Towards all electrically control ferromagnets by spin orbit torques at room temperature

Kaiyou Wang
（kywang@semi.ac.cn）

Institute of Semiconductors, CAS

Kavli Workshop

May/6th/2018

Acknowledgements

Dr. M. Y. Yang, Dr. K. M Cai, Y. Sheng, B. Zhang, Prof. J. H. Zhao, Prof. Y. Ji, Prof. H. Z. Zheng

SKLSM, Institute of Semiconductors, P. R. China

Dr. S. Liu, Dr. H. L. Ju, Prof. B. H. Li

Department of Physics, School of Sciences, Beijing Technology and Business University

University of Nottingham
UK | CHINA | MALAYSIA

Dr. K. W. Edmonds

School of Physics & Astronomy, University of Nottingham

Dr. S. M. Wang

Institute of Microelectronics, P. R. China

IMECAS

Prof. Shouguo Wang

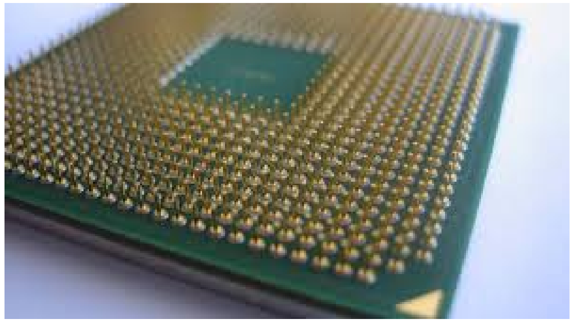
School of Materials Science and Engineering, USTB

NSFC

中华人民共和国科学技术部
Science and Technology of the People's Rep

中国科学院
CHINESE ACADEMY OF SCIENCES

Information processing and storage



Processing CPU,
Based on semiconductor CMOS

DRAM

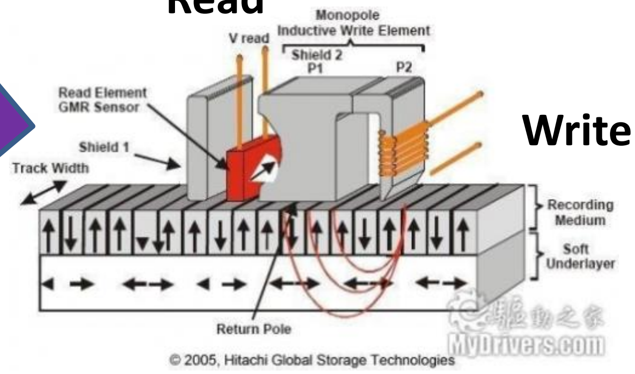
Lost information
after switching
off power

SSD（semiconductor）

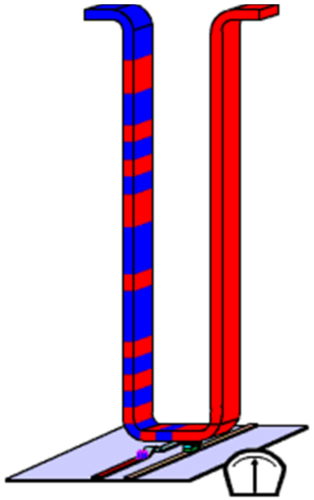
HD（ferromagnet）

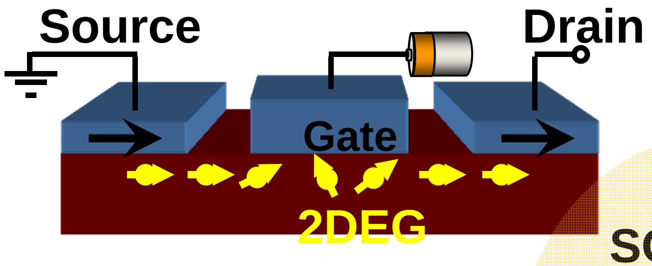
Read

Write



The development of Spintronics





GMR
1988

Read head

Spin FET
1990

FS
1992

TMR
1995

STT
1996

Spin LED
2001

O Spinstronics
2004

SHE
2004

TAMR
2004

AFM
Spintronics
2006

MRAM
2006

Spin Seebeck
2008

Skyrmions
2009

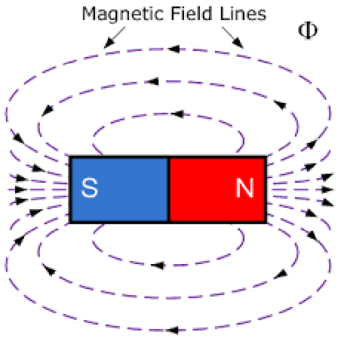
Spin FET
2009

SOT
2009

SH Transistor
2010

Neurocomputing
2015

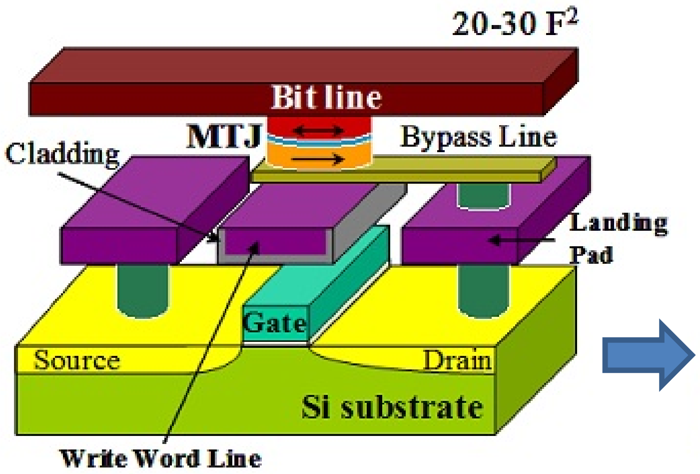
Control spin electrically



Diverge of the magnetic lines， restricting the devices shrinking further

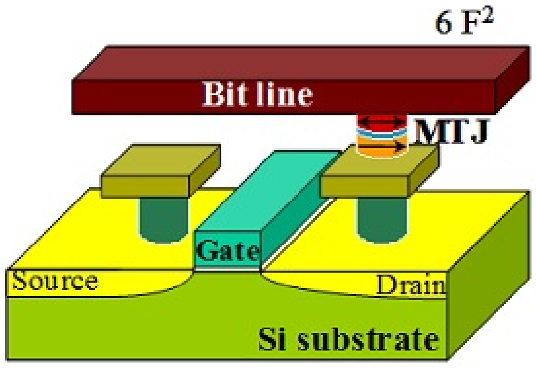
Acta Physica Sinica, 66, 027501 (2017)

Development of Magnetic（Spin） Memory



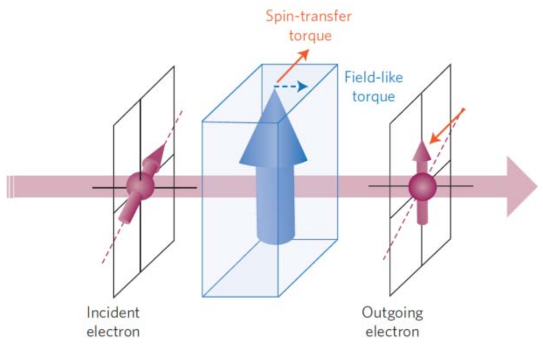
First generation MRAM

By magnetic field



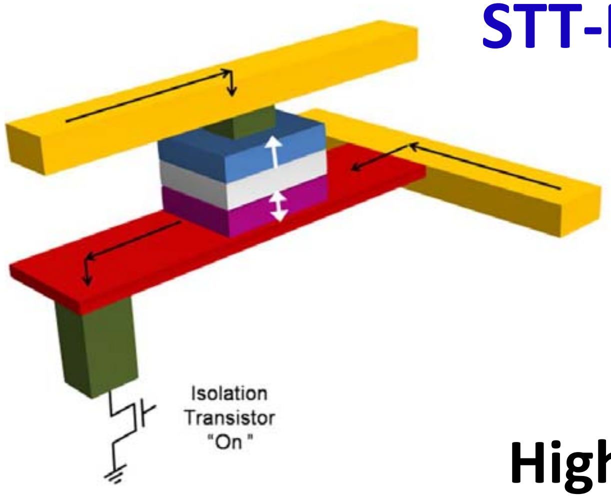
STT-MRAM

By electrical current



STT

STT-MRAM（on commercial development）



SOT-MRAM

Electrical control SOT-MRAM
Logic and Memory integration

Higher speed、lower power consumption、better endurance

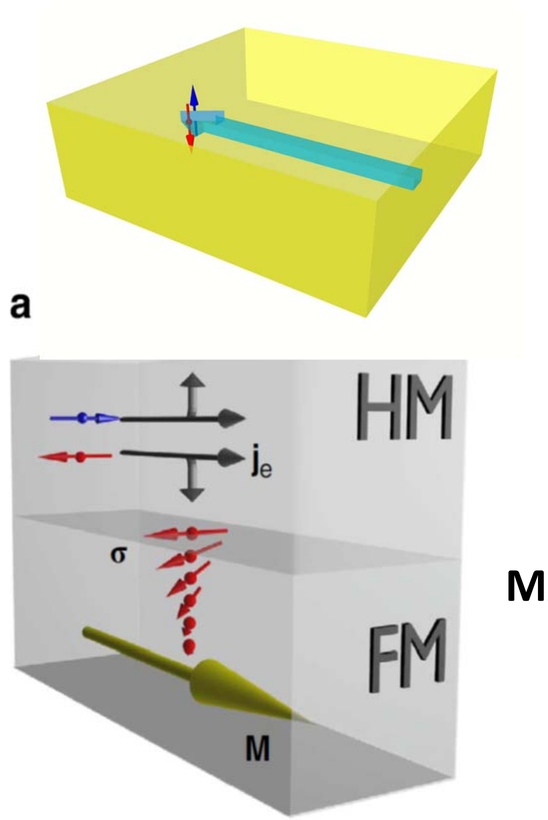
Outlines

- **Current induced the magnetization switching in Pt/CoNiCo/Pt by spin orbit torques**
- **Current induced magnetization switching without external magnetic field**
- **Perspective**

- **Current induced the magnetization switching in Pt/CoNiCo/Pt by spin orbit torques**

Spin orbit Torques

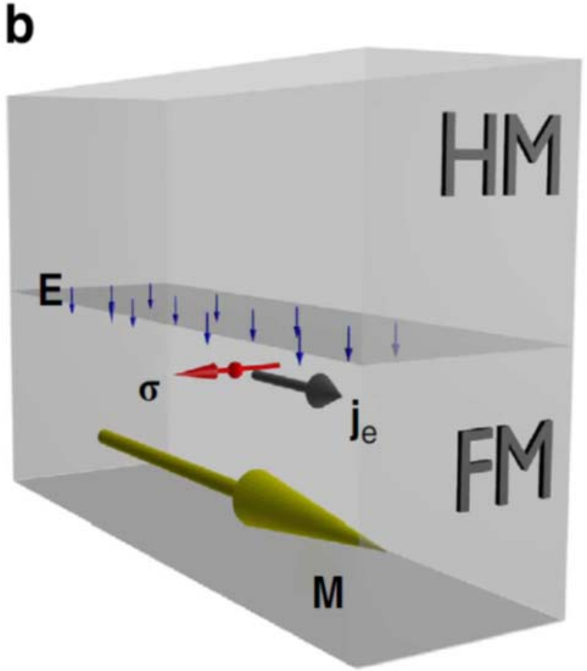
Spin Hall Effect



MxSxM

Crystal inversion asymmetry in the heavy metal (HM)

Rashba Effect

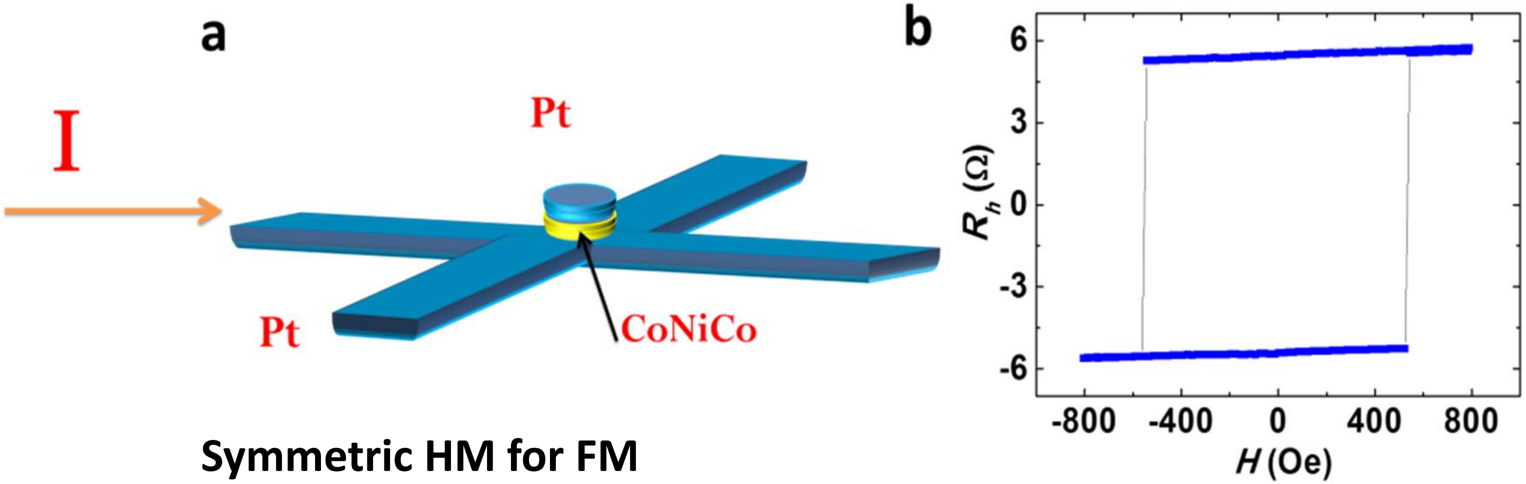


Interface inversion asymmetry at the heavy metal (HM) and ferromagnetic metal (FM) interface

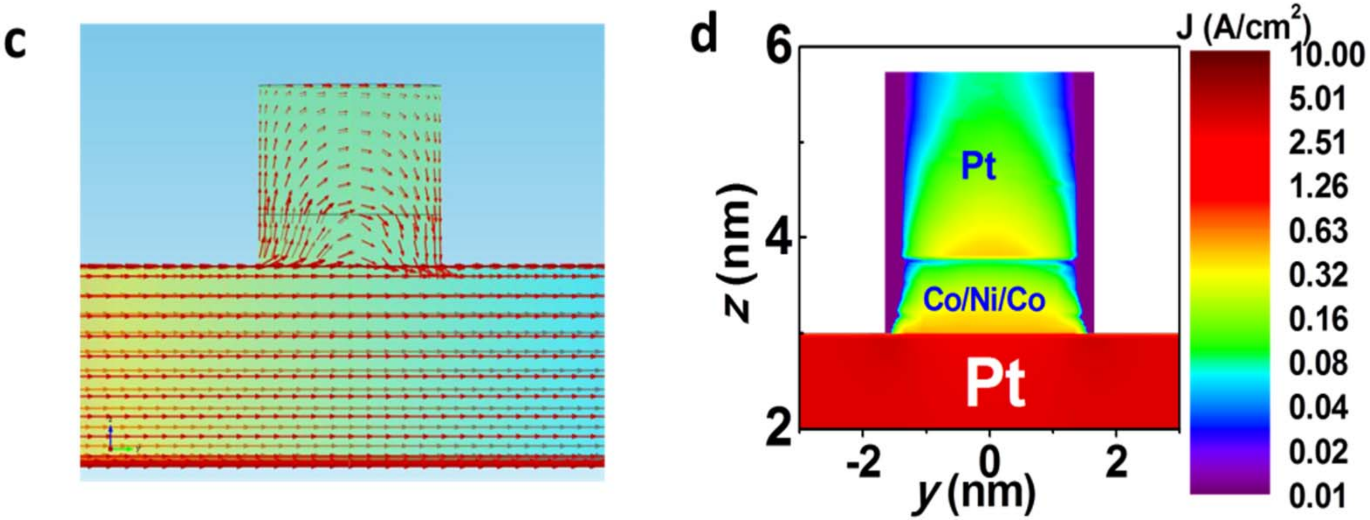
Both mechanisms could play a very important role in current switching magnetization in HM/FM system

X. Fan et al., Nature Comm. 4, 1799 (2013).

Strong perpendicular symmetric FM devices



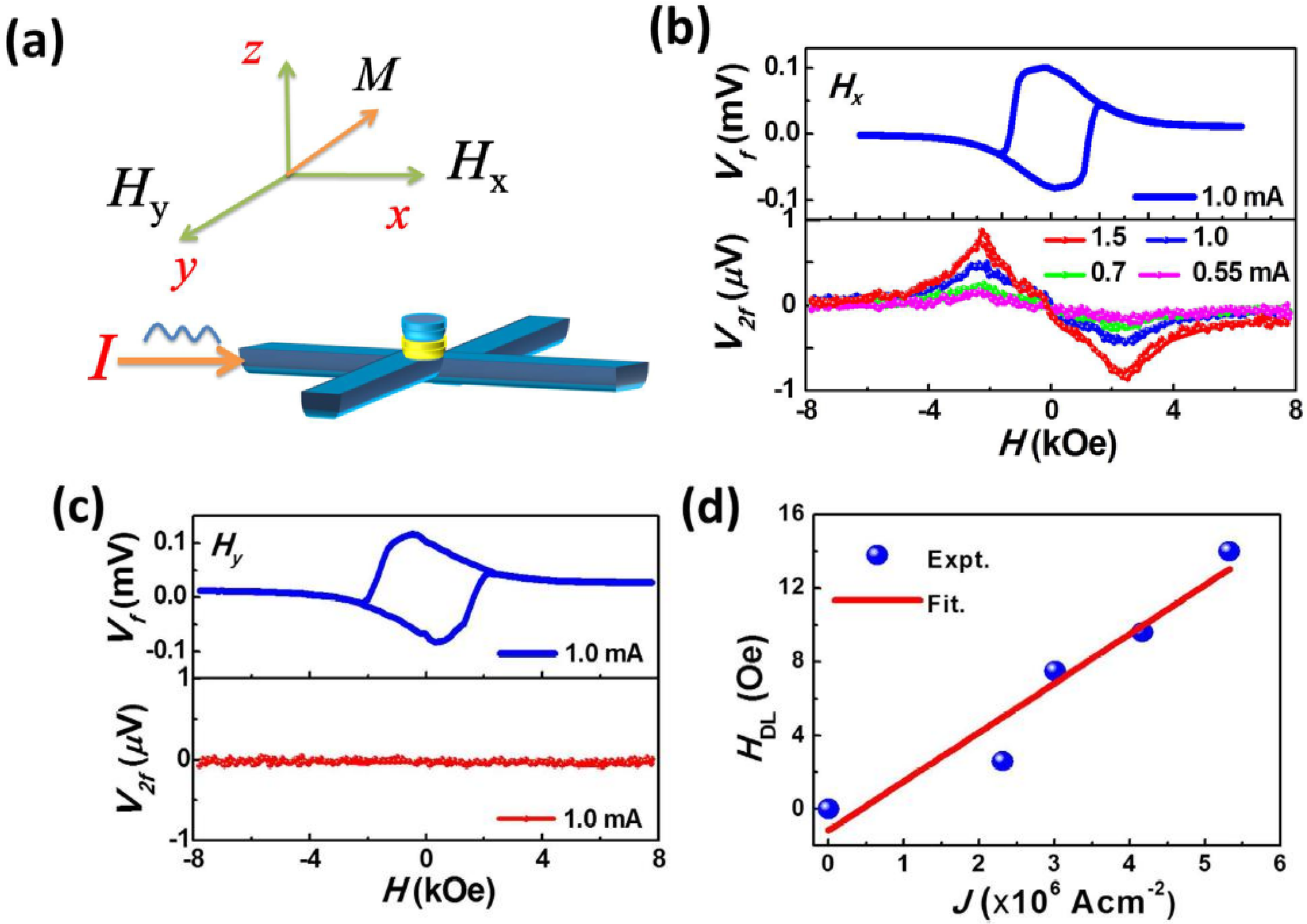
Symmetric HM for FM



Current distribution along the device

1000:13:1

Determine the effective field



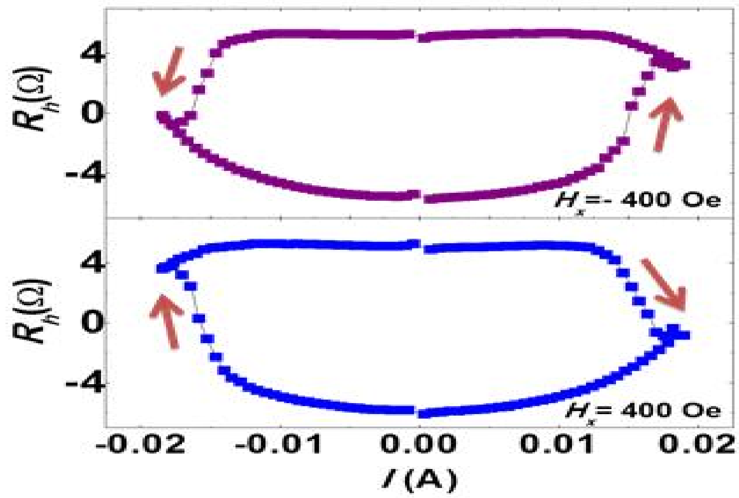
$$H_{DL(FL)} = -2\frac{H_{L(T)} \pm 2\xi H_{T(L)}}{1 - 4\xi^2},$$

$$H_{L,\pm} = \left(\partial V_{2f,L\pm}/\partial H_x\right)/\left(\partial^2 V_{f,L\pm}/\partial H_x{}^2\right)$$

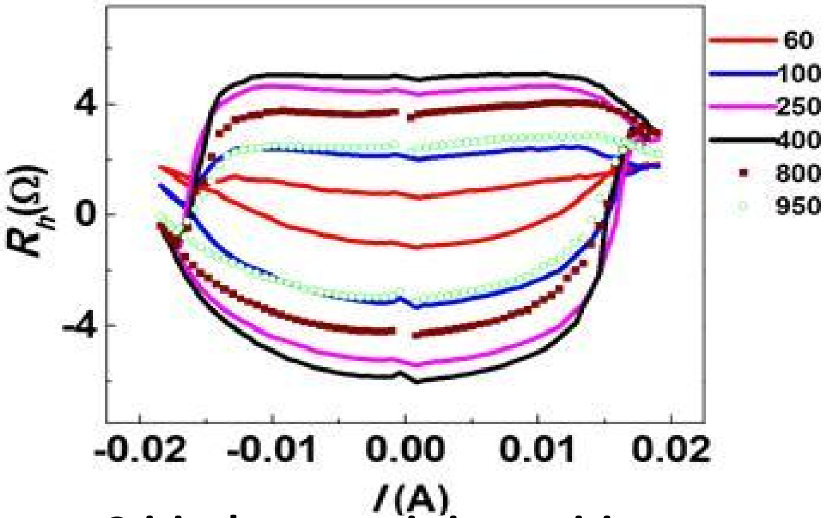
$$H_{T,\pm} = \left(\partial V_{2f,T\pm}/\partial H_y\right)/\left(\partial^2 V_{f,T\pm}/\partial H_y{}^2\right)$$

Only damping like effective field produced mainly by SHE, 25 Oe/10^7Acm^{-2}。

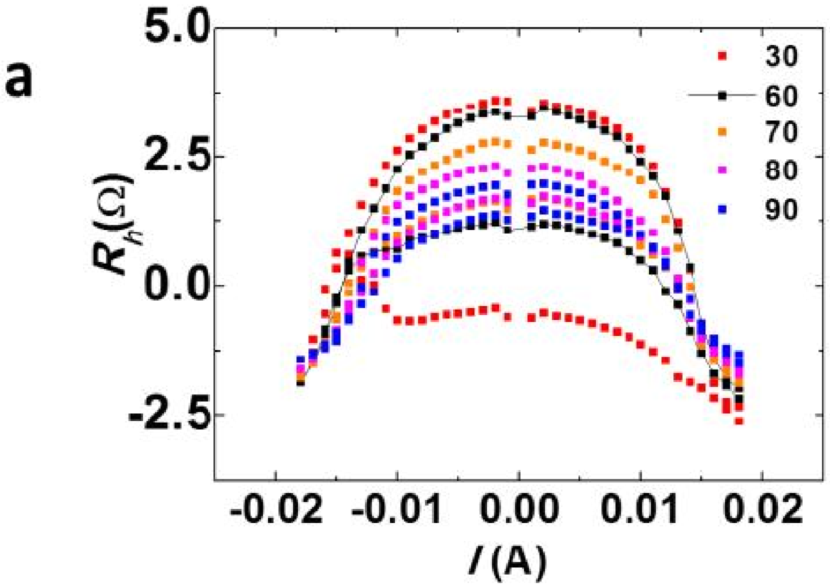
Switching ferromagnet with Hx by SHE



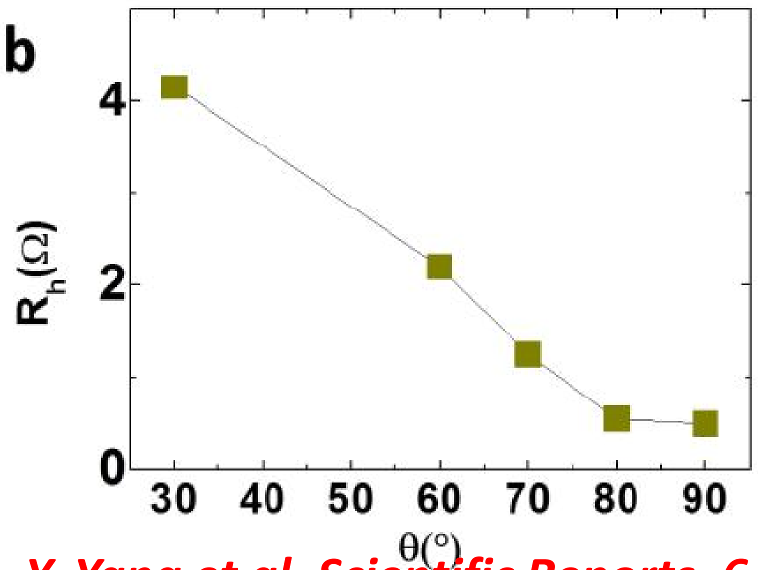
Hx direction controls the switching direction



Critical current is insensitive to the field magnitude



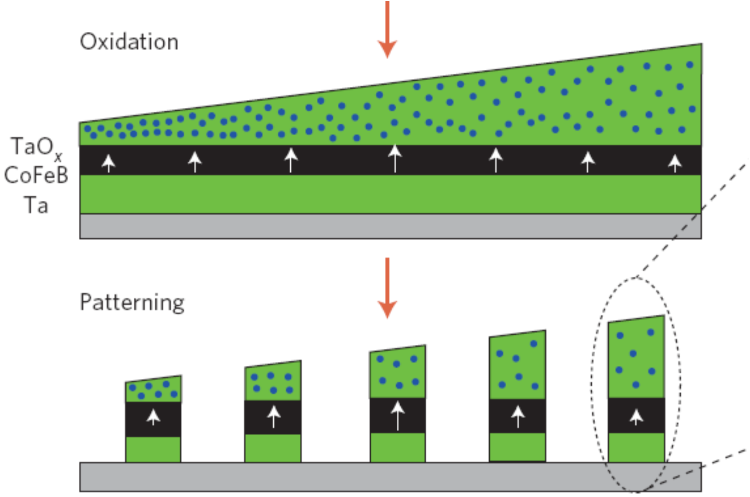
With field 400 Oe rotated in the plane

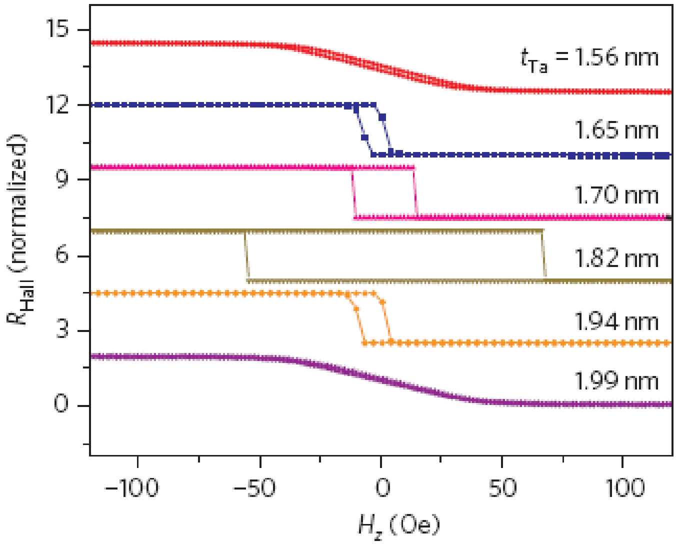


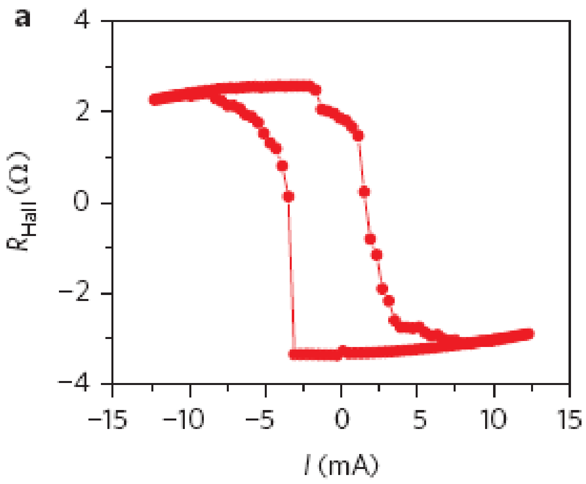
M. Y. Yang et al. Scientific Reports, 6 (2016)20778

- **Looking for electrically switching magnetization without external Magnetic field**

Determinsitic switching in Heavy metal/FM system without magnetic field





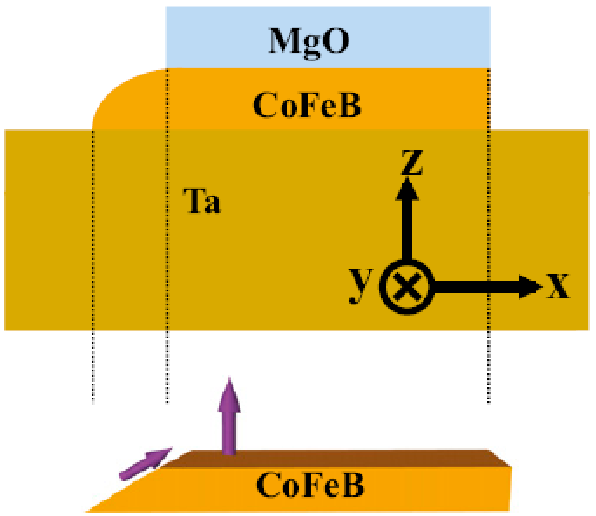


Using wedge structure to change the thickness of the oxide layer along x direction, symmetry breaking.

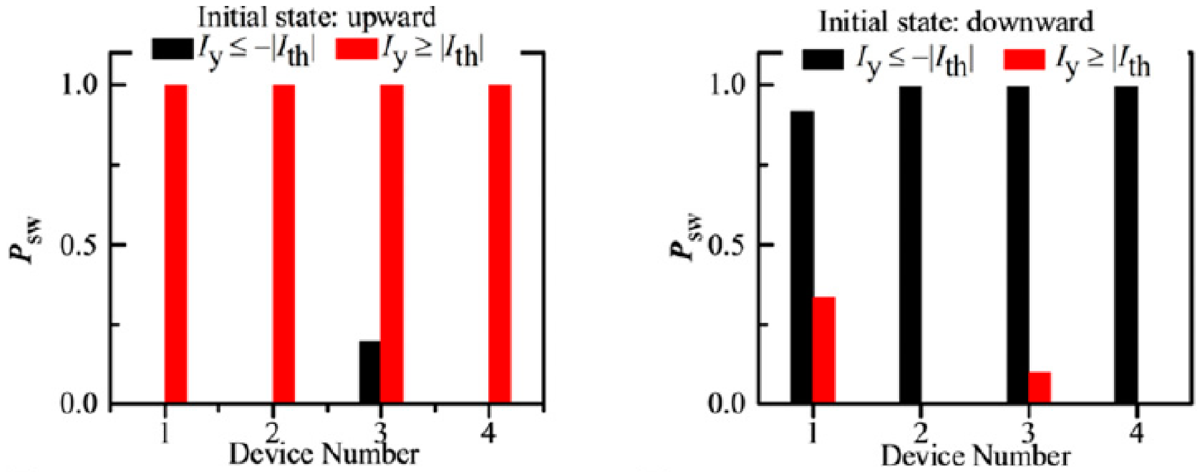
Shortcoming: non uniform magnetic properties materials

Yu, G. et al. *Nat. Nano*. 9, 548-554 (2014)

Breaking the symmetry of the magnetic materials

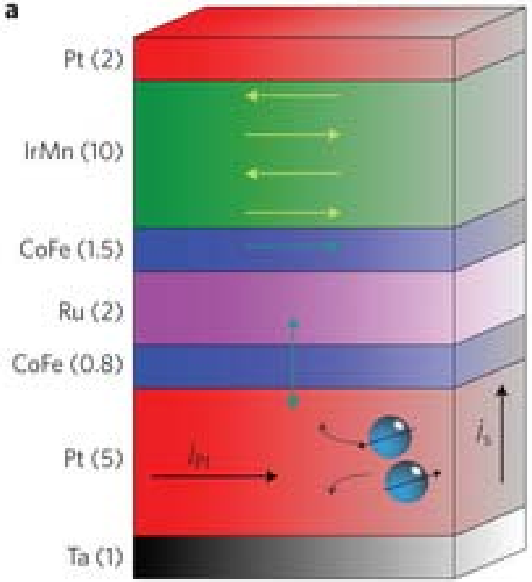


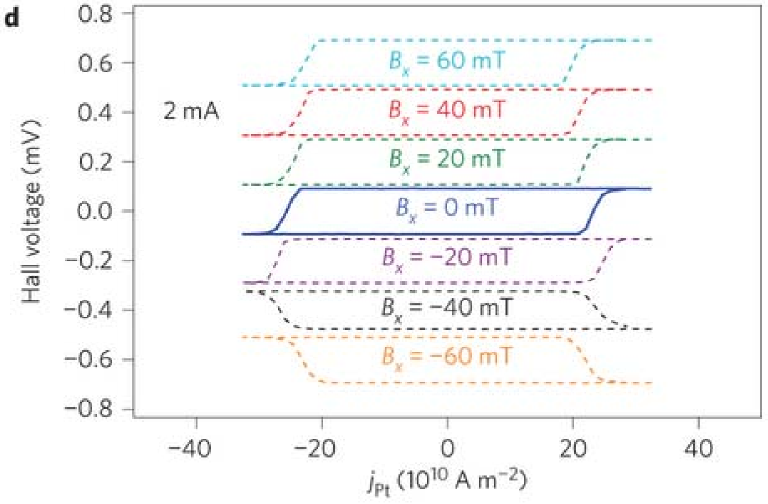
Etching the magnetic materials，
Change the magnetic anisotropy
Due to exchange coupling…



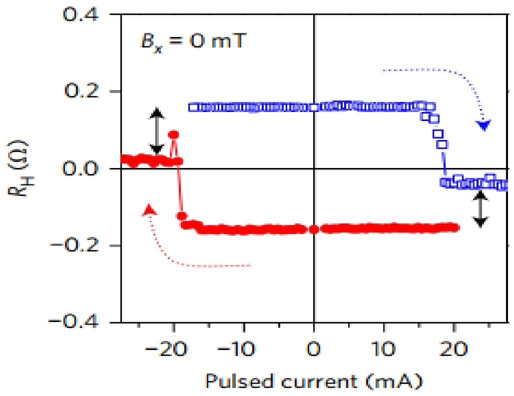
You, L. *et al*. PNAS **112**, 10310-10315 (2015).

Insert antiferromagentic layer





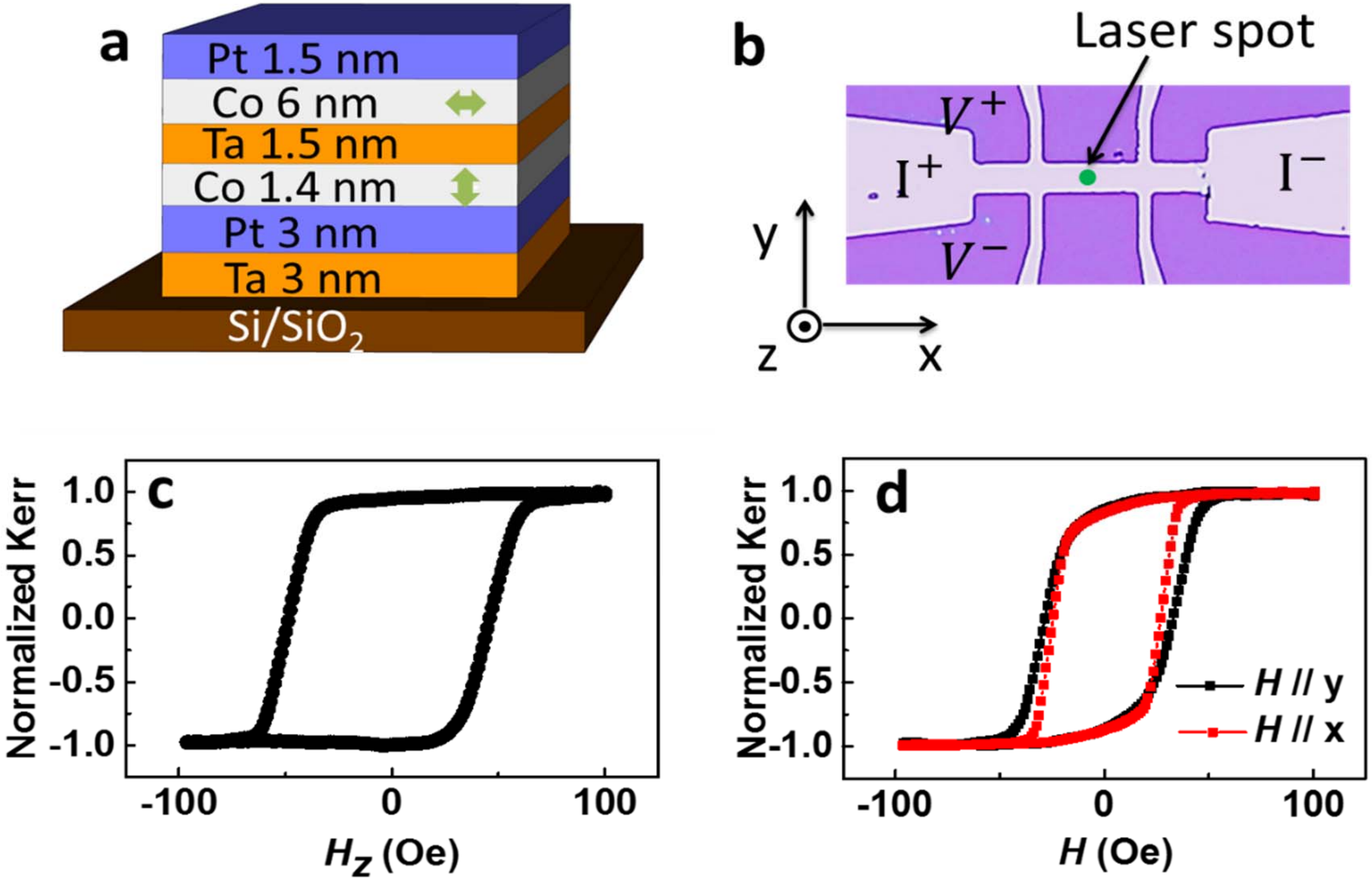
Yong-Chang Lau et al, *Nat. Nano.* **7**, 10854 (2016)



Insert antiferromagnetic layer（IrMn），produce an in-plane exchange field。

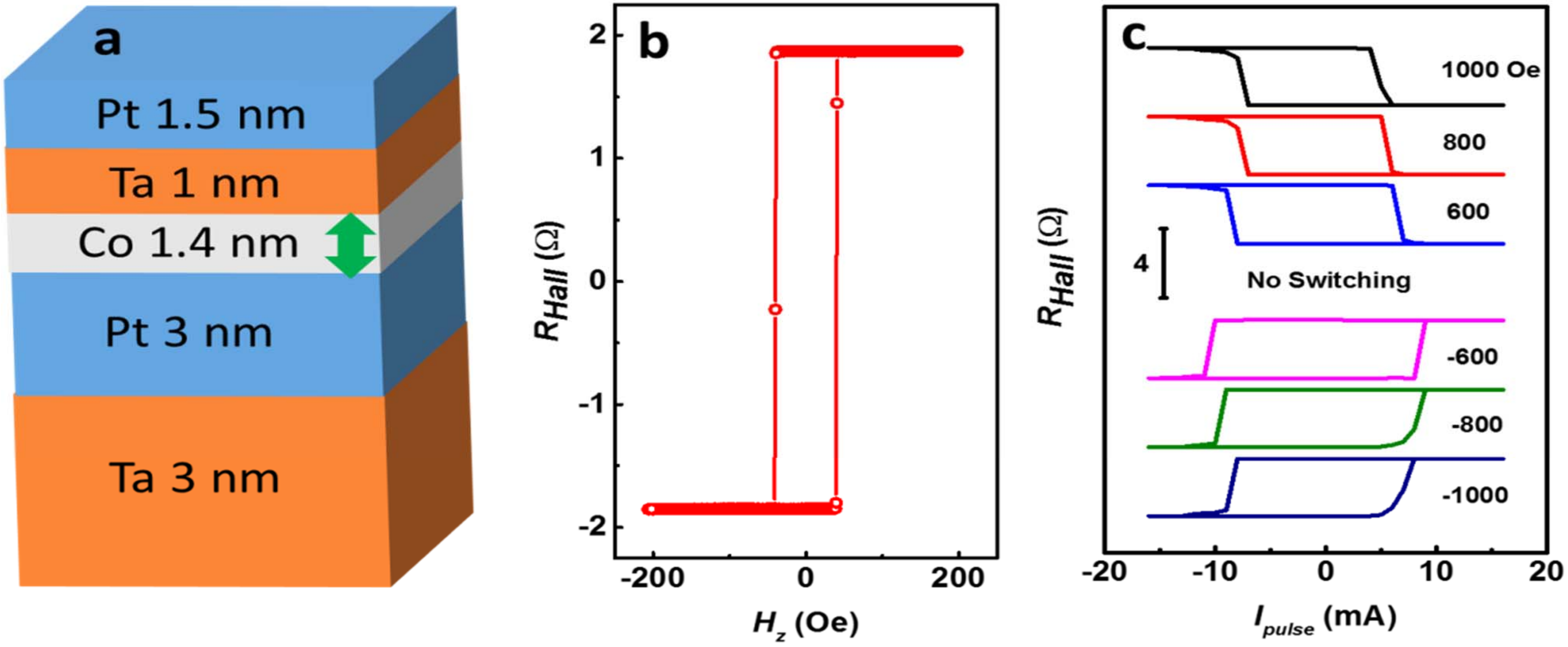
Young-Wan Oh, *Nat. Nano.* **109**, 10854 (2016)

Control switching with only ferromagnetic layers



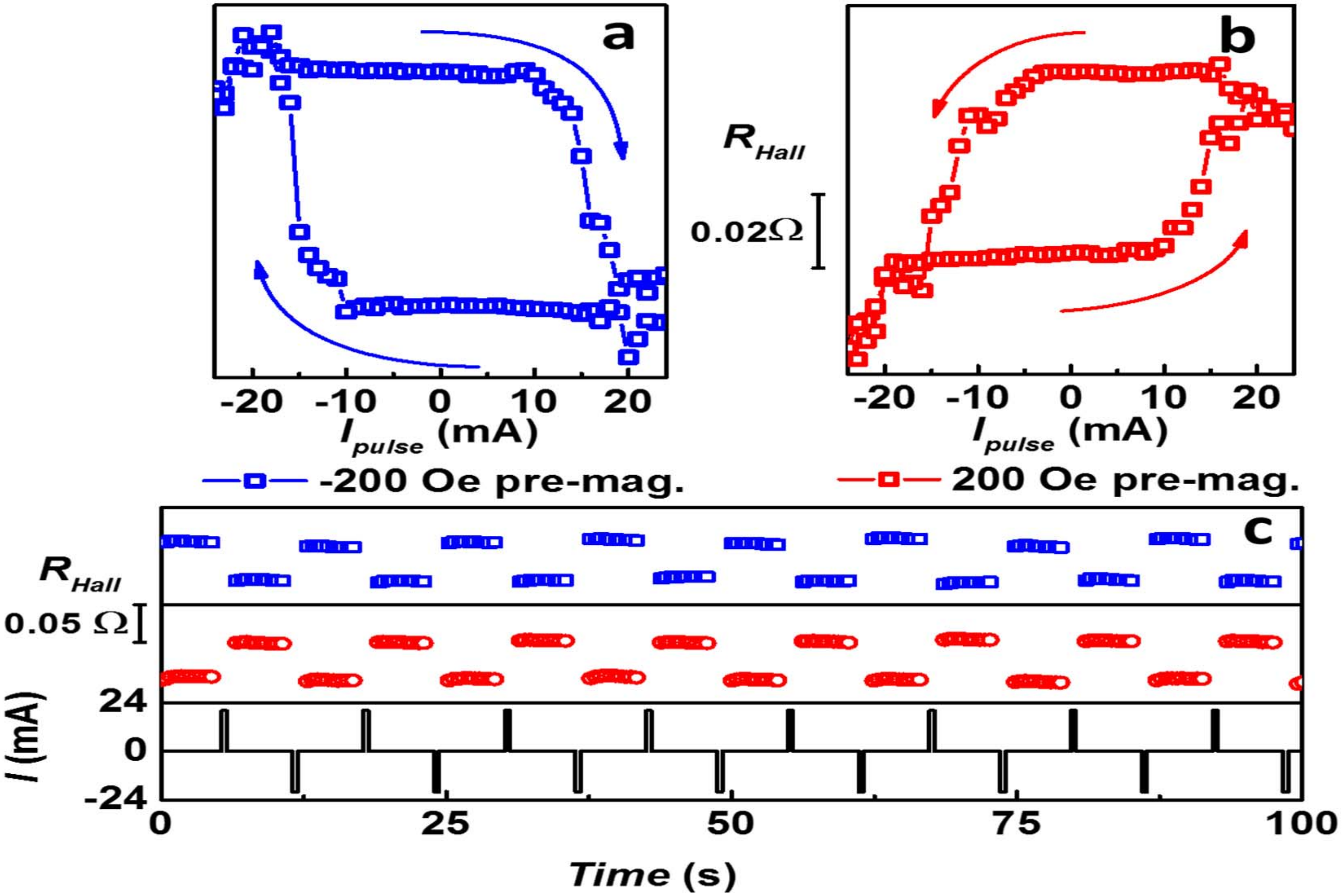
（c,d）magnetization hysteresis loops measured using a MOKE magnetometer in polar and longitudinal configurations, respectively.

Field assistant current induced magnetization switching in reference device



No deterministic switching observed when the external magnetic field is low for the reference sample

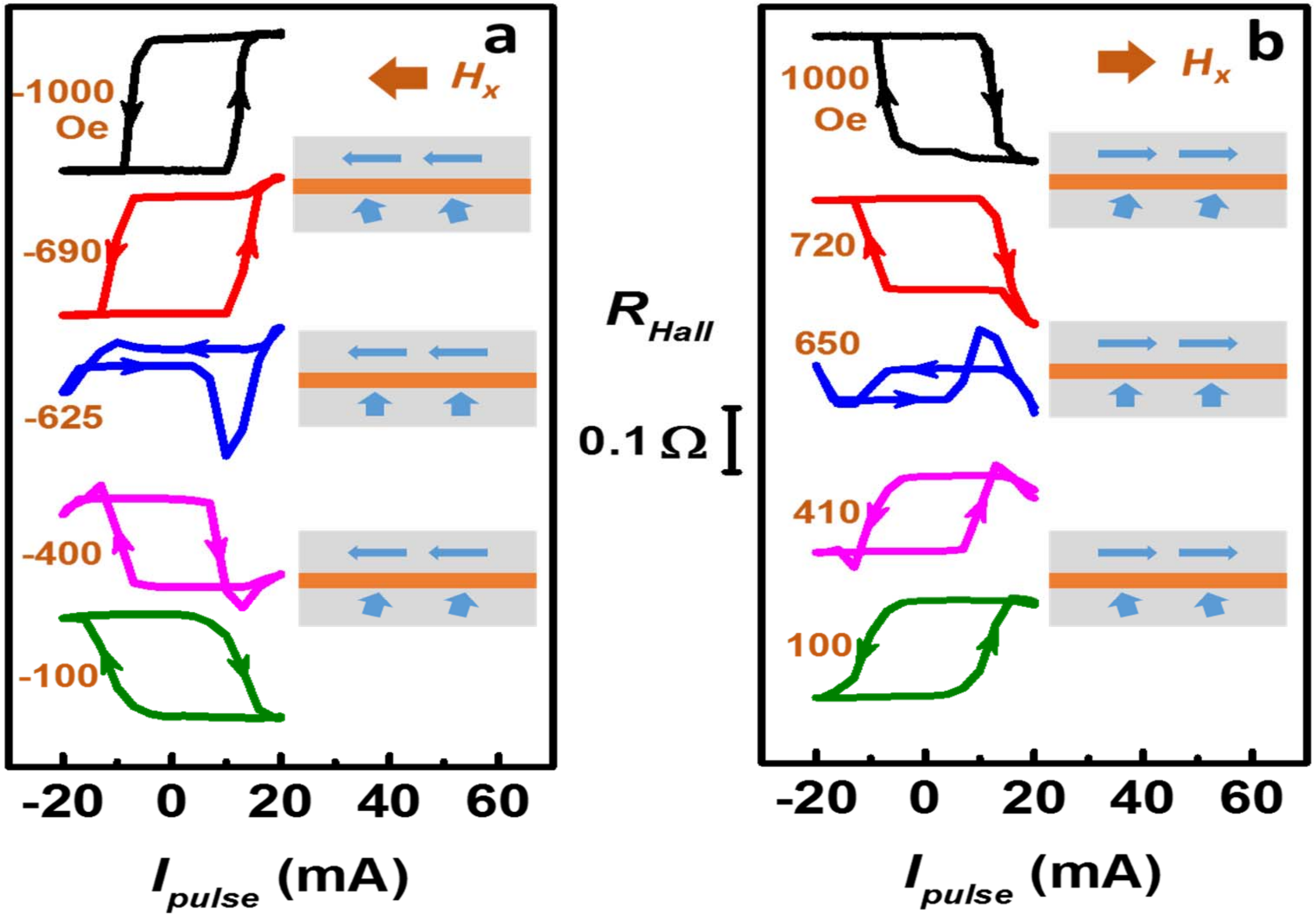
Current-induced magnetization deterministic switching at zero field



With pre-magnetized along current orientation, the current-induced switching is opposite with opposite pre-magnetized.

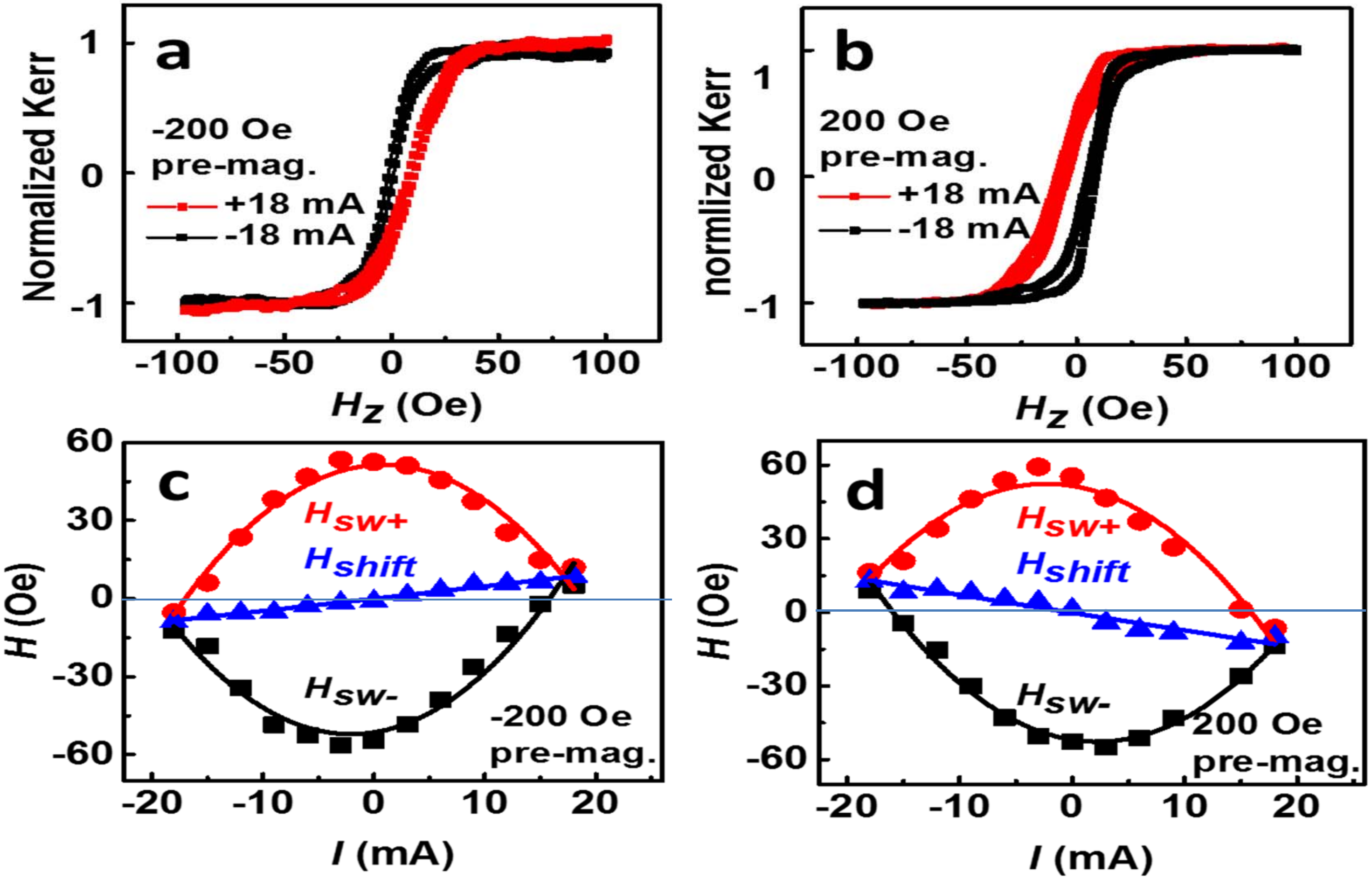
Proves the role of the top in-plane Co layer-

Adjustable Current-induced magnetization switching



The sign of the current induced magnetization with the magnitude and direction of the external magnetic field

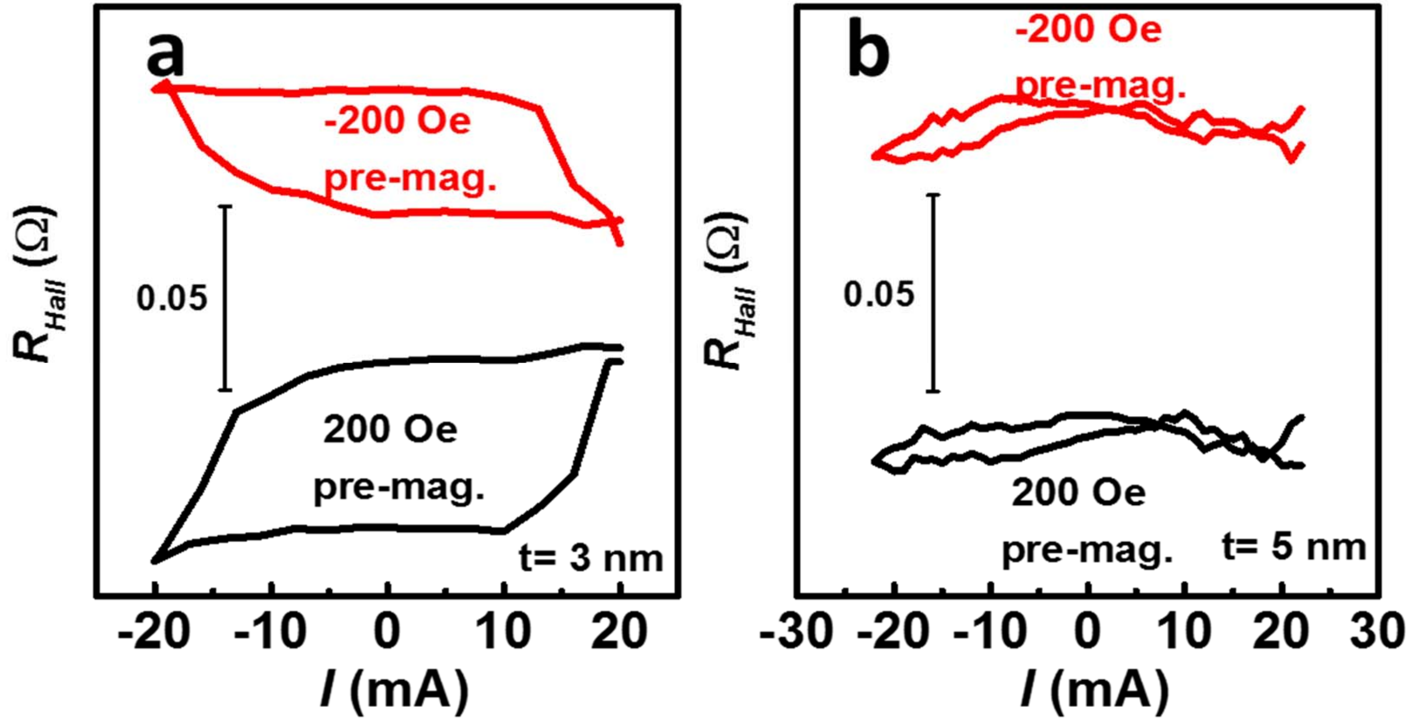
Perpendicular effective field induced by current

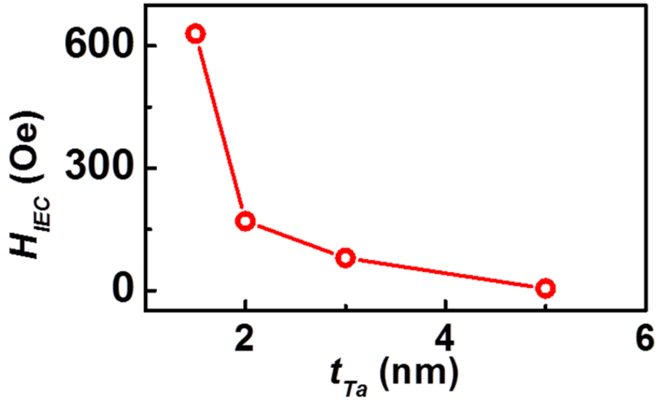


$H_{sw-(+)}=H_{0sw-(+)}+(-)\alpha\rho J^2+\beta J$ ***the second term is the Joule heating, and the third term is the spin orbit torques induced by current; β*** **of the device with** t_{Ta}**=1.5 nm is +/-9.2 Oe/(**10^7**Acm**$^{-2}$**).**

(exchange field +current ($H_x \times J_S$) induced Hz)

Thickness of Ta dependence on the current induced switching

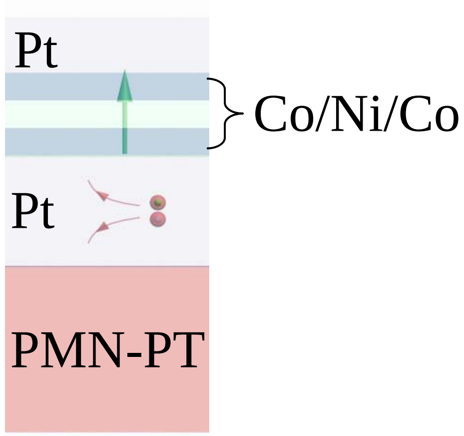


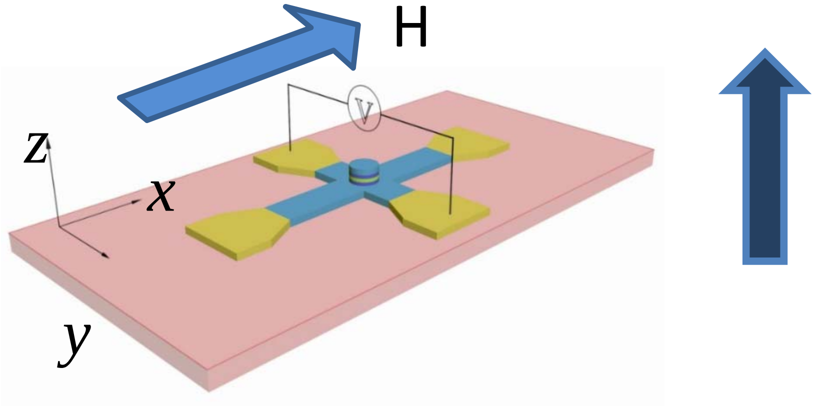


Interlayer interaction decreases with increasing the Ta thickness

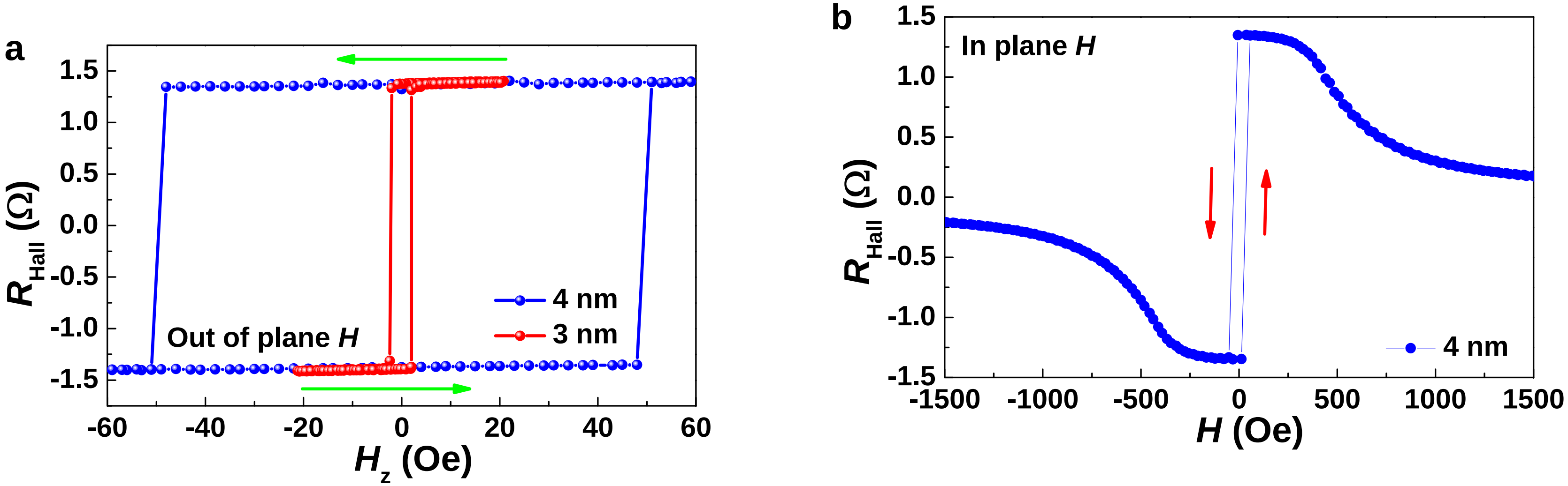
Under review

Voltage Switchable current-induced device structure



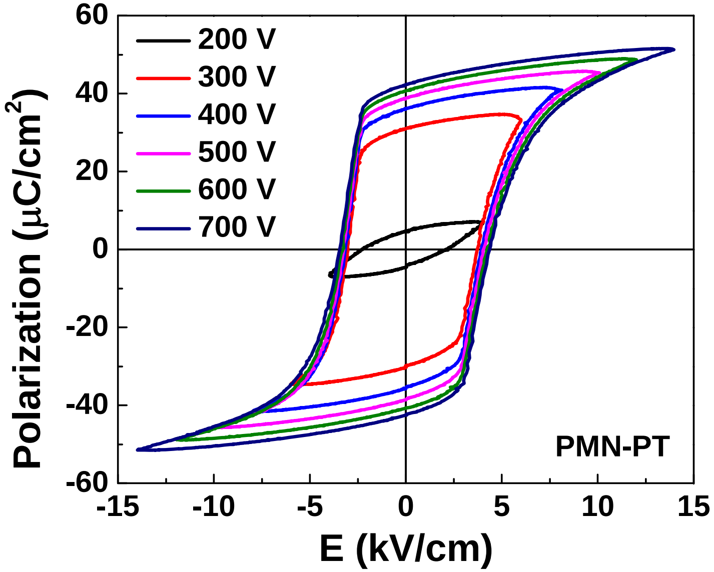


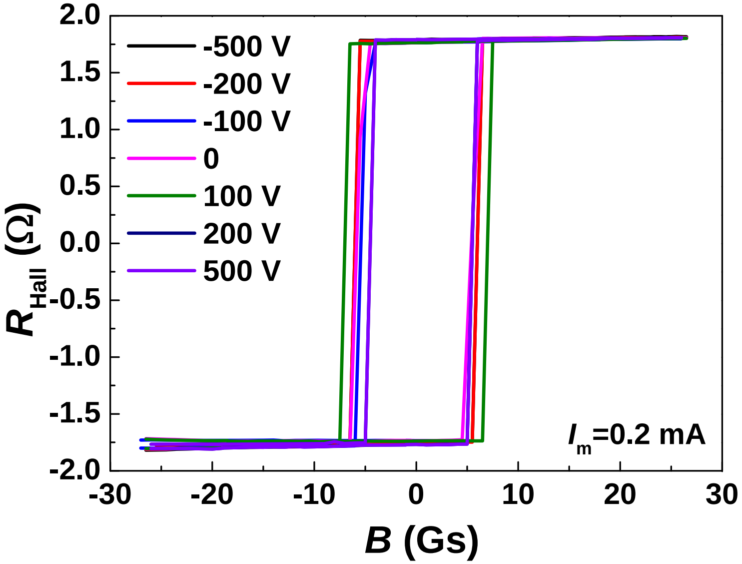
PMN-PT/Pt/CoNiCo/Pt



Device with good perpendicular magnetic properties

Ferroelectric properties of the substrate



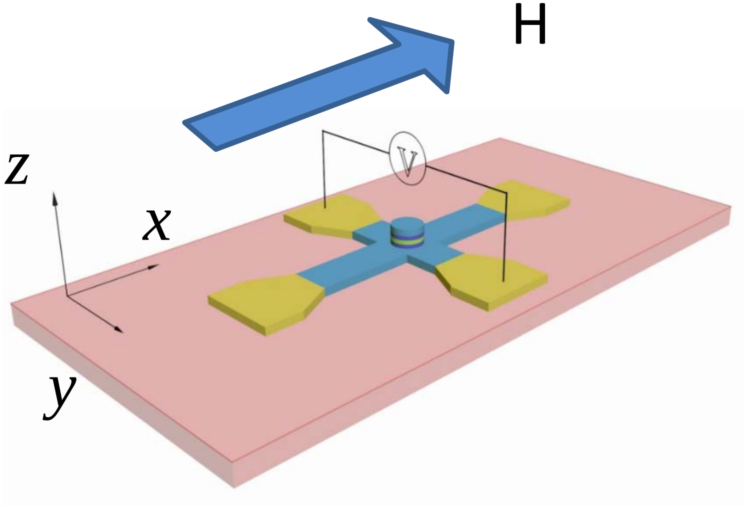


Ferroelectric hysteresis loops at different applied voltages.

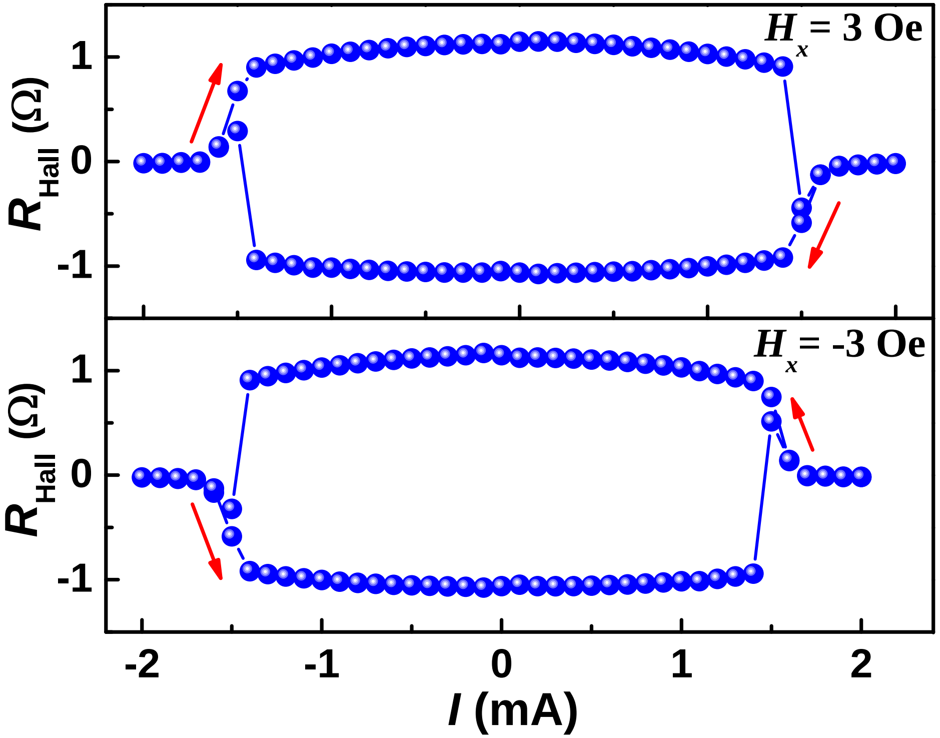
The AHE loops are not sensitive to the voltages applied to the substrate。

Piezo voltage effects are not important to the magnetic properties

Current induced switching under magnetic field

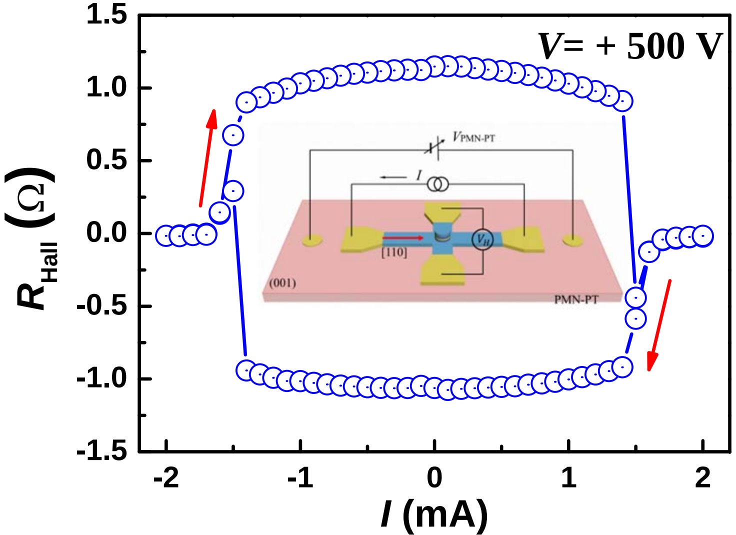


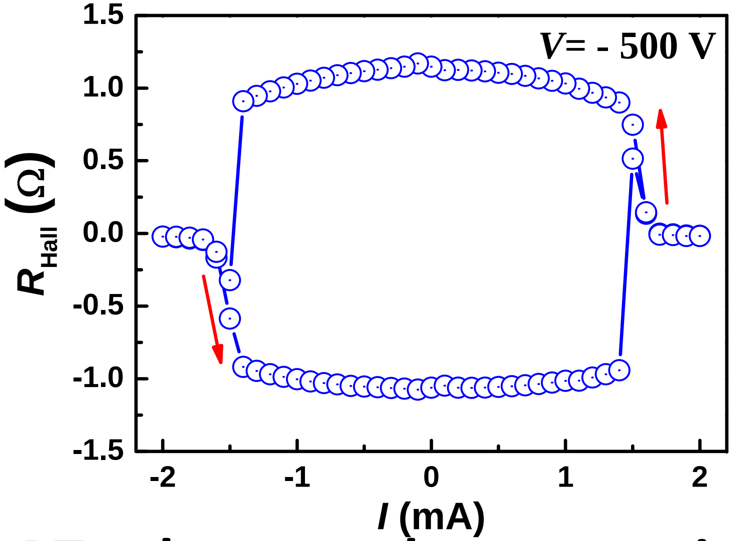
Without polarization，
Current pass through Pt layer



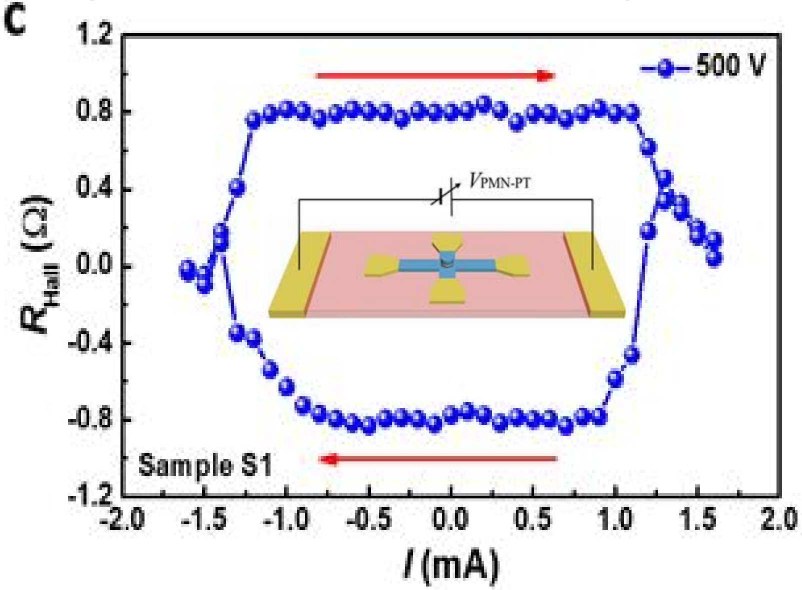
Under external magnetic field Hx，current-induced deterministic magnetization switching.

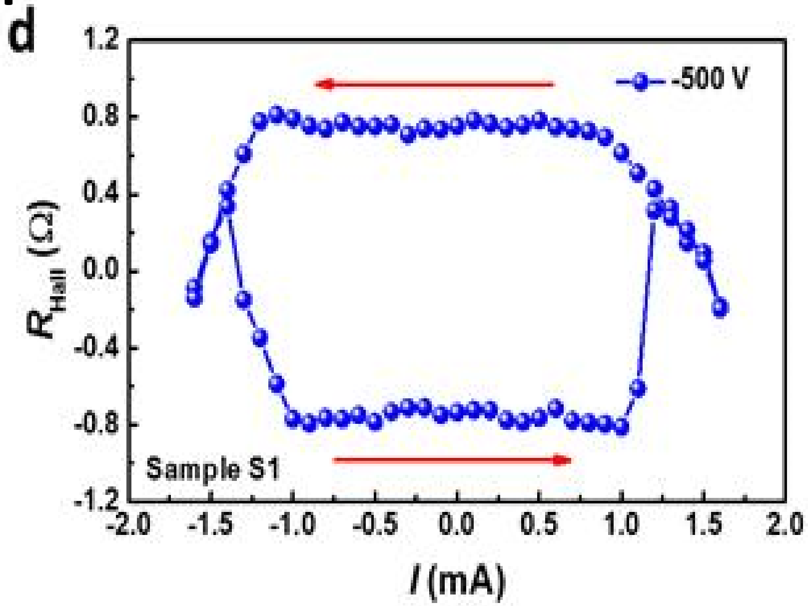
Electrically control deterministic switching at H=0



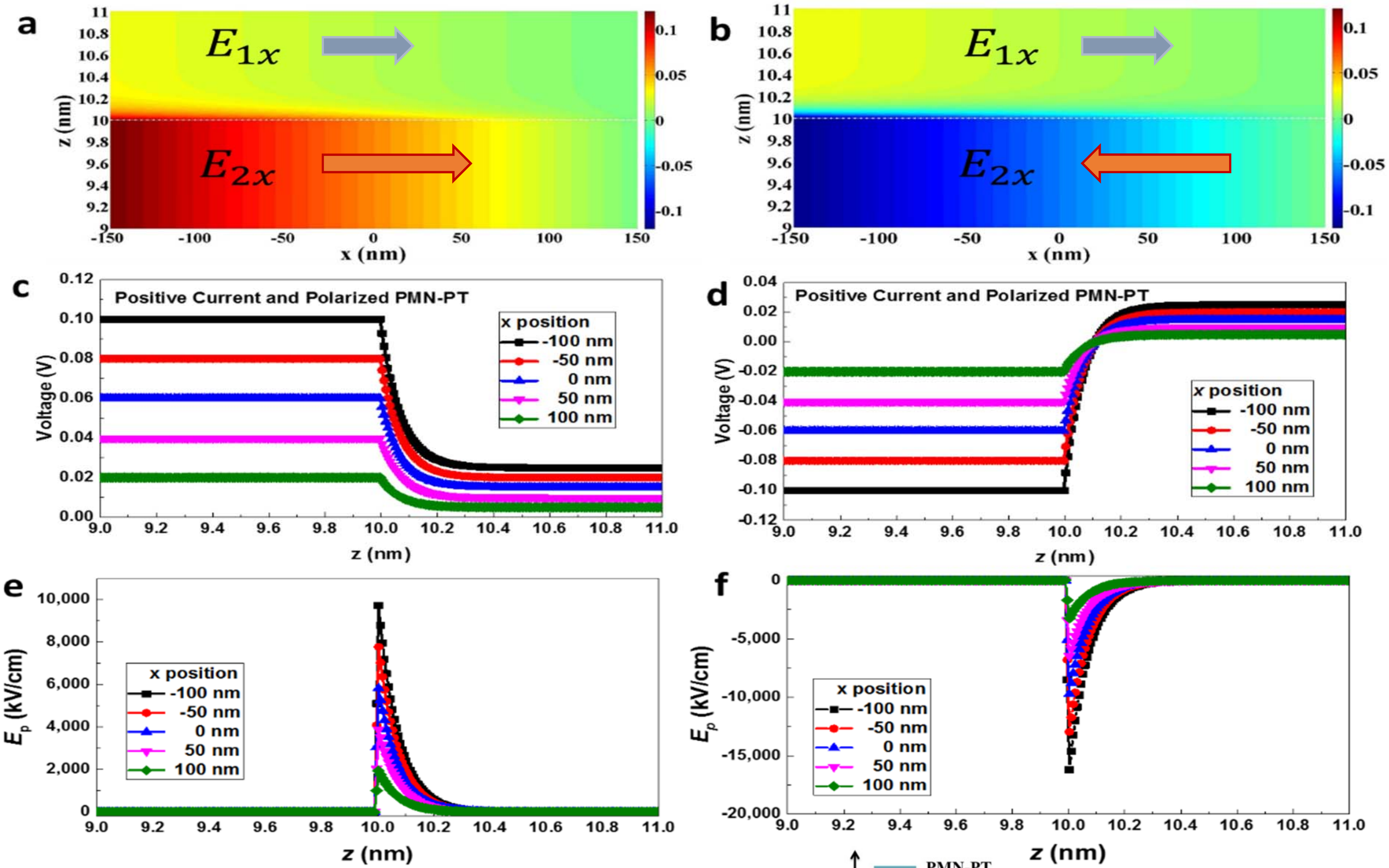


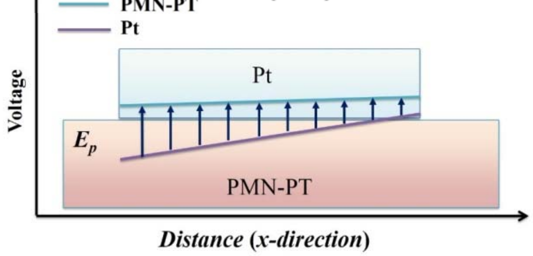
With +/- in plane polarized PMN-PT substrate, the current induced magnetization switchings are opposite.





Estimated the perpendicular electric field

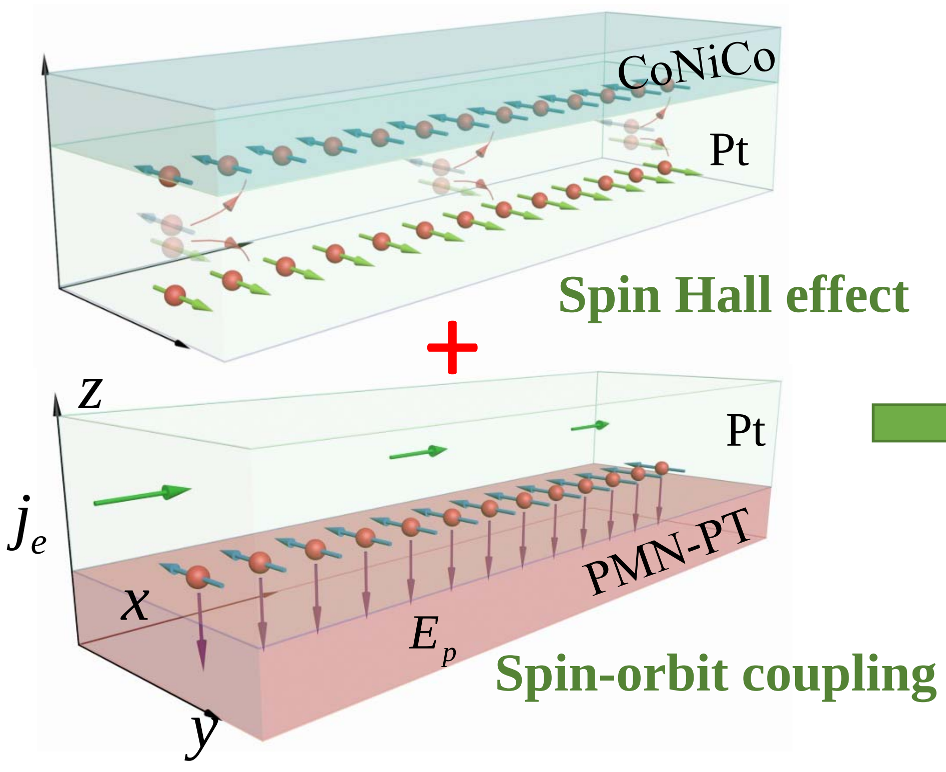


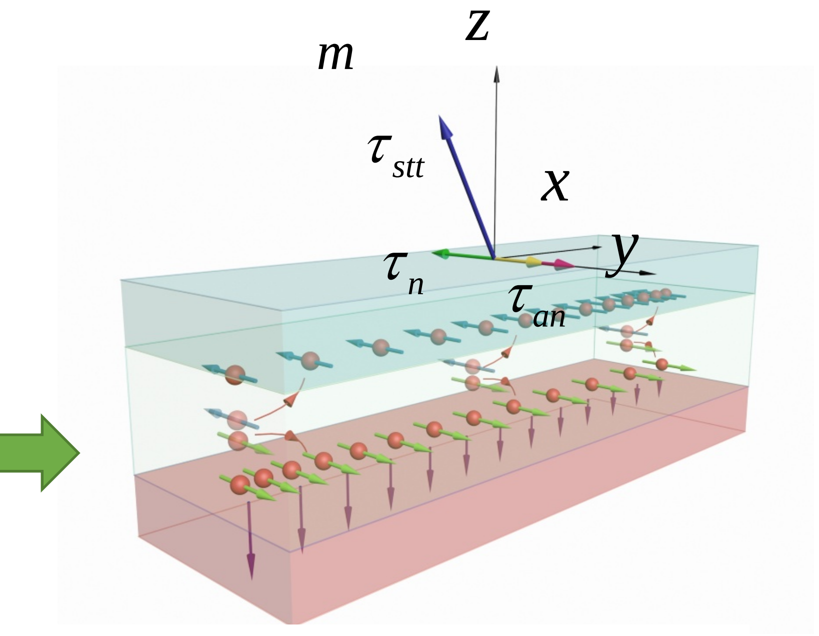


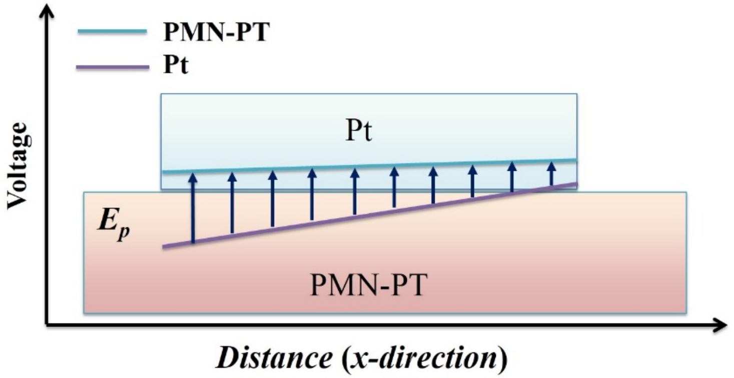
Through finite-element calculation,

$$\lambda_D = \sqrt{\varepsilon_0 k_B T_c / nq^2} \sim 0.07\ \text{nm}$$

Spin density gradient in x direction







$$H_R = \frac{\alpha_R}{h}(\hat{z} \times \hat{p}).\hat{\sigma}$$

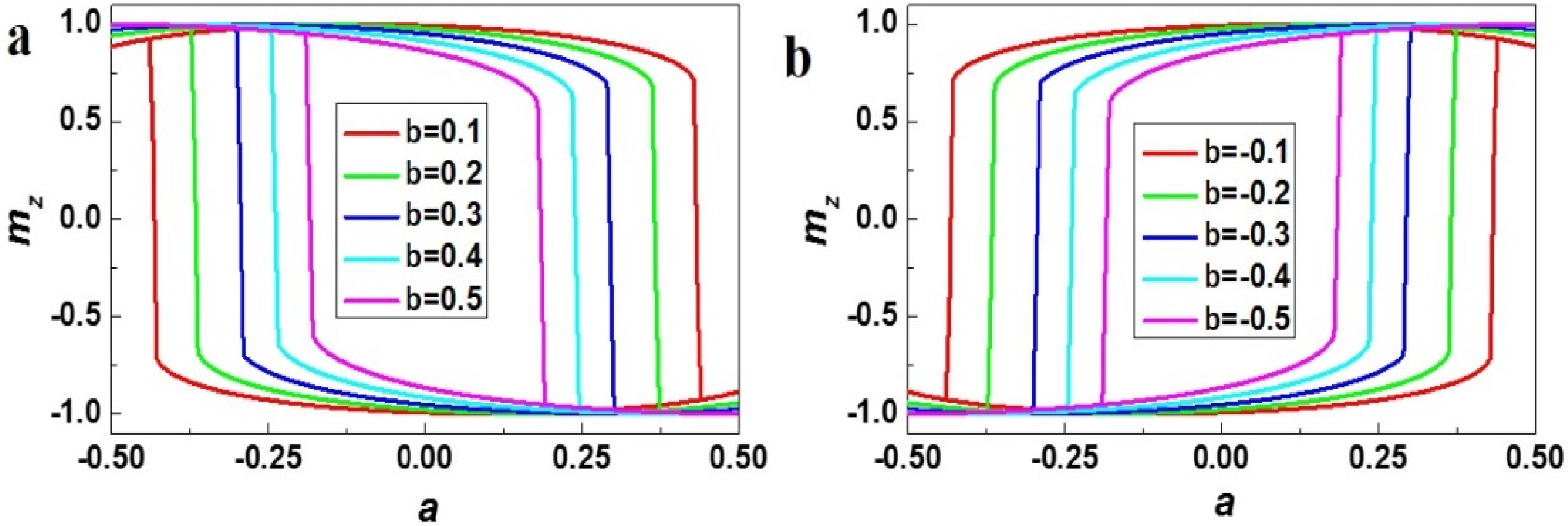
Due to the spin orbit coupling, the perpendicular electrical field can change the spin orientation of the interface Pt layer, Combining with the Spin Hall effect, the spin density gradient will be formed in x direction.

Macrospin model

$$\tau \approx -c_J / M_s \, \mathbf{M} \times \left(\partial \mathbf{M} / \partial x \right) \rightarrow \boxed{\tau_{\mathbf{n}} \approx -c\mathbf{M} \times \left(\partial \mathbf{J}_s / \partial x \right)}$$

Extra torque induced by the spin gradient

$$\vec{\tau}_{tot} = \vec{\tau}_{ST} + \vec{\tau}_{an} + \vec{\tau}_{n} = 0 \qquad \tau_{ST}^0 = \hbar J_s / 2eM_s t$$

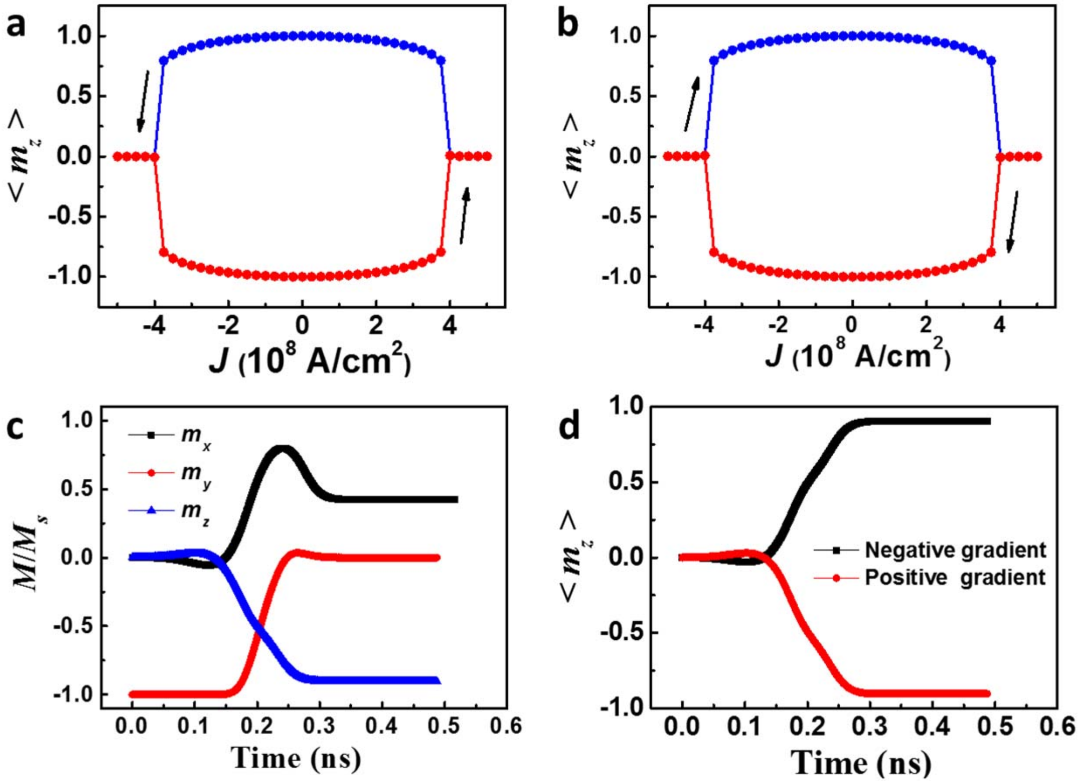


$$a = \tau_{ST}^0 / B_{an}^0 \qquad b = B_x / B_{an}^0 = \left(c\, \partial J_{sx} / \partial x \right) / B_{an}^0$$

Without external magnetic field 0， different spin density gradient will result in different deterministic switching

Micromagnetic simulations

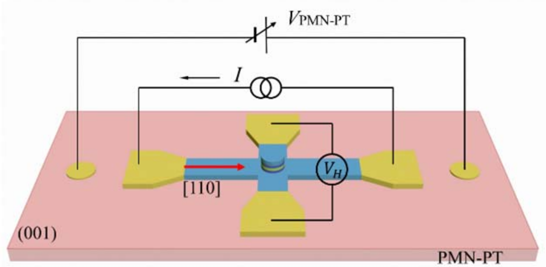
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \boxed{\frac{\alpha'}{M_s}\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \frac{\gamma p \hbar J}{2edM_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{S})} - \boxed{c\mathbf{M} \times \frac{\partial \mathbf{J}_s}{\partial x}}$$

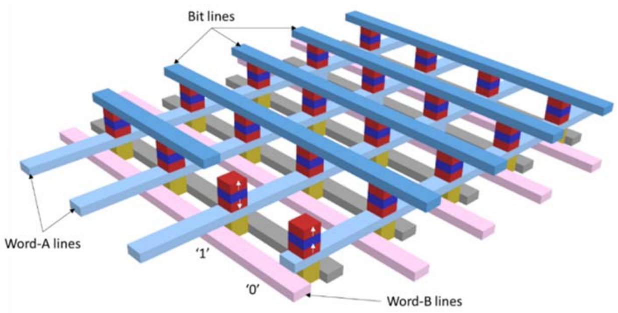


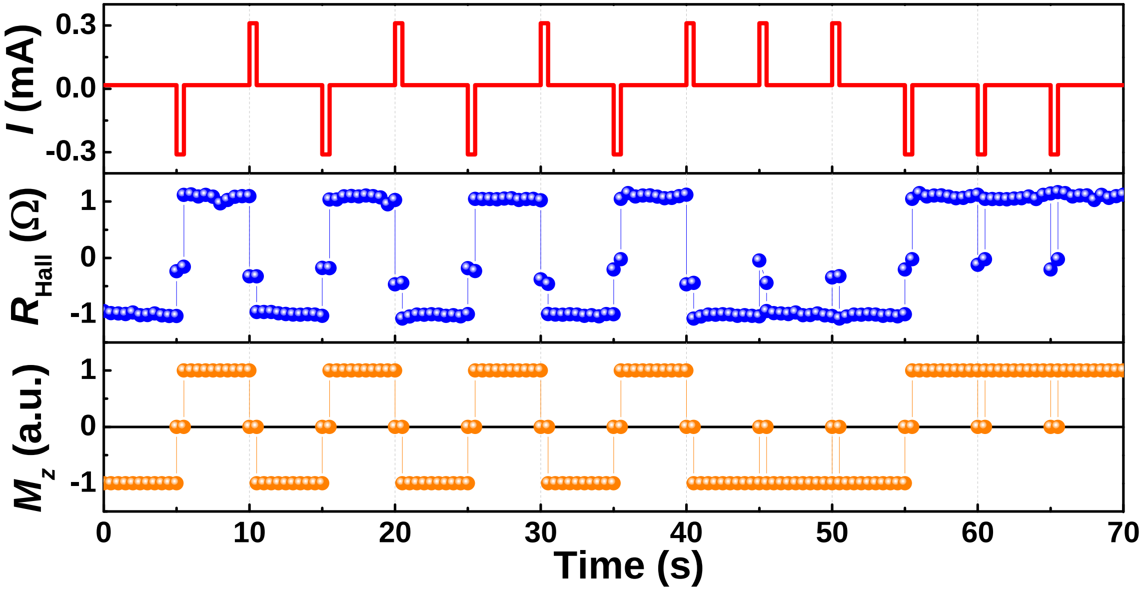
Micromagnetic simulated results are in good agreement with the experimental results.

K. M. Cai … K. Y. Wang, Nature Materials 16 (2017) 712

Using as an element for information







Information storage

nature materials

LETTERS

Electric field control of deterministic current-induced magnetization switching in a hybrid ferromagnetic/ferroelectric structure

Kaiming Cai[1†], Meiyin Yang[1†], Hailang Ju[2], Sumei Wang[3], Yang Ji[1], Baohe Li[2], Kevin William Edmonds[4], Yu Sheng[1], Bao Zhang[1], Nan Zhang[1], Shuai Liu[2], Houzhi Zheng[1] and Kaiyou Wang[1]*

Advantages：

1.without magnetic field at room temperature

2.simple device structure

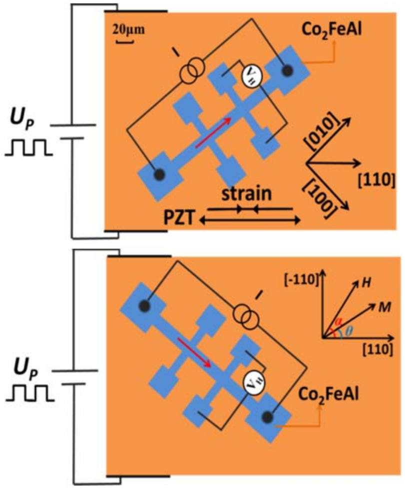
3.can fully switching clockwise and anticlockwise electrically

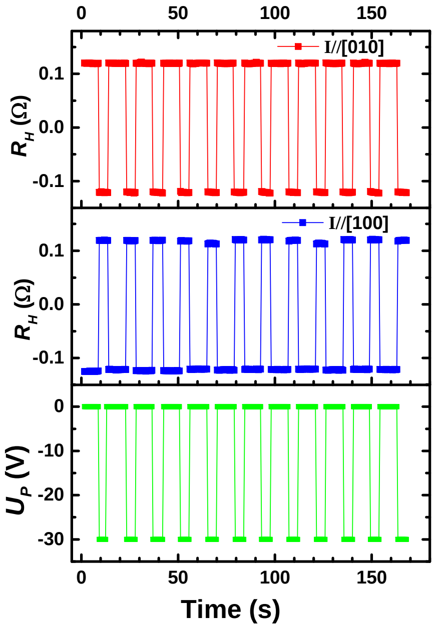
For practical applications:
--------still lots to do for both memory&logic

1: lower down the electrical voltage ---shrinking device size and using ferroelectric thin film

--------------or have both sign of switching in other simpler way

2: decreasing the current density---- finding some materials with large Spin Hall angle   -----or without electrical current





Voltage control magnetization switching

B. Zhang et al., Scientific Reports 6 (2016)28458