An Overview of Spintronics in 2D Materials

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Outline

I. Introduction to spintronics (Lecture I)

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

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

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

V. Acknowledgement

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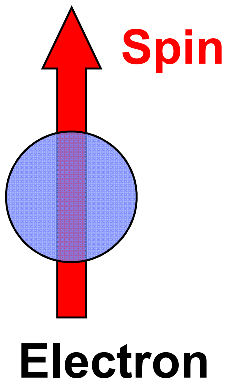
Introduction to Spintronics

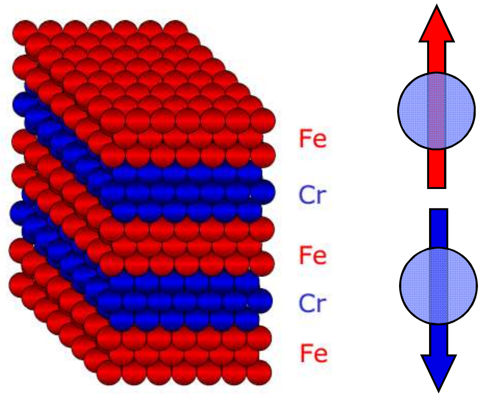
History

Introduction to Spintronics

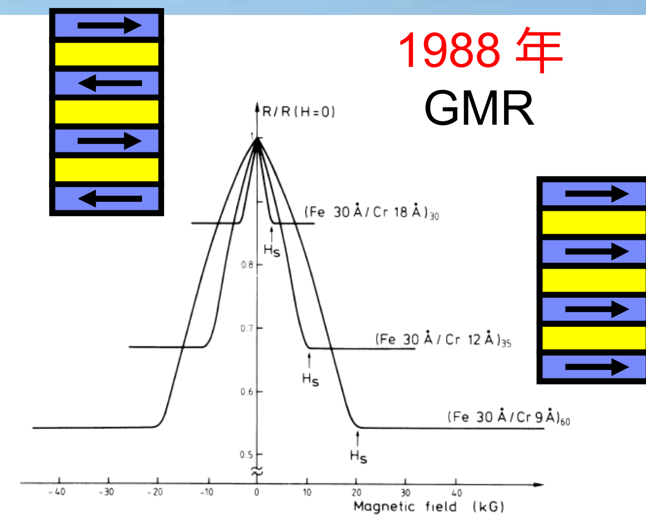
History



Magnetic structure



1988 年
GMR



Introduction to Spintronics

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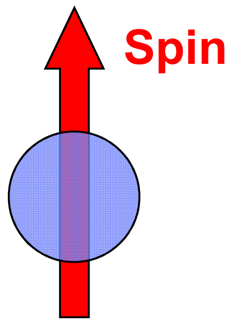
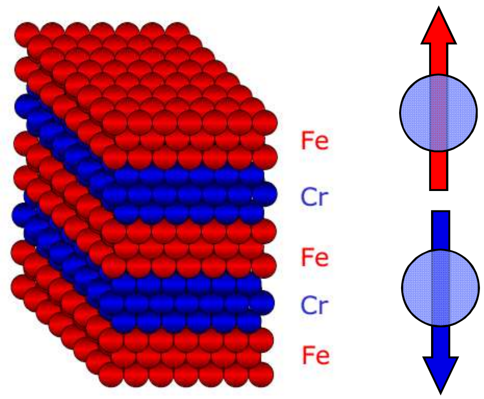


Electron

Magnetic structure



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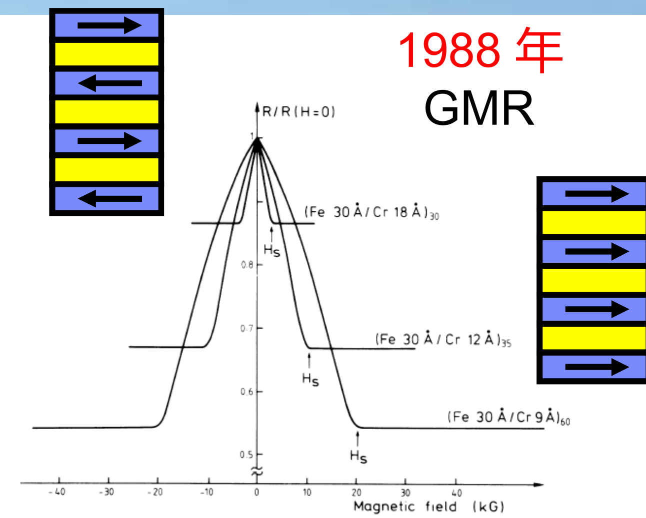
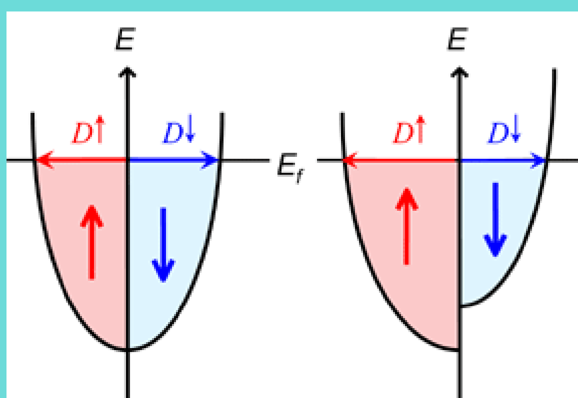
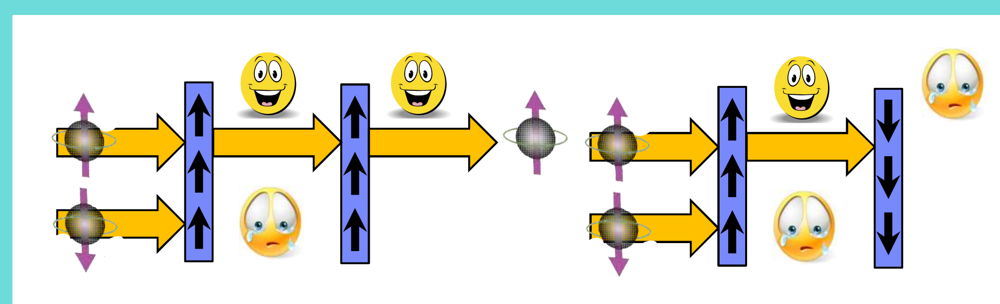




Nonmagnetic Ferromangetic

$$P = \frac{D_{\uparrow} - D_{\downarrow}}{D_{\uparrow} + D_{\downarrow}}$$

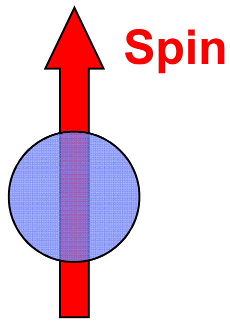
GMR



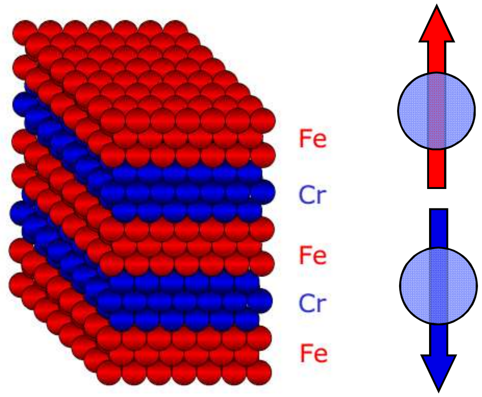
Introduction to Spintronics

History

Magnetic structure

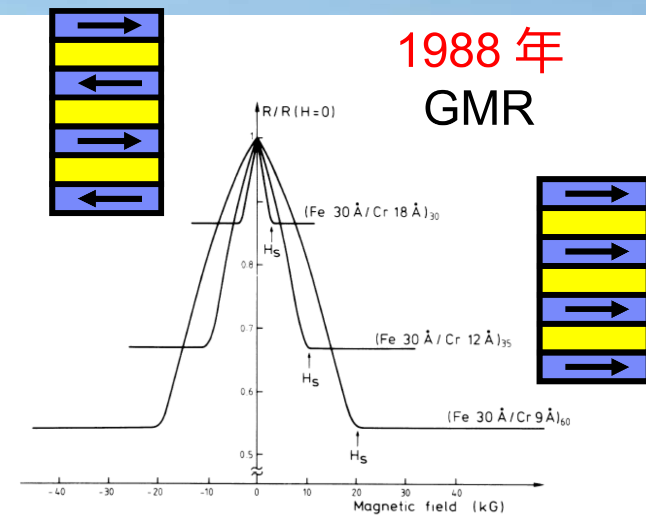


Electron



1988 年

GMR



~ 1997 年

Hard drive

Before 1997:1 GB/in^2

After GMR (in 2007): 300 GB/in^2

Introduction to Spintronics

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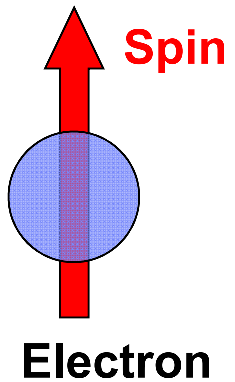

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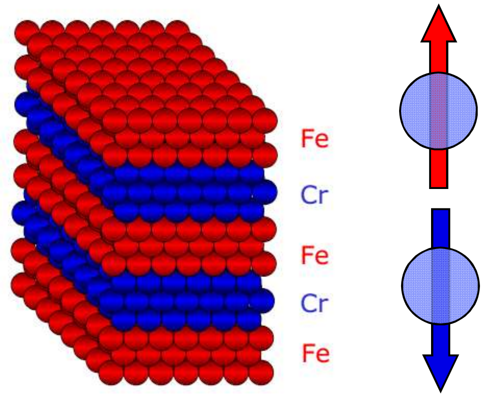
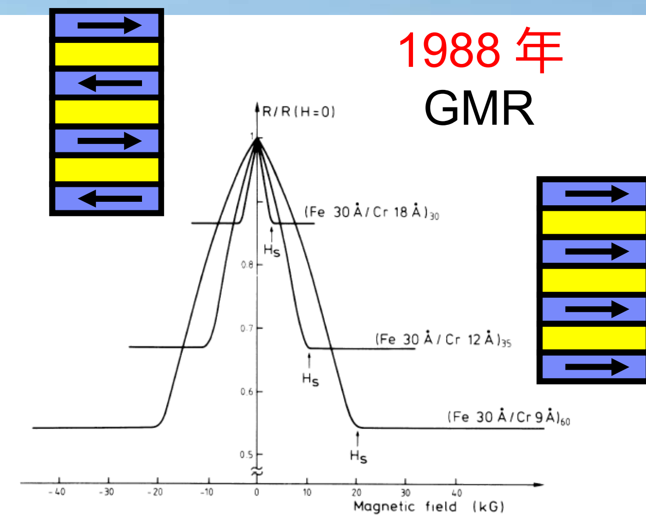
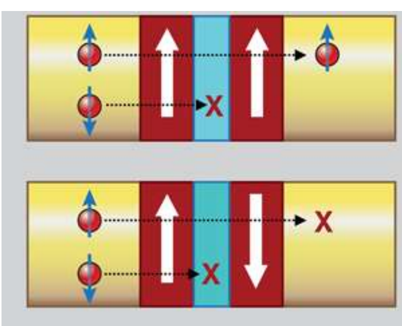


1988 年
GMR



~ 1997 年
Hard drive

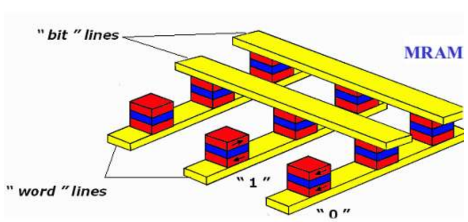
1991-2004
TMR



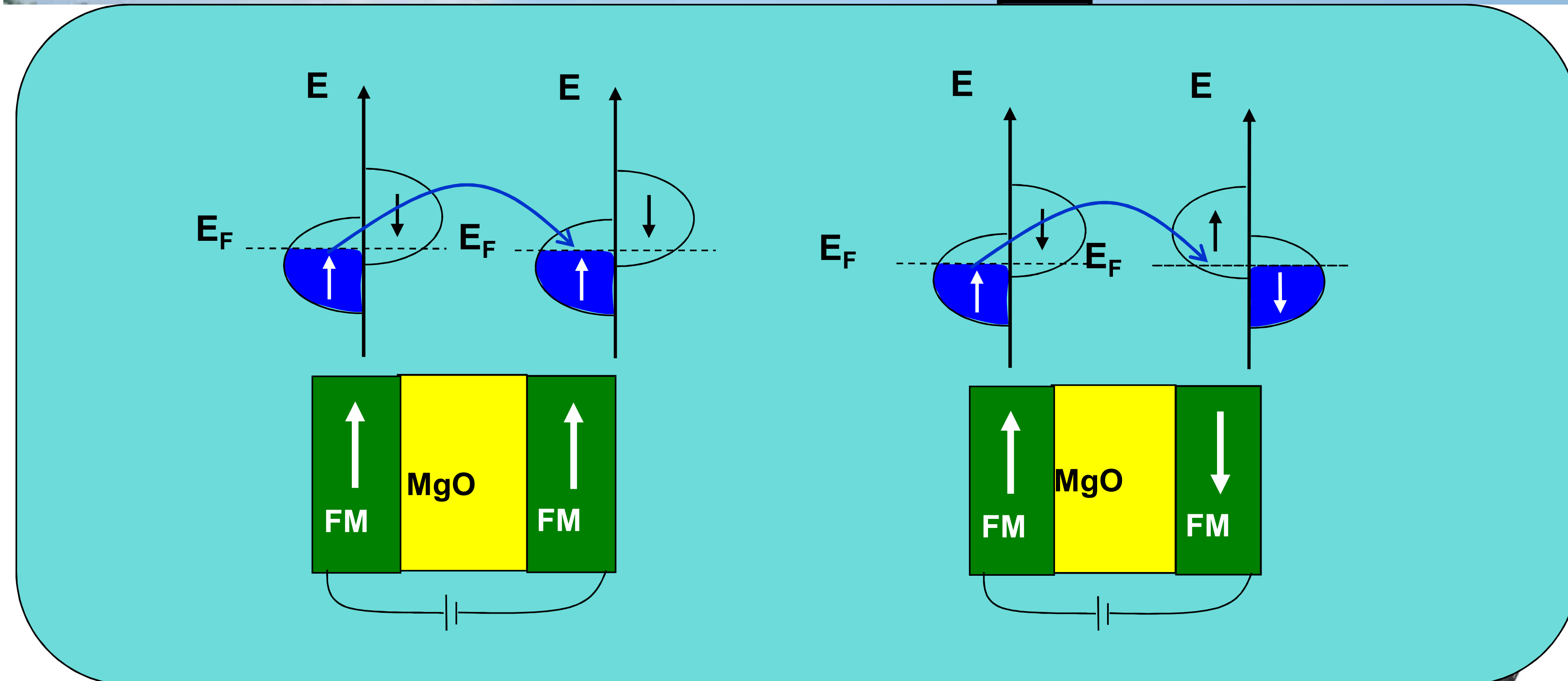
Low R

High R

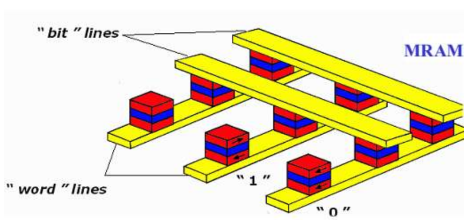
2001- present
MRAM



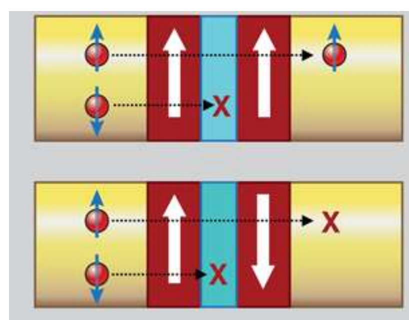
Introduction to Spintronics



2001-- Present
MRAM



TMR

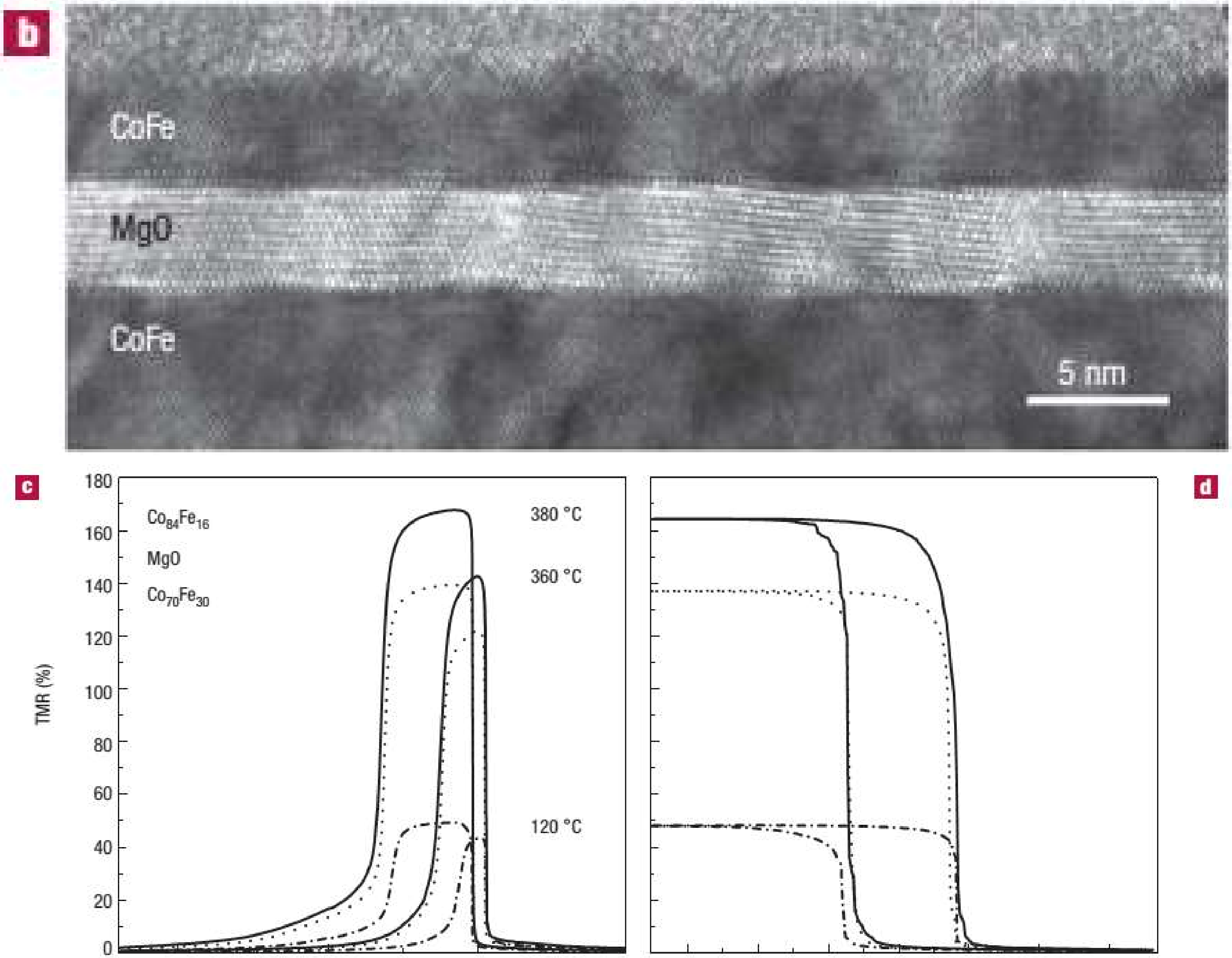


Low R

High R

~ 1997 年
Hard drive

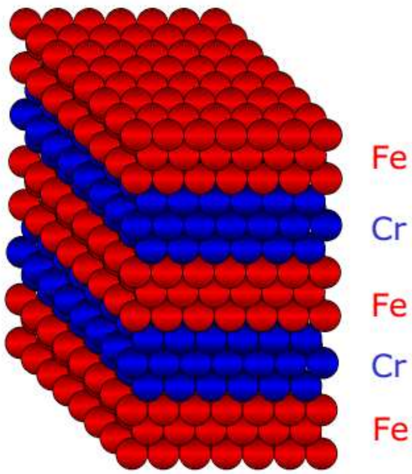
Introduction to Spintronics

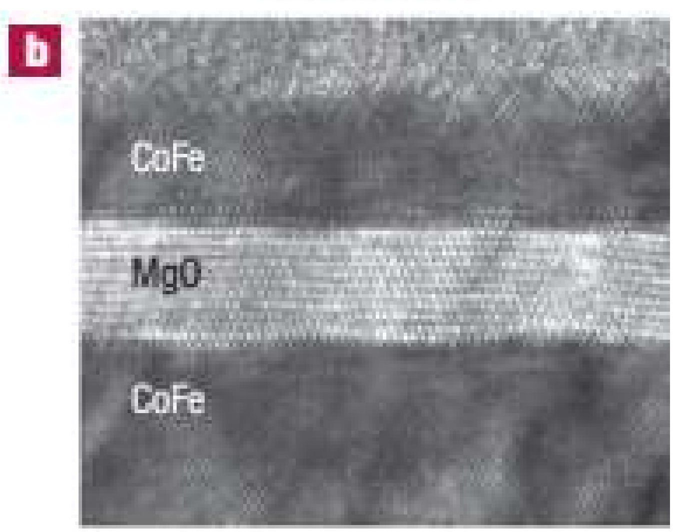


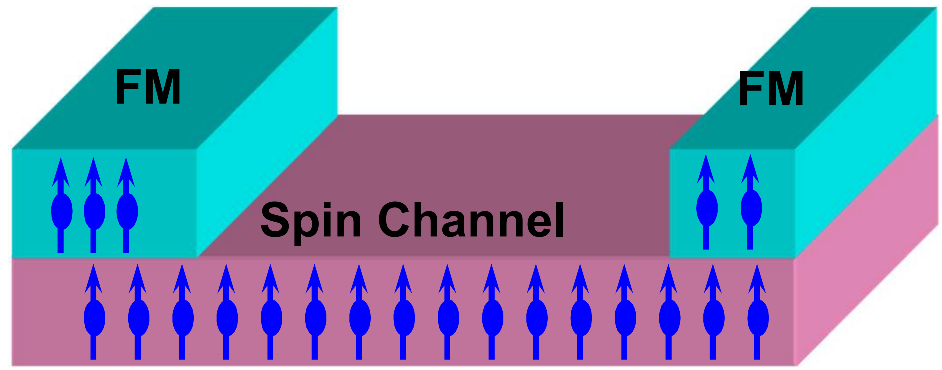
Parkin, et al, Nature Materials (2004)
Also see Yuasa, et al, Nature Materials (2004)

Introduction to Spintronics

From Vertical to Lateral





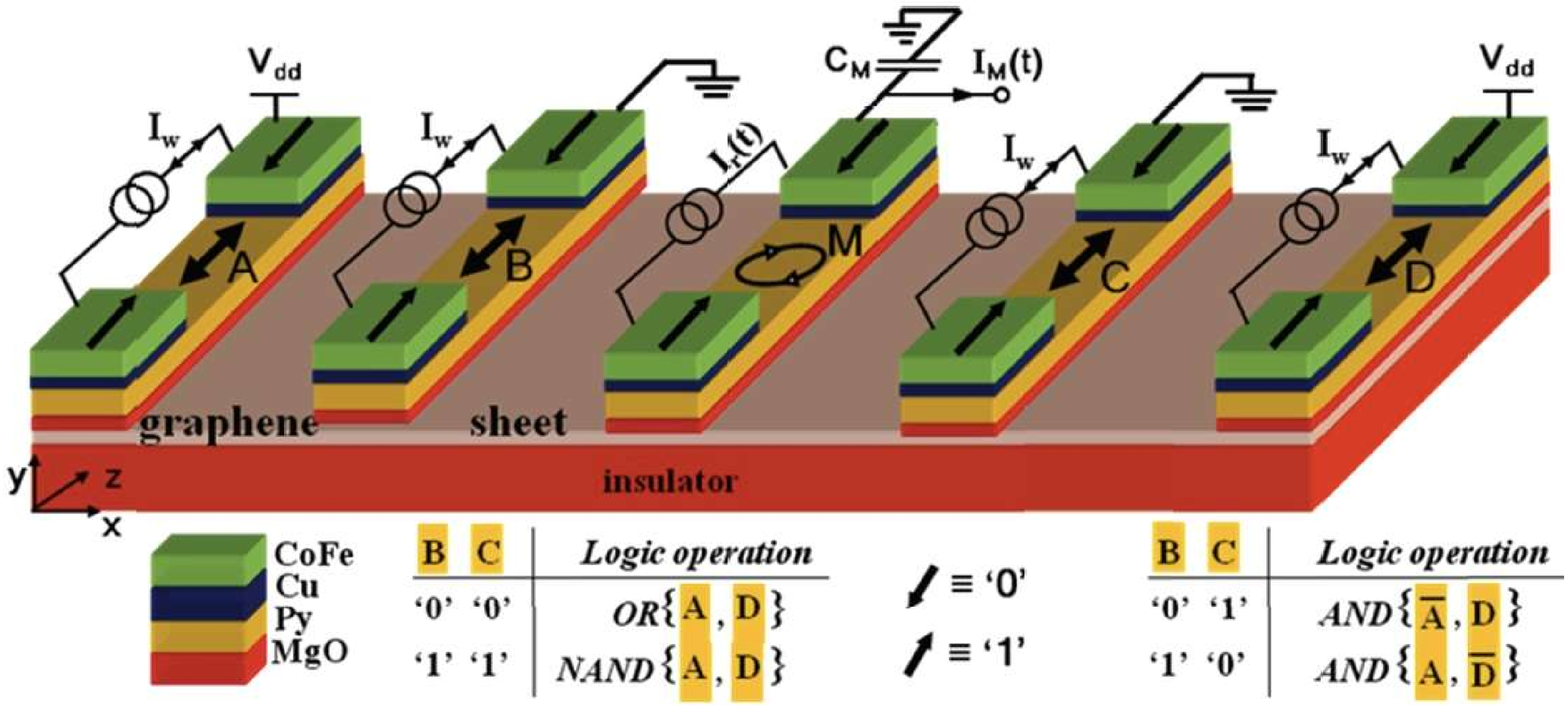


A route
→ to tune the spin

Wolf, et al, Science (2001)

Introduction to Spintronics

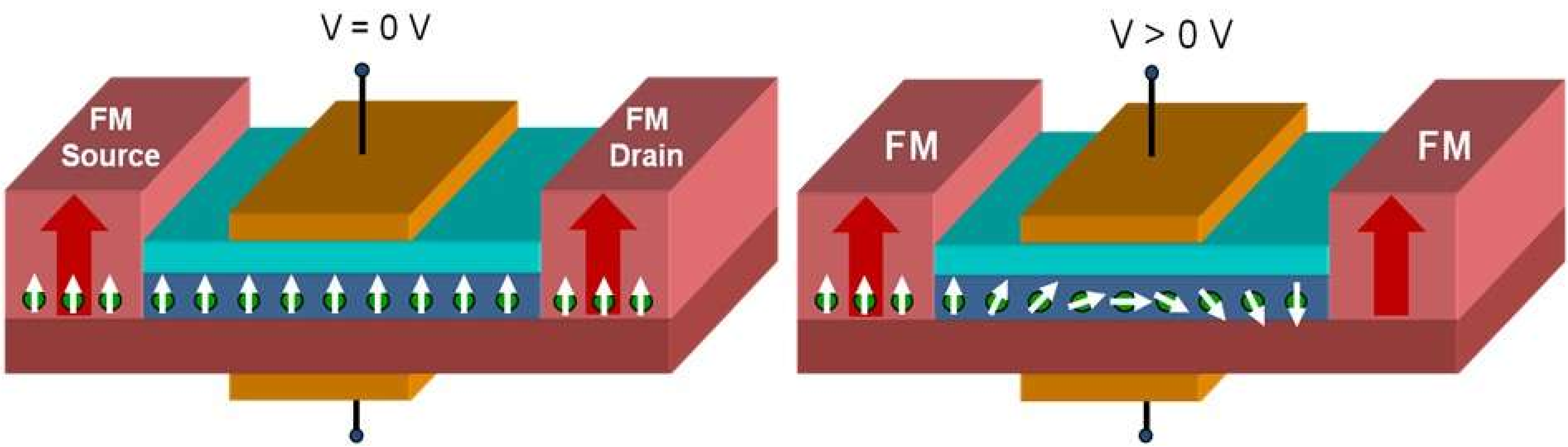
1) Spin logic applications



Dery, et al, Nature (2007)
Dery, et al, IEEE Trans. Elec. Dev. (2012)

Introduction to Spintronics

2) Spin transistor



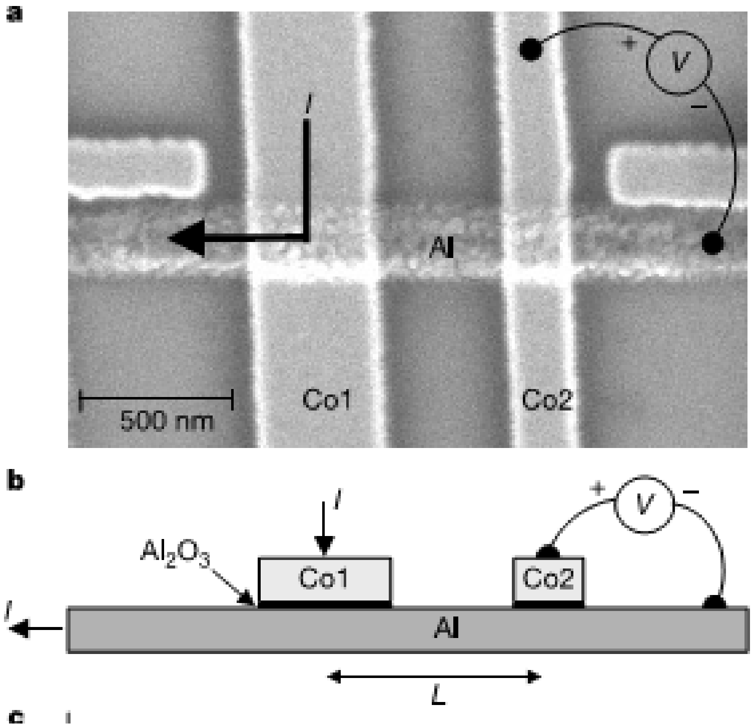
Electronic analog of the electro - optic modulator - Scitation

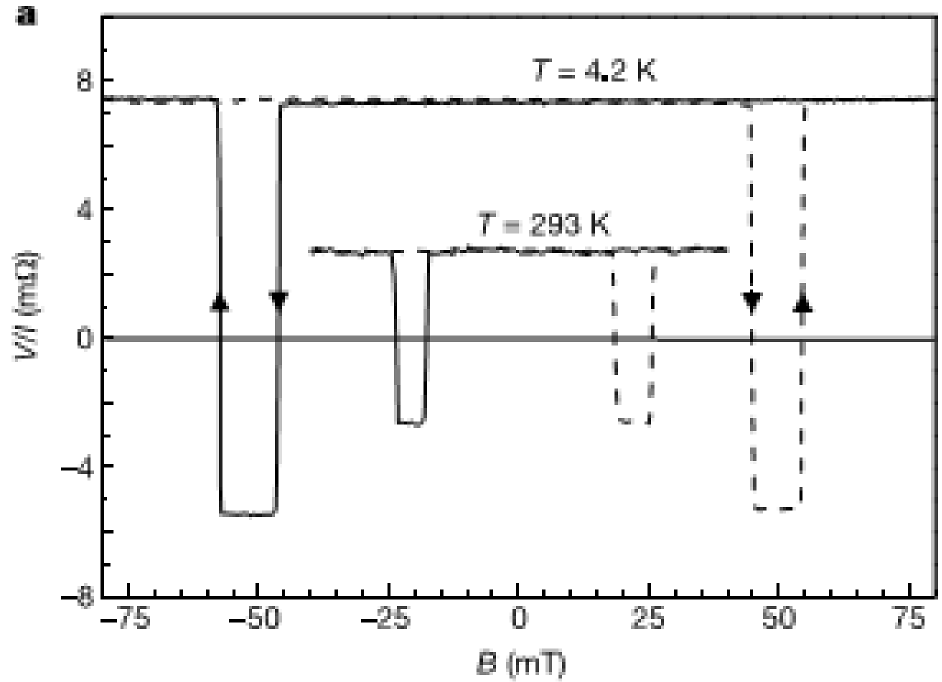
scitation.aip.org/content/aip/journal/apl/56/7/10.../1.102730 ▾ 翻译此页

作者：S Datta - 1990 - 被引用次数：4147 - 相关文章

1990年2月12日 - 10.1063/1.102730. Supriyo Datta[1] and Biswajit Das[1] ... Abstract; Full Text; References (12); Cited By (2579); Data & Media; Metrics; Related ...

Metal(Al, Cu, Ag, etc) as the spin channel





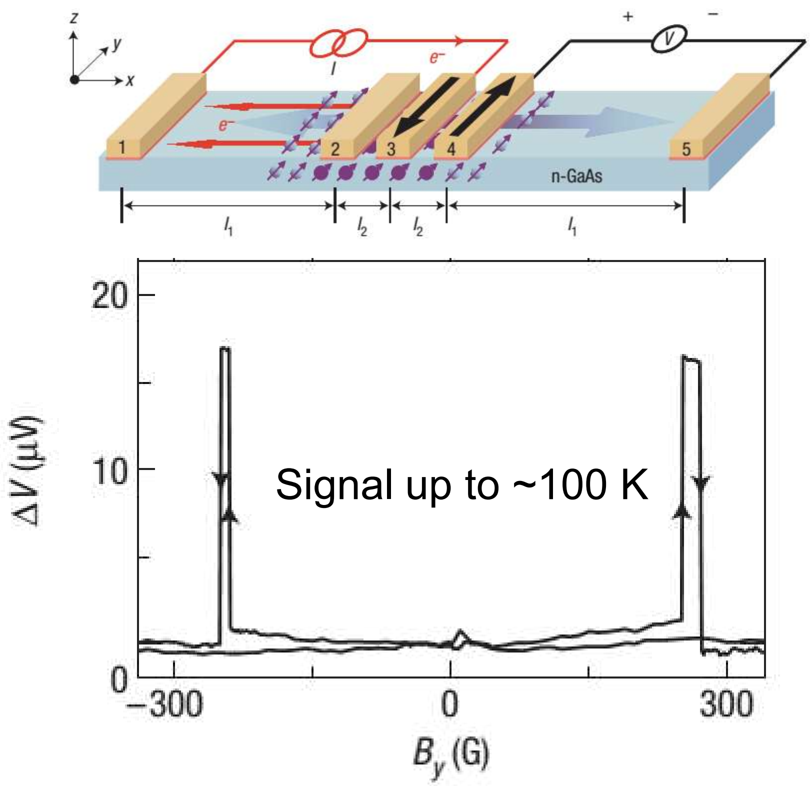
For example, Jedema, et al, Nature (2002)

More information, please see the results of
B. van Wees group (Netherlands), **S. Bader** group (Argonne National lab), **Y. Otani** (Japan)

Introduction to Spintronics

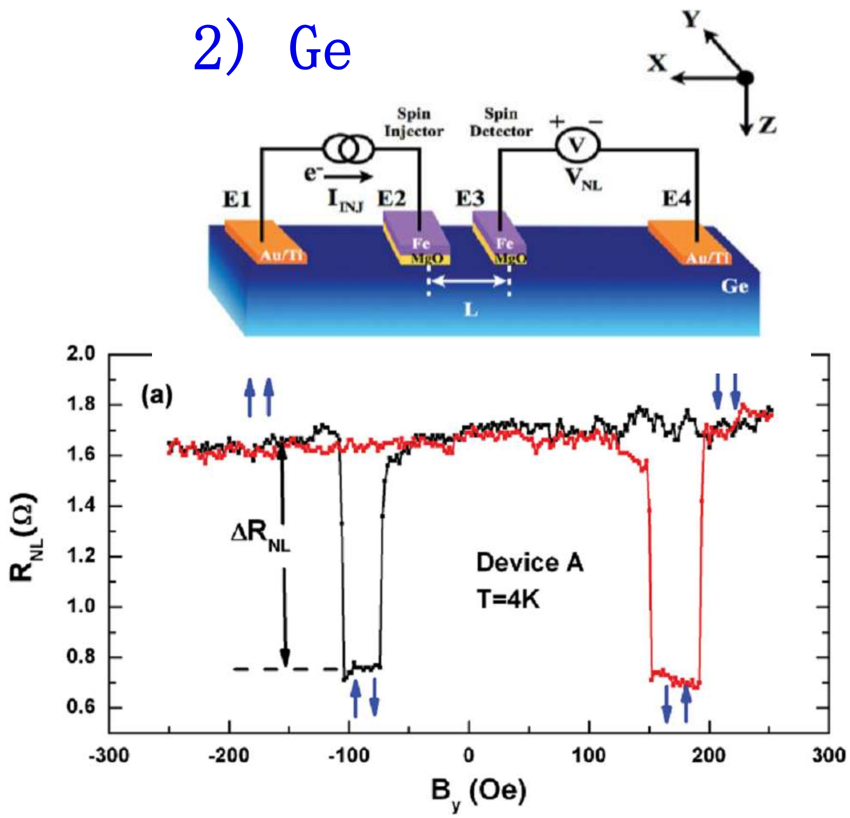
Semiconductor (GaAs, Si, Si, etc) as the spin channel

1) GaAs



Lou, et al. Nature Phys. (2007)

2) Ge



Zhou & Han, et al. PRB (2011)

More information, please see the results of
I. Appelbaum group (Maryland), **Jonker group (**NRL**)**; **K. Wang** group (UCLA), **M. Shiraishi** (Japan), **P. Crowell** (Minnesota), etc.

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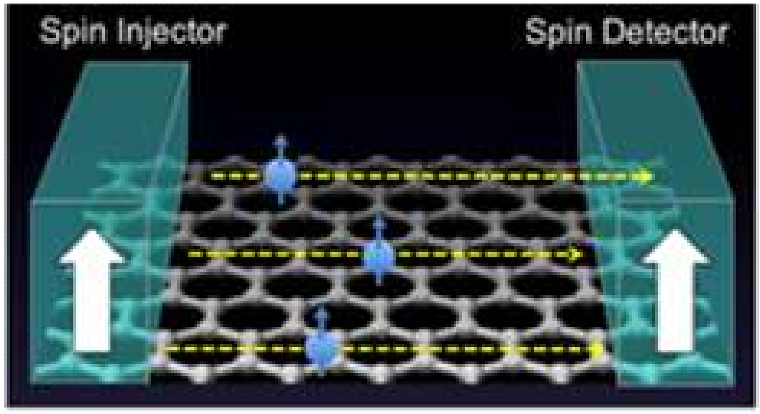
Spin in Graphene



Two minor topics:

1) Spin in TI
2) Graphene as a tunnel barrier

Spin transport in 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)

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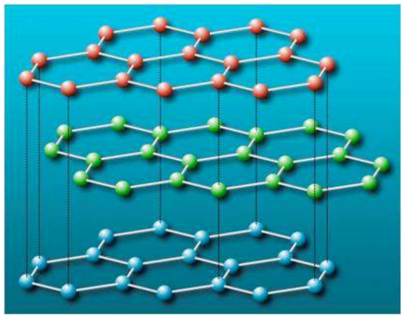
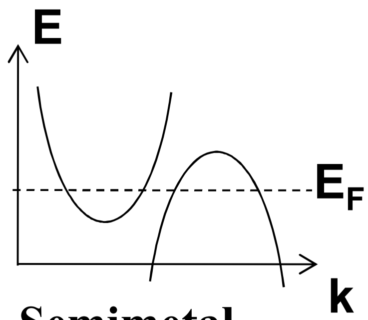
Graphene

Graphene combines the advantages of both metals and semiconductors

Spin transport in Graphene

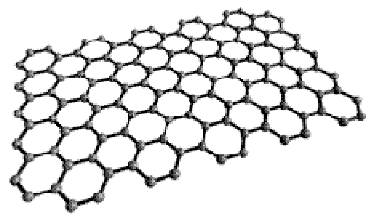
Graphite

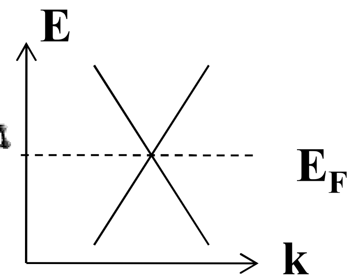




Semimetal

Graphene





Massless Dirac Fermions

Spin-dependent properties

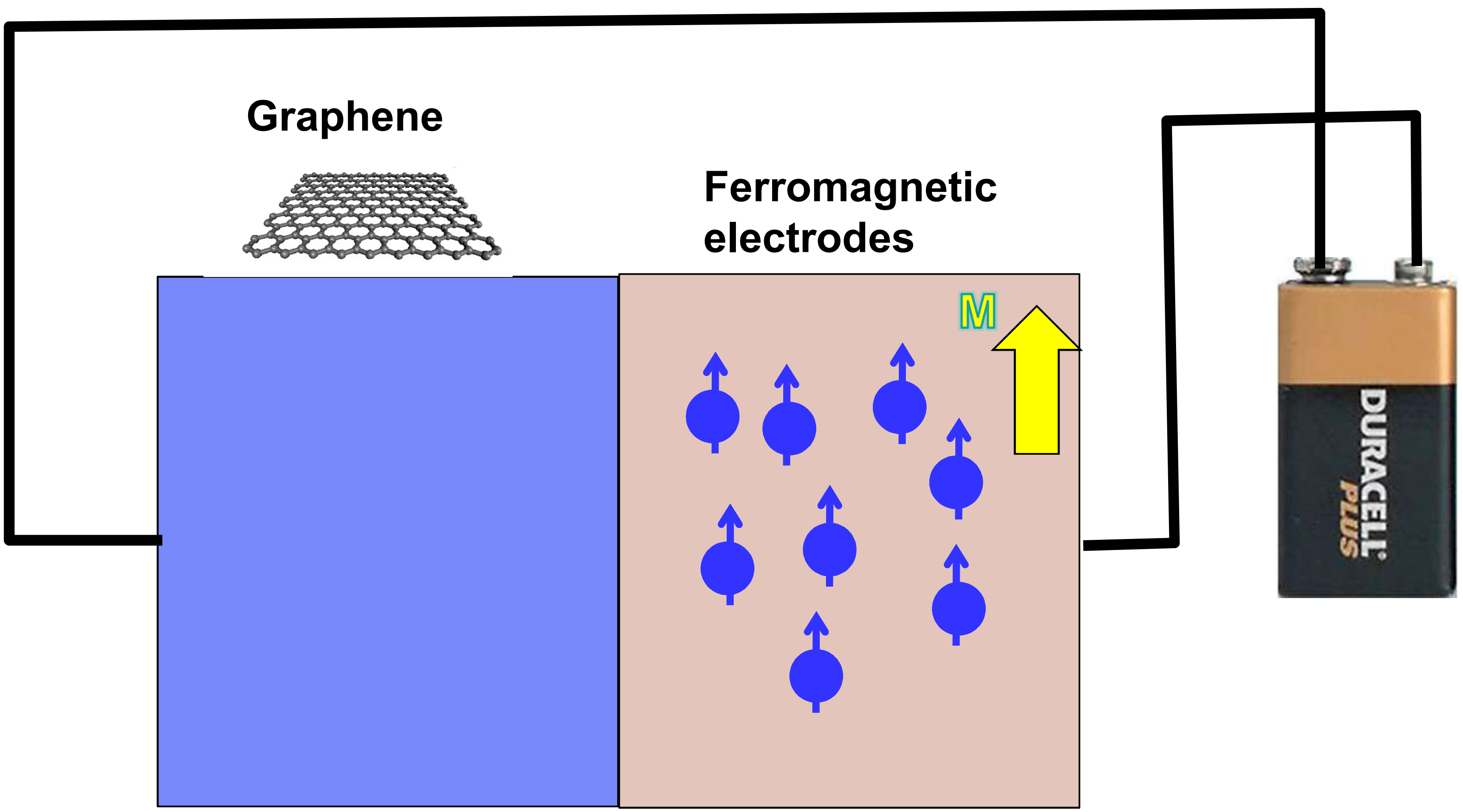
$$\lambda = \sqrt{D\tau}$$

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)

Spin transport in Graphene

How to put spin inside graphene?



Spin transport in Graphene

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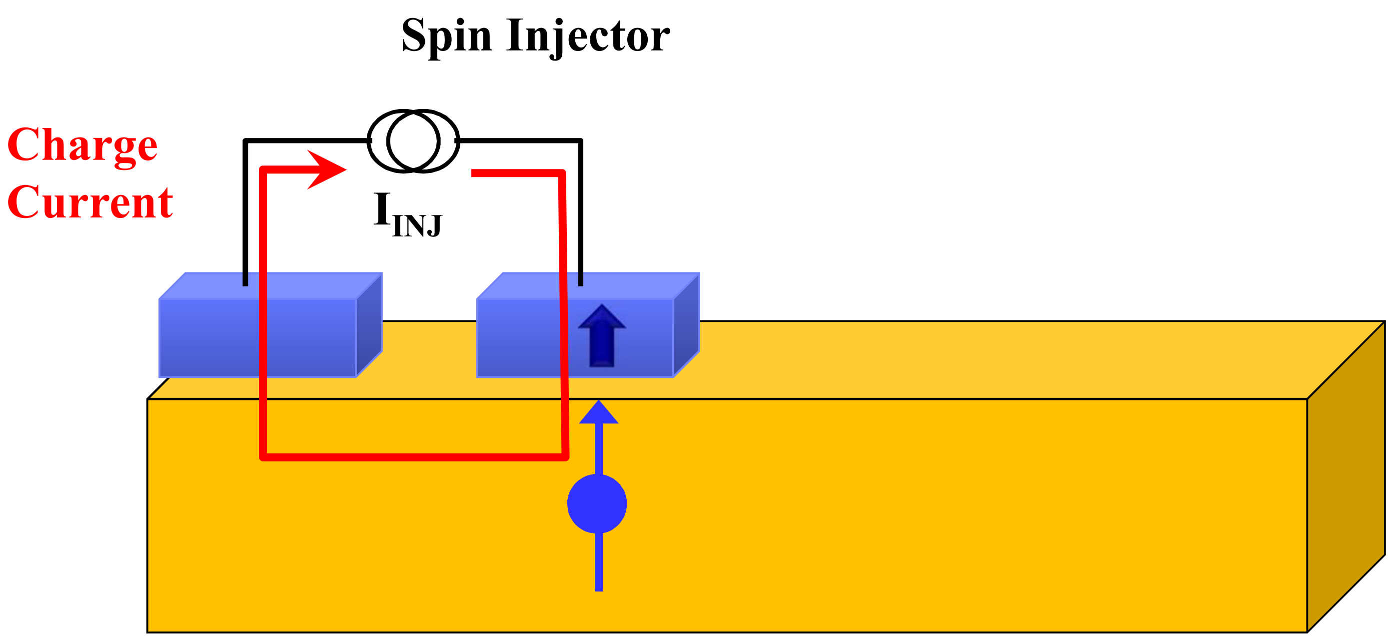
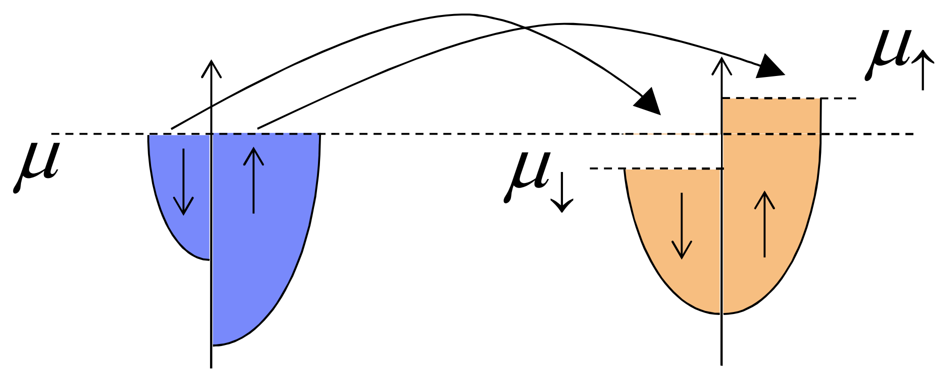
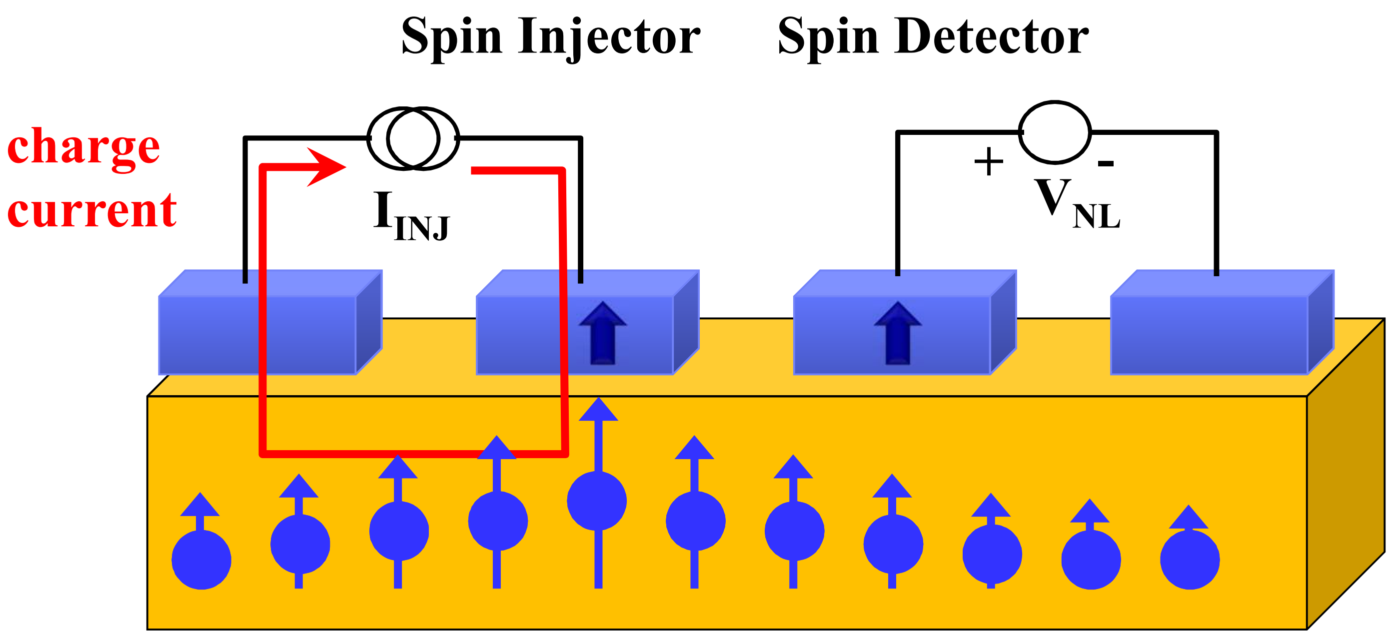


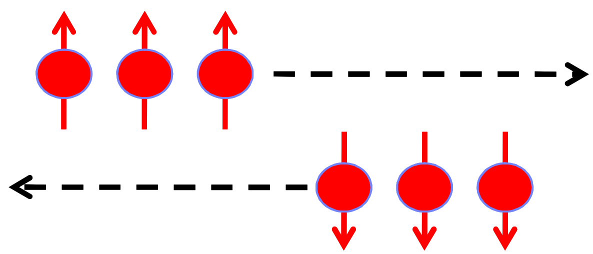
Chemical
Potential
(Fermi level)



Spin transport in Graphene

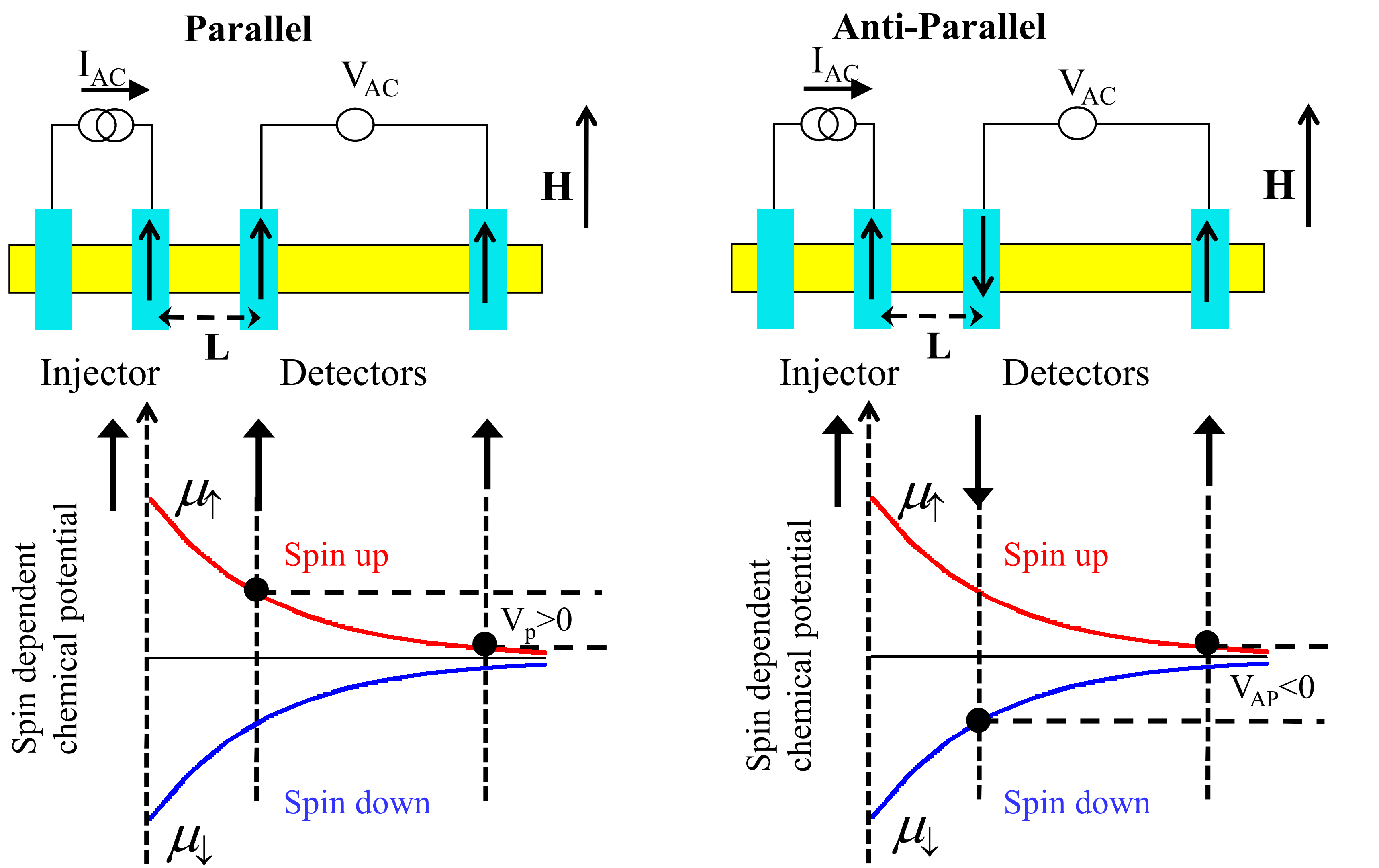


Pure spin current: **Flow of spin without net flow of charge**



Johnson and Silsbee, *PRL* (1985)

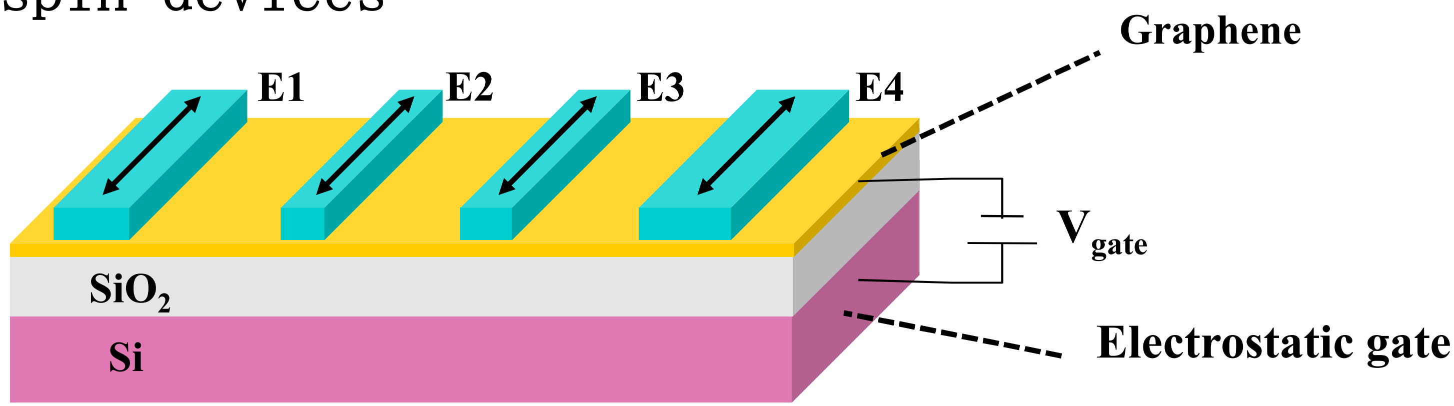
Spin transport in Graphene

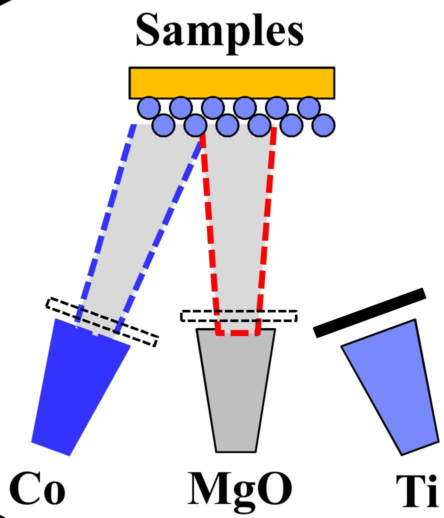


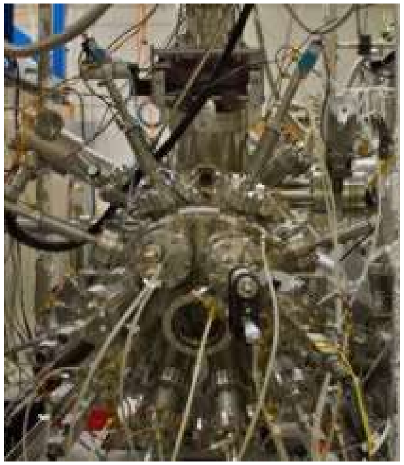
Nonlocal MR = $(V_P - V_{AP})/I_{INJ}$

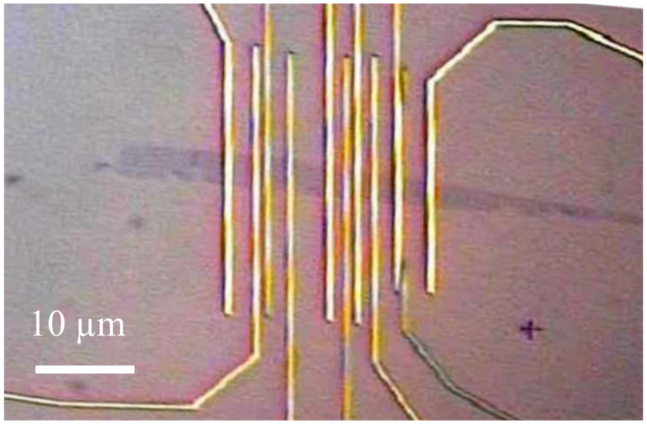
Spin transport in Graphene

Graphene spin devices

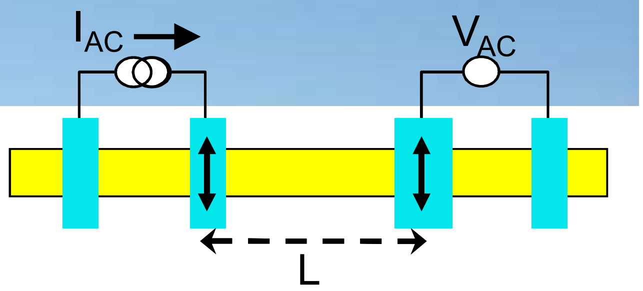


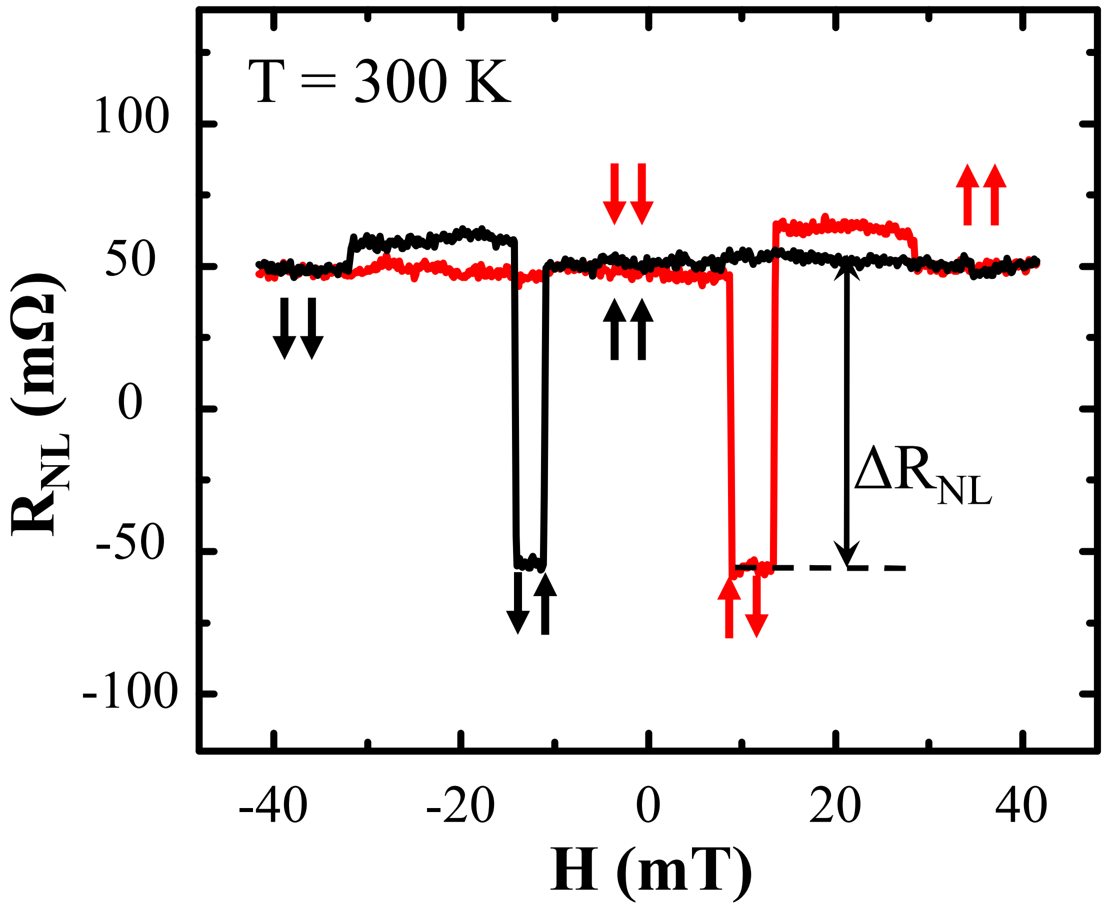


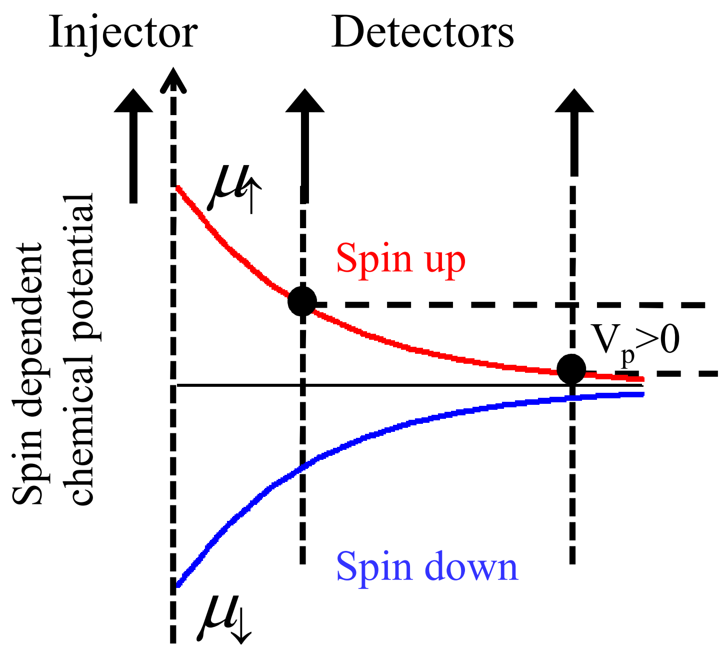




Spin transport in Graphene







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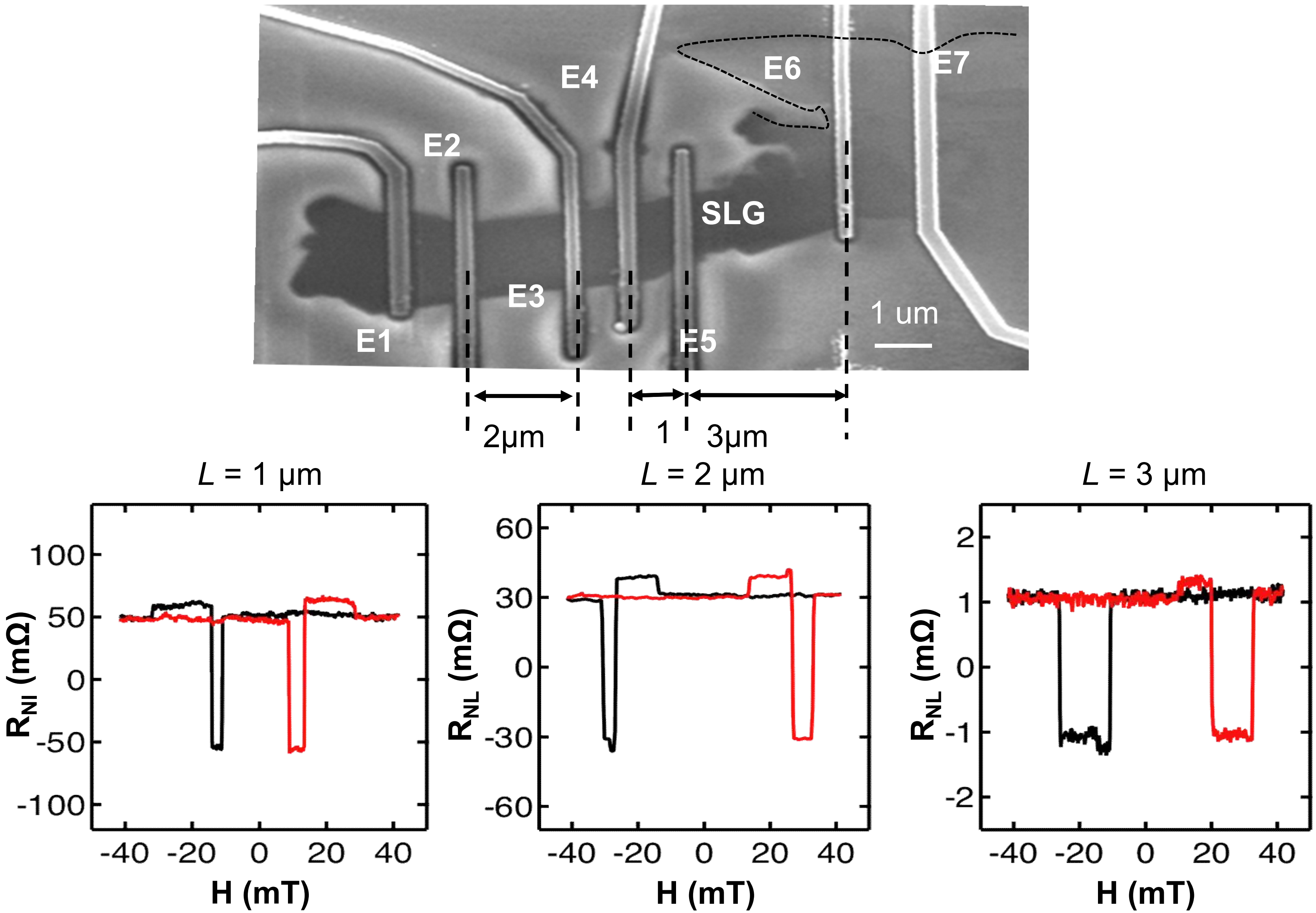
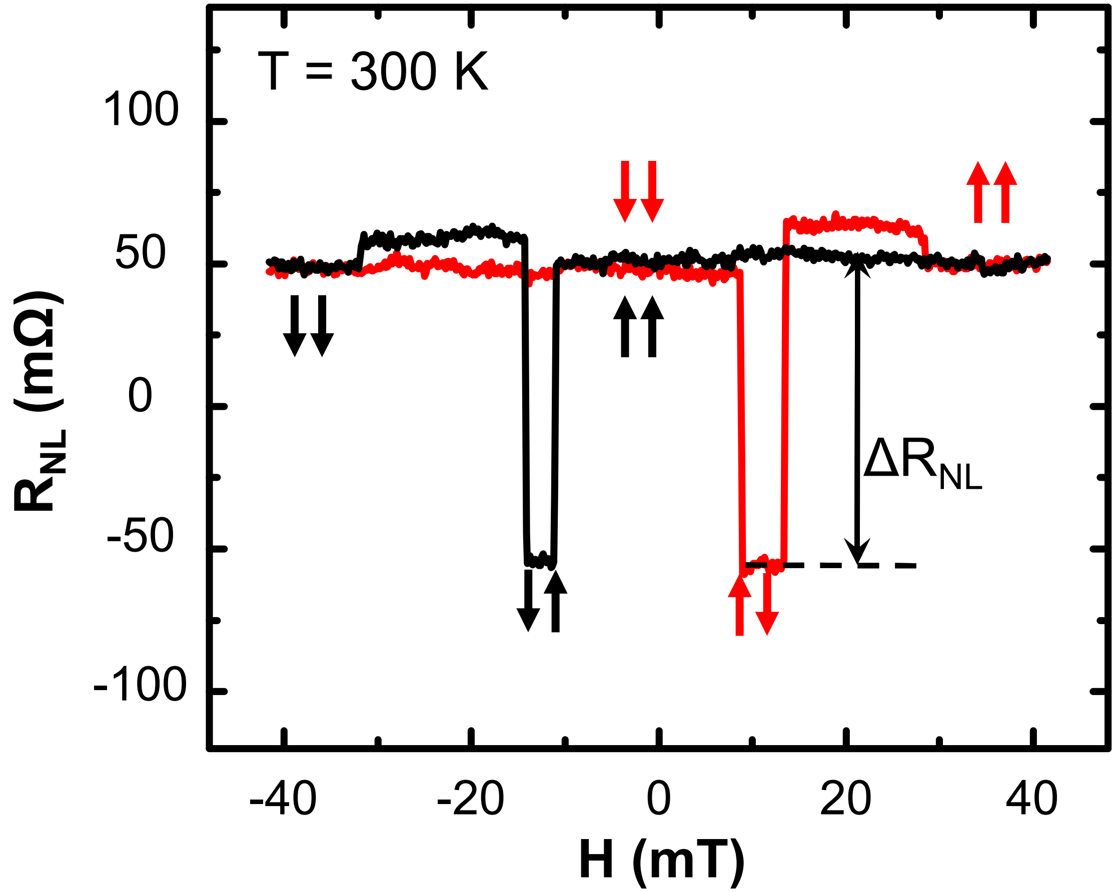
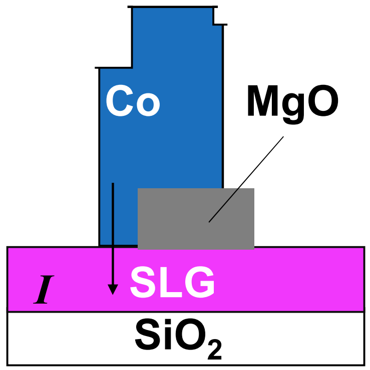


Spin transport in Graphene

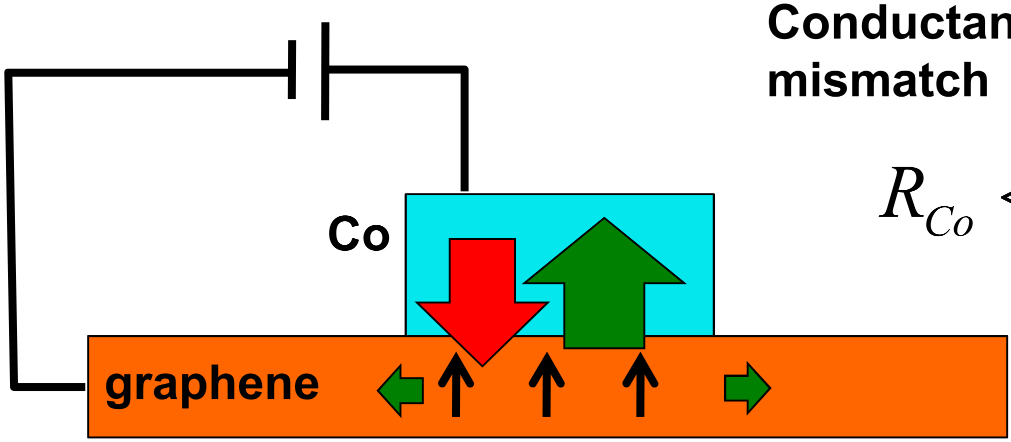


MR: ~ 100 mΩ
Spin Injection efficiency: P ~ 1%



Han, et al, PRL (2009)
Han, et al, APL (2009)

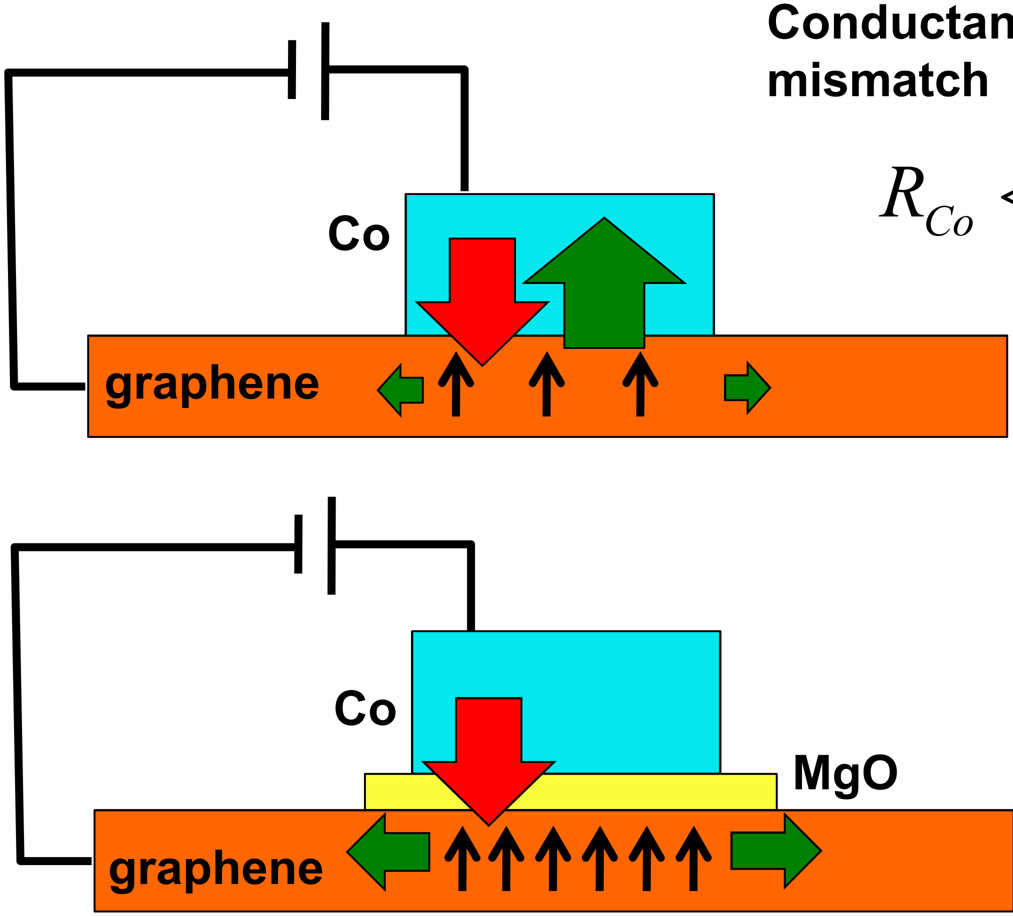
Enhance the spin injection efficiency



Conductance mismatch

$$R_{Co} << R_{graphene}$$

Enhance the spin injection efficiency



Conductance mismatch

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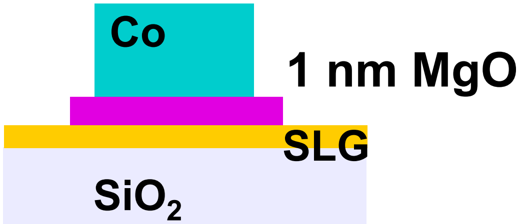
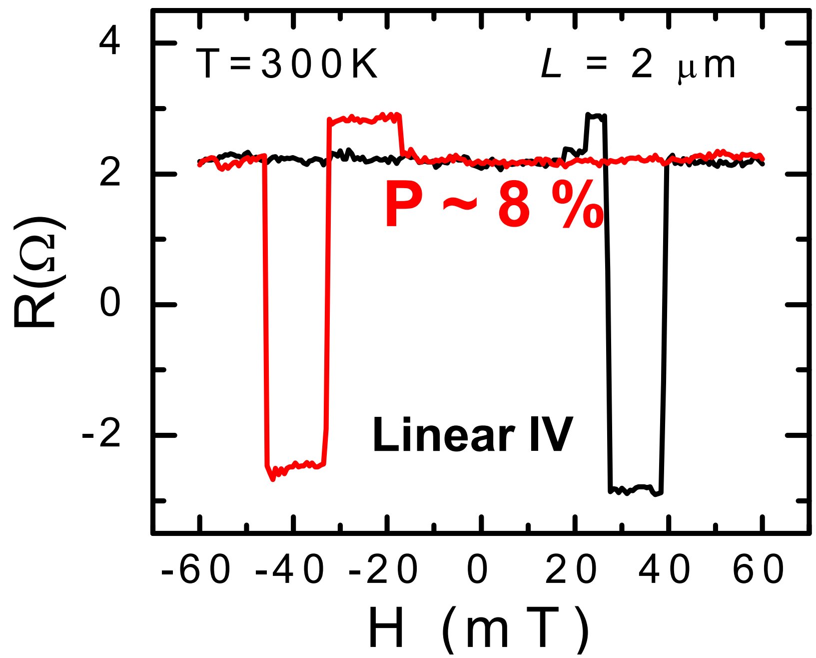
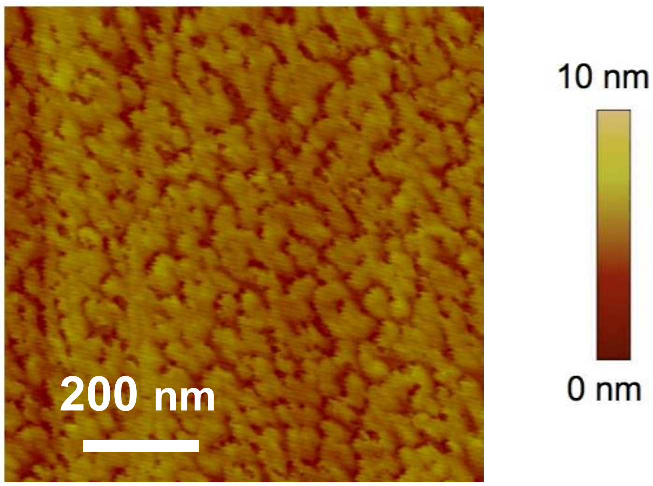
E.I. Rashba, Phys. Rev. B (2000)
A. Fert, H. Jaffres, Phys. Rev. B (2001)

Enhance the spin injection efficiency





1 nm MgO on HOPG
(Atomic Force Microscopy)



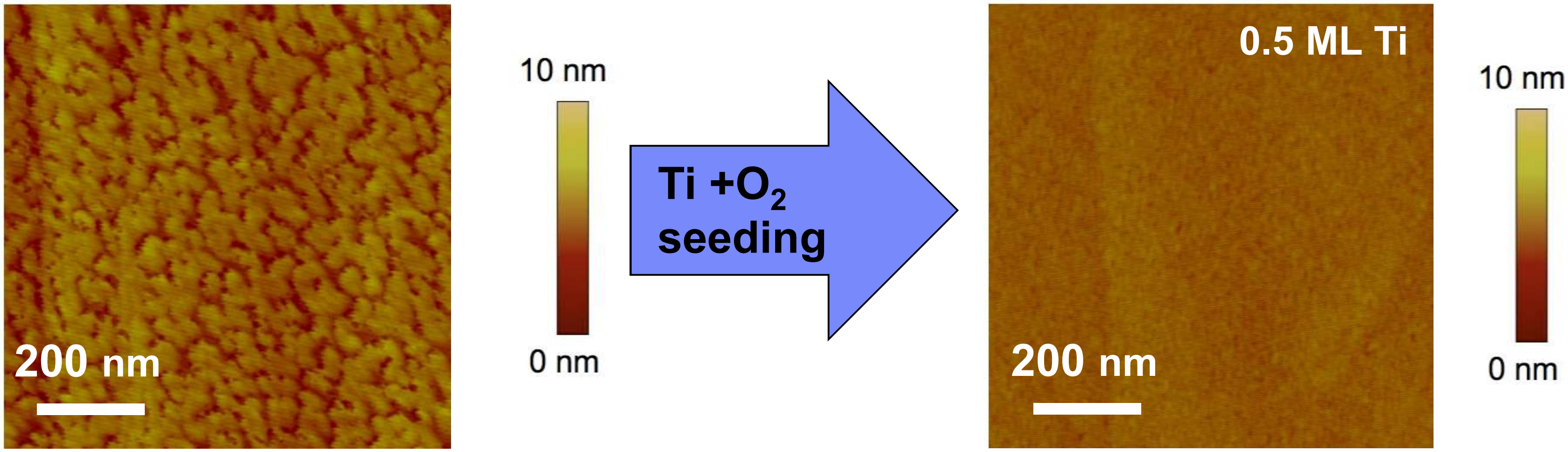
RMS roughness:
0.766nm

Volmer– Weber growth mode

Pinhole exists

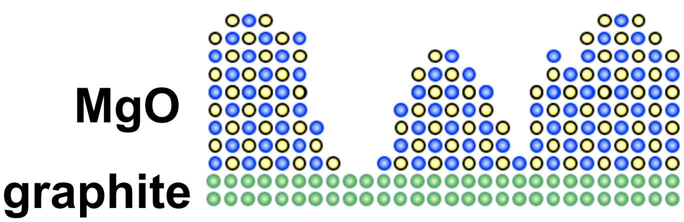
Enhance the spin injection efficiency

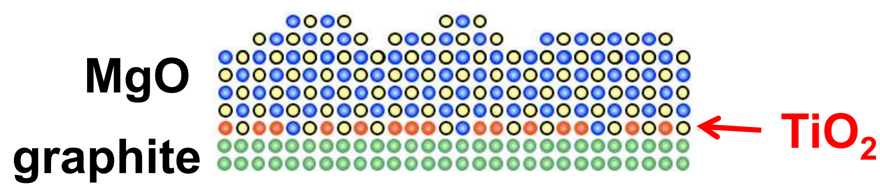
1 nm MgO on HOPG



RMS roughness: 0.766nm

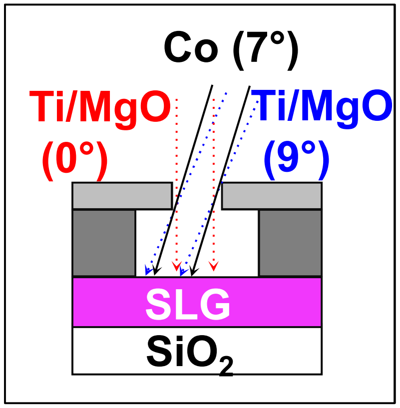
RMS roughness: 0.229nm

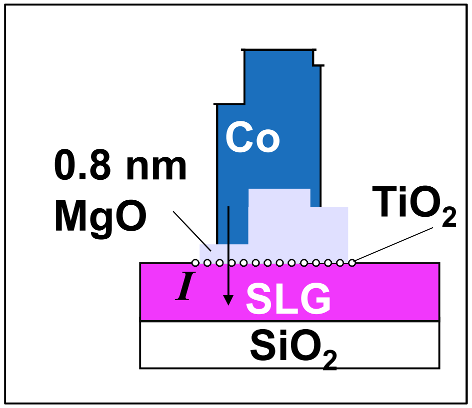


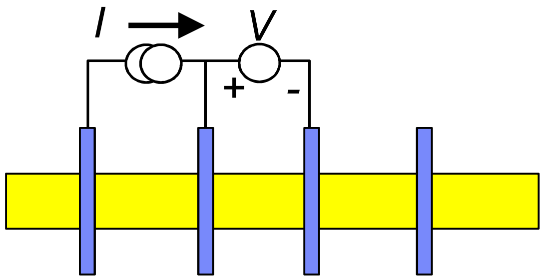


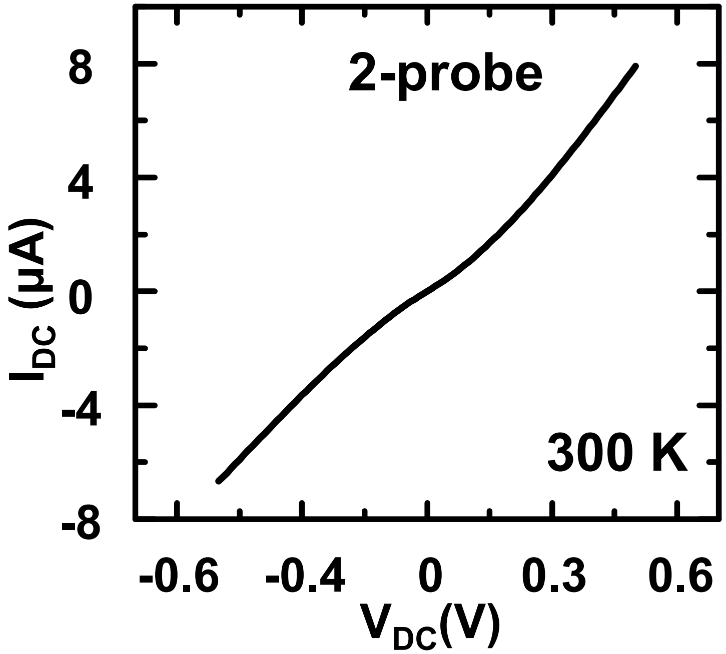
Wang, Han, et al, APL (2008)

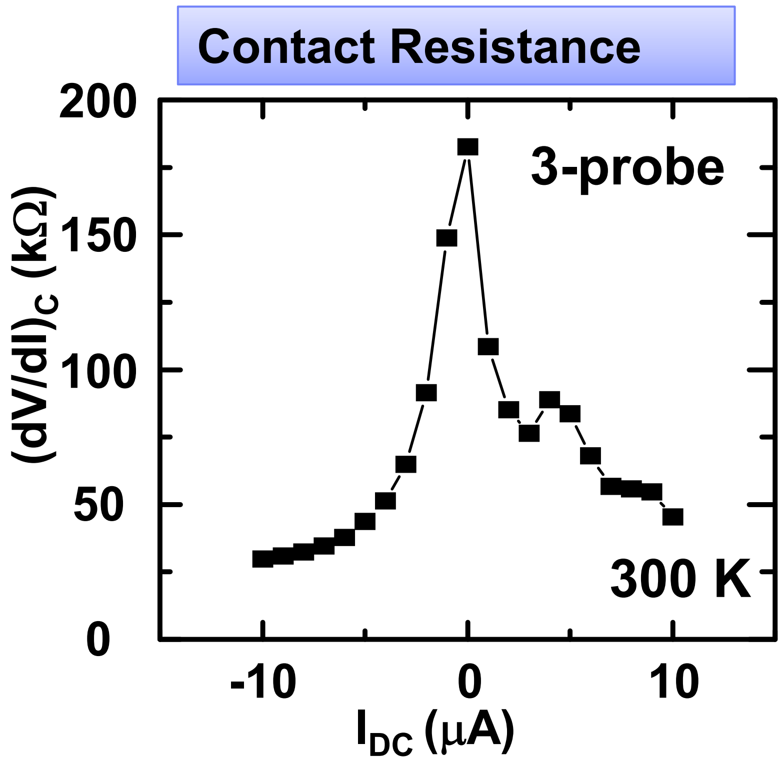
Tunneling spin injection into graphene



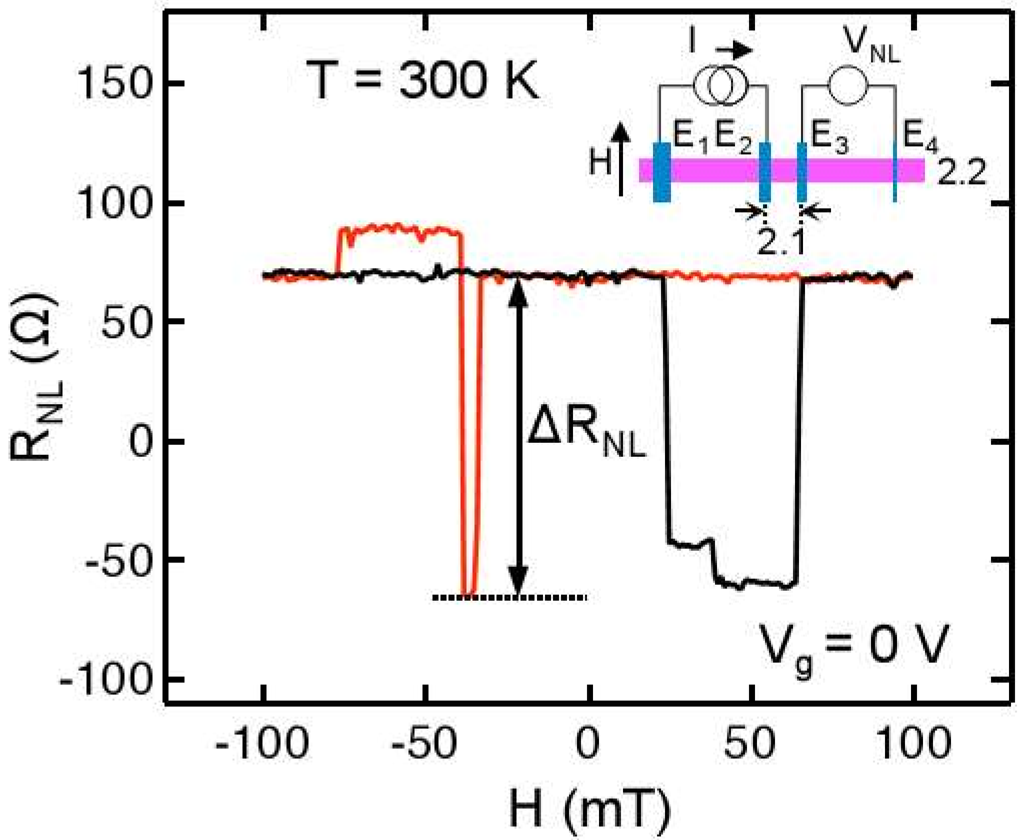








Tunneling spin injection into graphene



$$\Delta R_{NL} = \frac{P_J^2 \lambda_G}{W \sigma_G} e^{-L/\lambda_N}$$

Johnson &Silsbee, PRL, 1985.
Jedema, et al, Nature, 2002 .

$\sigma(0V) = 0.35mS,$

$\Delta R_{NL}(0V) = 130.4\Omega,$

$W \sim 2.2\mu m,$

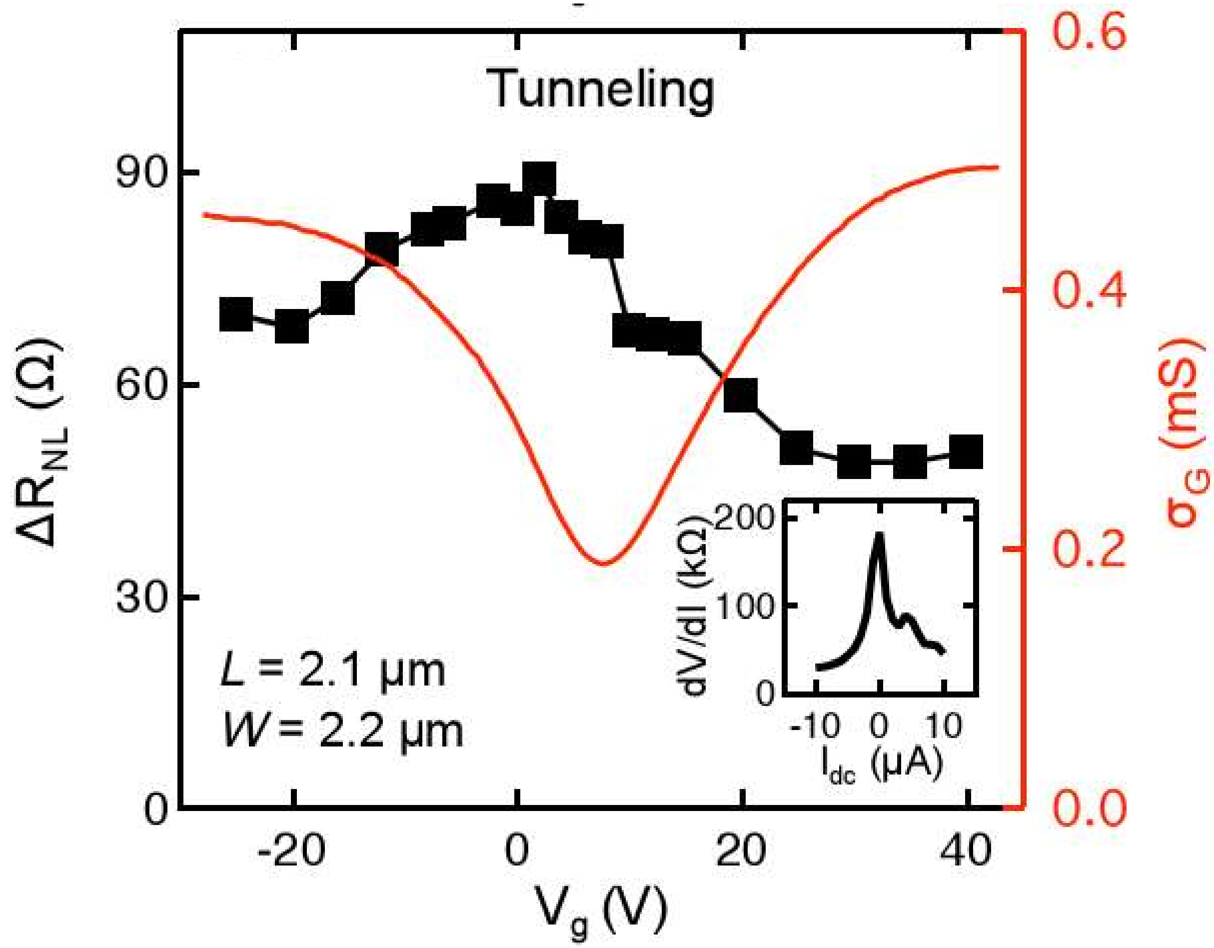
$L = 2.1\mu m,$

$\lambda_G = 2.5\mu m,$

ΔR_{NL}= 130 Ω , P_J ~30 %

Han, et al, PRL (2010)

Tunneling spin injection into graphene



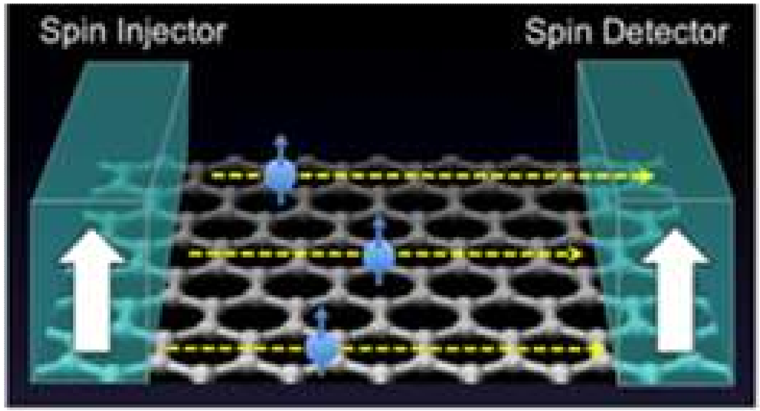
Gate tunable spin transport might be useful for "spin transistor" applications.

Outline

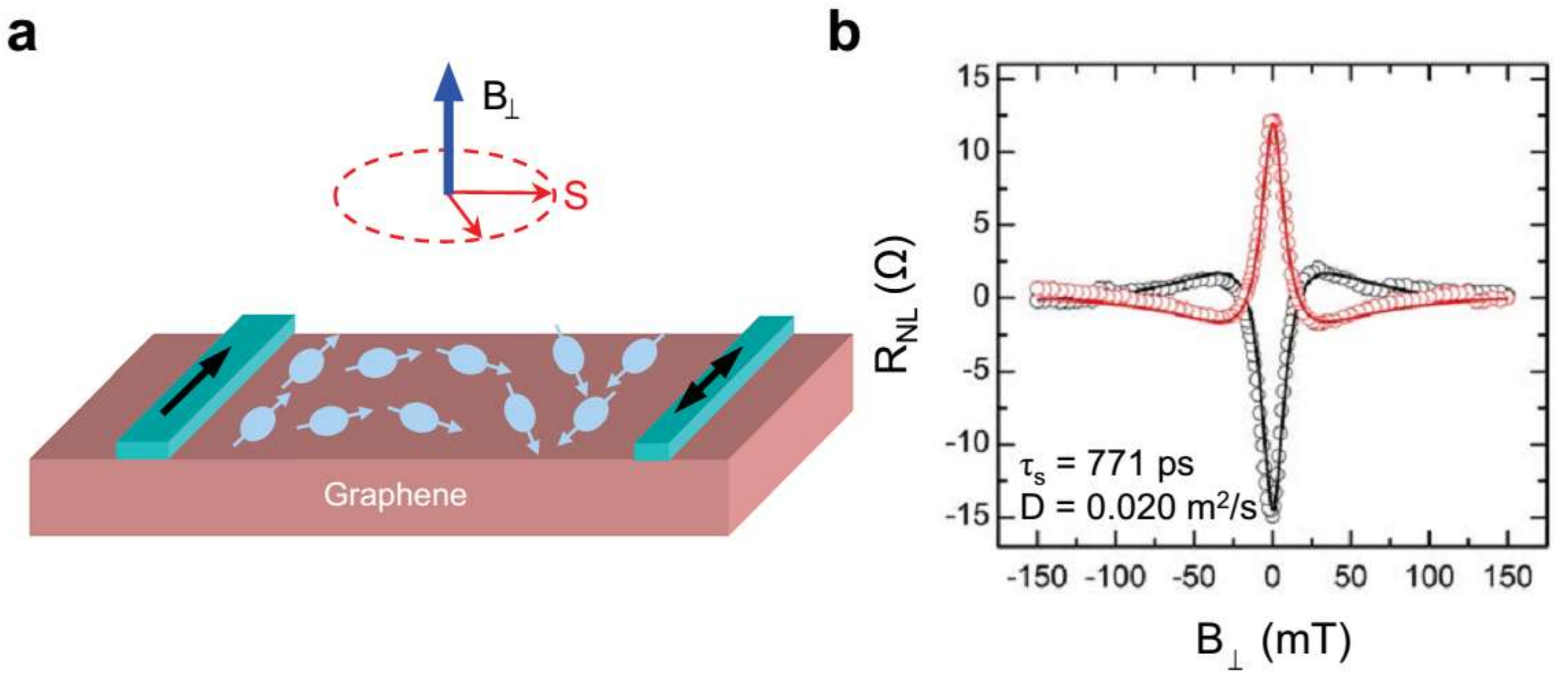
I. Introduction to spintronics (Lecture I)

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

Spin lifetime/relaxation in Graphene



Hanle spin measurement



$$R_{NL} \propto \pm \int_0^{\infty} \frac{1}{\sqrt{4\pi D t}} \exp\left[-\frac{L^2}{4Dt}\right] \cos(\omega_L t) \exp(-t/\tau_s) dt$$

Spin lifetime– Contact induced spin relaxation

PRL **105,** 167202 (2010) PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2010

Tunneling Spin Injection into Single Layer Graphene

Wei Han, K. Pi, K. M. McCreary, Yan Li, Jared J. I. Wong, A. G. Swartz, and R. K. Kawakami*

Department of Physics and Astronomy, University of California, Riverside, California 92521, USA

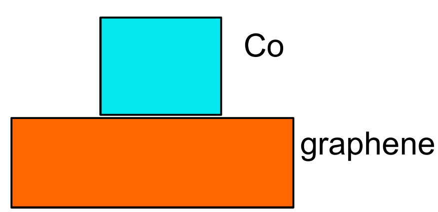
(Received 4 March 2010; published 12 October 2010)

We achieve tunneling spin injection from Co into single layer graphene (SLG) using TiO_2 seeded MgO barriers. A nonlocal magnetoresistance (ΔR_{NL}) of 130 Ω is observed at room temperature, which is the largest value observed in any material. Investigating ΔR_{NL} vs SLG conductivity from the transparent to the tunneling contact regimes demonstrates the contrasting behaviors predicted by the drift-diffusion theory of spin transport. Furthermore, tunnel barriers reduce the contact-induced spin relaxation and are therefore important for future investigations of spin relaxation in graphene.

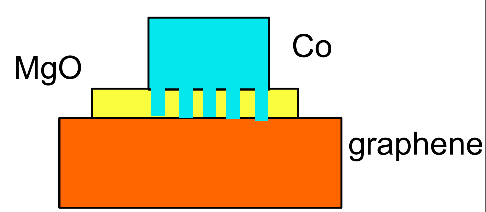
DOI: 10.1103/PhysRevLett.105.167202 PACS numbers: 85.75.−d, 72.25.Hg, 73.40.Gk, 81.05.ue

The systematic study of spin lifetimes in graphene using different **spin injector/detector**

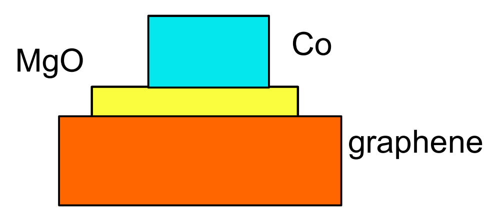
Transparent contact



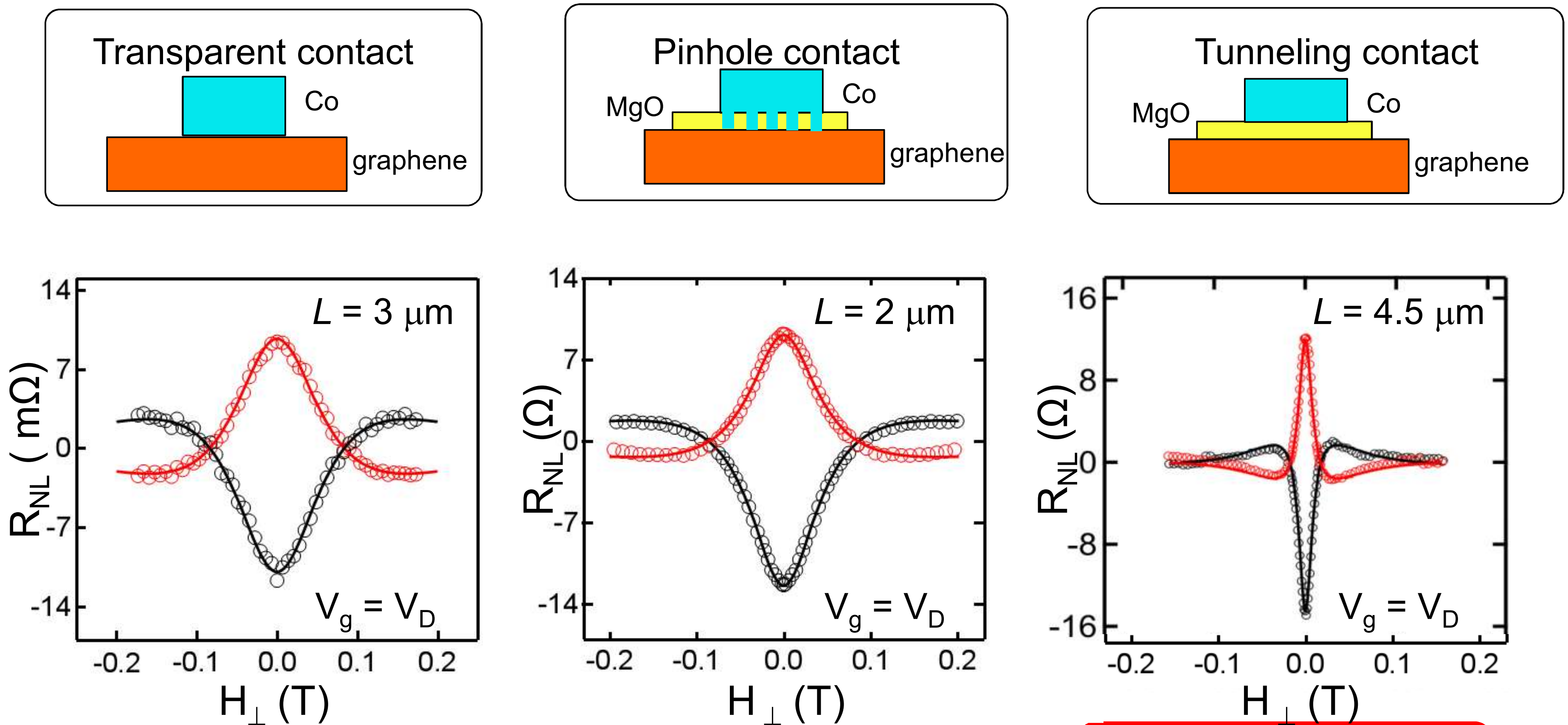
Pinhole contact



Tunneling contact



Spin lifetime– Contact induced spin relaxation



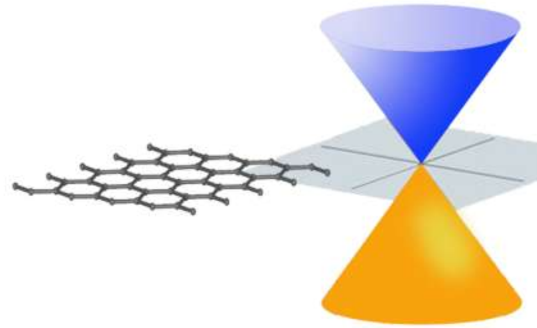
τ_s = 85 ps

τ_s = 134 ps

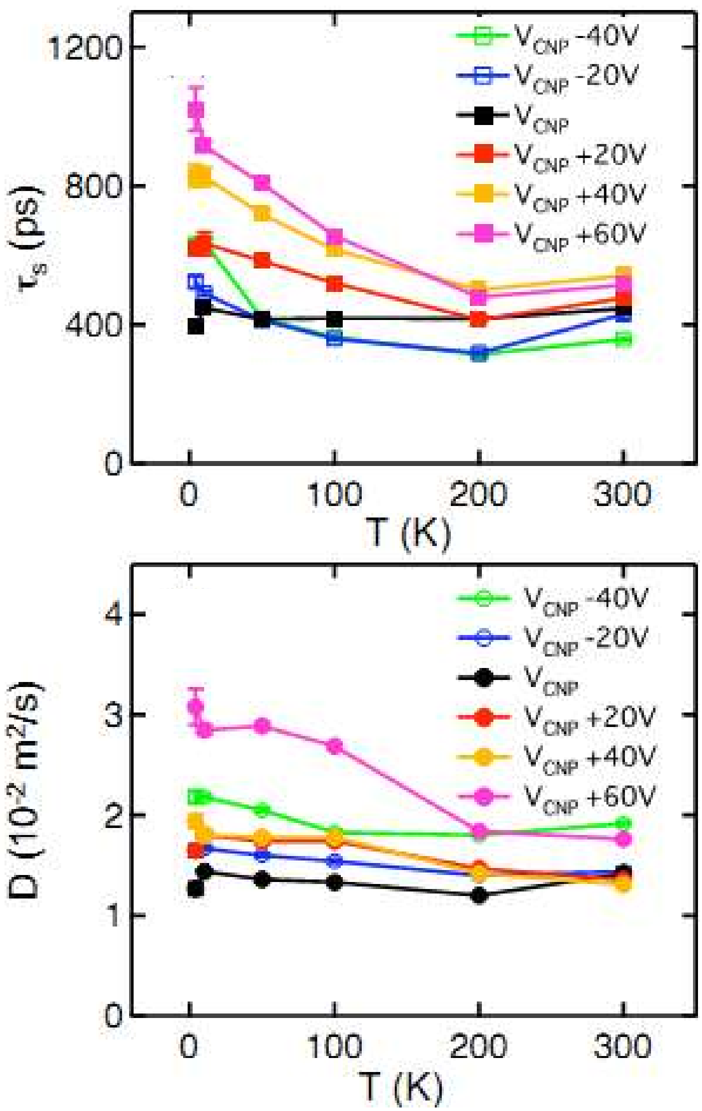
τ_s = 771 ps

Contact-induced spin relaxation is important

Spin relaxation in SLG and BLG

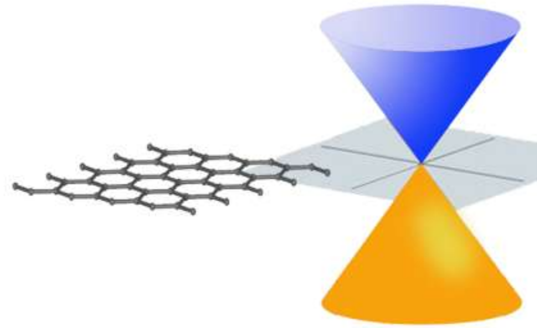


Spin Relaxation in SLG

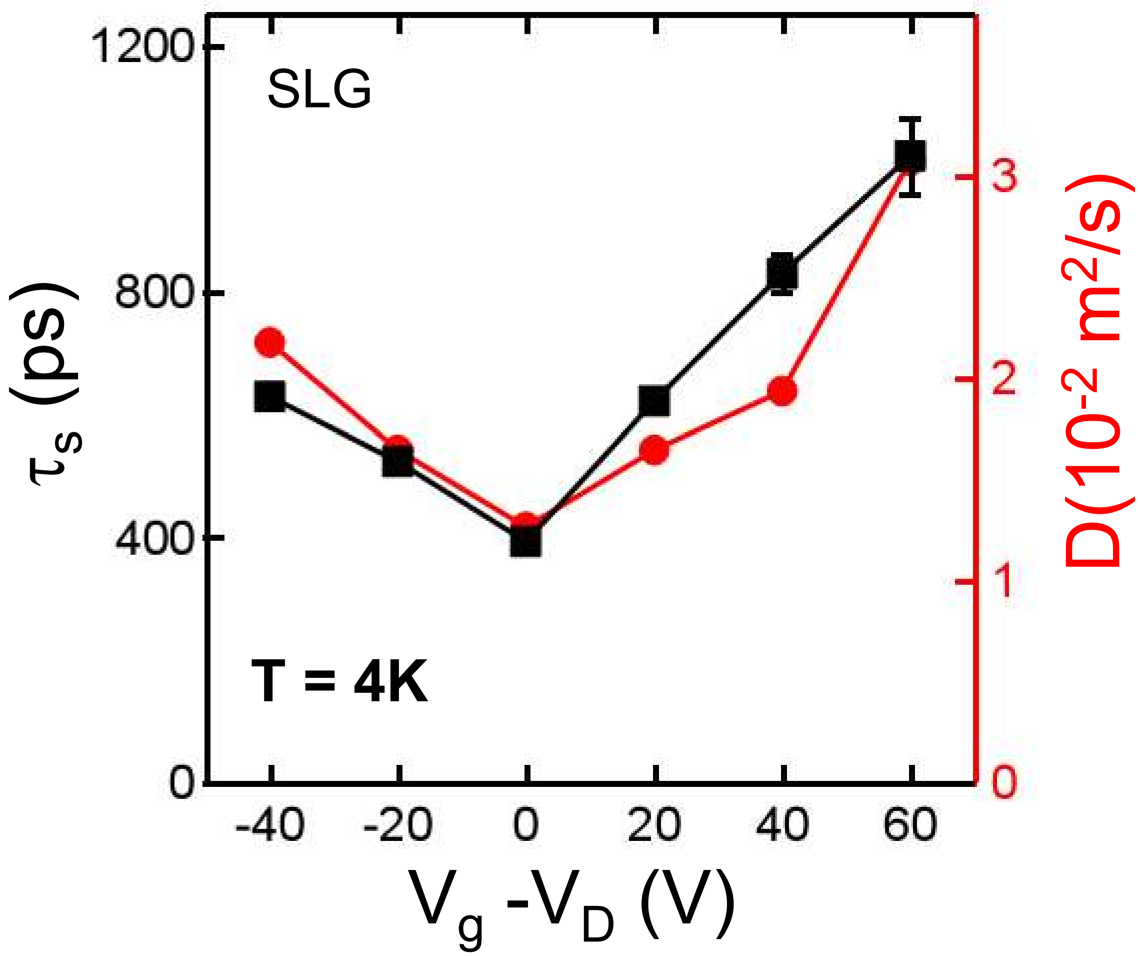


τ and D show the similar temperature behavior

Spin relaxation in SLG and BLG



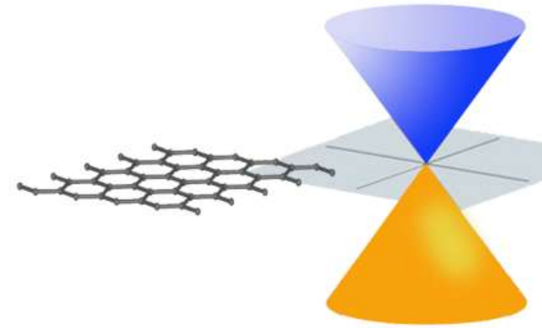
Spin Relaxation in SLG at 4 K



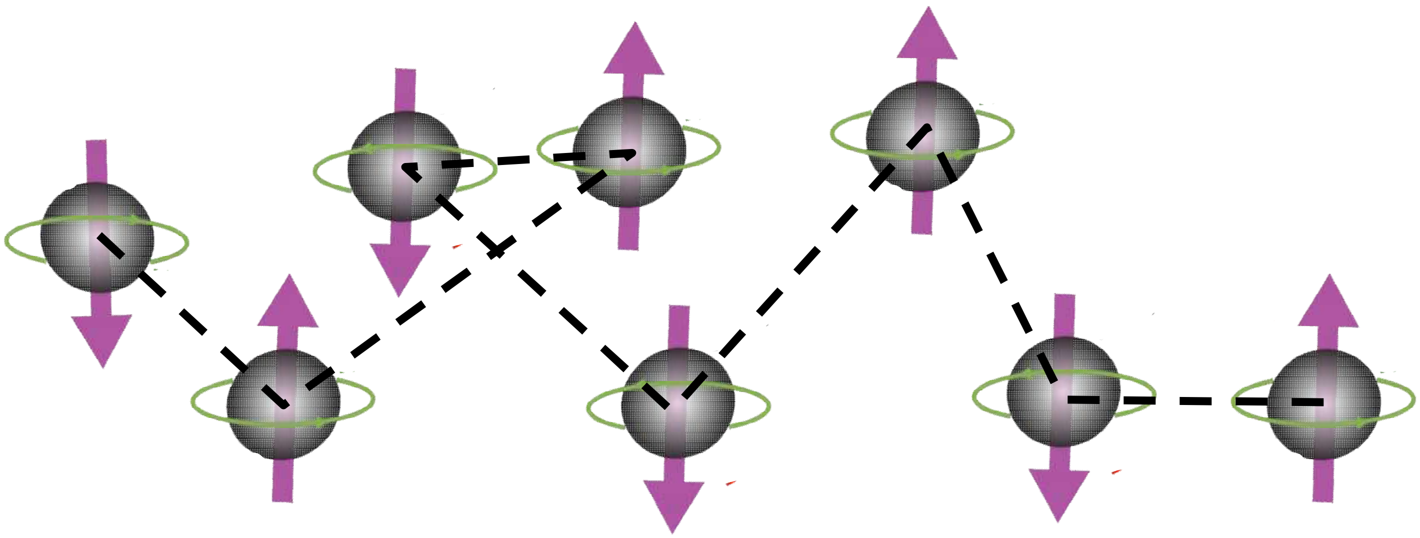
$\tau \sim$ **D**

Elliot-Yafet

Spin relaxation in SLG and BLG



Elliot-Yafet spin relaxation



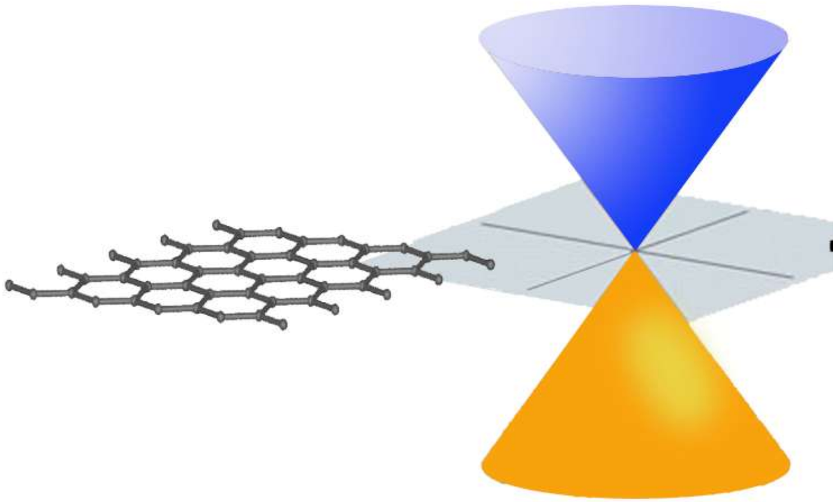
Spin flip during momentum scattering events:
More momentum scattering, more spin relaxation.

$\tau_s \sim \tau_p$ **(D)**

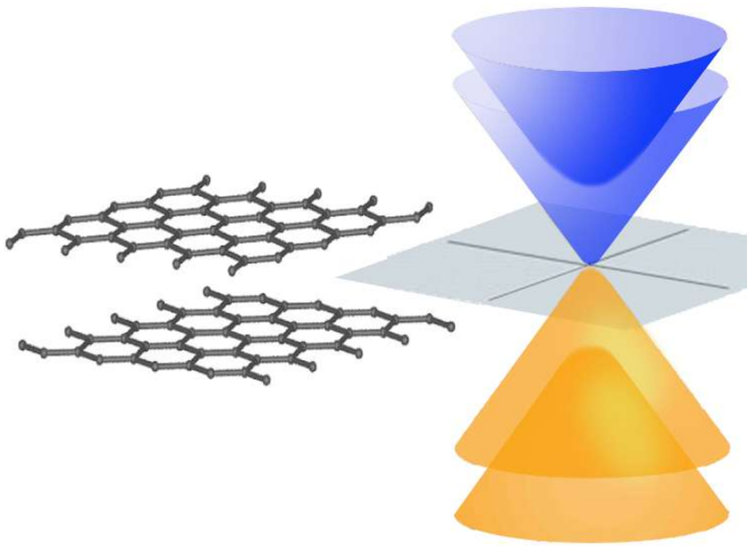
J. Fabian, et al, Acta Phys. Slovaca (2007)
R.J. Elliott, Phys. Rev. (1954)
F. Meier and B.P. Zachachrenya, Optical Orientation, (1984).
Josza, et al, Phys. Rev. B (2009)

Spin relaxation in SLG and BLG

SLG



BLG



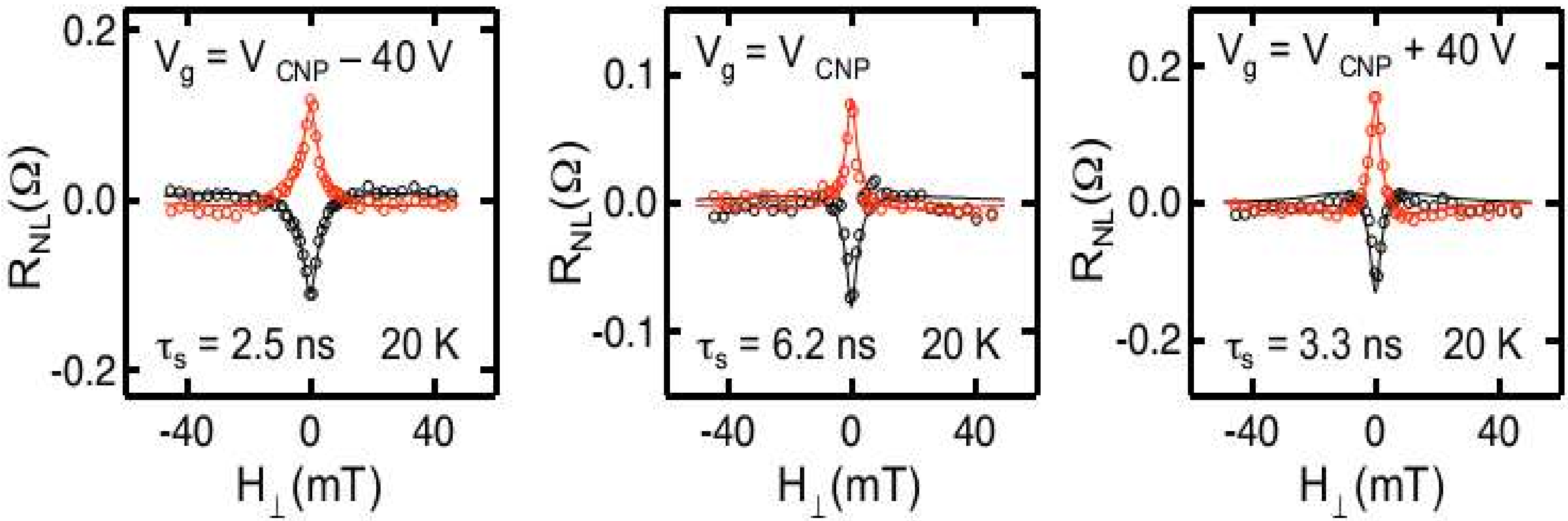
Band structure

Intrinsic spin orbit coupling

Surface to volume ratio

Geim, and Novoselov, Nature Materials (2007)
Guinea, New J. of Phys. (2010)

Longer spin lifetime observed



τ_s = 2.5 ns

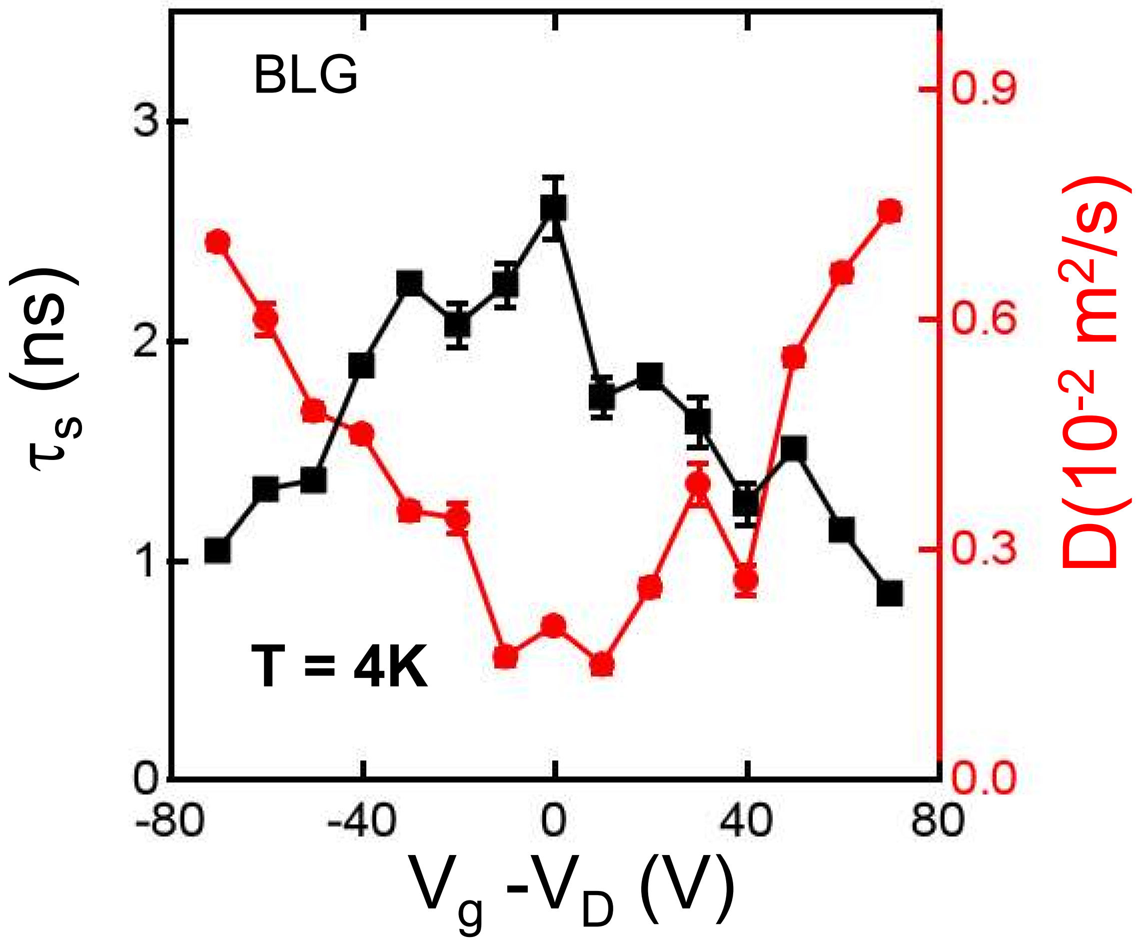
τ_s = 6.2 ns

τ_s = 3.3 ns

Longest spin lifetime in graphene reported so far

Spin relaxation in SLG and BLG

Spin Relaxation in BLG at 4 K



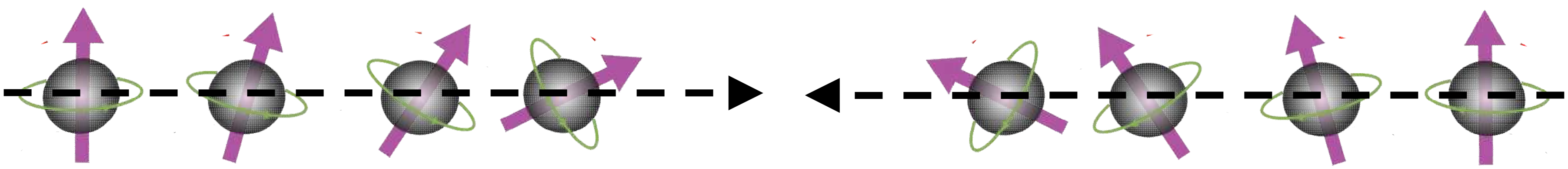
$\tau \sim 1/D$

Dyakonov-Perel

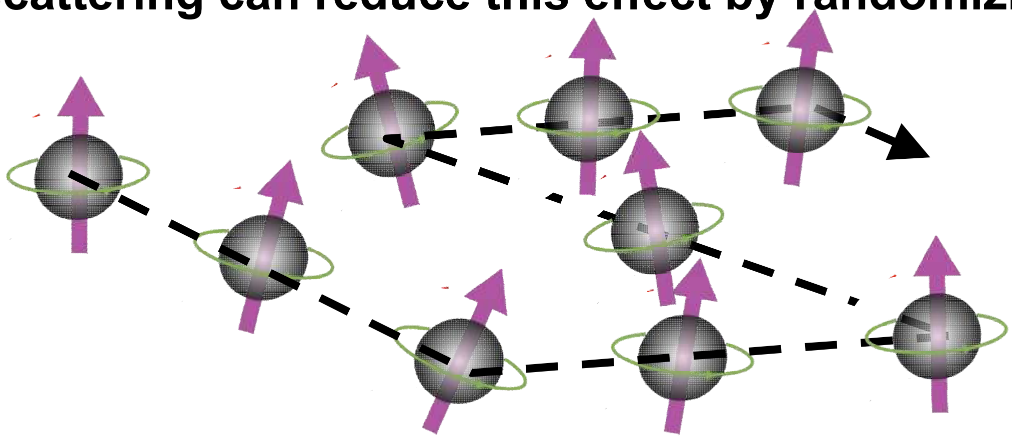
Spin relaxation in SLG and BLG

DP spin relaxation

Spins precess along internal spin-orbit “magnetic” field depending on the momentum.



Momentum scattering can reduce this effect by randomizing the field

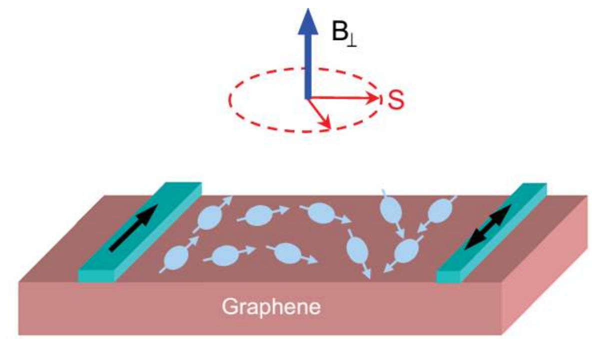


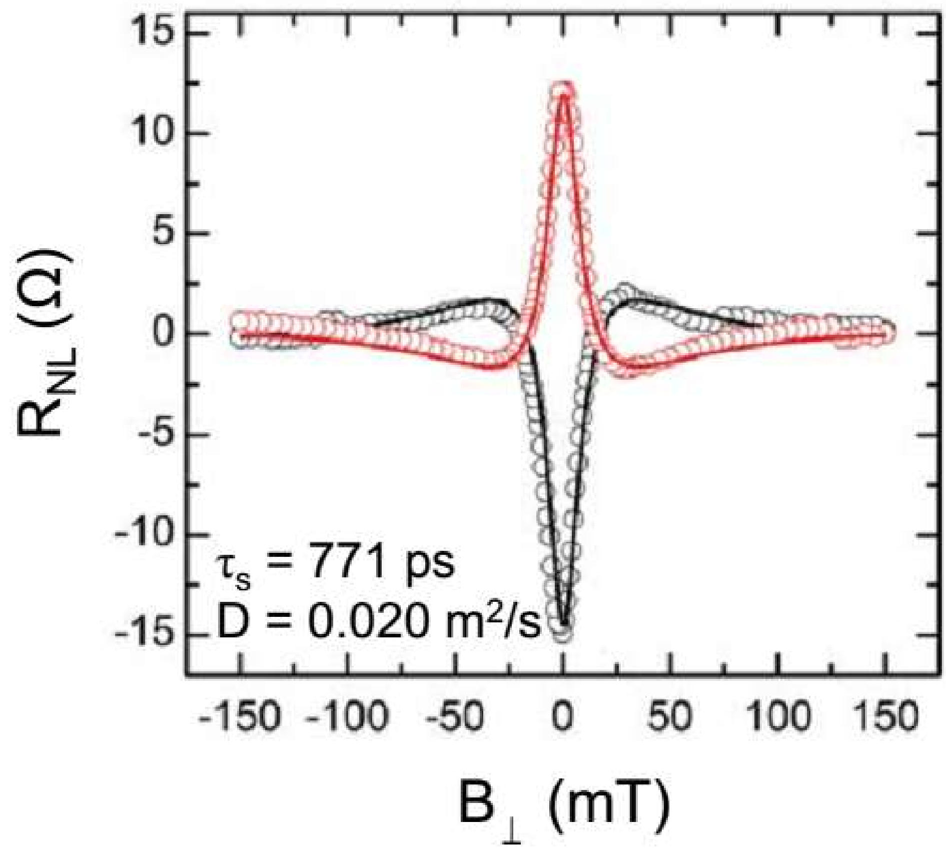
More momentum scattering, less spin relaxation

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

M. I. D'yakonov and V.I. Perel, Sov. Phys. Solid State (1972)
F. Meier and B.P. Zachachrenya, Optical Orientation, (1984).

Spin diffusion length

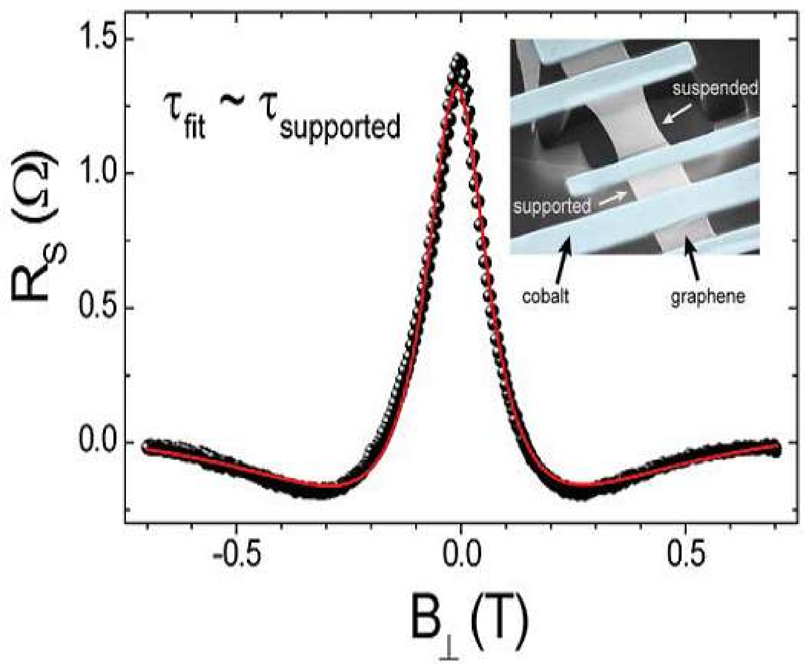


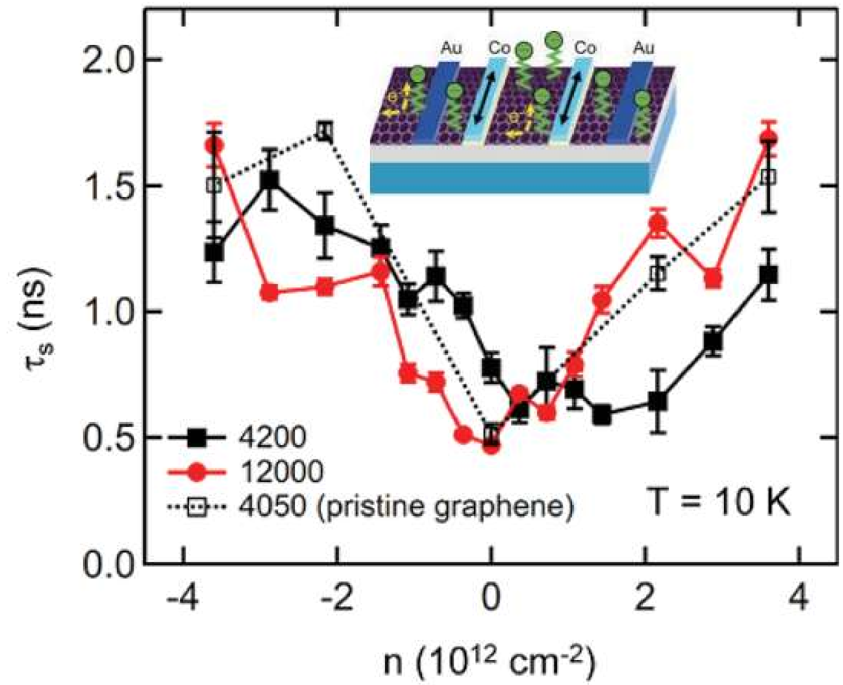


$$\lambda = \sqrt{D\tau}$$

Spin diffusion length

Suspended graphene

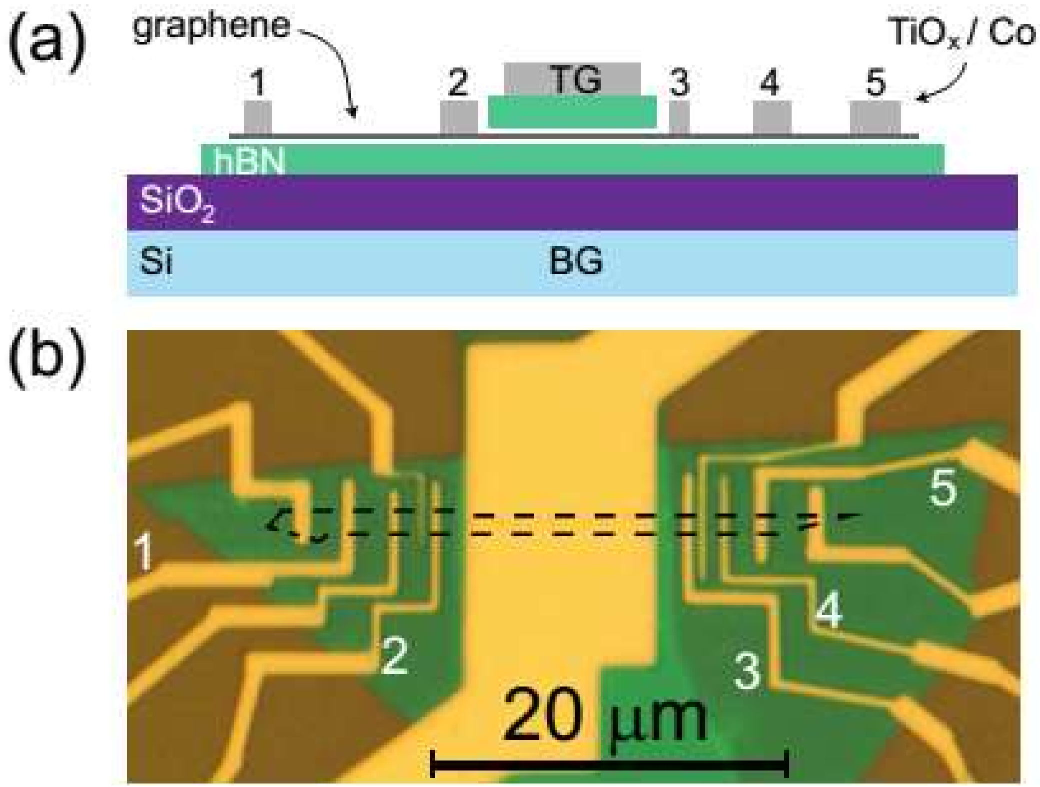




Spin diffusion lengths 1-5 microns

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

Spin diffusion length—high quality graphene



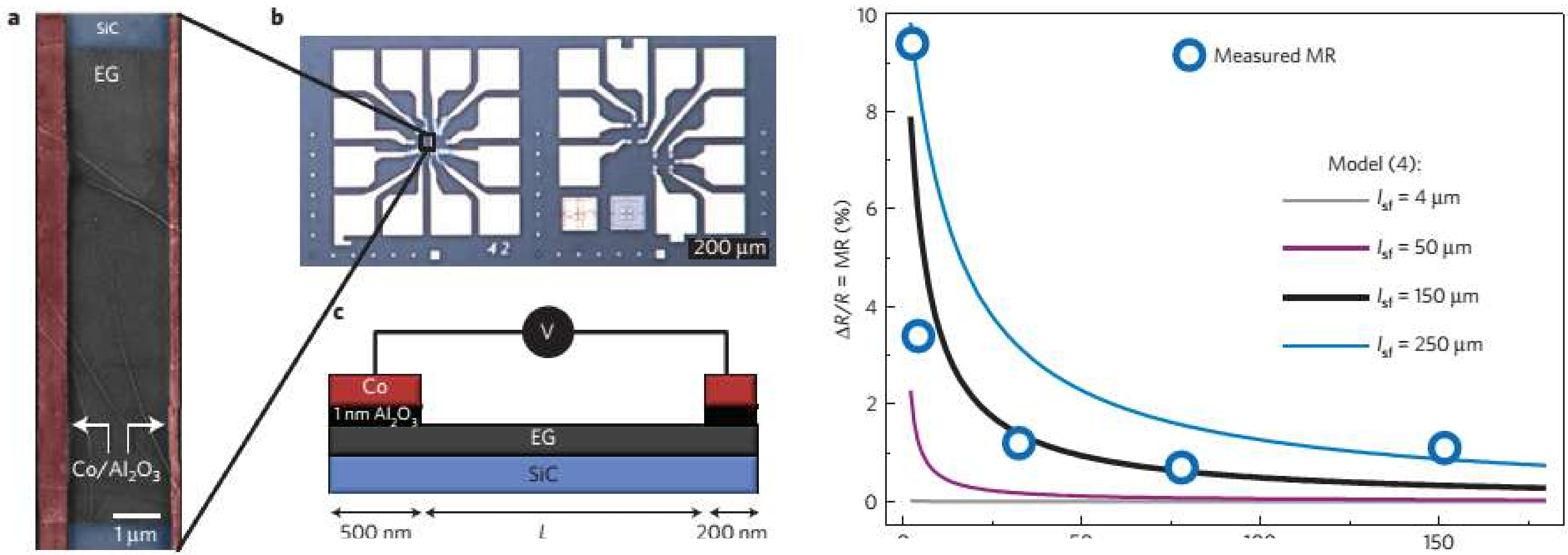
Mobility > 1.0 m²/Vs

Spin diffusion lengths >10 microns

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

Spin diffusion length—high quality graphene

An indirect method-- local MR measurement



Spin diffusion lengths >100 microns

Dlubak, et al, Nature Physics (2012)

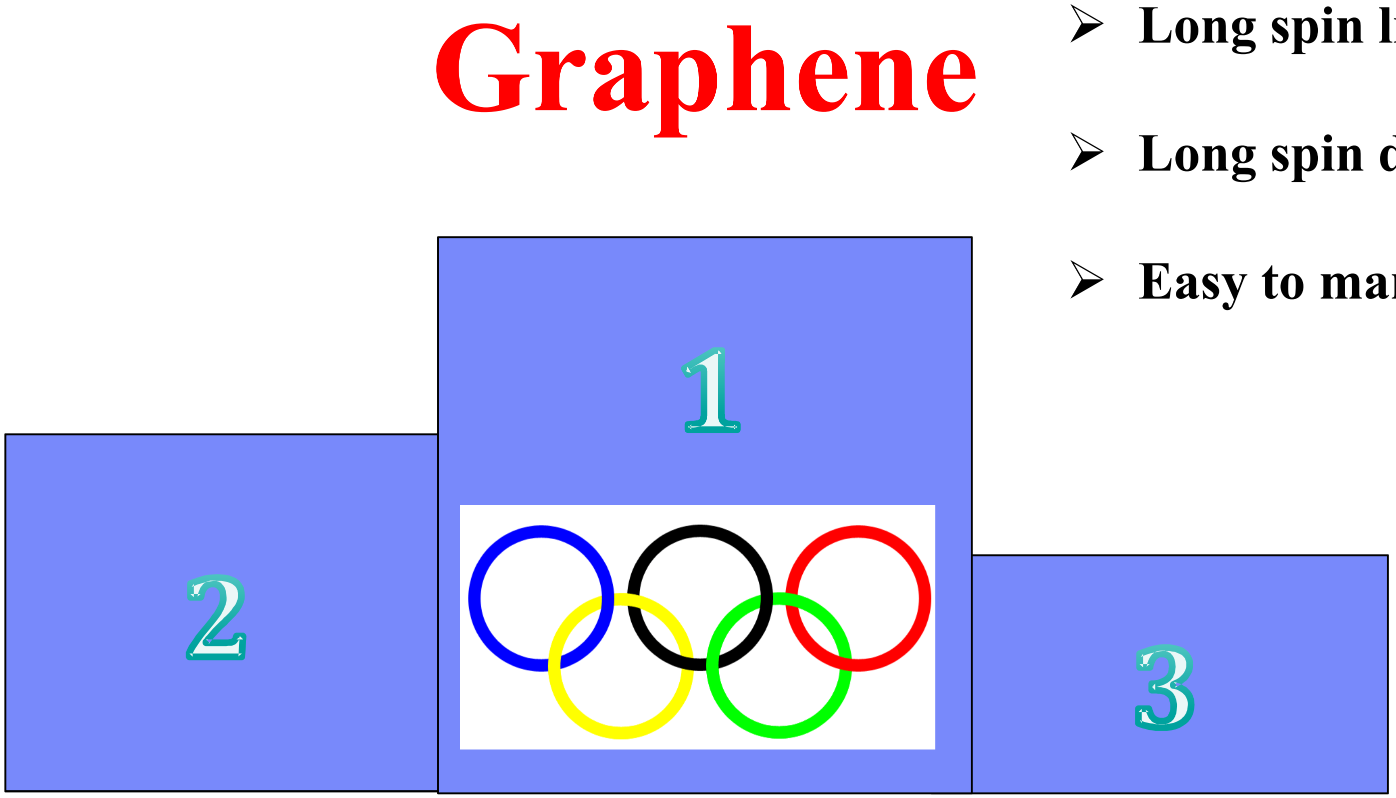
Summary of the spin dependent properties

	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**

Compared to Metal and Semiconductors

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)

Compared to Metal and Semiconductors



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

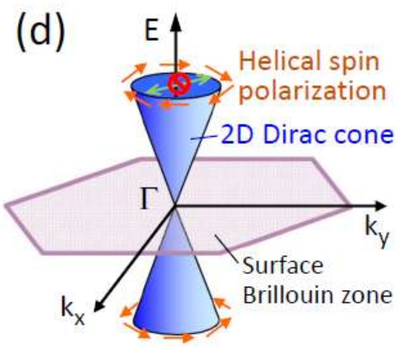
Wei Han, et al, Nature Nanotechnology 9, 794-807 (2014).

Outline

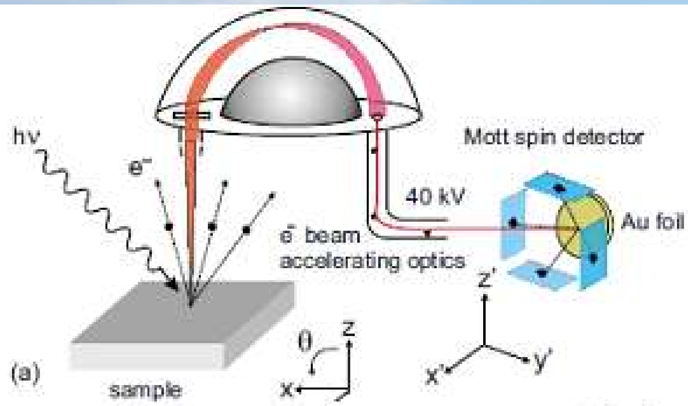
I. Introduction to spintronics (Lecture I)

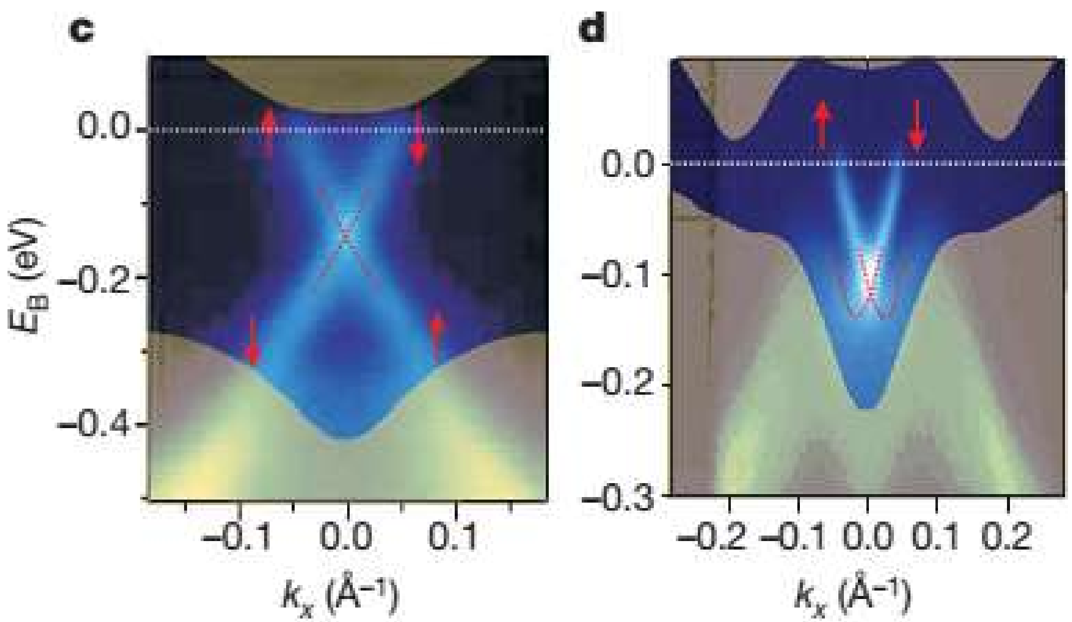
II. Spin injection and detection in 2D (Lecture I)

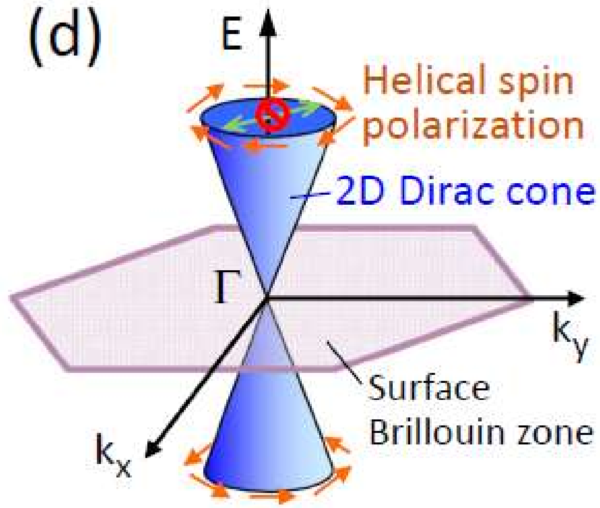
Spin in Topological insulator



Spin-momentum locking in TI

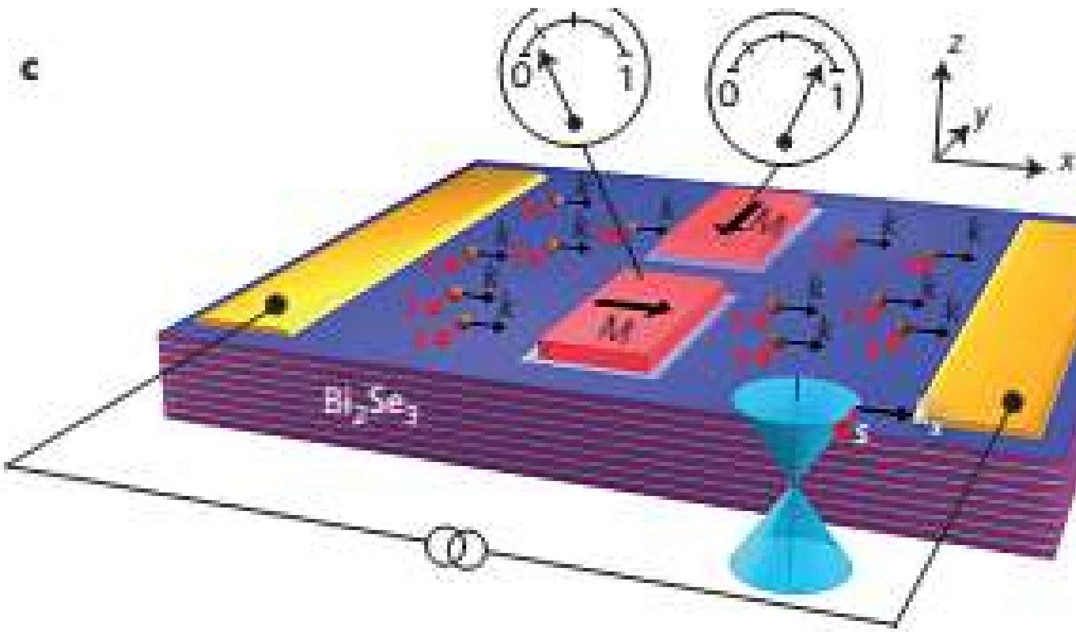






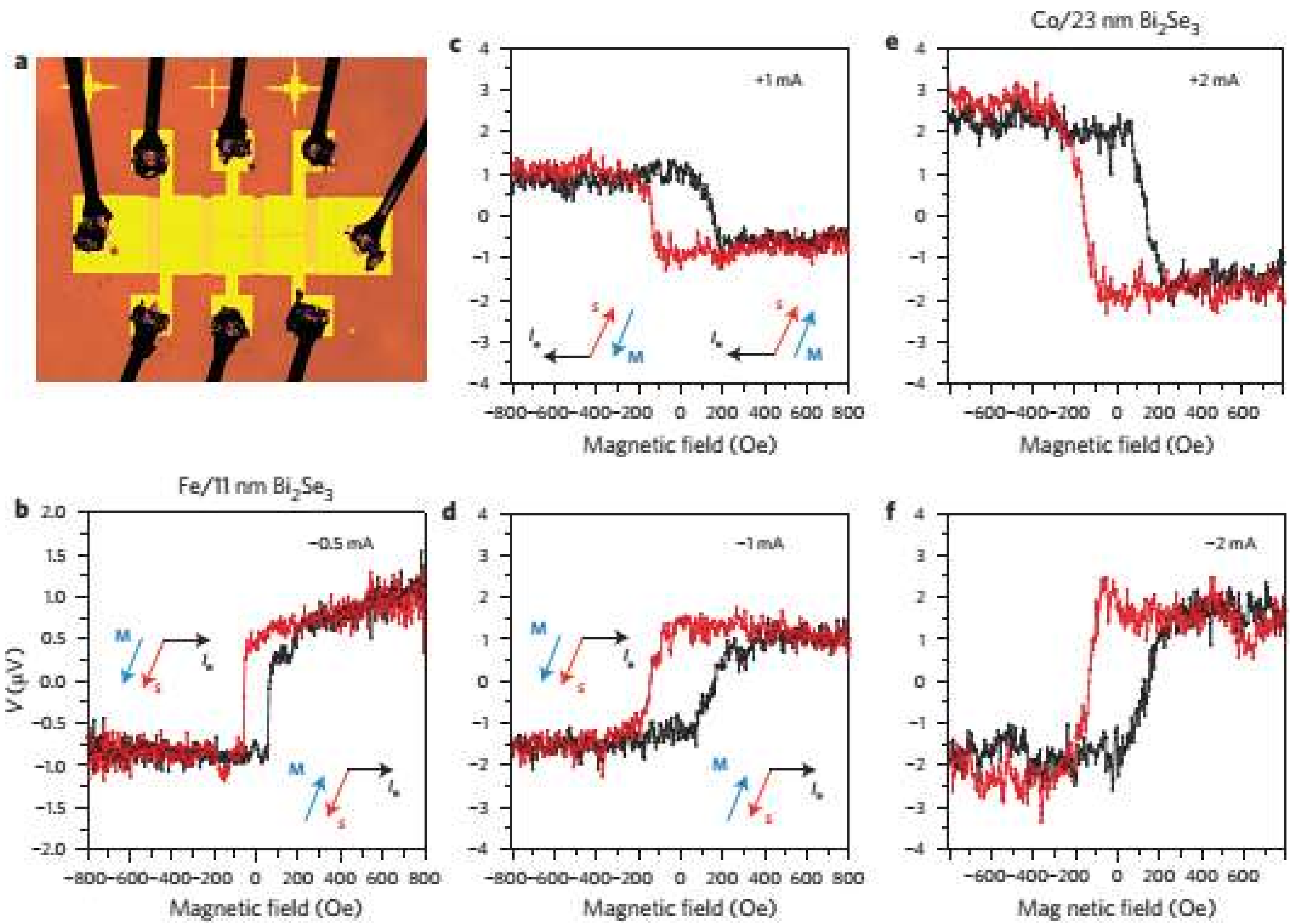
Spin ARPES**: Hasan** Group (Priceton University)

Spin-momentum locking in TI



Li, et al, Nature Nanotechnology (2014).

Spin-momentum locking in TI



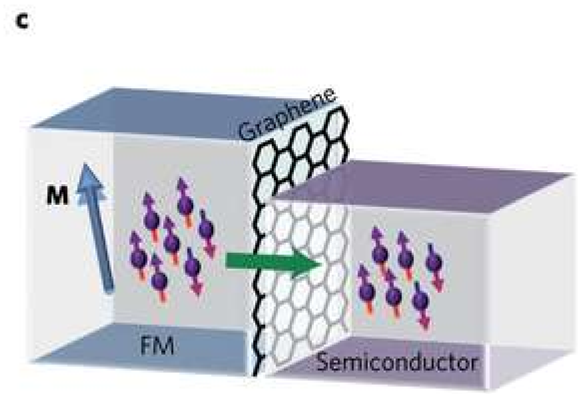
More information, please see the results of **Jonker** Group (Naval National Lab), **KL Wang** Group (UCLA) , **Y. Chen** Group (Purdue University) , etc

Outline

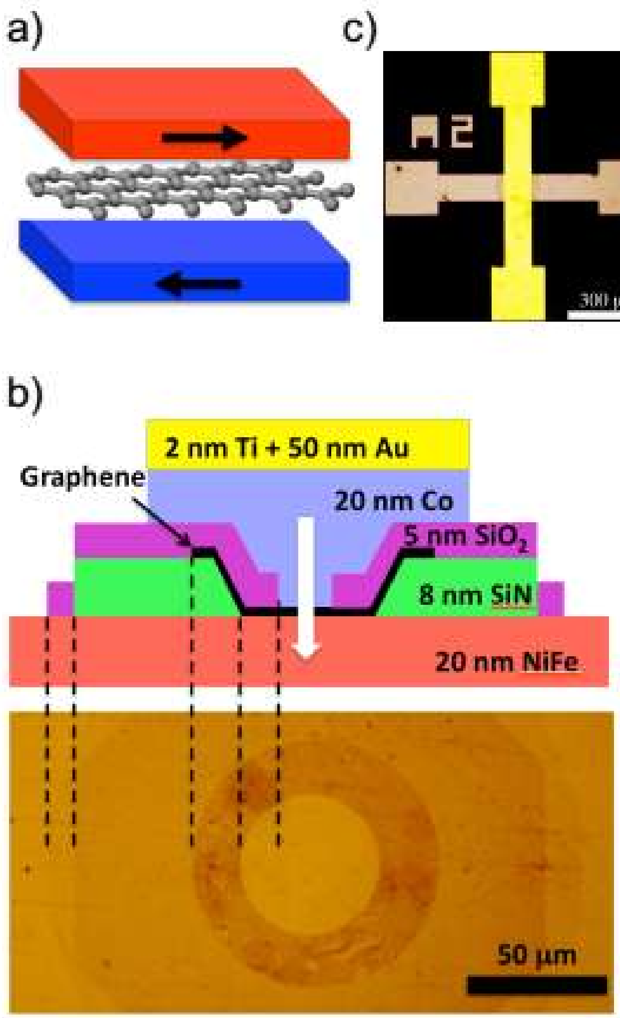
I. Introduction to spintronics (Lecture I)

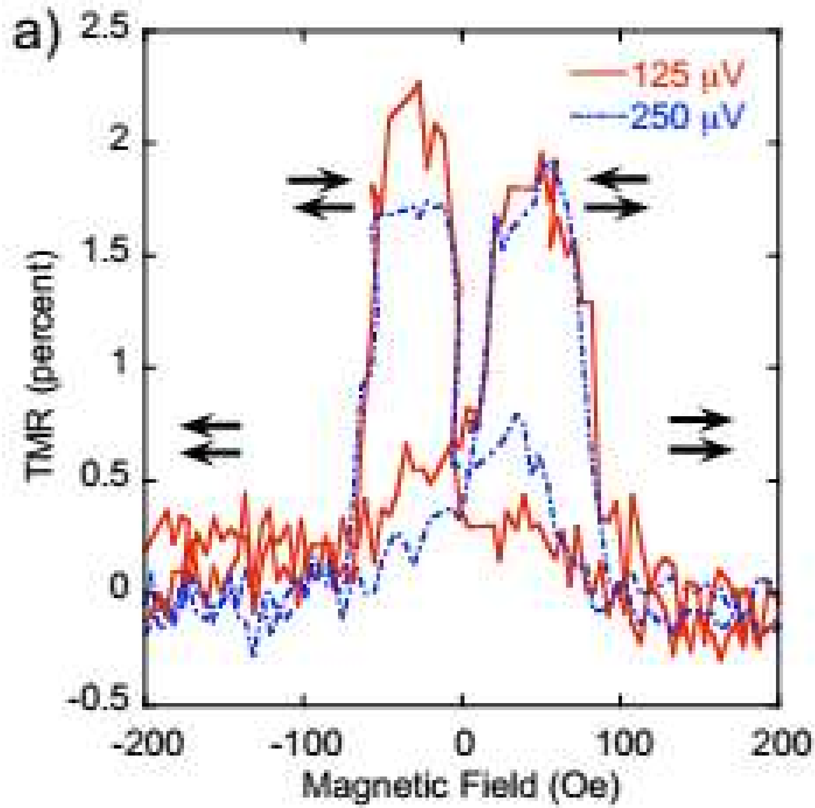
II. Spin injection and detection in 2D (Lecture I)

Graphene as a tunnel barrier



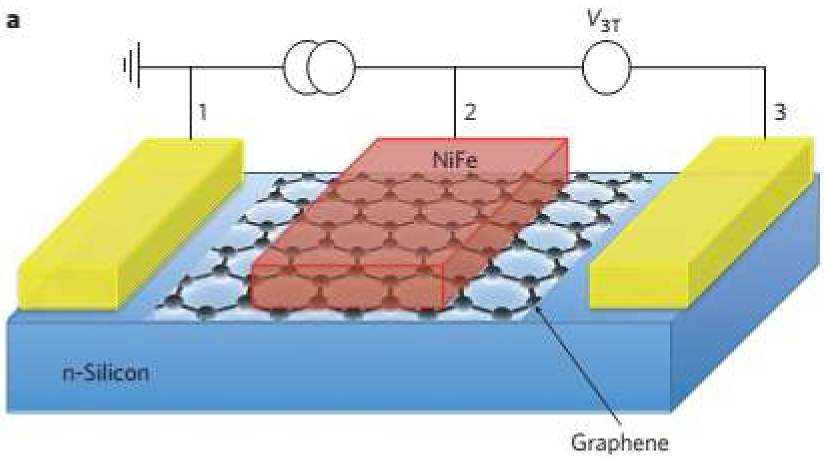
Graphene as tunnel barrier

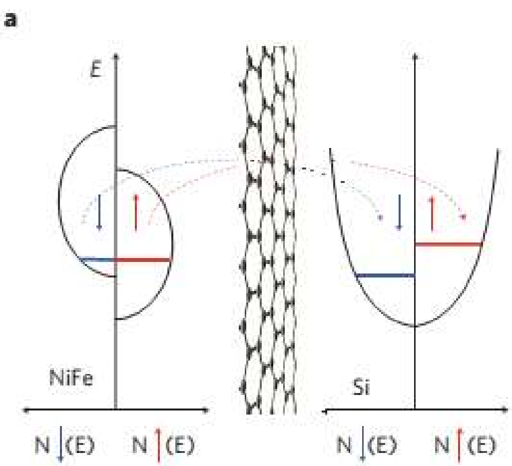


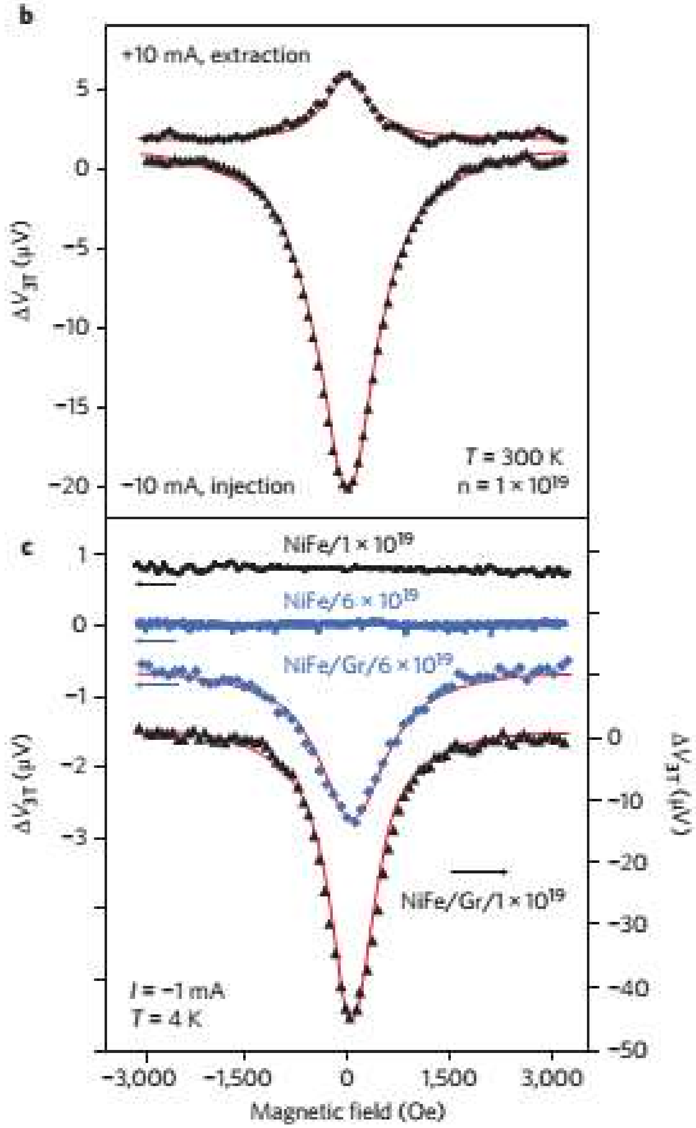


More information, please see the results of **Jonker** Group (Naval National Lab), **D. Yu** Group (PKU), **D. Ralph** Group (Cornell University) , etc

Graphene as tunnel barrier

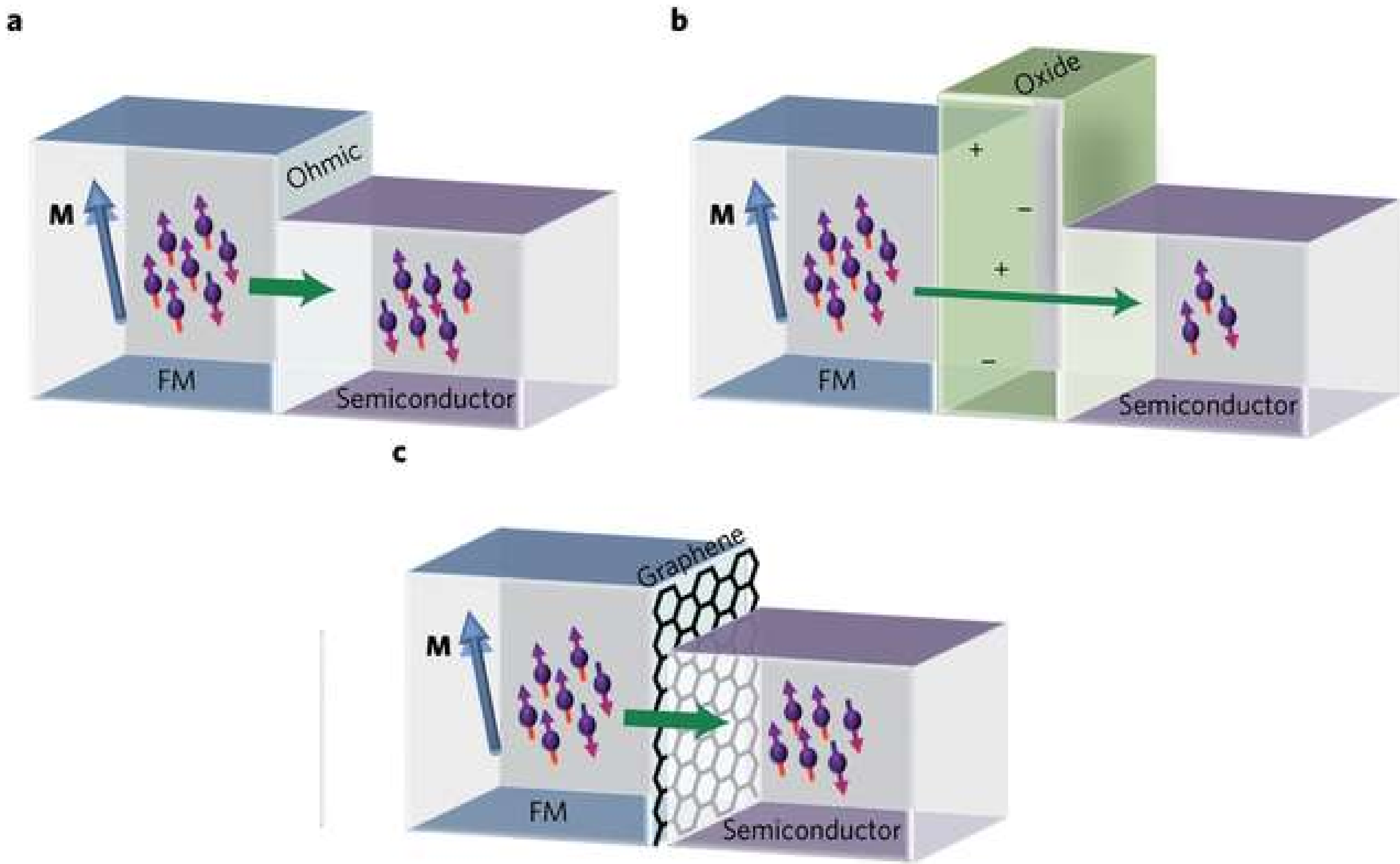






Van’t Erve et al, Nature Nanotech. (2012)
Van’t Erve et al, Nature Commun. (2015).

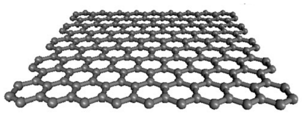
Graphene as tunnel barrier



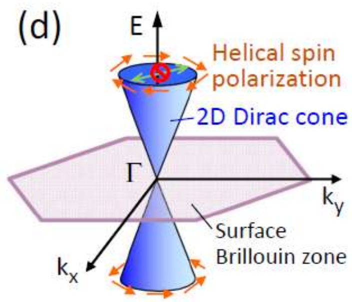
Dery, Nature Nanotech. (2012)

Summary of Lecture I

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

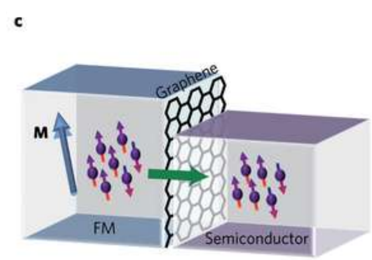


  - ➢ **Large spin signal (with tunnel barrier)**
  - ➢ **Long spin lifetime (6.2 ns in BLG)**
  - ➢ **Long spin diffusion length (> 10 micro meters at RT)**
  - ➢ **Easy to manipulate (Gate)**



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

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



Summary of Lecture I

Questions still to be answered:

- **Spin lifetime issue (Why?)**
- **Tune spin orbit coupling in graphene?**
- **Towards a spin device using G/TI?**
- **Robust S-M locking surface states of TI?**