Spintronics Beyond Magnetoresistance:
Putting Spin in Lasers

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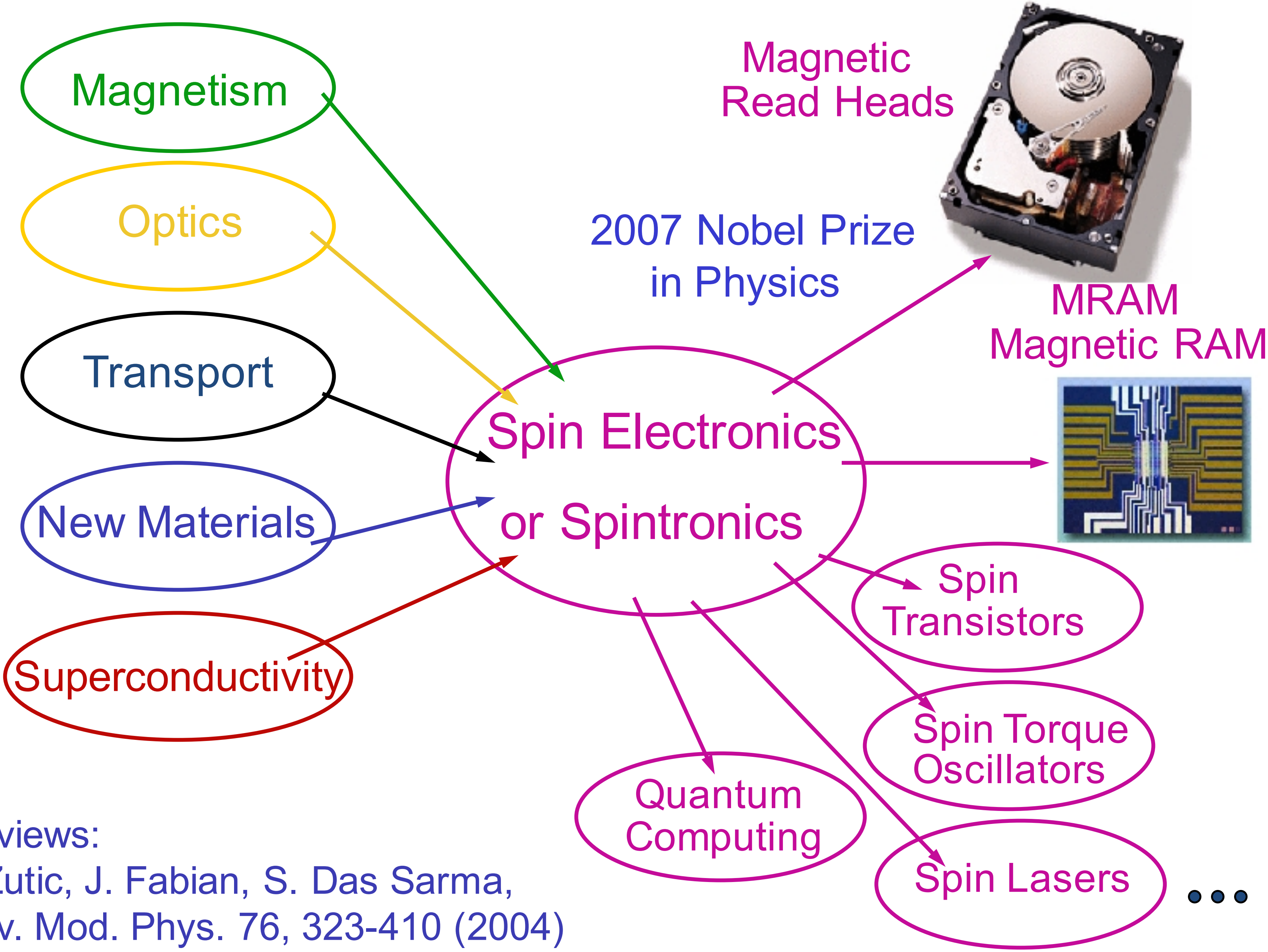
Outline

- Overview, History, Background
- Spin Diodes
- Conventional and Spin Lasers

  Analogies: Bucket, Harmonic Oscillator
- Spin Interconnects



Magnetism

Optics

Transport

New Materials

Superconductivity

Spin Electronics

or Spintronics

2007 Nobel Prize
in Physics

Magnetic
Read Heads

MRAM
Magnetic RAM

Spin
Transistors

Spin Torque
Oscillators

Quantum
Computing

Spin Lasers

• • •

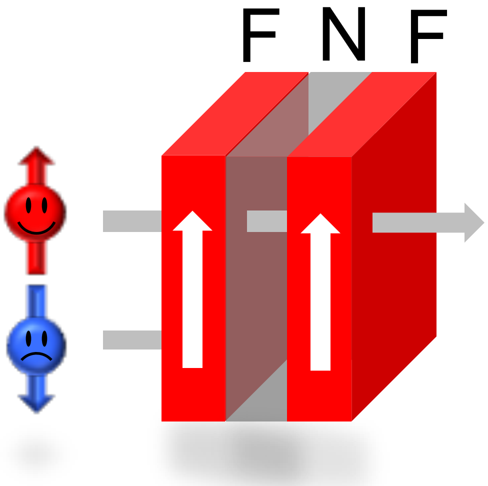
Reviews:
I. Zutic, J. Fabian, S. Das Sarma,
Rev. Mod. Phys. 76, 323-410 (2004)
J. Fabian et al., Acta Physica Slovaca 57, 565 (2007)

Now and Then

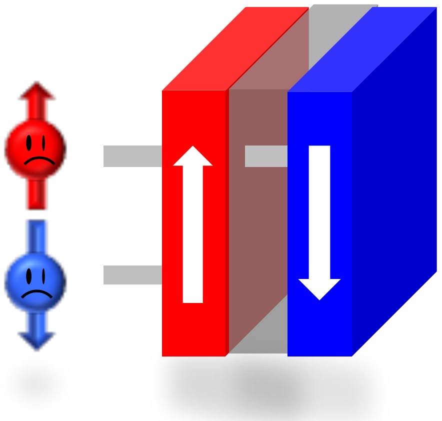
Hard Disk Drives: >200 Gbits/cm^2 >500 Mbits/sec < $0.0005/Mb

Operating Principles?

Low Resistance



High Resistance



Spin-Valve Effect

polarizer-analyzer analogy

Typically Unipolar Devices

linear regime, no Poisson eq.

only electrons

N< normal metal – giant magnetoresistance (GMR)
insulator – tunneling magnetoresistance (TMR)

replacing AlO by MgO 10-fold increase in TMR

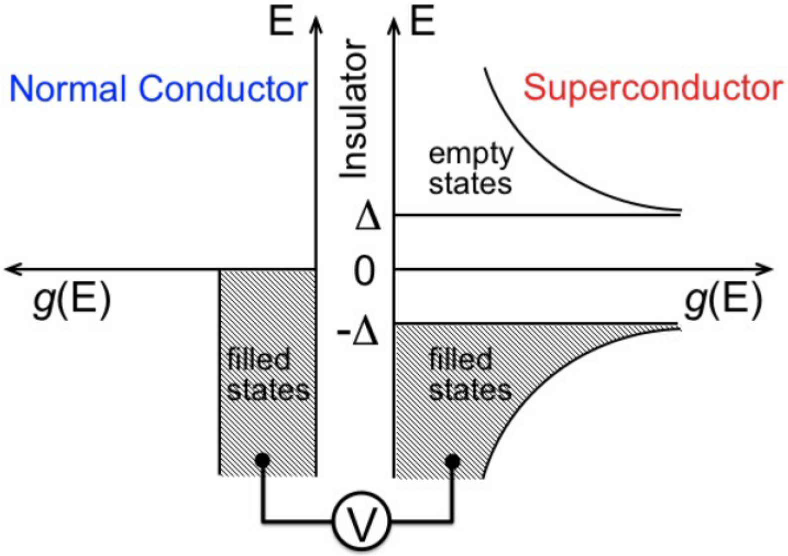
S. S. P. Parkin et al., Nature Mater. **3,** 862 (2004)
S. Yuasa, et al., Nature Mater. **3,** 868 (2004)

graphene: low-resistance tunnel barrier

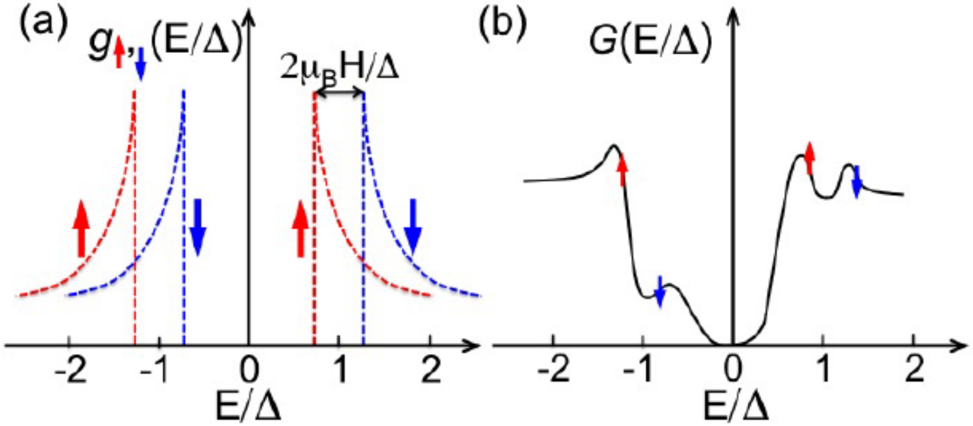
spin-orbit: Anisotropic MR (AMR) back in 1857 Lord Kelvin

TMR: Some History

N I S Tunneling



Late 60s P. Fulde ("F" from FFLO):
what about F I S Tunneling?



Early 70s exps. with P. M. Tedrow, R. Meservey

1. Spin-polarized current in S region

2. Measuring polarization of F region

F I S Tunneling Influence:

1975 M. Julliere 1st TMR Report not reproduced (Ge insulator); simple TMR model

1982 S. Maekawa, U. Gafvert 1st reproducible TMR (NiO insulator)

1976, 1977 A. G. Aronov, G. E. Pikus, theory of electrical spin injection

1980 R. H. Silsbee: 1985- with M. Johnson, electrical spin injection (concept & exps)

can spin be transported away from a magnetic interface?

Limited interest until TMR @ 300 K in mid 90s J. Moodera et al.; Miyazaki and Tezuka

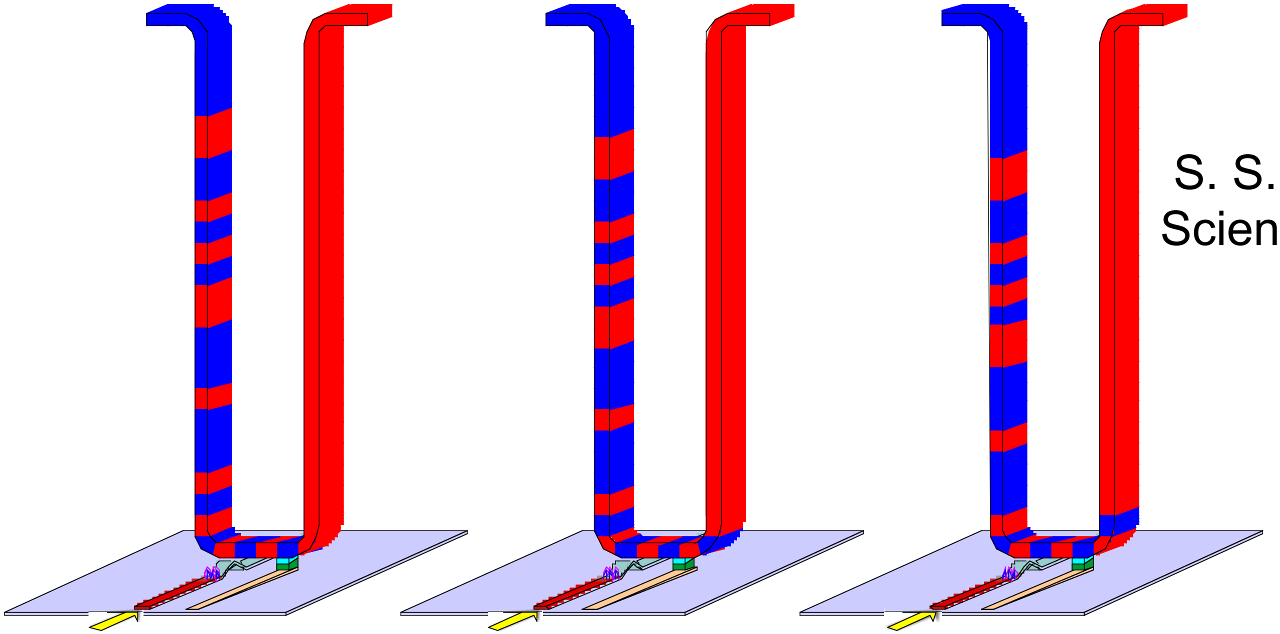
related references in Rev. Mod. Phys. 76, 323 (2004)

Using 3rd Dimension: Magnetic Racetrack

unify the best of hard drives & RAM

Stuart Parkin (IBM)

Shift current pushes domains through stack



US Patent 6834005,
Dec. 21, 2004

S. S. P. Parkin et al.,
Science 320, 190 (2008)

Write Element Read Element TMR

Domain Walls vs Skyrmions?

A. Fert, Nature Nanotech. 2013
also talk R. Wiesendanger – skyrmions @ 300 K

Semiconductor Spintronics?

- Started early, but did not get very far

  Datta-Das (1990) vs GMR (1988)

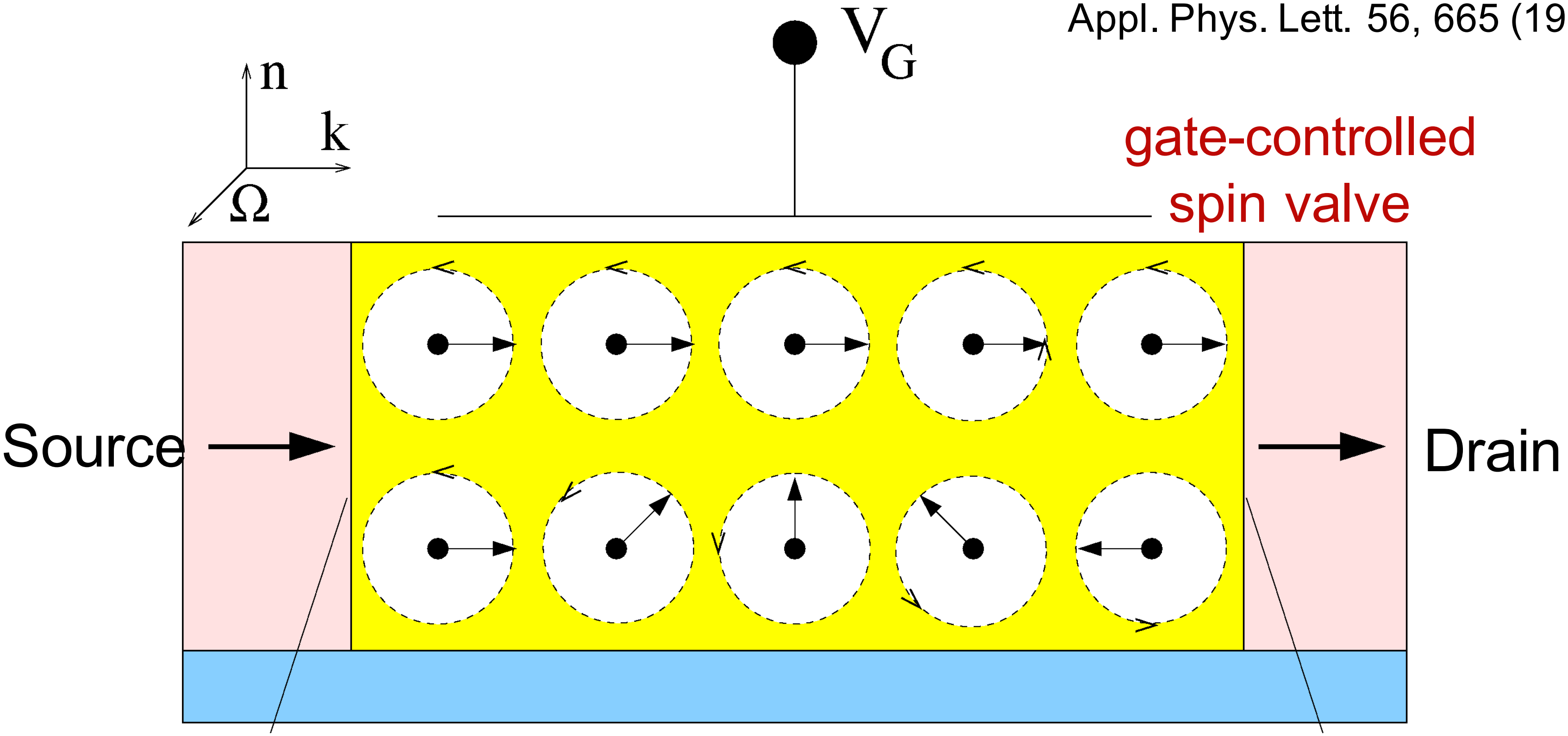
- Are there other opportunities?

- Yes, collaborators of A. Fert are exploring them

  Good track record:
  two-current model, SHE, skyrmions, GMR,…

Spin FET

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



gate-controlled
spin valve

spin injection spin transport/manipulation spin detection

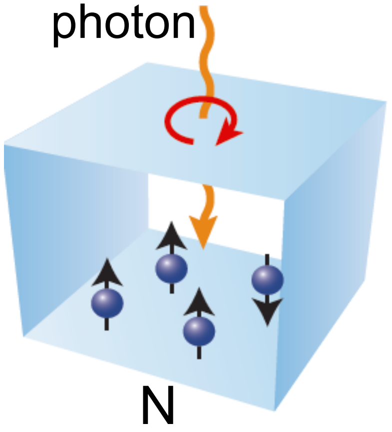
illustrates generic elements & challenges for spin logic devices
(magnetic) heterojunction -- building block

I. Zutic, J. Fabian, S. Das Sarma, RMP 76, 323 (2004)

Generating Spin Imbalance

Transfer of Angular Momentum: Carriers, Excitations, Photons, Nuclei

Optical Spin Injection (Orientation)

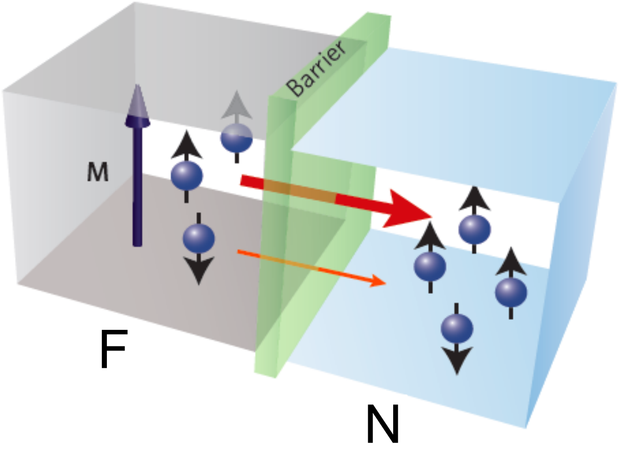


Spin-Orbit Coupling
(Friend & Foe)

spin-polarized electrons & holes
have different spin dynamics

G. Lampel, PRL 1967
NMR Detection in Si!

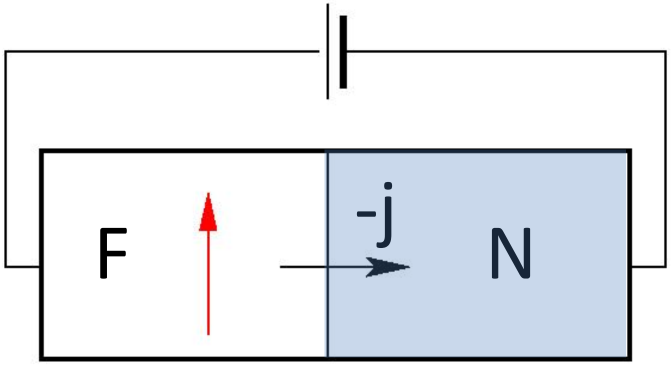
Electrical Spin Injection

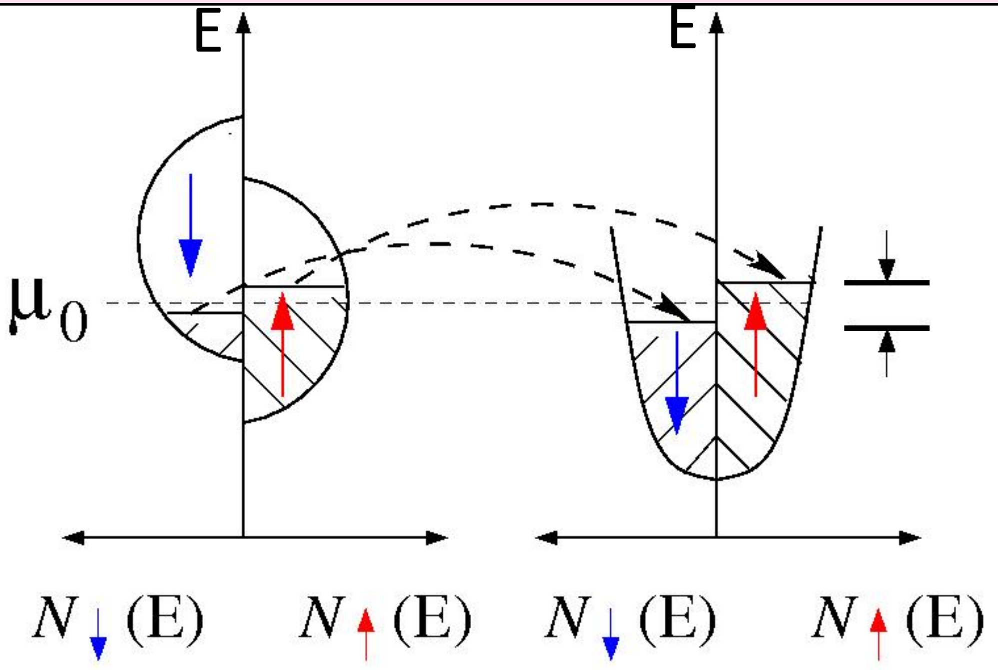


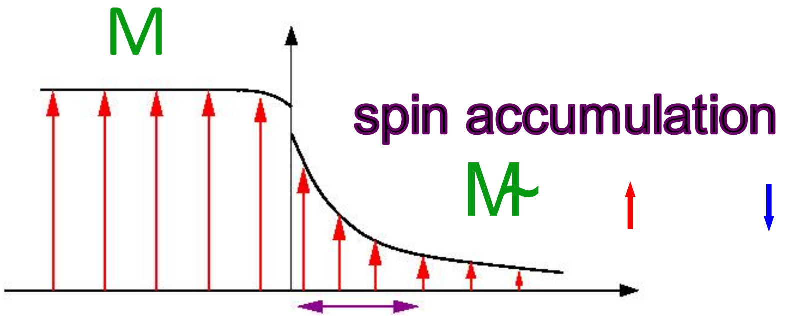
Pairing Symmetry
QHE Skyrmions
Spin-Charge Separation
Spin-Momentum Locking

S. A. Kivelson, D. S. Rokhsar, PRB 1990
Q. Si, PRL 1997,
H. B. Chan et al. & A. H. MacDonald, PRL 1997
Several Symposium Talks

Electrical Spin Injection







$L_S = (D\ t_s)^{1/2}$

spin diffusion length

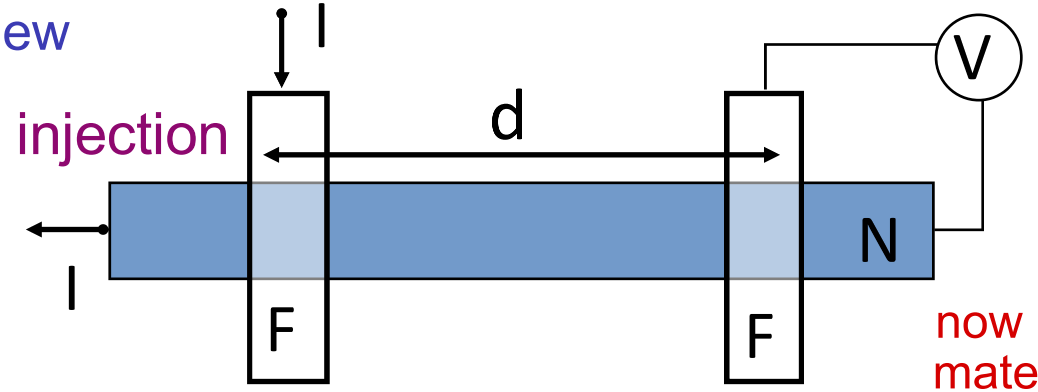
> m (GaAs, Si, Graphene…)

proximity effect (zero bias)
spin-dependent properties &
mag. moment in the N region
metals ~ 1 nm
graphene ~ 50 nm (not negligible)

P. Lazic et al., PRB 90, 085429 (2014)

Spin Injection & Detection in Lateral Spin Valves

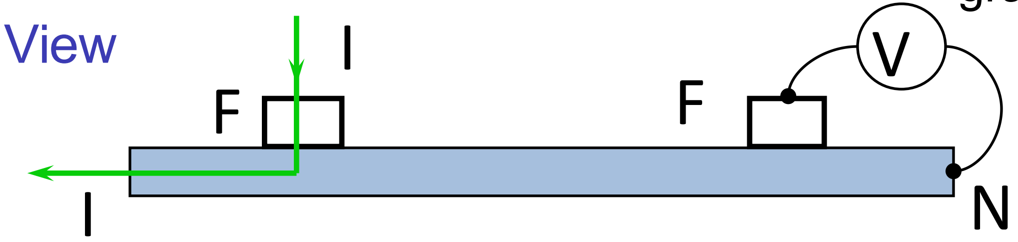
Top View

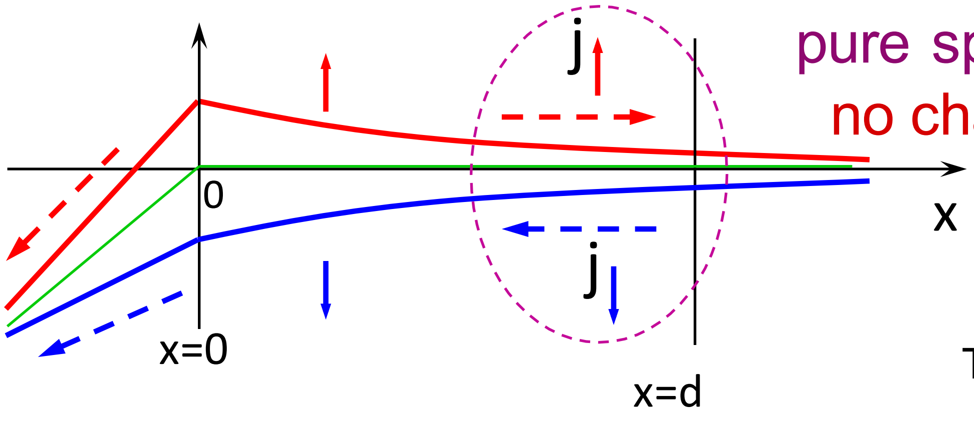


S. Takahashi and S. Maekawa
PRB 2003

now standard approach for many materials: metals, semiconductors, graphene, superconductors,TI's…

Side View



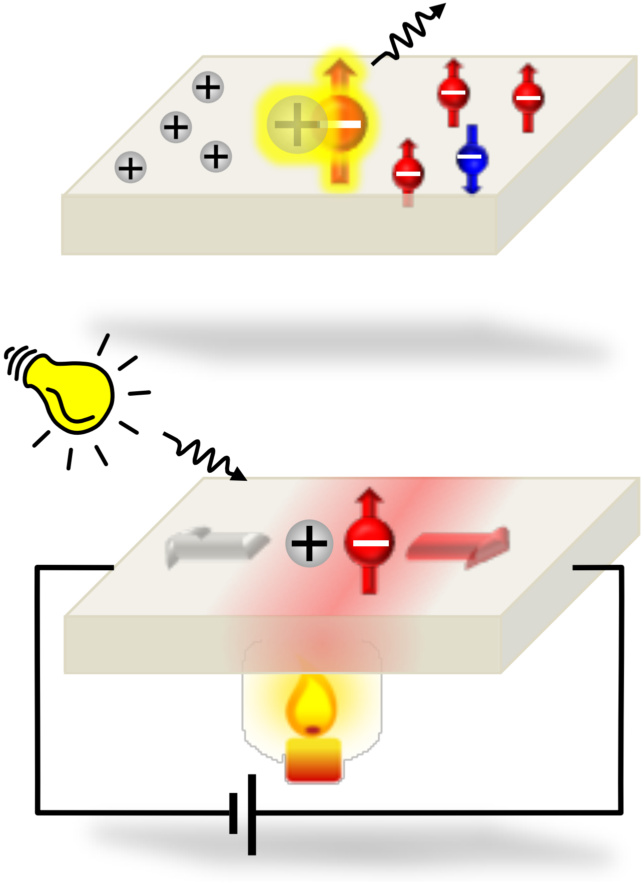


pure spin current !
no charge current

Magnetization Reversal
T. Yang, T. Kimura, and Y. Otani
Nat. Phys. **4**, 851 (2008)

Bipolar Spintronics

simultaneous presence of electrons & holes



electron-hole
recombination/generation

J. Sinova, I. Zutic
Nature Mater. 11, 368 (2012)

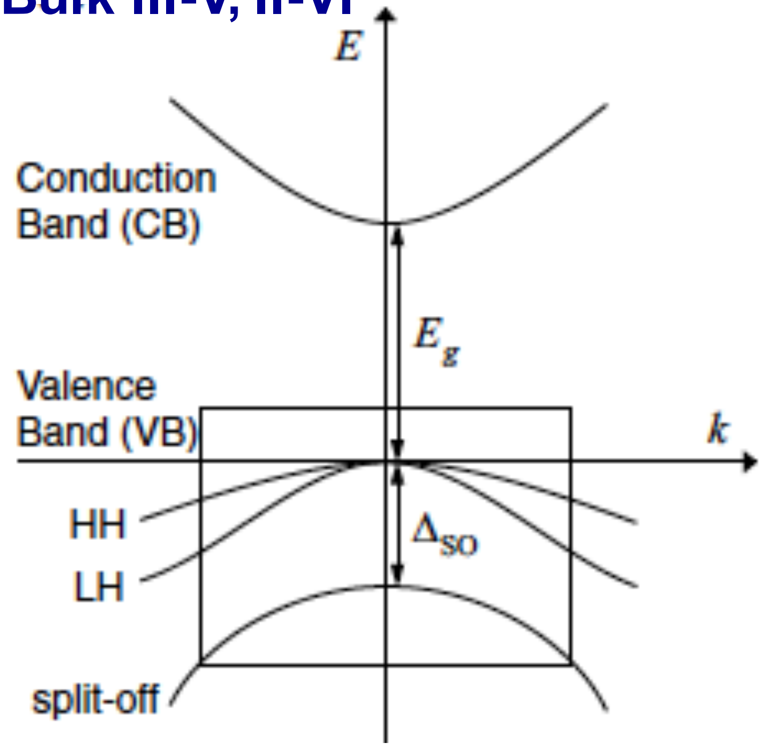
Experiments:

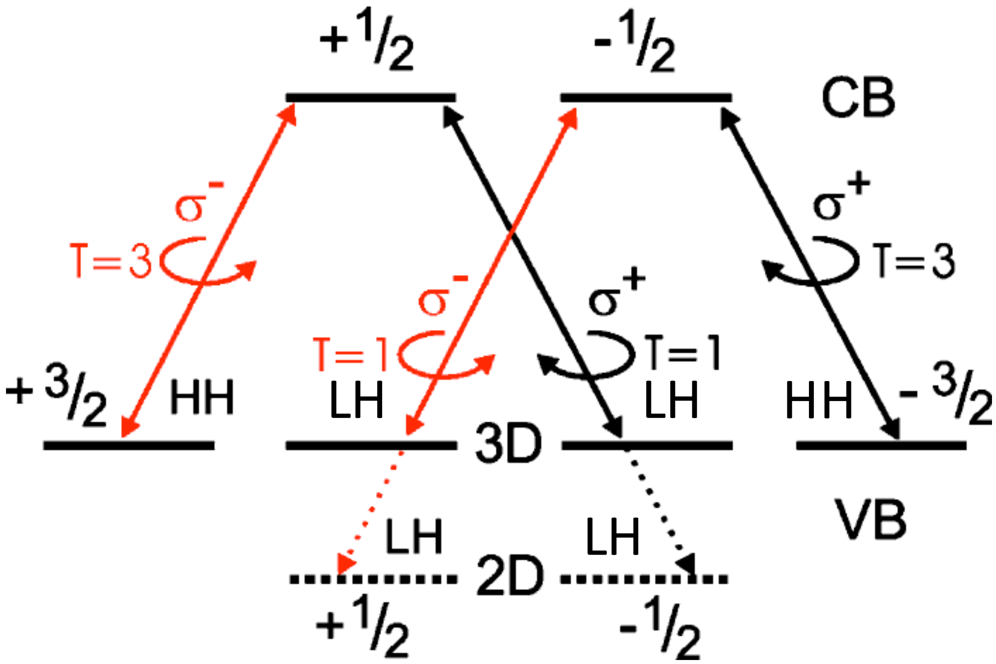
spin LEDs
spin p-n junctions
spin photo-diodes
magnetic bipolar transistors
spin lasers

holes loose spin faster than electrons
there are exceptions, like MoS_2

Optical Spin Injection and Detection

Bulk III-V, II-VI





dipole selection rules

$$\frac{|\langle 1/2,-1/2|\,Y_1^1\,|3/2,-3/2\rangle|^2}{|\langle 1/2,1/2|\,Y_1^1\,|3/2,-1/2\rangle|^2}=3$$

Splitting between HH & LH ?

In QW (strain + confinement)

- **degeneracy lifted**

I. Zutic, J. Fabian, S. Das Sarma, RMP 76, 323 (2004)

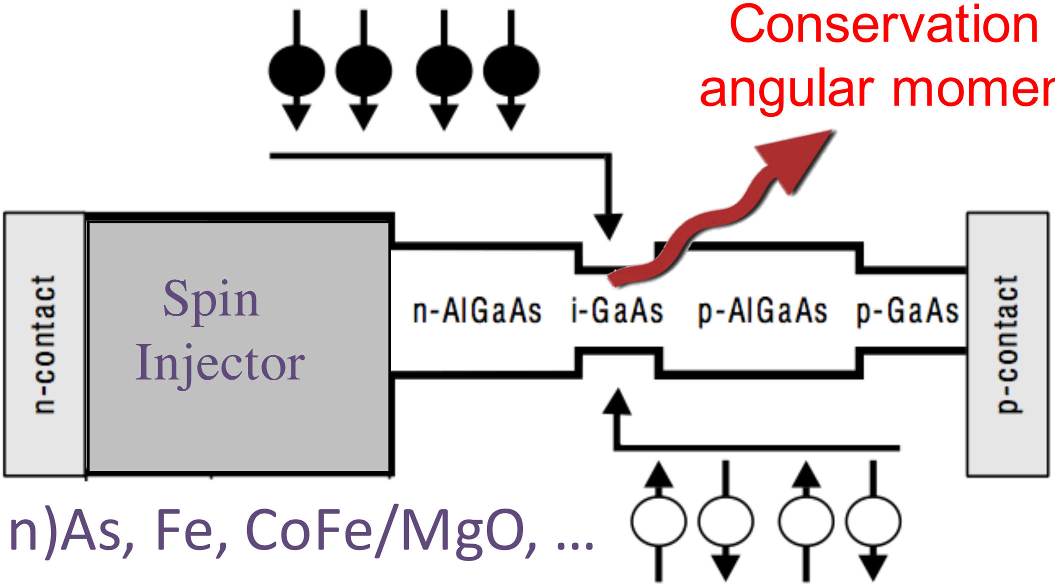
F. Meier and B. P. Zakharchenya, Optical Orientation, Elsevier (1984)

Spin LEDs

Basic Elements:

- Spin Injection
- Spin Transport
- Spin Relaxation
- Spin Detection

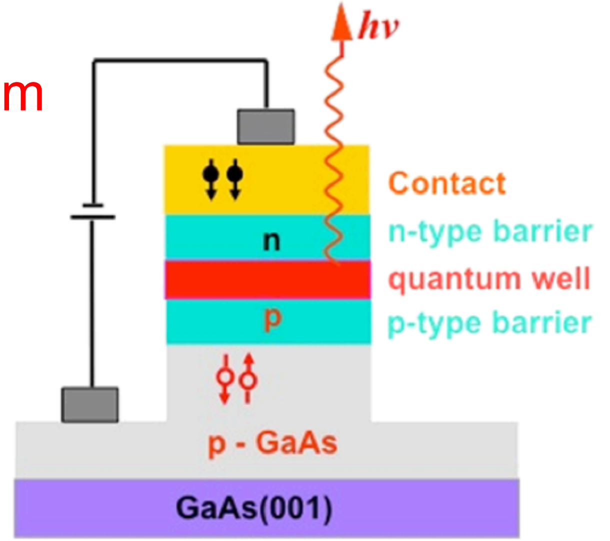
Conservation of angular momentum



(Ga,Mn)As, Fe, CoFe/MgO, …

R. Fiederling et al., Nature **402**, 787 (1999)

Top Emission



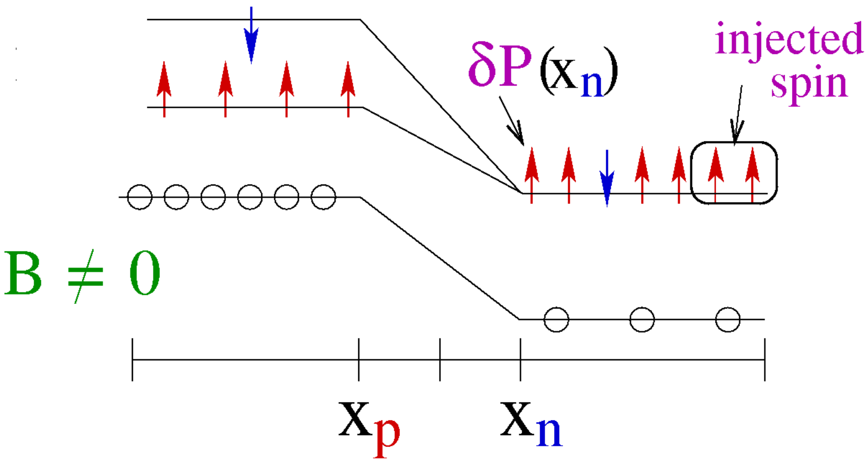
B. T. Jonker et al., PRB **62**, 818 (2000)
NRL/U. Buffalo

Circularly Polarized Light in TMDs
Talk Y. Iwasa

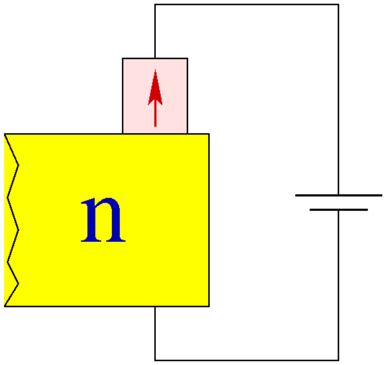
B. T. Jonker U.S. Patent No. 5,874,749
23 Feb. 1999

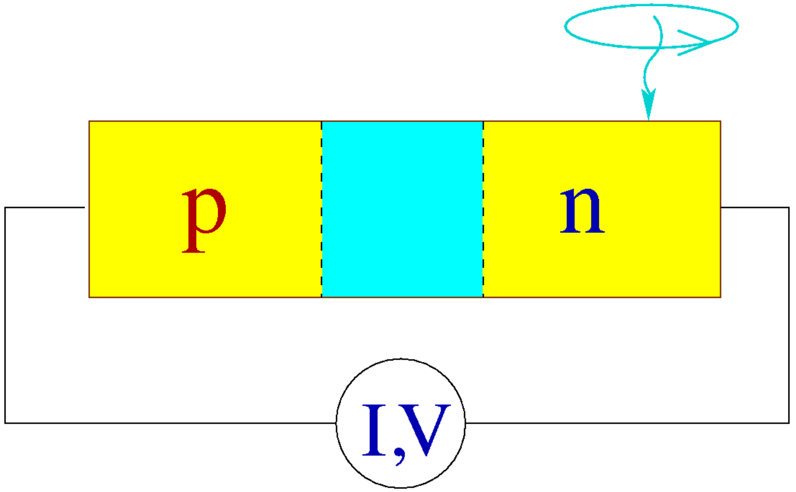
Prediction of Spin-Voltaic Effect

I. Zutic, J. Fabian, S. Das Sarma
PRL 88, 066603 (2002)



alternative realization:





spin detector

$$J_{sv} \sim P_0(B)\,\boxed{\delta P}\,e^{qV/k_BT}$$

nonequilibrium polarization

Works also for Indirect Band Gap Material

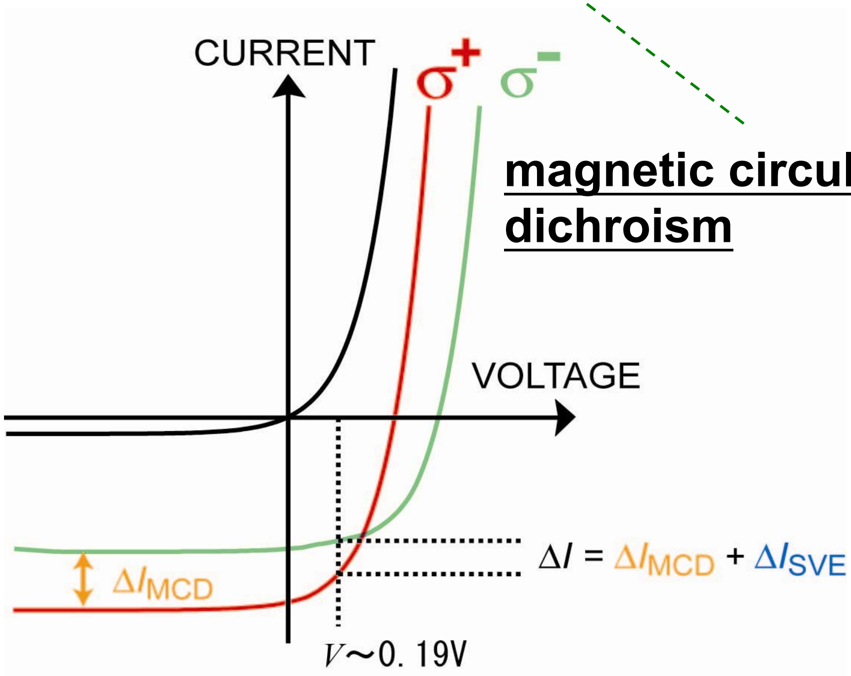
related spin-galvanic effect Ganichev et al., Nature (2002)

1st Spin-Photo Diode (experimental demonstration)

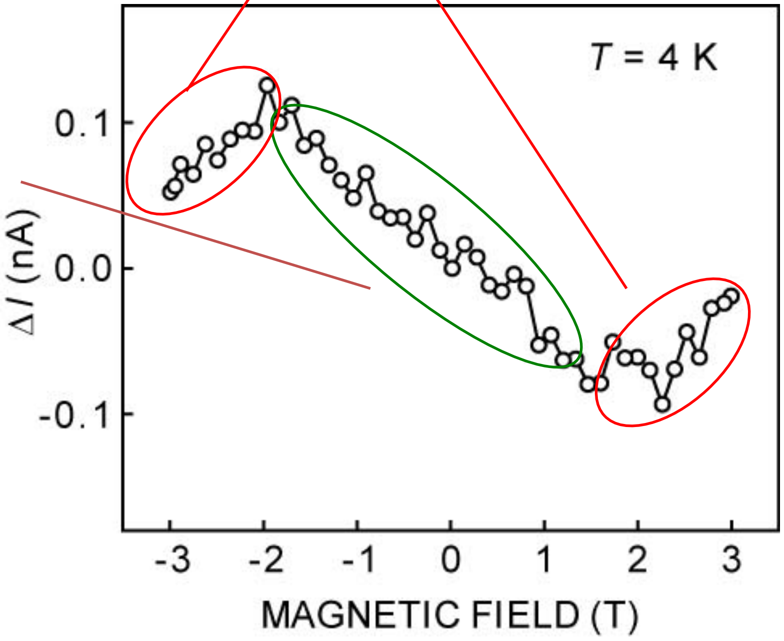
$$\Delta I = \Delta I_{\mathrm{MCD}} + \Delta I_{\mathrm{SVE}}$$

spin-voltaic effect

AlGaAs/InGaAs Junction



magnetic circular dichroism



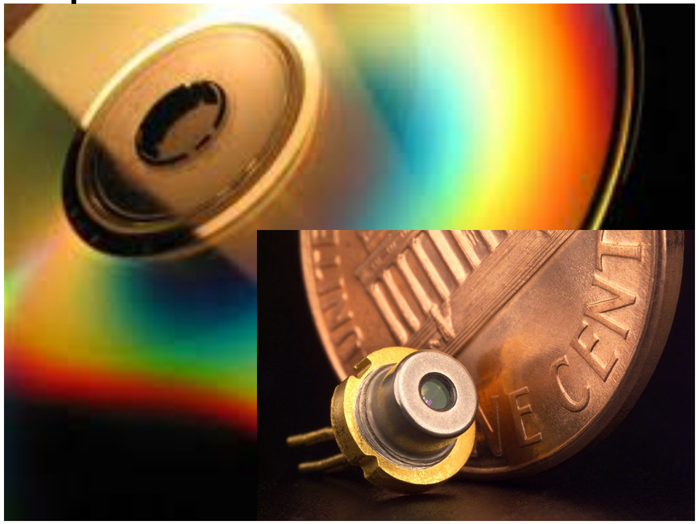
optical spin injection & electrical detection

T. Kondo et al., Jpn. J. Appl. Phys. 45, L663 (2006)

Lasers ?

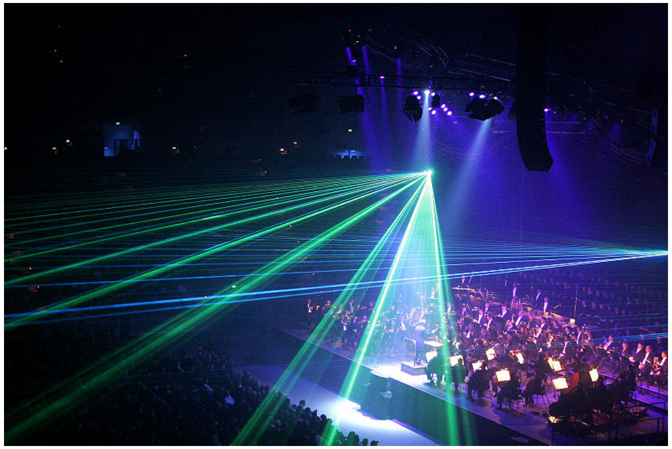
Optical Communication

Optical Media



Medicine

Art



Military

● ● ●

Why Spin Lasers?

- Operation Not Limited to Magnetoresistance
  (unexplored effects and applications)

- Transfer Carrier Spin Information to Photons to Travel Faster (v=c) and Farther ($>>L_S$)
  Talk of A. Oiwa single electrons/photons

- Moore’s Law: Energy Consumption Increasingly Dominated by Communication not Logic (Transistors)
  – Spin Lasers for Optical Interconnects

Lasers 101

- INPUT: Injecting/Pumping Carriers (population inversion)
- OUTPUT: Emitted Light of Coherent Photons

Rate Equations:

$$\frac{d}{dt}\boxed{\text{Carrier Density} \quad n} = \boxed{\text{Injection } J} - \boxed{\text{Gain}} - \boxed{\text{Spontaneous Recombination}}$$

$$\frac{d}{dt}\boxed{\text{Photon Density} \quad S} = \boxed{\text{Gain}} - \boxed{\text{Optical Loss}}$$

[**Gain**] Stimulated emission/absorption

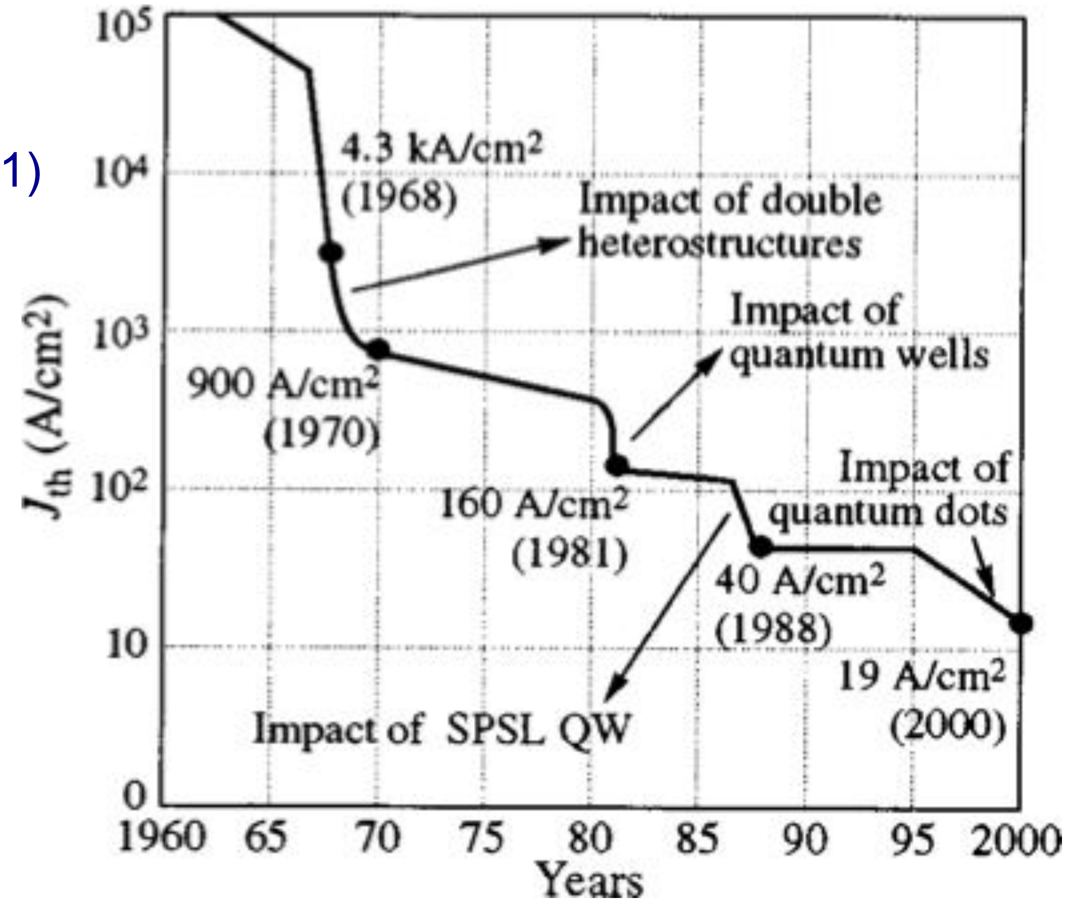
Adding Spin & Light Polarization: $J_{+,-}$ $n_{+,-}$ $S^{-,+}$

History and Future of Lasers?

Threshold Reduction: reduced dimensionality (quantum wells, dots,…)

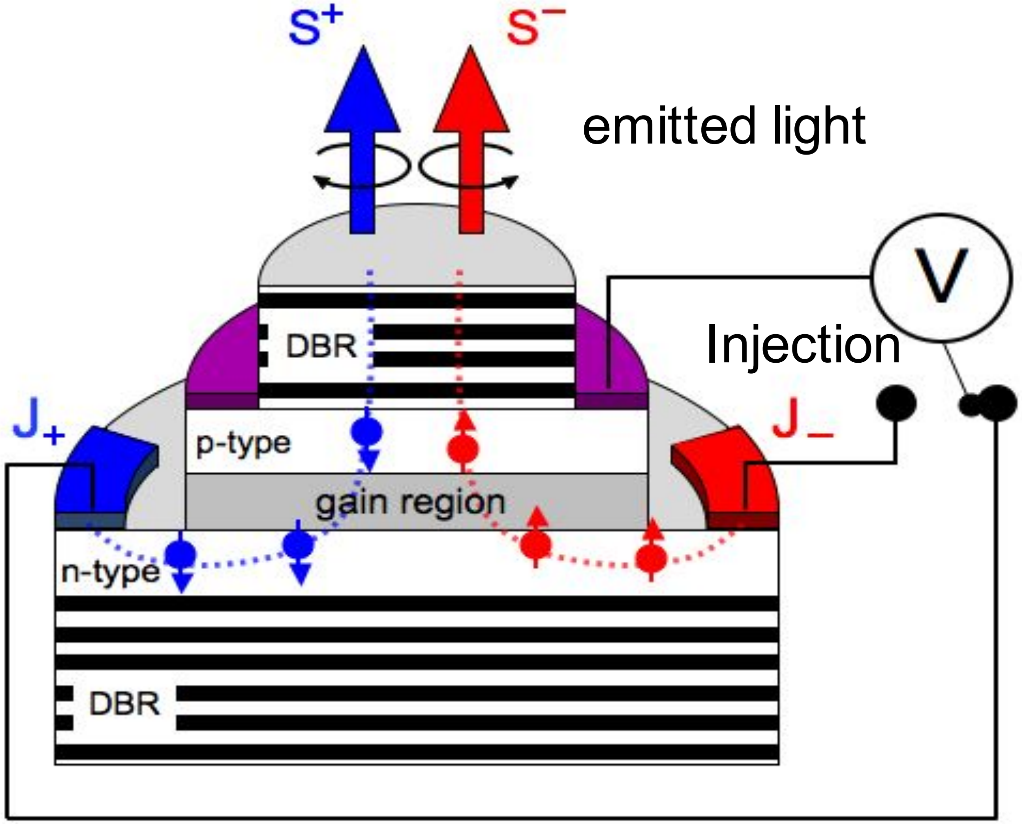
lower power consumption, improved dynamic performance,…

Nobel Lecture:
Z. I. Alferov, RMP (2001)



Threshold Reduction: alternative mechanisms (polaritons, spins,…)

Spin Lasers



Vertical Geometry, Top Emission
similar to Spin LEDs

Injection of spin-polarized carriers
electrical: magnetic contacts
optical: circularly polarized light

Gain region: III-V quantum wells (QWs)
or quantum dots (QDs)

DBR: distributed Bragg reflector mirrors

Typically VCSELs
Vertical Cavity Surface Emitting Lasers

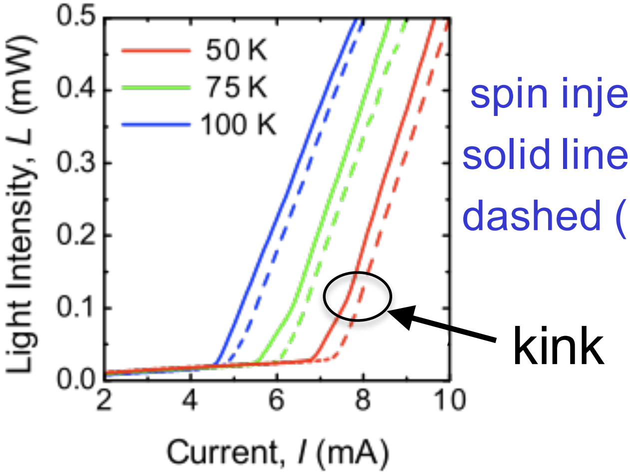
J. Sinova, I. Zutic
Nature Mater. 11, 368 (2012)

Transfer of angular momentum !

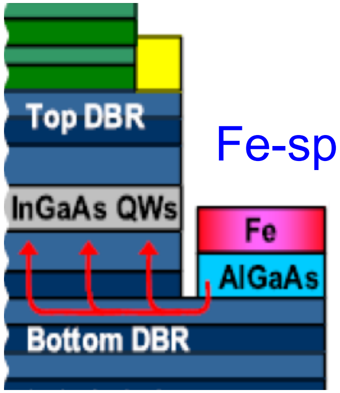
Experiments: Spin Makes a Difference

Injected Spin-Polarized Carriers: Lasing Threshold Reduction

Electrical Spin Injection



spin injection:
solid line (YES)
dashed (NO)

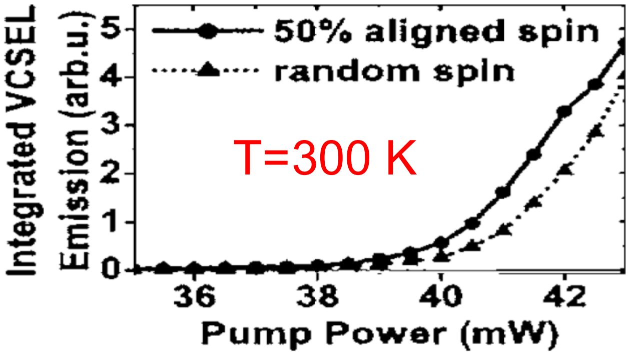


Fe-spin injector (+ B-field)

P. Bhattacharya (U. Mich.)

M. Holub et al., PRL 98, 146603 (2007)

Optical Spin Injection (circularly polarized light S^+,S^-)



J. Rudolph et al., Appl. Phys. Lett. 87, 241117 (2005)

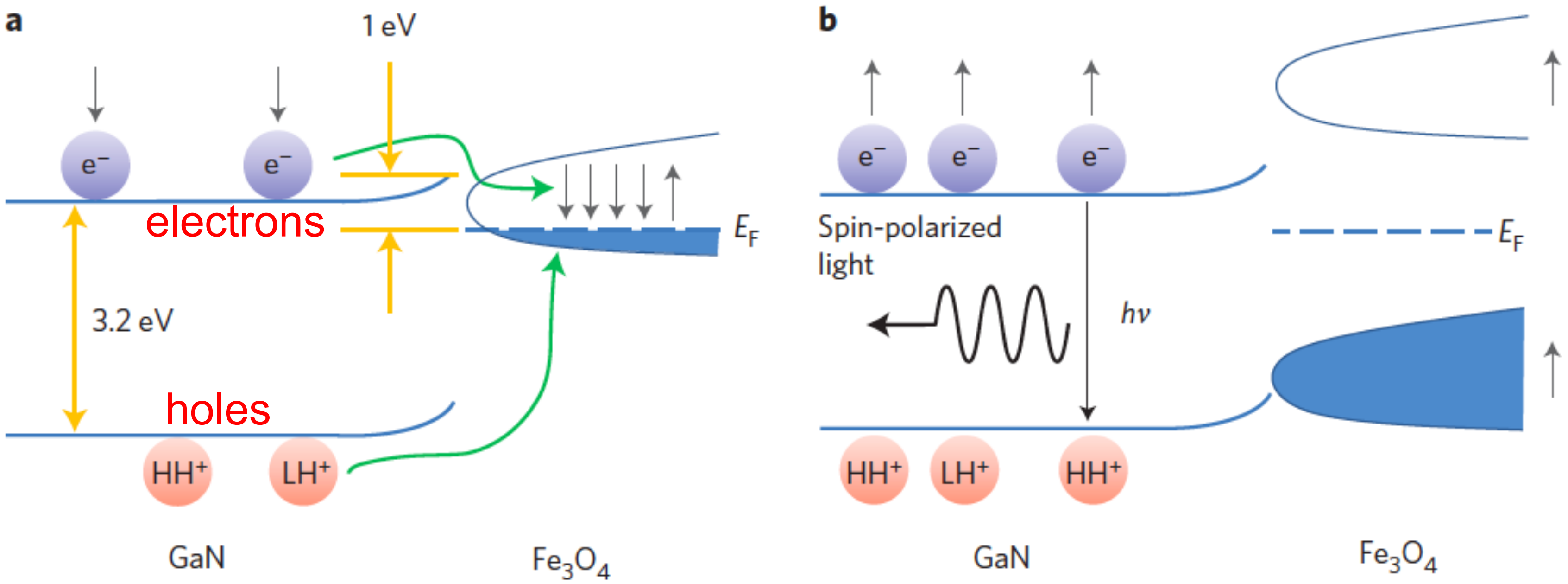
CW operation demonstrated in both Quantum Well and Quantum Dot-based spin-lasers

Other work: S. Hallstein et al., PRB (1997), H. Ando et al., APL (1998); S. Hovel et al., APL (2008)

Electrical Operation at 300 K?

Problem: injected spin loses orientation before reaching the active region, several mm away

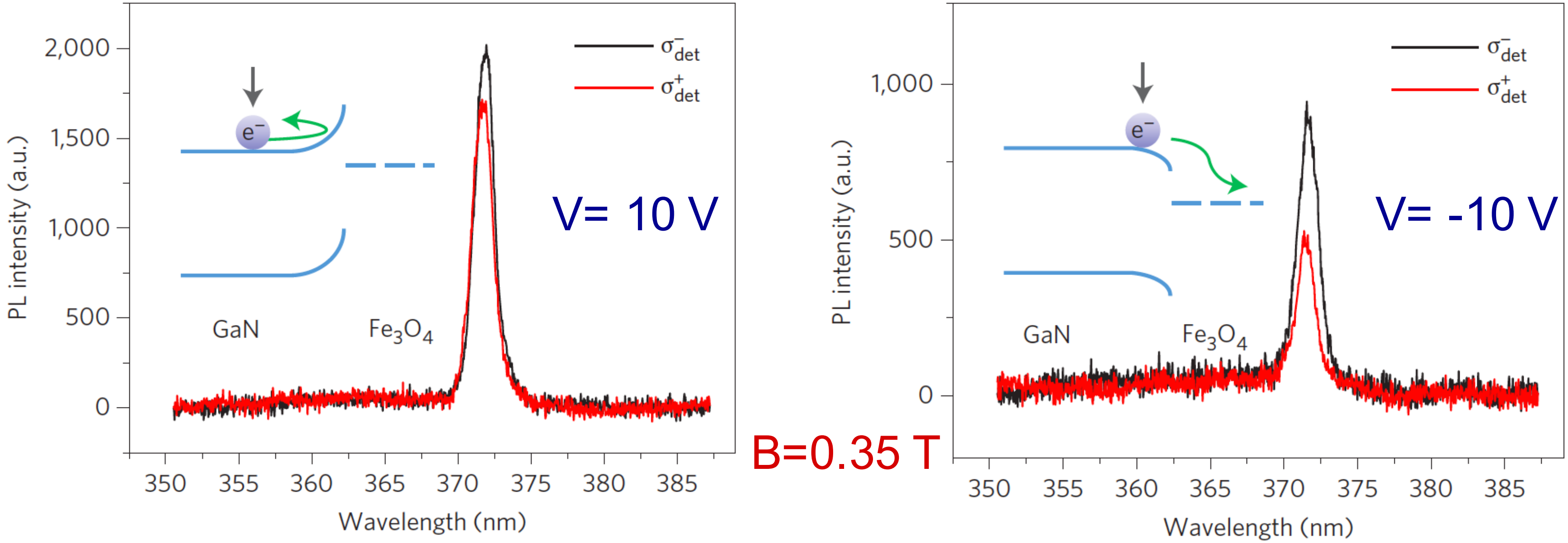
Solution: integrate magnets in the active region
spin-filtering at the GaN/Fe_3O_4 interface



J.-Y. Cheng et al.,
Nature Nanotech. 9, 845 (2014)

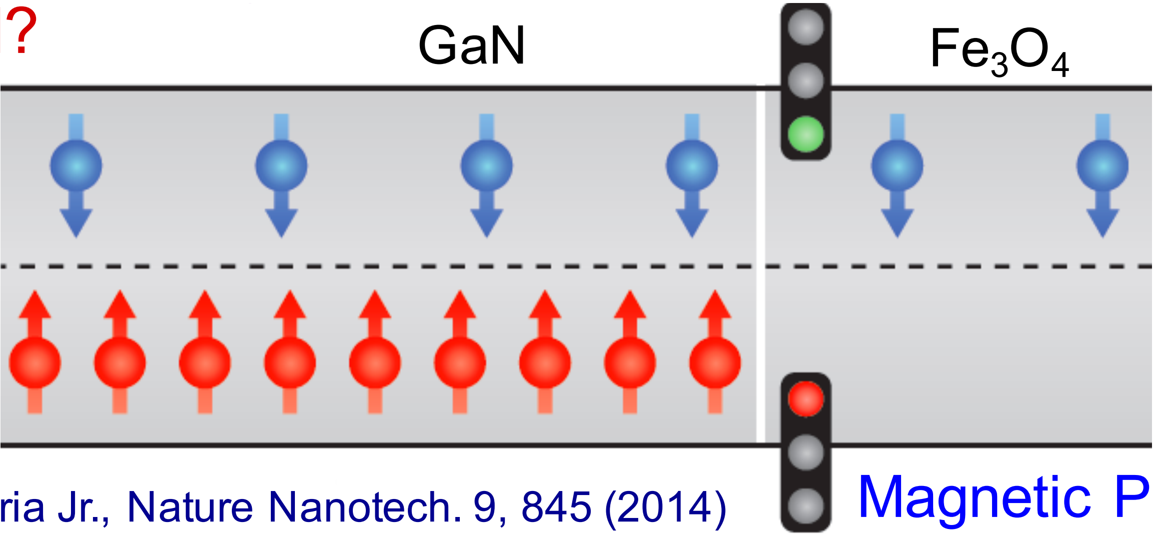
GaN LEDs 2014 Nobel Prize in Physics

Bias-Tunable Spin Polarization, Limitations?



J.-Y. Cheng et al., Nature Nanotech. 9, 845 (2014)

Why B-field?



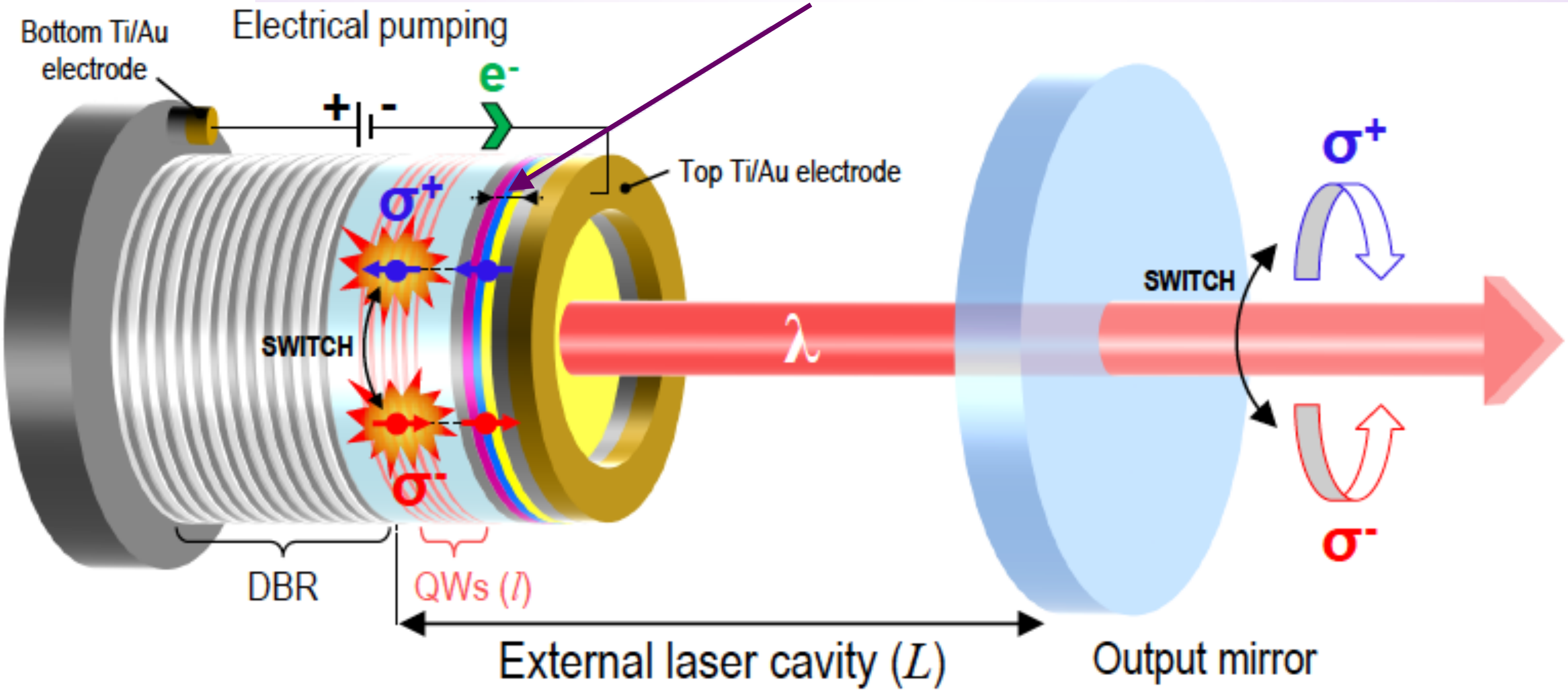
I. Zutic, P. E. Faria Jr., Nature Nanotech. 9, 845 (2014)

Magnetic Proximity Effects

Reducing Transfer Length: External Cavity

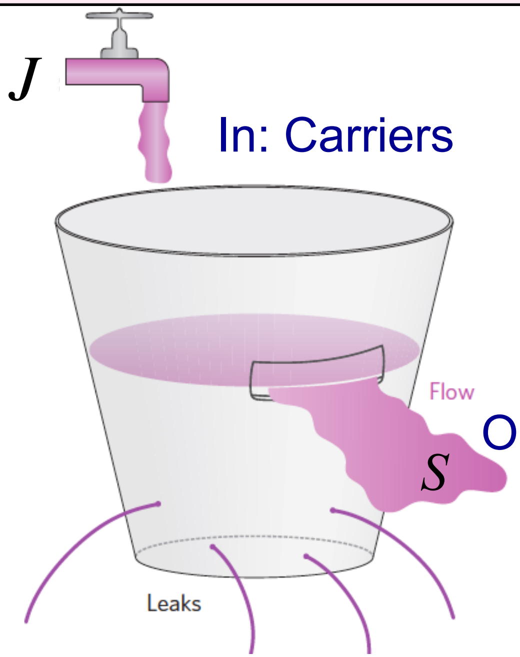
Spin-injector: (2,5nm) MgO/(1,2nm) CoFeB/(5nm) Ta

Two switchable perpendicular magnetic states at RT and B=0 T: ↓ or ↑



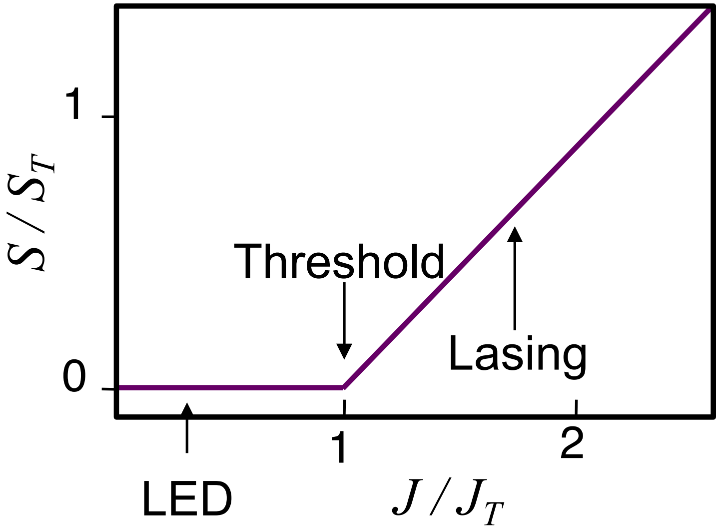
J. Frougier et al. Opt. Expr. 23 9573 (2015) collaborators of A. Fert

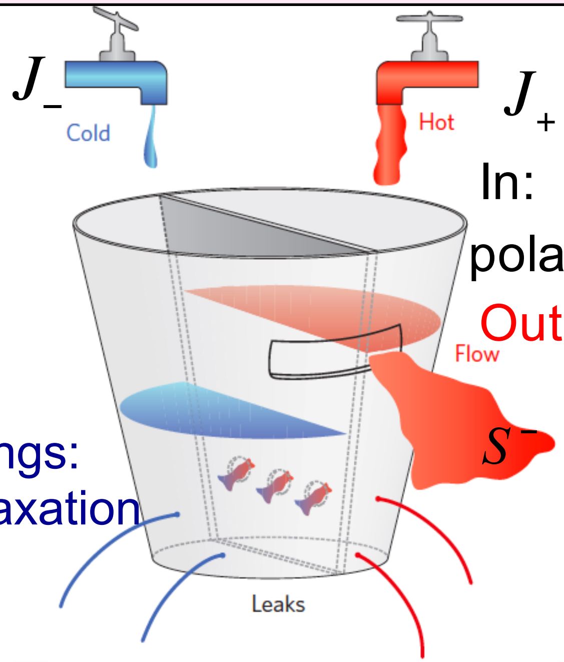
Bucket Model of Lasers



In: Carriers

Out: Light



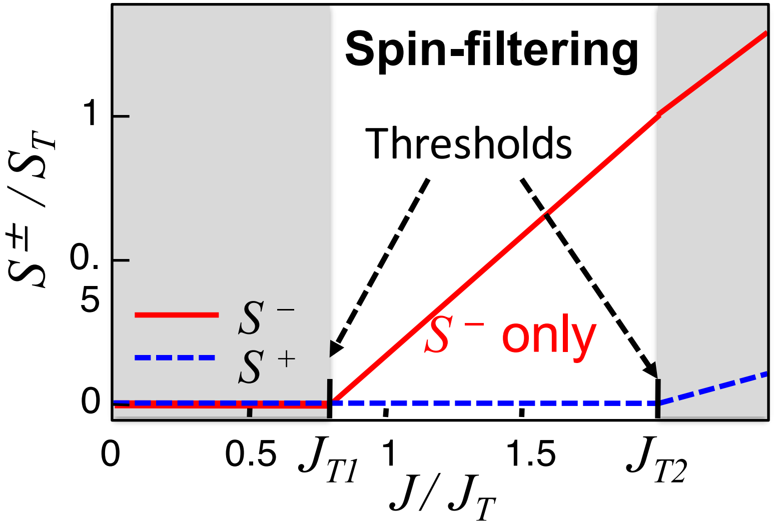


In: partially polarized

Out: fully polarized

50% Treshold Reduction!

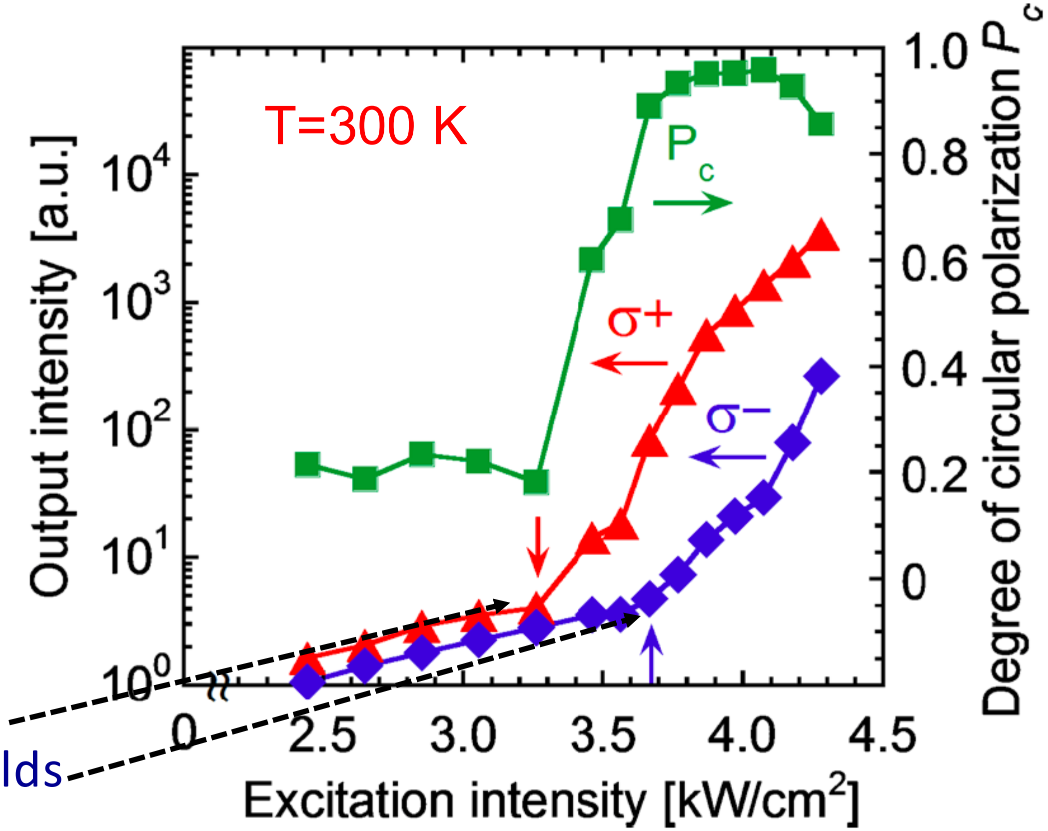
openings: spin relaxation



J. Lee, W. Falls, R. Oszwałdowski, and I. Žutić, APL **97**, 041116 (2010)
C. Gøthgen , R. Oszwałdowski, A. Petrou, I. Žutić, APL 93, 042513 (2008)

Spin-Filtering Experiments

Polarization In: 0.04, Polarization Out: 0.96



Choosing (110) QW

10 x longer

spin relaxation time!

Two thresholds

FIG. 2. (Color online) VCSEL output intensities ($\sigma+$ and $\sigma-$ components) and P_c as a function of excitation intensity at RT.

S. Iba, S. Koh, K. Ikeda, and H. Kawaguchi, APL 98, 081113 (2011)

Dynamic Operation of Spin-Lasers

$$J = J_+ + J_- \ , \ P_J = \frac{J_+ - J_-}{J_+ + J_-}$$

- **Amplitude Modulation (AM):**

$J(t)=J_0+\quad Jcos(\quad t)$ & $P_J(t)= P_{J0}$

- **Polarization Modulation (PM):**

$J(t)=J_0$ & $P_J(t)= P_{J0}+\quad P_Jcos(\quad t)$

J_+ (Spin Up) - **Hot** Water

J_- (Spin Down) - **Cold** Water

J. Lee et al, APL **97**, 041116 (2010)

Harmonic Oscillator, Resonance, Bandwidth

- Lasers – driven & damped harmonic oscillators

injection – extra carrier and photon densities through damped oscillations relax to their steady-state values so-called relaxation oscillation frequency, w_R

$$m\ddot{x} + c\dot{x} + kx = F_\circ e^{i\omega t}$$

$$x(t) = \mathrm{Im}\left[Ae^{i(\omega t-\phi)}\right] = A\sin(\omega t - \phi)$$

$$\boxed{A = \frac{F_\circ}{\left[\left(k - m\omega^2\right)^2 + c^2\omega^2\right]^{\frac{1}{2}}}}$$

Large w - Small A

Higher resonant frequency – higher bandwidth!

Small Signal Analysis: Enhanced Bandwidth

- Frequency Response Function

$$|R(\quad)| = \left| \frac{S}{(\quad) J(\quad)} \right|$$

- Normalized Frequency Response

(P_J=0)

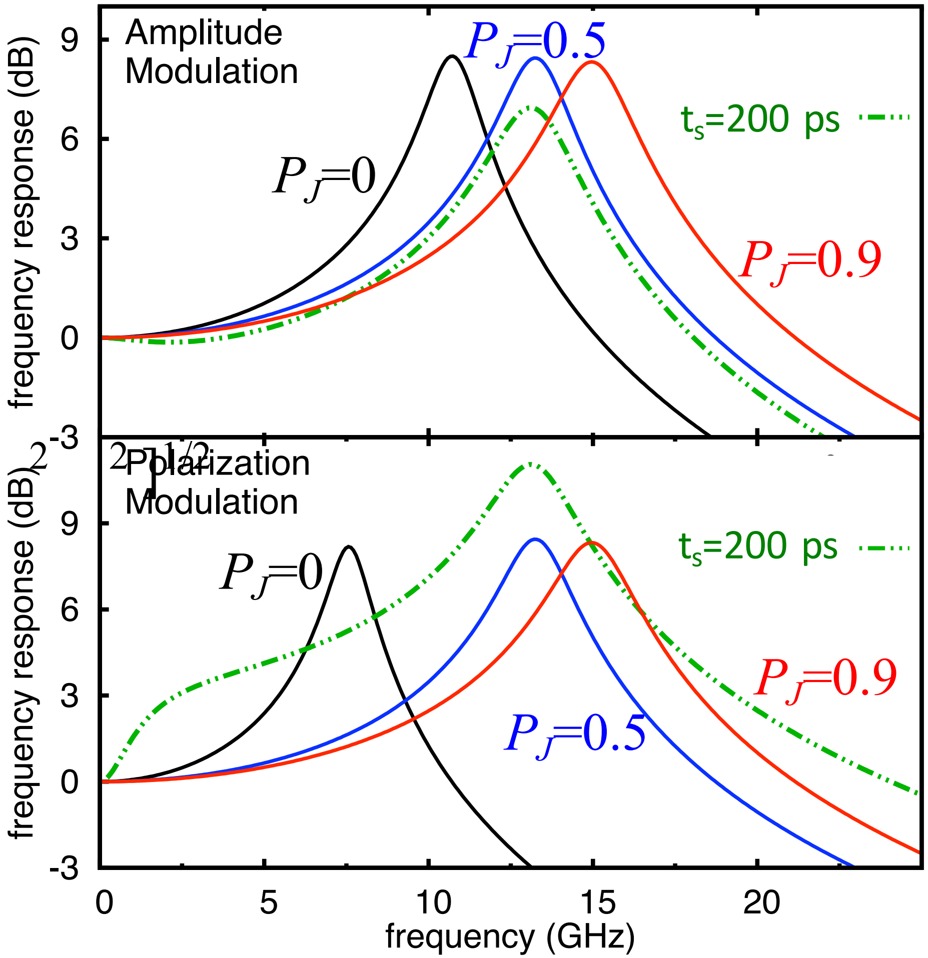
$$\frac{|R(\quad)|}{|R(0)|} = \frac{{}_R^{2}}{[\quad {}_R^{2} - \quad ^{2} \quad ^{2} \quad ^{2} \quad ^{2}\,]^{-1/2}}$$

driven, damped Harmonic Oscillator

- 3-dB bandwidth $\quad {}_R/2$

$${}_R^{2} \quad [J(1 + P_{J0}/2) - \quad J_T]$$

Injection polarization enhanced bandwidth



J. Lee et al, APL **97**, 041116 (2010)

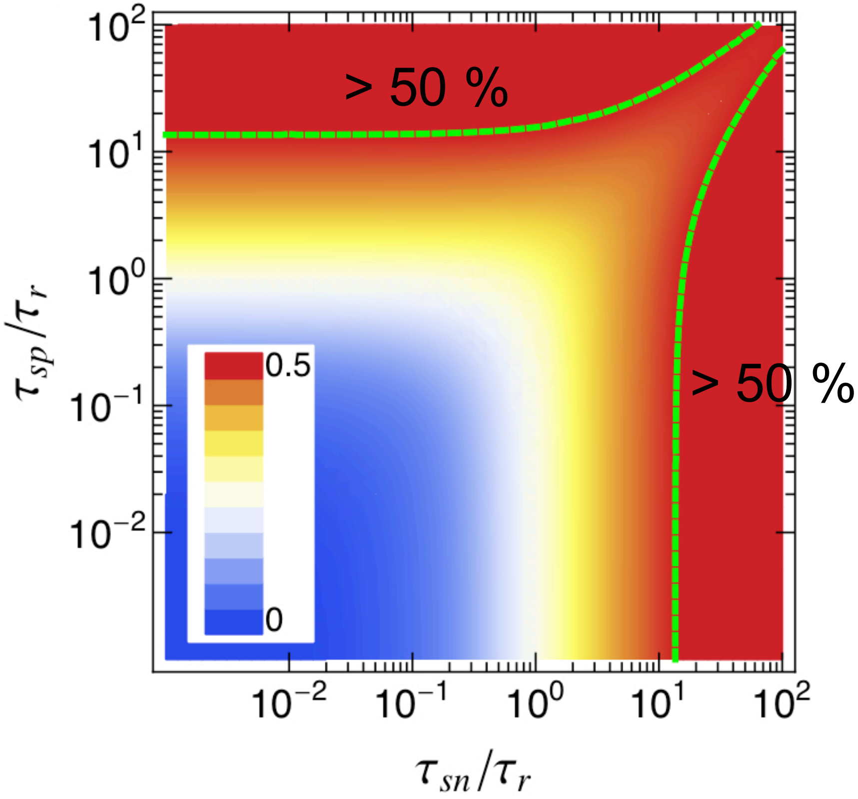
J. Lee et al, PRB **85**, 045314 (2012)

Spin Relaxation Time: Longer is Better ?

Common Understanding: longer spin relaxation time better for spintronics

Not so simple, short t_s can improve operation

Threshold Reduction: max 50% (bucket model)



$$dn_\pm/dt = \cdots - (n_\pm - n_\mp)/\tau_{sn}$$

$$dp_\pm/dt = \cdots - (p_\pm - p_\mp)/\tau_{sp}$$

$$dS^\pm/dt = \cdots$$

spin relaxation time
for electrons, holes

t_{sn} / t_{sp} >> 1 bulk GaAs
~ 1 quantum dots
<< 1 MoS_2

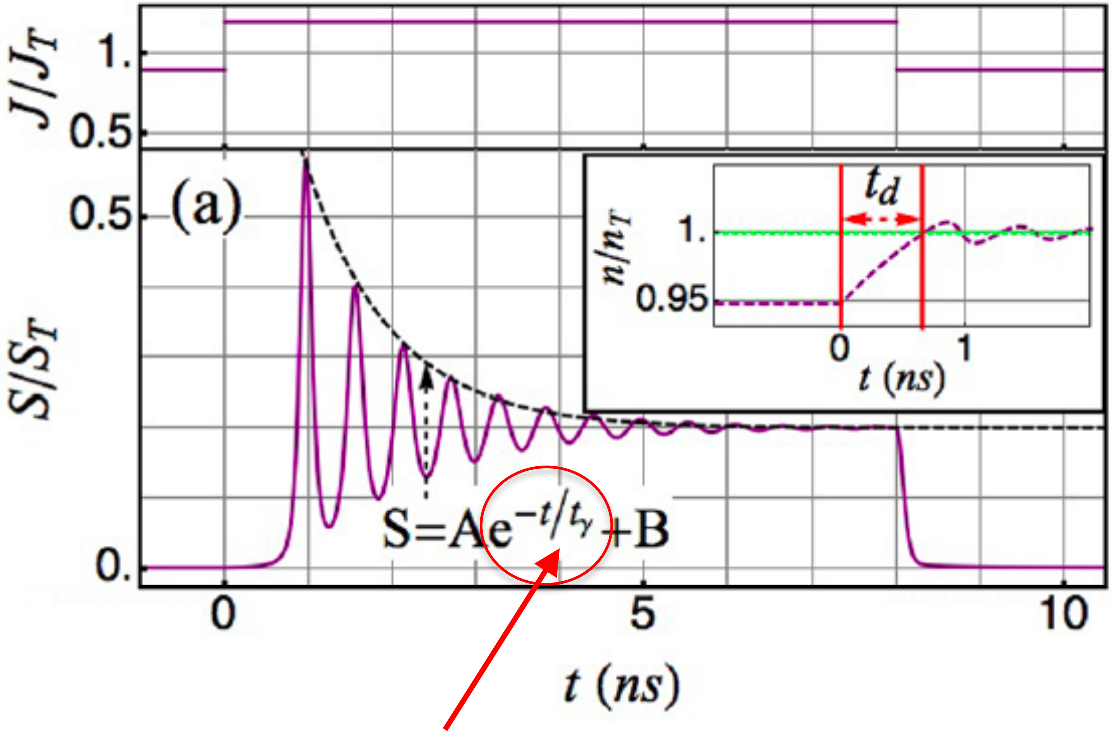
various trends nonmonotonic
in spin relaxation times

J. Lee, E. Wasner, S. Bearden, and I. Zutic, APL 105, 042411 (2014)

Large Signal Analysis: Digital Operation

Conventional Laser (P_J=0) Step-Like Injection

Overshoot in carrier & photon densities, damped oscillations to steady state



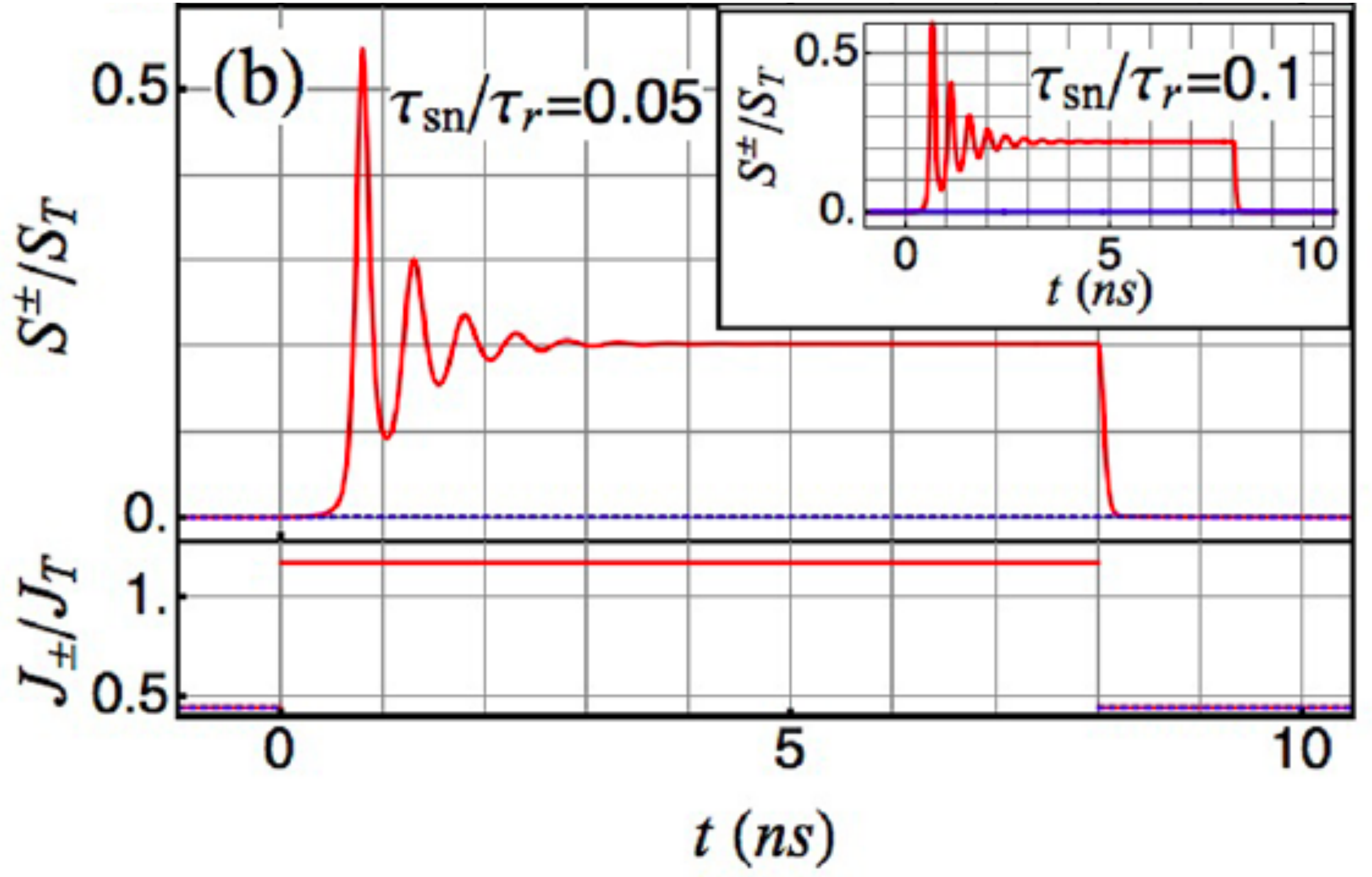
tg decay time for damped oscillations

Can we decrease tg and get a better step-like (digital) output ?

J. Lee et al., APL 105, 042411 (2014)

Large Signal Analysis: Decay Time

Spin Laser (P_J=1) Step-Like Injection

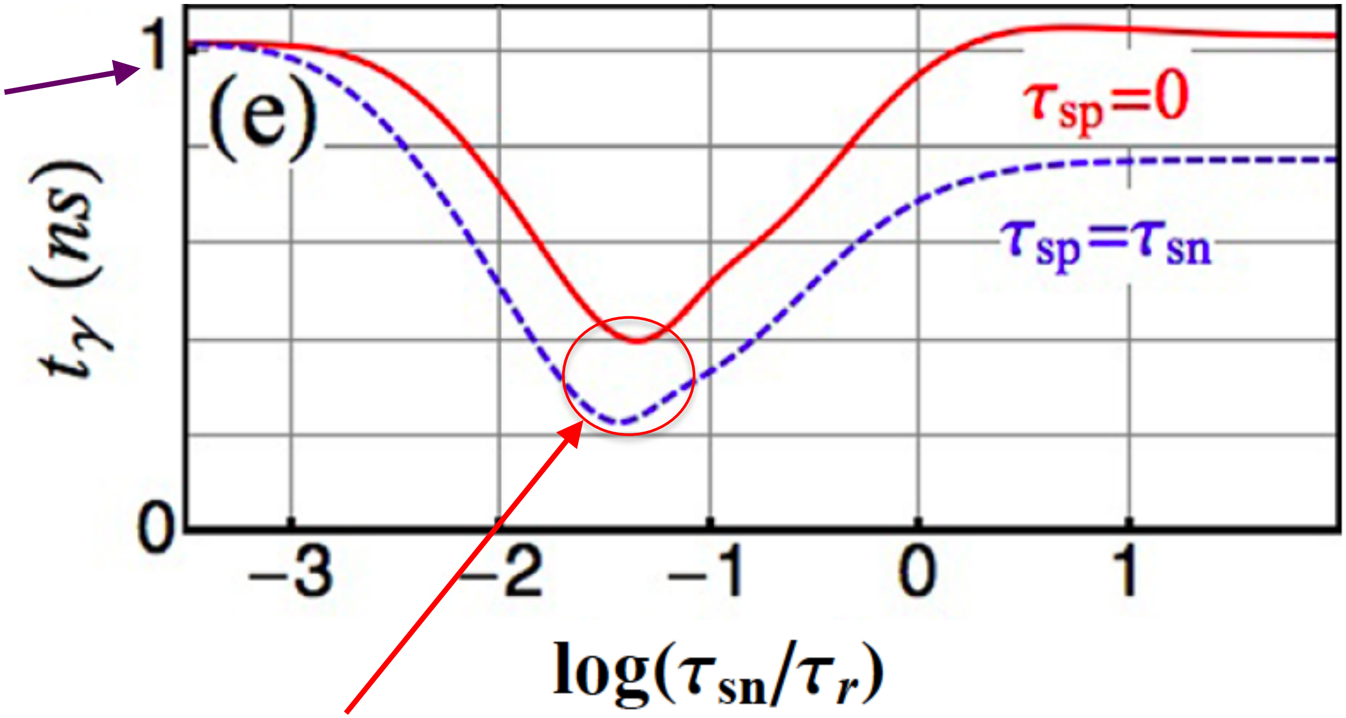


tg depends nonmonotonically on t_{sn}

J. Lee et al., APL 105, 042411 (2014)

Spin Lasers: Minimum Decay Time

t_g^0



unpolarized holes

Optimal Performance:

short, NOT long spin relaxation time!

$$1/t_g = 1/t_g^0 + 1/t_g^S$$

spin-independent spin-dependent

$$t_g^{MIN} = \begin{array}{ll} t_g^0/2 & t_{sp} = 0 \\ t_g^0/3 & t_{sn} = t_{sp} \end{array}$$

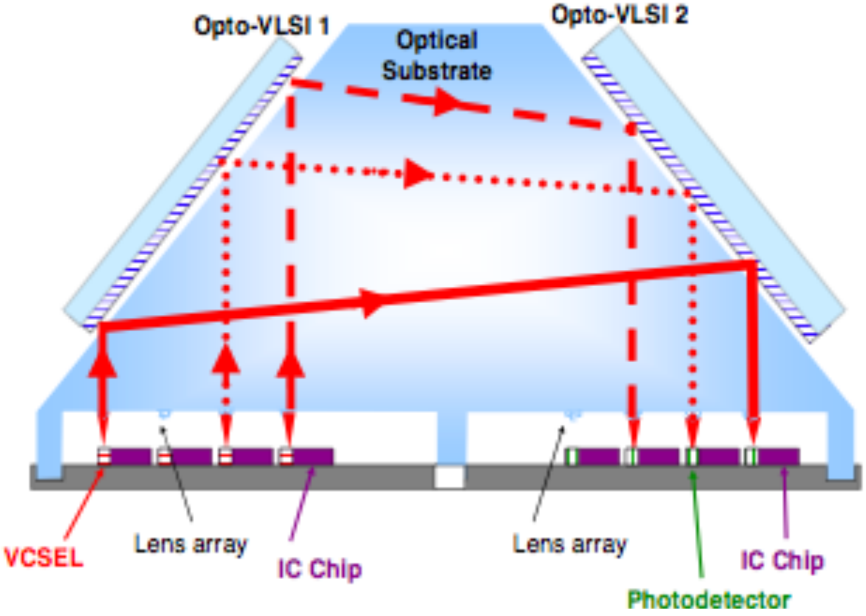
Information Transfer with Spin Lasers?

Interconnects Bottleneck !

Conventional Lasers already used for High-Performance Optical Interconnects

Potential advantages of Spin Lasers:

- Smaller Chirp (distortion) switching at fixed injection!
- Shorter Turn On Time
- Enhanced Light Emission
- Improved Stability
- Secure Communication
- Reconfigurable Interconnects



M. Aljada et al., Optics Express 15, 6823 (2006)

Other Ideas?   3D TV, Spin-Interconnects,…

E. Wasner, S. Bearden, J. Lee, and I. Zutic, preprint

Silicon Spin Interconnects (On Chip)

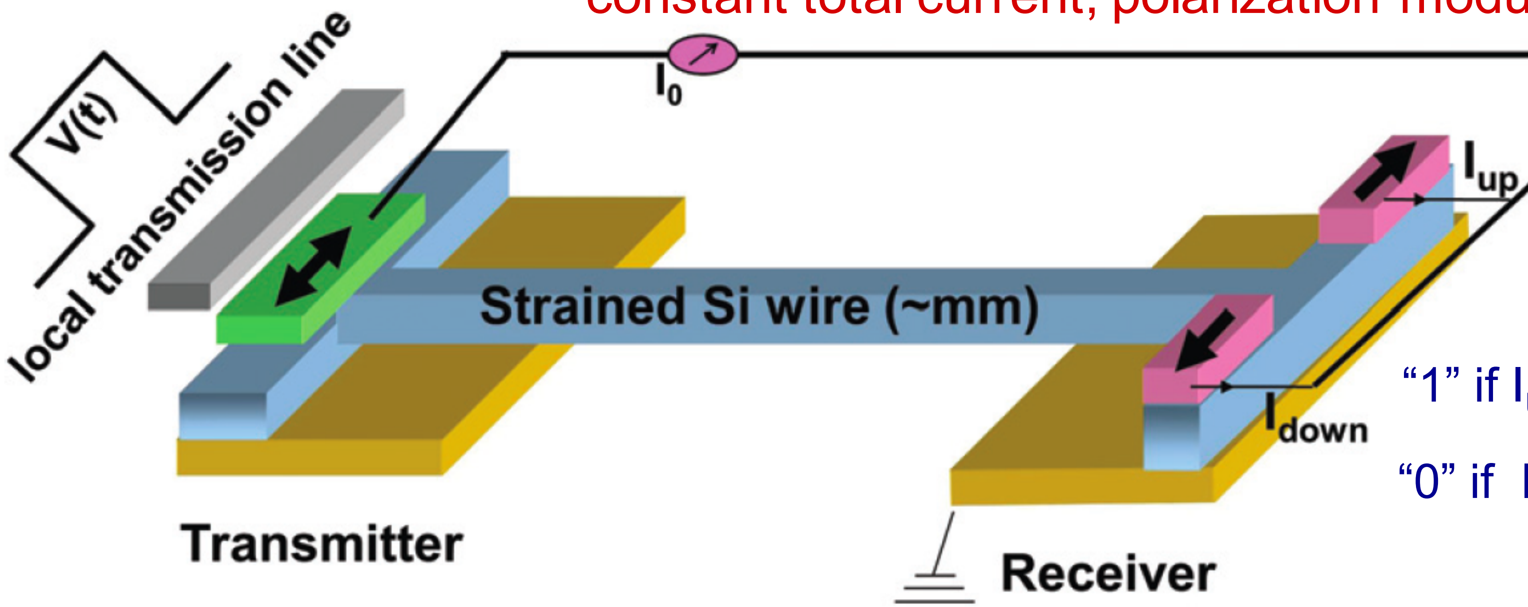
metallic interconnects: dynamical cross-talk, RC bottlenecks, electromigration,…

Si – long spin relaxation times (~10 ns @ 300 K), transfer length >100mm

B. Huang et al., APL 93, 162508 (2008)

other candidates: Ge, graphene

constant total current; polarization modulation



“1” if $I_{up} < I_{down}$

“0” if $I_{up} > I_{down}$

Effective bandwidth **100-1000 x greater** than in metallic interconnects

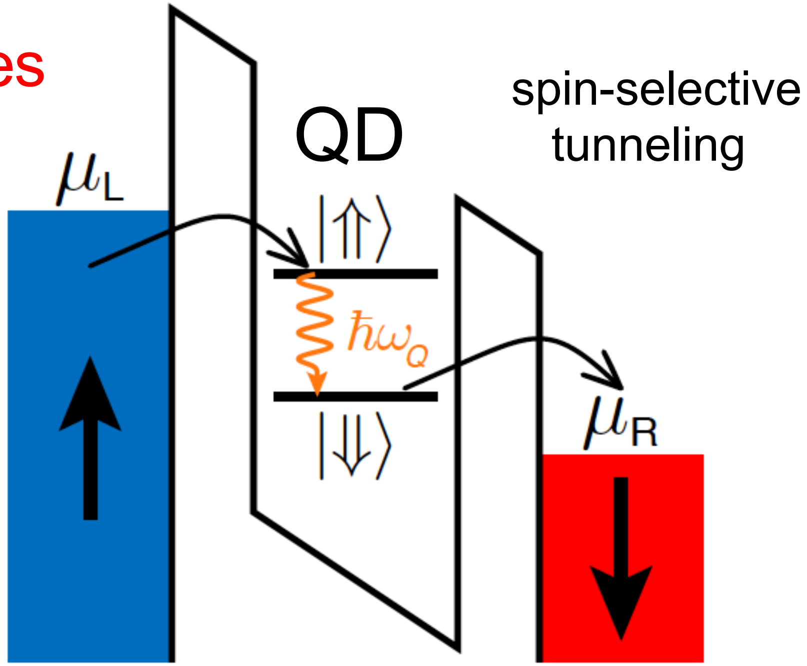
H. Dery, Y. Song, P. Li, I. Žutić, APL 99, 082502 (2011)

Other Opportunities ?

Phonon Laser using QD Spin States

1) population inversion
2) phonon emission dominant
3) overcome the lasing threshold

High phonon DOS obstacle for coherent phonon generation (acoustic phonons much slower than photons)



A. Khaetskii, V. N. Golovach, X. Hu, I. Žutić, PRL **111**, 186601 (2013)

Phonon Laser also proposed in Nanomagnets

E. M. Chudnovsky and D. A. Garanin, PRL 93, 257205 (2004)

Ultra-Fast Spin Lasers?

Polarization can be modulated faster than intensity

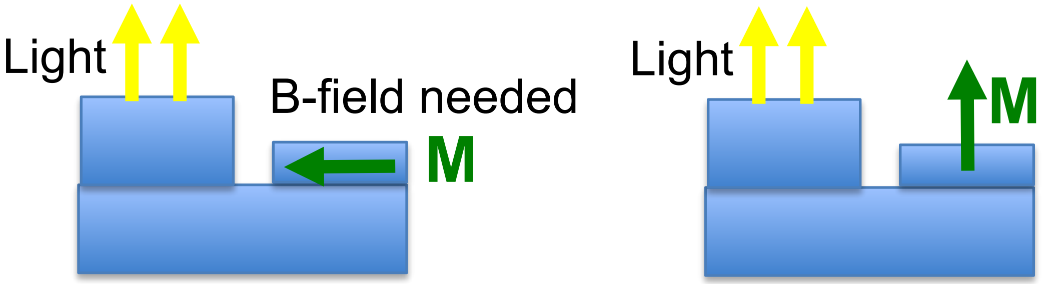
H. Hopfner et al., APL **104**, 022409 (2014)

Conclusions & Perspectives

- semiconductors highly nonlinear response: not limited to magnetoresistace
- optimal digital operation for short spin relaxation times
- our microscopic analysis: spin-laser faster than the best $P_J=0$ lasers

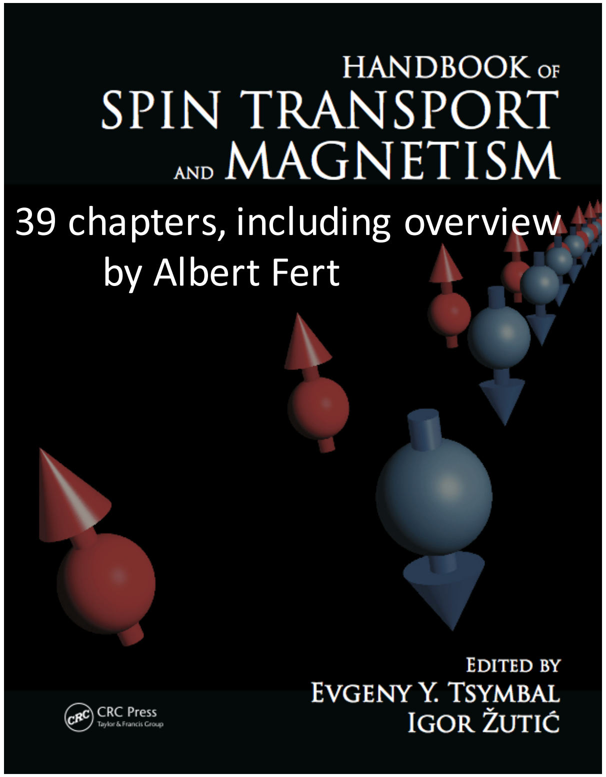
more on spintronics, lasers

Perpendicular Anisotropy Good (MRAM)



FeCoB-MgO S. Ikeda et al., Nature Mater. (2010)

Ultra-Fast Magnetization Switching

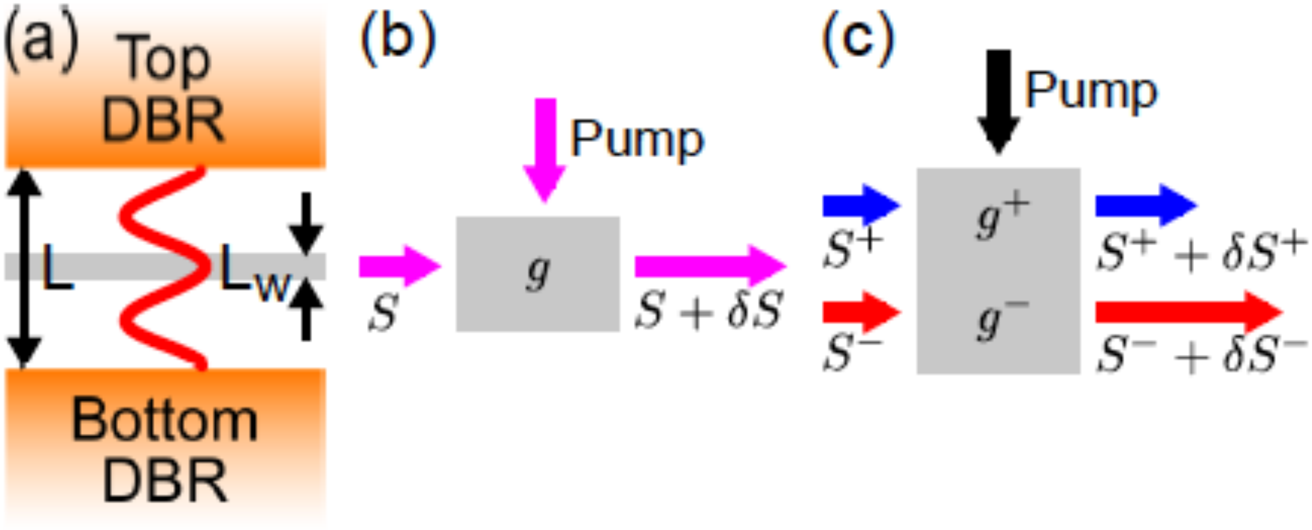

HANDBOOK OF
SPIN TRANSPORT
AND MAGNETISM

39 chapters, including overview
by Albert Fert

EDITED BY
EVGENY Y. TSYMBAL
IGOR ŽUTIĆ

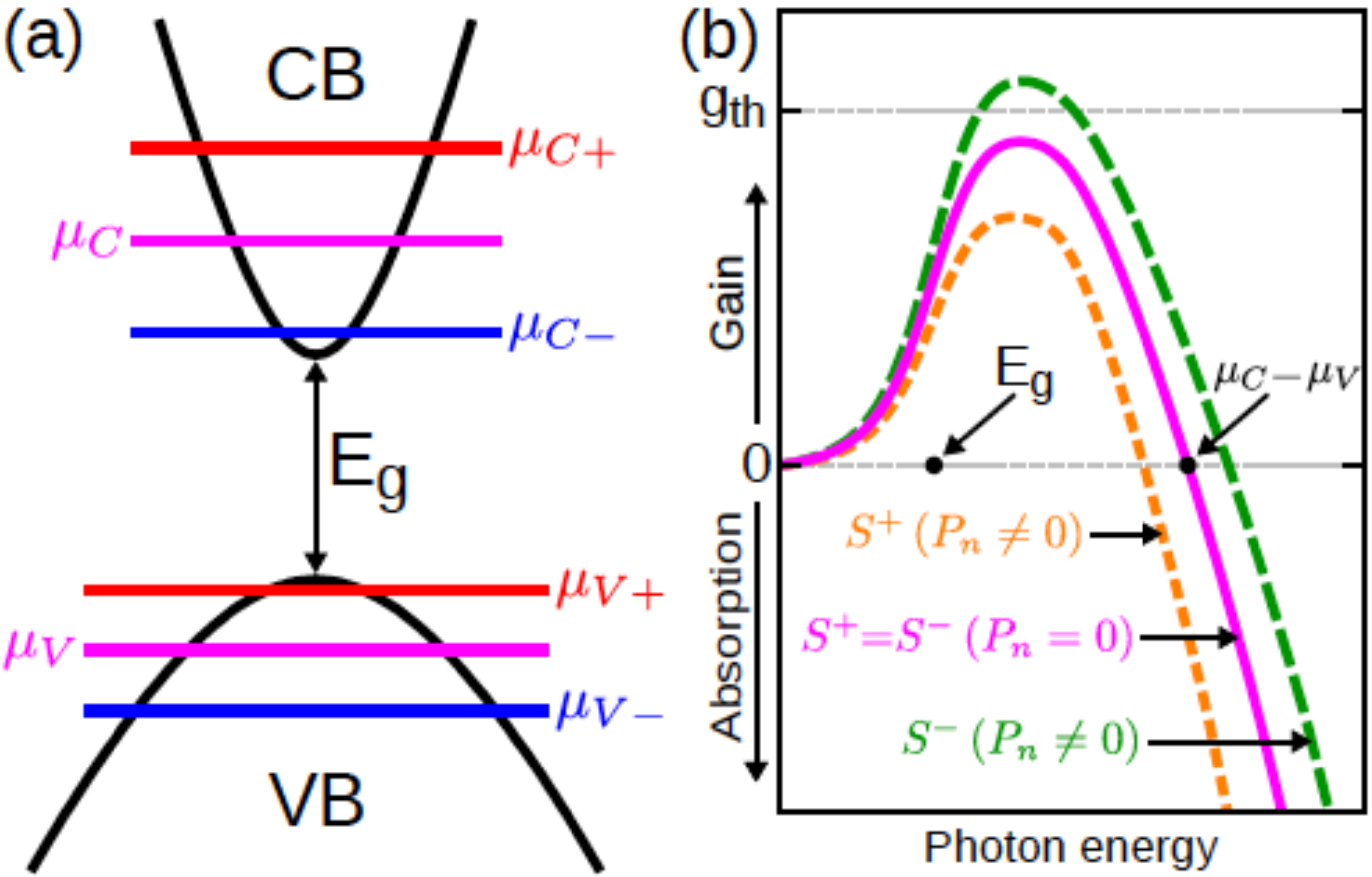
CRC Press
Taylor & Francis Group

Optical Gain



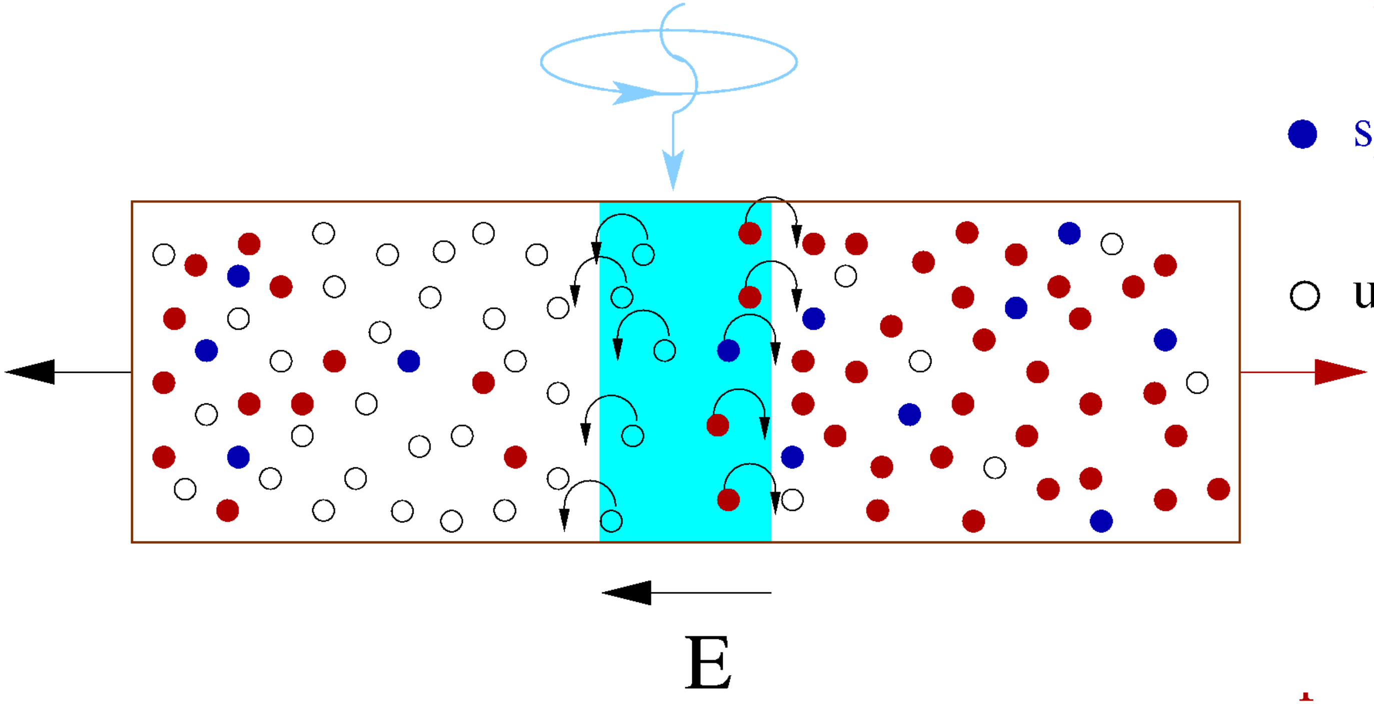
$$g^a(\omega) = -\frac{\omega}{c n_r} \epsilon_i^a(\omega)$$

Optical Gain



Spin Solar Cell ("Battery") Spin EMF

I. Zutic, J. Fabian, S. Das Sarma, APL 79, 1558 (2001)



● spin up electrons

● spin down electrons

○ unpolarized holes

A source of spin-dependent current & voltage

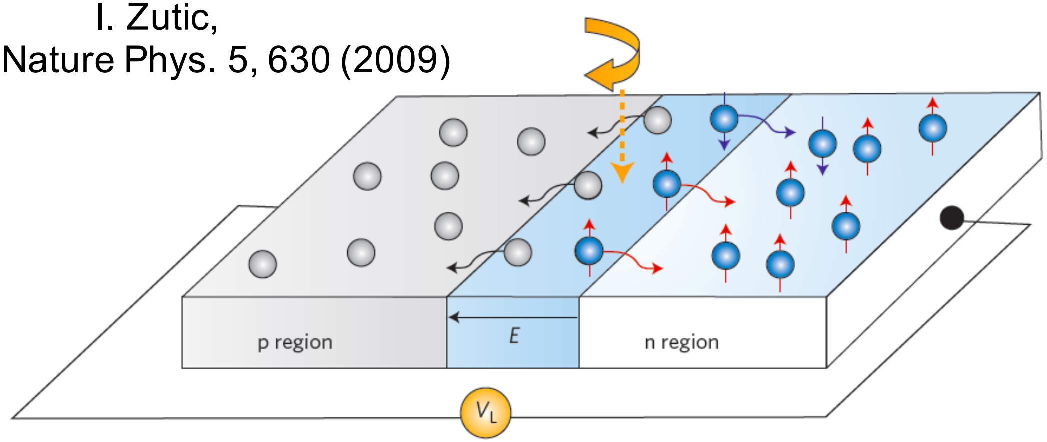
Inhomogeneous doping and carrier density:
important to self-consistently solve Poisson & drift-diffusion equations

Spin Injection Hall Effect: Transverse Photo-Induced Voltage
J. Wunderlich et al., Nature Phys. 5 (2009)

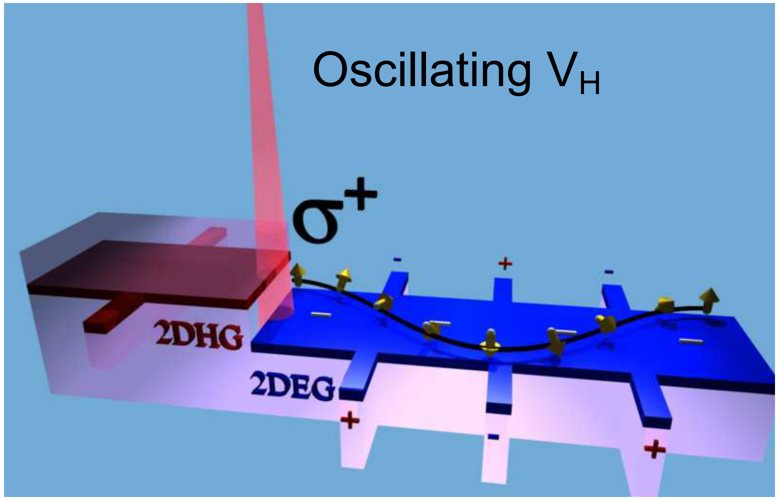
Longitudinal & Transverse Voltage

many experimental possibilities
even in GaAs-based junctions

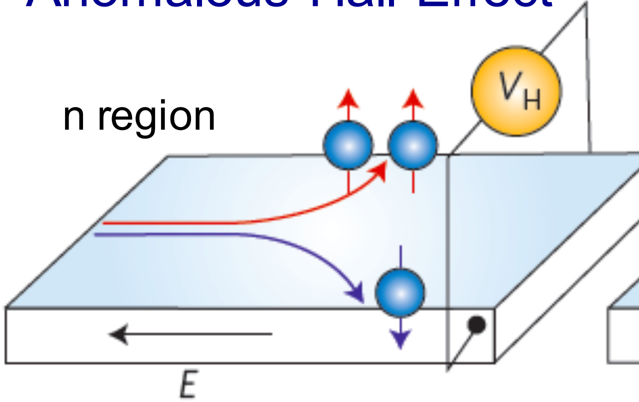
I. Zutic,
Nature Phys. 5, 630 (2009)



J. Wunderlich et al.
Nature Phys. 5, 675 (2009)

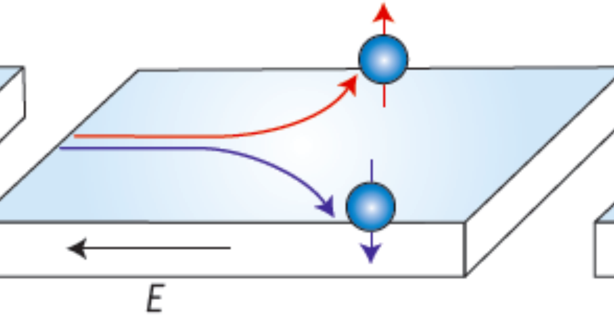


Anomalous Hall Effect



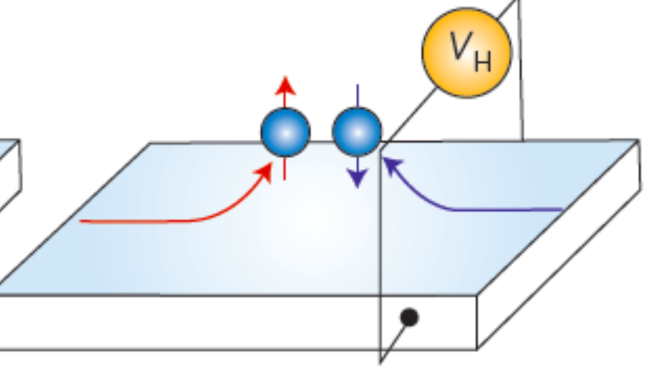
spin imbalance & V_H
spin-dependent scattering
due to spin-orbit coupling

Spin Hall Effect



M. I. D'yakonov, V. I. Perel
Phys. Lett. 35A, 459 (1971)

Inverse Spin Hall Effect



pure spin currents

S. O. Valenzuela, M. Tinkham
Nature 442, 176 (2006)

Magnetic Bipolar Transistor

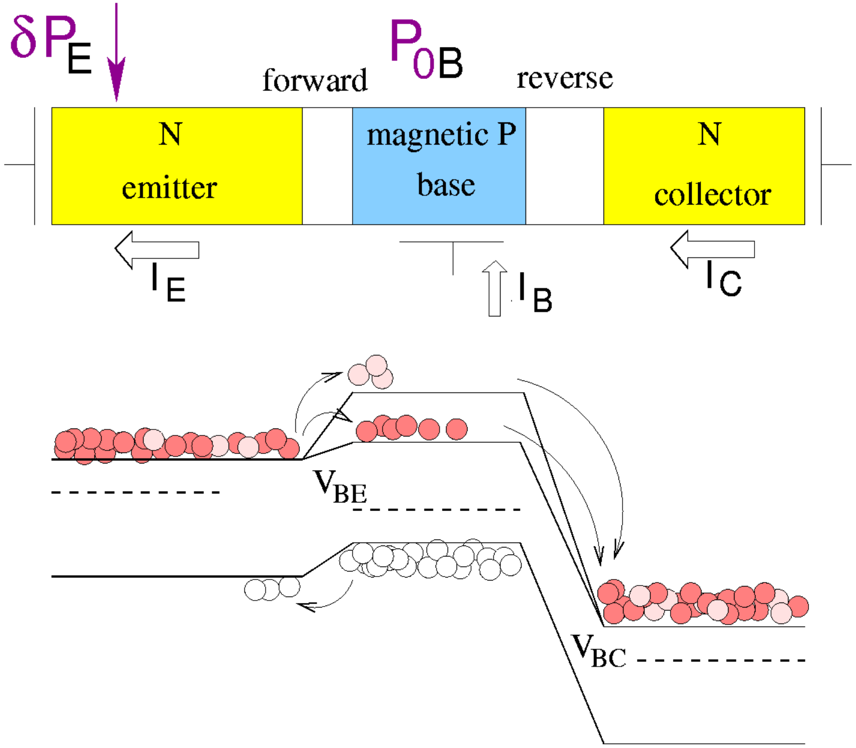
δP_E nonequilibrium spin polarization in the Emitter

P_{0B} equilibrium spin polarization in the Base

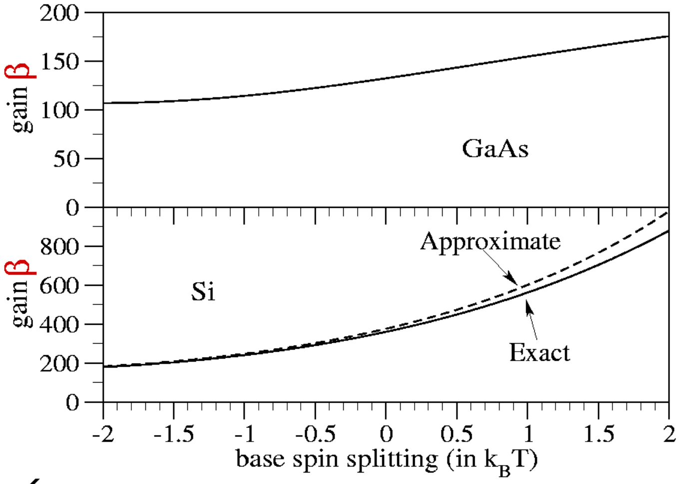
spin-voltaic effect

$$\beta = \frac{I_C}{I_B}$$ Amplification (Current Gain)

$$\beta \rightarrow \boxed{\delta P_E \; P_{0B}}$$ dynamically tunable



$$\beta = I_C / I_B \sim (1+\delta P_E P_{0B}) / \sqrt{1 - P_{0B}^2}$$

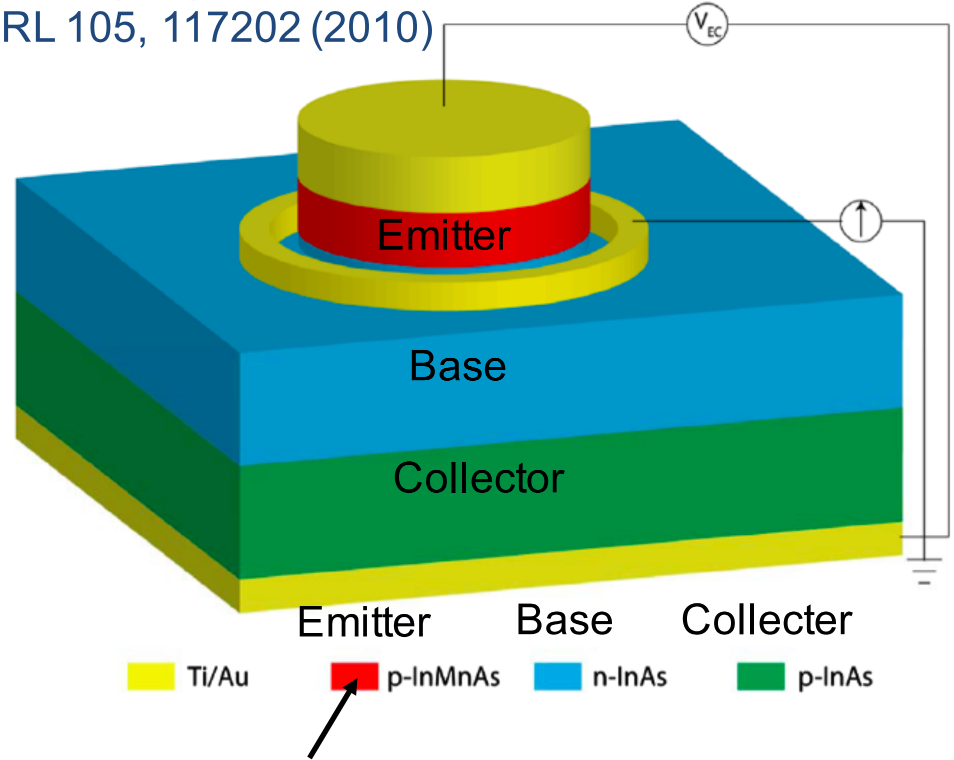


Si – based favorable!

J. Fabian and I. Zutic, PRB 69, 115314 (2004)
APL 84, 85 (2004), APL 86, 133506 (2005)

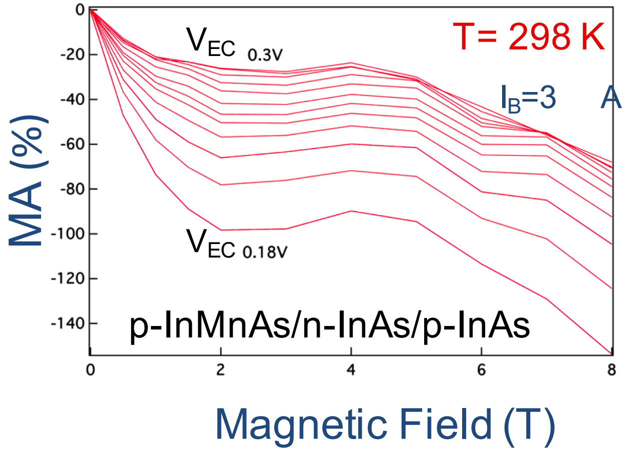
Magnetic Bipolar Transistor: Experiment

N. Rangaraju, J.A. Peters, B.W. Wessels
PRL 105, 117202 (2010)



Ferromagnetic

Magneto Amplification (MA):



MA = dc / dc dc

dc

dc

C B C

Magnetic Bipolar Transistor:
B-field changes spin-splitting & amplification

we also proposed other possibilities :
using nonequilibrium spin and control of ferromagnetism

theory:
J. Fabian, I. Zutic, PRB B 69, 115314 (2004)