Chapter 4

Spin Valves

韩伟

量子材料科学中心

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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 Nonlcoal spin valves

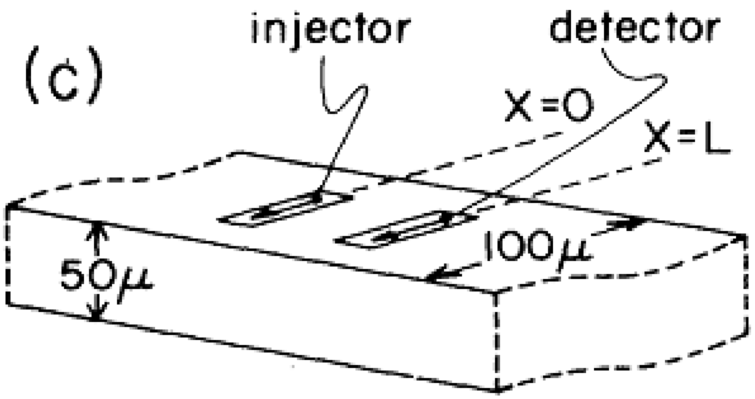
Hanle spin precession

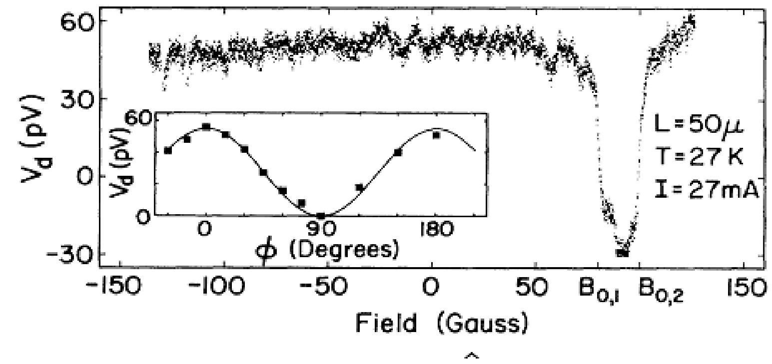
Nano devices (Thanks to cleanroom)

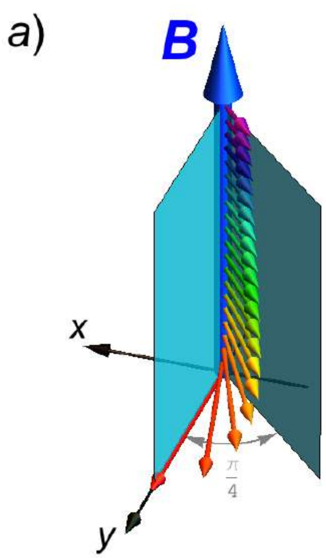
Spin injection efficiency

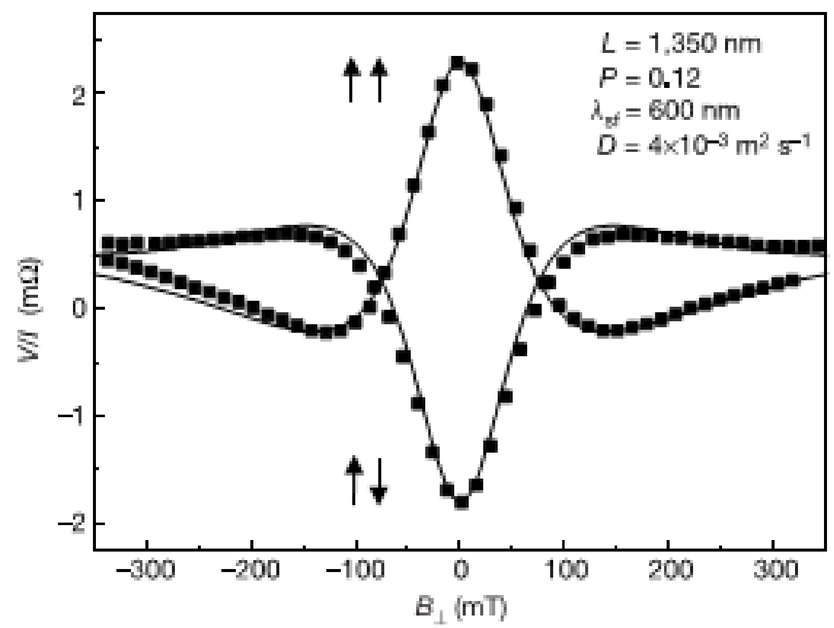
Spin relaxation in Metals: EY

Review of last class









Review of last class

Spin Injection efficiency

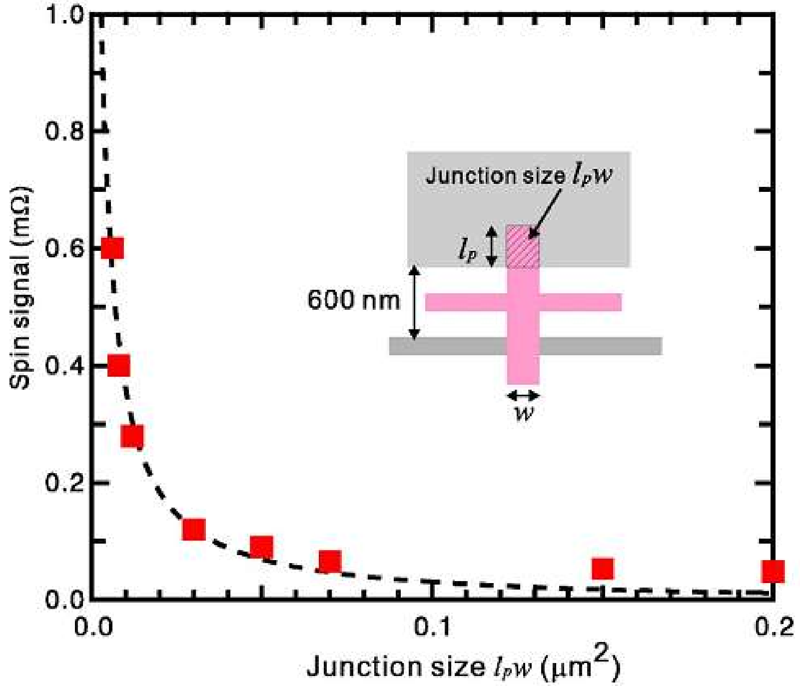
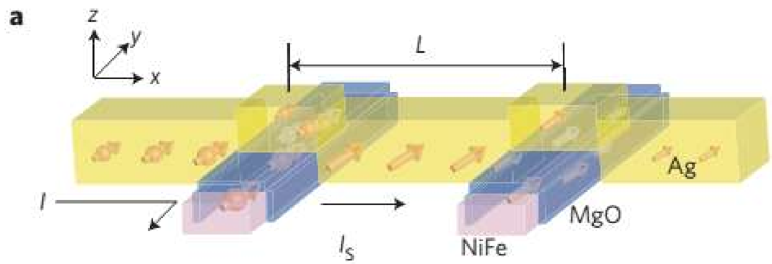
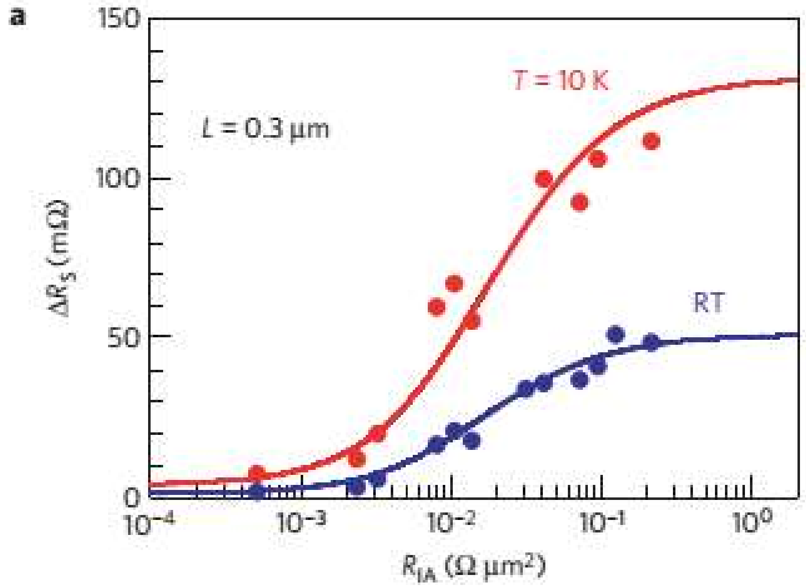
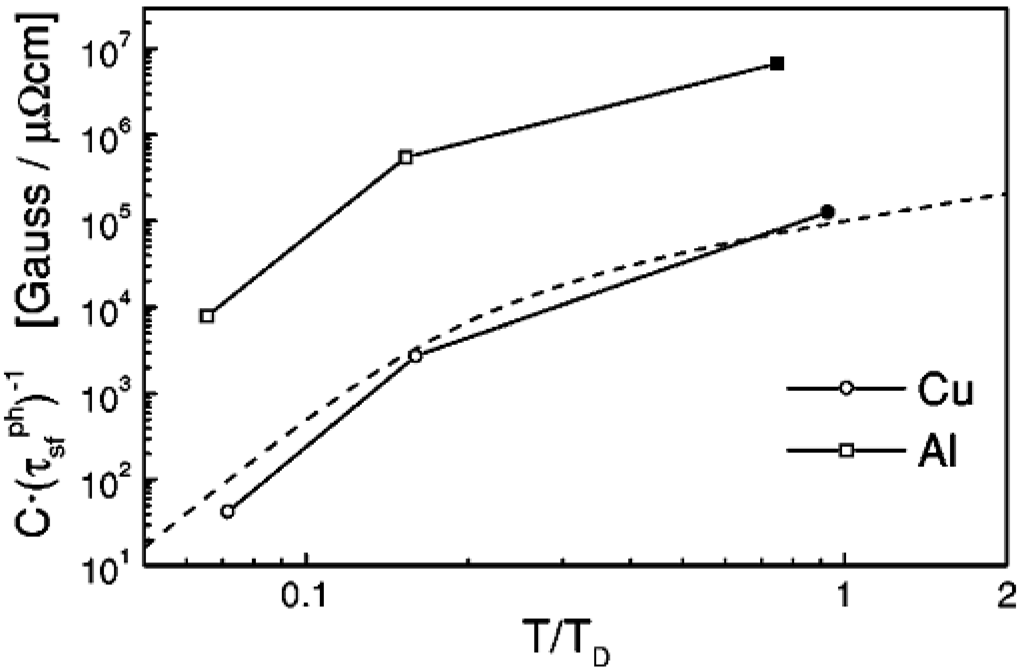


FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size $l_p w$. The dotted curve is the best fitting to the data points using Eq. (2).





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

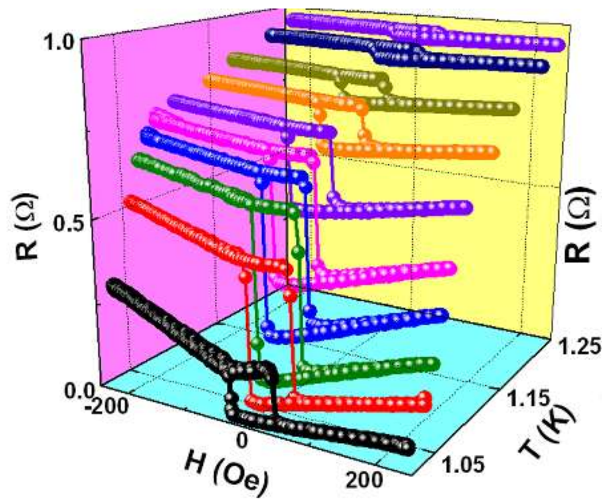
Large MR and control of T_C

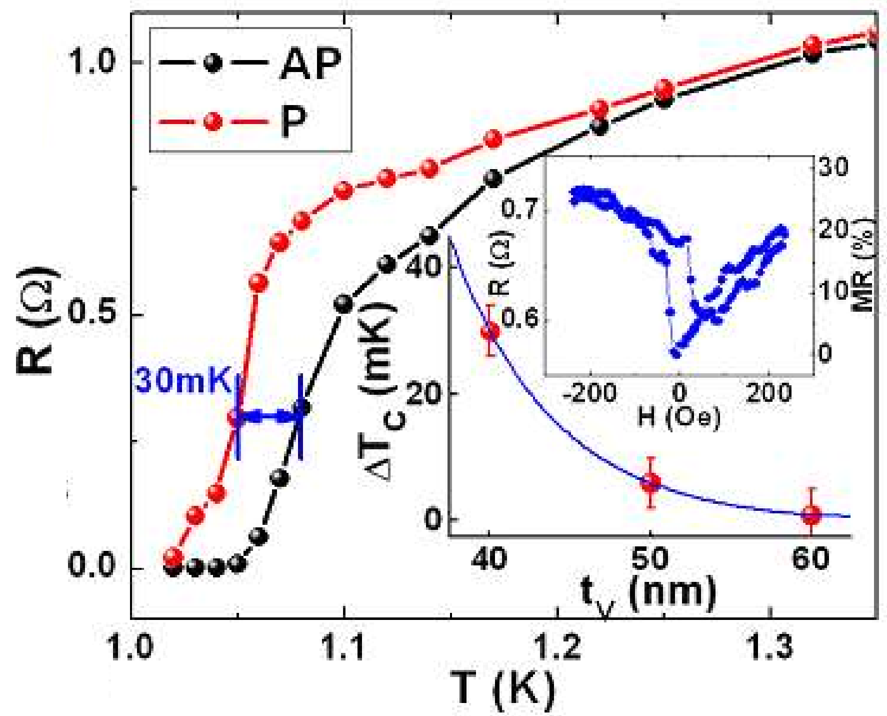
Josephson junction, Spin-triplet

Spin injection, Long spin lifetime

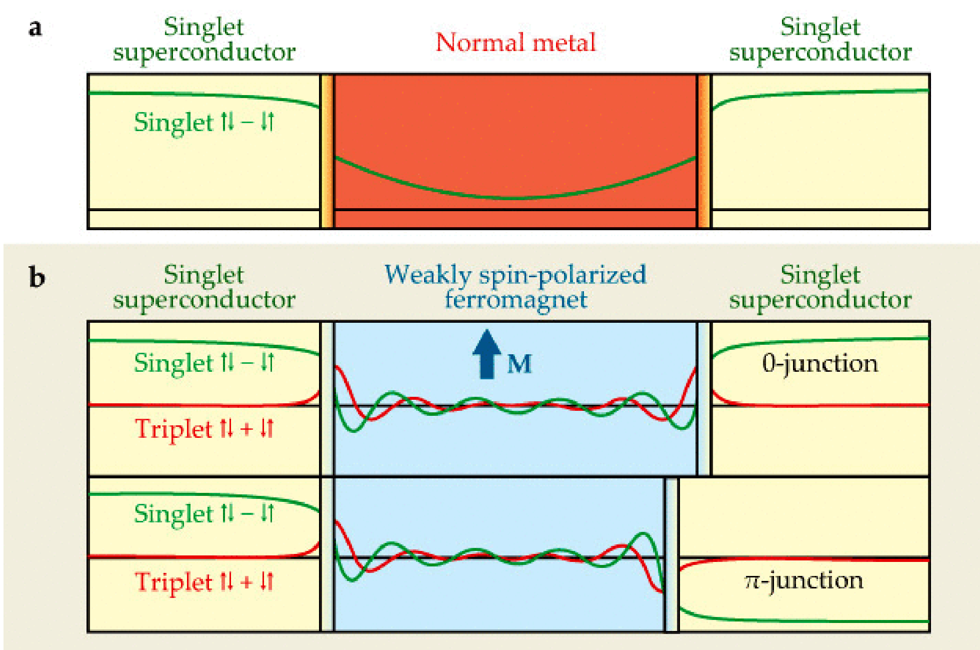
Large spin Hall

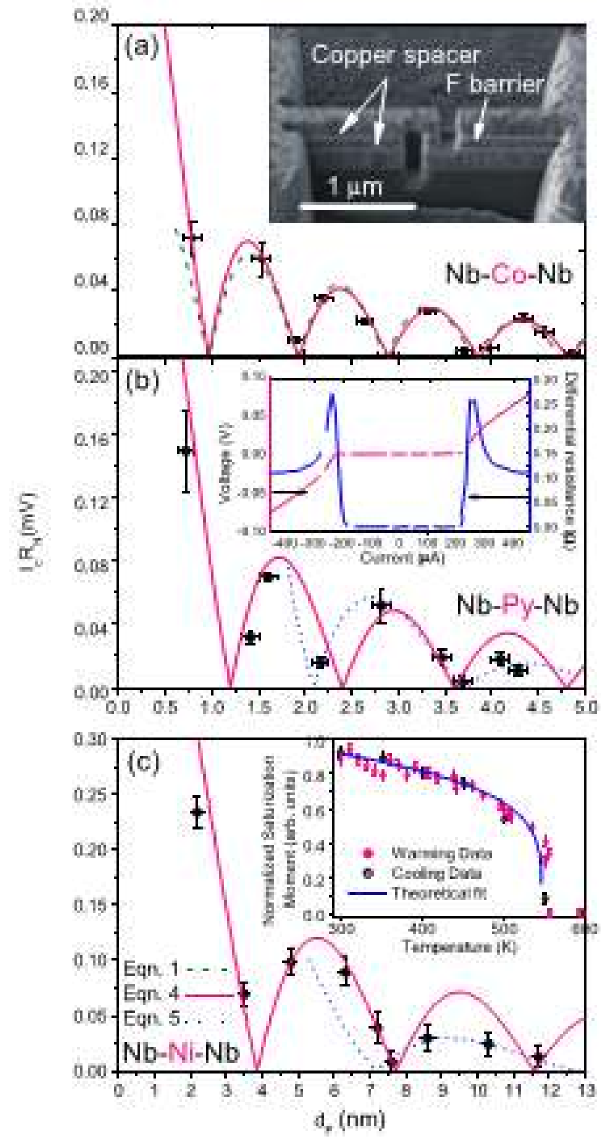
Review of last class





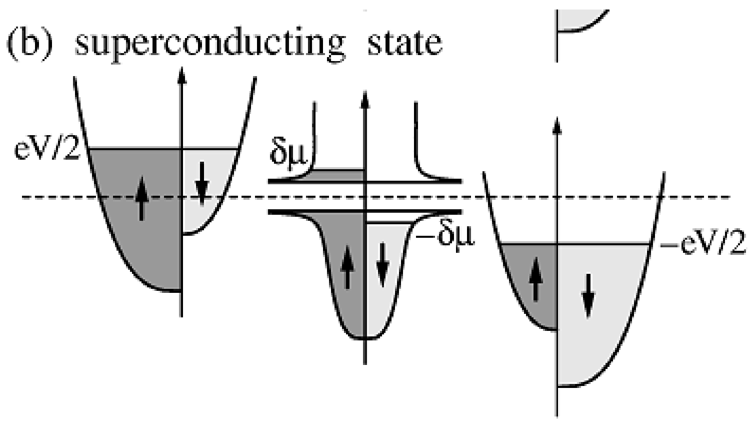
Review of last class



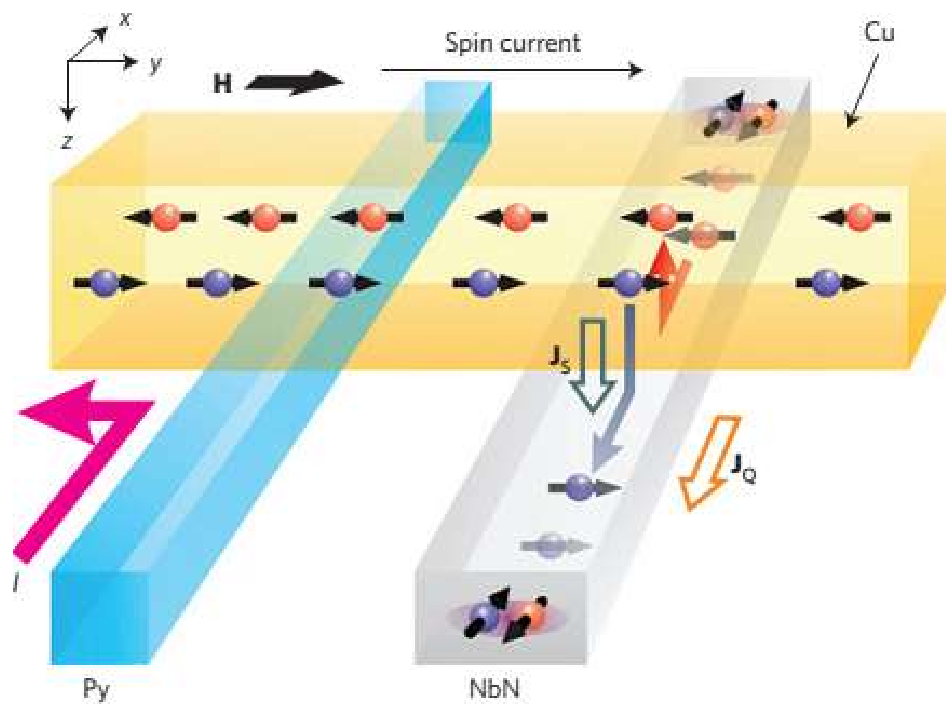


Review of last class

Spin injection



Spin Hall



This Class

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 Spintronics

Semiconductor

Information logic and computing

- Transistor
- CPU

Advantages：

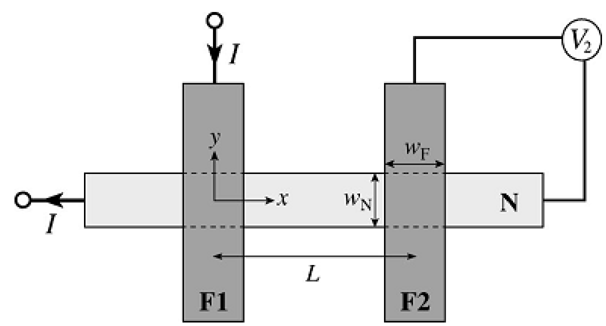
- Tunable carrier densities
- Bipolar (electron/hole)

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) interficial resistances between FM (injector, detector) and nonmetal material.

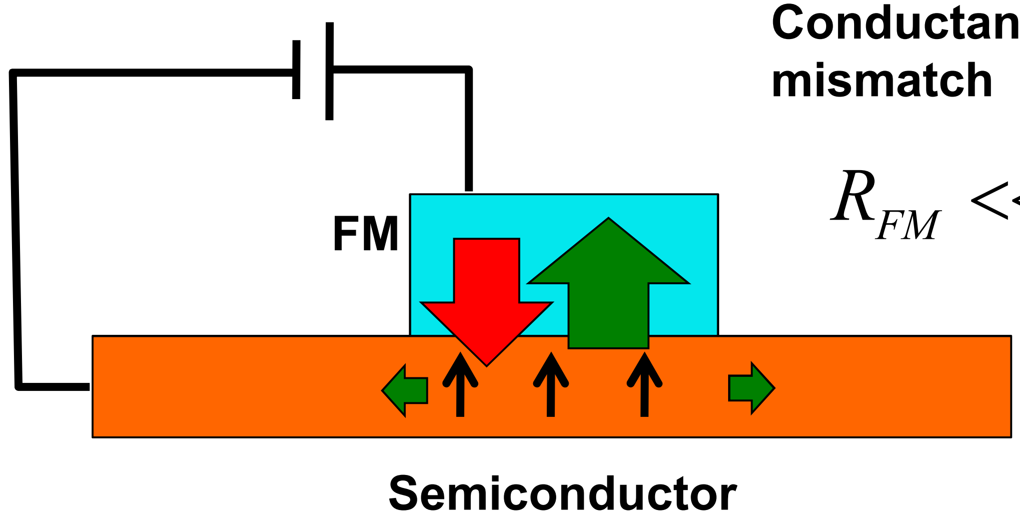
Conductance mismatch problem

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

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

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

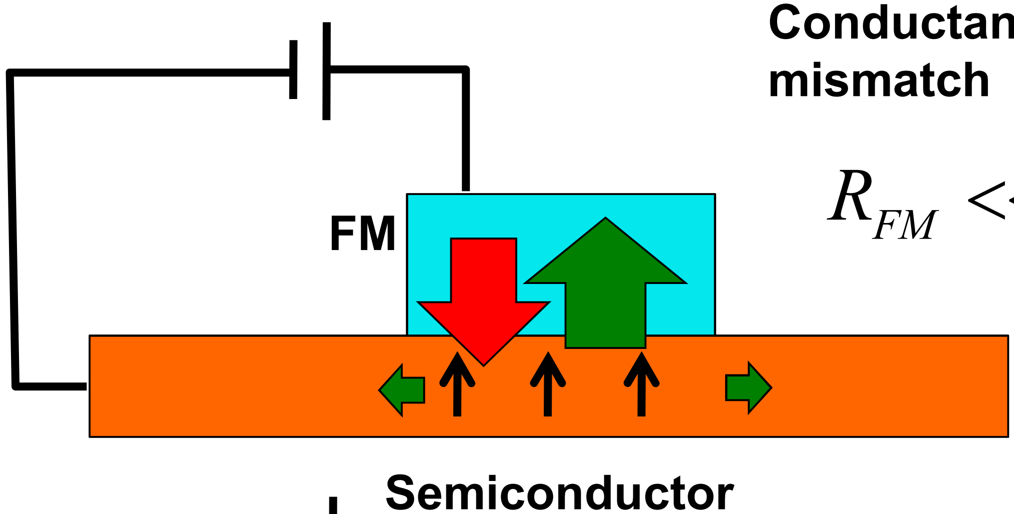
Conductance mismatch problem



Conductance mismatch

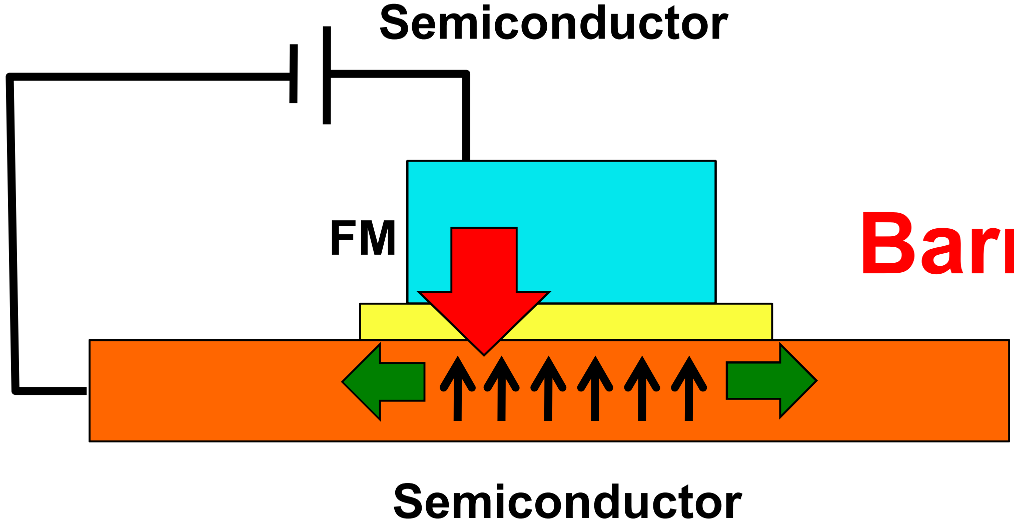
$$R_{FM} << R_{semiconductor}$$

Conductance mismatch problem



Conductance mismatch

$$R_{FM} \ll R_{semiconductor}$$

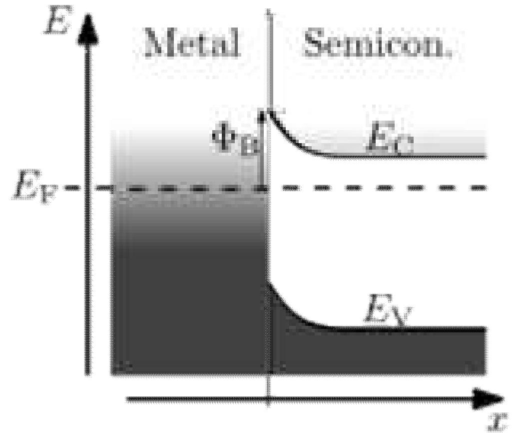


Barrier

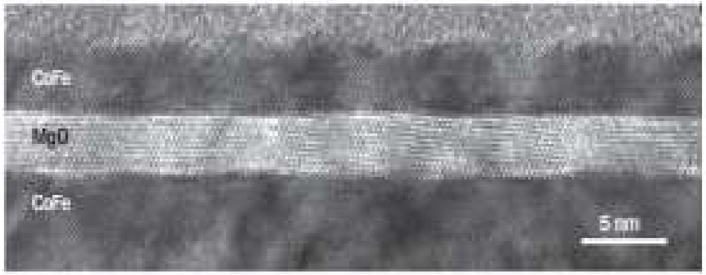
E.I. Rashba, Phys. Rev. B (2000)
A. Fert, H. Jaffres, Phys. Rev. B (2001)

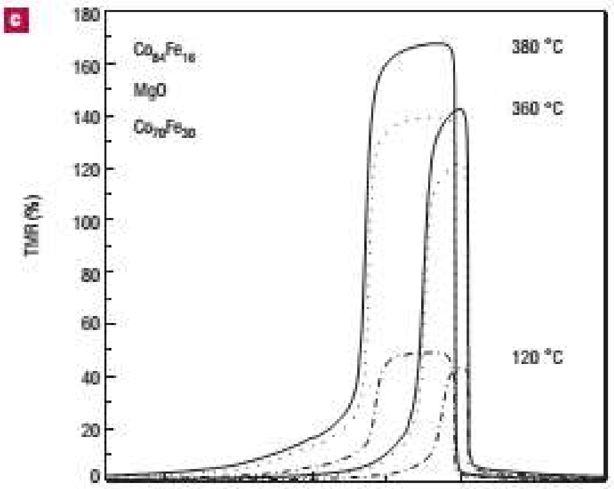
Two types of tunnel barrier

1) Schottky barrier

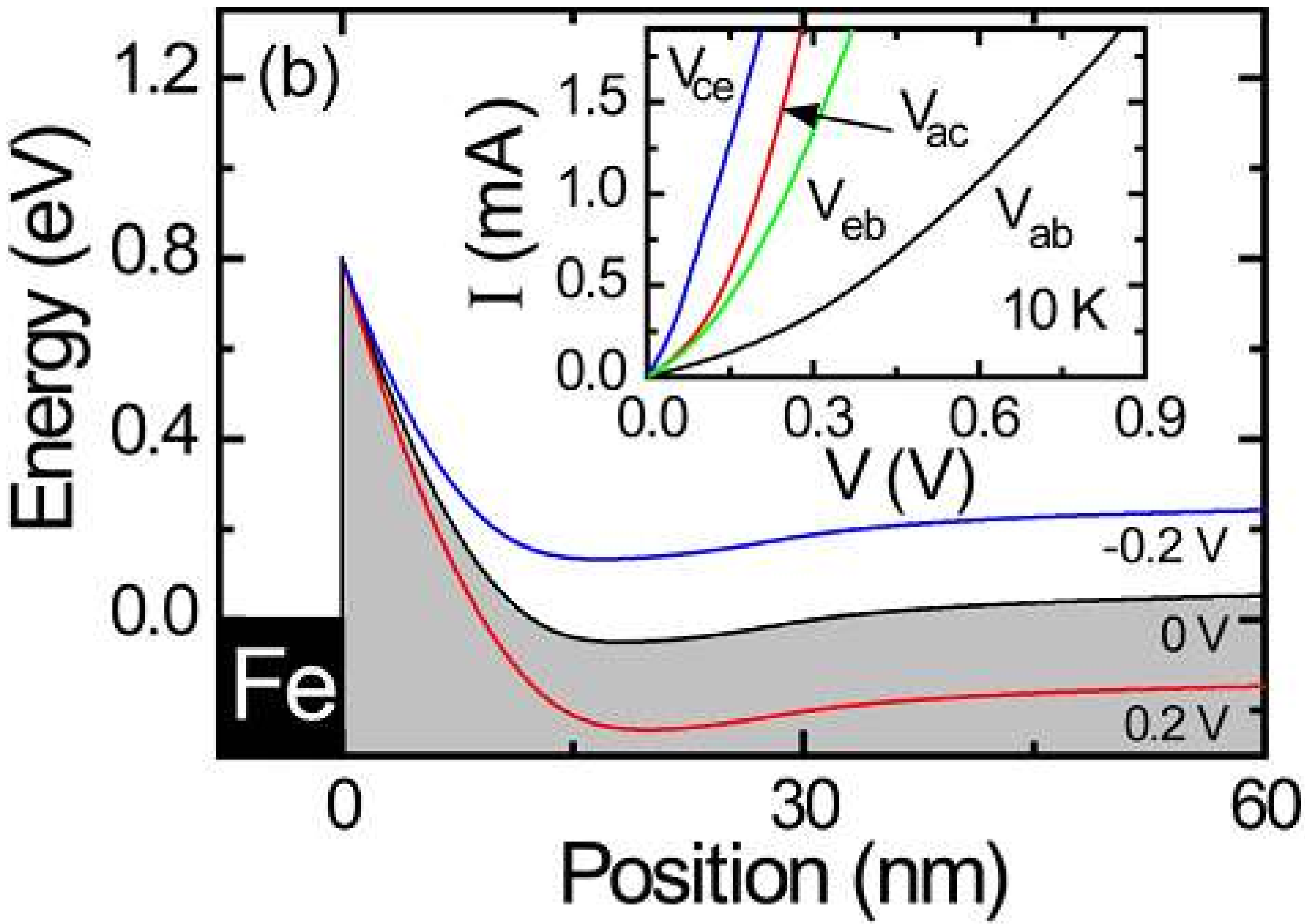


2) Insulating barrier, Al_2O_3, MgO



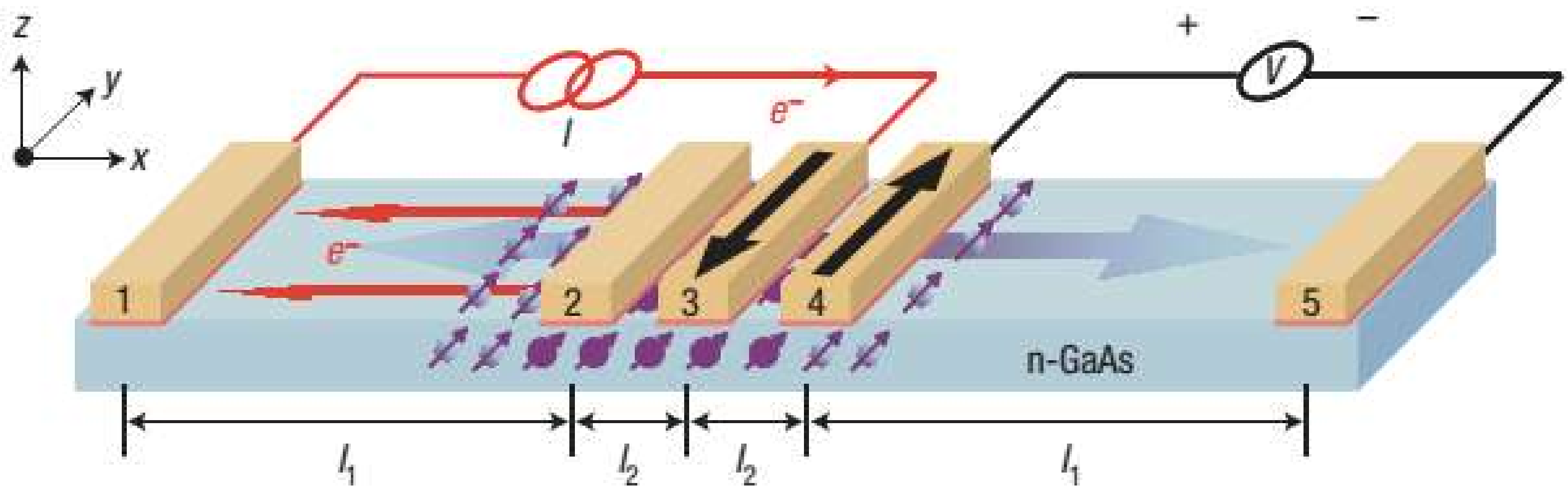


Spin in GaAs



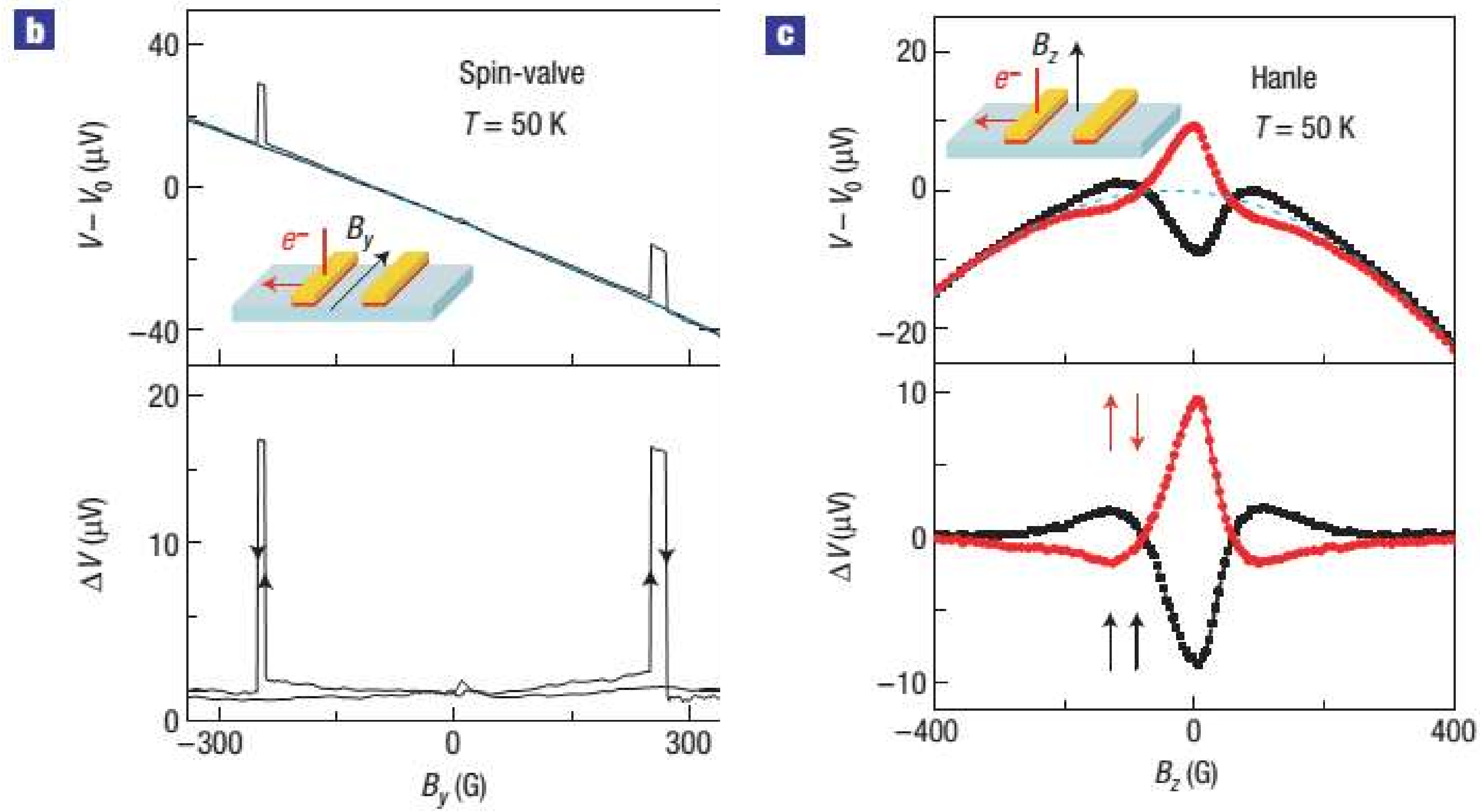
Lou, et al, PRL (2006)

Spin in GaAs



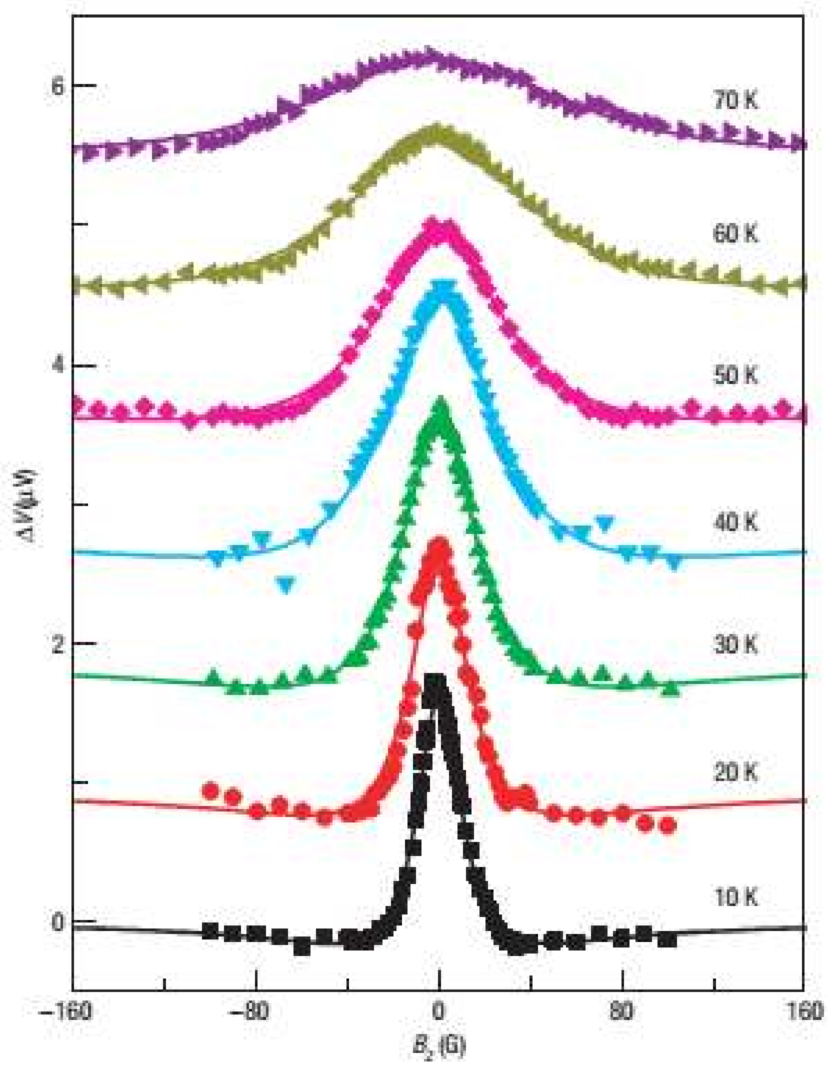
Lou, et al, Nature Physics (2007)

Spin in GaAs



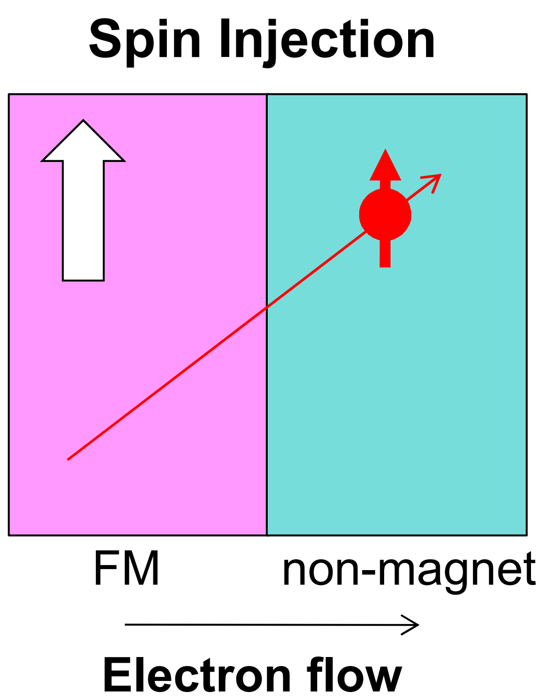
b
Spin-valve
T = 50 K
e^-
B_y
$V - V_0$ (μV)
ΔV (μV)
B_y (G)
c
Hanle
T = 50 K
e^-
B_z
$V - V_0$ (μV)
ΔV (μV)
B_z (G)

Spin in GaAs

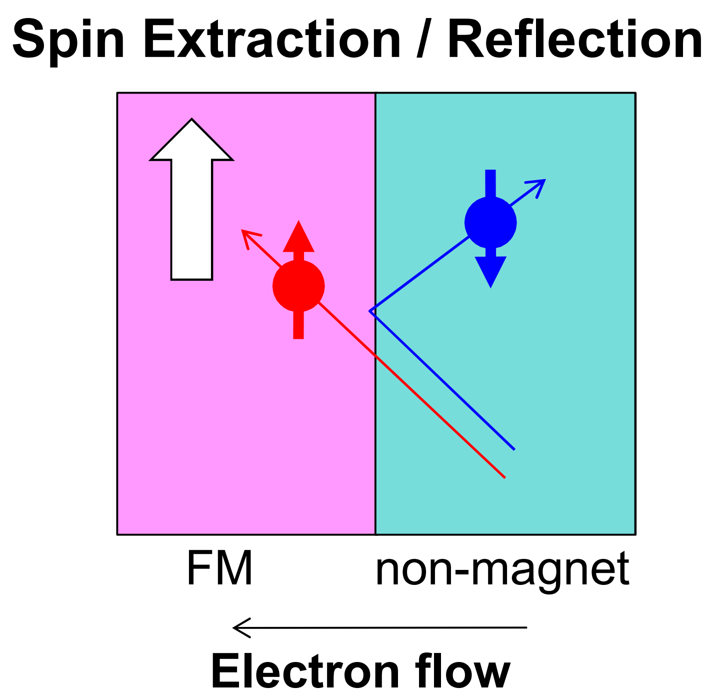


$$S_y(x_1, x_2, B) = S_0 \int_0^{\infty} \frac{1}{\sqrt{4\pi D t}} e^{-(x_2 - x_1 - v_d t)^2/4Dt} \times \cos(g\mu_B B t/\hbar) e^{-t/\tau_s} dt,$$

Spin in GaAs

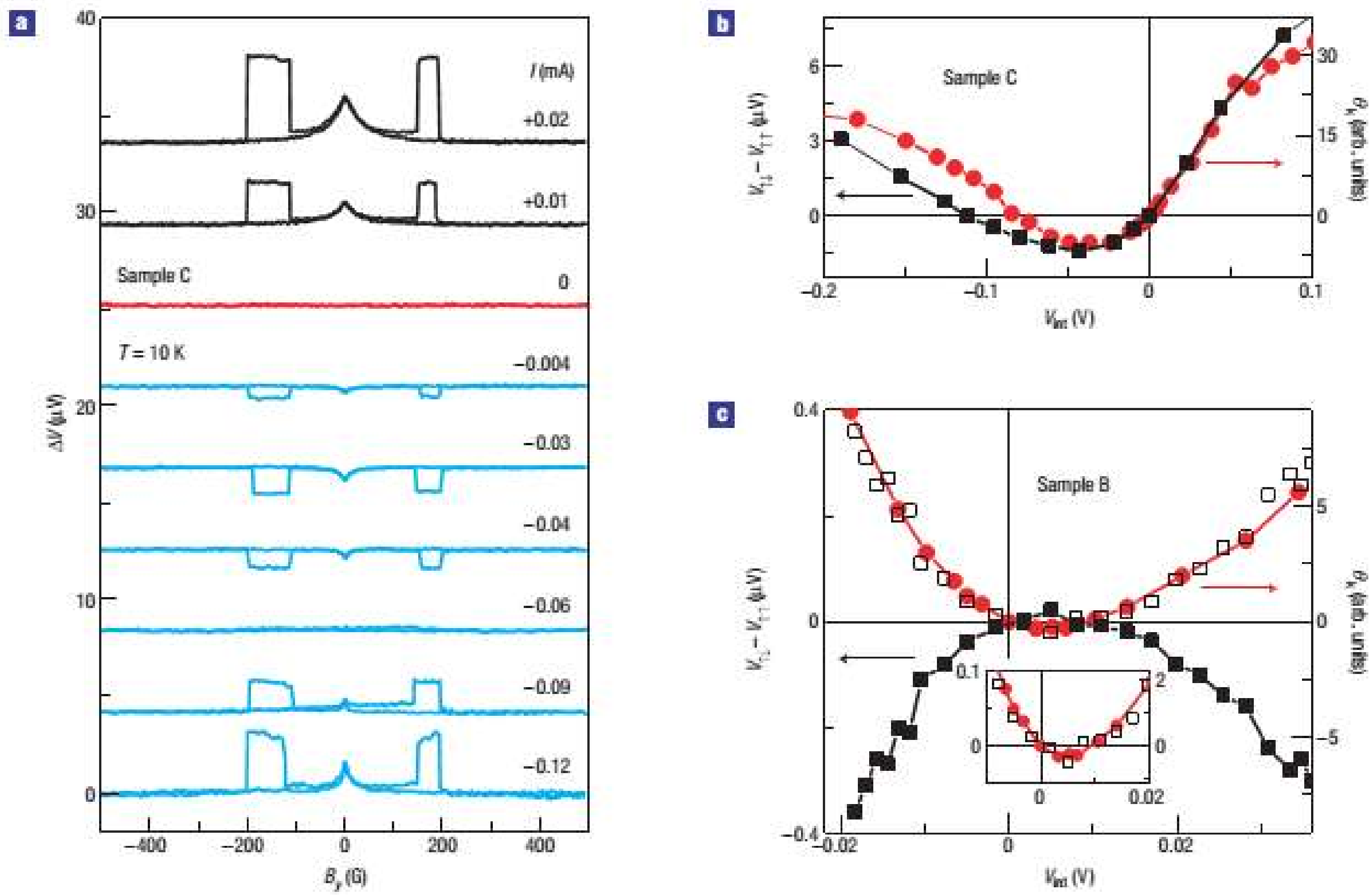


Spin Injection
FM
non-magnet
Electron flow



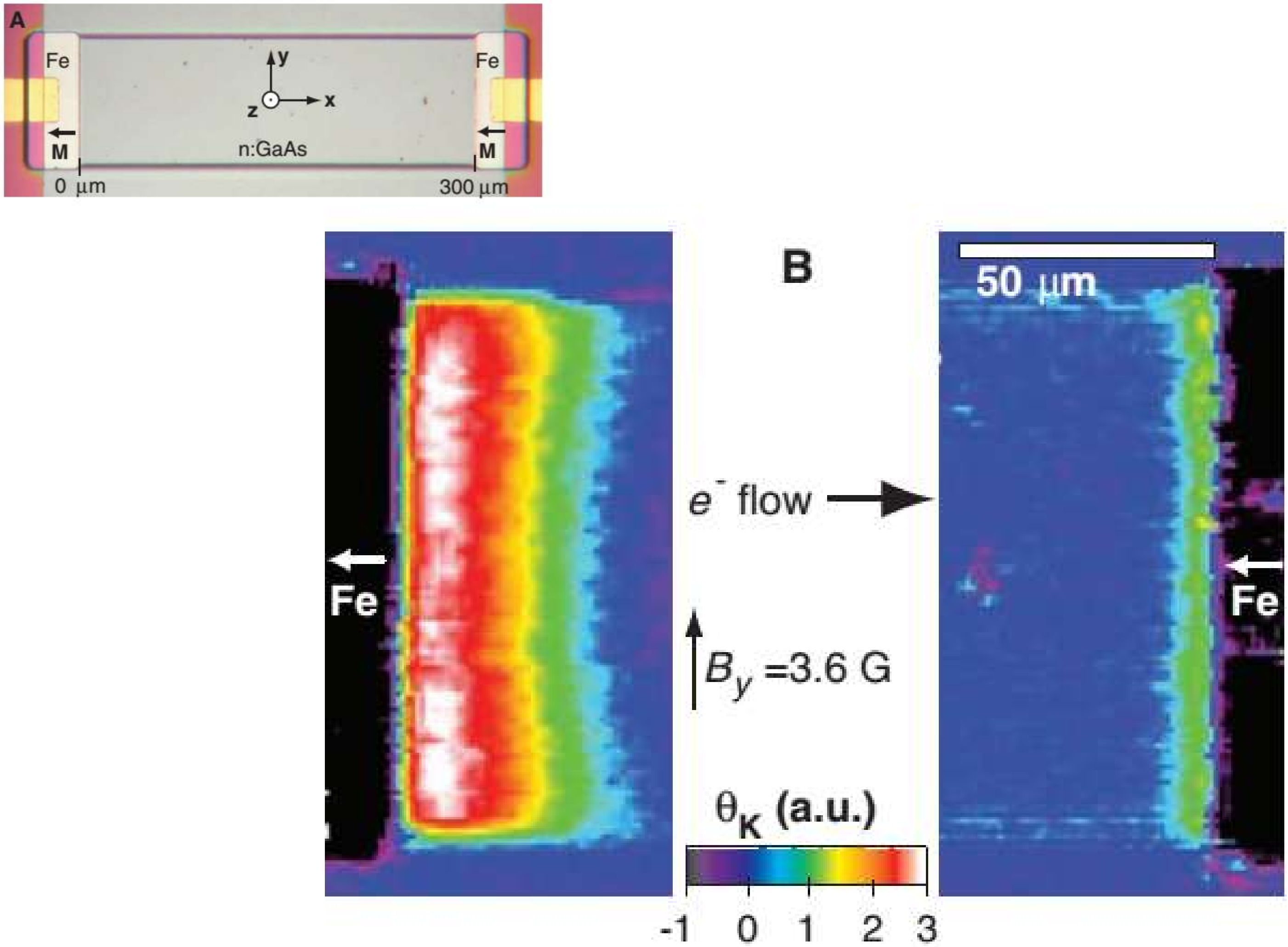
Spin Extraction / Reflection
FM
non-magnet
Electron flow

Spin in GaAs



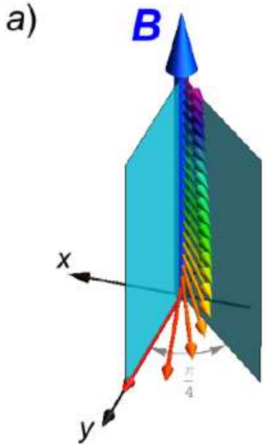
a
I (mA)
+0.02
+0.01
Sample C
0
T = 10 K
−0.004
−0.03
−0.04
−0.06
−0.09
−0.12
ΔV (μV)
B_y (G)
b
Sample C
$V_{\uparrow\downarrow} - V_{\uparrow\uparrow}$ (μV)
θ_s (arb. units)
V_{int} (V)
c
Sample B
$V_{\uparrow\downarrow} - V_{\uparrow\uparrow}$ (μV)
θ_s (arb. units)
V_{int} (V)

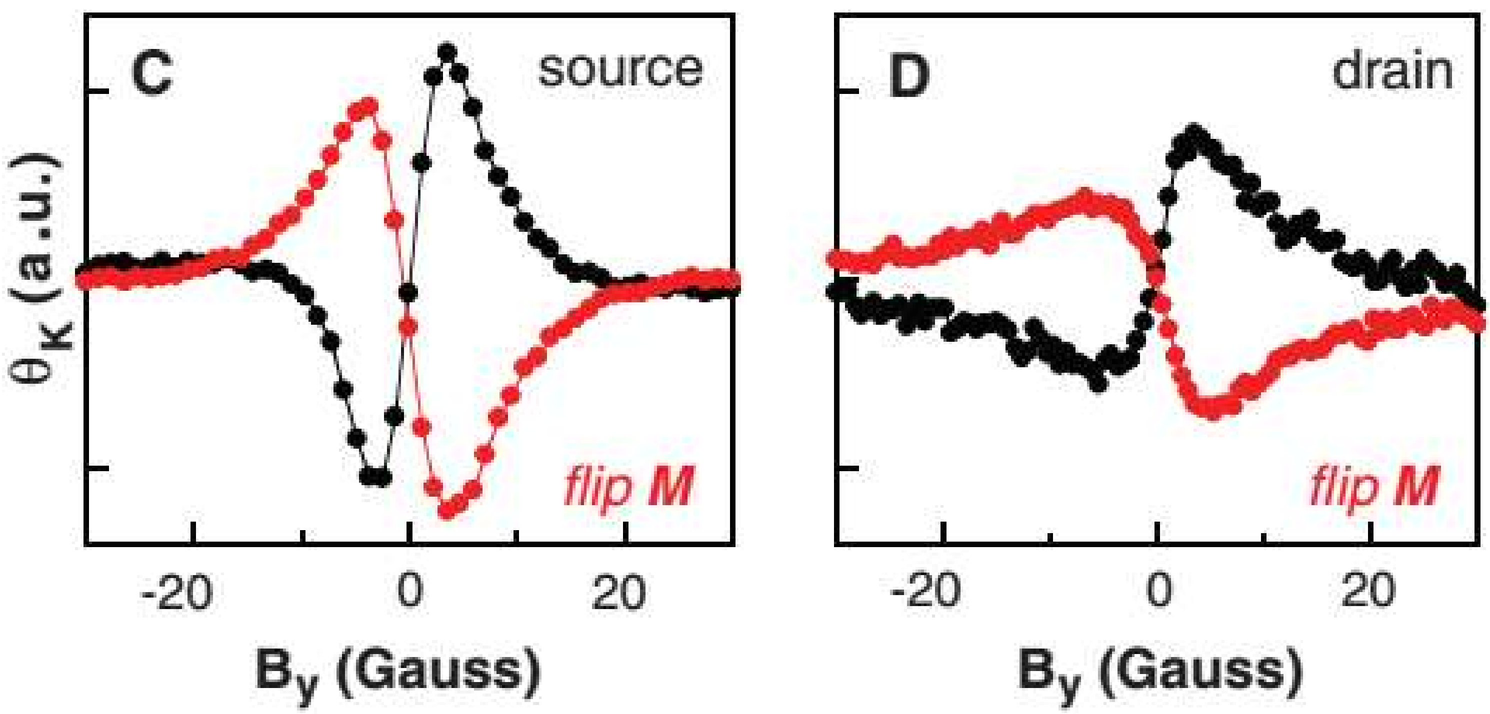
Spin in GaAs



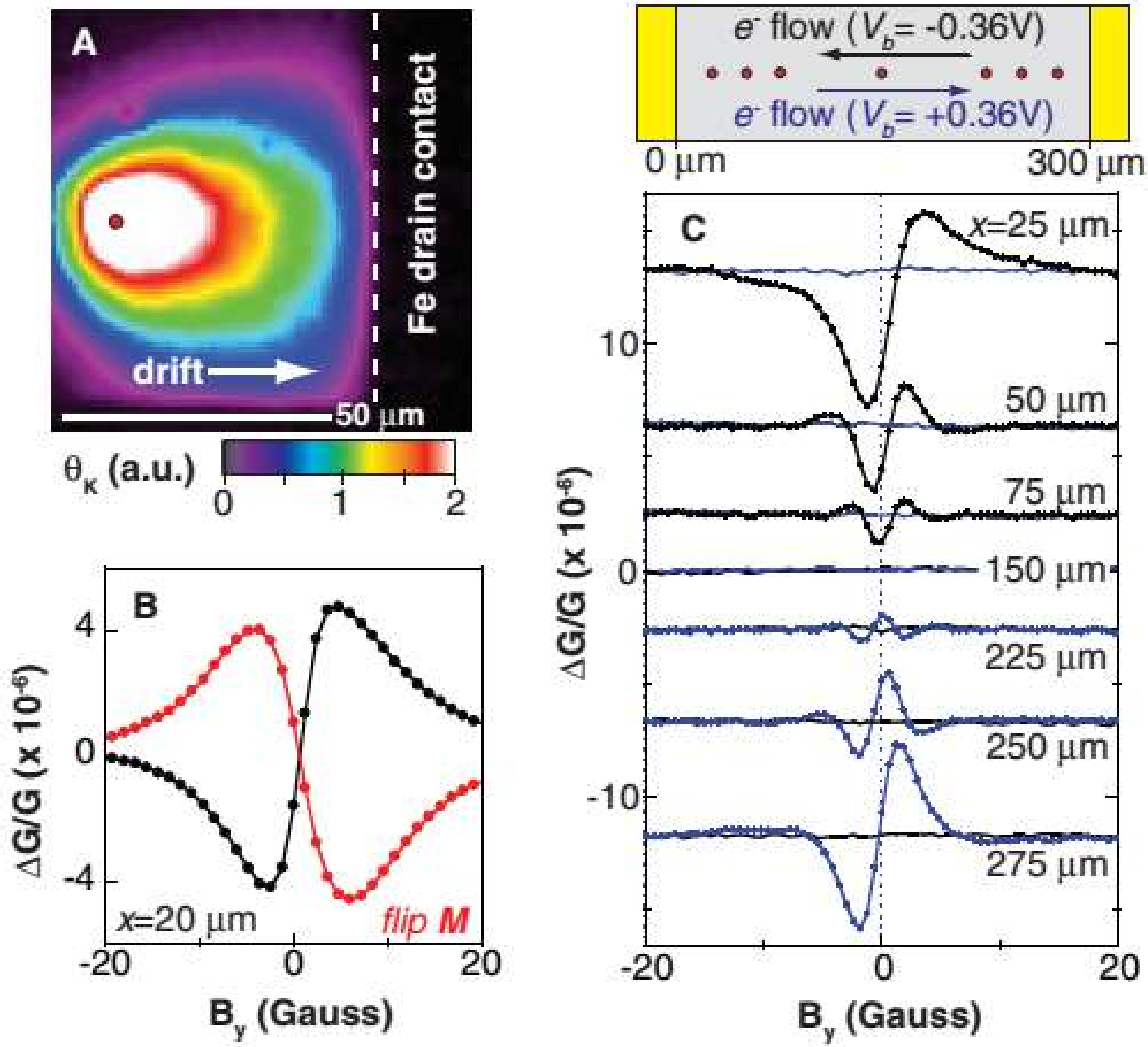
Crooker, et al, Science (2005)

Spin in GaAs

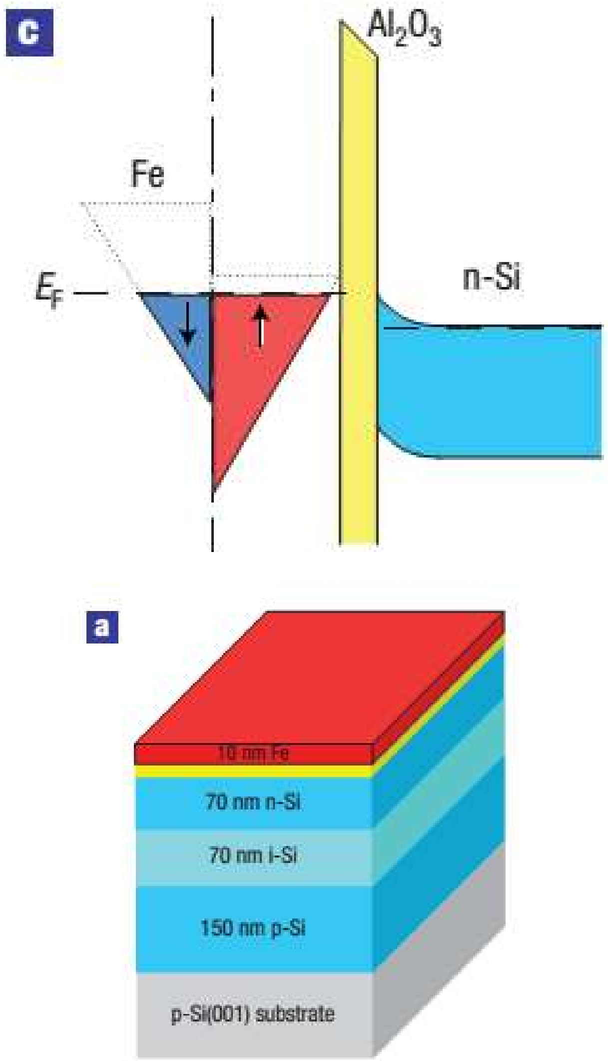

a)
B
x
y

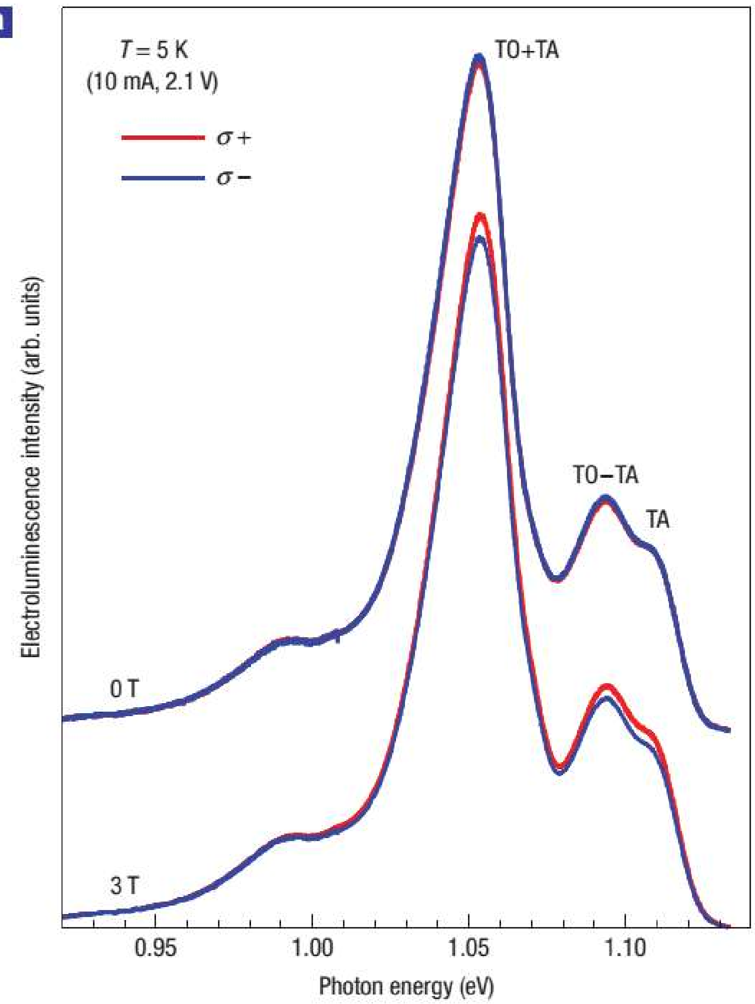

C
source
flip M
D
drain
flip M
θK (a.u.)
-20
0
20
By (Gauss)
-20
0
20
By (Gauss)

Spin in GaAs


A
Fe drain contact
drift
50 μm
θK (a.u.)
0
1
2
B
ΔG/G (x 10^-6)
4
0
-4
x=20 μm
flip M
-20
0
20
By (Gauss)
e- flow (Vb= -0.36V)
e- flow (Vb= +0.36V)
0 μm
300 μm
C
x=25 μm
50 μm
75 μm
150 μm
225 μm
250 μm
275 μm
10
0
-10
-20
0
20
ΔG/G (x 10^-6)
By (Gauss)

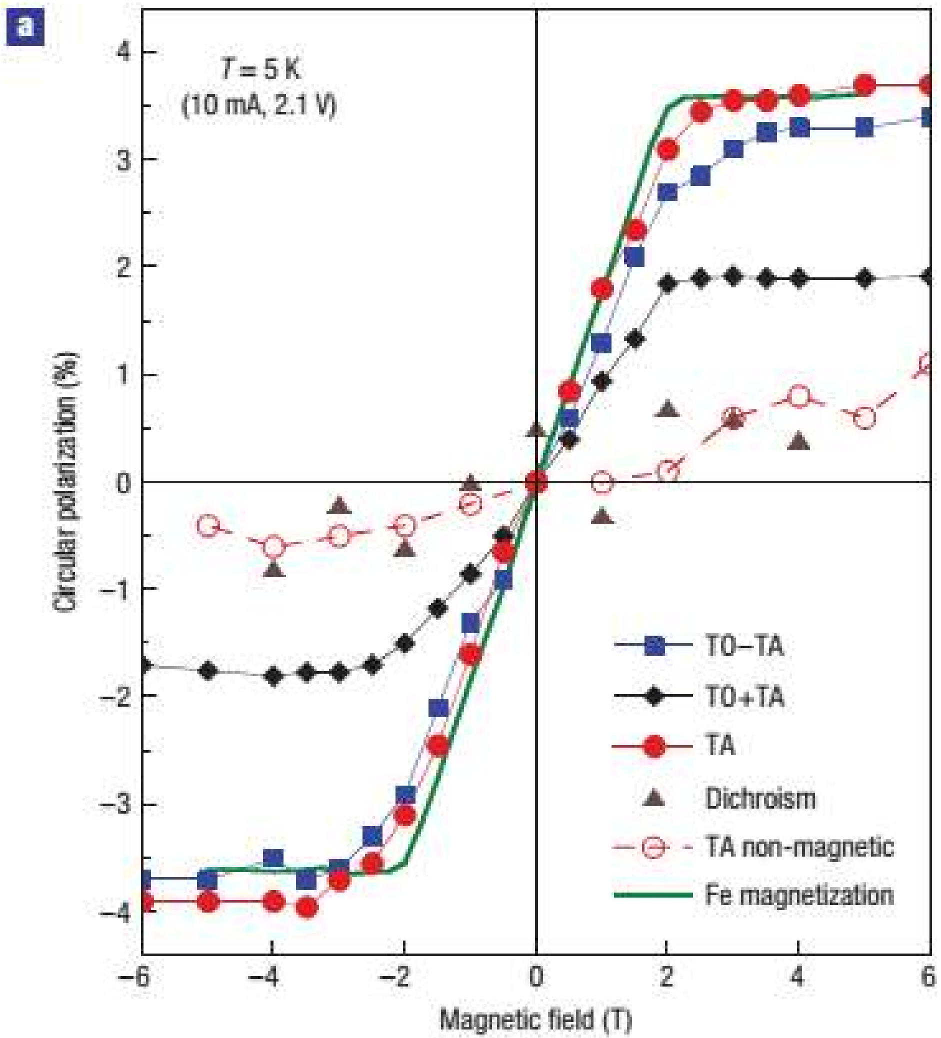
Spin in Silicon





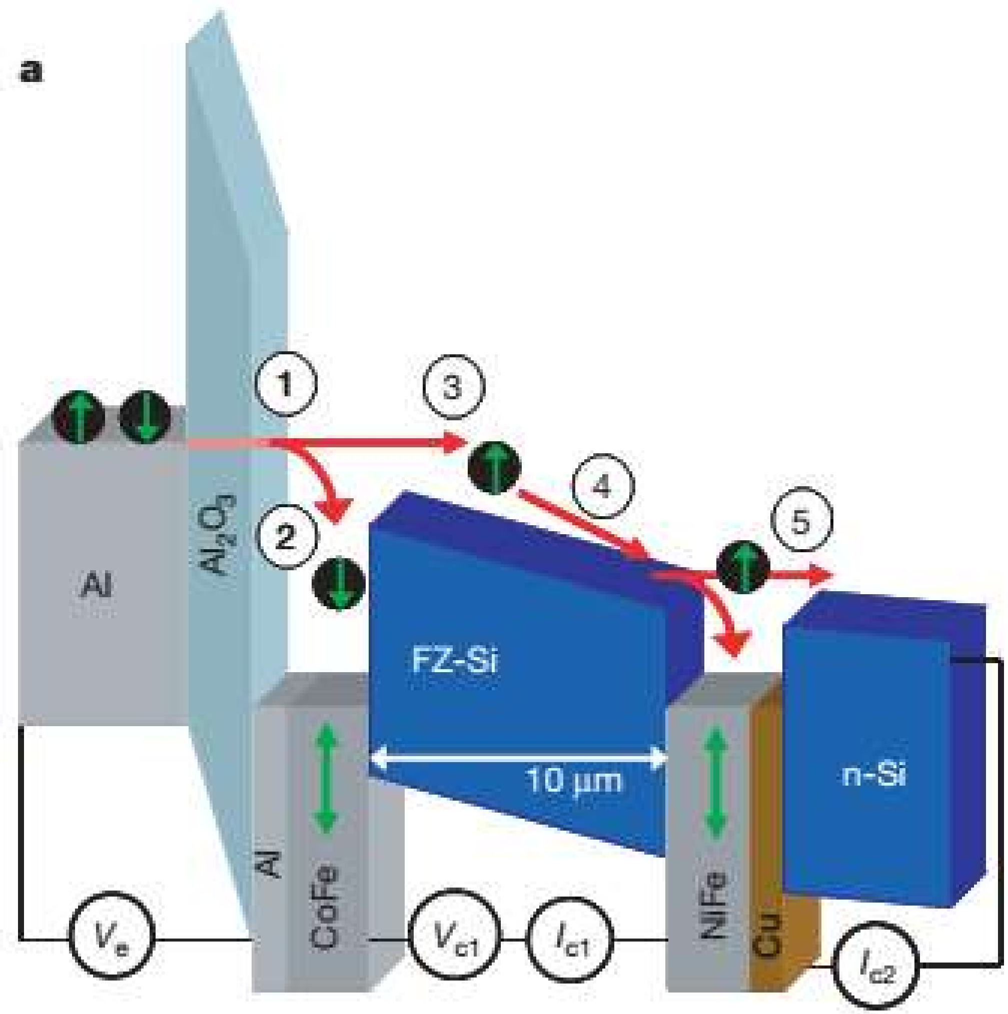
Jonker, et al, Nature Physics (2007)

Spin in Silicon



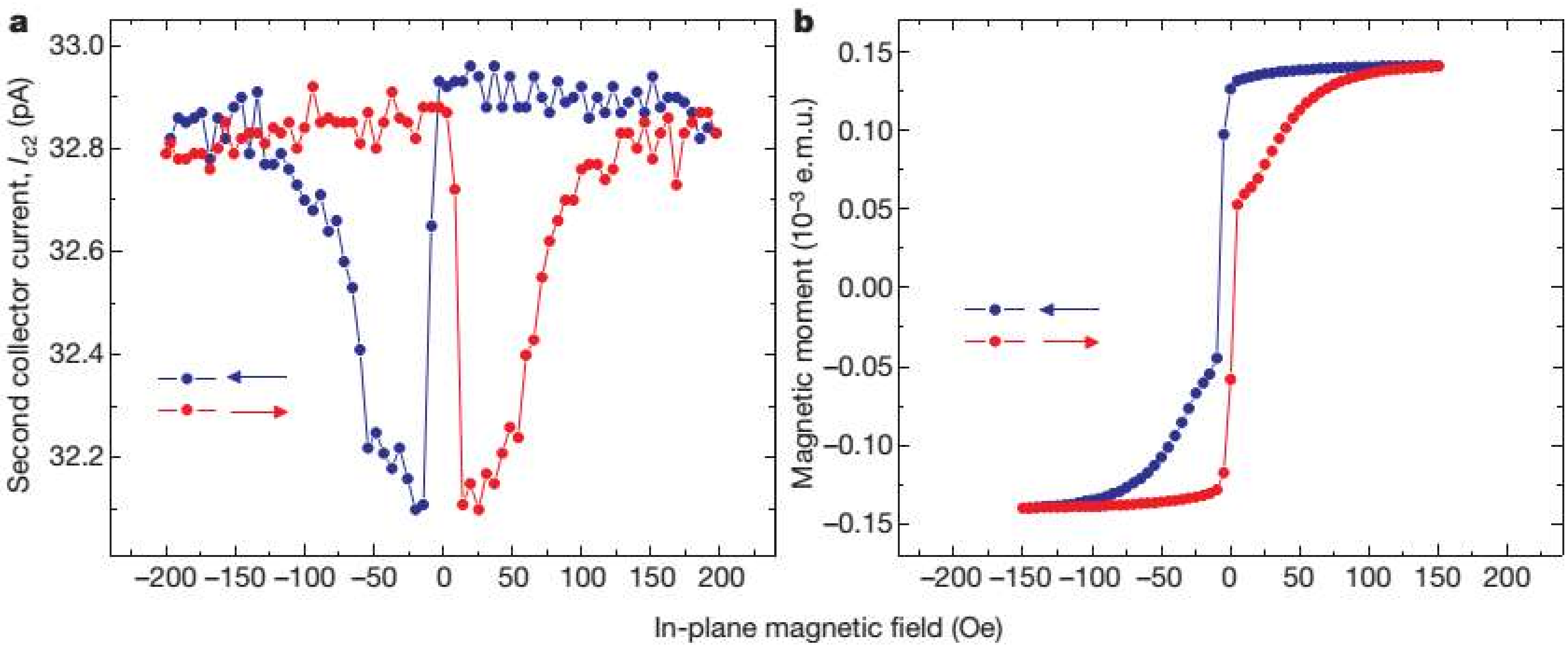
Jonker, et al, Nature Physics (2007)

Spin in Silicon

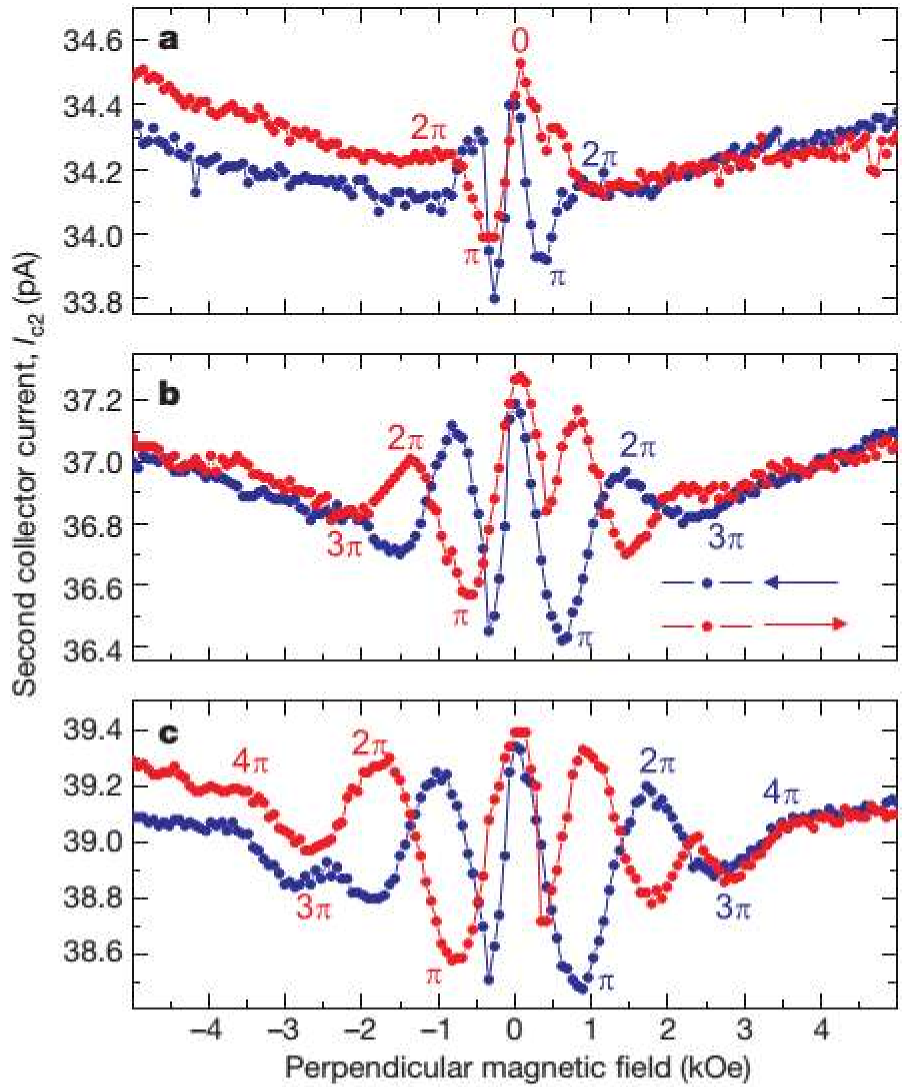


Appelbaum, et al, Nature (2007)

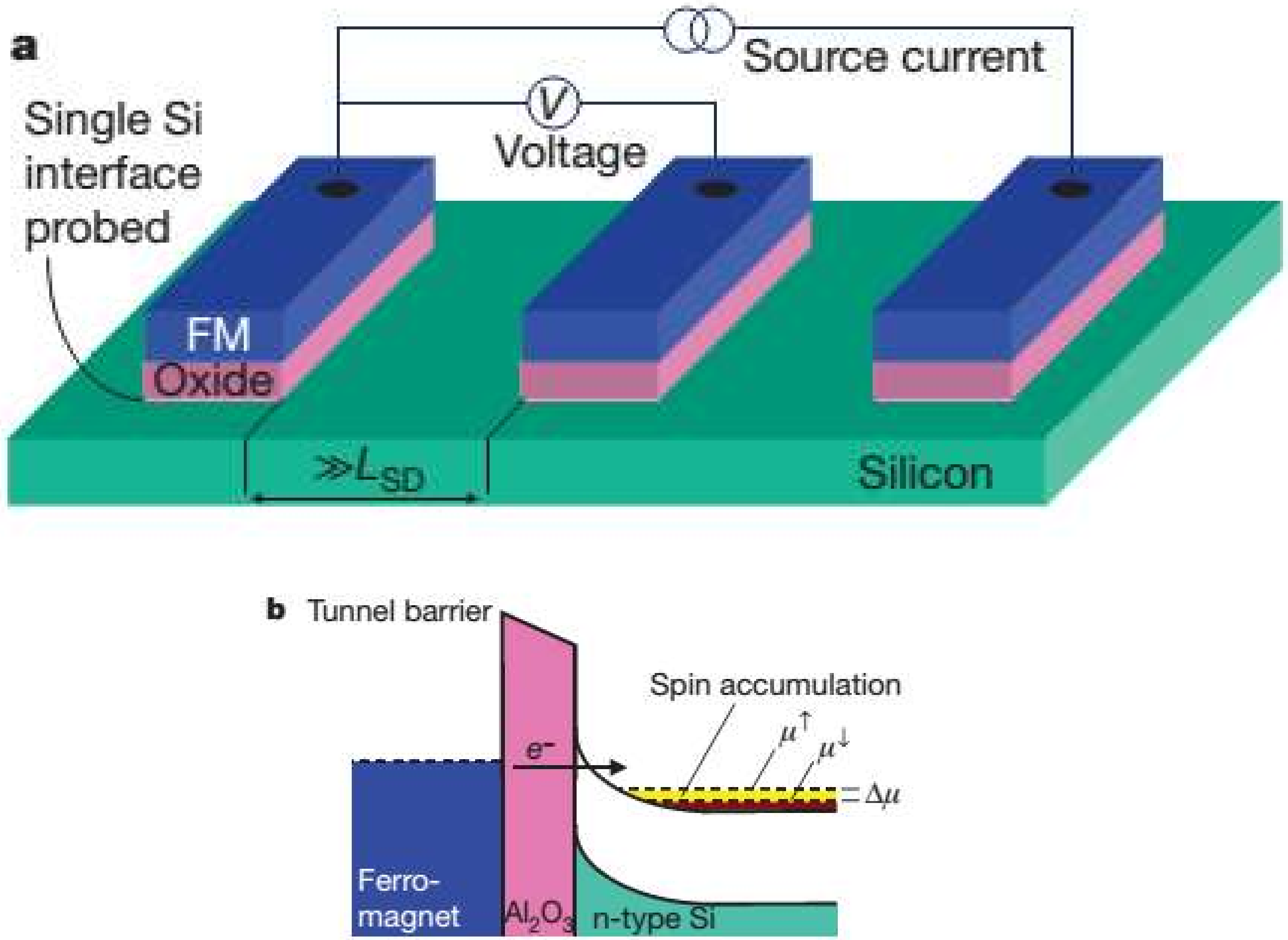
Spin in Silicon



Spin in Silicon

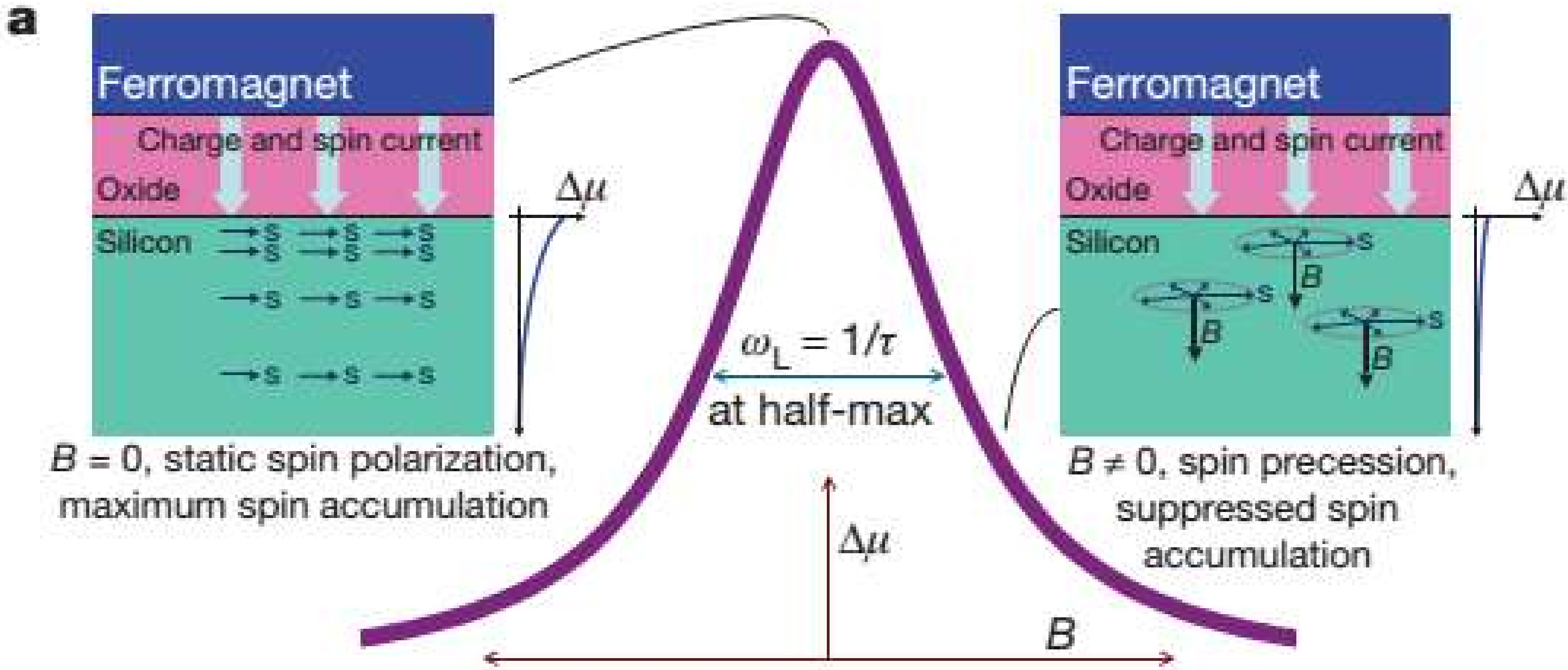


Spin in Silicon

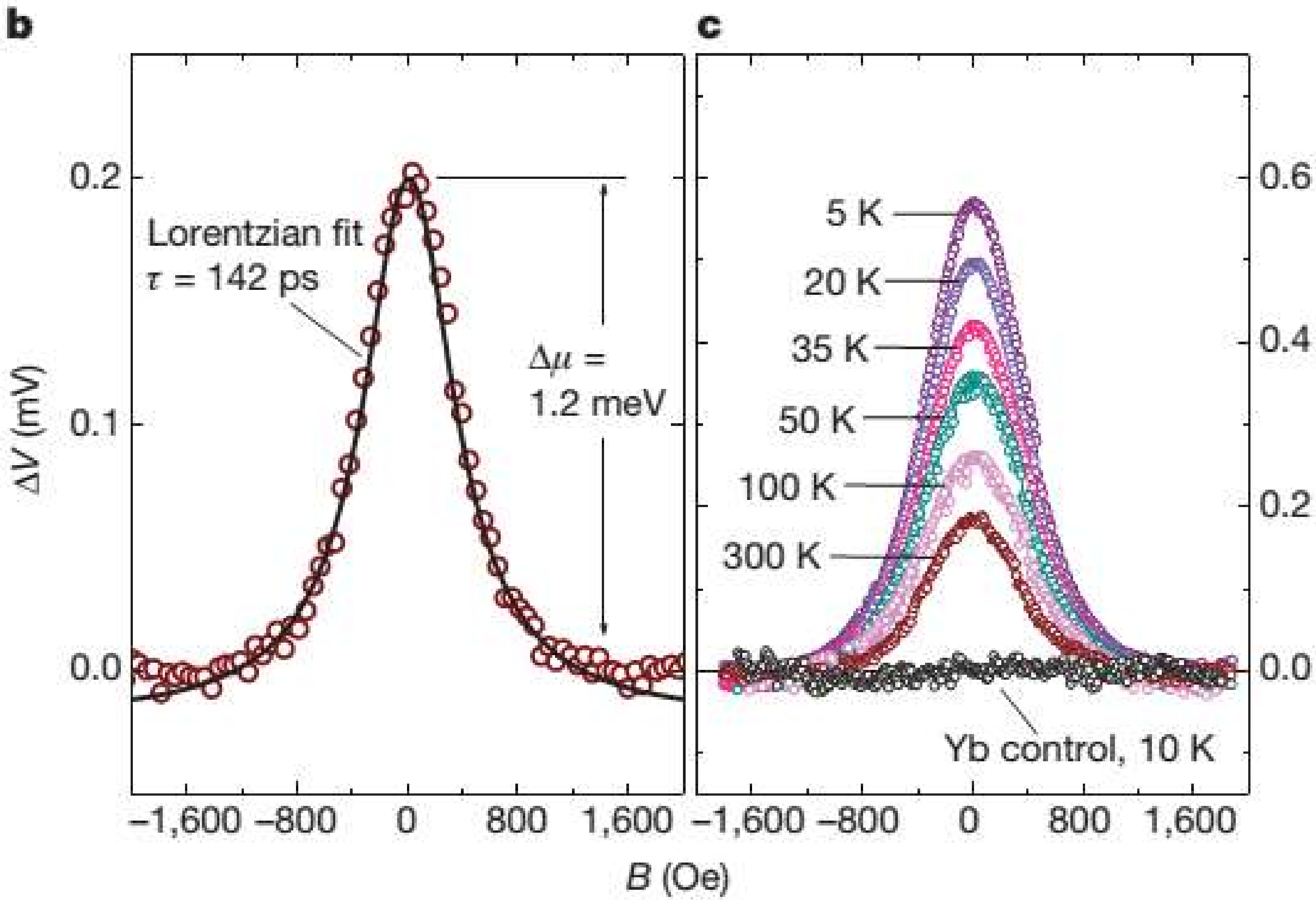


Dash, et al, Nature (2009)

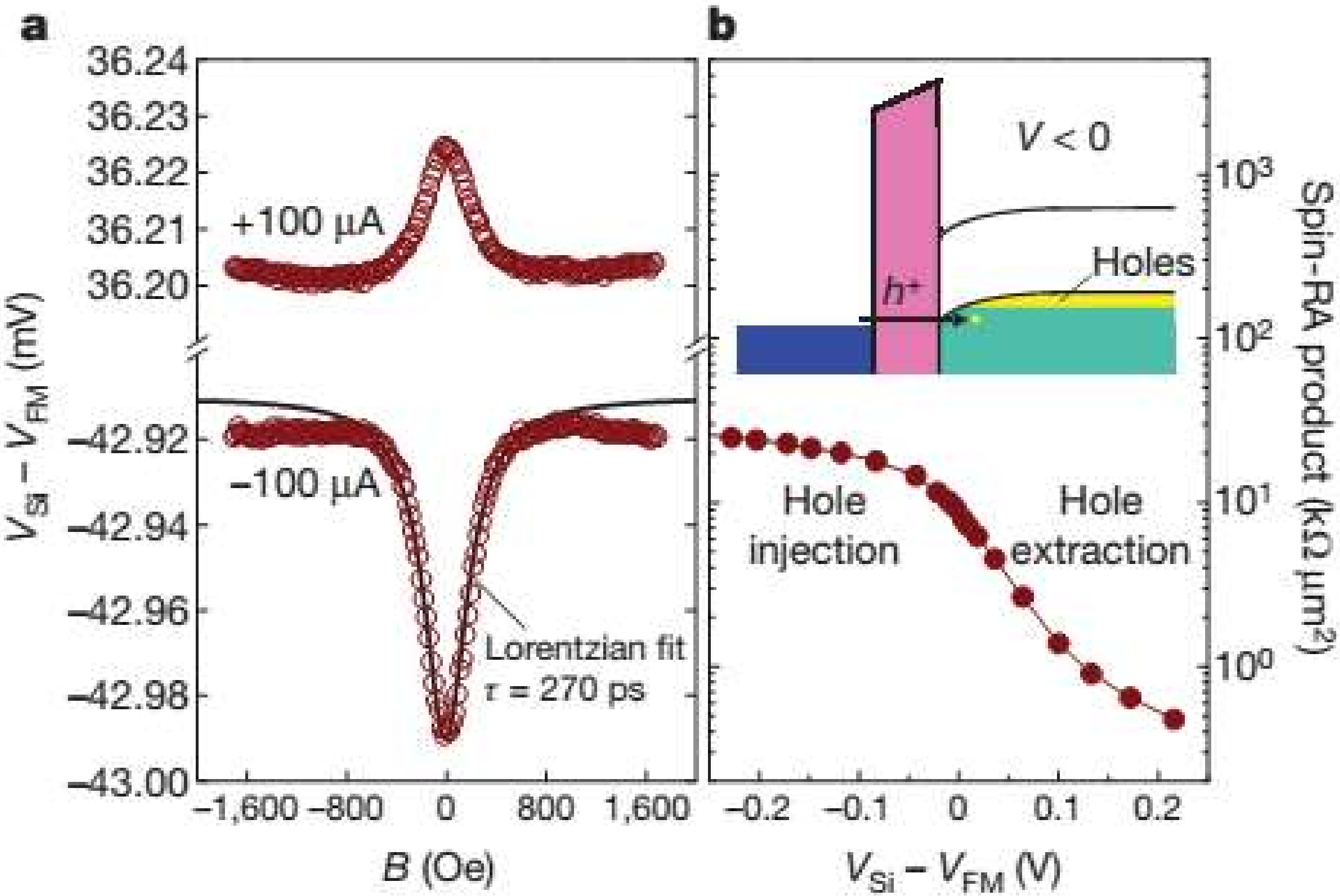
Spin in Silicon



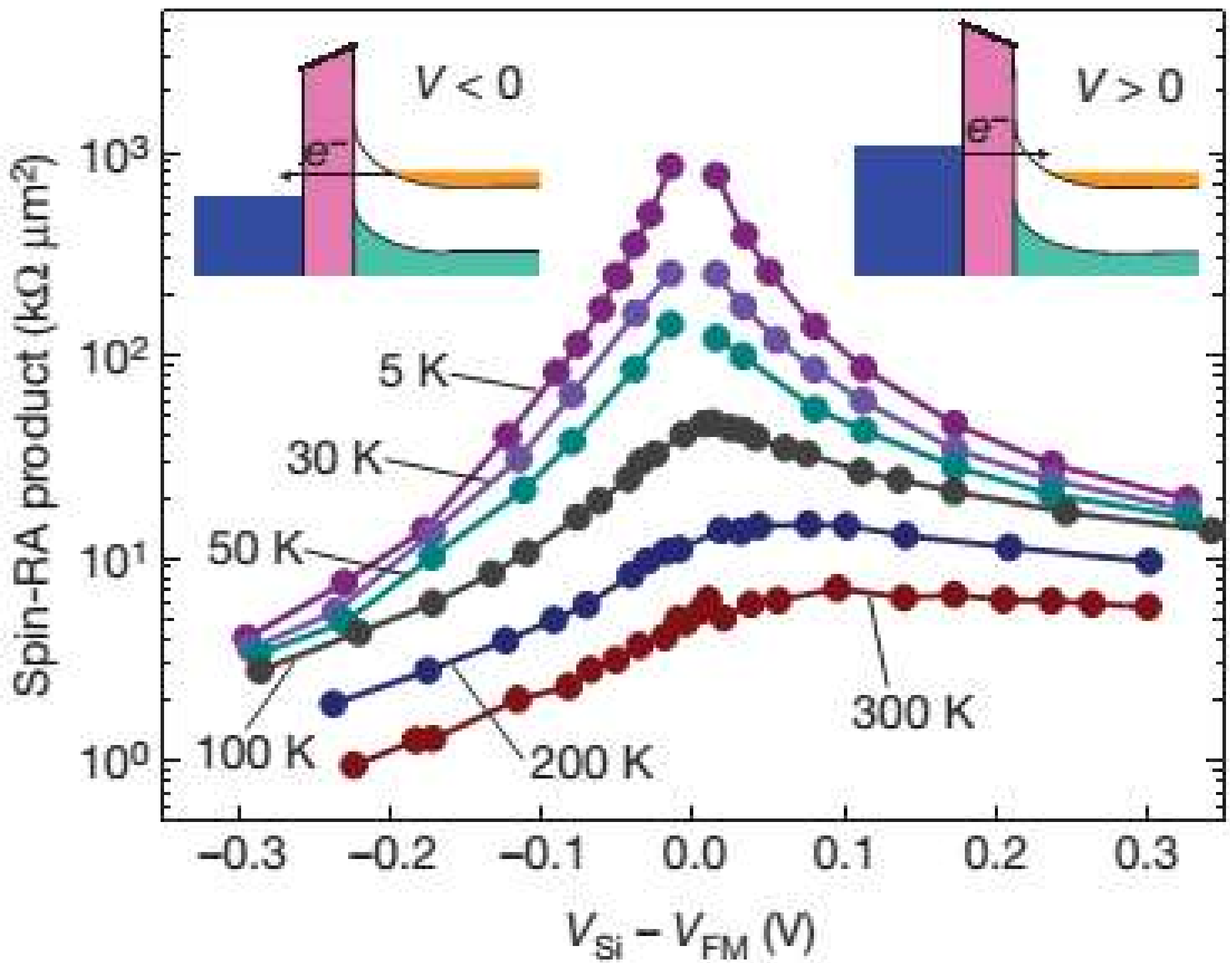
Spin in Silicon



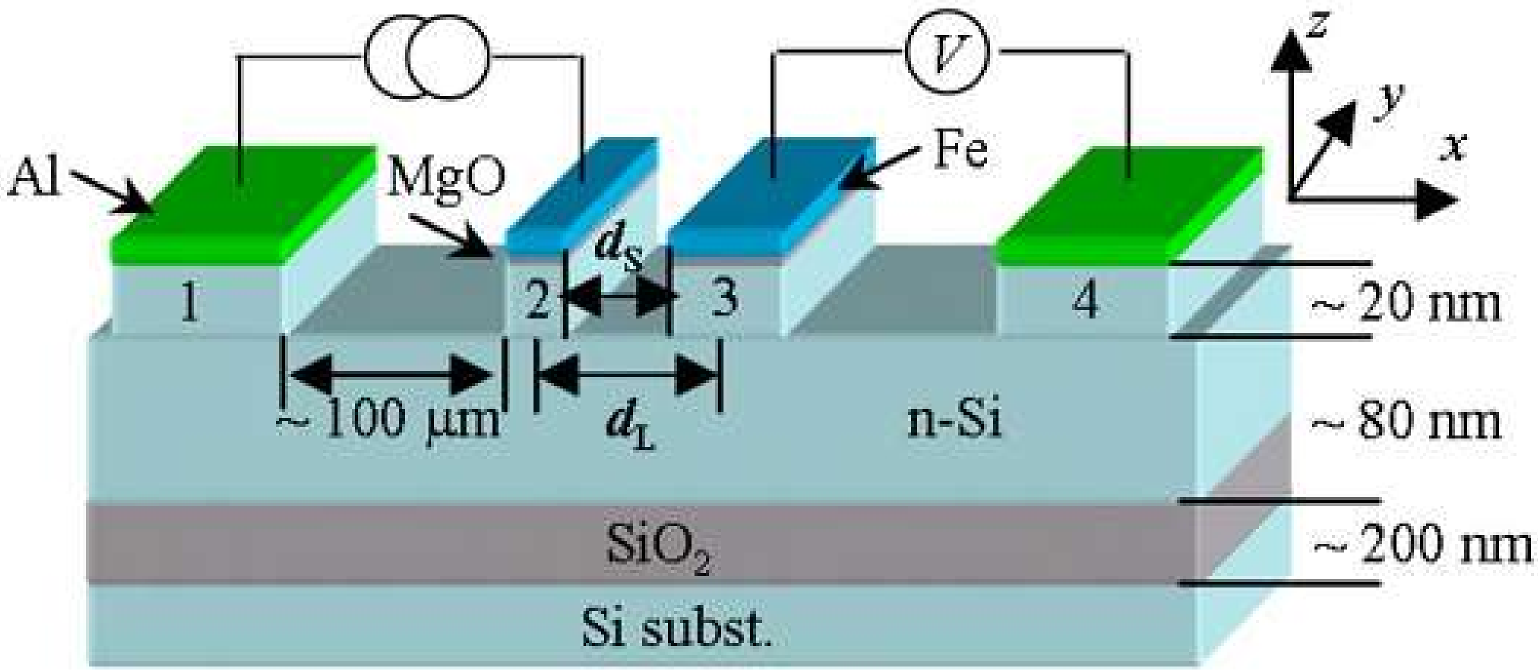
Spin in Silicon



Spin in Silicon

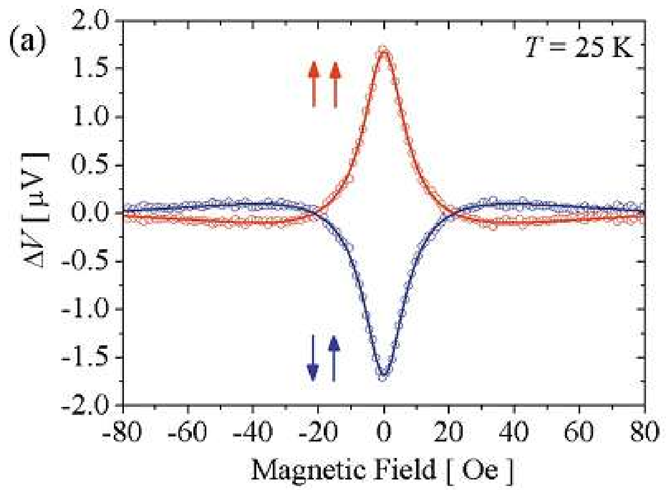


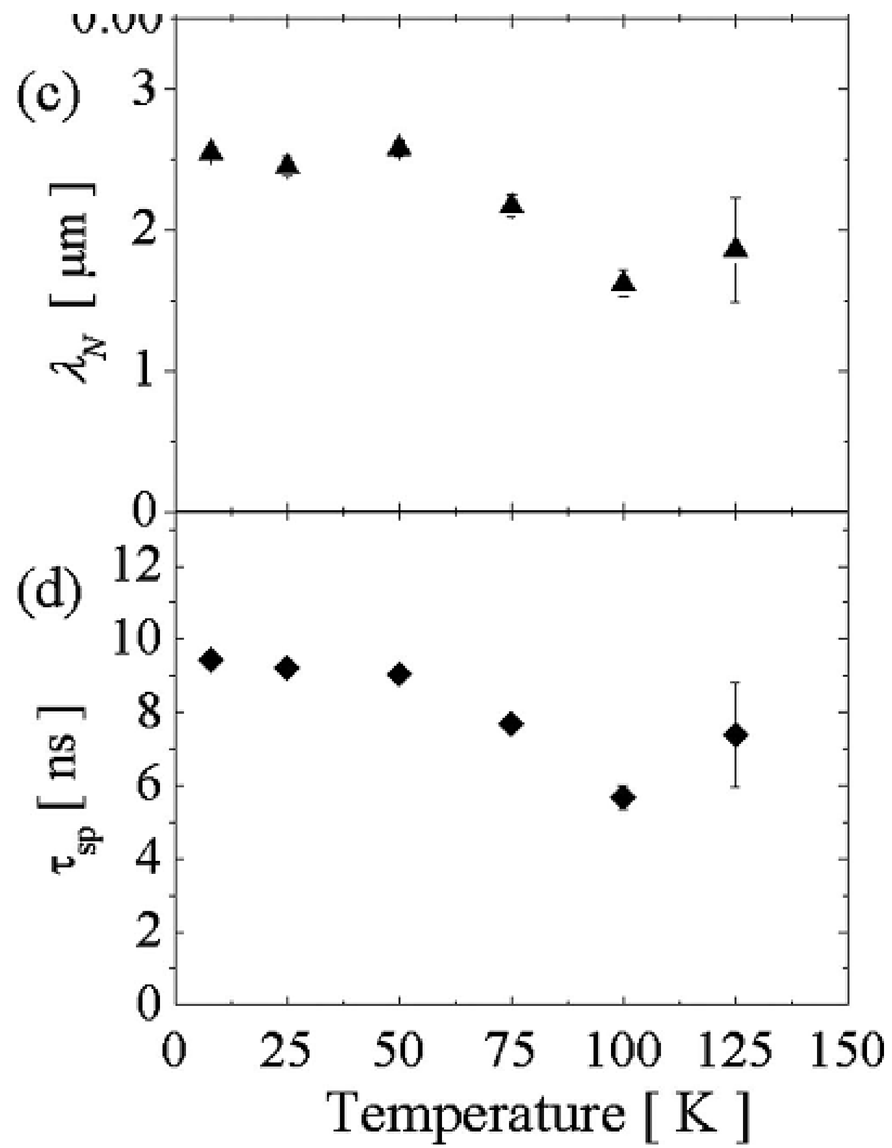
Spin in Silicon



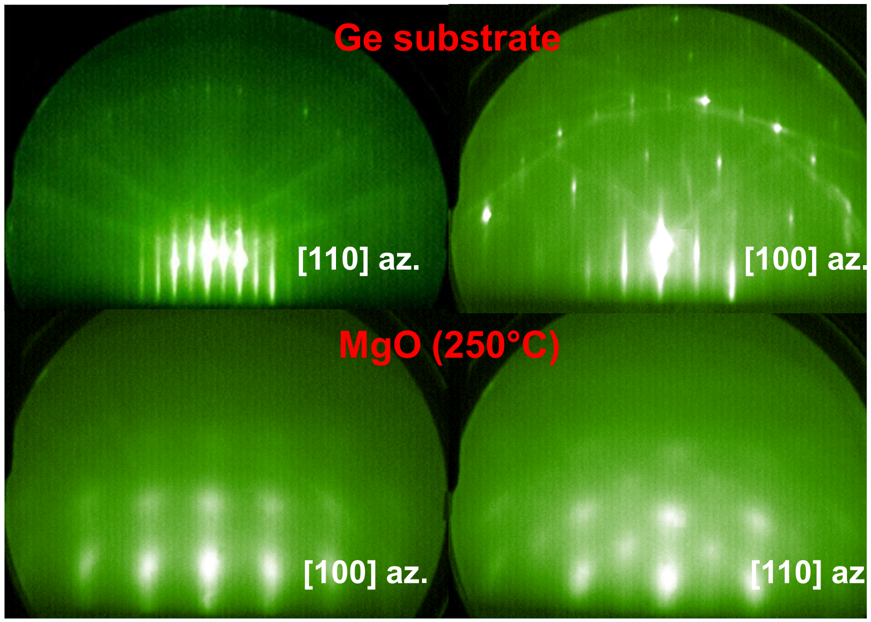
Sasaki, et al, APL (2010)

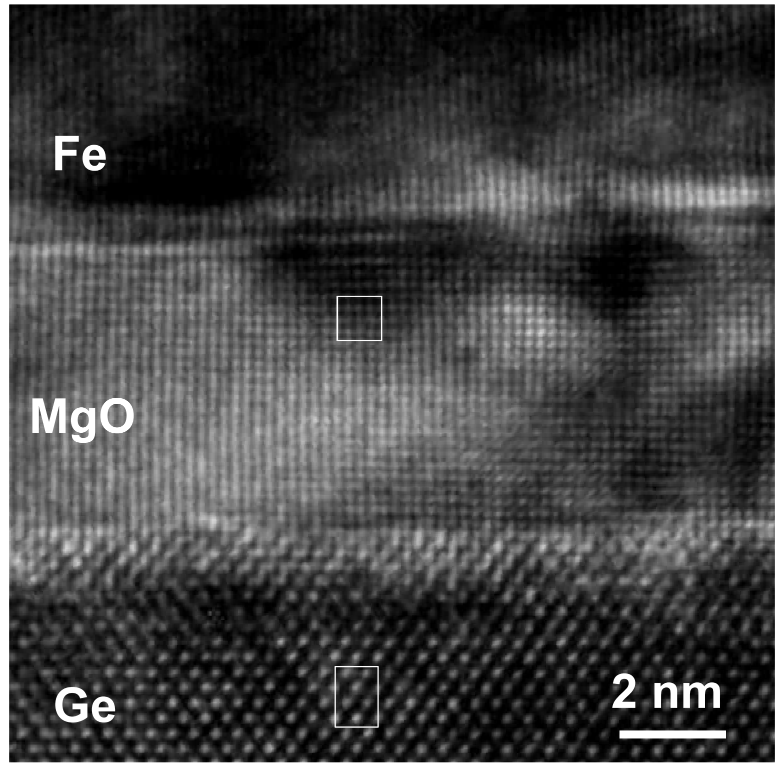
Spin in Silicon





Spin in Germanium



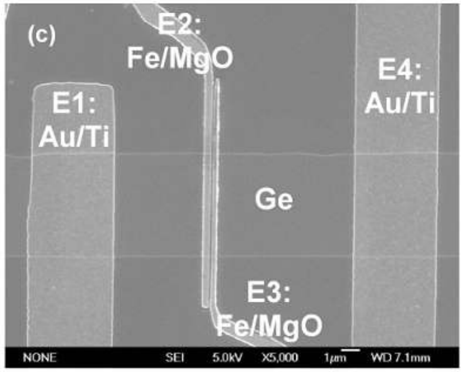


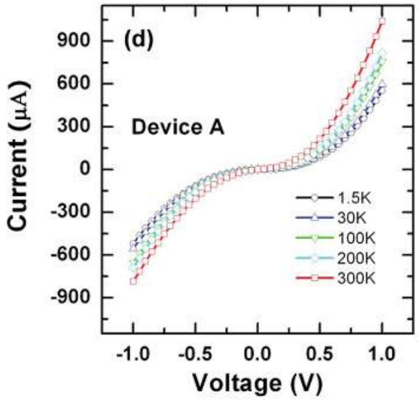
Epitaxial Fe/MgO/Ge junction is achieved
MgO/Ge 45^0 rotation

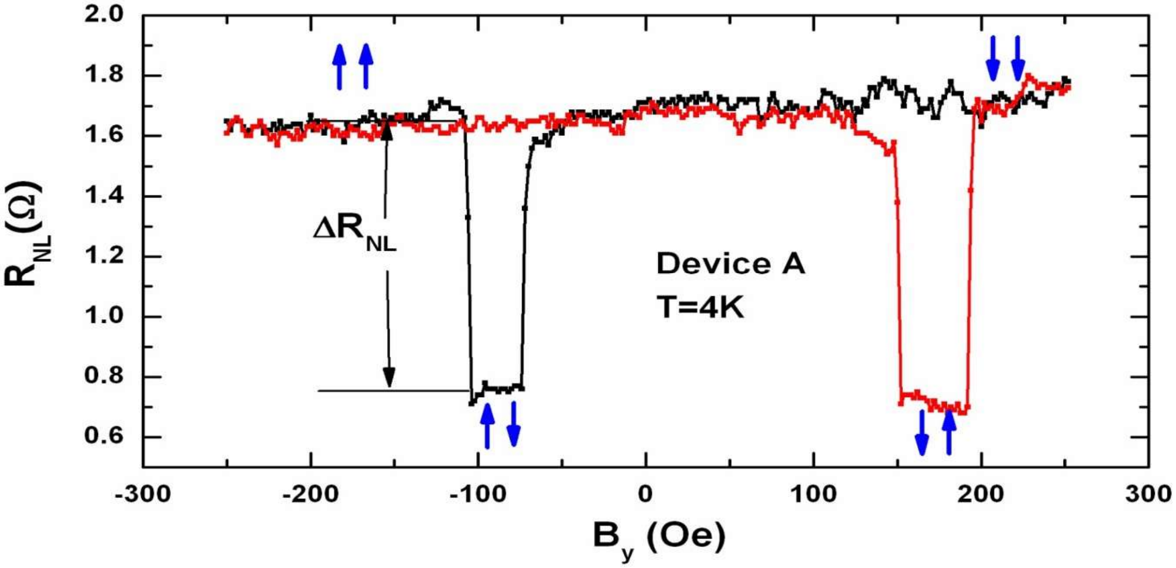
Han, et al, J. Crystal Growth (2010)

Spin in Germanium

Ge spin valve

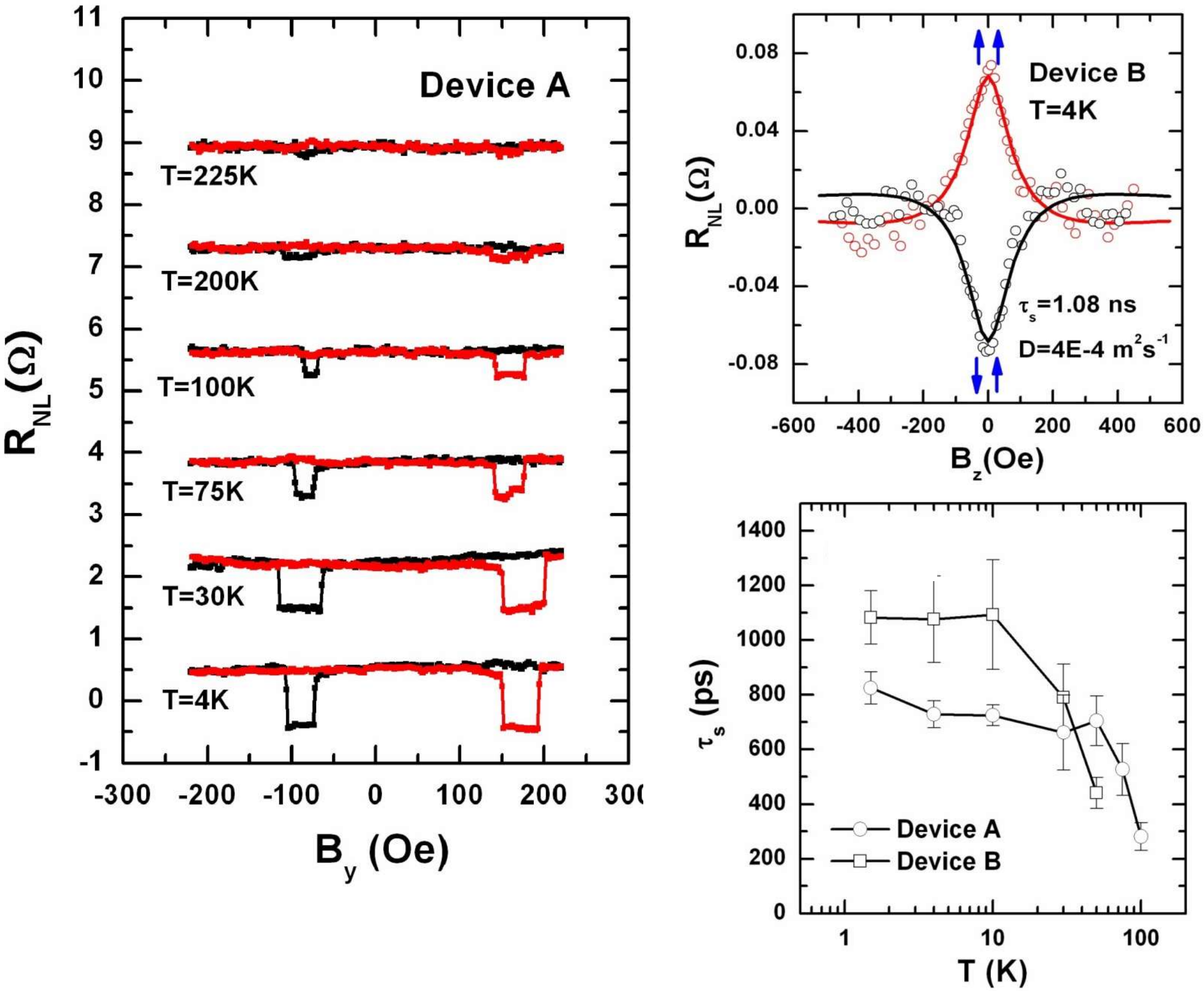






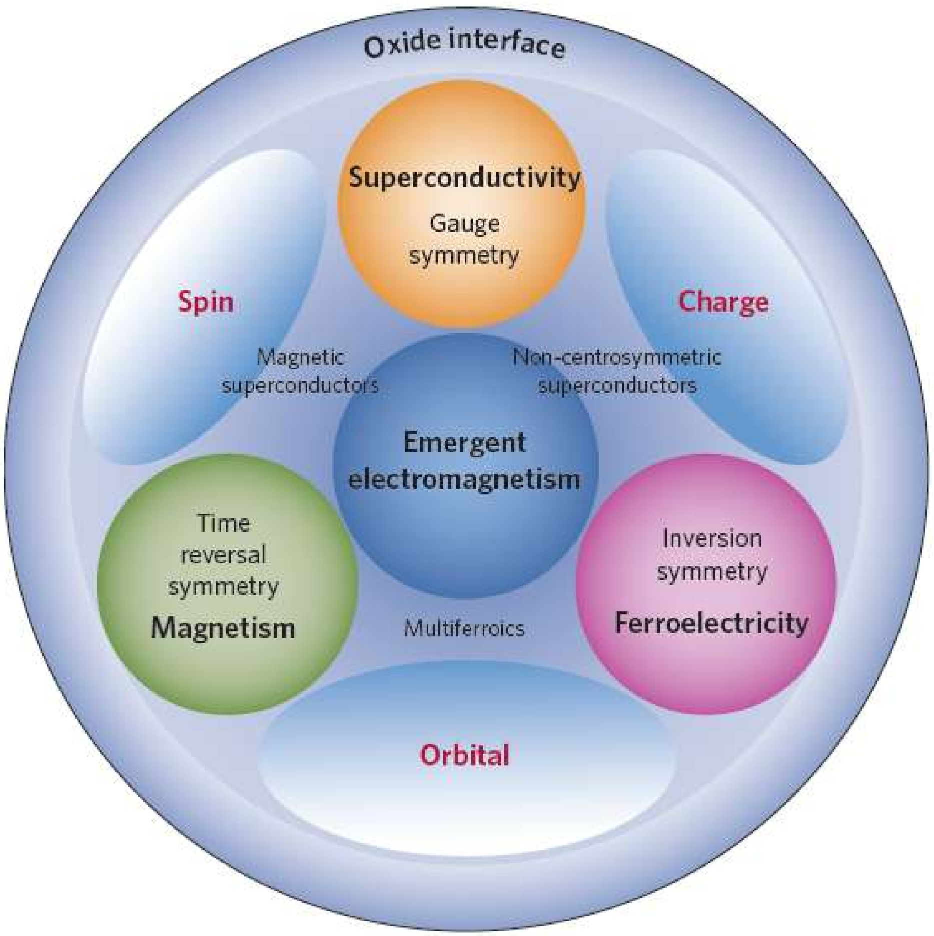
Zhou & Han, et al, PRB (2011)

Spin in Germanium



Spin in complex oxides

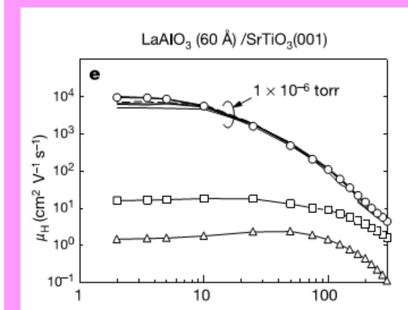
Oxide Interface

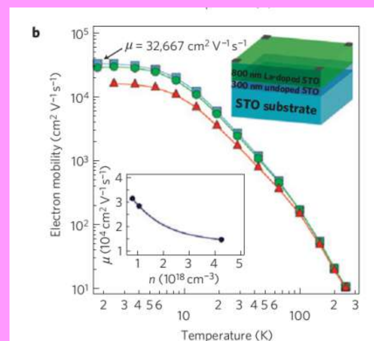


Hwang, et al. Nat. Mater. (2012)

Spin in complex oxides

High mobility

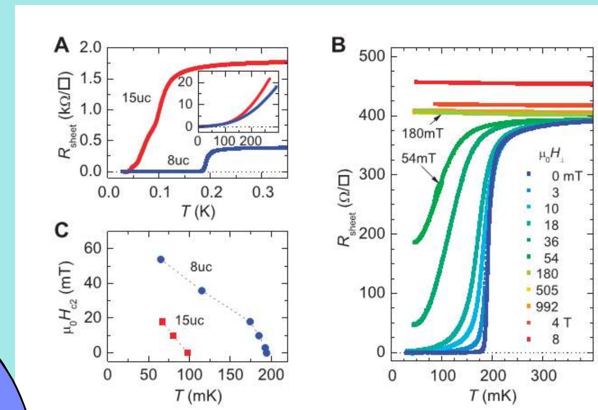




Ohtomo & Hwang
Nature 427, 423-426 (2004)

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

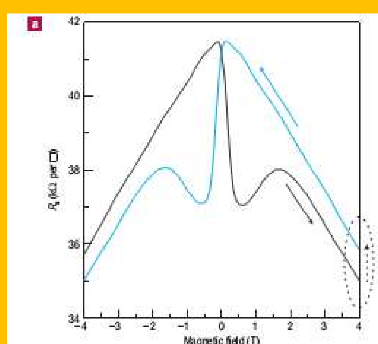
Gate tunable Superconductivity

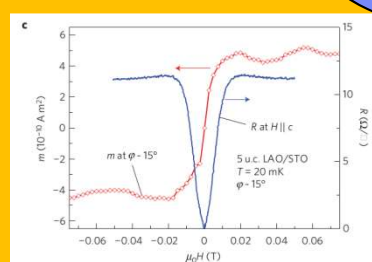


Reyren, et al, Science 317, 1196-1199 (2007)

SrTiO3

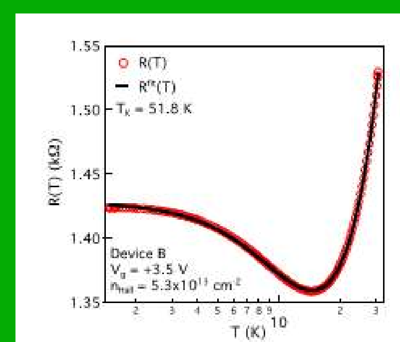
Magnetism + Superconductivity





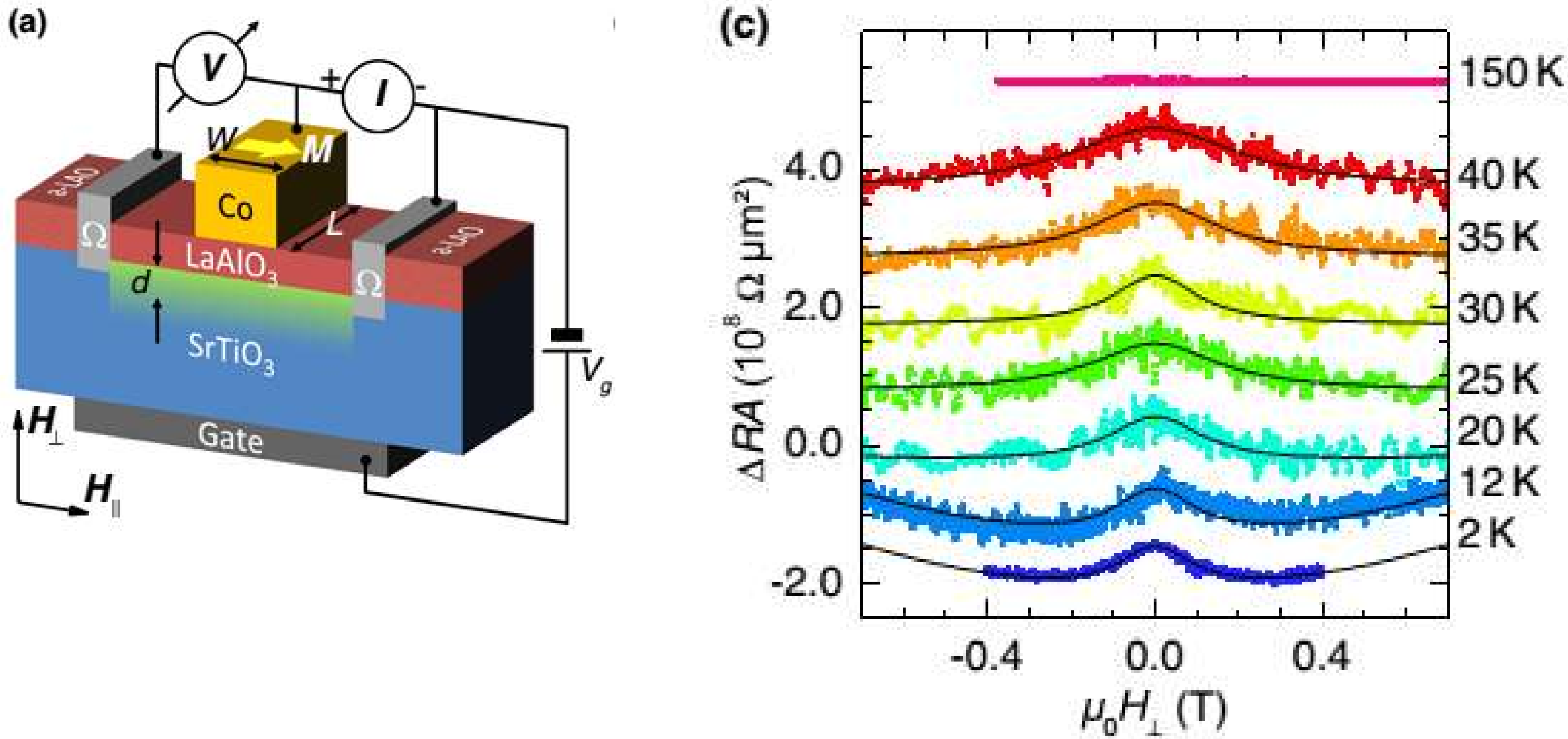
Brinkman, et al, *Nat Mater* **6**, 493-496 (2007).
Li, et al, *Nat Phys* **7**, 762-766 (2011).
Bert, et al, *Nat Phys* **7**, 767-771 (2011).

Kondo effect



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

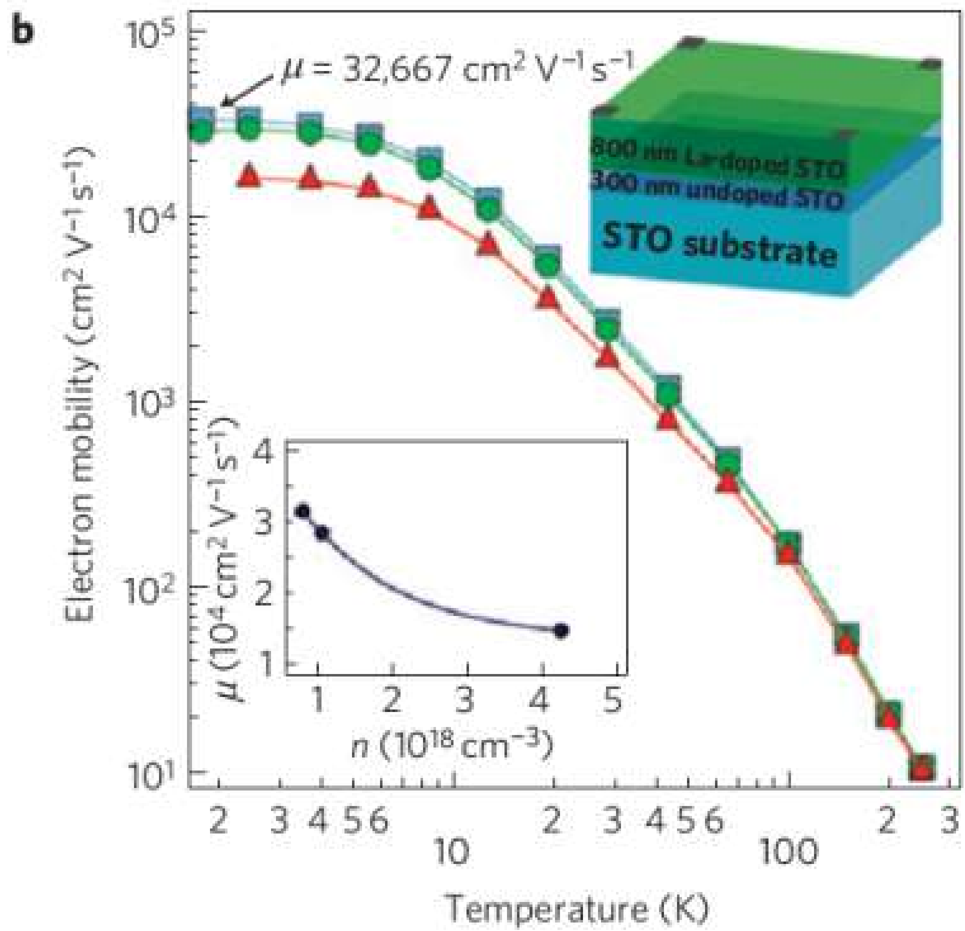
Spin in complex oxides



Reyren, et al, PRL (2012)

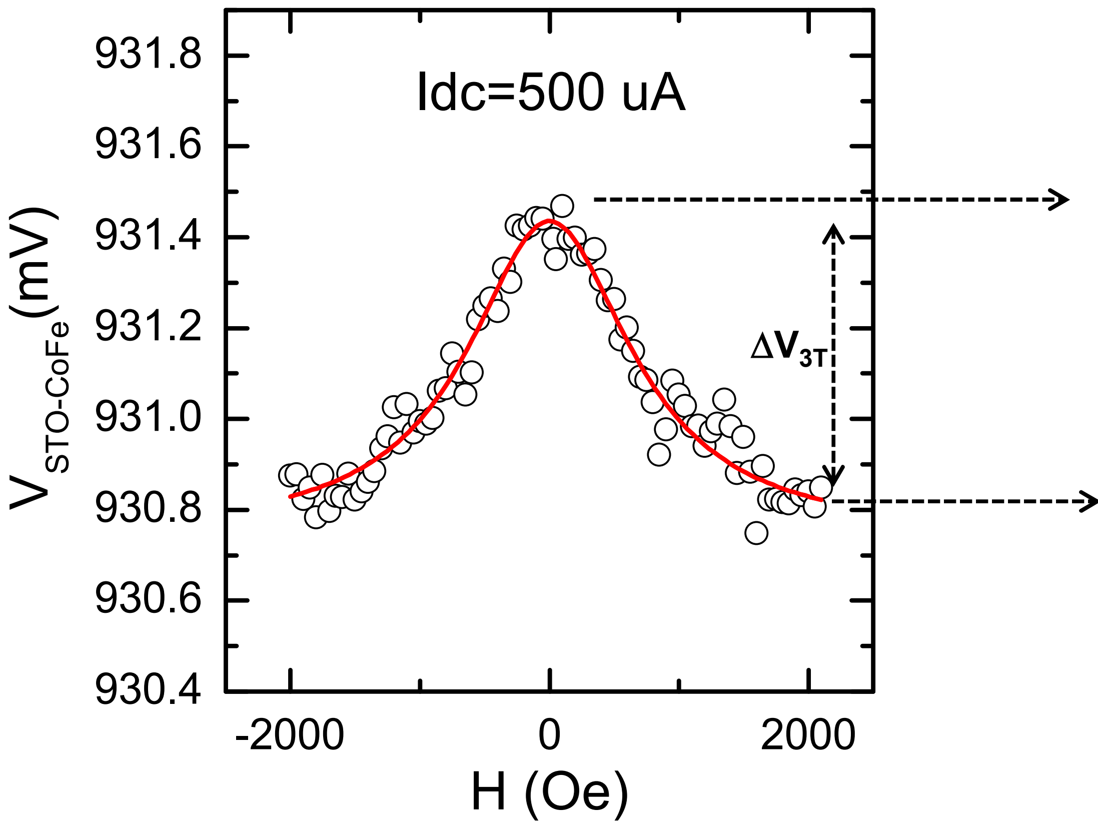
Spin in complex oxides

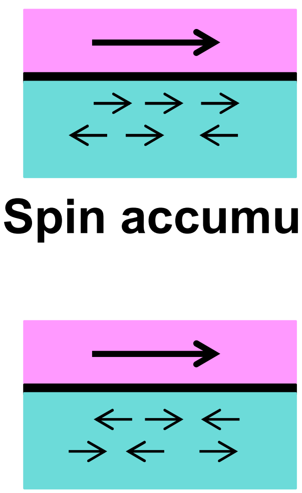
La, Nb doped STO



Son, et al, Nature Materials (2010)

Spin in complex oxides



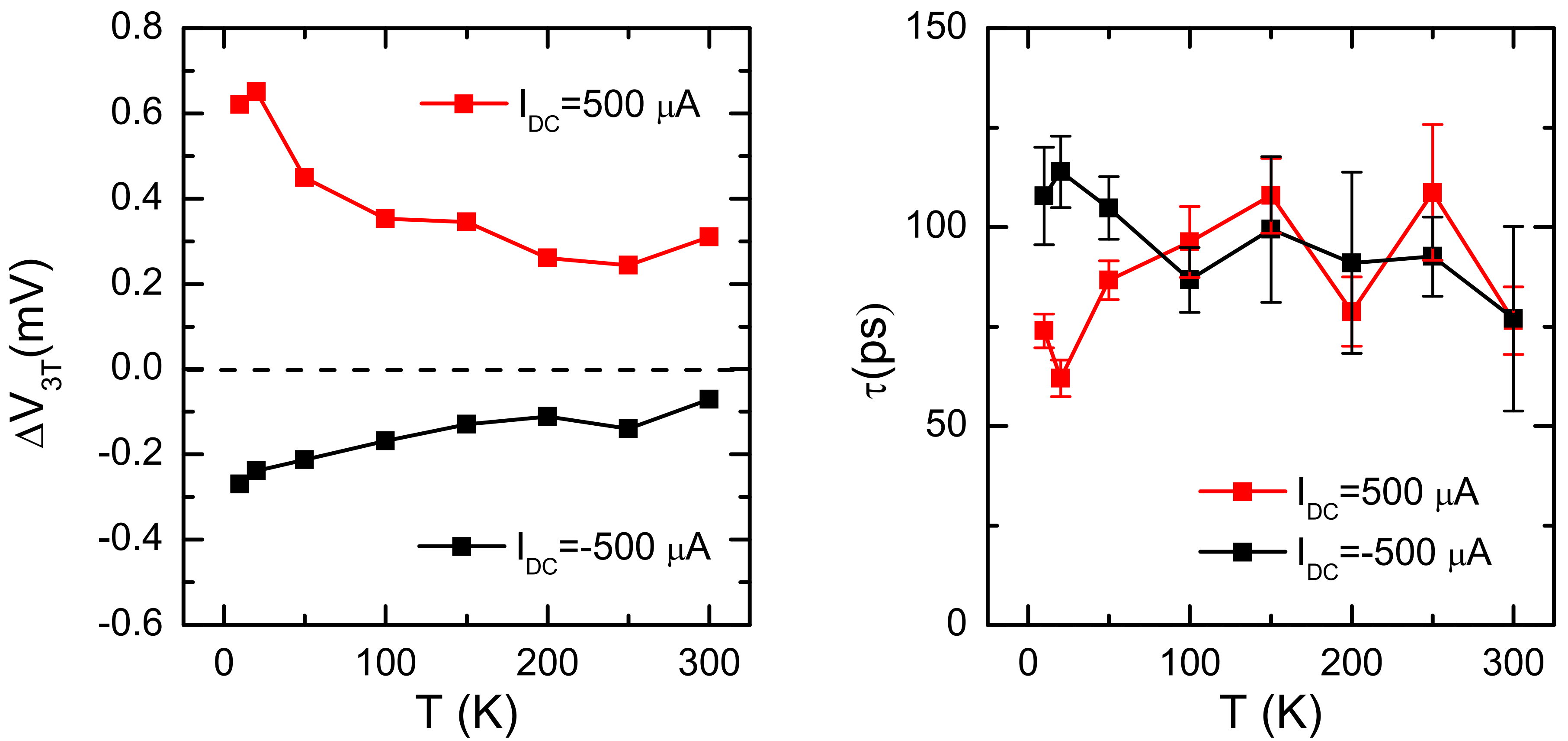


Spin accumulation

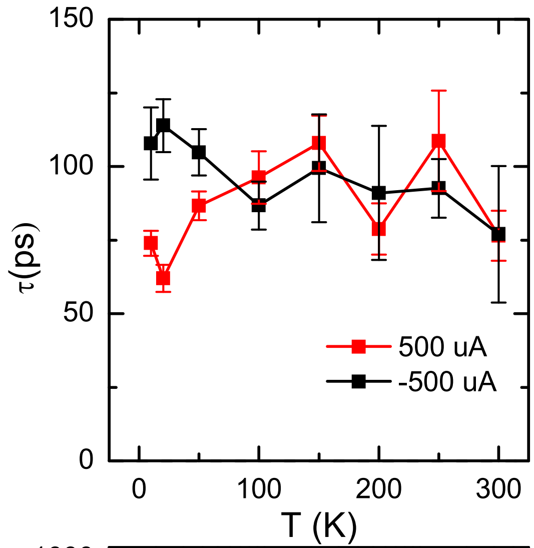
Average spin: 0
due to spin precession

Han, et al, Nature Communications (2013)

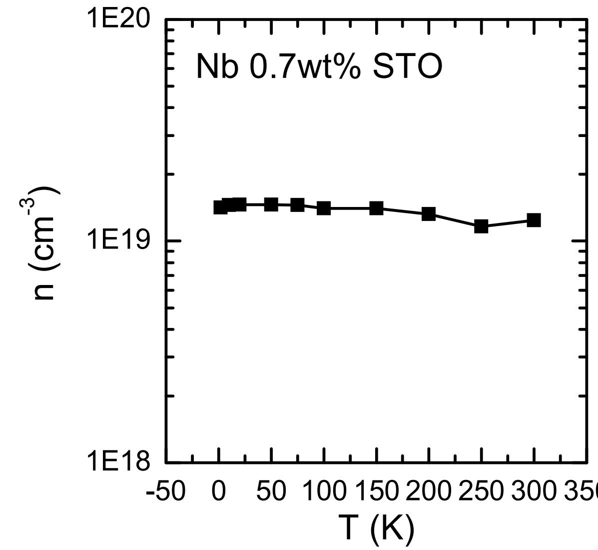
Spin in complex oxides

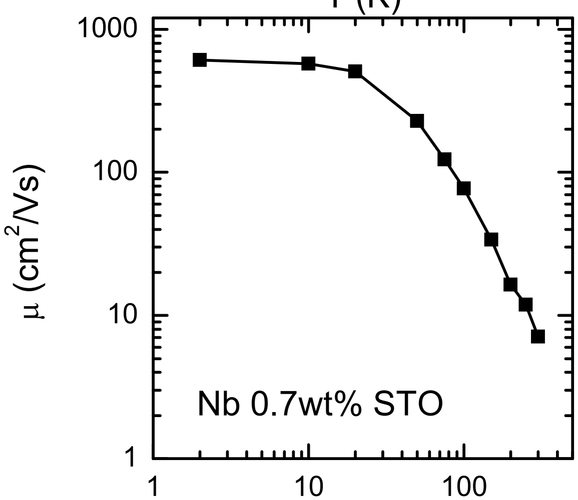


Spin in complex oxides

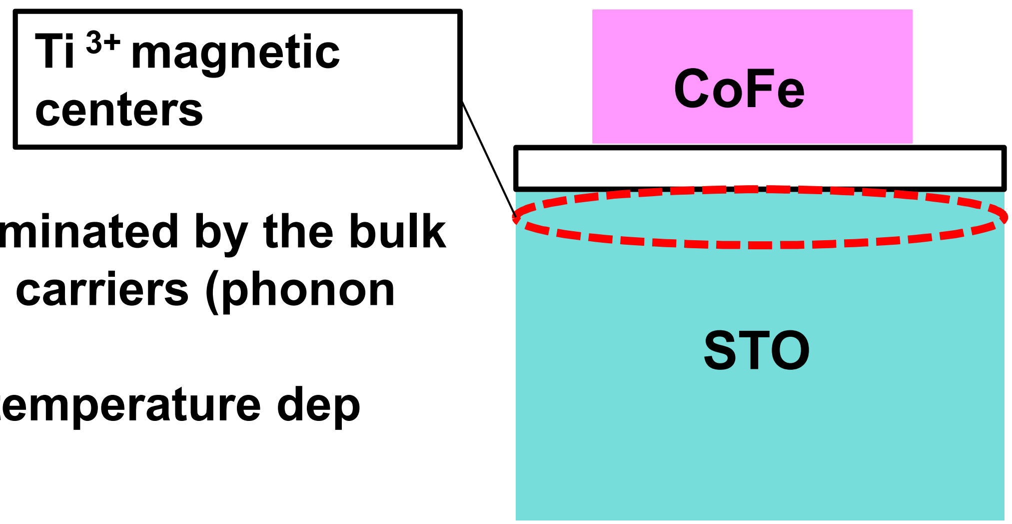


Spin relaxation time dominated by spin scattering at the STO surface
--- little temperature dep

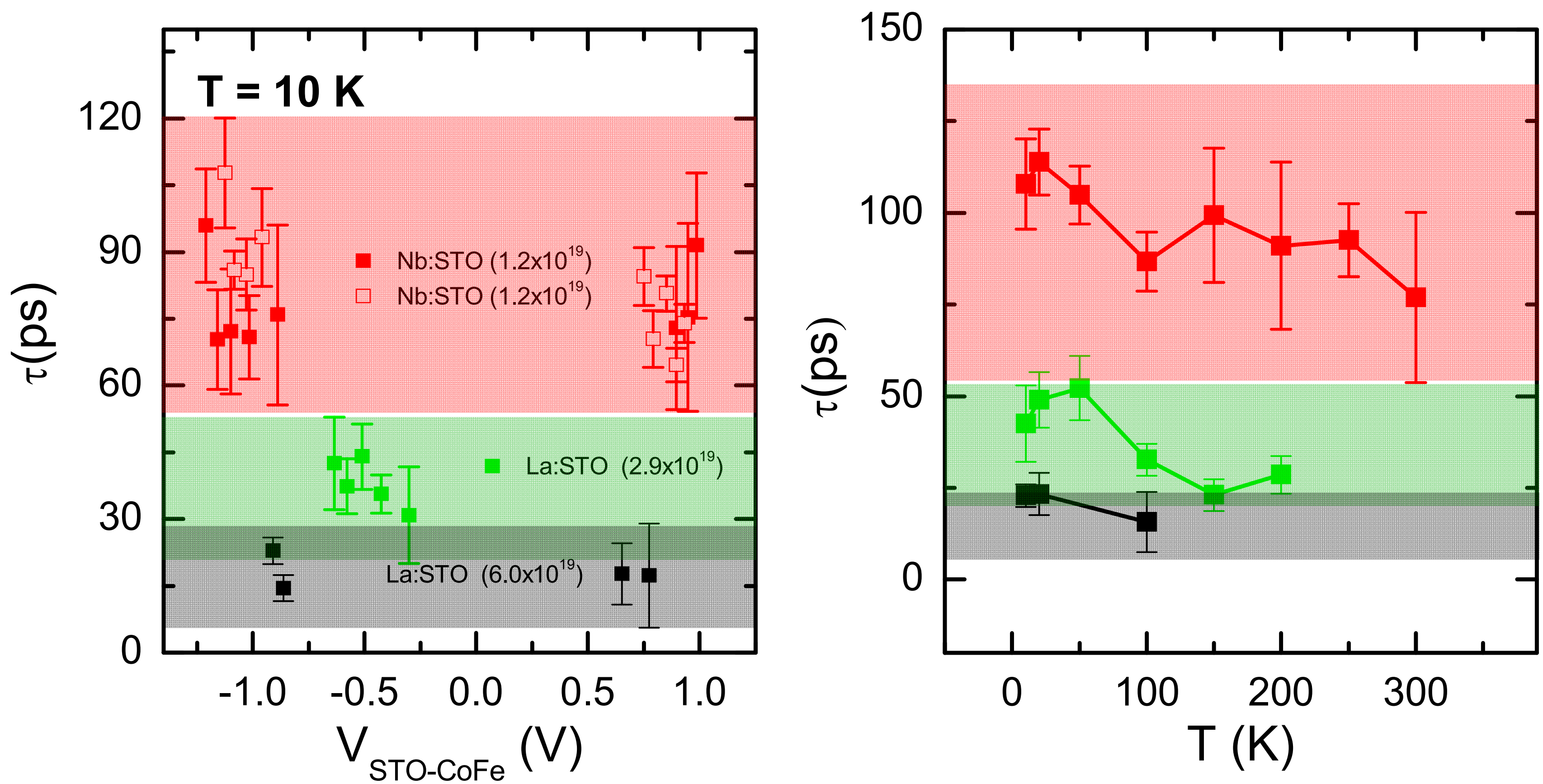




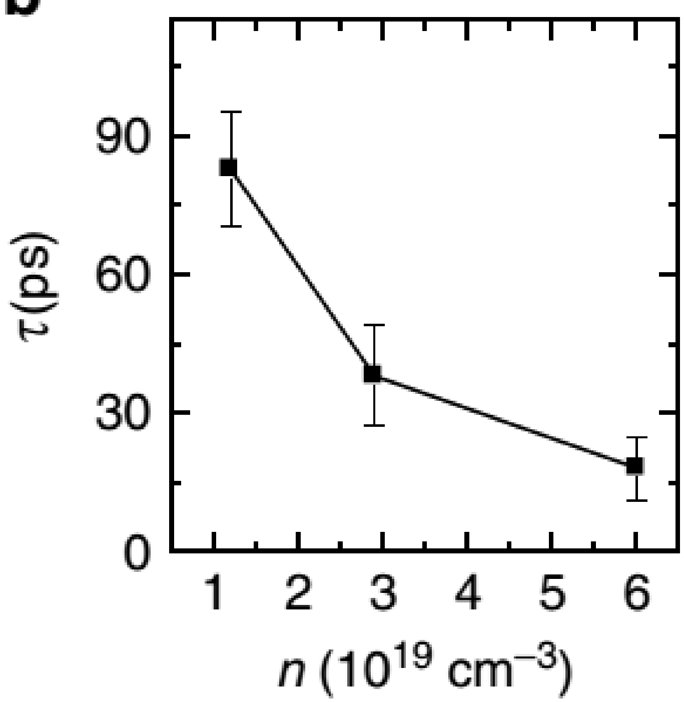
Mobility dominated by the bulk conducting carriers (phonon scattering)
— Strong temperature dep

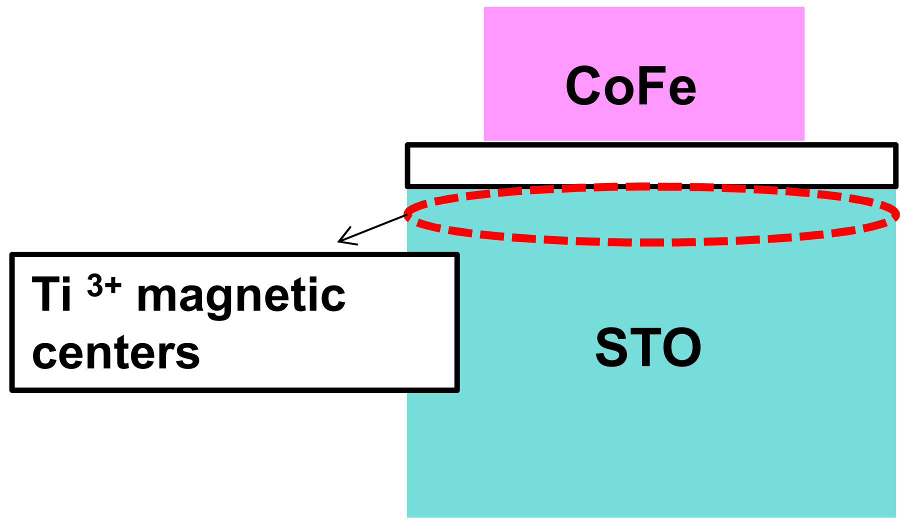


Spin in complex oxides



Spin in complex oxides





Higher doping → **More Ti^{3+} magnetic centers** → **Shorter Spin lifetime**

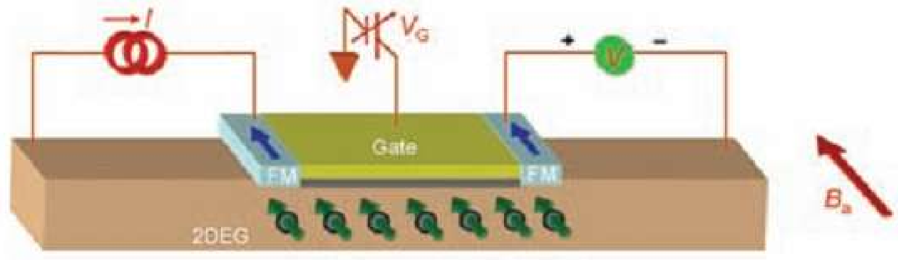
$La^{3+}{}_{x}Sr^{2+}{}_{1-x}Ti^{4+}{}_{1-x}Ti^{3+}{}_{x}O3$

$Sr^{2+}Nb^{5+}{}_{x}Ti^{4+}{}_{1-2x}Ti^{3+}{}_{x}O3$

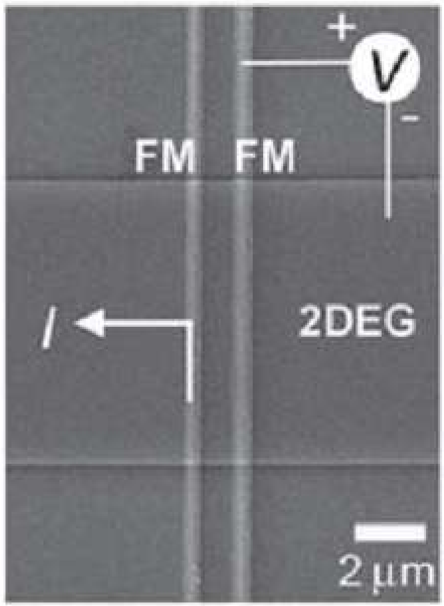
Spin FET

InAs channel

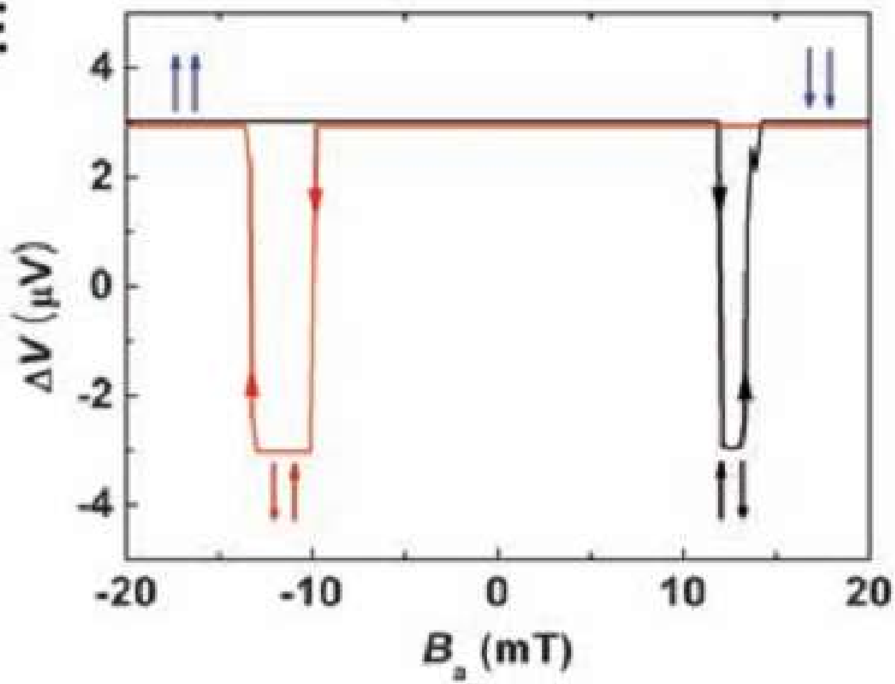
A



C

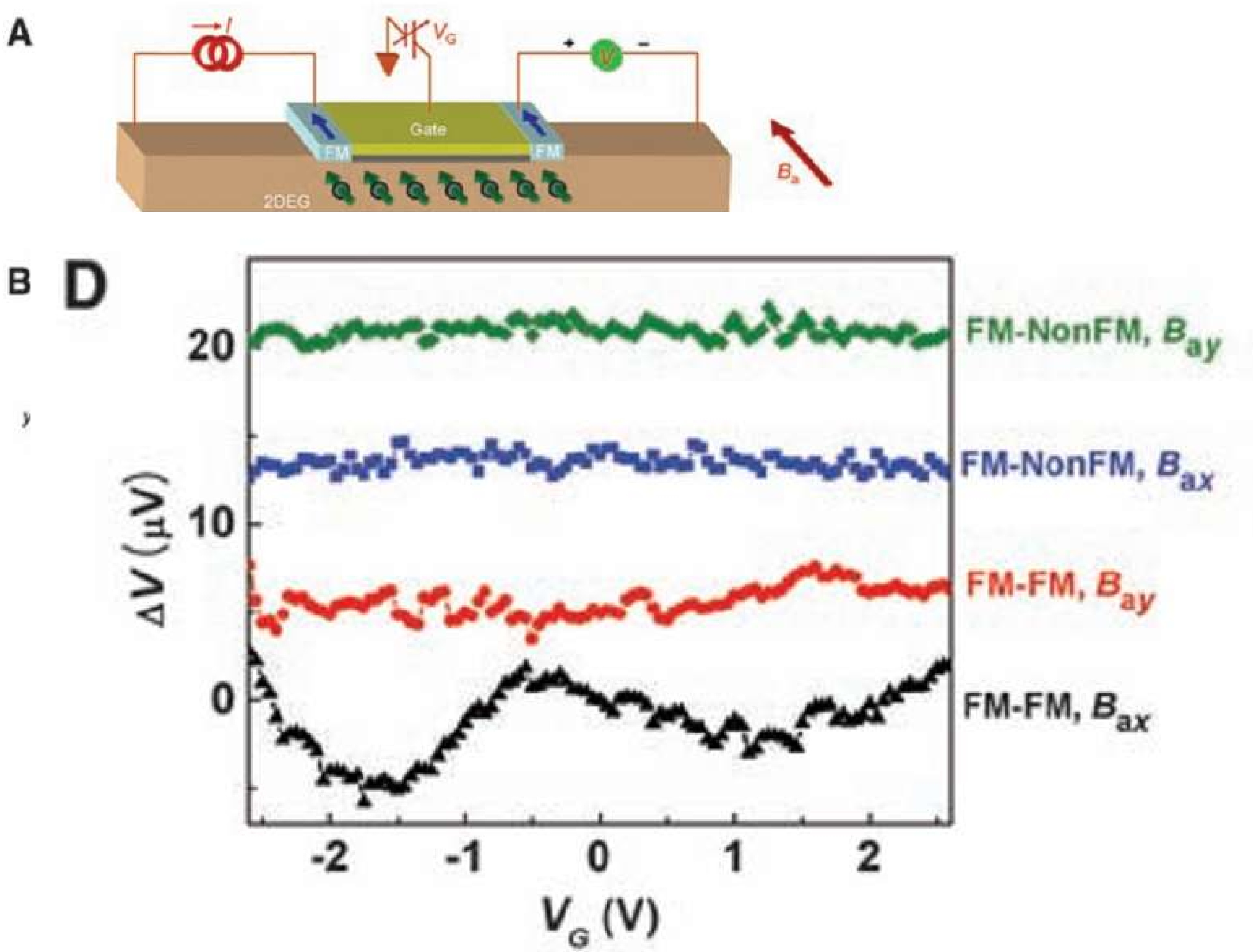


E

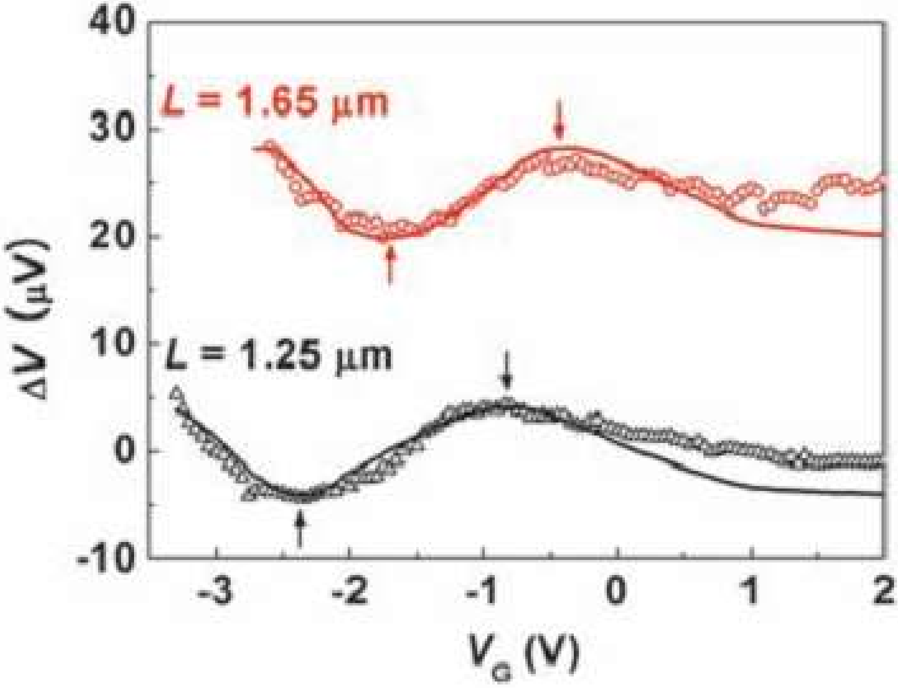


Koo, et al, Science (2009)

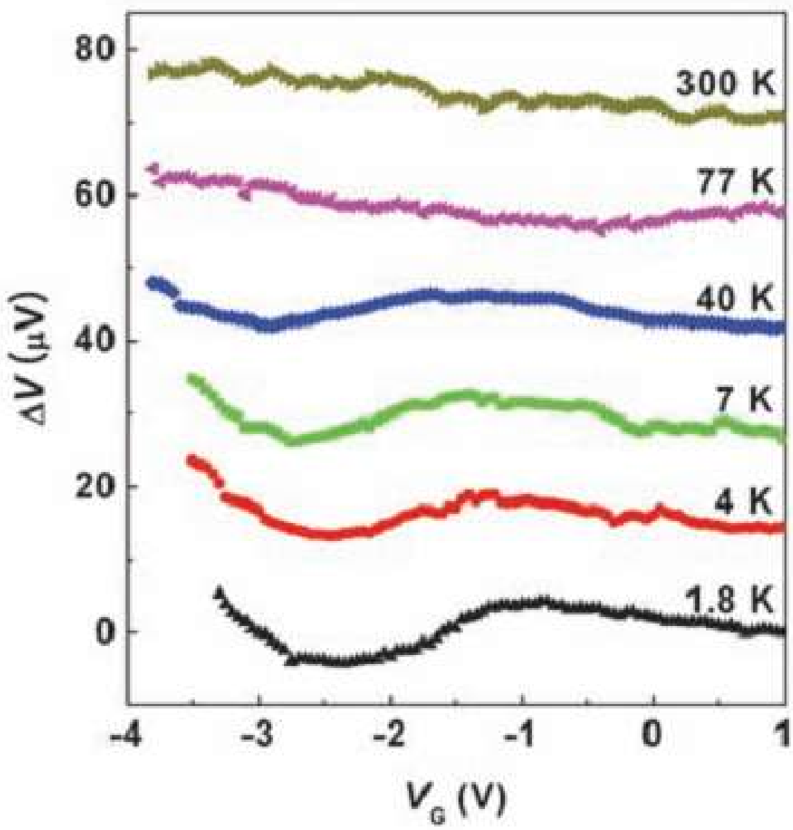
Spin FET


A
I
V_G
V
Gate
FM
FM
2DEG
B_a
B
D
FM-NonFM, B_{ay}
FM-NonFM, B_{ax}
FM-FM, B_{ay}
FM-FM, B_{ax}
$\Delta V\,(\mu V)$
V_G (V)
20
10
0
-2
-1
0
1
2

Spin FET

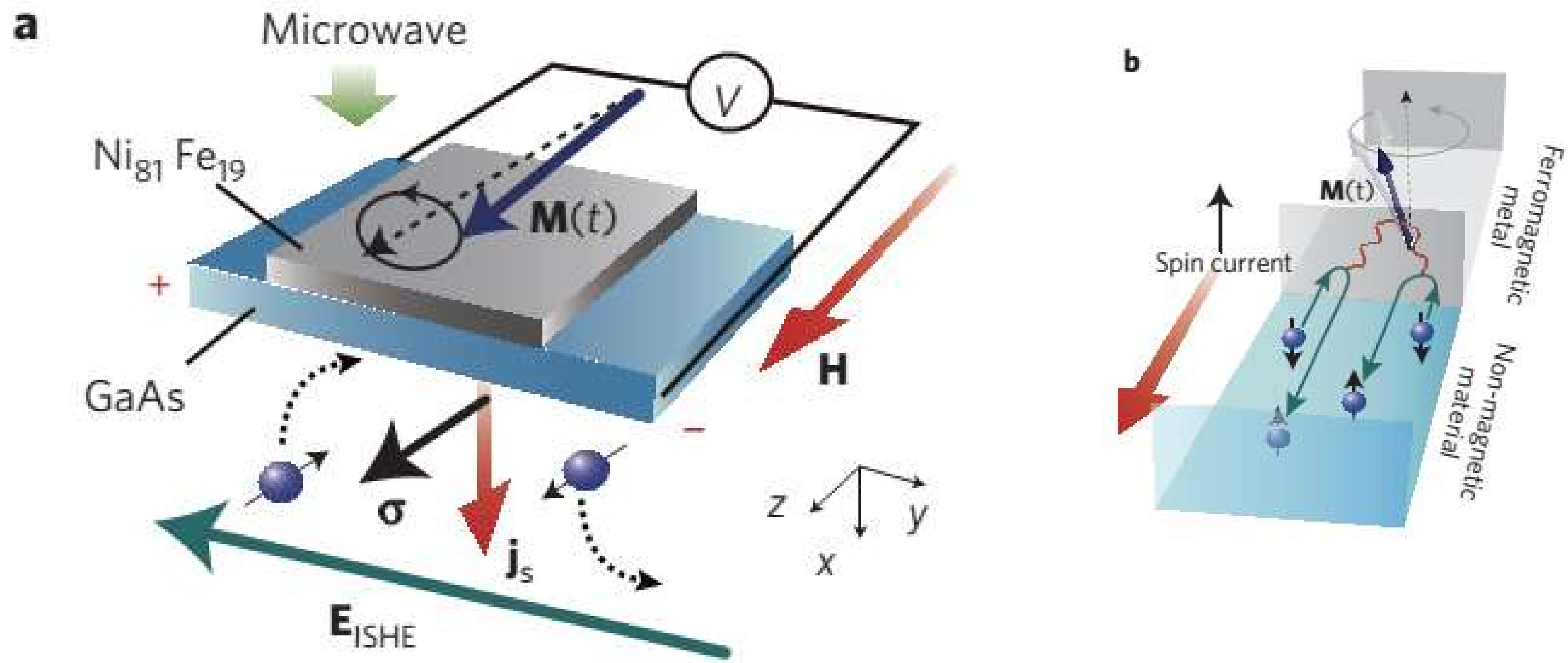


L = 1.65 μm
L = 1.25 μm
ΔV (μV)
V_G (V)
40
30
20
10
0
-10
-3
-2
-1
0
1
2



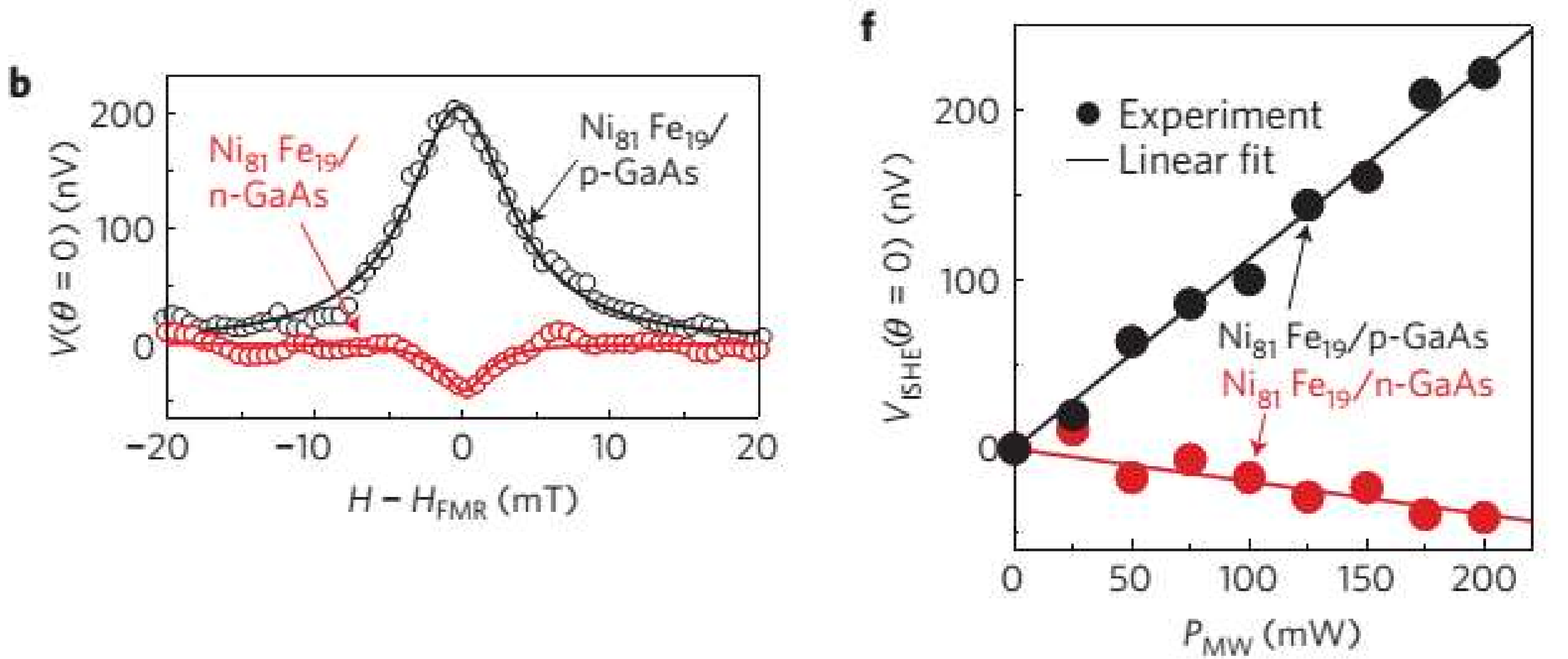
300 K
77 K
40 K
7 K
4 K
1.8 K
ΔV (μV)
V_G (V)
80
60
40
20
0
-4
-3
-2
-1
0
1

Another solution

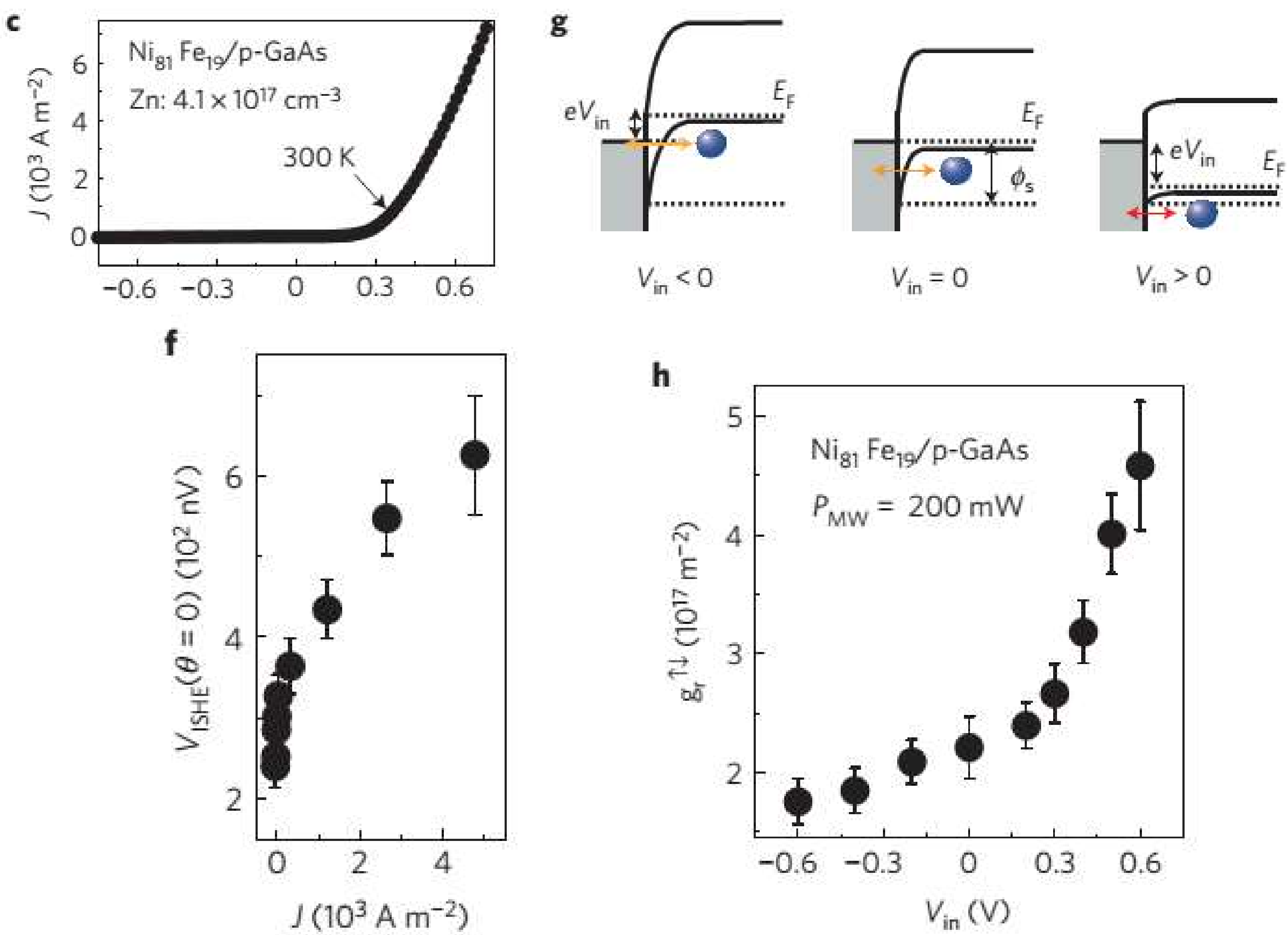


Ando, et al, Nature Mater. (2011)

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)

61

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)

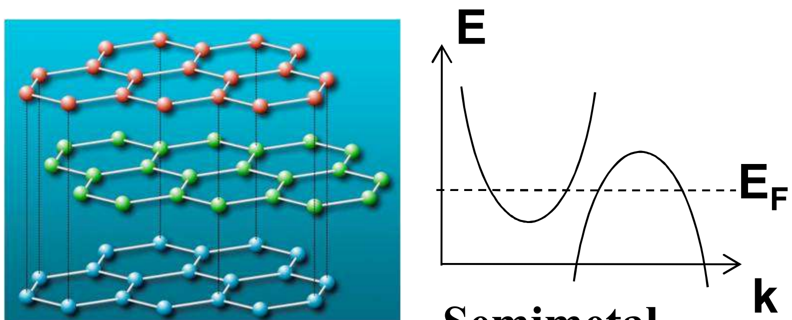
Graphene

Graphene combines the advantages of both metals and semiconductors

62

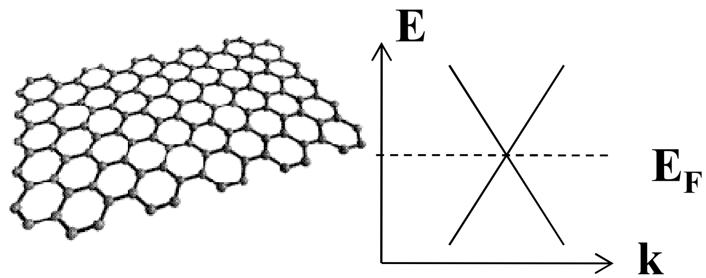
Graphene

Graphite



Semimetal

Graphene



Massless Dirac Fermions

Spin-dependent properties

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

Low intrinsic spin-orbit coupling → Long spin lifetime (~ μs)

High mobility

→ Long spin transport length

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

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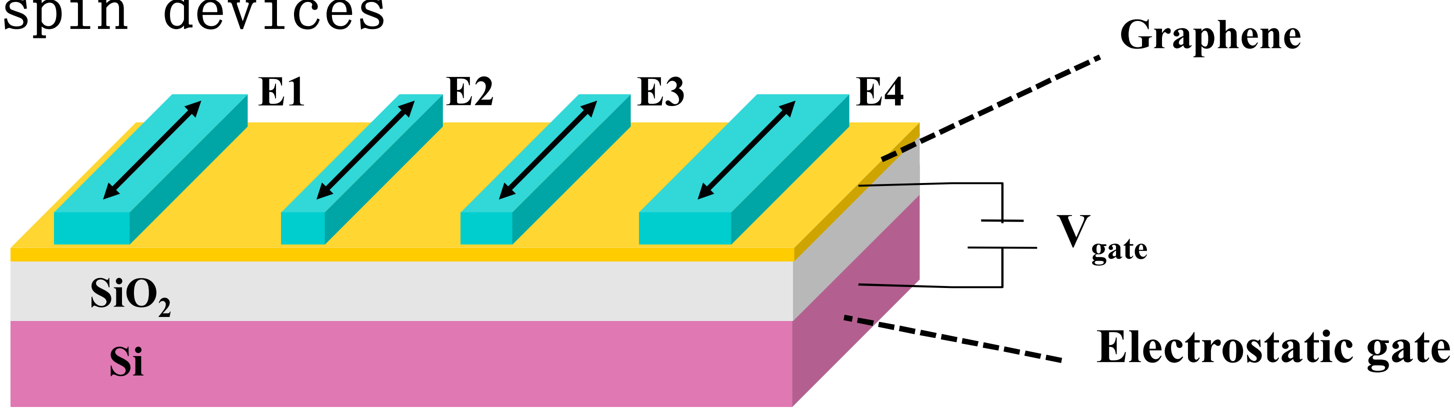
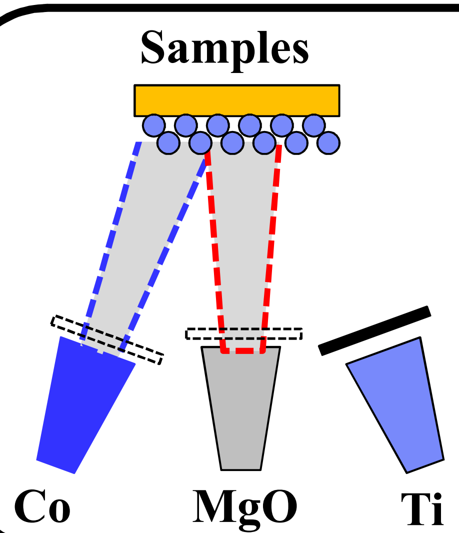
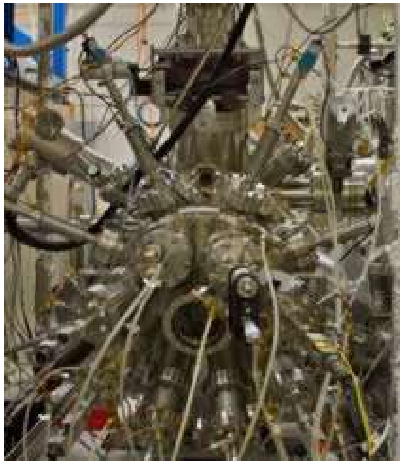
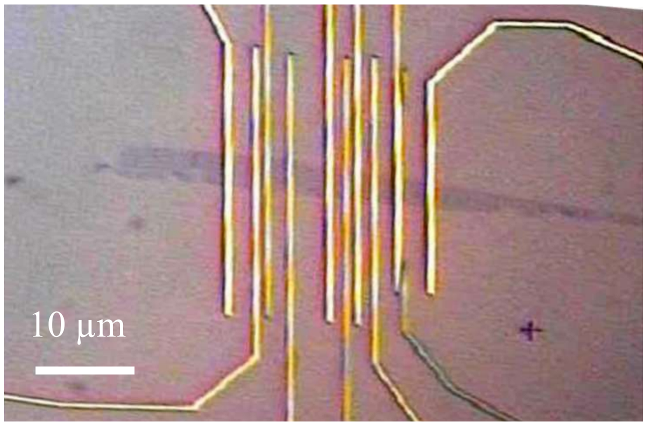
Graphene spin valves

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 ~ 2

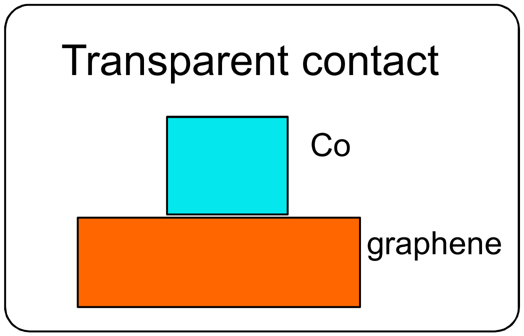
Spin relaxation length: $\lambda = \sqrt{D\tau}$

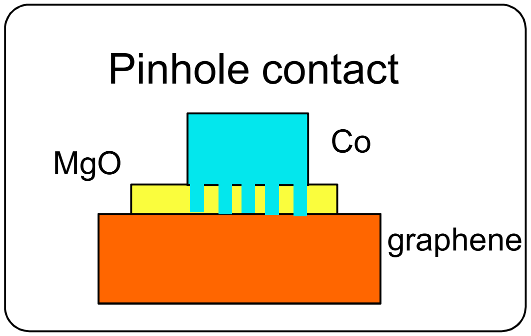
Diffuse without precession

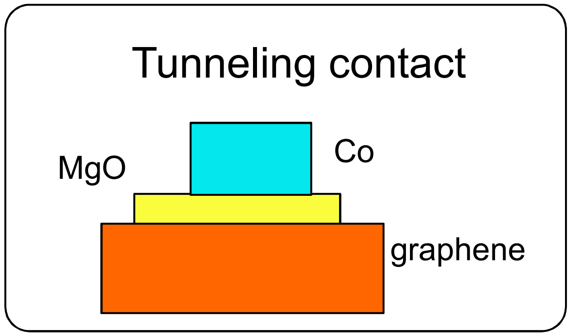
$$B_\perp = 0, \frac{\partial \mu}{\partial t} = 0,$$

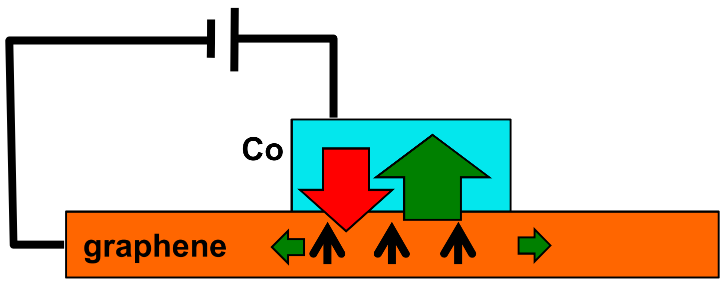
$$\mu(x) = \mu_0 \exp(-x/\lambda)$$

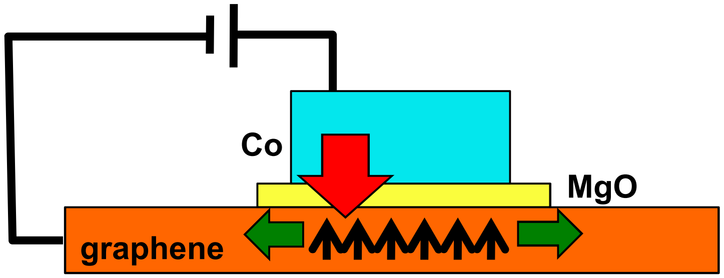
Graphene spin valves





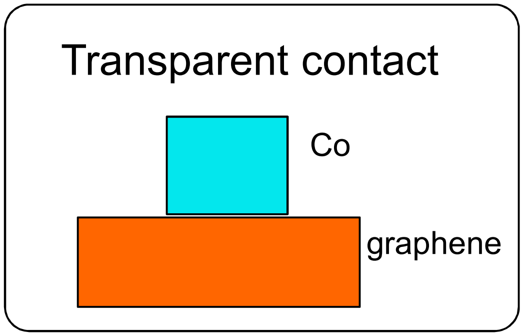


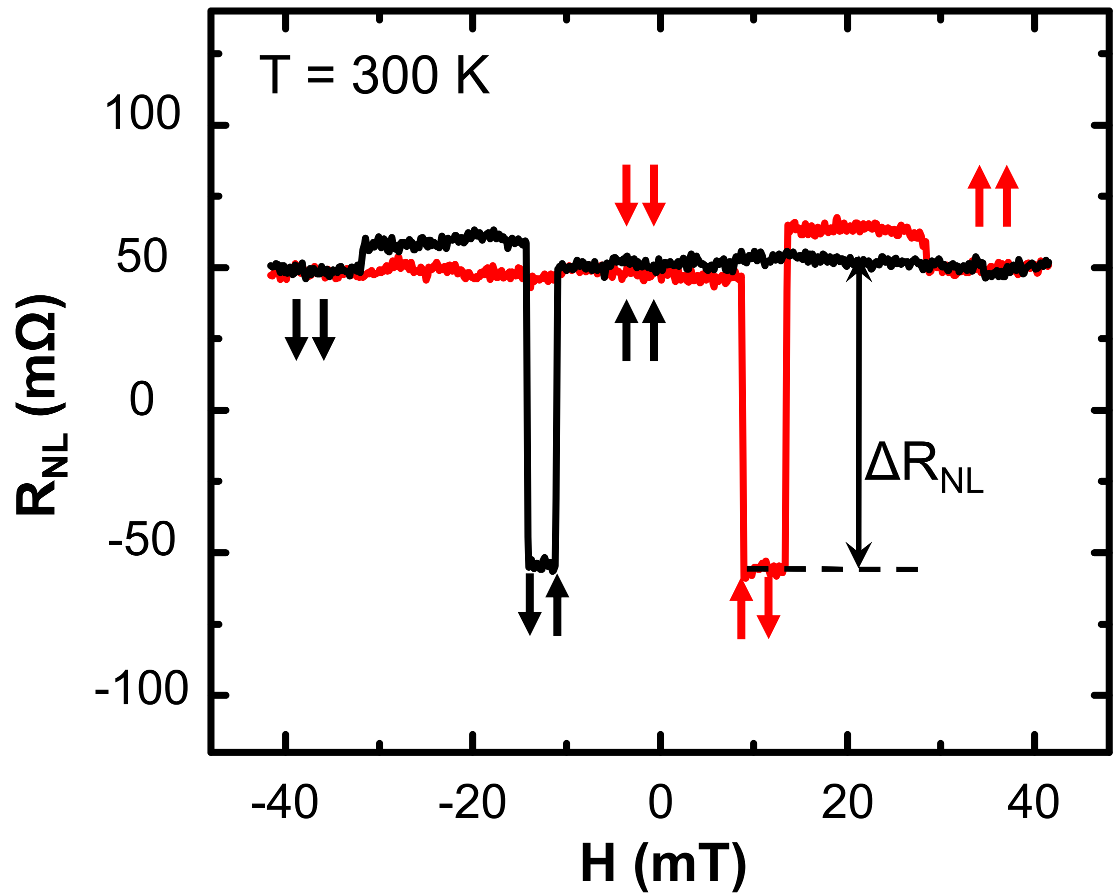




E.I. Rashba, Phys. Rev. B 62, R16 267 (2000)
A. Fert, H. Jaffres, Phys. Rev. B 64, 184420 (2001).

Graphene spin valves

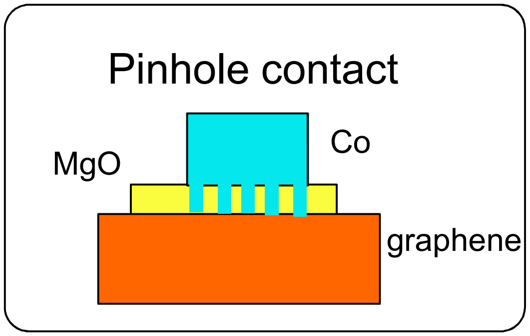


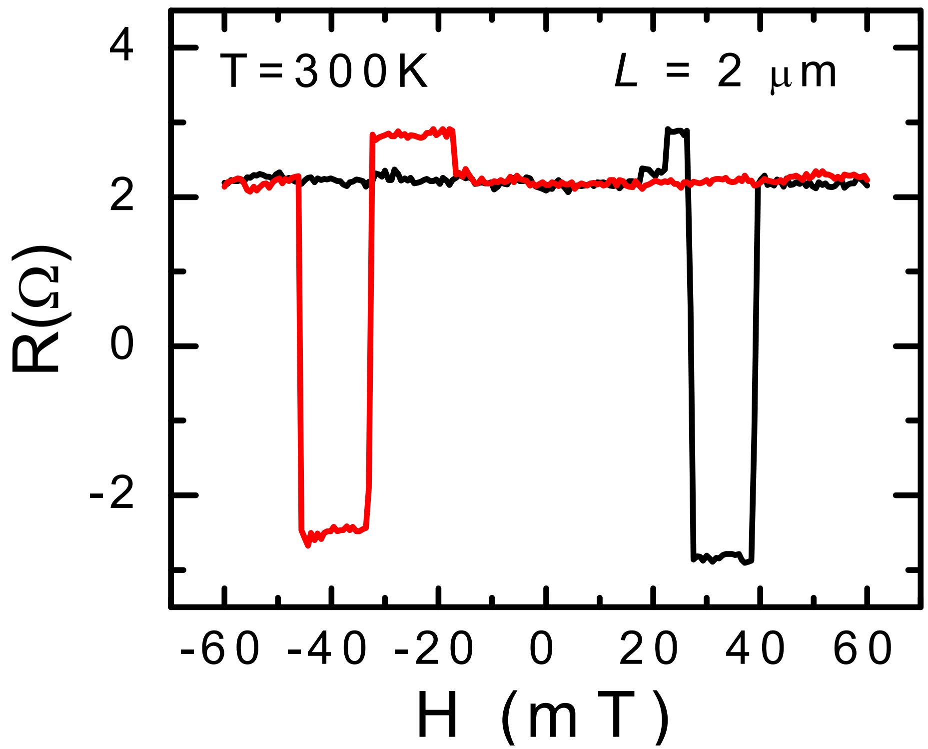


Nonlocal MR: ~ 0.1 ohms

Spin injection efficiency: ~ 1 %

Graphene spin valves

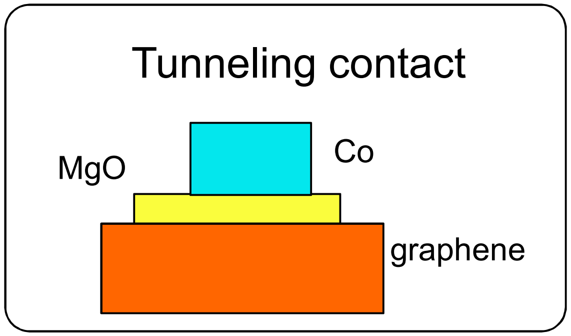


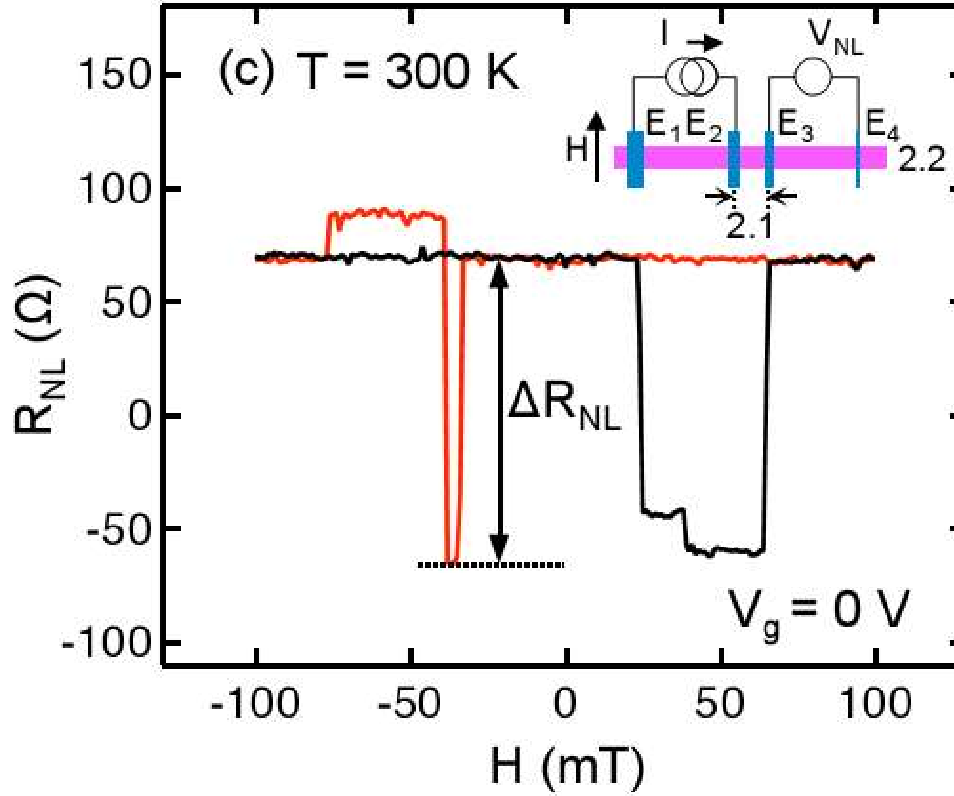


Nonlocal MR: ~ 10 ohms

Spin injection efficiency: ~ 8 %

Graphene spin valves

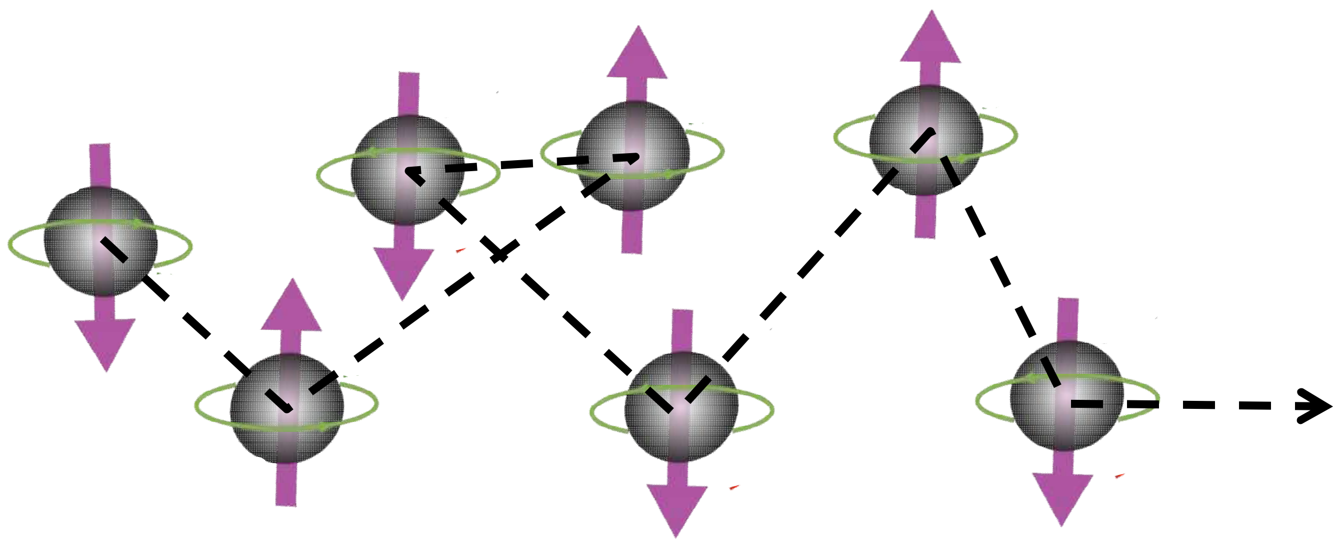




Nonlocal MR: ~130 ohms

Spin injection efficiency: ~ 30 %

Spin relaxation in graphene



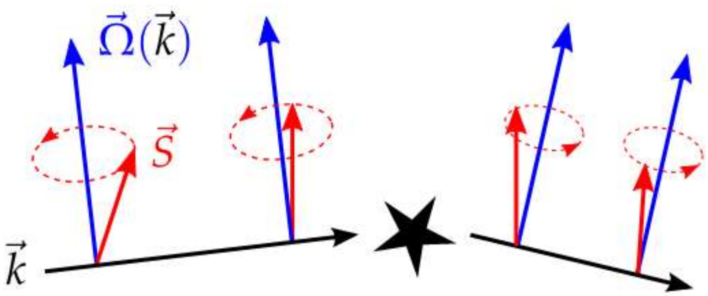
Spin flip during momentum scattering events:
More momentum scattering, more spin relaxation.

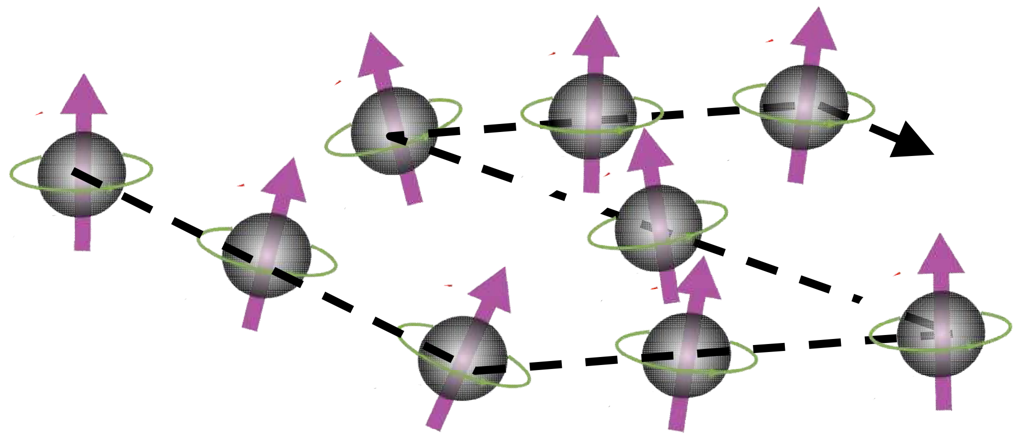
$\tau_s \sim \tau_p$

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



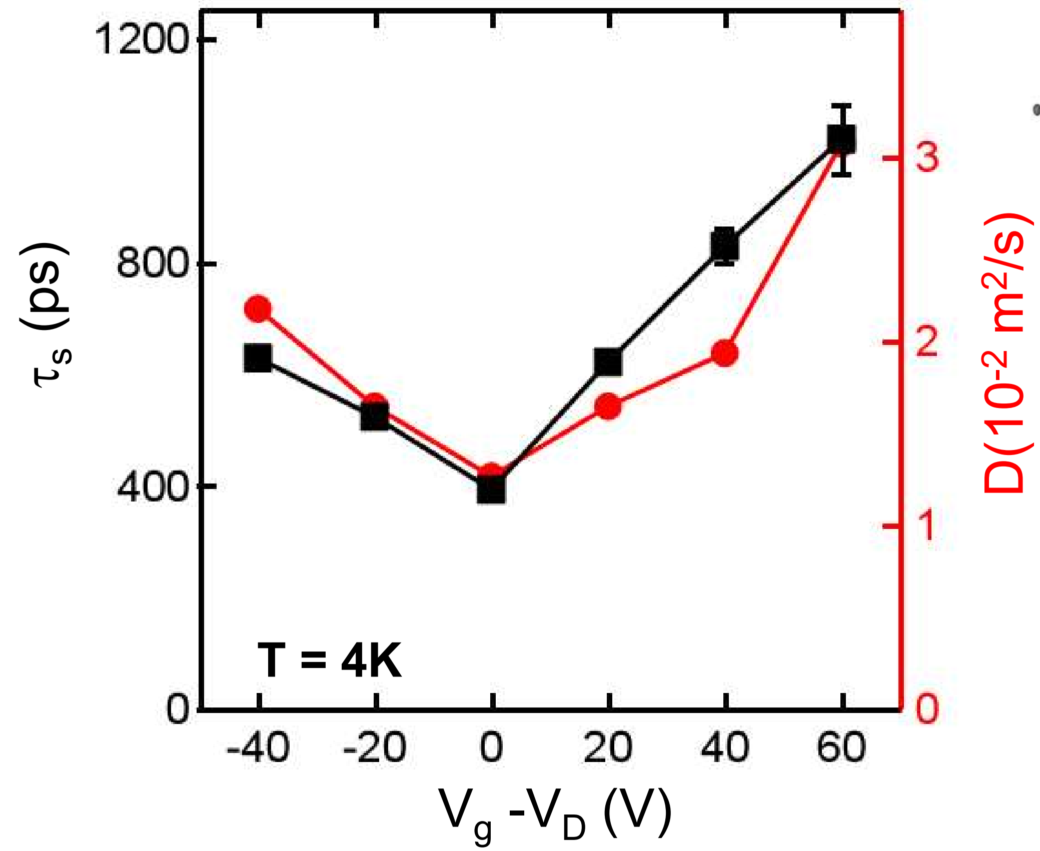


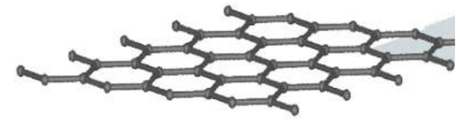
More momentum scattering, less spin relaxation

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

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

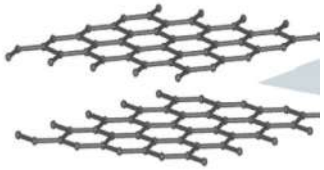
Spin relaxation in graphene

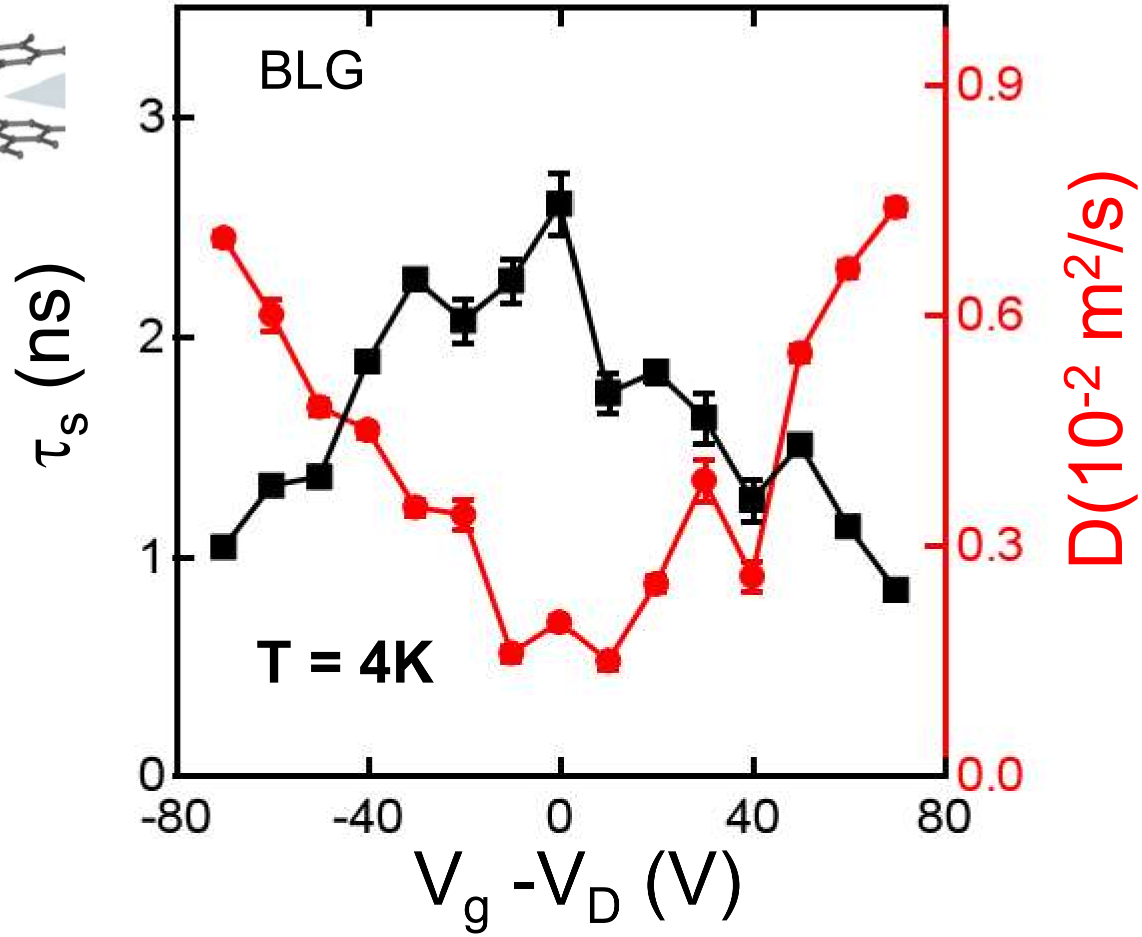




$\tau_s \sim \tau_p \sim$ **D** → **Elliot-Yafet**

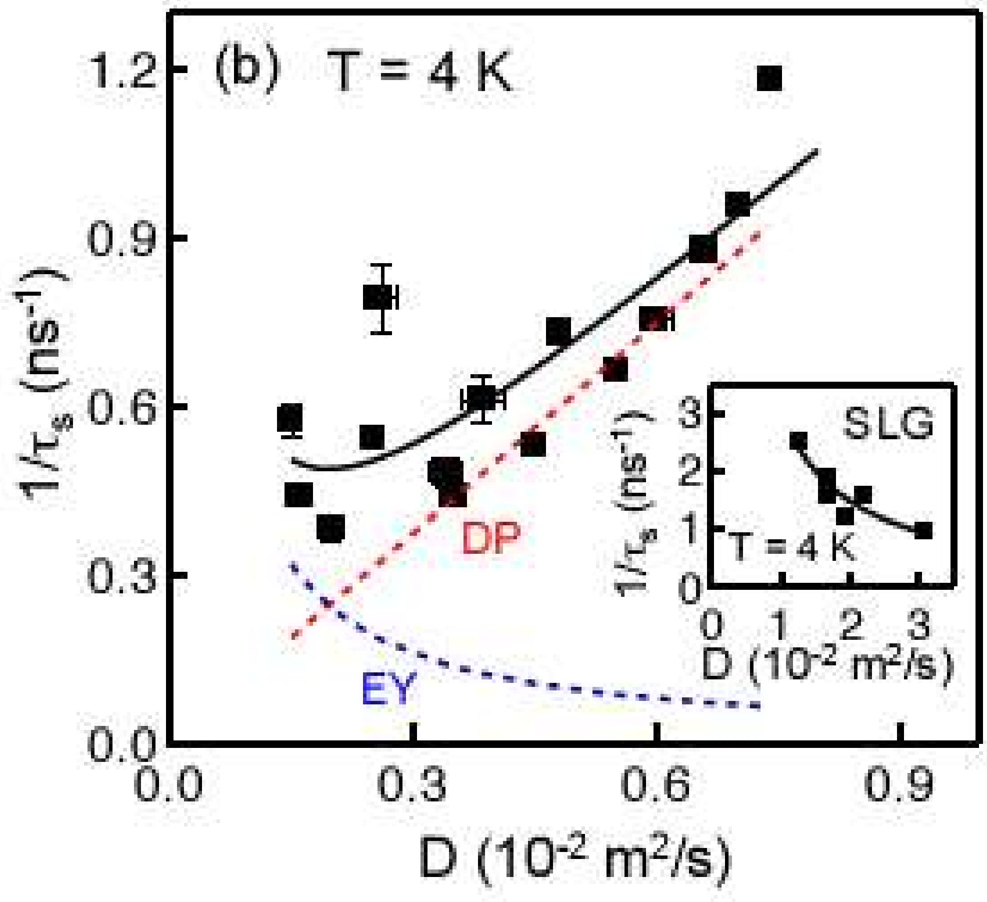
Spin relaxation in graphene





$\tau_s \sim 1/\tau_p \sim 1/D$ → **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

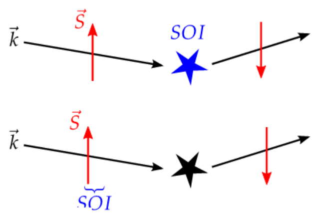
K_{EY} = 0.05 ± 0.01 (10^{-2} m^2s^{-1}) ns^{-1}
K_{DP} = 1.24 ± 0.09 (10^{-2} m^2s^{-1})$^{-1}$ ns^{-1}

SLG

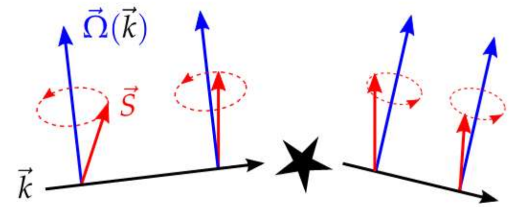
K_{EY} = 3.05 ± 0.35 (10^{-2} m^2s^{-1})ns^{-1}
K_{DP} = -0.02 ± 0.10 (10^{-2} m^2s^{-1})$^{-1}$$ns^{-1}$

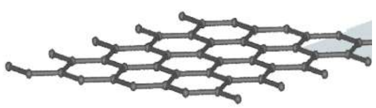
Spin relaxation in graphene

Elliot-Yafet



Dyakonov-Perel



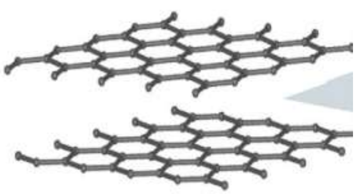


Tombros, et al, Nature (2007) ~ 150 ps, impurity (EY)

Tombors, et al, PRL(2008) Anisotropy (EY)

Jozsa, et al, PRB (2009) Linear scaling of λ & D (EY)

Han and Kawakami, PRL (2011) ~1 ns, $\tau_s \sim \tau_p(D)$ (EY)



Han and Kawakami, PRL (2011) Up to 6 ns, $\tau_s \sim 1/\tau_p(1/D)$ (DP)

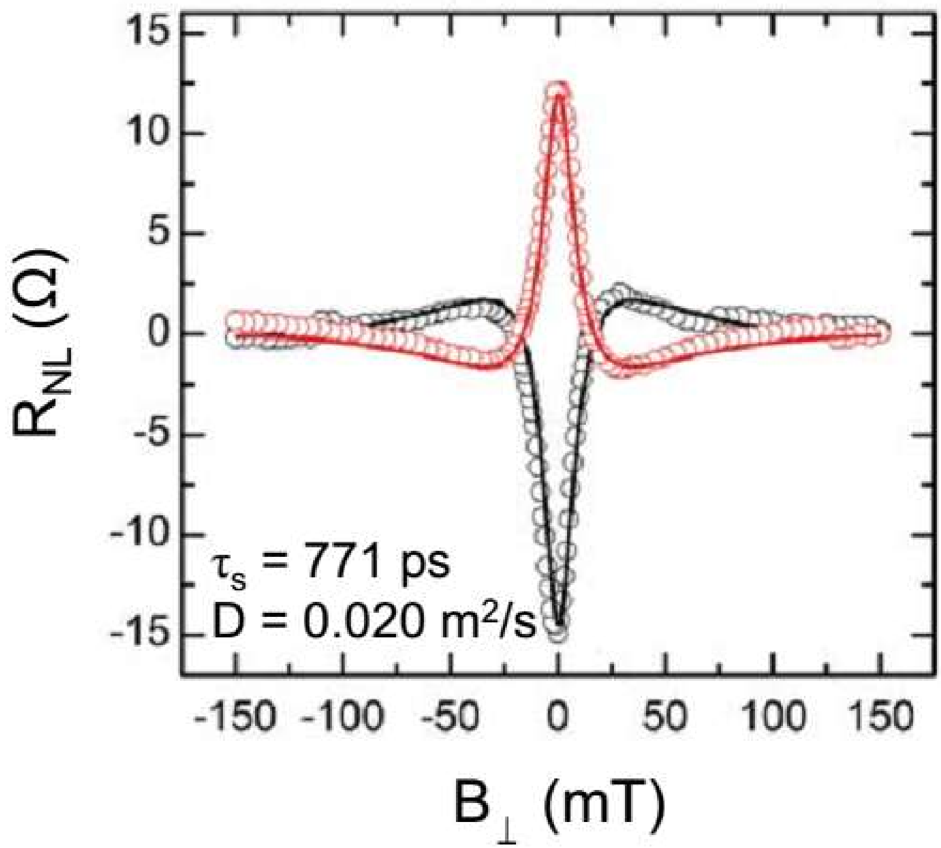
Yang, et al, PRL (2011) Up to 2 ns, $\tau_s \sim 1/\mu$ (DP)

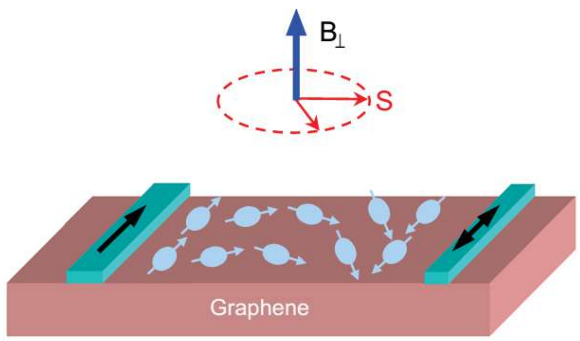
Being under investigation:
- **Random Rashba field**
- **Magnetic resonant scattering**

Wang and Wu, et al, NJP (2012)

Kochan, et al, arXiv:1306.0230 (2013)

Spin diffusion length





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

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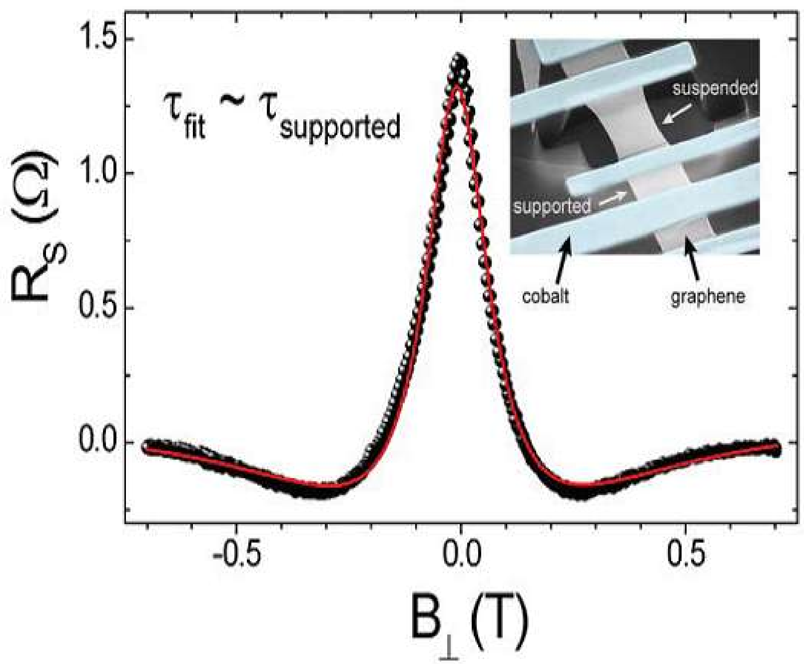
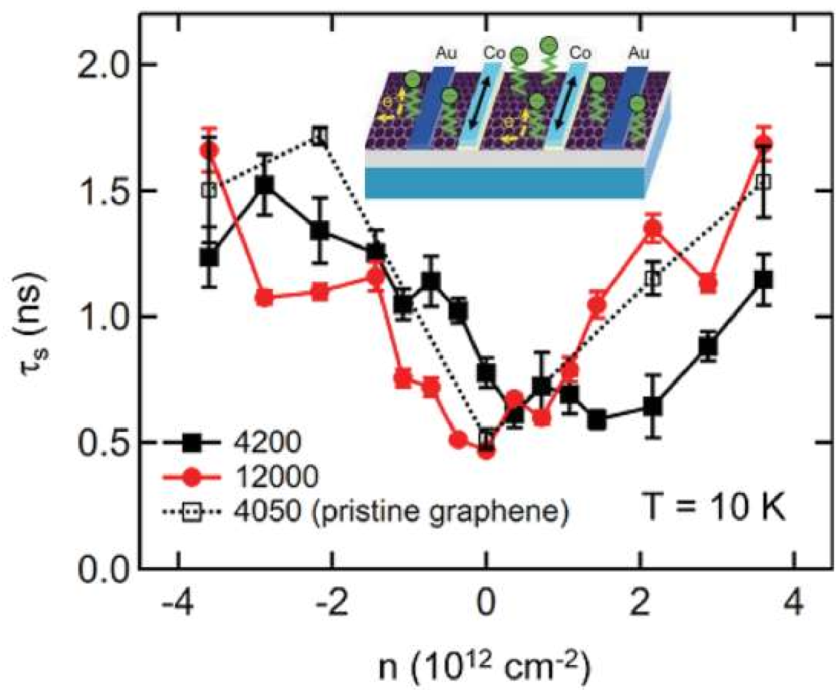
Spin diffusion length

Suspended graphene





Spin diffusion lengths 1-5 microns

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

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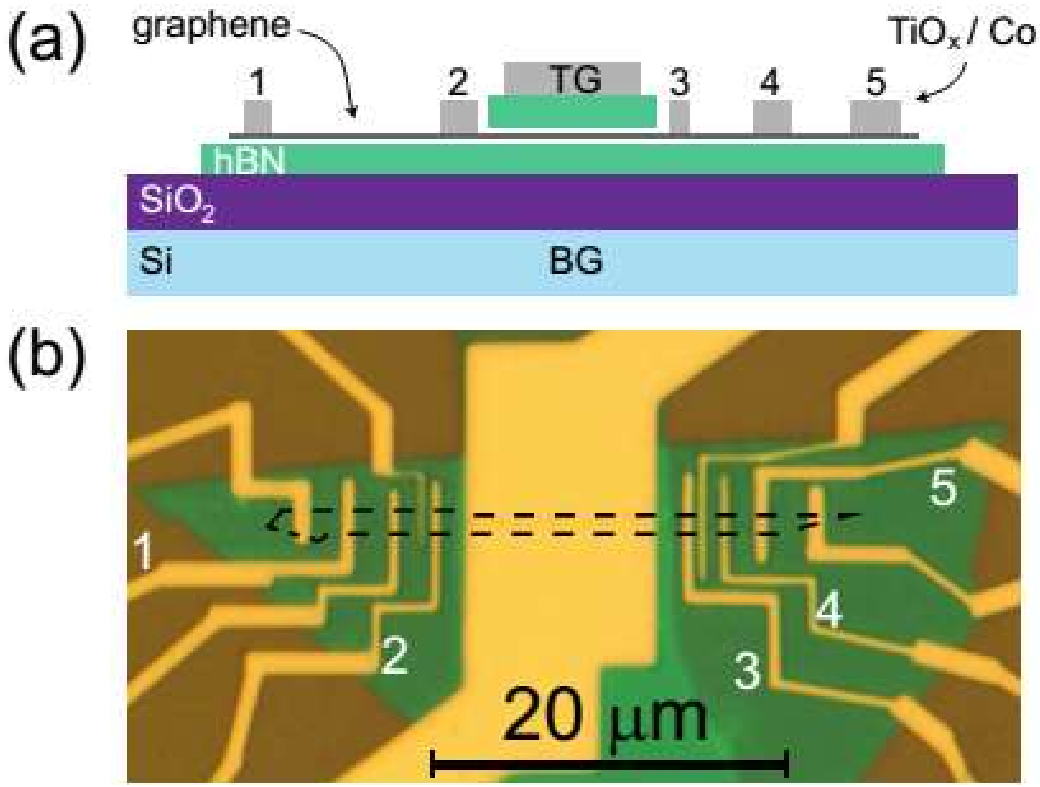
Spin diffusion length



Mobility > 1.0 m^2/Vs

Spin diffusion lengths >10 microns

Guimarães, et al, PRL (2014)
Drogeler, et al, Nano Letter (2014)

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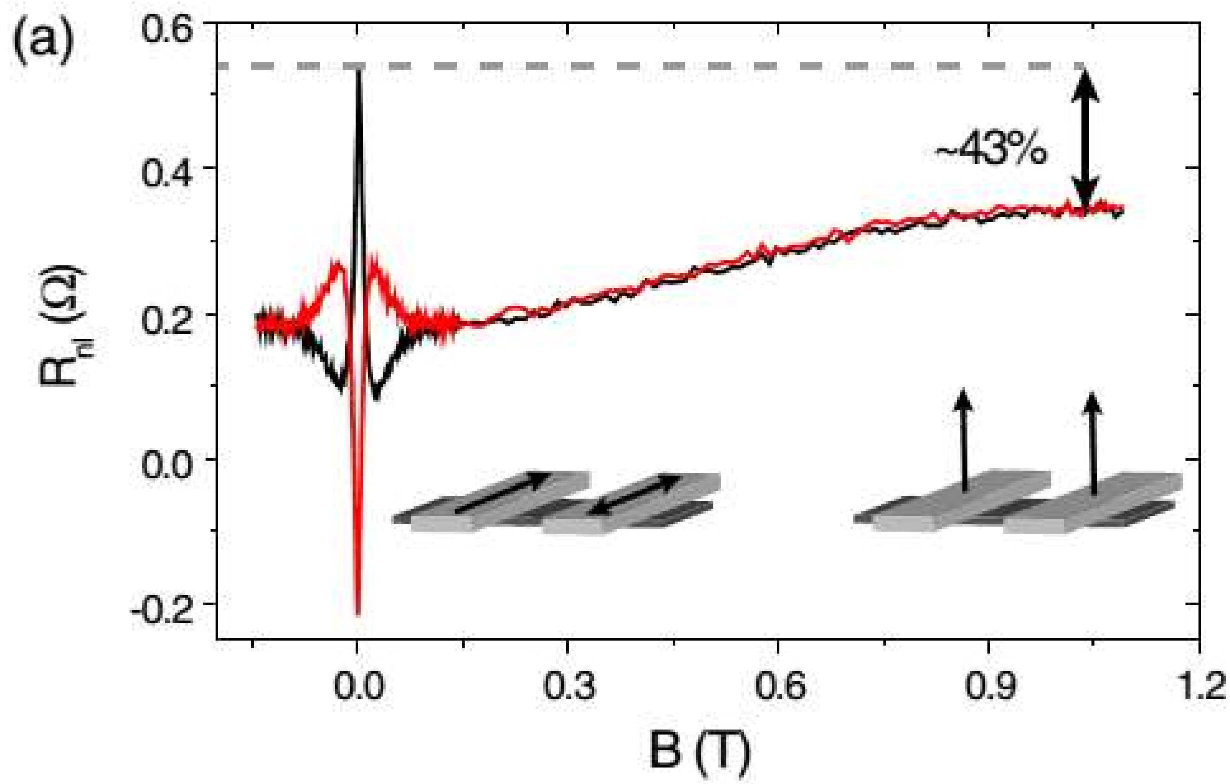
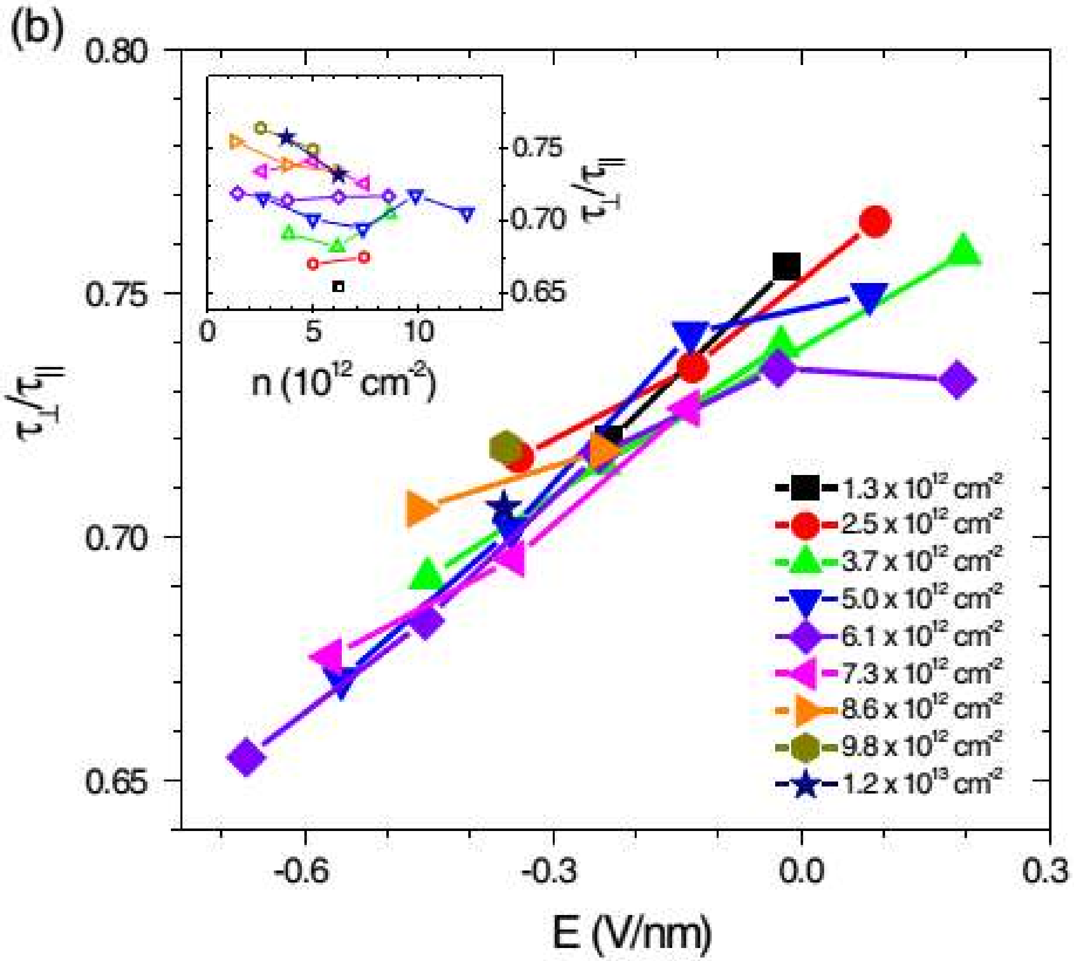
Anisotropy



Guimarães, et al, PRL (2014)

79

Anisotropy



Guimarães, et al, PRL (2014)

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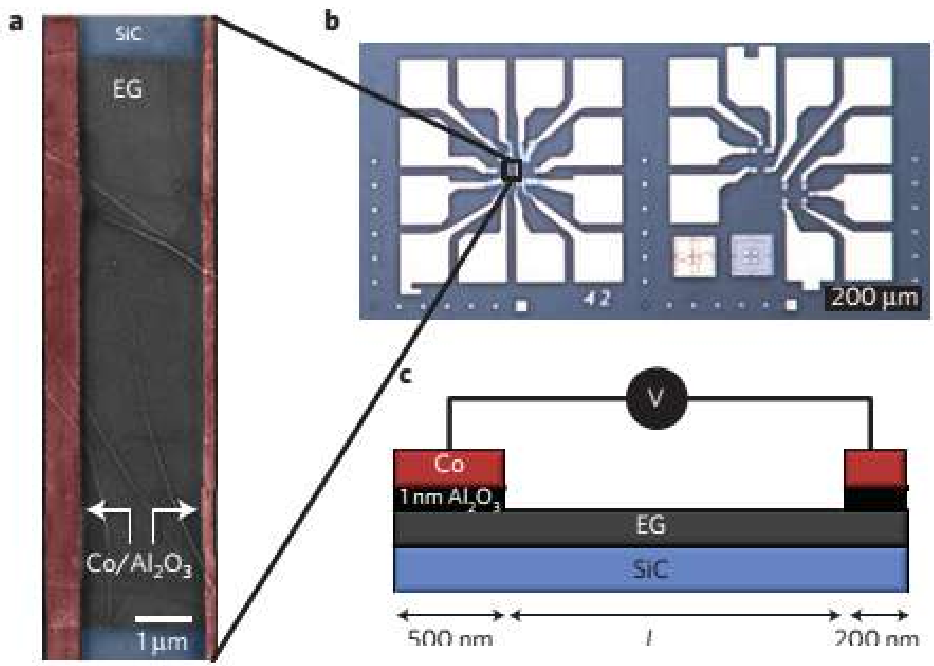
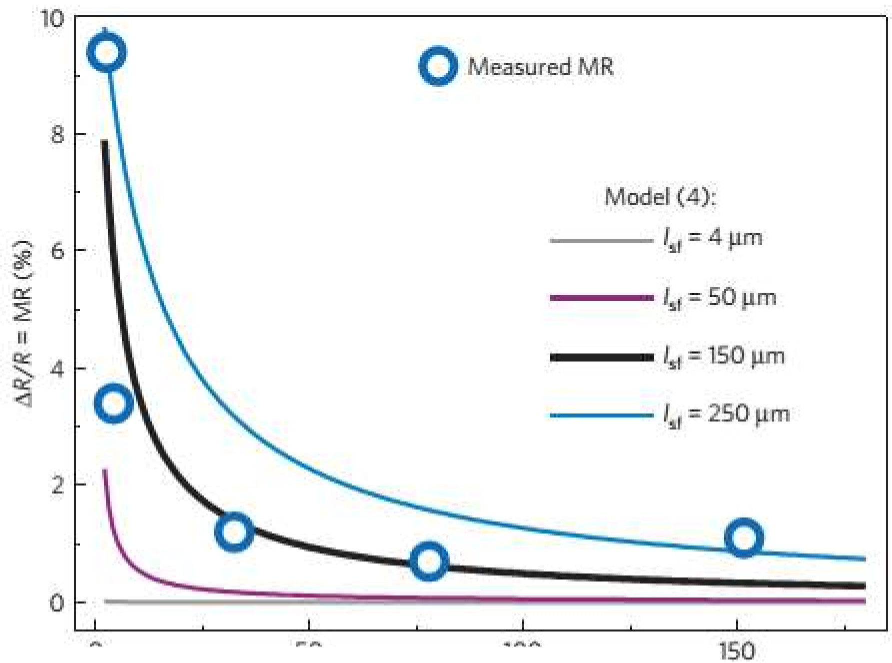
Spin diffusion length

An indirect method-- local MR measurement





Spin diffusion lengths >100 microns

Dlubak, et al, Nature Physics (2012)

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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**

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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)

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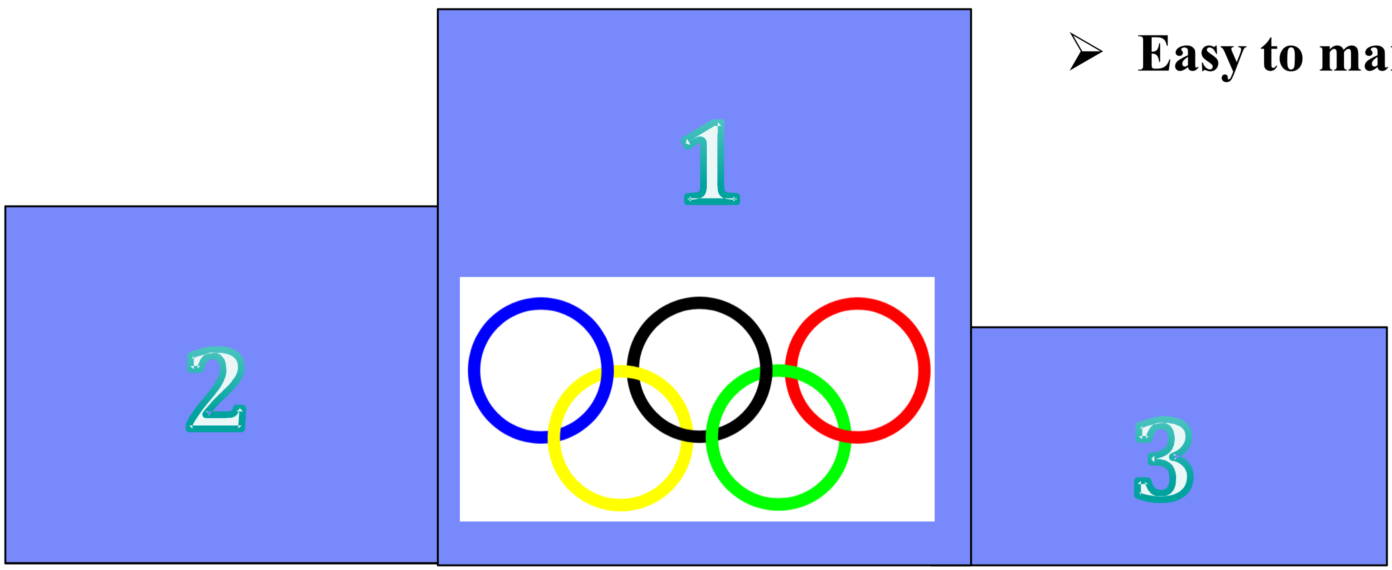
Spin properties of graphene

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

Graphene



Han, et al, Nature Nanotechnology (2014)

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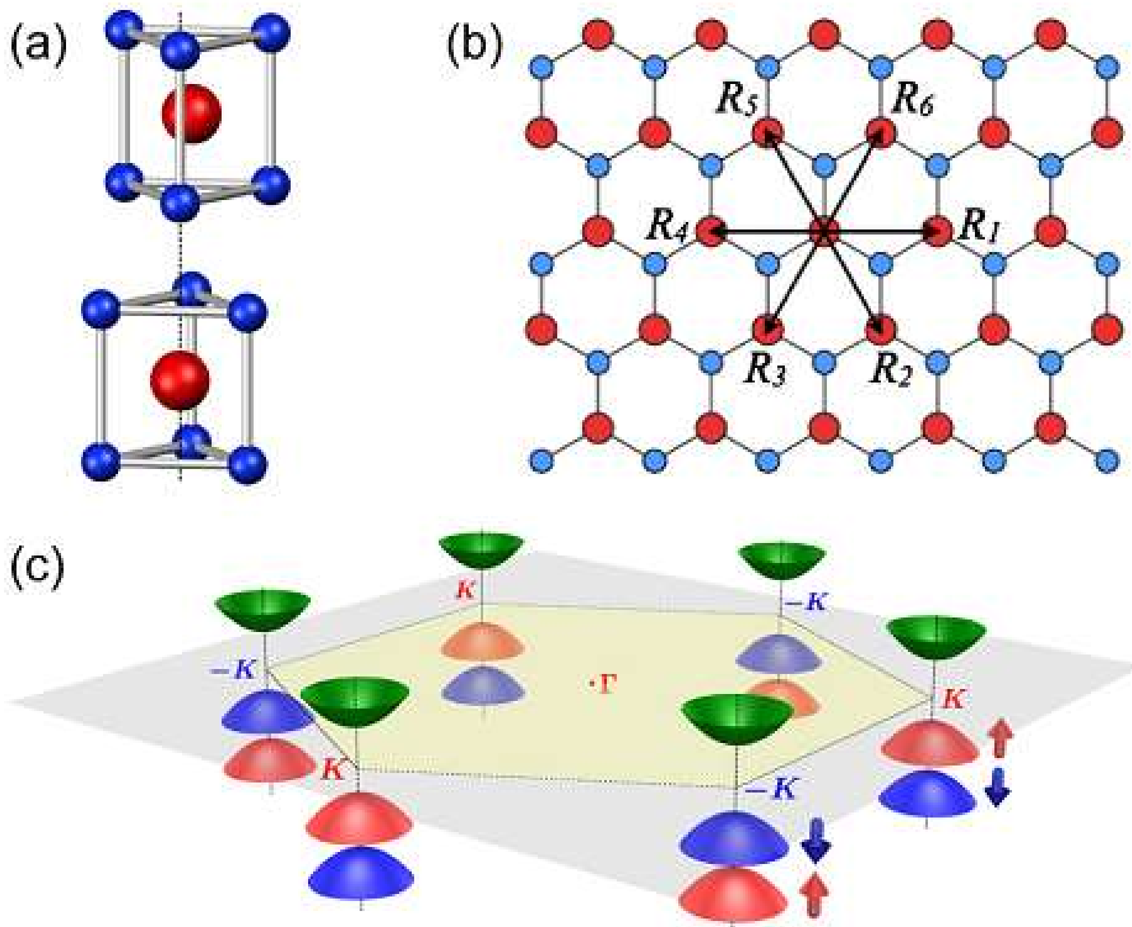
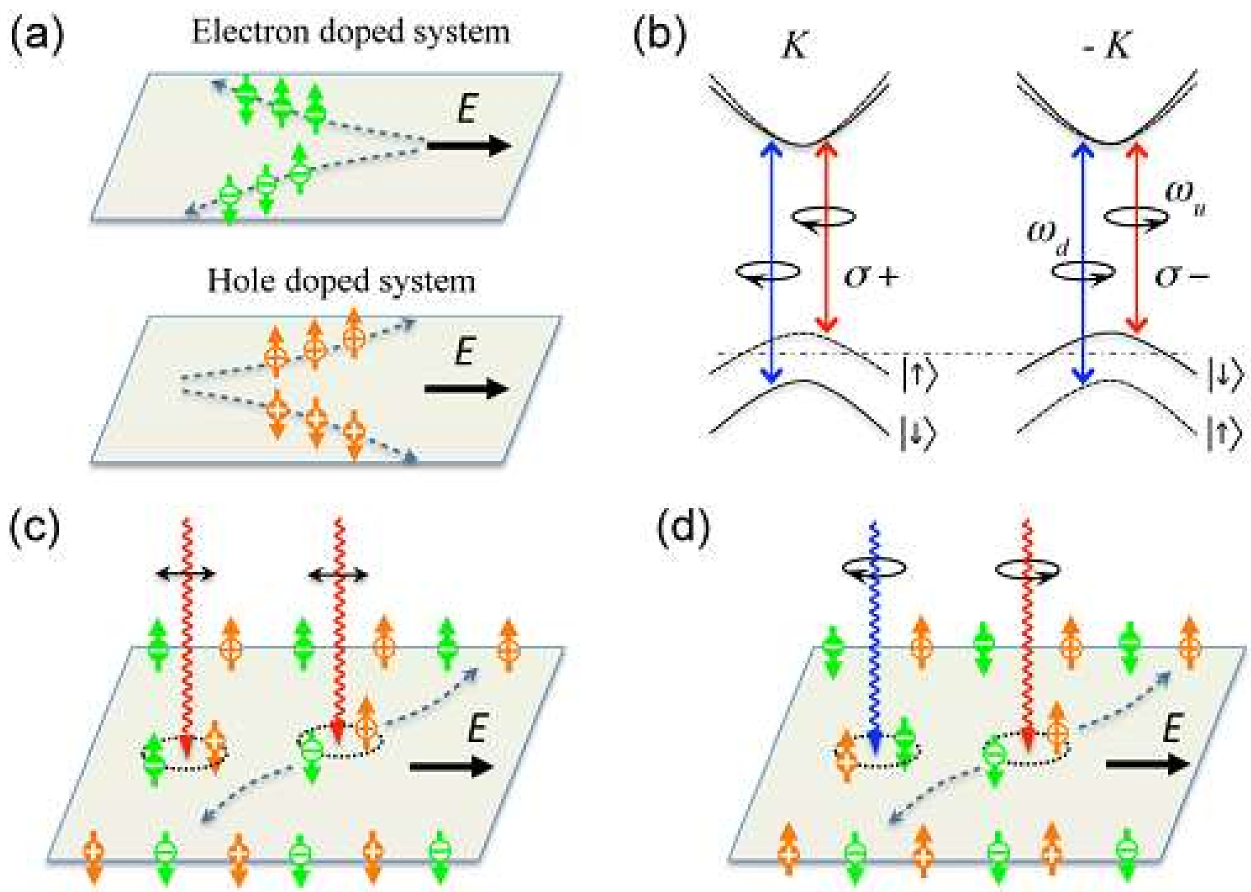
MoS2



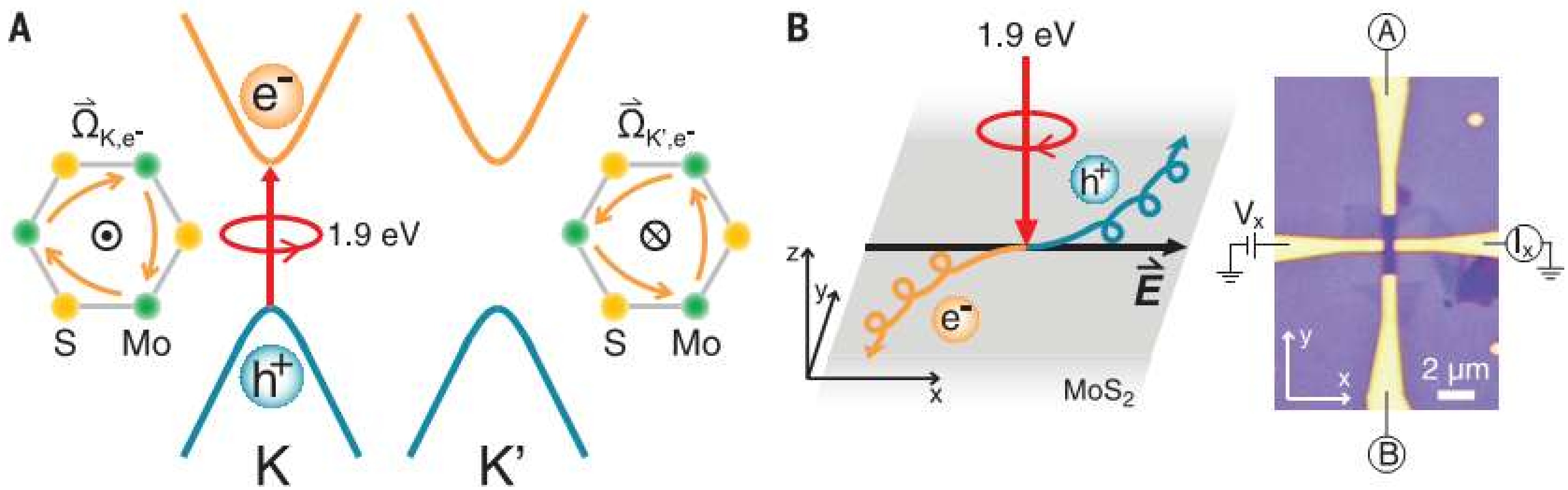
Xiao, et al, PRL (2013)

Spin and Valley Hall in MoS2



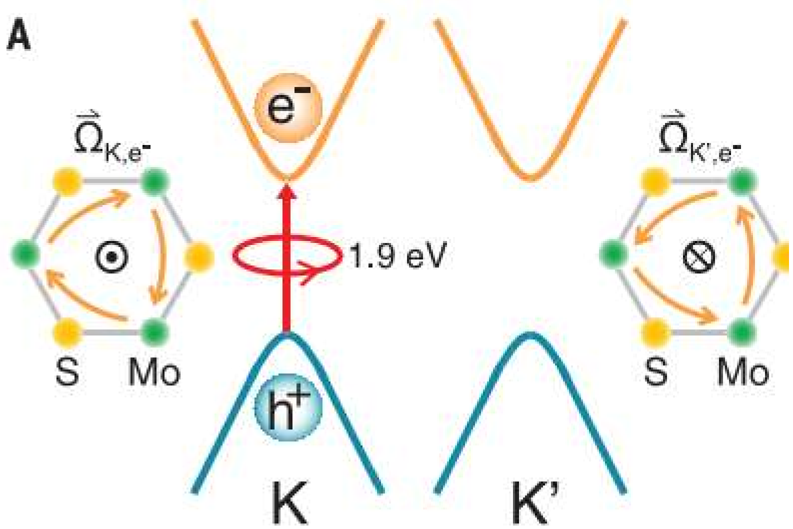
Xiao, et al, PRL (2013)

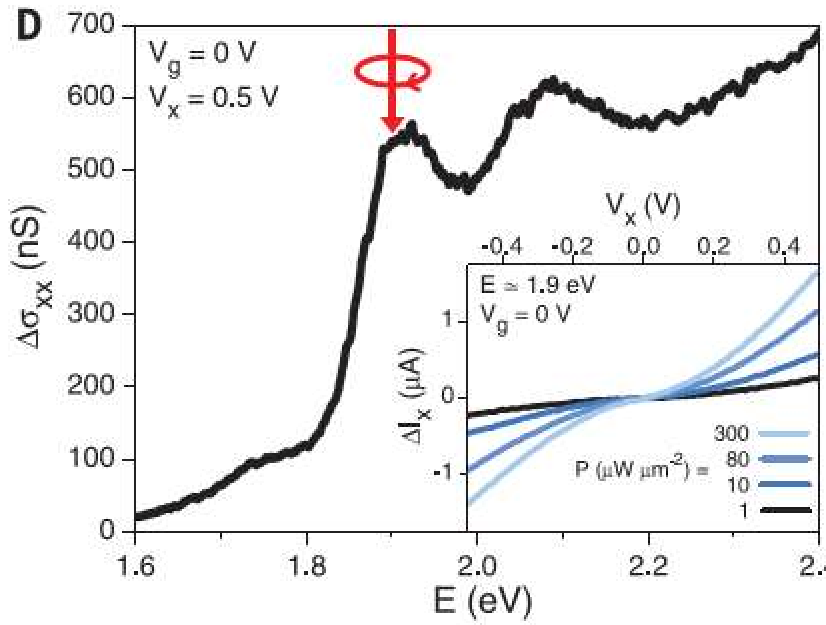
Spin and Valley Hall in MoS2



Mak, et al, Science (2014)

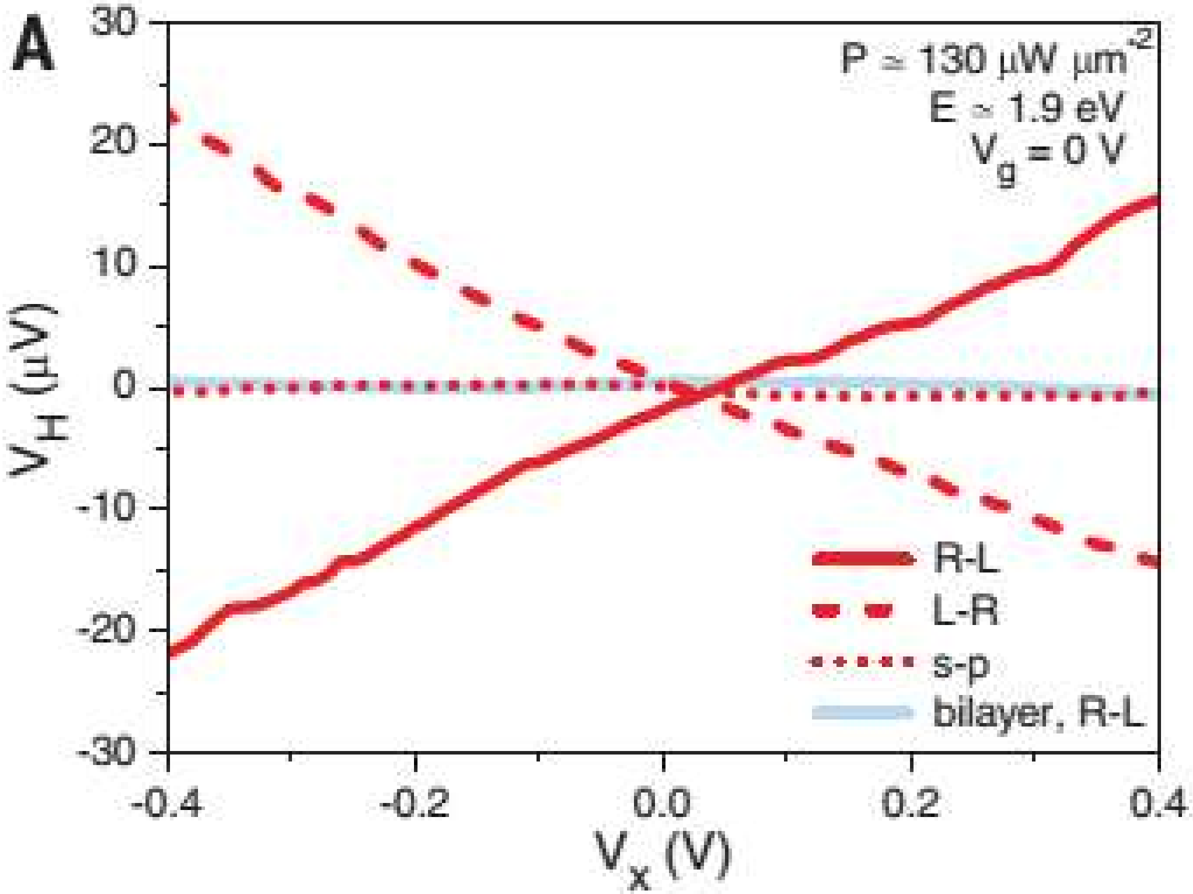
Spin and Valley Hall in MoS2



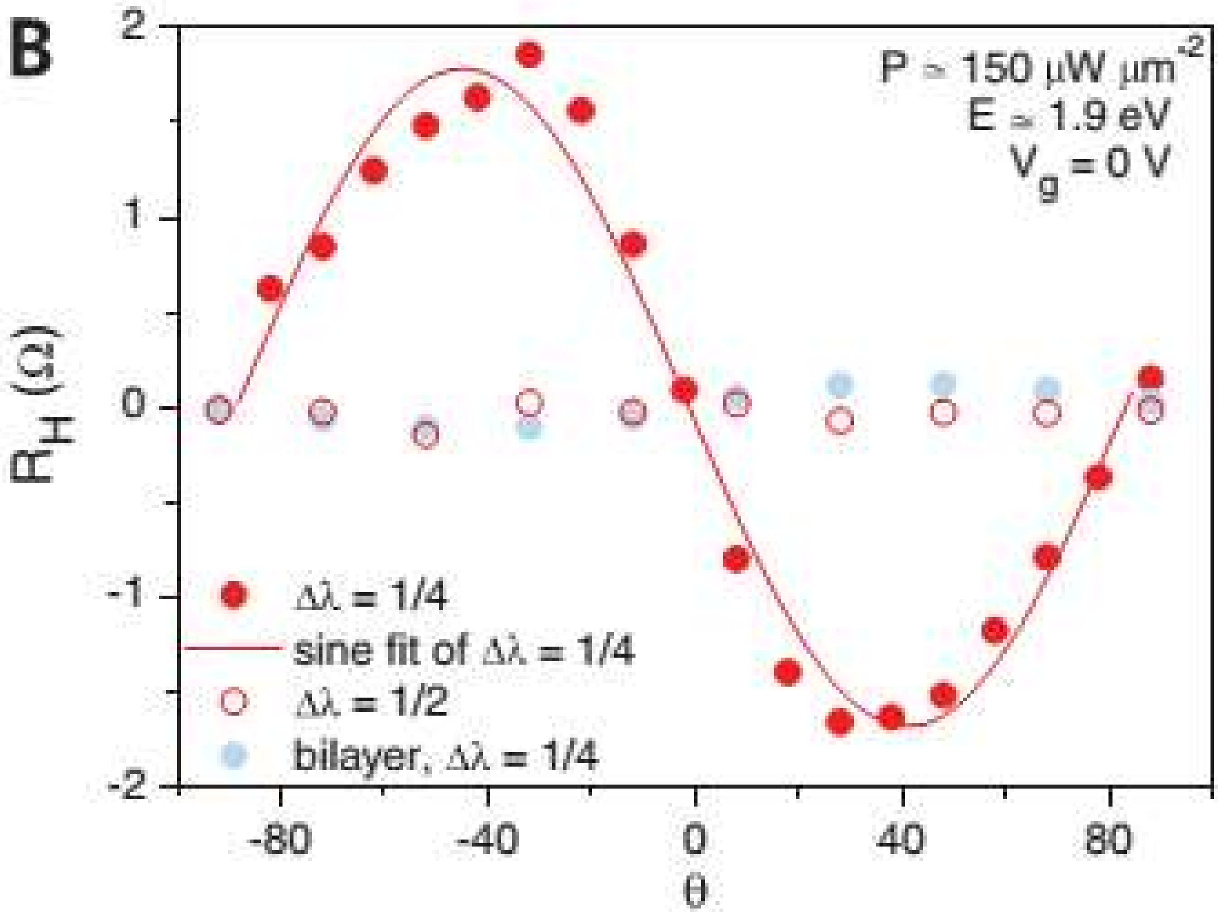


Mak, et al, Science (2014)

Spin and Valley Hall in MoS2

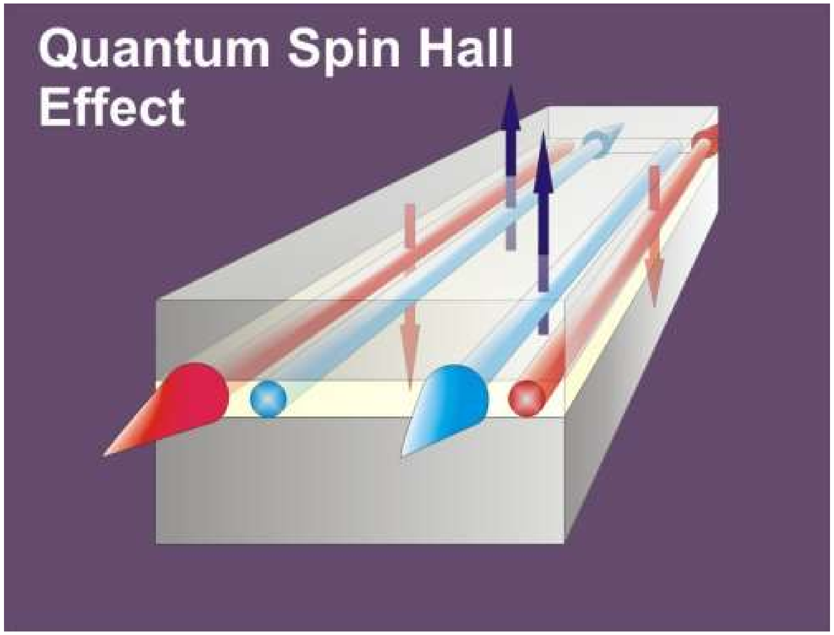


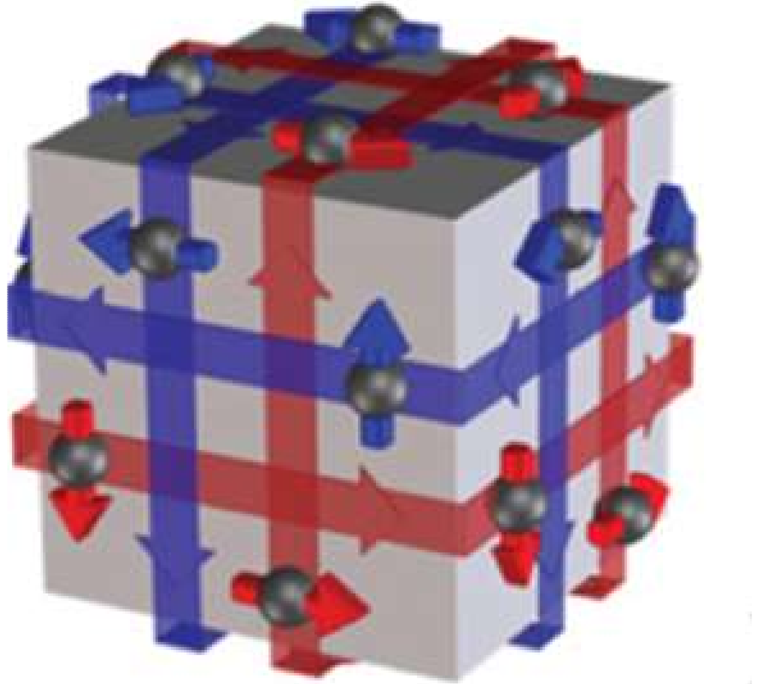
Spin and Valley Hall in MoS2



Topological insulator

Topological insulators– Spin-Momentum locking



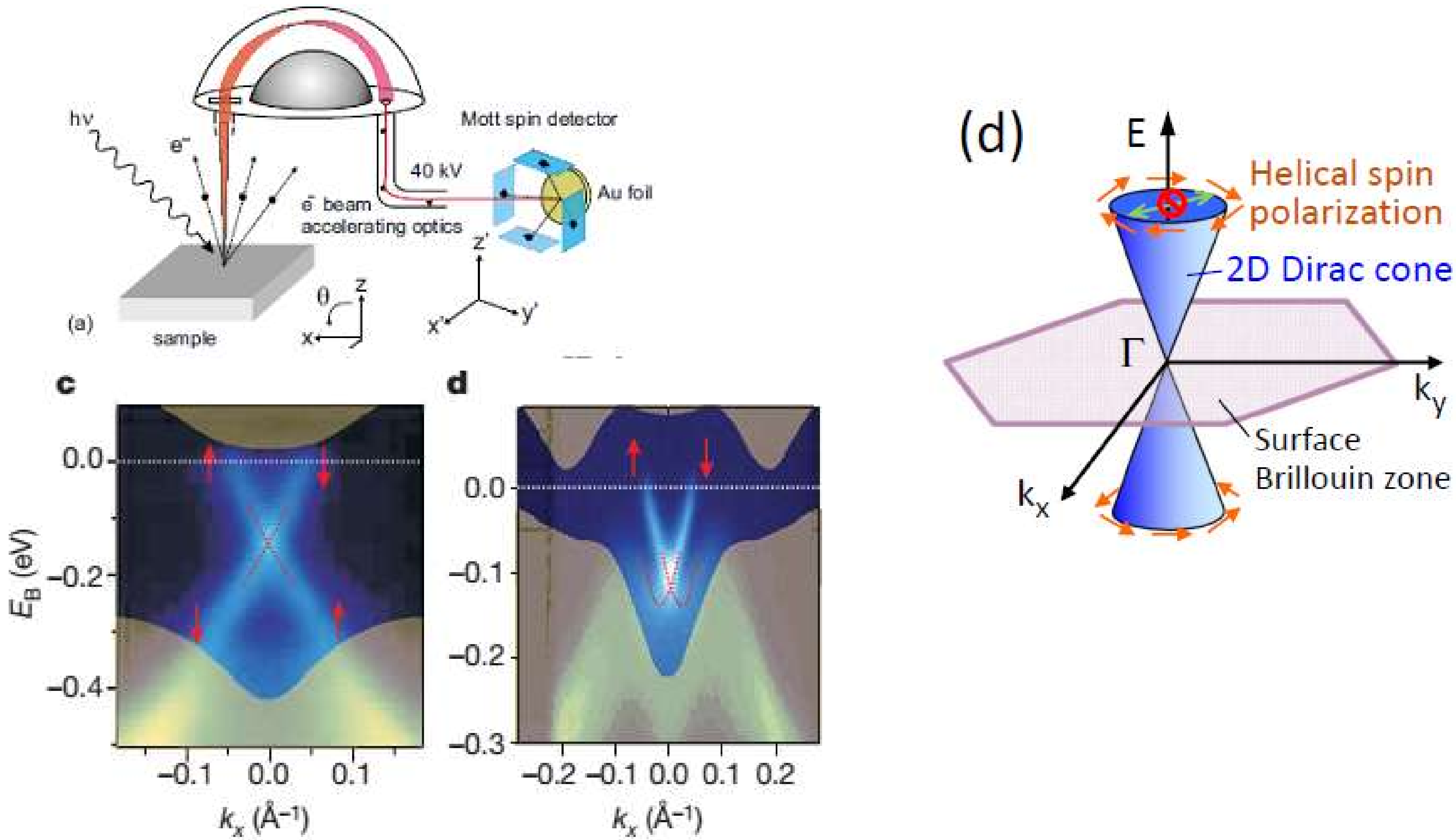


2D Topological insulator

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 (Priceton University)

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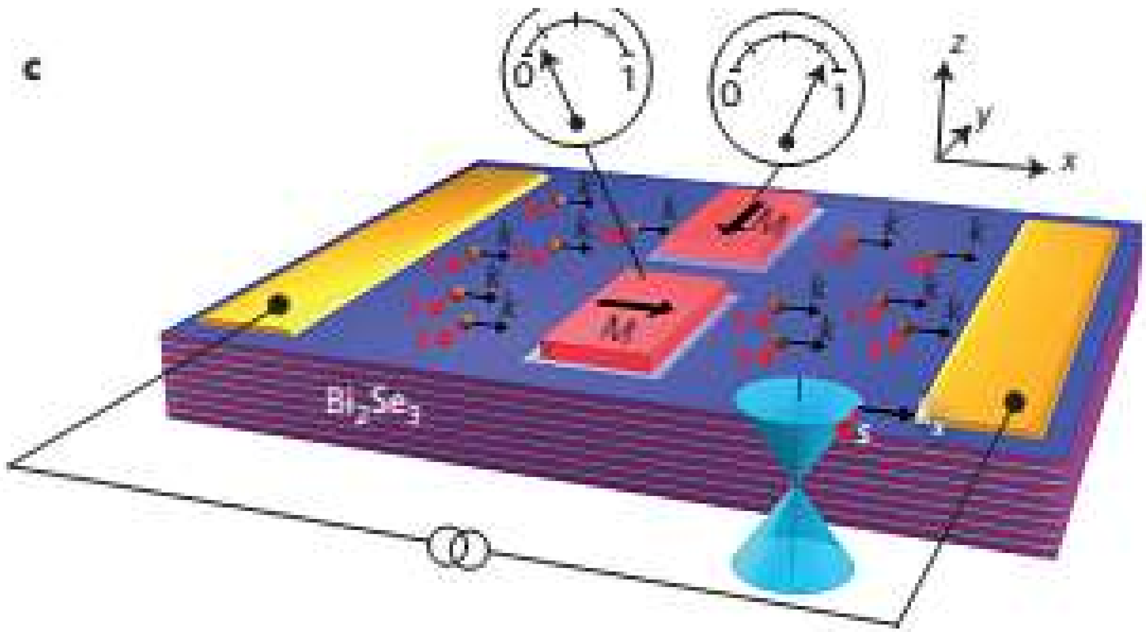
Topological insulator



Li, et al, Nature Nanotechnology (2014).

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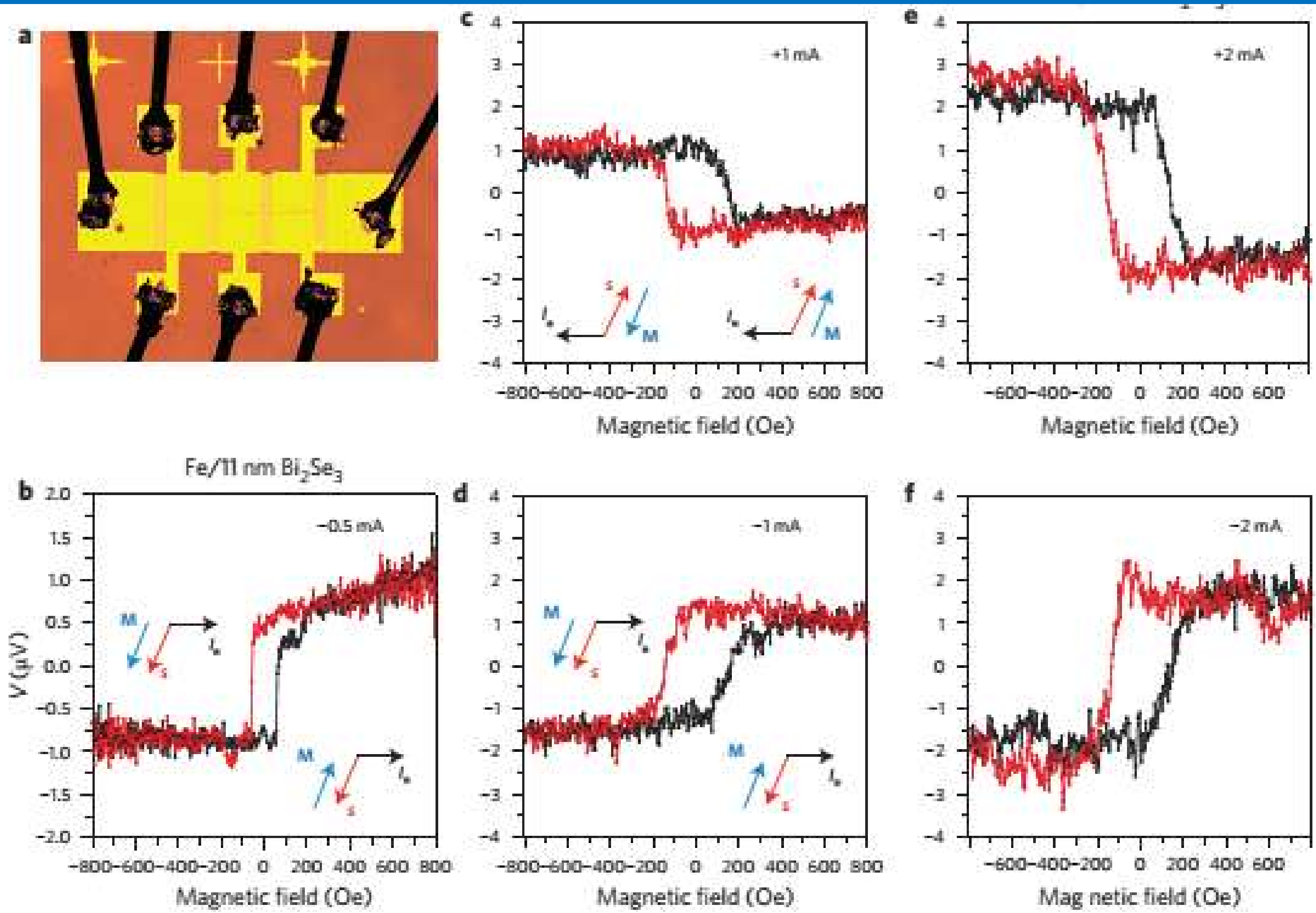
Topological insulator



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

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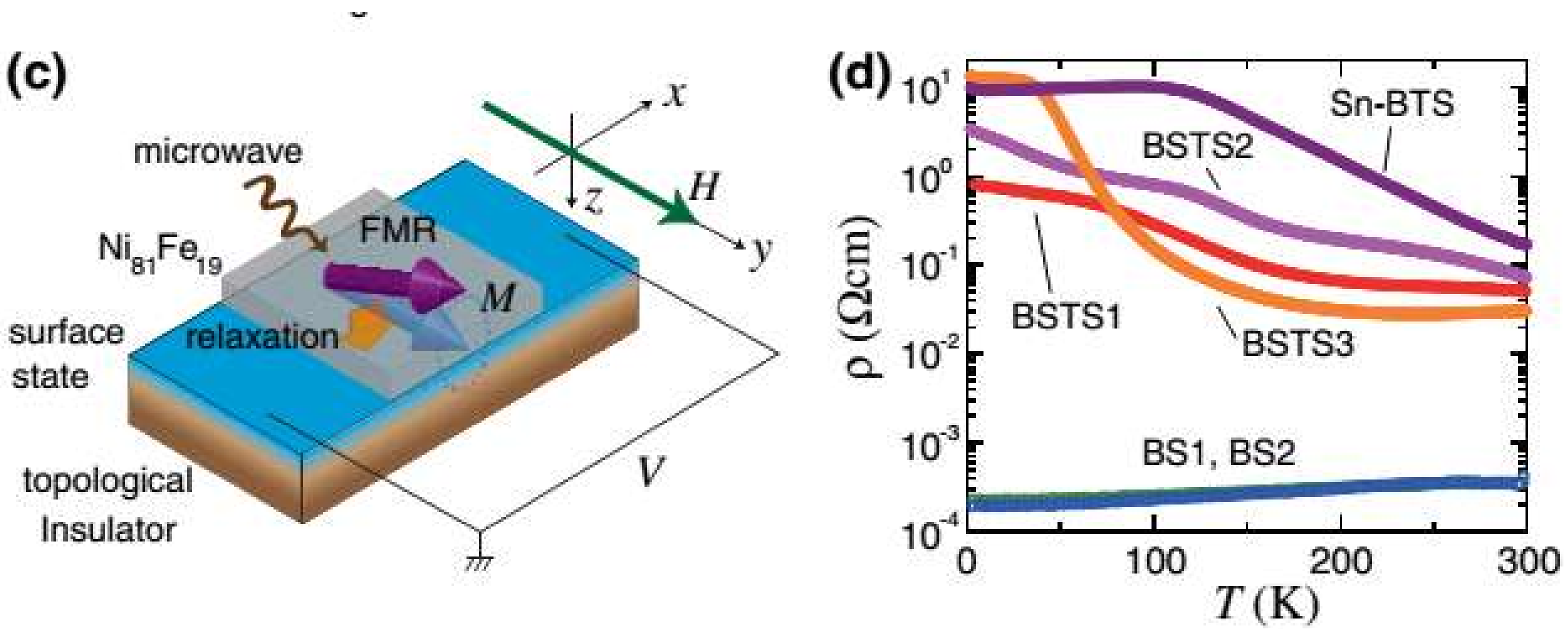
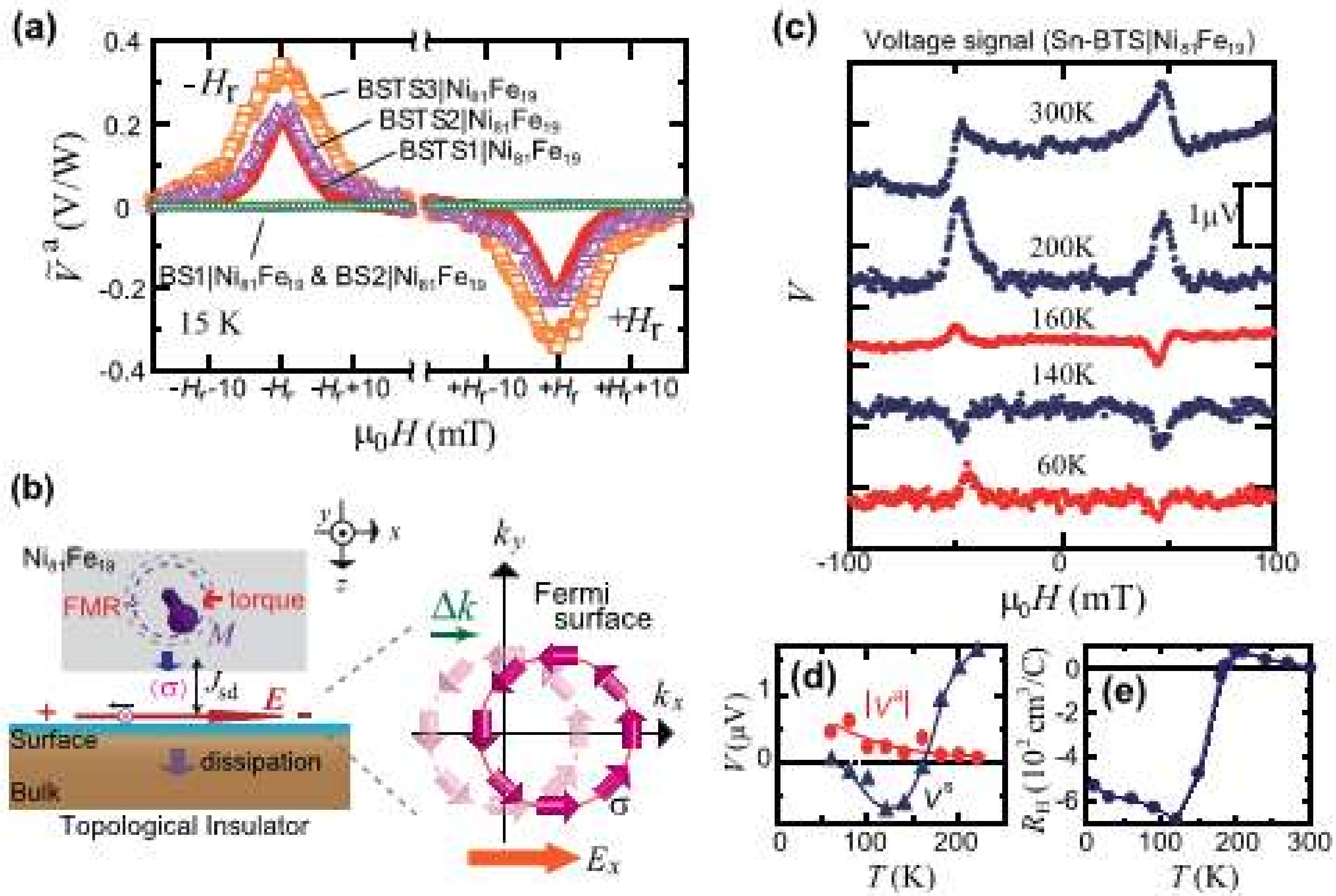
Topological insulator



Shiomi, et al, PRL (2014)

Topological insulator



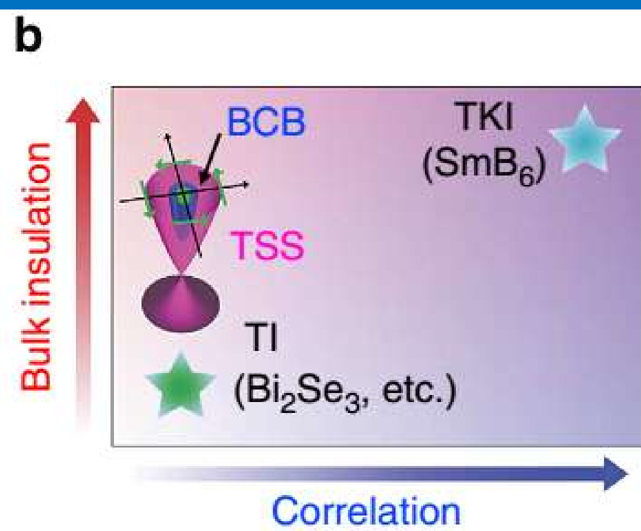
Topological insulator

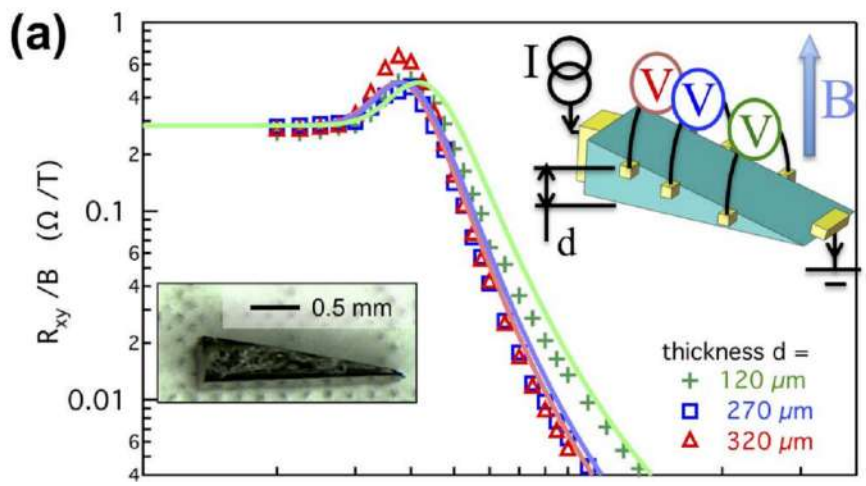
Challenge

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

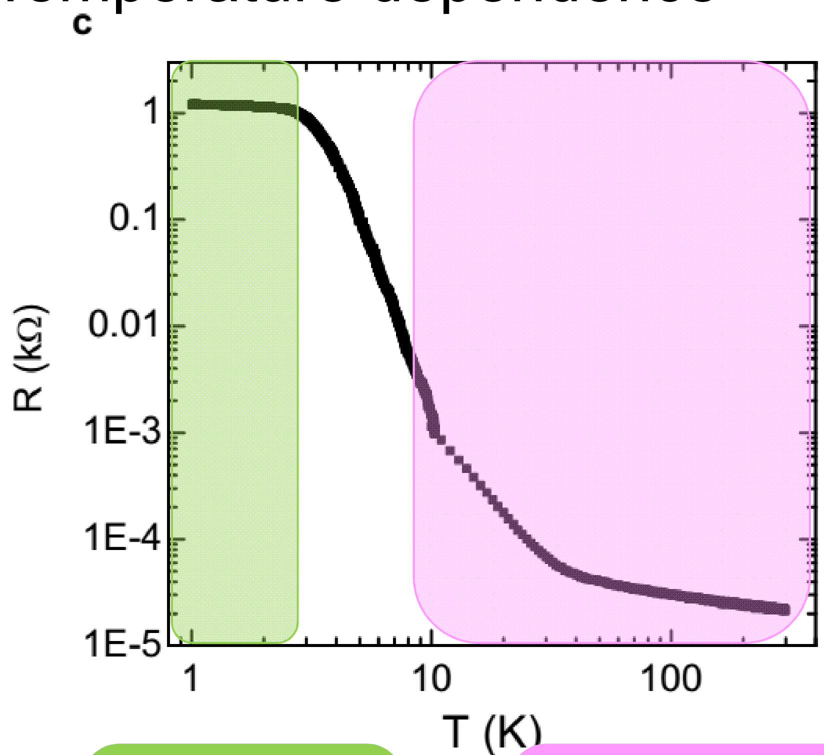




Kim et al, Scientific Reports (2013)

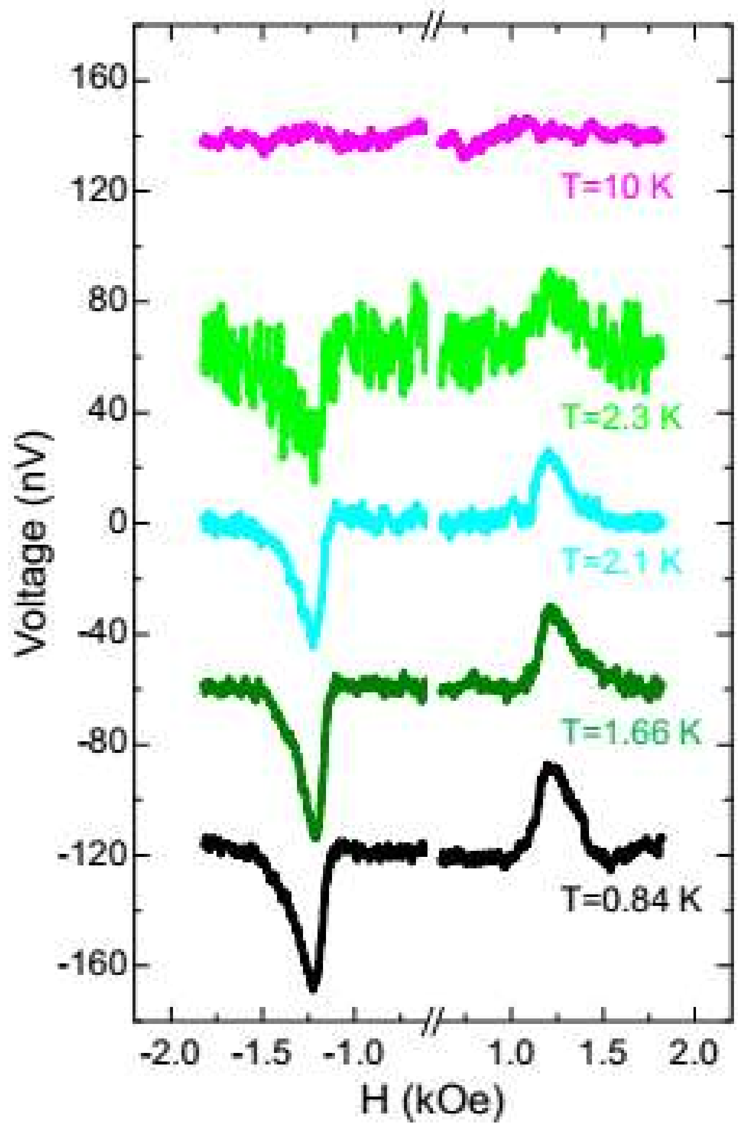
Topological insulator

Temperature dependence

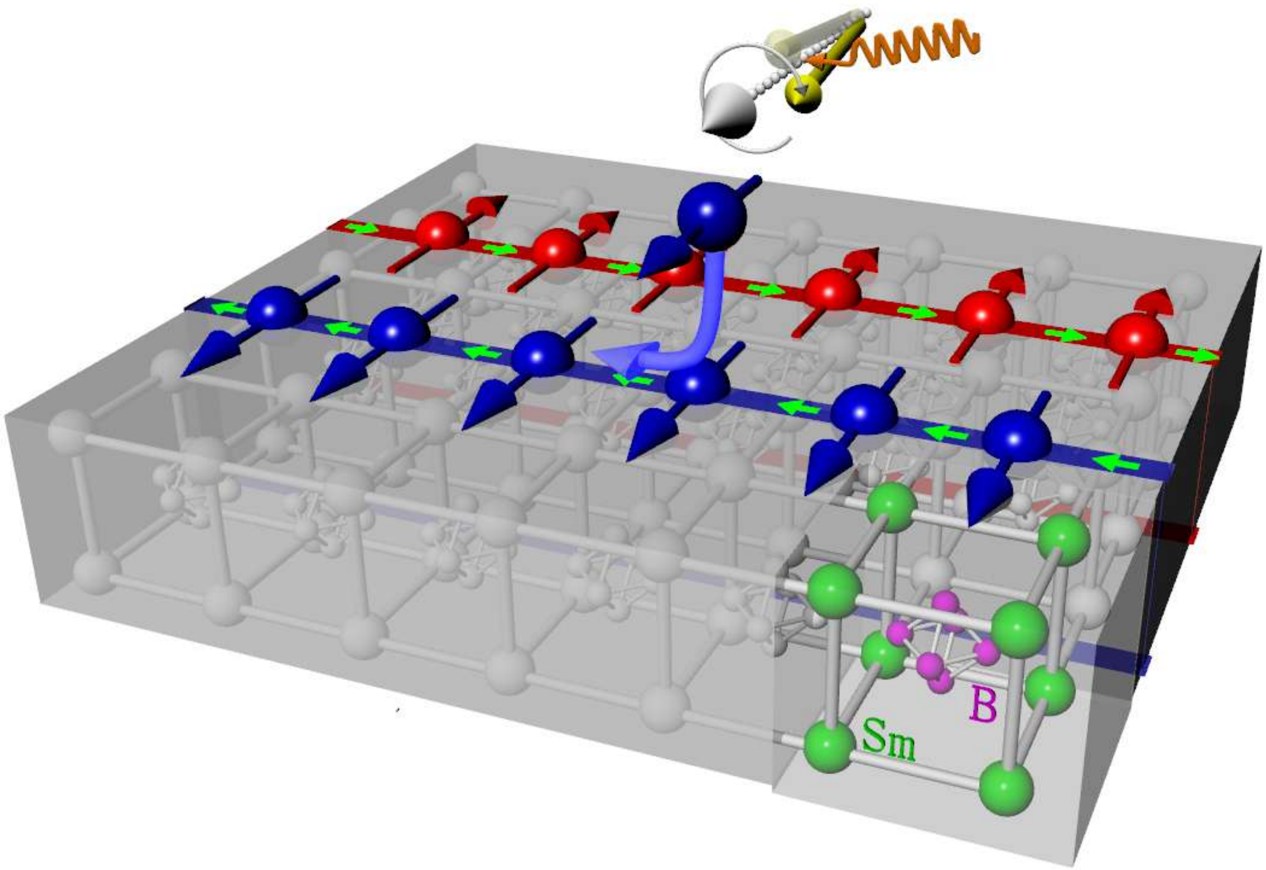


Surface states

Bulk states



Topological insulator



Song, et al, Nature Commun. (2016)

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. 8th

Chapter 5: Spin transfer torque

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

谢谢！