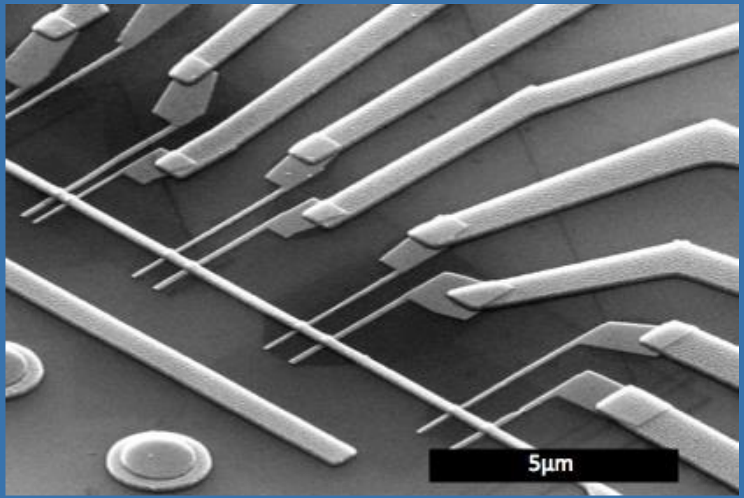
CIC nanoGUNE
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

Introduction to spintronics: Spin generation, transport and manipulation

School on Magnetism 2023, Milano (Italy)
June 6th 2023



Fèlix Casanova
Nanodevices group, CIC nanoGUNE
San Sebastian, Basque Country

OUTLINE

1. Introduction to spintronics
- Introduction
- Spin valves
- Pure spin currents (electrically, thermally, pumping, spin Hall)

2. Spin injection (electrical)
- Electronic transport in FM metals
- Spin accumulation: the basic idea
- Non-local spin valves
- Spin polarization

3. Spin transport
- Spin relaxation mechanisms
- Spin diffusion length (metals, semiconductors, graphene)

4. Spin manipulation
- By magnetic field (Hanle effect)
- By electric field (spin transistor)
- Spin transfer torque

5. Spin-based logic proposals

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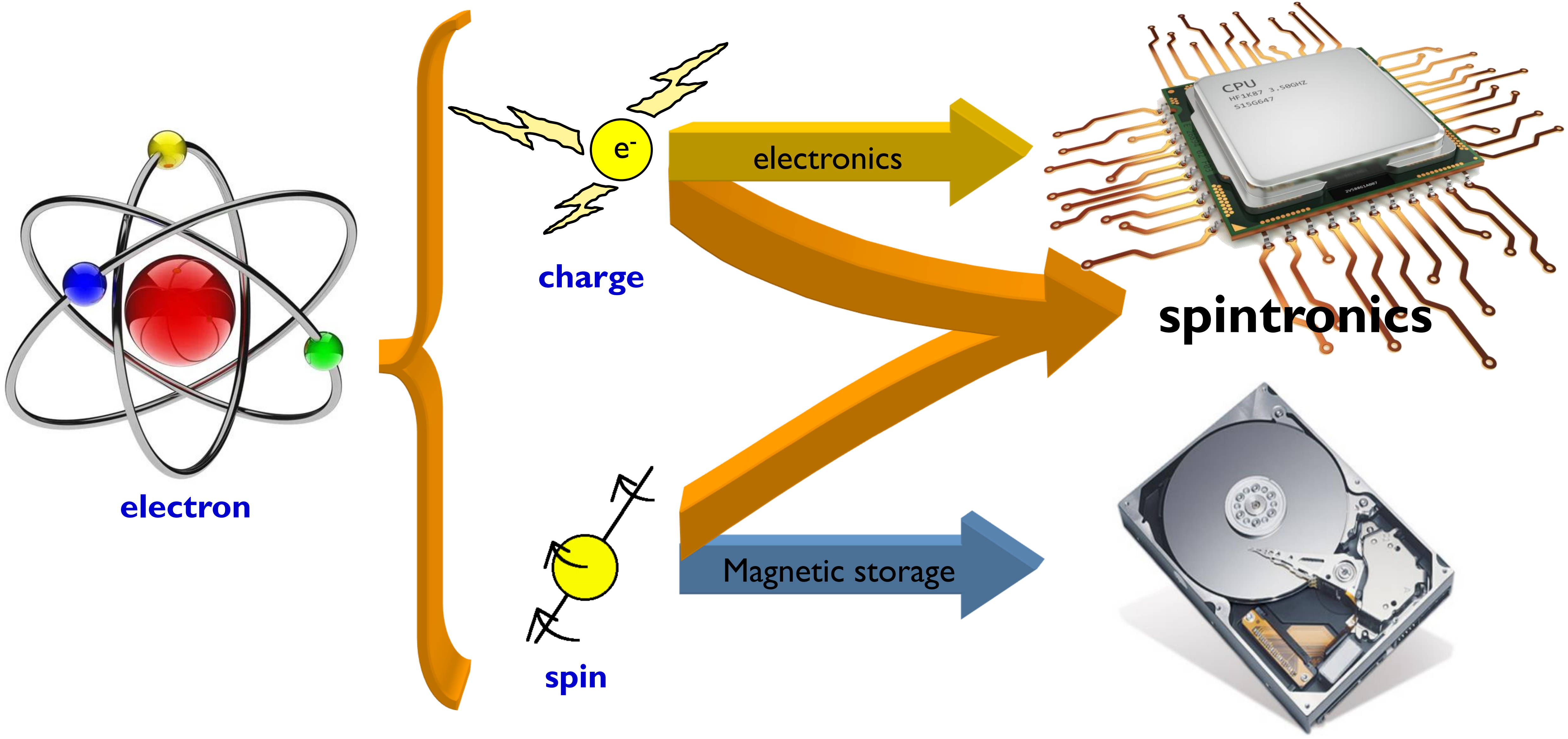
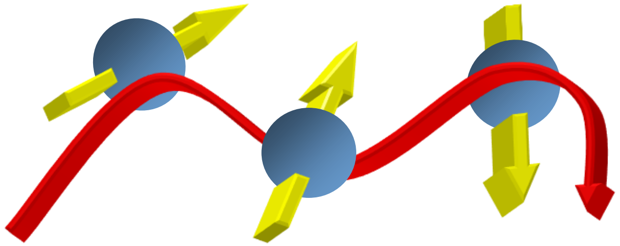
INTRODUCTION : SPINTRONICS



Spintronics' paradox:

best non-volatile information storage

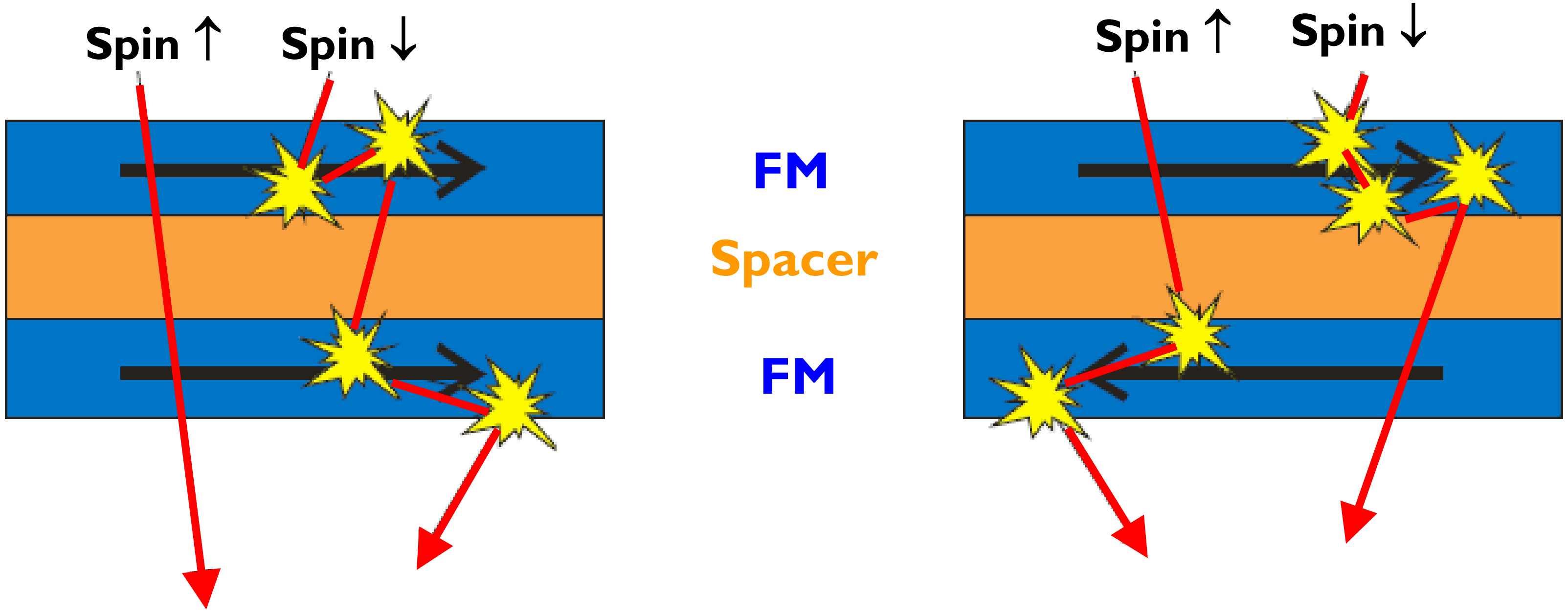
But spin information is highly volatile when transfered !



We need to improve the transport and make manipulation real!!!

INTRODUCTION: SPIN VALVES

•BASIC spintronic devices use two ferromagnets (**FM**) in a polarizer/analyzer arrangement: **spin valves**



Parallel magnetization: Low resistance

Antiparallel magnetization: High resistance

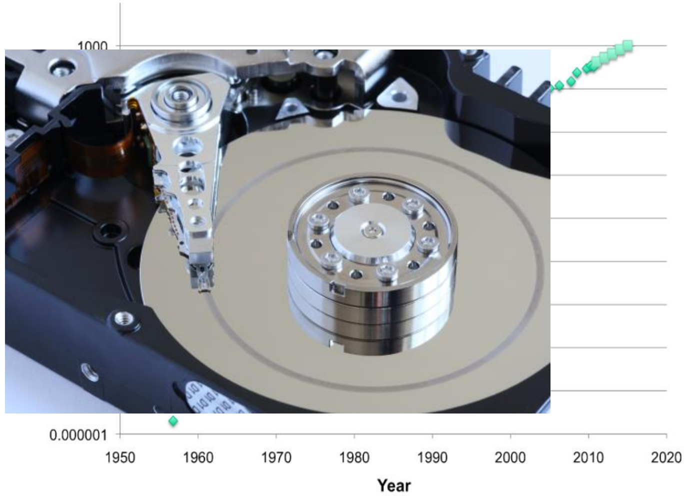
- Terminology depends on spacer:
  - Metal: giant magnetoresistance (GMR)
  - Insulator: tunnelling magnetoresistance (TMR)
  - Domain wall: domain wall magnetorresistance (DWMR)

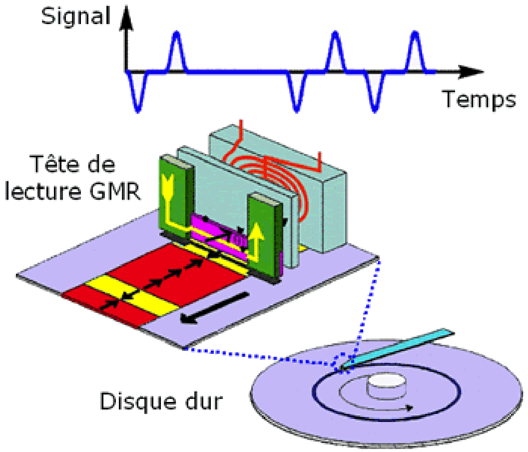
- Very simple device
- Magnetic information converted into electrical information

INTRODUCTION: SPIN VALVES

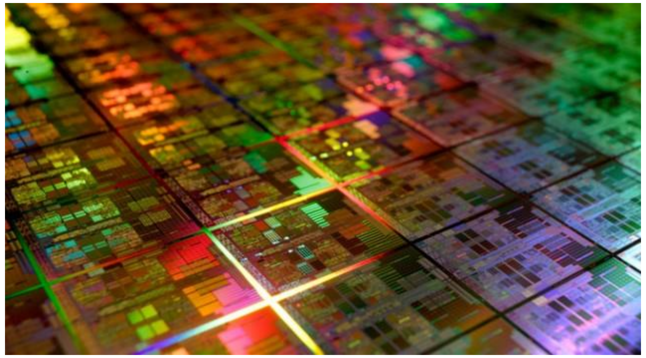
- **SPIN VALVES** in a <u>vertical</u> structure – two-terminal devices

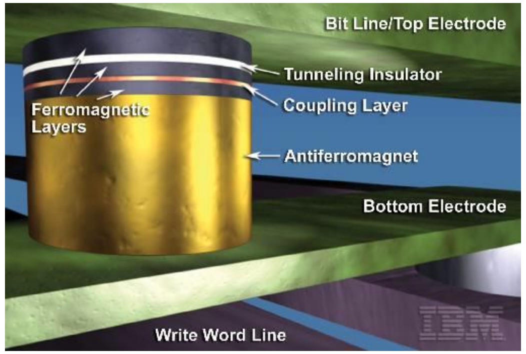
Magnetoresisitive read head
Basic phenomena: 1988
Market: IBM 1997





Magnetic RAM
4 Mbit chip
Revisited: 1995
Market: Freescale 2006



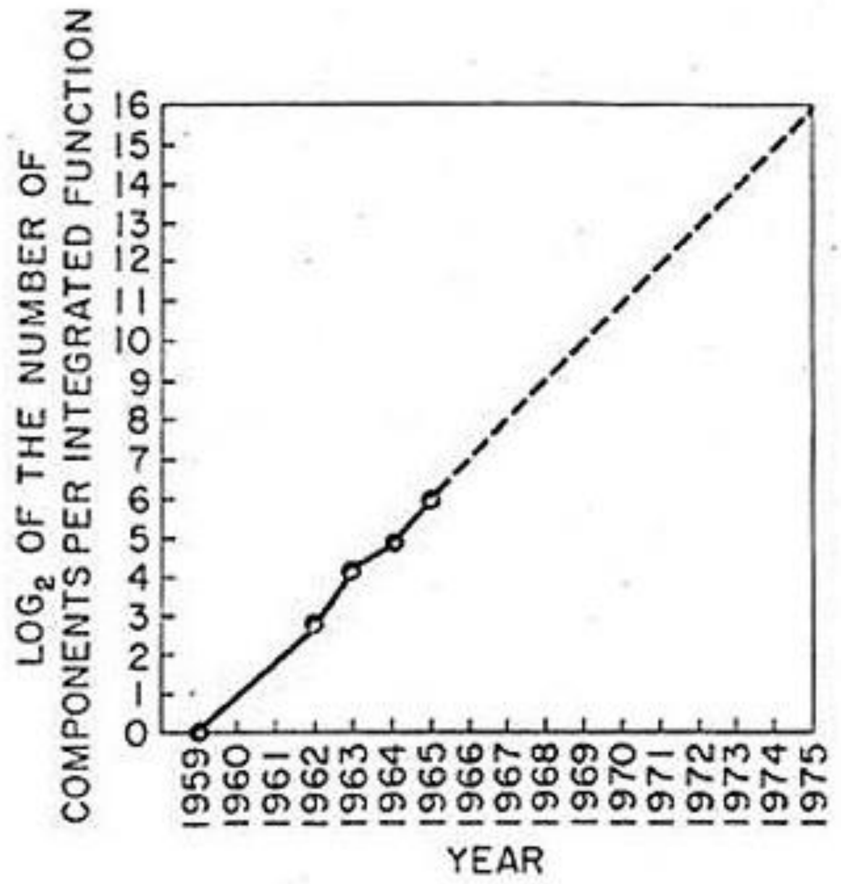


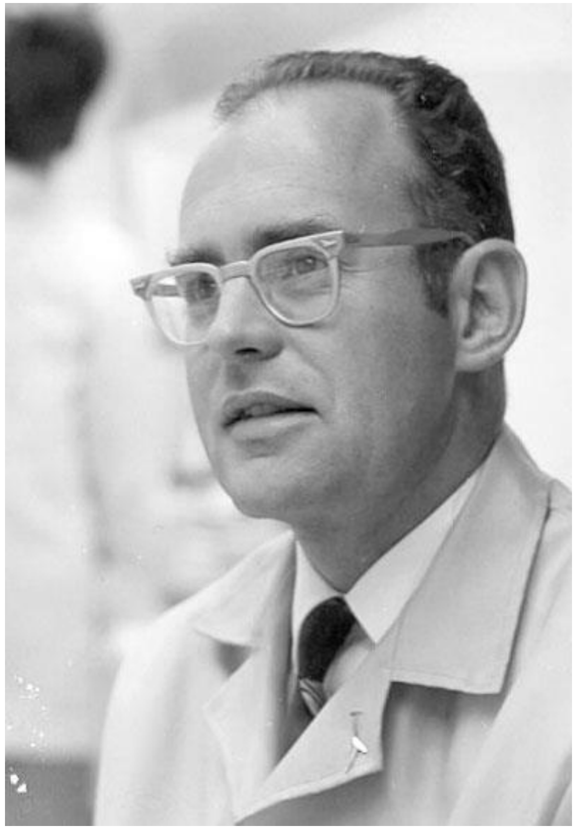
INTRODUCTION

How do we move from here?

Towards a new generation of spintronic devices

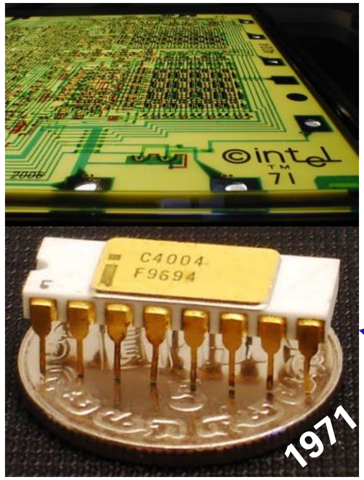
INTRODUCTION: MOORE'S LAW

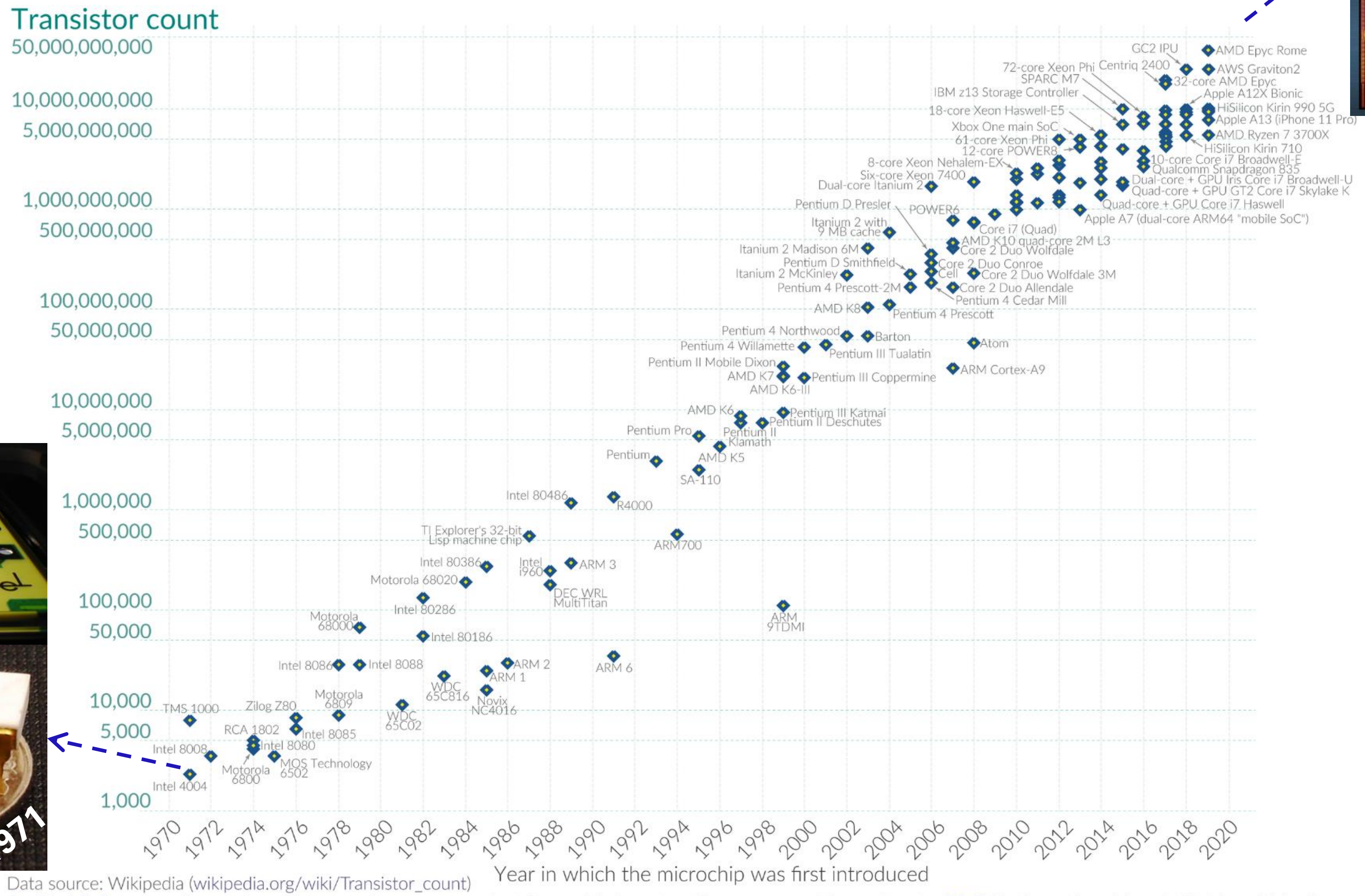


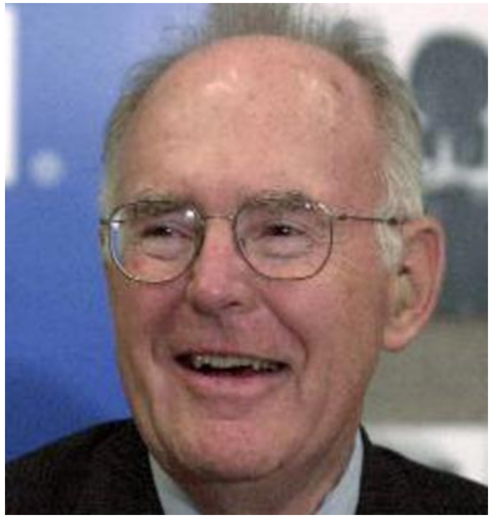


Gordon Moore (1968)

INTRODUCTION: MOORE'S LAW



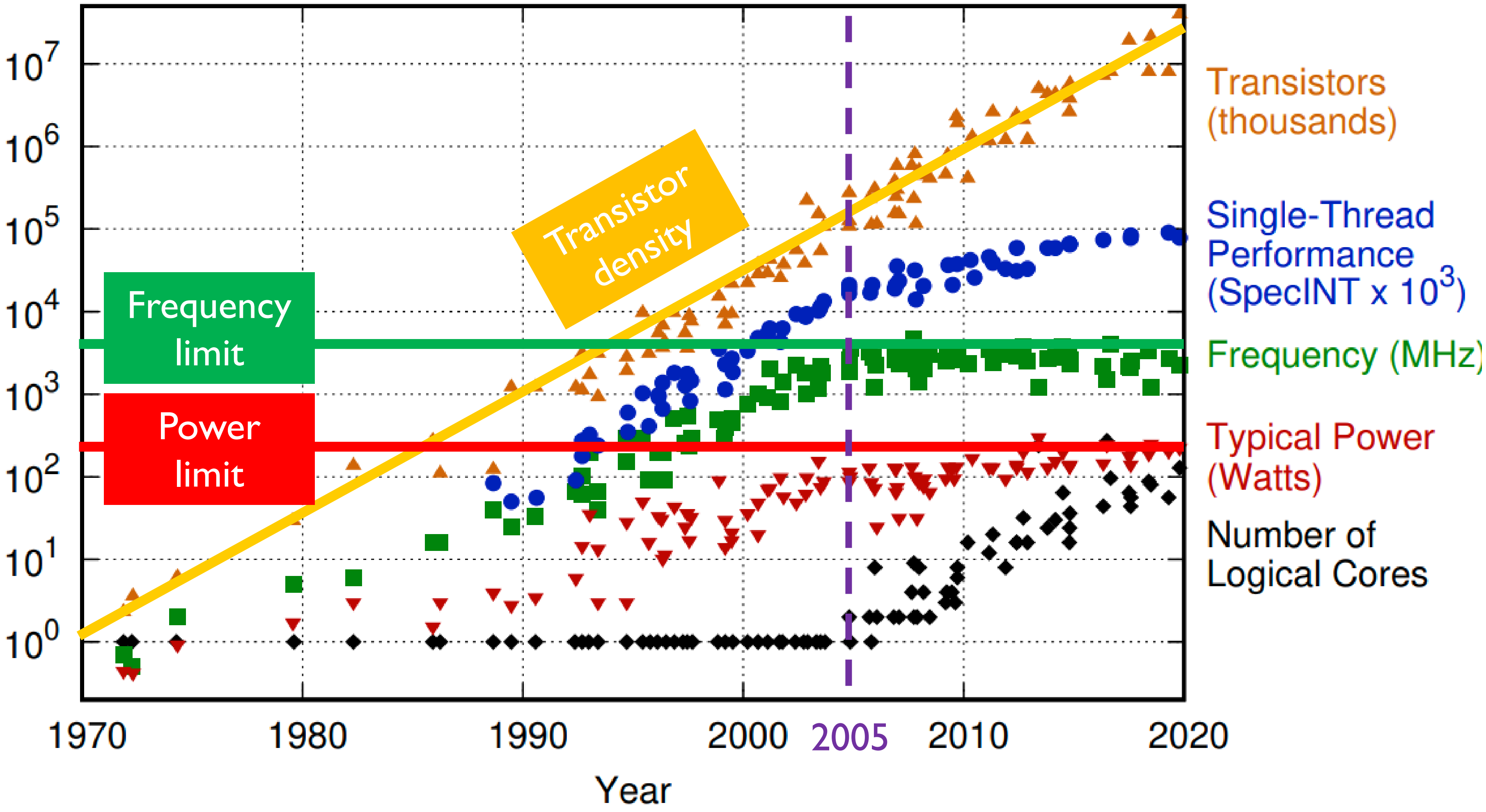




Gordon Moore (2020)

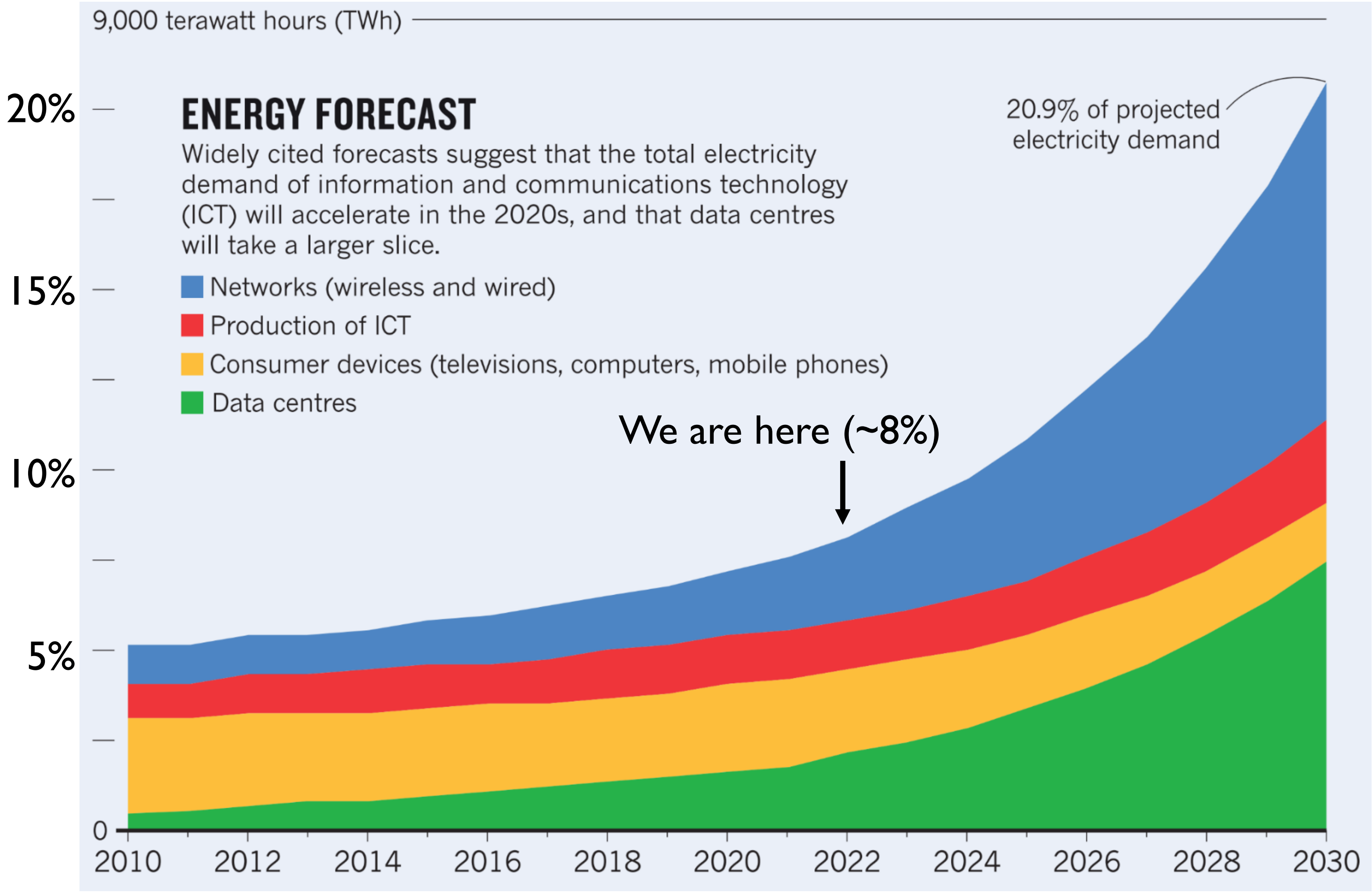
INTRODUCTION: ENERGY CONSUMPTION

Other parameters also relevant for the future trend



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2019 by K. Rupp

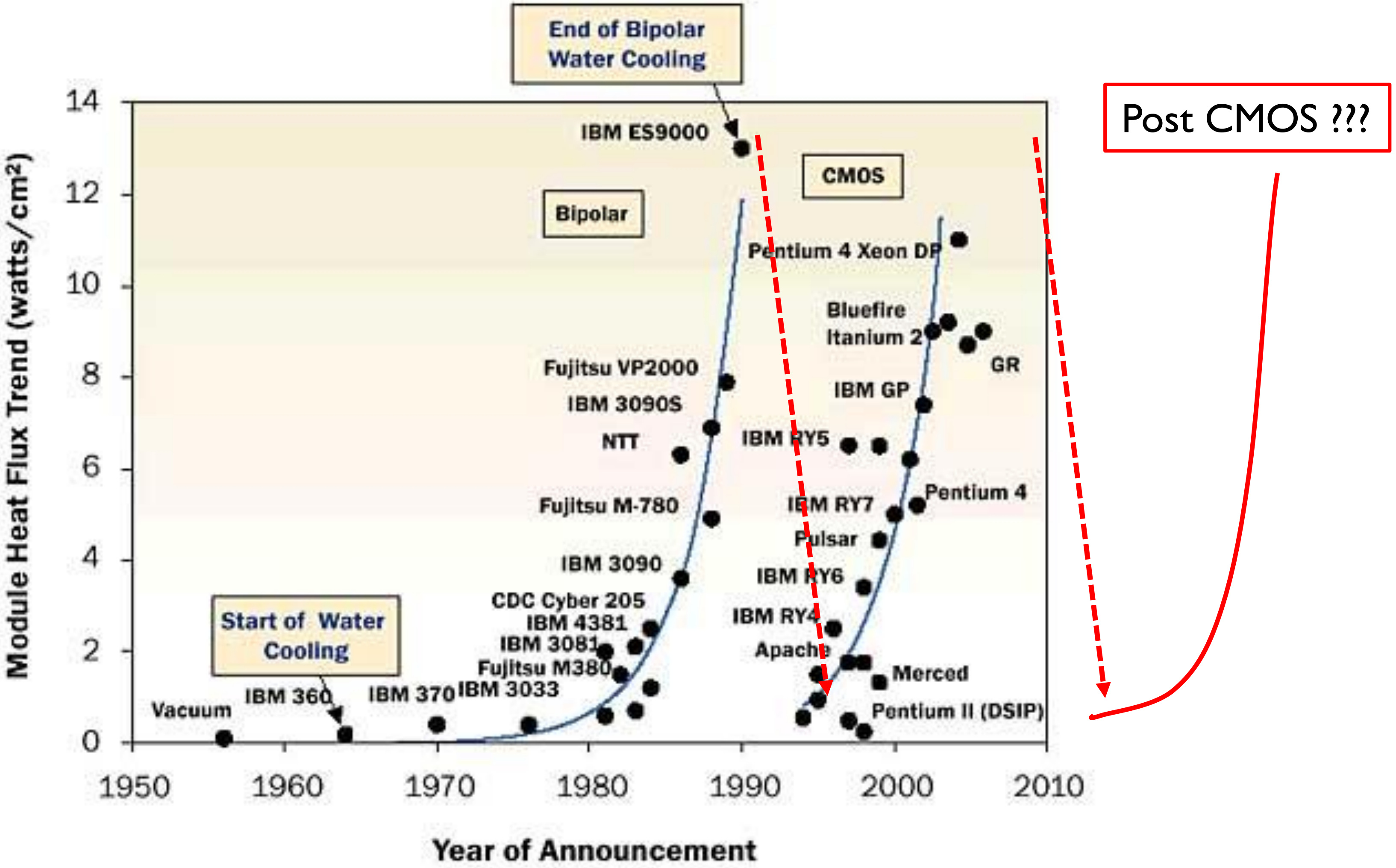
INTRODUCTION: ENERGY CONSUMPTION



Google data center

Andrea and Edler; Challenges **6**, 117 (2015); N. Jones, Nature **561**, 163 (2018)

INTRODUCTION: ENERGY CONSUMPTION



Semiconductor industry faced this situation before with bipolar transistors

Courtesy of Ian Young (Research Components, Intel)

INTRODUCTION: PURE SPIN CURRENTS

Charge vs. Spin Currents

Charge

$$\overrightarrow{j_e} = \frac{d}{dt}(q\vec{r})$$

$$\overrightarrow{j_e} = q\vec{v}$$

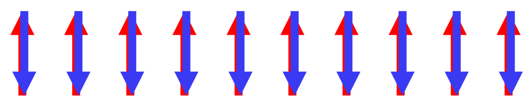
Spin

$$\overrightarrow{j_s} = \frac{d}{dt}(\sigma\vec{r})$$

$$\overrightarrow{j_s} = \sigma\vec{v} + \frac{d\sigma}{dt}\vec{r}$$

Moving Spins

Spin Dynamics

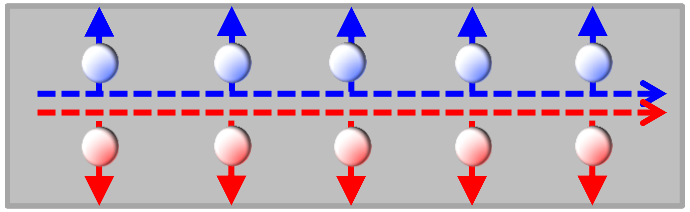


No Need for Moving Spin:
Potential for Low Power Dissipation!

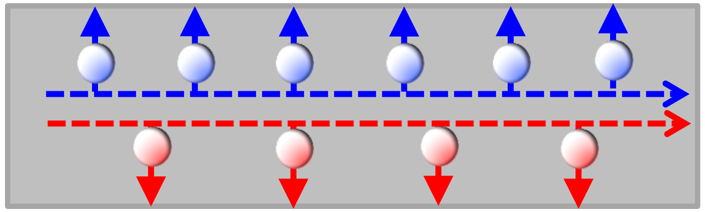
J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006)

INTRODUCTION: PURE SPIN CURRENTS

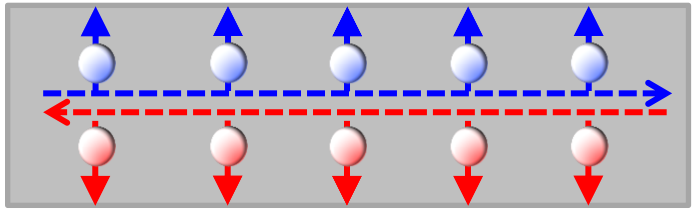
$I_c = I_\uparrow + I_\downarrow$, $I_s = I_\uparrow - I_\downarrow$



Charge current $\quad I_c \neq 0$, $I_s = 0$



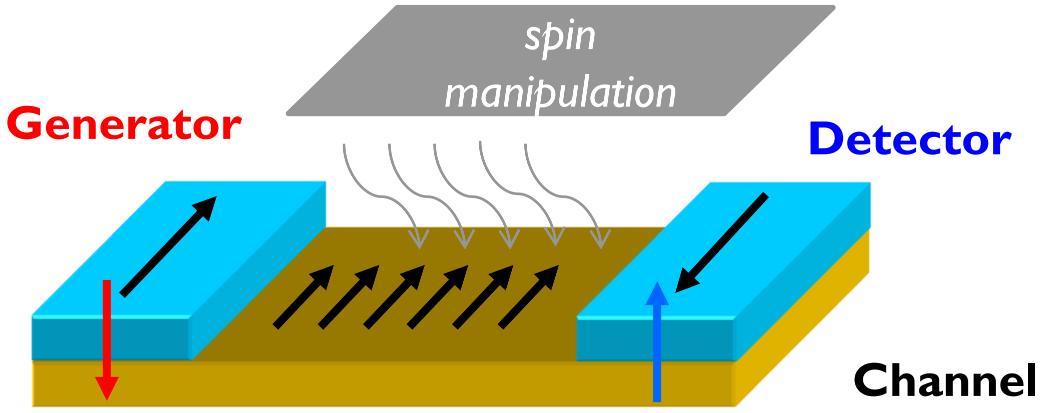
Spin-polarized current $\quad I_c \neq 0$, $I_s \neq 0$



Pure spin current $\quad I_c = 0$, $I_s \neq 0$

INTRODUCTION: PURE SPIN CURRENTS

- **New generation of spintronic devices: PURE SPIN CURRENTS**



•Spin generation (electrical spin injection, spin pumping, spin Hall effect…)

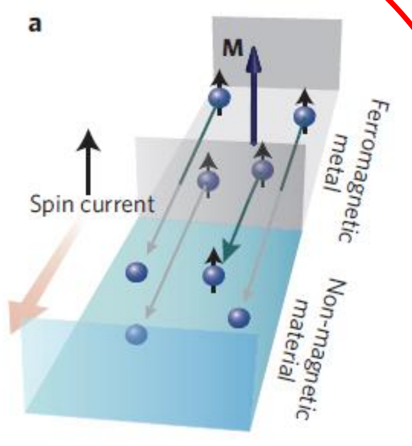
•Spin transport (non-magnetic material)

•Spin manipulation (electric field, magnetic field…)

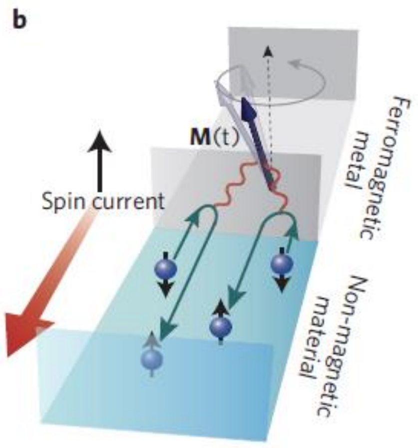
•Spin detection (reciprocal of generation)

INTRODUCTION: PURE SPIN CURRENTS

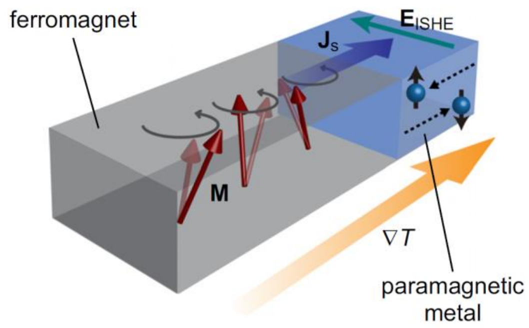
How can we generate pure spin currents in paramagnetic materials?



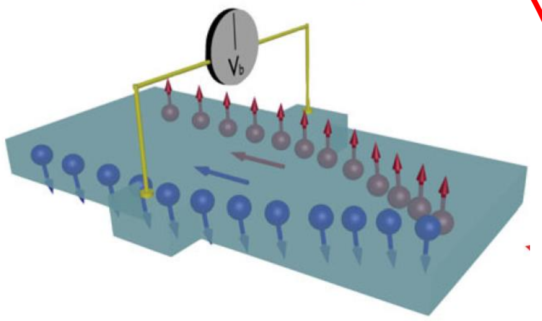
Electrical spin injection



Spin pumping



Spin Seebeck effect



Spin Hall effect

THIS TALK

THURSDAY'S TALK
(BY LUIS E. HUESO)

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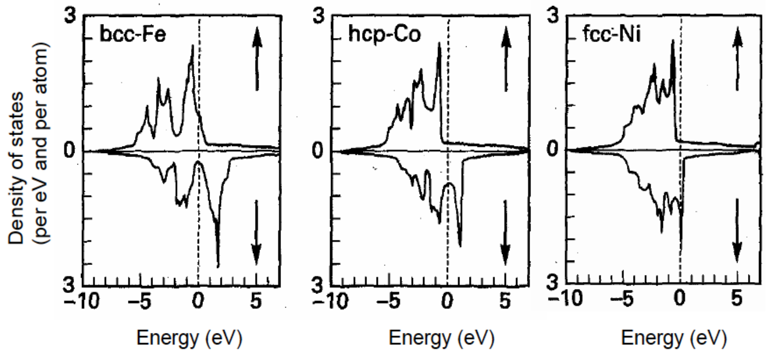
ELECTRON TRANSPORT IN FERROMAGNETIC METALS

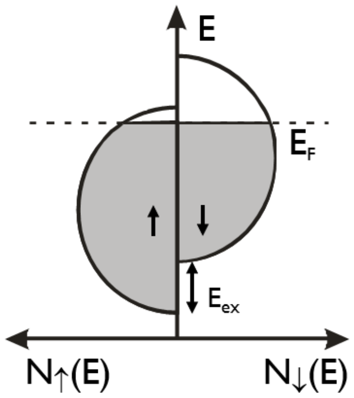


Explained by the **two-channel model**:

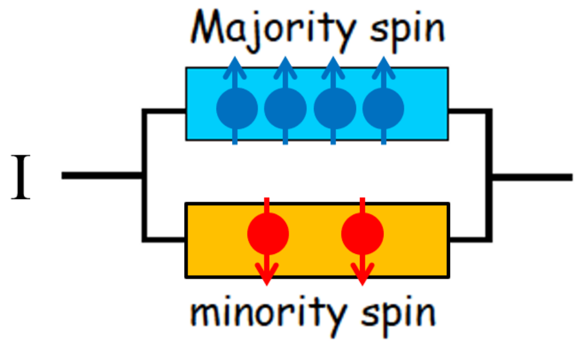
- First introduced by Mott (1936)
- Later used by Fert and Valet to explain GMR (1993)

Two basic ideas

1. Exchange splitting of spin up and spin down electron subbands due to <u>exchange interaction</u>
2. <u>Spin-flip scattering is negligible</u> (spin diffusion length >>mean free path)



Electrons with different spins have different m^*, v_F, k_F, $N(E_F)$ $\Rightarrow$ **conductivity is different for spin-up and spin-down electrons**:
$\sigma_{\uparrow,\downarrow}=N(E_F)_{\uparrow,\downarrow}e^2D_{\uparrow,\downarrow}$ ($D_{\uparrow,\downarrow}$ are diffusion coefficients)



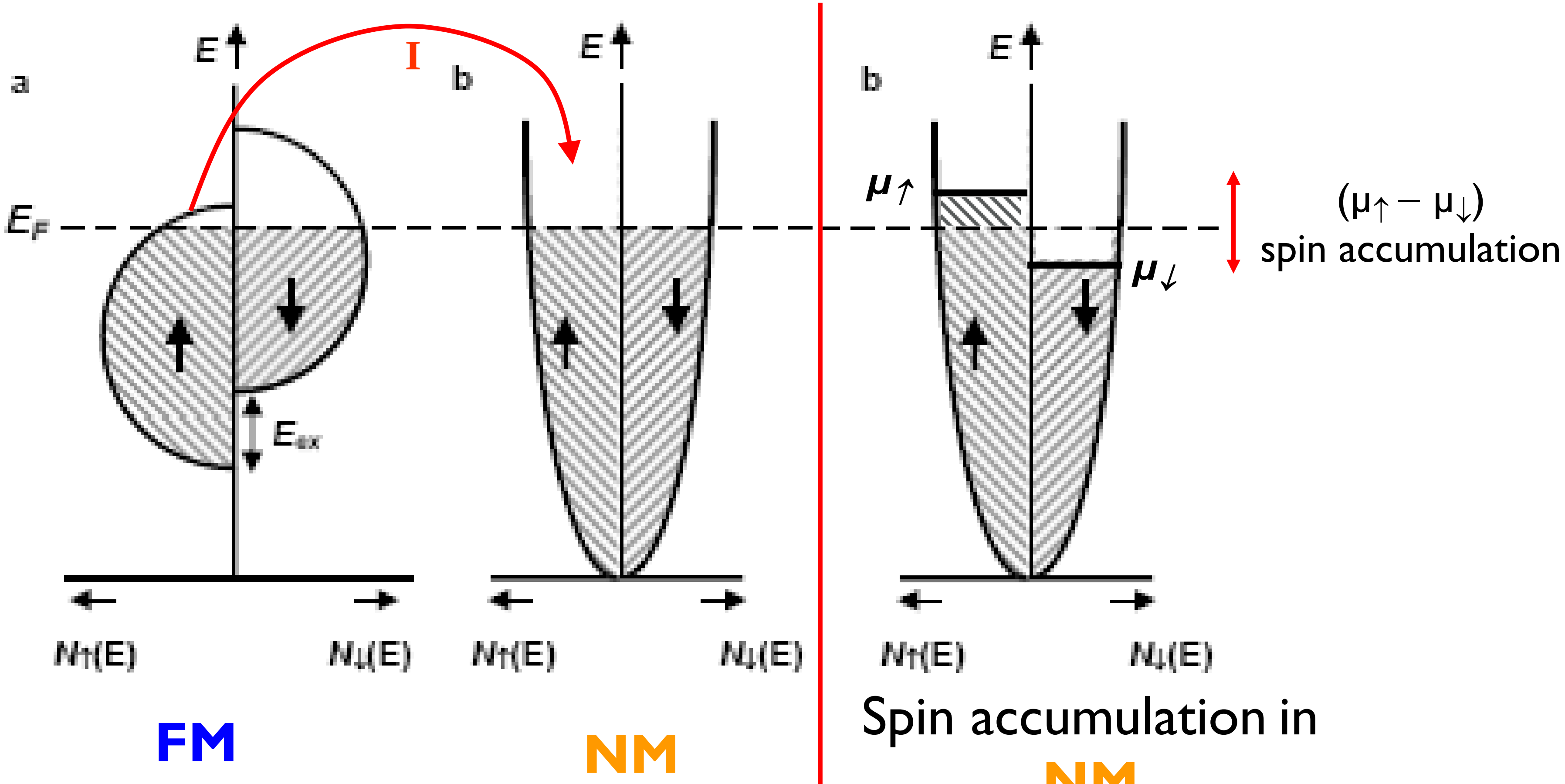
$$\alpha_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Spin polarization of the current

Two-channel model: spin up and spin down carriers are treated as <u>independent</u> channels with different <u>conductivity</u>

SPIN ACCUMULATION: THE BASIC IDEA

- When a current goes from **FM** to **NM**, one spin-type carrier is dominant
- Spin accumulation at both sides of the interface
- Chemical potential μ splits for spins up ($\mu_\uparrow$) and down ($\mu_\downarrow$)



Spin accumulation in **NM**

F. J. Jedema, PhD Thesis, University of Groningen (2002)

SPIN ACCUMULATION: THE BASIC IDEA

1. Diffusion equation for **spin accumulation**:

$$D\frac{\partial^2\left(\mu_\uparrow-\mu_\downarrow\right)}{\partial x^2}=\frac{\left(\mu_\uparrow-\mu_\downarrow\right)}{\tau_{sf}}$$

2. General solution:

$$\mu_\uparrow=A+Bx+\frac{C}{\sigma_\uparrow}\exp\left(-x/\lambda_{sf}\right)+\frac{D}{\sigma_\uparrow}\exp\left(x/\lambda_{sf}\right)$$

$$\mu_\downarrow=A+Bx-\frac{C}{\sigma_\downarrow}\exp\left(-x/\lambda_{sf}\right)-\frac{D}{\sigma_\downarrow}\exp\left(x/\lambda_{sf}\right)$$

$$\lambda_{sf}=\sqrt{D\tau_{sf}}$$

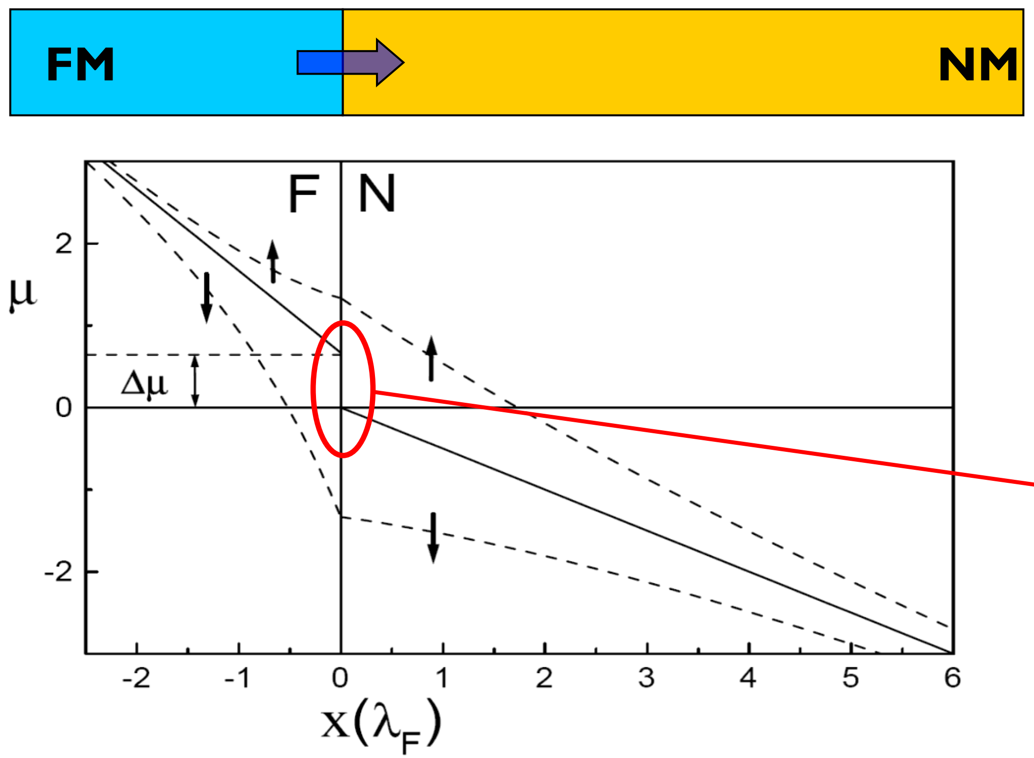
3. Boundary conditions:

- Transparent interface
- Tunnel barrier
- …

SPIN ACCUMULATION: THE BASIC IDEA

For transparent FM/NM interface

1) continuity of $\mu_\uparrow$ and $\mu_\downarrow$ at the interface
2) conservation of spin-up and spin-down currents $j_\uparrow, j_\downarrow$ across the interface



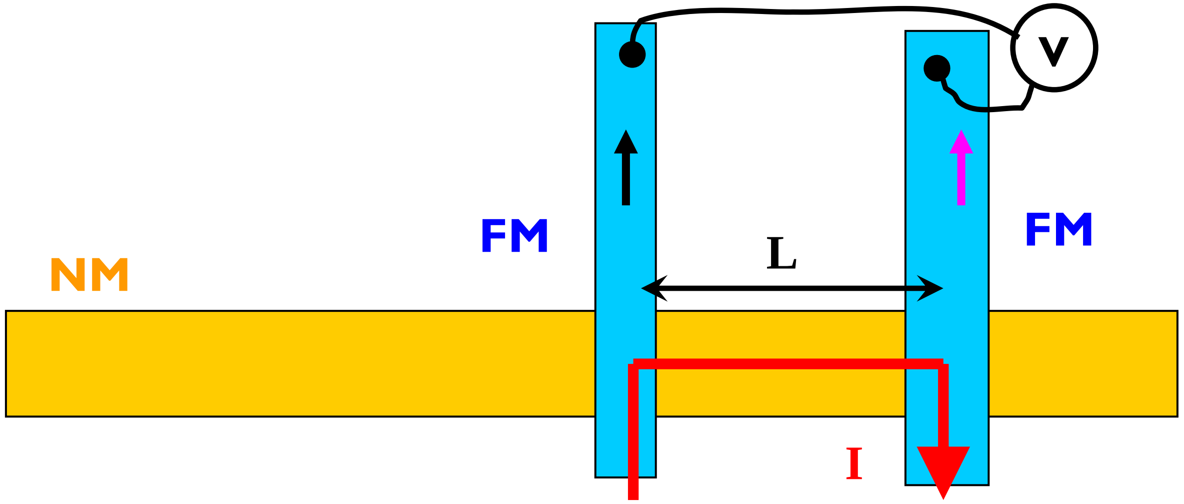
F. J. Jedema, PhD Thesis, University of Groningen (2002)

Two main effects:

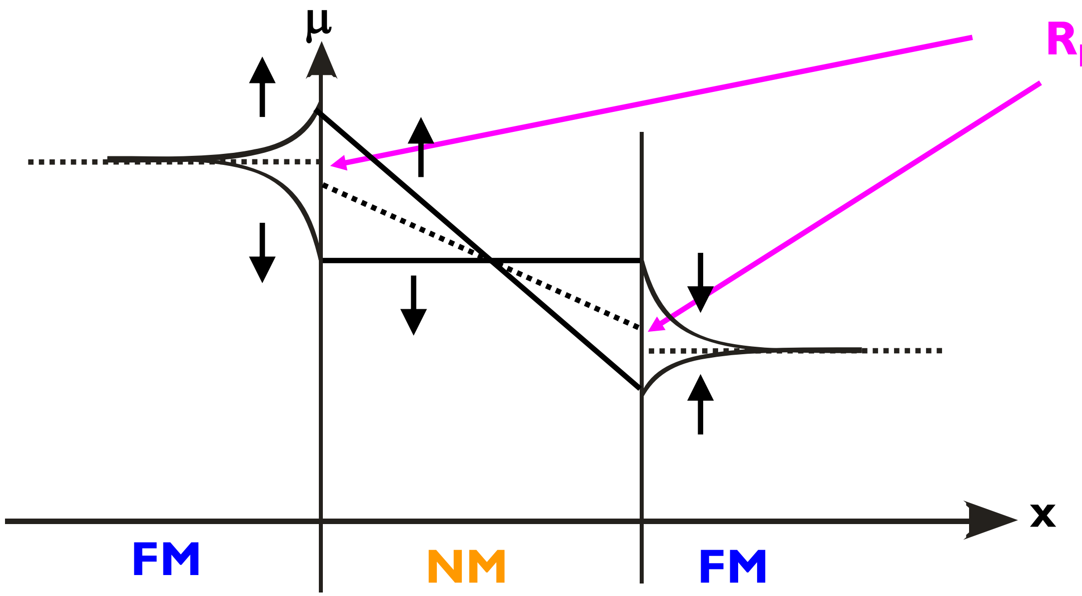
- Chemical potential μ splits for spins up ($\mu_\uparrow$) and down ($\mu_\downarrow$)
- "Spin-coupled" interface resistance appears:

$$R_I = \frac{\Delta\mu}{eI} = \frac{\alpha_F^2(\sigma_N^{-1}\lambda_N)(\sigma_F^{-1}\lambda_F)}{(\sigma_F^{-1}\lambda_F) + (1-\alpha_F^2)(\sigma_N^{-1}\lambda_N)}$$

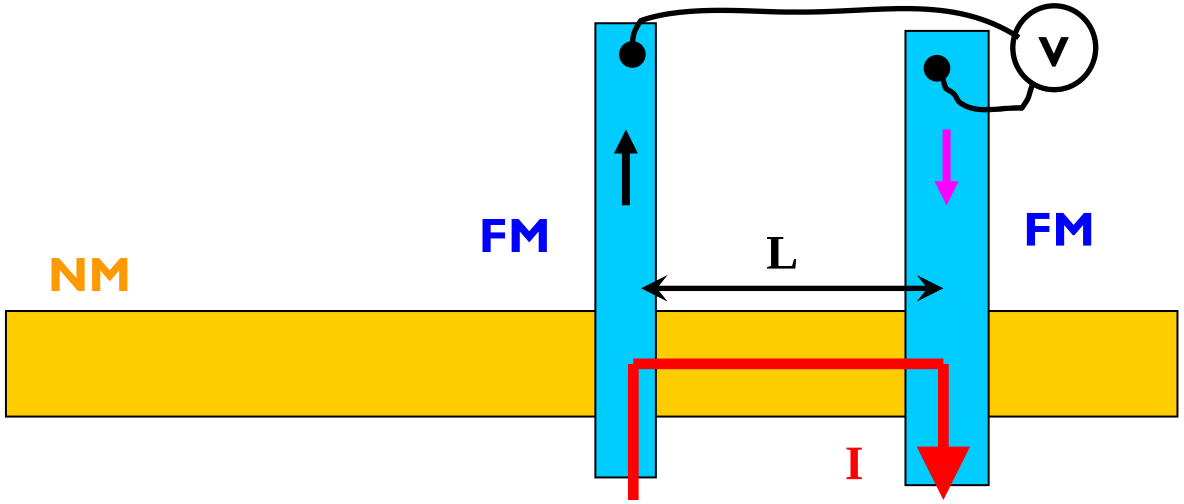
LATERAL SPIN VALVES: LOCAL

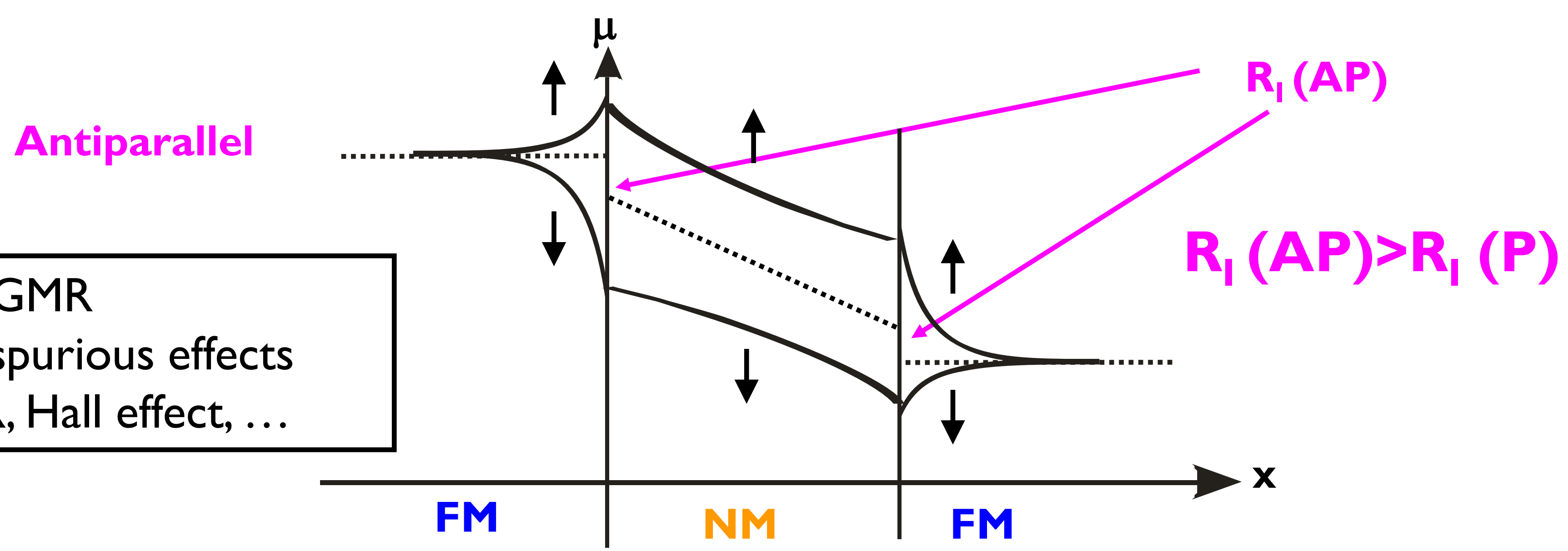


Parallel



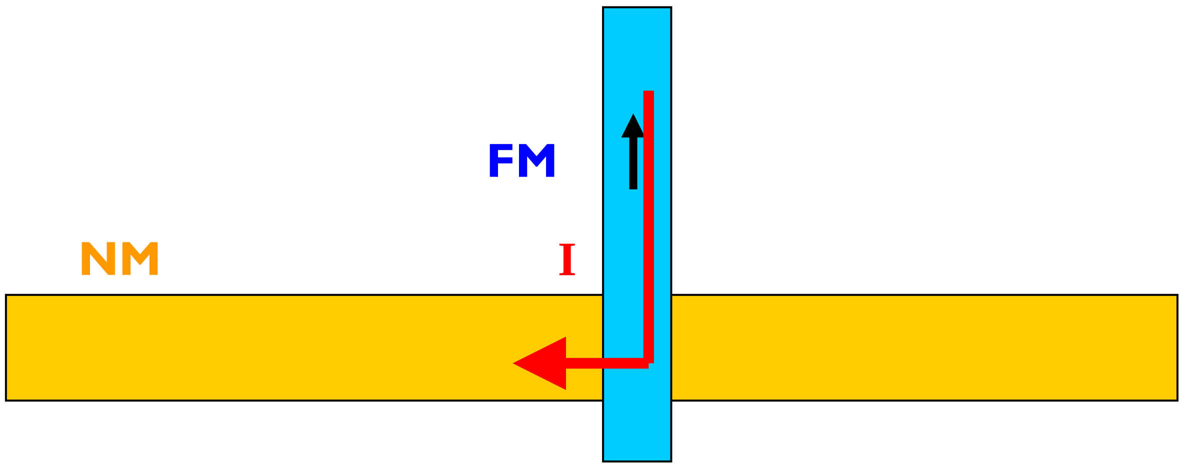
LATERAL SPIN VALVES: LOCAL

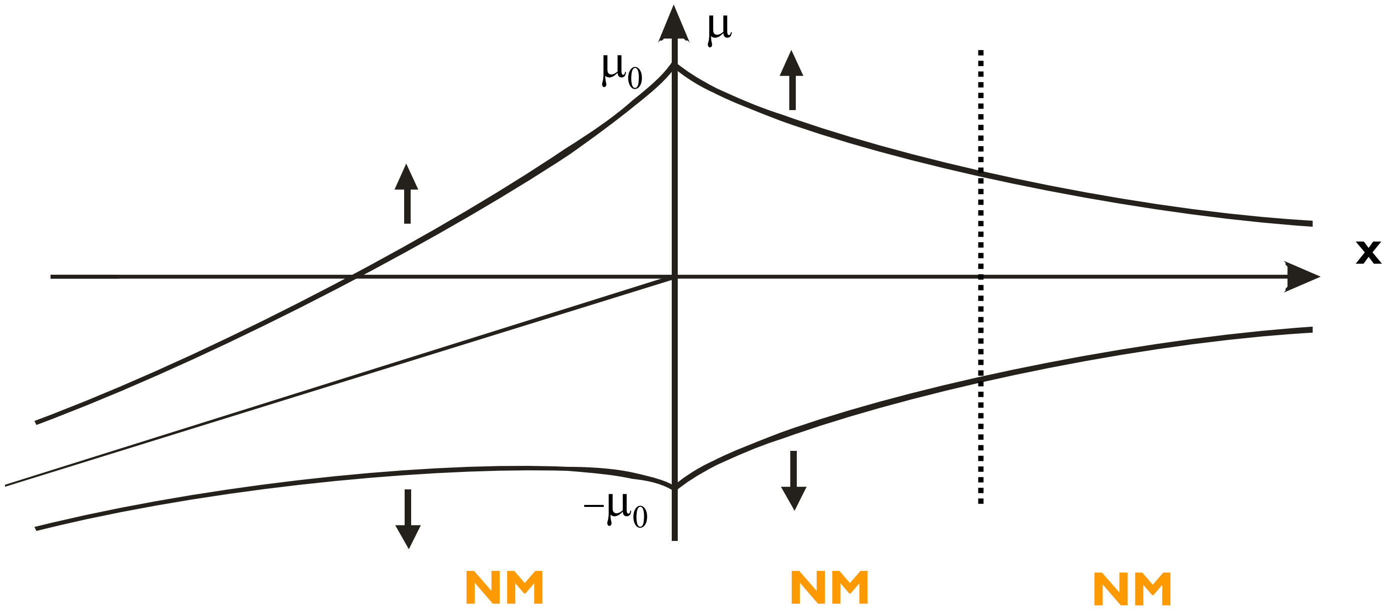




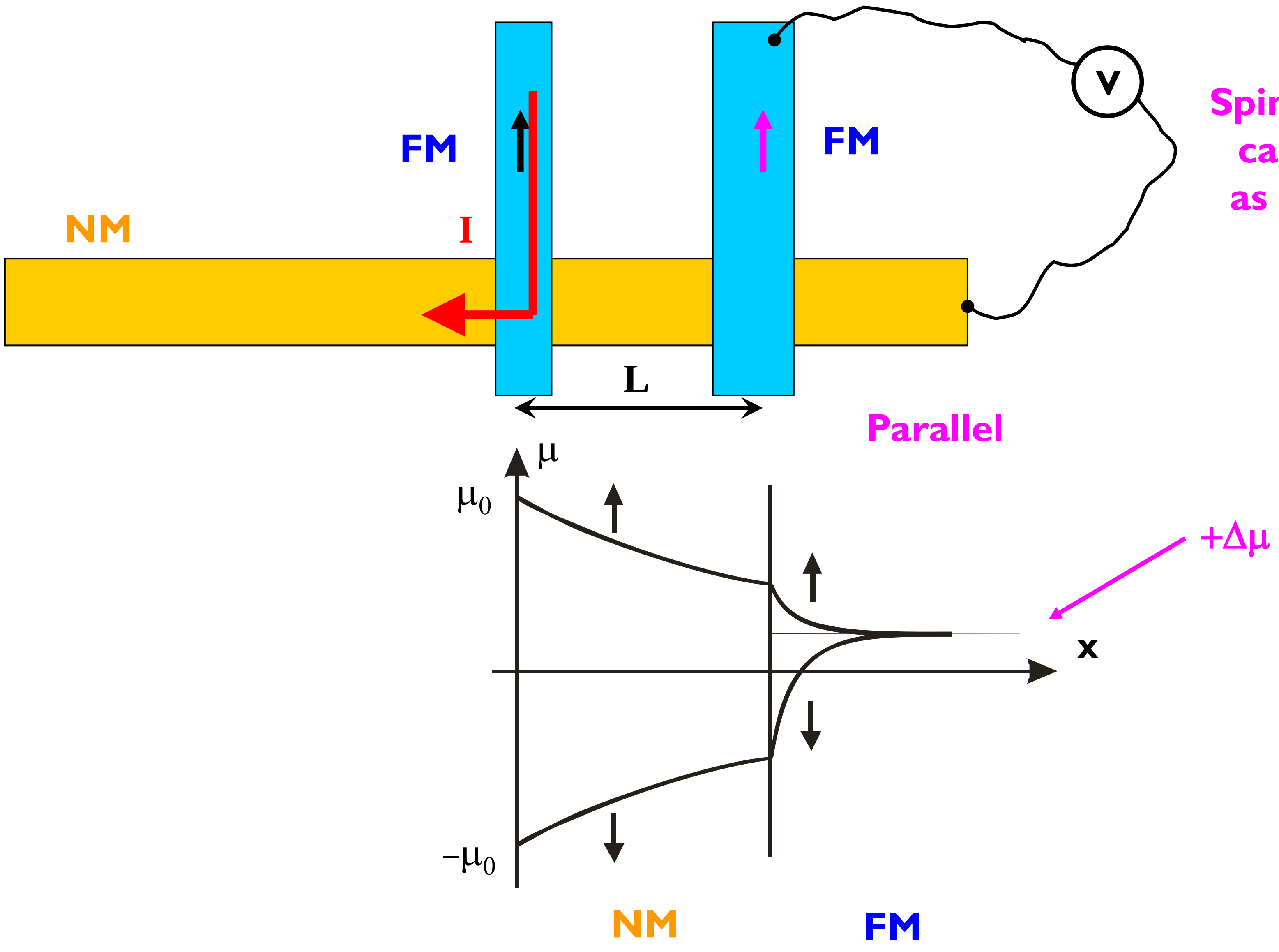
- Identical to GMR
- Drawback: spurious effects such as AMR, Hall effect, …

LATERAL SPIN VALVES: NON-LOCAL





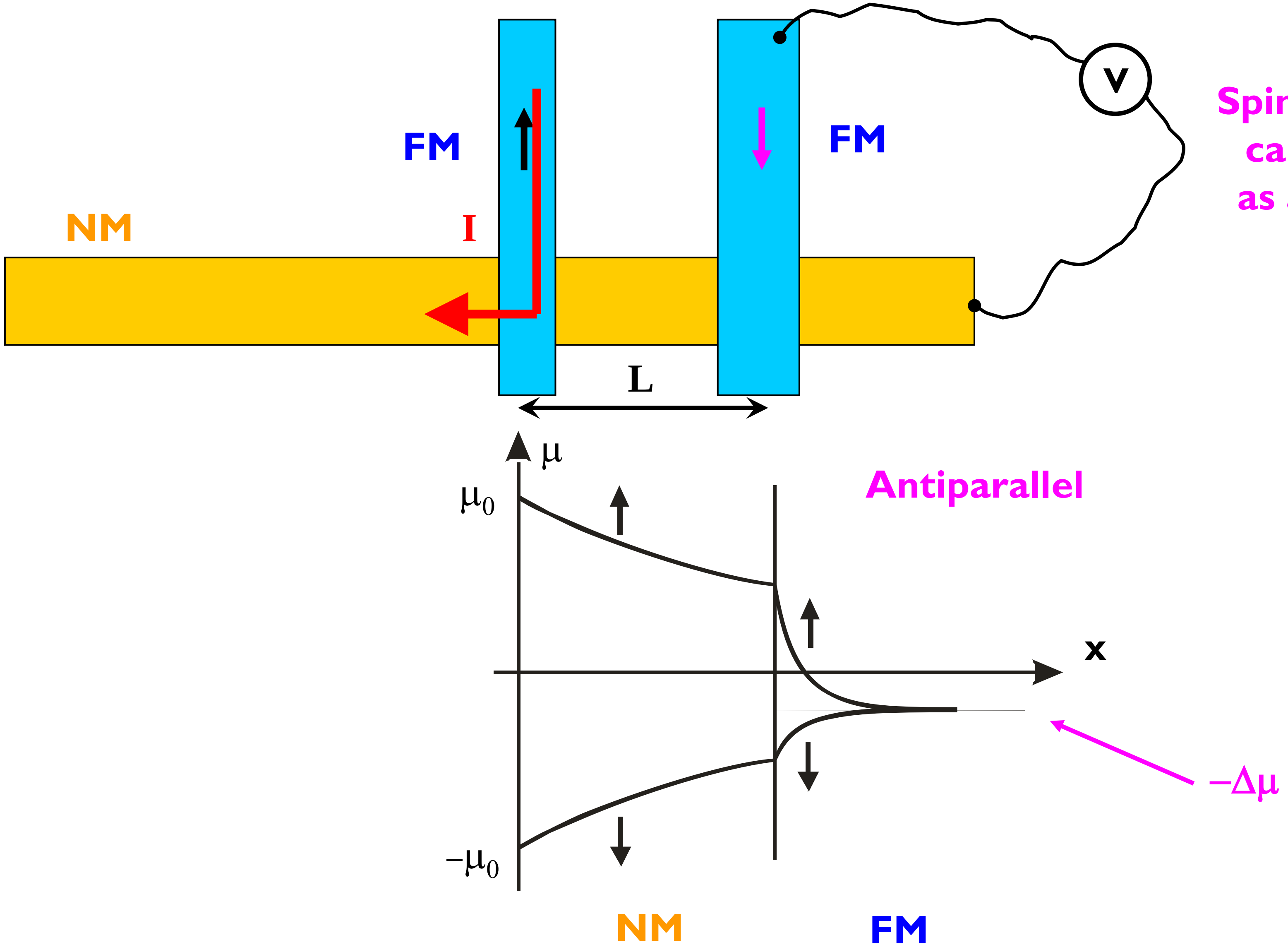
LATERAL SPIN VALVES: NON-LOCAL



Spin accumulation can be measured as a voltage drop

$V_P = +\Delta\mu/e$

LATERAL SPIN VALVES: NON-LOCAL

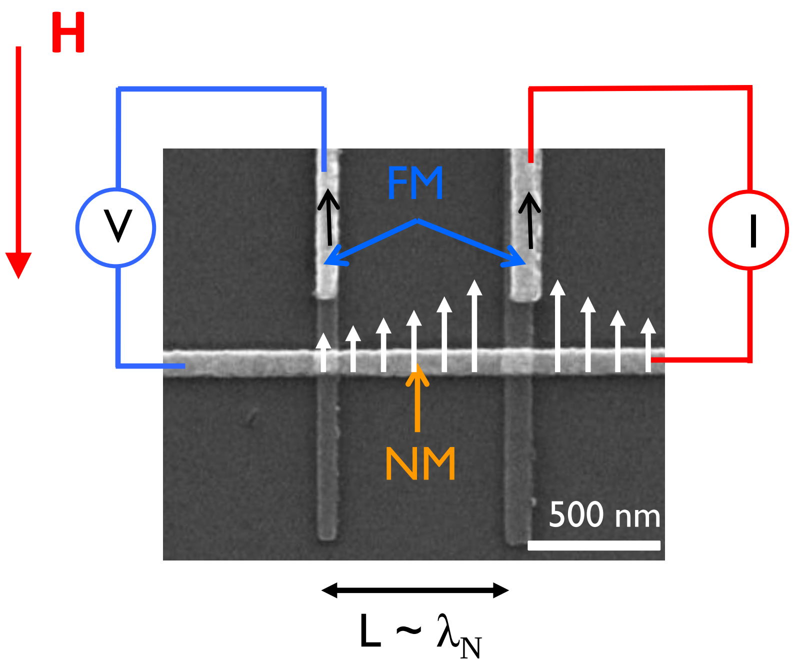


Spin accumulation can be measured as a voltage drop

$V_{AP} = -\Delta\mu/e$

LATERAL SPIN VALVES: NON-LOCAL

Aim: Inject, transport and detect pure **spin currents**



LSV consist of:

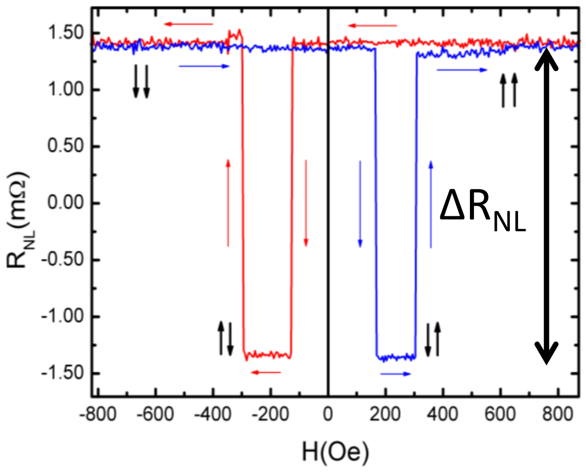
- Two ferromagnetic (FM) electrodes
- Non-magnetic (NM) channel

Non-local measurement:

- Spin polarized current is injected from a FM electrode into a NM
- Spin accumulation is detected in NM by the voltage in the second FM

$$R_{NL} = \frac{V}{I}$$

$$\Delta R_{NL} = \frac{V_P - V_{AP}}{I}$$



Spin signal

F. J. Jedema et al., Nature **410**, 345 (2001)
S. O. Valenzuela et al., APL **85**, 5914 (2004)
T. Kimura et al., PRB **72**, 014461 (2005)
Y. Ji et al., J. Phys. D: Appl. Phys. **40**, 1280 (2007)
F. Casanova et al., PRB **79**, 184415 (2009)
P. Laczkowski et al., APEX **4**, 063007 (2011)

LATERAL SPIN VALVES: NON-LOCAL

Spin signal equations

- General case:

$$\Delta R_{NL} = 4R_N \frac{\left(\alpha_F \frac{R_F}{R_N} + \alpha_J \frac{R_{i,S}}{R_N}\right)^2 e^{-L/\lambda_N}}{\left(1 + 2\frac{R_F}{R_N} + 2\frac{R_{i,S}}{R_N}\right)^2 - e^{-2L/\lambda_N}}$$

- Tunnel junction:

$$\Delta R_{NL} = \alpha_J^2 R_N e^{-L/\lambda_N}$$

$(R_{i,S} \gg R_N, R_F)$

- Transparent interface:

$(R_N, R_F \gg R_{i,S})$

$$\Delta R_{NL} = 4R_N \frac{\left(\alpha_F \frac{R_F}{R_N}\right)^2 e^{-L/\lambda_N}}{\left(1 + 2\frac{R_F}{R_N}\right)^2 - e^{-2L/\lambda_N}}$$

Spin resistance:

$$R_N = \frac{\rho_N \lambda_N}{A_N}$$

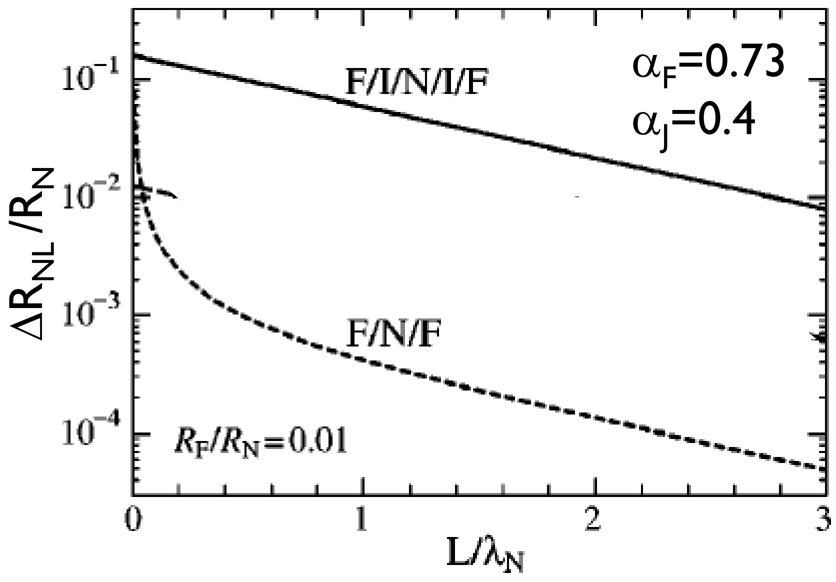
$$R_F = \frac{\rho_F \lambda_F}{(1-\alpha_F^2)A_J}$$

$$R_{i,S} = \frac{R_i}{(1-\alpha_J^2)A_J}$$

Spin polarization:

$$\alpha_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

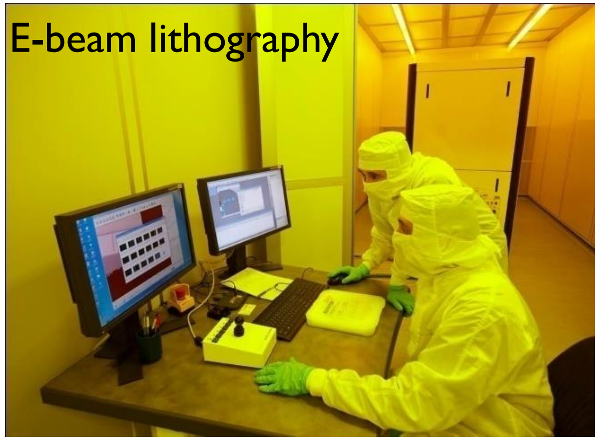
$$\alpha_J = \frac{G_\uparrow - G_\downarrow}{G_\uparrow + G_\downarrow}$$

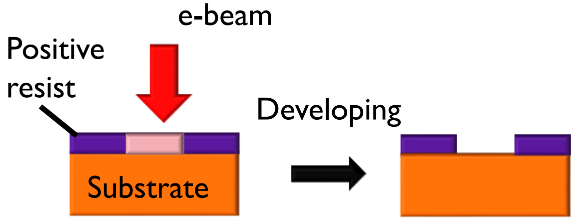


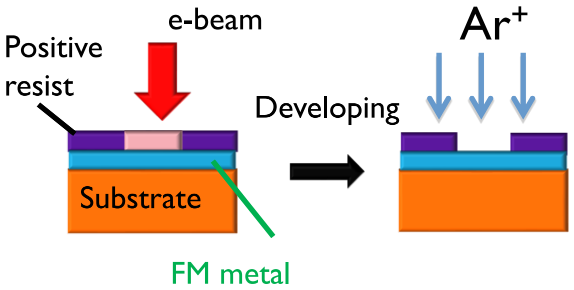
Takahashi and Maekawa, PRB **67**, 052409 (2003)

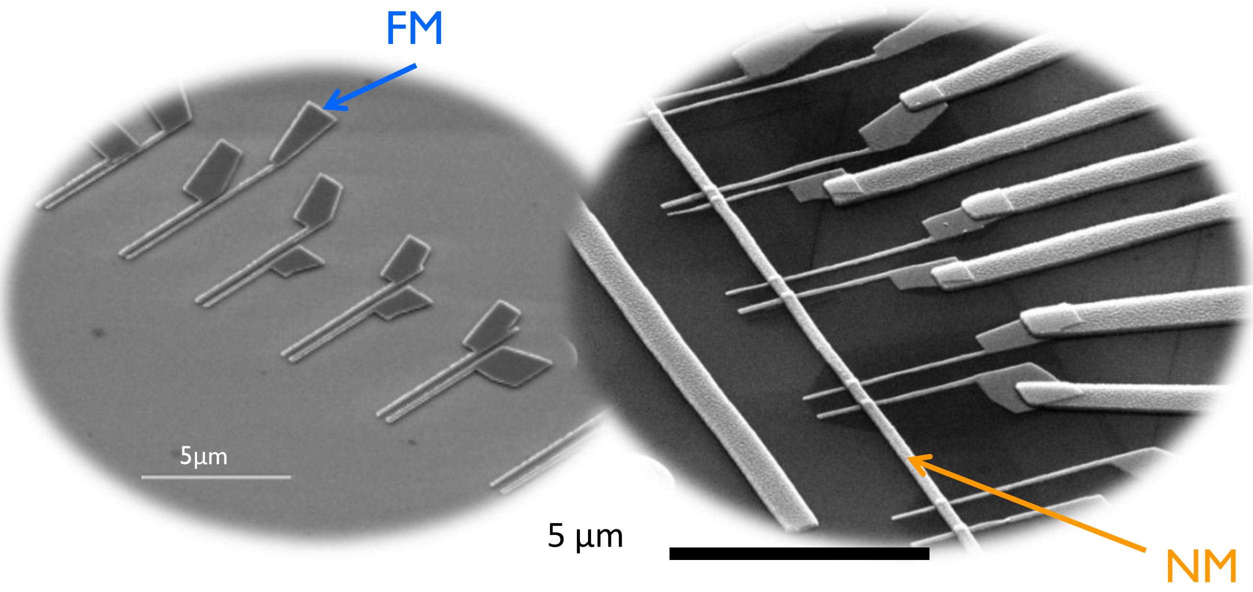
DEVICE FABRICATION

Two-step lithography and deposition process

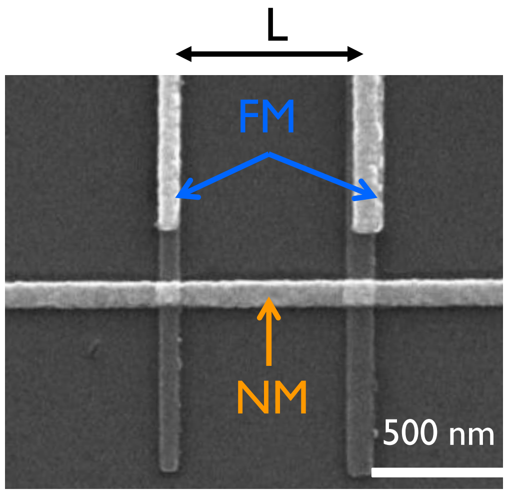


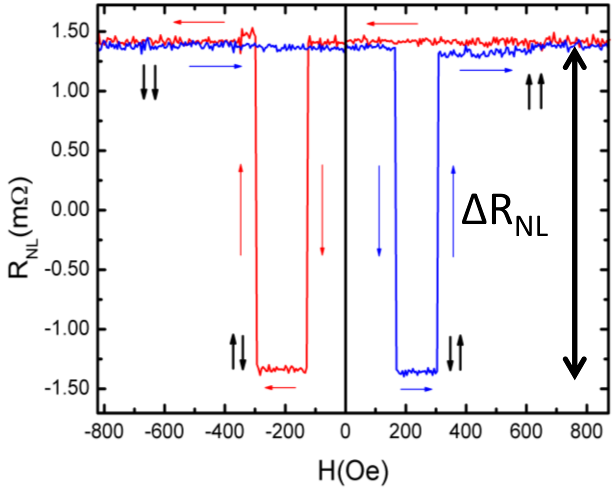


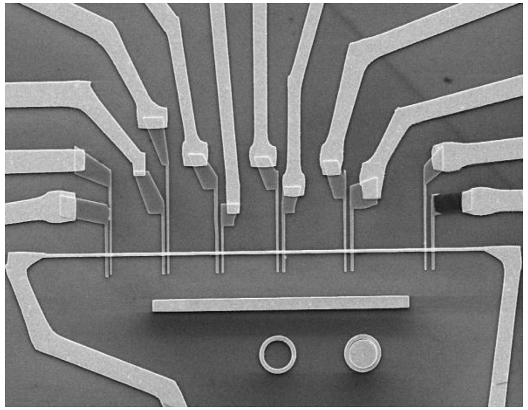




MEASUREMENTS



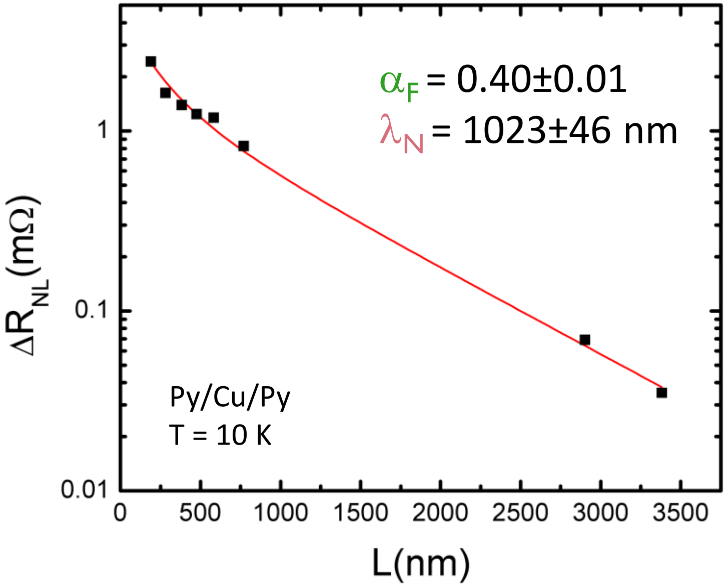




$$\Delta R_{NL} = 4R_N \frac{\left(\alpha_F \frac{R_F}{R_N}\right)^2 e^{-L/\lambda_N}}{\left(1 + 2\frac{R_F}{R_N}\right)^2 - e^{-2L/\lambda_N}}$$

λ_N : Distance at which the spin current decays in the NM

α_F : Efficiency of the FM to inject a spin current.



E. Villamor *et al.*, Phys. Rev. B **87**, 094417 (2013)
E. Villamor *et al.*, Phys. Rev. B **88**, 184411 (2013)

SPIN POLARIZATION

- Tunnel barrier case: $$\alpha_J = \frac{G_\uparrow - G_\downarrow}{G_\uparrow + G_\downarrow}$$
  - Usual tunnel barriers: Al_2O_3 and MgO

T (K)	Material	α_J	Reference
4.2	Co/Al_2O_3	0.11	Jedema, Nature **416**, 713 (2002)
4.2	$CoFe/Al_2O_3$	0.25	Valenzuela, APL **85**, 5914 (2004)
4.2	Co/Al_2O_3	0.055	Garzon, PRL **94**, 176601 (2005)
2	Py/Al_2O_3	0.037	Vogel, APL **94**, 122510 (2009)
4.2	Co/Al_2O_3	0.014	Wang, PRB **81**, 104409 (2010)
10/300	Py/MgO	0.11/0.11	Fukuma, APL **97**, 012507 (2010)
10/300	Py/MgO	0.44/0.42	Fukuma, Nat. Mater. **10**, 527 (2011)

Large dispersion in the literature:
interface quality (α_F , α_J)

- Transparent case: $$\alpha_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$
  - Usual FM metals: Py and Co
  - Py (~0.2-0.4) better than Co (~0.1)
  - CoFe seems to be a better injector (~0.5-0.6)

T (K)	FM	α_F	Reference
10	Co	0.074	Ji, APL **88**, 052509 (2006)
4.2	Co	0.08	Casanova, PRB **79**, 184415 (2009)
4.2	Co	0.02	Jedema, PRB **67**, 085319 (2003)
4.2	Co	0.1	Wang, JAP **105**, 093907 (2009)
10/300	Co	0.12/0.12	Villamor, PRB **87**, 184411 (2013)
4.2	Py	0.35	Erekhinsky, APL **96**, 022513 (2010)
4.2	Py	0.29	Casanova, PRB **79**, 184415 (2009)
4.5	Py	0.21	Zou, APL **101**, 082401 (2012)
4.2	Py	0.24	Jedema, PRB **67**, 085319 (2003)
80	Py	0.35	Kimura, NPG Asia Mater. **4**, e9 (2012)
4.2	Py	0.33	Erekhinsky, APL **100**, 212401 (2012)
77	Py	0.25	Kimura, PRB **73**, 132405 (2006)
10/300	Py	0.4/0.34	Villamor, PRB **87**, 094417 (2013)
300	Py	0.17-0.26	Zhand, Nanotech. **27**, 035201 (2016)
300	CoFe	0.5-0.58	Zhand, Nanotech. **27**, 035201 (2016)

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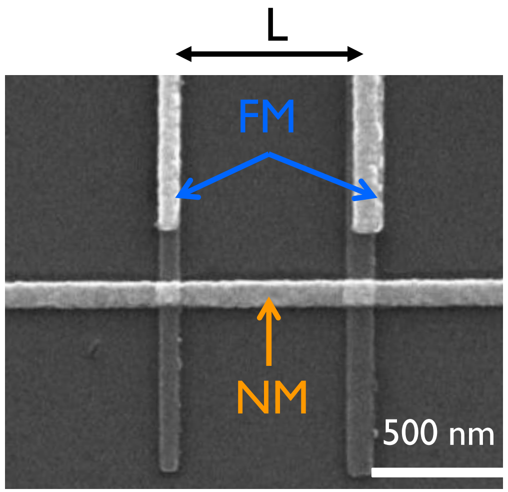
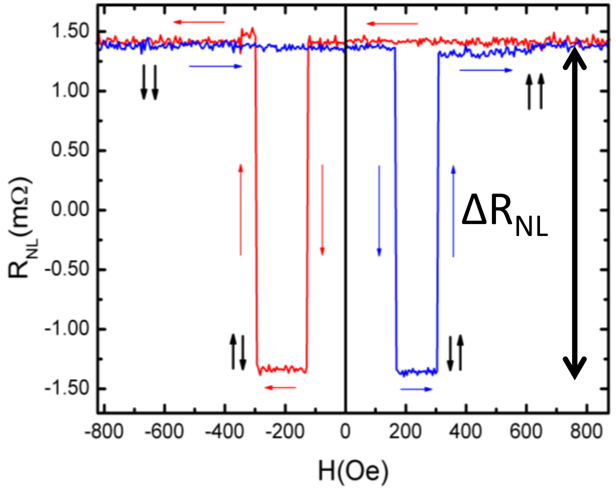
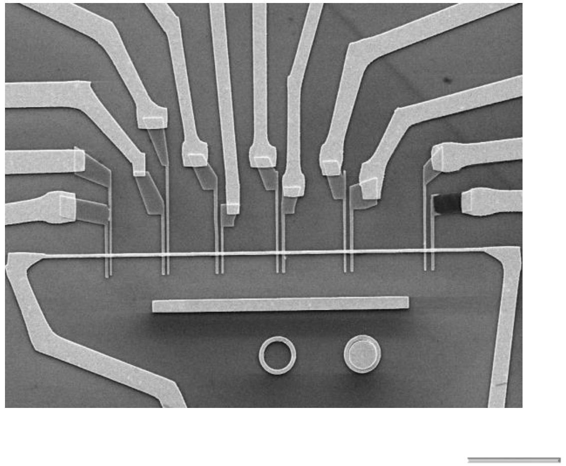
MEASUREMENTS







$$\Delta R_{NL} = 4R_N \frac{\left(\alpha_F \frac{R_F}{R_N}\right)^2 e^{-L/\lambda_N}}{\left(1 + 2\frac{R_F}{R_N}\right)^2 - e^{-2L/\lambda_N}}$$

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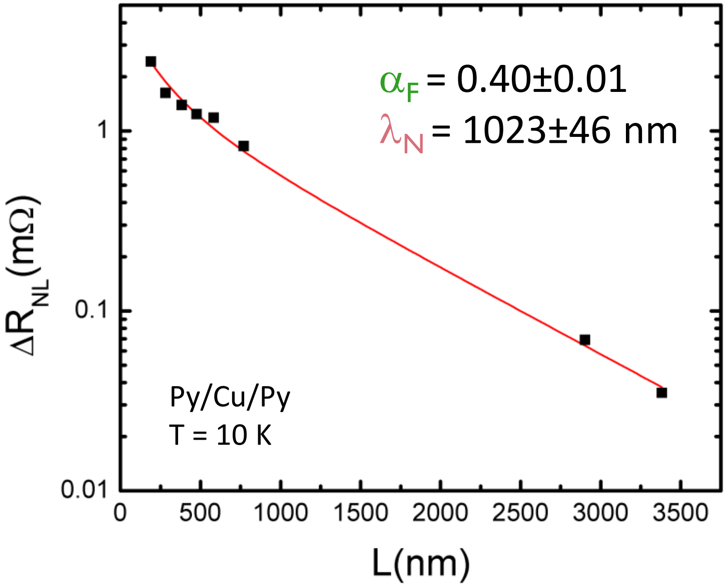
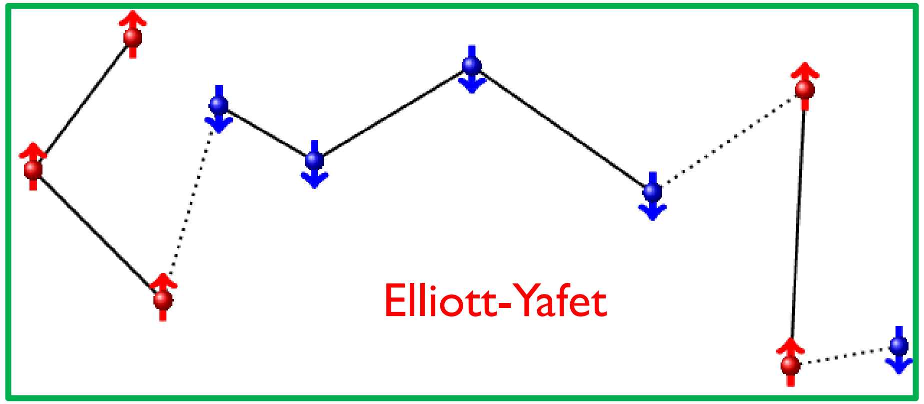


E. Villamor *et al.*, Phys. Rev. B **87**, 094417 (2013)
E. Villamor *et al.*, Phys. Rev. B **88**, 184411 (2013)

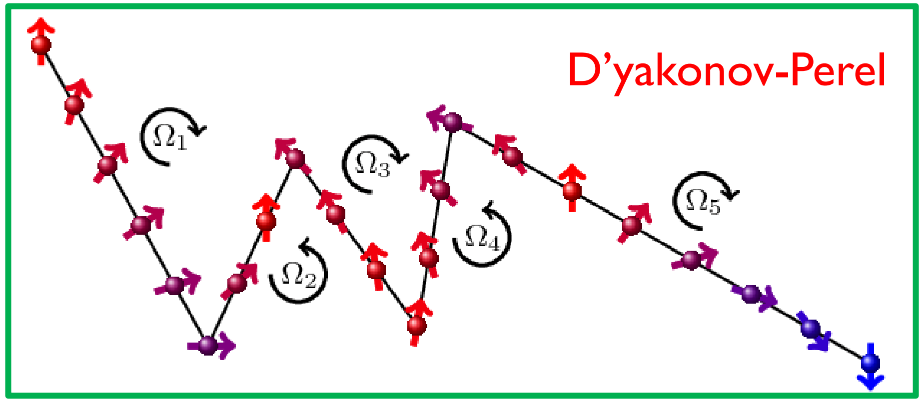
SPIN RELAXATION MECHANISMS

Spin relaxation mechanisms for conduction electrons



- Momentum scattering at impurities, boundaries, phonons has some spin-flip probability *a*
- Due to spin-orbit coupling

$$\boxed{\tau_e = a\tau_{sf}}$$



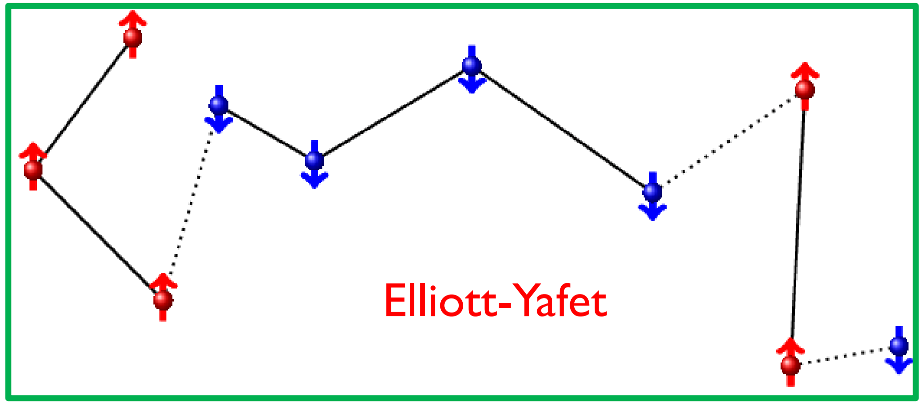
- In non-centrosymmetric crystals spin-bands are no longer degenerate: in the same momentum state, spin up and down have different energy
- Equivalent to having an internal magnetic field along which the spin precesses (spin polarization changes)
- Momentum scattering resets the precession (acts against relaxation)

$$\boxed{\tau_e = c\tau_{sf}^{-1}}$$

Fabian and Das Sarma, J. Vac. Sci. Technol. B **17**, 1708 (1999)

SPIN RELAXATION MECHANISMS

Spin relaxation mechanisms for conduction electrons

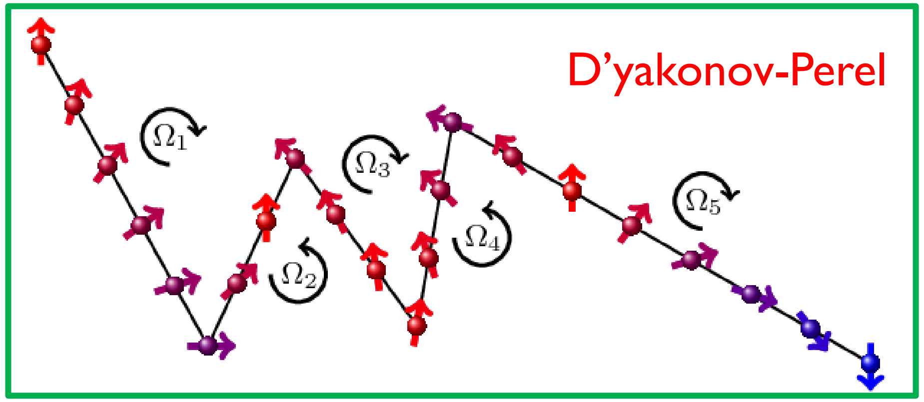


METALS

SEMICONDUCTORS
(with inversion symmetry)

GRAPHENE

$\boxed{\tau_e = a\tau_{sf}}$ $\lambda_N = \sqrt{D\tau_{sf}} \propto \frac{1}{\rho}$



SEMICONDUCTORS
(without inversion symmetry)

GRAPHENE

$\boxed{\tau_e = c\tau_{sf}^{-1}}$ $\lambda_N = cnt.$

Momentum scattering time

$$\tau_e = \frac{3}{v_F^2 N(E_F)e^2\rho}$$

Diffusion constant

$$D = \frac{1}{N(E_F)e^2\rho}$$

Spin-flip scattering time

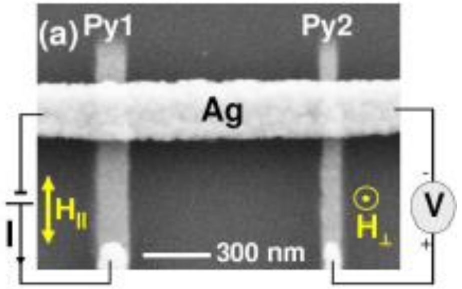
$$\tau_{sf} = \frac{\lambda_N^2}{D}$$

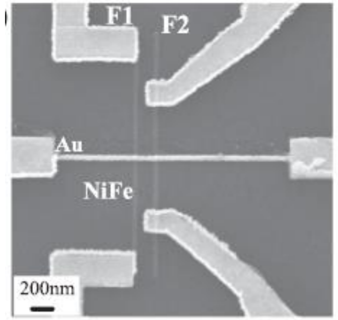
Fabian and Das Sarma, J. Vac. Sci. Technol. B **17**, 1708 (1999)

SPIN TRANSPORT

Spin diffusion into NM materials

METALS

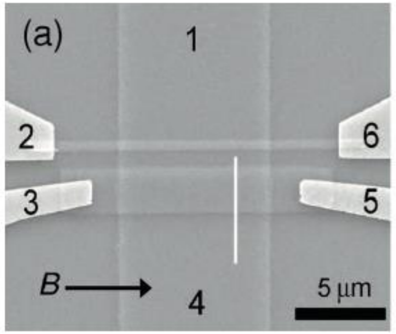


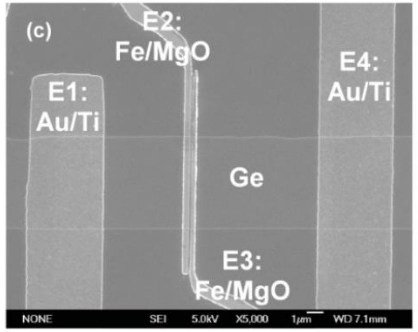


Cu: λ_N =1.3 μm
Al: λ_N =1.2 μm
Ag: λ_N =1.5 μm
Au: λ_N =0.1 μm

Elliott-Yafet

SEMICONDUCTORS

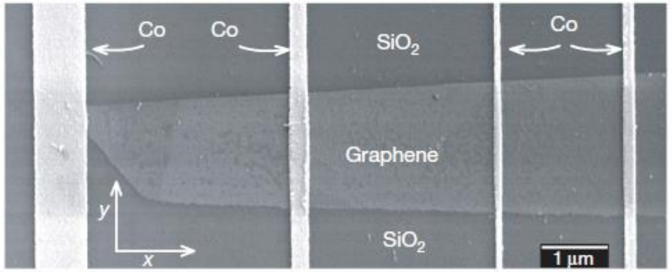


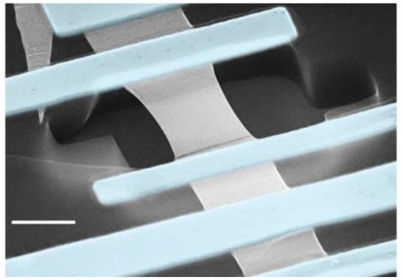


GaAs: λ_N =6.0 μm
Si: λ_N =38 μm
InAs: λ_N =1.8 μm
Ge: λ_N =0.6 μm

Elliott-Yafet
OR
D'yakonov-Perel

GRAPHENE





Exfoliated: λ_N =2.4 μm
SiC: λ_N = 1.0 μm
Suspended: λ_N =1.9 μm
On h-BN: λ_N =24 μm

Elliott-Yafet
AND
D'yakonov-Perel

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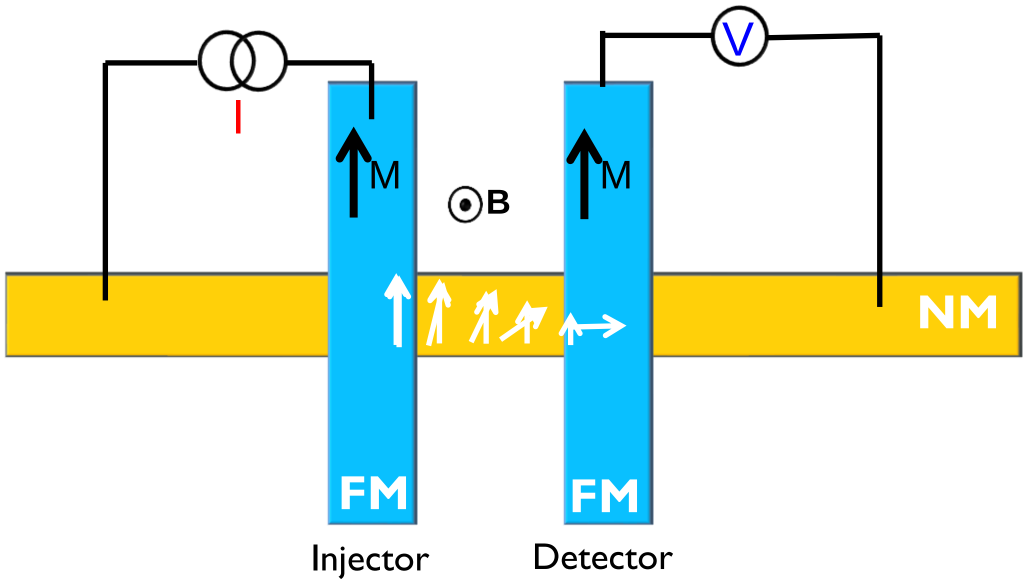
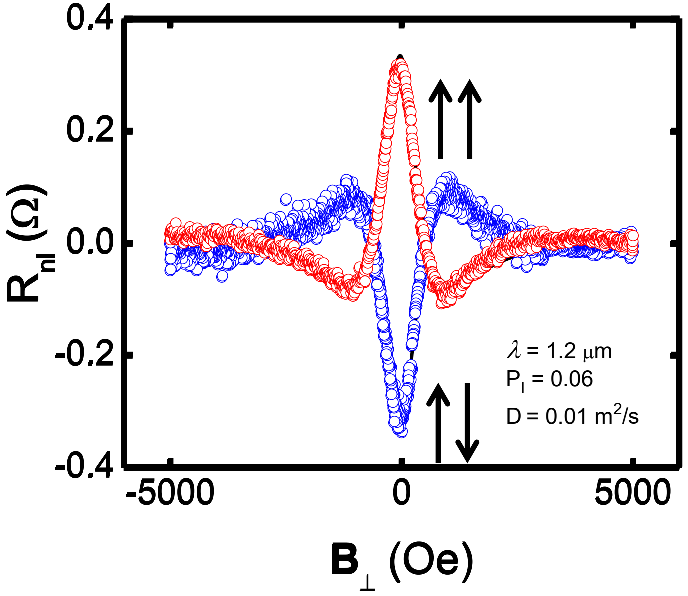
SPIN MANIPULATION: MAGNETIC FIELD

Magnetic field control: Hanle precession



W.Yan et al, Nature Comms. **7**, 13372 (2016)



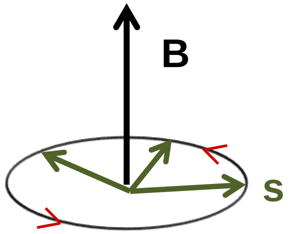
Spin precession
by applying **B** out of plane

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

diffusion precession relaxation

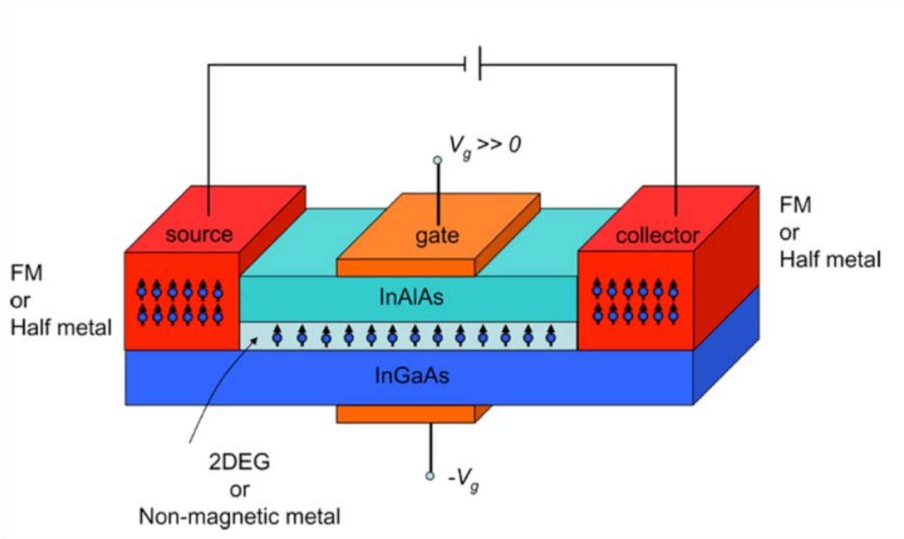
Larmor frequency:

$$\boxed{\omega_L = -\frac{g\mu_B}{\hbar} B}$$



SPIN MANIPULATION: ELECTRIC FIELD

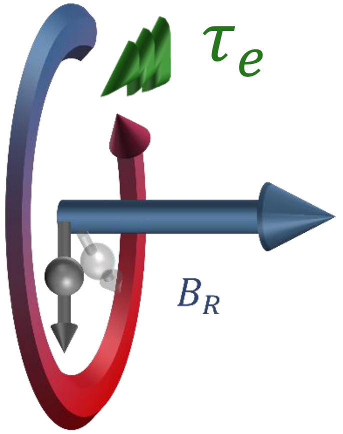
Electric field control: spin transistor



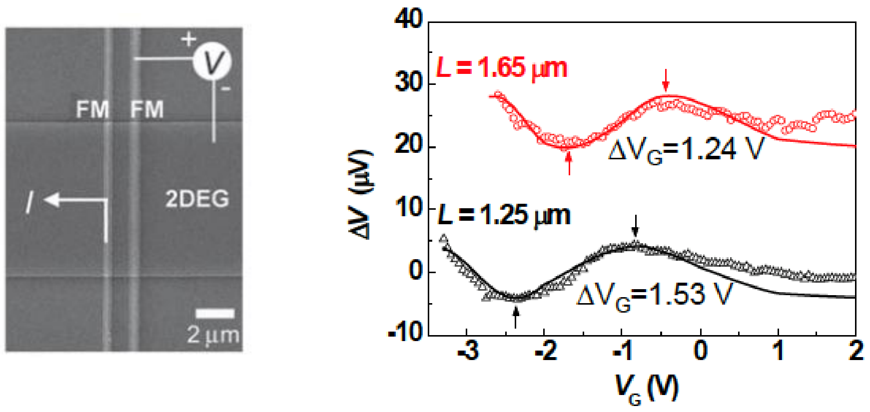
Rashba effect

- Broken inversion symmetry induced by external $\vec{E}$ in a 2DEG
- Spin-orbit coupling acts as an effective magnetic field (B_R)
- Spins will precess around B_R

$$\boxed{\overrightarrow{B_R} = -\frac{\hbar}{mc^2}(\vec{k} \times \vec{E})}$$



Only in ballistic systems at low T



Datta and Das, Appl. Phys. Lett. **56**, 665 (1990)

H. C. Koo et al. Science **325**, 1515 (2009)

P. Chuang et al. Nature Nano. **10**, 35 (2014)

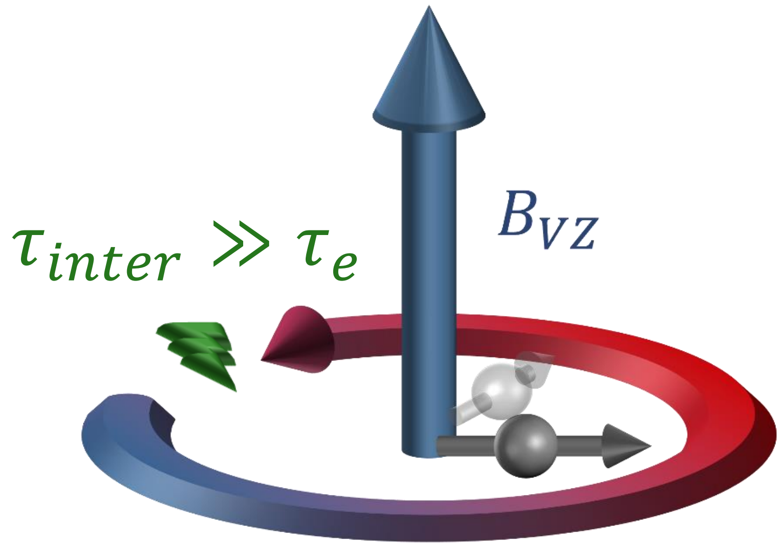
SPIN MANIPULATION: ELECTRIC FIELD

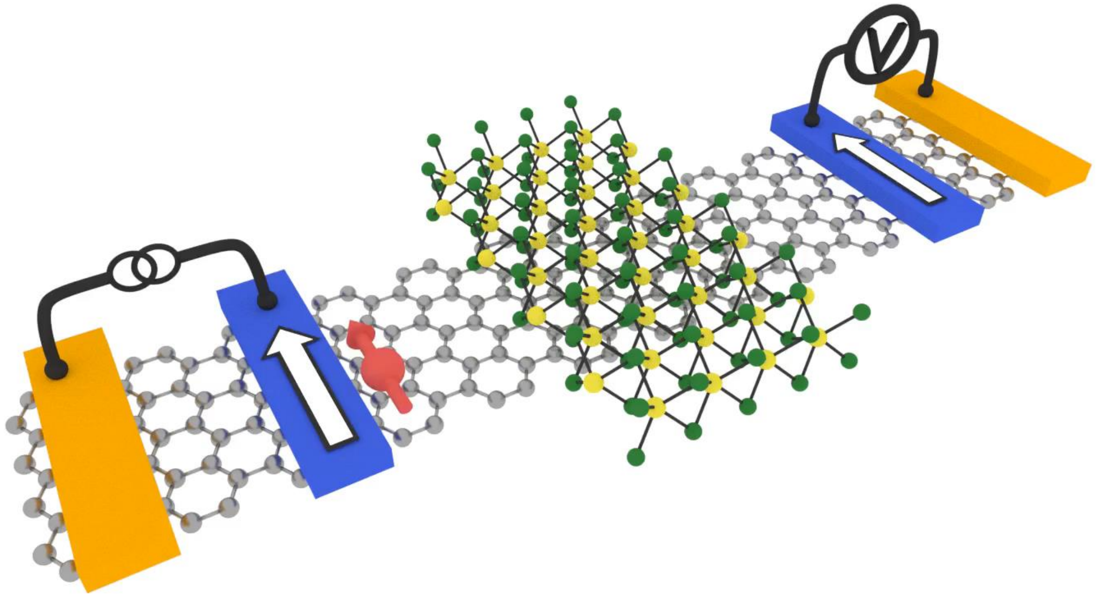
Electric field control: spin transistor

Valley-Zeeman effect

Origin: broken sublattice symmetry in TMD

B_{VZ} has opposite sign for K and K′ valley



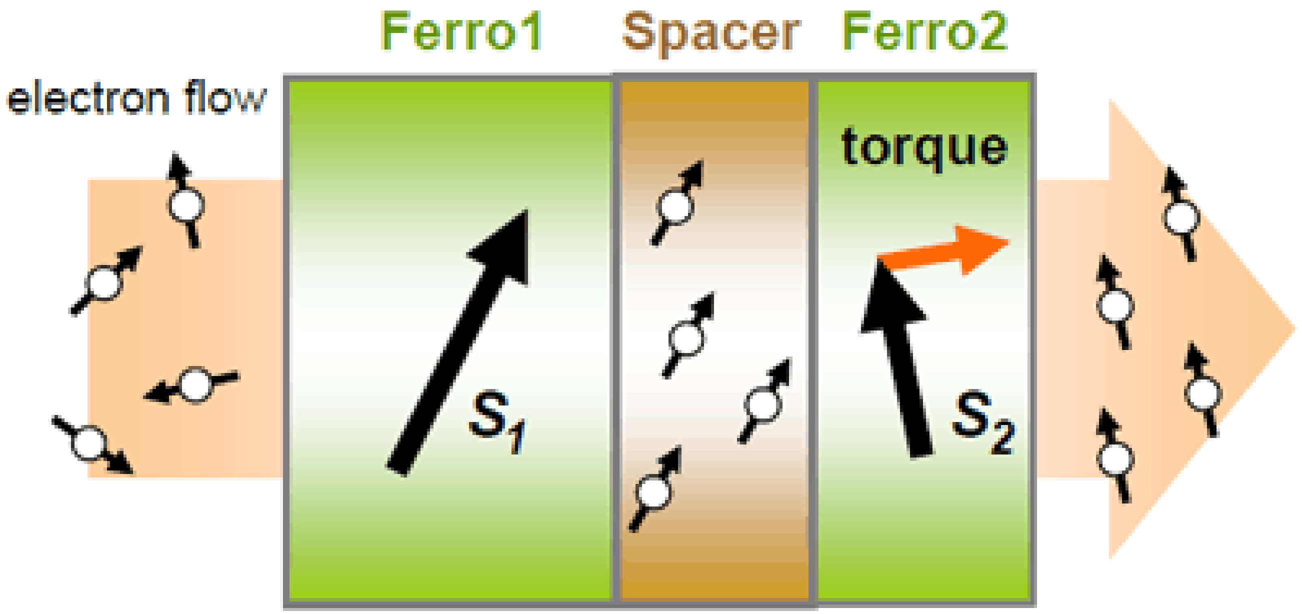


Observed in graphene/WSe_2 at room temperature!

J. Ingla-Aynes *et al.* Phys. Rev. Lett. **127**, 047202 (2021)

SPIN MANIPULATION: SPIN TRANSFER TORQUE

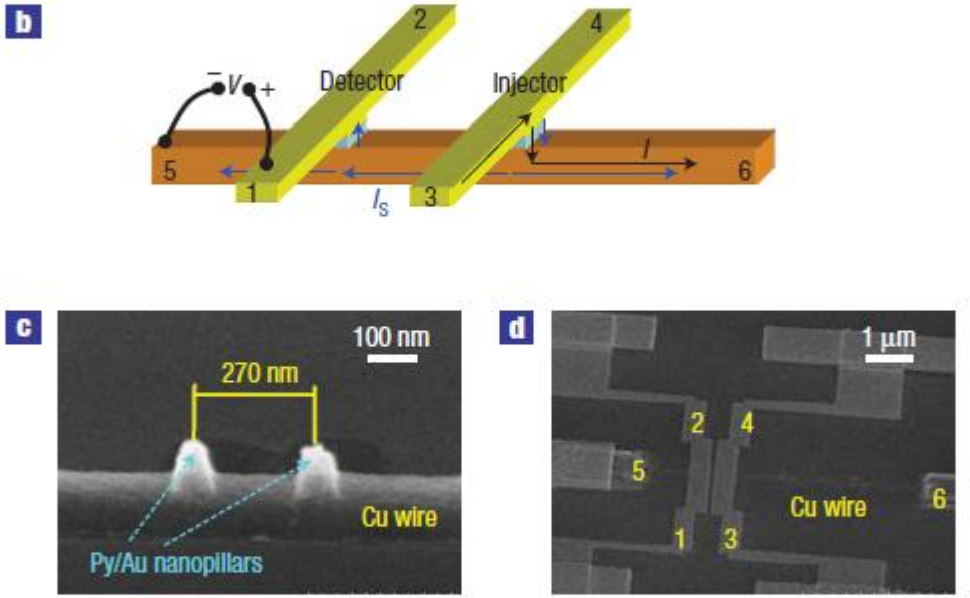
If a FM magnetization defines the orientation of a spin current,
reciprocally the spin current can define the orientation of a FM magnetization

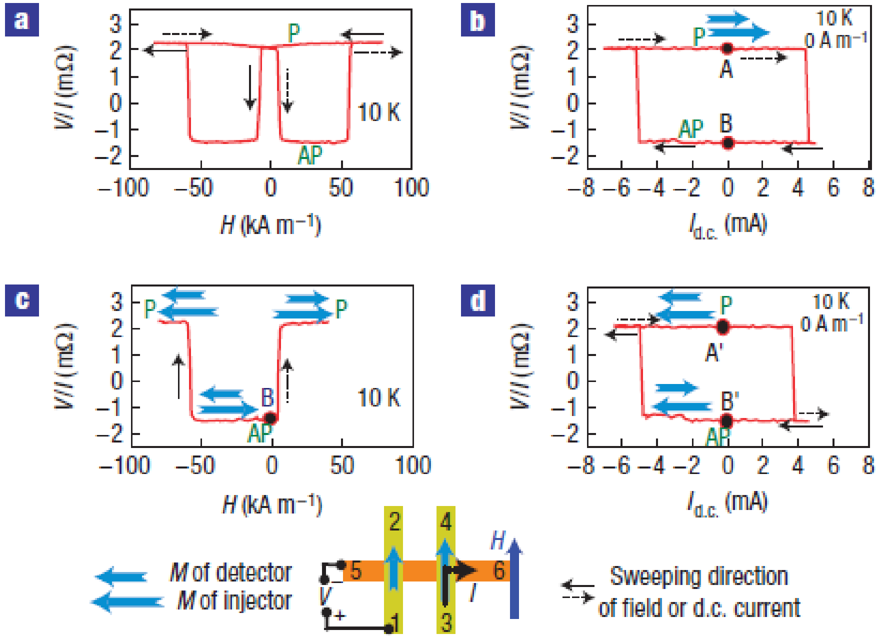


J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1(1996)
L. Berger, Phys.Rev.B 54,9353 (1996)

SPIN MANIPULATION: SPIN TRANSFER TORQUE

Magnetic switching using pure spin currents





Towards integration of magnetic memory and spin current logics in multiterminal devices

T. Yang *et al.*, Nature Physics **4**, 851 (2008)

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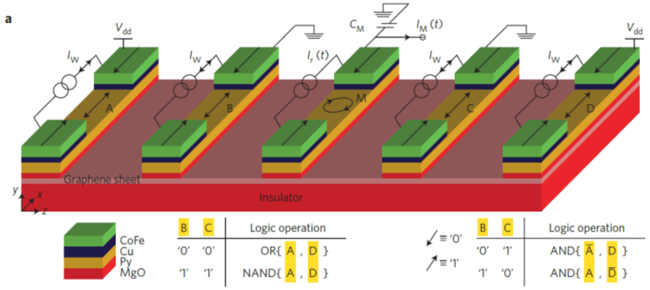
SPIN-BASED LOGIC PROPOSALS

theoretical:

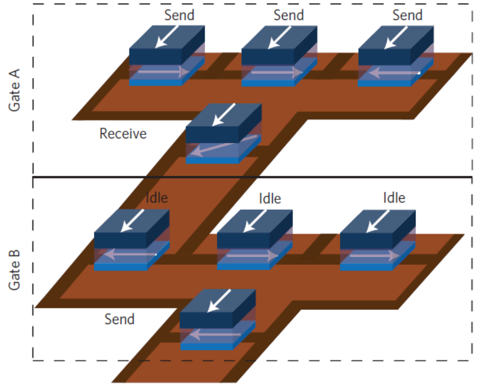
Spin-based magnetologic



H. Dery et al. , Nature **447**, 573 (2007)

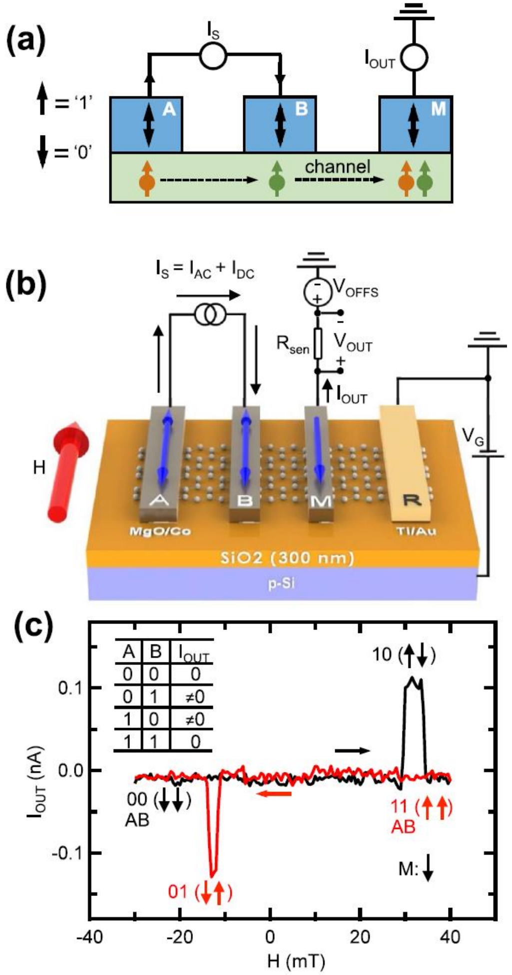
H. Dery et al. , IEEE Trans. Electr. Dev. **59**, 259 (2012)

All-spin logic

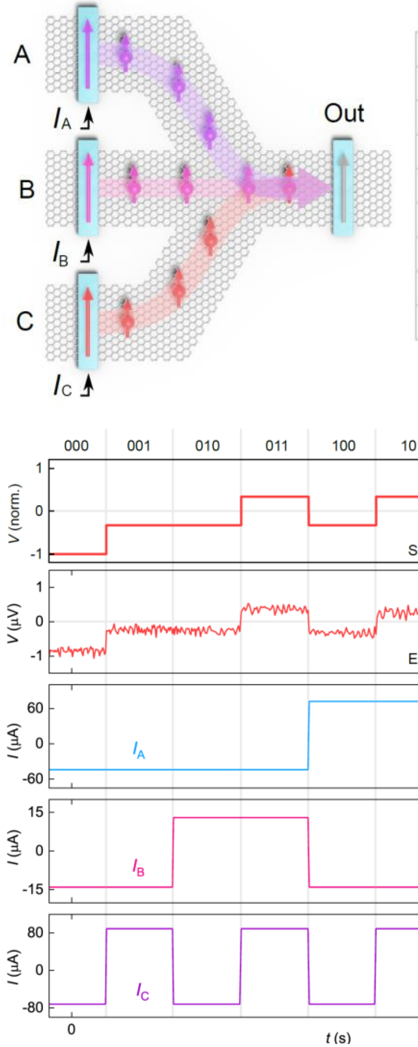


B. Behin-Aein et al., Nat. Nanotechnol. **5**, 266 (2010)

experimental:



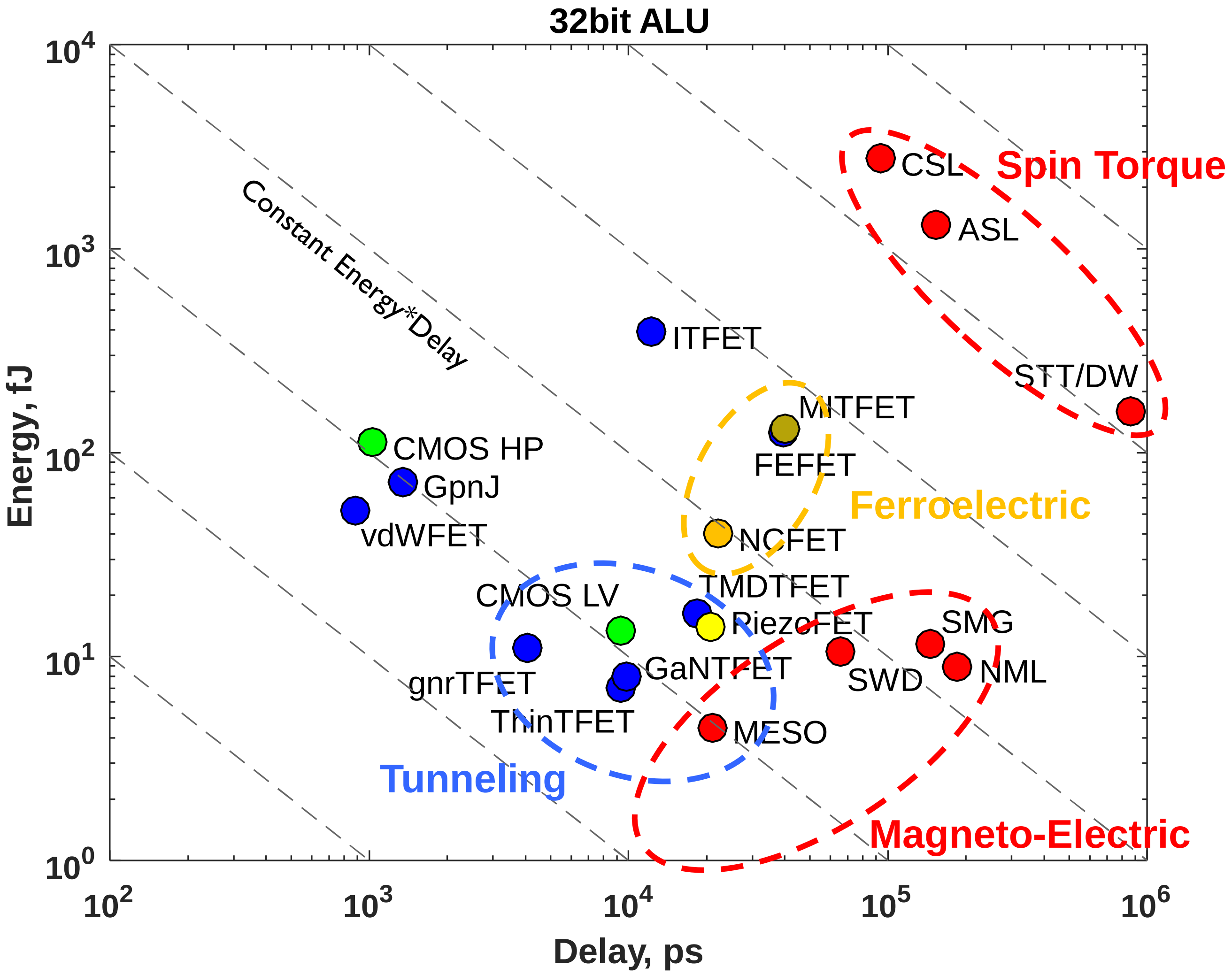
H. Wen et al., Phys. Rev. Appl. **5**, 044003 (2016)



A	B	C	Out
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

D. Khokhriakov et al., Phys. Rev. Applied **18**, 064063 (2022)

SPIN-BASED LOGIC PROPOSALS



- CMOS Ref
- Electronic
- Spintronic
- Ferroelectric
- Orbitronic
- Straintronic

MESO logic: slower, but **lower energy** while enabling:

- ✓ **higher density (per functionality)**
- ✓ **voltage scalability**
- ✓ **non-volatile logic-in-memory**
- ✓ **compatibility with traditional and future architectures**

THURSDAY'S TALK
(BY LUIS E. HUESO)

D. E. Nikonov and I. A. Young, *IEEE J. Explor. Comput. Devices and Circuits* **1**, 3-11 (2015)
S. Manipatruni et al., Nature **565**, 35 (2019)

THE END