An Overview of Spintronics in 2D Materials

Wei Han (韩伟)

北京大學
PEKING UNIVERSITY

北京大学量子材料科学中心
International Center for Quantum Materials, PKU

Outline

I. Introduction to spintronics (Lecture I)

II. Spin injection and detection in 2D (Lecture I)

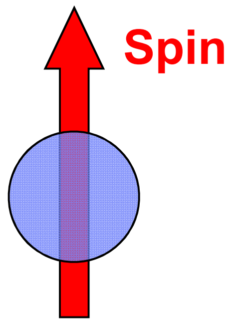
III. Putting magnetic moment in 2D (Lecture II)

IV. Spin Hall effect and spin orbit torque in 2D (Lecture II)

V. Acknowledgement

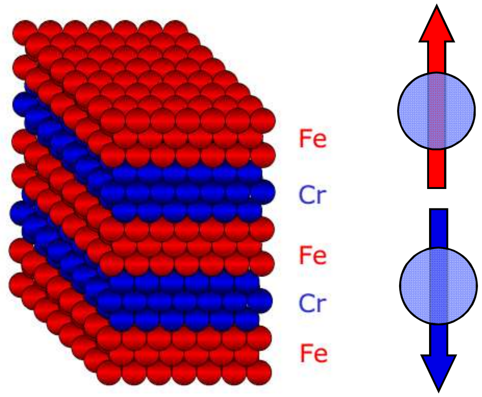
Summary of Lecture I

History

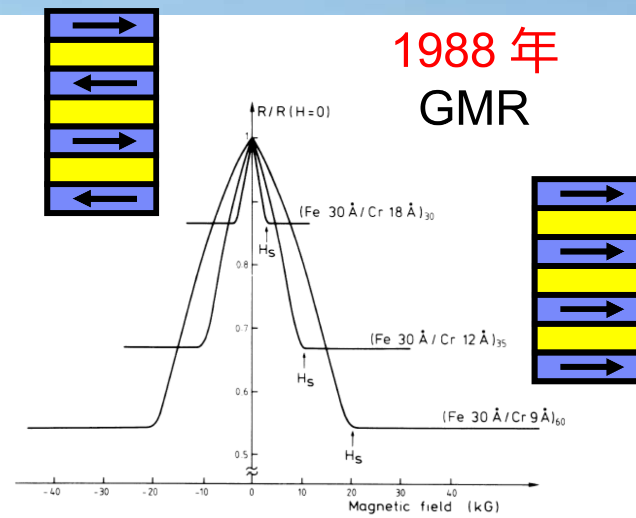


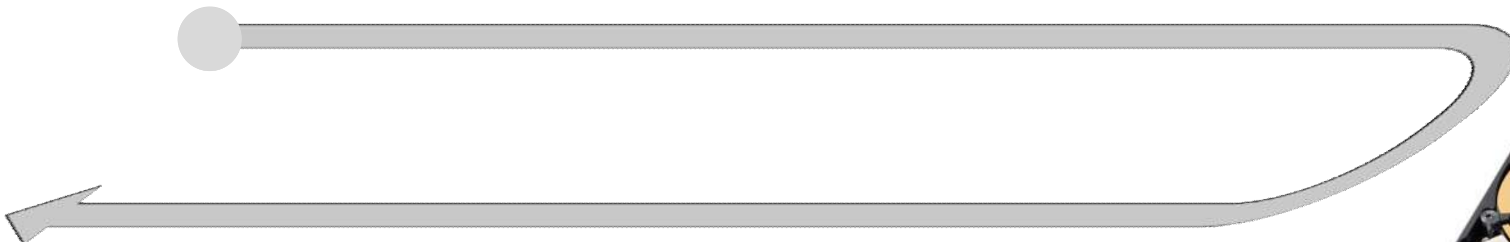
Electron

Magnetic structure



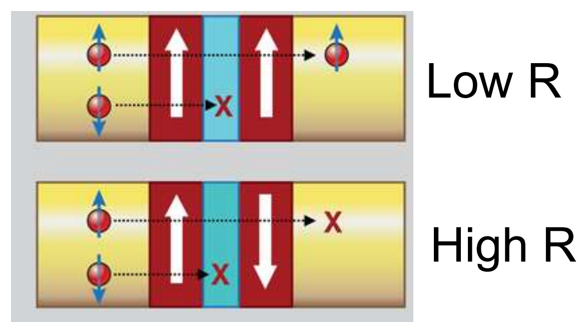
1988 年
GMR



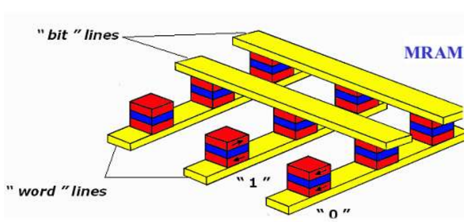


~1997 年
Hard drive

1991-2004
TMR

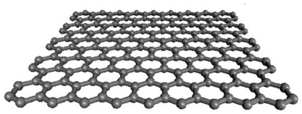


2001- present
MRAM



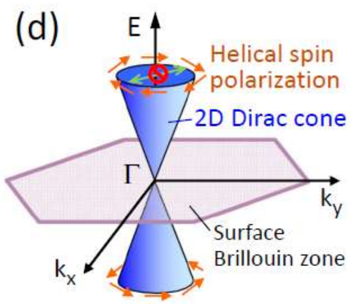
Summary of Lecture I

- ✓ **Graphene is a very good candidate material for spin channels**

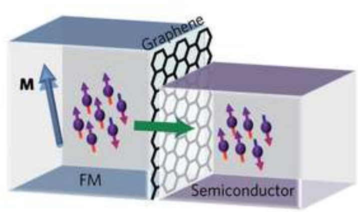


- ➢ **Large spin signal (with tunnel barrier)**
- ➢ **Long spin lifetime (6.2 ns in BLG)**
- ➢ **Long spin diffusion length (> 10 micro meters at RT)**
- ➢ **Easy to manipulate (Gate)**

- ✓ **Electrical detection of spin --momentum locking in TI**



- ✓ **Graphene "wins" the match for tunnel barrier**



Outline

I. Introduction to spintronics (Lecture I)

II. Spin injection and detection in 2D (Lecture I)

III. Putting magnetic moment in 2D (Lecture II)

IV. Spin Hall effect and spin orbit torque in 2D (Lecture II)

V. Acknowledgement

Outline

I. Introduction to spintronics (Lecture I)

II. Spin injection and detection in 2D (Lecture I)

III. Putting magnetic moment in 2D (Lecture II)

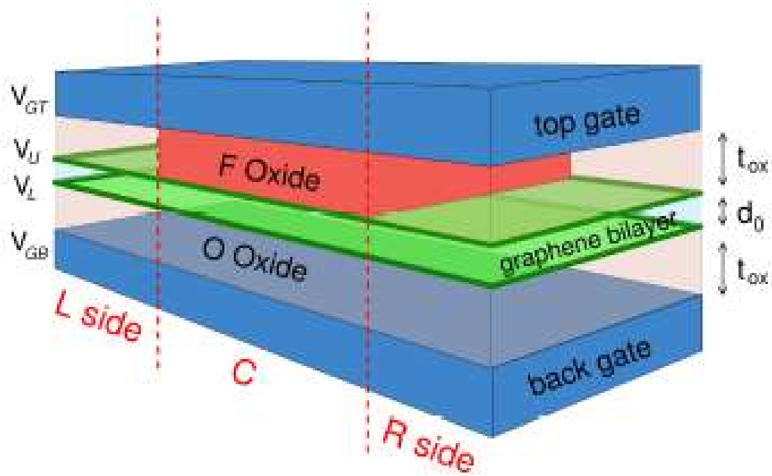
- Graphene
- Topological insulator

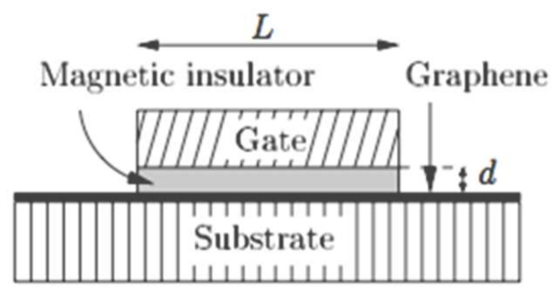
Why make graphene magnetic

PHYSICAL REVIEW B **83**, 155447 (2011)

Quantum anomalous Hall effect in single-layer and bilayer graphene

Wang-Kong Tse,[1] Zhenhua Qiao,[1] Yugui Yao,[1,2] A. H. MacDonald,[1] and Qian Niu[1,3,*]





PHYSICAL REVIEW B **77**, 115406 (2008)

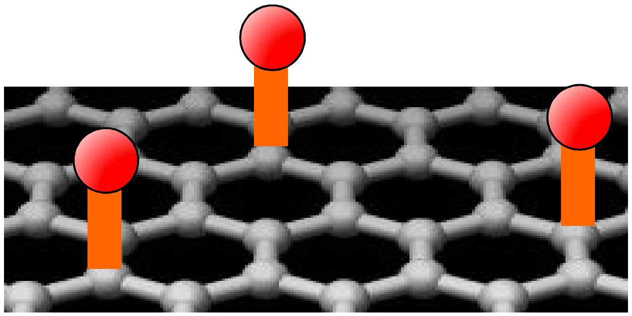
Spin transport in proximity-induced ferromagnetic graphene

Håvard Haugen,* Daniel Huertas-Hernando, and Arne Brataas

Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

How to make graphene magnetic

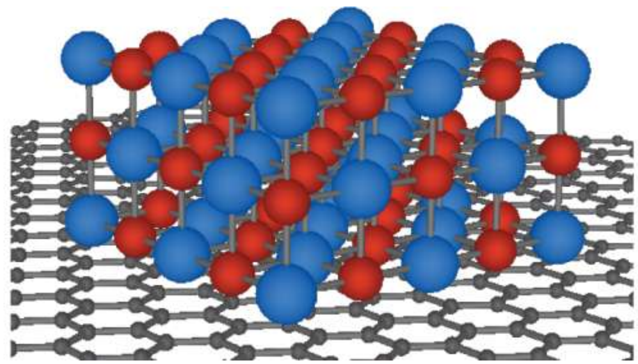
Adatom and molecule doping of graphene



Doping effect

Examples:
Mn doped GaAs
ZnO

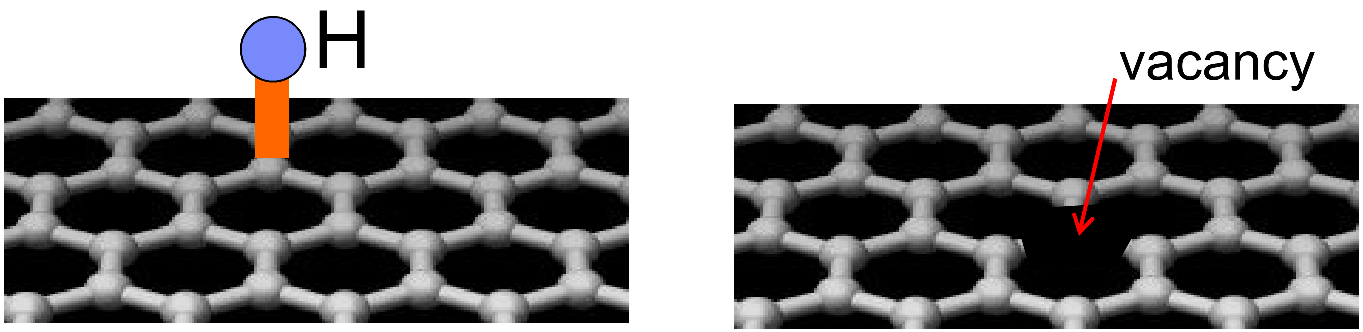
Ferromagnetic oxides/graphene

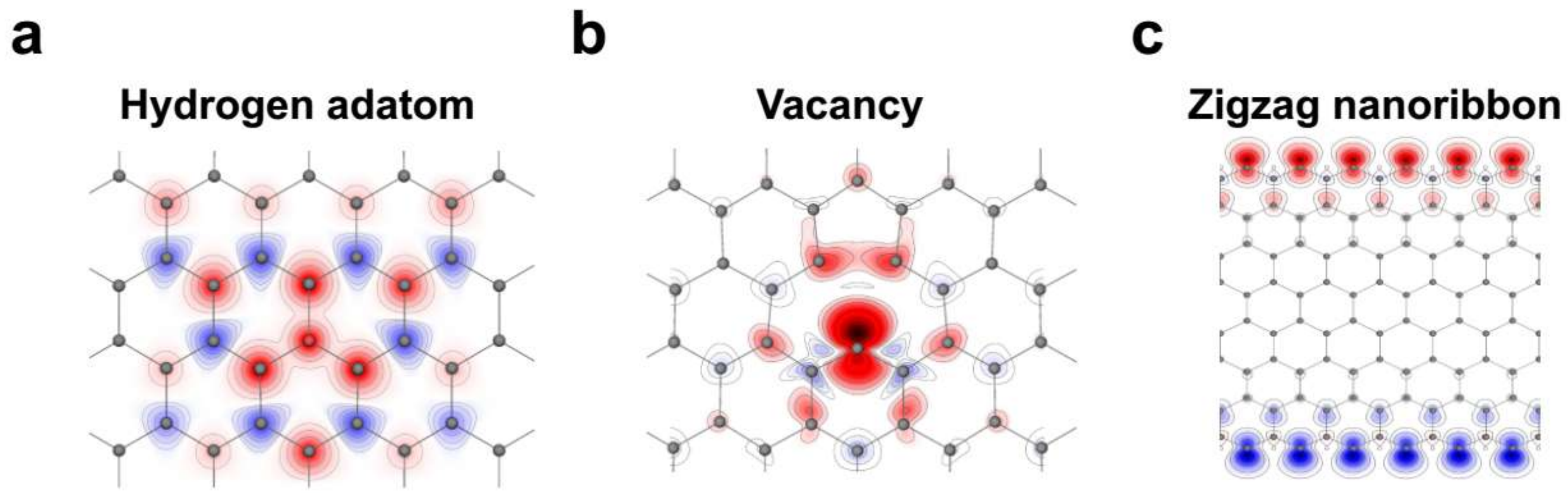


Proximity effect

Examples:
Co-Pt (Magnetism in Pt)

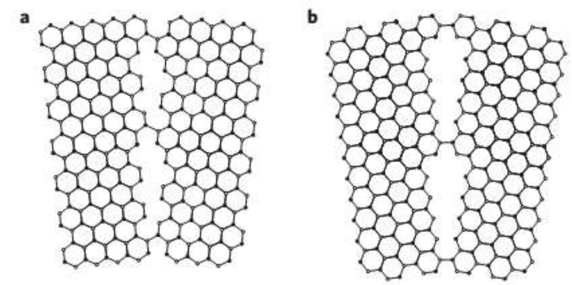
Making graphene magnetic



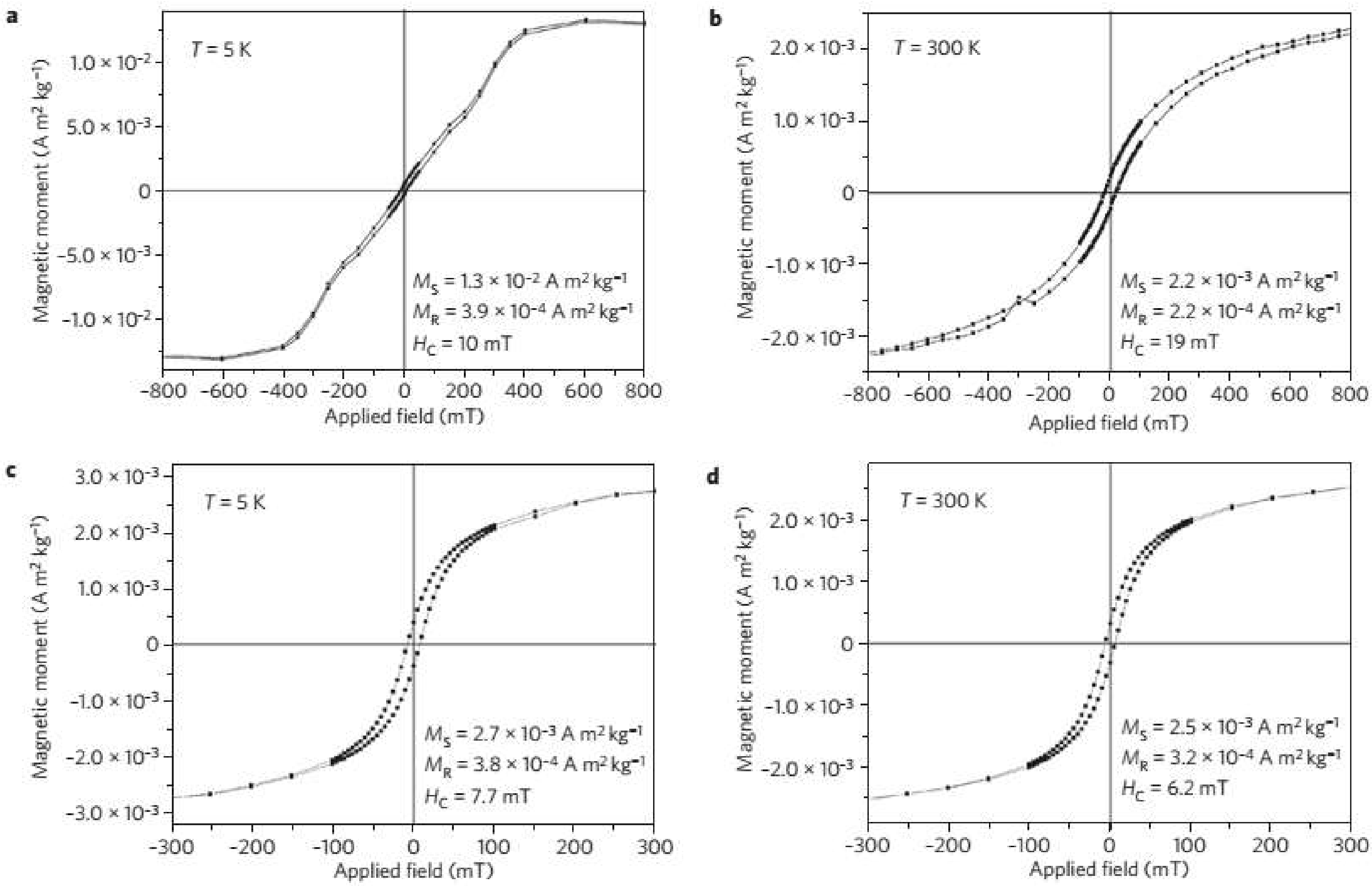


Yazyev and Helm, PRB (2007)

Making graphene magnetic



Ferromagnetic ??

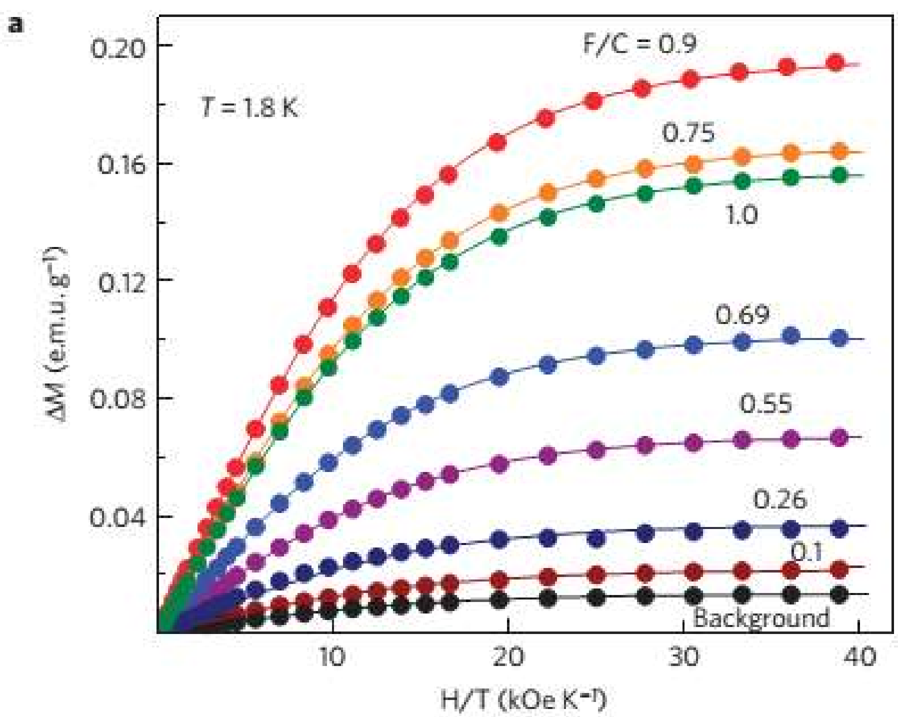


Cervenka, et al, Nature Physics (2009)

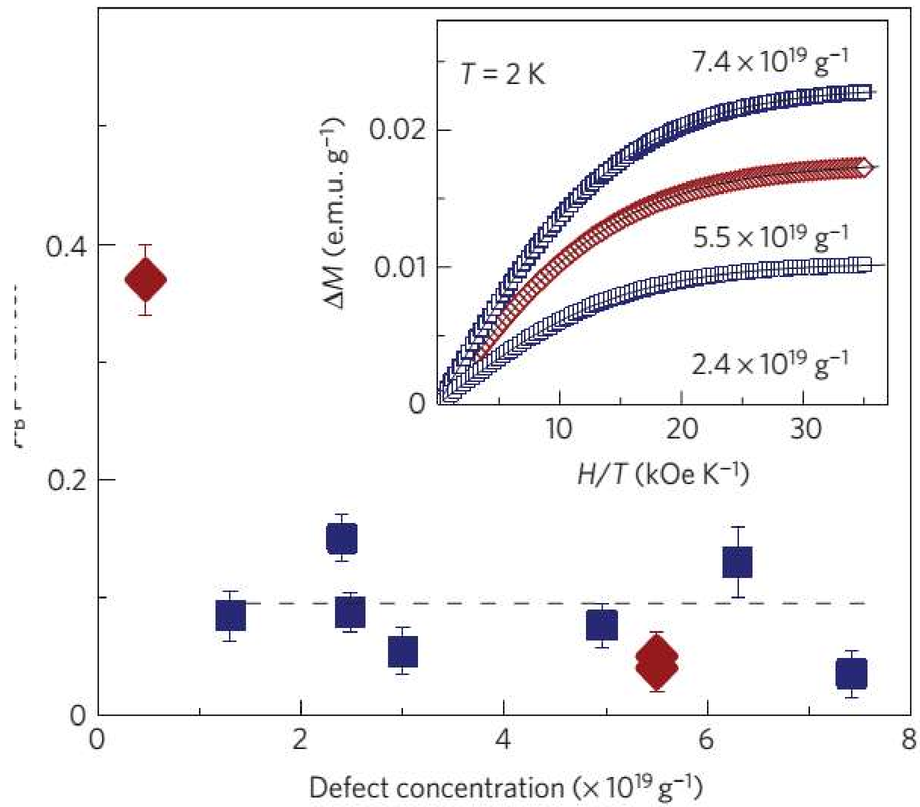
Making graphene magnetic

Paramagnetic ??

- **F doped**



- **Defects**

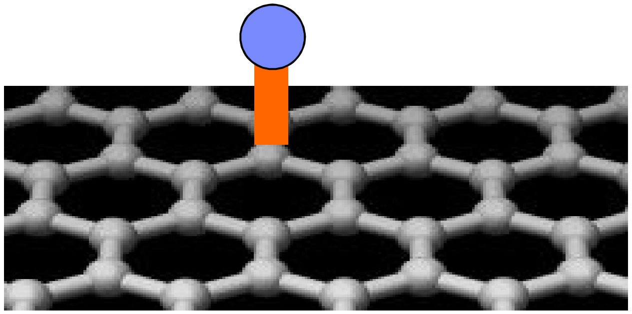


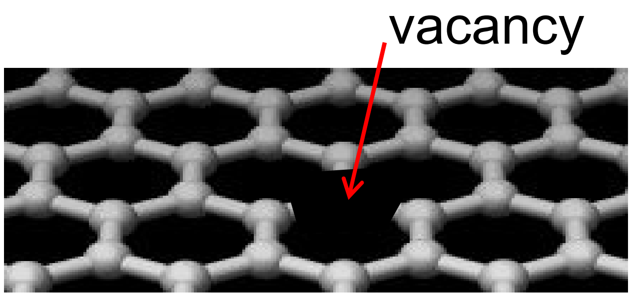
Nair, et al, Nature Physics (2012)

Question

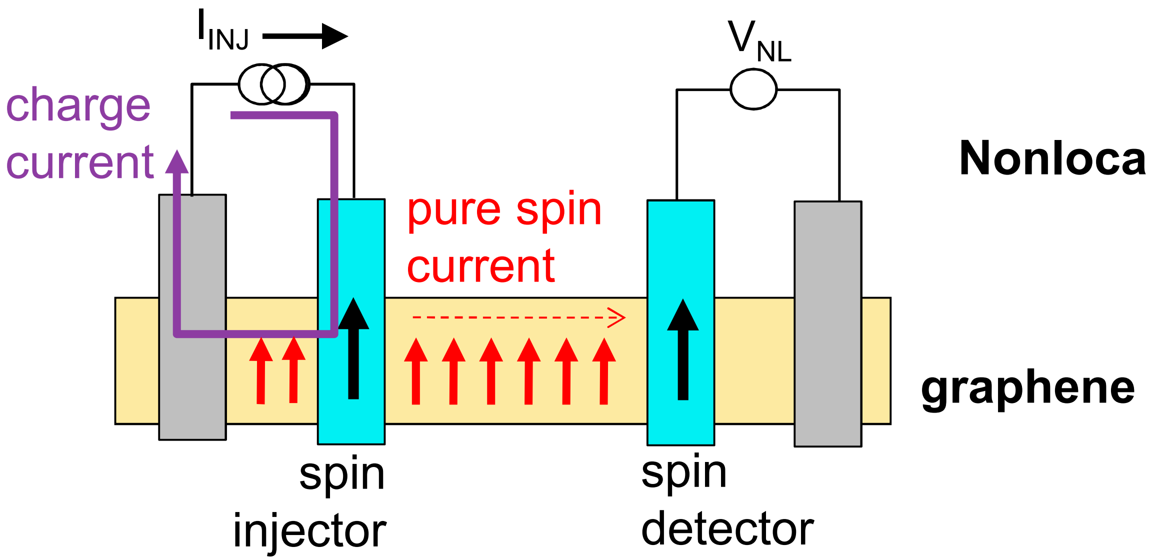
Ferromagnetic ??

Paramagnetic ??



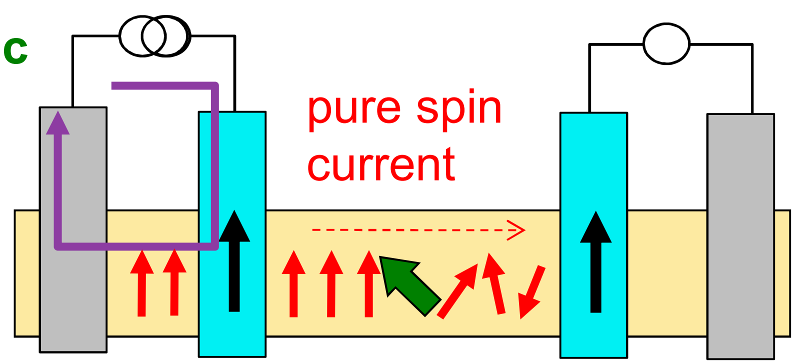


Making graphene magnetic



Nonlocal spin transport geometry

With magnetic moment



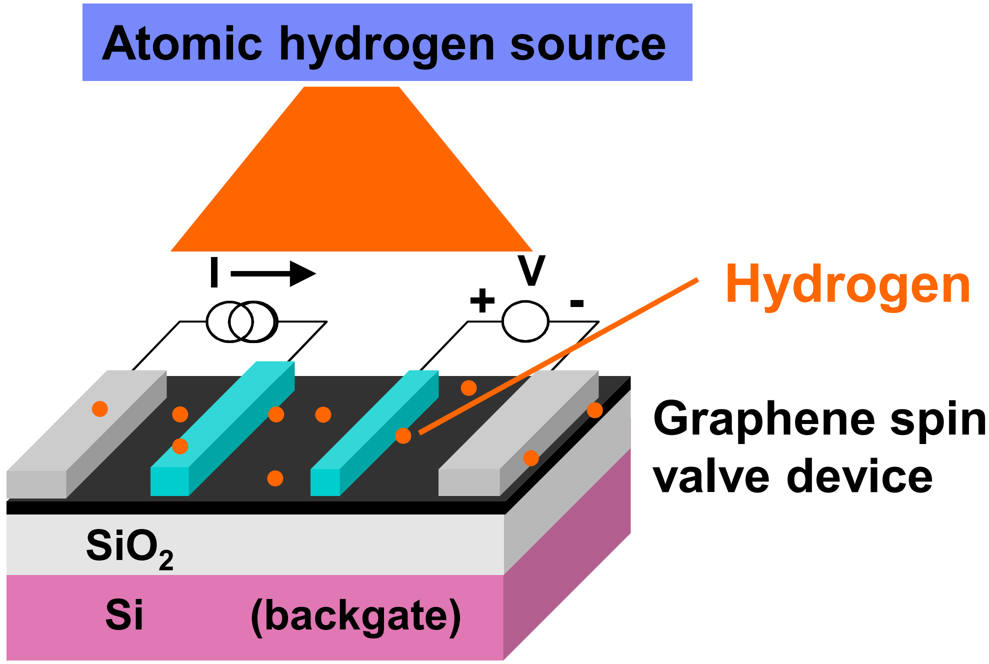
Magnetic moment could scatter pure spin current through exchange interaction:

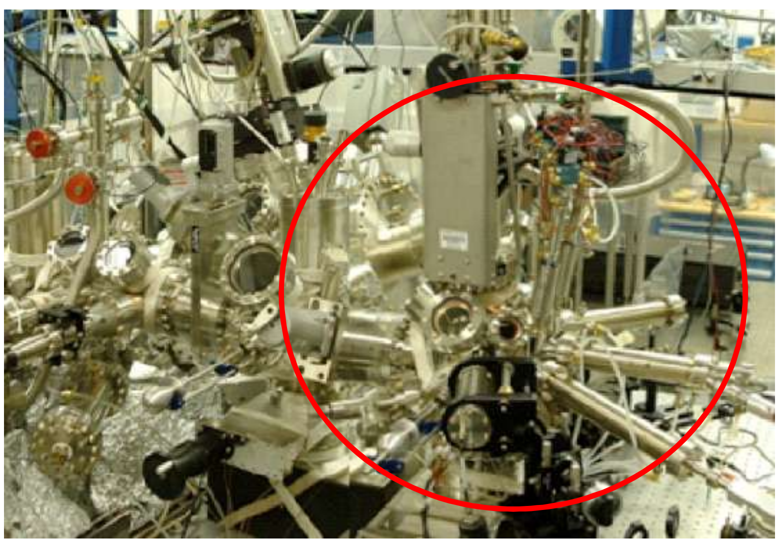
$$\mathcal{H}_{ex} = A_{ex}\,\vec{S}_e \cdot \vec{S}_M$$

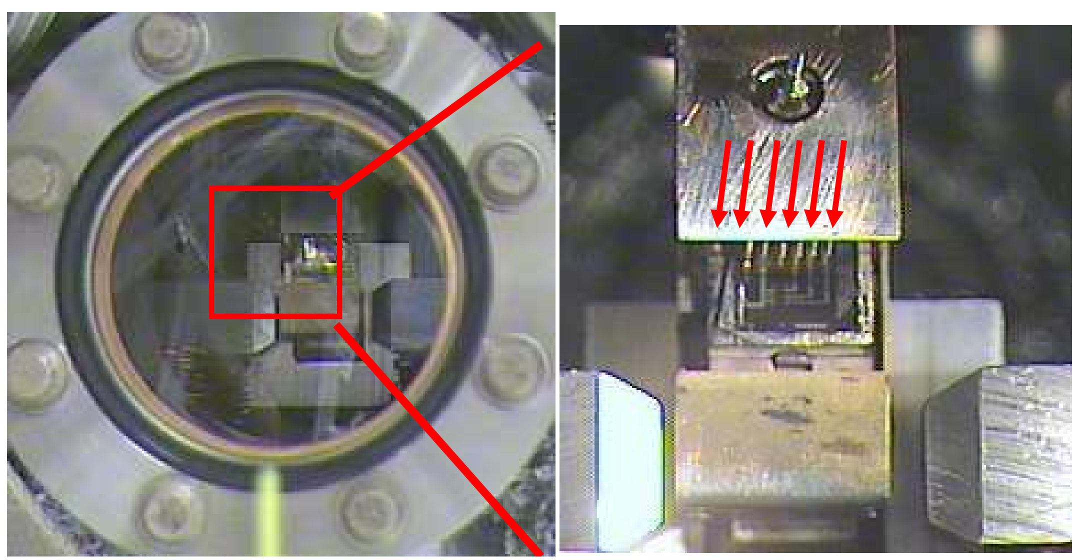
- Localized measurement
- Direct coupling of spin to magnetic moment

Making graphene magnetic

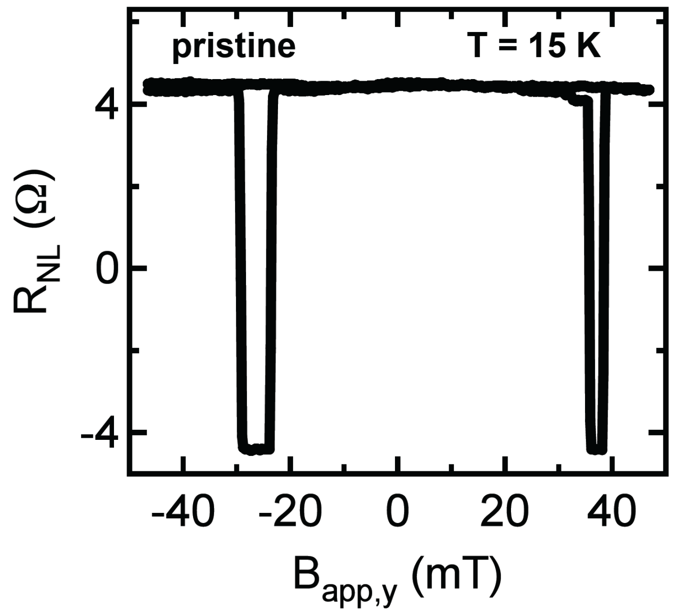
- All measurements done in ultrahigh vacuum (UHV)
- Compare immediately before and after hydrogen doping





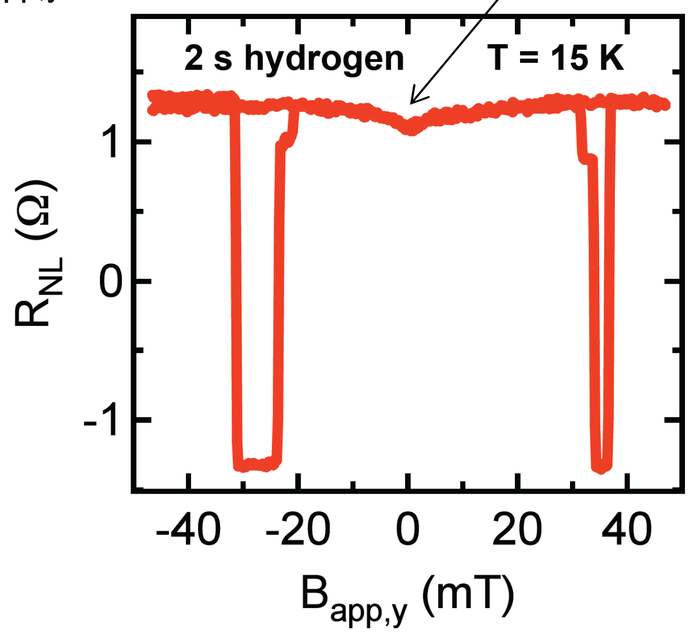


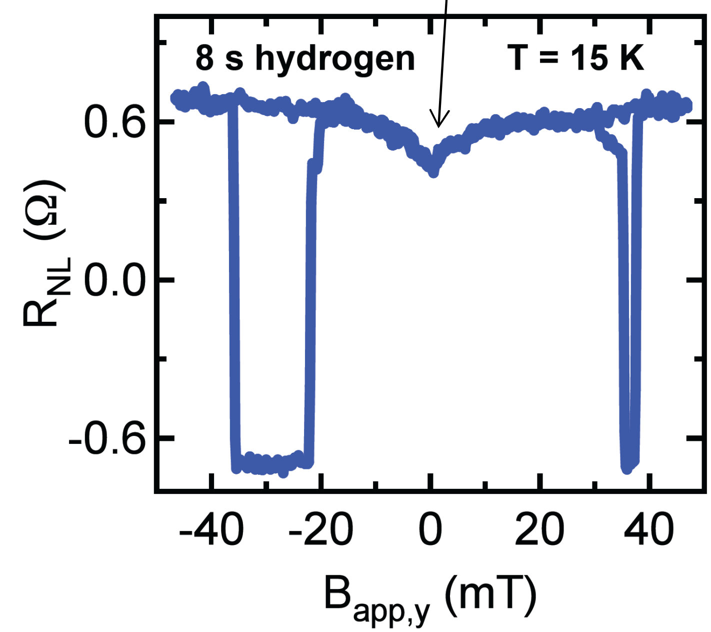
Making graphene magnetic



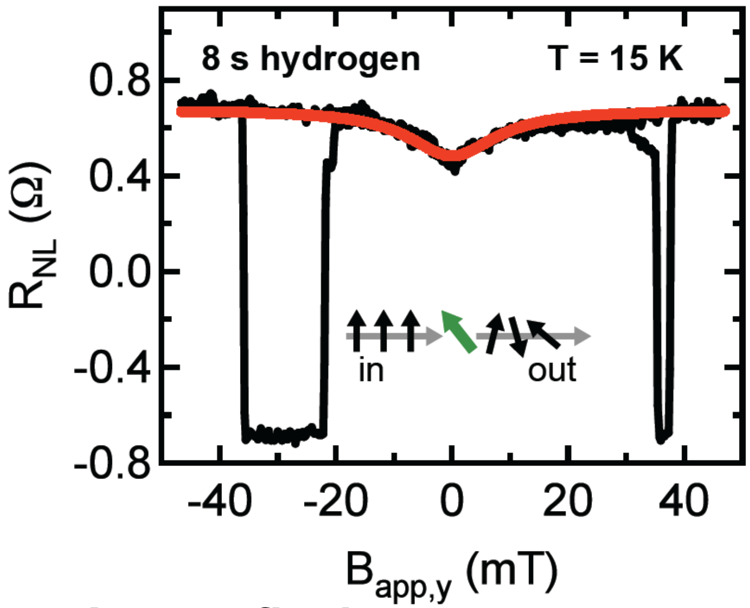
Aha! A dip in the nonlocal spin signal.

This may be the magnetic moment!

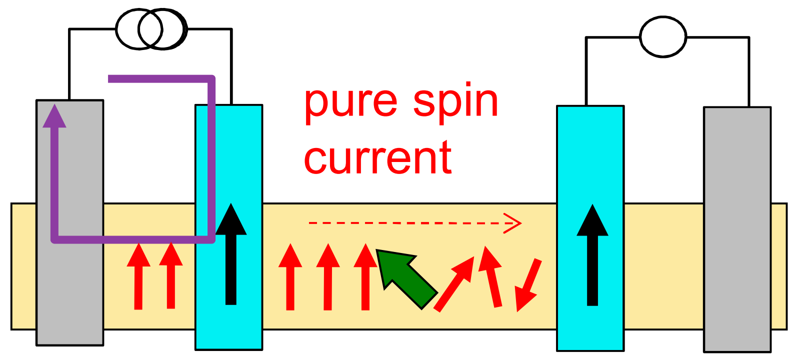




Making graphene magnetic



Orange arrows = amount of spin at the spin detector



At zero field

$$H_{ex} = A_{ex}\,\vec{S}_e \cdot \vec{S}_M$$

Due to exchange coupling, pure spin current is scattered by magnetic moment

Fewer spins at detector

At high field

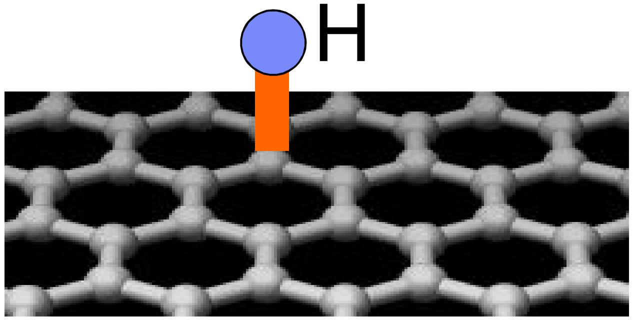
$\vec{S}_e$ and $\vec{S}_M$ decouple!

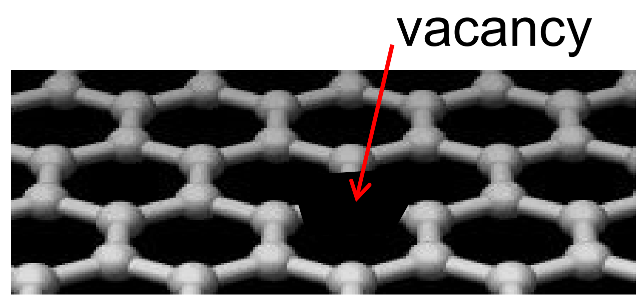
Scattering by exchange coupling is suppressed

More spins at detector

Making graphene magnetic

Doping effect





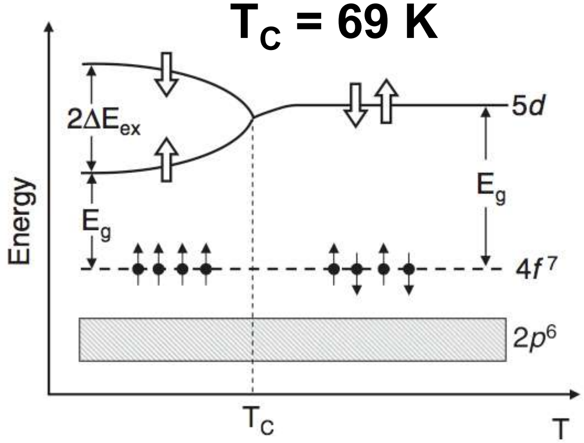
→ Paramagnetic !!

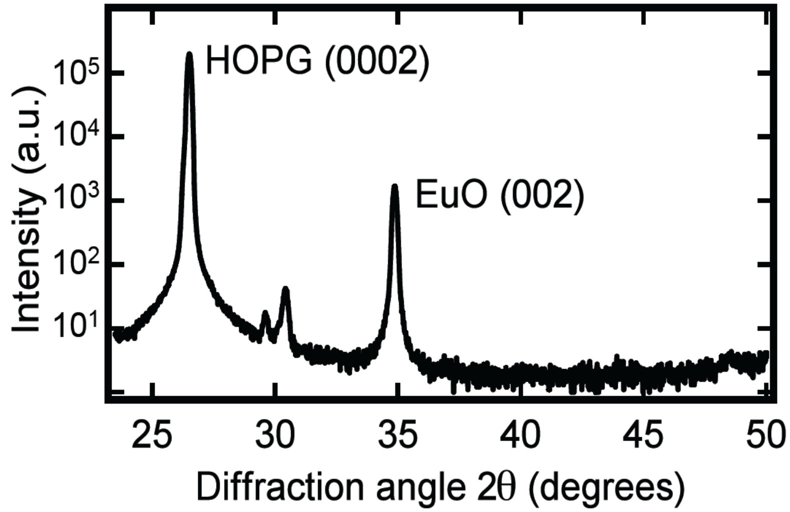
McCreary, et. al, PRL (2012)

Making graphene magnetic

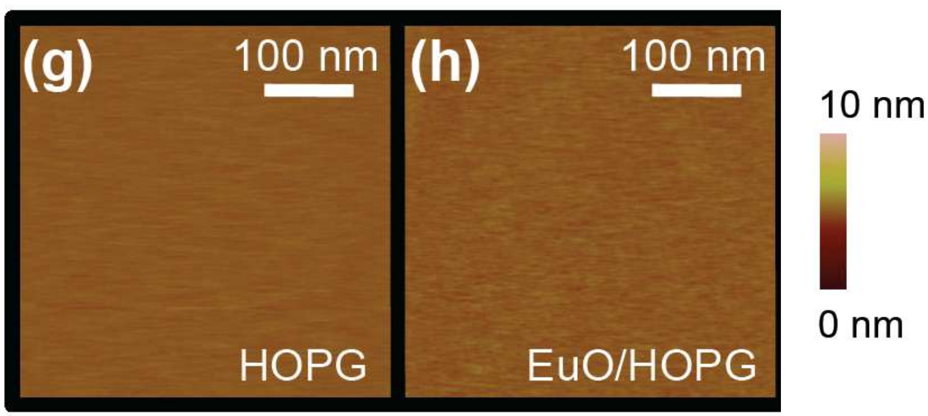
Proximity effect with EuO

T_C = 69 K

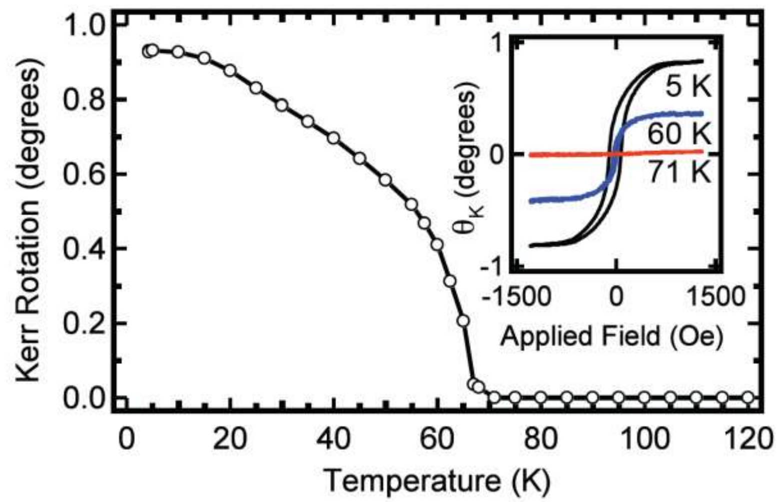




T. Santos, et. al., *PRL* 101, 147201 (2008)

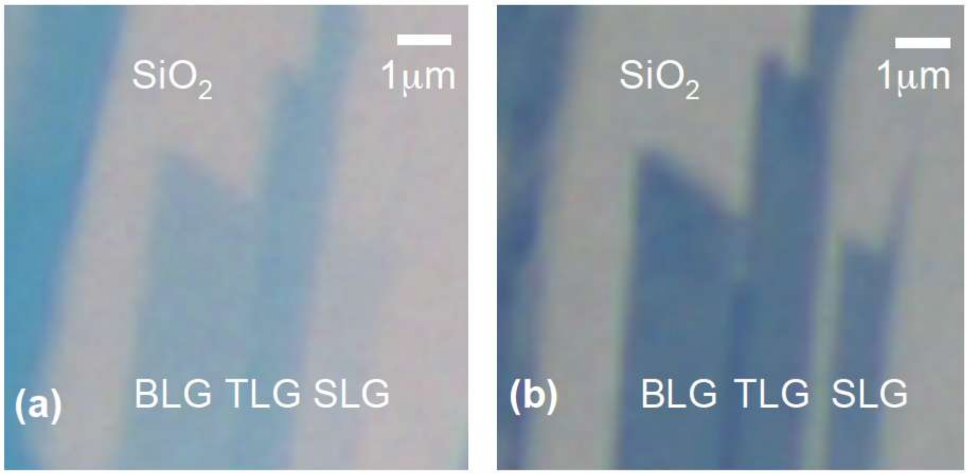


0.1 nm rms **0.2 nm rms**



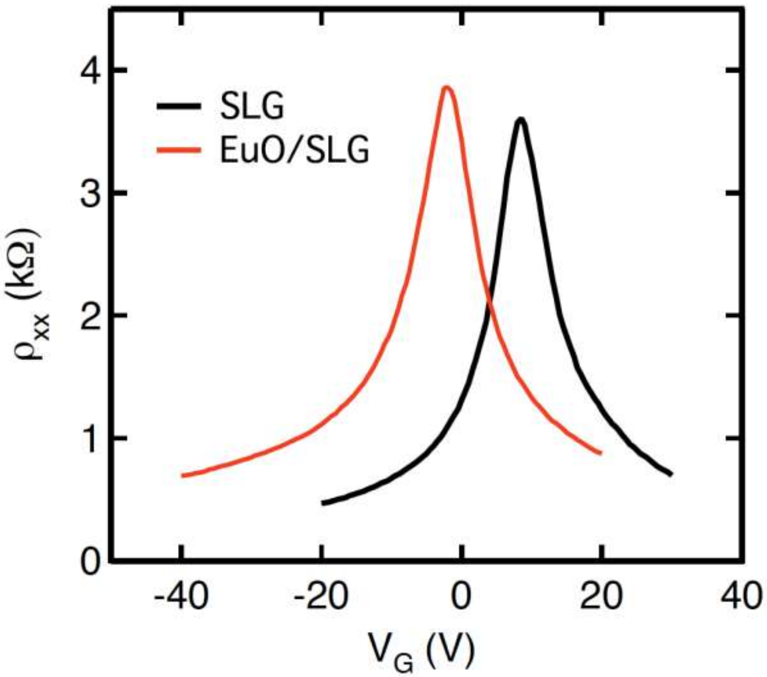
Making graphene magnetic

Proximity effect with EuO



Graphene on SiO_2

5 nm EuO on Graphene on SiO_2

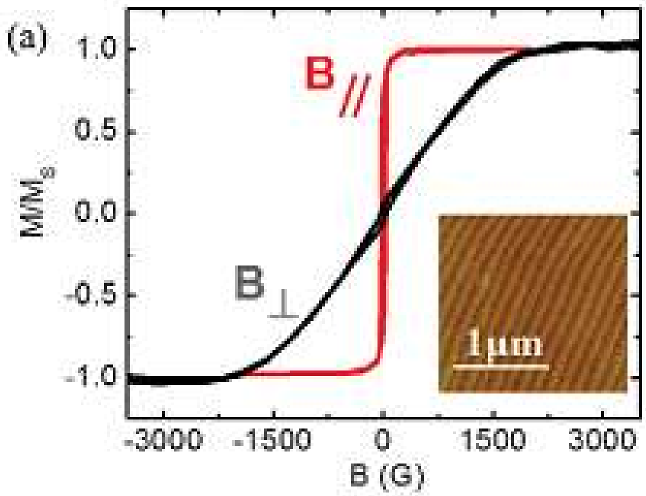


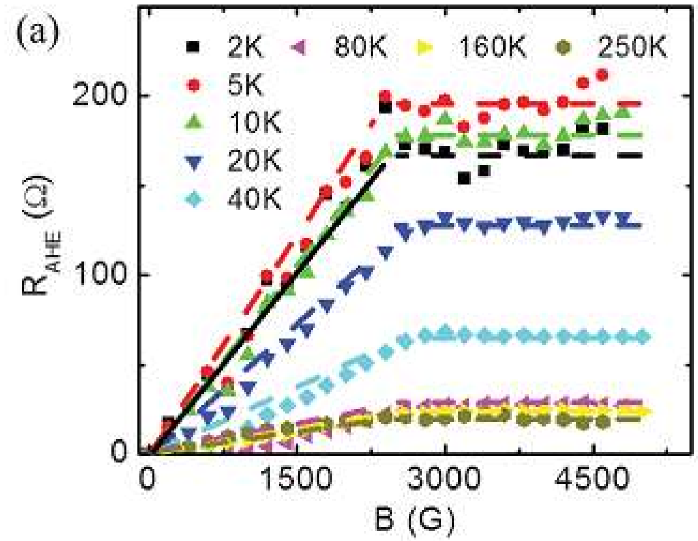
- **No success of observing magnetic graphene/EuO in our group**

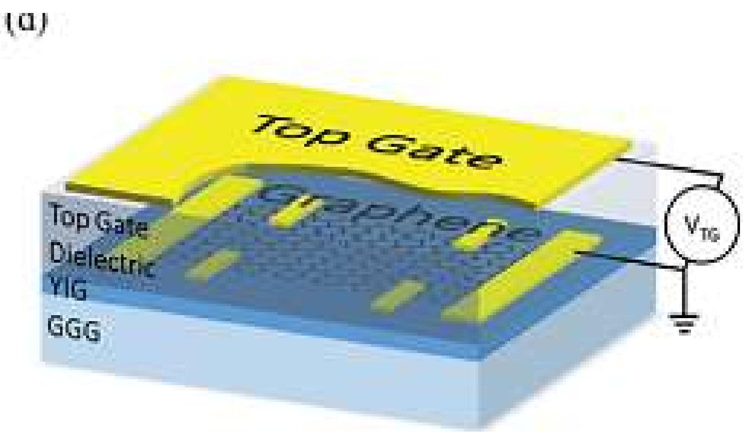
A. Swartz, et. al, ACS Nano (2012)

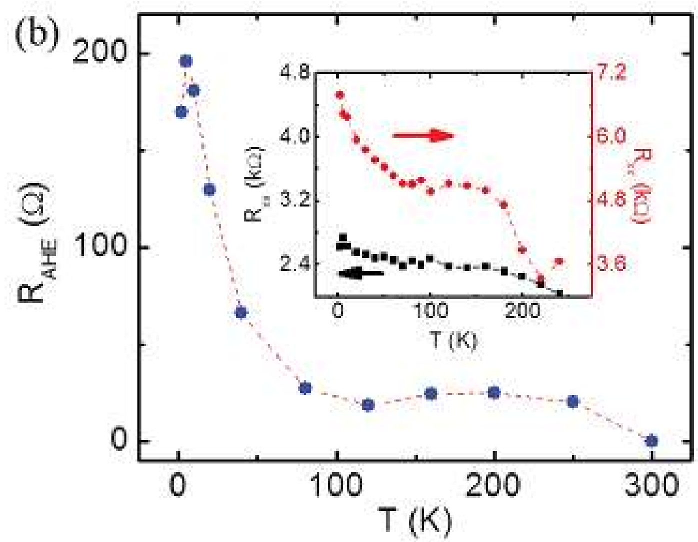
Making graphene magnetic

The first observation of Proximity effect in graphene with YIG





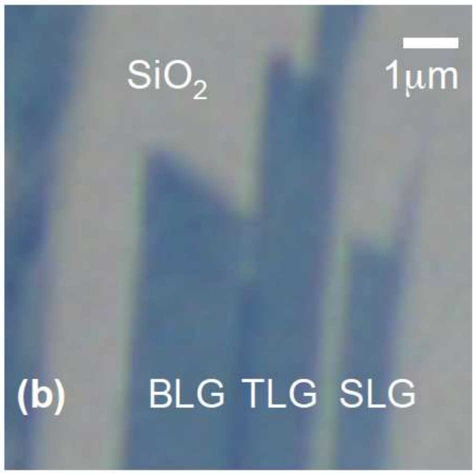




Wang, et al, PRL (2015)

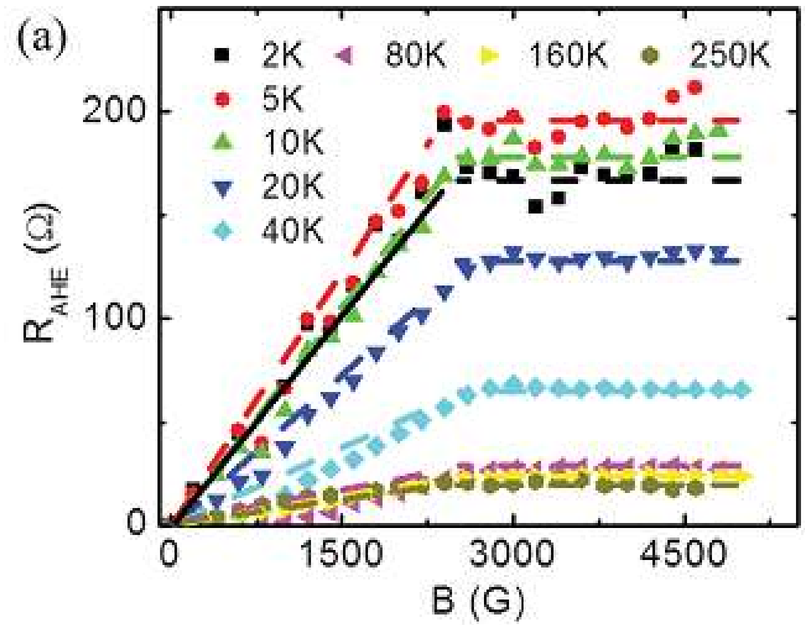
Making graphene magnetic

What if we try harder on EuO/Graphene?



5 nm EuO on Graphene

??



However, there is NO if.

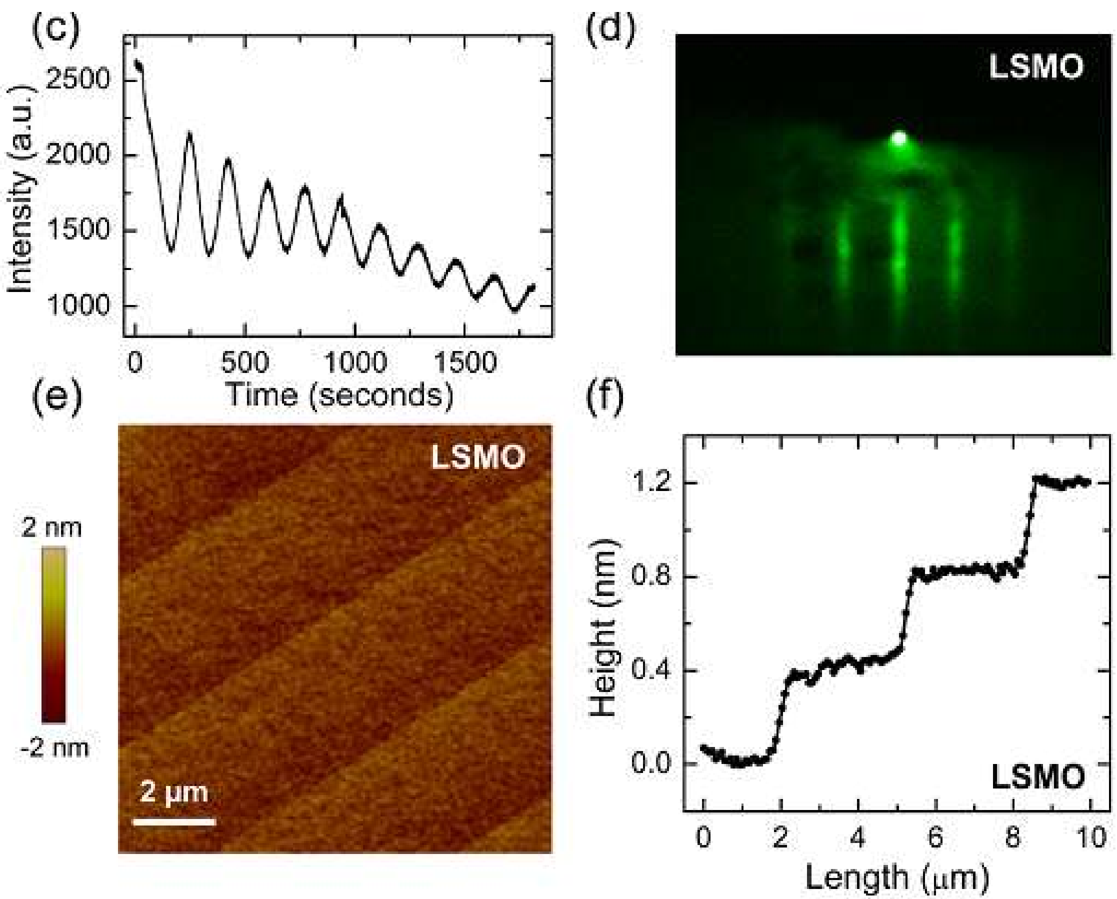
Note: Sometimes, you are so close to the peak.
Just try harder and move one more step!!

Making graphene magnetic

Note: Sometimes, you are so close to the peak. Just try harder and move one more step!

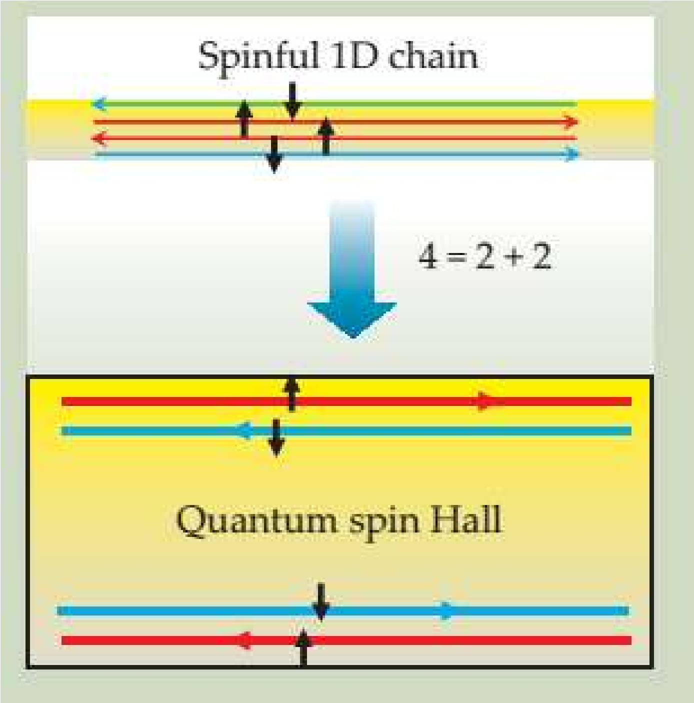
Making graphene magnetic

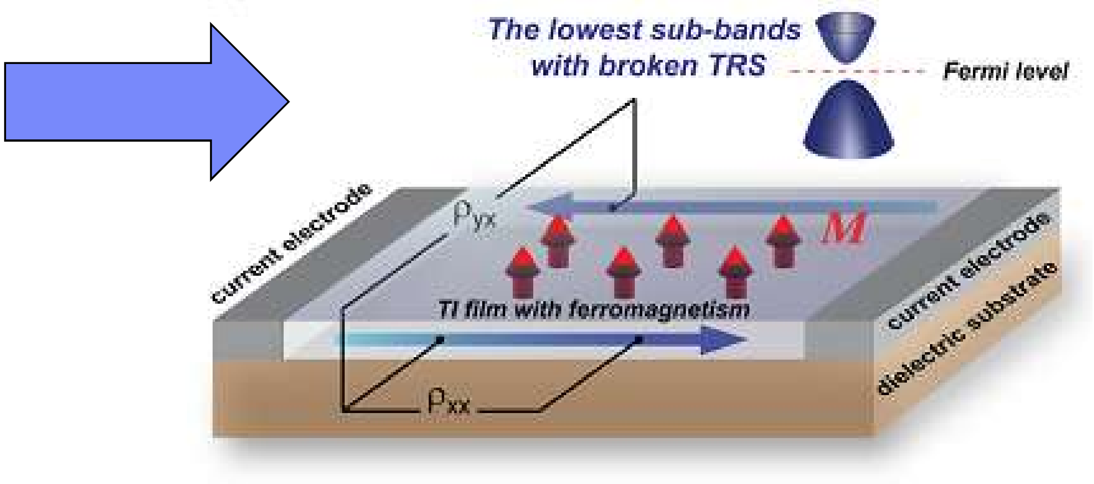
Moving forward



Wei Yuan, Yuelei Zhao, Chi Tang, Tang Su, Qi Song, Jing Shi*, and Wei Han*, Appl. Phys. Lett. 107, 022404 (2015).

Why make TI magnetic



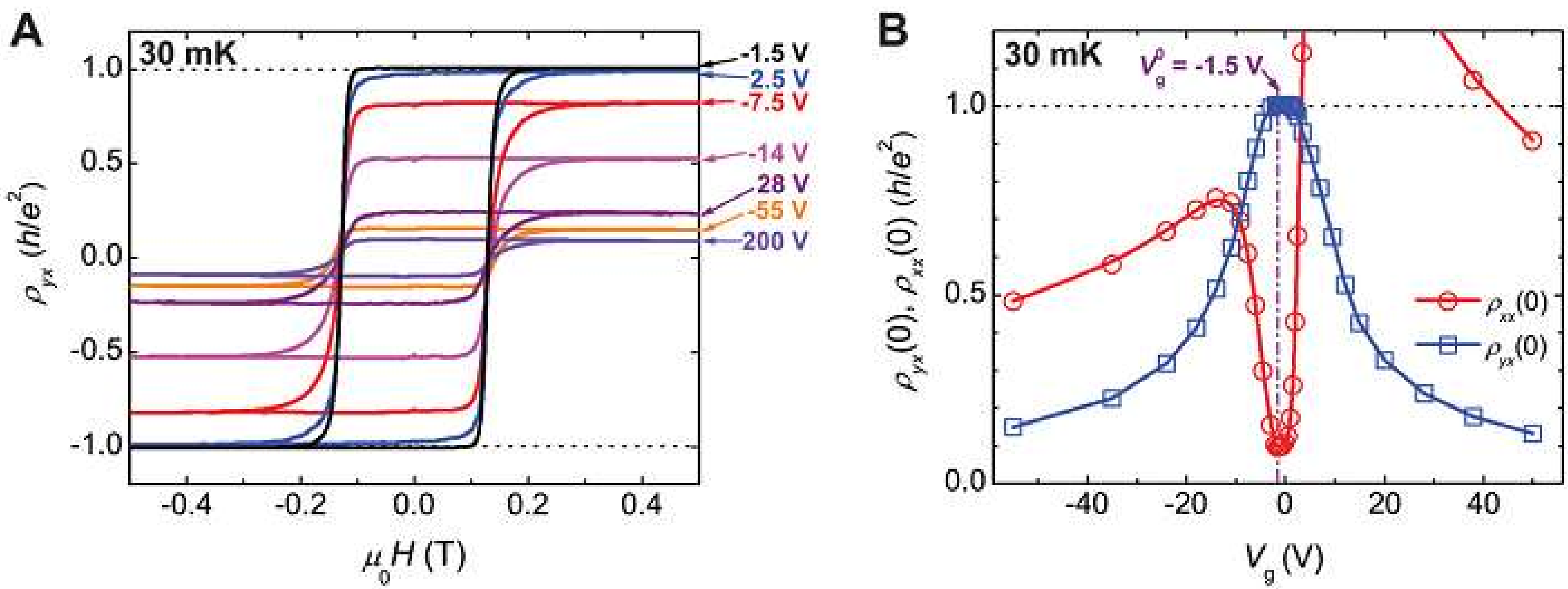


Quantum Anomalous Hall effect

How to make TI magnetic

Doping effect by Cr/V

Observation of the QAH

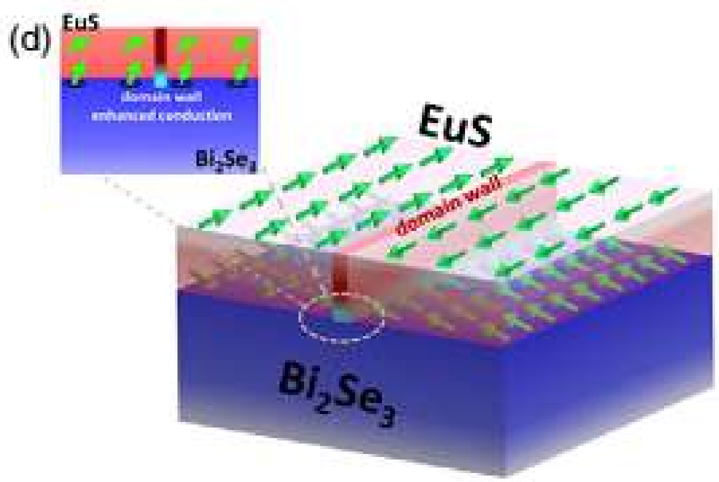


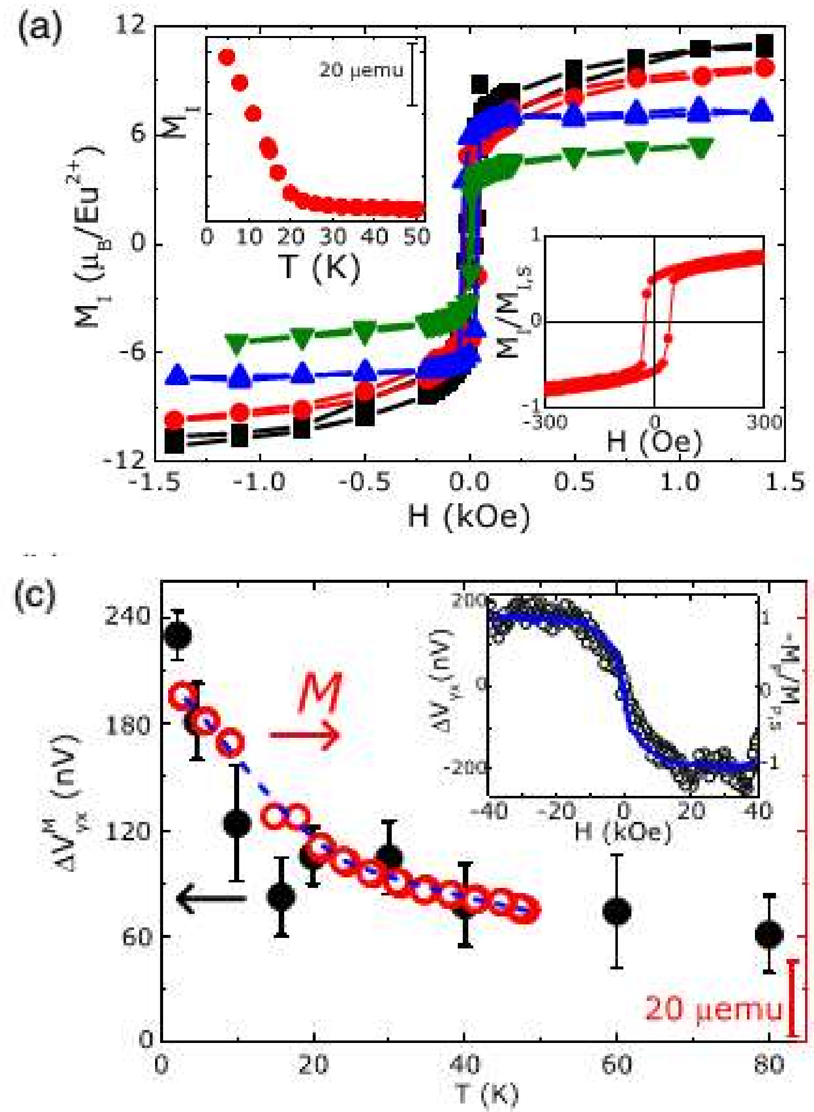
Chang, et al, Science (2013)

More information, please see the results of **Q. Xue** group (Tsinghua University), **K. Wang** group (UCLA), **J. Moodera** (MIT), etc

How to make TI magnetic

Proximity effect





Wei, et al, PRL (2013)

Outline

I. Introduction to spintronics (Lecture I)

II. Spin injection and detection in 2D (Lecture I)

III. Putting magnetic moment in 2D (Lecture II)

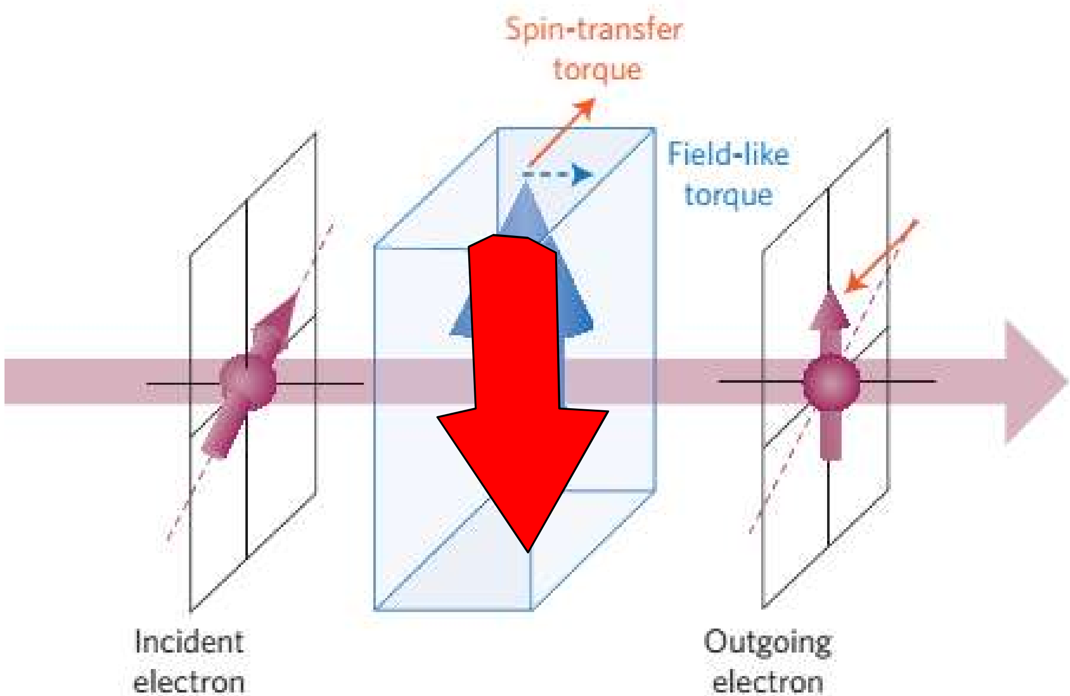
IV. Spin Hall effect and spin orbit torque in 2D (Lecture II)

V. Acknowledgement

Introduction to spin-orbit torque

Spin transfer torque

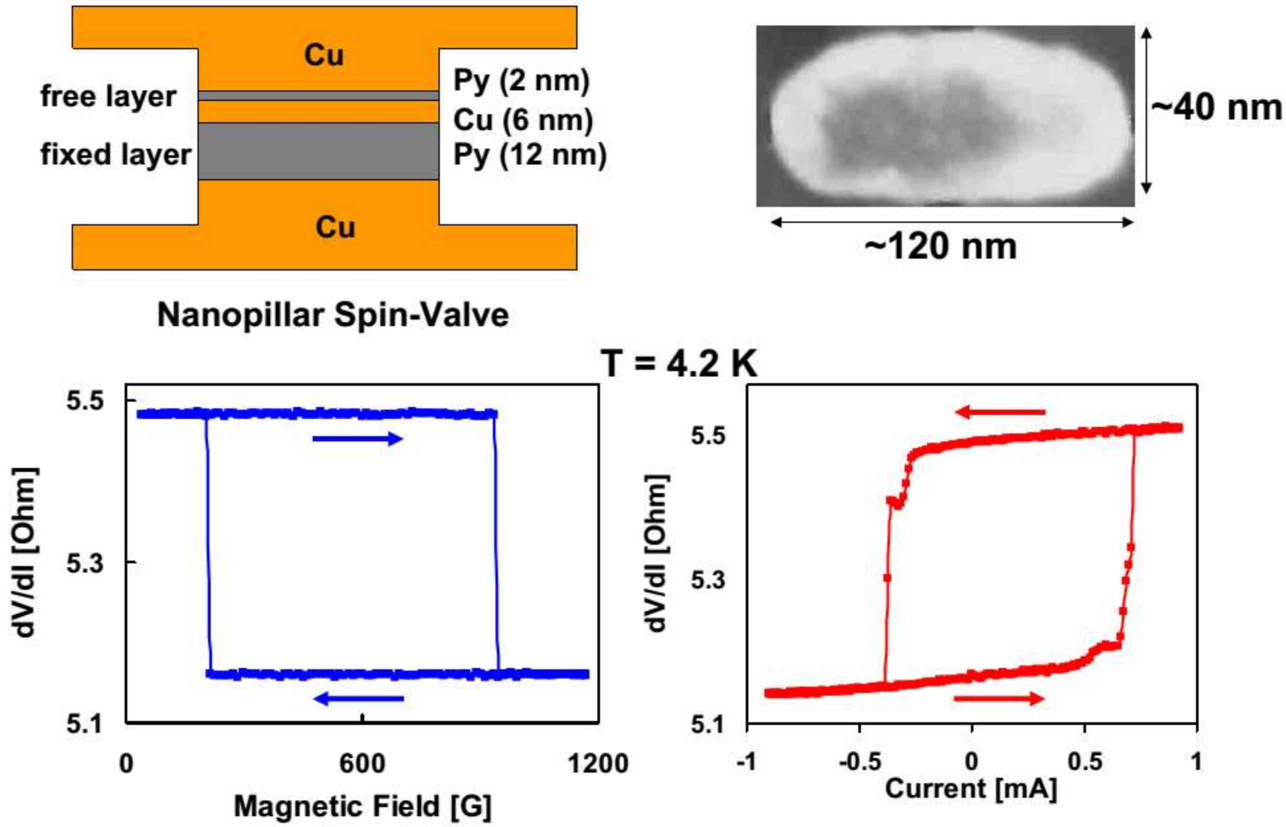
$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$



Brataas, et al. Nature Mater. 11, 372-381 (2012)

Introduction to spin-orbit torque

Experimental observation of the spin transfer torque

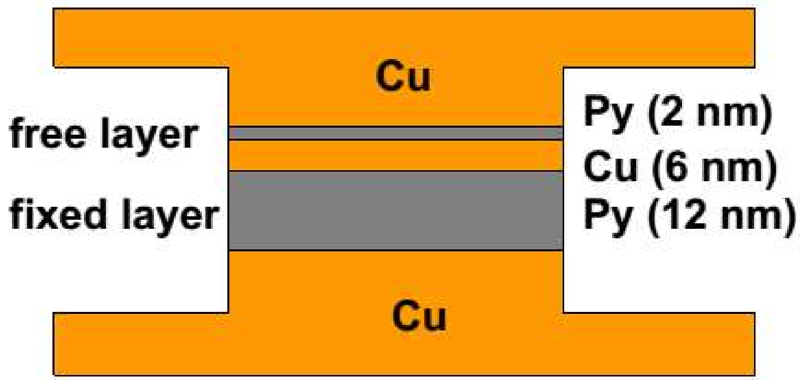


Charge Current + Spin Current

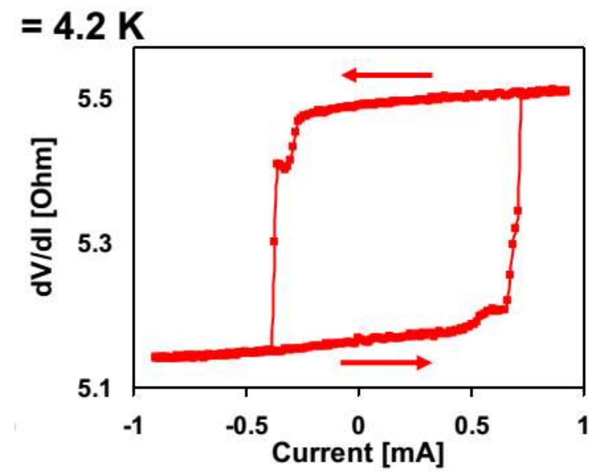
Ralph, D. C. & Stiles, JMMM.
320, 1190-1216 (2008).

Introduction to spin-orbit torque

Disadvantage



Nanopillar Spin-Valve

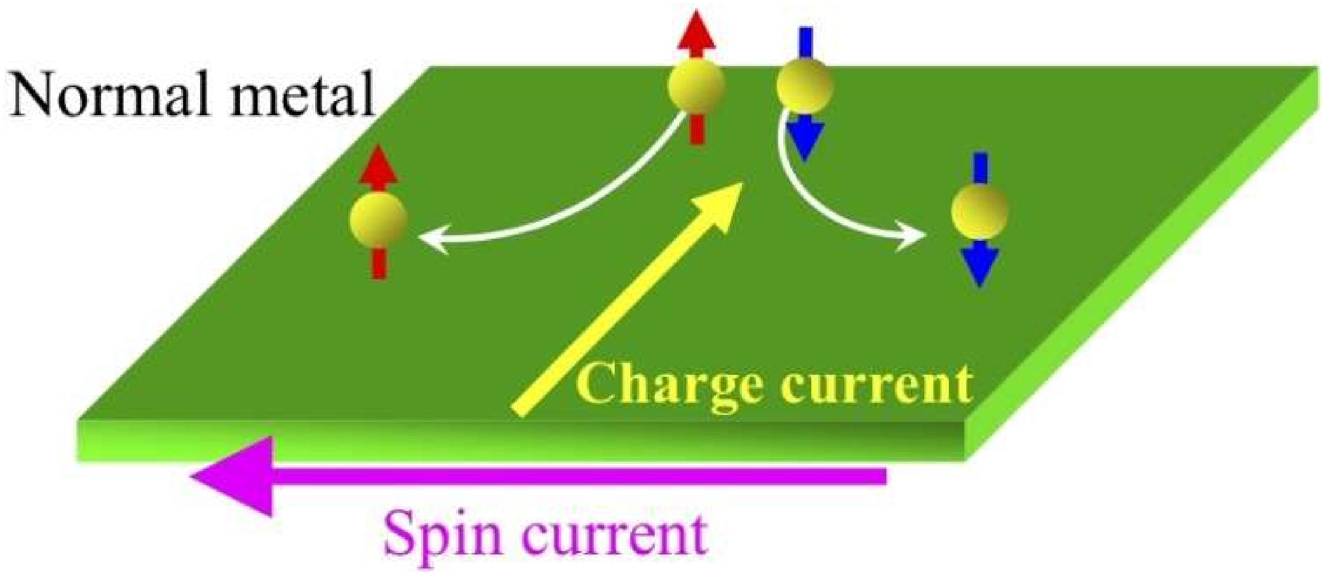


Charge Current → **Heat!!!**

Ralph, D. C. & Stiles, JMMM. 320, 1190-1216 (2008).

Introduction to spin-orbit torque

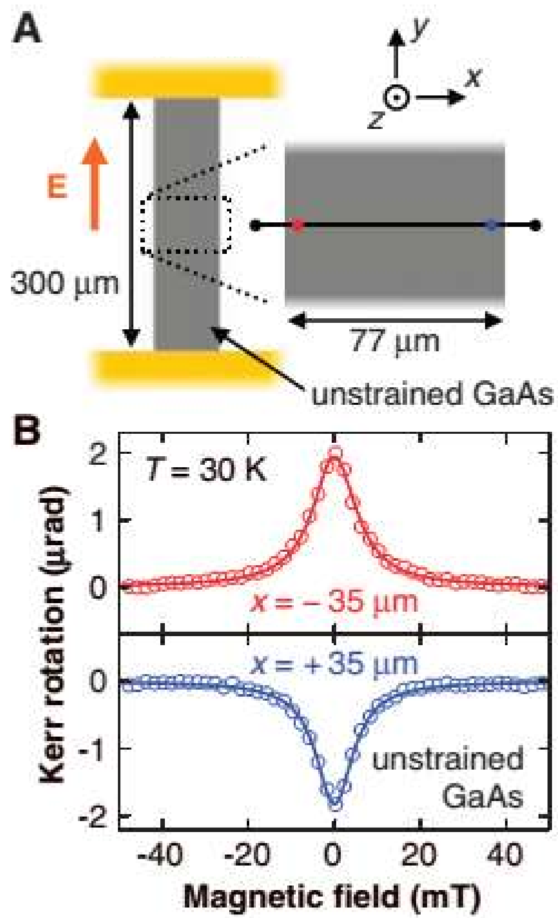
How about **pure** spin current? ⟵ Spin orbit coupling **(spin Hall effect)**

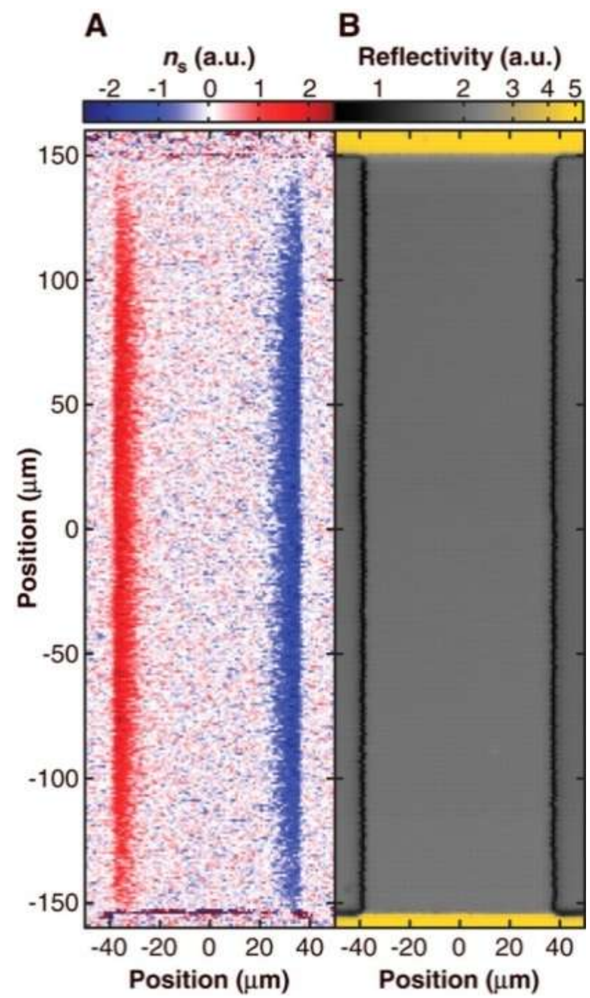


D'yakonov, M. I. & Perel', J. Exp. Theor. Phys. Lett. 13, 467-469, (1971).
Hirsch, J. E. Phys. Rev. Lett. 83, 1834-1837, (1999).
Zhang, S. Phys. Rev. Lett. 85, 393-396, (2000).

Introduction to spin-orbit torque

The first observation of spin Hall effect

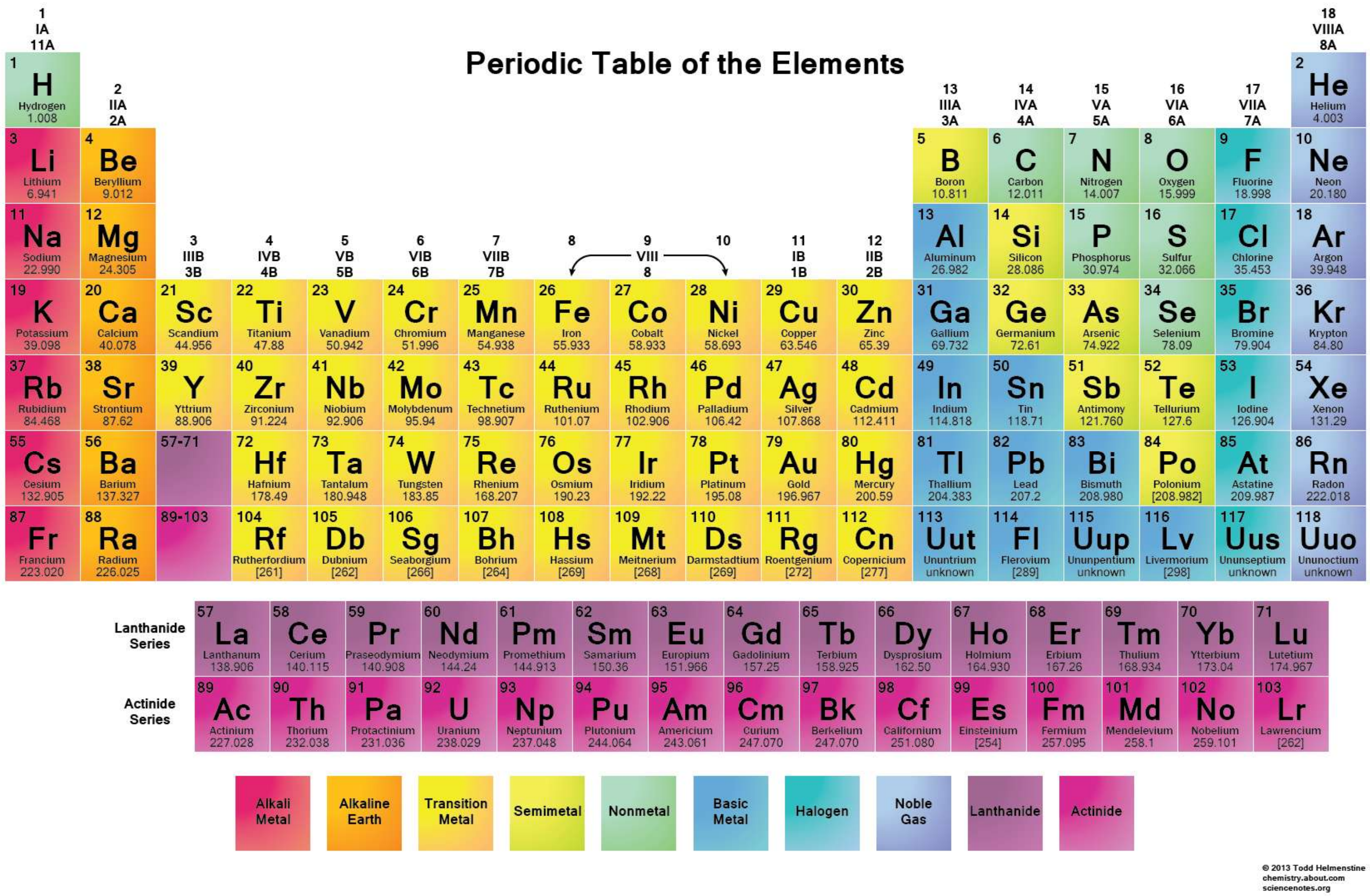


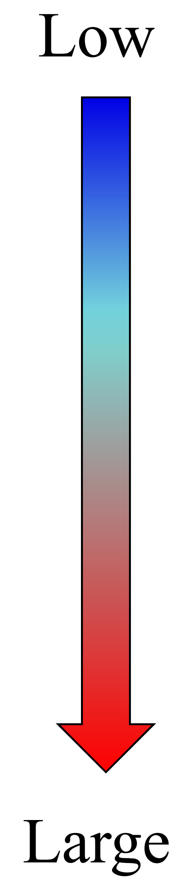


Kato et al., Science 306 (5703) 2004

Introduction to spin-orbit torque

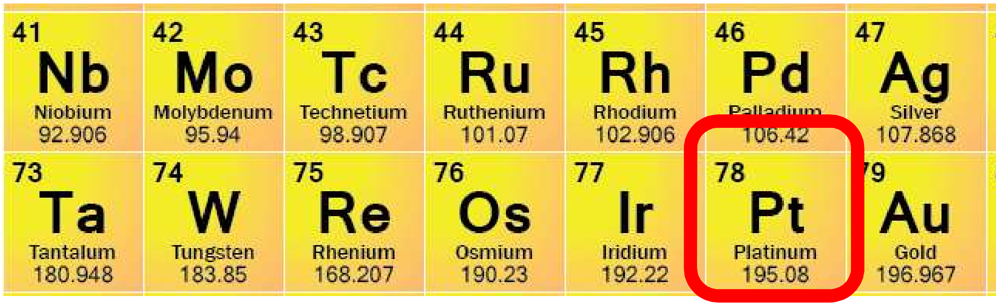
Materials with large spin orbit couplings – high *Z* materials



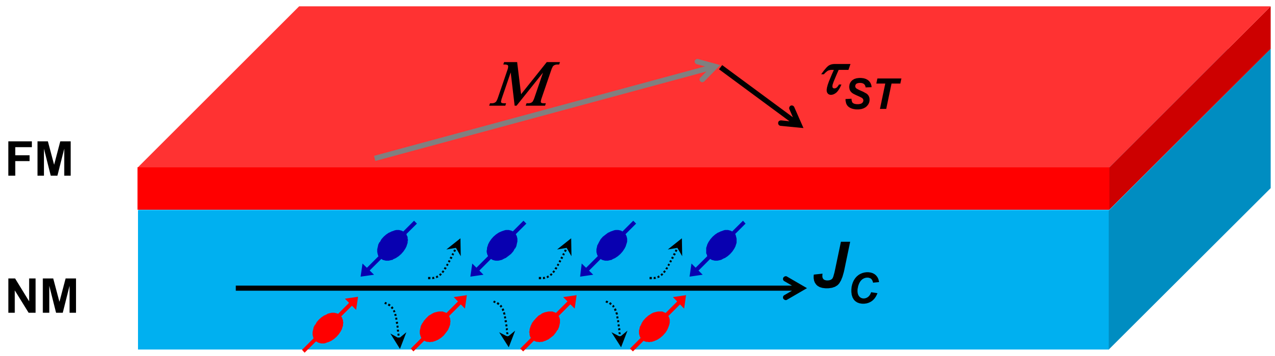


Introduction to spin-orbit torque

Materials with large spin orbit couplings – high *Z* materials

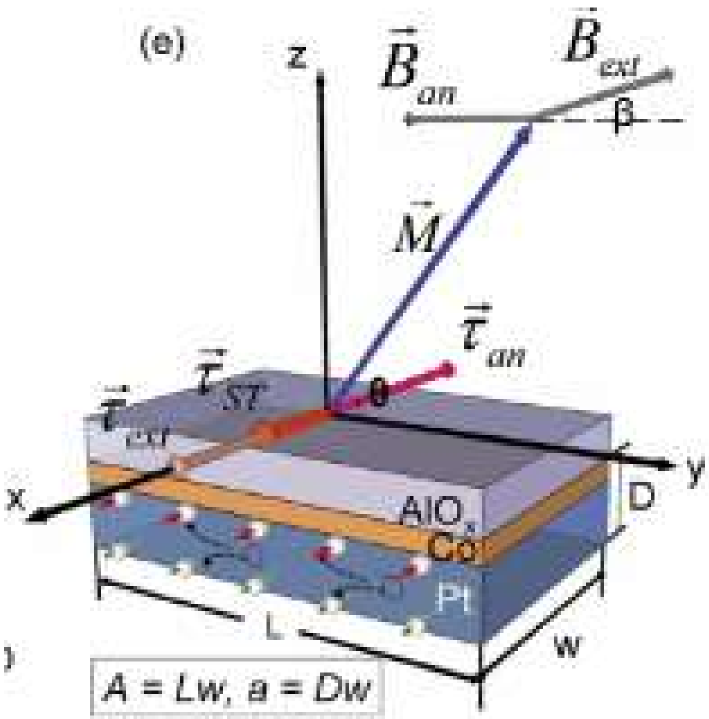


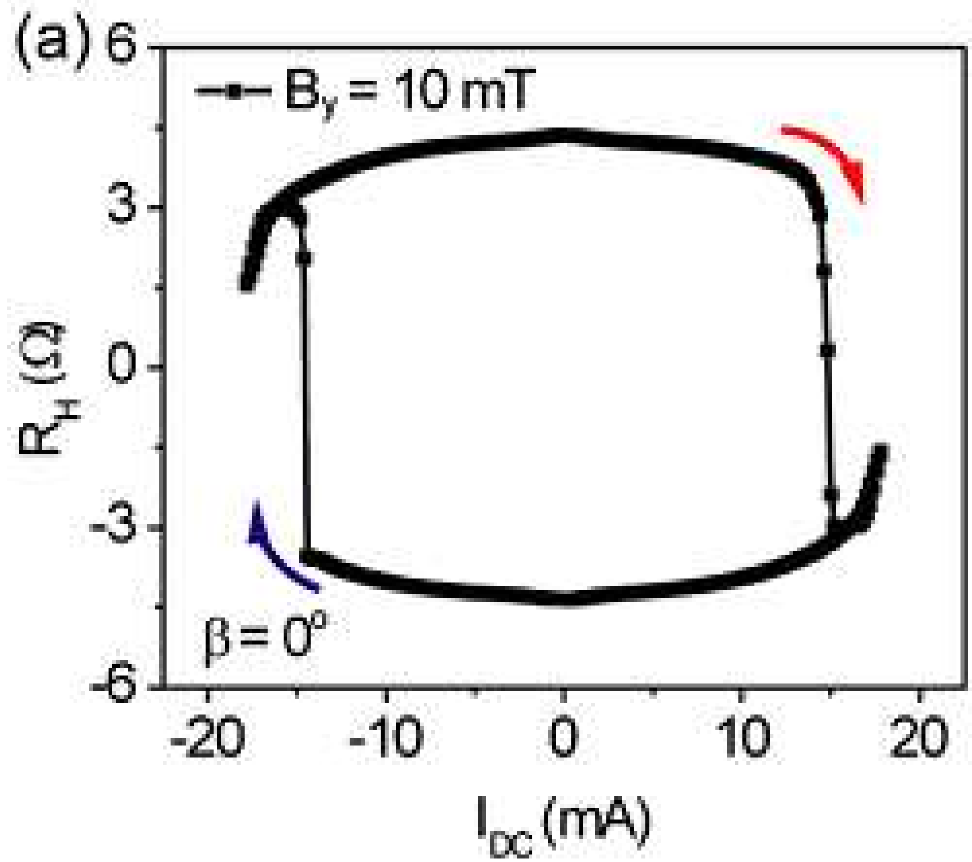
Spin Hall current torque to FM



$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$

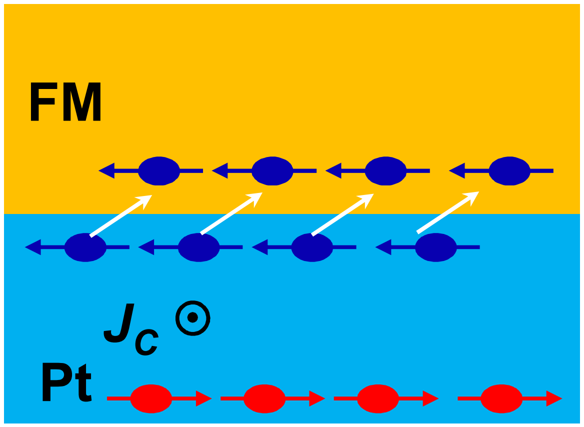
Spin Hall current torque to FM





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

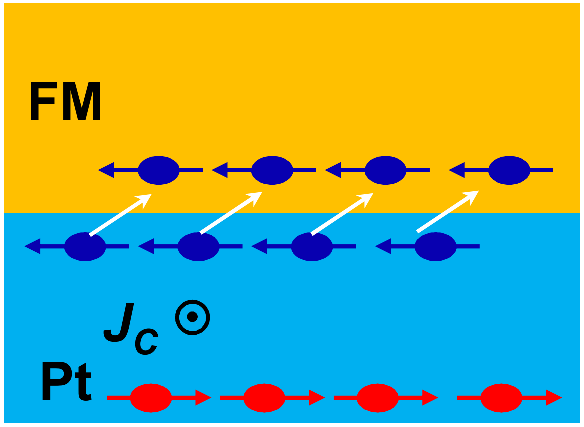
How to get larger spin orbit torque?



- Increase the Efficiency of the SOT
- Search for larger SOT in quantum materials

Introduction to spin-orbit torque

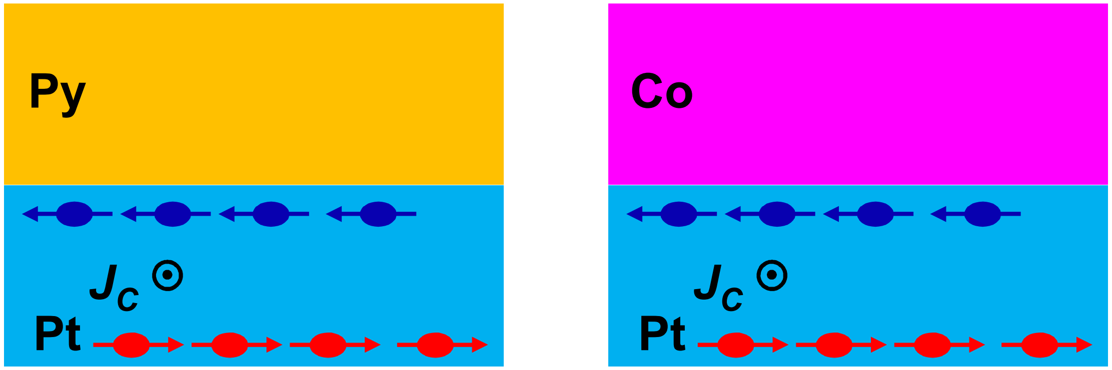
Interface transparency of the spin current



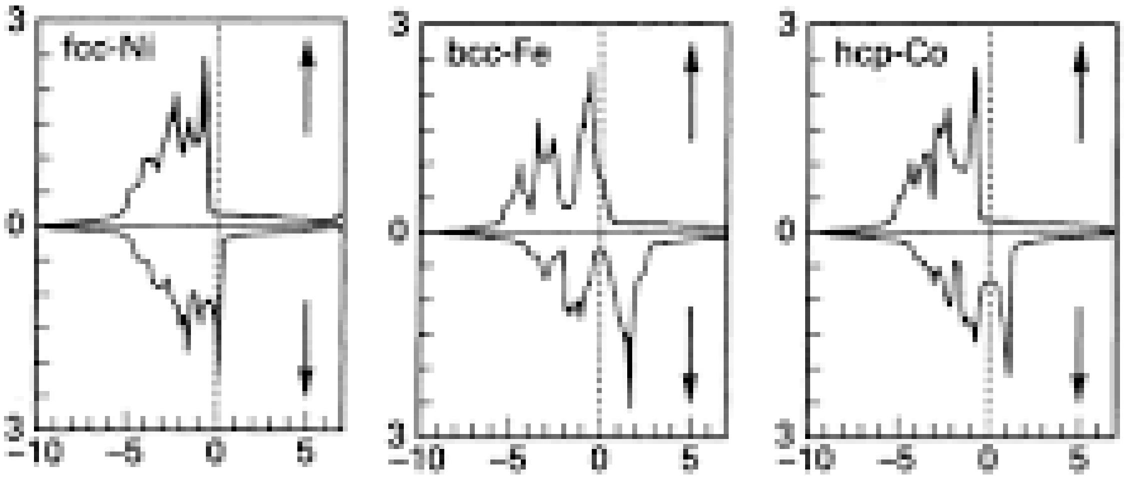
Question: 100%?

Efficient spin orbit torque in Pt/Co and Pt/Py

Our approach



eg: Different spin density states



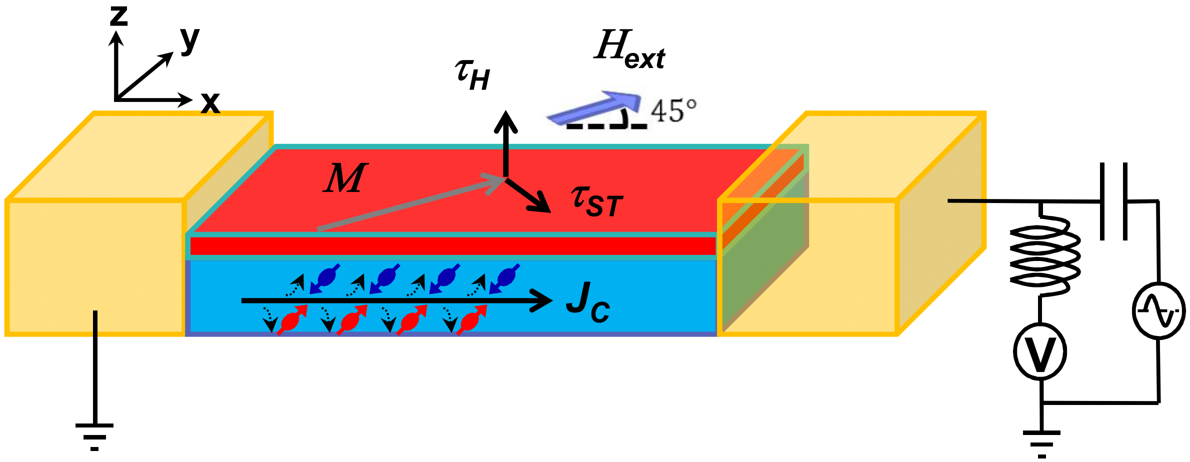
E_F (eV)

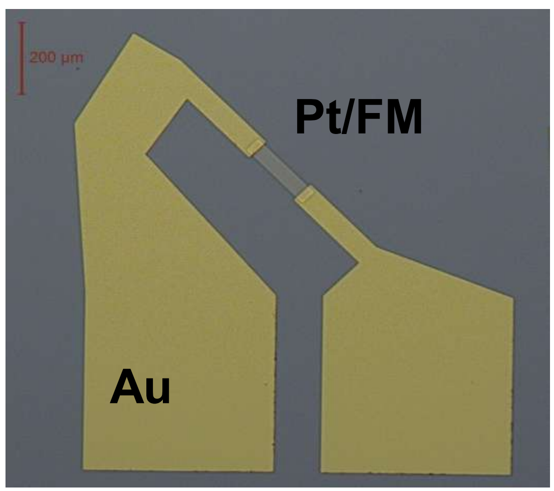
Book: Magnetic Multilayers and Giant Magnetoresistance
(editor: Uwe Hartmann & R. Coehoorn)

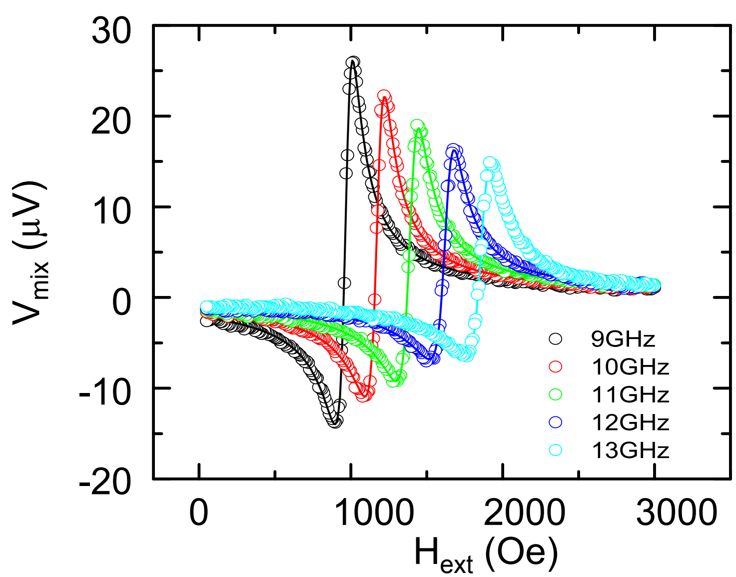
Spin Torque FerroMagnetic Resonance

ST-FMR

Liu et al., PRL 106, 036601 (2011)







Photolithography
Ion Beam etching/deposition

Spin torque ferromagnetic resonance

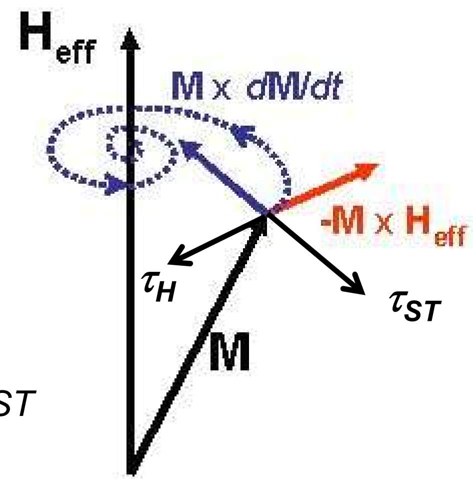
Landau-Lifshitz-Gilbert equation

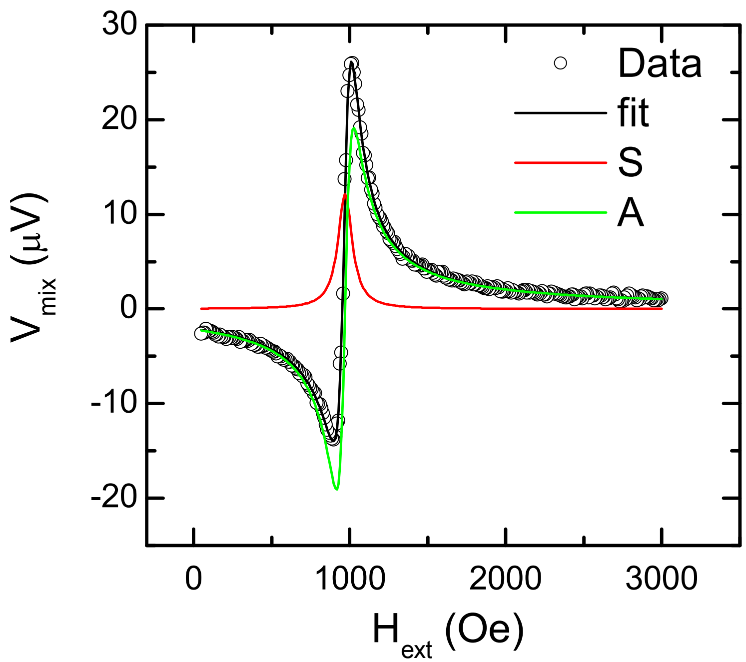
$$\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \vec{H}_{eff}$$ →external effective field

$$+\alpha \hat{m} \times \frac{d\hat{m}}{dt}$$ →damping

$$+\gamma \frac{\hbar}{2\,\mu_0 M_s t} \times J_{S,rf}(\hat{m} \times \hat{\sigma} \times \hat{m})$$ →spin torque τ_{ST}

$$-\gamma \hat{m} \times \vec{H}_{rf}$$ →torque from RF field τ_H



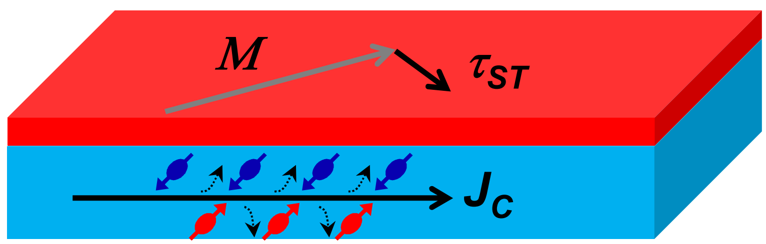


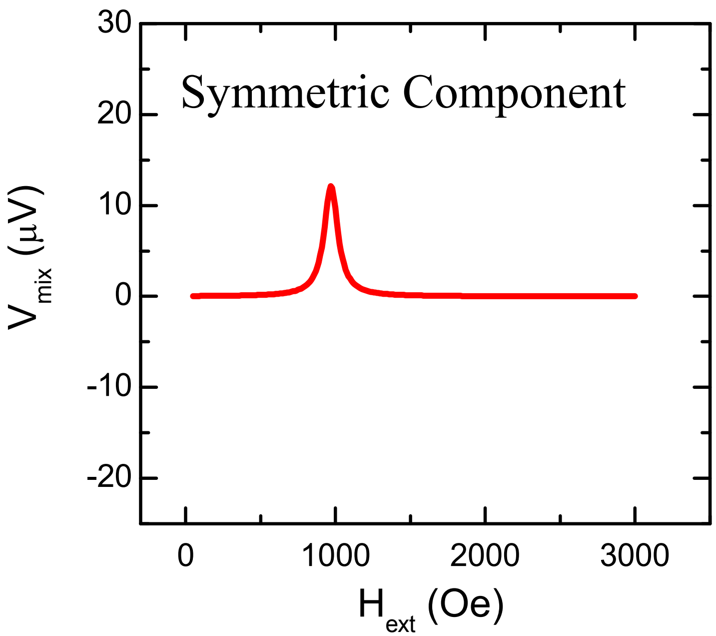
Symmetric Component: Spin Hall torque

Antisymmetric Component:
Torque from RF field

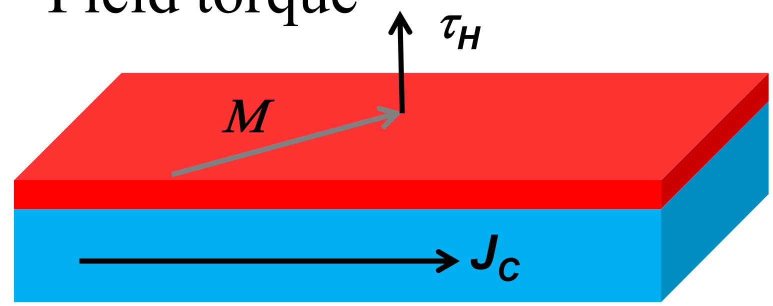
Efficient spin orbit torque in Pt/Co and Pt/Py

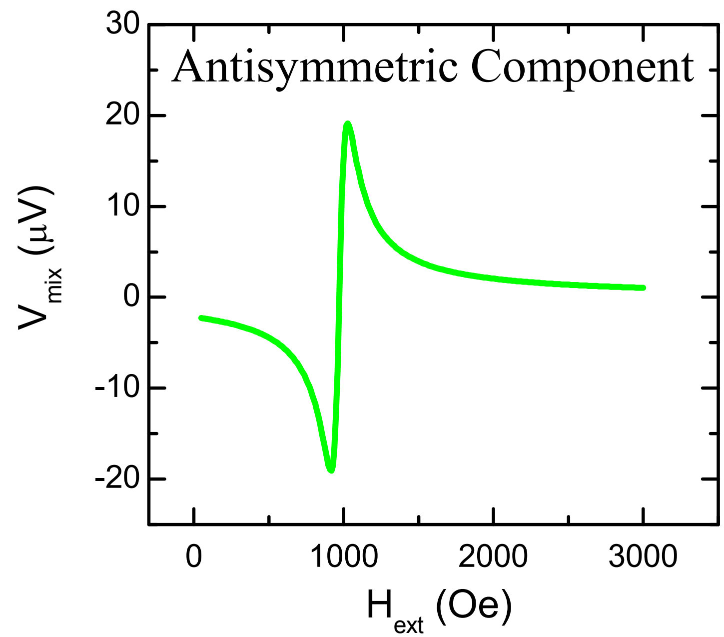
Spin torque





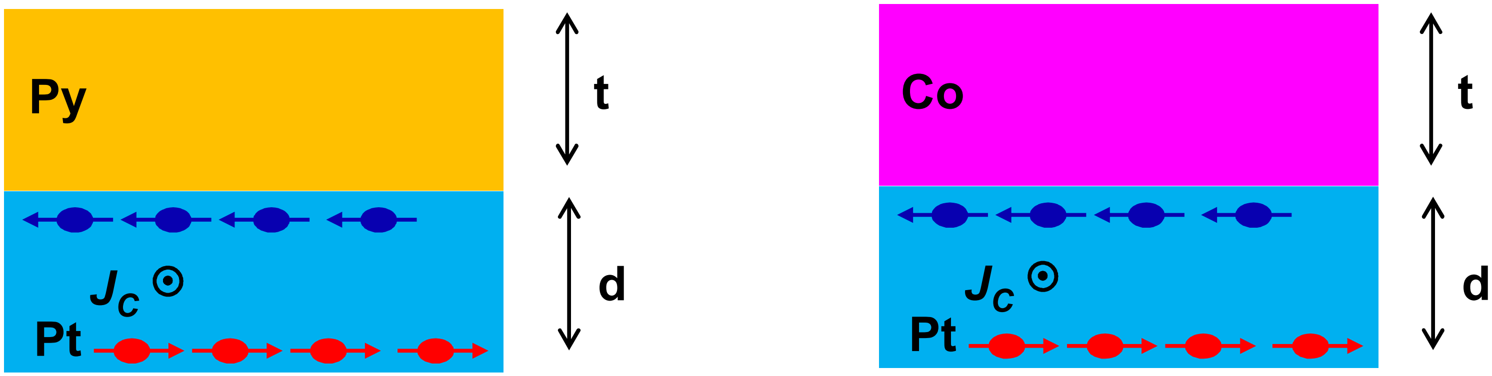
Field torque

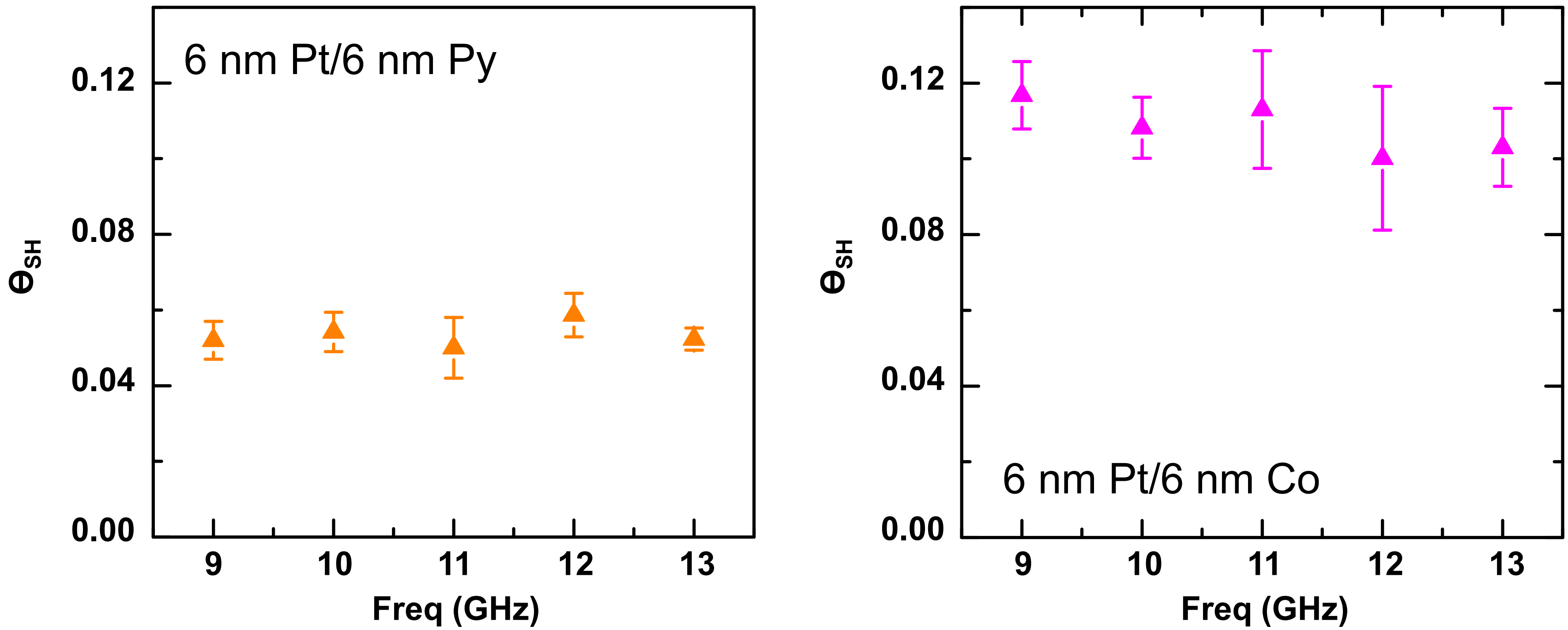




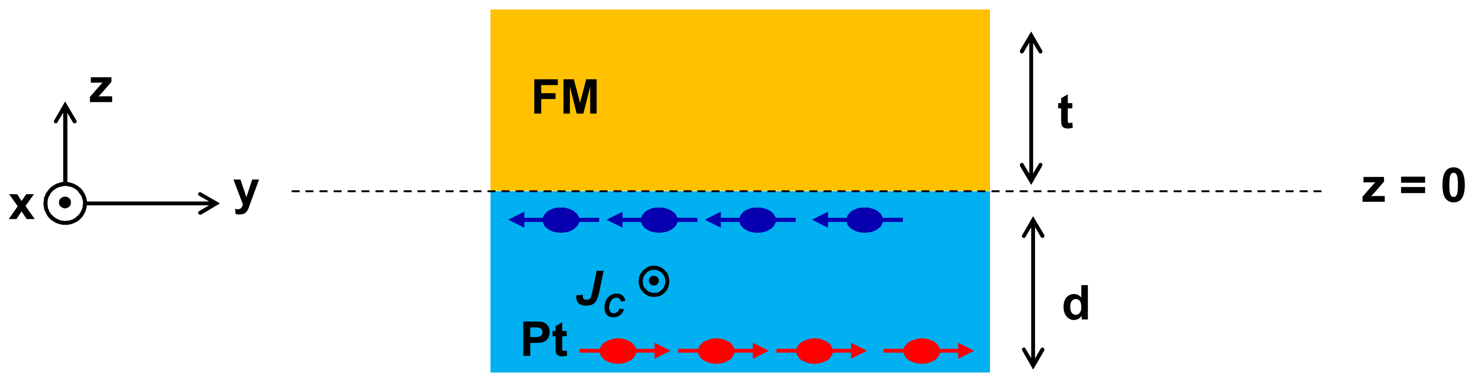
$$SHA = \frac{S}{A}\frac{e\mu_0 M_s t d}{\hbar}\left[1 + (4\pi M_{eff}/H_{ext})\right]^{1/2}$$

Efficient spin orbit torque in Pt/Co and Pt/Py





Interface transparency



In Pt layer:

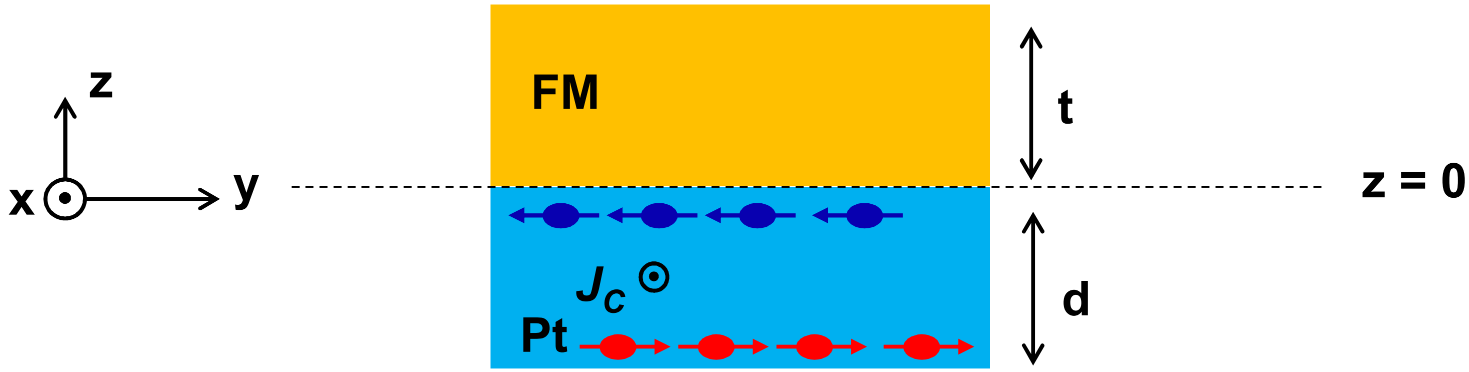
$$\overrightarrow{j_s^z}(z) = -\frac{\sigma}{2e}\partial_z\overrightarrow{\mu_s} - J_{SH,rf}\,\hat{y}$$

$$\overrightarrow{\mu_s}(z) = \vec{A}e^{-z/\lambda} + \vec{B}e^{z/\lambda}$$

In FM layer:

$$\overrightarrow{j_s^z}(0) = \overrightarrow{j_s^F}(\hat{m}) = G_r(\hat{m} \times (\hat{m} \times \overrightarrow{\mu_s})) * \mathrm{e/h}$$

Interface transparency

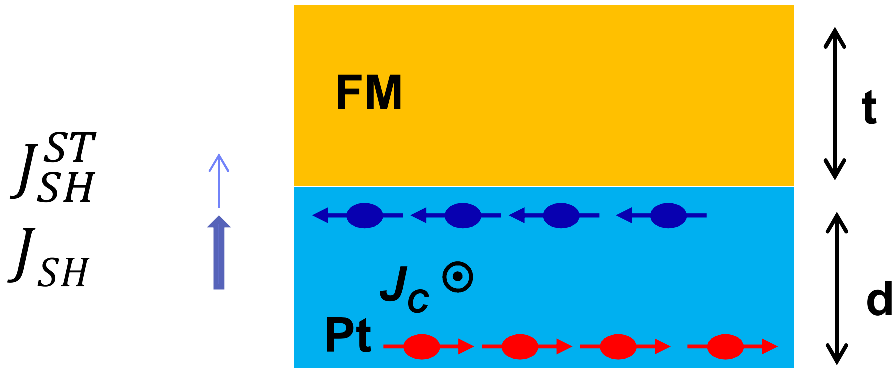


The continuity of the spin current density at the interface (z = 0, and z = -d)

$$\overrightarrow{\mu_s}(z) = -\hat{y}\,(2e\,\lambda/\sigma)J_{SH,rf}\tanh\left(\frac{d_n}{2\lambda}\right)\frac{\sinh\left(\frac{2z+d_{Pt}}{2\lambda}\right)}{\sinh\left(\frac{d_{Pt}}{2\lambda}\right)} - \overrightarrow{j_F^z}(0)\,\frac{\cosh\left(\frac{z+d_{Pt}}{2\lambda}\right)}{\sinh\left(\frac{d_{Pt}}{2\lambda}\right)}$$

$$\overrightarrow{j_F^z} = J_{SH,rf}(\hat{m}\times(\hat{m}\times\hat{y}))\sigma\frac{G_r}{G_r\coth\left(\frac{d_{Pt}}{\lambda}\right)+\frac{\sigma}{\lambda}\frac{h}{2e^2}}$$

Interface transparency model



Interface transparency of the spin current

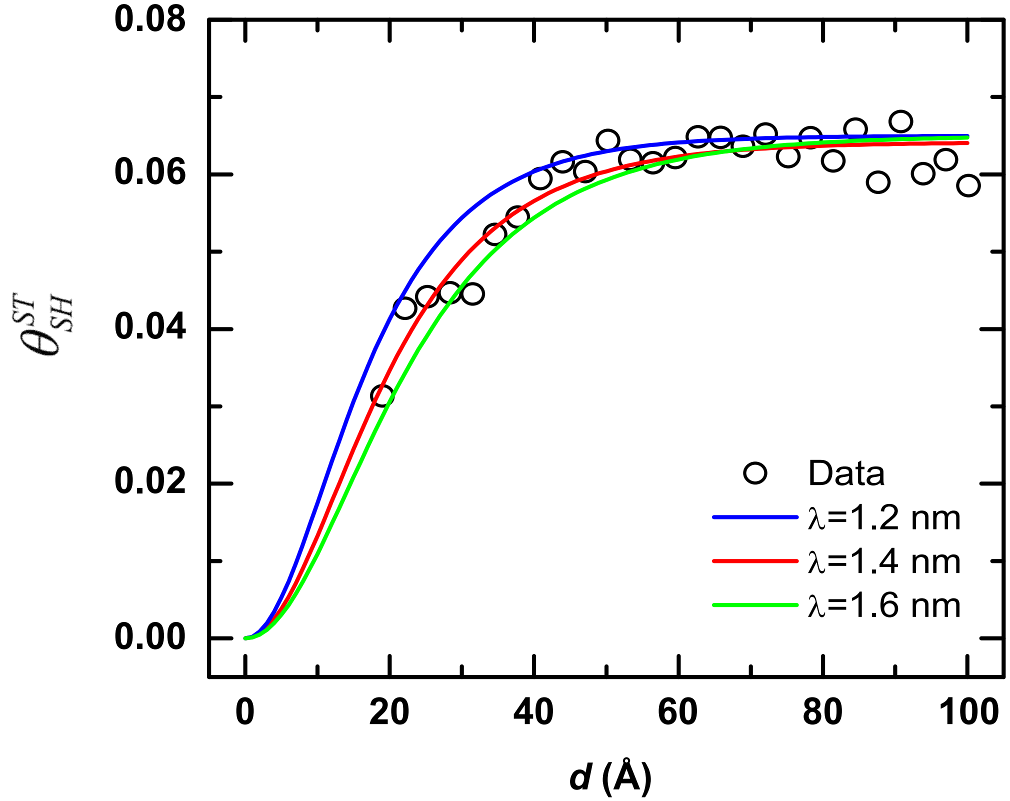
$$T = \frac{J_{SH}^{ST}}{J_{SH}} = \frac{G_{\uparrow\downarrow}\tanh(\frac{d_{Pt}}{2\lambda})}{G_{\uparrow\downarrow}\coth\left(\frac{d_{Pt}}{\lambda}\right) + \frac{\sigma}{\lambda}\frac{h}{2e^2}}$$

$G_{\uparrow\downarrow}$: intrinsic spin mixing conductance
λ: spin diffusion length of Pt
σ: conductivity of Pt

Interface transparency

Spin diffusion length

d Pt/6 nm Py



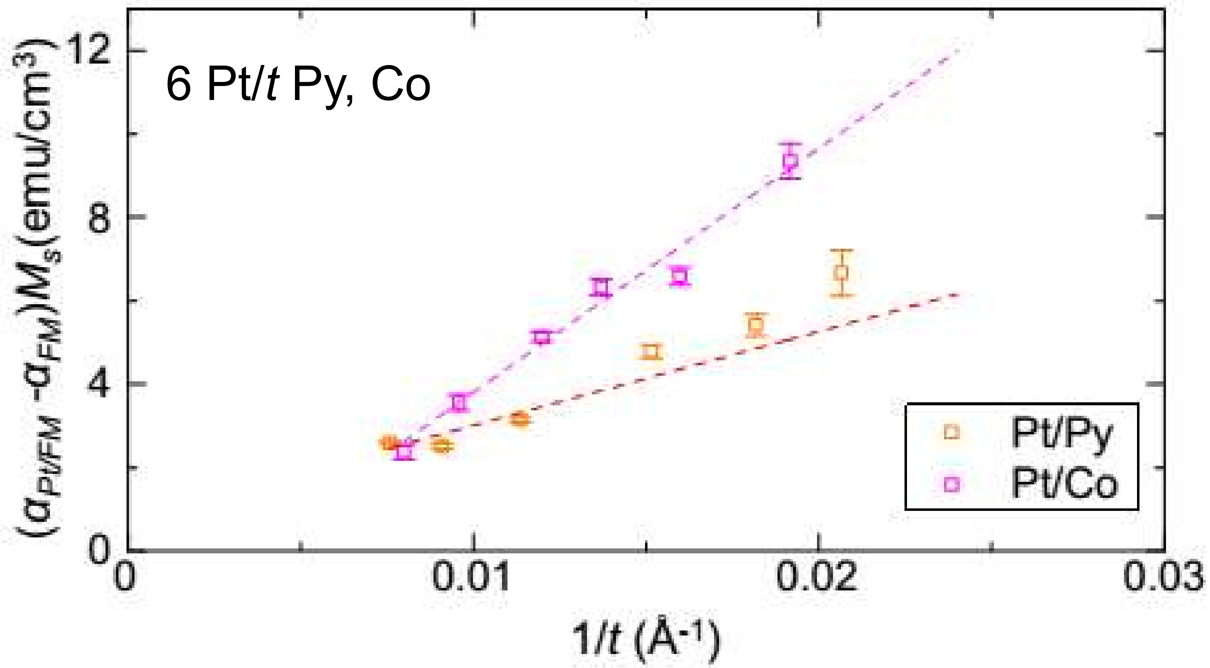
$$\frac{\theta_{SH}(d)}{\theta_{SH}(\infty)} = \left(1 - \operatorname{sech}\left(\frac{d}{\lambda}\right)\right)$$

λ = 1.4 nm

Interface transparency

Intrinsic mixing conductance

Damping parameters for FM and Pt/FM obtained from conventional FMR



$$G_{eff} = \frac{4\pi M_S t}{g\mu_B}(\alpha_{Pt/FM} - \alpha_{FM})$$

	Pt/Py	Pt/Co
G_{eff} ($10^{19}m^{-2}$)	1.52±0.34	3.96±0.39

Interface transparency

Intrinsic mixing conductance

	Pt/Py	Pt/Co
G_{eff} ($10^{19}m^{-2}$)	1.52 ± 0.34	3.96 ± 0.39
σ_{Pt} (μΩ*cm)	15 ± 1	15 ± 1
λ (nm)	1.4 ± 0.2	1.4 ± 0.2
$G_{\uparrow\downarrow}$ ($10^{19}m^{-2}$)	2.4 ± 0.4	11.1 ± 3.1
T	0.25 ± 0.05	0.65 ± 0.06

$$\frac{1}{G_{eff}} = \frac{1}{G_{\uparrow\downarrow}} + \frac{1}{\frac{\sigma_{Pt}}{\lambda}\frac{h}{2e^2}}$$

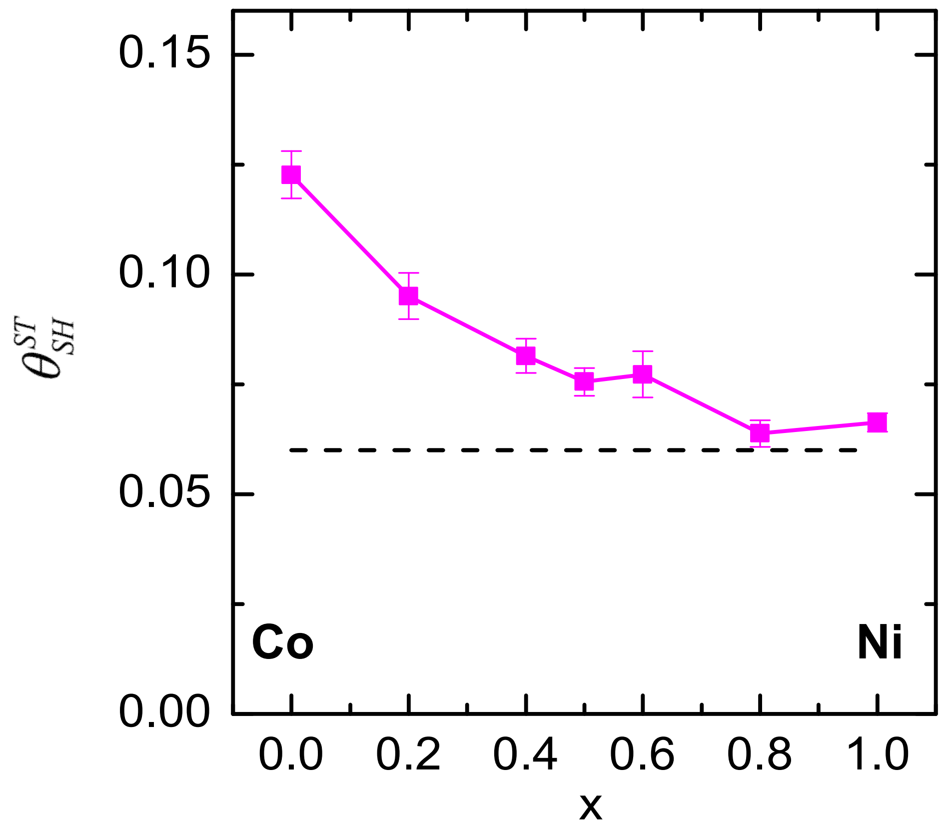
$$T = \frac{J_{SH}^{ST}}{J_{SH}} = \frac{G_{\uparrow\downarrow}\tanh(\frac{d_{Pt}}{2\lambda})}{G_{\uparrow\downarrow}\coth\left(\frac{d_{Pt}}{\lambda}\right) + \frac{\sigma}{\lambda}\frac{h}{2e^2}}$$

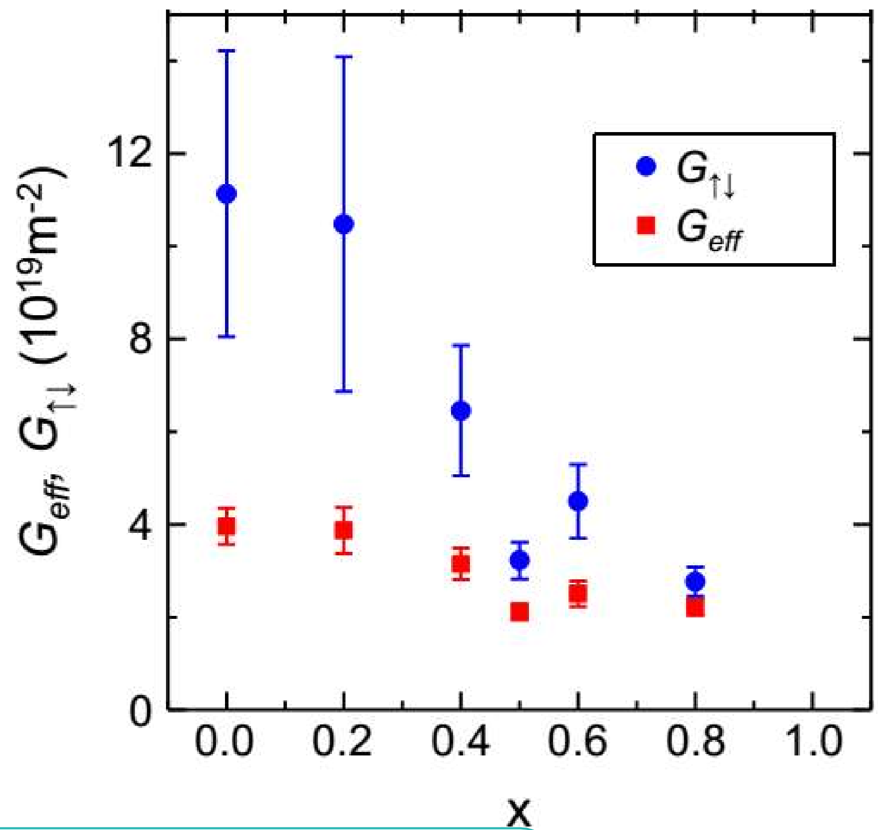
SHA of Pt ~ 0.19

Interface transparency

SHA of Pt in 6 nm Pt- 6 nm $Co_{1-x}Ni_x$

$$T = \frac{J_{SH}^{ST}}{J_{SH}} = \frac{G_{\uparrow\downarrow}\tanh(\frac{d_{Pt}}{2\lambda})}{G_{\uparrow\downarrow}\coth\left(\frac{d_{Pt}}{\lambda}\right) + \frac{\sigma}{\lambda}\frac{h}{2e^2}}$$

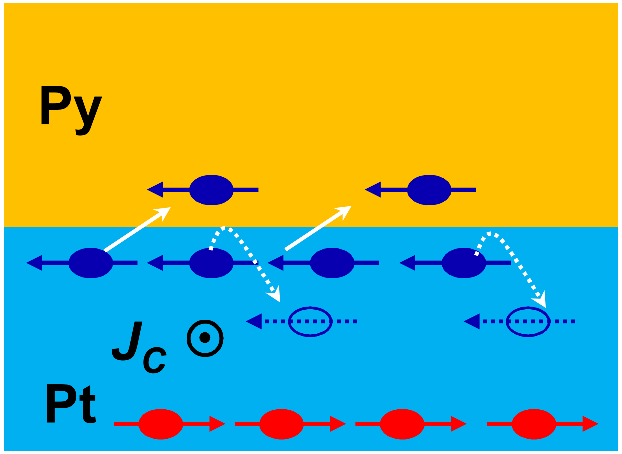


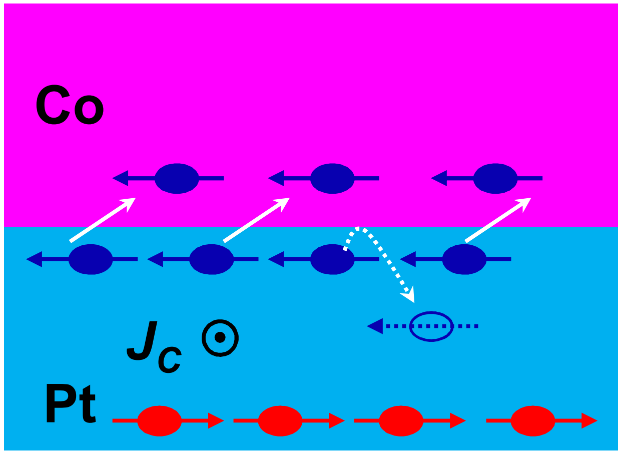


higher G→ larger T→ higher SHA

Interface transparency

- ✓ **Interface transparency plays an important role for spin orbit torque**

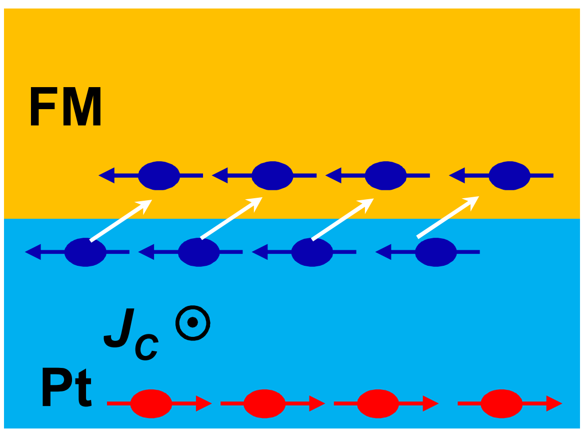




W. Zhang*, Wei Han*, Xin Jiang, See-Hun Yang, Stuart Parkin, Nat Phys. (2015)

The main Challenge

How to get larger spin orbit torque?



- Increase the Efficiency of the SOT

- Search for larger SOT in 2D Quantum materials

1) Large SHE in 2D Ir-Mn

Motivated by a recent theoretical work of AHE in $IrMn_3$

PRL **112,** 017205 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism

Hua Chen, Qian Niu, and A. H. MacDonald
Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
(Received 3 October 2013; published 10 January 2014)

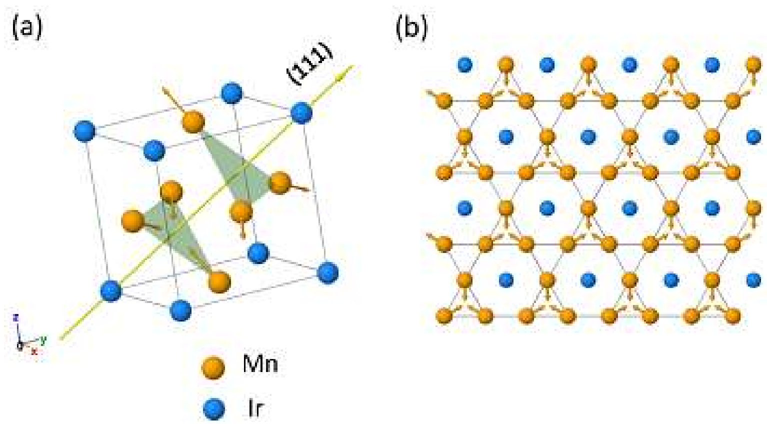
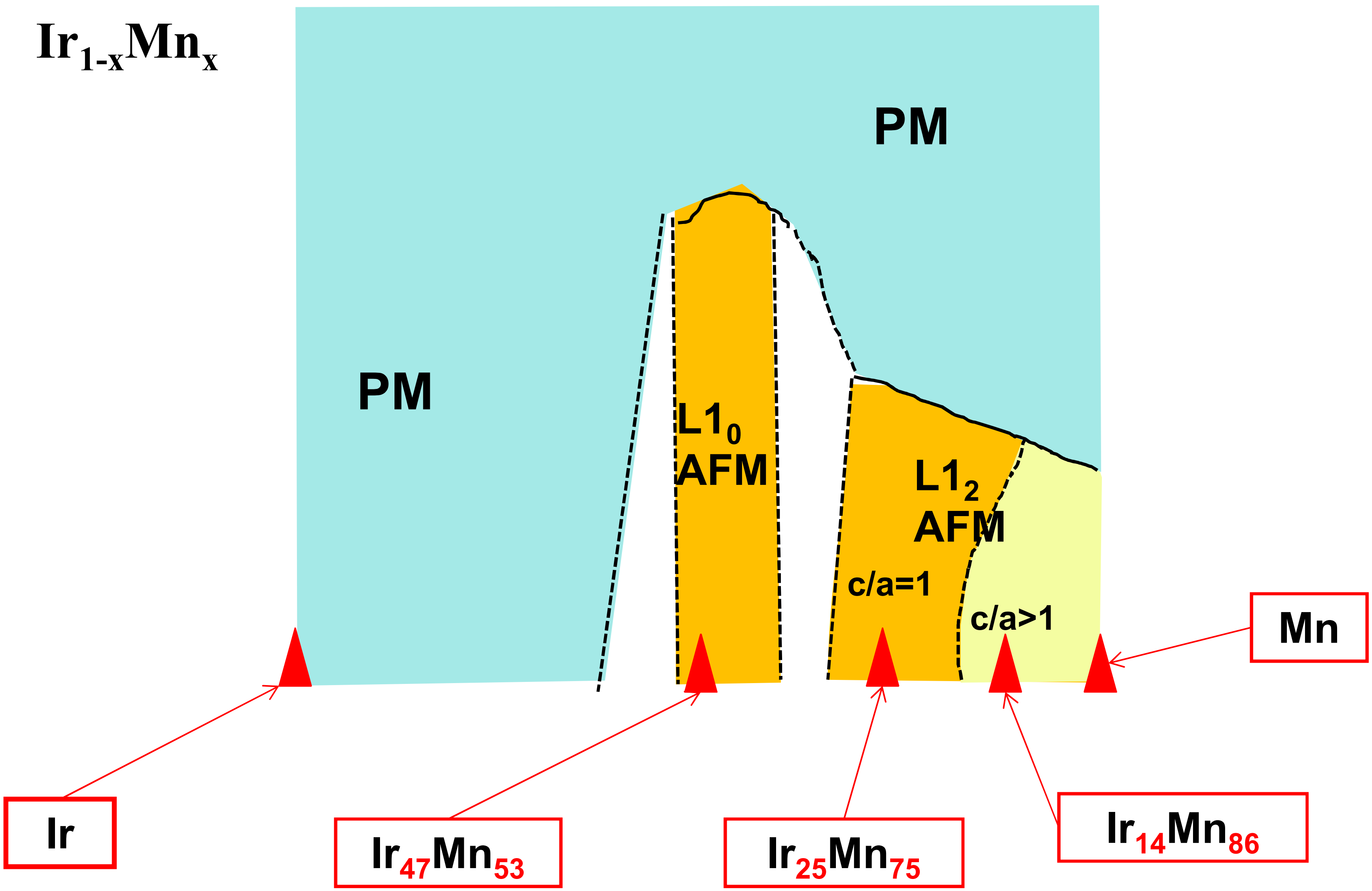


FIG. 1 (color online). Structure of Mn_3Ir. (a) Unit cell of Mn_3Ir with triangular antiferromagnetic order. (b) An individual (111) plane of Mn_3Ir. The Mn atoms form a kagome lattice.

- **Large spin orbit coupling of Ir transfer to Mn.**
- **Non-collinear antiferromagnetism**

1) Large SHE in 2D Ir-Mn

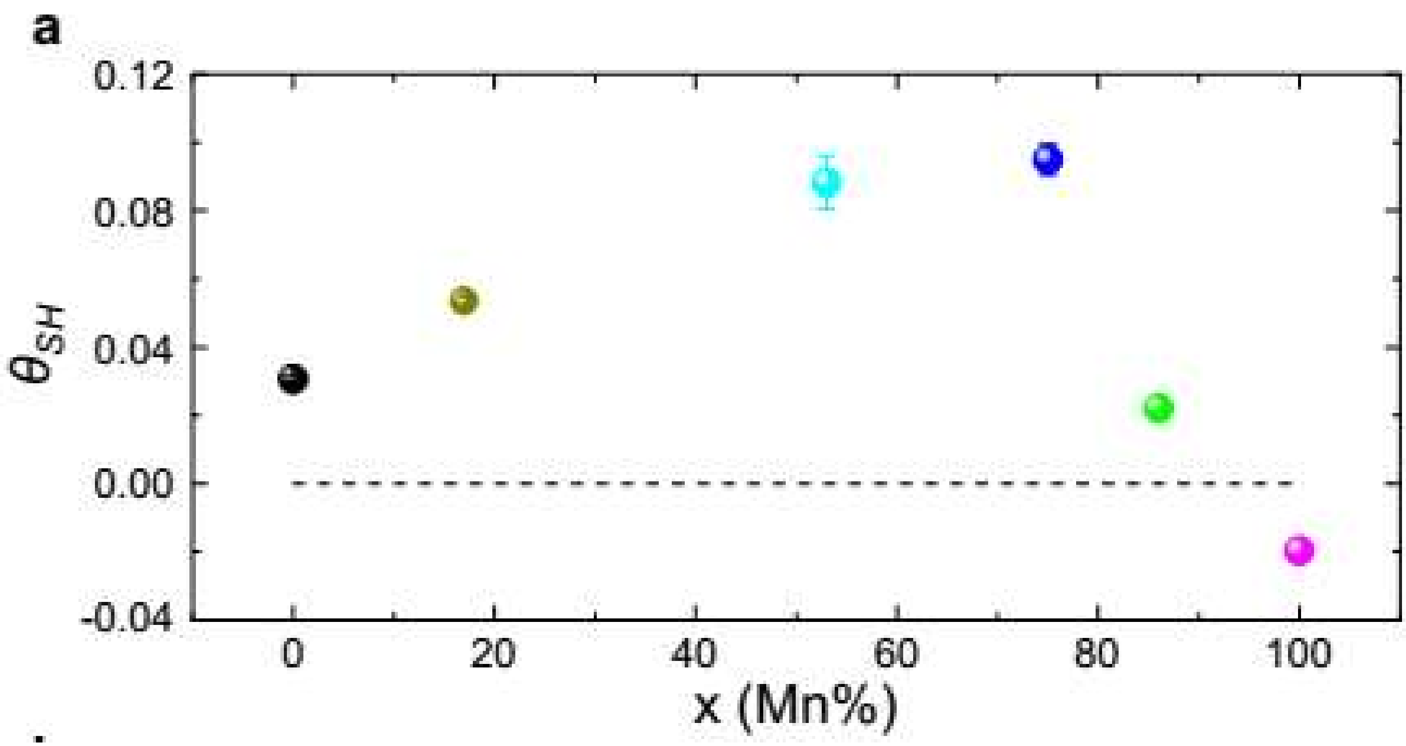
$Ir_{1-x}Mn_x$



1) Large SHE in 2D Ir-Mn

$Ir_{1-x}Mn_x$

Grown on SiO2/Si substrates

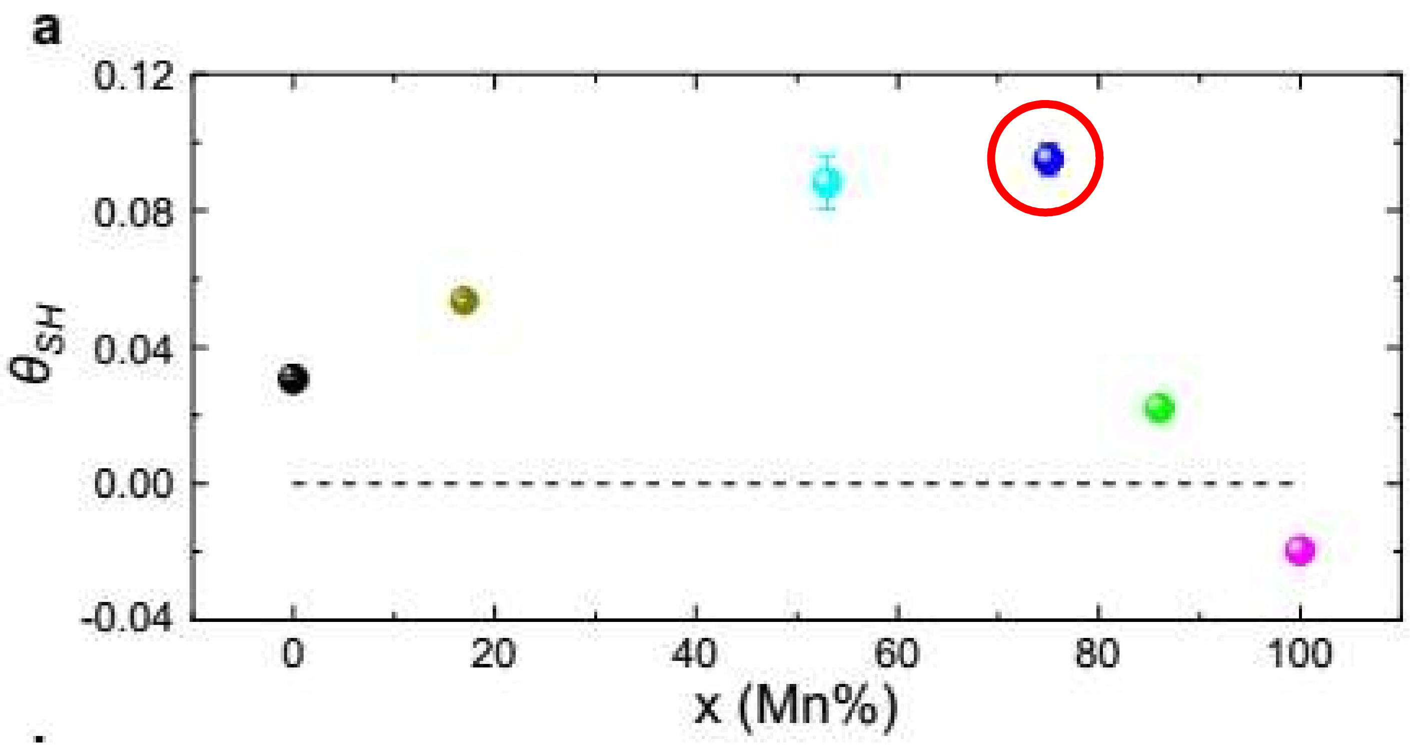


Related work on $Ir_{20}Mn_{80}$ and IrMn have also been seen by other groups.
IrMn: Zhang, W. et al. Phys. Rev. Lett. 113, 196602, (**2014**).
$Ir_{20}Mn_{80}$: Mendes, J. B. S. et al. Phys. Rev. B 89, 140406, (**2014**)

1) Large SHE in 2D Ir-Mn

$Ir_{1-x}Mn_x$

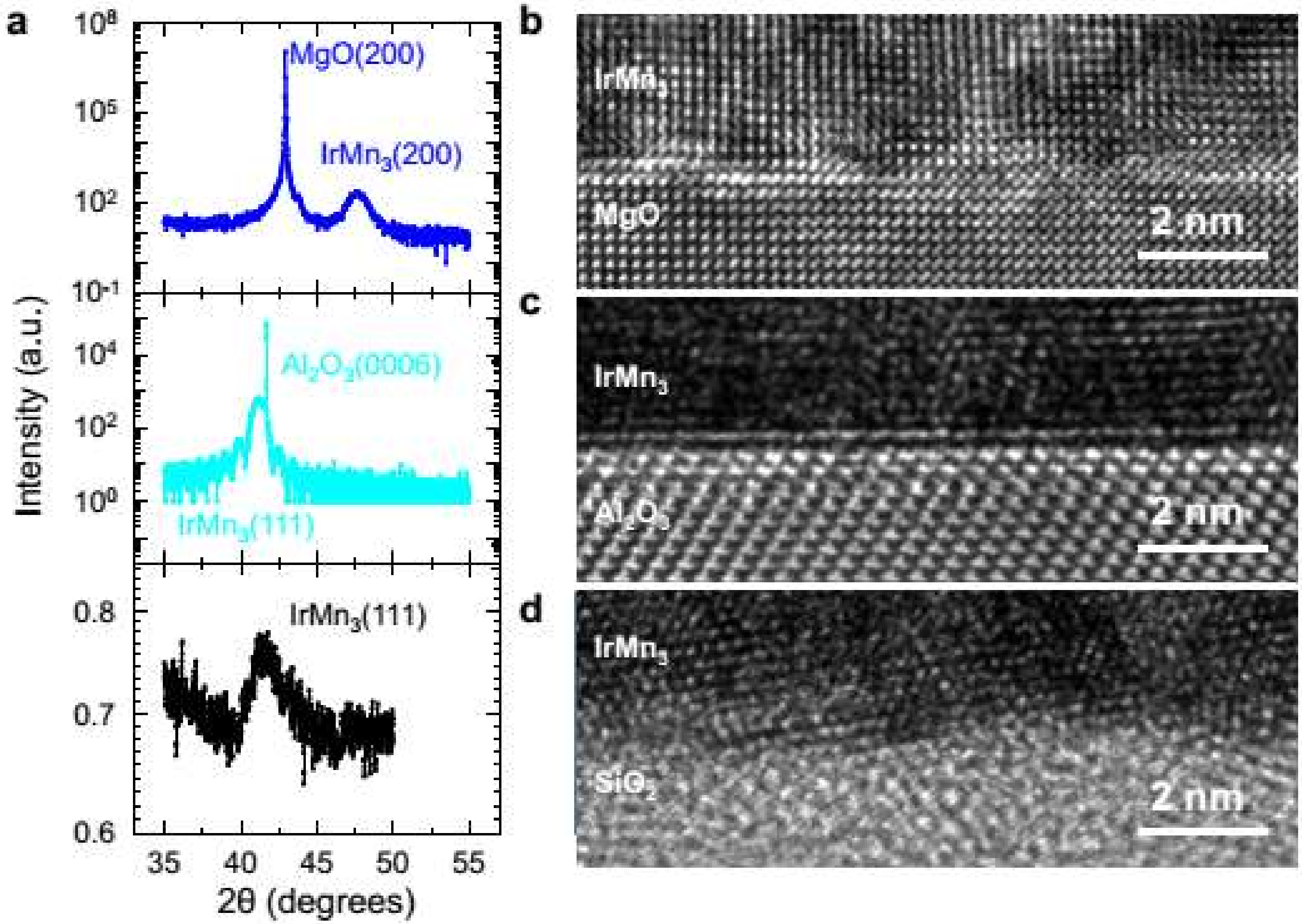
Grown on SiO2/Si substrates



Related work on $Ir_{20}Mn_{80}$ and IrMn have also been seen by other groups.
IrMn: Zhang, W. et al. Phys. Rev. Lett. 113, 196602, (**2014**).
$Ir_{20}Mn_{80}$: Mendes, J. B. S. et al. Phys. Rev. B 89, 140406, (**2014**)

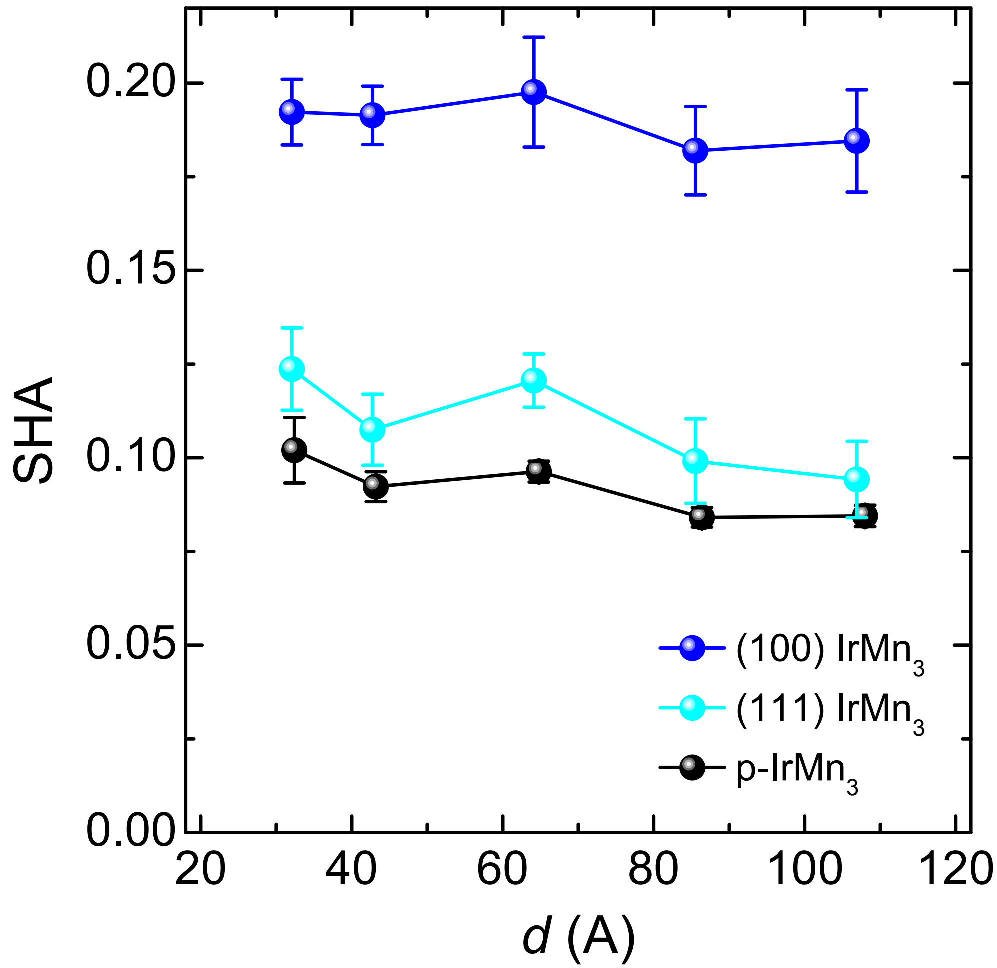
1) Large SHE in 2D Ir-Mn

Facet dependent SHE



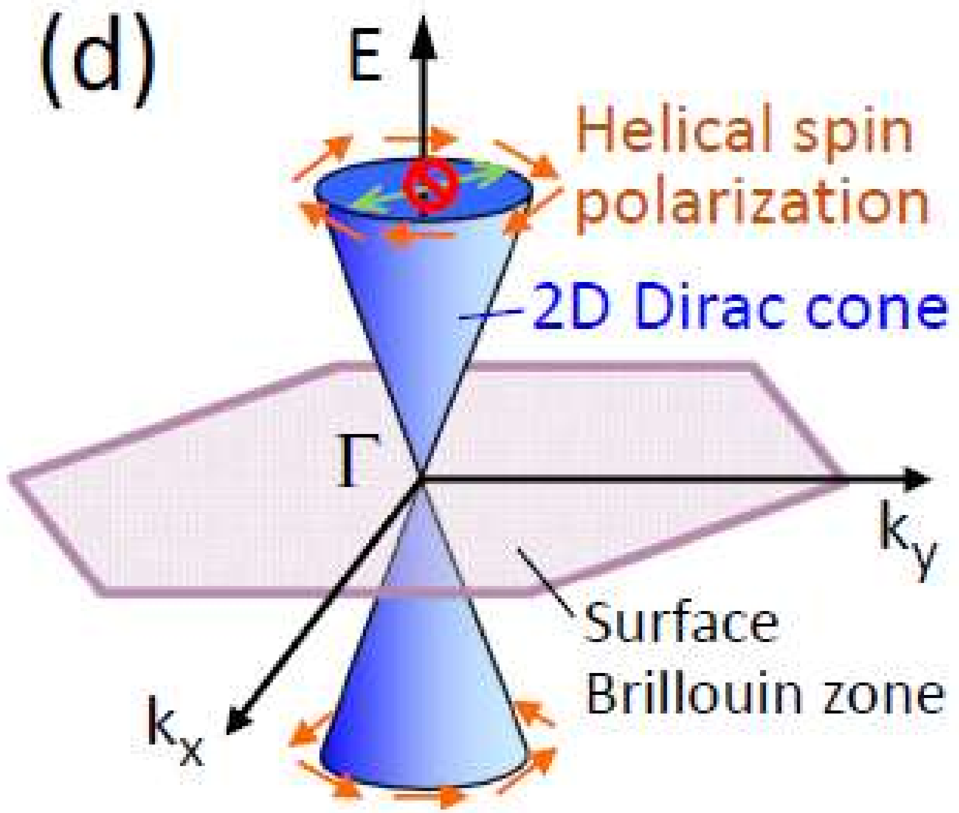
1) Large SHE in 2D Ir-Mn

Facet dependent SHE



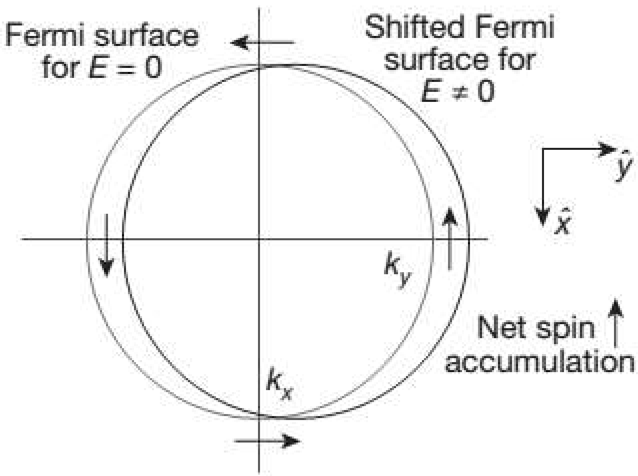
W. Zhang*, Wei Han*, Xin Jiang, See-Hun Yang, Stuart Parkin, under review

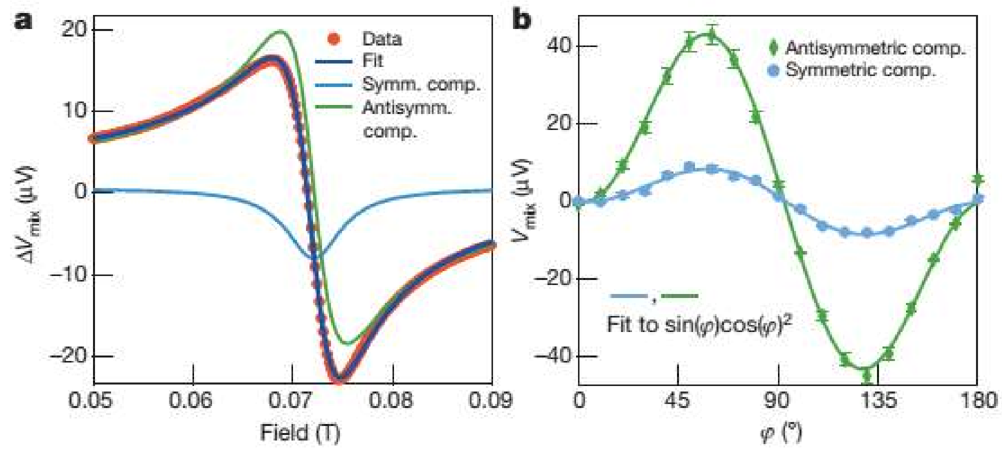
2) Spin orbit Torque in Topological insulators



2) Spin orbit Torque in Topological insulators

Bi_2Se_3





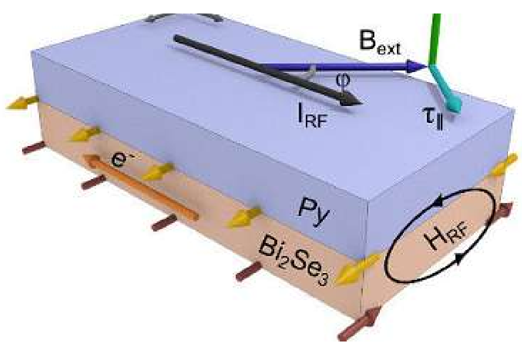


Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for Bi_2Se_3 with other materials

Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
$\theta_{\parallel}$	2.0–3.5	0.08	0.15	0.24	0.3
$\sigma_{S,\parallel}$	1.1–2.0	3.4	0.8	—	1.8

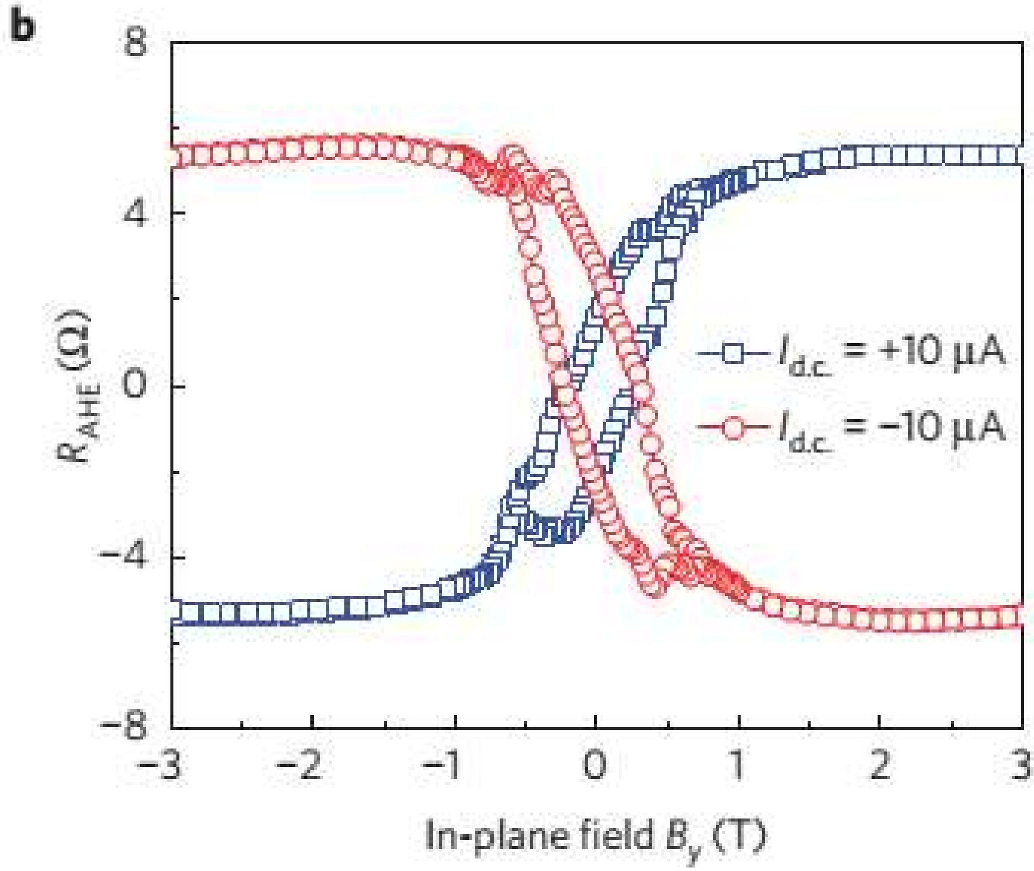
$\theta_{\parallel}$ is dimensionless and the units for $\sigma_{S,\parallel}$ are $10^5\hbar/2e\,\Omega^{-1}\,m^{-1}$.

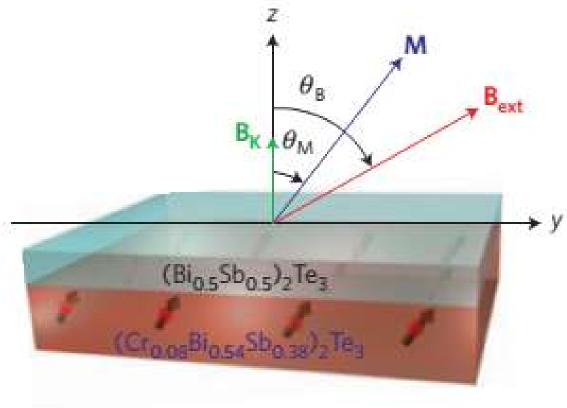
Spin Hall angle: 2.0-3.5

Mellink, et al. Nature (2014)

Spin orbit Torque in Topological insulators

$(Bi_{0.5}Sb_{0.5})_2Te_3$





T=1.9 K

SHA > 100

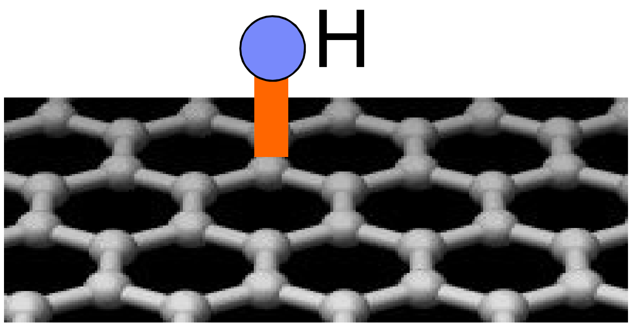
Fan, et al, Nature Mater. (2014)

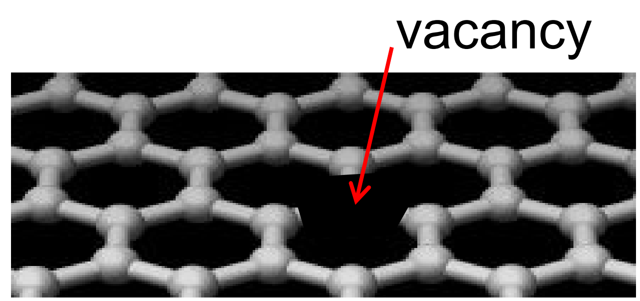
Current Status of Spin orbit Torque

	Materials	Effective SHA	Research group
Semiconductor	GaAs	0.0005-0.005	UCSB (Awschalom)
Metal	Pt	0.19	PKU (Han) & IBM (Parkin) Cornell (Ralph & Burhman)
	β-Ta	0.15	Cornell (Ralph & Burhman)
	β-W	0.3	Cornell (Ralph & Burhman)
	Bi doped Cu	0.24	Japan (Otani) & France (Fert)
Quantum Materials	TI	2.0-3.5 (~500?) >100 (1.9 K)	Cornell (Ralph & Burhman) UCLA (Wang)
	$IrMn_3$	~0.3	PKU (Han) & IBM (Parkin)

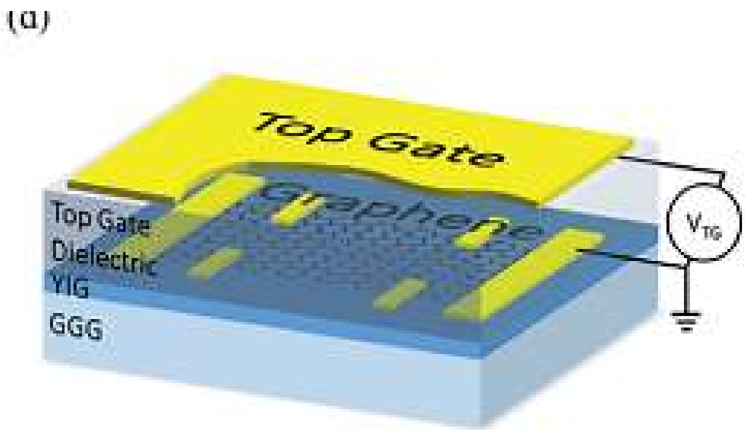
Summary of Lecture II

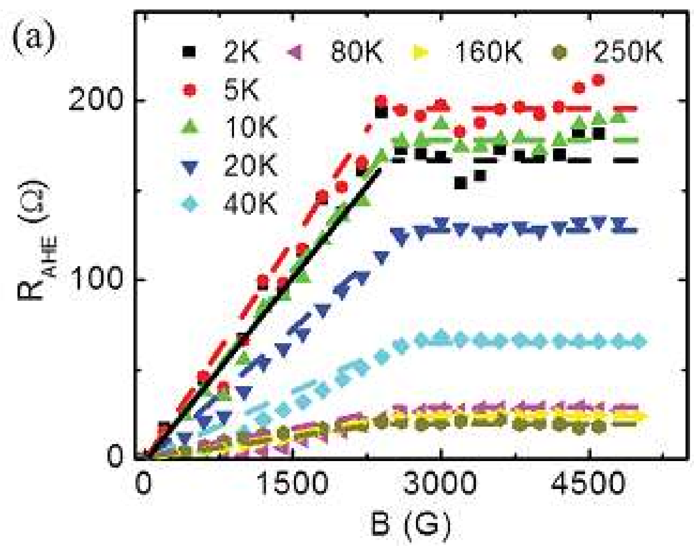
✓ **Doped graphene, Paramagnetic moment**





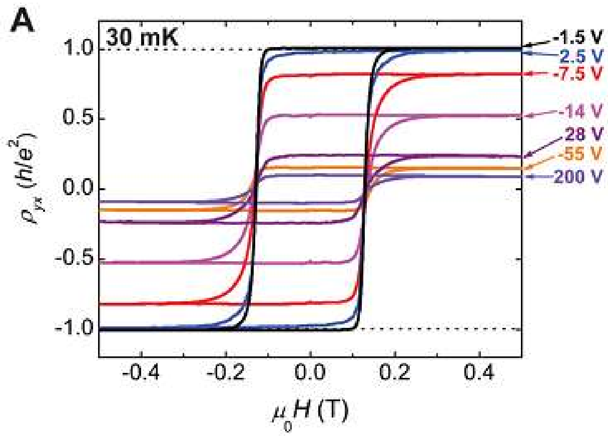
✓ **FM in graphene by proximity effect**



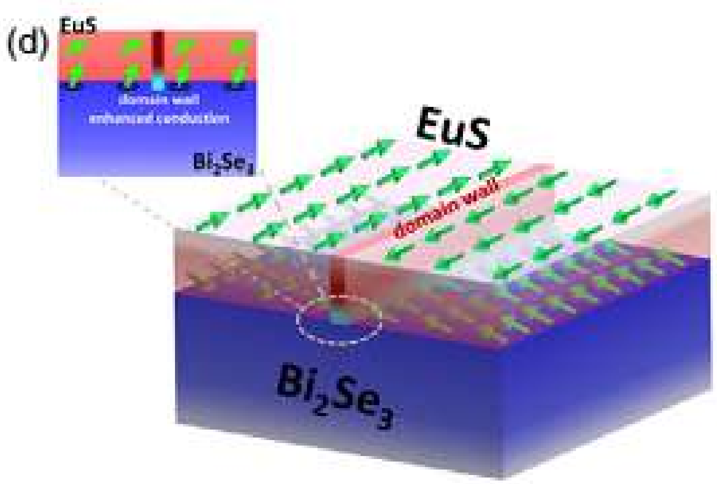


Summary of Lecture II

✓ **Doped TI, QAH**

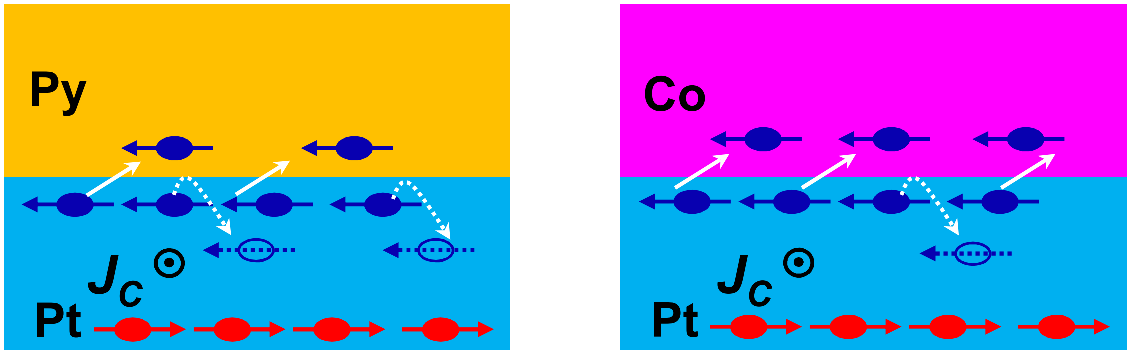


✓ **FM in TI by proximity effect**

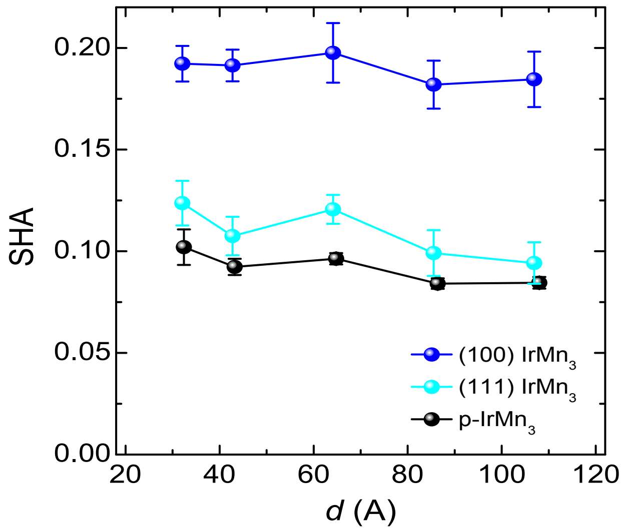


Summary of Lecture II

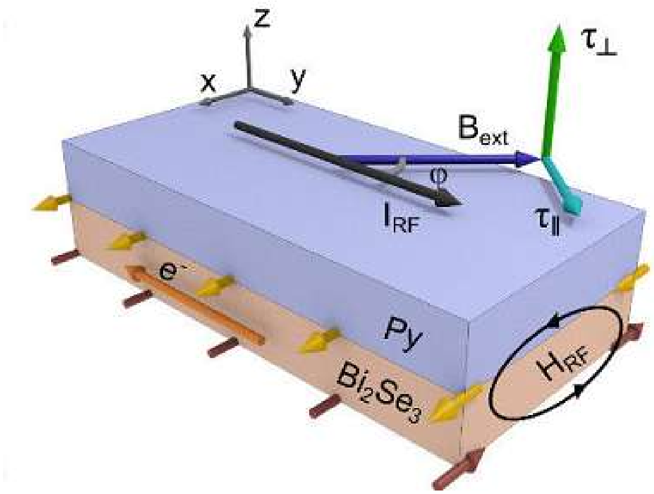
✓ **Interface Transparency for SOT**



✓ **Facet dependent SOT in $IrMn_3$**



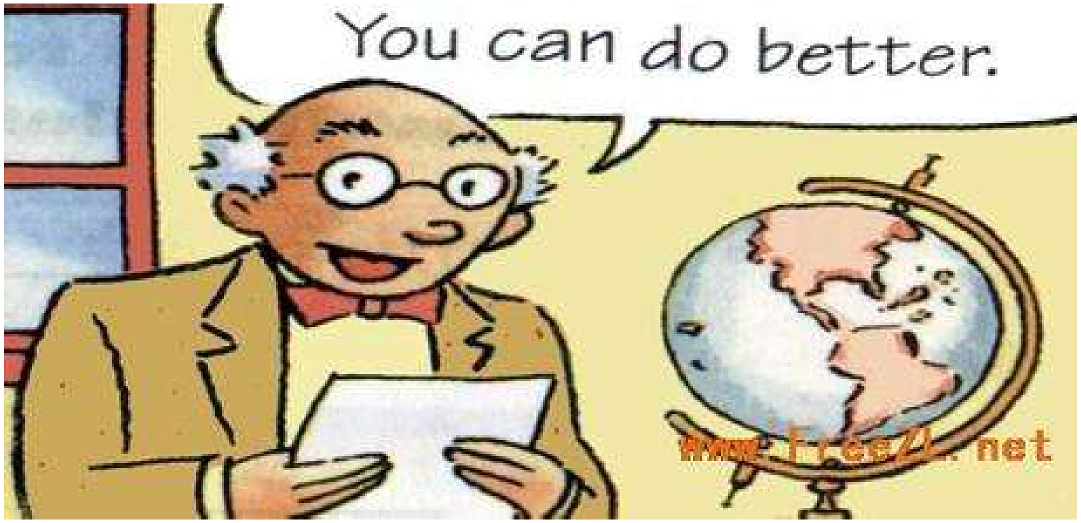
✓ **TI has very large SOT**



Summary of Lecture II

Questions still to be answered:

- **FM in graphene by doping**
- **QAH in Graphene heterostructures**
- **Robust QAH at higher temperature**
- **More effective SOT in quantum materials**



Acknowledgement

To the mentors for my research life

Acknowledgement

To the mentors for my research life

Roland K. Kawakami

Stuart. S. P. Parkin

Acknowledgement

The good team@PKU

Lab for Spintronics and Emergent Materials

Summary

Lab for Spintronics and Emergent Materials

HOME | MEMBERS | RESEARCH | PUBLICATIONS | NEWS | TEACHING | LINKS | GROUP LIFE | JOIN US

Open Positions

Postdoctors

One post-doctor position open.

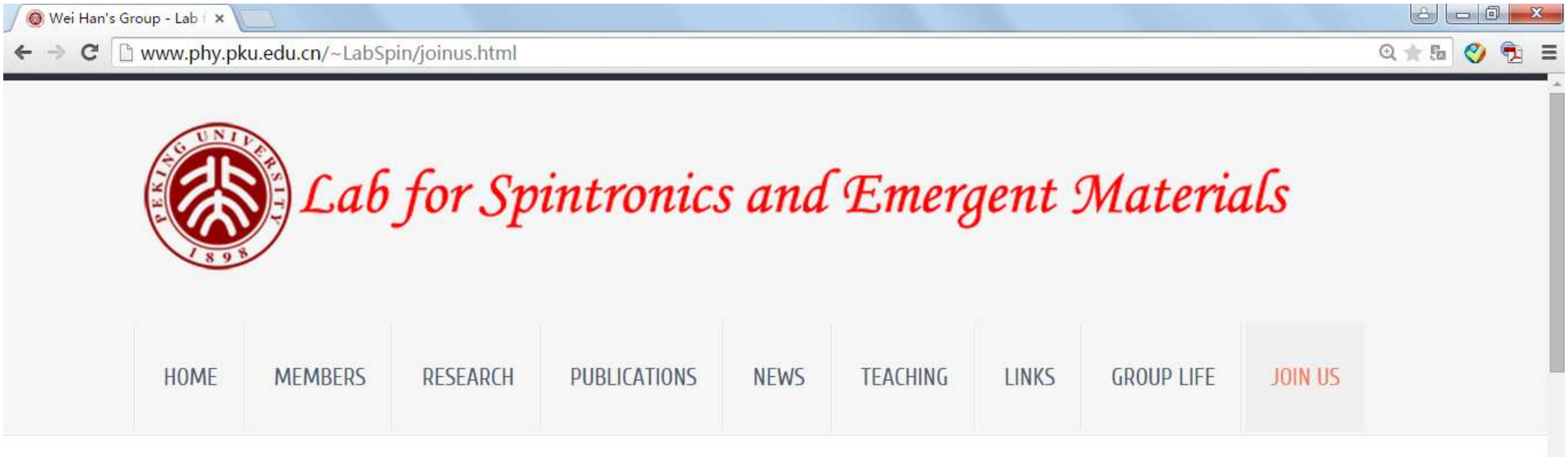
Graduates

One or two PH.D students each year.

Undergraduates

Welcome to our Lab!

Summary



Thank you for your attention!

Email: weihan@pku.edu.cn