Chapter 4

Spin Valves

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Review of Last Class

1. Magnetoresistance and ordinary MR

2. Anisotropic MR

3. Tunneling AMR

4. Colossal MR

5. Giant MR

6. Tunneling MR

7. Spin Hall MR

8. Nonlocal MR

9. Hanle MR

Outline

1. Spin valves and spin injection

2. Spin valves based on Metal and Superconductor

3. Spin valves based on Semiconductor and Quantum materials

This Class

1. Spin valves and spin injection

Outline

1. Vertical Spin valves

2. From Vertical to Lateral Spin valves

3. Spin injection

Outline

1. Vertical Spin valves

Spin valve

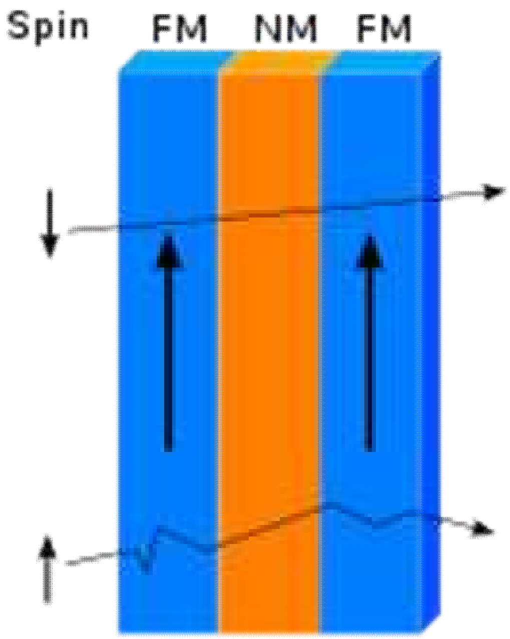
Valve

Spin valve

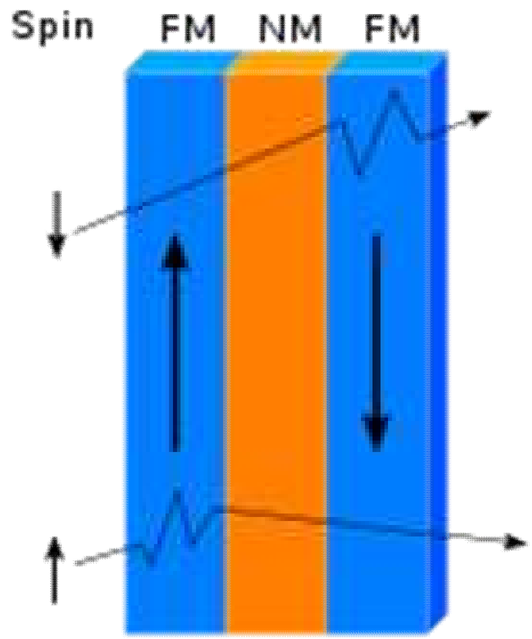
Valves

Cold Water | Hot Water

Spin valve

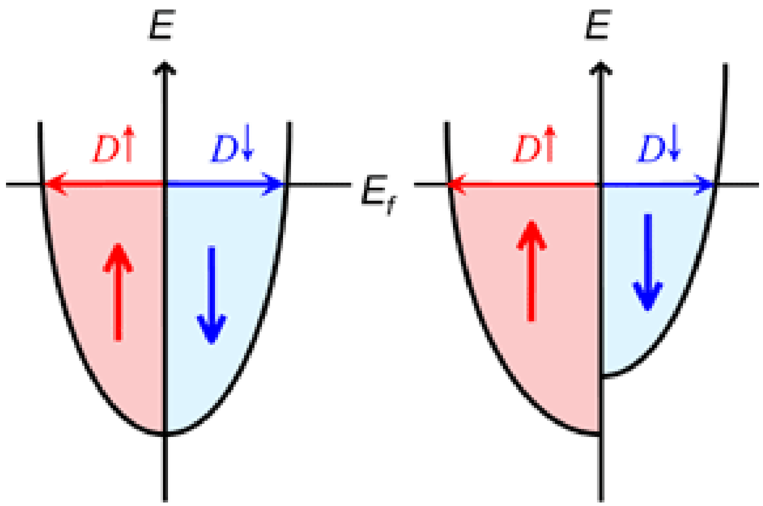


Low Resistance State



High Resistance State

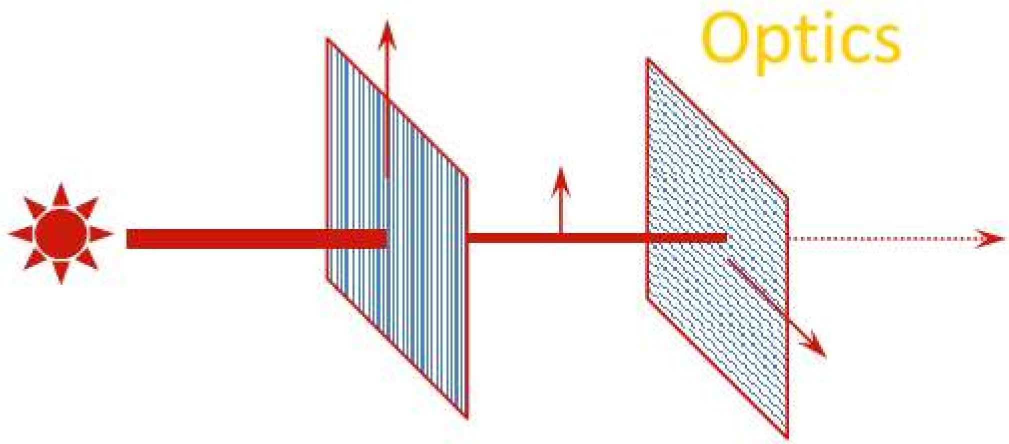
Spin valve

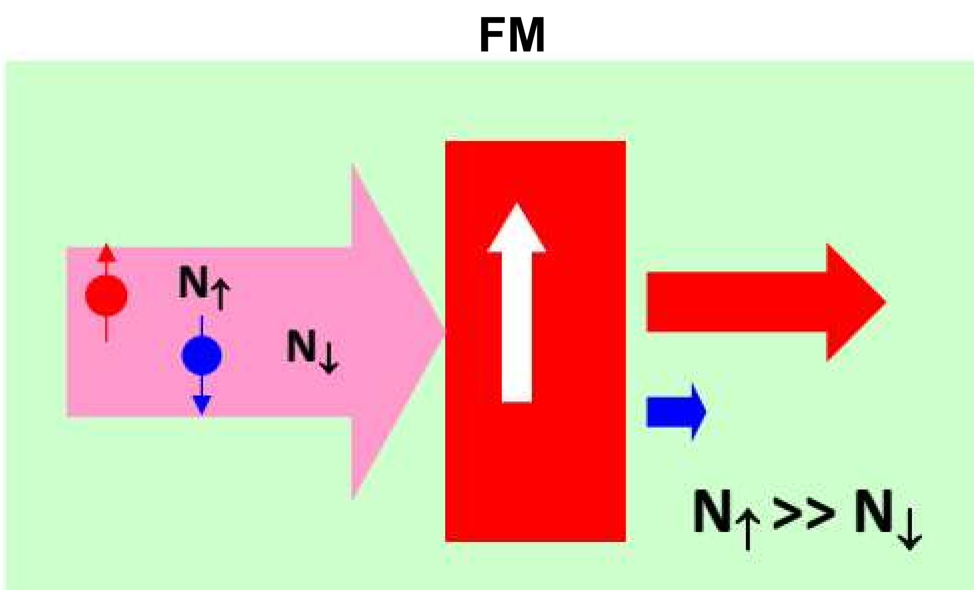


Nonmagnetic Ferromangetic

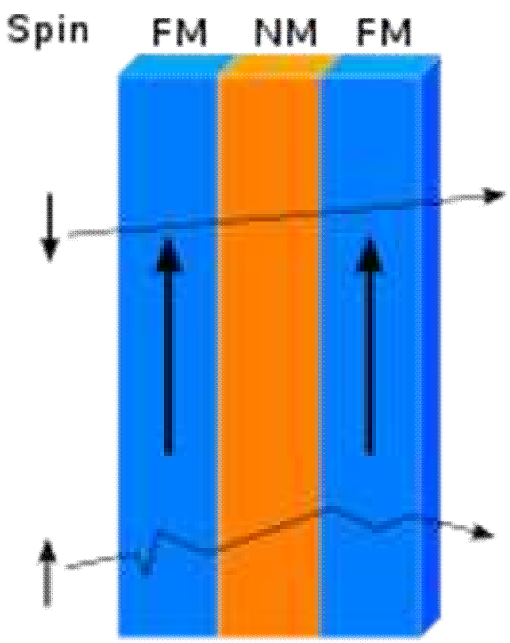
$$P = \frac{D_\uparrow - D_\downarrow}{D_\uparrow + D_\downarrow}$$

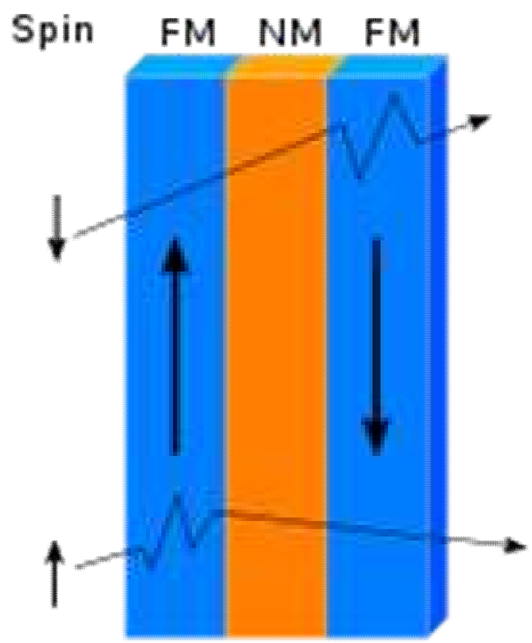
Julie Model





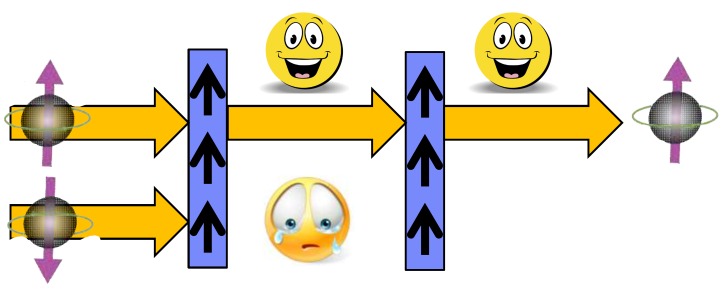
Julie Model

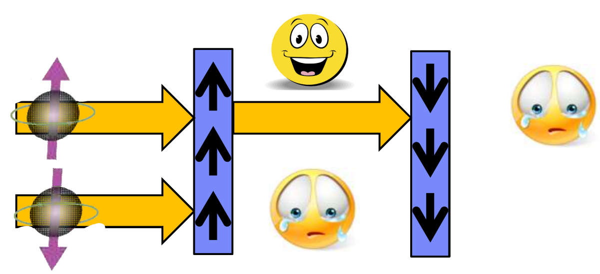




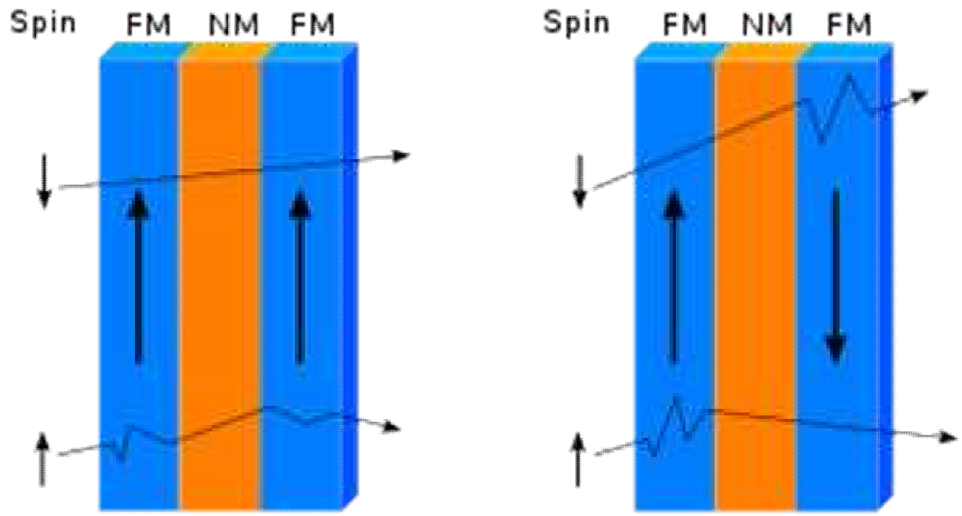
Parallel

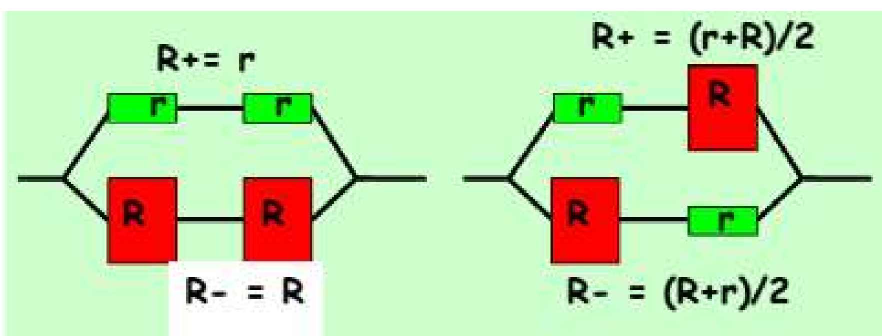
Anti-Parallel





Julie Model





$$R_P = \frac{Rr}{R+r} \approx r < R_{AP} = \frac{R+r}{4}$$

When Julie model fails

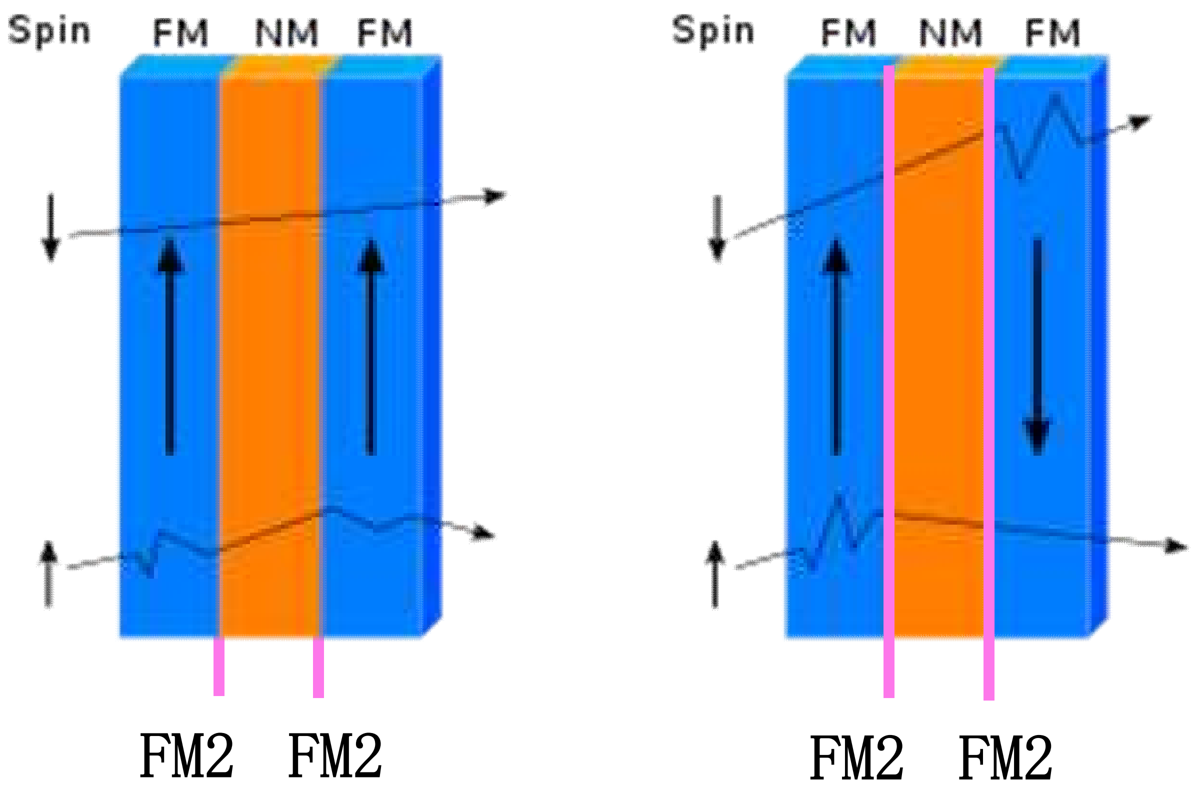
Two examples:

1) Insertion of thin FM layer

2) MgO tunnel barrier

When Julie model fails

1) Insertion of thin FM layer



Question: What happens?

When Julie model fails

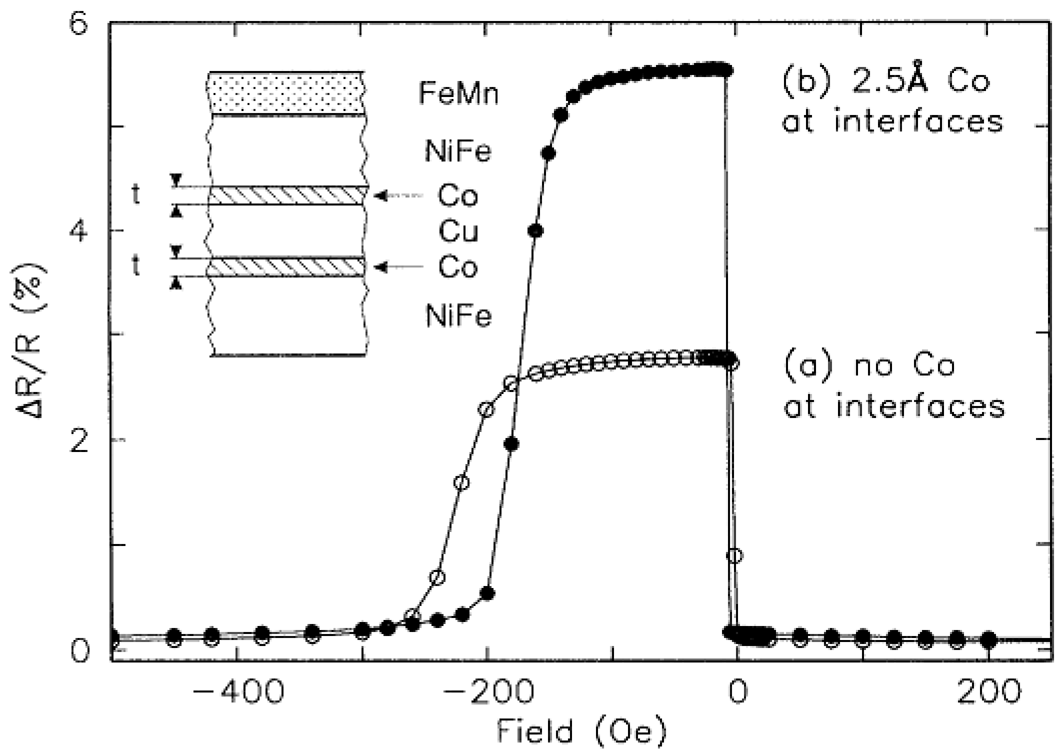
1) Insertion of thin FM layer

Julie model: two spin current model, then the interface should not matter. The MR depends on the spin polarization of the FMs.

However, this is not the experimental observation.

When Julie model fails

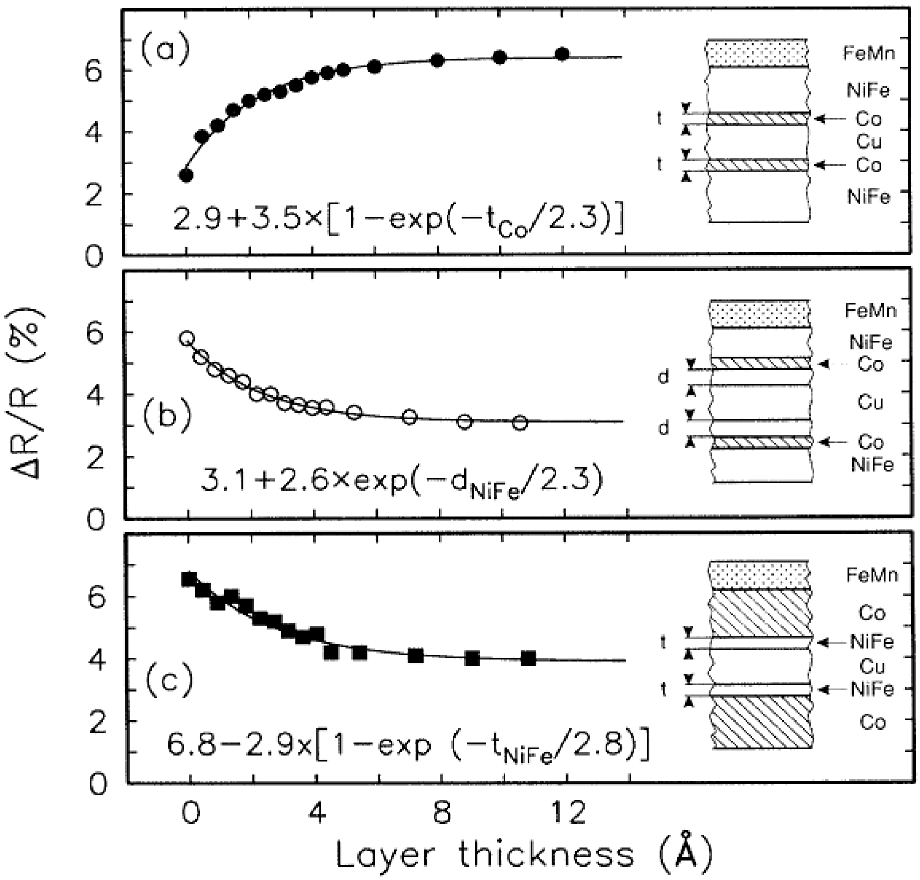
1) Insertion of thin FM layer



Parkin, PRL (1993)

When Julie model fails

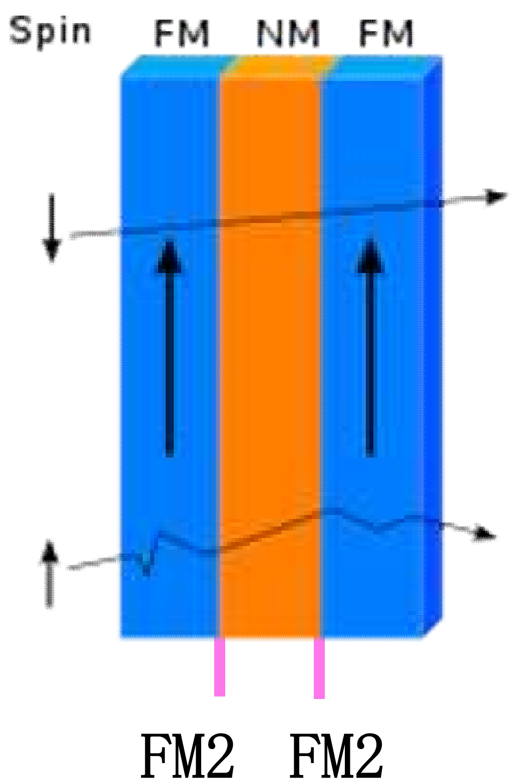
1) Insertion of thin FM layer



Parkin, PRL (1993)

When Julie model fails

1) Insertion of thin FM layer



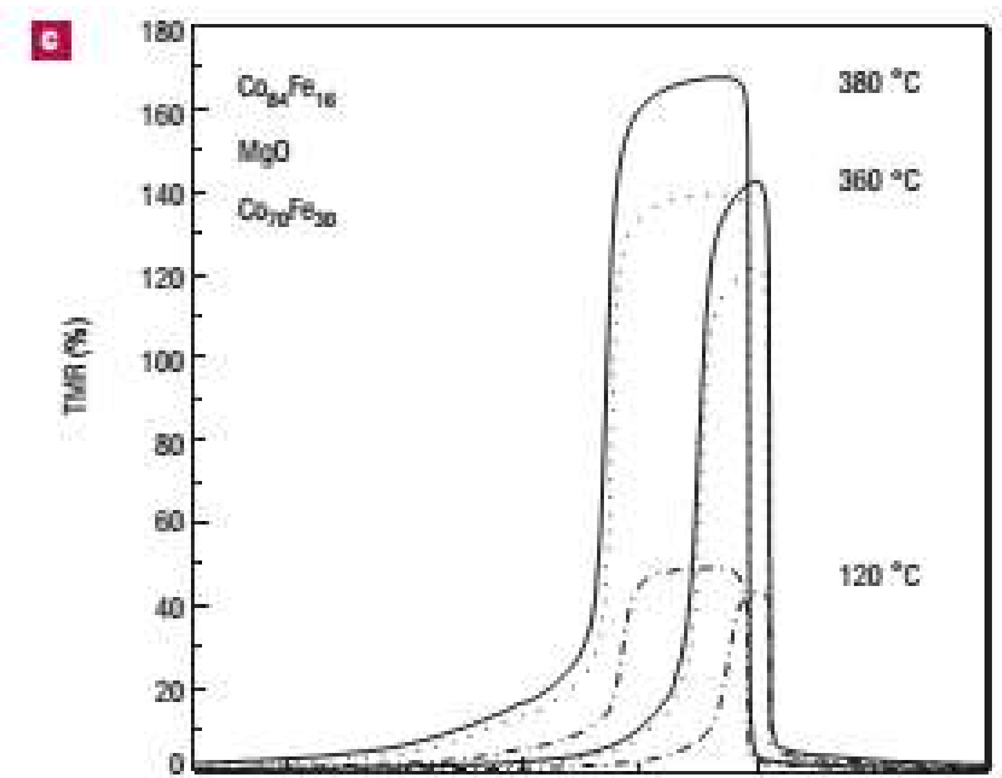
Origin of Enhanced MR of Magnetic Multilayers:

Spin-Dependent Scattering from Magnetic Interface States

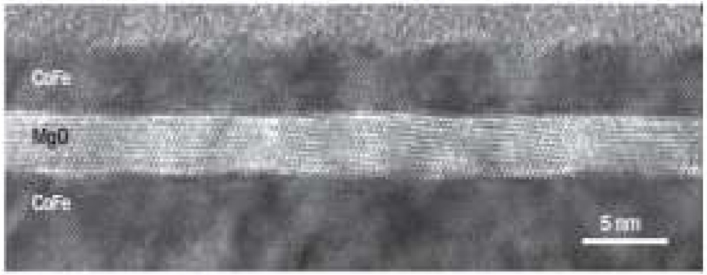
Parkin, PRL (1993)

When Julie model fails

2) MgO tunnel barrier



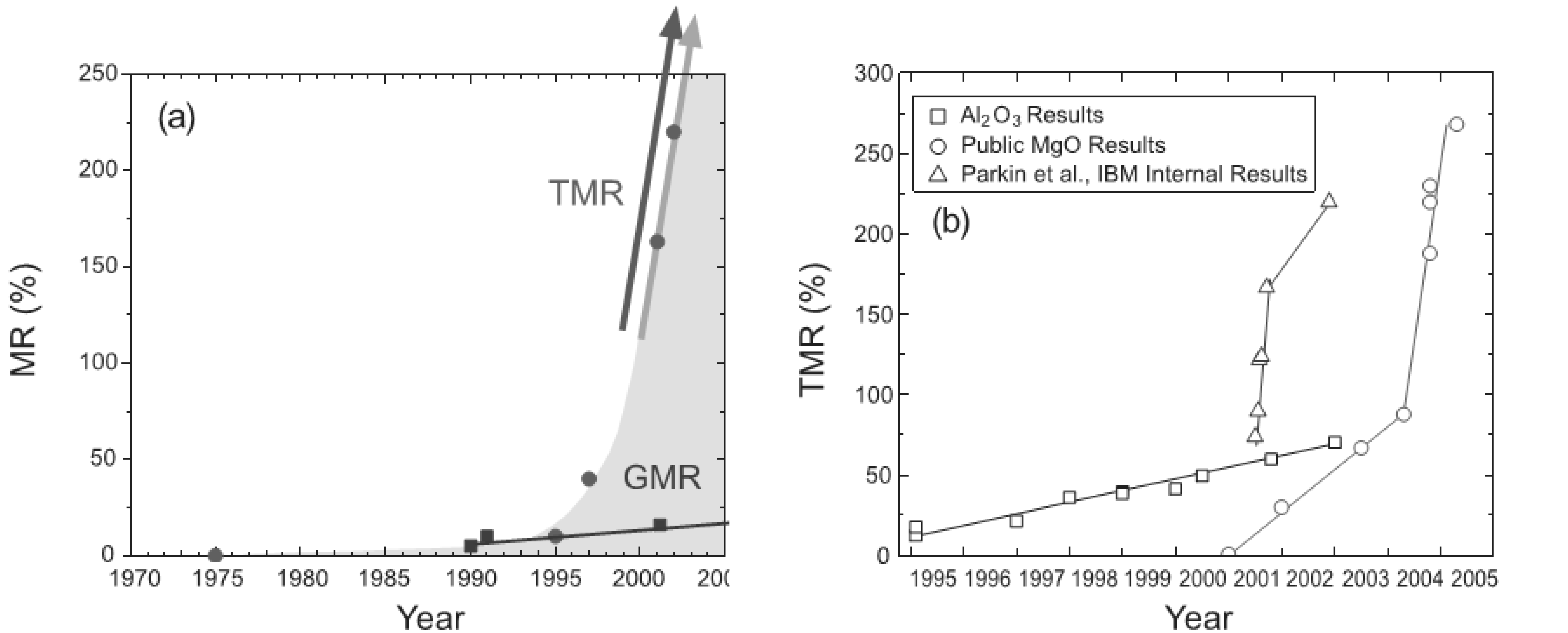
Epitaxial MgO



Parkin, et al, Nature Mater (2004)
Yuasa, et al, Nature Mater (2004)

When Julie model fails

2) MgO tunnel barrier

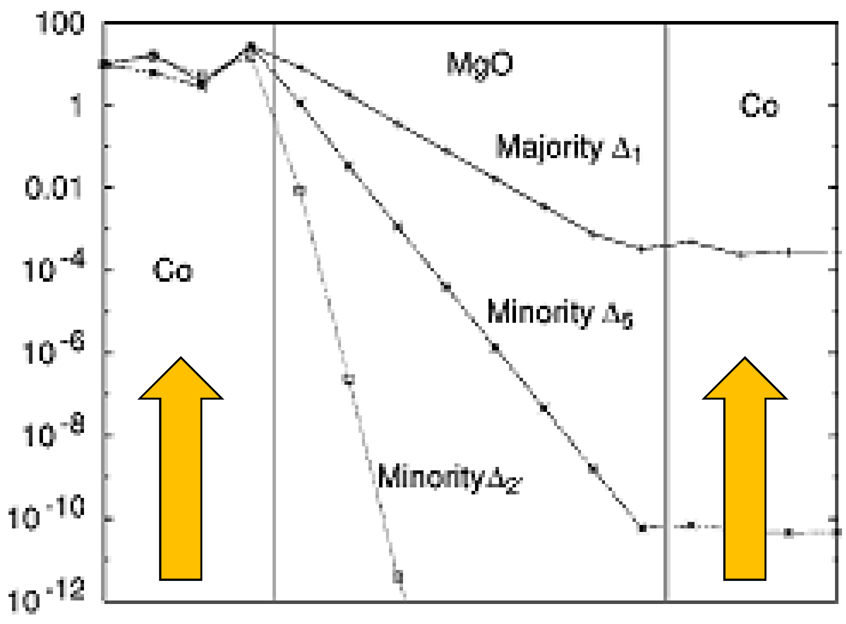


Maekawa, Book Concepts in Spin electronics (2006)

When Julie model fails

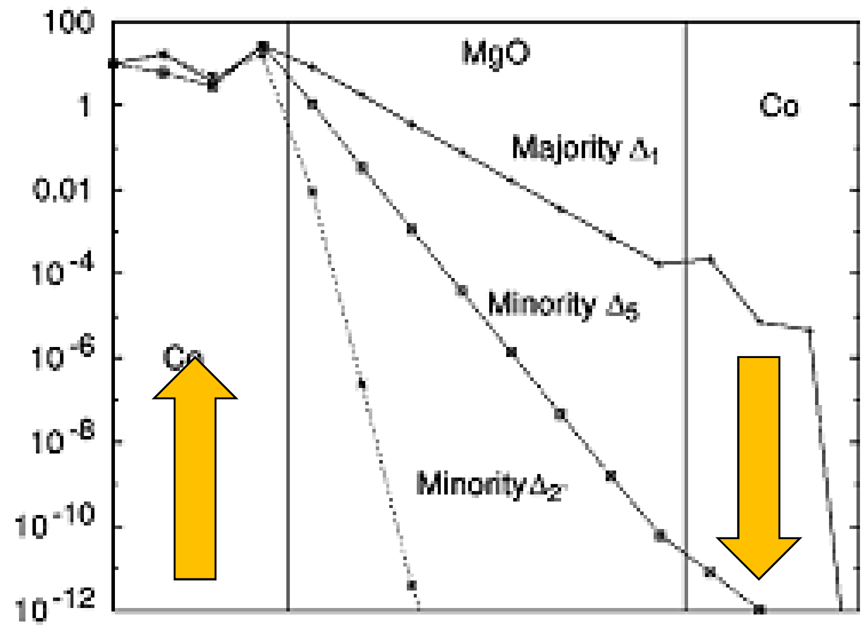
MgO barrier for tunneling: MR >100%

Parallel



(a)

Anti-Parallel

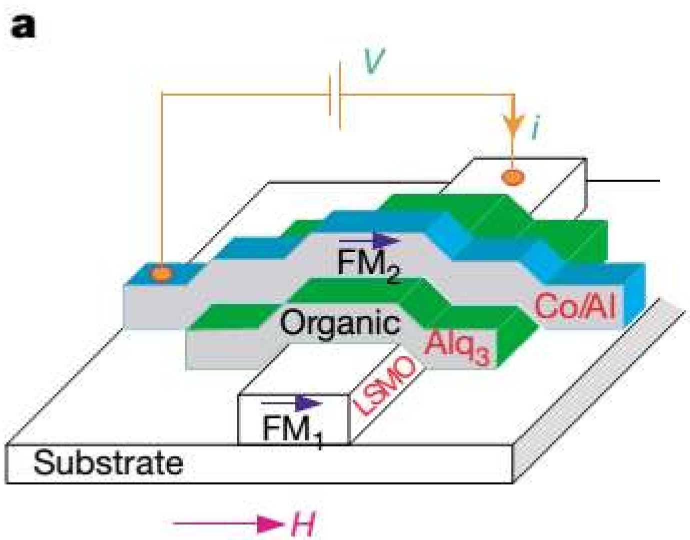


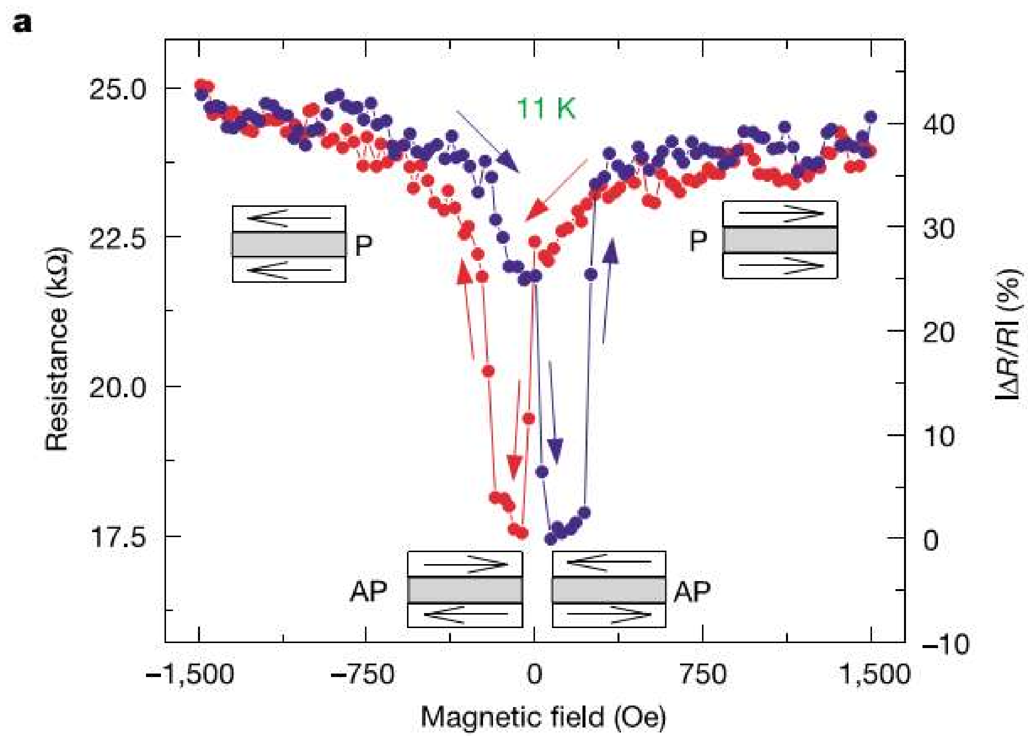
(b)

Δ_1, symmetry, slow decaying
Tunneling of Co majority spin (SP)

Zhang & Butler, et al, PRB (2004)

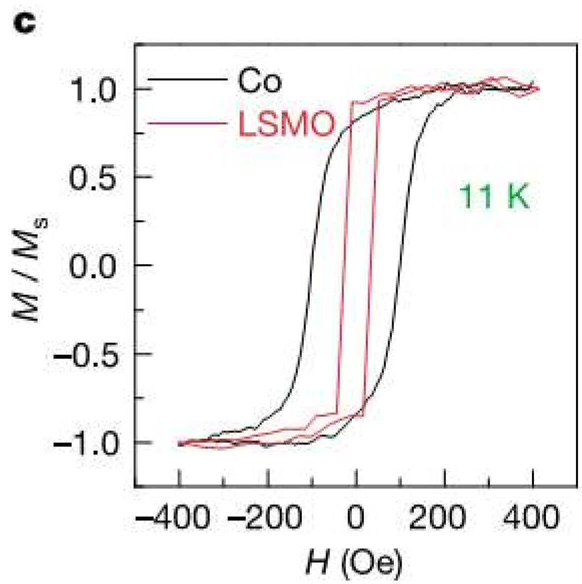
Organic Materials

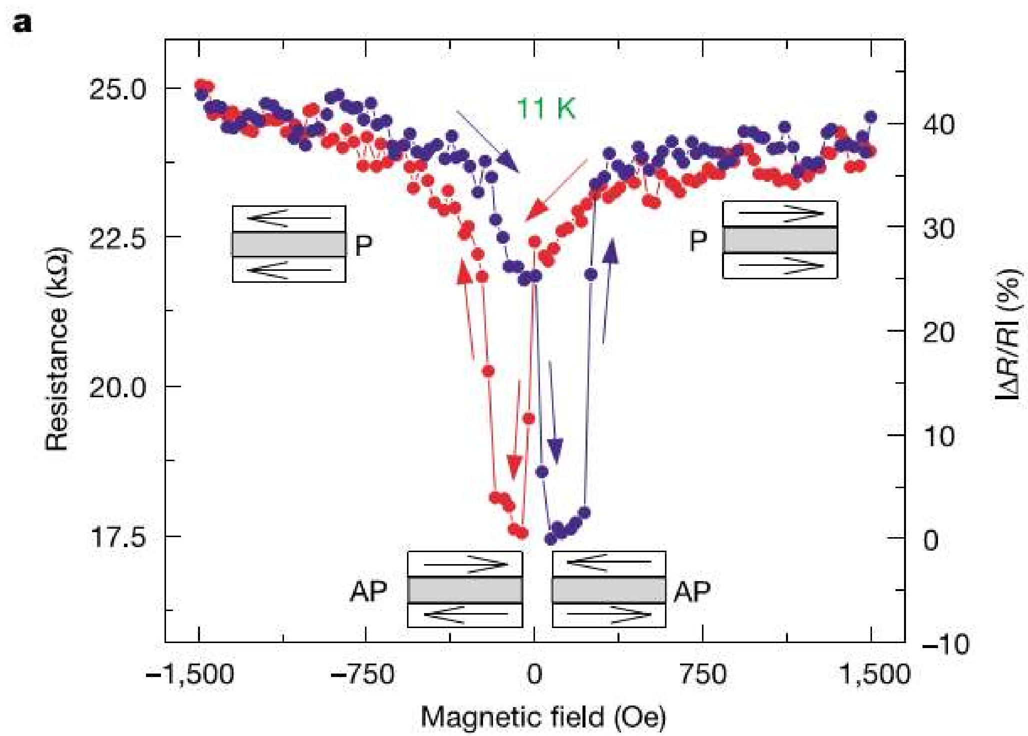




Xiong, et al, Nature (2004)

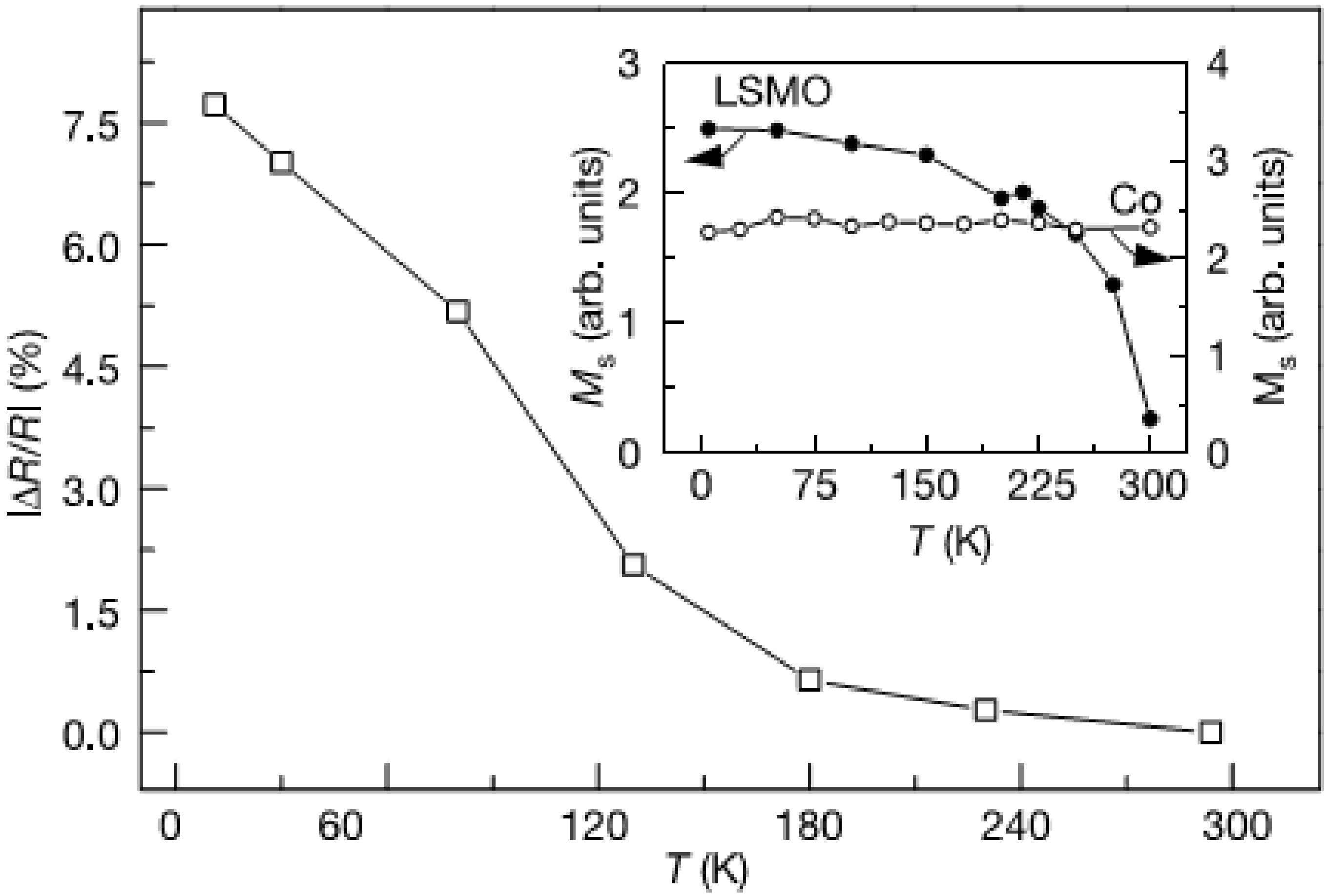
Organic Materials





Organic Materials

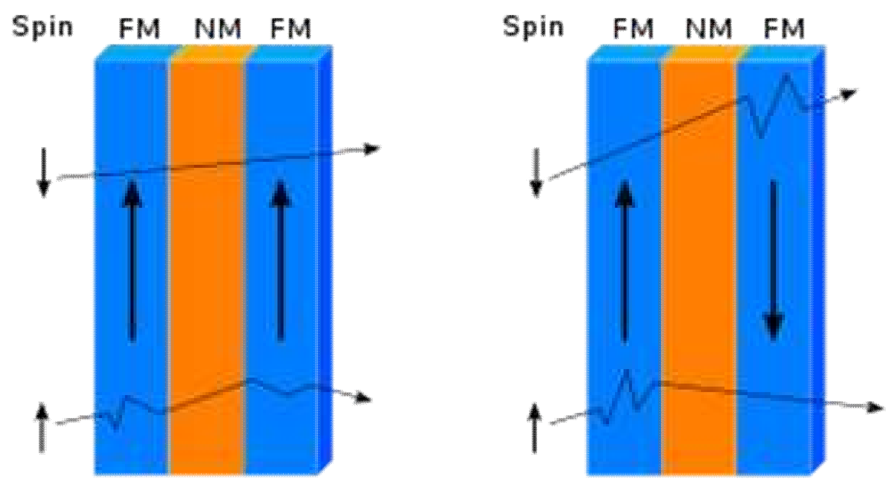
a

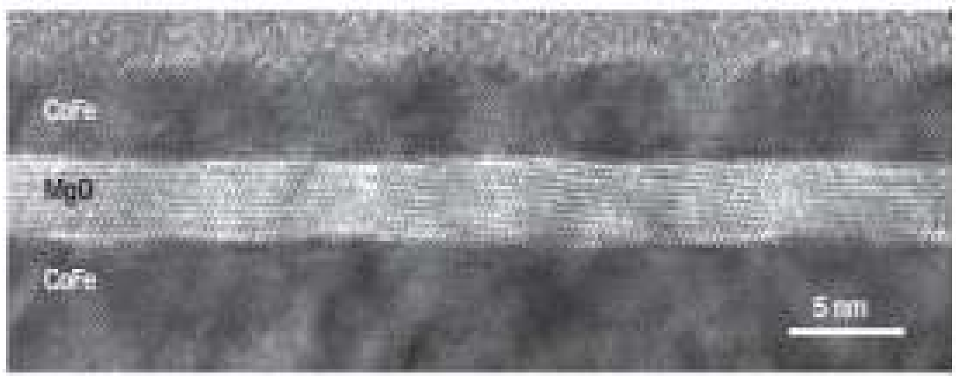


b

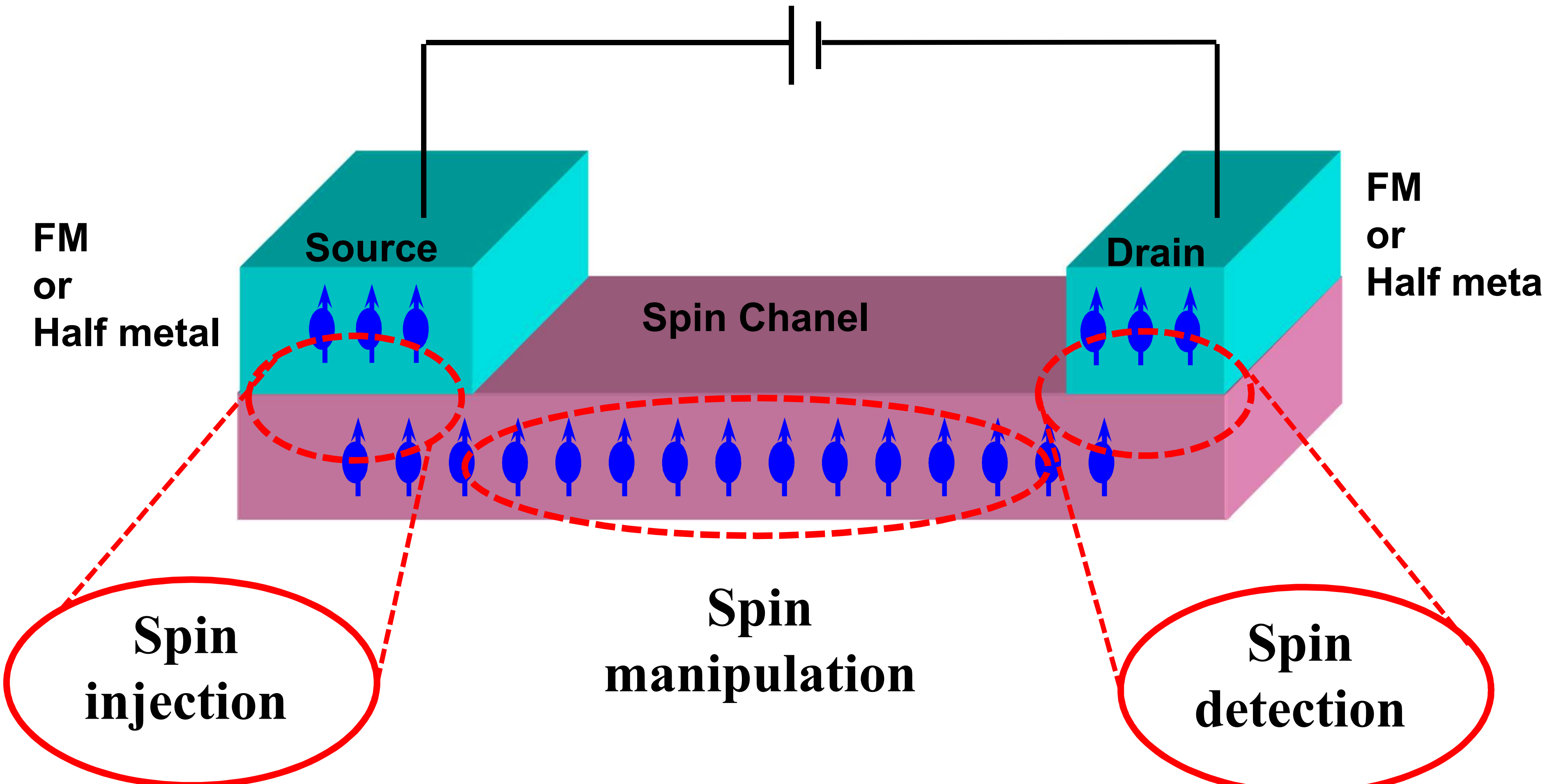
2. Why Lateral Spin Valves

Lateral Spin valves



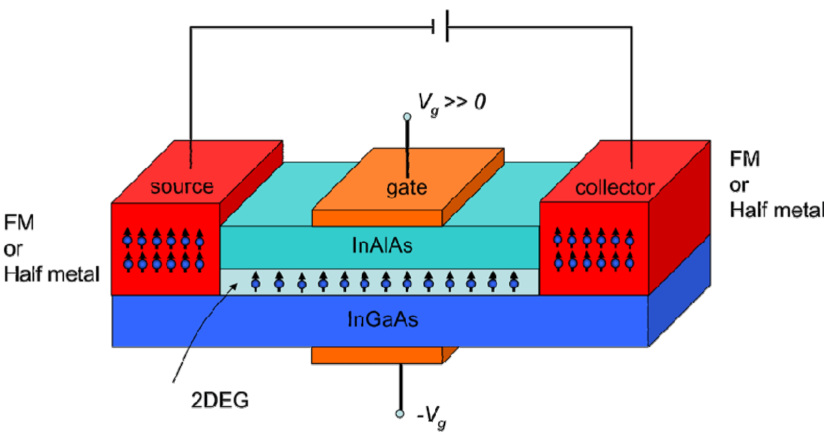


Lateral Spin valves



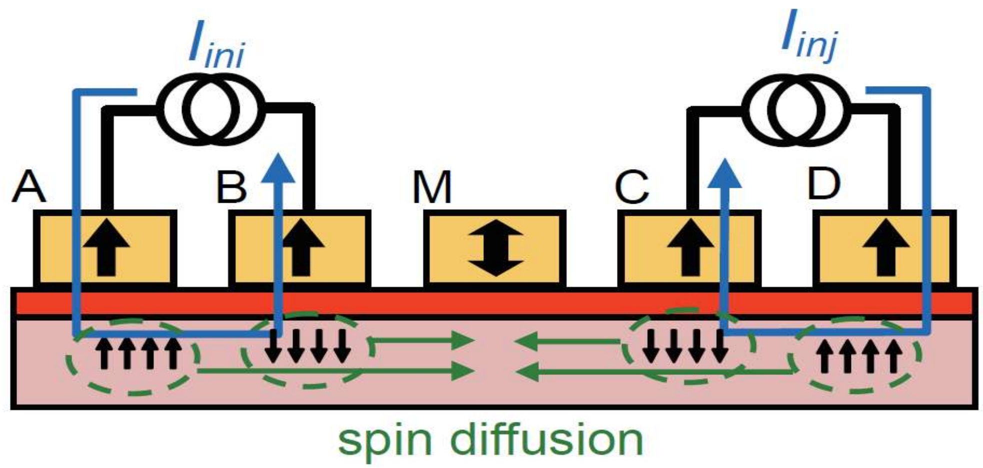
Lateral Spin valves

Spin transistor



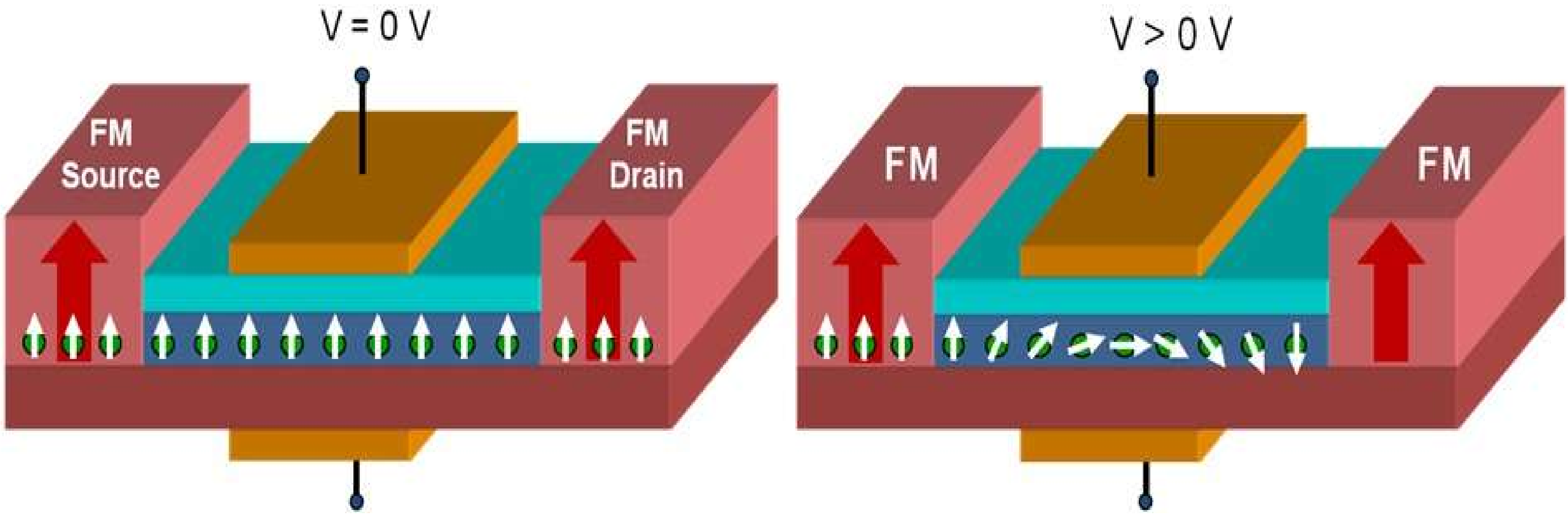
Datta & Das, APL (1990)

Spin logic and computing



Dery, et al, Nature (2007)
Behin-Aein, et al, Nat. Nano (2010).
Dery, et al, IEEE Trans. Elec. Dev. (2012)

Spin transistor



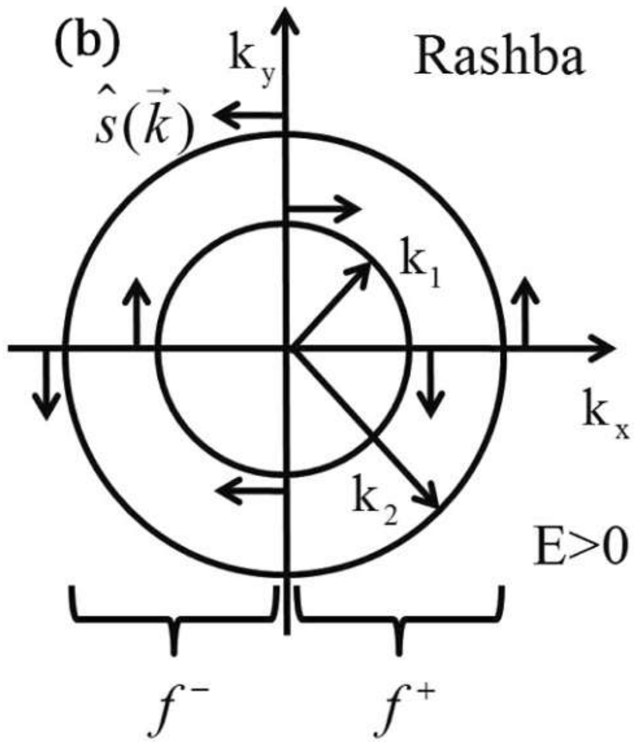
Electronic analog of the electro - optic modulator - Scitation

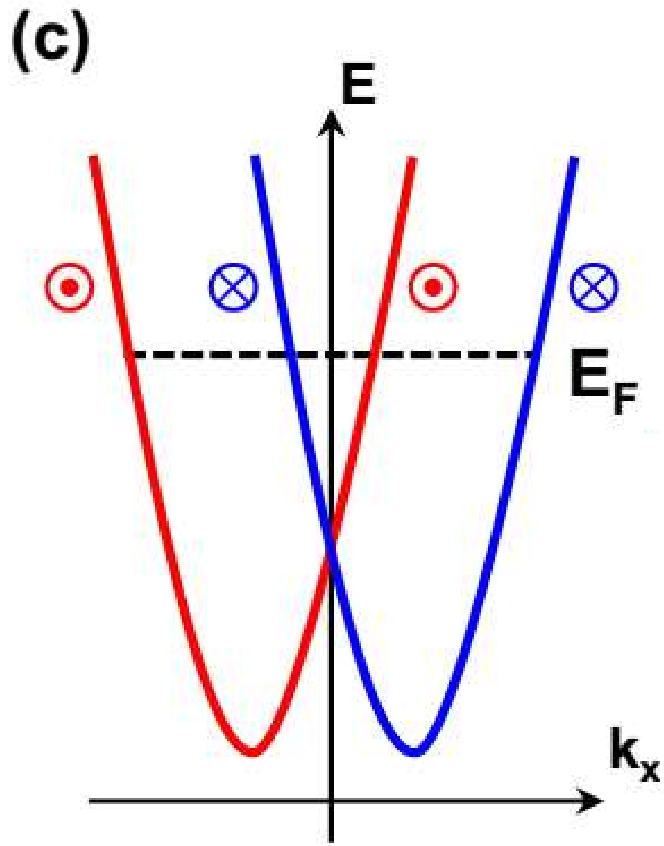
scitation.aip.org/content/aip/journal/**apl**/56/7/10.../1.102730 ▾ 翻译此页

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 ...

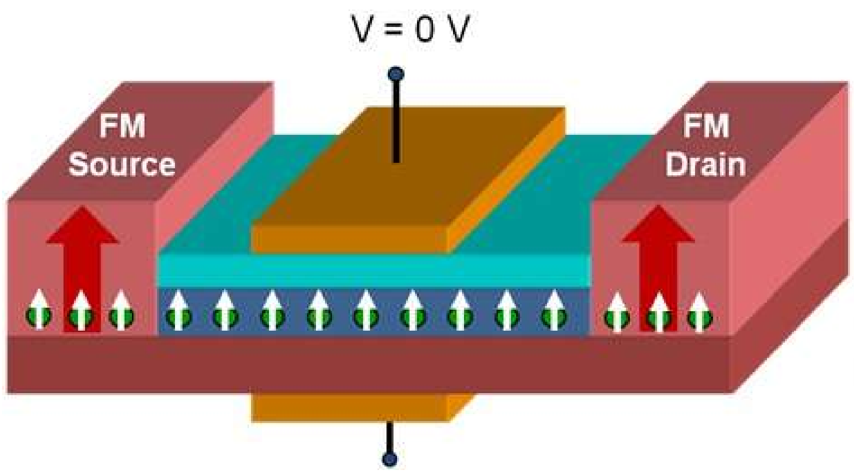
Rashba field





$$H_{\text{Rashba}} = \frac{\hbar^2}{2m}\left(k_x^2 + k_y^2\right) I_2 + \alpha(\sigma_x k_y - \sigma_y k_x),$$

Spin FET



1) Long spin diffusion length

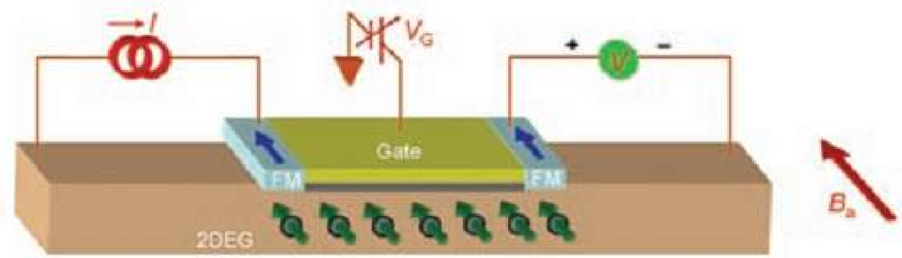
2) Large Rashba parameter → Rashba field

Datta & Das, APL (1990)

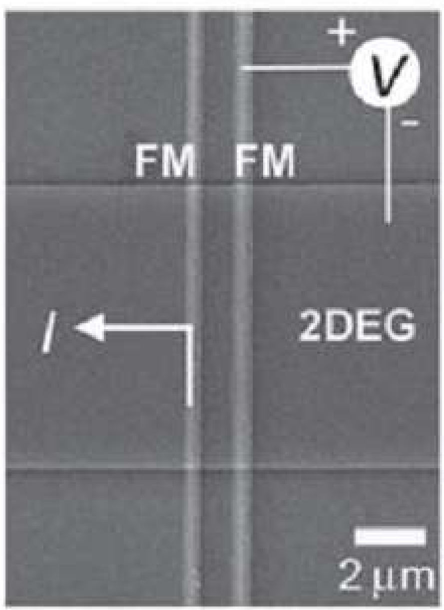
Spin FET

InAs channel

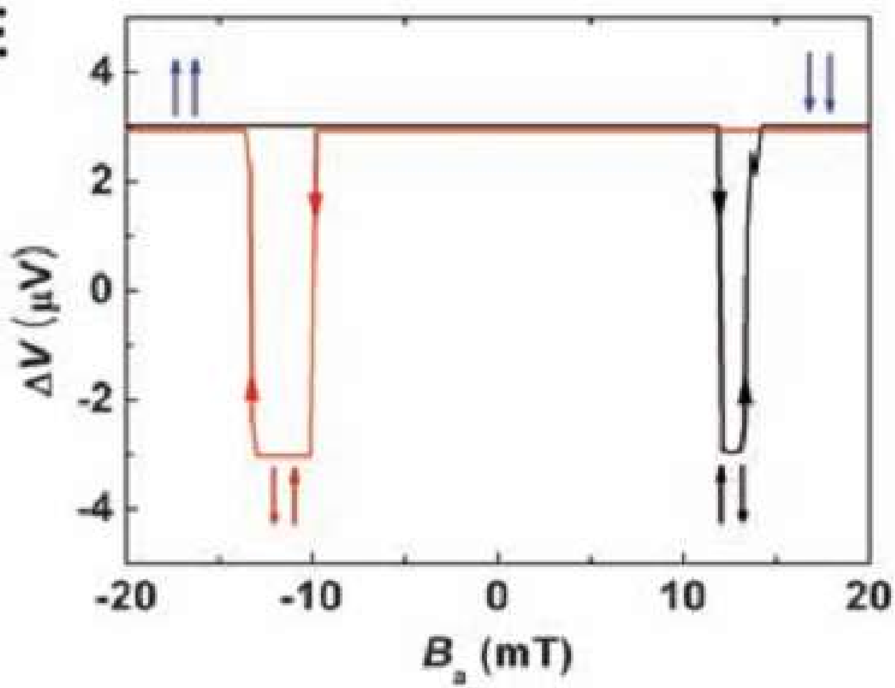
A



C

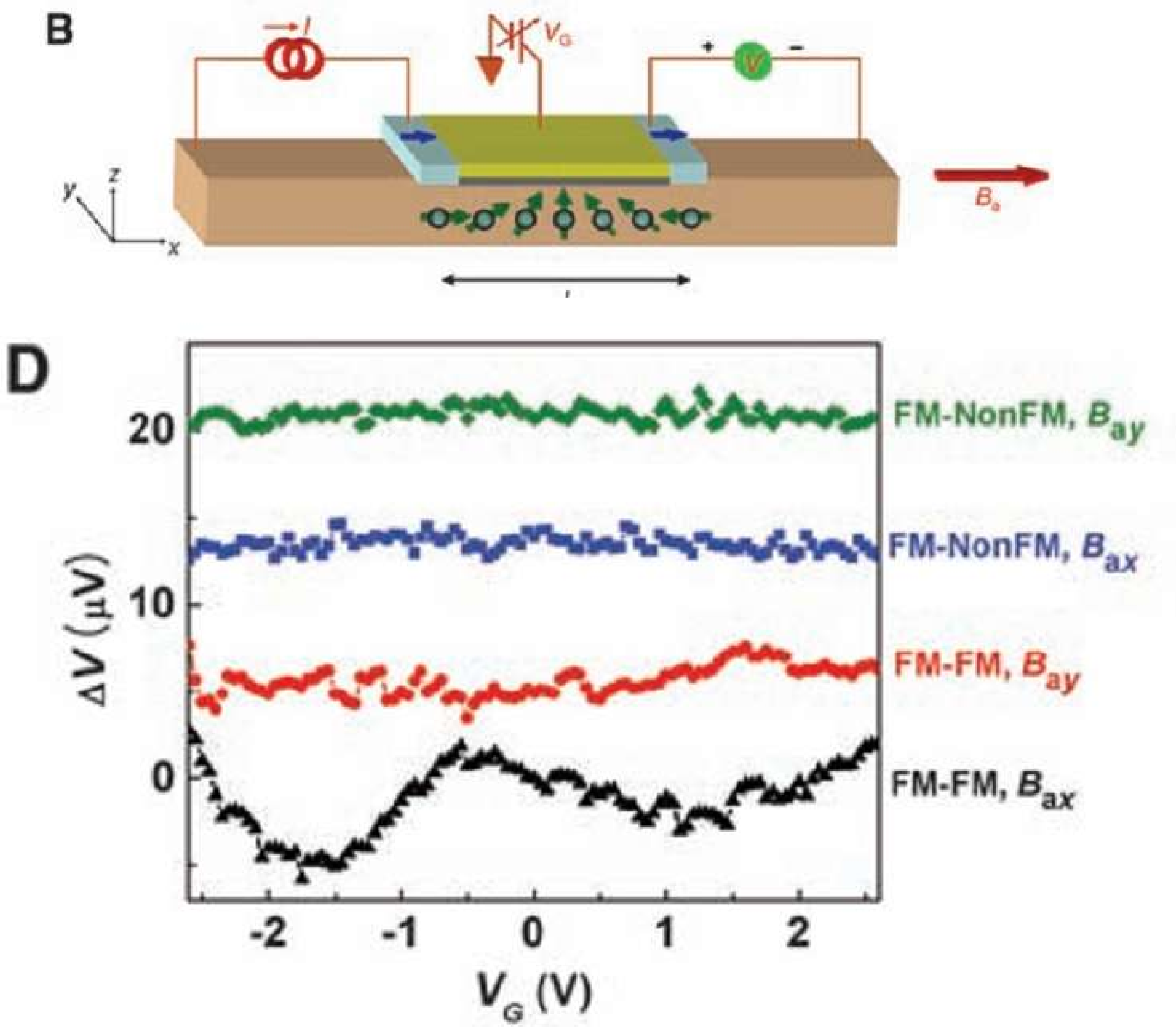


E



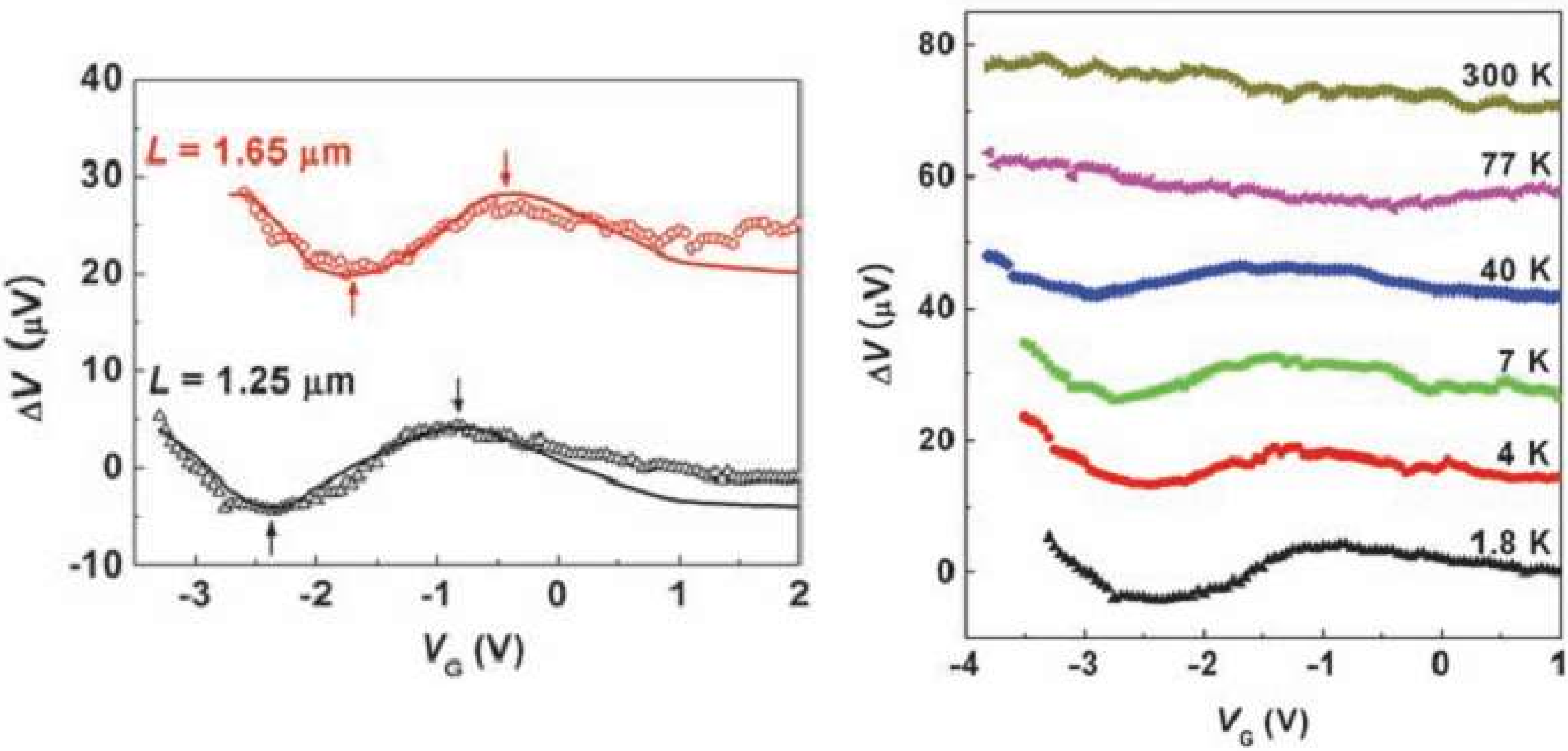
Koo, et al, Science (2009)

Spin FET

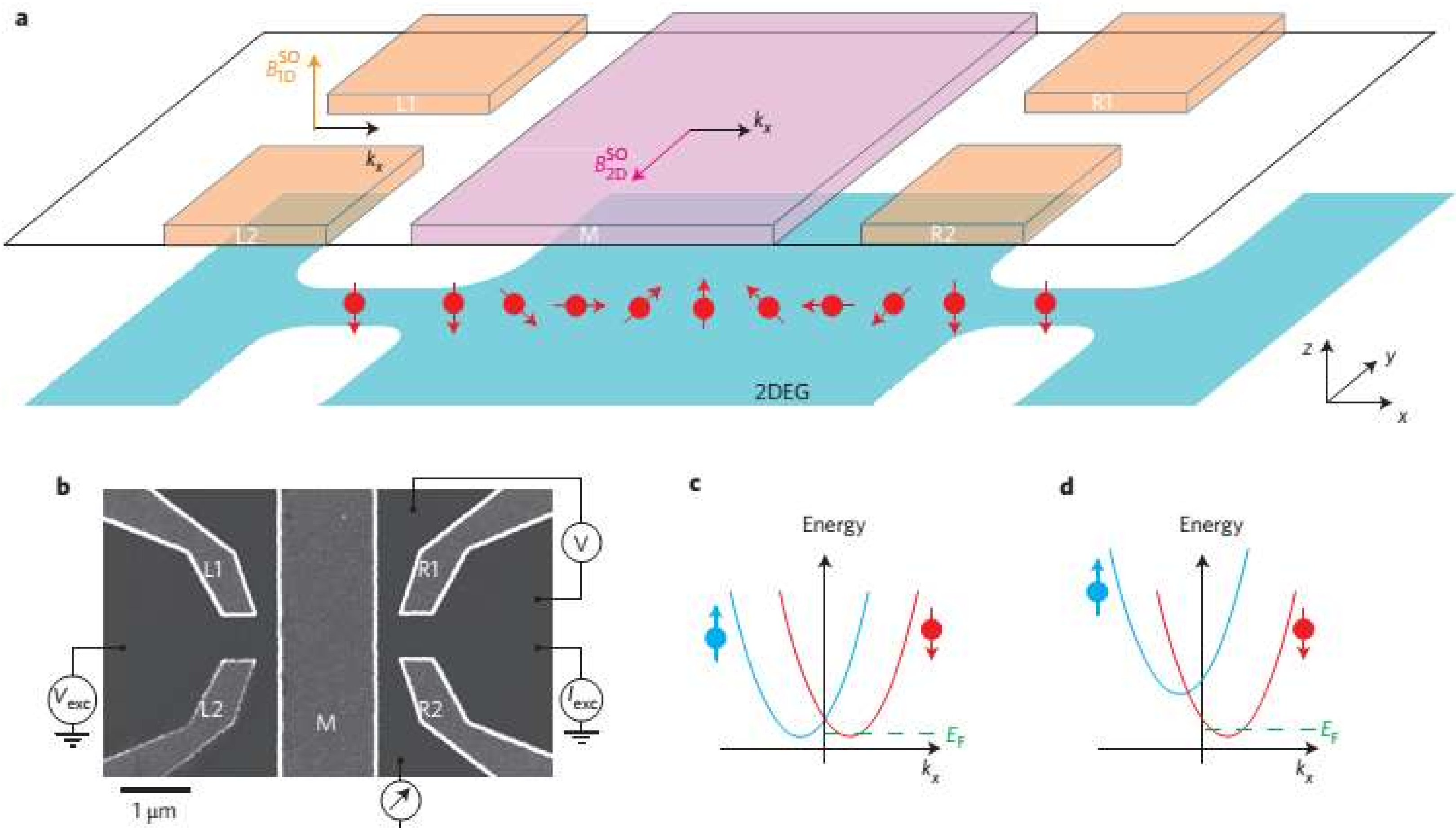


B
I
V_G
V
+
-
y
z
x
B_a
D
20
10
0
ΔV (μV)
-2
-1
0
1
2
V_G (V)
FM-NonFM, B_{ay}
FM-NonFM, B_{ax}
FM-FM, B_{ay}
FM-FM, B_{ax}

Spin FET

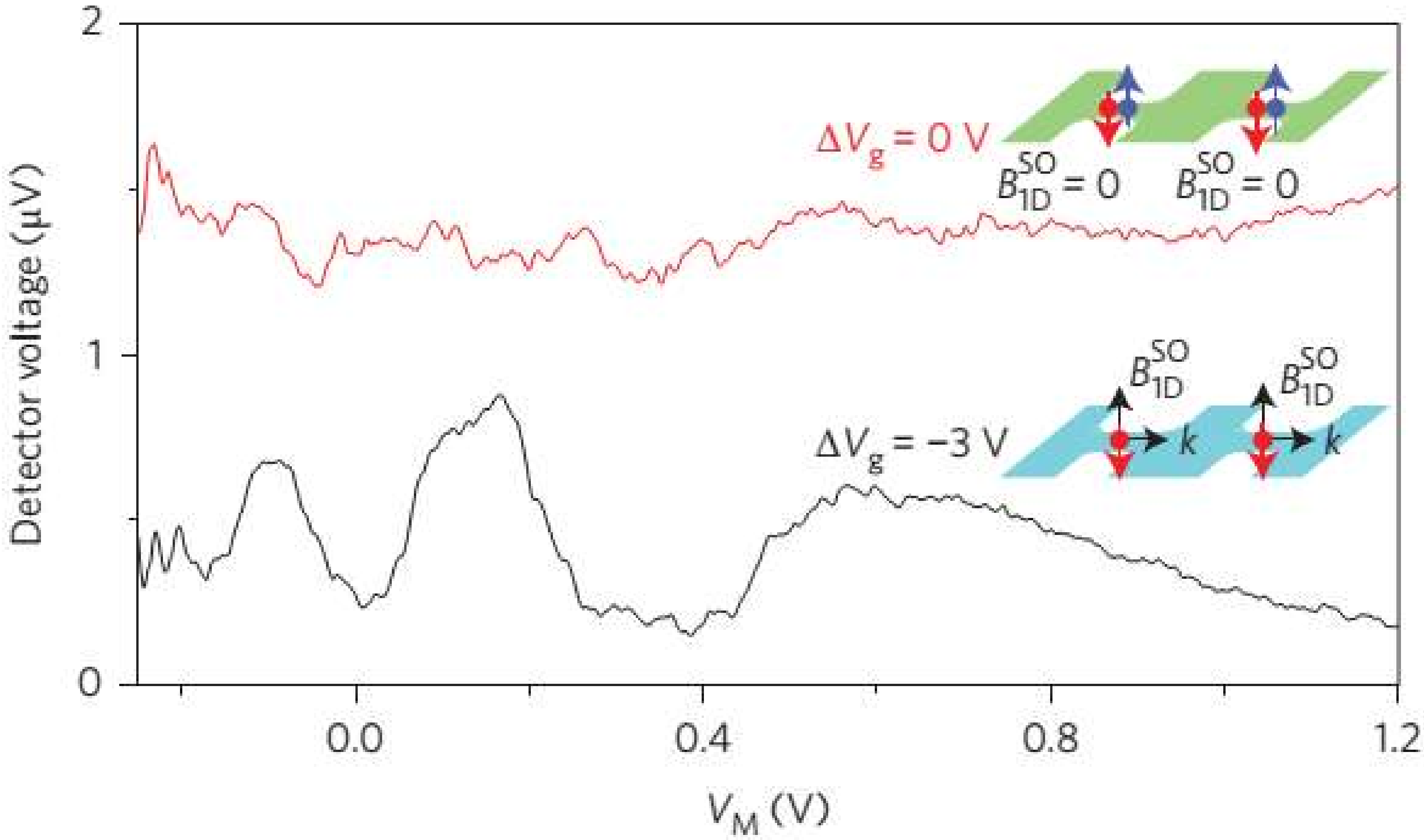


Spin FET



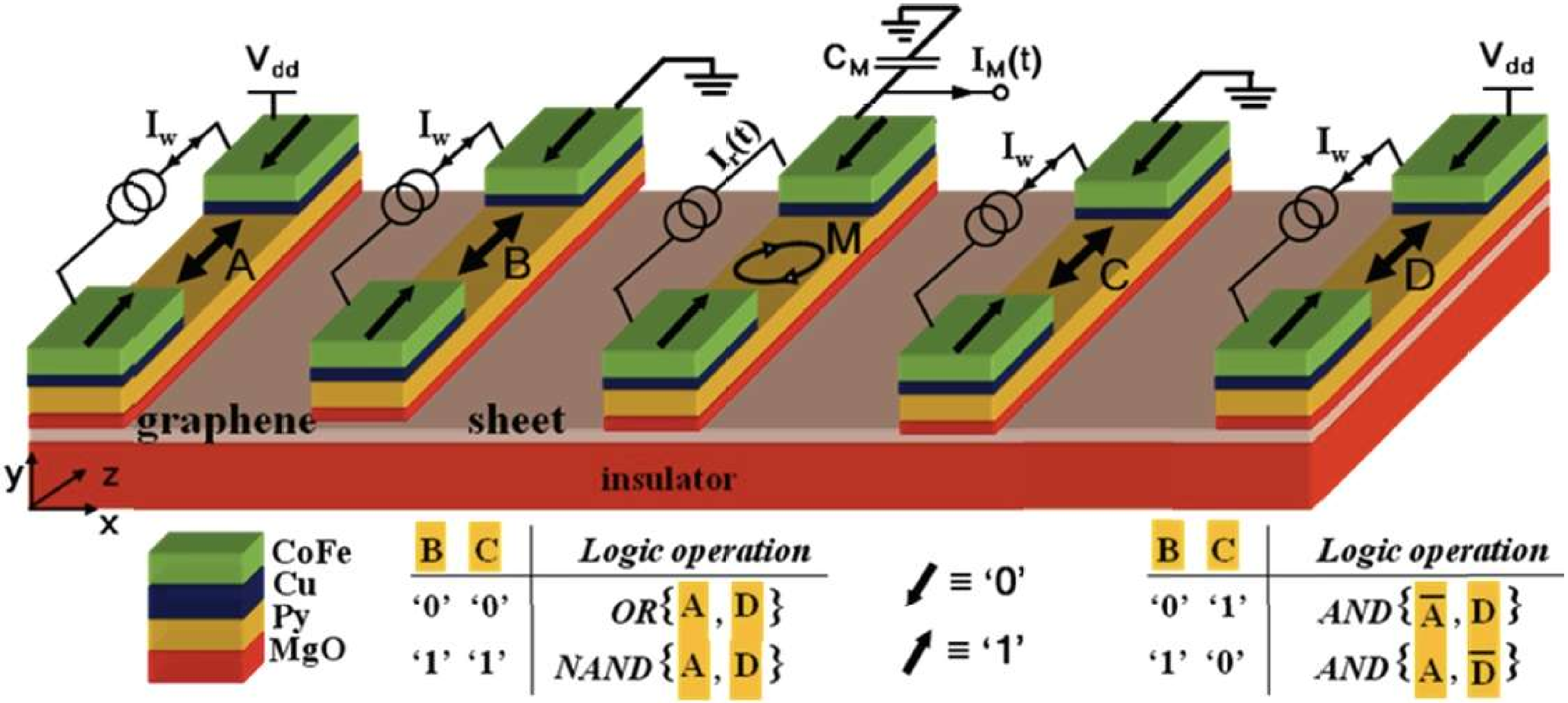
Chuang, et al, Nature Nanotech (2014)

Spin FET



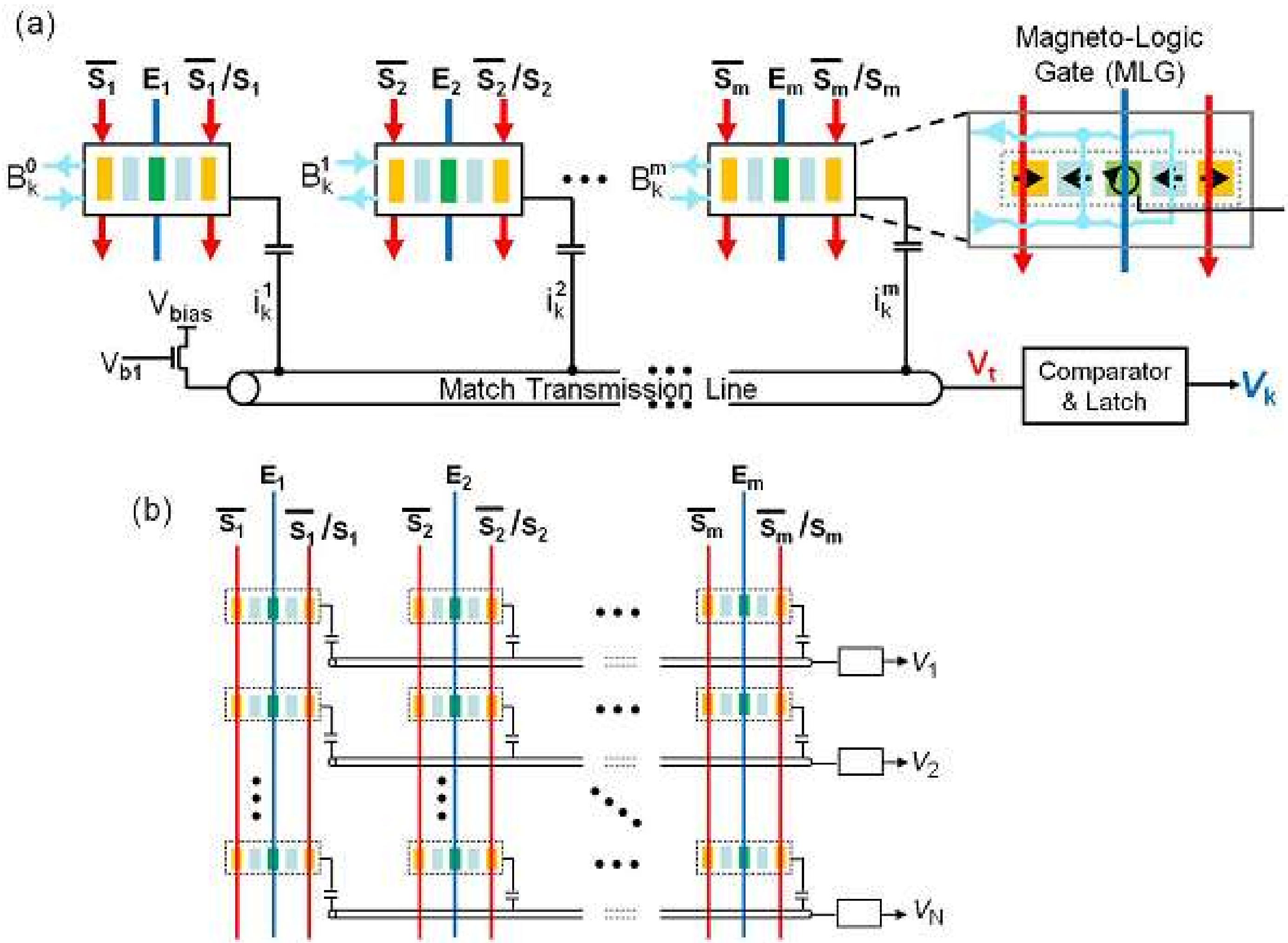
2
1
0
Detector voltage (μV)
$\Delta V_g = 0$ V
$B_{1D}^{SO} = 0$
$B_{1D}^{SO} = 0$
B_{1D}^{SO}
B_{1D}^{SO}
$\Delta V_g = -3$ V
k
k
0.0
0.4
0.8
1.2
V_M (V)

Spin Logic



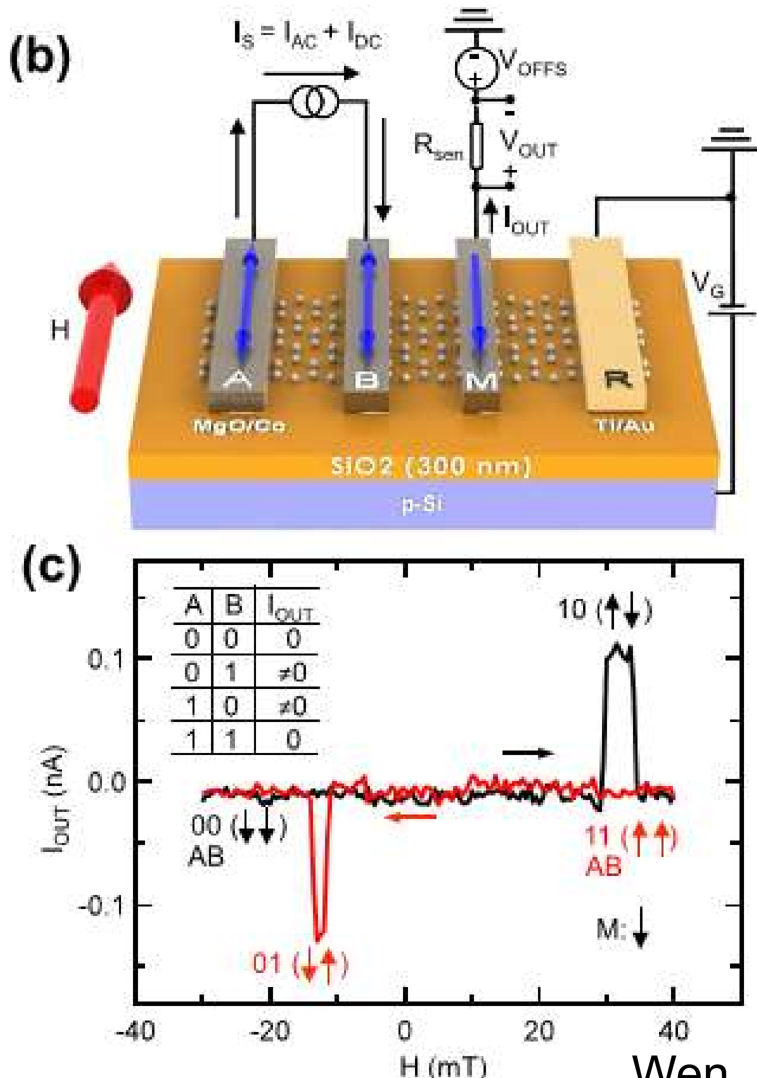
Dery, et al, Nature (2007)
Dery, et al, IEEE Trans. Elec. Dev. (2012)

Spin Logic



(a)
Magneto-Logic Gate (MLG)
V bias
V b1
Match Transmission Line
Comparator & Latch
(b)

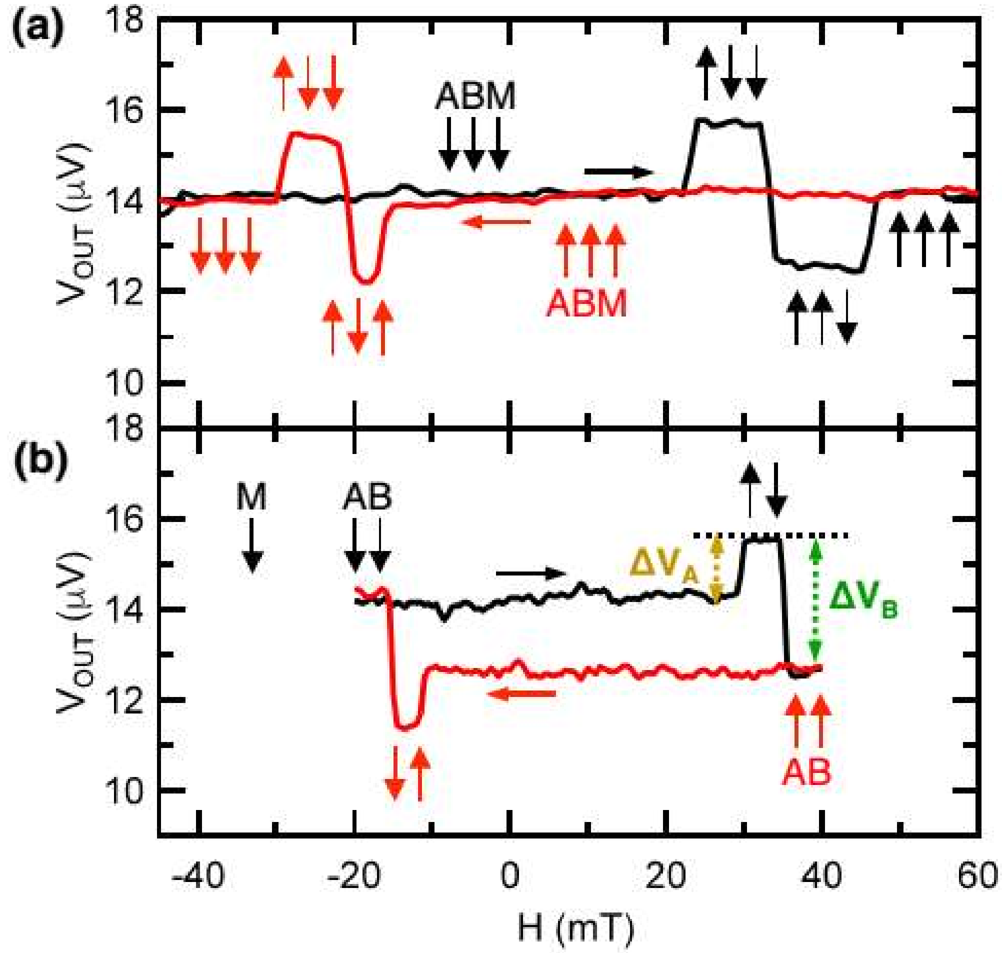
Spin Logic



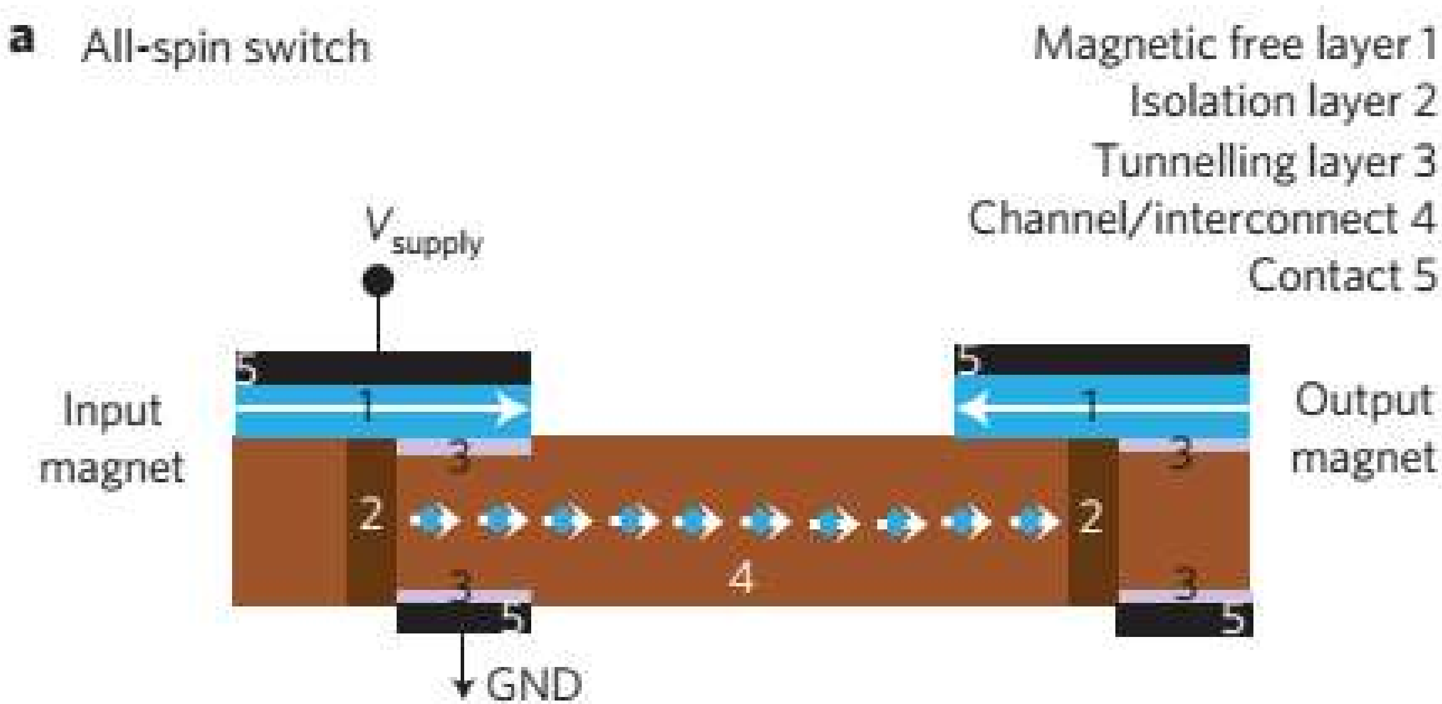
A	B	I_{OUT}
0	0	0
0	1	≠0
1	0	≠0
1	1	0

Wen, et al, PR Applied (2016)

Spin Logic

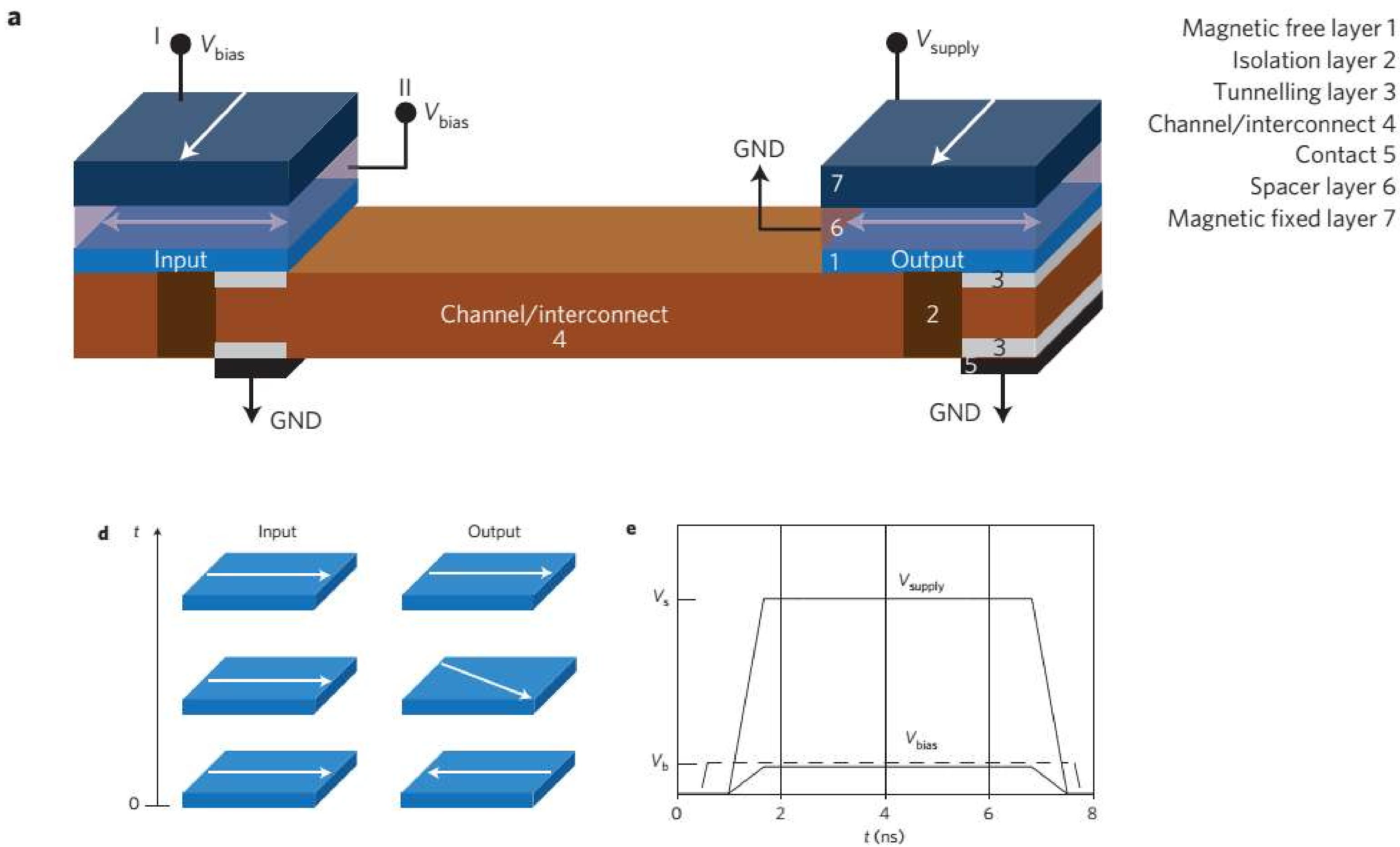


Spin Logic



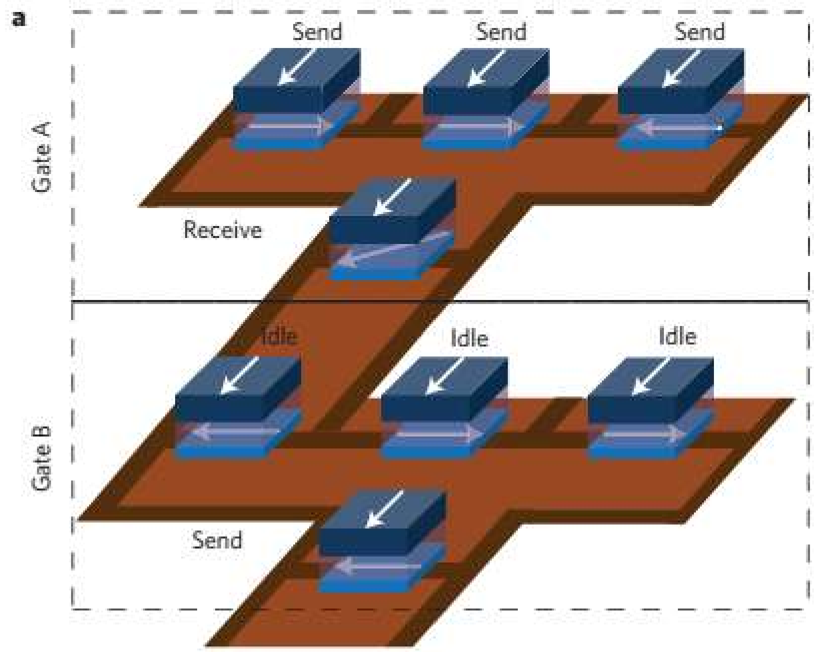
a All-spin switch
Magnetic free layer 1
Isolation layer 2
Tunnelling layer 3
Channel/interconnect 4
Contact 5
V_{supply}
Input magnet
Output magnet
GND

Spin Logic

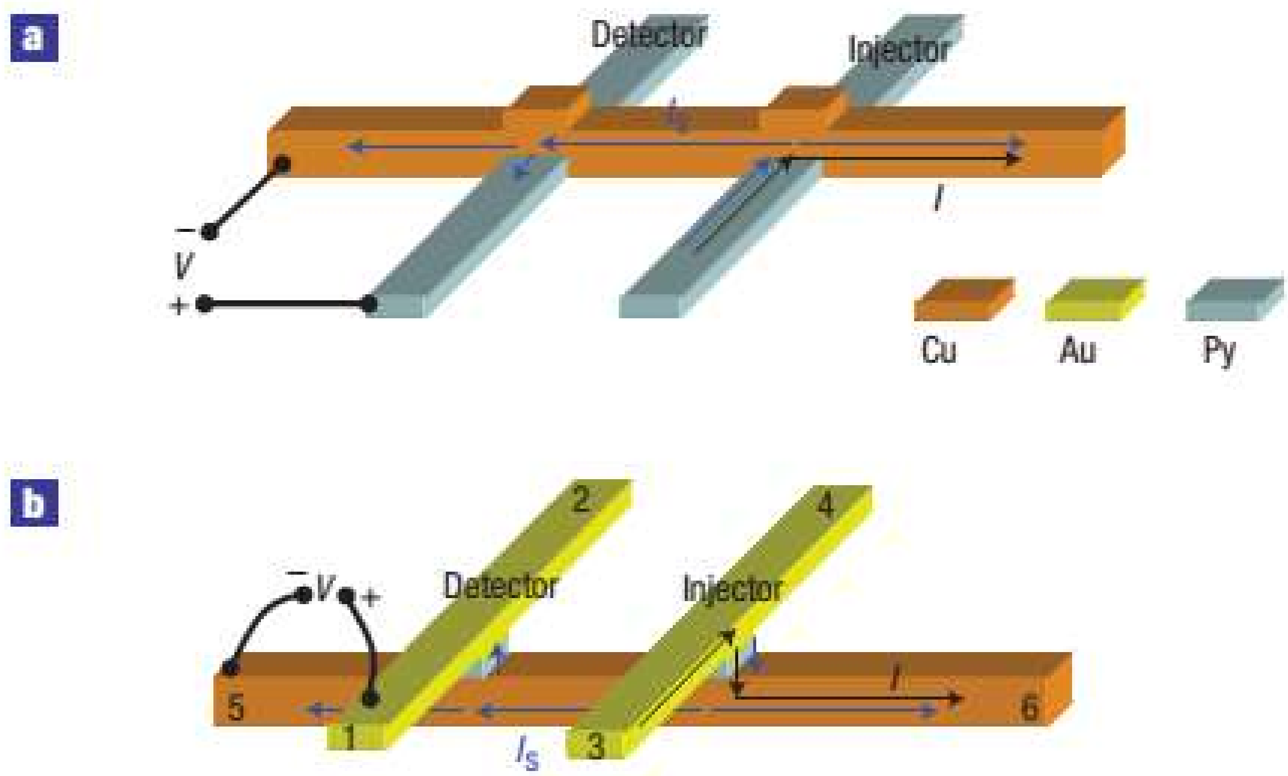


Behin-Aein, et al. Nature Nanotech. (2010)

Spin Logic

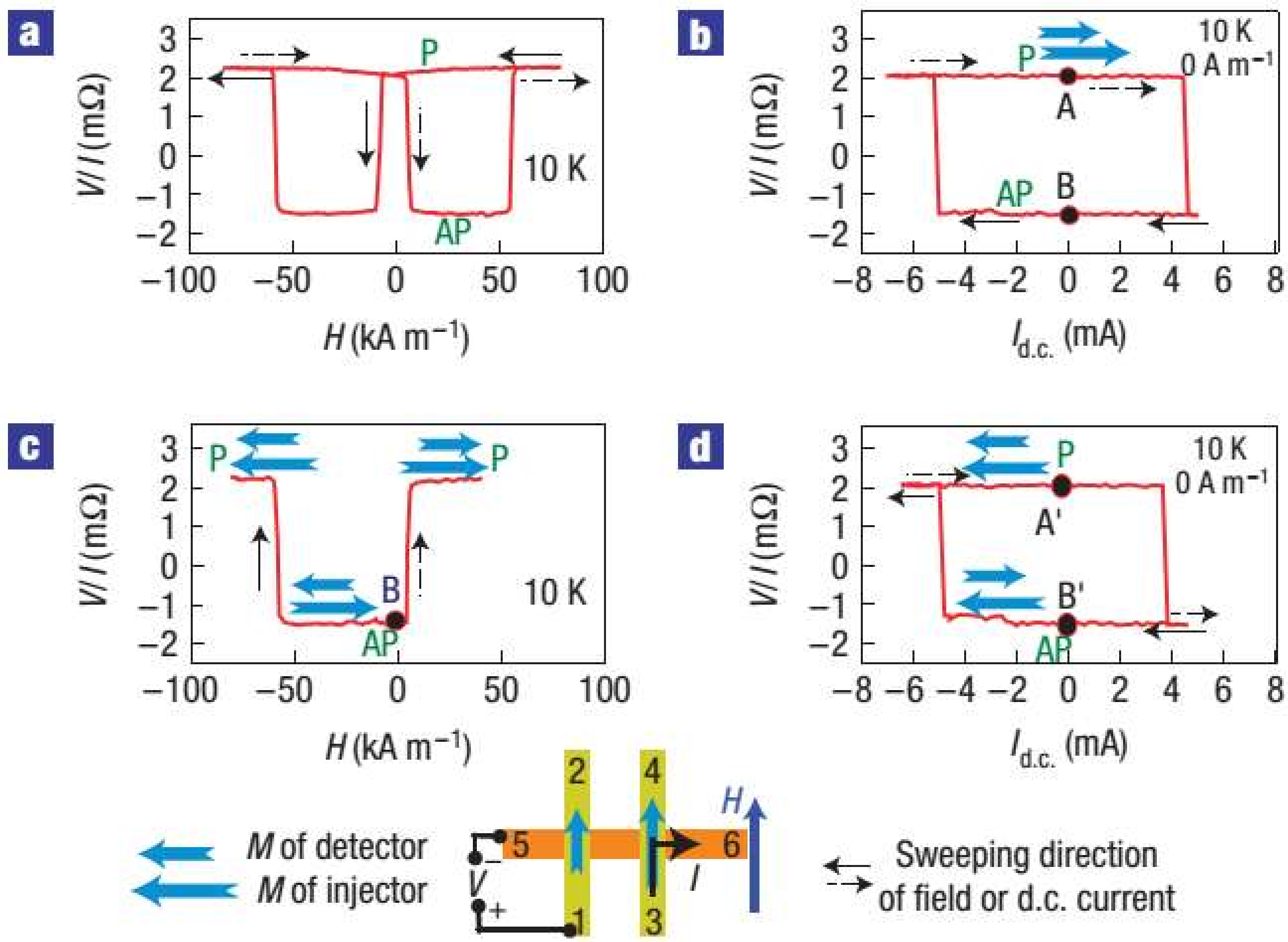


Spin Logic

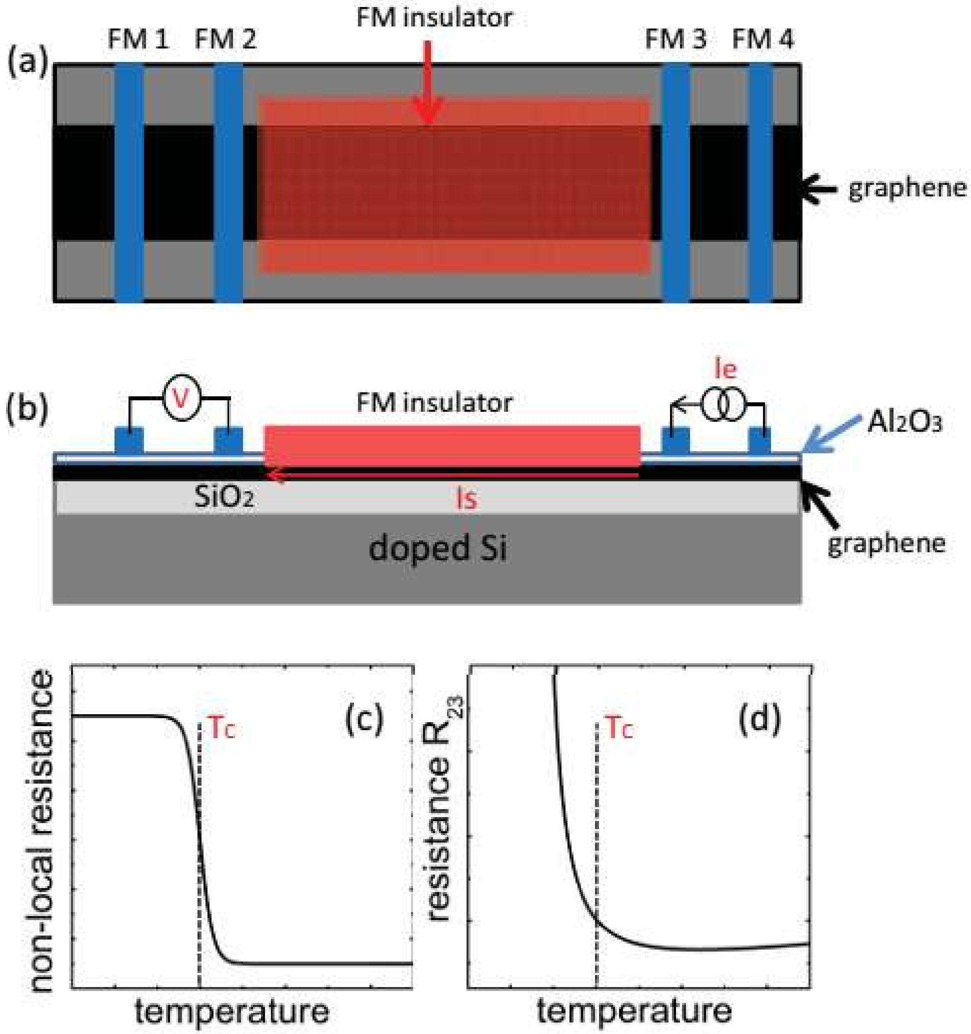


Yang, et al. Nature Nanotech. (2008)

Spin Logic


a
b
c
d
V/I (mΩ)
H (kA m⁻¹)
I_d.c. (mA)
10 K
0 A m⁻¹
P
AP
A
B
A'
B'
M of detector
M of injector
Sweeping direction
of field or d.c. current

Spin Superconductor

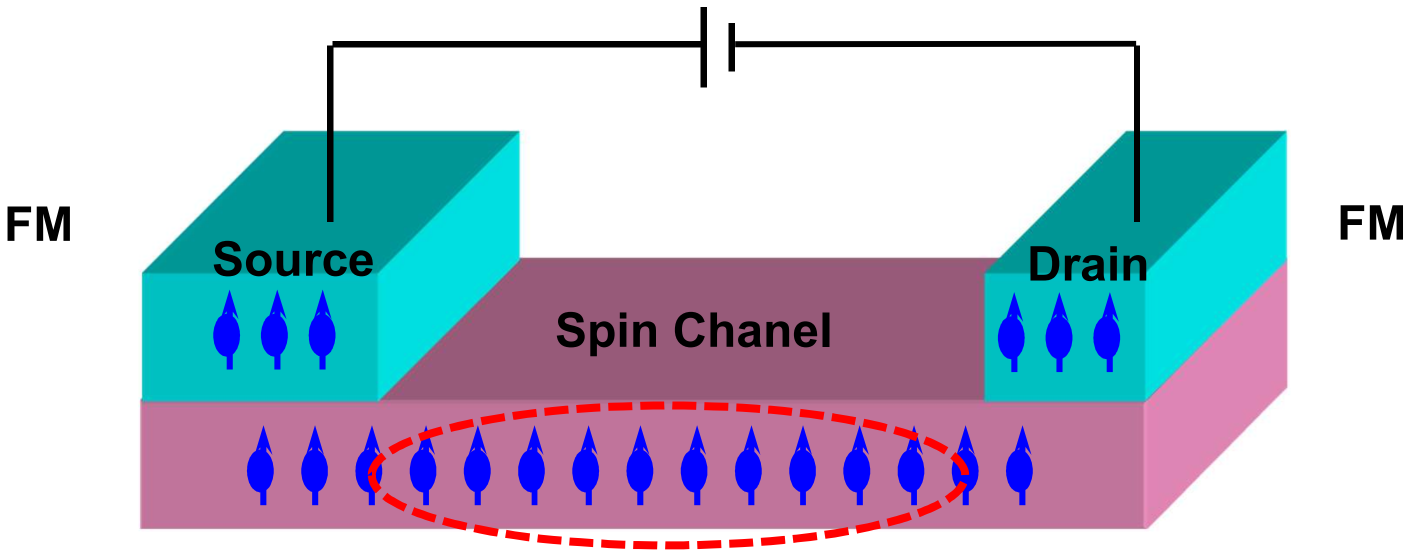


ICQM: Sun & Xie, PRB (2011), Nature Comm (2013)

Summary

Vertical Spin valves

Lateral Spin valves



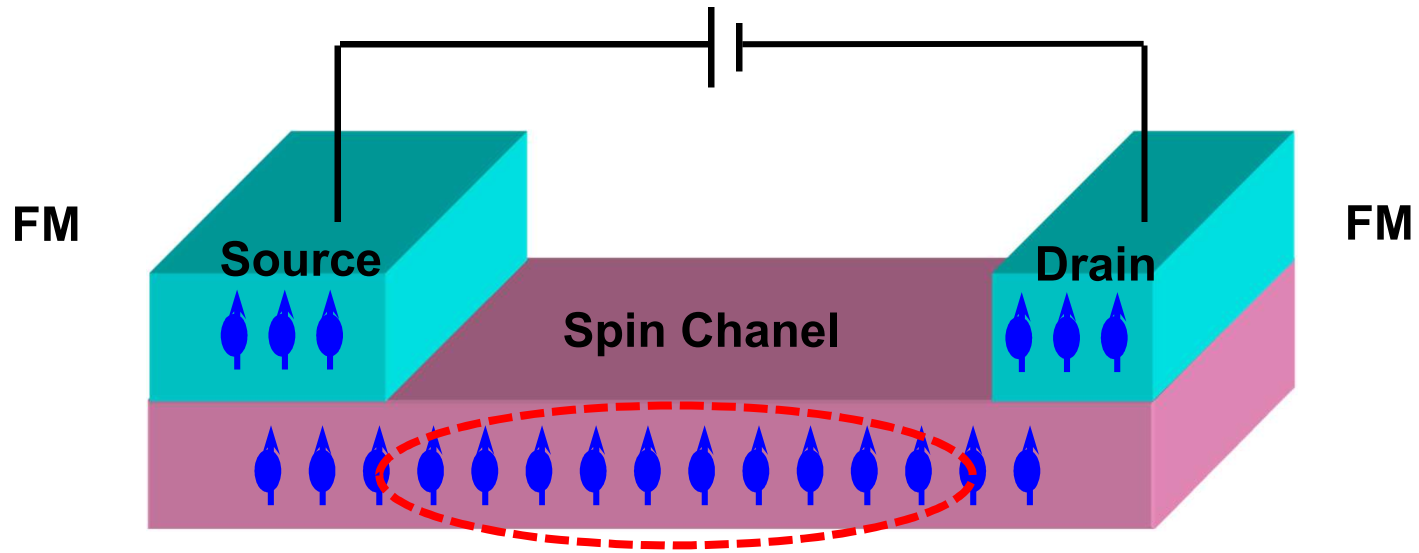
Spin manipulation

休息10分钟

Summary

Vertical Spin valves

Lateral Spin valves



Spin manipulation

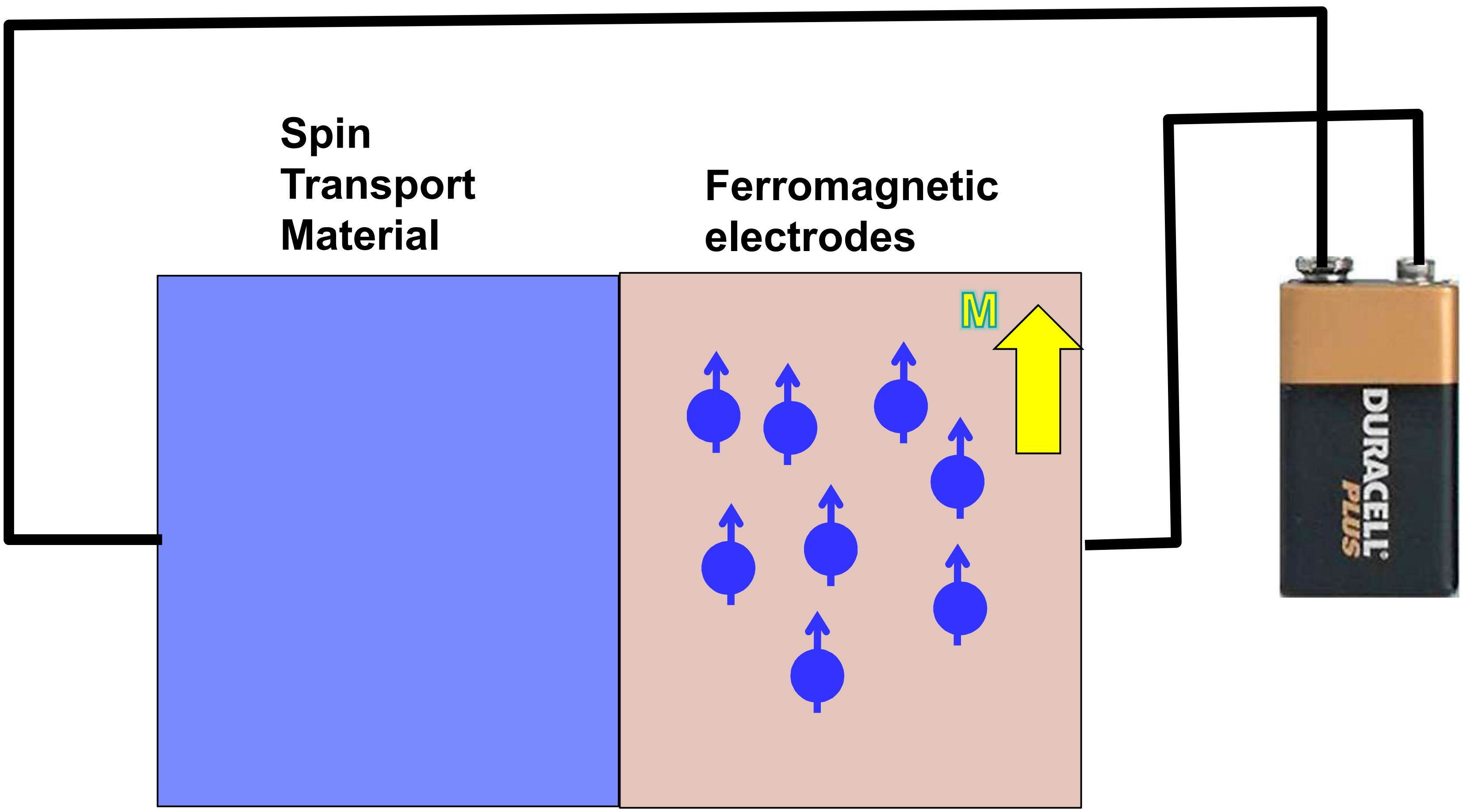
3. Spin injection

- ❑ **Electrical**
- ❑ **Optical**
- ❑ **Dynamic**

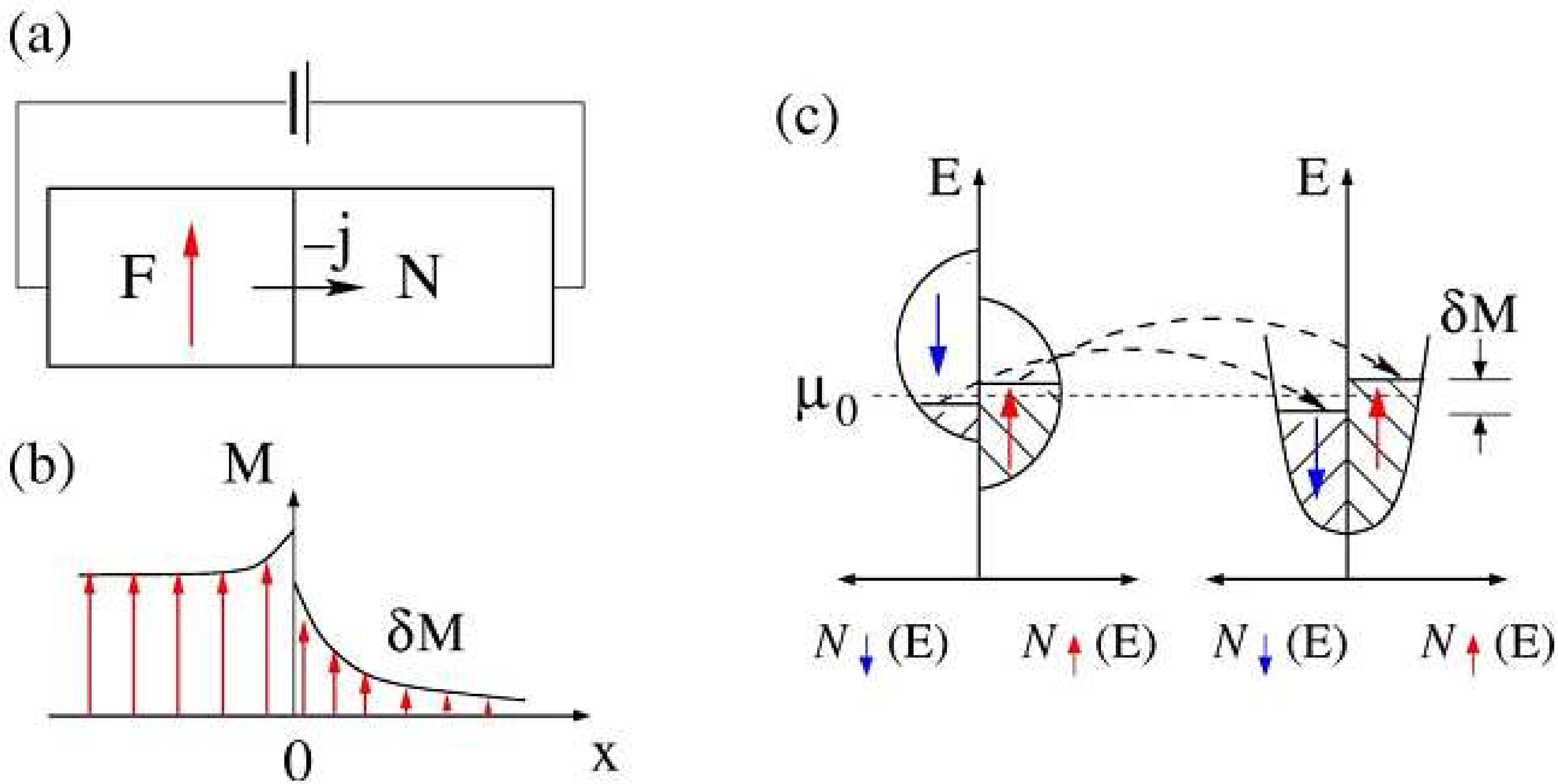
3. Spin injection

- **Electrical**

Electrical Spin injection



Electrical Spin injection



Zutic, et al, Rev. Mod. Phys. (2004)

Electrical Spin injection

Charge current:

$$\boldsymbol{j} = \boldsymbol{\sigma} \nabla \boldsymbol{\mu}$$

Einstein relation

$$\boldsymbol{\sigma} = \boldsymbol{q}^2 \boldsymbol{N} \boldsymbol{D}$$

Spin current:

$$\boldsymbol{j}_{\uparrow} = \boldsymbol{\sigma}_{\uparrow} \nabla \boldsymbol{\mu}_{\uparrow} \qquad \boldsymbol{\sigma}_{\uparrow} = \boldsymbol{q}^2 \boldsymbol{N}_{\uparrow} \boldsymbol{D}_{\uparrow}$$

$$\boldsymbol{j}_{\downarrow} = \boldsymbol{\sigma}_{\downarrow} \nabla \boldsymbol{\mu}_{\downarrow} \qquad \boldsymbol{\sigma}_{\downarrow} = \boldsymbol{q}^2 \boldsymbol{N}_{\downarrow} \boldsymbol{D}_{\downarrow}$$

Electrical Spin injection

Spin dependent chemical potential:

$$\boldsymbol{\mu}_{\uparrow} = \left(\frac{\boldsymbol{qD}_{\uparrow}}{\boldsymbol{\sigma}_{\uparrow}}\right)\boldsymbol{\delta n}_{\uparrow} - \emptyset$$

$$\boldsymbol{\mu}_{\downarrow} = \left(\frac{\boldsymbol{qD}_{\downarrow}}{\boldsymbol{\sigma}_{\downarrow}}\right)\boldsymbol{\delta n}_{\downarrow} - \emptyset$$

$$\boldsymbol{\delta n}_{\uparrow} = \boldsymbol{n}_{\uparrow} - \boldsymbol{n}_{\uparrow \mathbf{0}}$$

D: diffusion coefficient

σ: conductivity

$\emptyset$: **electrical potential**

Electrical Spin injection

Continuity:

$$\nabla \boldsymbol{j}_{\uparrow} = +\boldsymbol{q}\left[\frac{\boldsymbol{\delta n}_{\uparrow}}{\boldsymbol{\tau}_{\uparrow\downarrow}} - \frac{\boldsymbol{\delta n}_{\downarrow}}{\boldsymbol{\tau}_{\downarrow\uparrow}}\right]$$

$$\nabla \boldsymbol{j}_{\downarrow} = -\boldsymbol{q}\left[\frac{\boldsymbol{\delta n}_{\downarrow}}{\boldsymbol{\tau}_{\downarrow\uparrow}} - \frac{\boldsymbol{\delta n}_{\downarrow}}{\boldsymbol{\tau}_{\downarrow\uparrow}}\right]$$

Electrical Spin injection

Charge vs. Spin

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_{\uparrow} + \boldsymbol{\sigma}_{\downarrow}$$

$$\boldsymbol{N} = \boldsymbol{N}_{\uparrow} + \boldsymbol{N}_{\downarrow}$$

At the balance:

$$\frac{\boldsymbol{N}_{\uparrow}}{\boldsymbol{\tau}_{\uparrow\downarrow}} - \frac{\boldsymbol{N}_{\downarrow}}{\boldsymbol{\tau}_{\downarrow\uparrow}} = \mathbf{0}$$

Electrical Spin injection

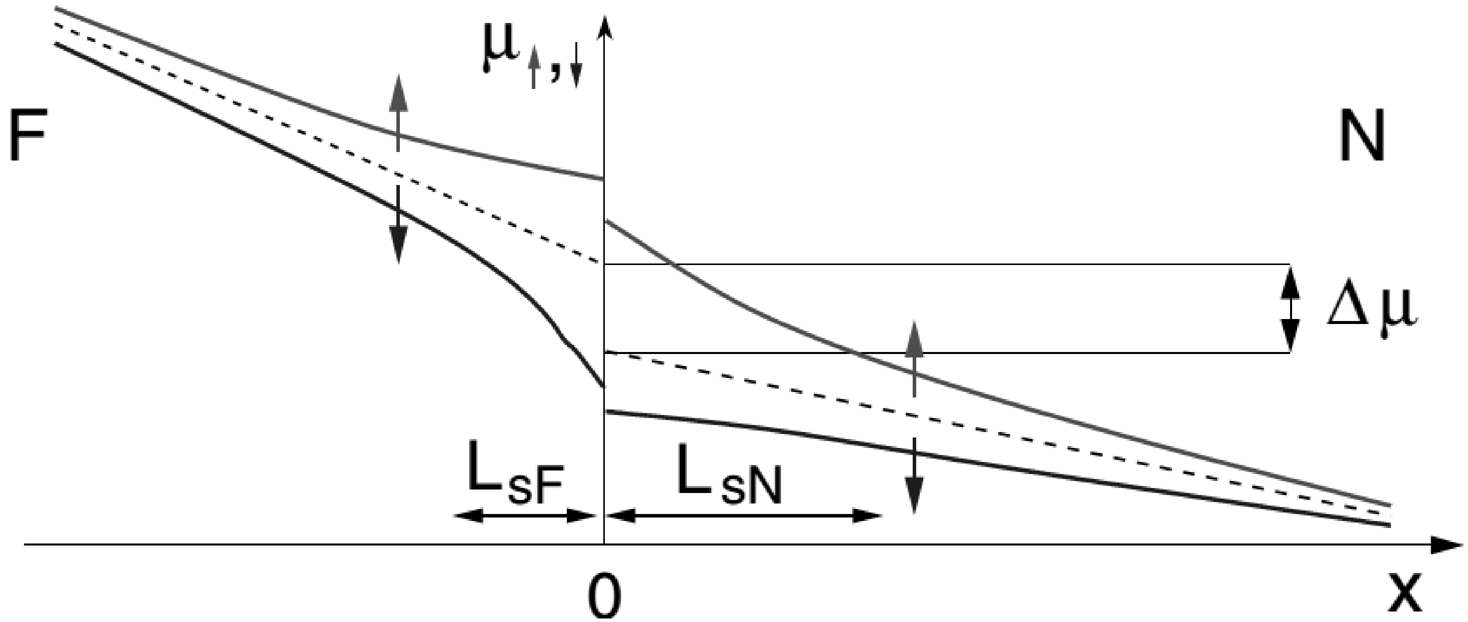
Interfacial Spin accumulation

$$\mu_s = \mu_{\uparrow} - \mu_{\downarrow}$$

$$\delta S = \delta n_{\uparrow} - \delta n_{\downarrow}$$

$$\mu_s = \frac{1}{2q} \frac{N_{\uparrow} + N_{\downarrow}}{N_{\uparrow} N_{\downarrow}} (\delta n_{\uparrow} - \delta n_{\downarrow})$$

Electrical Spin injection



Zutic, et al, Rev. Mod. Phys. (2004)

Electrical Spin injection

Spin diffusion length

$$\boldsymbol{L_{SF} = \sqrt{D_{SF}\tau_{sF}}}$$

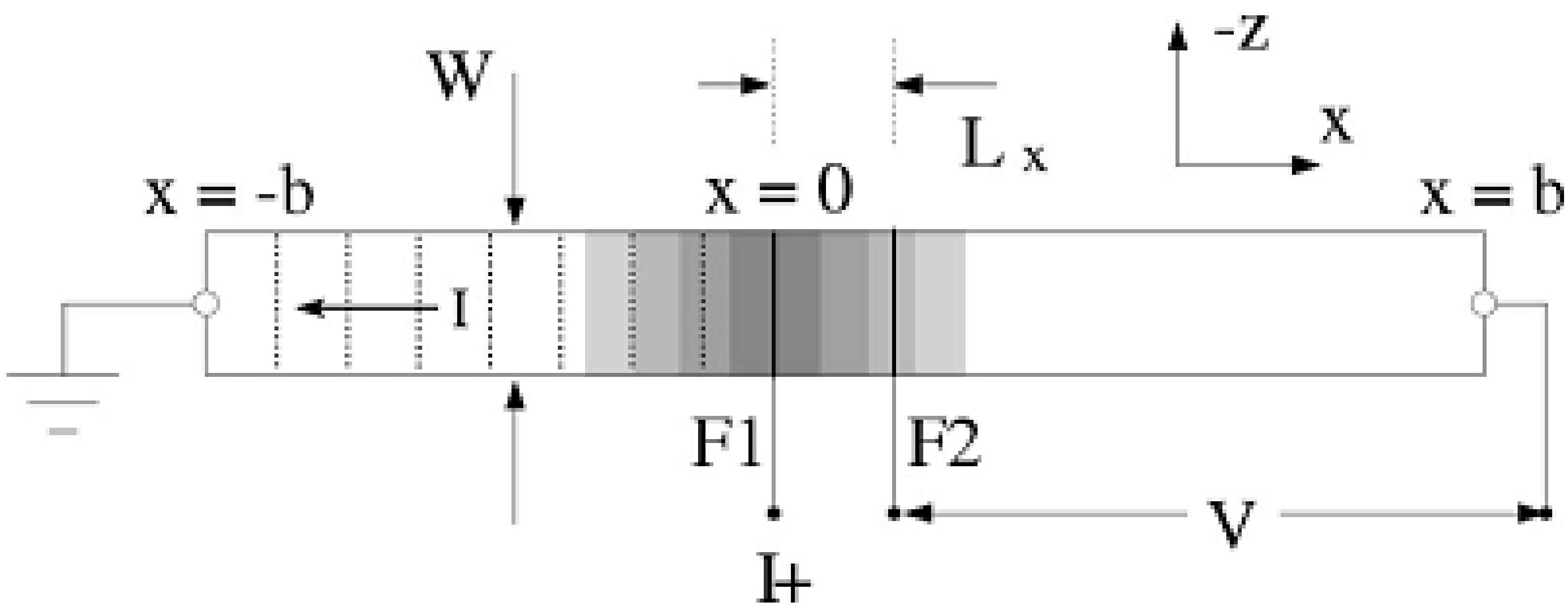
$$\boldsymbol{L_{SN} = \sqrt{D_{SN}\tau_{sN}}}$$

Diffusion equation:

$$\boldsymbol{\nabla^2\mu_{SF} = \mu_{SF}/LSF^2}$$

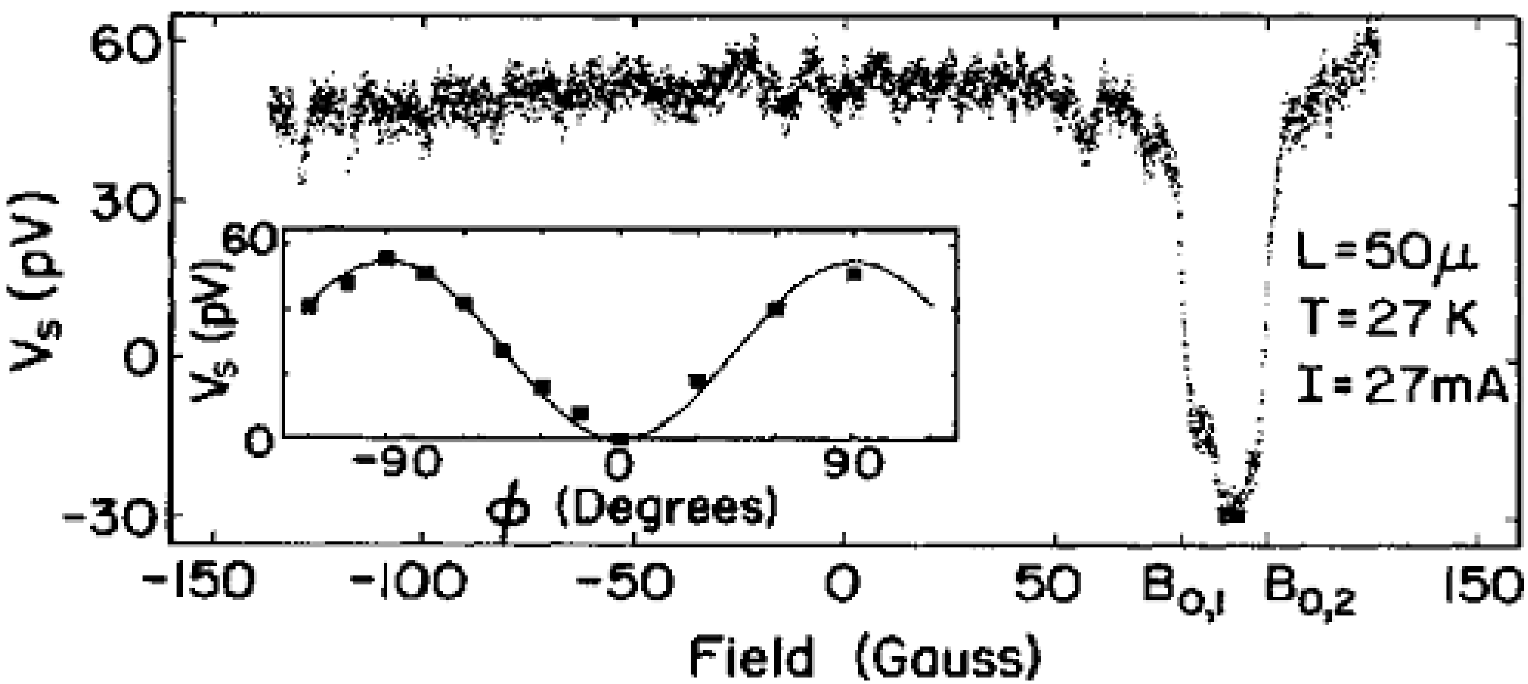
$$\boldsymbol{\nabla^2\mu_{SN} = \mu_{SN}/LSN^2}$$

Electrical Spin injection



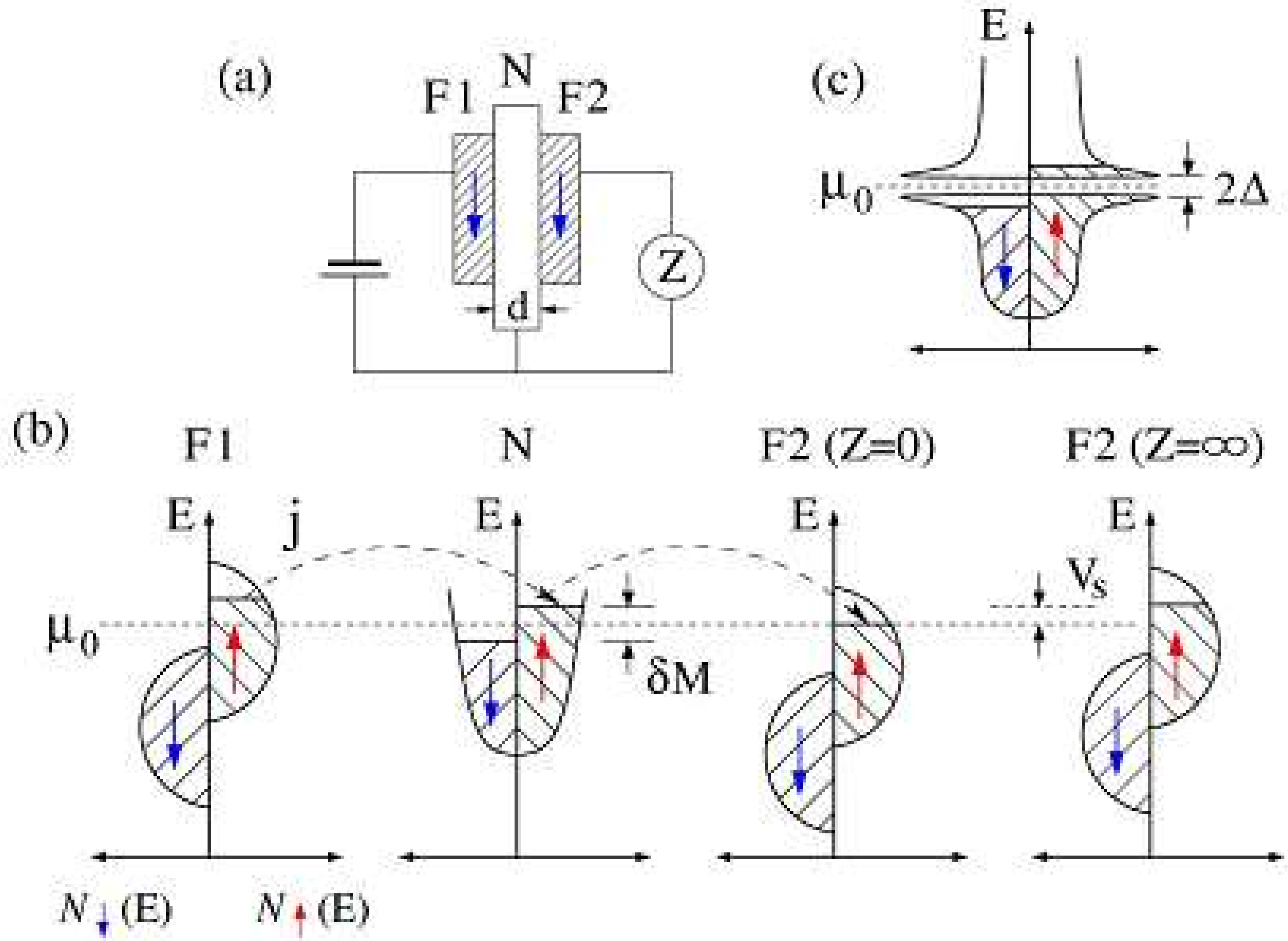
Johnson & Silsbee, PRL (1985)

Electrical Spin injection

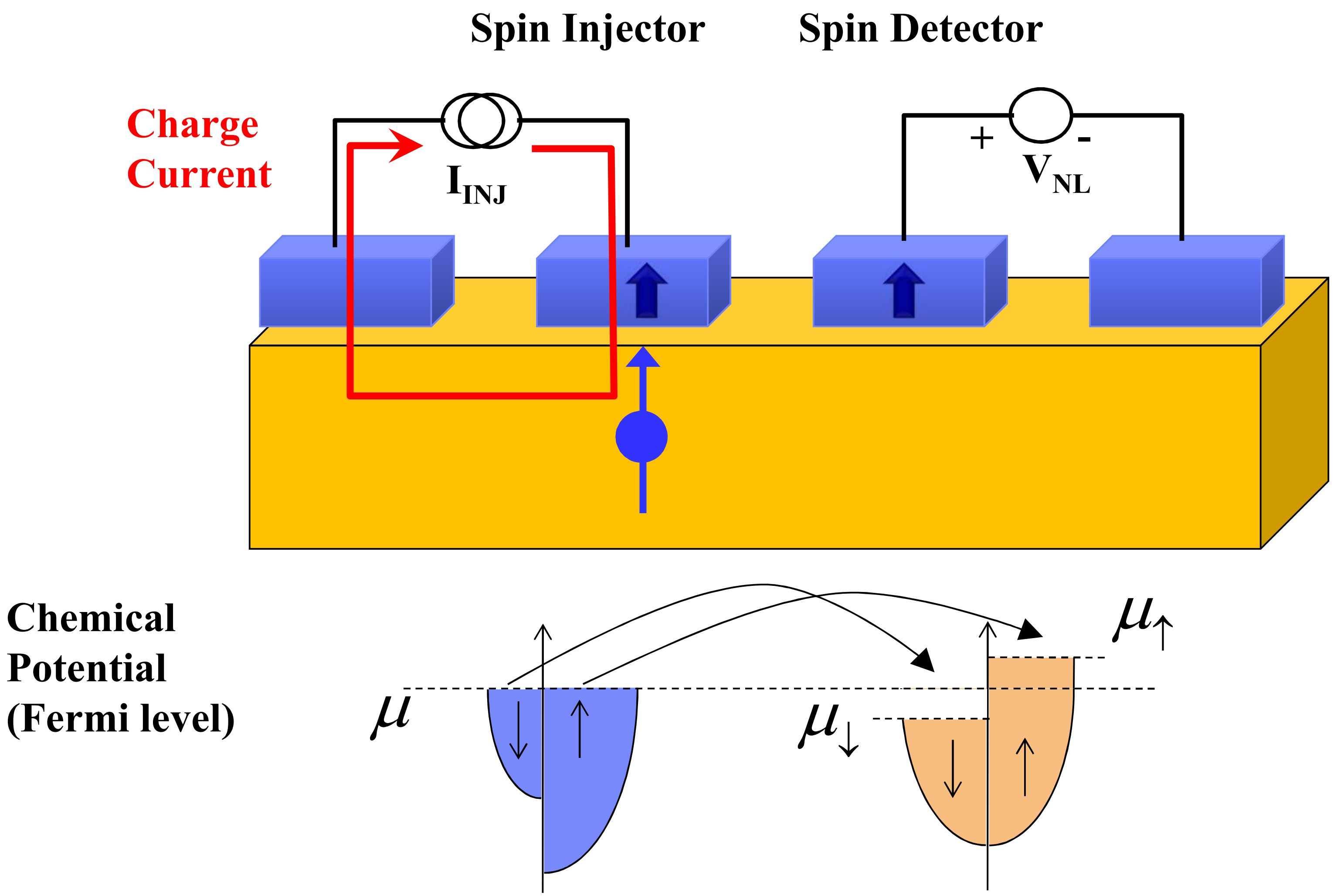


Johnson & Silsbee, PRL (1985)

Electrical Spin detection

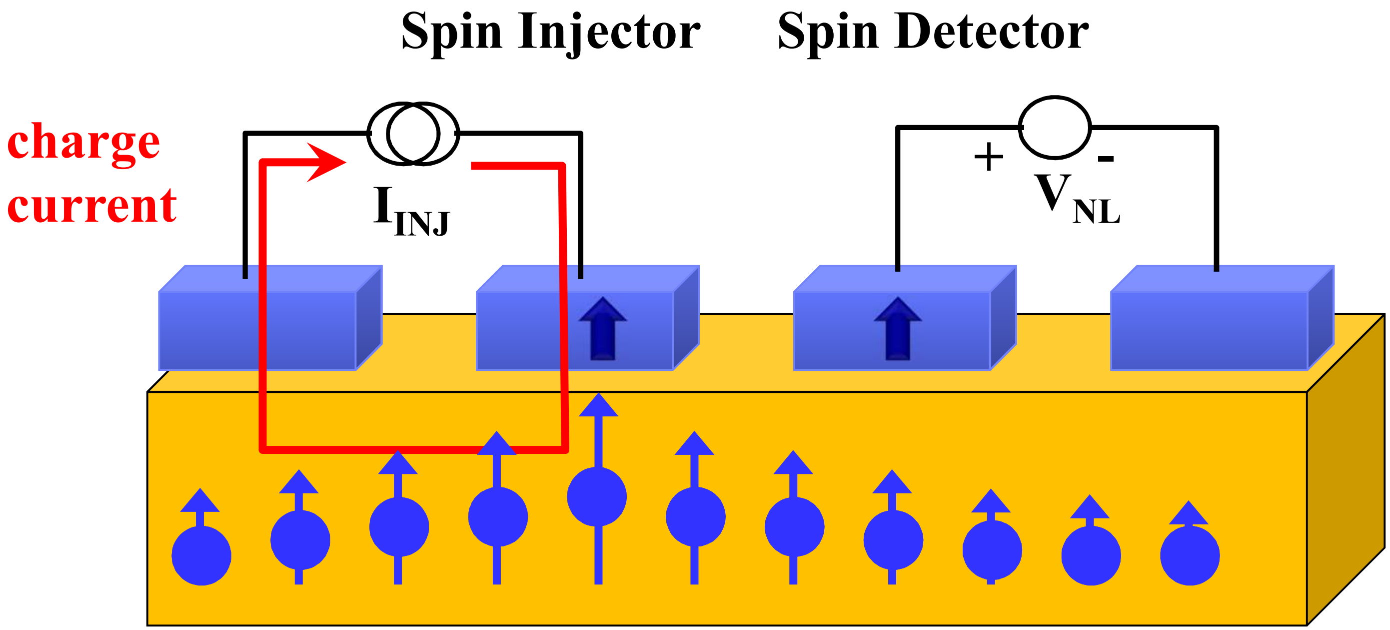


Nonlocal Spin valve

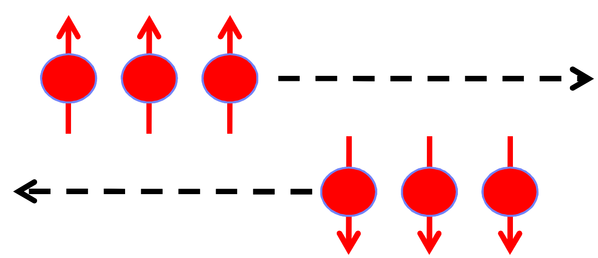


Johnson and Silsbee, PRL (1985)

Nonlocal Spin valve

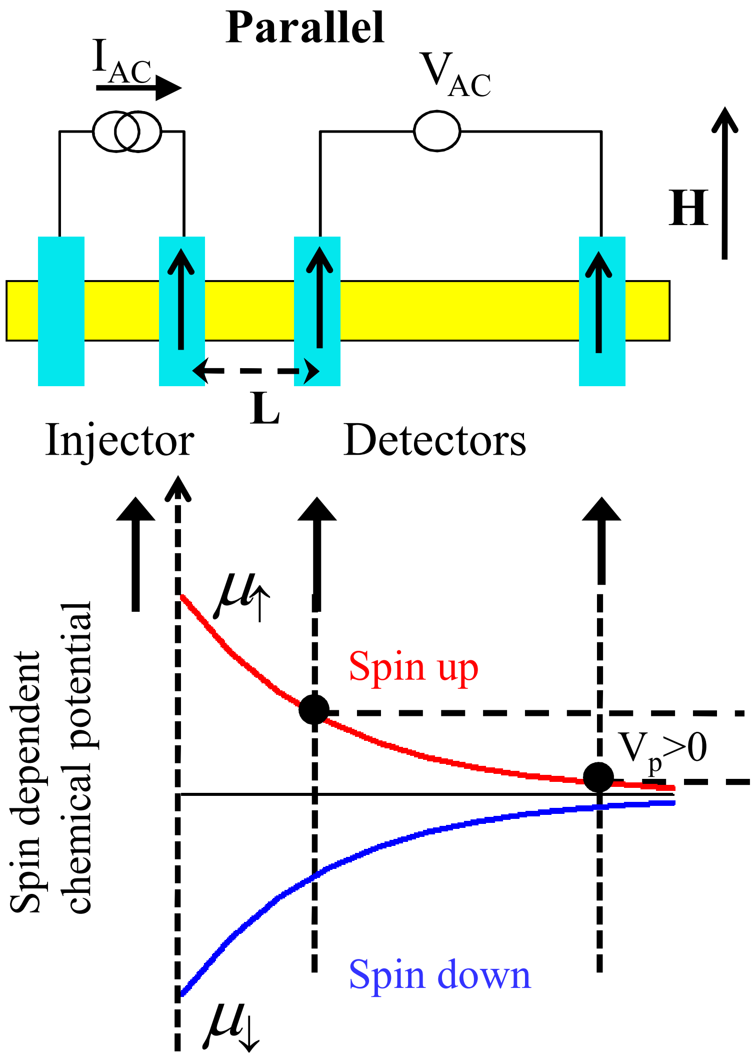


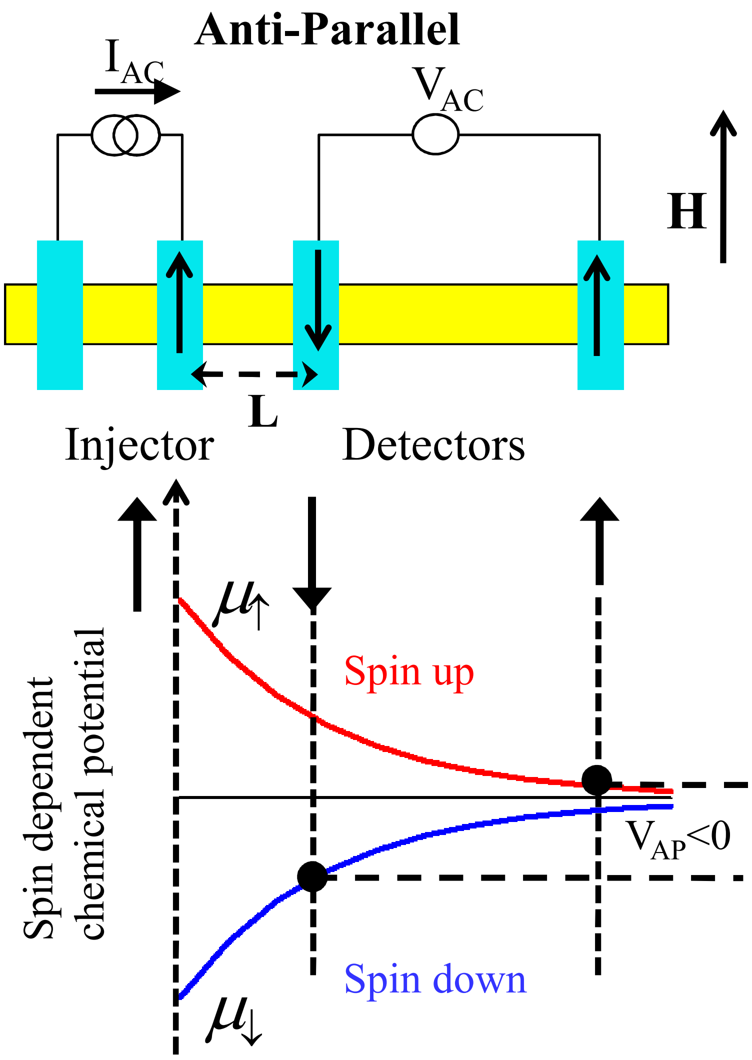
Pure spin current: **Flow of spin without net flow of charge**



Johnson and Silsbee, PRL (1985)

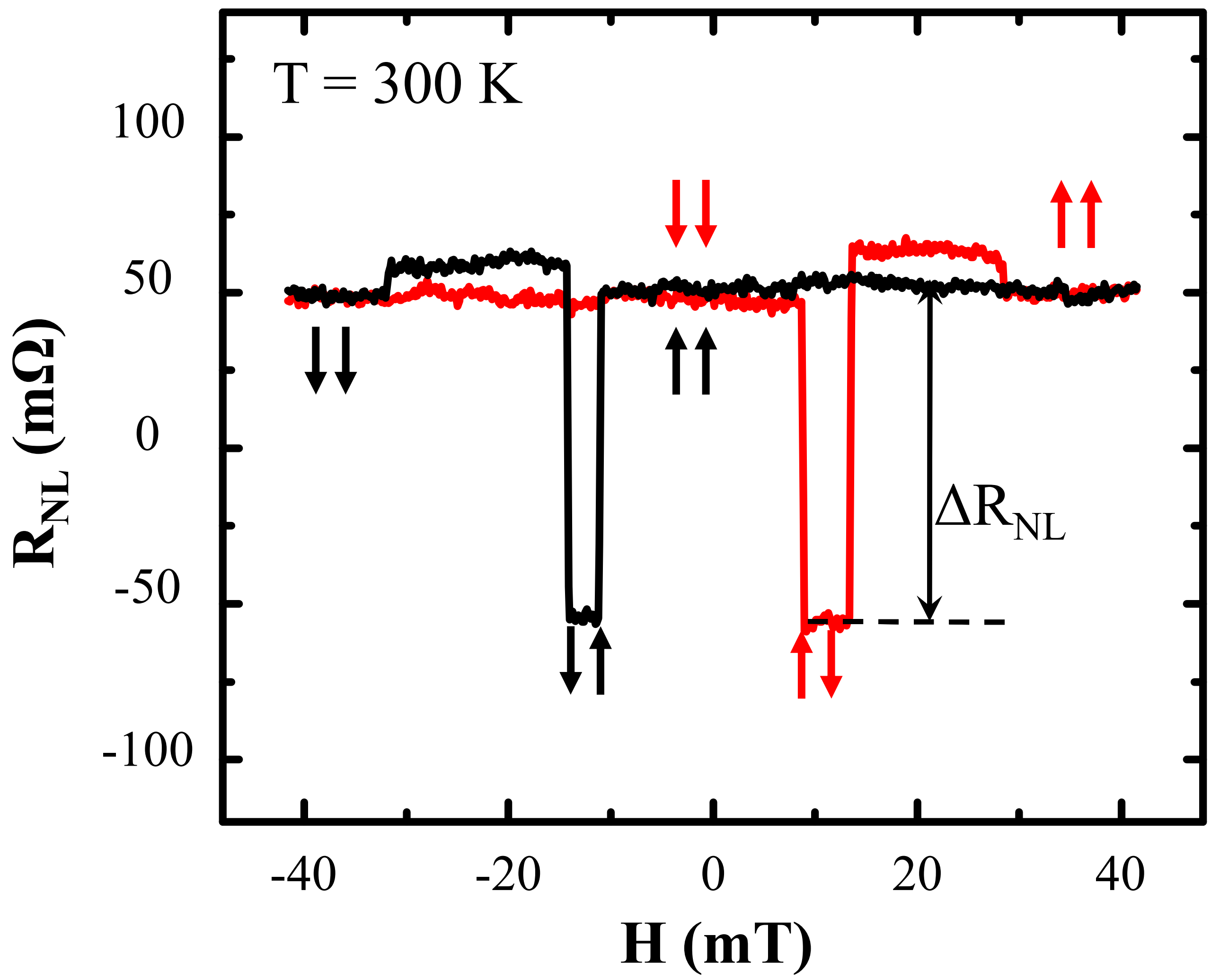
Nonlocal Spin valve





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

Nonlocal Spin valve



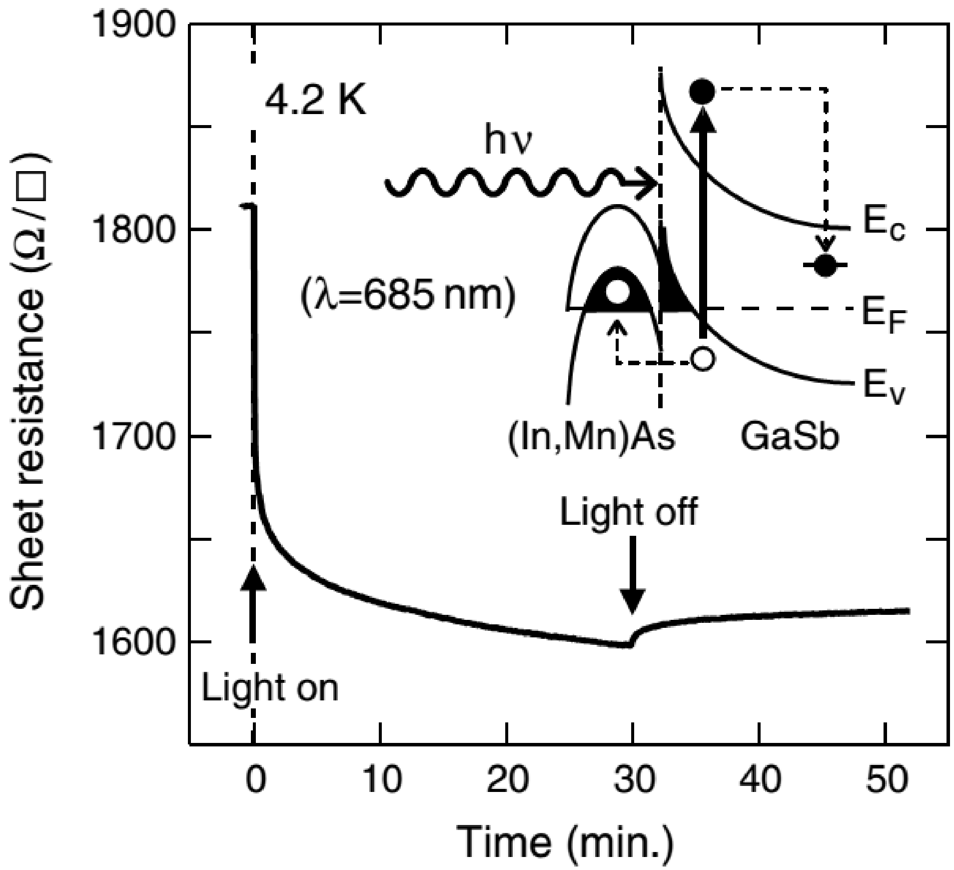
Han, et al, APL (2009)

3. Spin injection

- **Optical**

Optical spin injection

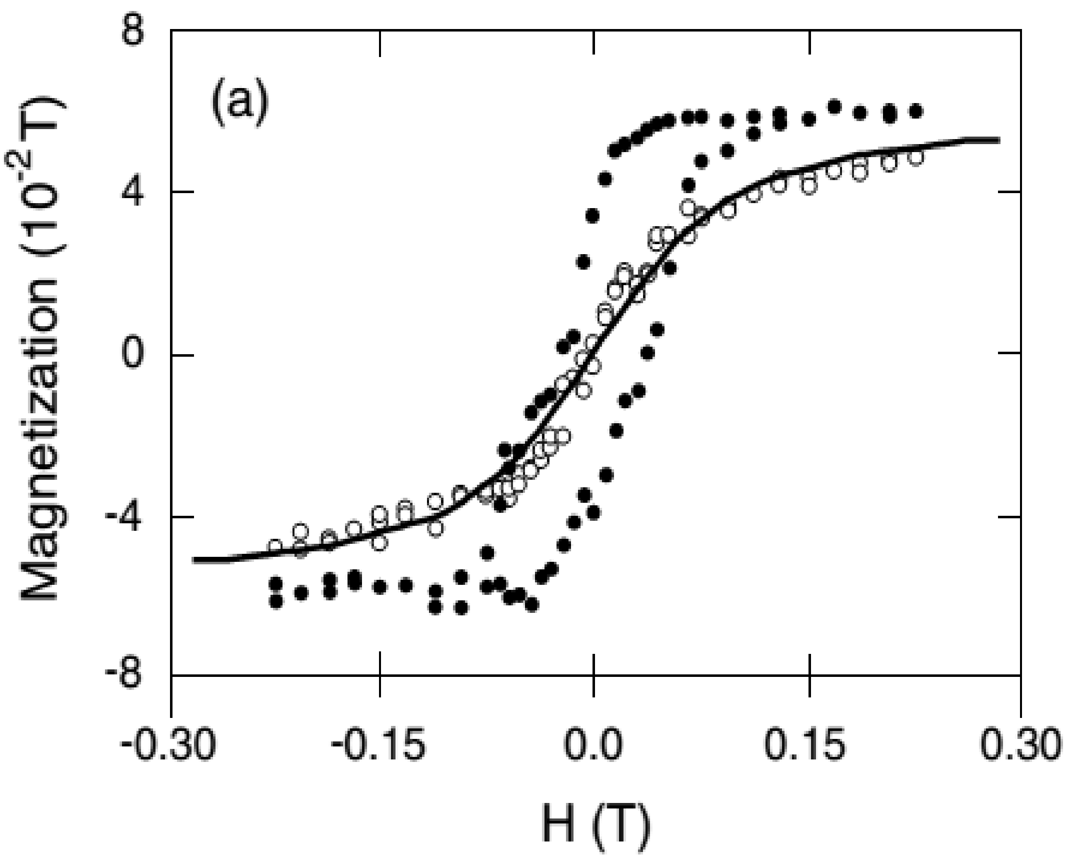
GaMnAs

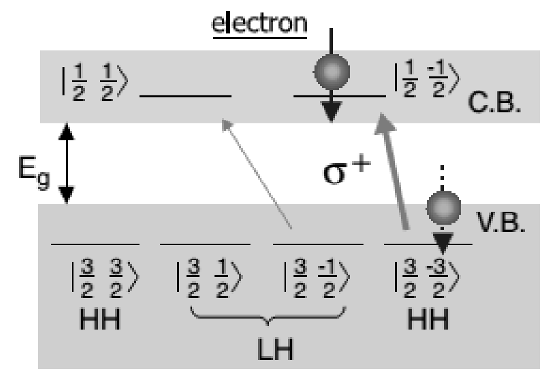


Maekawa, Book Concepts in Spin electronics (2006)

Optical spin injection

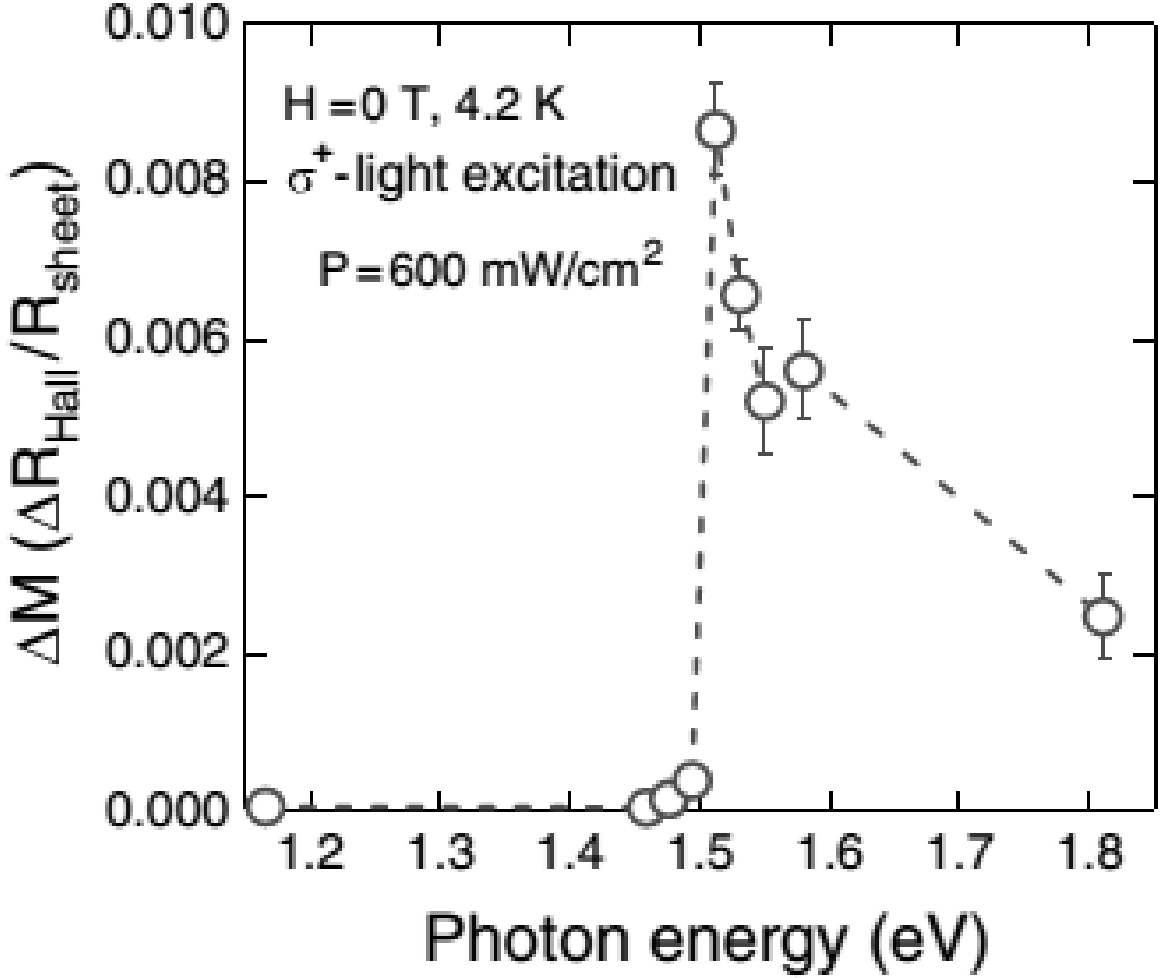
GaMnAs



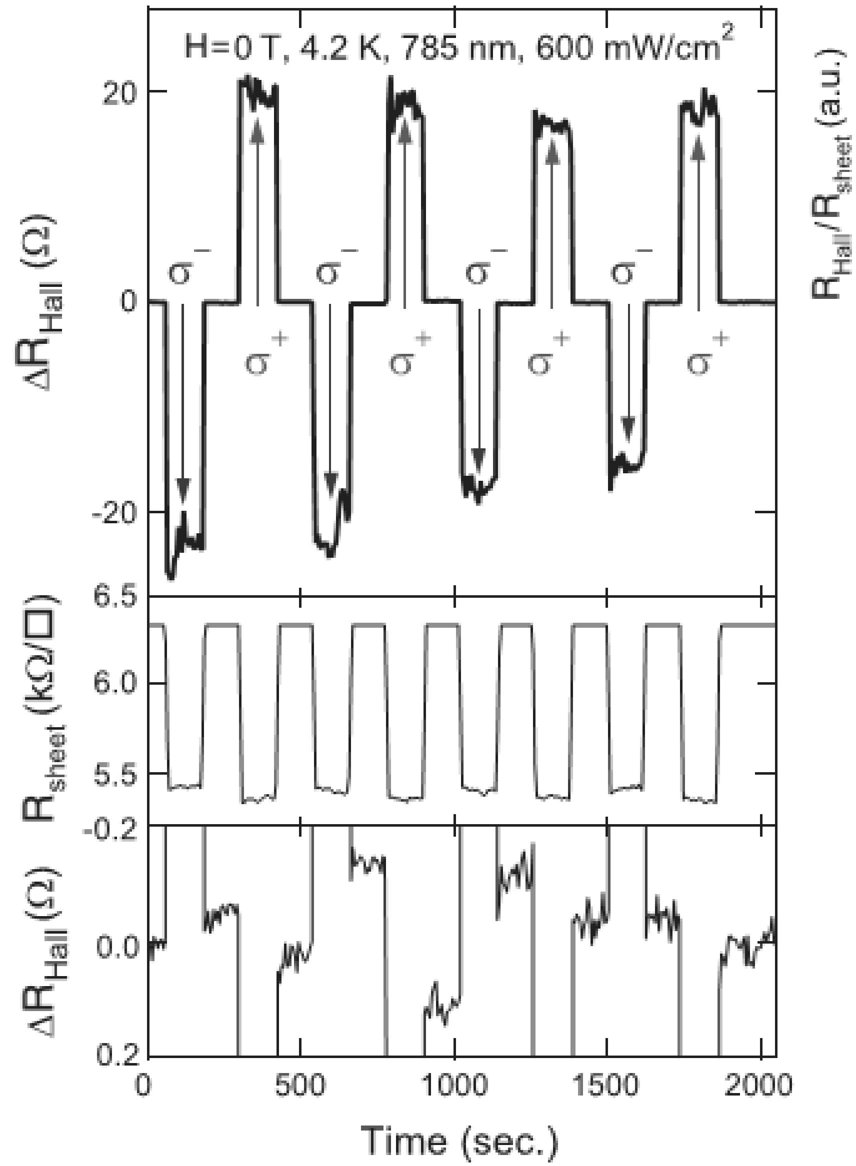


Optical spin injection

GaMnAs



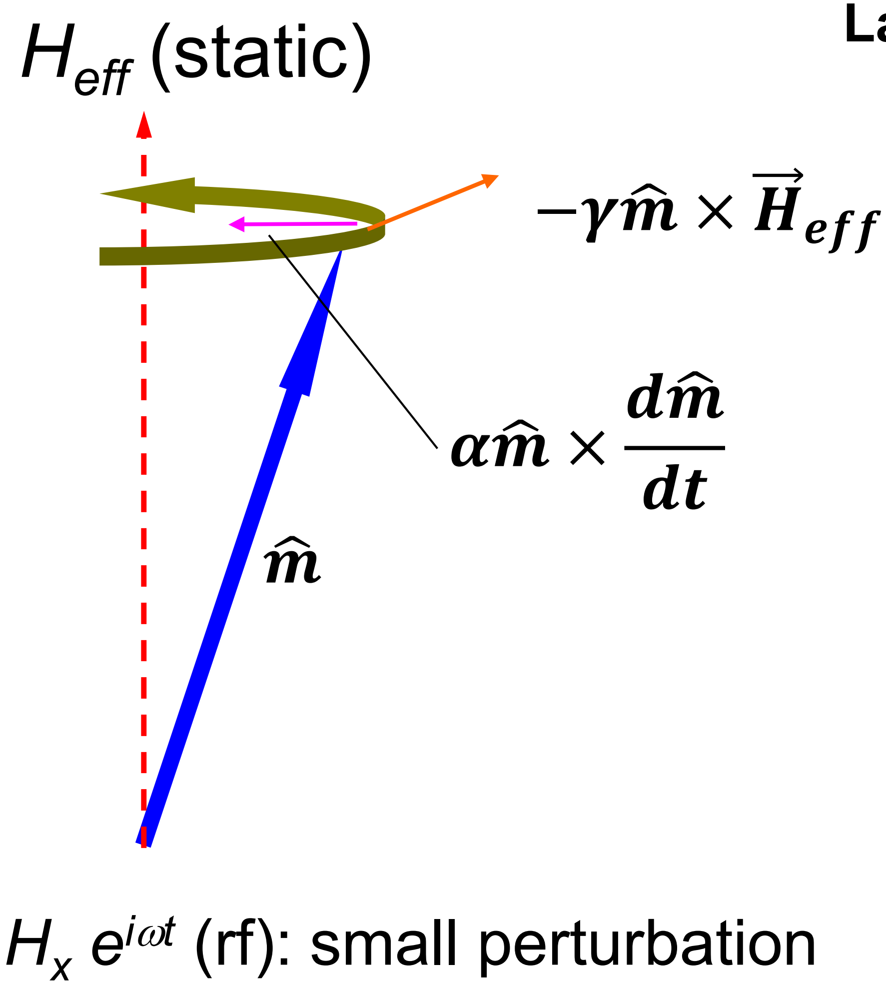
Optical spin injection



3. Spin injection

- **Dynamical**

Magnetic resonance



Landau-Lifshitz-Gilbert equation

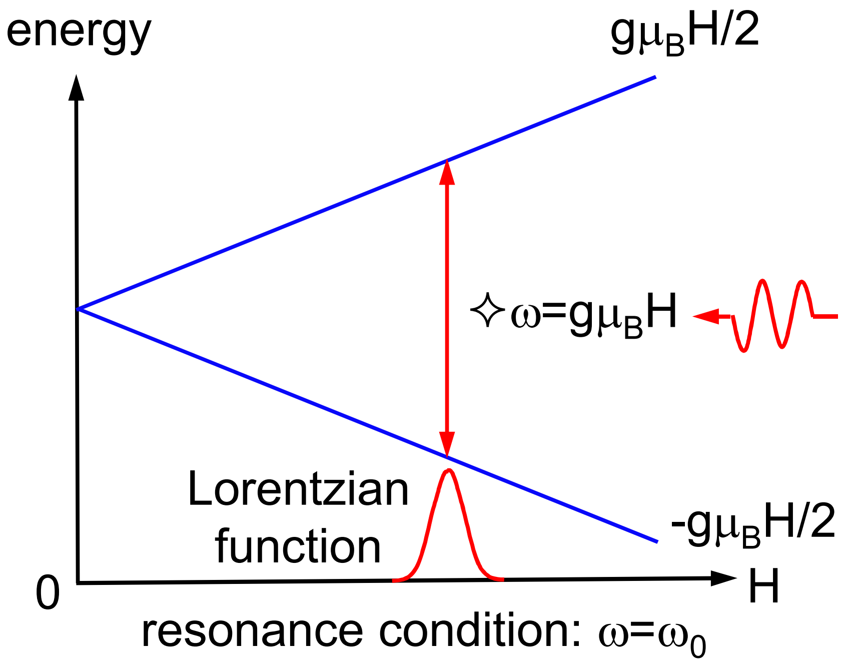
$$\frac{d\hat{m}}{dt} = -\gamma\hat{m} \times \vec{H}_{eff} + \alpha\hat{m} \times \frac{d\hat{m}}{dt}$$

$\gamma = \frac{g\, e}{2\, m_e c}$ is gyromagnetic ratio

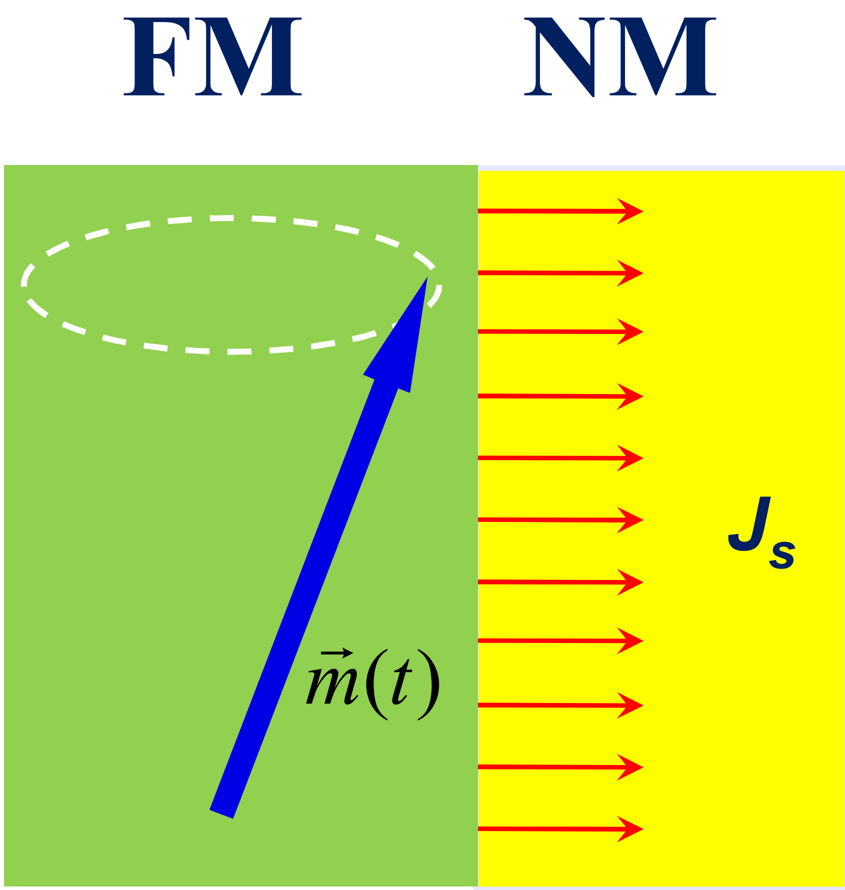
α is the Gilbert damping

Magnetic resonance

FMR



Dynamical Spin injection



$$\vec{J}_S = \frac{\hbar g_r^{\uparrow\downarrow}}{4\pi M^2}\left(\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right)$$

Precessing magnetization in FM layer pump spin current into NM layer (Angular momentum conservatoin)

Dynamical Spin injection

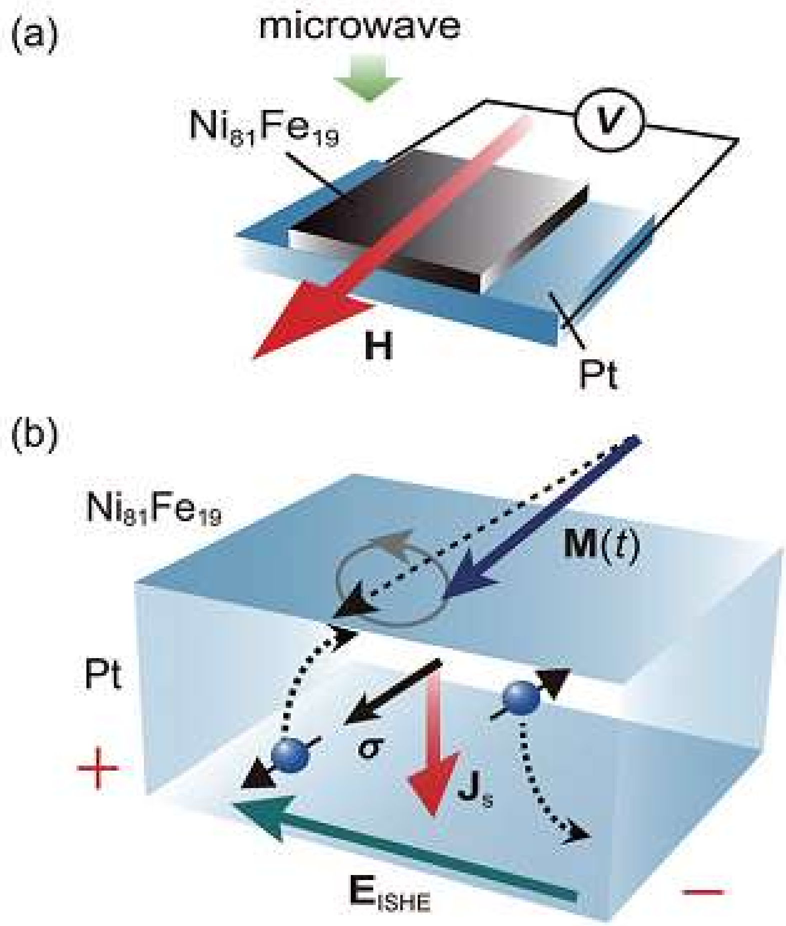
$$\frac{d\mathbf{M}(t)}{dt} = -\gamma \mathbf{M}(t) \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s} \mathbf{M}(t) \times \frac{d\mathbf{M}(t)}{dt}.$$

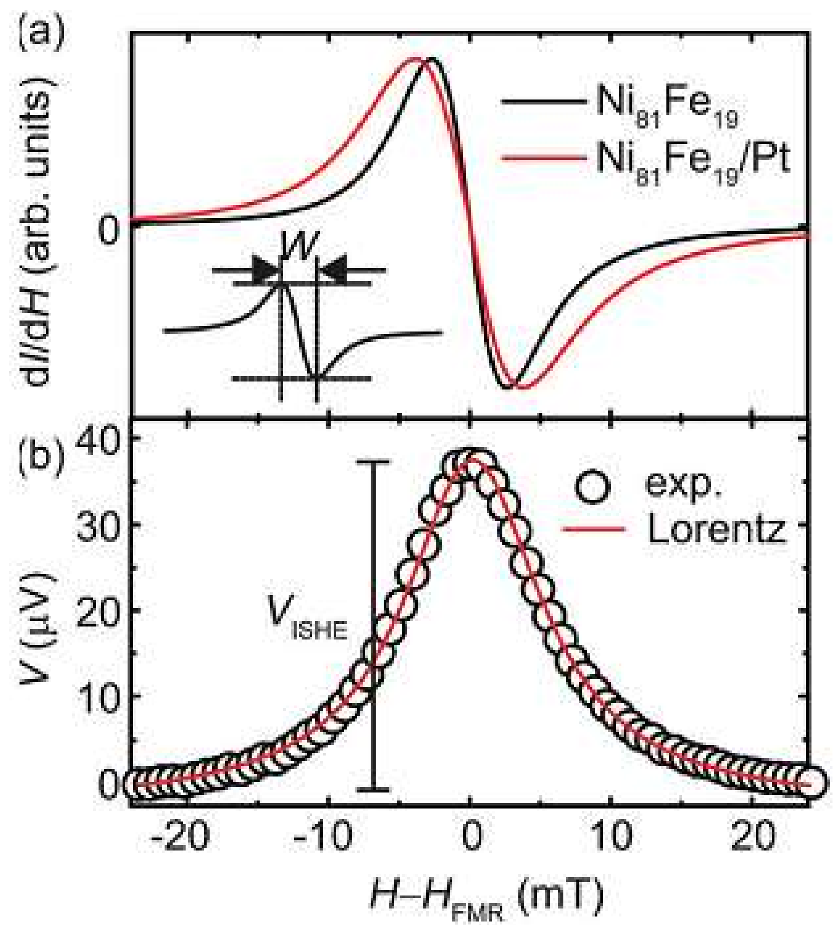
$$\boldsymbol{\tau} = -\mathbf{m} \times \mathbf{I}_s \times \mathbf{m}.$$

$$\mathbf{I}_{s,R}^{\mathrm{pump}} = \frac{\hbar}{4\pi}\left(\mathcal{A}_r^{\uparrow\downarrow} \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathcal{A}_i^{\uparrow\downarrow} \frac{d\mathbf{m}}{dt} \right)$$

Tserkovnyak, et al, RMP (2005)

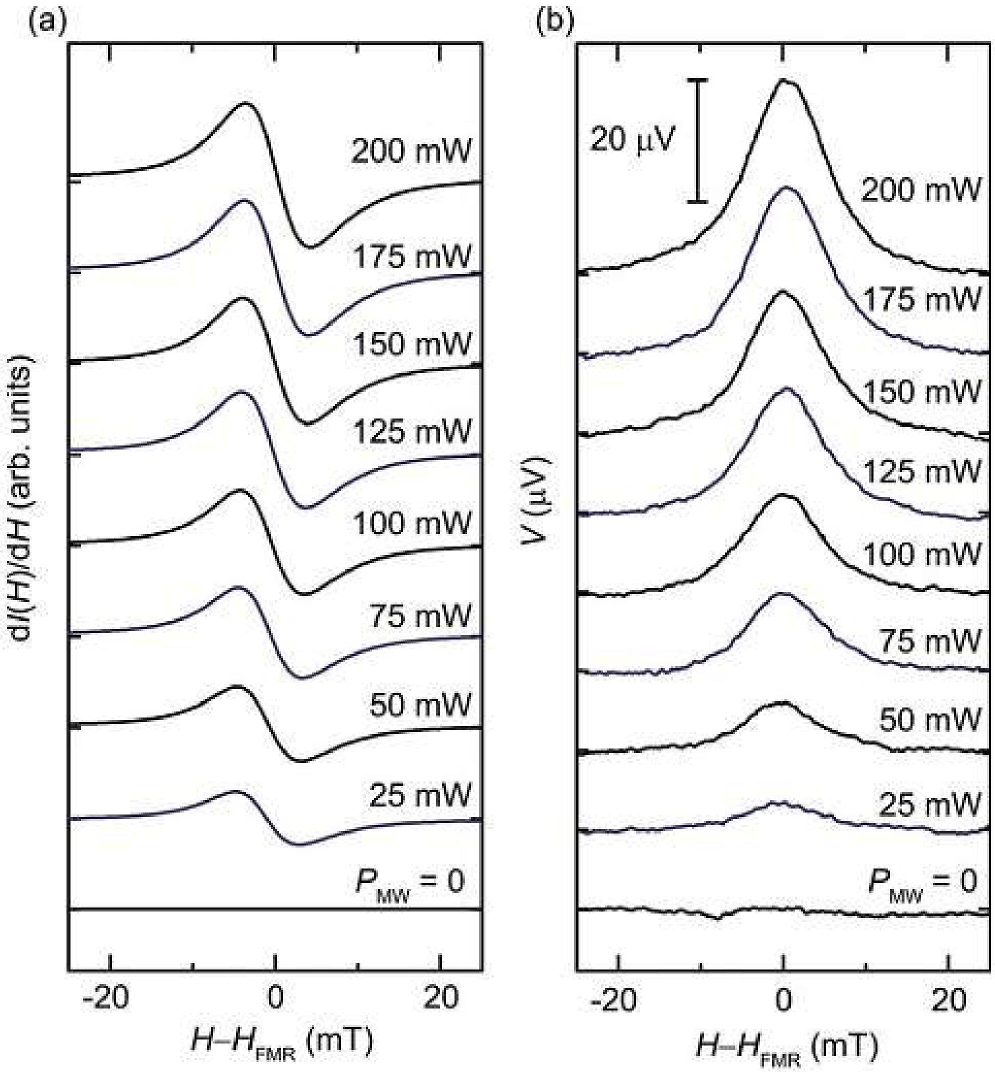
Dynamical Spin injection

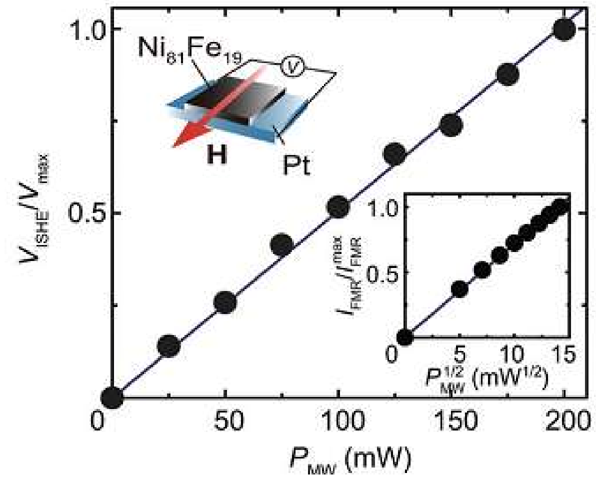




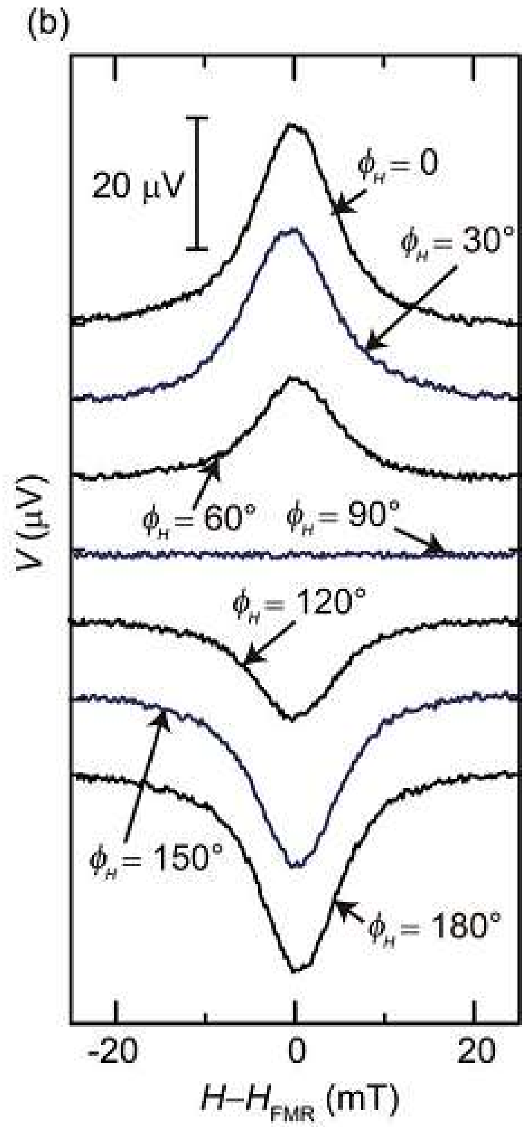
Ando, et al, JAP (2011)

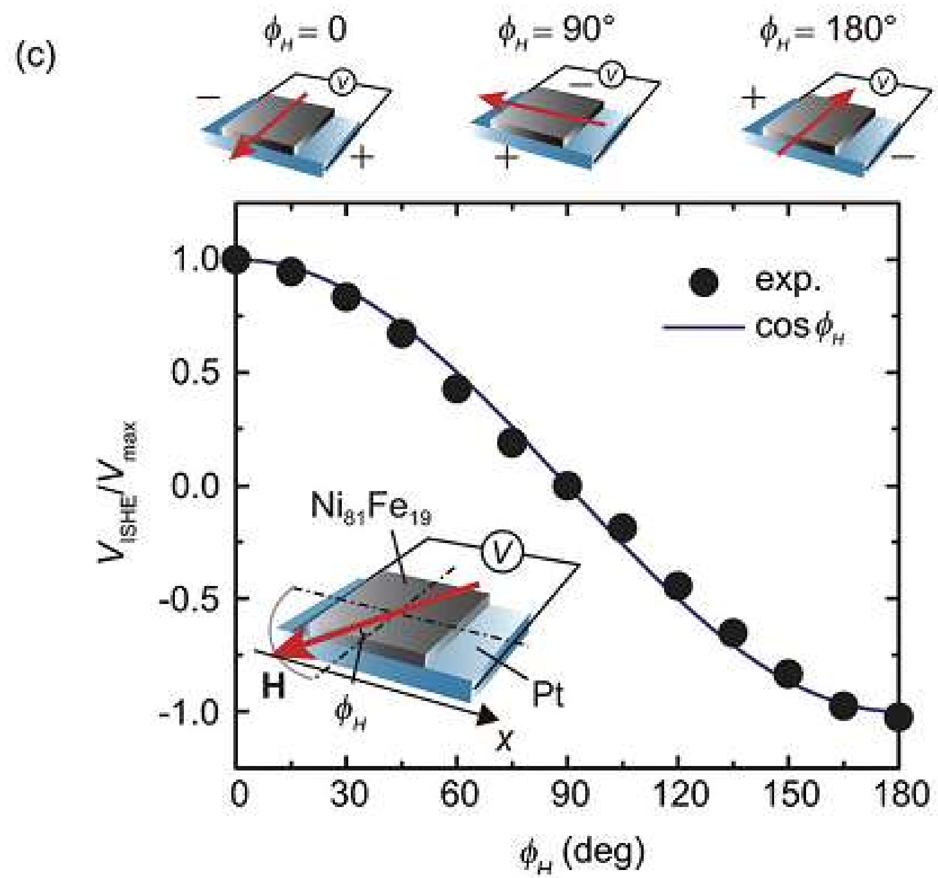
Dynamical Spin injection



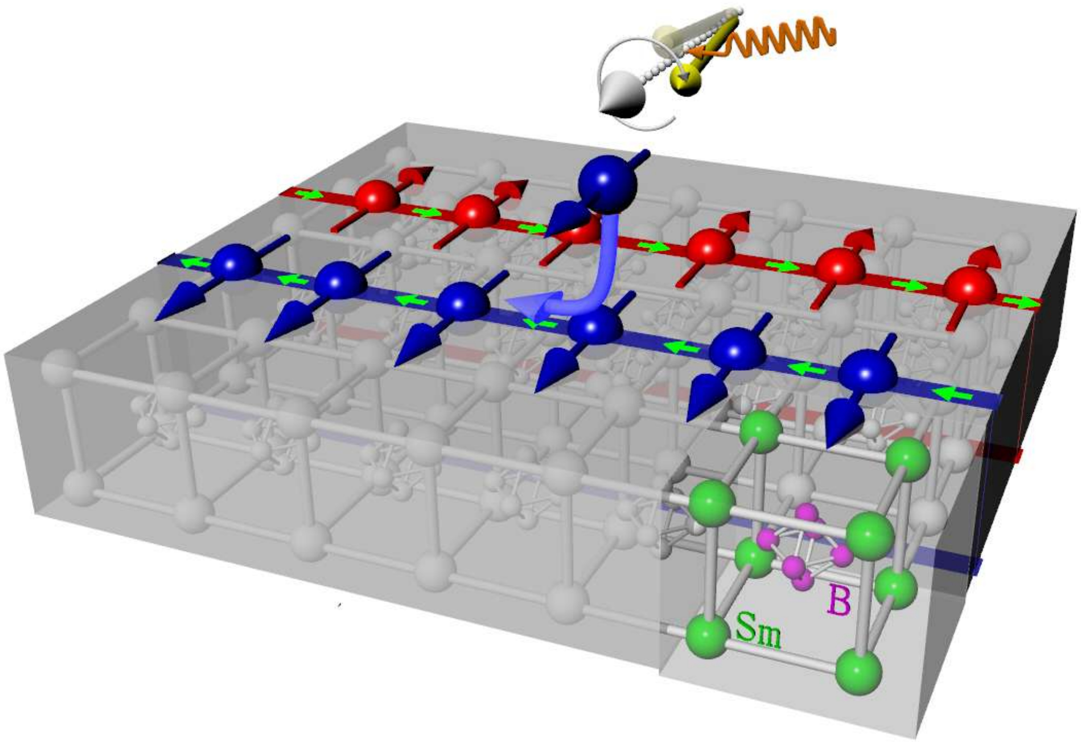


Dynamical Spin injection

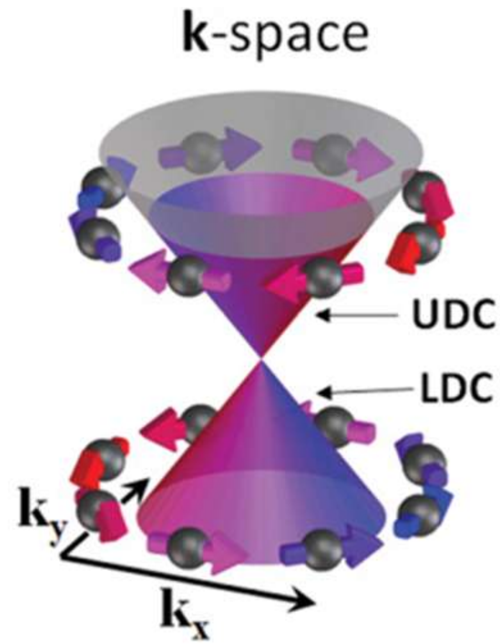




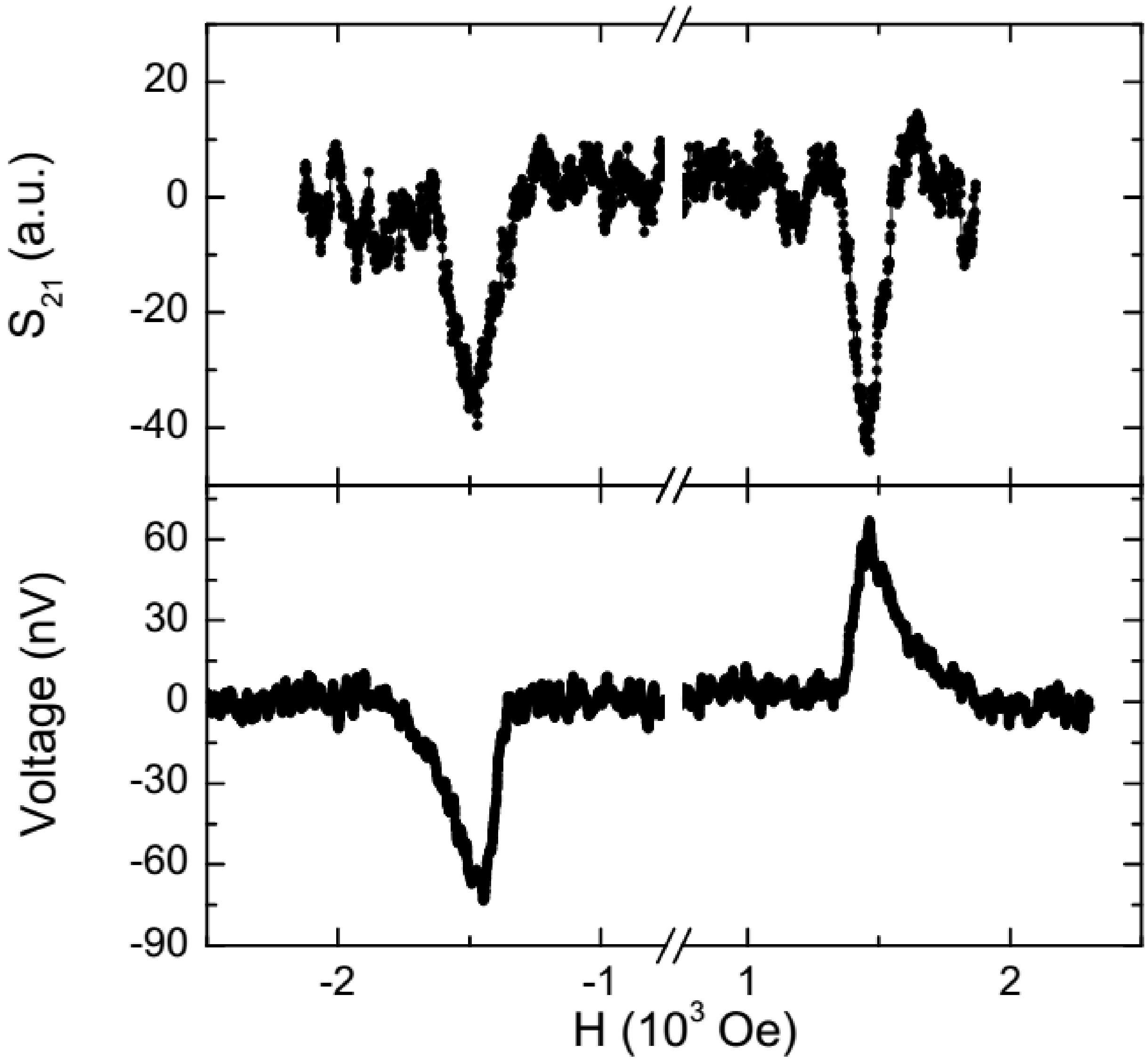
Dynamical Spin injection



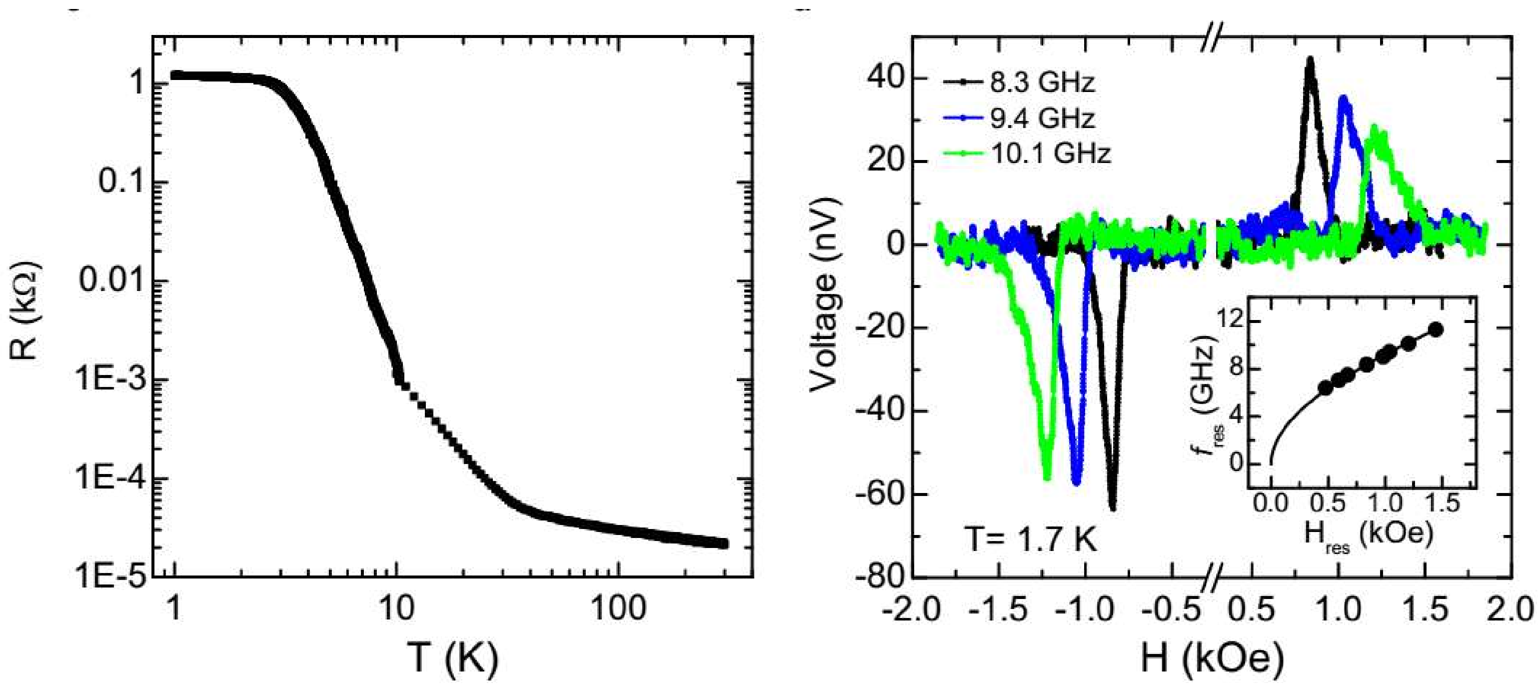
Spin-Momentum Locking



Dynamical Spin injection



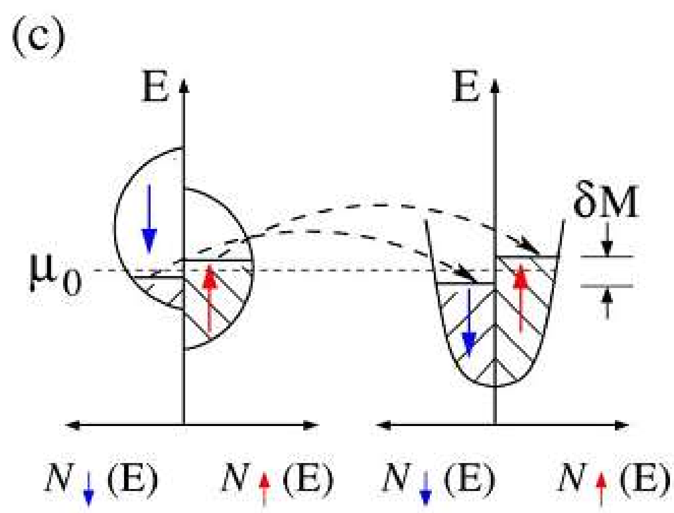
Dynamical Spin injection



Song, et al, Nature Communications (2016)

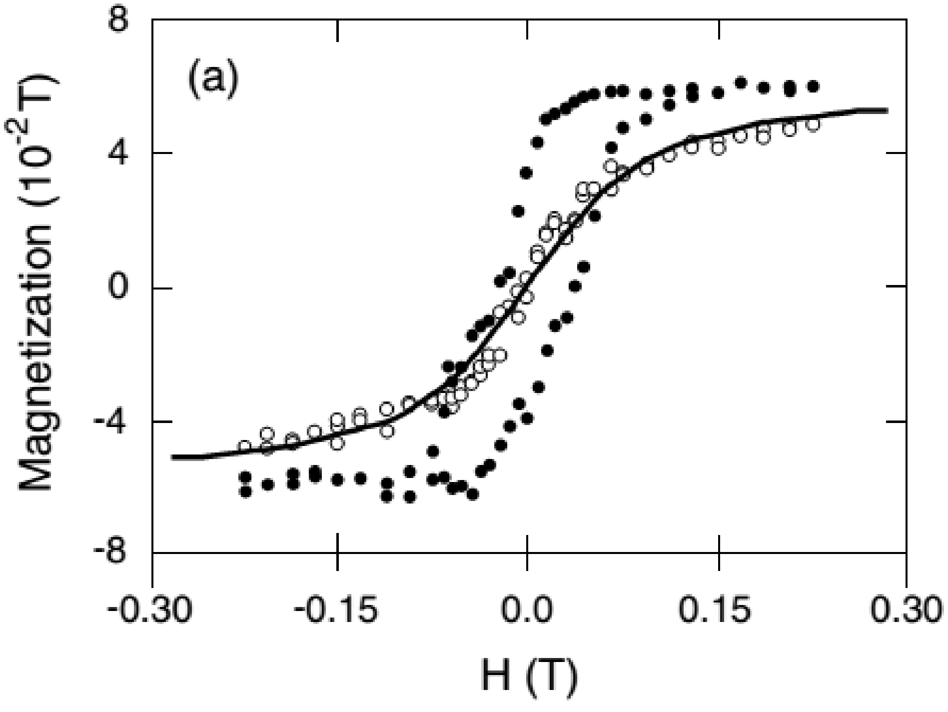
3. Spin injection

- ❑ **Electrical**



3. Spin injection

❑ Optical

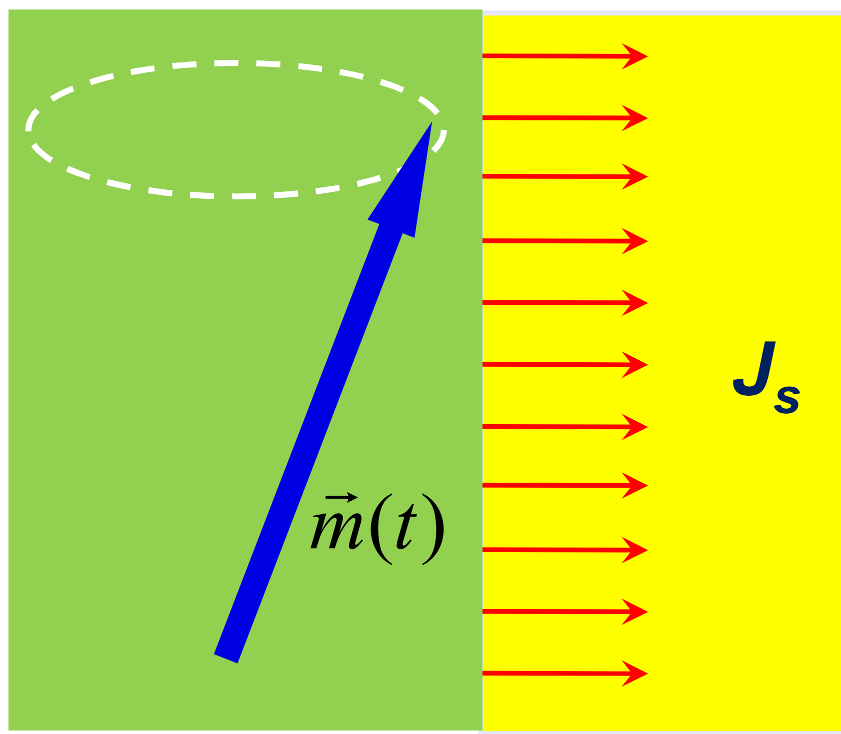


Summary

3. Spin injection

- Dynamical

FM



NM

下一节课: Oct. 25th

Chapter 4: Spin Valves

2. Spin valves based on Metal and Superconductor

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

谢谢！