Efficient switching of magnetization using spin-orbit torque

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NanoSpintronics Lab

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1. Introduction : Spin-orbit torque (SOT)

2. Material engineering for SOT enhancement

3. Field-free SOT switching

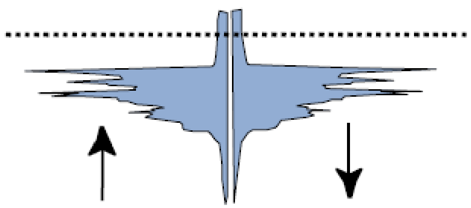
4. SOT-based spintronic devices

5. Summary

Spintronics

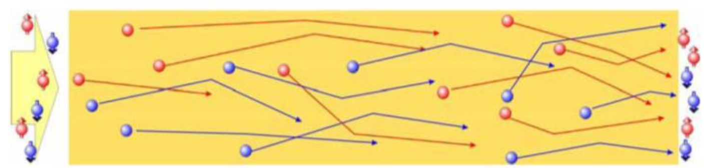
Utilization of the intrinsic **spin** of the electron,
in addition to its fundamental electronic **charge**, **in solid-state devices**

Non-magnet **Cu (29) 3d** ^{10}

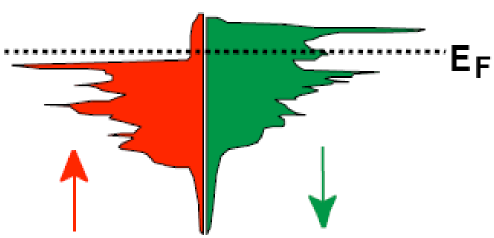


Cu: $P = 0$

$\rho_\uparrow = \rho_\downarrow$

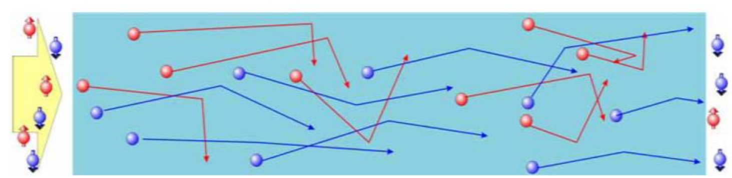


Ferromagnet **Co (27) 3d** ^{7}



Co: $P < 0$

$\rho_\uparrow \neq \rho_\downarrow$

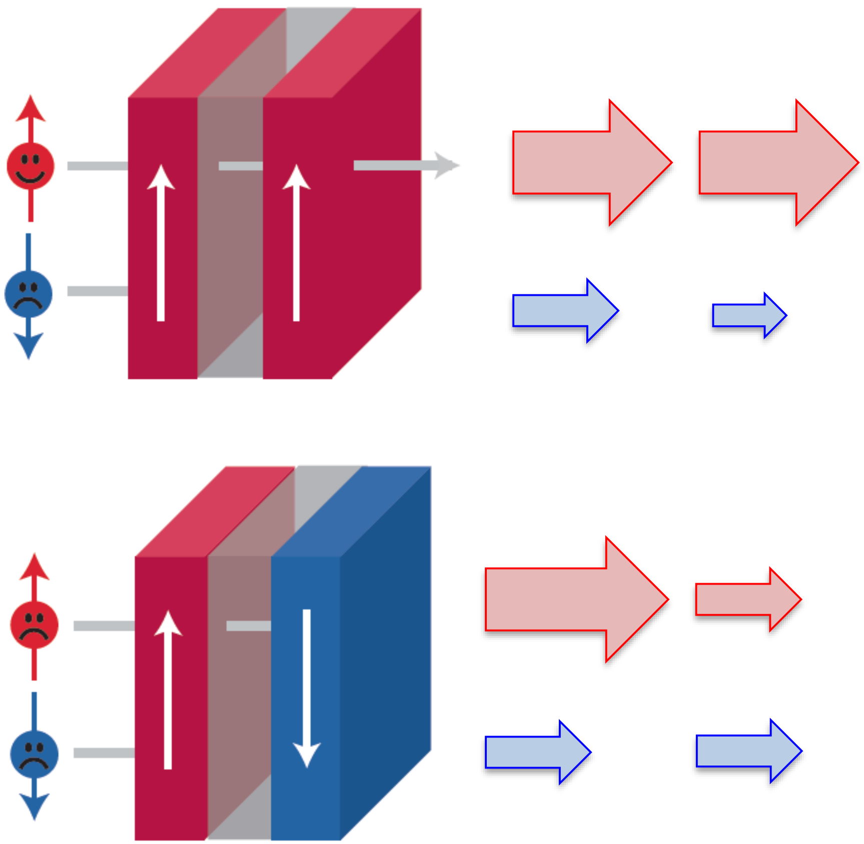


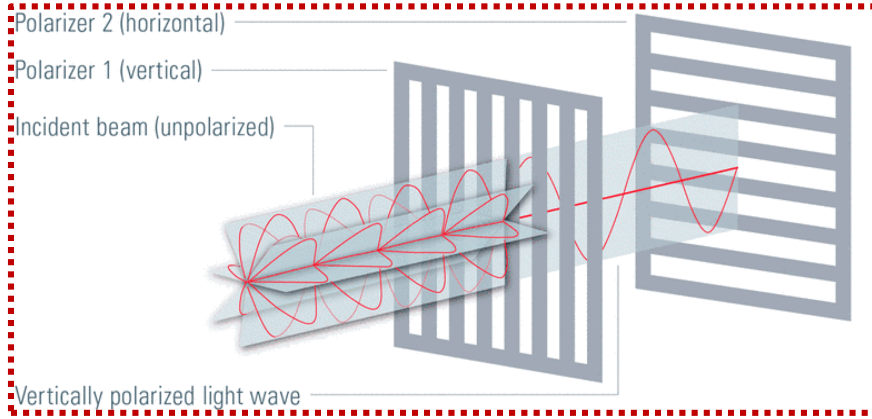
Spin dependent scattering

FM acts as spin filter

Can we change R in FM?

Giant (tunneling) magnetoresistance

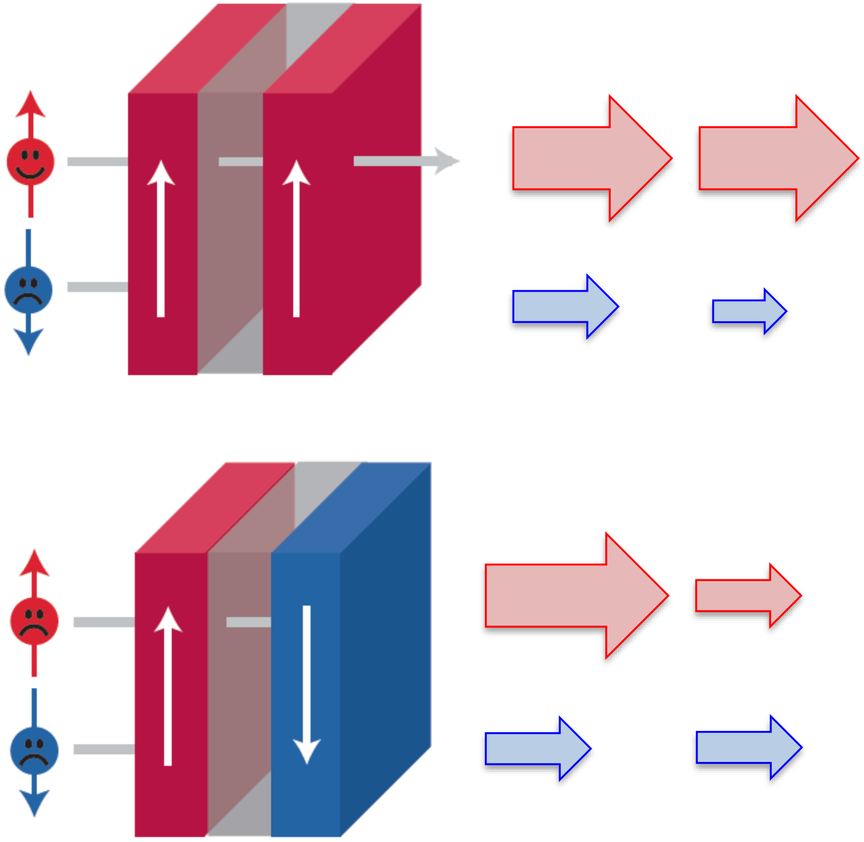


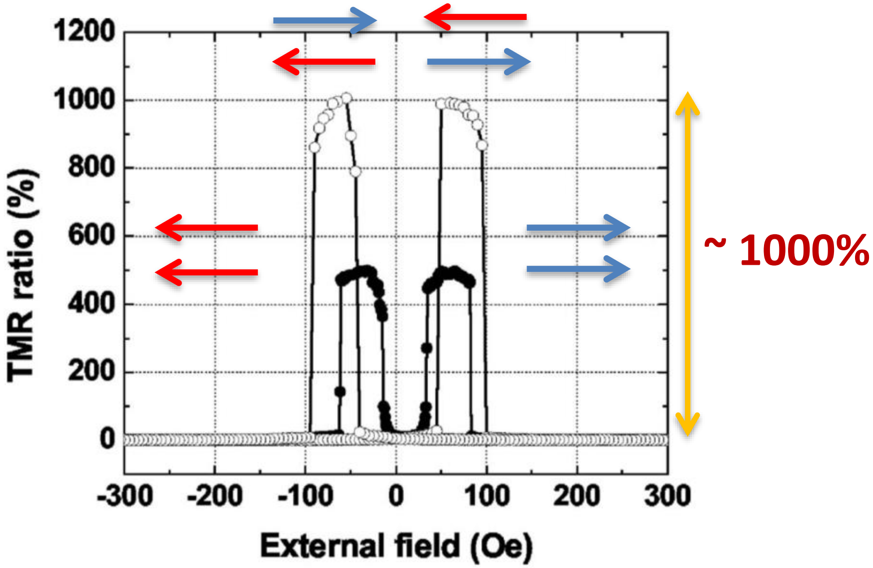


Control R by rearrangement of magnetization direction

Can we change R in FM?

Giant (tunneling) magnetoresistance



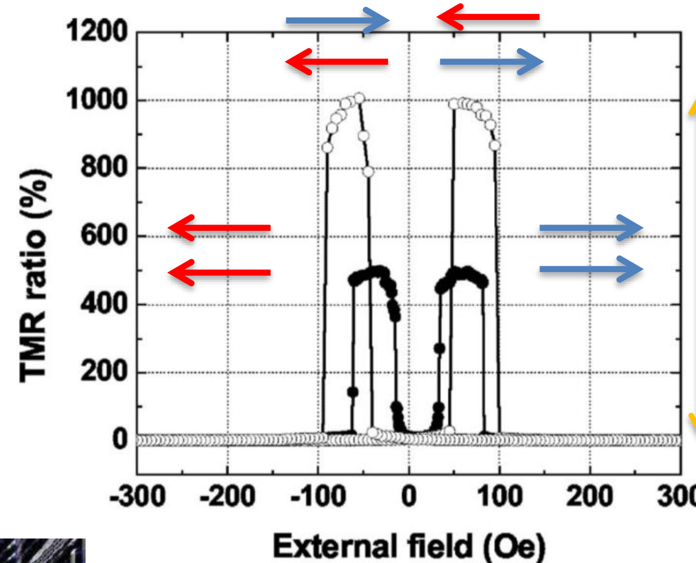


Control R by rearrangement of magnetization direction

Application of the Spintronics

HDD read heads

> 50% of data Stored in HDD



Data center

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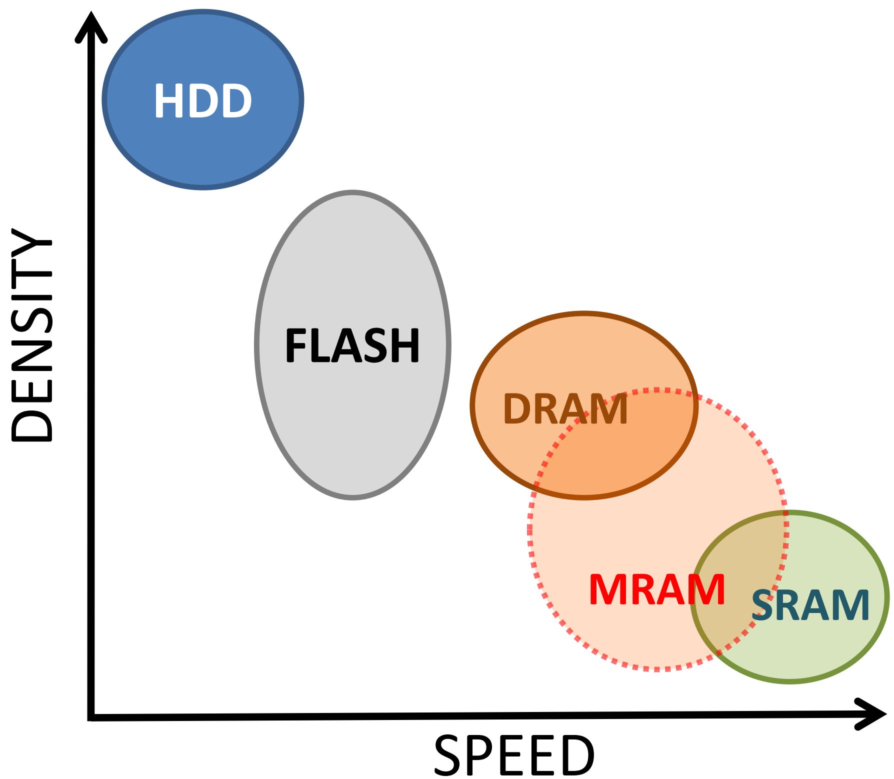
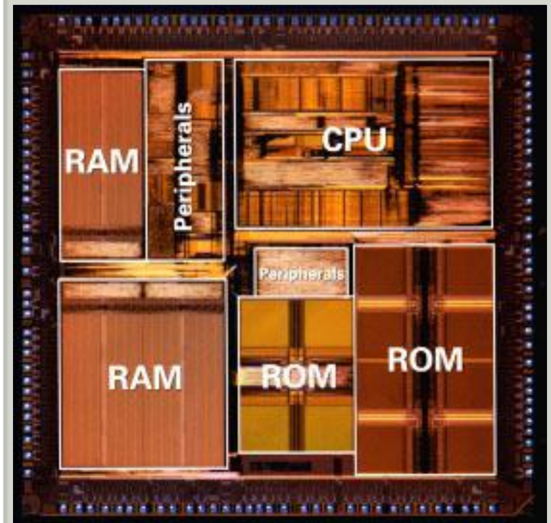
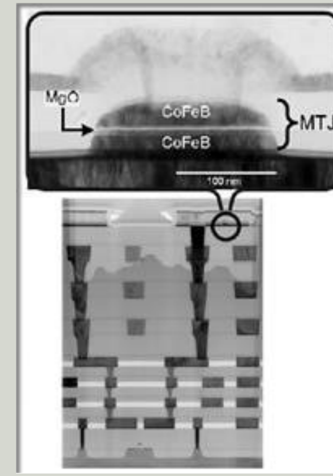
Magnetic memory

MRAM
- Non-volatile
- Endurance
- High speed



Embedded MRAM





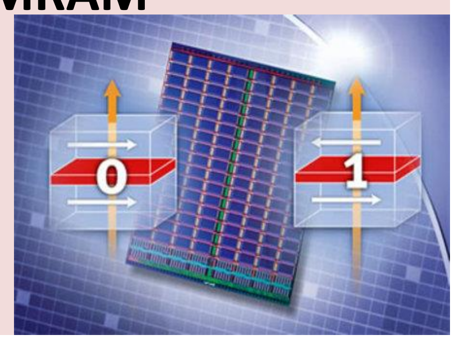
(Fujitsu and University of Toronto 2009)

non-volatile CMOS : instant-on

Low power & High density

Stand alone memory

STT-MRAM



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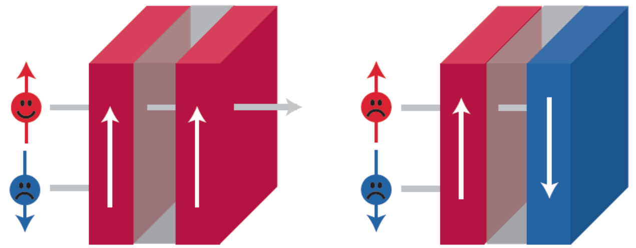
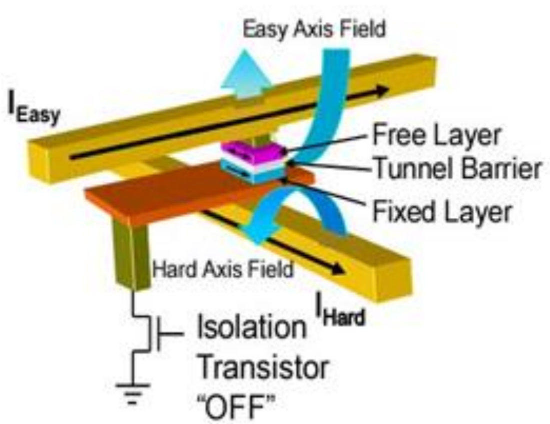
Operation of spintronic devices



$$R_P < R_{AP}$$

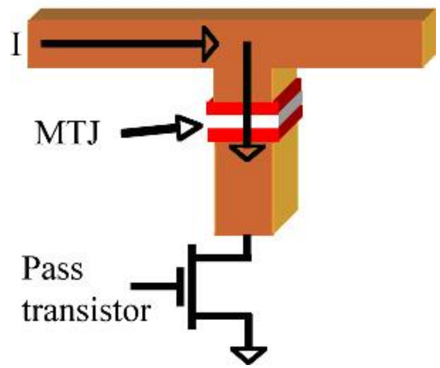
Operation speed & capacity
: How to switch magnetization direction

1. Magnetic field

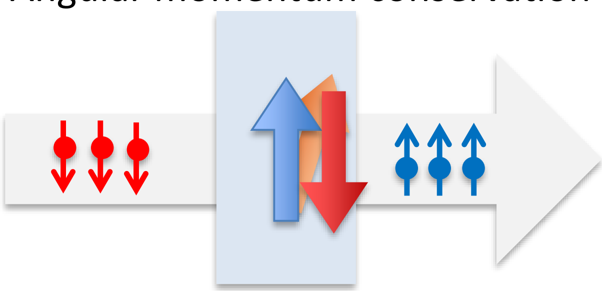


Low capacity

2. Spin-transfer torque (STT)

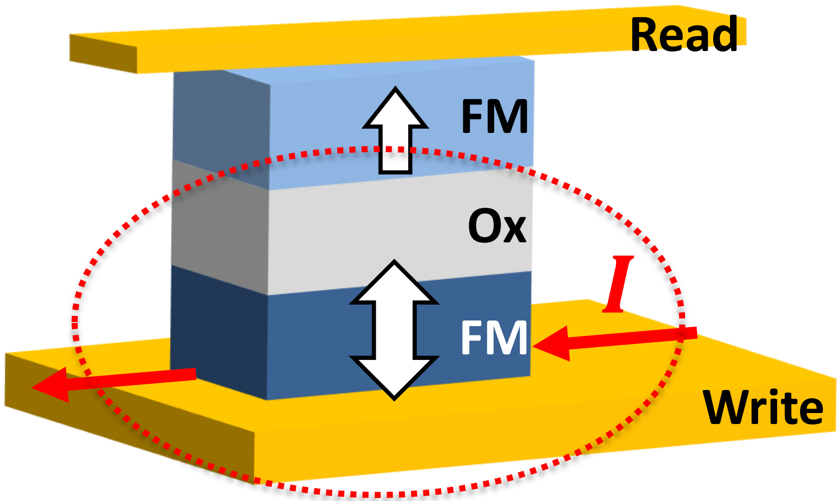


Angular momentum conservation



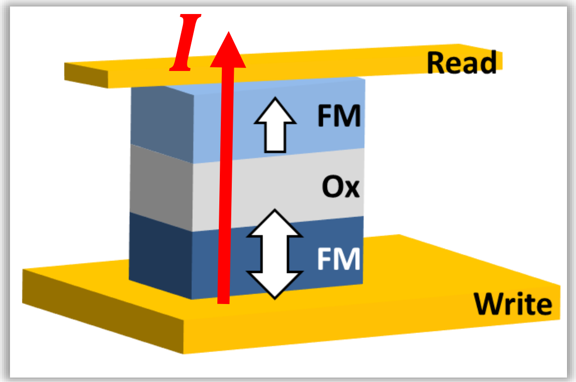
Spin orbit torques

Alternative method of electric manipulation of magnetization



- based on spin-orbit coupling
- by **in-plane** current

VS



Conventional spin-transfer torque

Advantages

- Reliability
- High speed
- Combined with voltage control
- Simultaneous switching

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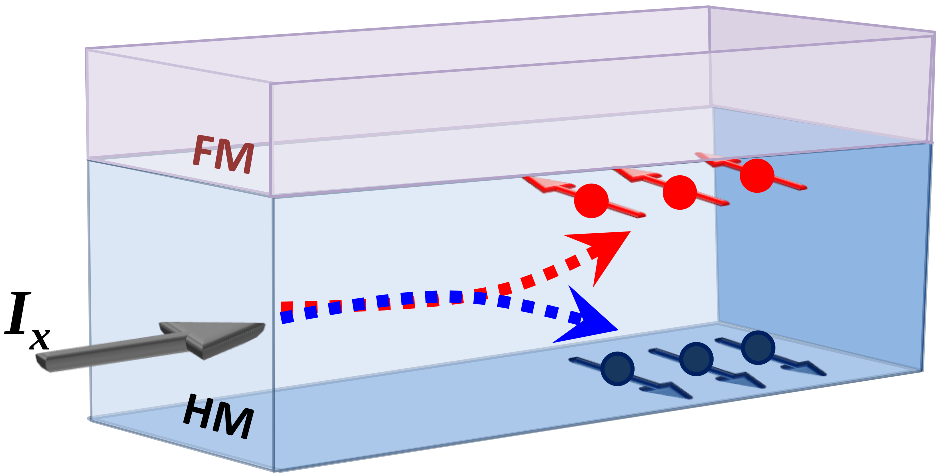
Spin orbit torques

: Spin torque generated by spin-orbit coupling

❖ Manipulation of magnetization by in-plane current

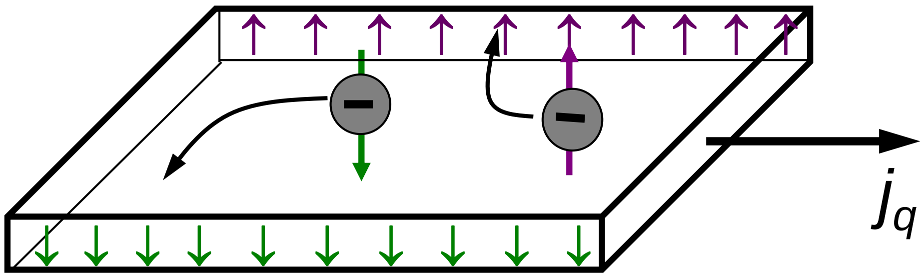
Oxide (MgO)
FM (CoFeB, Co)
HM (Pt, Ta, W)

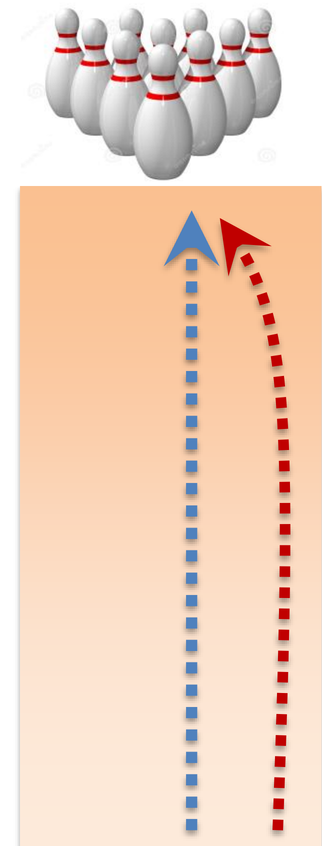


Spin Hall effect (in-plane current) induces spin accumulation at HM/FM interface

Spin Hall effects

Electron motion is affected by electrons spin direction





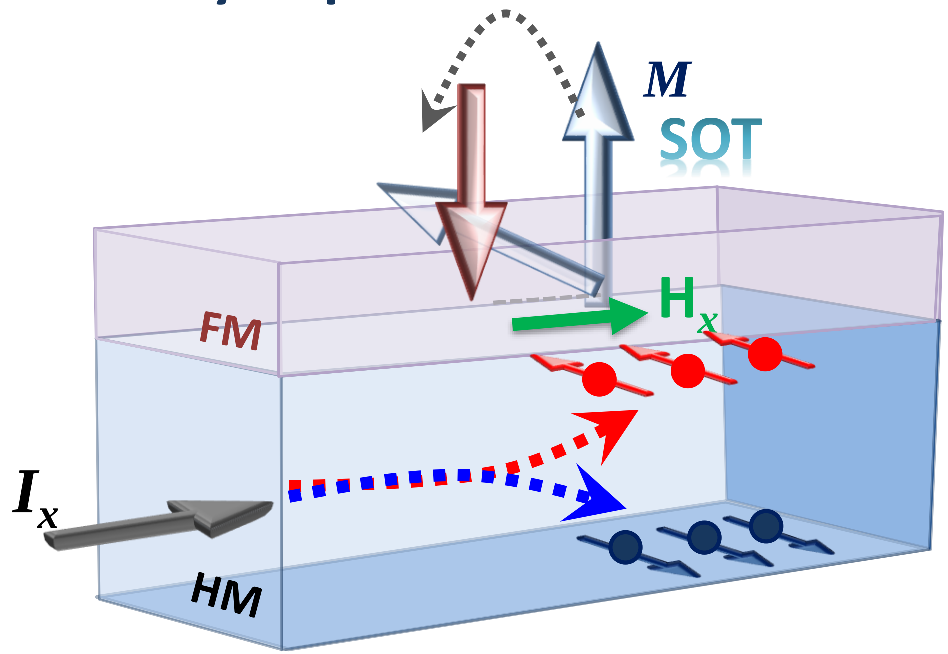
Spin Hall effect
→ spin accumulation at the edge

Spin orbit torques

: Spin torque generated by spin-orbit coupling

❖ **Manipulation of magnetization by in-plane current**

Oxide (MgO)
FM (CoFeB, Co)
HM (Pt, Ta, W)

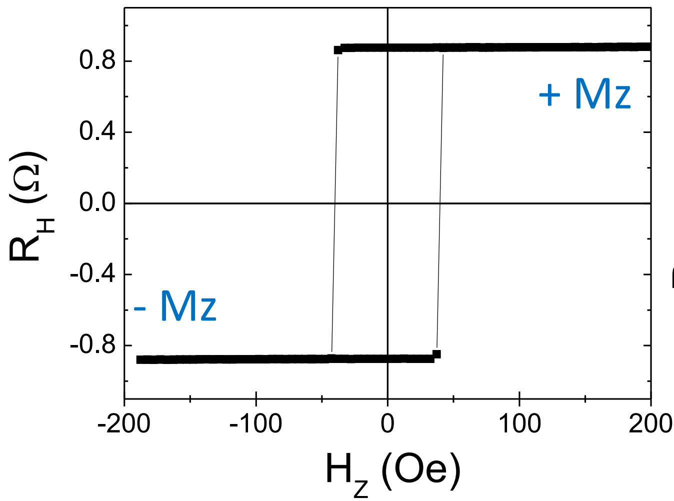


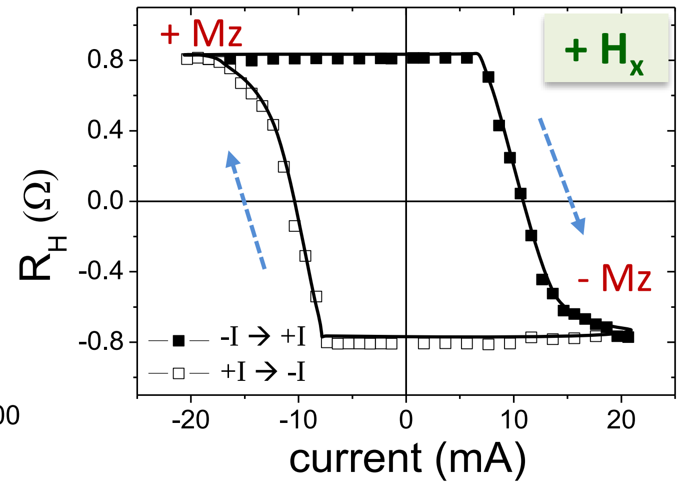
Spin Hall effect (in-plane current)
induces spin accumulation at HM/FM interface
→ Torques to FM

For switching, in-plane magnetic field is required

SOT-induced M switching

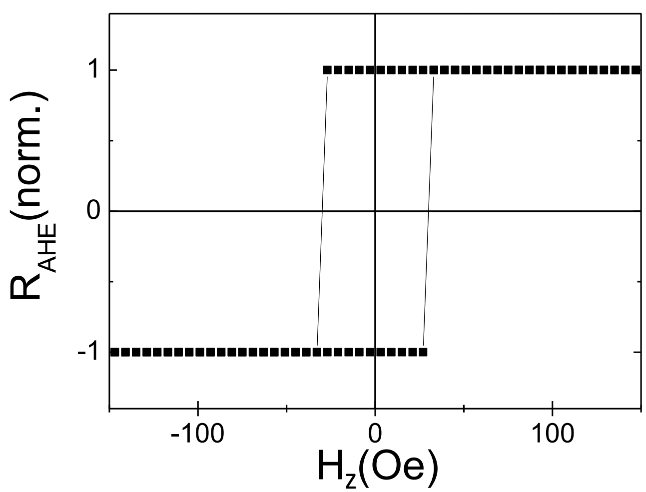
Pt/CoFeB/MgO

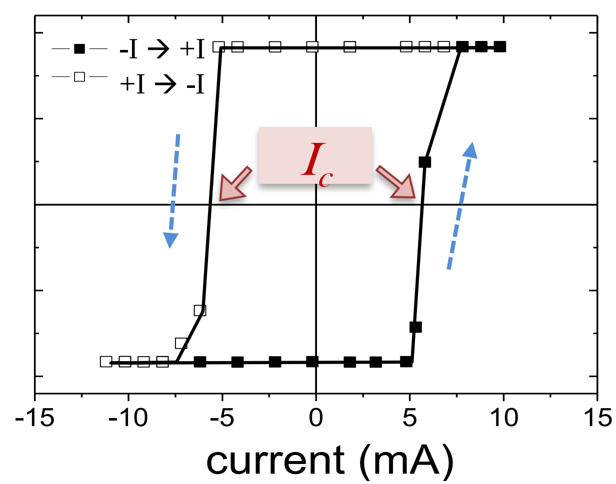




+ I favors - M_z
→ (+) Spin Hall angle

W/CoFeB/MgO





+ I favors + M_z
→ (-) Spin Hall angle

Spin Hall angle : switching polarity & I_c

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Spin orbit torques

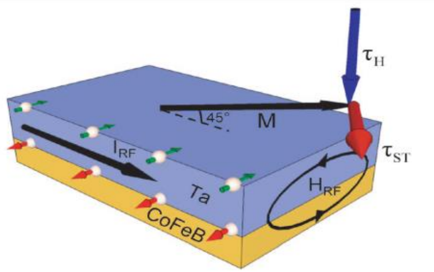
- Critical current density for SOT switching

$$J_{SOT} = \frac{2e}{\hbar}\frac{M_S V t_F}{\theta_{SH}}\left(\frac{H_{K,eff}}{2} - \frac{H_x}{\sqrt{2}}\right) \rightarrow \text{Increase } \boldsymbol{\theta_{SH,eff}}$$

[Lee, et al., APL (2013)]

Bulk Spin Hall effect

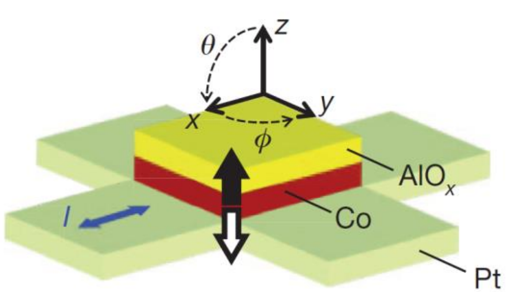
- from bulk heavy metal (Ta, Pt, W)
- **spin Hall angle (θ_{SH})**



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

Interface spin-orbit coupling

- from HM/FM interface inversion asymmetry
- **HM/FM combination**



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

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Spin-Hall angle

$$\vec{J_s} = \theta_{SH}\left(-\frac{\hbar}{2e}\right)\vec{J_C} \times \vec{\sigma} \qquad \vec{J_s}: spin\ currnet, \qquad \vec{J_C}: charge\ current$$

- **Pt: 0.07~0.1** [Liu, et al., PRL (2012), Wang, et al, APL(2014), Wang, et al, PRL(2014)]
- **Ta: -0.15** [Liu, et al., Science (2012)]
- **W: -0.30** [Pai, et al., APL (2012)]

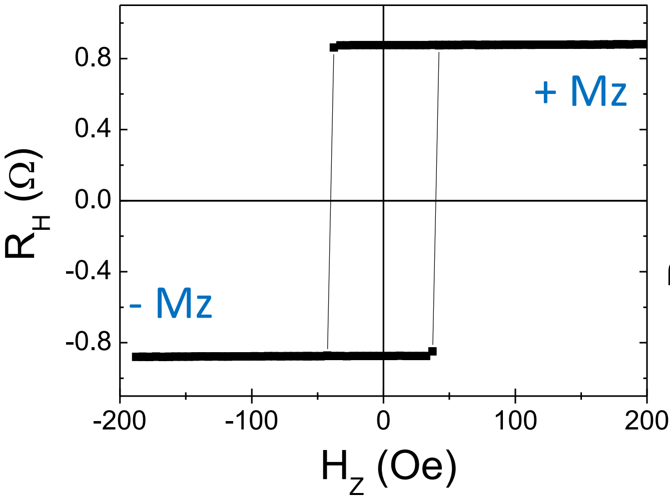
$\rho_{\beta\text{-W}} > \rho_{\beta\text{-Ta}} > \rho_{\text{Pt}}$

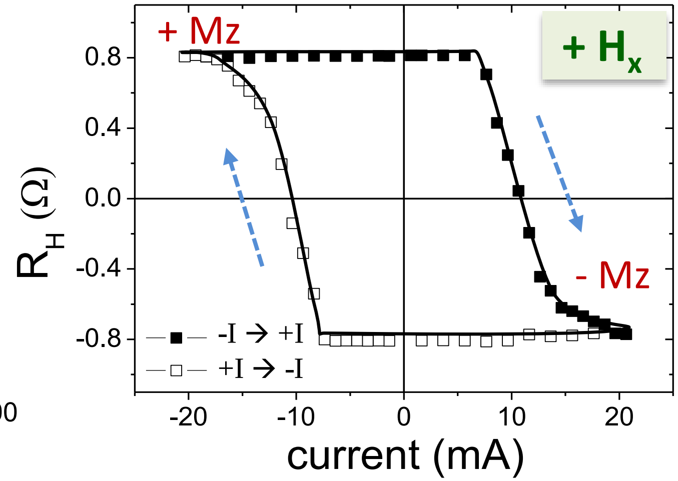
- Intrinsic Spin Hall effect : $\theta_{SH} \sim \rho$
- Interface spin Hall effect in FM/HM [Wang, et al., PRL (2016)]

Spin Hall effect in FM/HM bilayers vs resistivity of HM?

SOT-induced M switching

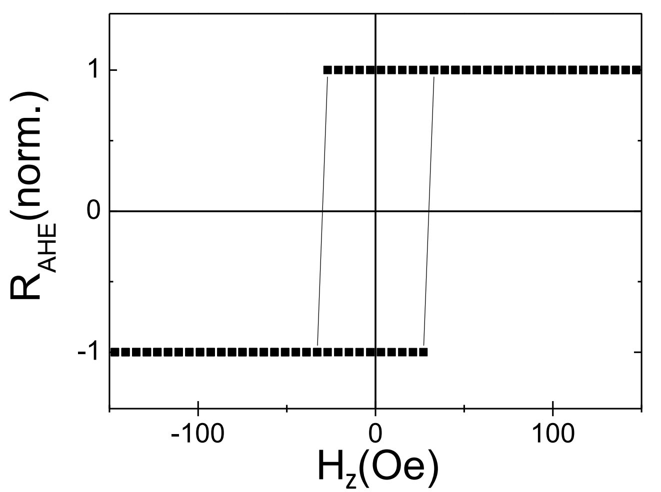
Pt/CoFeB/MgO

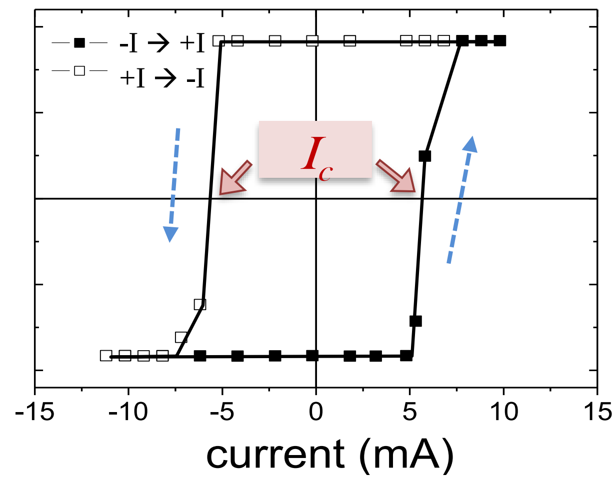




+ I favors - M_z
→ (+) Spin Hall angle

W/CoFeB/MgO





+ I favors + M_z
→ (-) Spin Hall angle

Spin Hall angle : switching polarity & I_c

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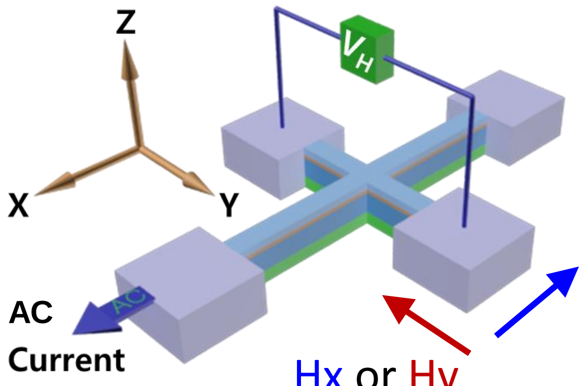
SOT measurement ($H_{eff, SOT}$)

- Harmonic AHE



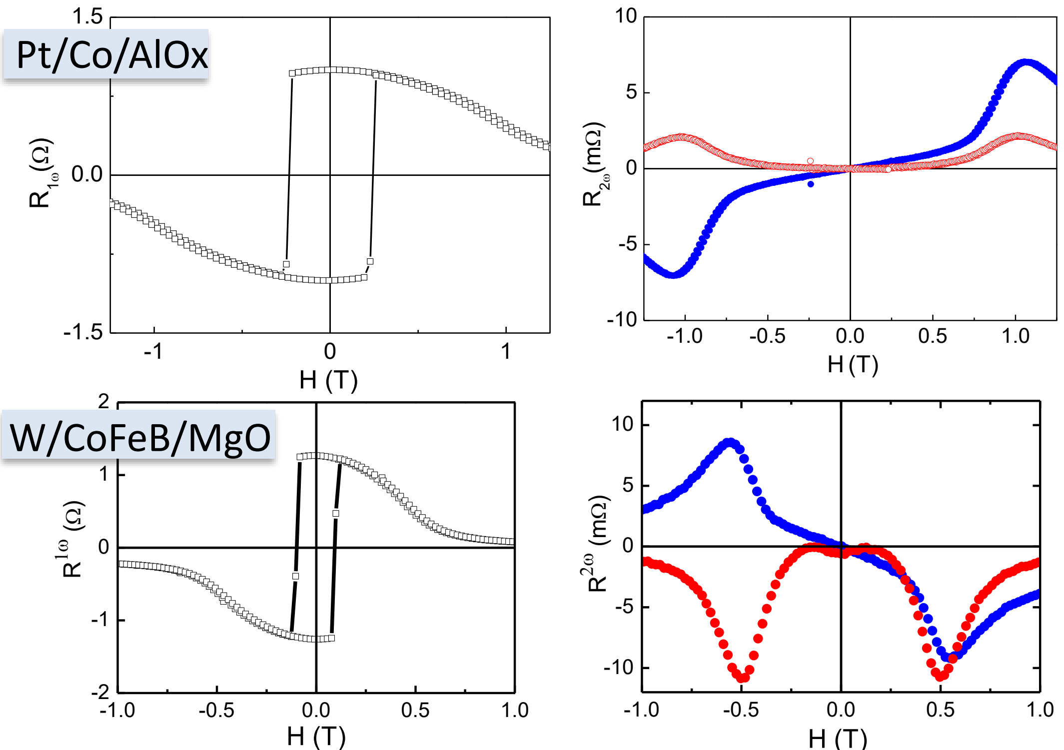
$$V_{Hall} = V_{dc} + V_{1\omega} sin\omega t + V_{2\omega} cos2\omega t$$

1st harmonic signal $\propto M_z$

2nd harmonic signal $\propto H_{eff, SOT}$

$$H_{DL(FL)} \sim -2\, V_{2\omega} / \frac{\partial V_{1\omega}}{\partial H_{x(y)}}$$

[Pi, et. al., APL (2012)]



$H = H_x$
Damping like torque (DLT)

$H = H_y$
Field like torque (FLT)

Sign & magnitude of $H_{eff, SOT}$

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1. Introduction : Spin-orbit torque (SOT)

2. Material engineering for SOT enhancement

- Engineering Pt resistivity
- Ti interfacial layer in Pt/CoFeB structure

3. F

4. SOT-based spintronic devices

5. Summary

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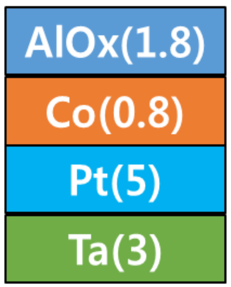
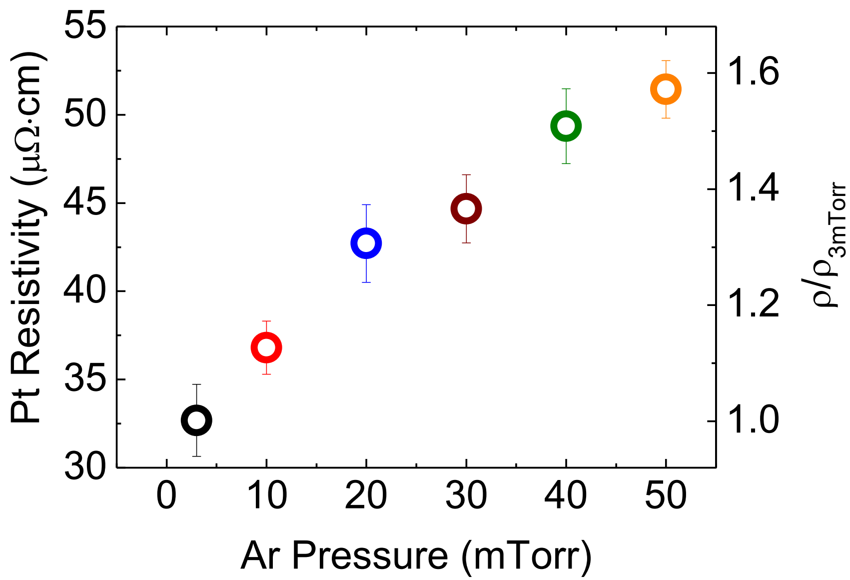
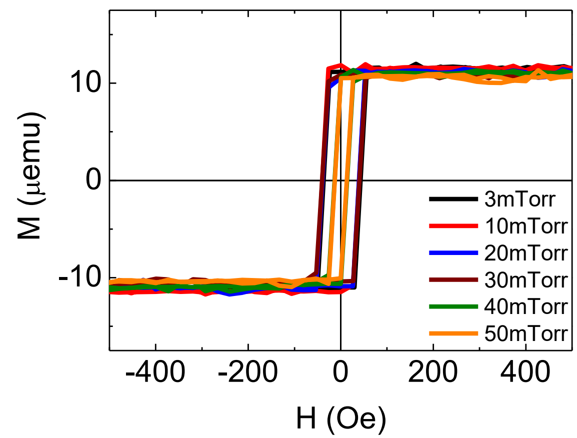
Engineering Pt resistivity

Spin Hall effect(angle) in FM/HM bilayers vs resistivity of HM?

Resistivity control using different sputtering pressure (3~50mtorr)



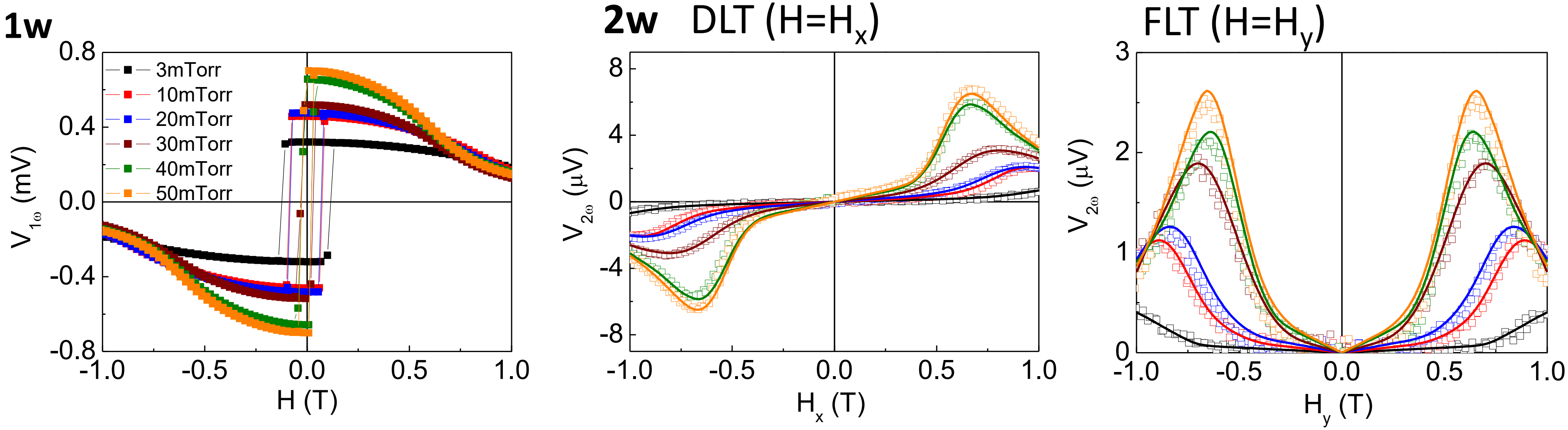




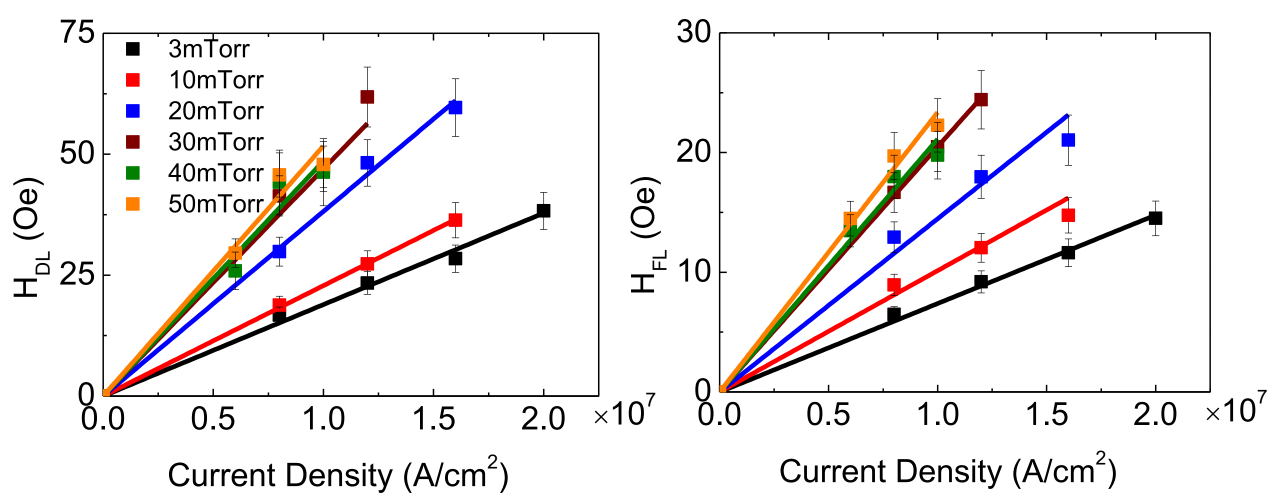
- Resistivity increases by a fact of 1.6 times with variation of Ar pressure 3~50 mtorr

SOT-induced effective fields

Ta/Pt/Co/AlOx



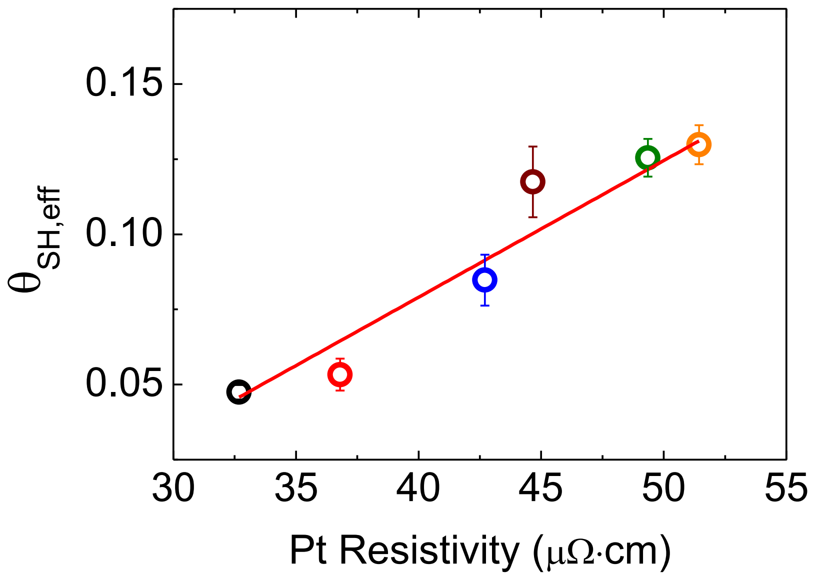
Enhancement of H_{DL}, H_{FL} by increasing ρ_{Pt}



Enhanced spin Hall angle and SOT-induced switching

$$\theta_{\mathrm{SH,eff}} = 2eM_s t_F H_{\mathrm{DL}}/\hbar\,|j_e|$$

[Khvalkovskiy, et al., PR B (2013)]

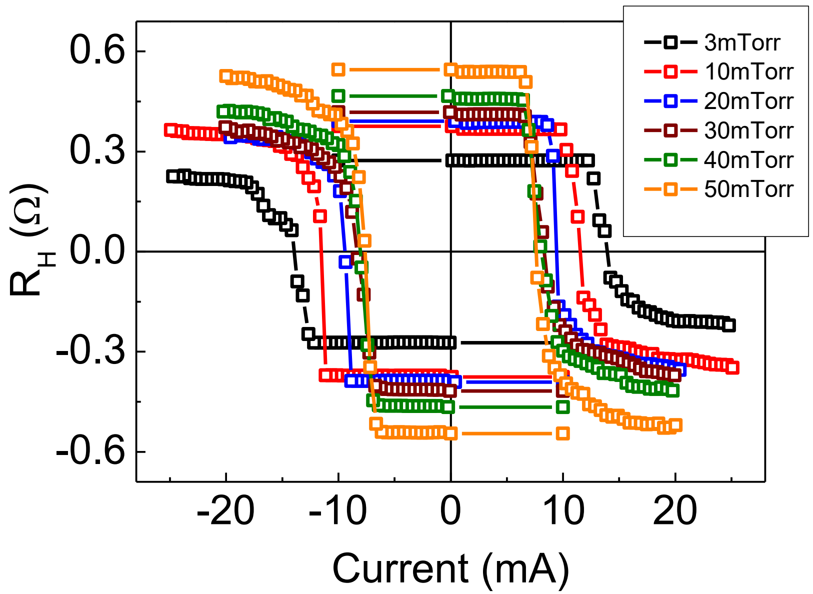


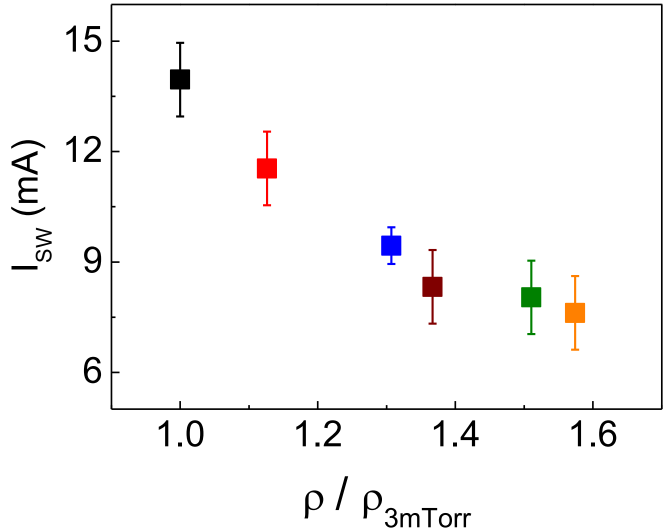
- Enhancement of $\theta_{\mathrm{SH,eff}}$ ~ 3 times
  → reduction of critical current

$\theta_{SH,\,Pt}$ ~ ρ_{Pt}

Interfacial Spin Hall effect ?

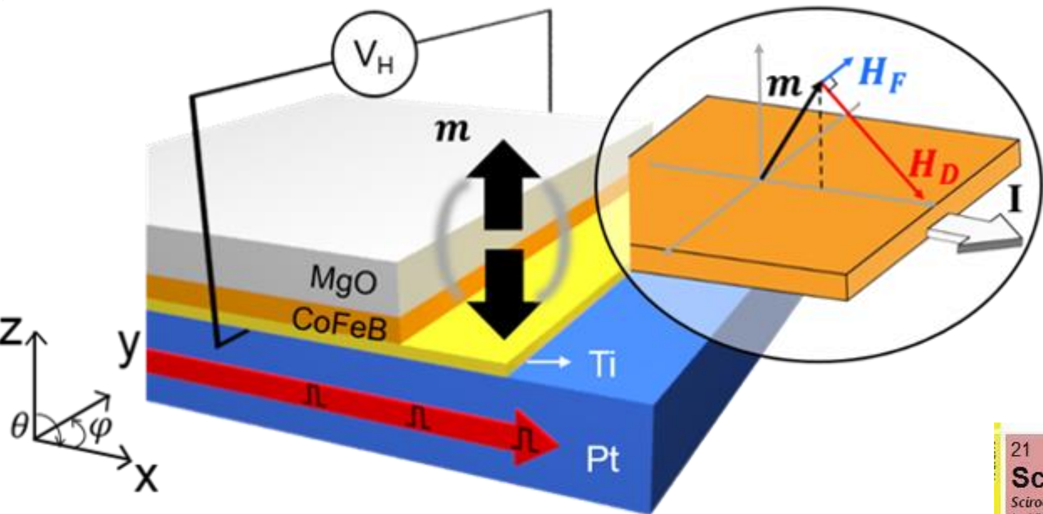
SOT-induced Switching

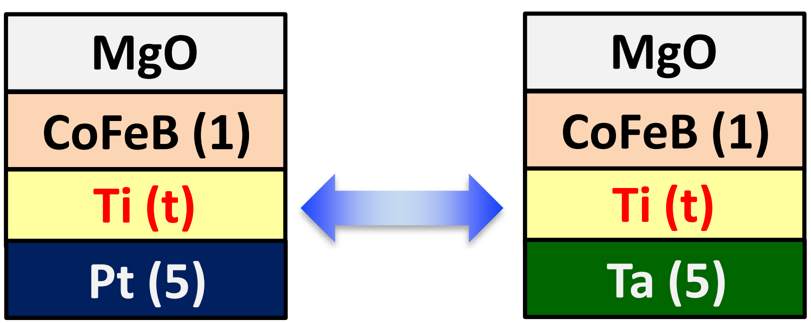




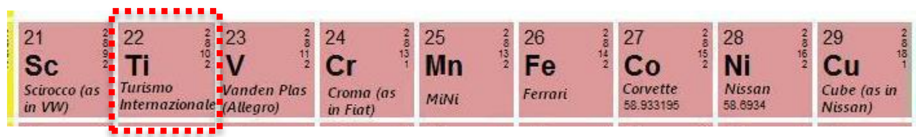
Interfacial engineering

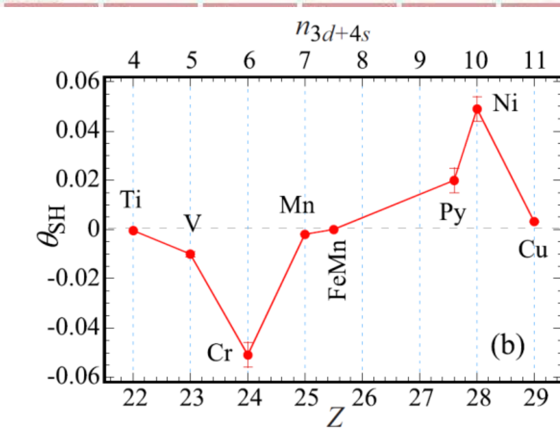
Modification of Pt/CoFeB interface by Ti layer (weak SOC)





Spin Hall angle (3d metal)





Du et al., *Phys. Rev. B* **90**, 140407 (2014)

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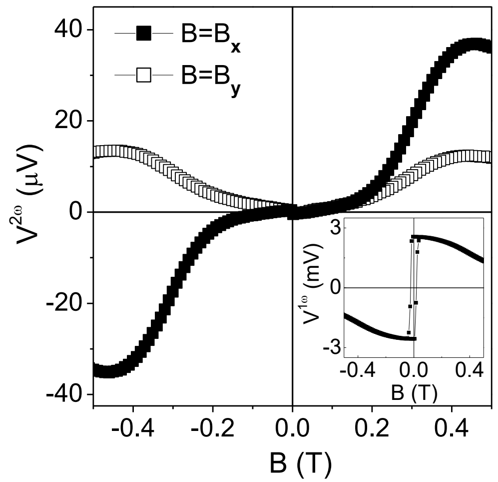
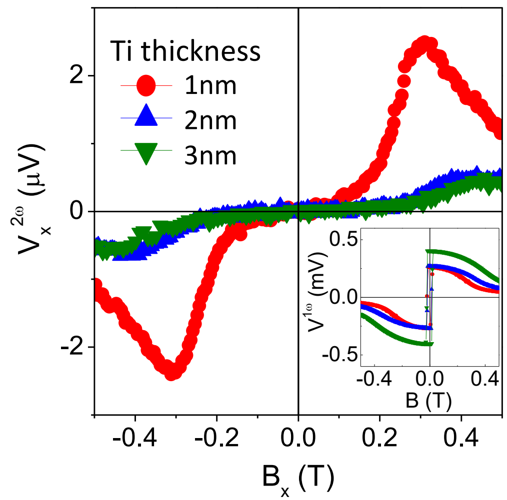
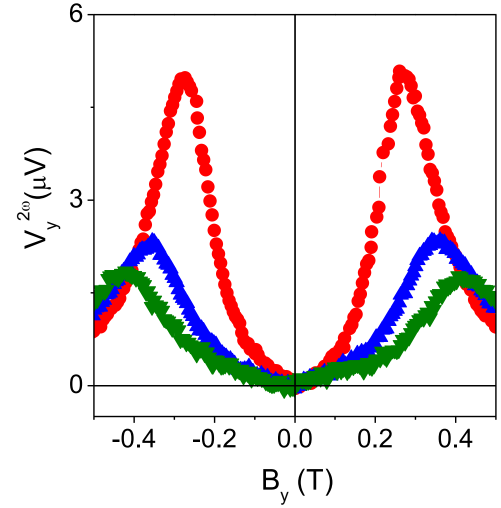
SOT-induced effective fields

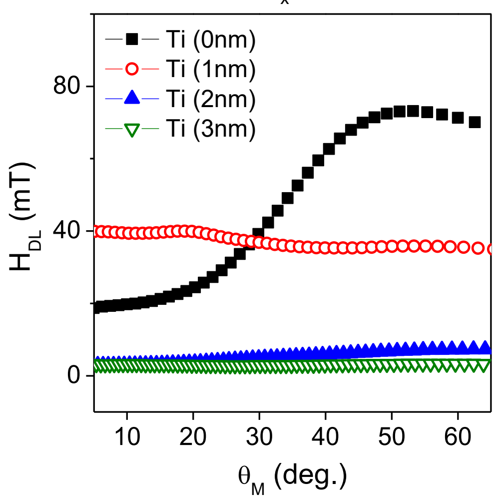
Pt(5nm)/Ti(x)/CoFeB (1nm)/MgO(1.6nm)

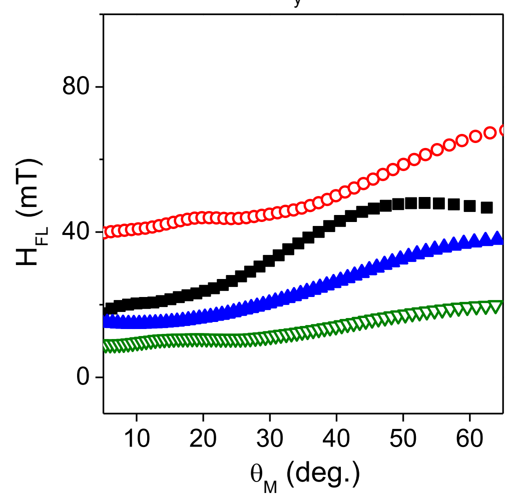






- DLT > FLT w/o Ti
- FLT > DLT w/ Ti





- Enhancement in $H_{DL,\ FL}$ by Ti (1nm)

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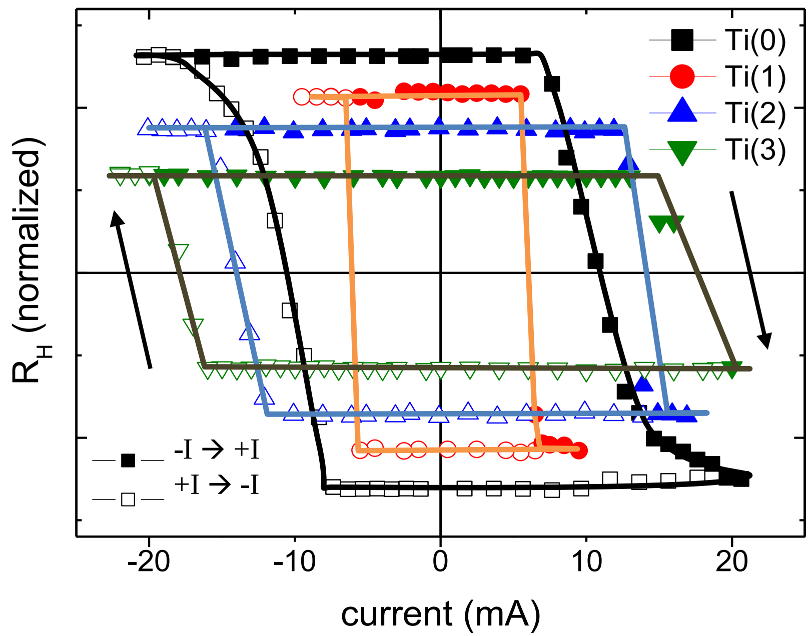
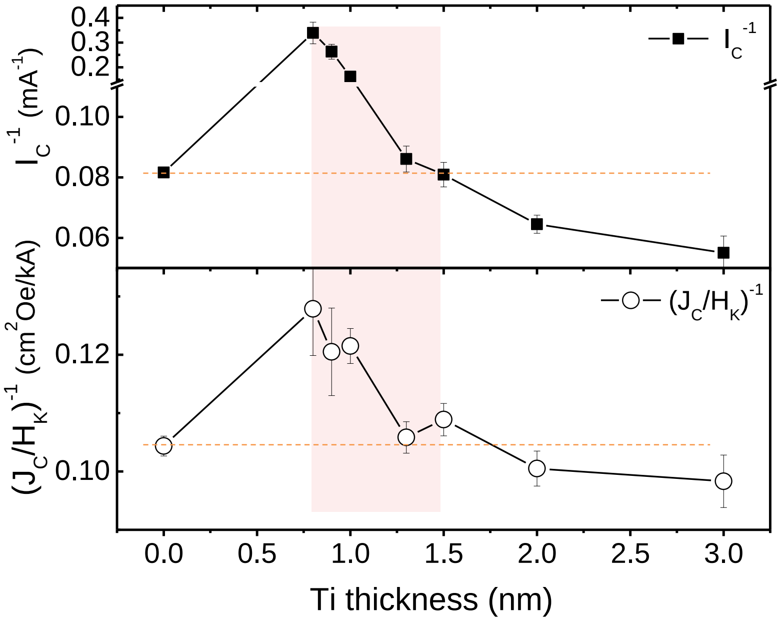
SOT-induced Switching

Magnetization vs in-plane current





I_C : switching current
$(J_C/H_K)^{-1}$ ~ magnitude of SOT

- **No change in switching polarity (Pt)**
- ***I_C is minimum* when Ti is ~1 nm**
- **I_C increases when Ti gets thicker**

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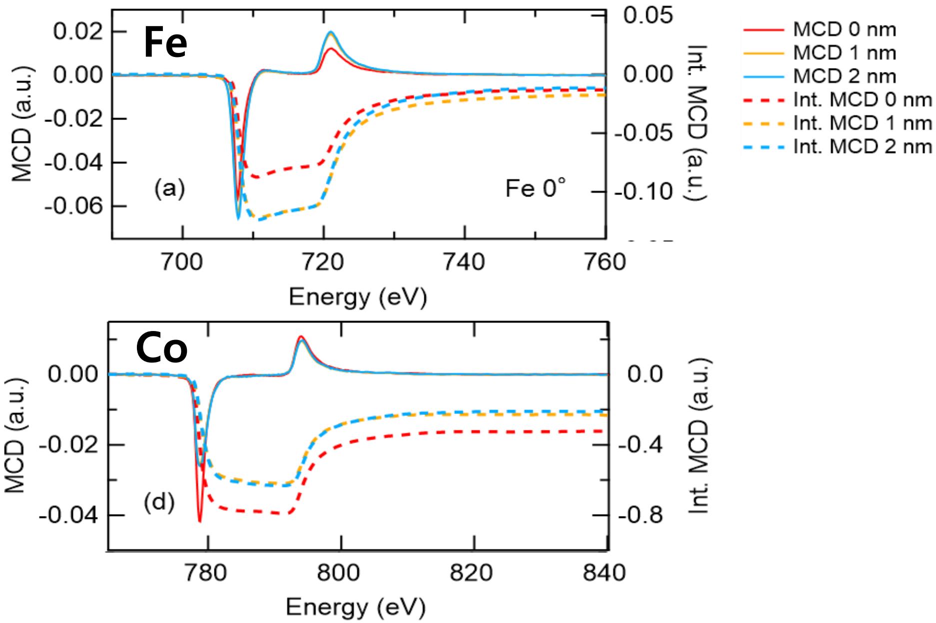
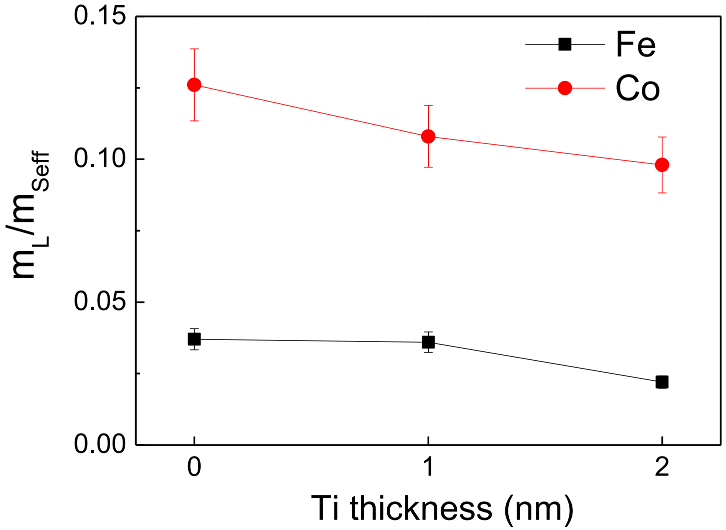
Interfacial spin-orbit coupling

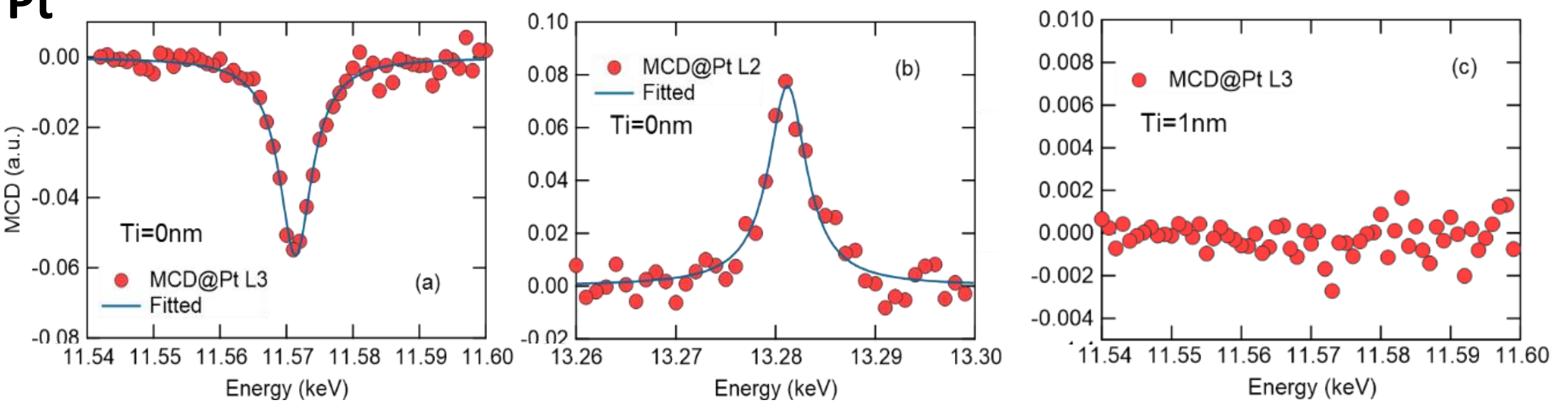
X-ray Magnetic Circular Dichroism (XMCD)





No significant interfacial SOC

Pt



- **Suppression of Pt proximity effect by Ti**

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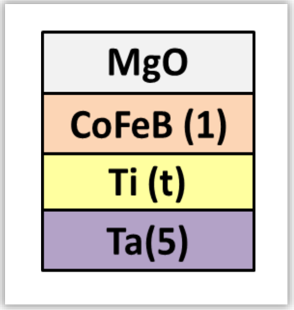
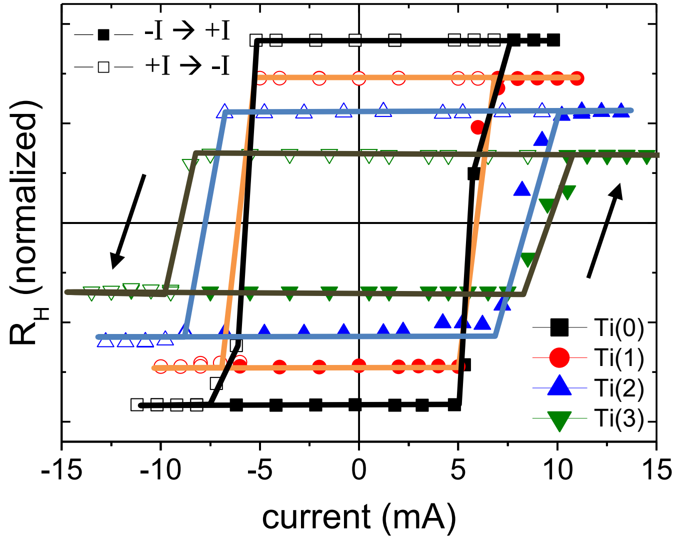
Comparison with Ta sample

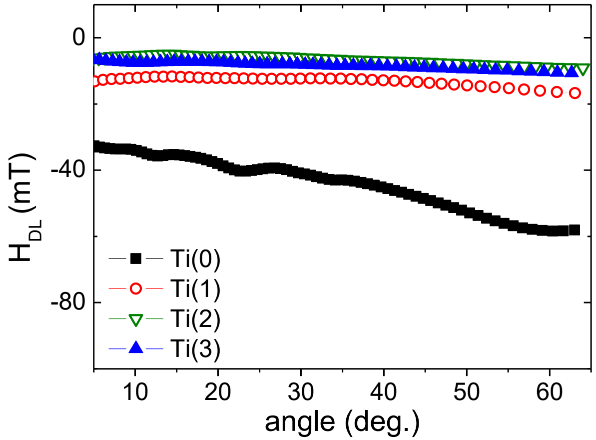
Switching performance

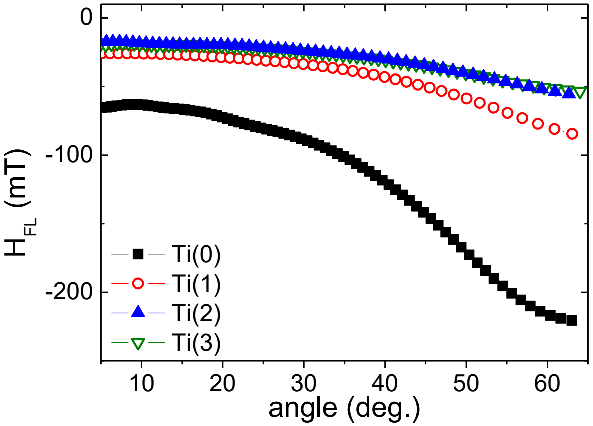




- switching sequence same as Ta
- **No Enhancement of efficiency**

Effective magnetic field of SOT





→ **No Enhancement of SOT**

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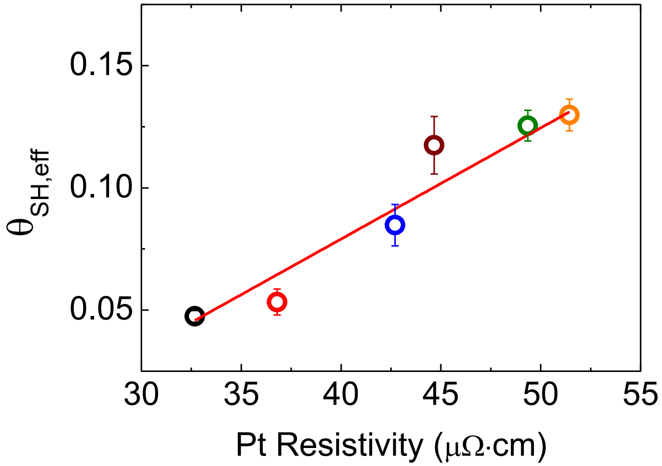
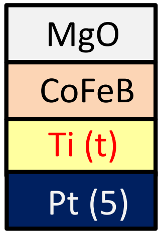
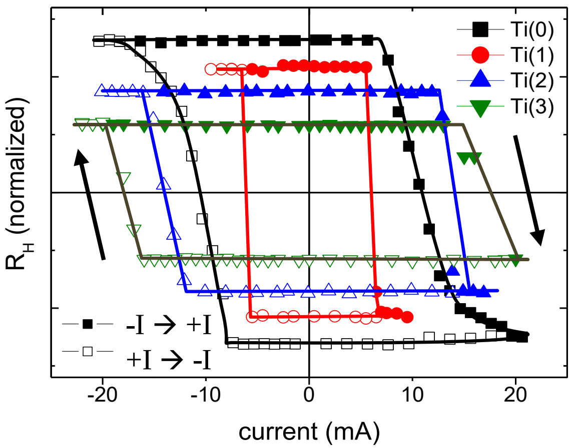
Summary I

- **Successful enhancement of SOT using materials engineering**







1. Spin Hall effect engineering

- **Linear increase in effective spin Hall angle with Pt resistivity**
- **Non-negligible interfacial Spin Hall effect**

2. Interface engineering

- **Increase of SOT and switching efficiency In Pt/Ti(~1nm)/CoFeB/MgO**
- **Reduction in Pt proximity effect**

Contents

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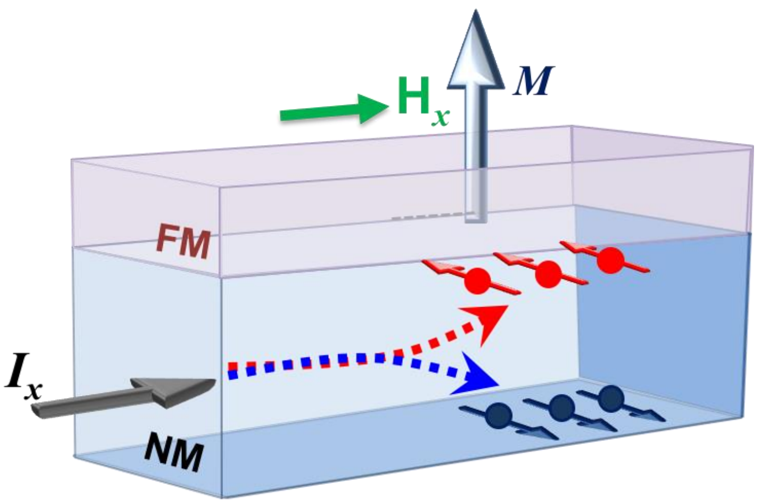
SOT with antiferromagnets

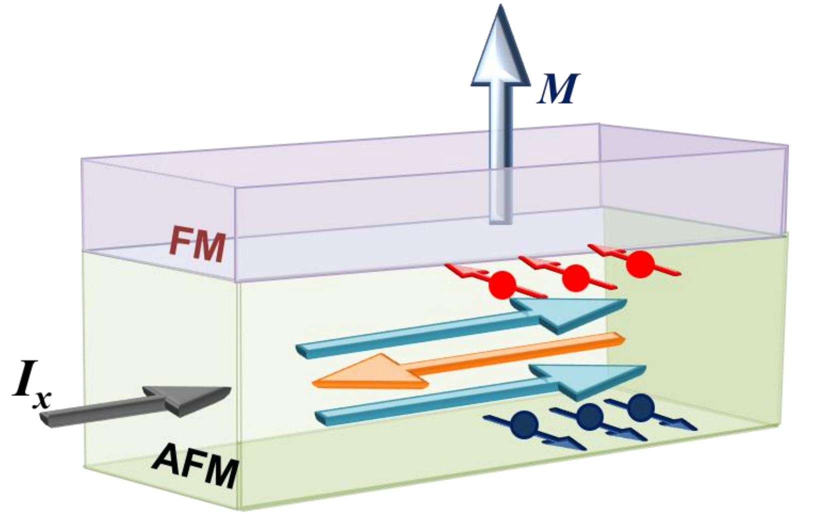
Replacement of HM with AFM

→ **Spin-orbit coupling + (in-plane) exchange field**

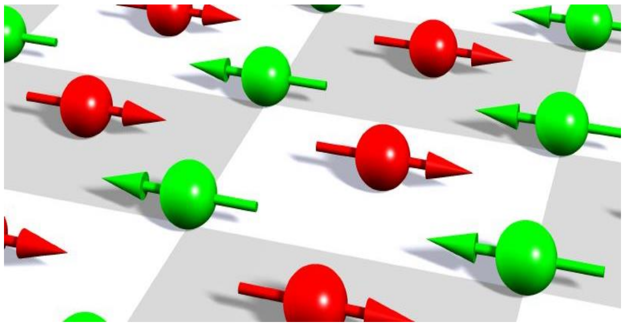
- **HM SOT structure**
  : in-plane H field

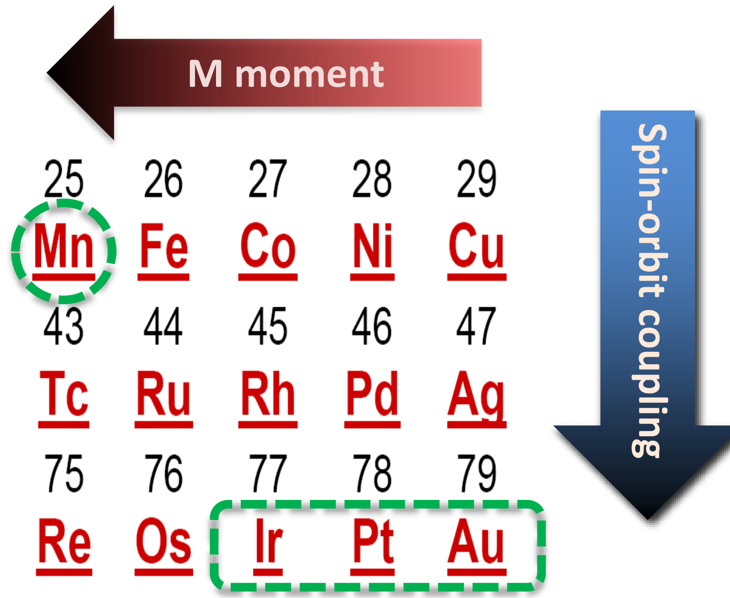
- **AFM SOT structure**
  : exchange biased effective H field
  (no external H field)





Antiferromagnets





- Alternating M (No net M)
- Majority of magnetic ordered materials
- **Exchange bias** in GMR/TMR

➔ effective magnetic field

: **in-plane H** for SOT

AuMn, PtMn, IrMn

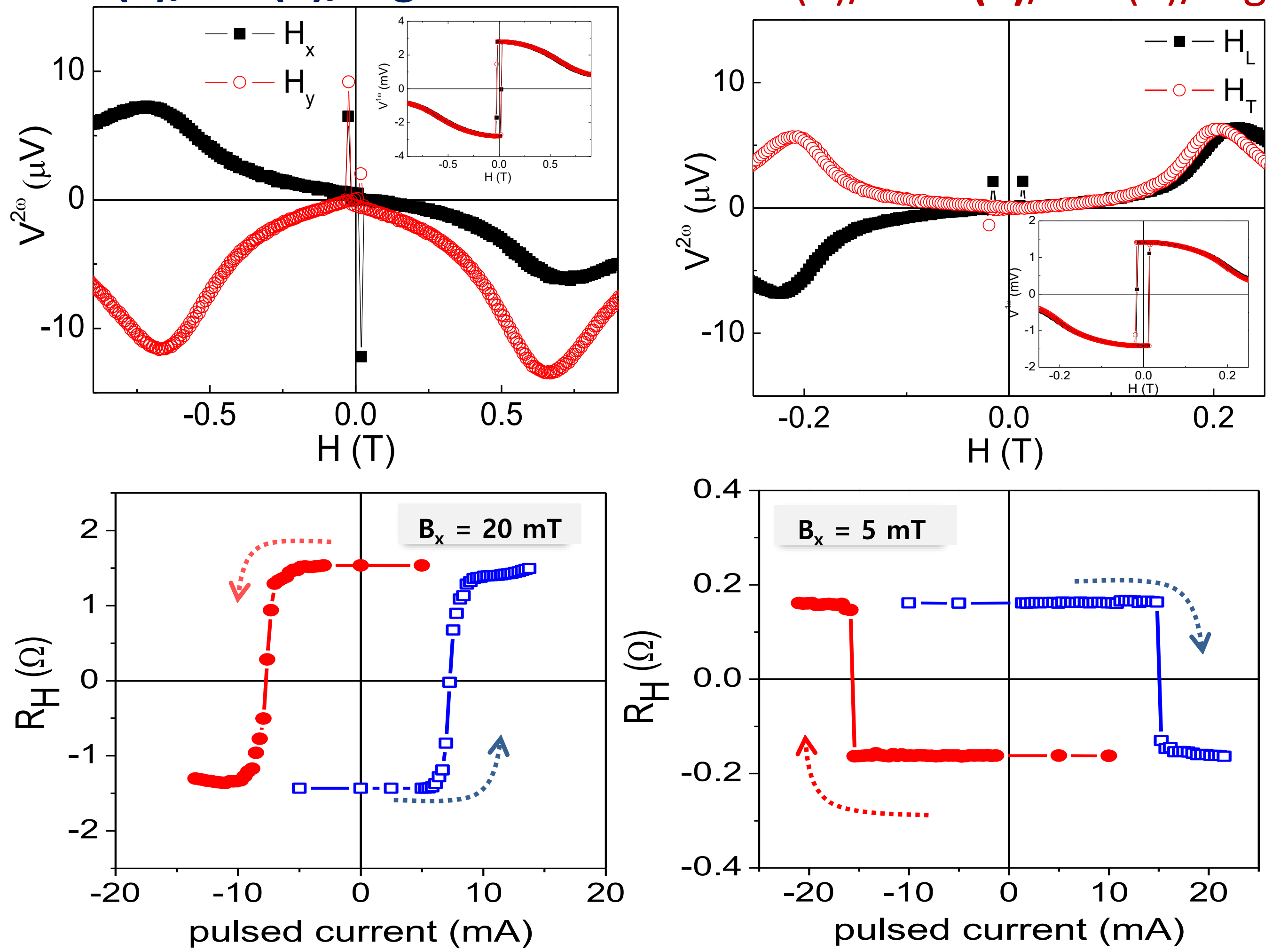
→ **Spin-orbit effect**

AMR, Spin-orbit torque

Field-Free magnetization switching for SOT

Spin orbit torques with AFM

Ta(5)/CFB(1)/MgO — Ta(5)/**IrMn(3)**/CFB(1)/MgO



- SOT in IrMn is comparable to Ta & (+) θ_{SH}

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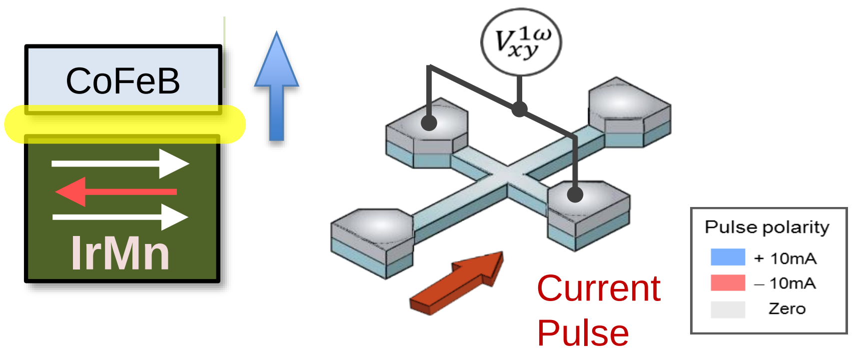
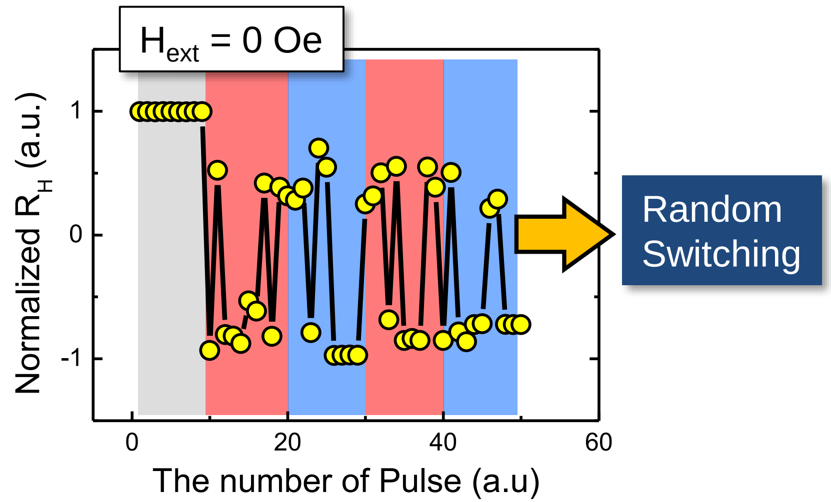
SOT-induced M switching

In-plane exchange-biased effective H field at the AFM/FM interface

→ Field-free deterministic switching ?

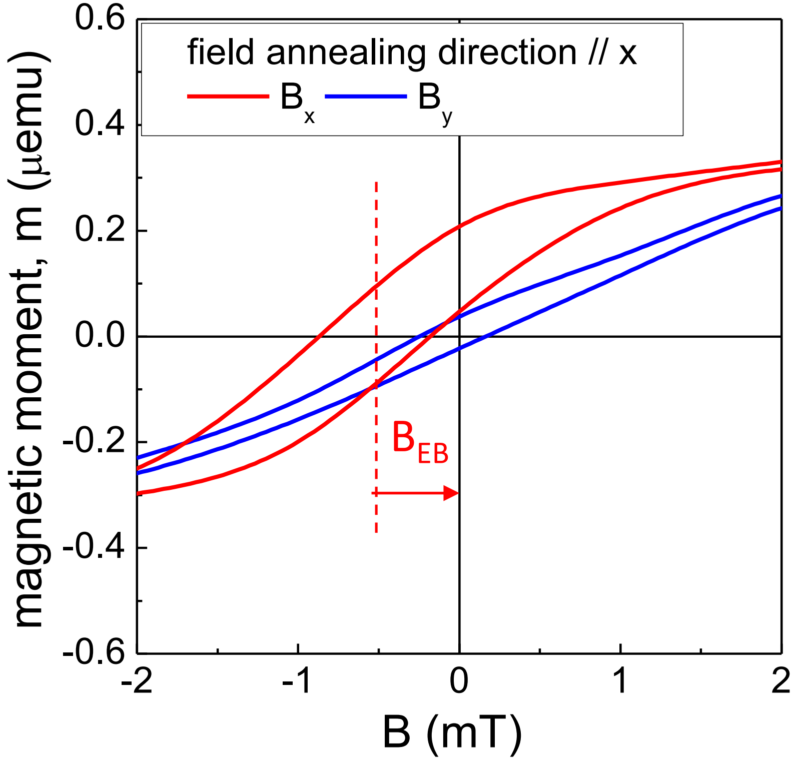


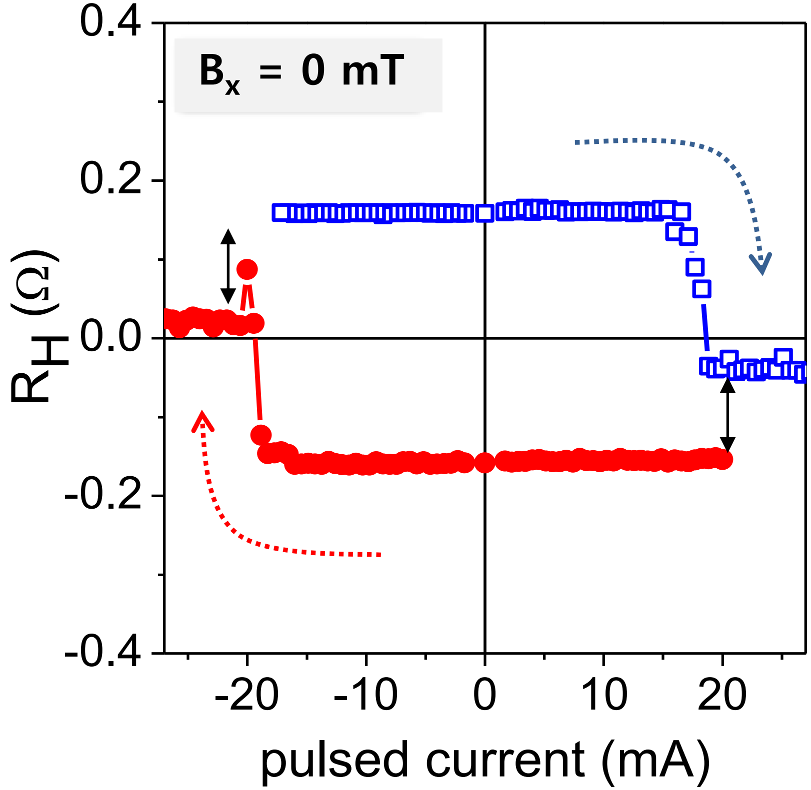


- **No in-plane exchange-biased H field**

Thicker IrMn (9nm) & field annealing

Ta(5)/**IrMn(9)**/CFB(1)/MgO *Annealed @ 190C & 0.8T*





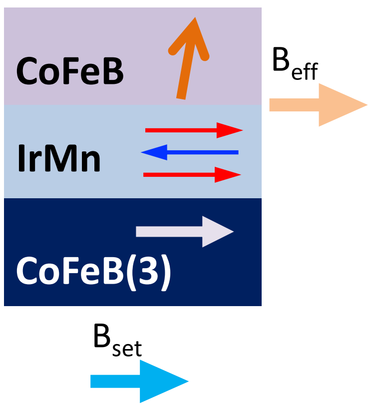
- Exchange bias field : 0.5 mT
- Field-free SOT switching, but not completly

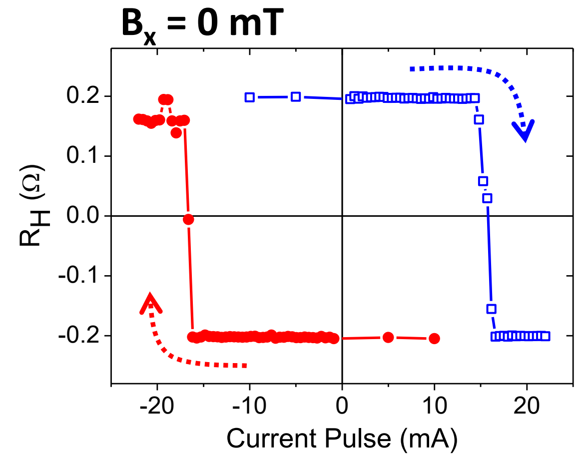
  → Need stronger exchange bias field

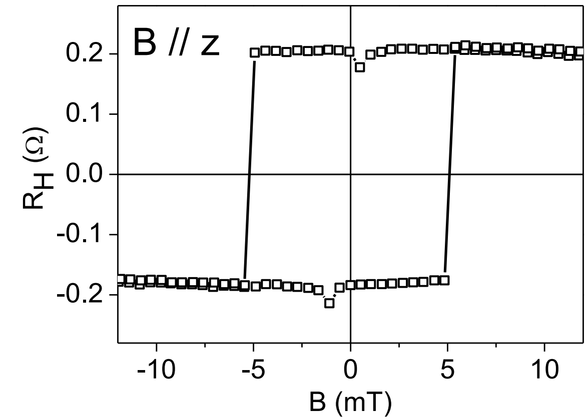
Field-free SOT switching

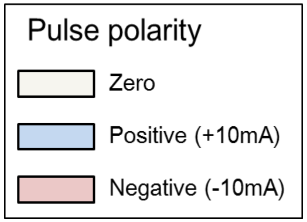
Ta(5)/**CoFeB(3)**/**IrMn(3)**/CFB(1)/MgO

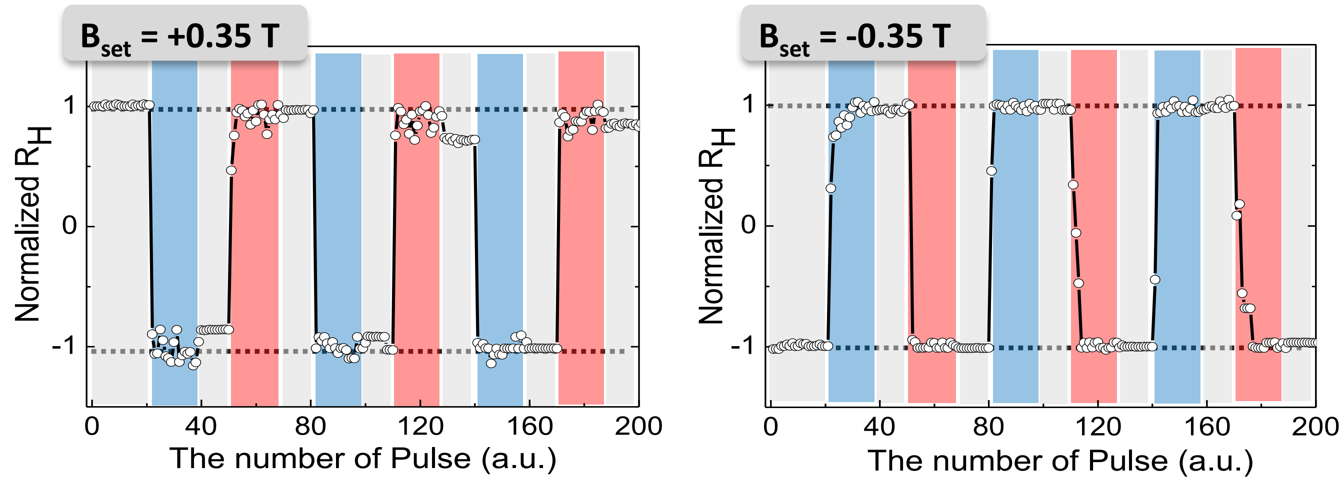
Develop in-plane exchange bias











· Field free deterministic switching

Oh, Park, et al., Nature Nanotech (2016)

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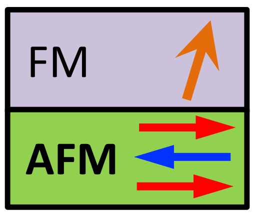
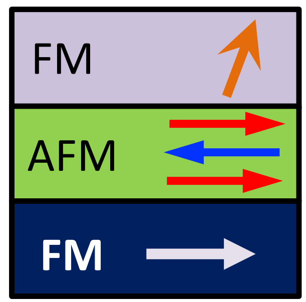
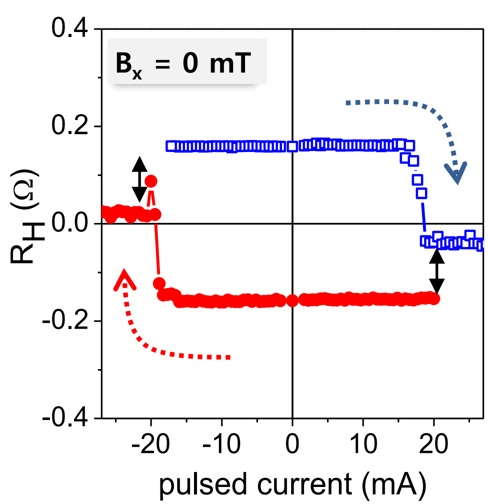
Summary II

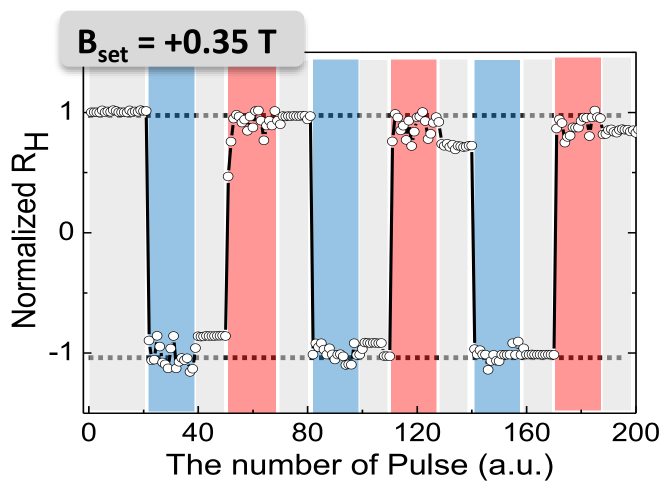
1. Spin-orbit torque in antiferromagnet

: a sizable SOT & in-plane exchange-biased effective field allows field-free magnetization switching









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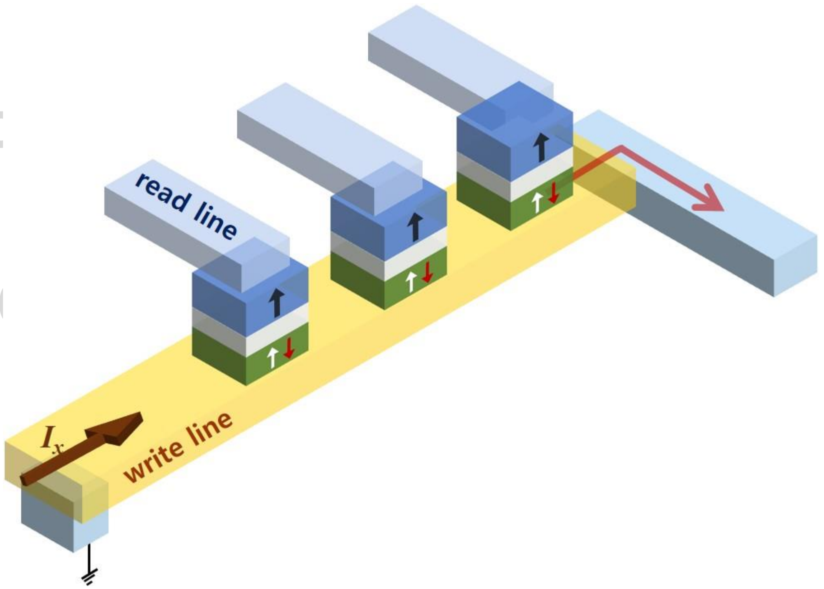
Contents

1. Introduction : Spin-orbit tc

2. Material engineering for S

3. Field-free SOT switching



4. SOT-based spintronic devices

- Simultaneous switching of (more than 2) devices
- Electric-field effect on SOT switching

5. Su

Summary

1. Spin orbit torque is an alternative for electric switching of perpendicularly magnetization, which can be utilized in various spintronic devices including MRAM

2. The SOT is significantly enhanced by material engineering ; manipulation of HM resistivity & interfacial modification

3. Field-free SOT switching is achieved by the introduction of antiferromagnet which has a sizable SOT and exchange bias

4. SOT switching allows for simultaneous switching and easy integration of electric gate