Control of Spin-Polarized Currents for Semiconductor Spintronics

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Collaborators

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Essence of Spintronics

Memory: electron spin → magnetization of FM
Processing: electron charge → voltage in CMOS

The Problem: integration of its two functions

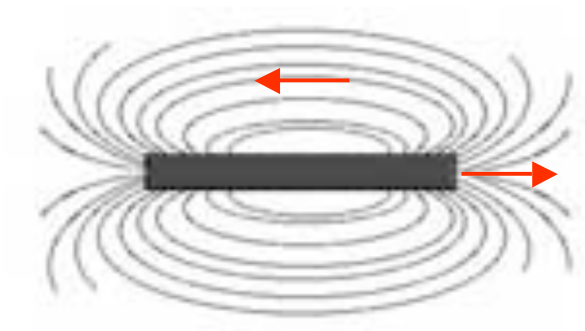
- **Generation of spin polarization in an electron current in a semiconductor from ferromagnet**
- **Control of the spin-polarized current**
- **Spin expression (measurement or passing on to the next device)**

A symptom of an approaching nervous breakdown is the belief that one's work is terribly important. - *Bertrand Russell*

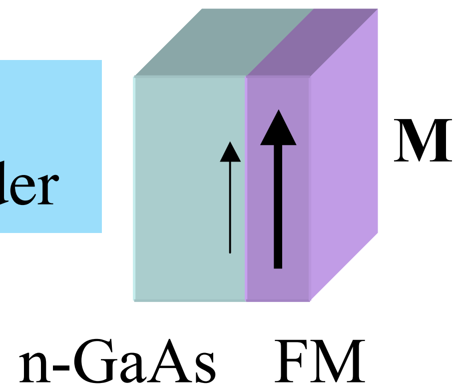
Issues and Solutions

1. Aim: a spintronics device on paper
2. Criteria
   a. Room temperature
   b. Existing capability
   c. Spin expression - electrical rather than optical
3. A spin transistor - transpinstor
   a. Spin injection & extraction
   b. Spin transference
   c. Magneto-resistance amplification
4. Summary

Reflection generated spin polarization vs other effects

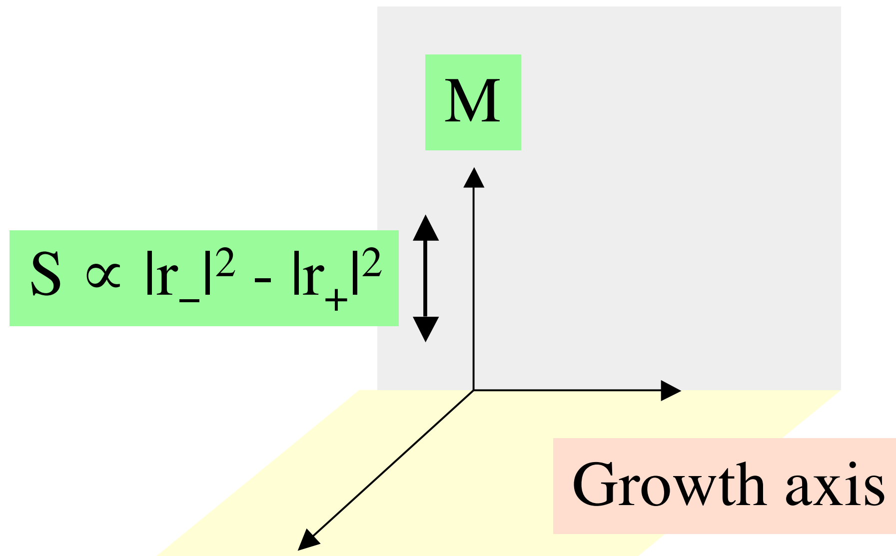


Proximity induced order



Fringe field has a definite orientation with respect to the magnetization **M**

The reflection generated spin polarization can be either PARALLEL or ANTIPARALLEL to the magnetization **M**

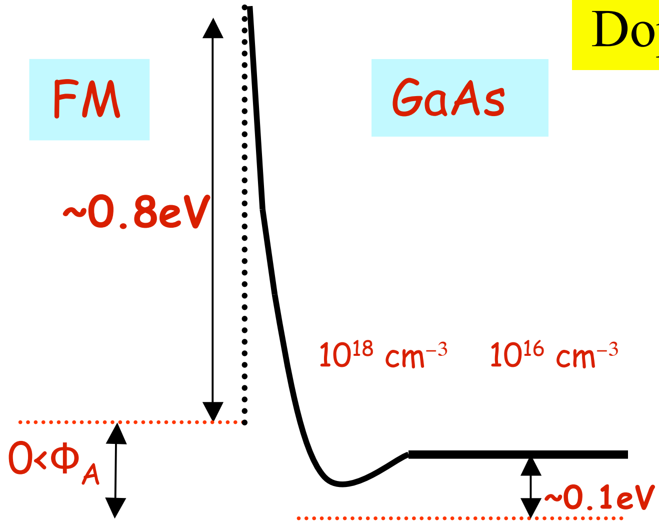


Expts by Stephens et al., by Epstein et al. and by Crowell et al.

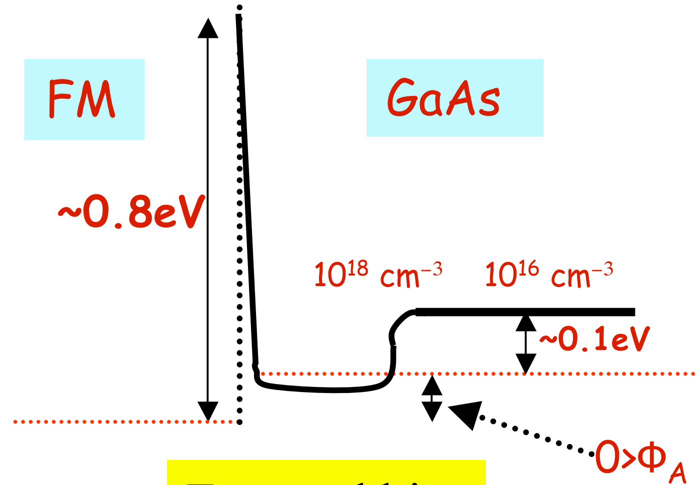
Theory by Ciuti, McGuire & Sham

Calculation of polarized tunnel currents

Doping profile



E_F

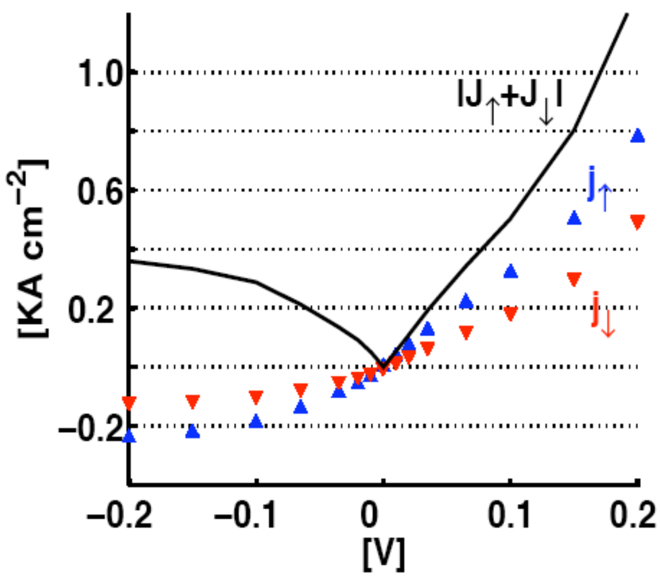


Reverse bias

Forward bias

Spin current vs voltage bias

Conductance ~ 10^2 - 10^3 /Ω cm^2

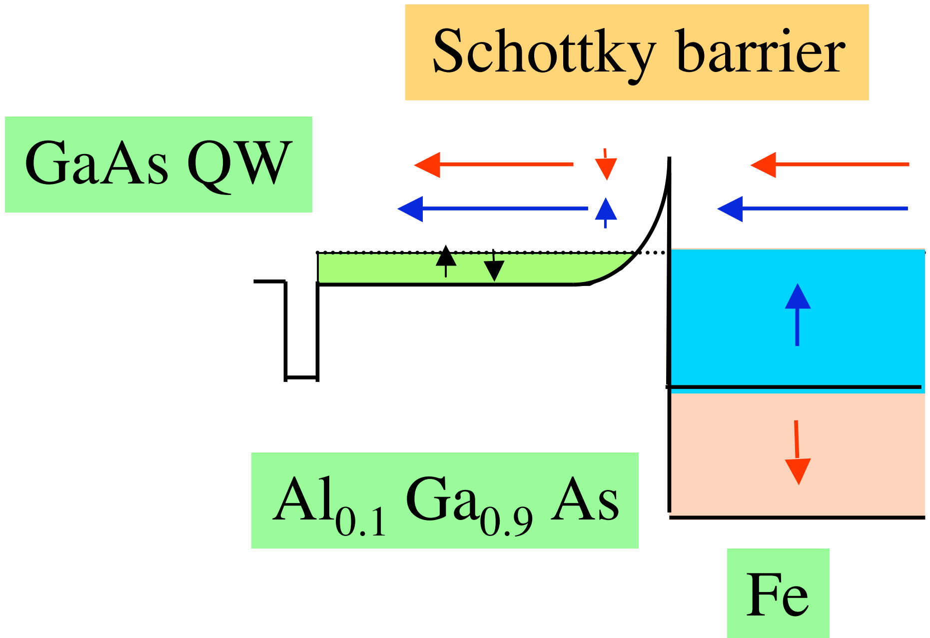


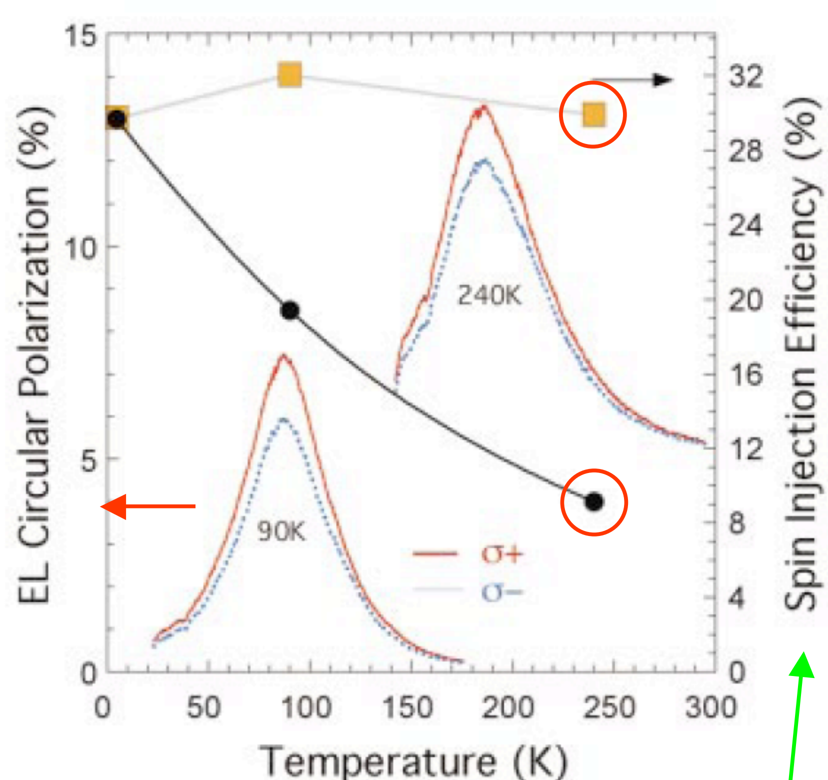
Current polarization

$$\alpha = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}$$

25% -- 30%

Spin injection in the reverse direction





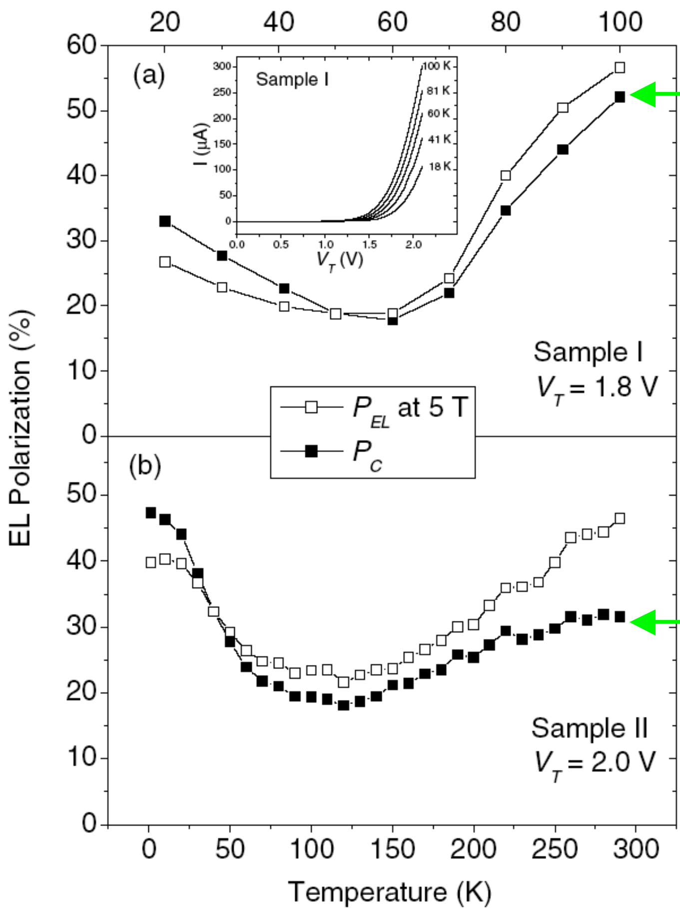
$$\alpha = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}$$

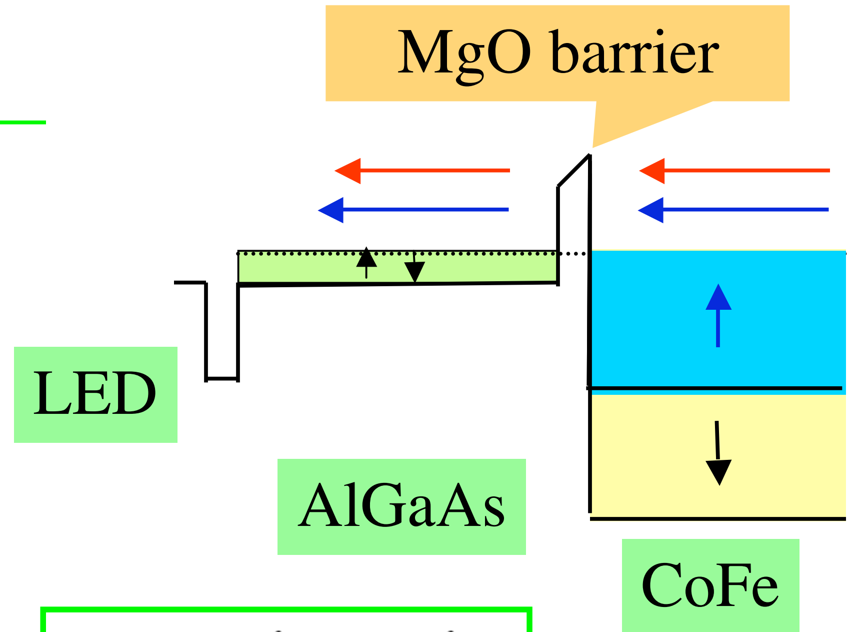
A. T. Hanbicki and B. T. Jonker

G. Itskos, G. Kioseoglou, and A. Petrou

APL (2002)

Spin injection in the reverse direction





$$\alpha = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}$$

X. Jiang, R. Wang, R. M. Shelby, R. M. Macfarlane, S. R. Bank, J. S. Harris, and S. S. P. Parkin, PRL (2005)

Spin transport in semiconductor

Two weakly coupled spin populations (spin-flip but no coherence)

Spin accumulation => diffusion current; E field => drift

Spin-dependent scattering theory provides spin accumulation and barrier resistances to constitutive and continuity equations for the spin components of density and current

Literature on spin transport through metal/semiconductor structures

- **P.C. van Son et al. PRL 1987**
- **T. Valet and A . Fert, PRB 1993**
- **S. Hershfield and H.L. Zhao, PRB 1997**
- **E. I. Rashba, PRB 2000**
- **J. D. Albrecht and D. L. Smith, PRB 2002**
- **Z.G. Yu and M.E. Flatte, PRB 2002**
- **and many others…**

Spin transport in semiconductor

Two weakly coupled spin populations (spin-flip but no coherence)

Spin accumulation => diffusion current; E field => drift

$$\mathbf{j}_s = \sigma_s \mathbf{E} + \frac{1}{e} D_s \nabla \rho_s \qquad s = \pm$$

Yu-Flatté $\sigma_s \propto n_s$

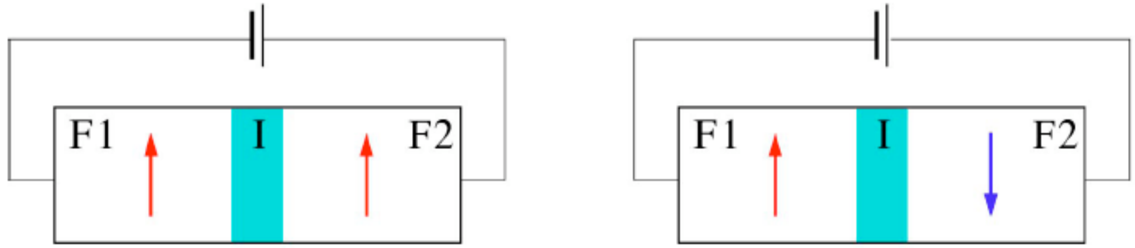
Spin-dependent diffusion coefficient

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot \mathbf{j}_s = \frac{1}{\tau_{sf}} (\rho_s - \rho_{-s})$$

Spin-flip rate

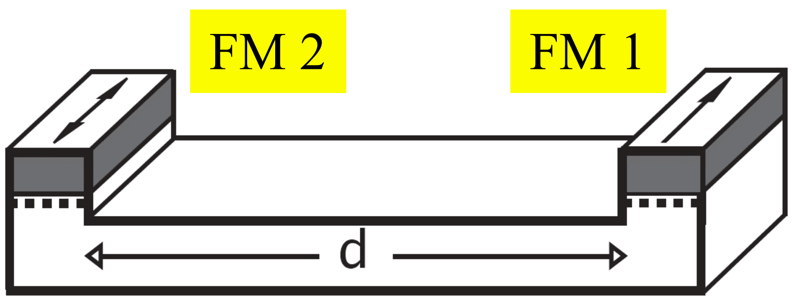
Electrical Expression by Spin Valve

Metal spin valve



$$MR = \frac{J_P - J_{AP}}{J_P} \approx 10\% \ in\ commercial\ devices$$

Semiconductor spin valve



FM/SC tunnel barrier

200 nm

1 µm GaAs

Magneto-resistance

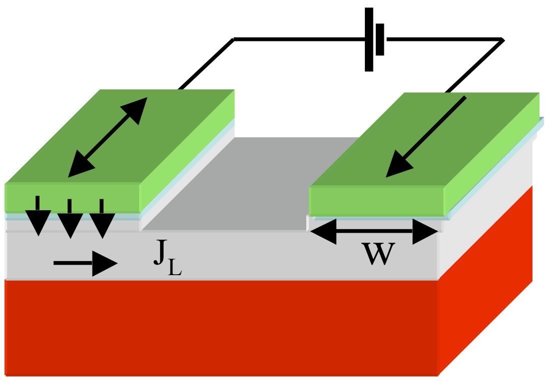
$$\mathrm{MR} \sim \left(\frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}\right)^2 \frac{R_{sc}}{R_b}\frac{L_{sc}}{d}$$

~1%

Barrier resistance must be large for spin injection

Planar (horizontal) devices

Semiconductor spin valve



2D flow important

Barrier/channel: conductance ratio α spin finesse β

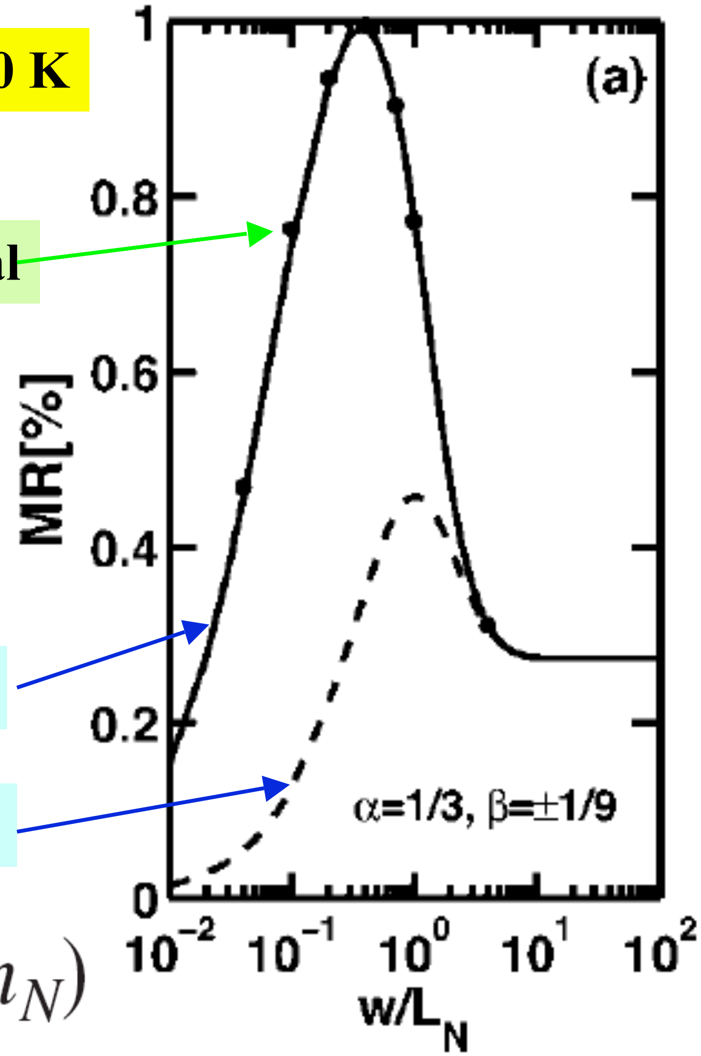
T = 300 K

2D numerical

1D transverse flow approx

Closed channel

Open channel



$$(\alpha, \beta) = 2L_N^2(G_+ \pm G_-)/(\sigma_N h_N)$$

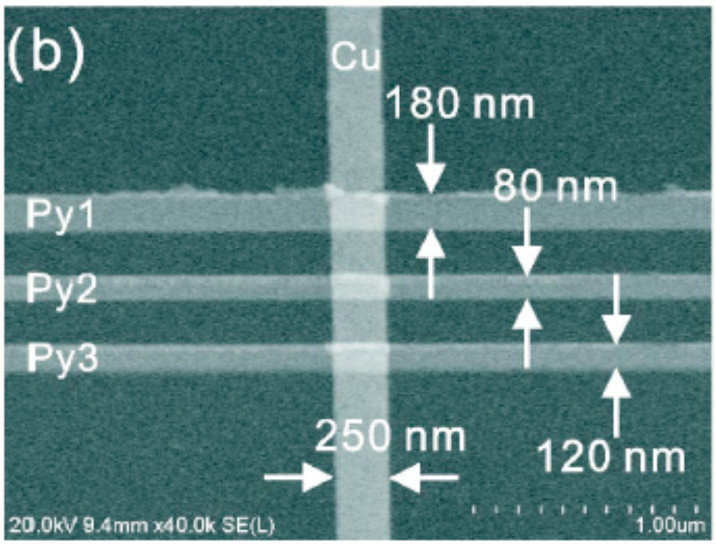
Dery, Cywinski & Sham, PRB **73**, 161307 R (2006))

Three terminal planar (horizontal) devices

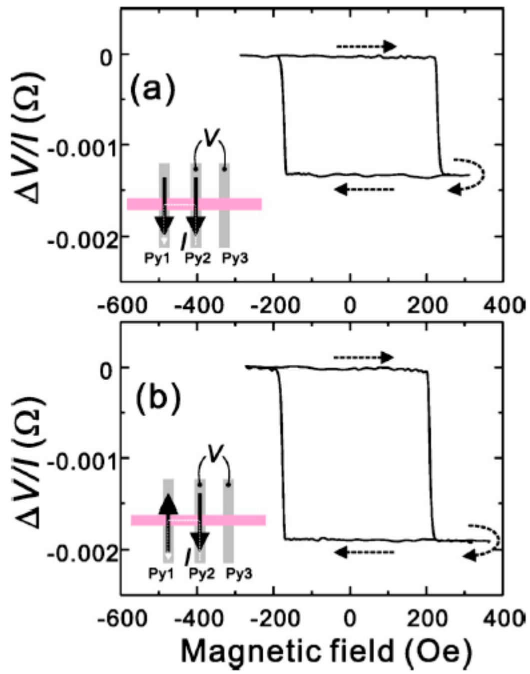
All metal

- Johnson & Silsbee
- Gerrit Bauer et al.
- Jedema et al.

Otani



T= 4 K



Switch Py3

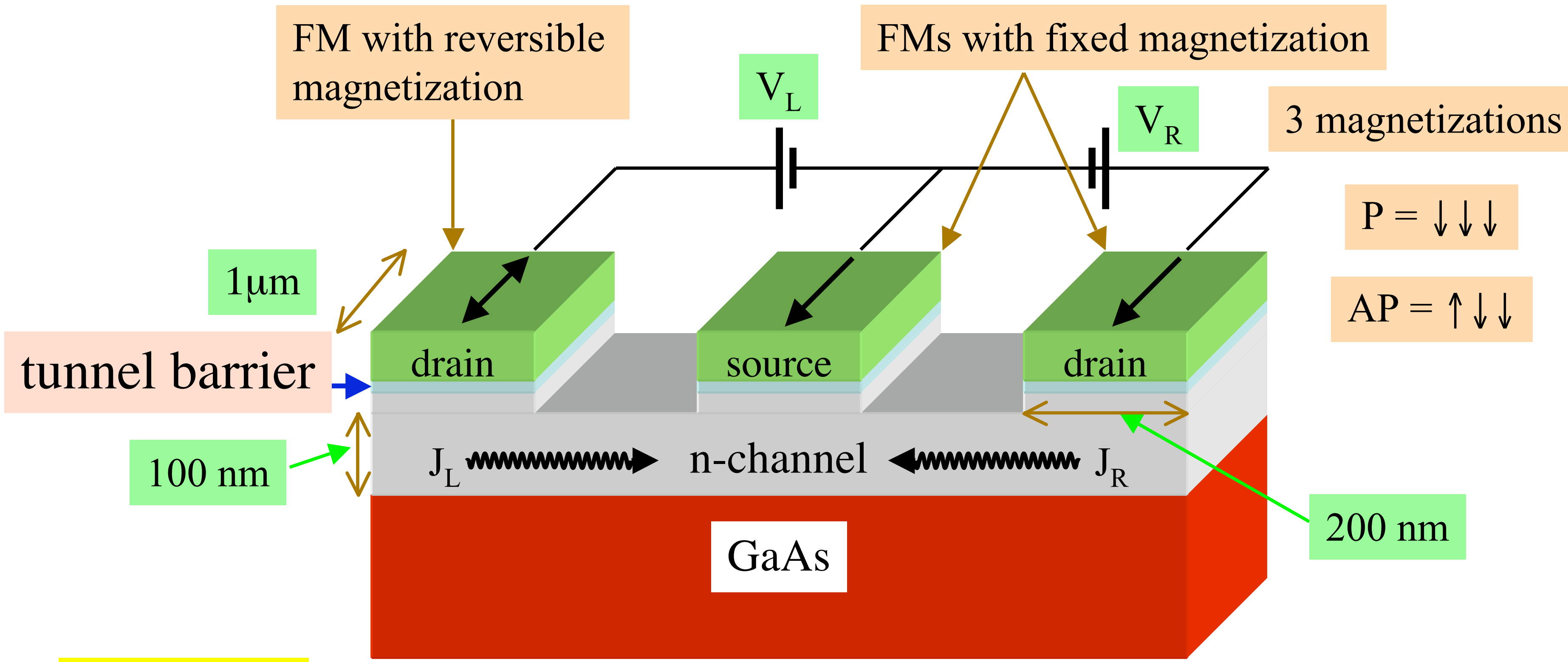
Ratio ~1.5

Semiconductor

Crowell's talk

- Datta & Das
- Ciuti, McGuire, Sham
- Zutic, Fabian, Das Sarma
- Flatté, Yu, Halperin-Johnson, & Awschalom
- Schliemann, Egues, Loss

A three-terminal spin transistor



Operation

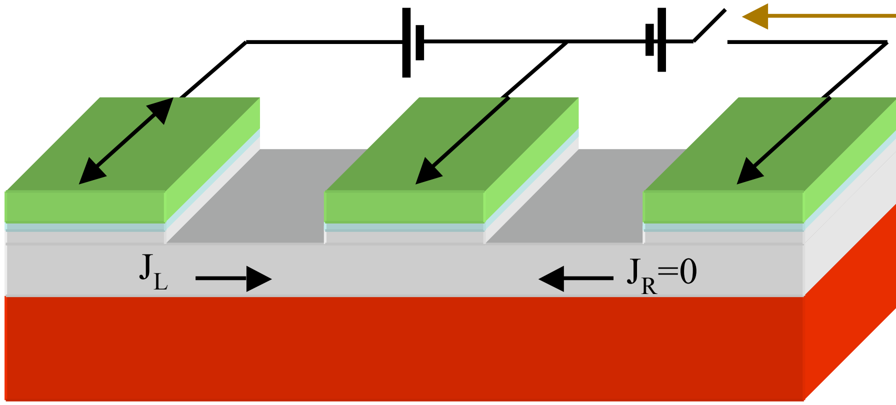
Kircoff's law

Spin Physics

- In P, adjust V_L/V_R so that $J_R^P = 0$.
- W/o changing voltages, in AP, J_R^{AP} is measurably finite.
- Memory (↑=1,↓=0) ==> current measured ($J_R^{AP} \neq 0$, $J_R^P = 0$).

integrable in a circuit -- ECE

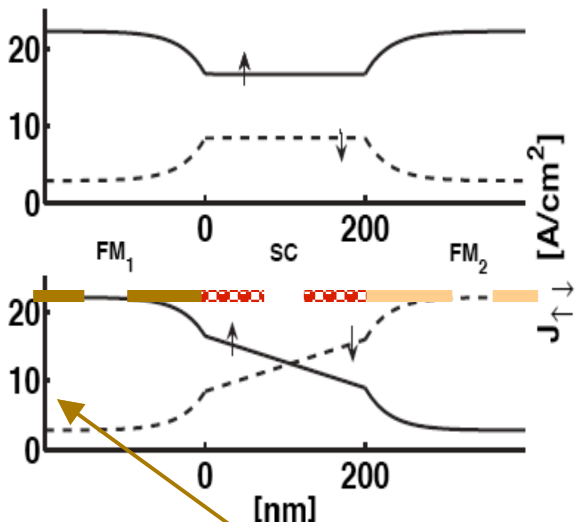
Two-terminal nonequilibrium spin physics



Open

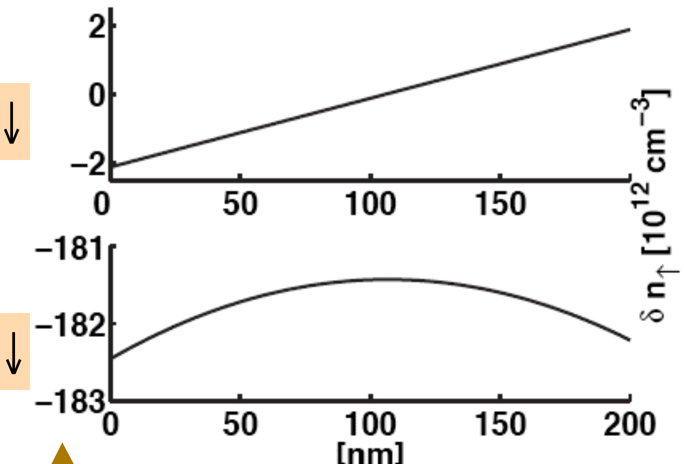
Non-equilibrium spin density
~ electrochemical potential

spin current density



$P = \downarrow\downarrow$

$AP = \uparrow\downarrow$

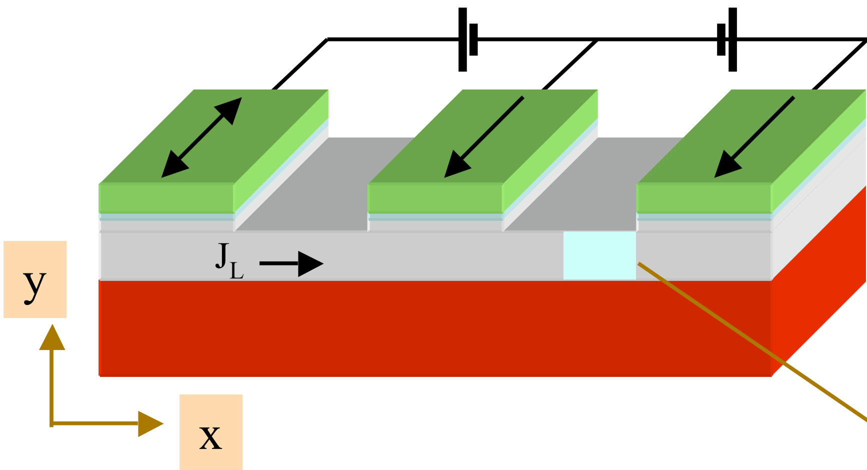


small

large

Difference between P and AP

Three-terminal nonequilibrium spin physics ($J_R^P = 0$)

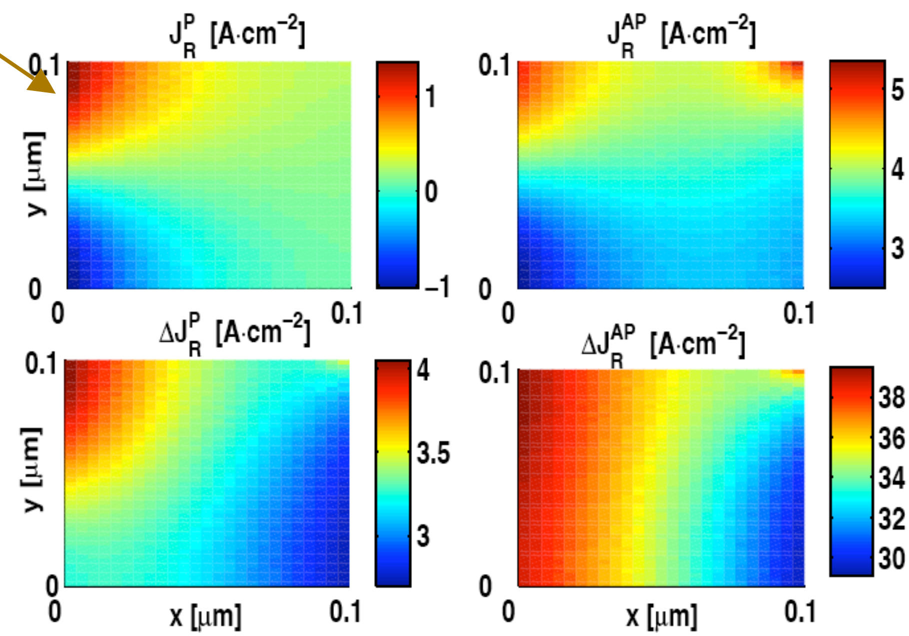


$$\nabla^2 \mu_s(x,y) = \frac{\mu_s(x,y) - \mu_{-s}(x,y)}{2L_{sc}^2}$$

$\mu_s \propto \delta n_s$

Current density distribution in 2D

$P = \downarrow\downarrow\downarrow$ $AP = \uparrow\downarrow\downarrow$



Spin effect transference

- In P, small spin current L to R
- In AP, spin current on L creates large spin current on R
- MR transferred from L to R

Analogy with bipolar transistor

http//:www.st-andrews.ac.uk/~www_pa/Scots_Guide/info/comp/comp.htm

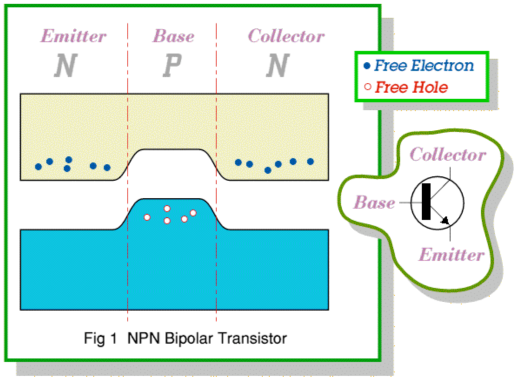


Fig 1 NPN Bipolar Transistor

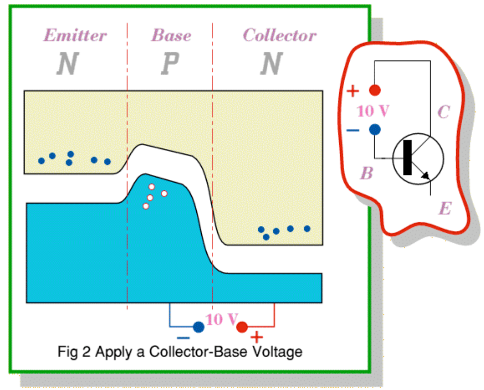


Fig 2 Apply a Collector-Base Voltage

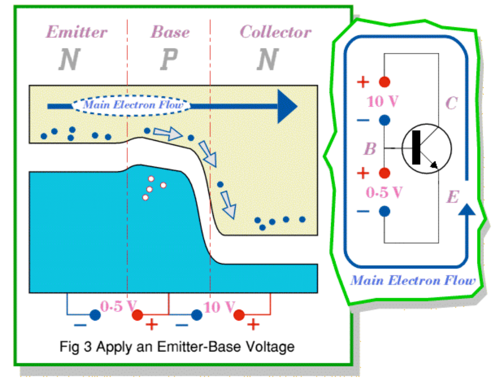
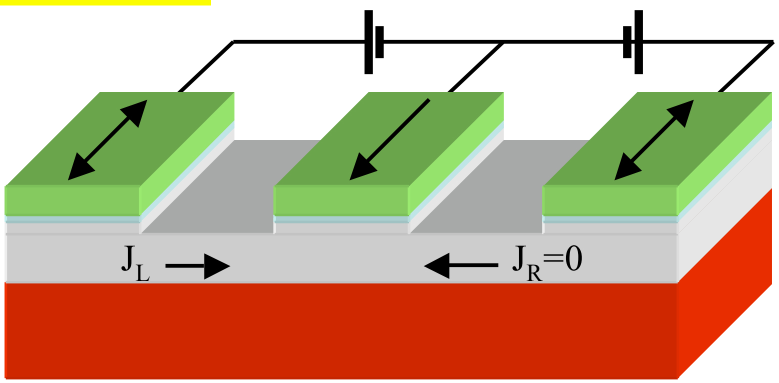


Fig 3 Apply an Emitter-Base Voltage

L~Emitter M~Base R~collector



P = ↓↓↓ AP = ↑↓↓

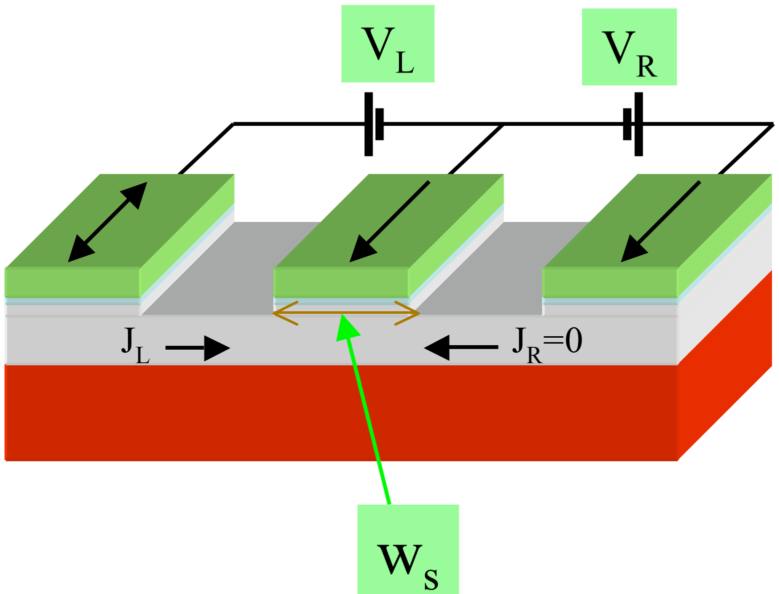
Transistor action

- two diodes np + np ~ two back-to-back spin valves
- recombination ~ spin diffusion
- eb voltage from 0 to 0.5V ~ L-M from P to AP
- bc current from 0 to finite ~ M-R current J_R from 0 to finite

Non-volatile memory

Robustness of conditions $J_R^P = 0$ and spin diff length

L drain M source R drain

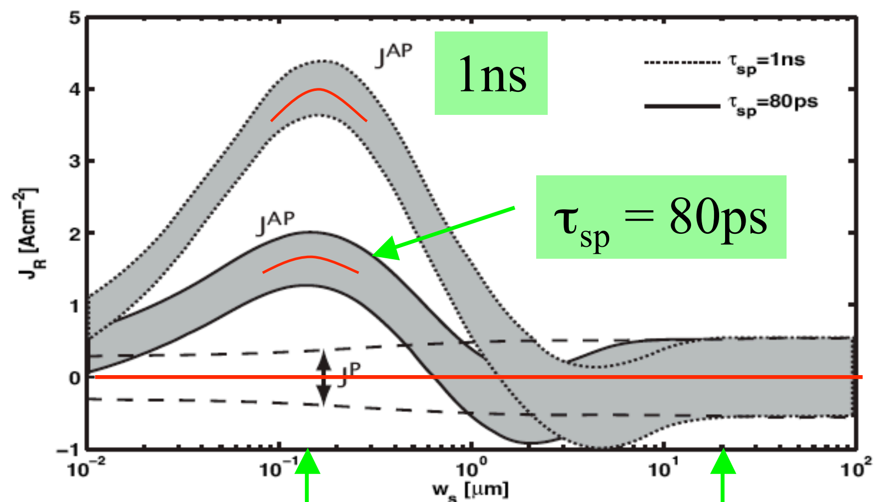


P = ↓↓↓

AP = ↑↓↓

Add noise boundaries:
V_R/V_L = optimal ± 0.2%

Effect on current on R vs source width



Optimal w_s

No transference

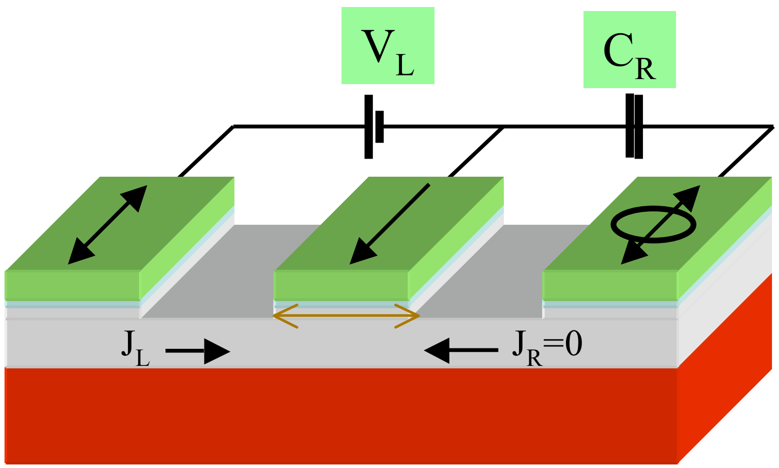
Dery, Cywinski & Sham, PRB **73**, 041306 R (2006)

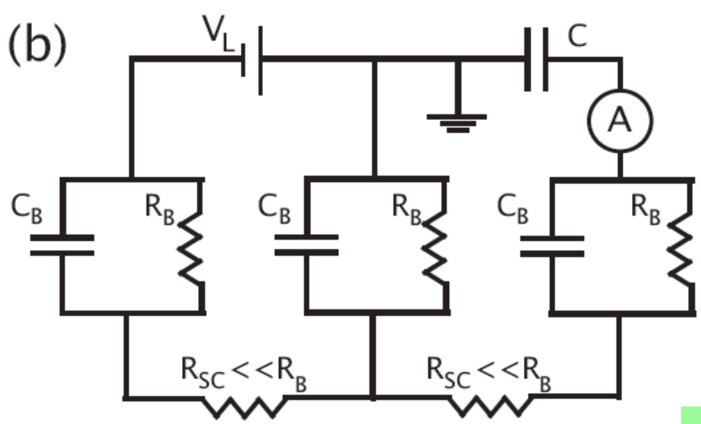
Magnetization dynamics and AC spin current

L drain

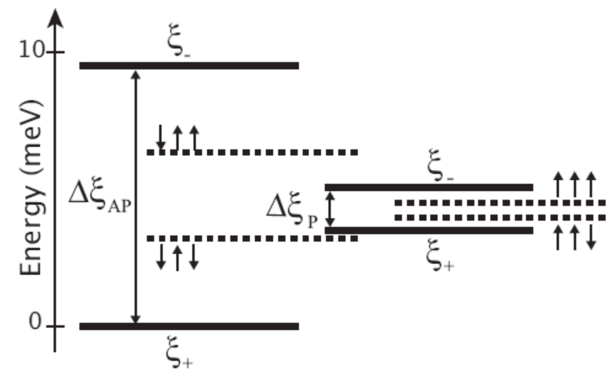
M source

R drain

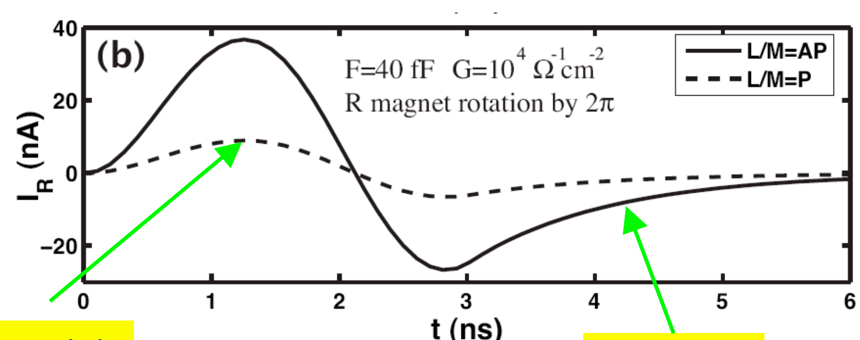




R chemical potentials



R current signals on R 2π rot



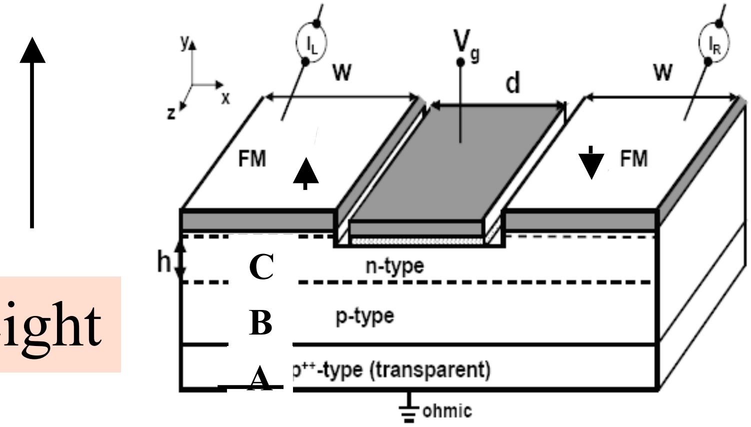
LM ↓↓

LM ↑↓

L reversal detected by R current signal

Dery, Cywinski & Sham, cond-mat/0601632

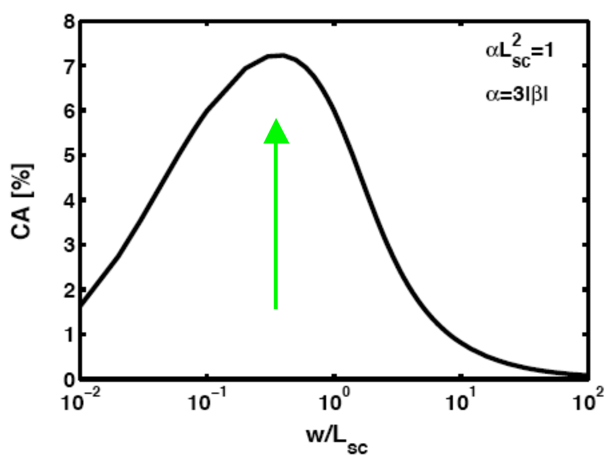
Measurement of circular polarization of light

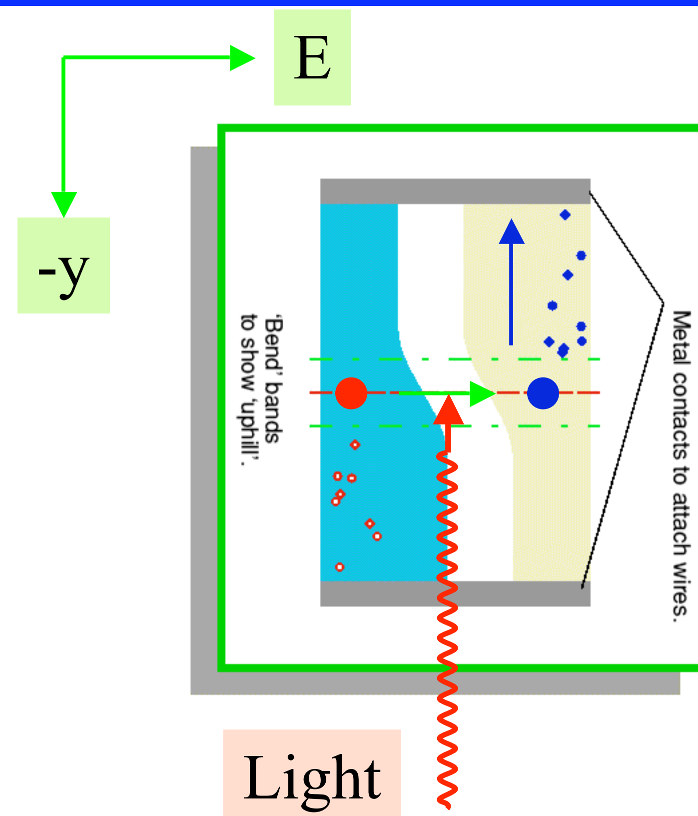


Light

Current asymmetry

$$CA = \left| \frac{I_L}{I_R} - 1 \right|$$





σ−(LCP) => e↑

σ+ (RCP) => e↓

Contact width/spin diffusion length

Cywinski, Dery & Sham, cond-mat/0601632

Summary

- **Three terminal = 2 back-to-back spin valves**
- **Nonlinear action: spin effect transfer**
- **Expression: amplification of magneto-resistance**
- **Basic components: FM/SC tunnel junctions at room temperature, proven experimentally**
- **Key decay: spin diffusion length**
- **Five electrodes for a NAND gate, reconfigurable and scalable**
- **Future: magneto-computer on paper?**