

Chapter 4

Spin Valves

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Outline

1. Spin valves and spin injection

**2. Spin valves based on Metal and
Superconductor**

**3. Spin valves based on semiconductor
and Quantum materials**

Review of last class

1. Metal Spin Valves

Local and Nonlocal spin valves

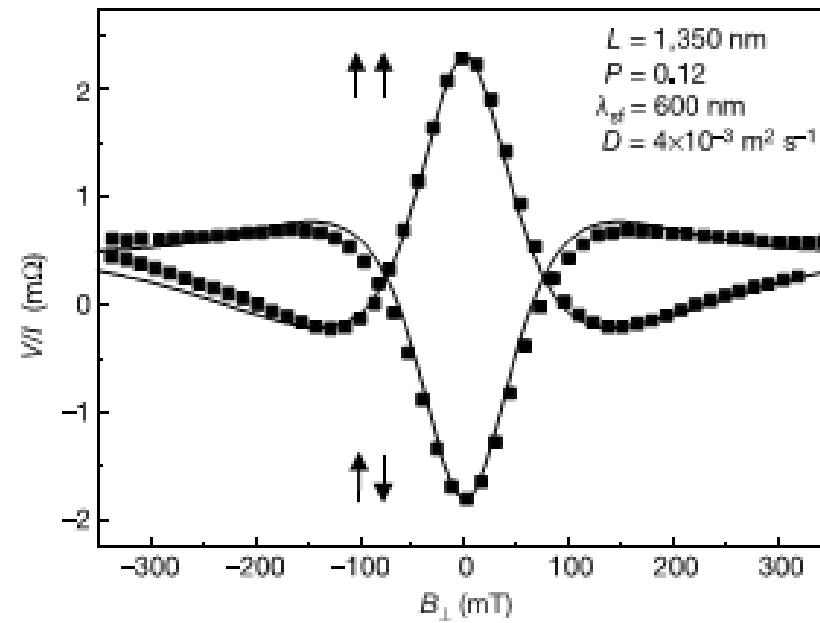
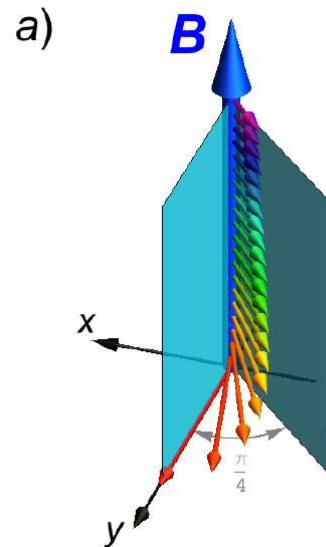
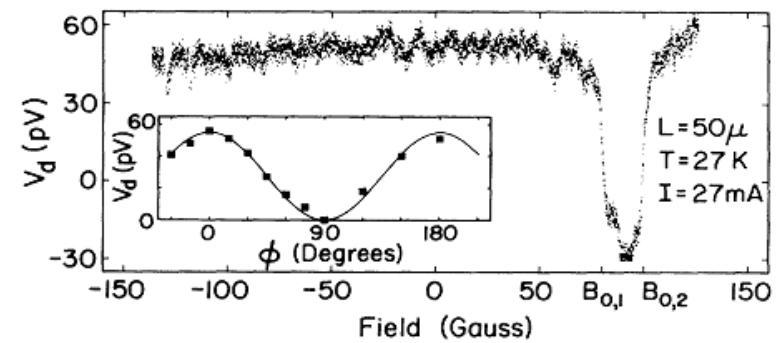
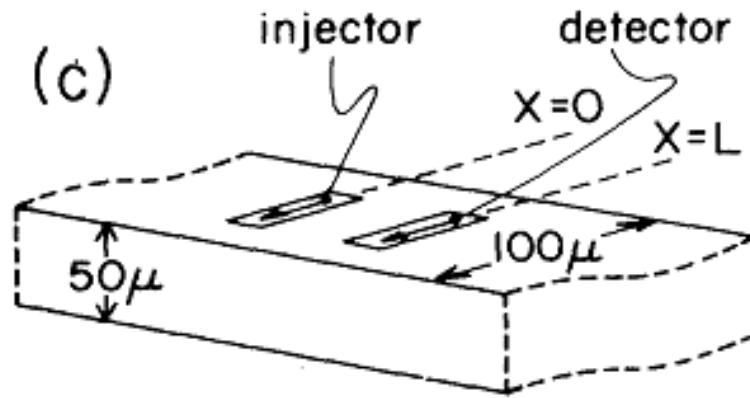
Hanle spin precession

Nano devices (Thanks to cleanroom)

Spin injection efficiency

Spin relaxation in Metals: EY

Review of last class



Review of last class

Spin Injection efficiency

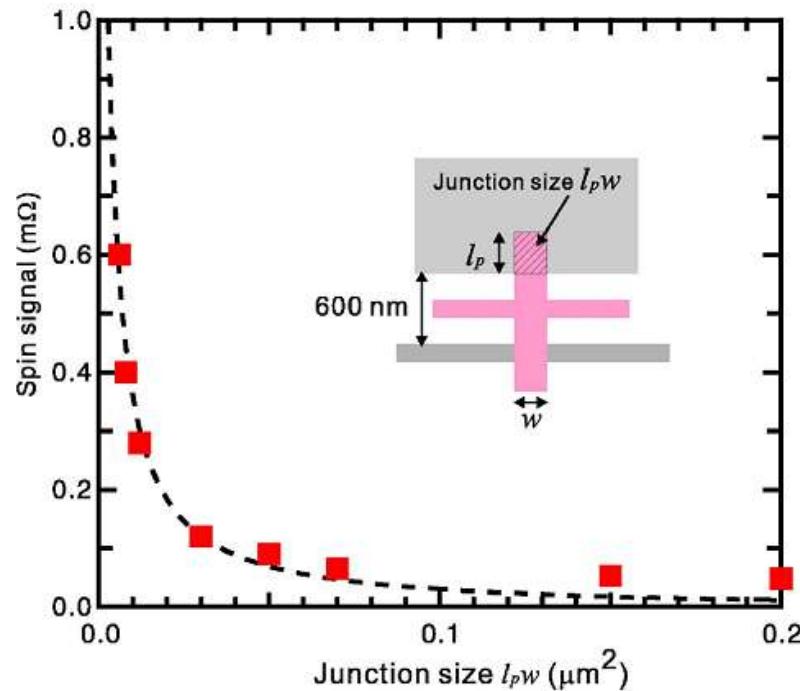
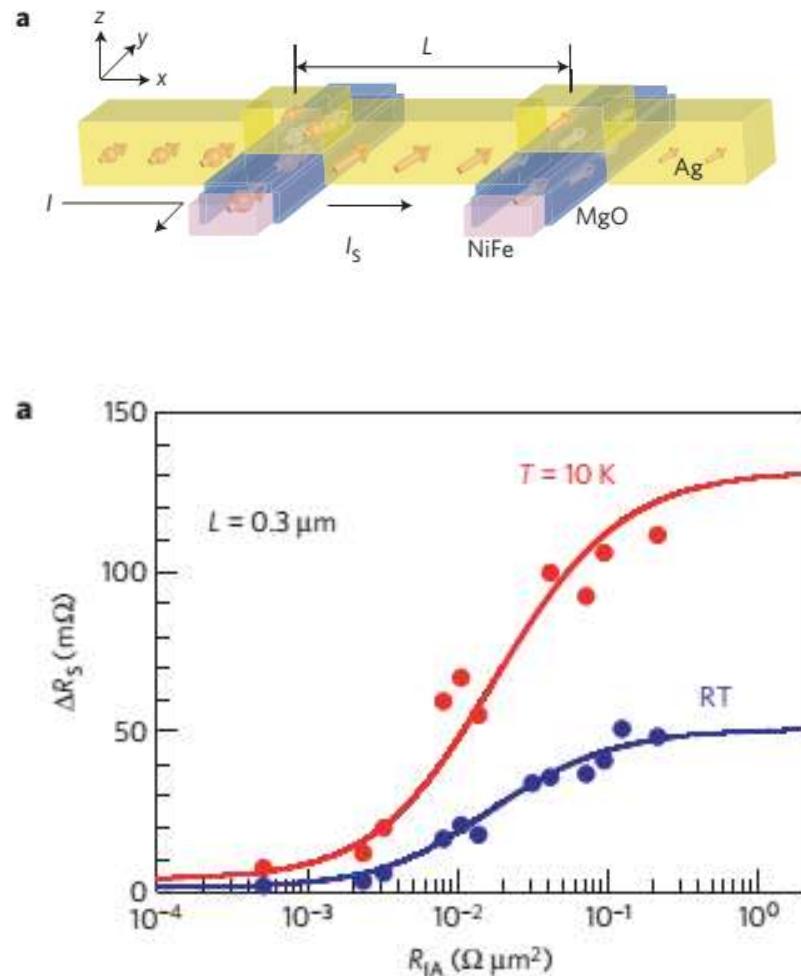
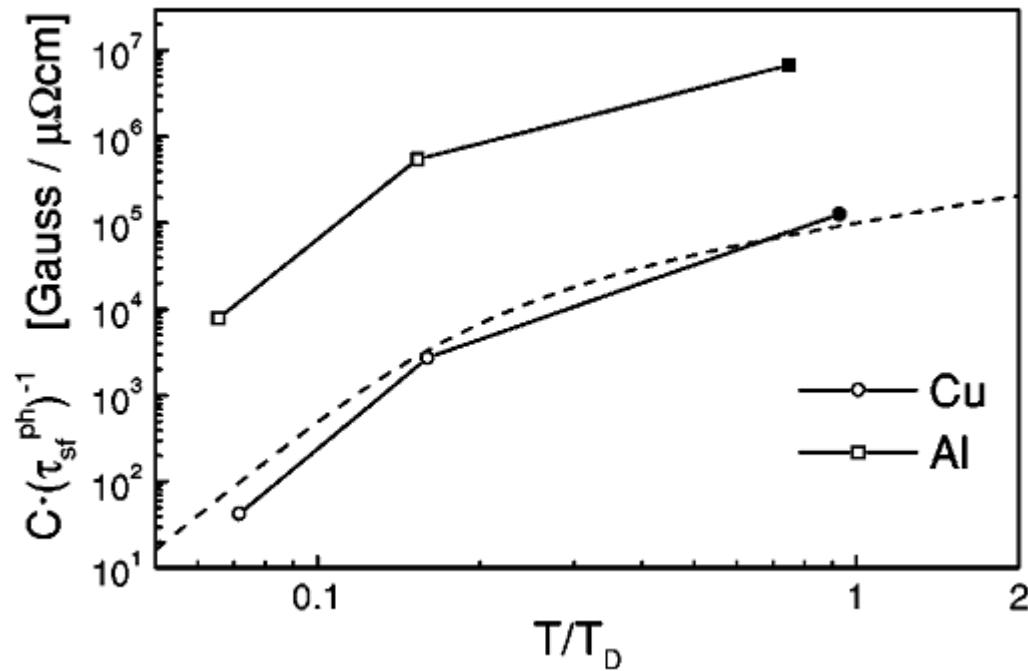


FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size $l_p w$. The dotted curve is the best fitting to the data points using Eq. (2).



Review of last class



$$\frac{\tau_e}{\tau_{sf}} = a \propto \left(\frac{\lambda}{\Delta E} \right)^2$$

Jedema, et al, PRB (2003)
Fabian & Das Sarma, PRL (1998)

Review of last class

2. Superconductor Spin Valves

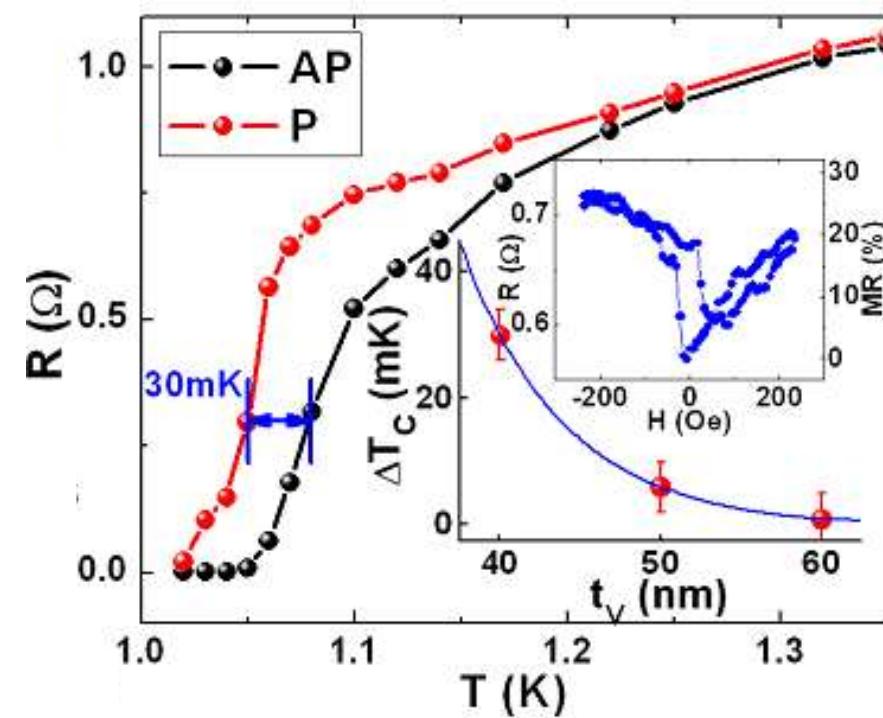
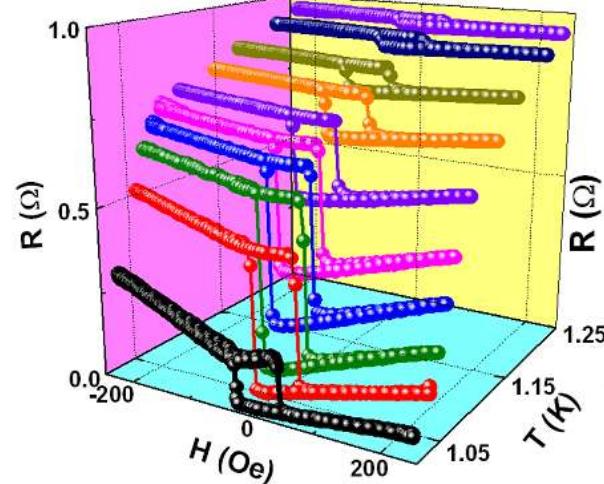
Large MR and control of T_C

Josephson junction, Spin-triplet

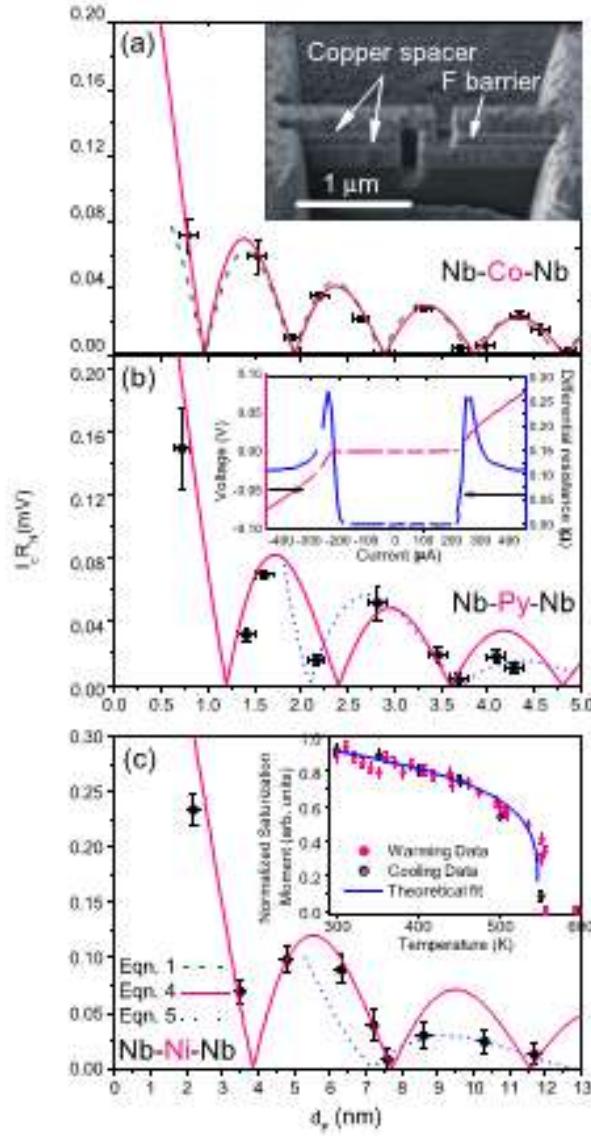
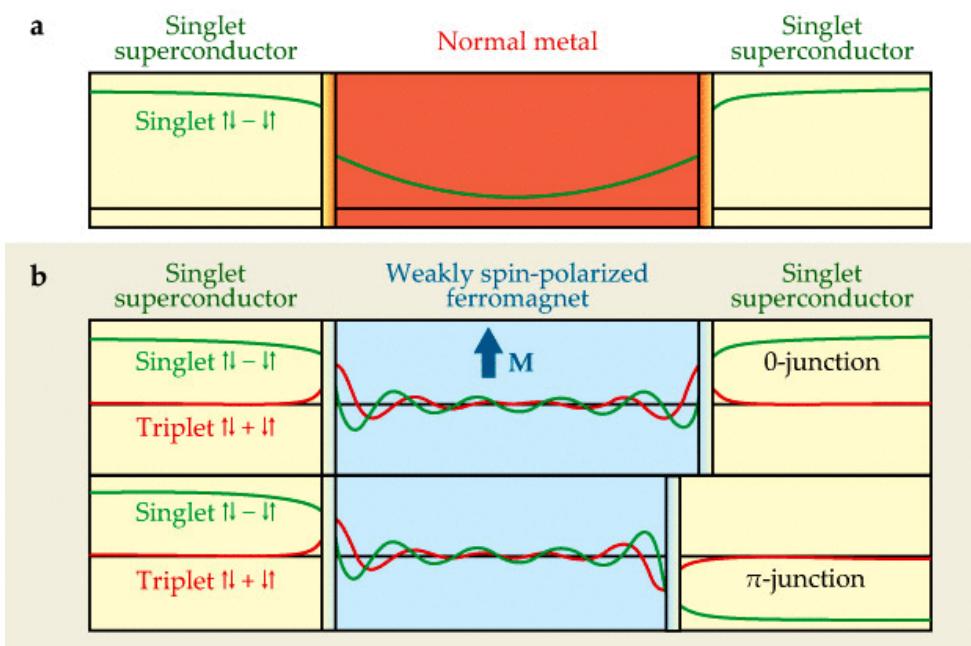
Spin injection, Long spin lifetime

Large spin Hall

Review of last class

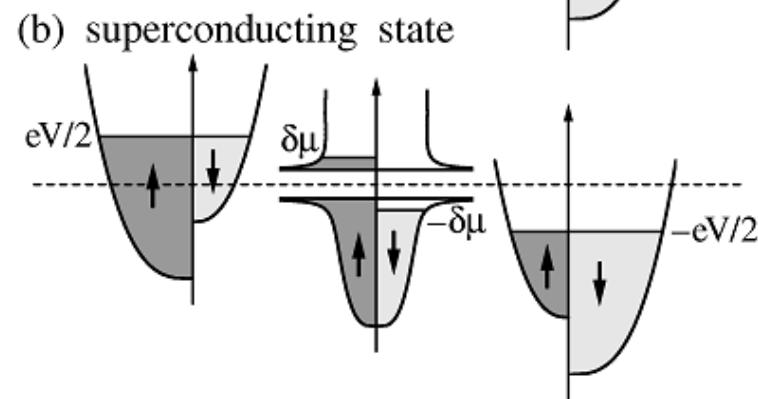


Review of last class

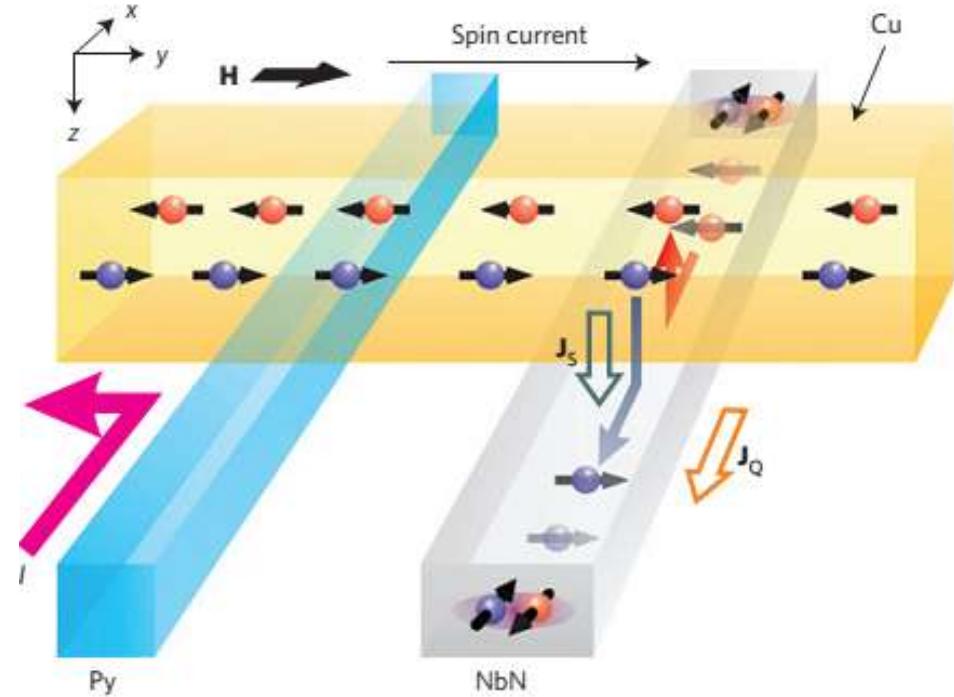


Review of last class

Spin injection



Spin Hall



3. Spin valves based on Semiconductor and Quantum materials

Outline

1. Semiconductor Spin Valves

When spintronics meets semiconductor

GaAs

Silicon and Germanium

Complex oxides

Spin FET

Why semiconductor Spintronics

Magnetic materials

Information storage

- Hard disks
- Tapes
- MRAM

Advantages :

- Non-volatile
- Fast switching



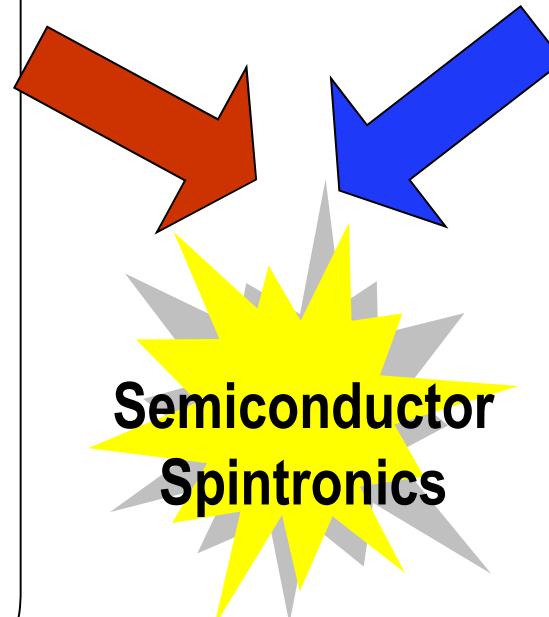
Semiconductor

Information logic and computing

- Transistor
- CPU

Advantages :

- Tunable carrier densities
- Bipolar (electron/hole)



Conductance mismatch problem

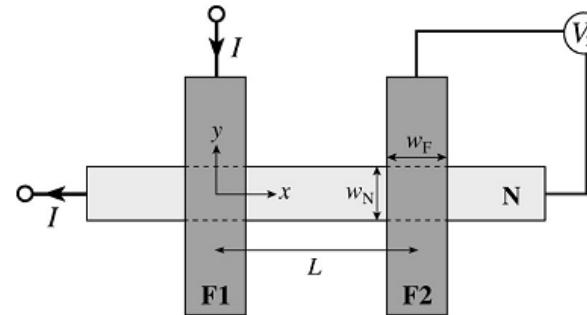
$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^2 \left(\frac{P_J \frac{R_i}{R_N}}{1 - P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1 - P_F^2} \right) \times \left[\prod_{i=1}^2 \left(1 + \frac{2 \frac{R_i}{R_N}}{1 - P_J^2} + \frac{2 \frac{R_F}{R_N}}{1 - P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

$$P_F = (\sigma_F^\uparrow - \sigma_F^\downarrow) / (\sigma_F^\uparrow + \sigma_F^\downarrow)$$

$$P_J = (G_i^\uparrow - G_i^\downarrow) / (G_i^\uparrow + G_i^\downarrow)$$

$$R_N = \rho_N \lambda_N / A_N$$

$$R_F = \rho_F \lambda_F / A_J$$



R_i (R_1, R_2) interfacial resistances between
FM (injector, detector) and nonmetal material.

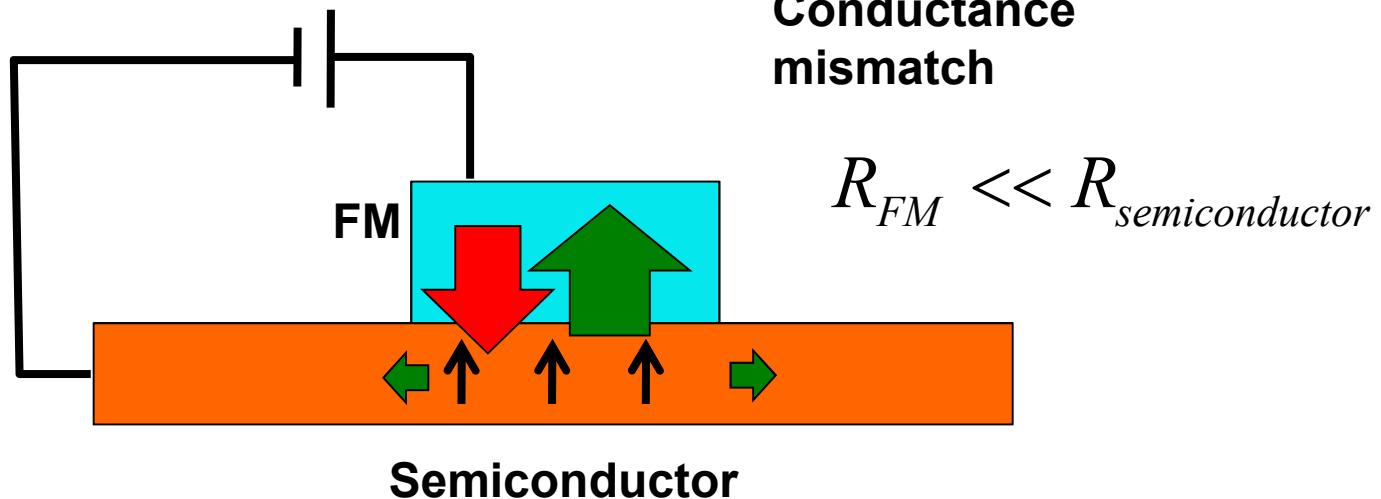
Conductance mismatch problem

$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^2 \left(\frac{P_J \frac{R_i}{R_N}}{1 - P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1 - P_F^2} \right) \times \left[\prod_{i=1}^2 \left(1 + \frac{2 \frac{R_i}{R_N}}{1 - P_J^2} + \frac{2 \frac{R_F}{R_N}}{1 - P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

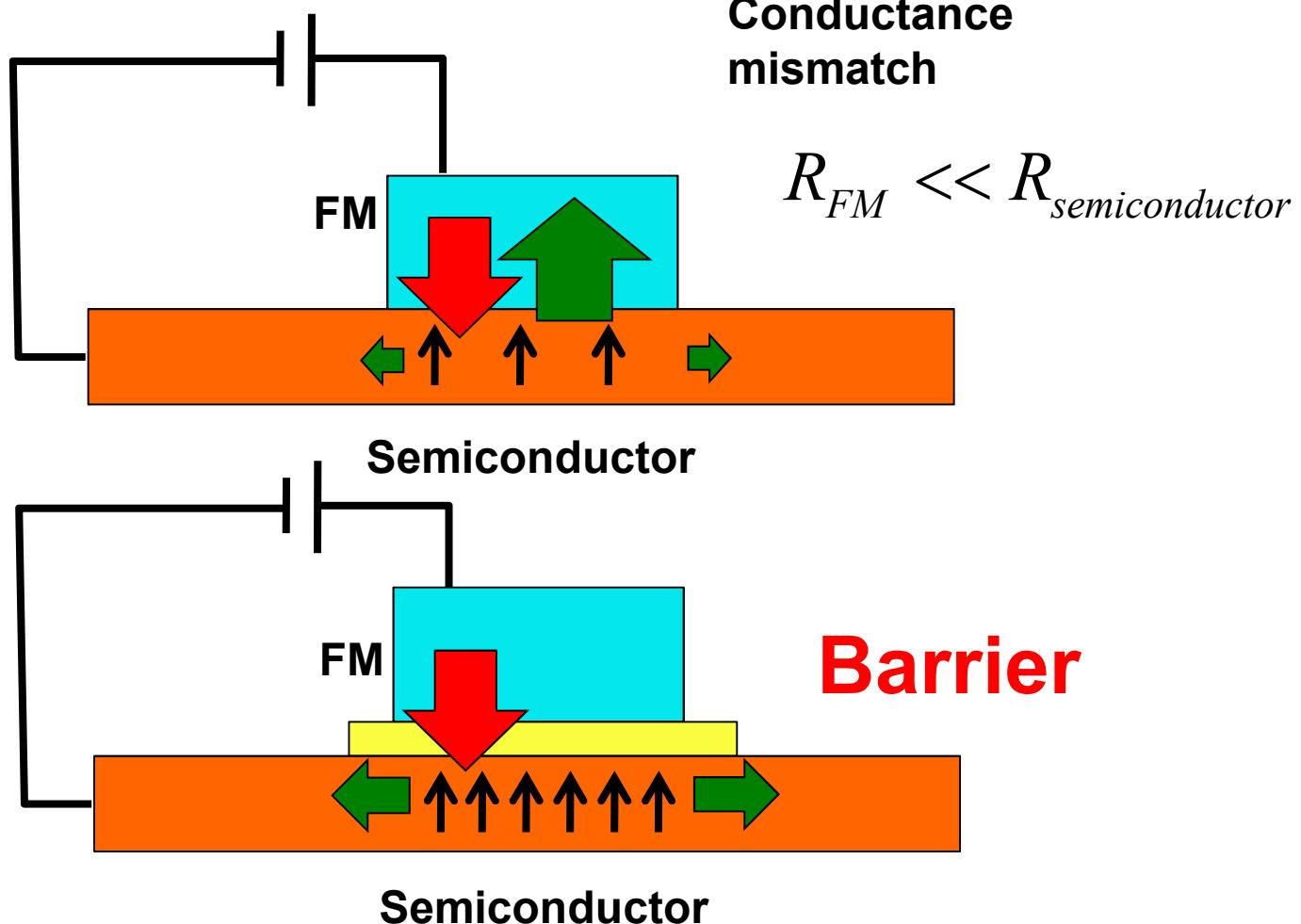
$$R_{NL} = \frac{4p_F^2}{(1-p_F^2)^2} R_N \left(\frac{R_F}{R_N} \right)^2 \frac{e^{-L/\lambda_G}}{1 - e^{-2L/\lambda_G}} = \frac{4p_F^2}{(1-p_F^2)^2} \frac{R_F^2}{R_N} \frac{e^{-L/\lambda_G}}{1 - e^{-2L/\lambda_G}}$$

$$P^2 = \frac{4p_F^2}{(1-p_F^2)^2} \left(\frac{R_F}{R_N} \right)^2$$

Conductance mismatch problem



Conductance mismatch problem

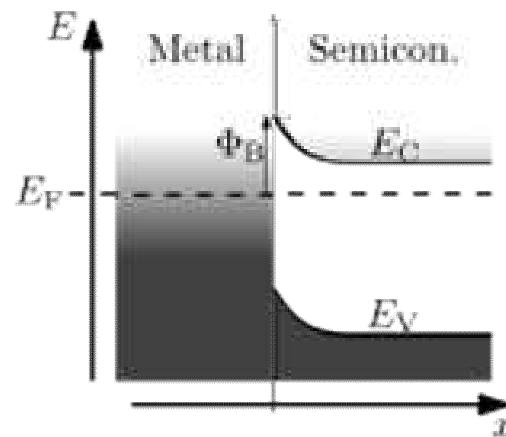


E.I. Rashba, Phys. Rev. B (2000)

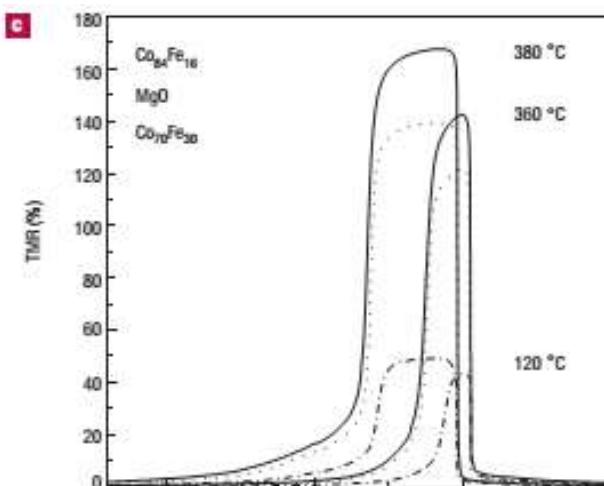
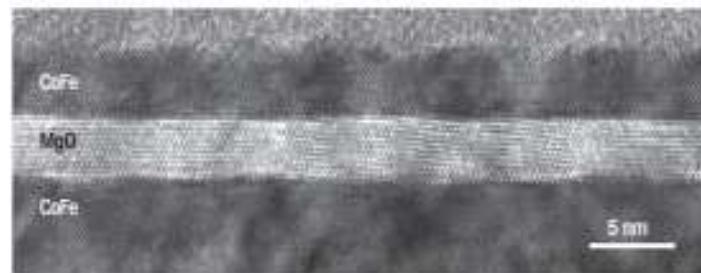
A. Fert, H. Jaffres, Phys. Rev. B (2001)

Two types of tunnel barrier

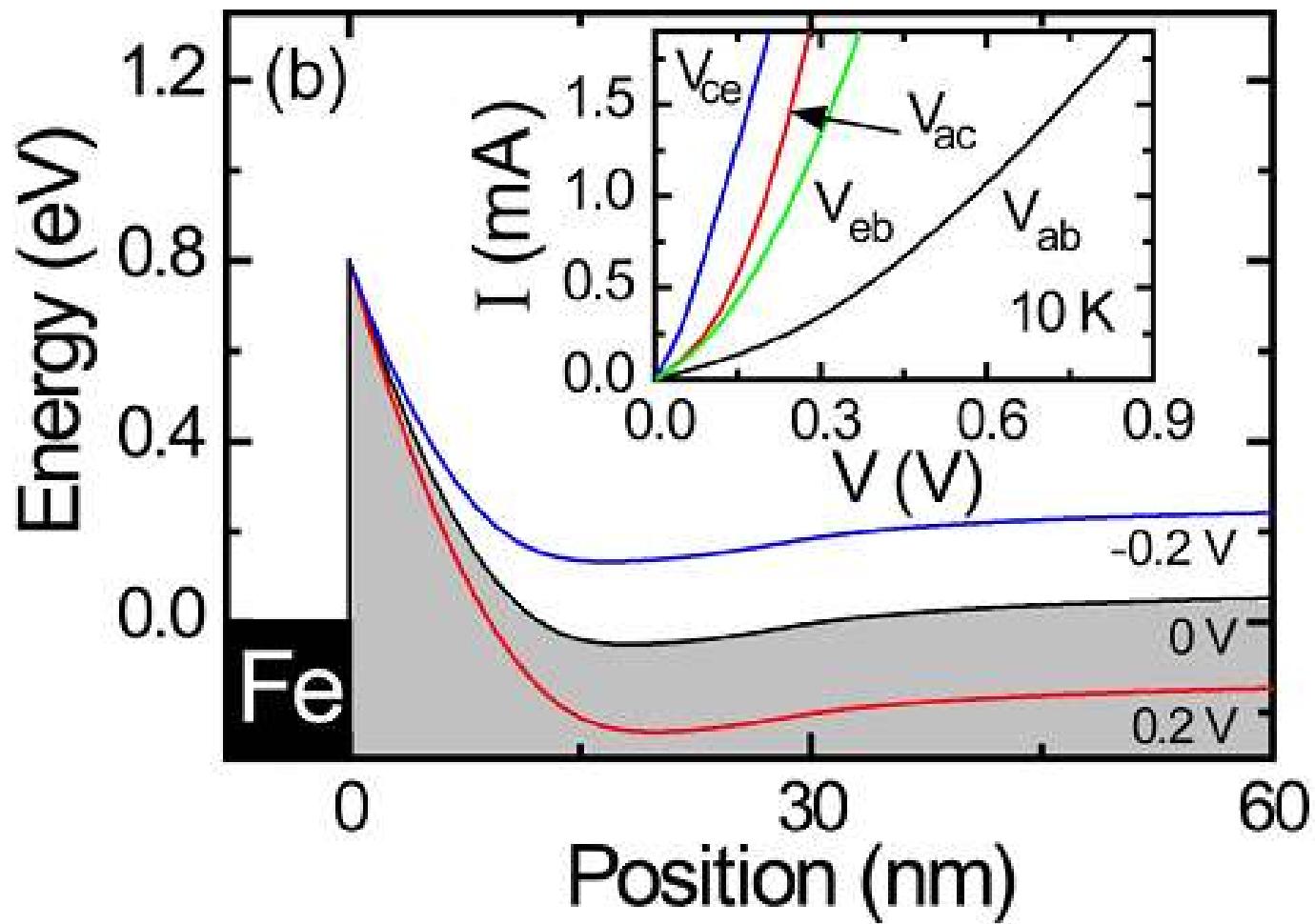
1) Schottky barrier



2) Insulating barrier, Al_2O_3 , MgO

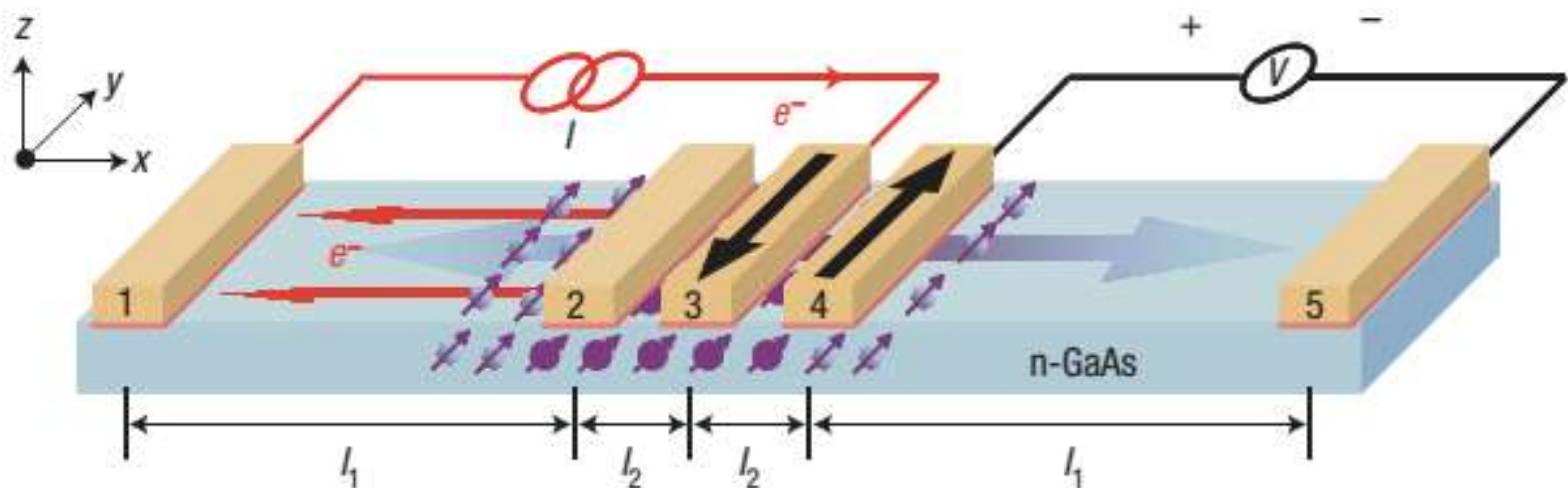


Spin in GaAs



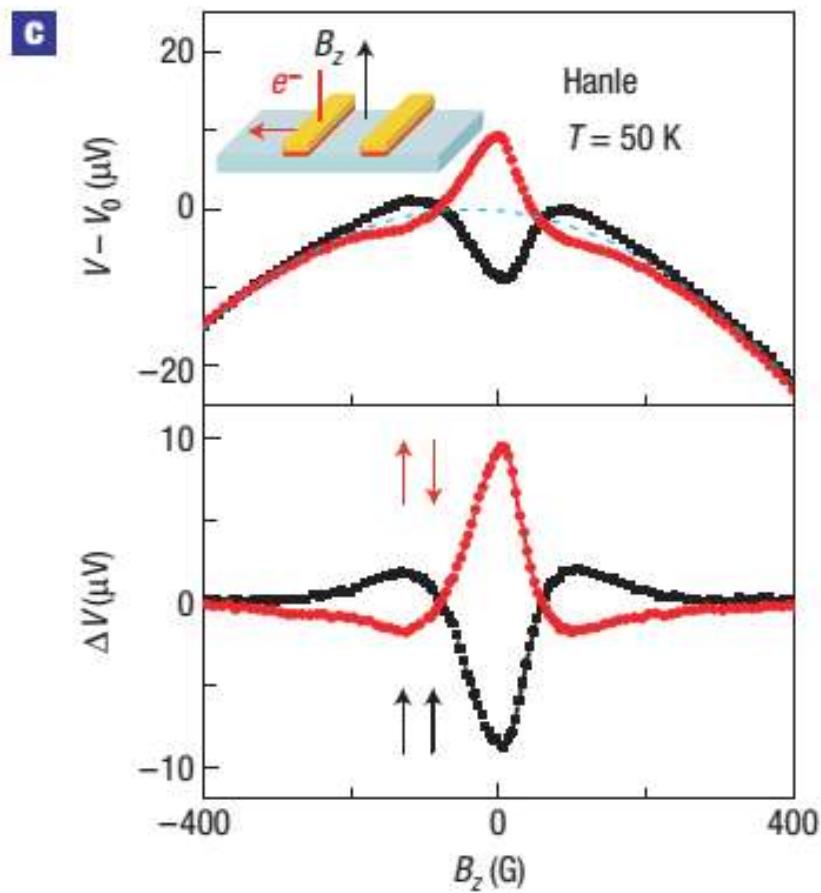
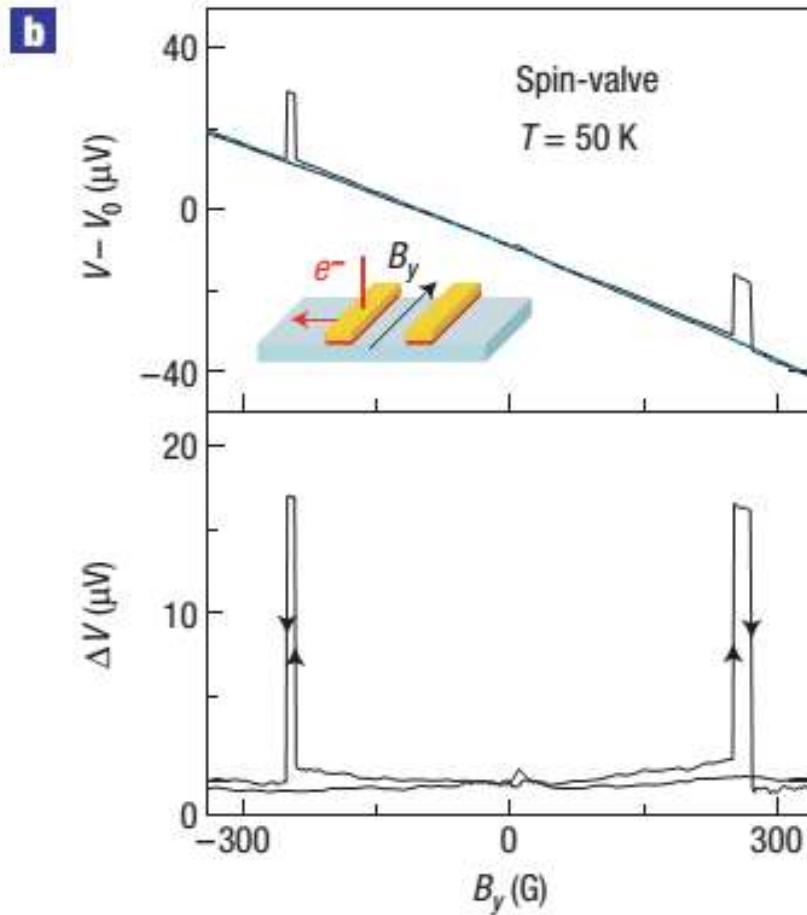
Lou, et al, PRL (2006)

Spin in GaAs

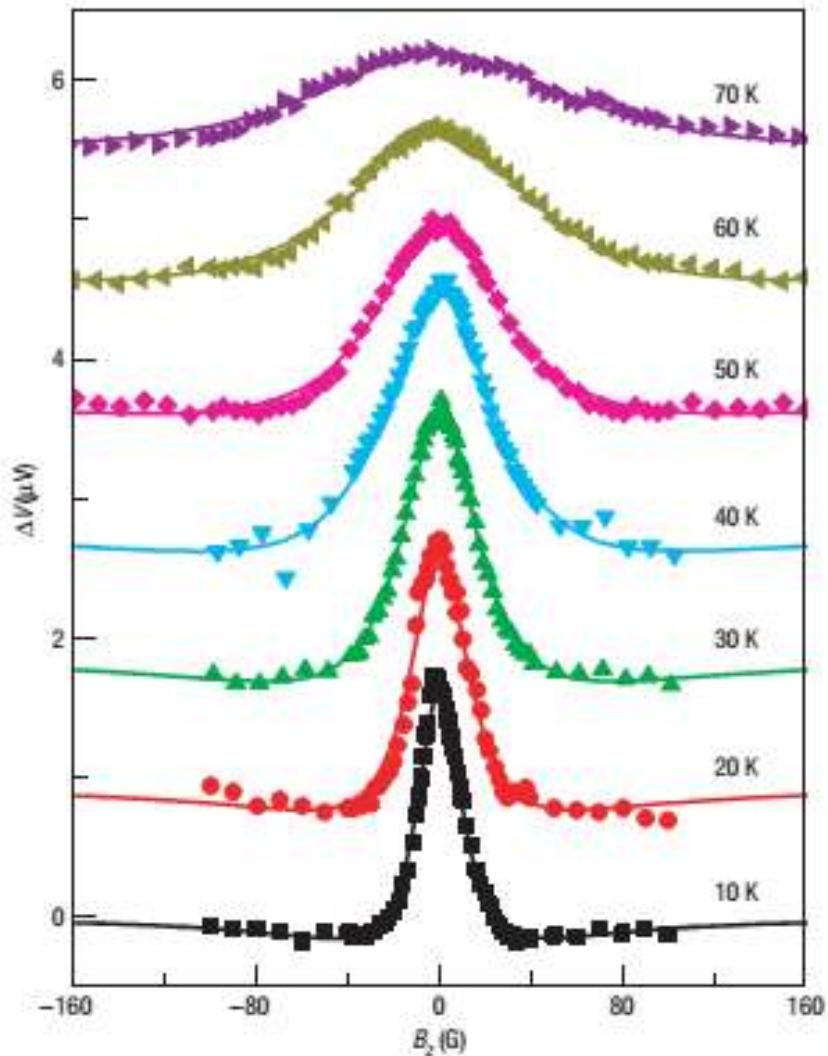


Lou, et al, Nature Physics (2007)

Spin in GaAs



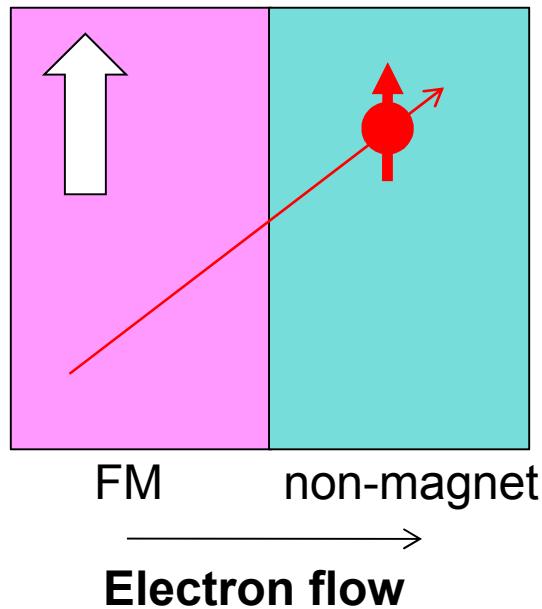
Spin in GaAs



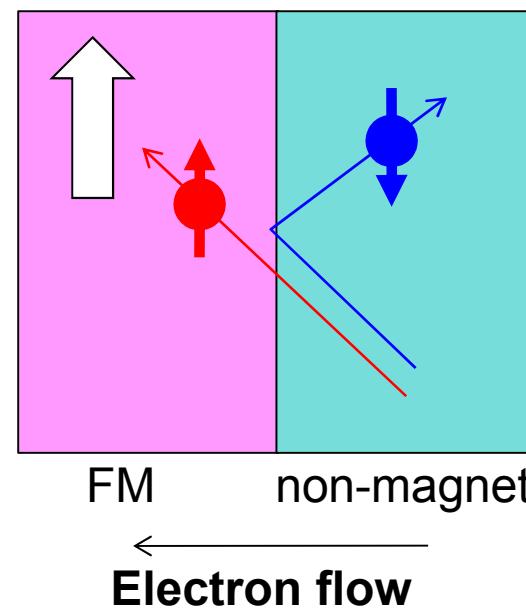
$$S_r(x_1, x_2, B) = S_0 \int_0^{\infty} \frac{1}{\sqrt{4\pi D t}} e^{-(x_2 - x_1 - v_d t)^2 / 4Dt} \times \cos(g\mu_B B t / \hbar) e^{-t/\tau_s} dt,$$

Spin in GaAs

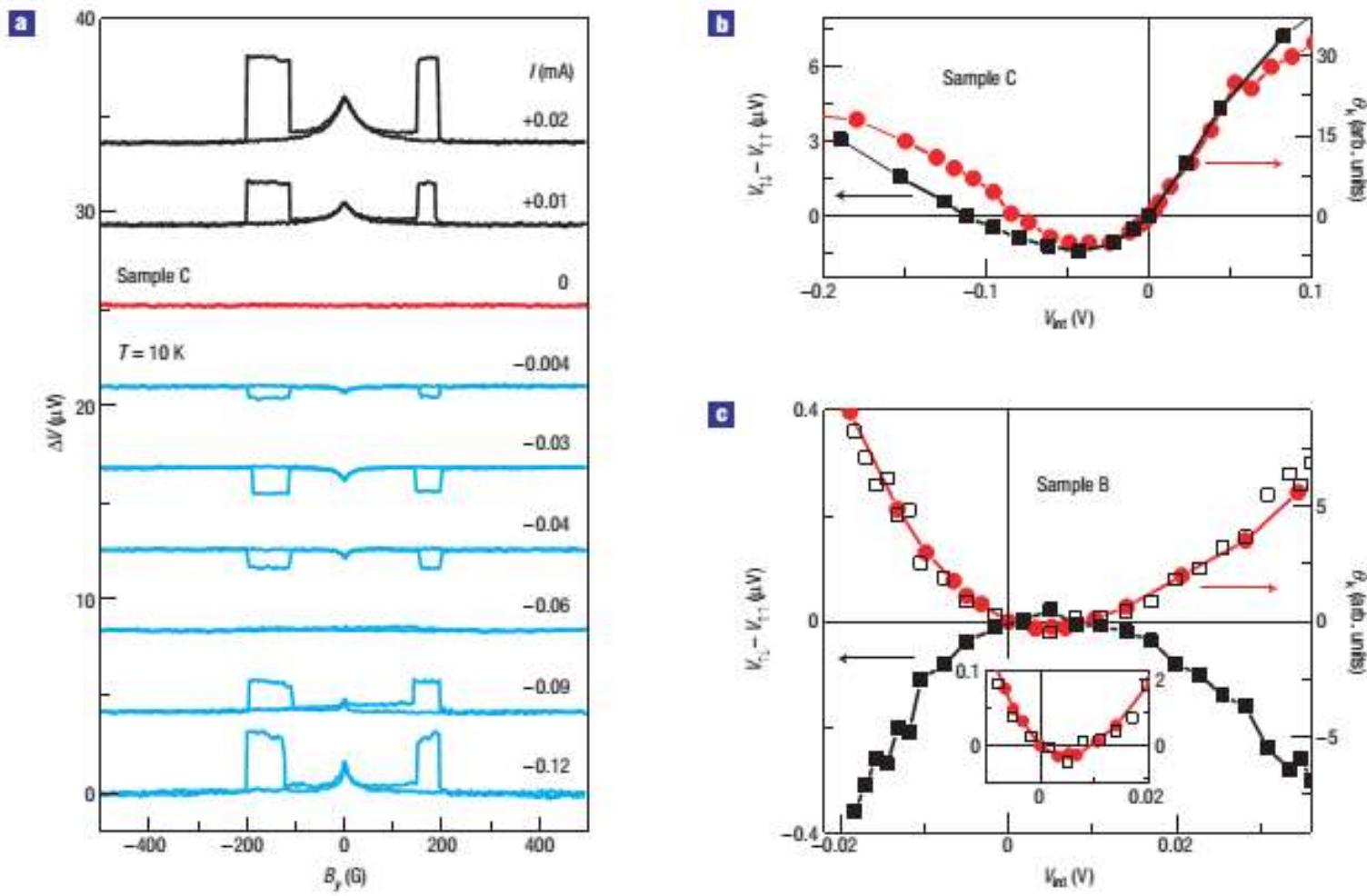
Spin Injection



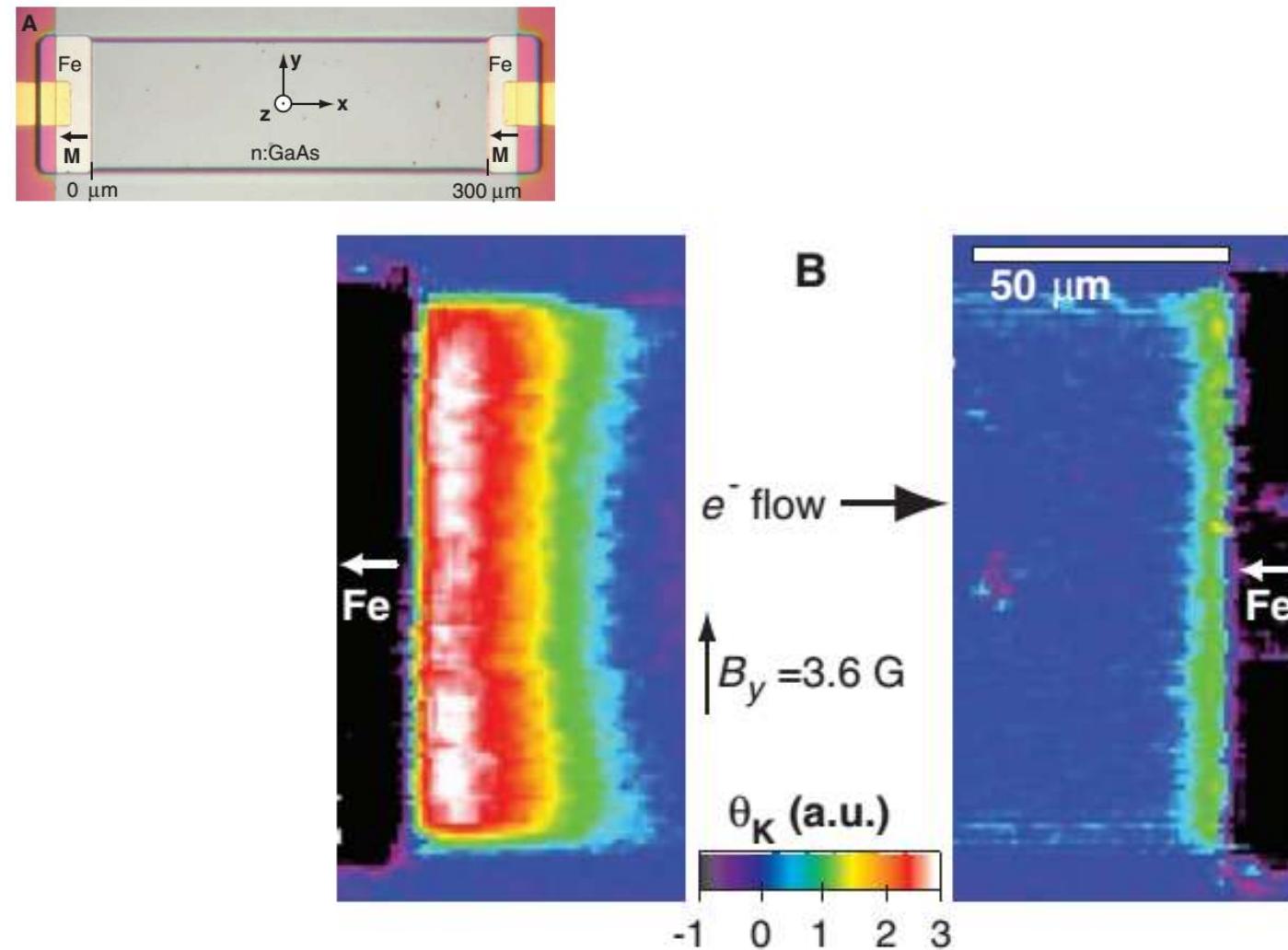
Spin Extraction / Reflection



Spin in GaAs

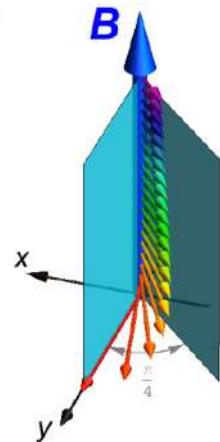


Spin in GaAs

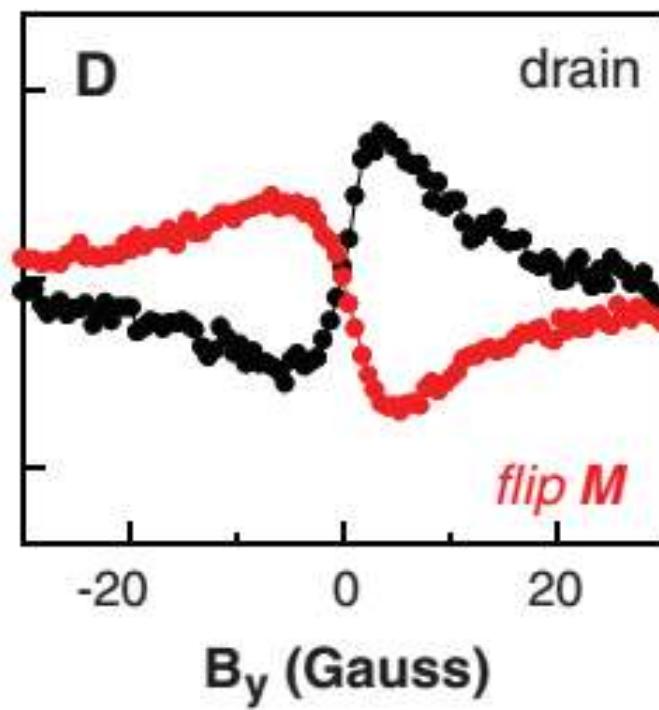
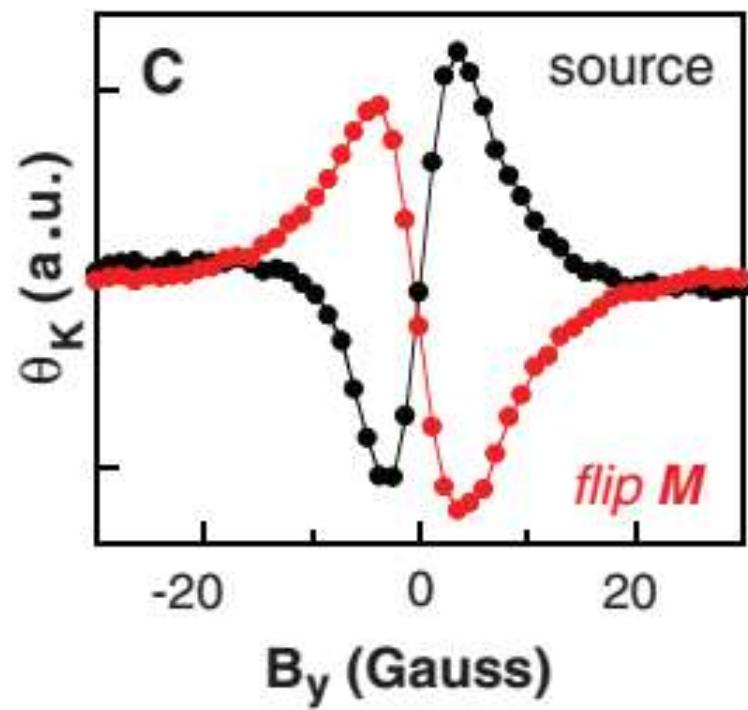


Crooker, et al, Science (2005)

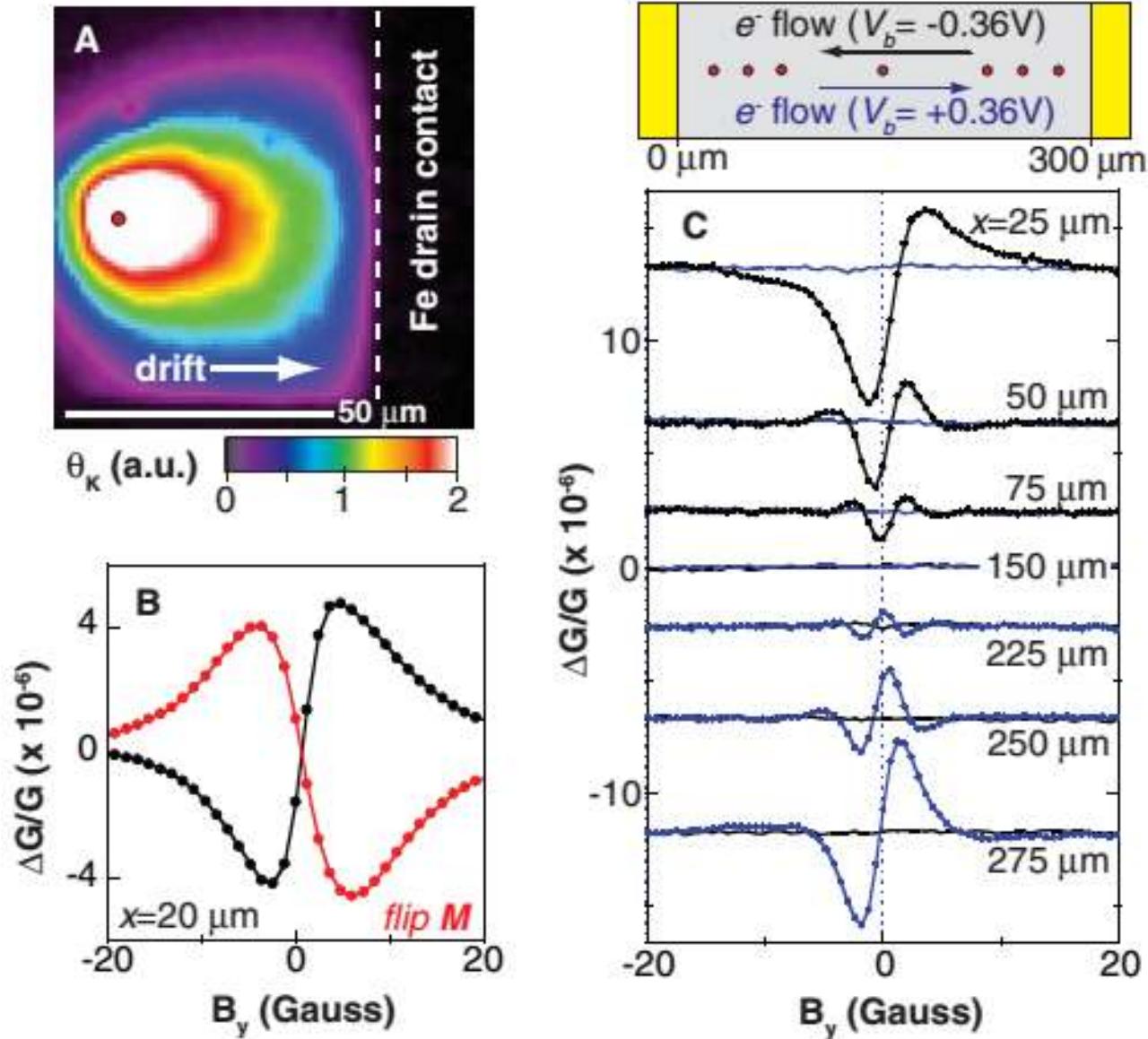
a)



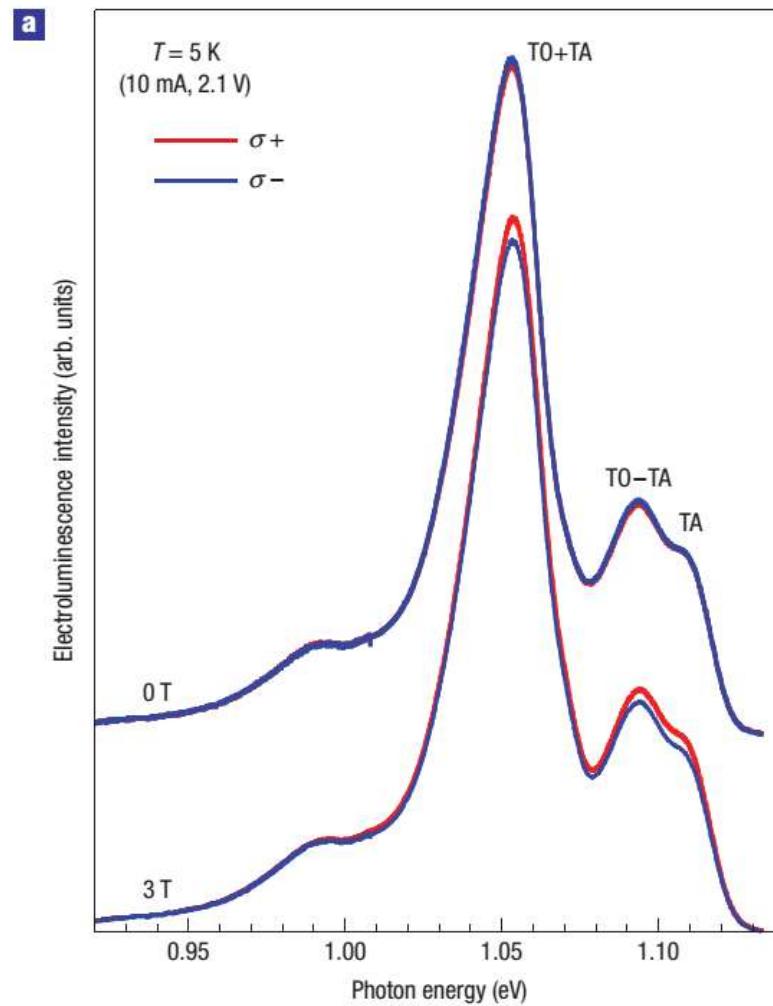
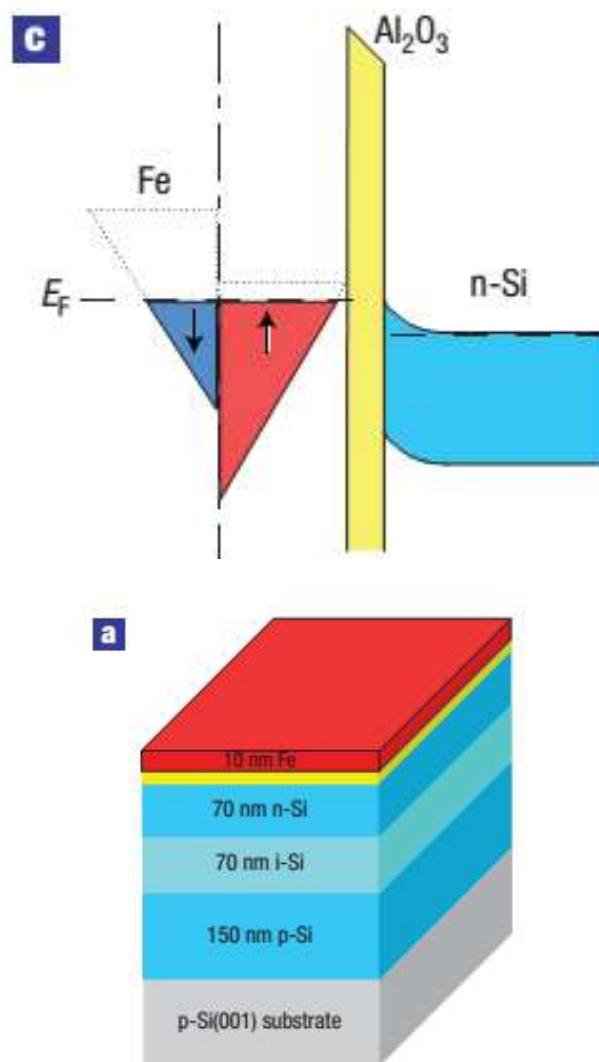
Spin in GaAs



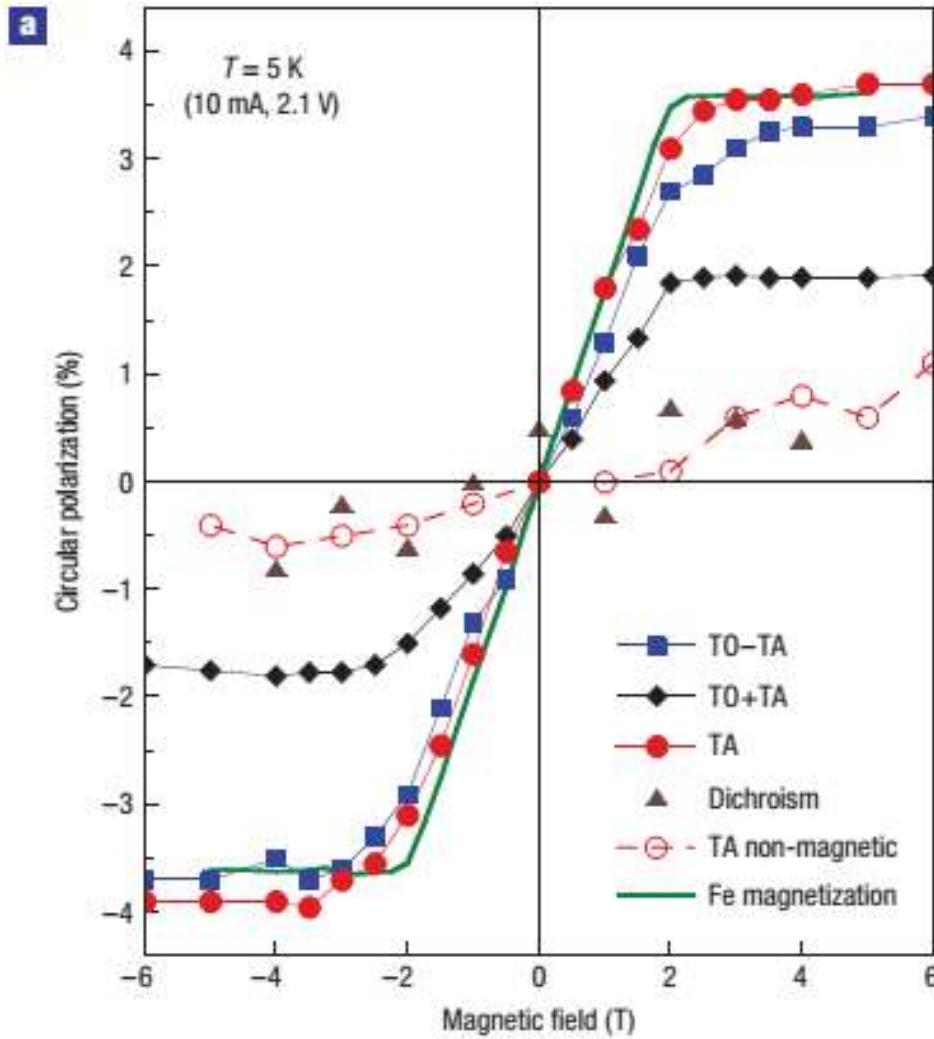
Spin in GaAs



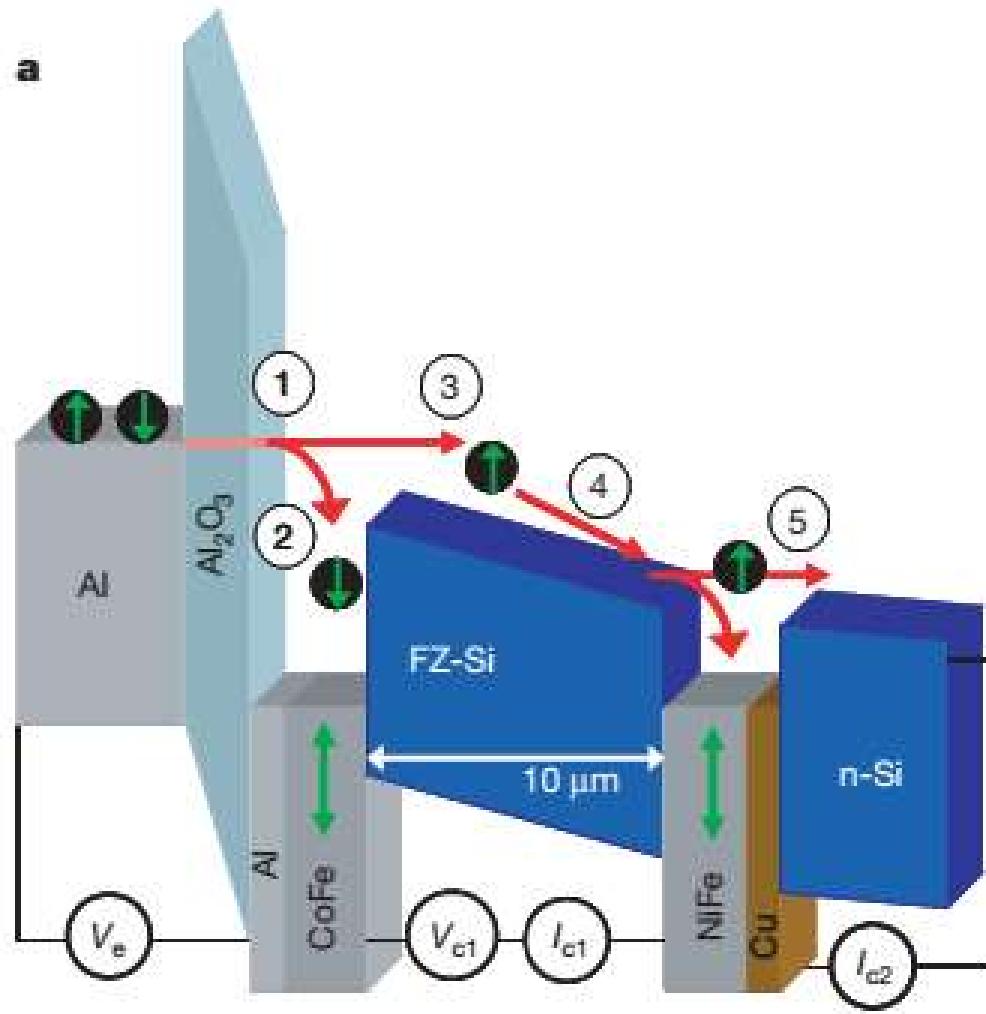
Spin in Silicon



Spin in Silicon



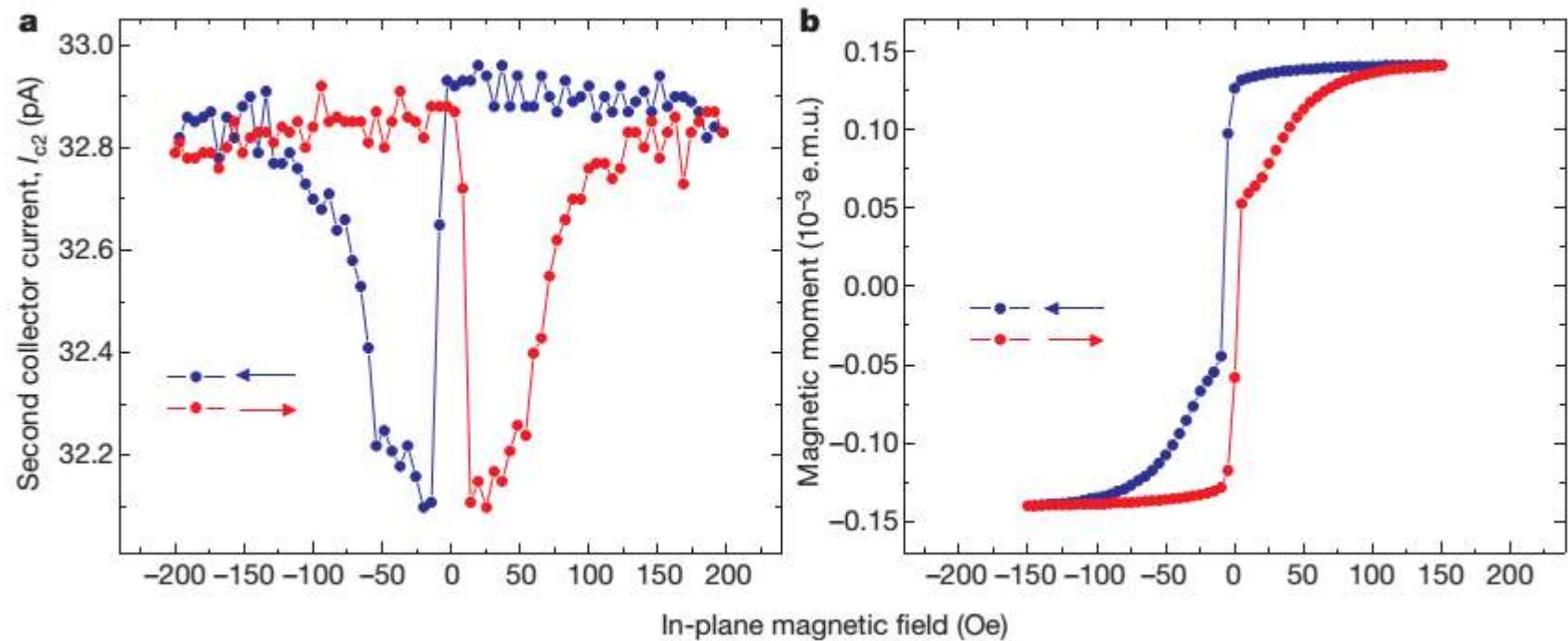
Spin in Silicon



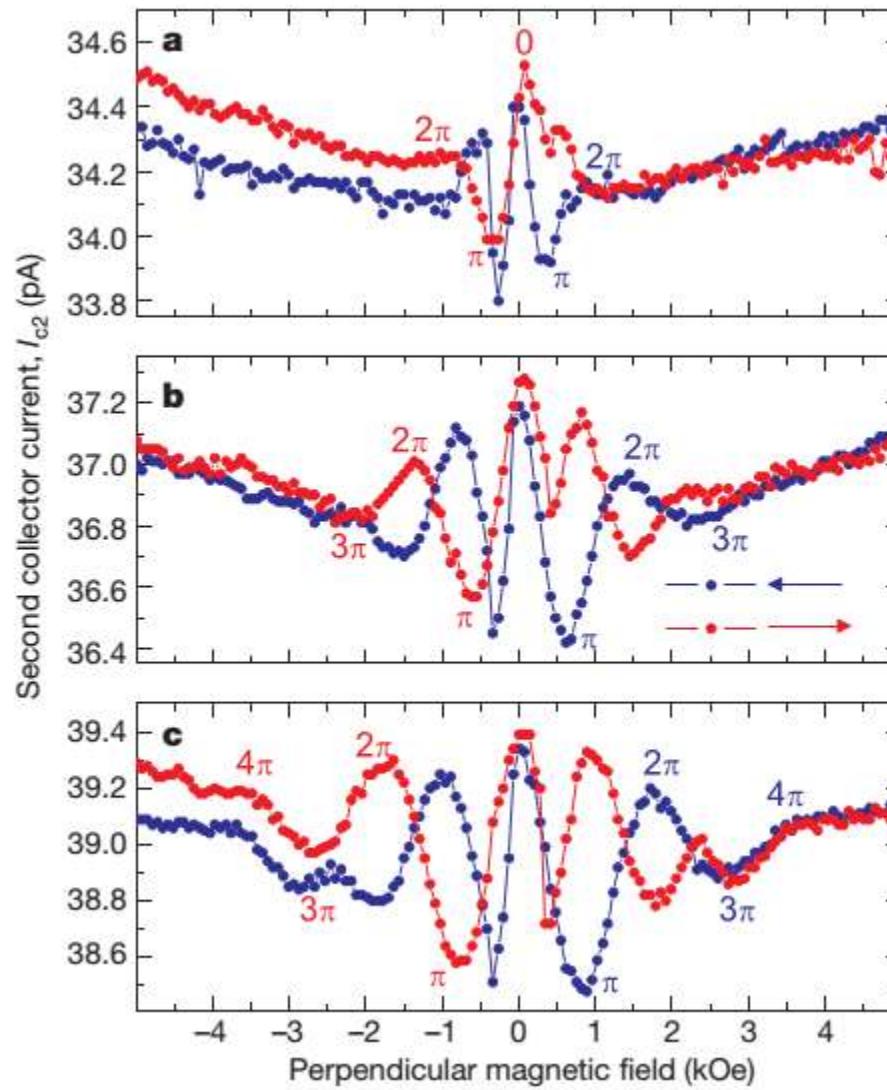
Appelbaum, et al, Nature (2007)

30

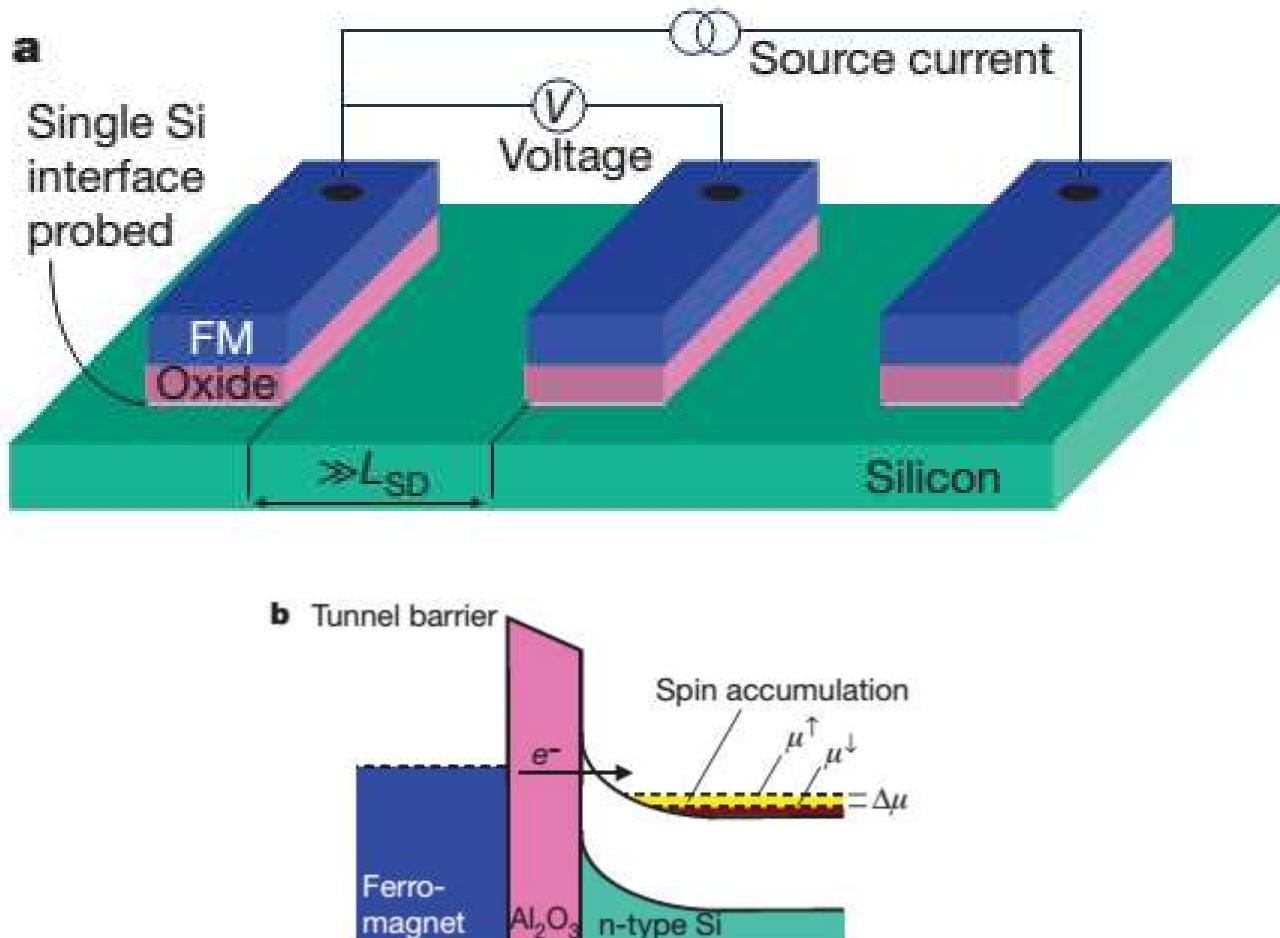
Spin in Silicon



Spin in Silicon

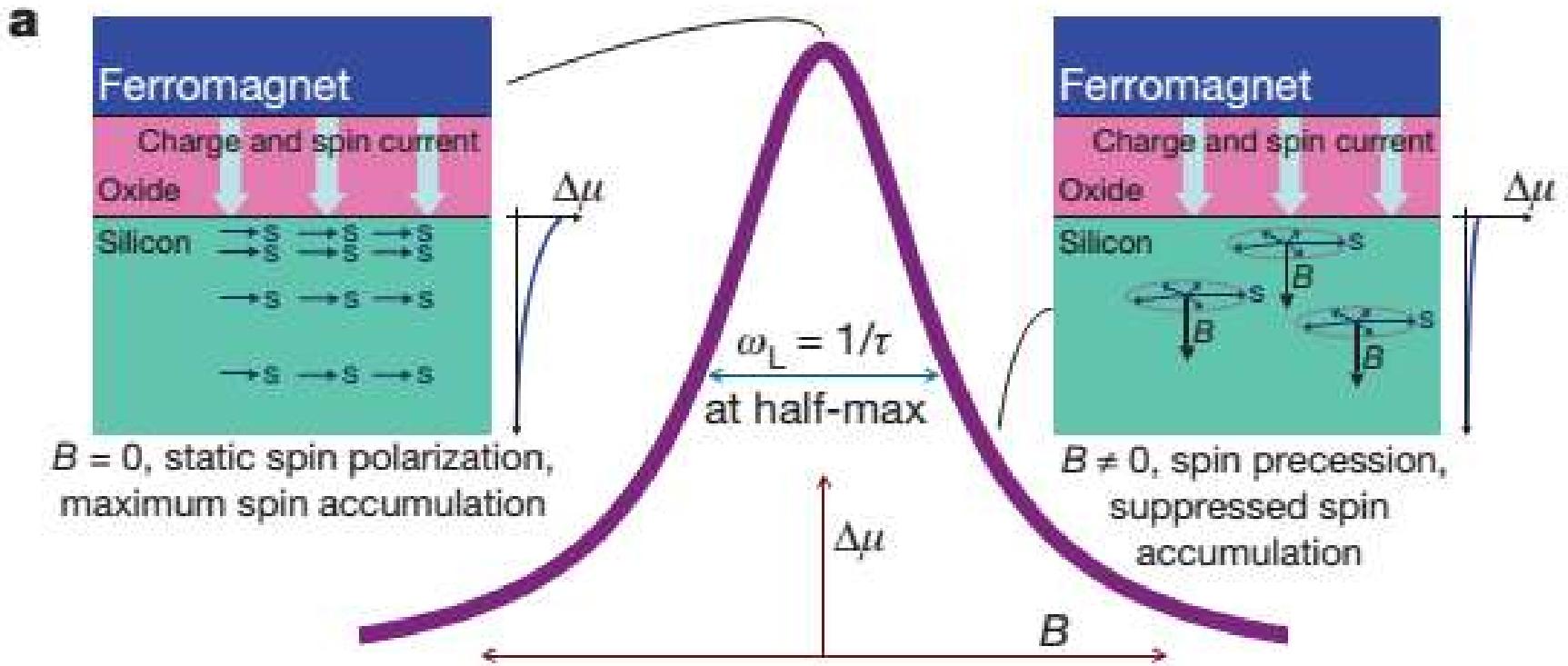


Spin in Silicon

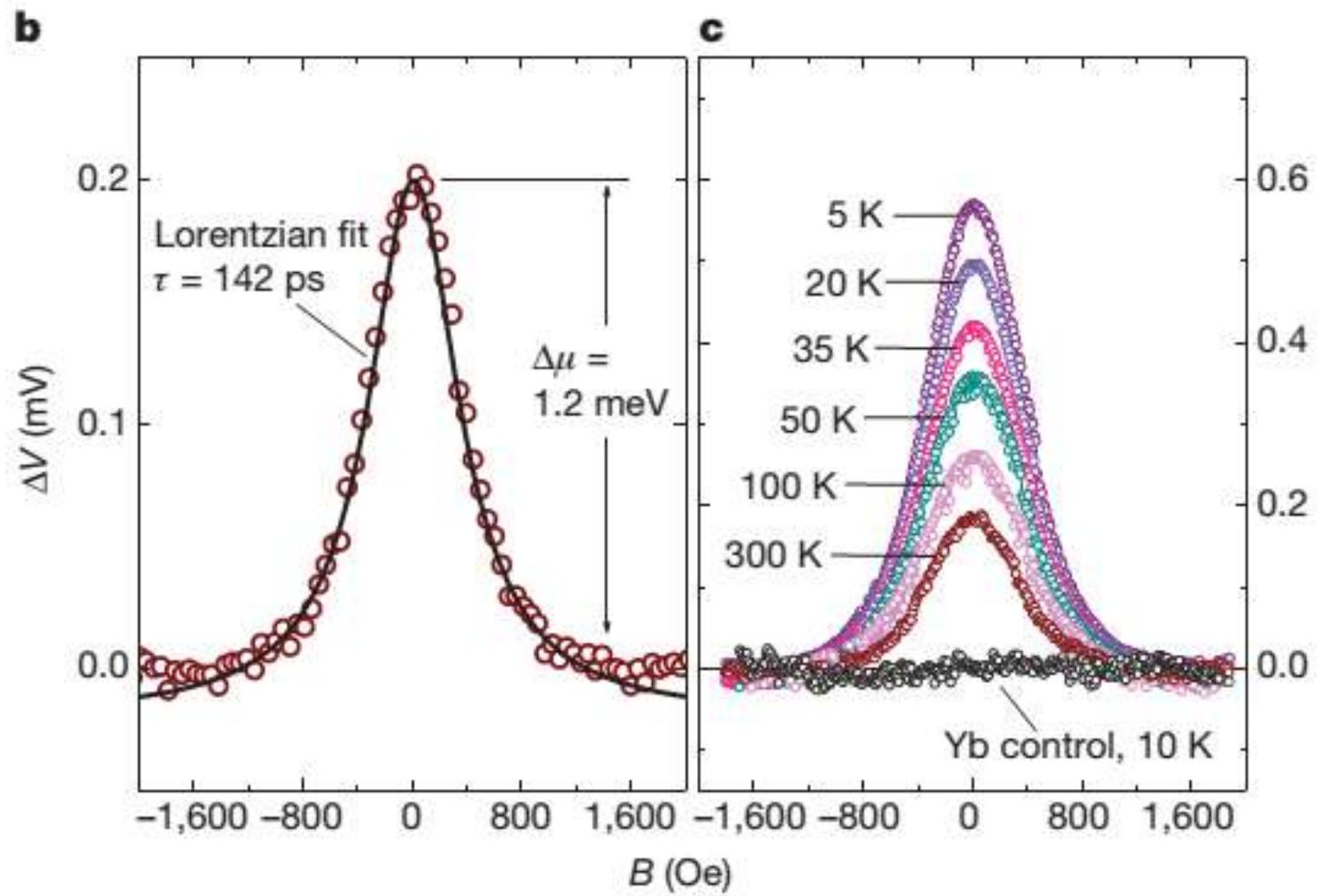


Dash, et al, Nature (2009)

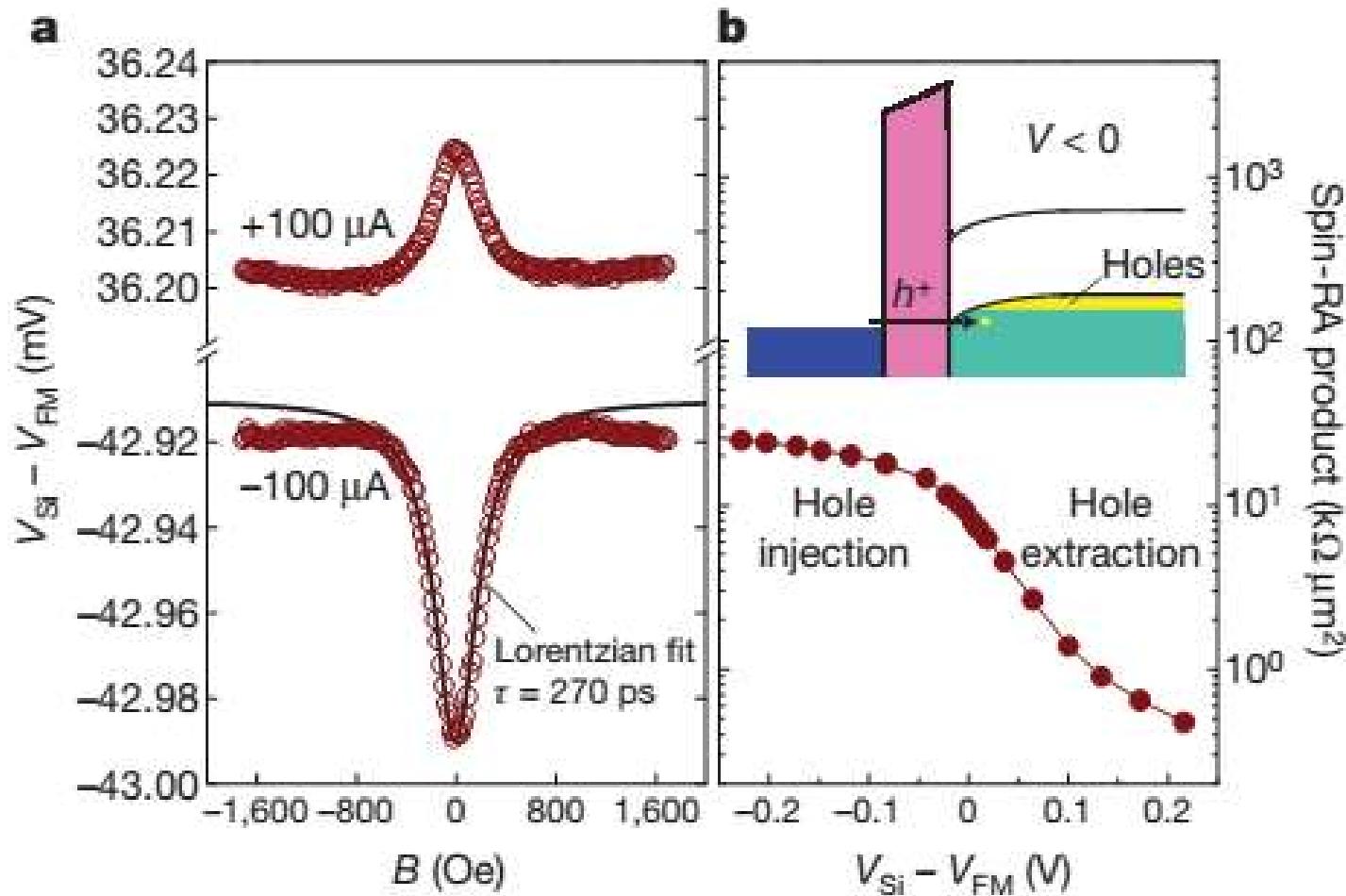
Spin in Silicon



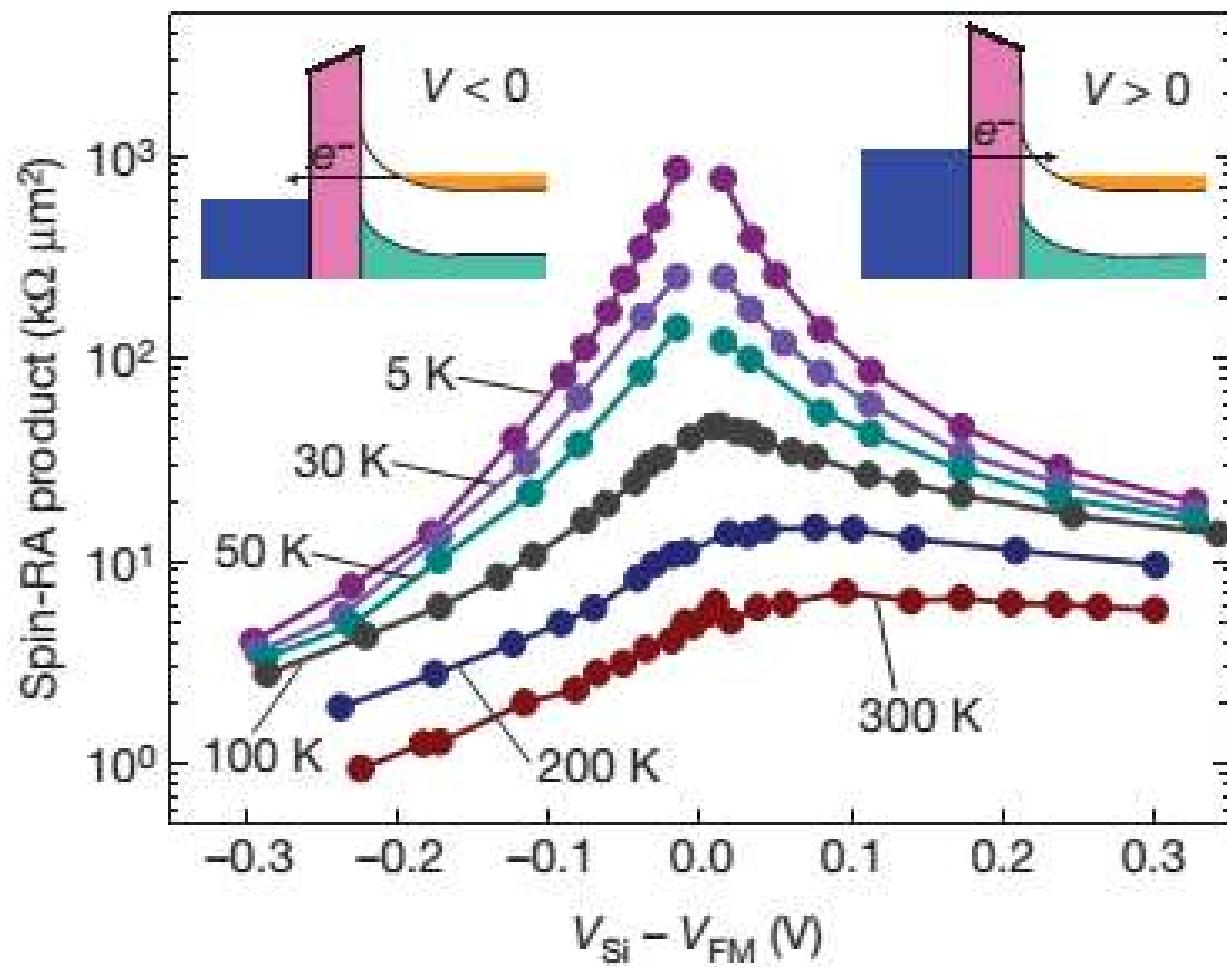
Spin in Silicon



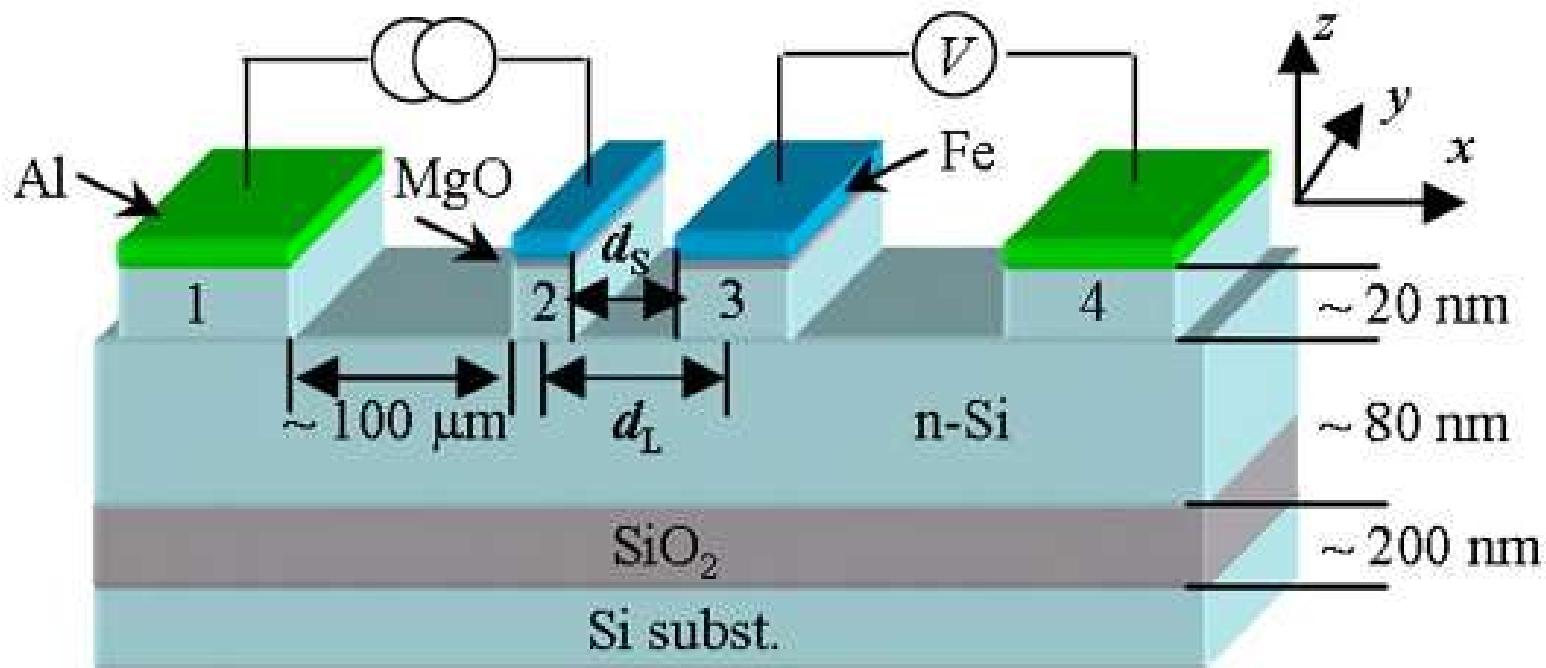
Spin in Silicon



Spin in Silicon

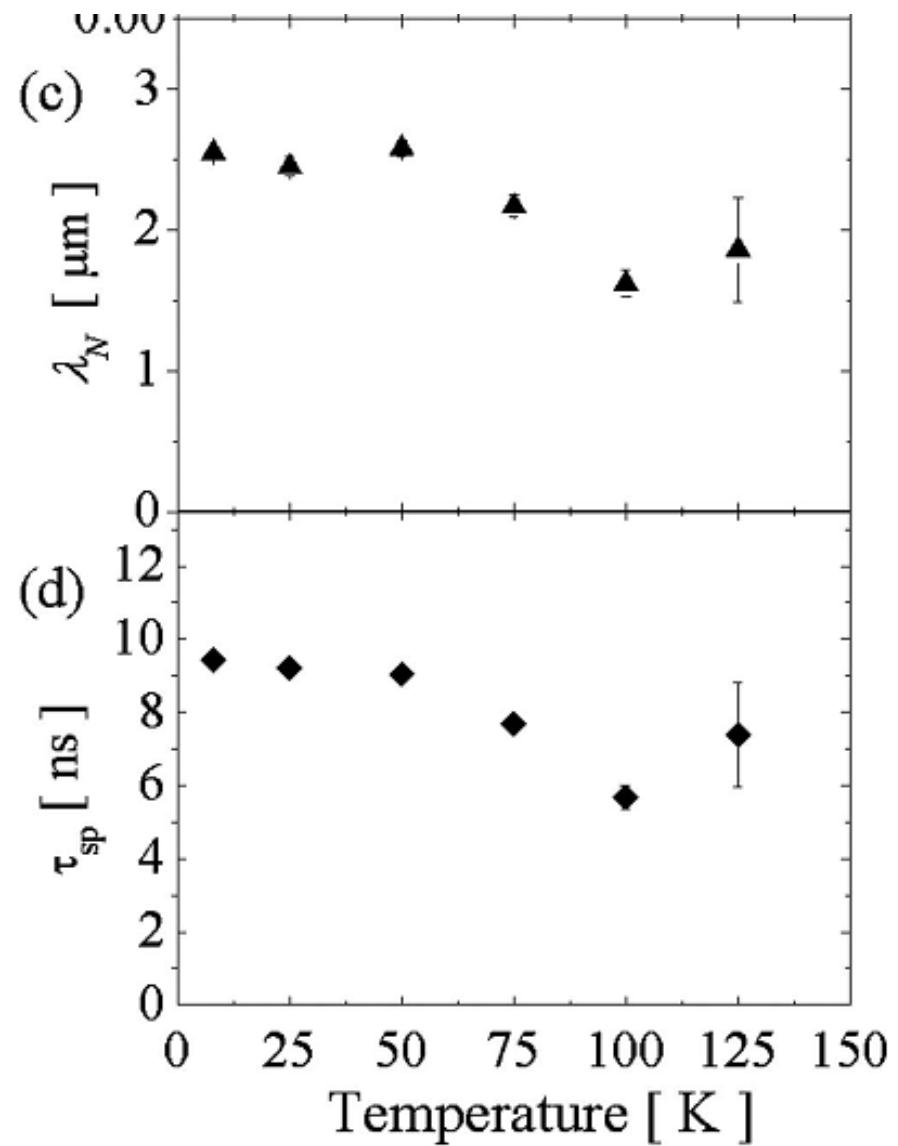
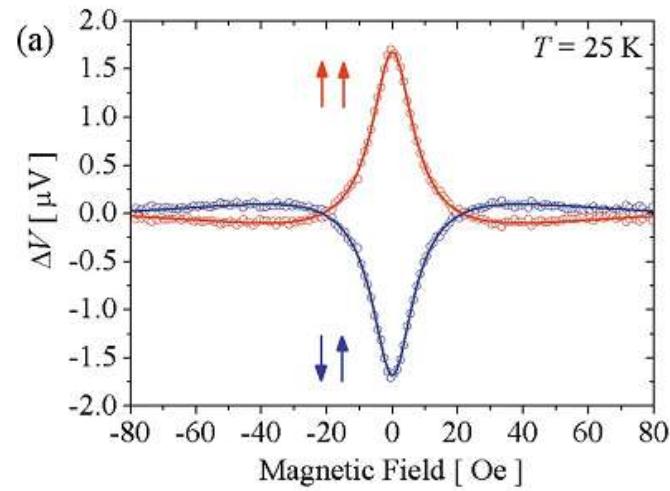


Spin in Silicon

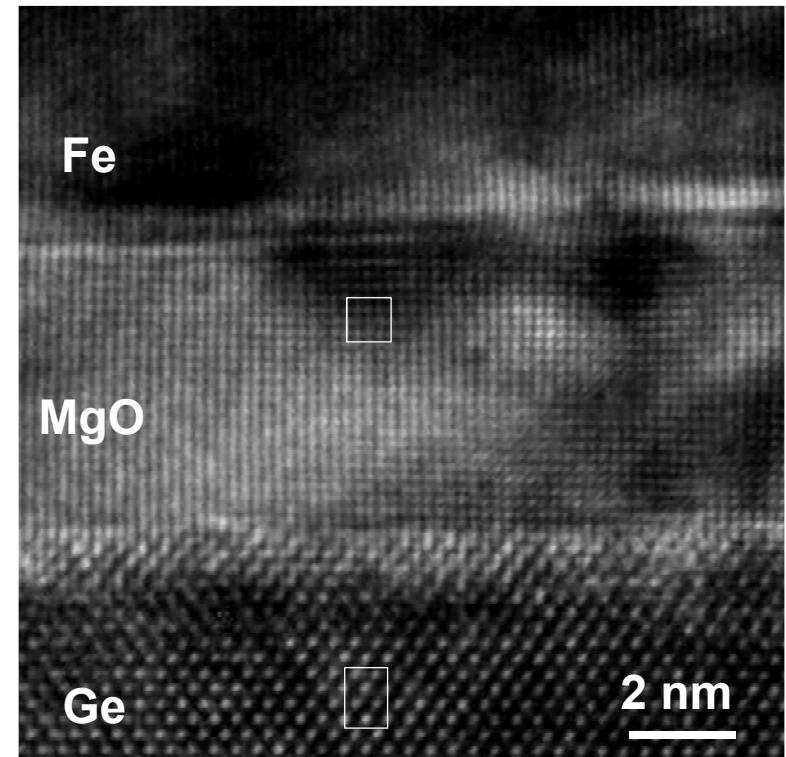
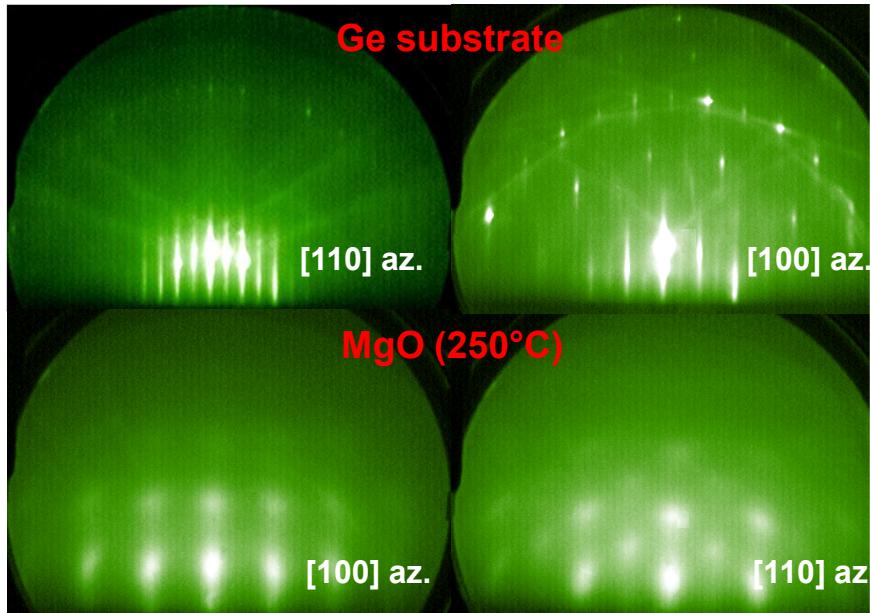


Sasaki, et al, APL (2010)

Spin in Silicon



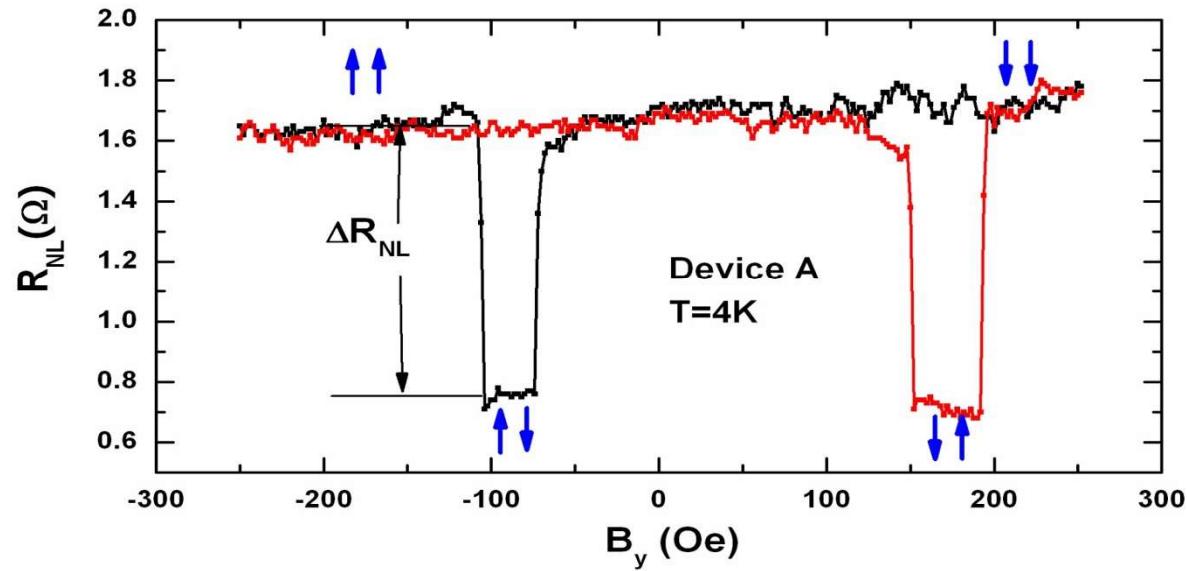
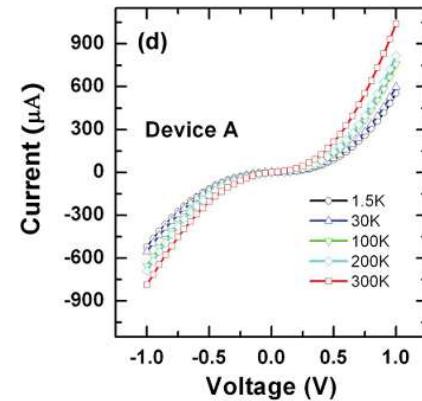
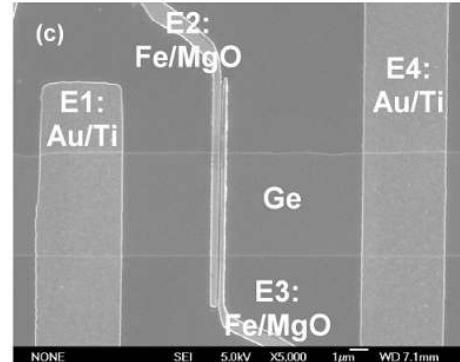
Spin in Germanium



**Epitaxial Fe/MgO/Ge junction is achieved
MgO/Ge 45° rotation**

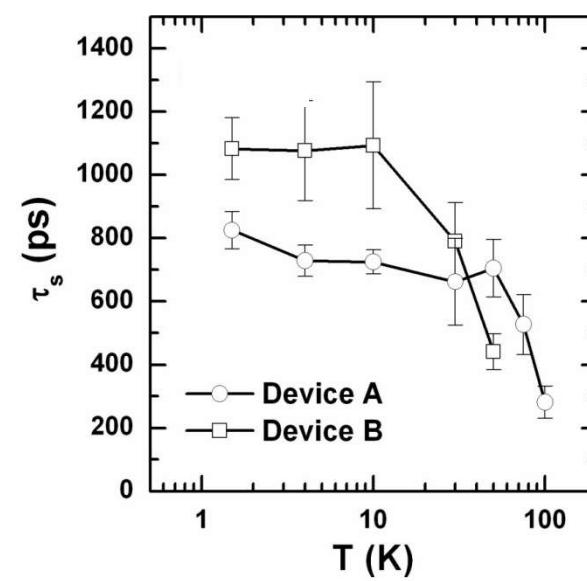
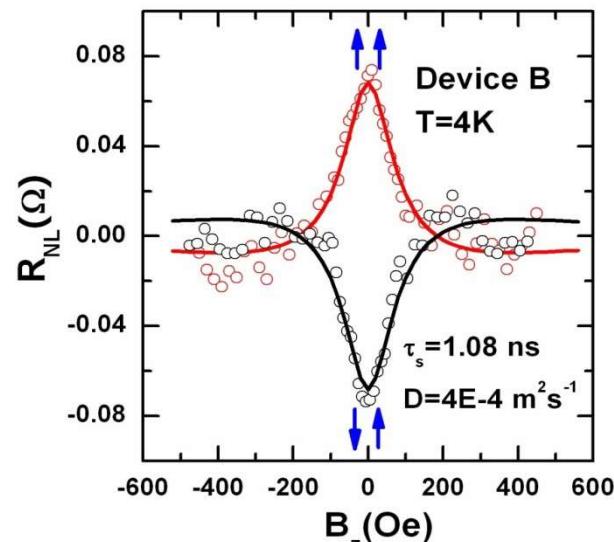
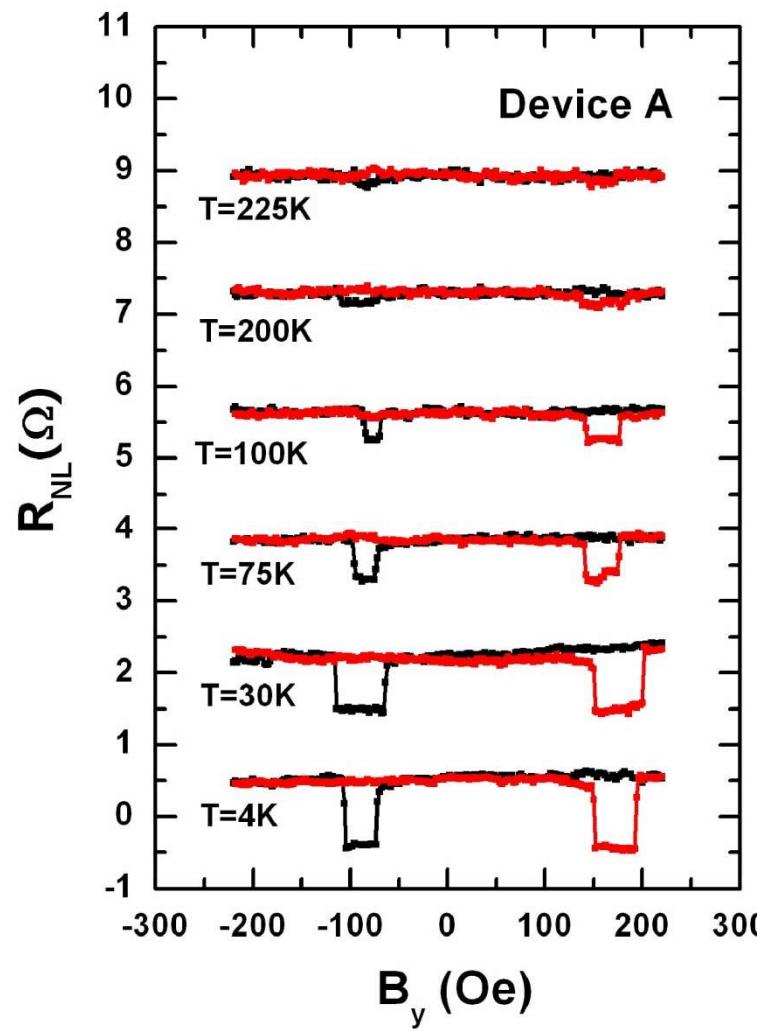
Spin in Germanium

Ge spin valve



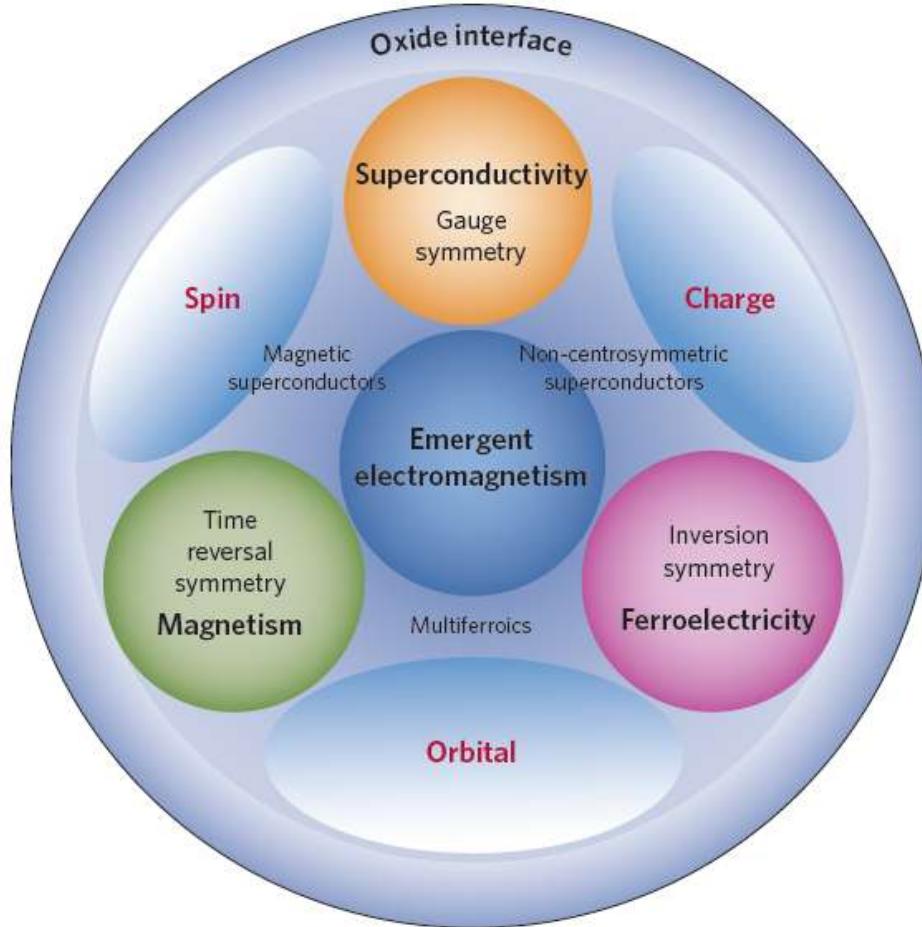
Zhou & Han, et al, PRB (2011)

Spin in Germanium



Spin in complex oxides

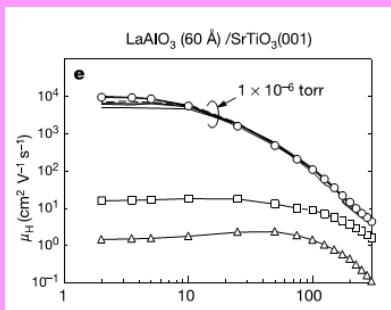
Oxide Interface



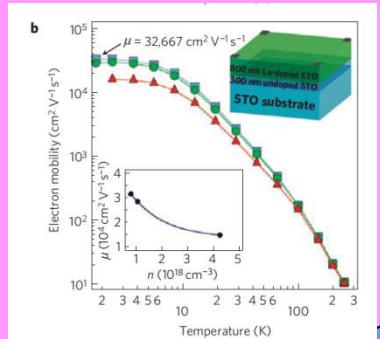
Hwang, et al. Nat. Mater. (2012)

Spin in complex oxides

High mobility

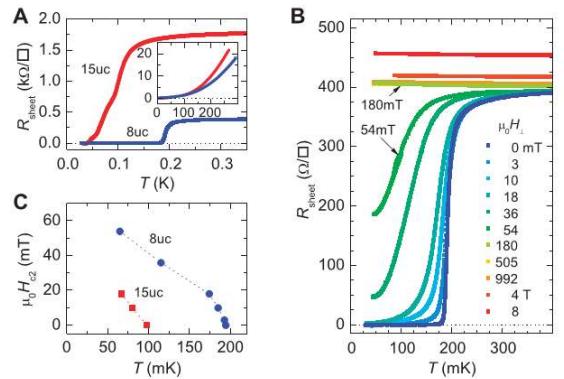


Ohtomo & Hwang
Nature 427, 423-426 (2004)



Son, et al., Nat Mater 9, 482-484 (2010)

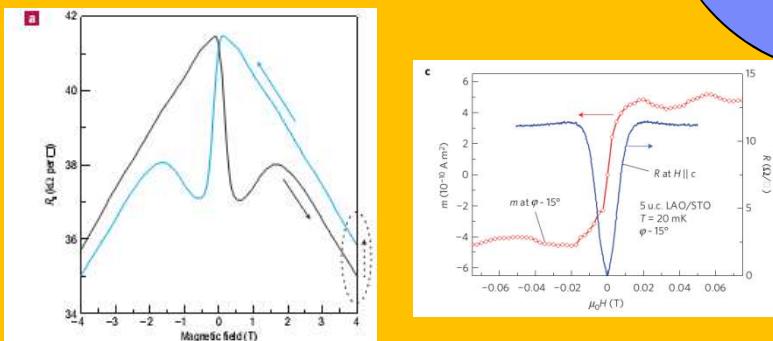
Gate tunable Superconductivity



Reyren, et al., Science 317, 1196-1199 (2007)

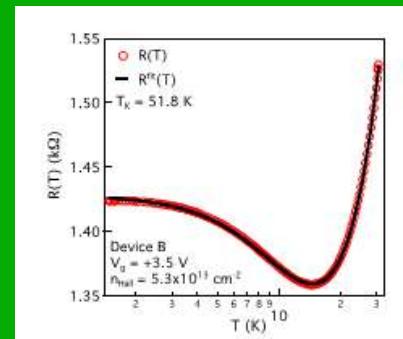
SrTiO₃

Magnetism + Superconductivity



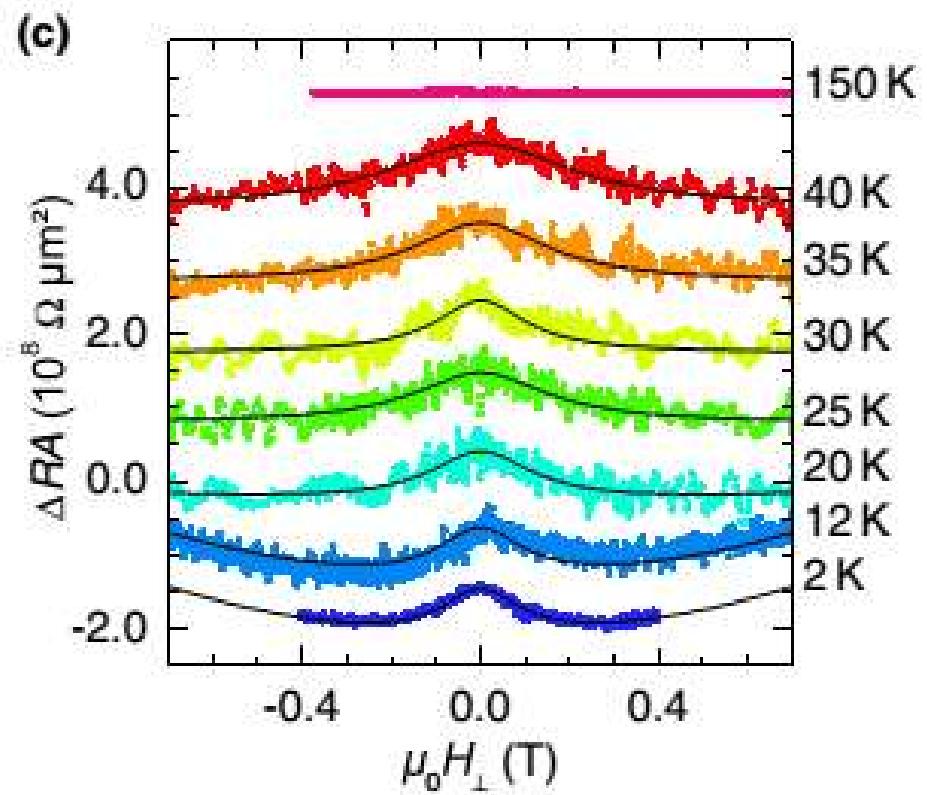
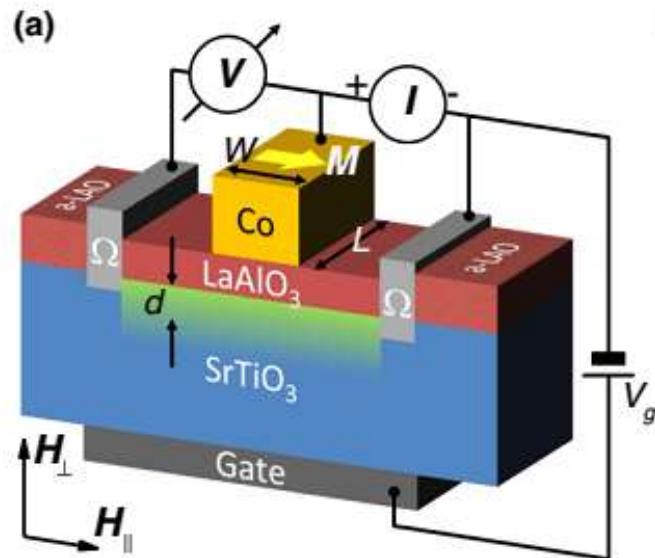
Brinkman, et al., Nat Mater 6, 493-496 (2007).
Li, et al., Nat Phys 7, 762-766 (2011).
Bert, et al., Nat Phys 7, 767-771 (2011).

Kondo effect



Lee, et al., Phys. Rev. Lett. 107, 256601 (2011).
Li, et al., Phys. Rev. Lett. 109, 196803 (2012).

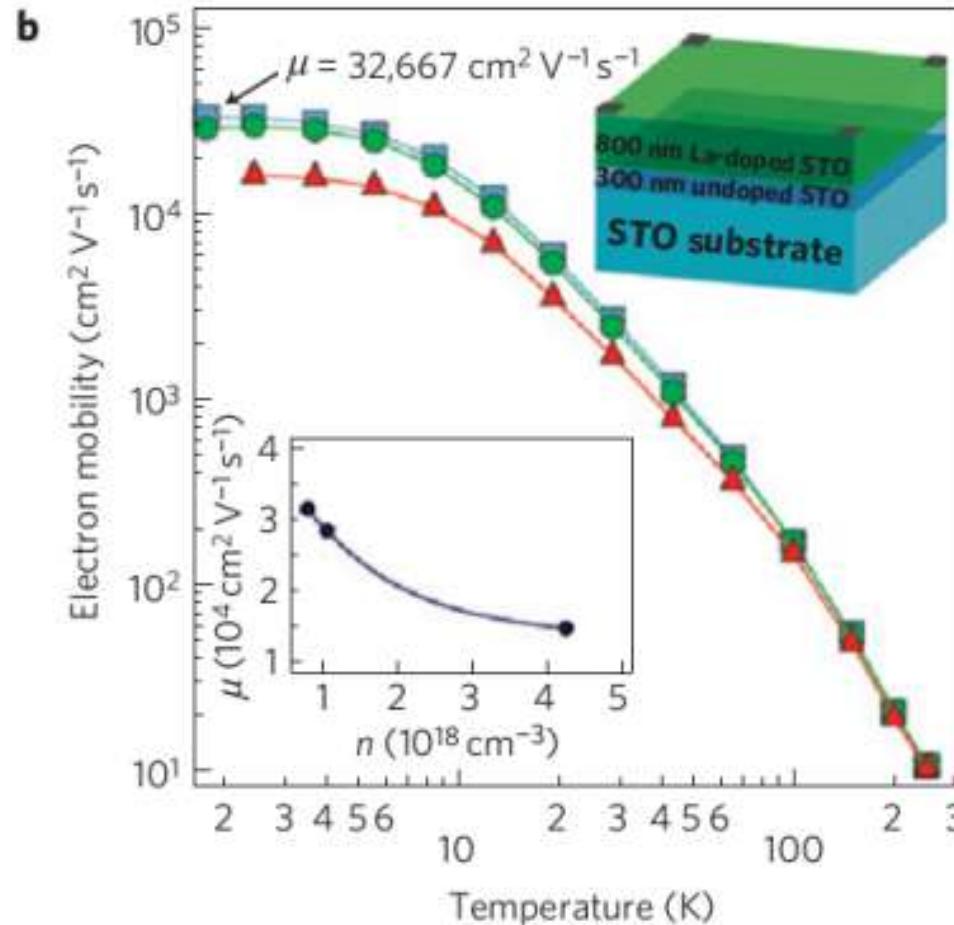
Spin in complex oxides



Reyren, et al, PRL (2012)

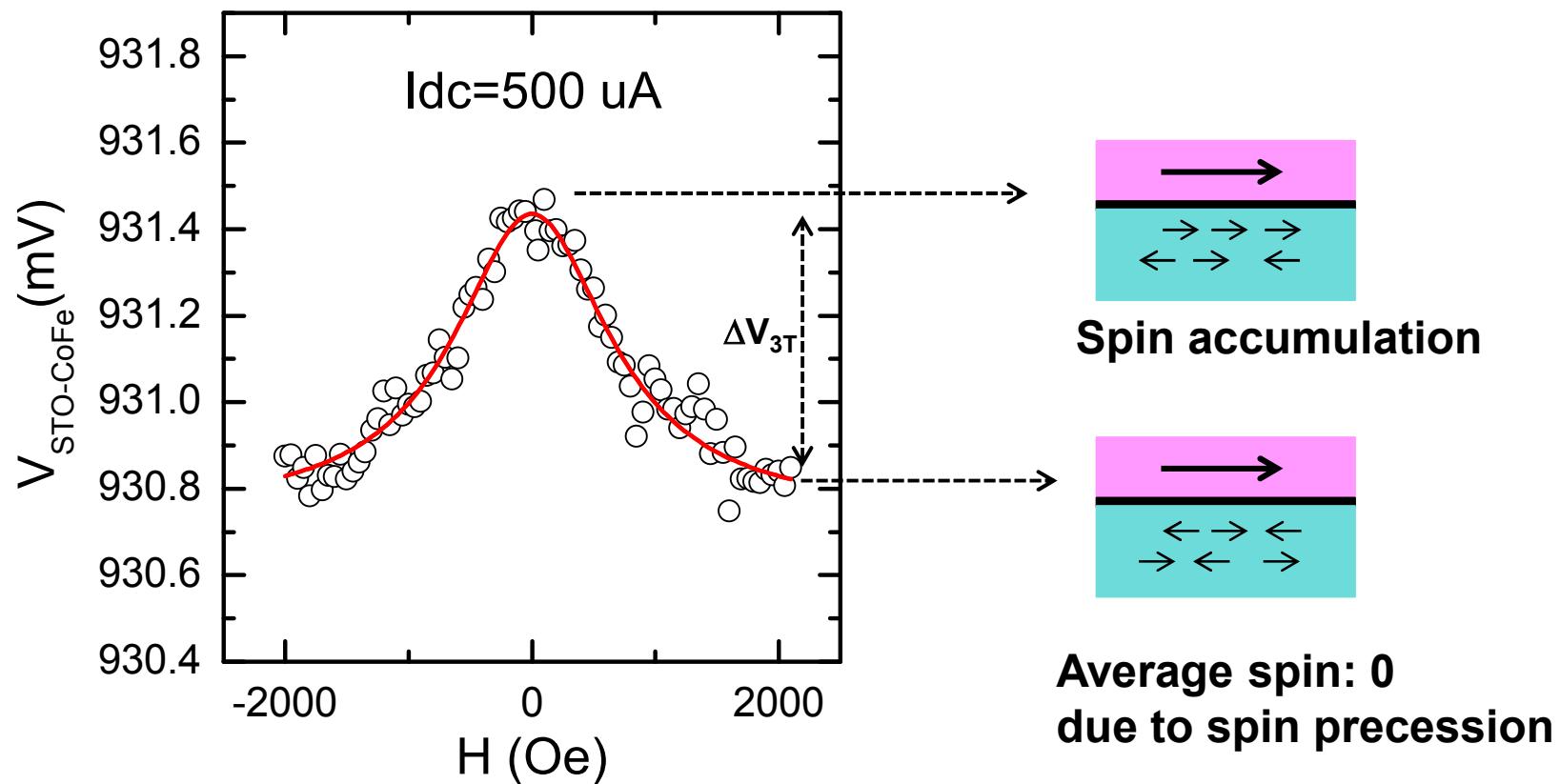
Spin in complex oxides

La, Nb doped STO



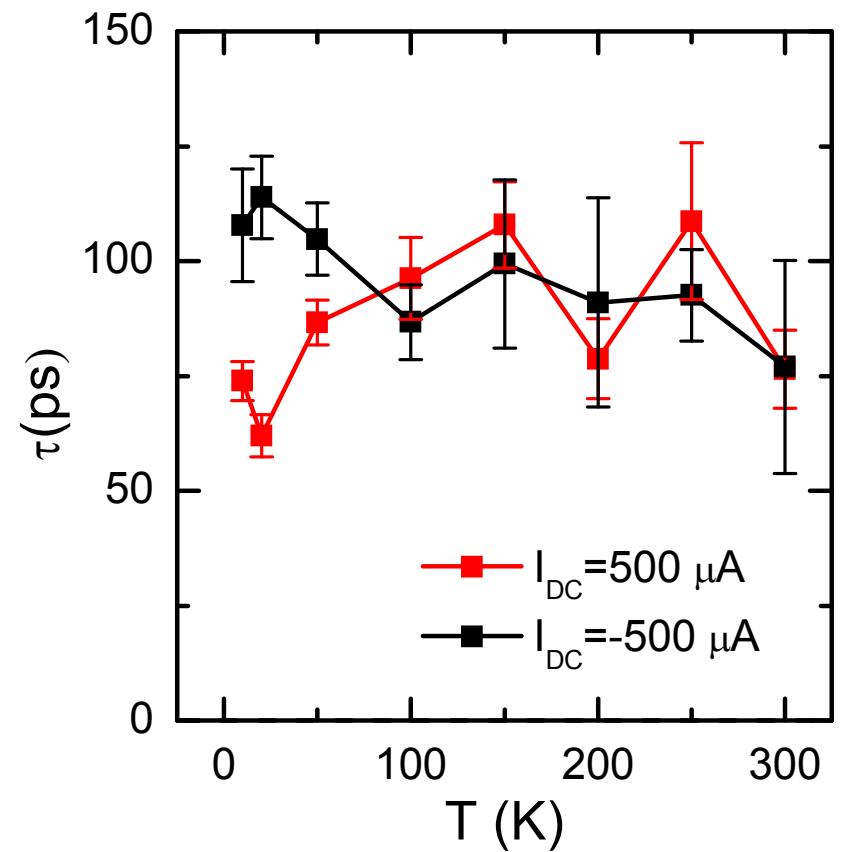
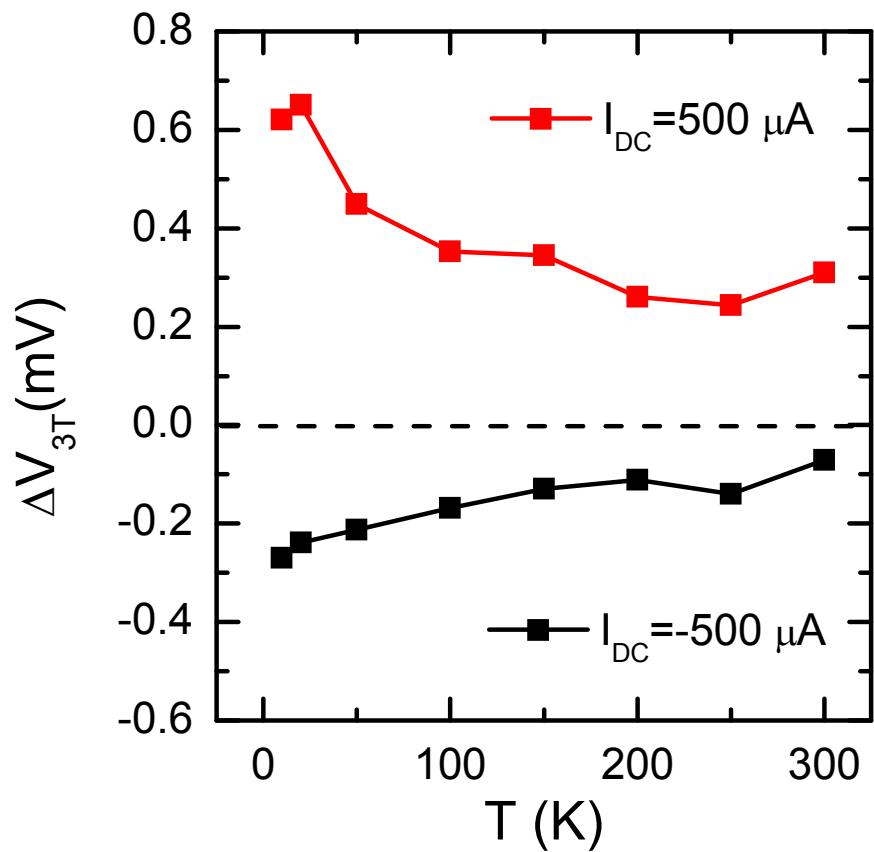
Son, et al, Nature Materials (2010)

Spin in complex oxides

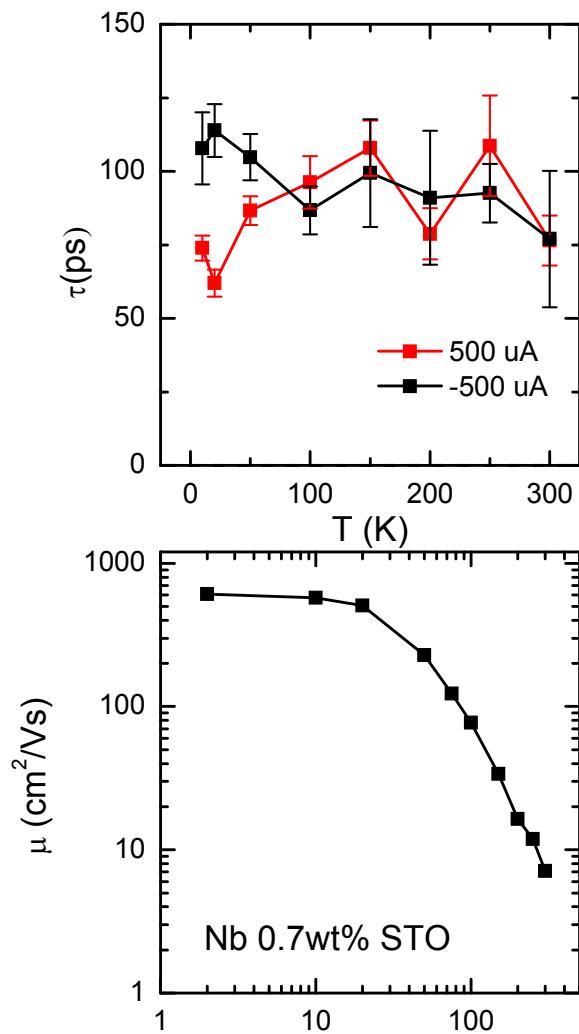


Han, et al, Nature Communications (2013)

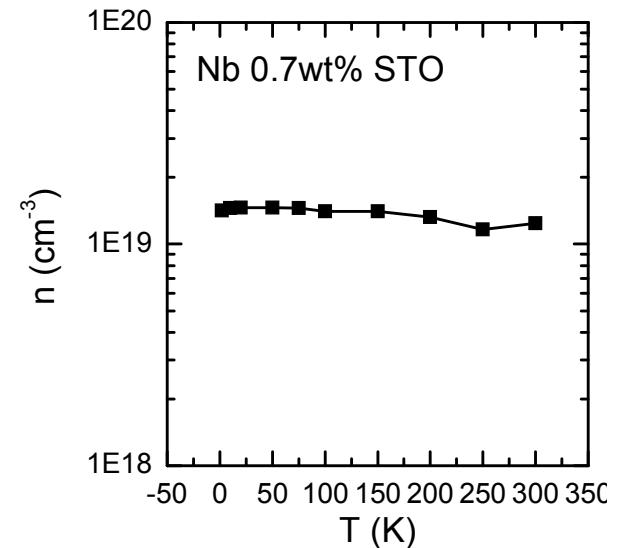
Spin in complex oxides



Spin in complex oxides

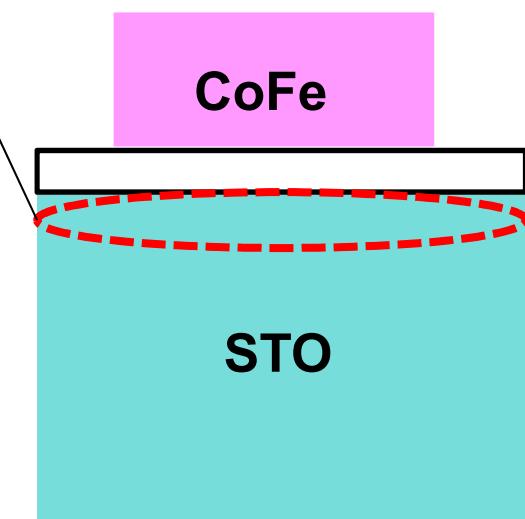


**Spin relaxation time
dominated by spin
scattering at the STO
surface**
--- little temperature
dep

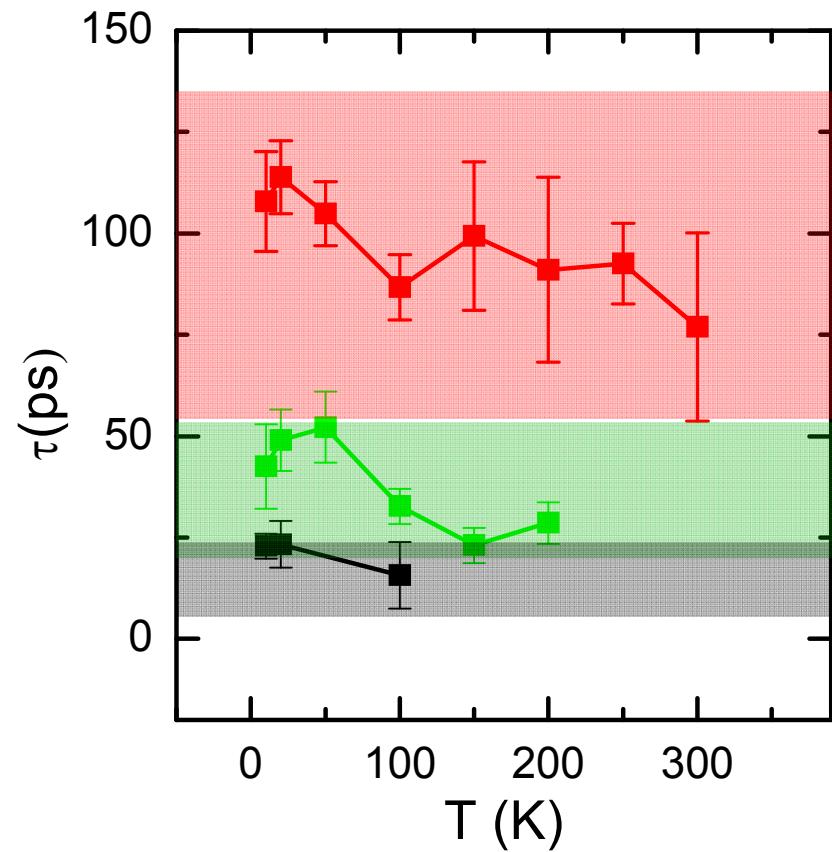
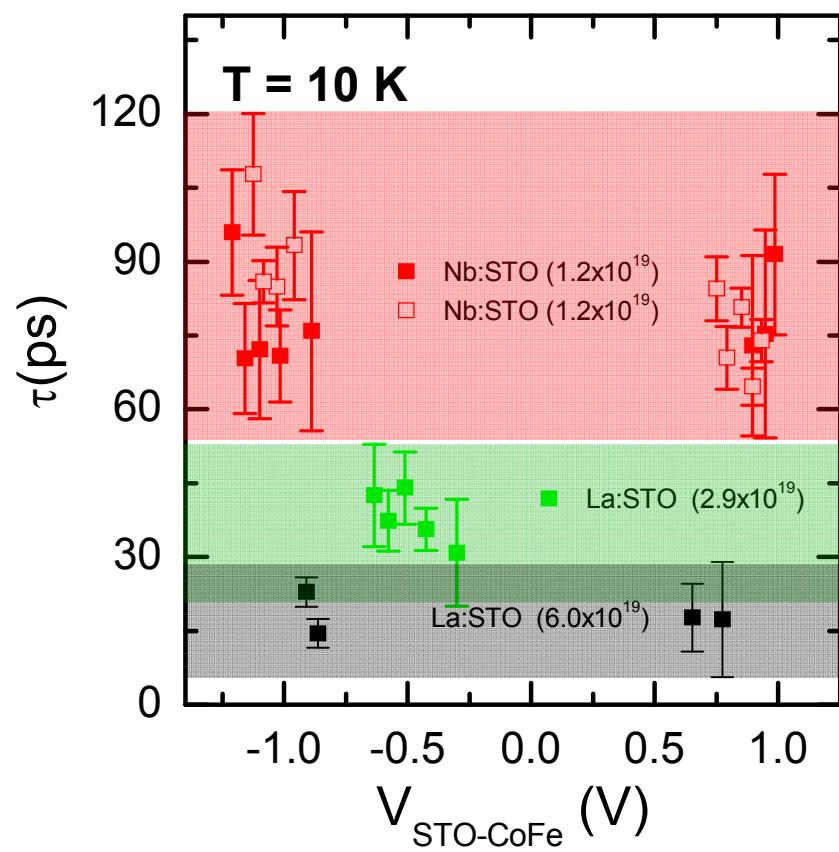


**Ti³⁺ magnetic
centers**

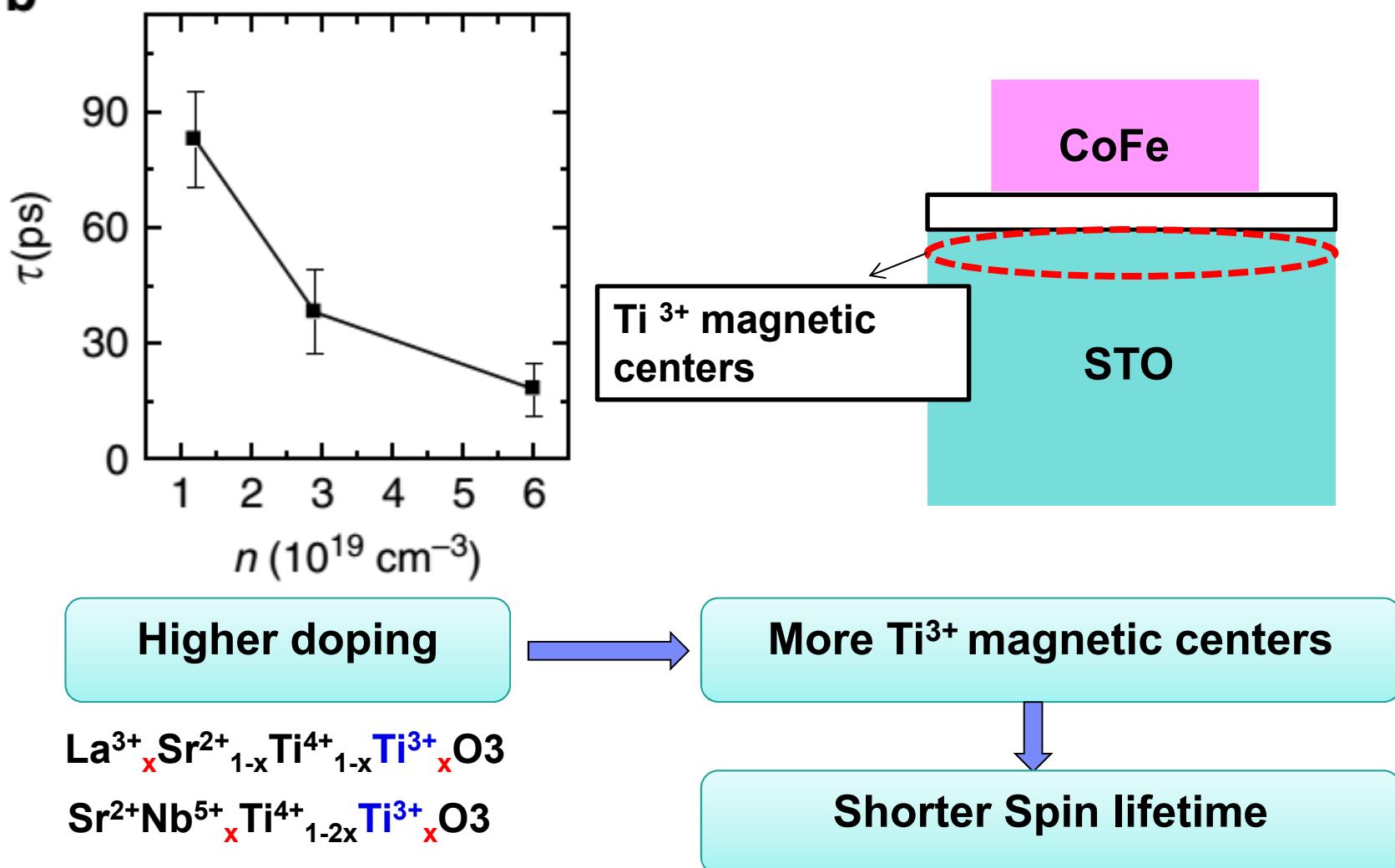
**Mobility dominated by the bulk
conducting carriers (phonon
scattering)**
— Strong temperature dep



Spin in complex oxides



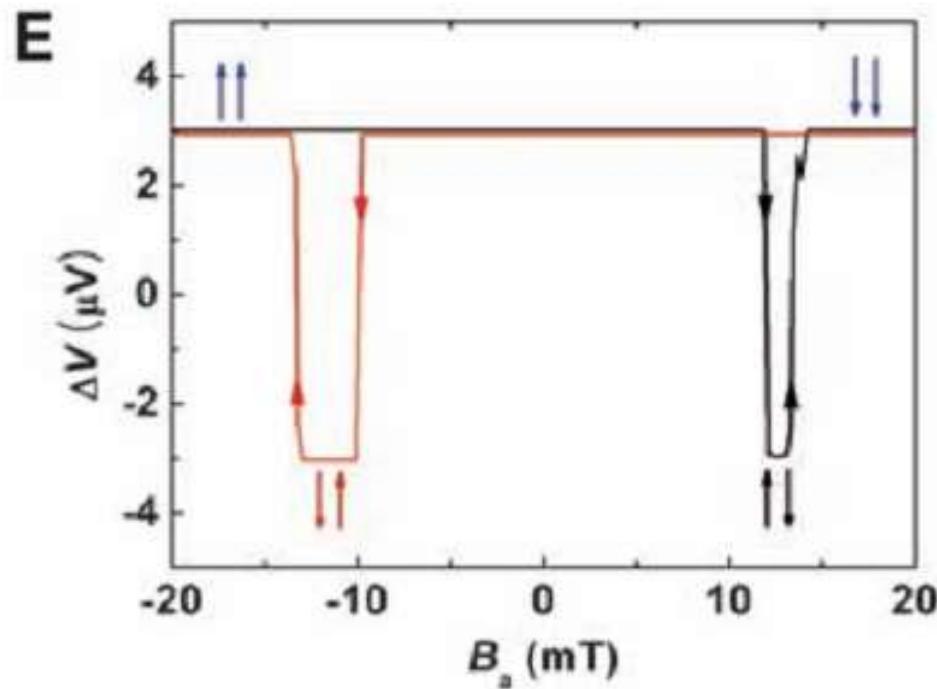
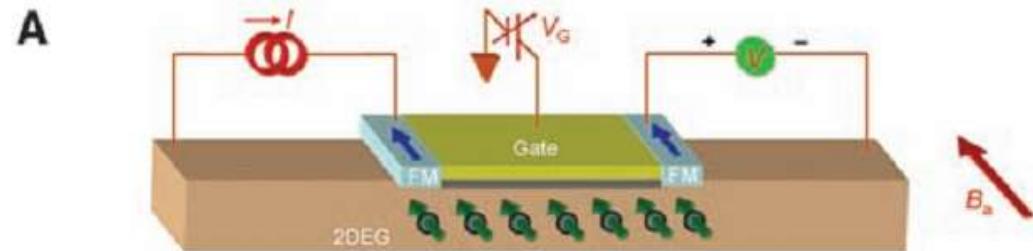
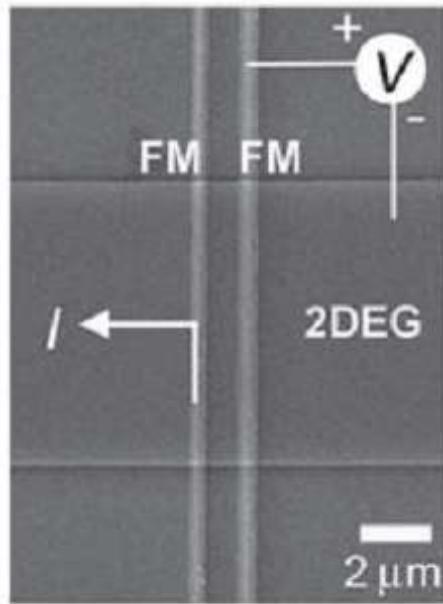
Spin in complex oxides



Spin FET

InAs channel

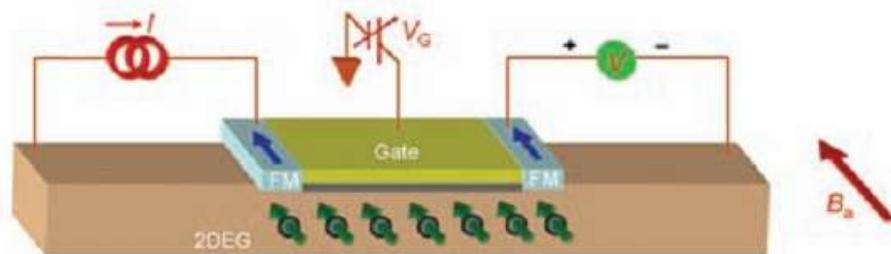
C



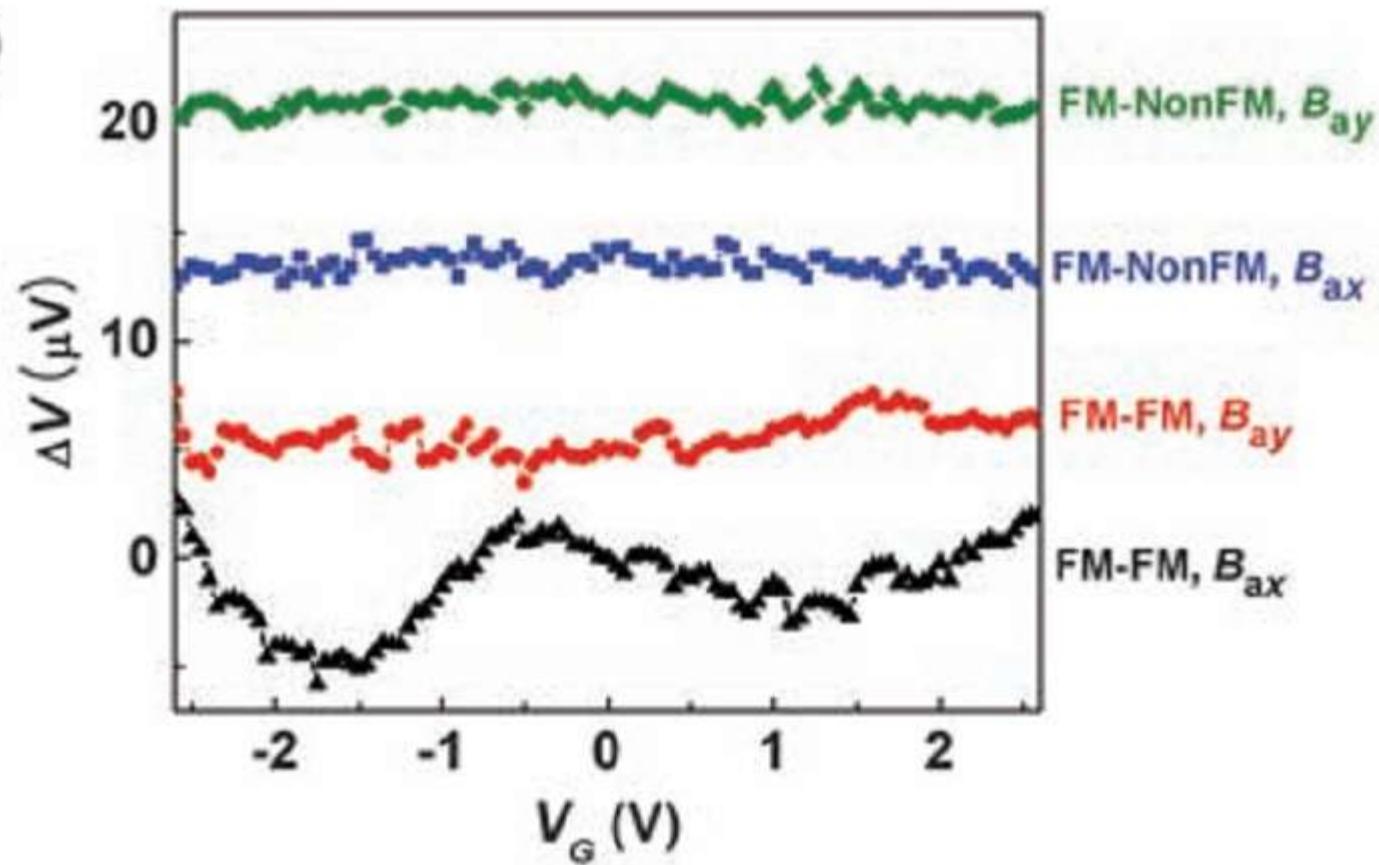
Koo, et al, Science (2009)

Spin FET

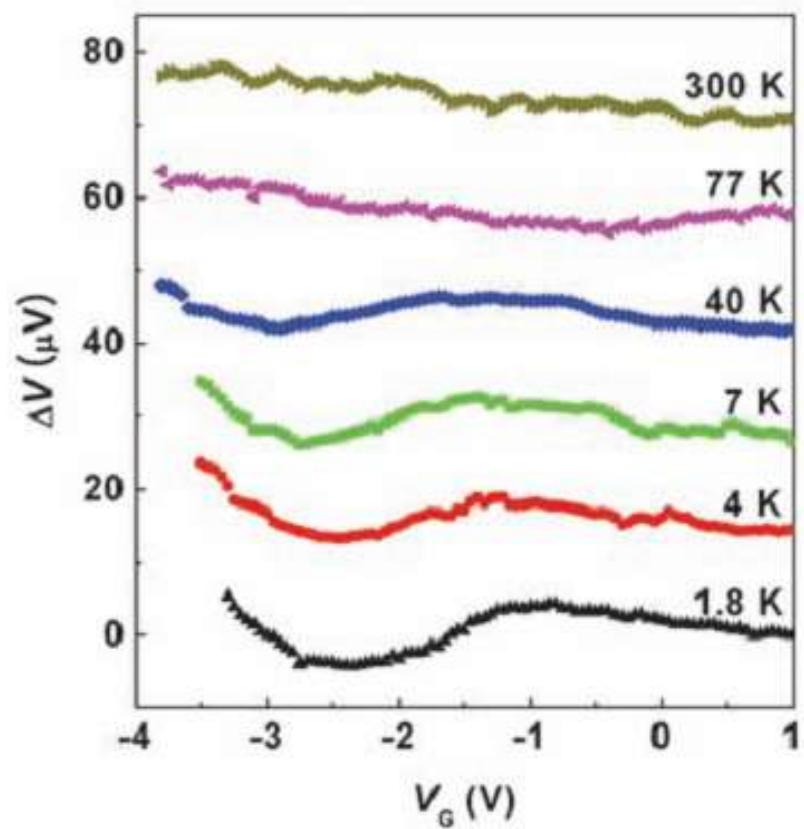
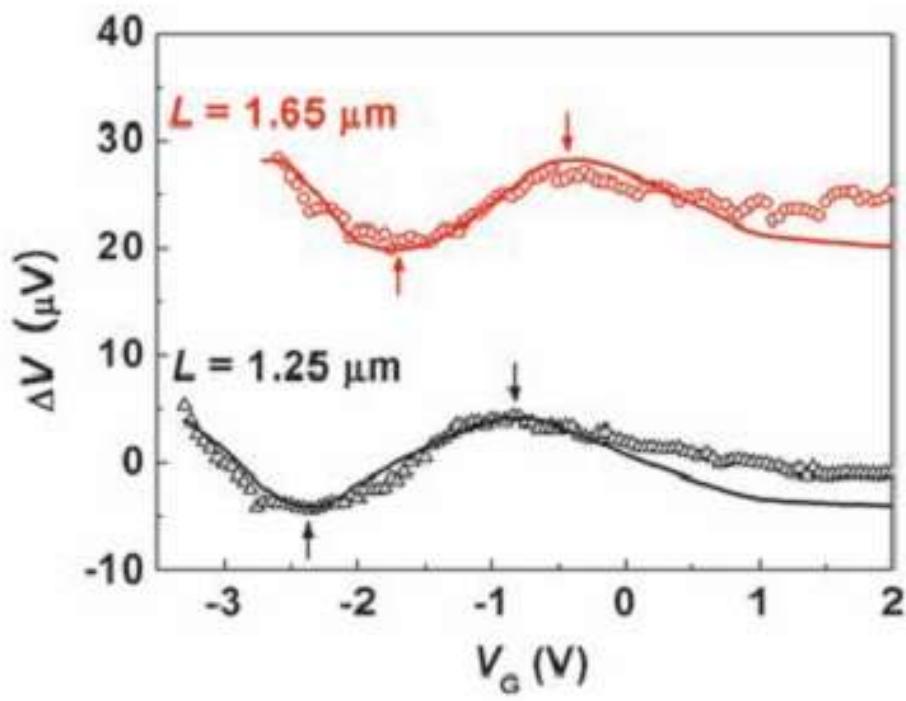
A



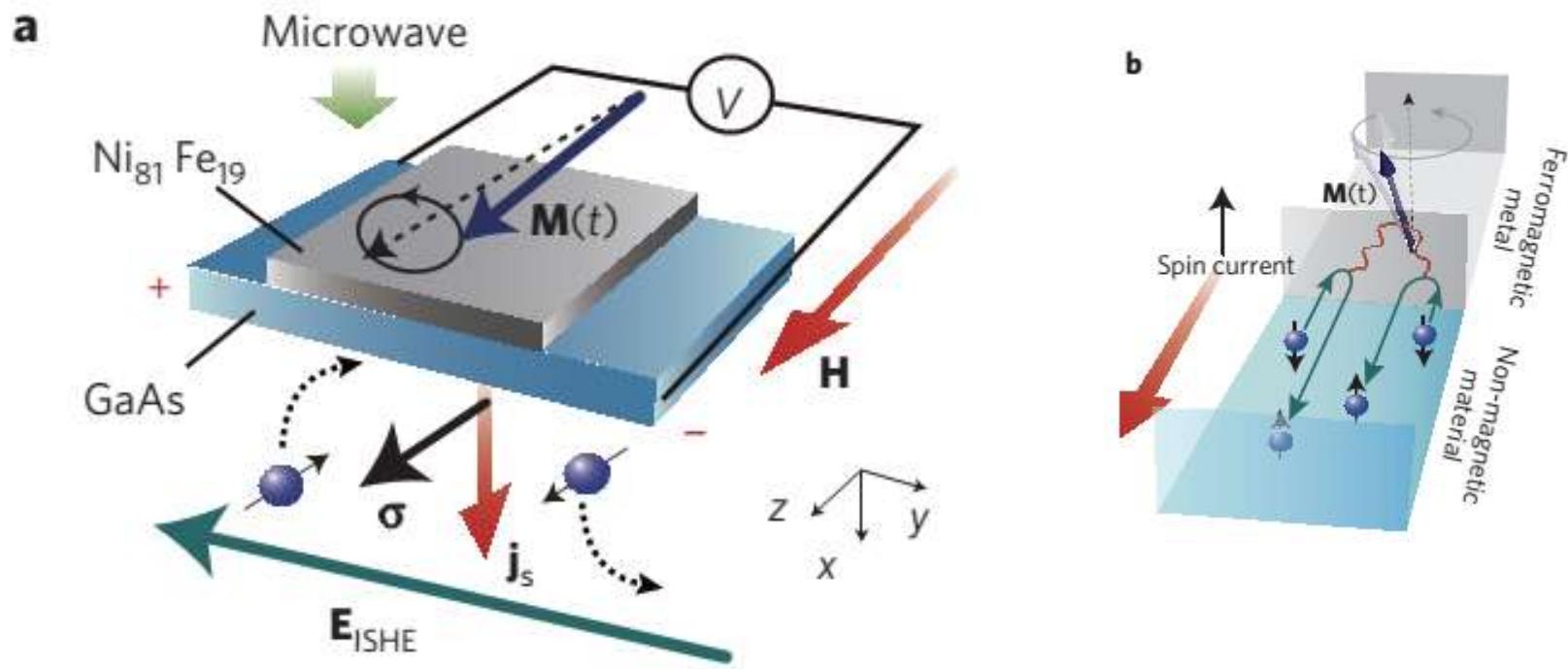
B D



Spin FET

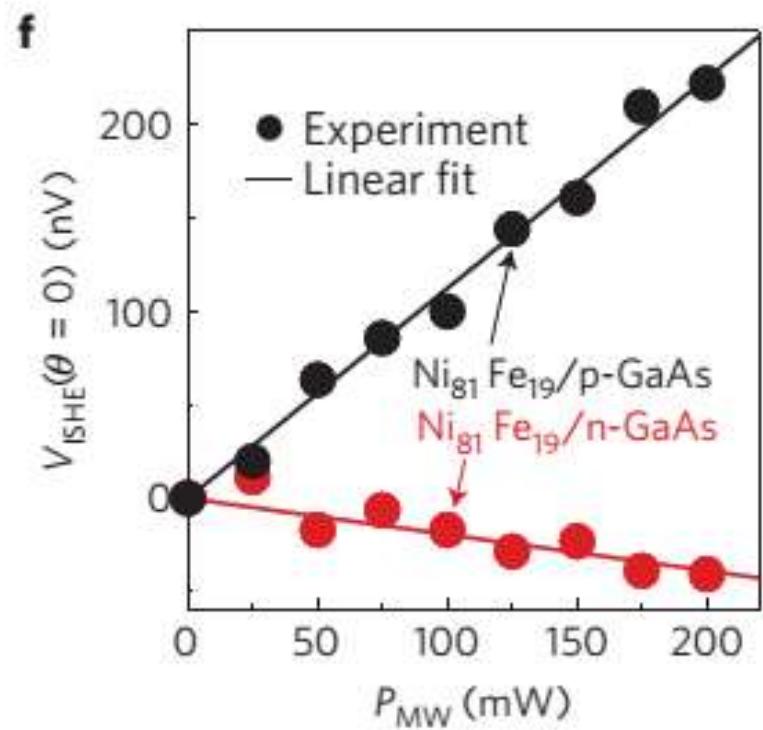
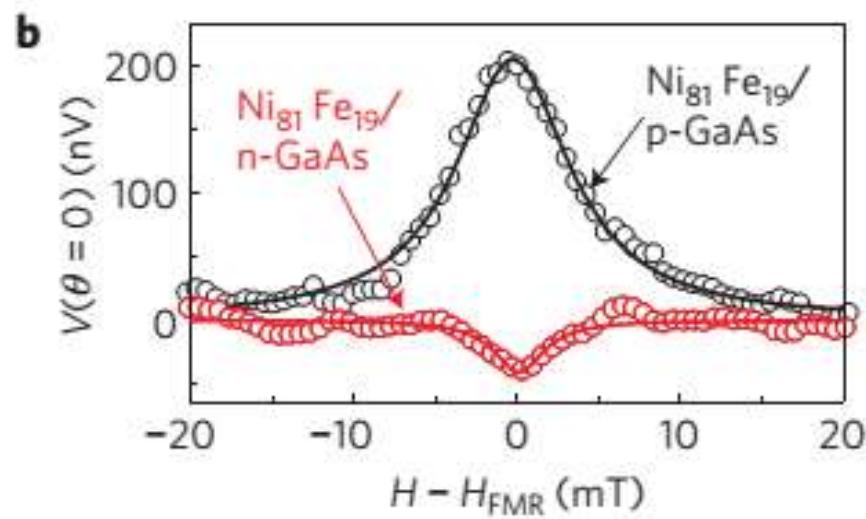


Another solution

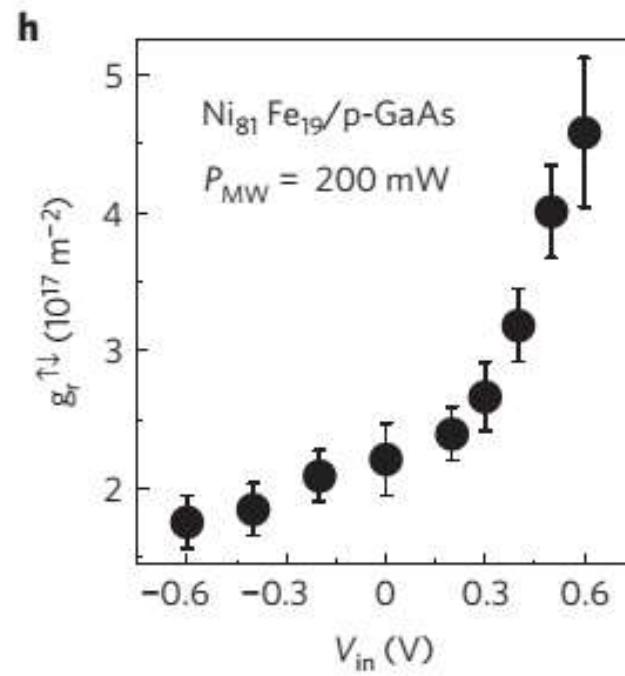
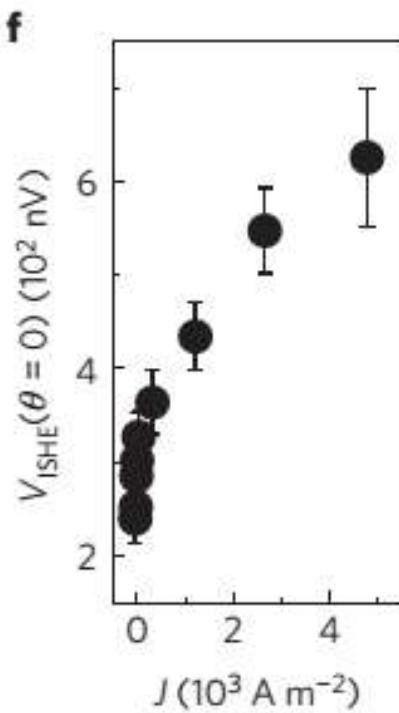
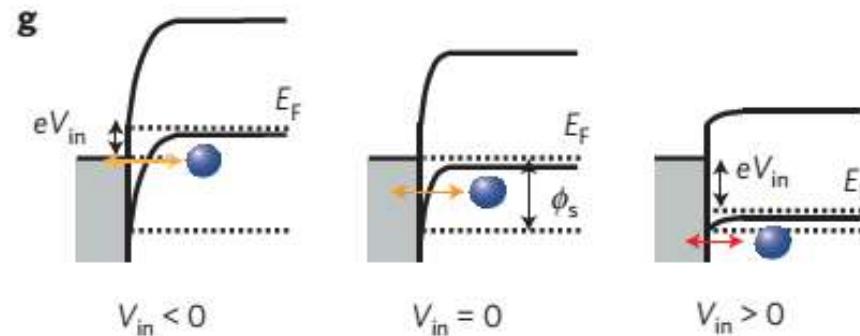
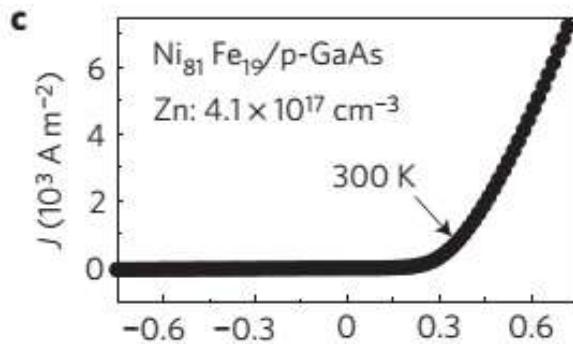


Ando, et al, Nature Mater. (2011)

Spin pumping



Another solution



休息10分钟

Outline

2. Spin valves based on Quantum materials

石墨烯

➤ 弱自旋-轨道耦合→ 长自旋寿命

二硫化钼等

➤ 自旋-谷

拓扑绝缘体

➤ 自旋流的拓扑保护

Graphene

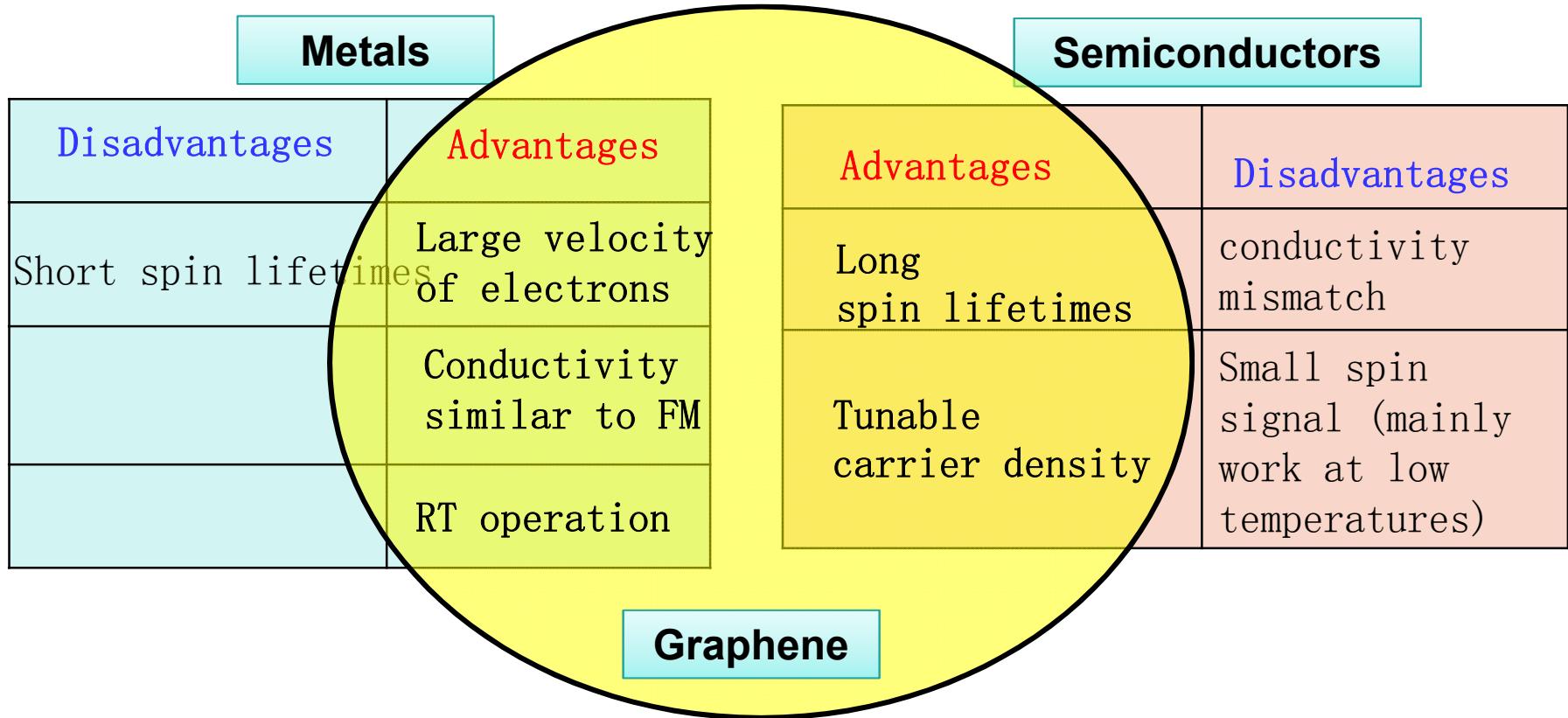
Metals

Disadvantages	Advantages
Short spin lifetimes	Large velocity of electrons
	Conductivity similar to FM
	RT operation

Semiconductors

Advantages	Disadvantages
Long spin lifetimes	conductivity mismatch
Tunable carrier density	Small spin signal (mainly work at low temperatures)

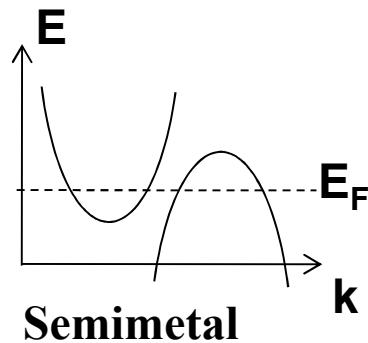
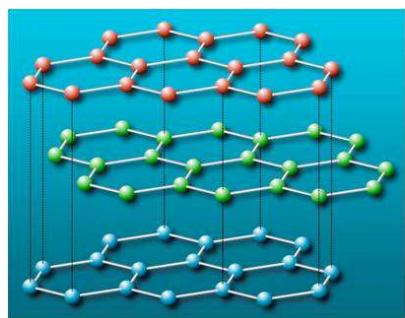
Graphene



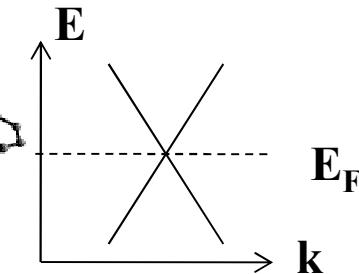
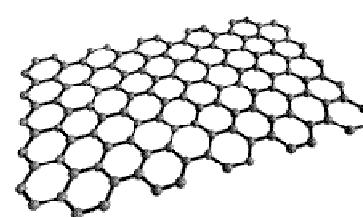
Graphene combines the advantages of both metals and semiconductors

Graphene

Graphite



Graphene



Spin-dependent properties

Low intrinsic spin-orbit coupling →

Long spin lifetime
($\sim \mu\text{s}$)
High mobility

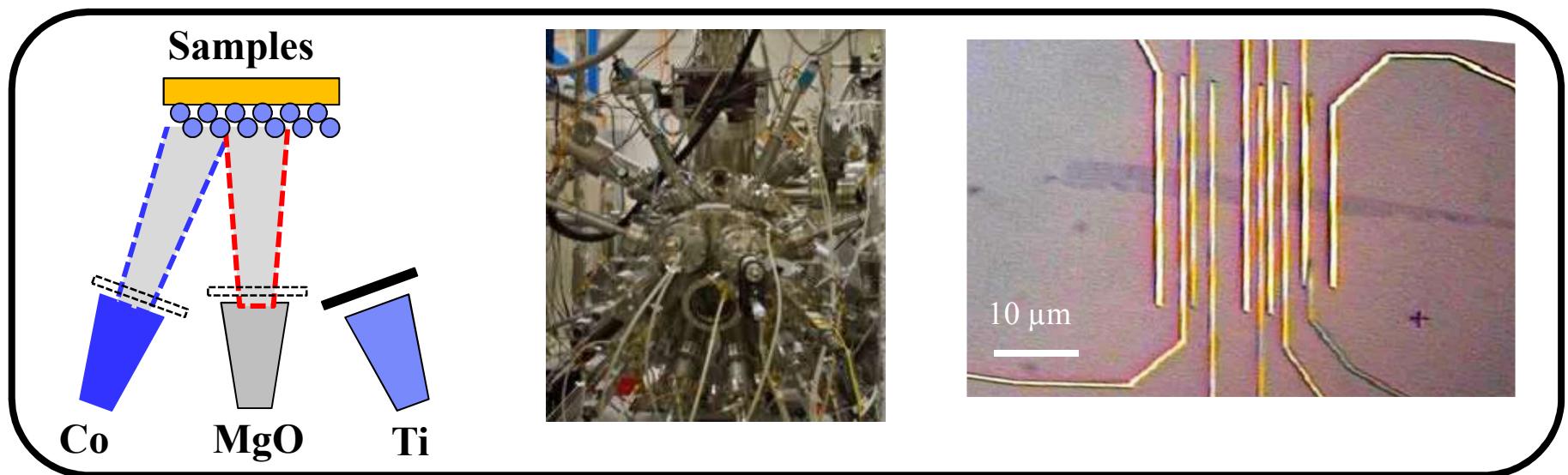
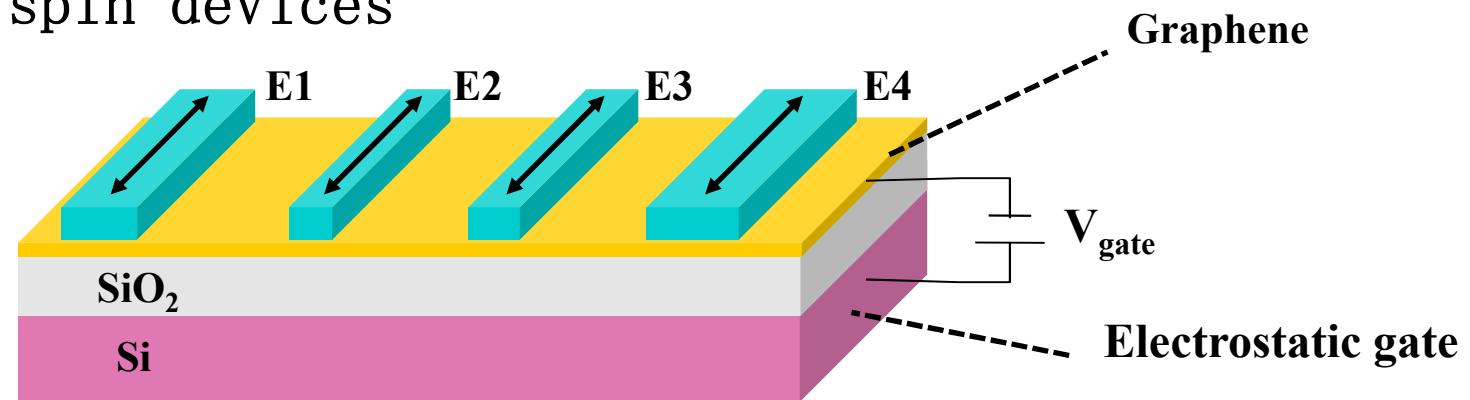
$$\lambda = \sqrt{D\tau}$$

Long spin transport length

Gmitra, et al, *Phys. Rev. B* (2009)
Abdelouahed, et al, *Phys. Rev. B* (2010)

Graphene spin valves

Graphene spin devices



Graphene spin valves

$$\frac{\partial \vec{\mu}}{\partial t} = D \nabla^2 \vec{\mu} - \frac{\vec{\mu}}{\tau} + \left(\frac{g\mu_B}{\hbar} \vec{B} \times \vec{\mu} \right)$$

- 1) Diffusion D : diffusion constant
- 2) Relaxation τ : spin relaxation time
- 3) Larmor spin precession: $g \sim 2$
Spin relaxation length: $\lambda = \sqrt{D\tau}$

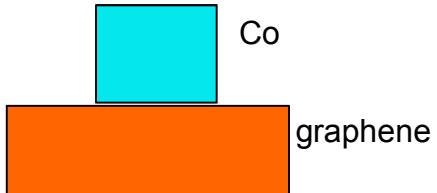
Diffuse without precession

$$B_{\perp} = 0, \frac{\partial \mu}{\partial t} = 0,$$

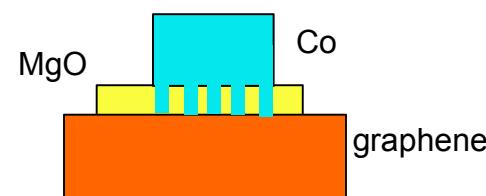
$$\mu(x) = \mu_0 \exp(-x/\lambda)$$

Graphene spin valves

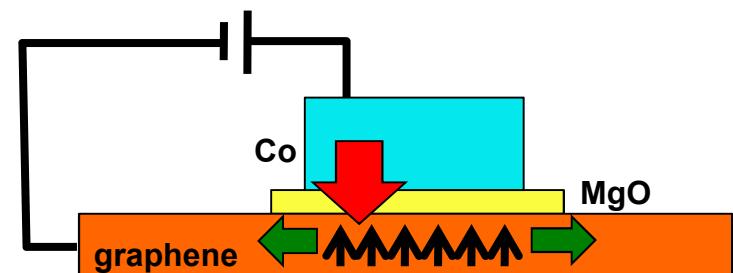
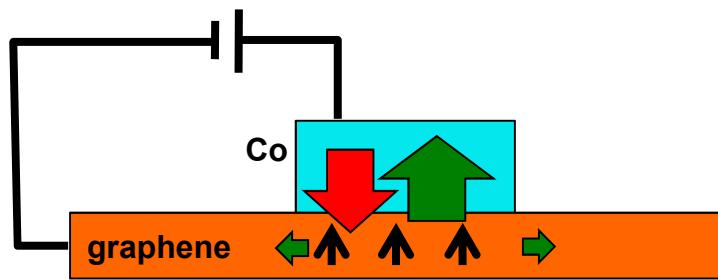
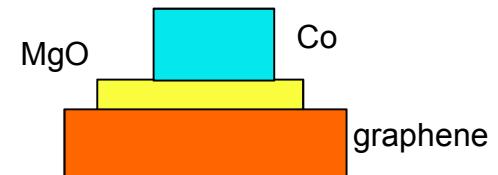
Transparent contact



Pinhole contact

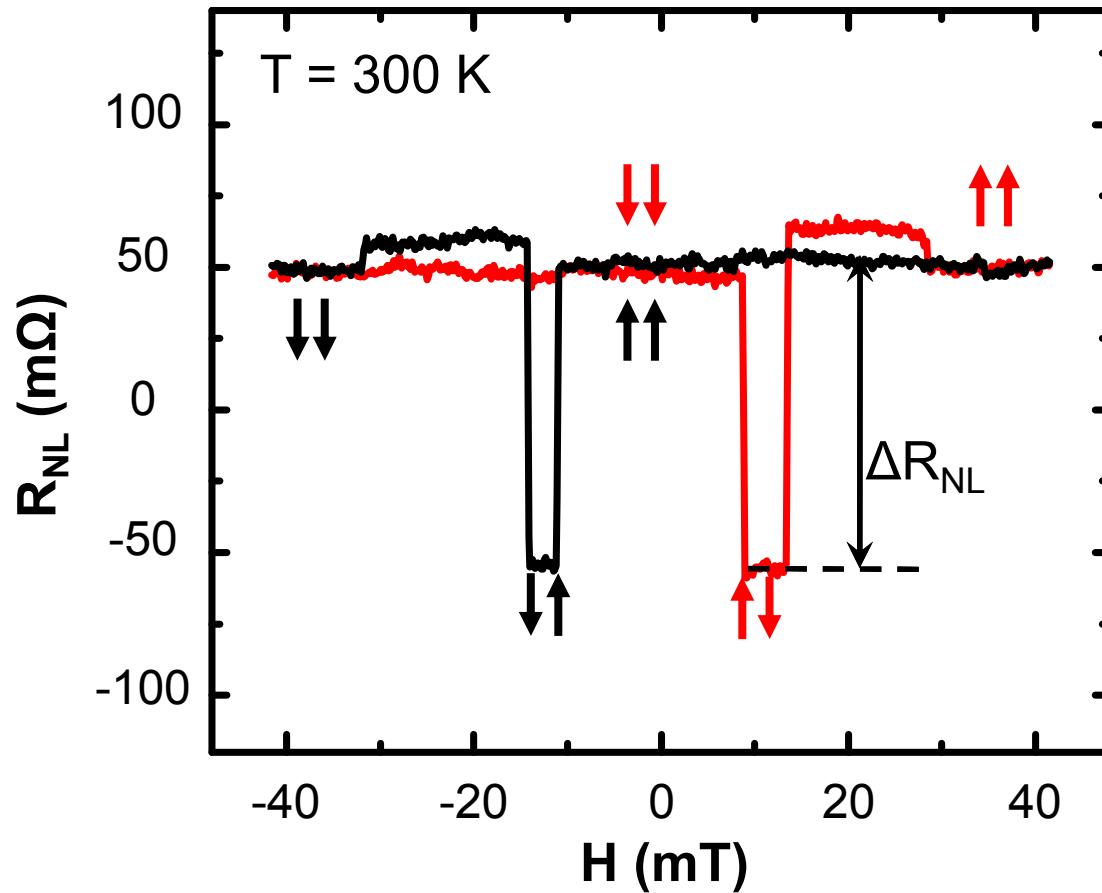
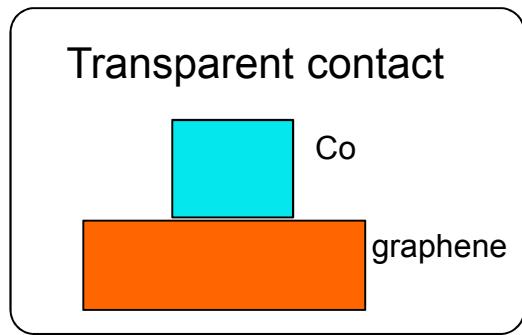


Tunneling contact



E.I. Rashba, Phys. Rev. B 62, R16
267 (2000)
A. Fert, H. Jaffres, Phys. Rev. B 64,
184420 (2001).

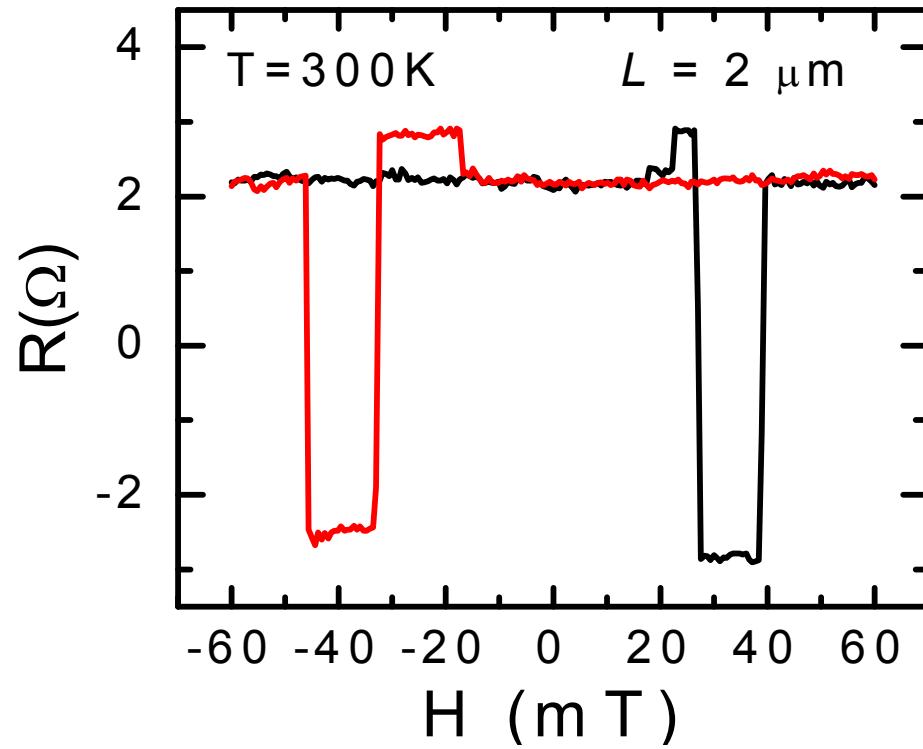
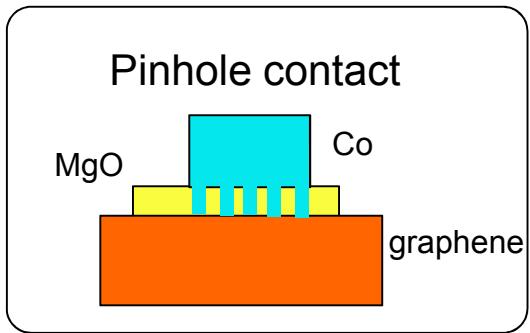
Graphene spin valves



Nonlocal MR: ~ 0.1 ohms

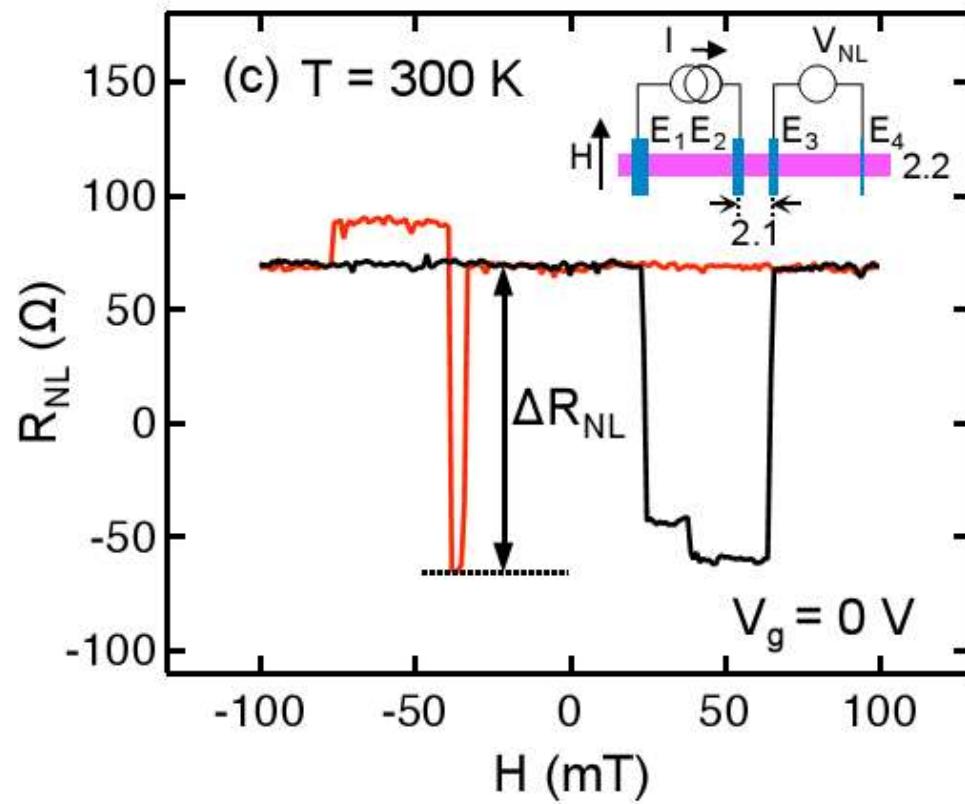
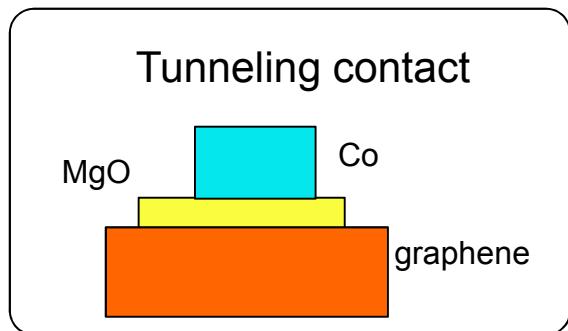
Spin injection efficiency: ~ 1 %

Graphene spin valves



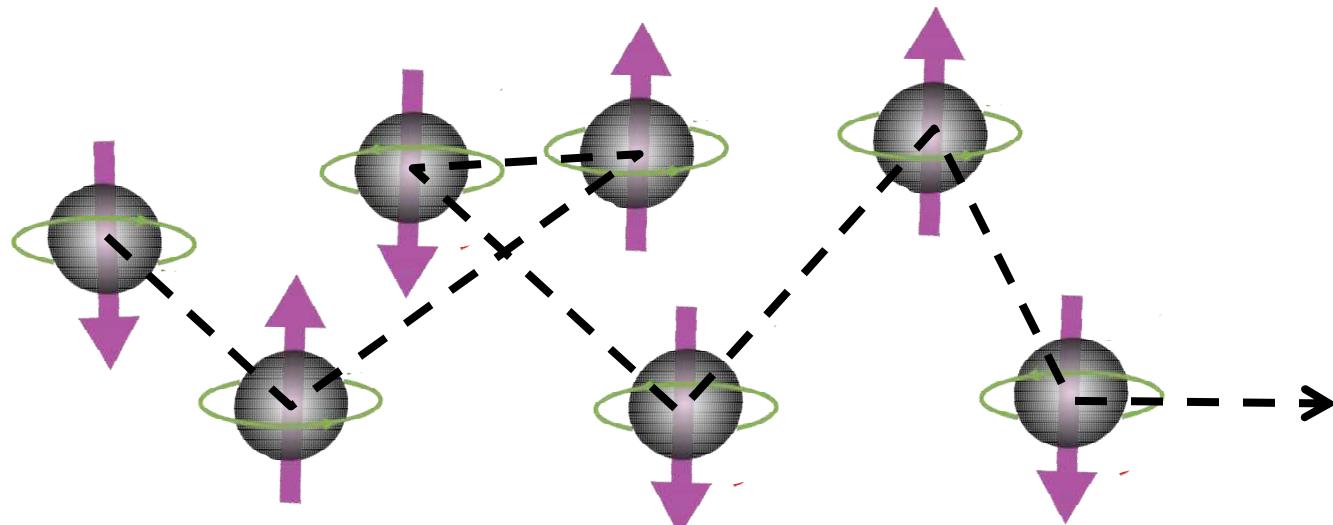
Nonlocal MR: ~ 10 ohms
Spin injection efficiency: ~ 8 %

Graphene spin valves



Nonlocal MR: $\sim 130 \text{ ohms}$
Spin injection efficiency: $\sim 30 \%$

Spin relaxation in graphene



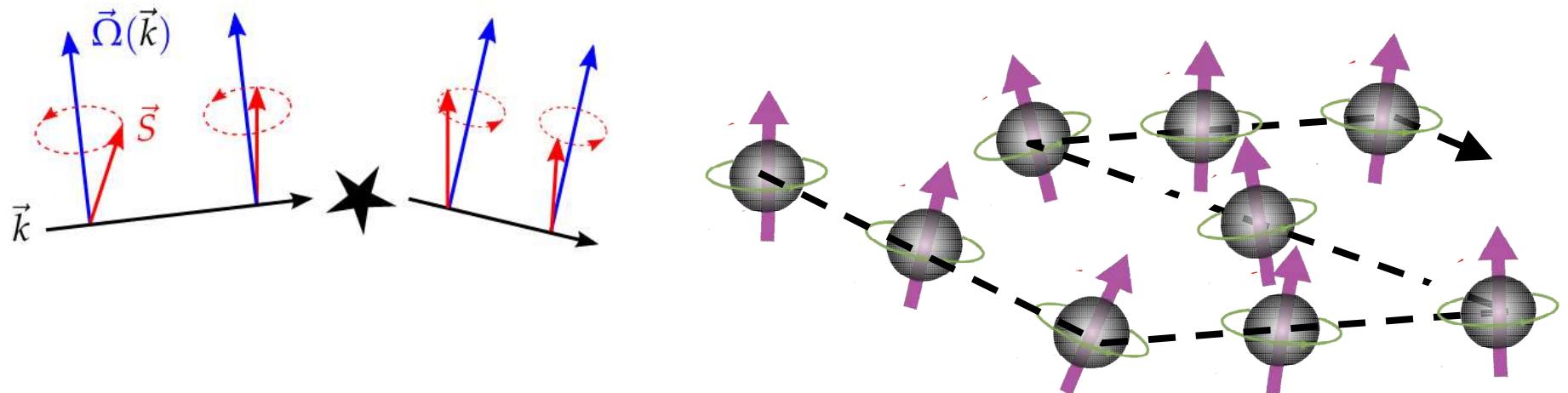
**Spin flip during momentum scattering events:
More momentum scattering, more spin relaxation.**

$$\tau_s \sim \tau_p$$

J. Fabian, et al, Acta Phys. Slovaca (2007)
R.J. Elliott, Phys. Rev. (1954)
F. Meier and B.P. Zachachrenya, Optical Orientation, (1984).
Josza, et al, Phys. Rev. B (2009)

Spin relaxation in graphene

Momentum scattering can reduce this effect by randomizing the field

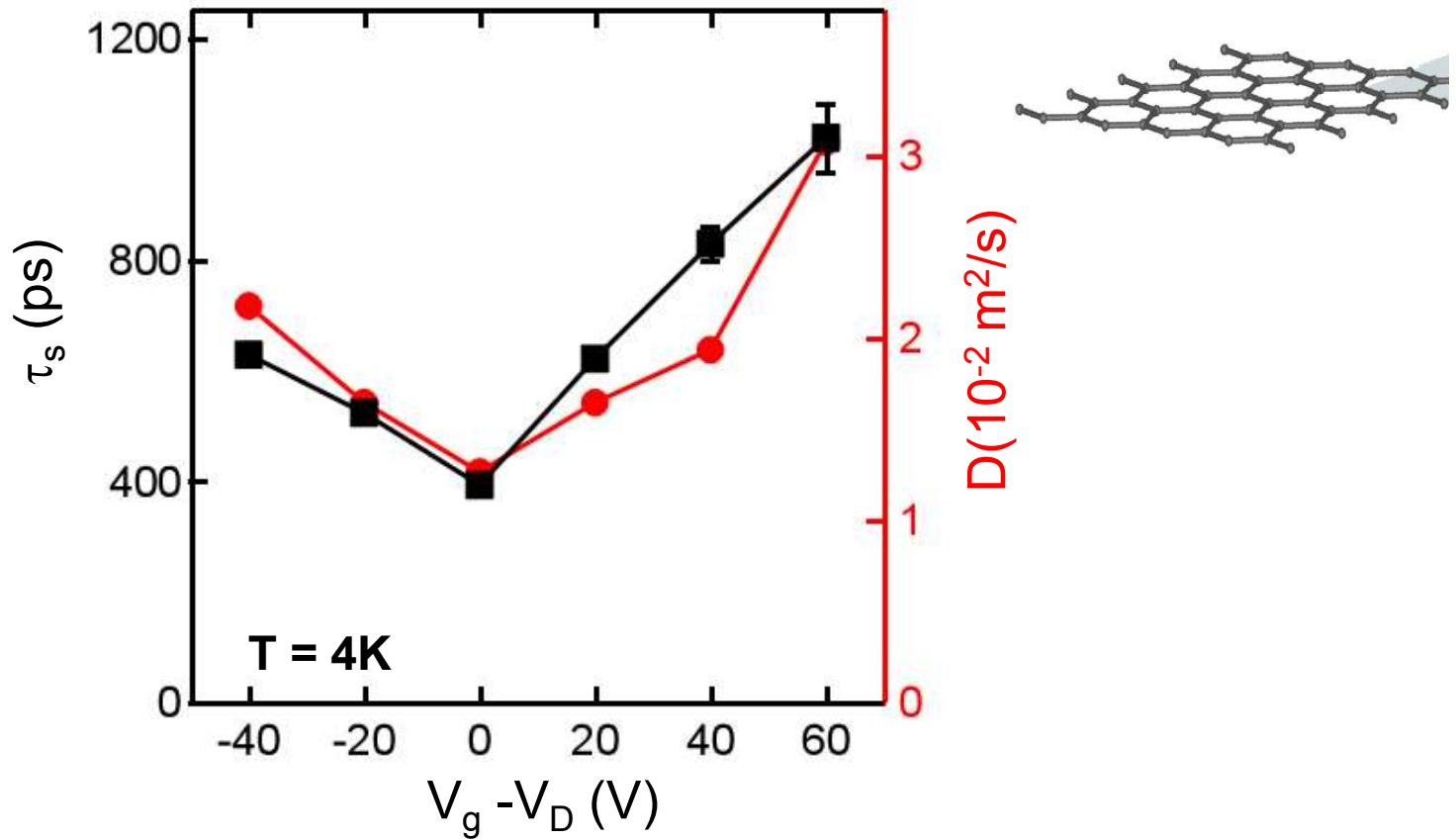


More momentum scattering, less spin relaxation

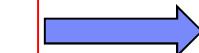
$$\tau_s \sim 1/\tau_p$$

M. I. D'yakonov and V.I. Perel, Sov. Phys. Solid State (1972)

Spin relaxation in graphene

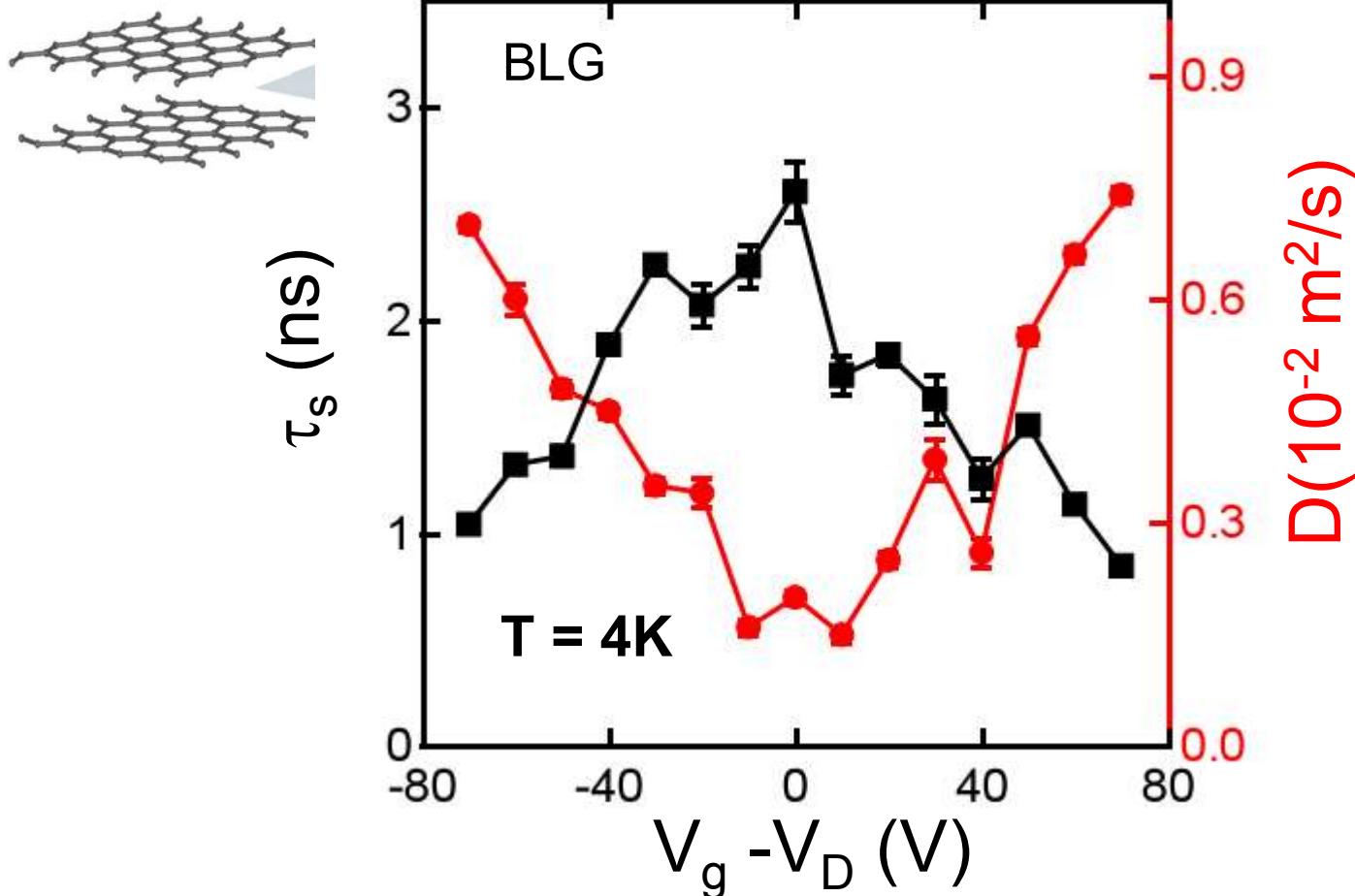


$\tau_s \sim \tau_p \sim D$



Elliot-Yafet

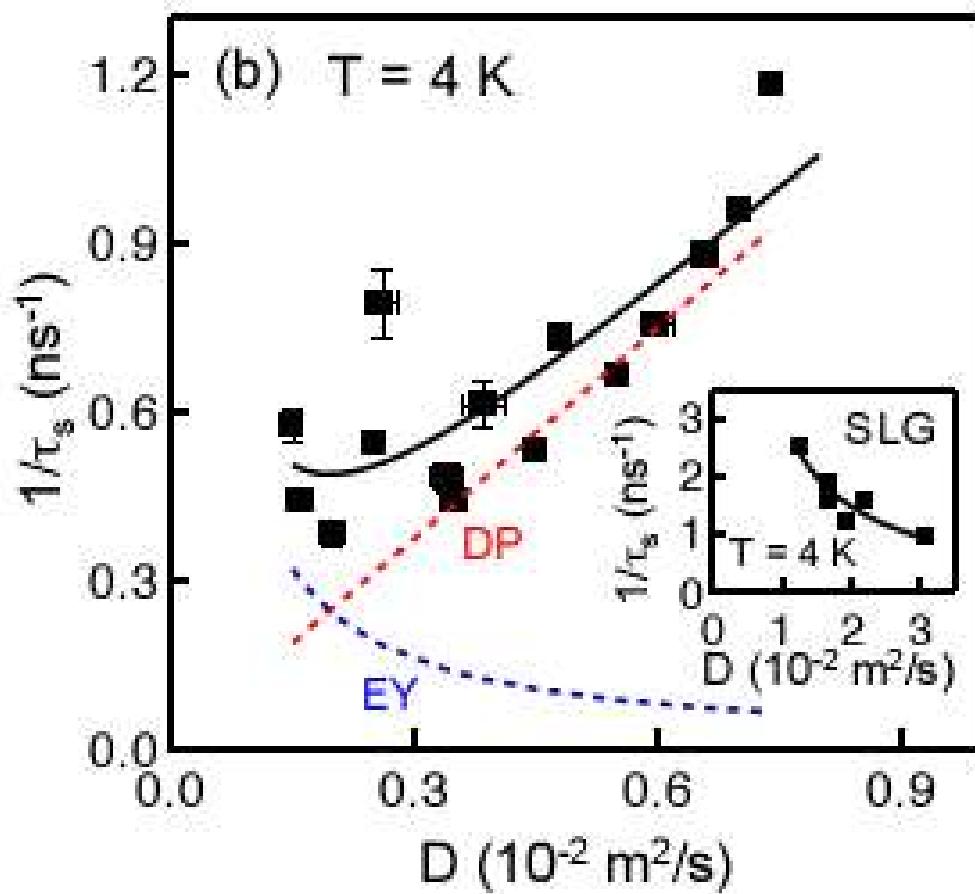
Spin relaxation in graphene



$$\tau_s \sim 1/\tau_p \sim 1/D$$

Dyakonov-Perel

Spin relaxation in graphene



$$\frac{1}{\tau_s} = \frac{1}{\tau_s^{EY}} + \frac{1}{\tau_s^{DP}} = \frac{K_{EY}}{D} + K_{DP}D$$

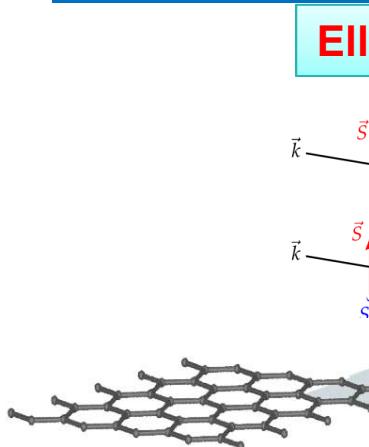
BLG

$$K_{EY} = 0.05 \pm 0.01 (10^{-2} \text{ m}^2\text{s}^{-1}) \text{ ns}^{-1}$$
$$K_{DP} = 1.24 \pm 0.09 (10^{-2} \text{ m}^2\text{s}^{-1})^{-1} \text{ ns}^{-1}$$

SLG

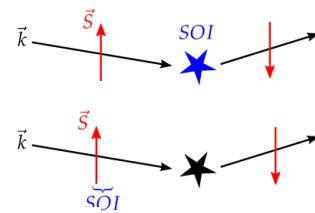
$$K_{EY} = 3.05 \pm 0.35 (10^{-2} \text{ m}^2\text{s}^{-1}) \text{ ns}^{-1}$$
$$K_{DP} = -0.02 \pm 0.10 (10^{-2} \text{ m}^2\text{s}^{-1})^{-1} \text{ ns}^{-1}$$

Spin relaxation in graphene



Elliot-Yafet

Dyakonov-Perel



Tombros, et al, Nature (2007)

Tombors, et al, PRL(2008)

Jozsa, et al, PRB (2009)

Han and Kawakami, PRL (2011)

~ 150 ps, impurity (EY)

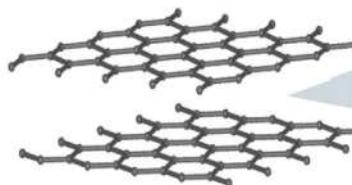
Anisotropy (EY)

Linear scaling of λ & D (EY)

~ 1 ns, $\tau_s \sim \tau_p(D)$ (EY)

Up to 6 ns, $\tau_s \sim 1/\tau_p(1/D)$ (DP)

Up to 2 ns, $\tau_s \sim 1/\mu$ (DP)



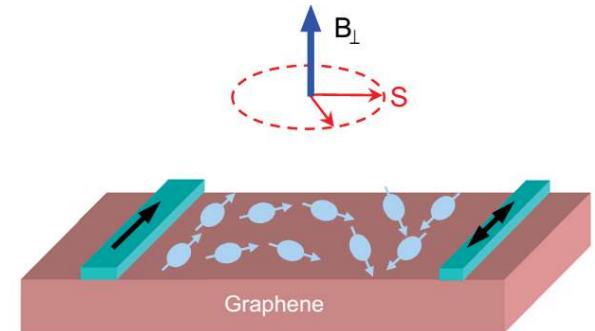
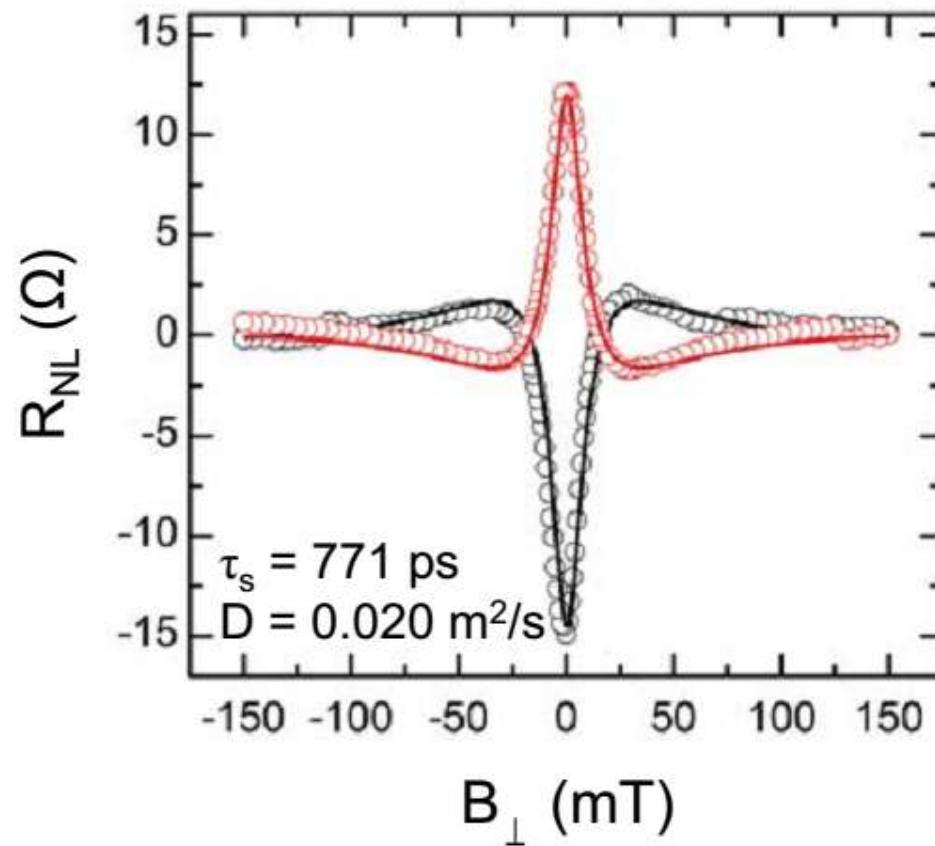
Being under investigation:

- Random Rashba field
- Magnetic resonant scattering

Wang and Wu, et al, NJP (2012)

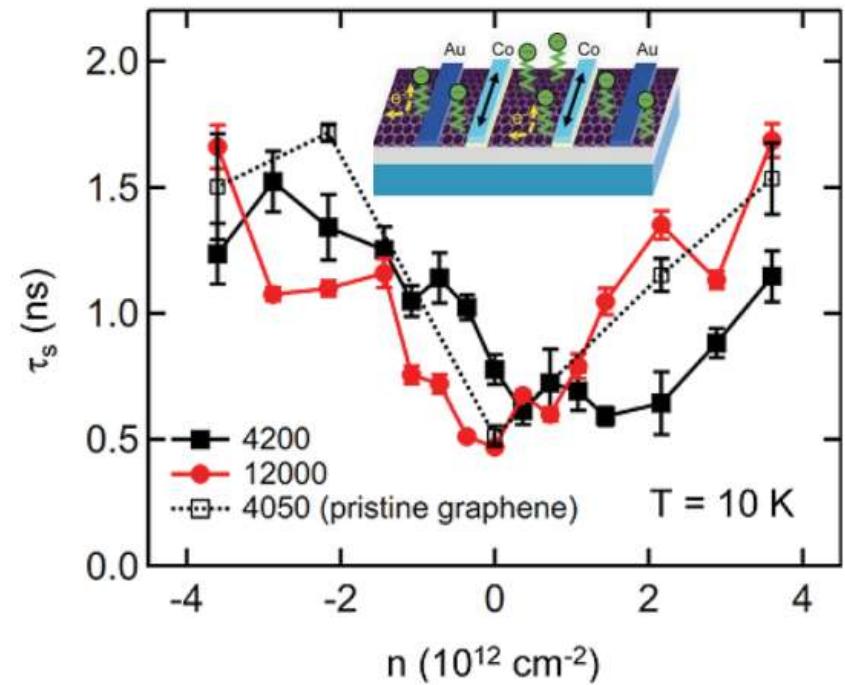
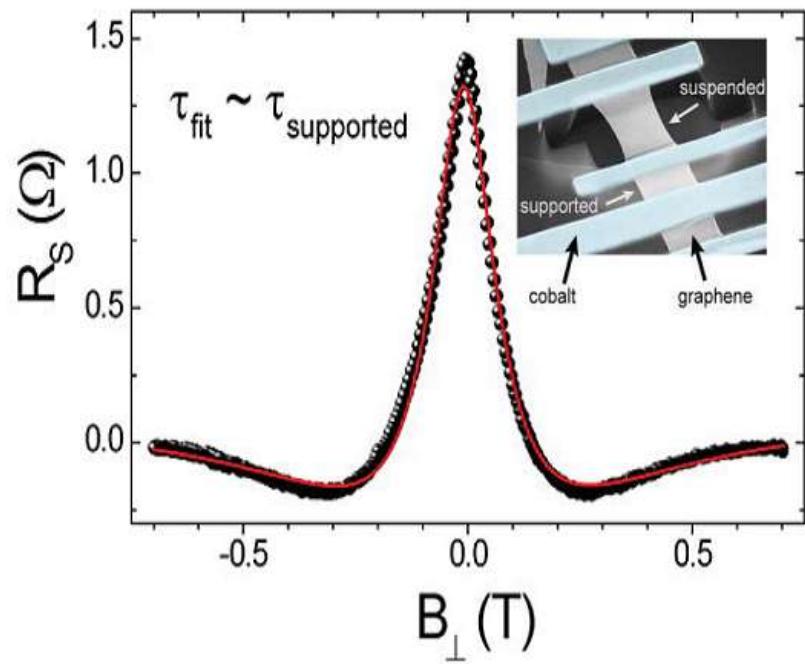
Kochan, et al, arXiv:1306.0230 (2013)

Spin diffusion length



Spin diffusion length

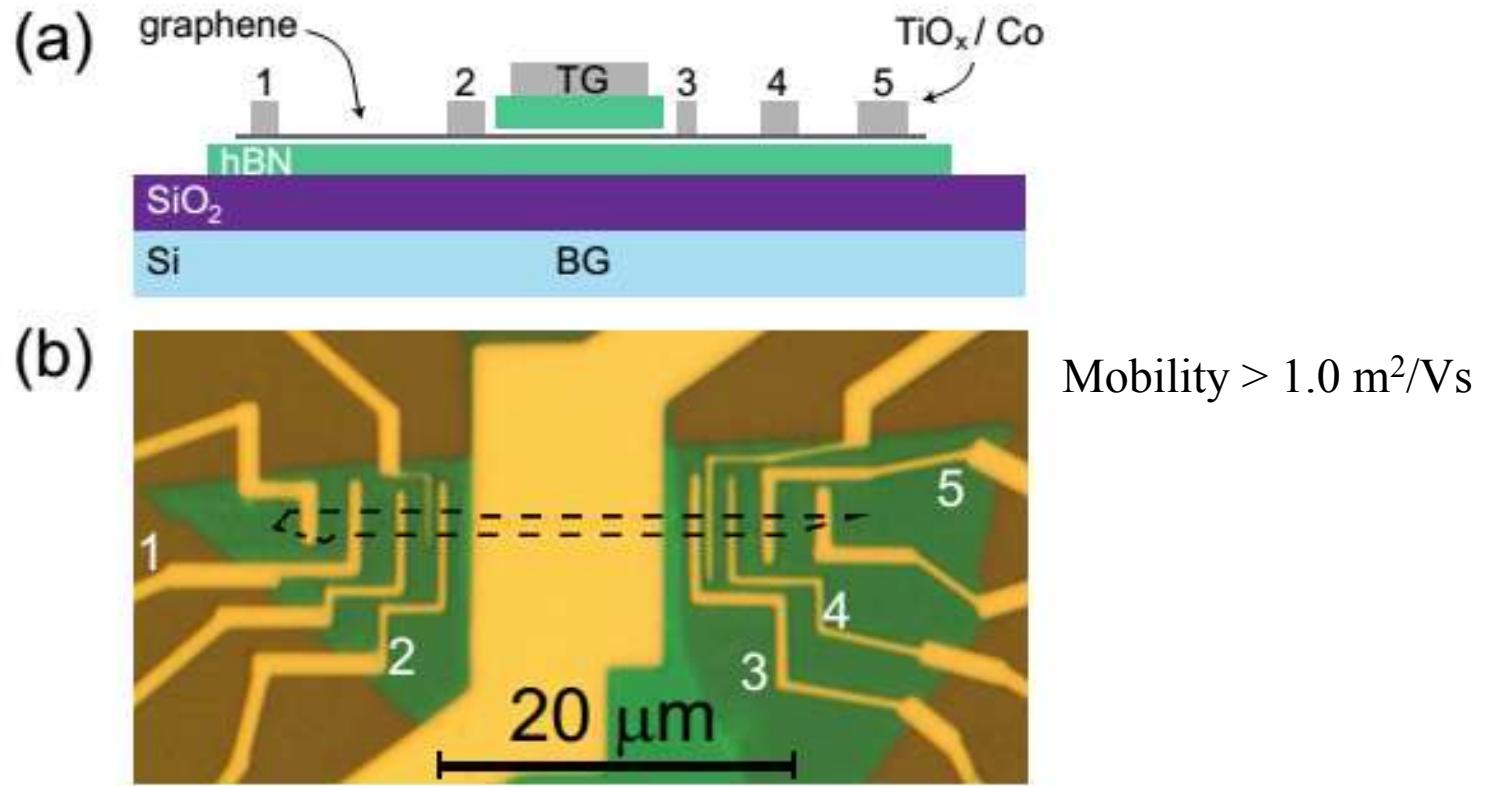
Suspended graphene



Spin diffusion lengths 1-5 microns

Guimarães, et al, Nano Letters (2012).
Han, et al, Nano Letter (2012).

Spin diffusion length

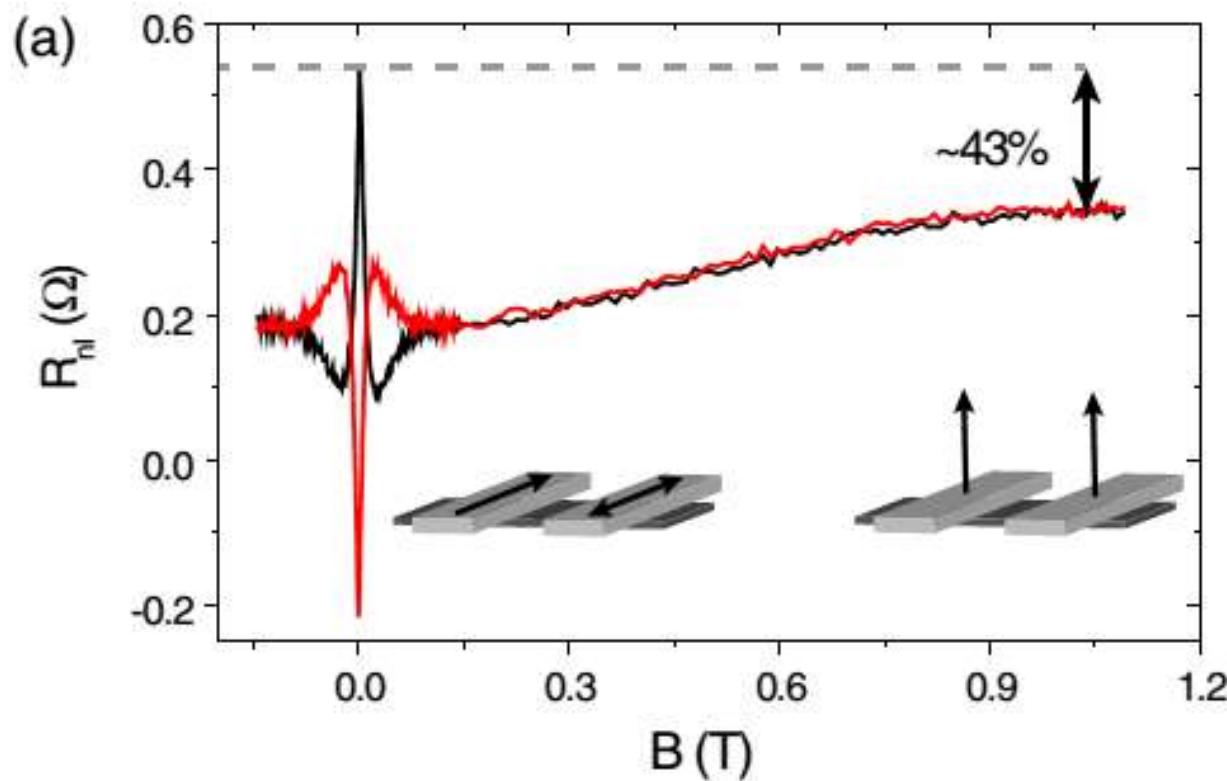


Spin diffusion lengths >10 microns

Guimarães, et al, PRL (2014)

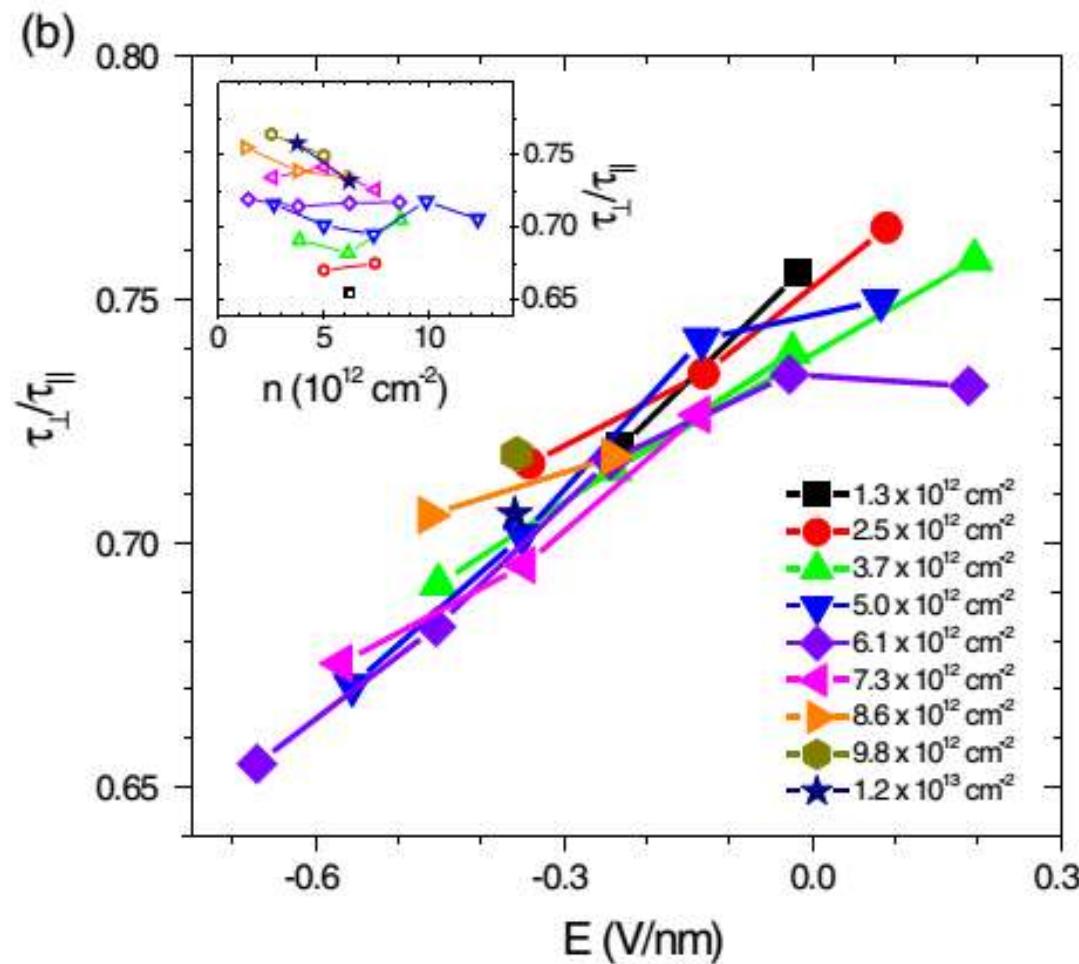
Drogeler, et al, Nano Letter (2014)

Anisotropy



Guimarães, et al, PRL (2014)

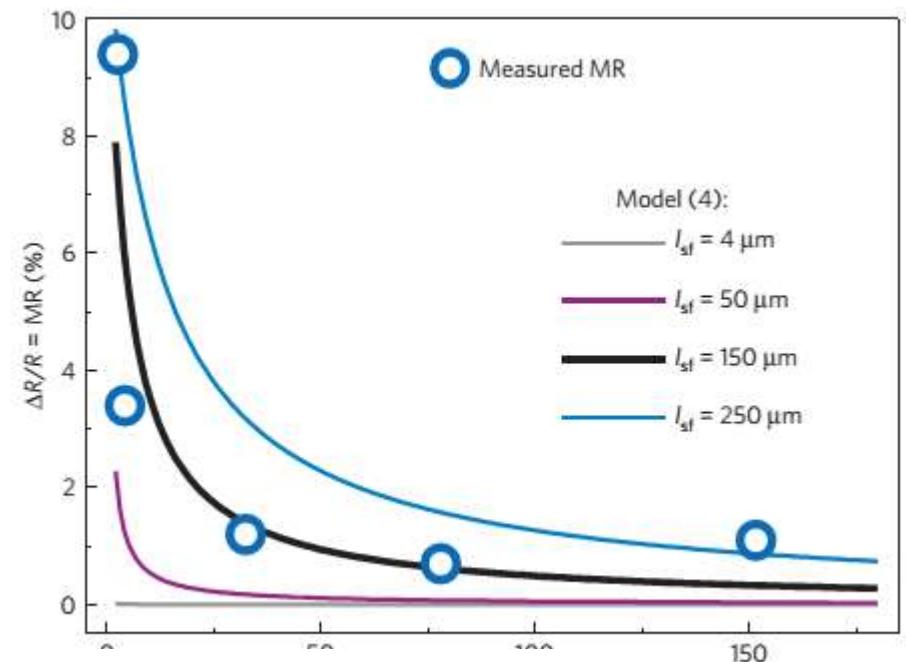
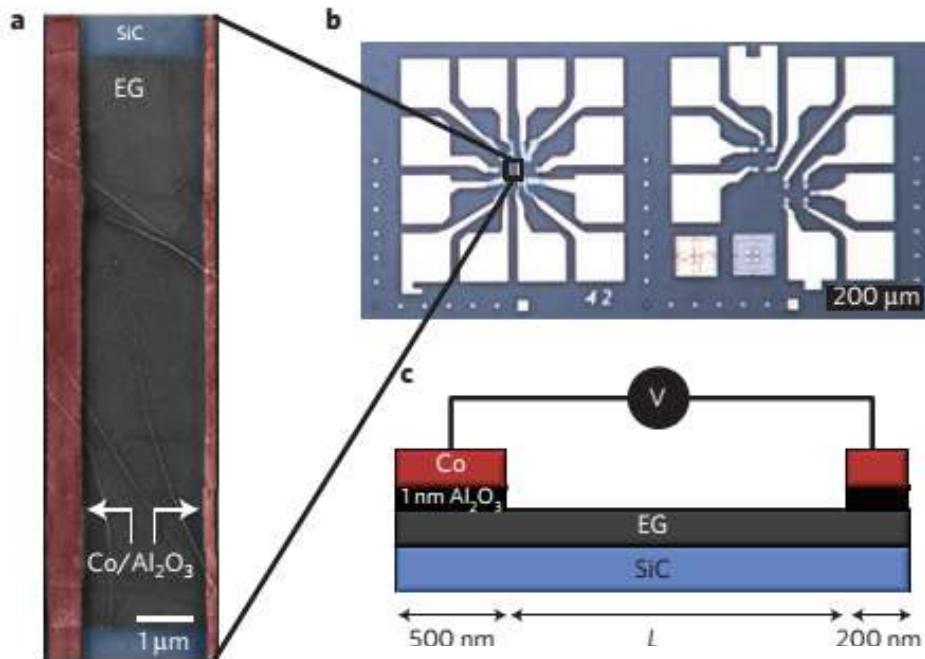
Anisotropy



Guimarães, et al, PRL (2014)

Spin diffusion length

An indirect method-- local MR measurement



Spin diffusion lengths >100 microns

Dlbak, et al, Nature Physics (2012)

Spin properties of graphene

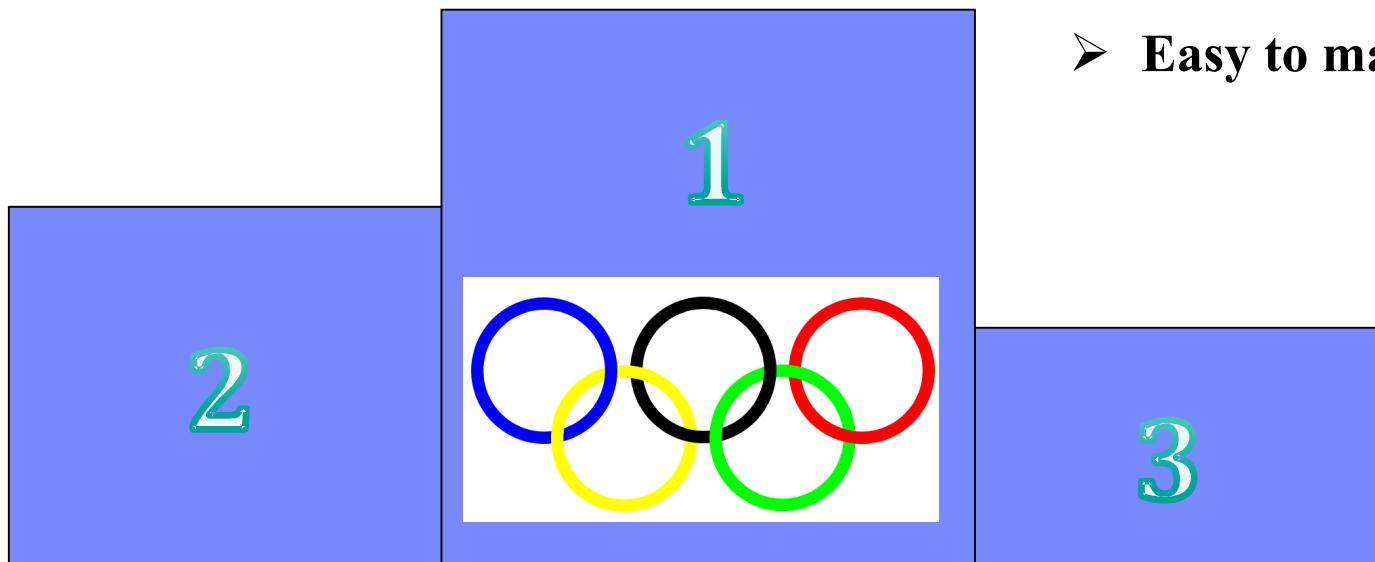
	Spin lifetime	Spin diffusion lengths	Spin signals
Room Temperature	0.5 - 2 ns	> 10 μm	130 Ω
Low Temperature	1 - 6 ns	> 10 μm (> 100 μm indirect)	1 MΩ for local MR

Spin properties of graphene

Spin Channel		Spin lifetime	Spin diffusion lengths	Spin signals
Metals	Cu ^{15,131}	~42 ps at 4.2 K ~11 ps at 300 K	~1 μm at 4.2 K ~0.4 μm at 300 K	~1 mΩ at 4.2 K ~0.5 mΩ at 300 K
	Al ¹⁰⁸	~100 ps at 4.2 K ~45 ps at 300 K	~0.6 μm at 4.2 K ~0.4 μm at 300 K	~12 mΩ at 4.2 K ~0.5 mΩ at 300 K
	Ag ¹³²	~20 ps at 5 K ~10 ps at 300 K	~1 μm at 5 K ~0.3 μm at 300 K	~9 mΩ at 5 K ~2 mΩ at 300 K
Semiconductor	Highly doped Si ^{129,153}	~10 ns at 8 K ~1.3 ns at 300 K	~2 μm at 8 K ~0.5 μm at 300 K	~30 mΩ at 8 K ~1 mΩ at 300 K
	GaAs ¹⁵⁴	24 ns at 10 K 4 ns at 70 K	6 μm at 50 K	~30 mΩ at 50 K
	Highly doped Ge ¹³⁰	~1 ns at 4 K ~300 ps at 100 K	~0.6 μm at 4 K	0.1-1 Ω at 4 K 0.02 ~ 0.1 Ω at 200 K
Graphene ^{6,9,10}		0.5 - 2 ns at 300 K 1 - 6 ns at 4 K	3 - 10 μm at 300 K (~100 μm fit from local MR data)	130 Ω at 300 K (1 MΩ for local MR at 1.4 K)

Spin properties of graphene

Graphene



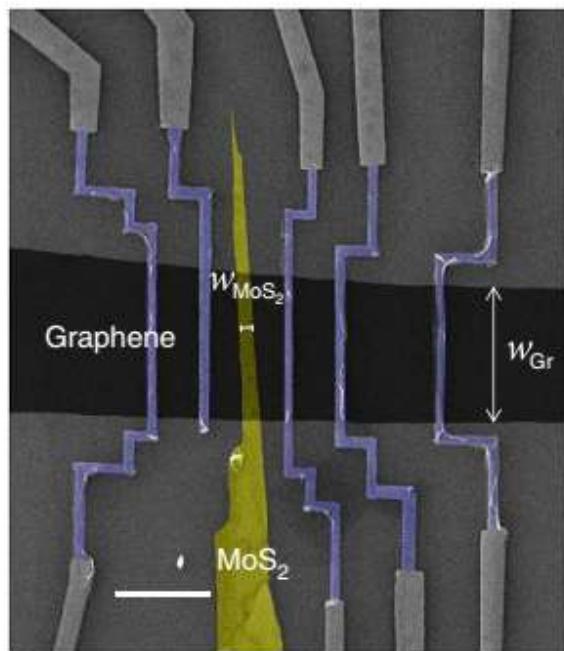
- Large spin signal
- Long spin lifetime
- Long spin diffusion length
- Easy to manipulate

Han, et al, Nature Nanotechnology (2014)

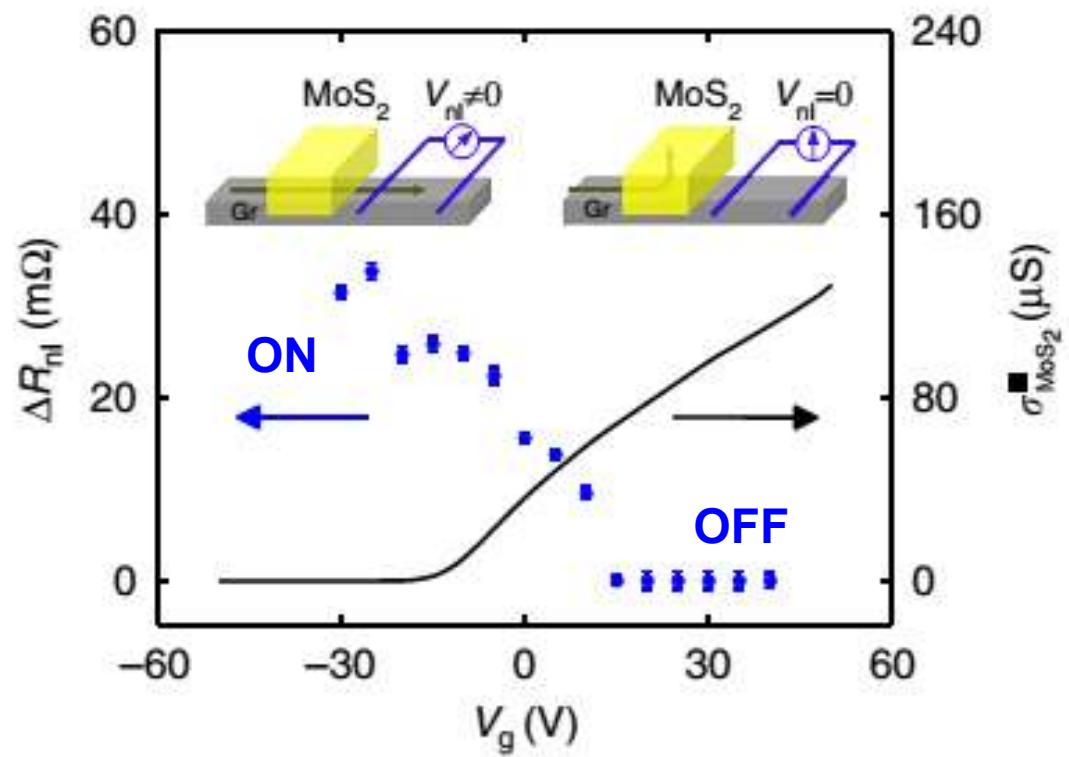
Graphene spin transistor

Graphene/MoS₂ channel

(a)



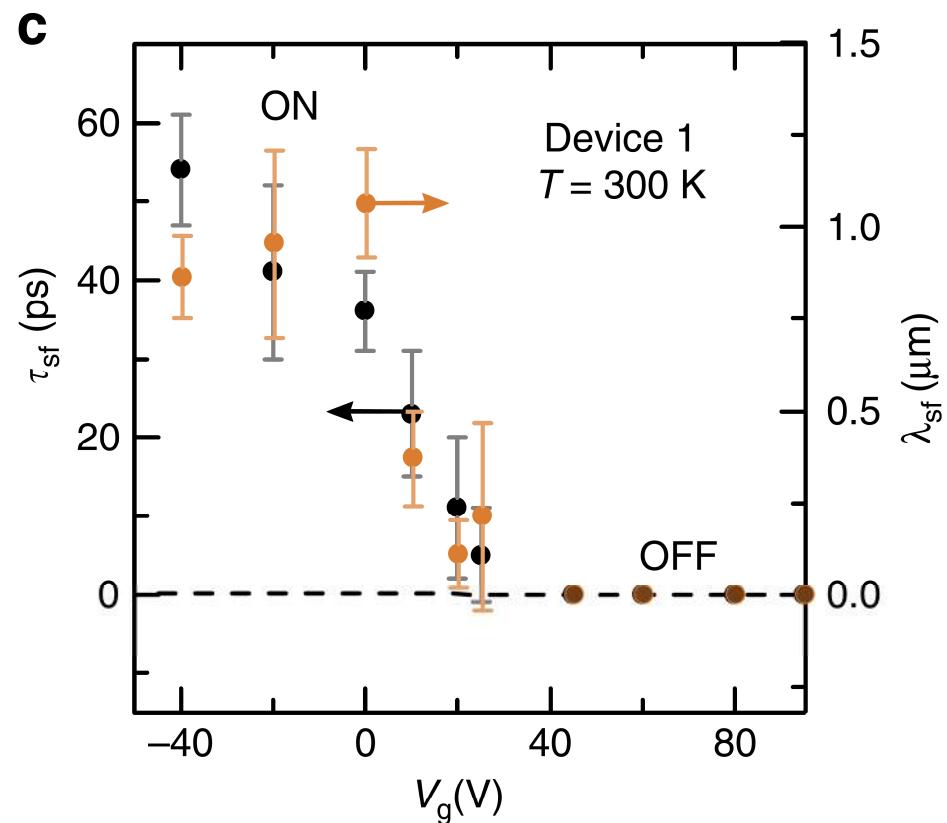
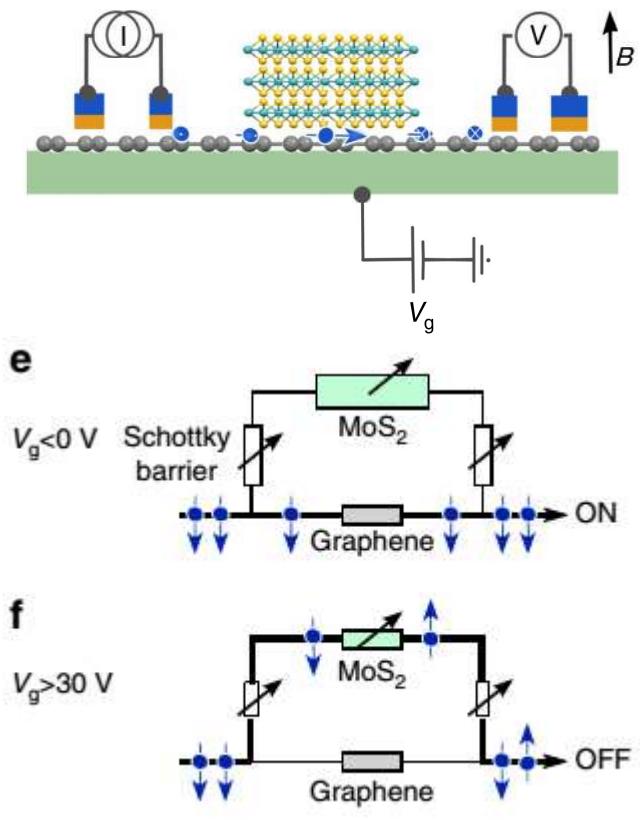
(b)



Yan, et al, *Nat. Commun.* 7, 13372 (2016).
Dankert and Dash, *Nat. Commun.* 8, 16093 (2017).

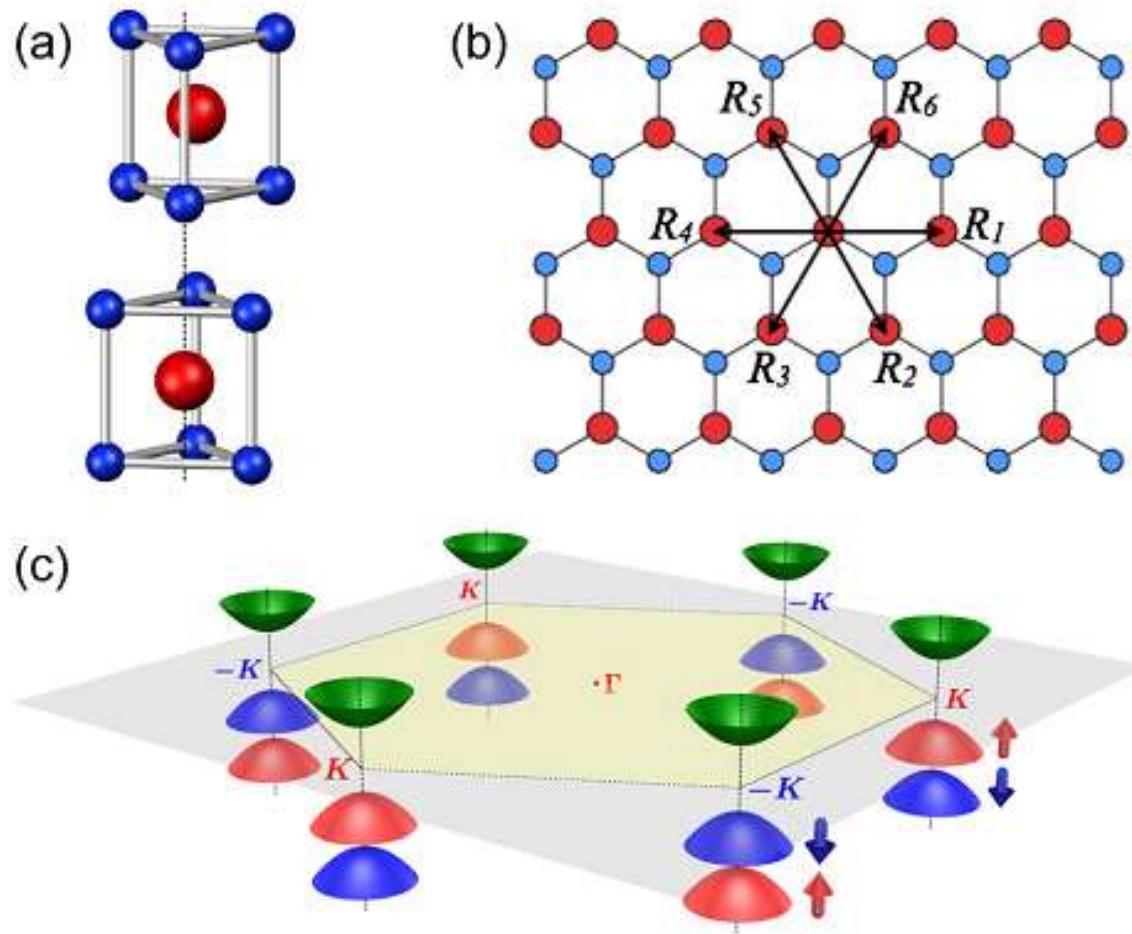
Graphene spin transistor

Graphene/MoS₂ channel: gate tuning the channel and spin lifetimes



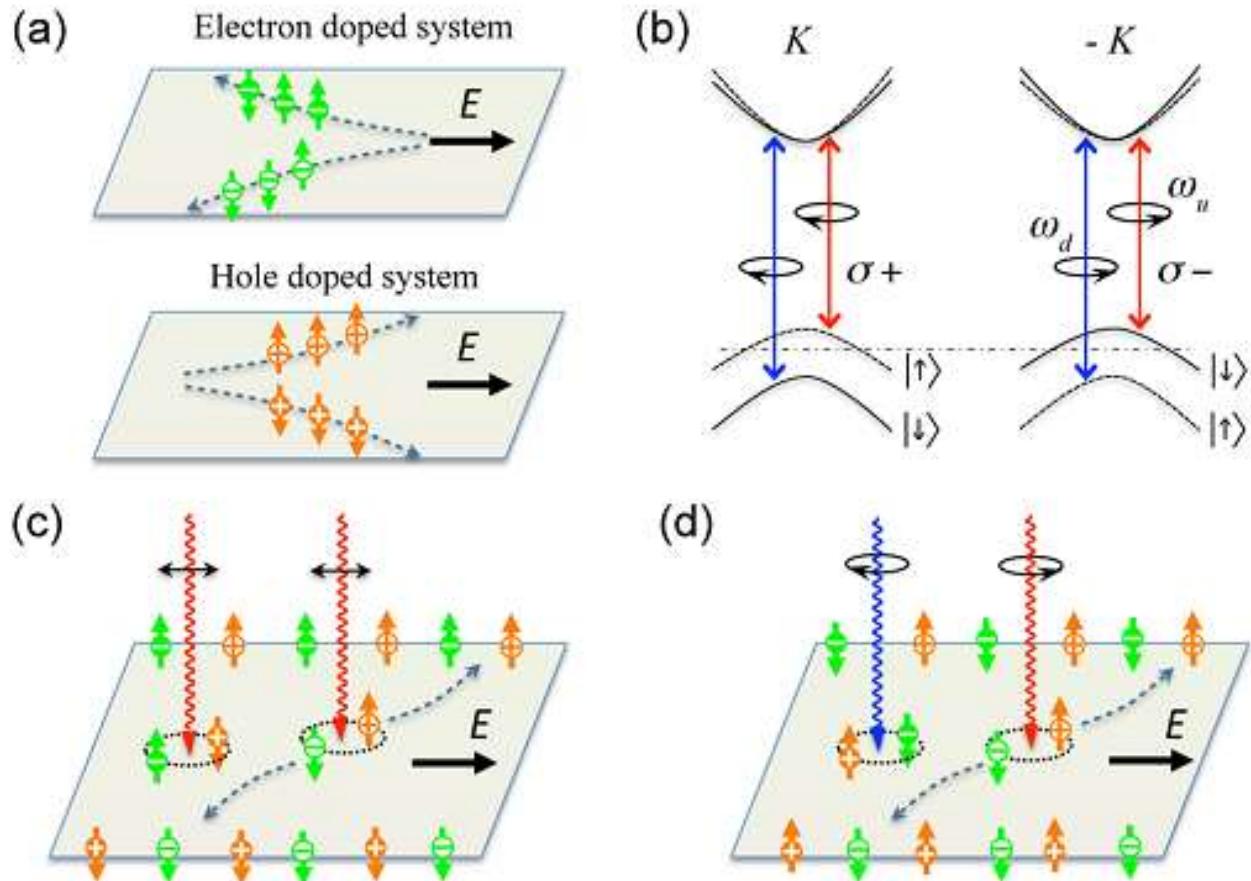
Yan, et al, *Nat. Commun.* 7, 13372 (2016).
Dankert and Dash, *Nat. Commun.* 8, 16093 (2017).

MoS₂



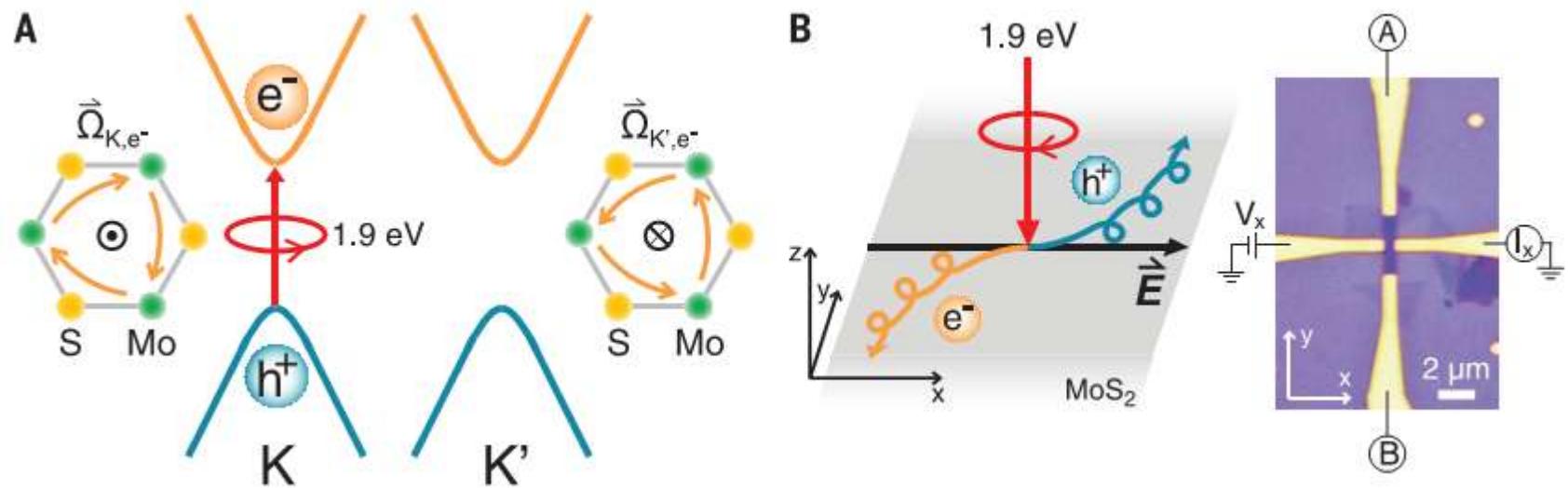
Xiao, et al, PRL (2013)

Spin and Valley Hall in MoS₂



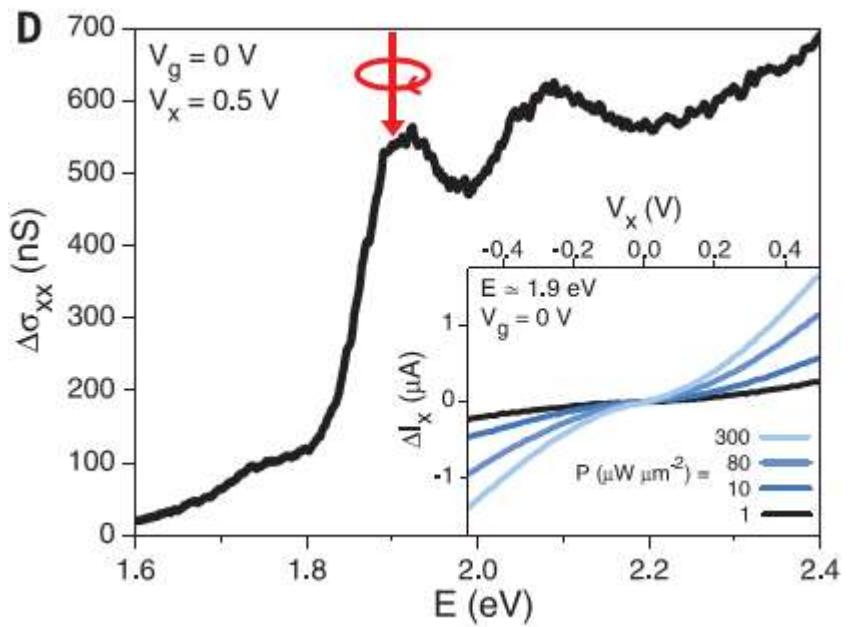
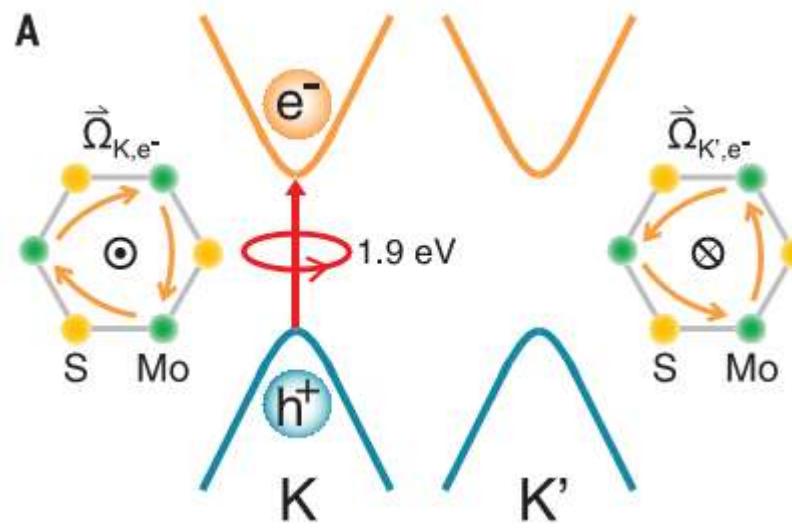
Xiao, et al, PRL (2013)

Spin and Valley Hall in MoS₂



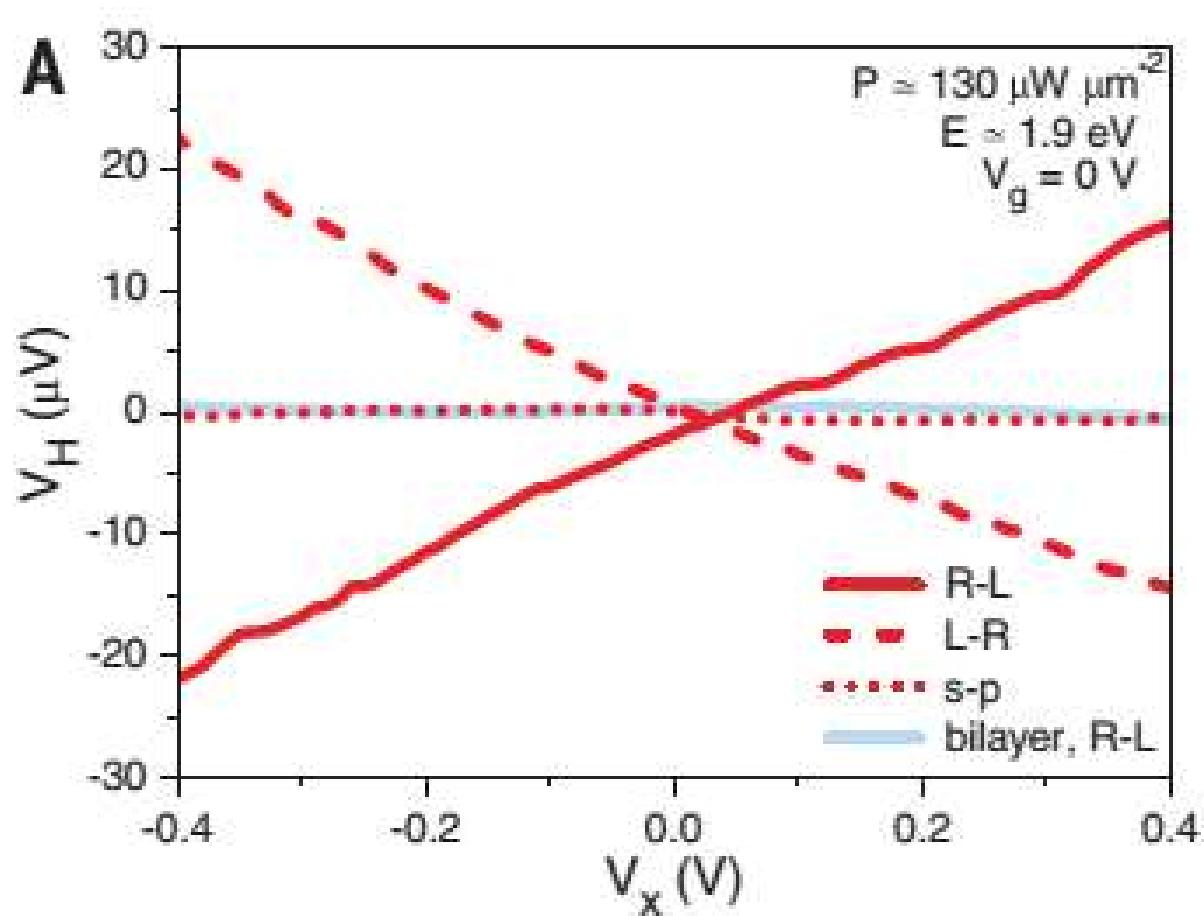
Mak, et al, Science (2014)

Spin and Valley Hall in MoS₂

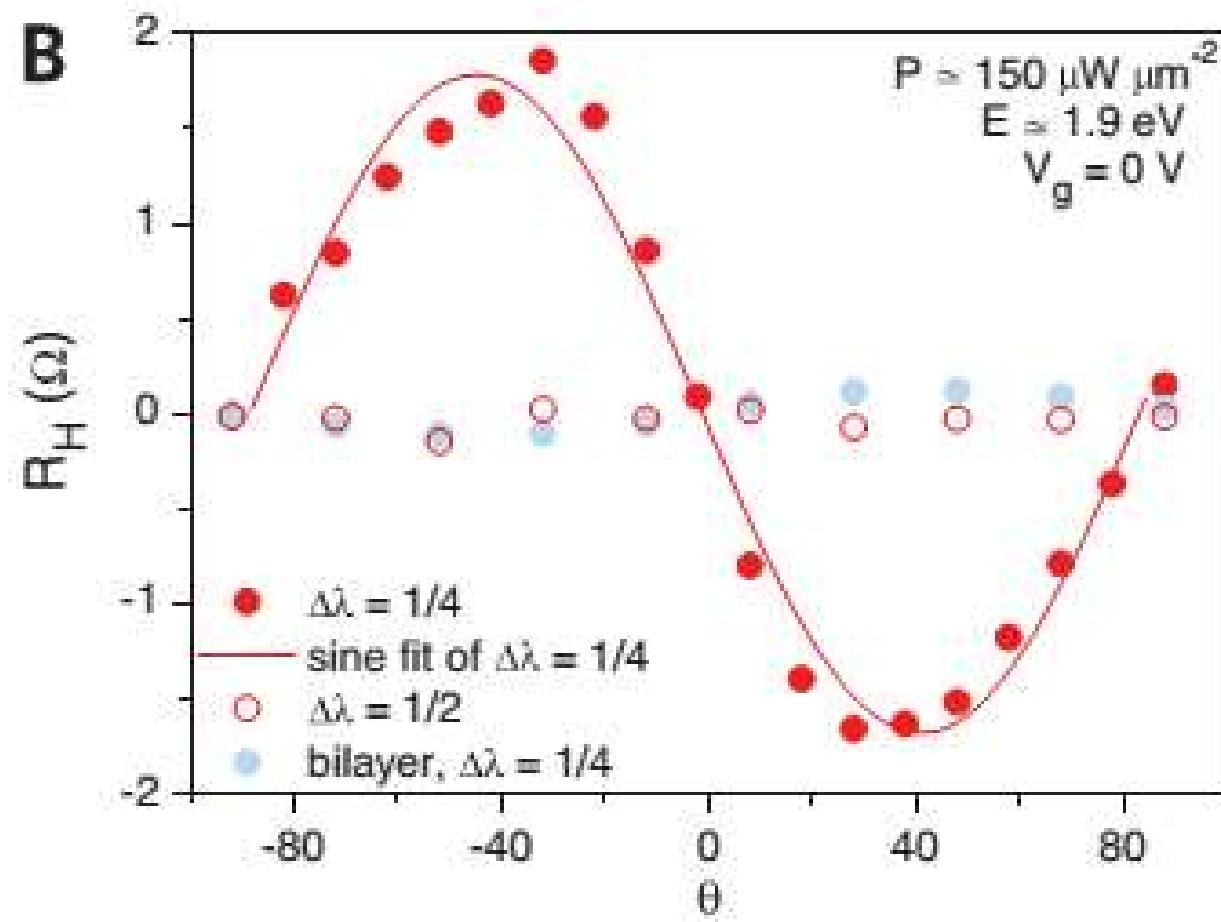


Mak, et al, Science (2014)

Spin and Valley Hall in MoS₂

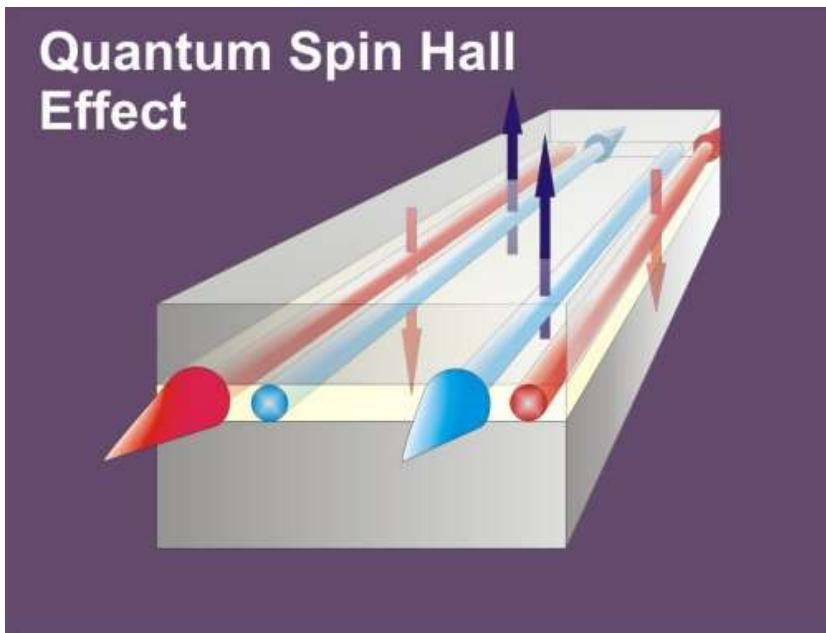


Spin and Valley Hall in MoS₂

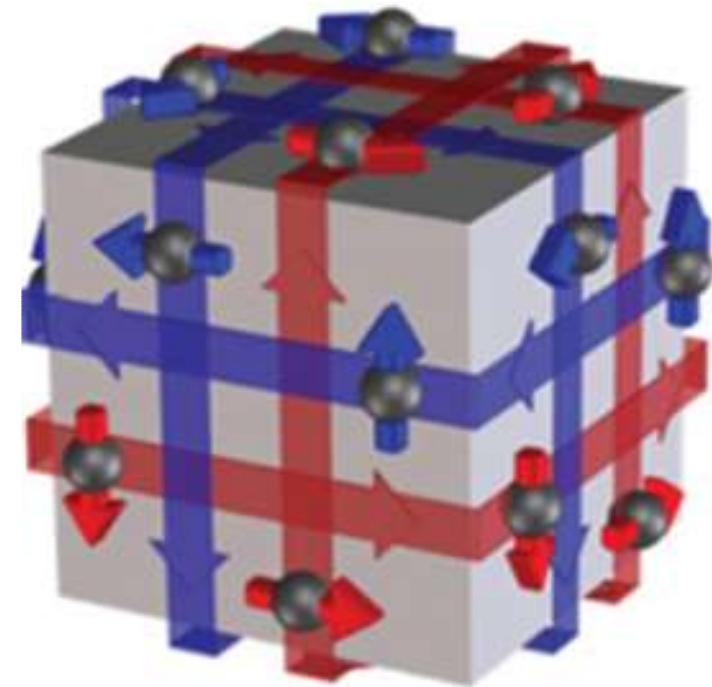


Topological insulator

Topological insulators— **Spin-Momentum locking**



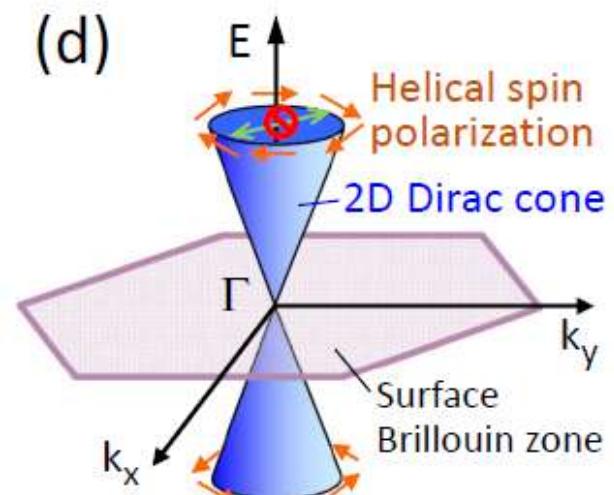
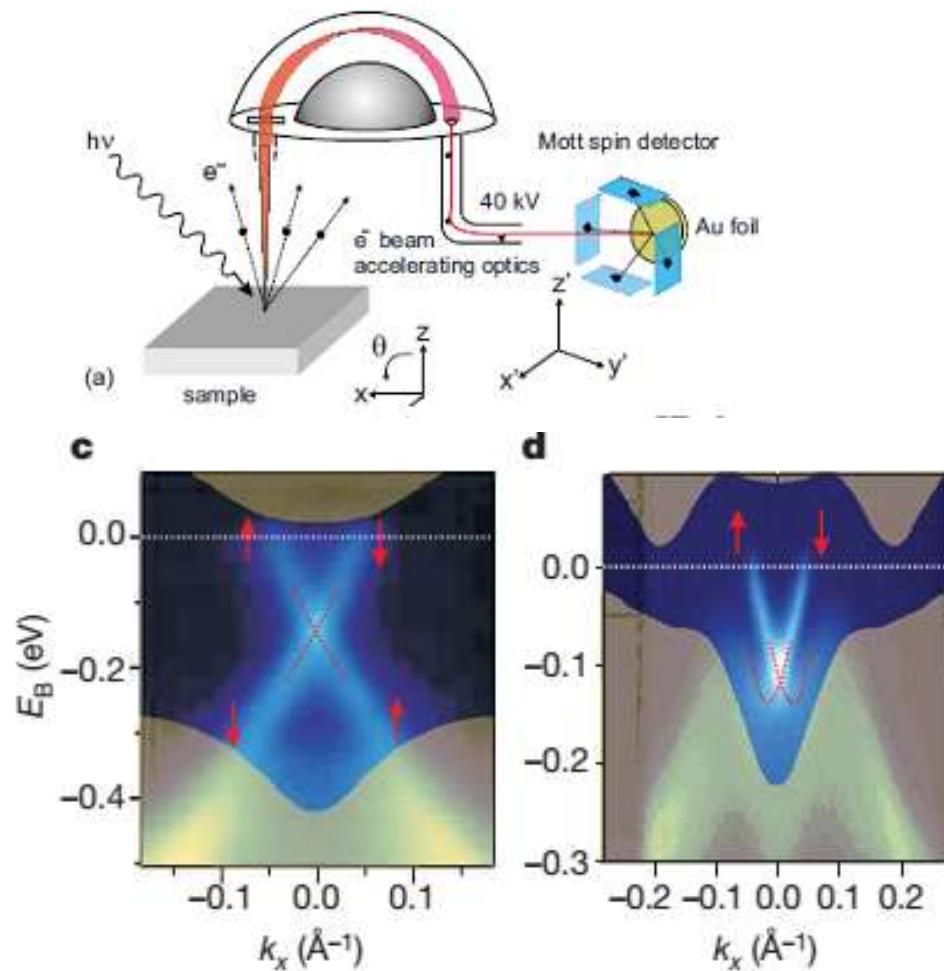
2D Topological insulator



3D Topological insulator

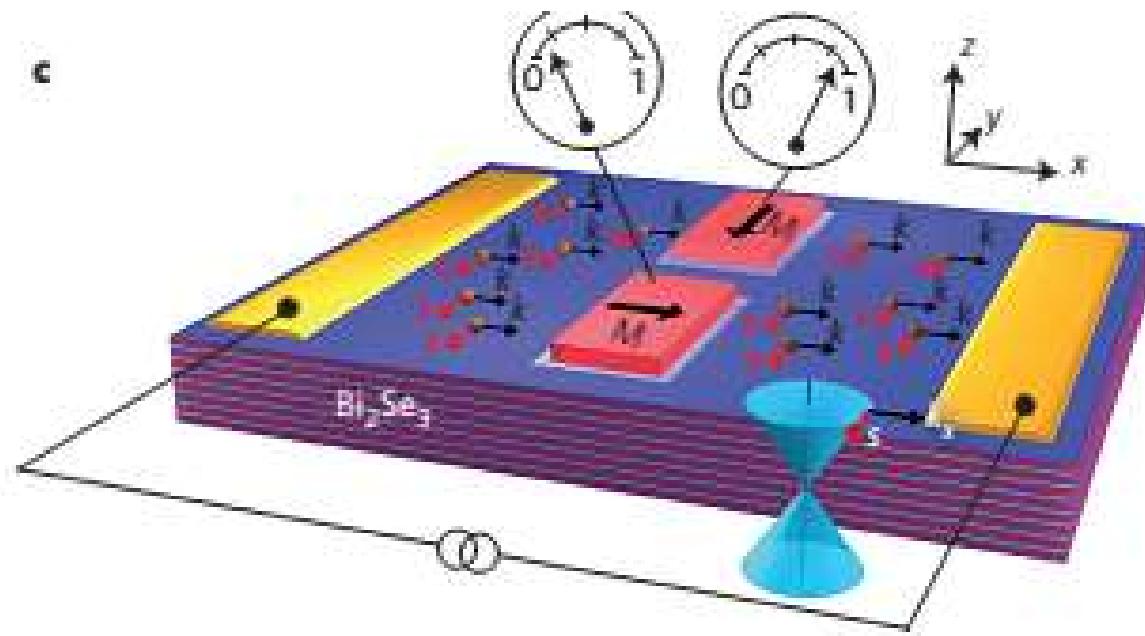
Qi&Zhang, *Rev. Mod. Phys.* (2011)
Hasan& Kane, *Rev. Mod. Phys.* (2010)
Yazyev, et al, *Phys. Rev. Lett.* (2010).

Topological insulator



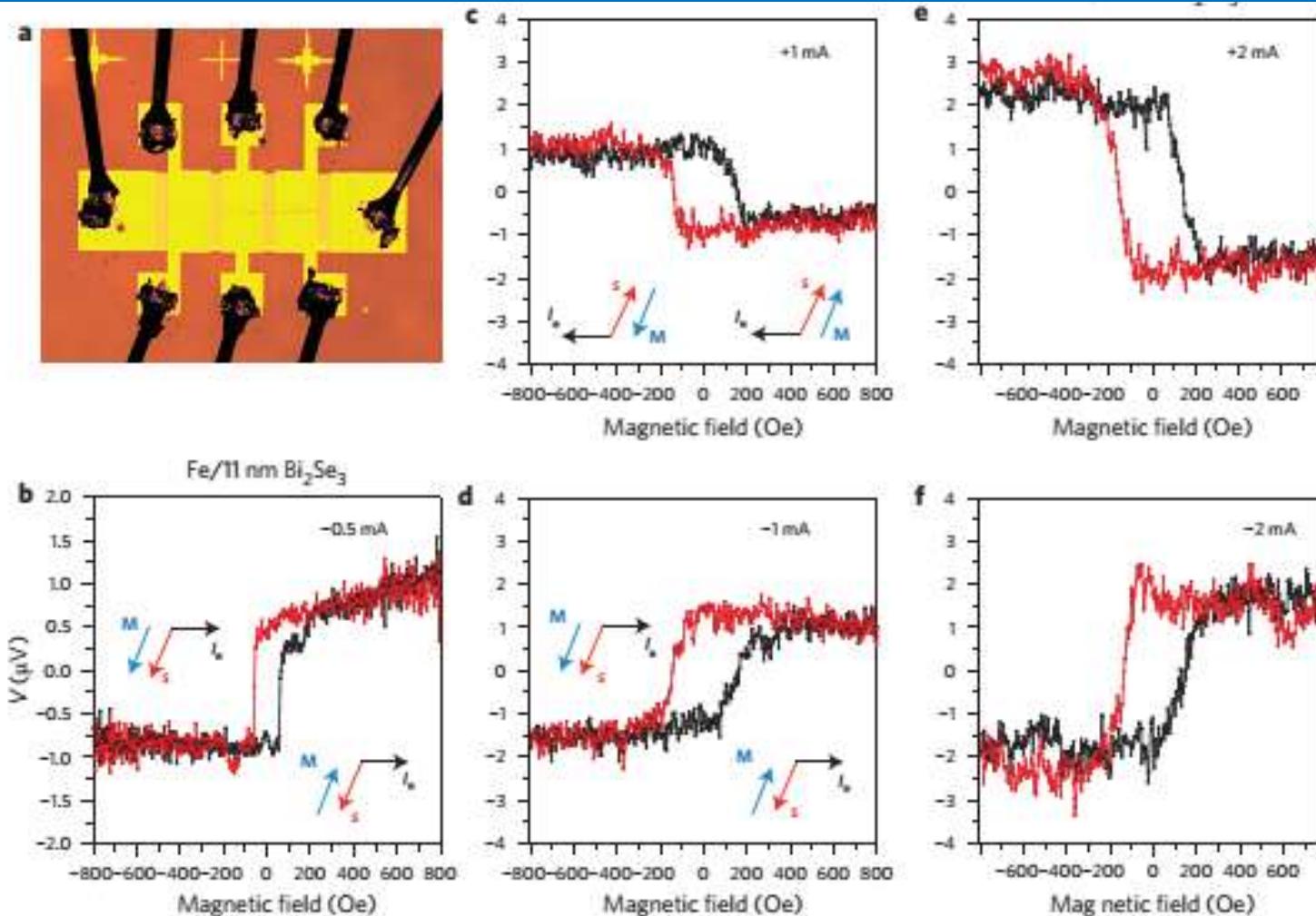
Spin ARPES: Hasan Group (Princeton University)

Topological insulator



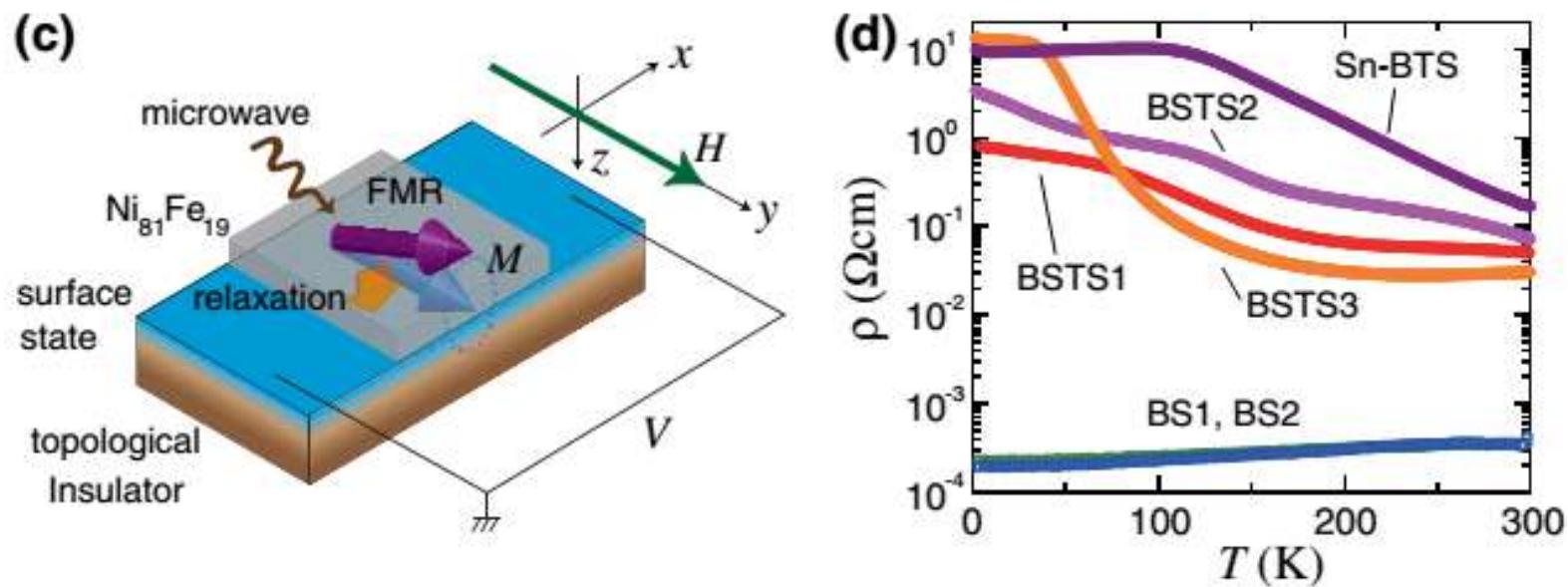
Li, et al, Nature Nanotechnology (2014).

Topological insulator



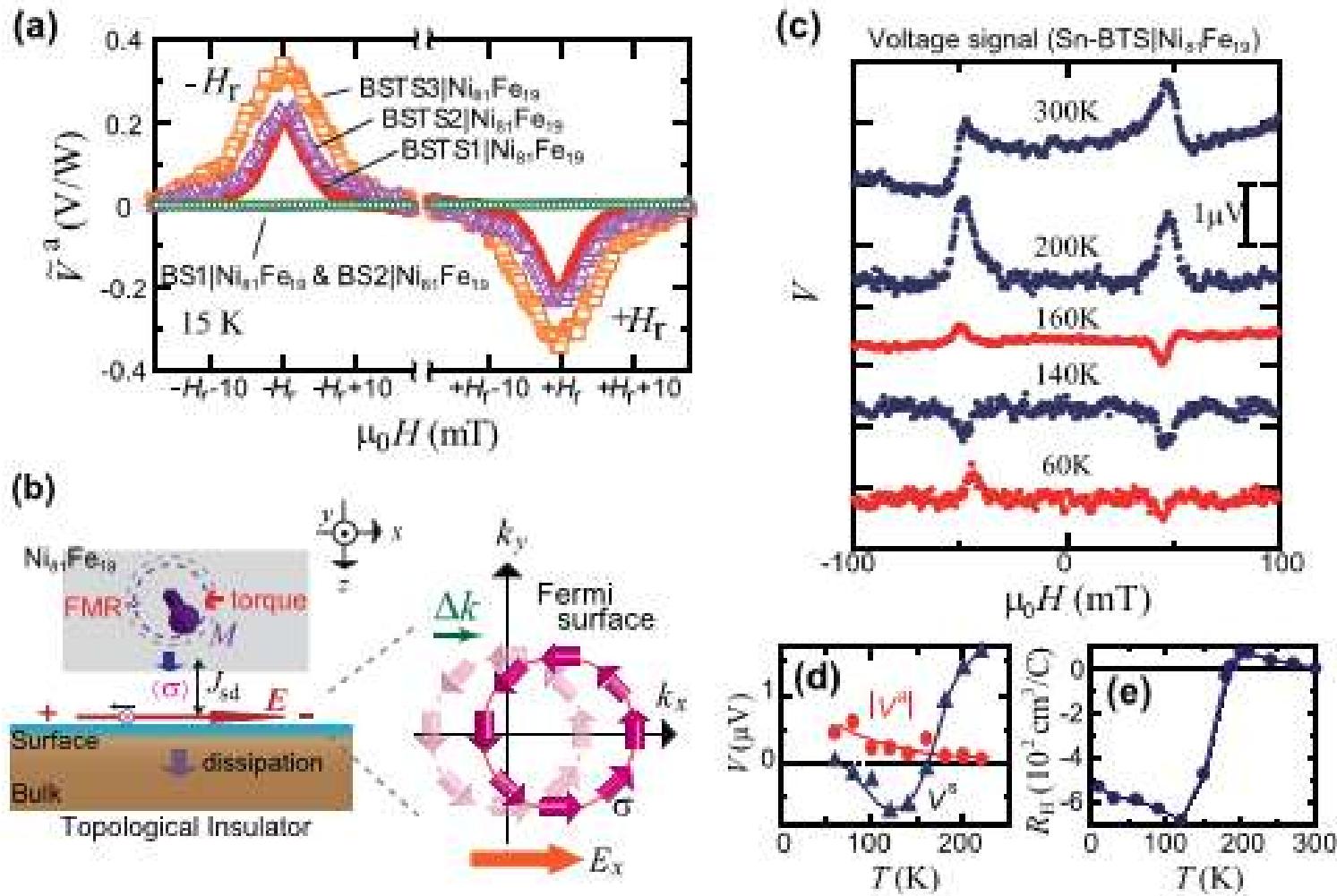
More information, please see the results of
Jonker Group (Naval National Lab), **KL Wang Group**
(UCLA) , **Y. Chen Group** (Purdue University) , etc

Topological insulator



Shiomi, et al, PRL (2014)

Topological insulator



Topological insulator

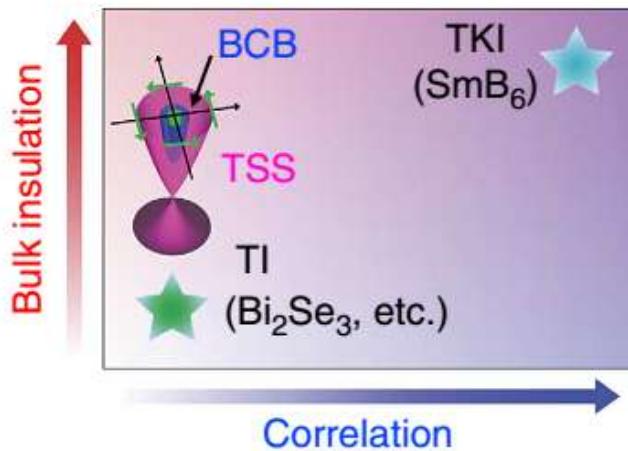
Challenge

experimental data, the value of η is estimated to be $\sim 10^{-4}$ for BSTS1 and BSTS2. Here, because of imperfect insulation of bulk states, about 15% of the injected spins contribute to the spin-electricity conversion effect [11].

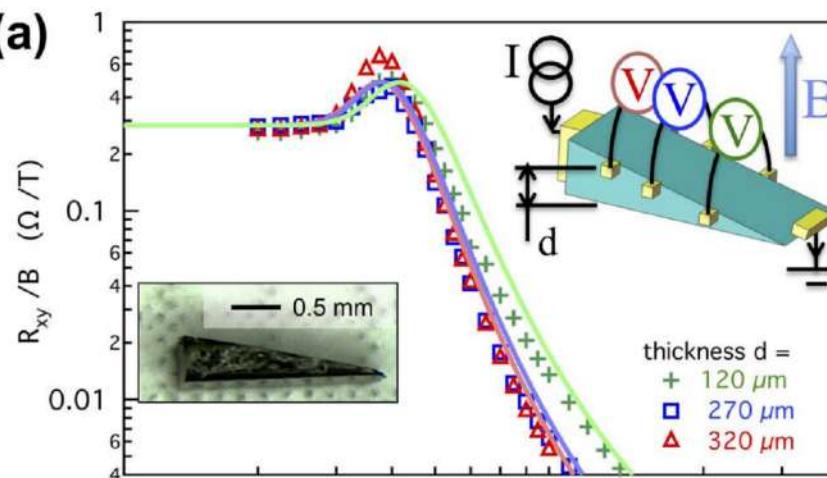
Shiomi, et al, PRL (2014)

Topological insulator

b



(a)

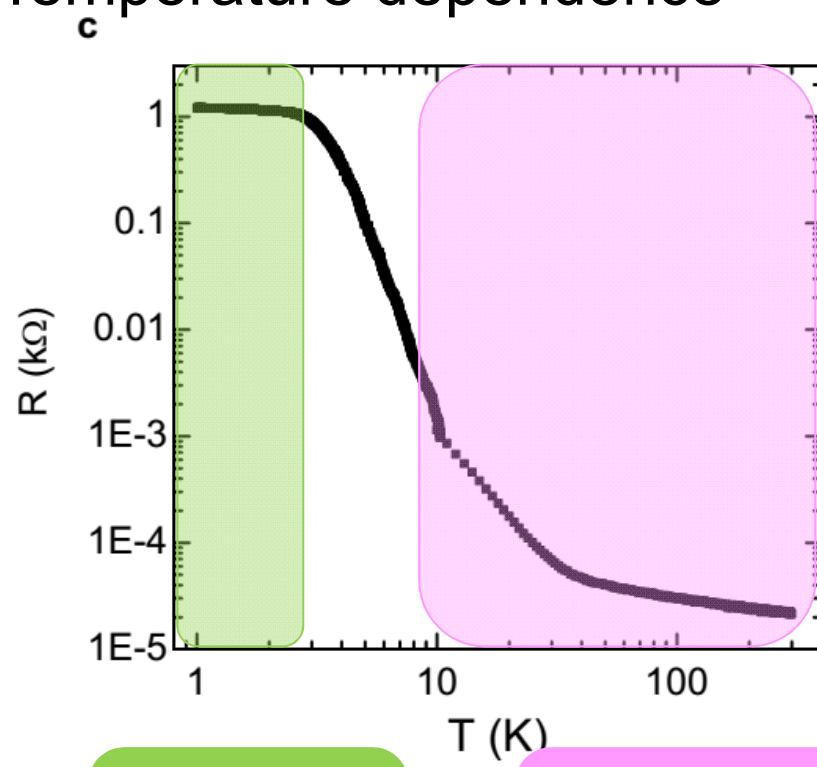


Kim et al, Scientific Reports (2013)

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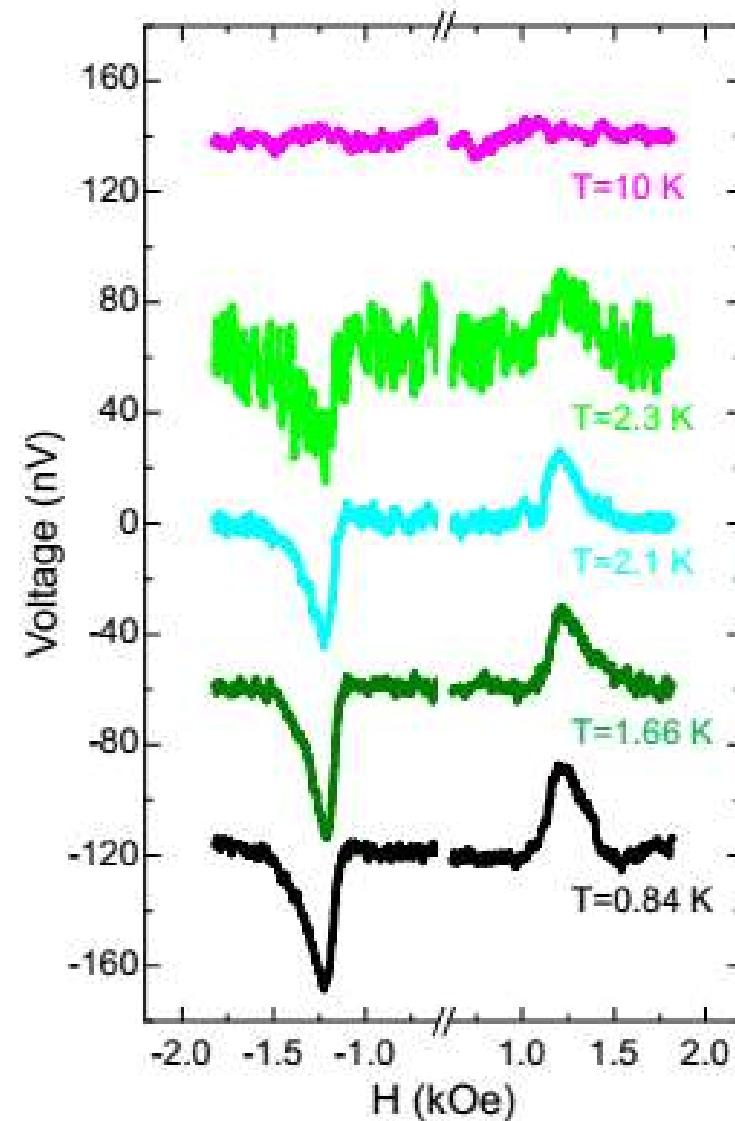
Topological insulator

Temperature dependence

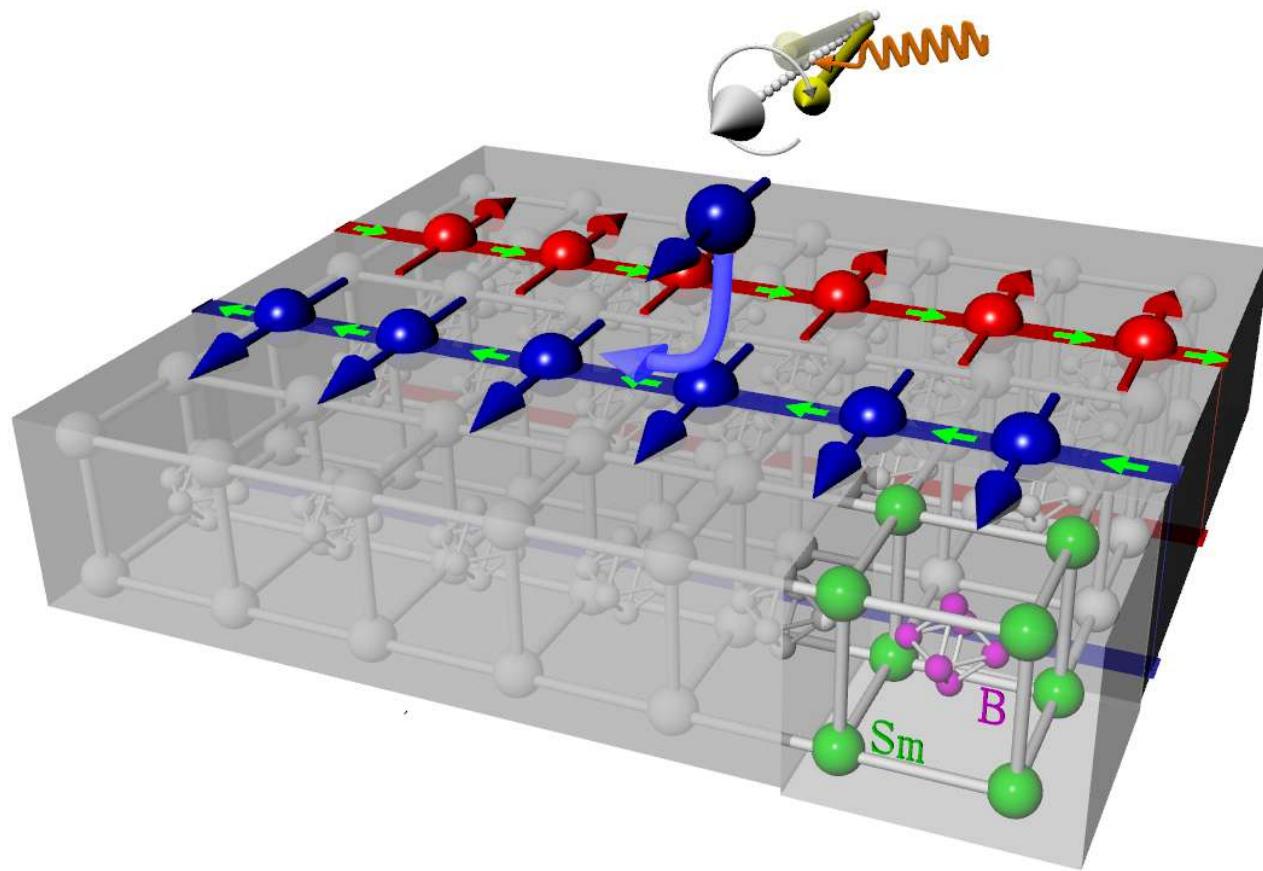


Surface
states

Bulk
states



Topological insulator



Song, et al, Nature Commun. (2016)

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Summary

1. Semiconductor Spin Valves

When spintronics meets semiconductor

GaAs

Silicon and Germanium

Complex oxides

Spin FET

Summary

2. Spin valves based on Quantum materials

石墨烯

➤ 弱自旋-轨道耦合→ 长自旋寿命

二硫化钼等

➤ 自旋-谷

拓扑绝缘体

➤ 自旋流的拓扑保护

下一节课: Nov. 10th

Chapter 5: Spin transfer torque

课件下载 :

<http://www.phy.pku.edu.cn/~LabSpin/teaching.html>