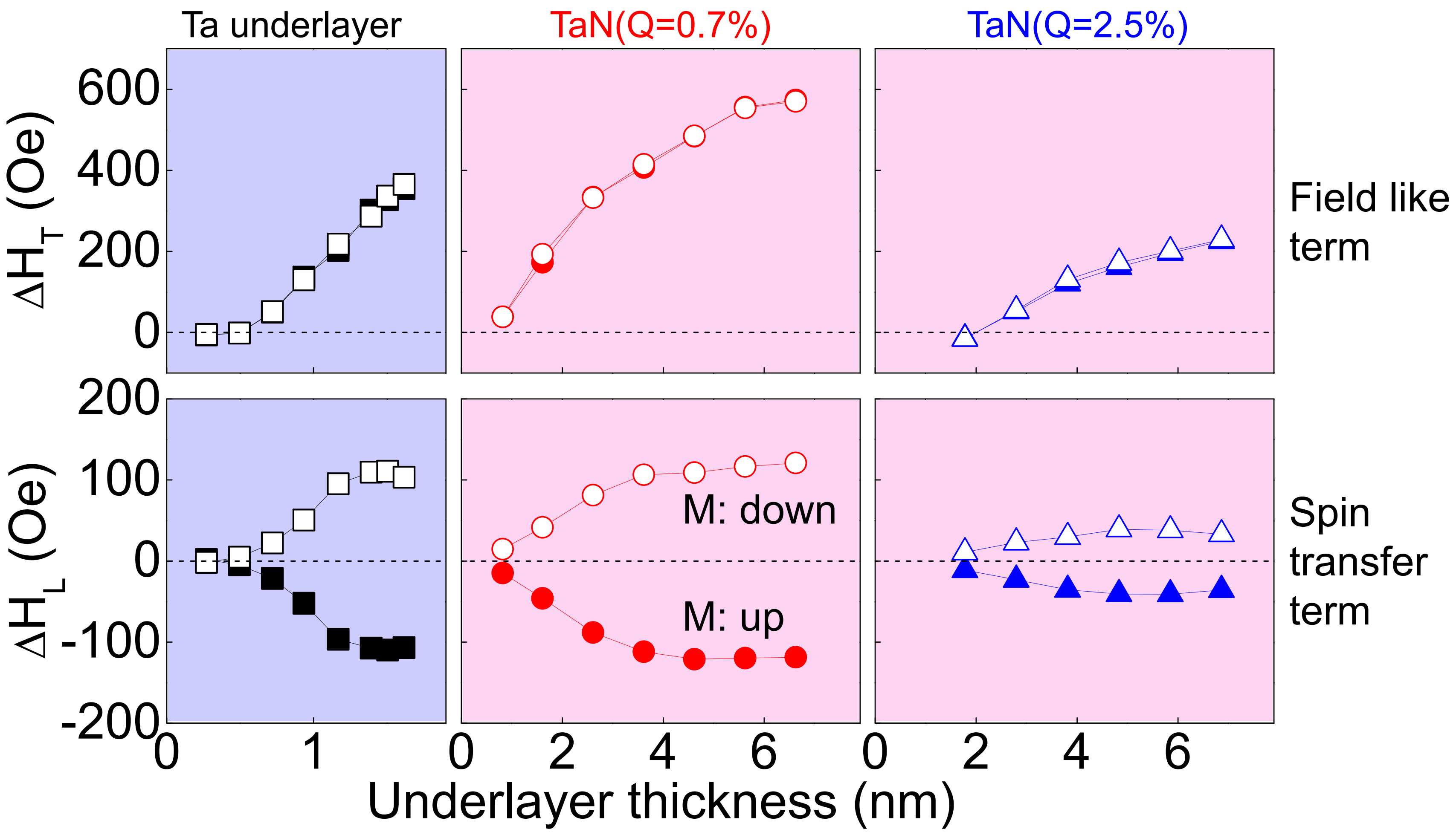


- Domain wall moves in opposite direction for Ta and TaN underlayers

# Sign of the spin Hall effect in Ta and TaN

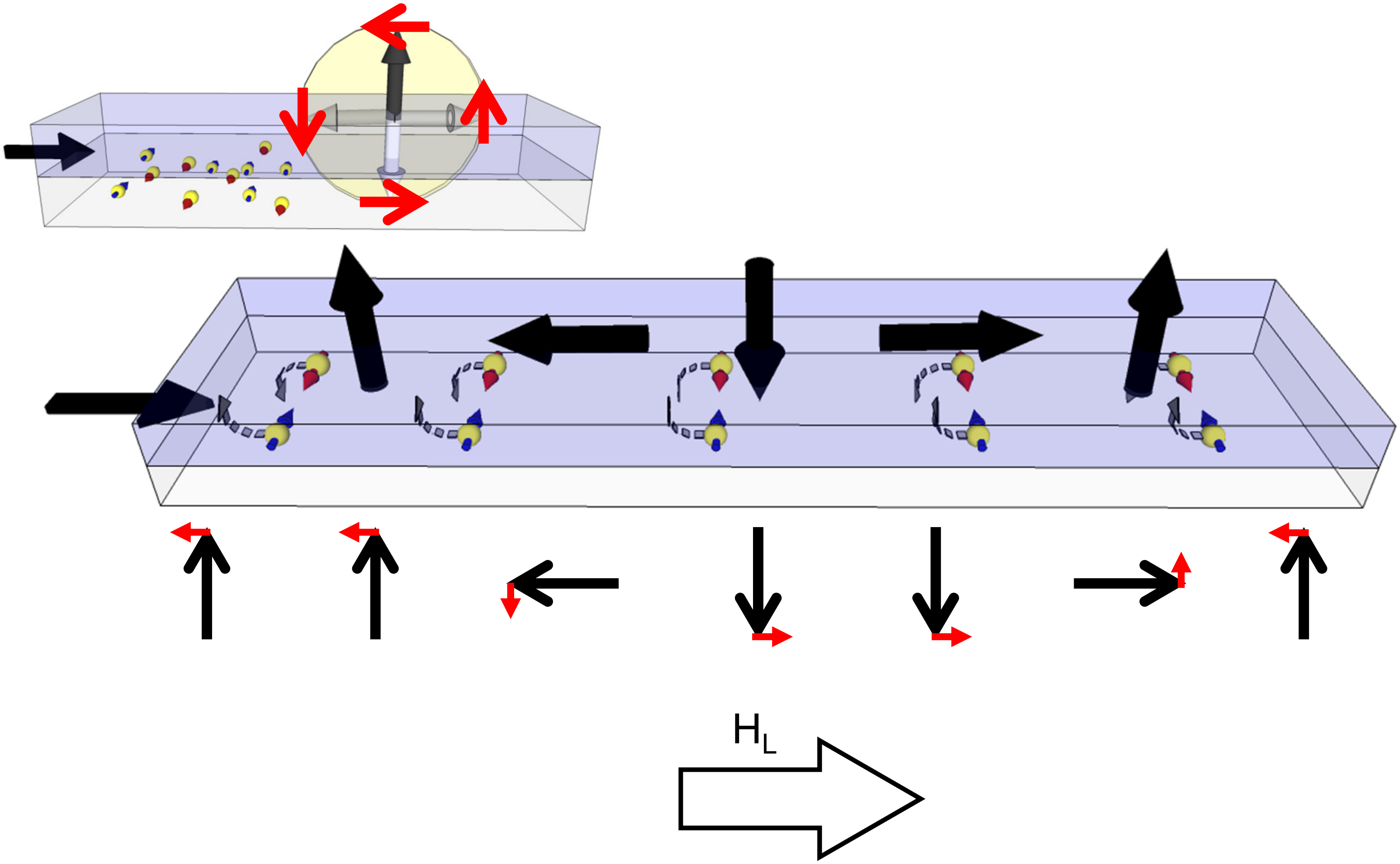
*Torrejon et al., arXiv:1308.1751*

- Effective field if current density of 1x10$^8$ A/cm$^2$ were to be passed in the underlayer



- Sign of the spin Hall effect is the same for Ta and TaN
  (But spin diffusion length varies)

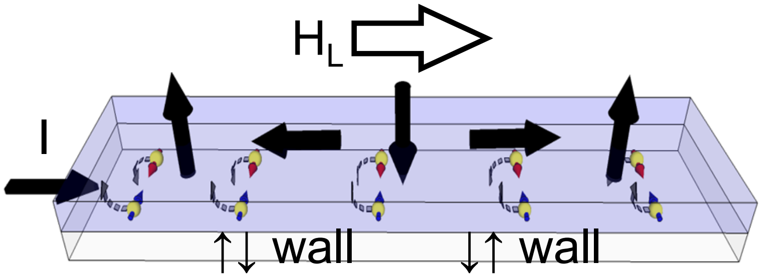
# Current driven domain wall motion: $H_L$ dependence



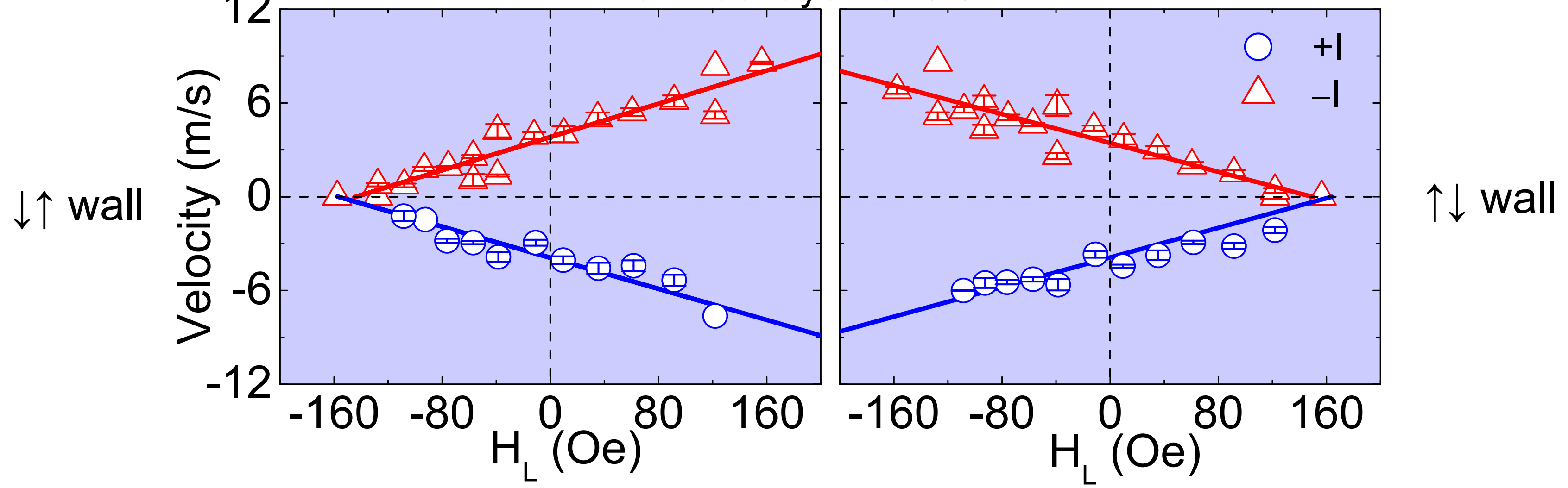
- Application of the "Longitudinal Field"

  → stabilizes Neel walls with one chirality

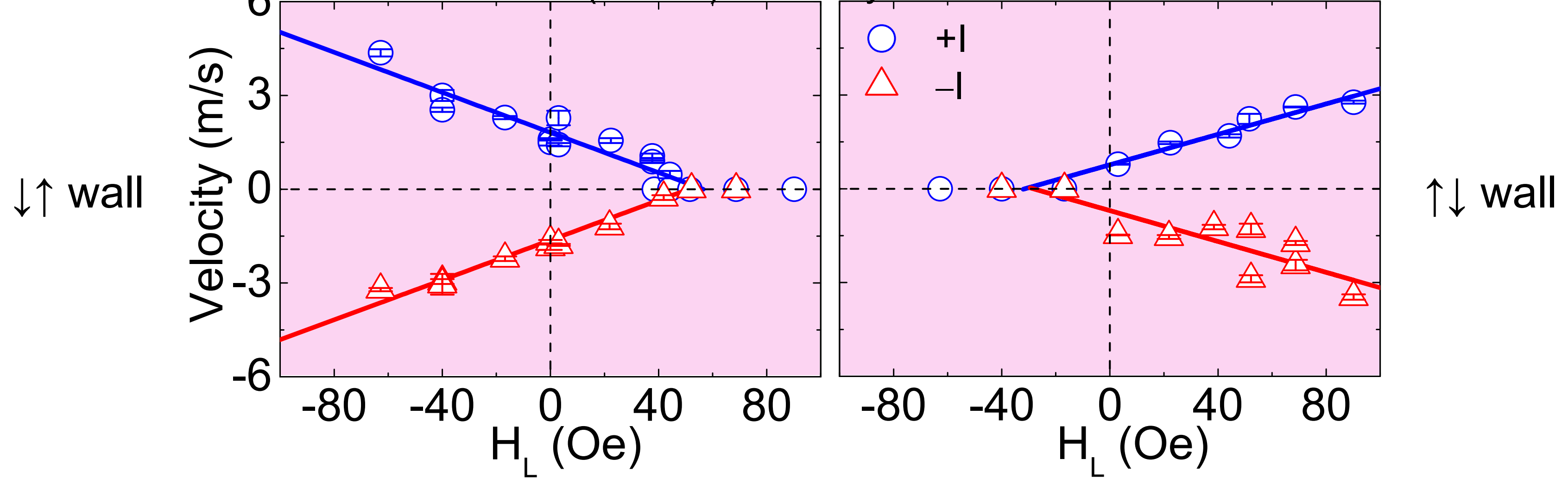
# Current driven domain wall motion: $H_L$ dependence



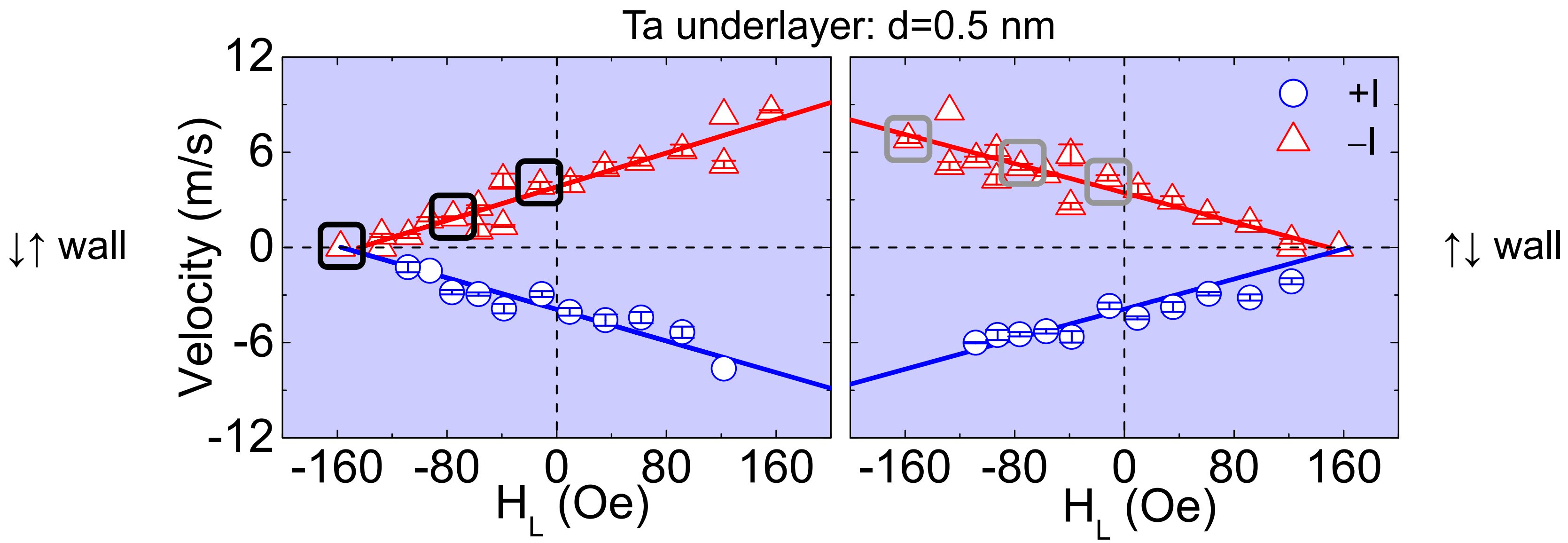
Ta underlayer: d=0.5 nm

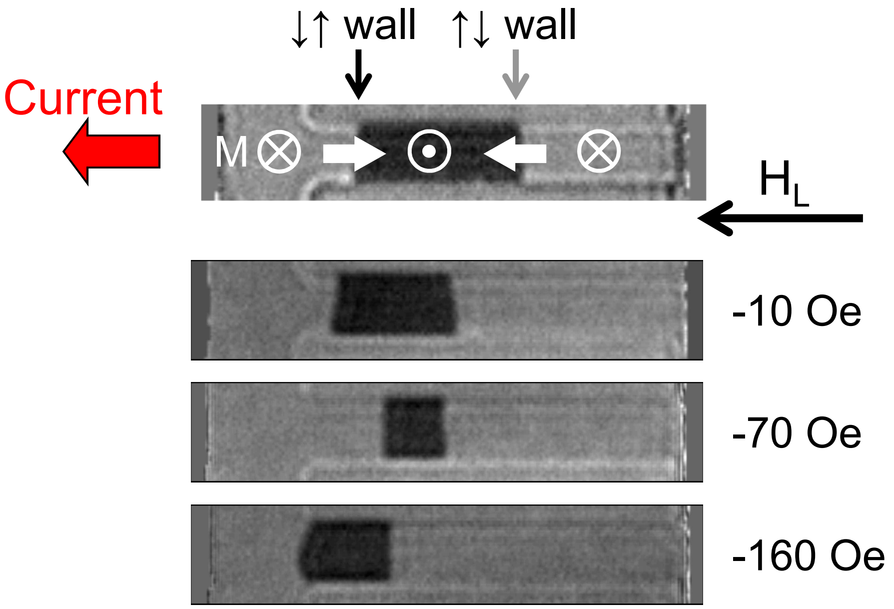


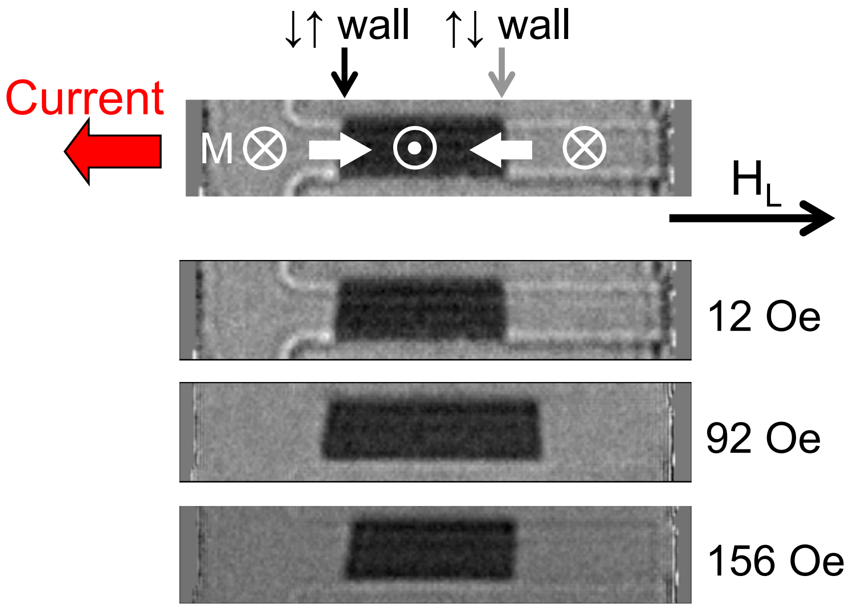
TaN (Q~1%) underlayer: d=3.6 nm



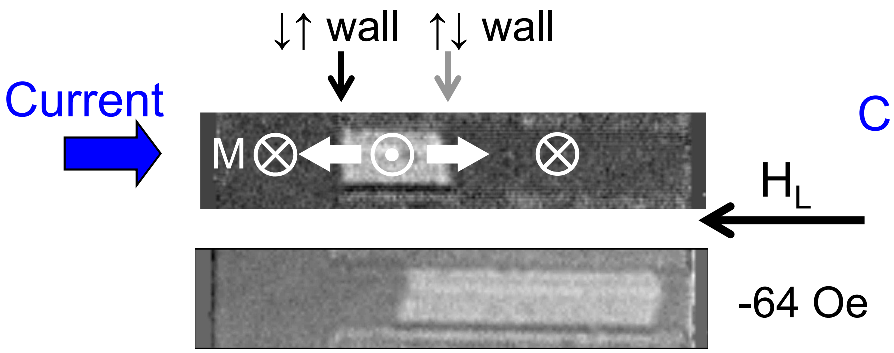
# Chirality dependent current driven domain walls

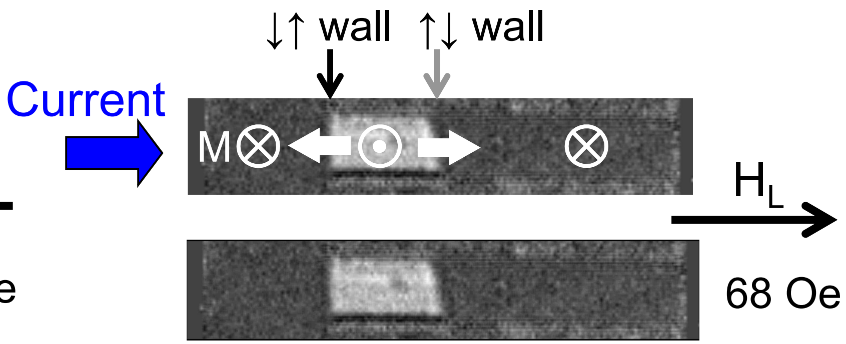






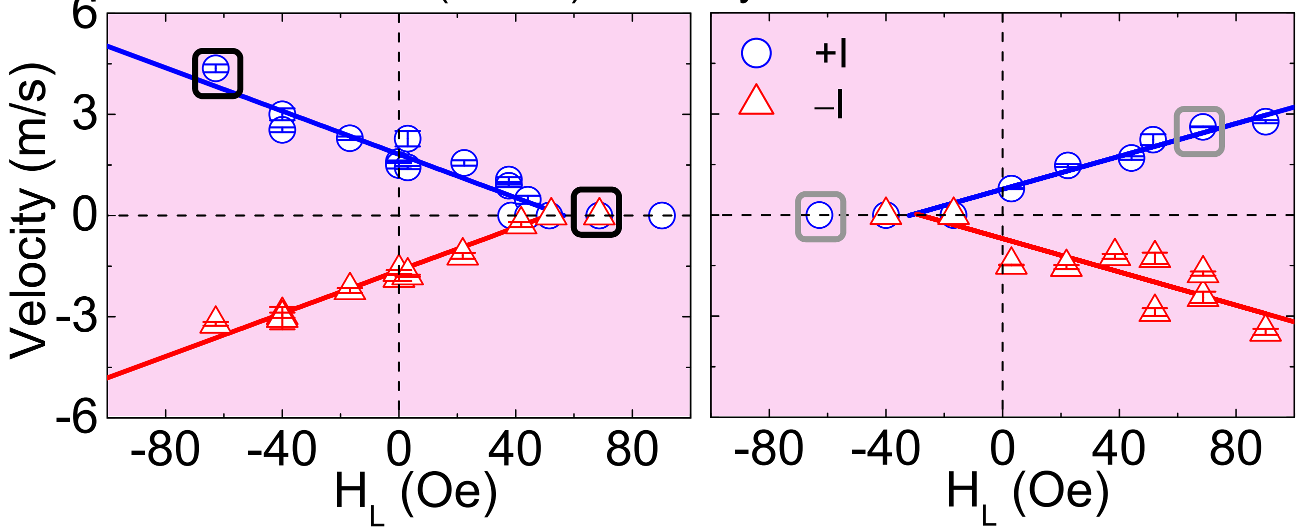
# Chirality dependent current driven domain walls





TaN (Q~1%) underlayer: d=3.6 nm

↓↑ wall



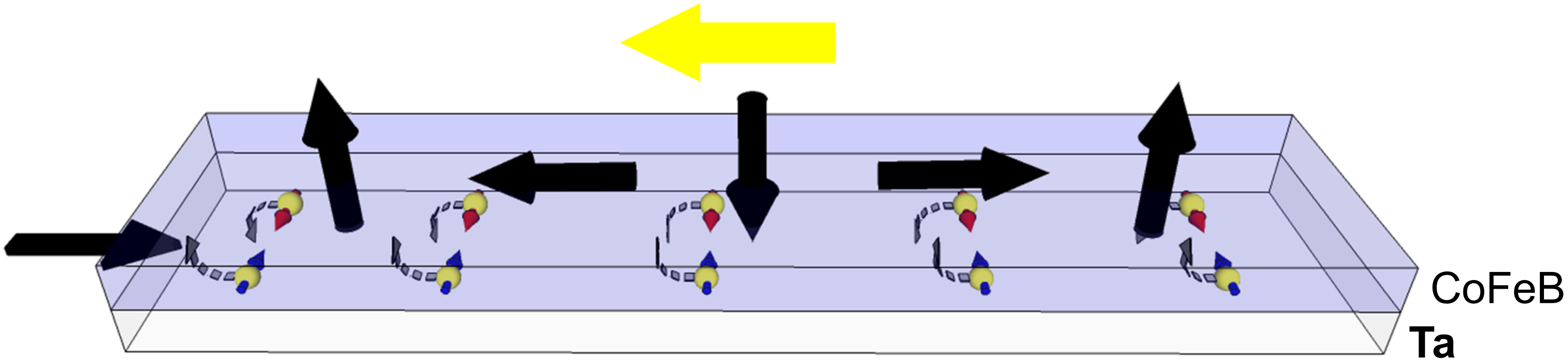
↑↓ wall

# Chiral domain walls

*Torrejon et al., arXiv:1308.1751*

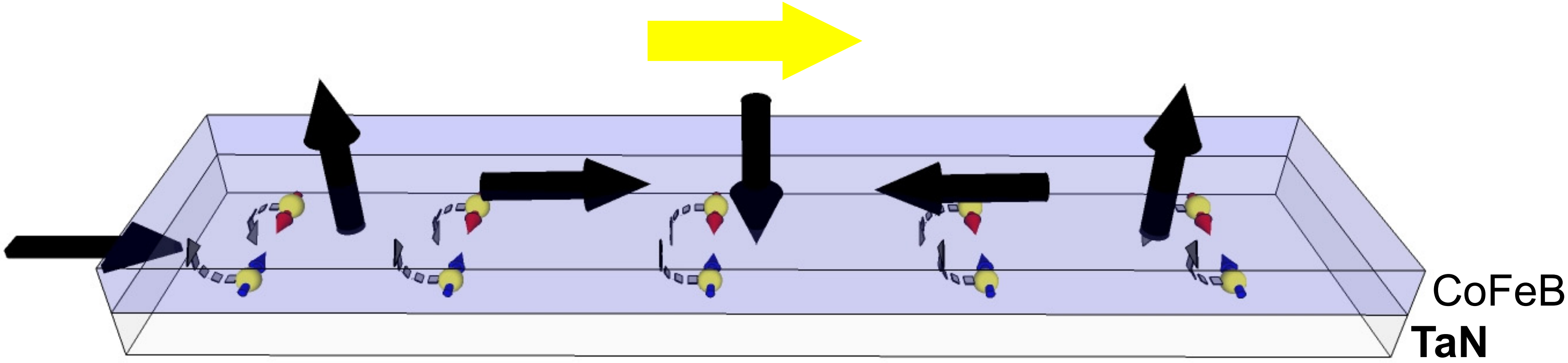
- Chirality set by the underlayer!

Domain wall moves **against** the current flow



Left handed walls

Domain wall moves **along** the current flow

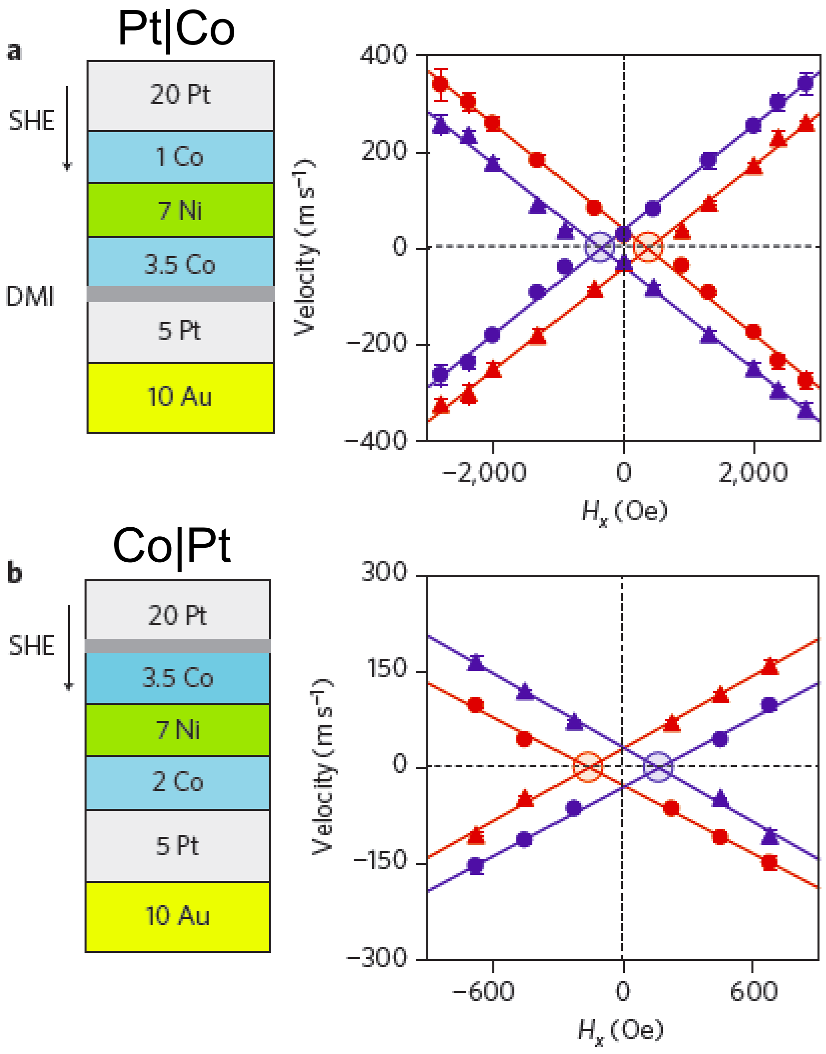


Right handed walls

Same sign of the spin Hall effect → Bulk spin orbit coupling carries the same sign

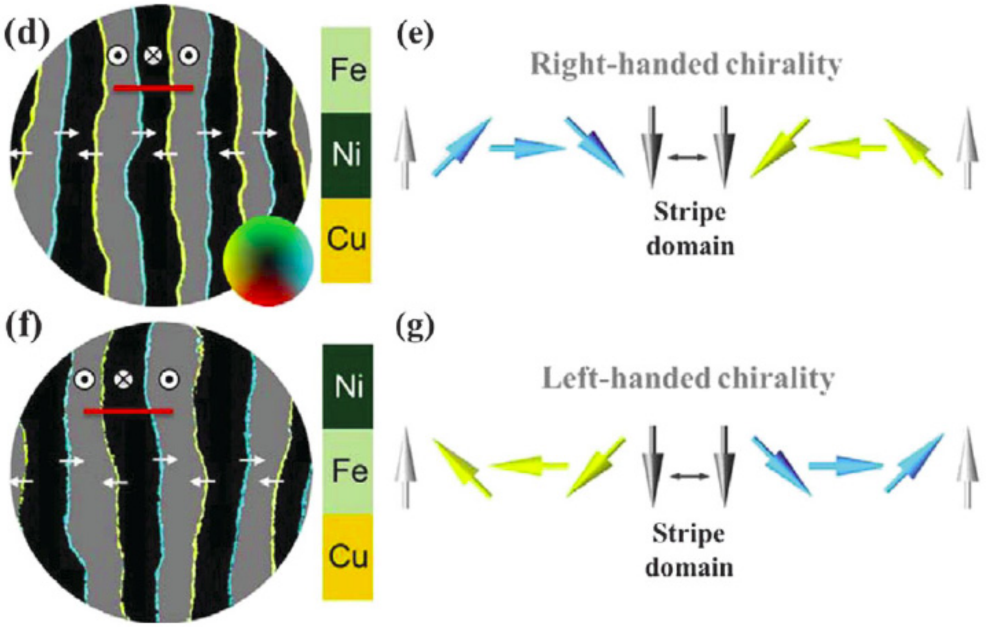
# Dzyaloshinskii-Moriya interaction at the interface

- Chirality depends on the order of interface

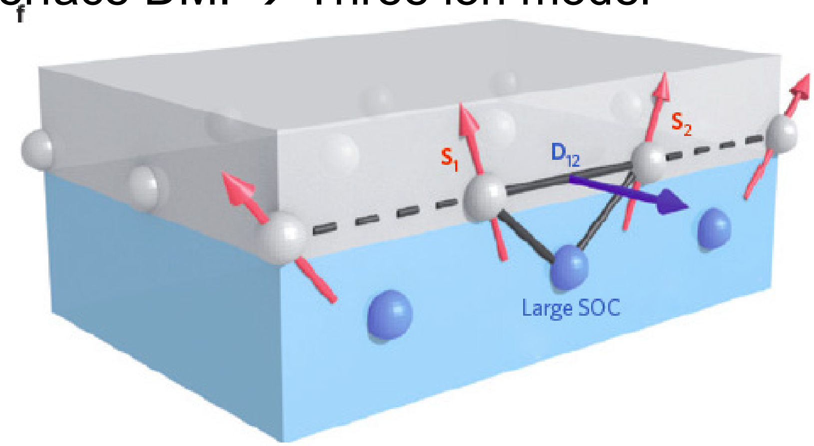


*Ryu et al., Nature Nanotech.* ***8****, 531 (2013)*

*Chen et al., PRL 110, 177204 (2013)*



- Interface DMI → Three ion model

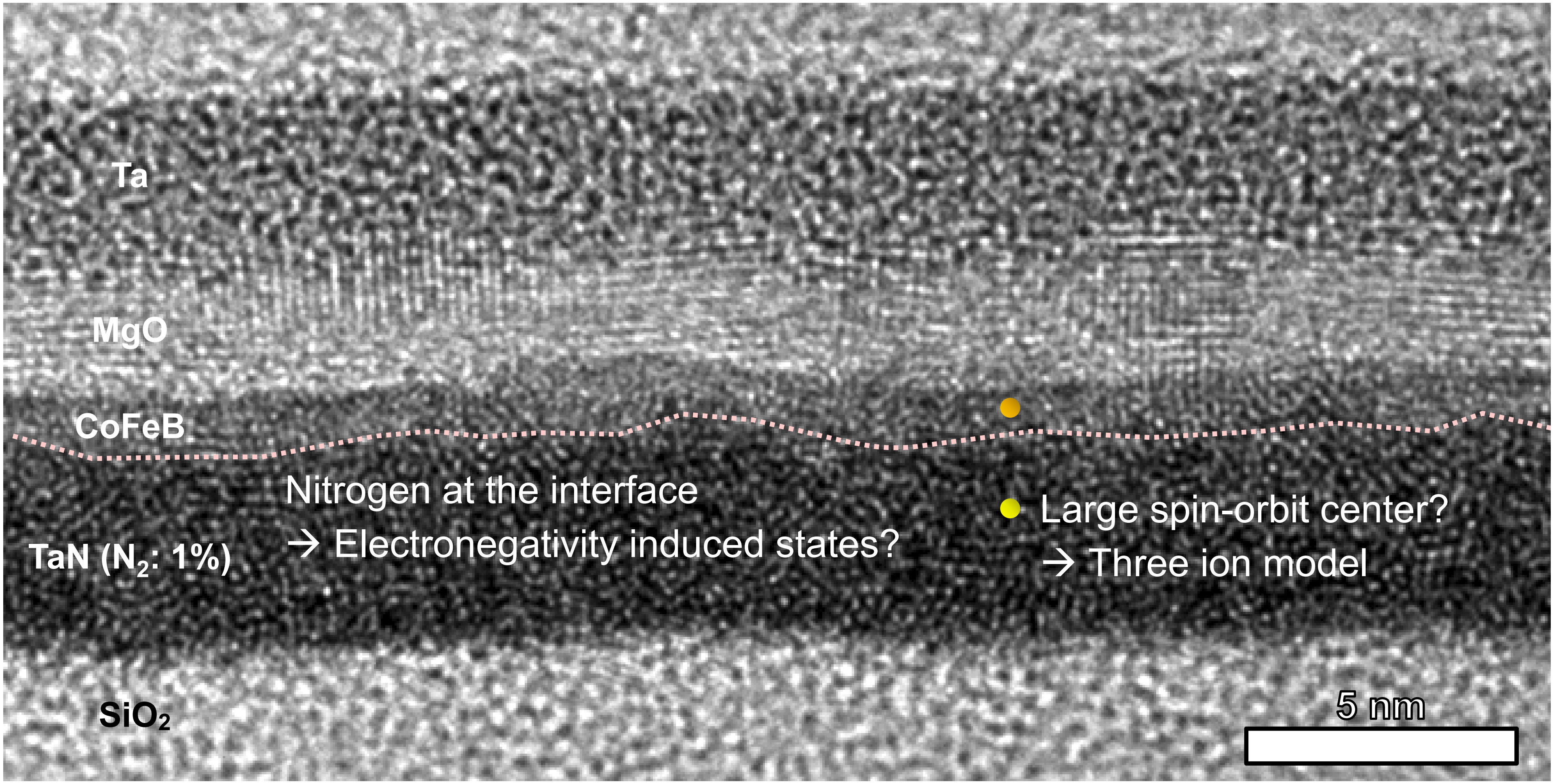


*Fert et al., Nature Nanotech.* ***8****, 152 (2013)*

# Origin of interface DMI

- Cross section transmission electron microscopy image

4 TaN ($N_2$: 1%) | 1.2 CoFeB | 2 MgO | 1 Ta
After annealing (300 °C)



Nitrogen at the interface
→ Electronegativity induced states?

● Large spin-orbit center?
→ Three ion model

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# Summary

- Current induced effective fields in magnetic heterostructures
  - Transverse effective field (field-like torque)
    - Causes current induced random nucleation
  - Longitudinal effective field (Slonczewski torque)
    - Spin torque switching of nano-magnet
    - Drives Neel walls
- Current driven domain wall motion in magnetic heterostructures
  - Domain wall moves in opposite direction for Ta and TaN underlayers
    - Sign of the spin Hall angle is the same
    - Magnetic chirality is different → interface DMI changes