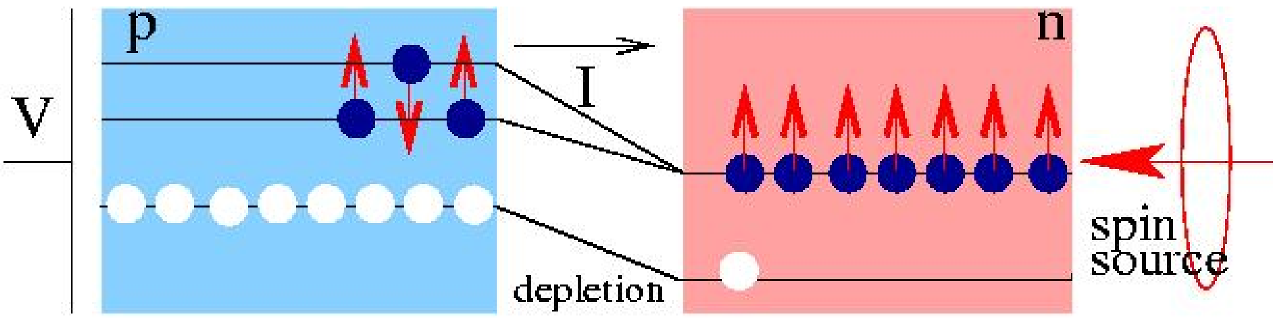
SPIN RELAXATION & SPIN TRANSPORT IN ELECTRONIC MATERIALS

Jaroslav Fabian

Institute for Theoretical Physics
Karl-Franzens University Graz



Collaborators:
Igor Žutić[1,2] and Sankar Das Sarma[1]

[1]Condensed Matter Theory Center
University of Maryland at College Park

[2]Naval Research Laboratory, Washington DC

OUTLINE

1. SPINTRONICS

2. SPIN RELAXATION

3. BIPOLAR SPINTRONICS:

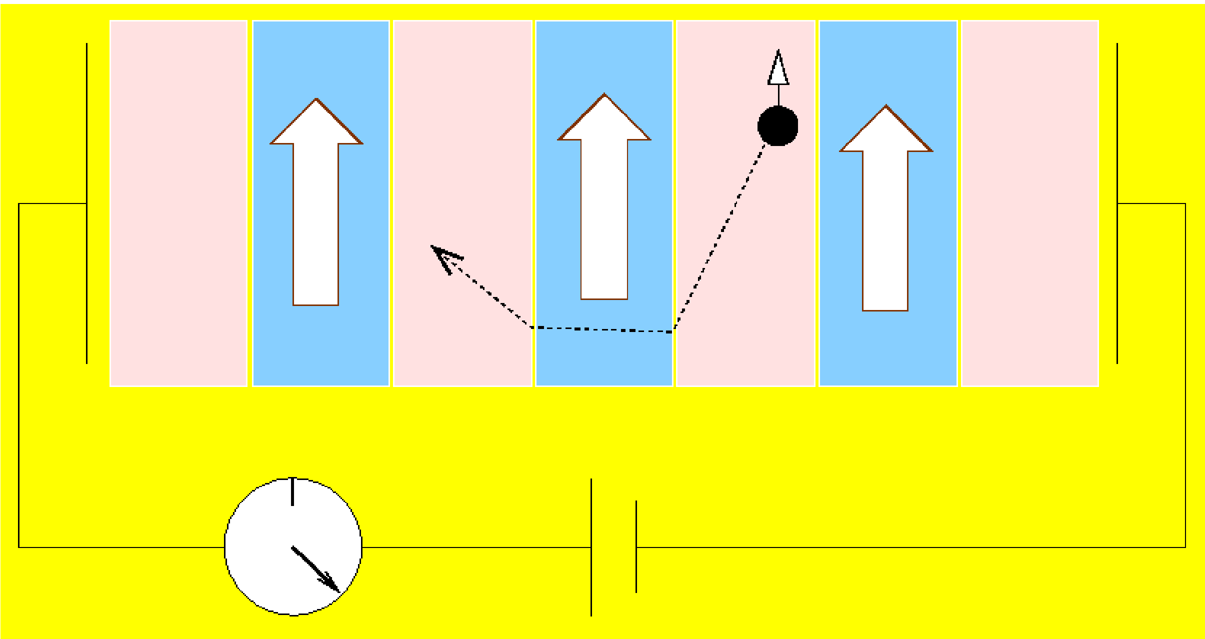
   MAGNETIC BIPOLAR DIODE
   MAGNETIC BIPOLAR TRANSISTOR

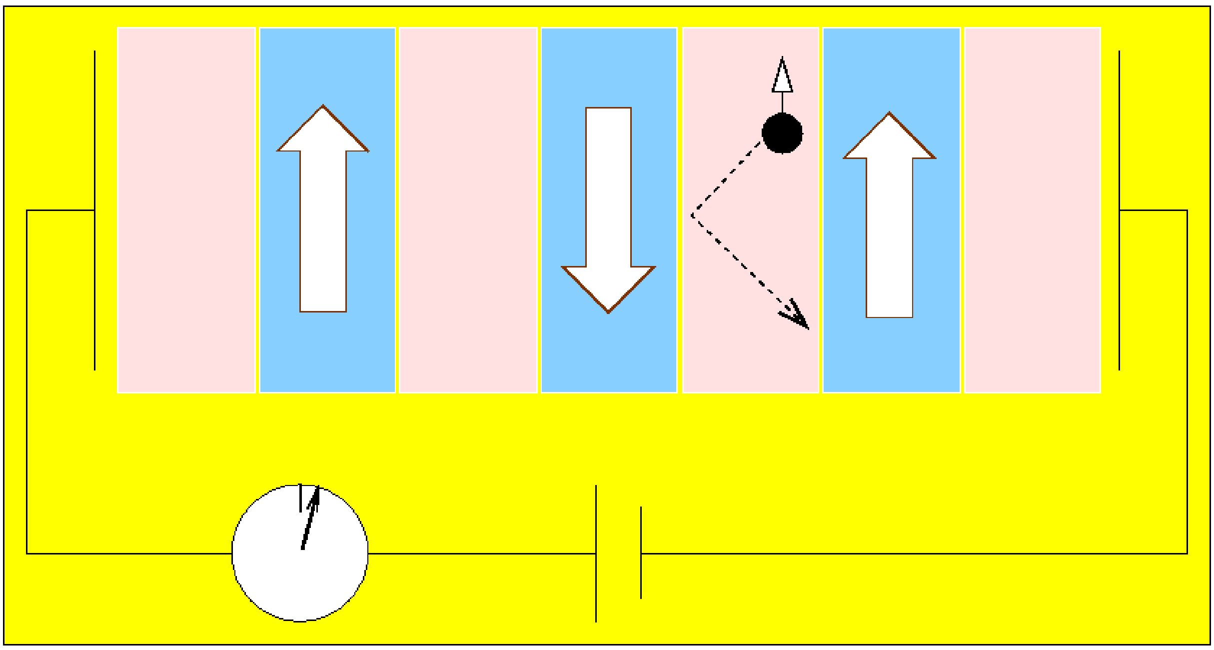
4. SUMMARY AND OUTLOOK

1. SPINTRONICS

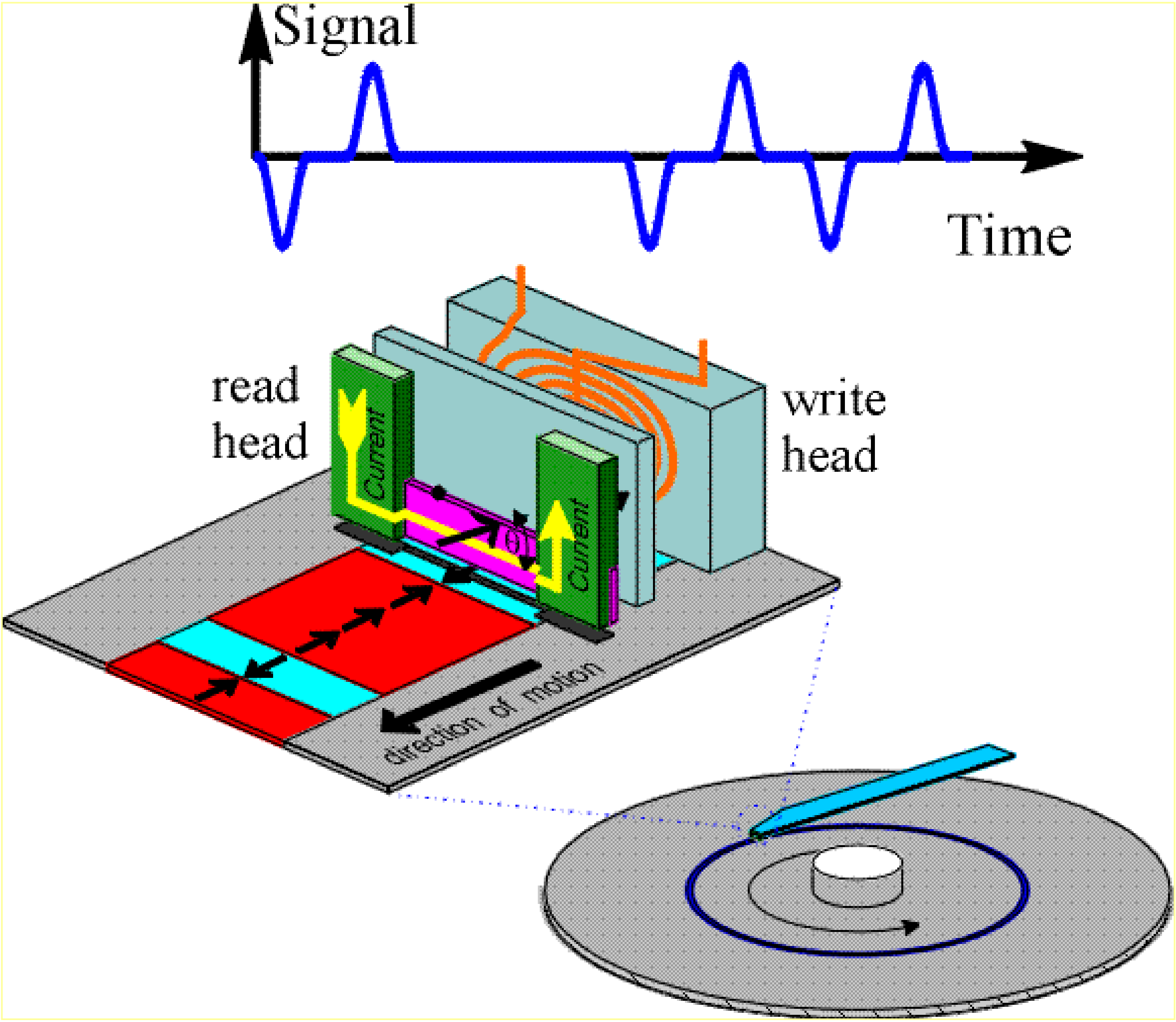
ELECTRONICS WITH A SPIN

GIANT MAGNETORESISTANCE (GMR)
MAGNETOELECTRONICS





MODERN COMPUTER HARD DISK READ HEAD



Source: IBM web site

SEMICONDUCTOR SPINTRONICS

WHY SEMICONDUCTORS?

- MORE VERSATILE THAN METALS
- INFORMATION TECHNOLOGY BASED ON SEMICONDUCTORS (Si)
- HYBRID STRUCTURES (quantum wells, quantum dots)

GOAL?

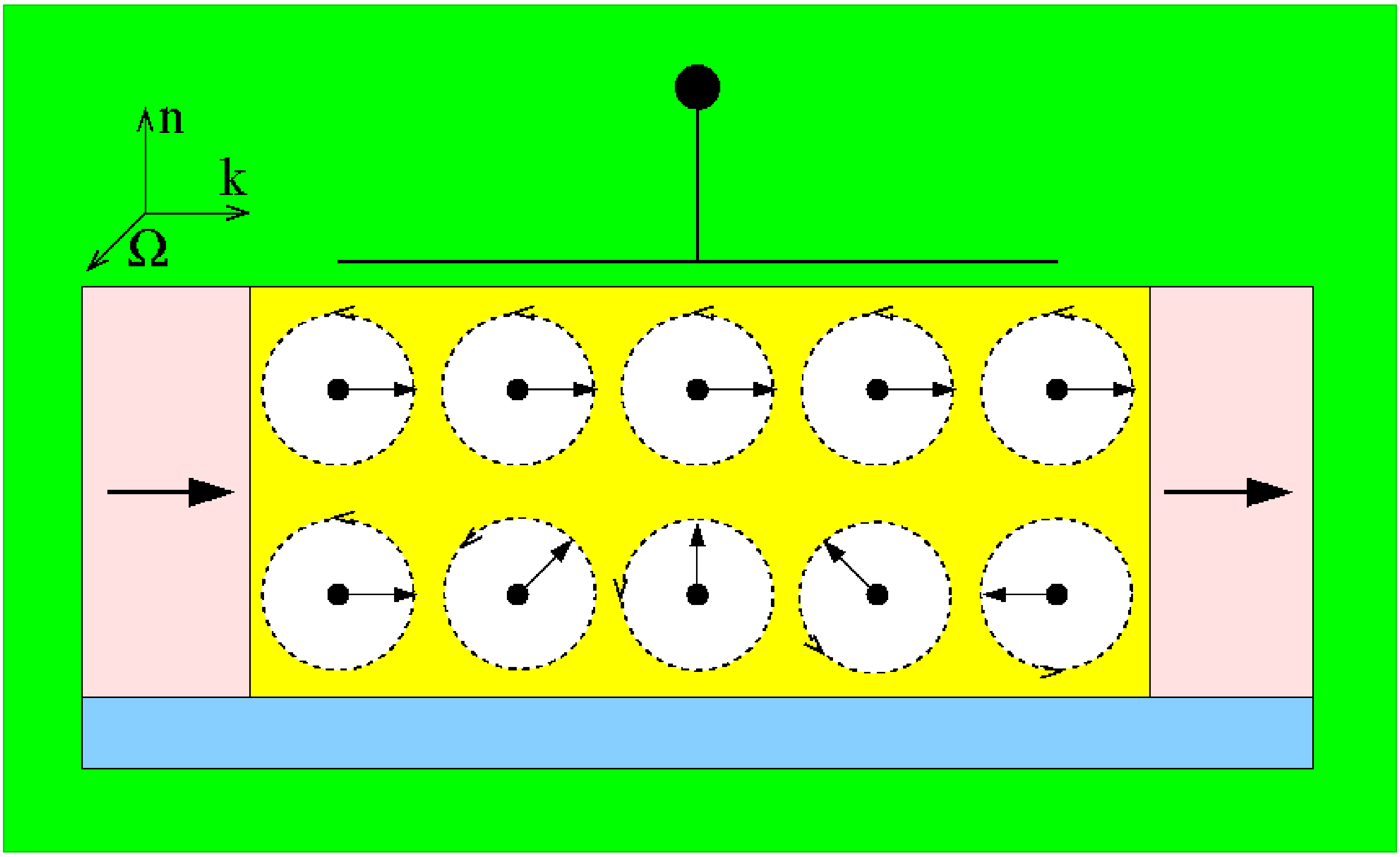
SPIN CONTROL OF ELECTRICAL PROPERTIES
(I-V CHARACTERISTICS, …)
ELECTRICAL CONTROL OF SPIN
(MAGNETIZATION DIRECTION,…)

APPLICATIONS?

MAGNETIC FIELD SENSORS
NONVOLATILE MEMORY
QUANTUM COMPUTING

DATTA-DAS
FIELD-EFFECT
SPIN TRANSISTOR

PROTOTYPICAL SEMICONDUCTOR
SPINTRONICS DEVICE

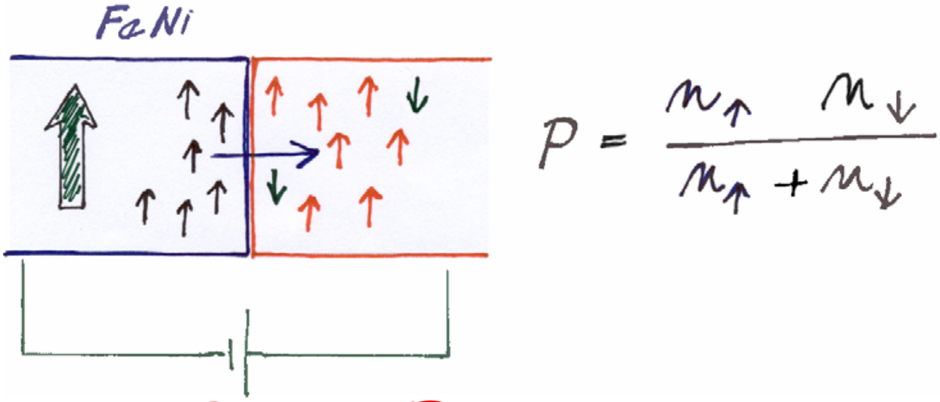


S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990)

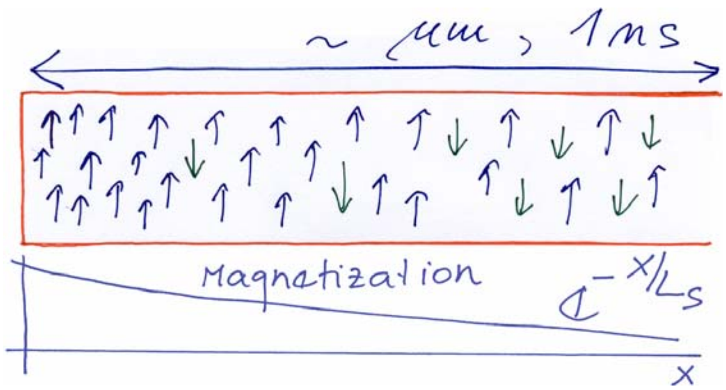
SPINTRONICS'

3 REQUIREMENTS

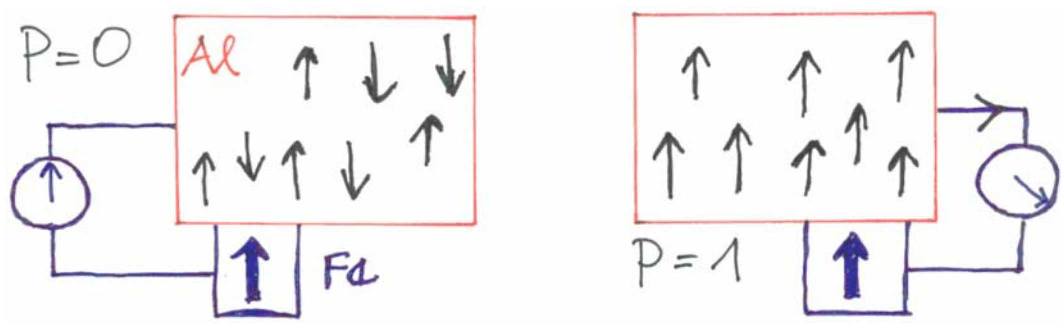
- **EFFICIENT SPIN INJECTION**



- **SLOW SPIN RELAXATION**



- **RELIABLE SPIN DETECTION**



SPIN INJECTION INTO SEMICONDUCTORS

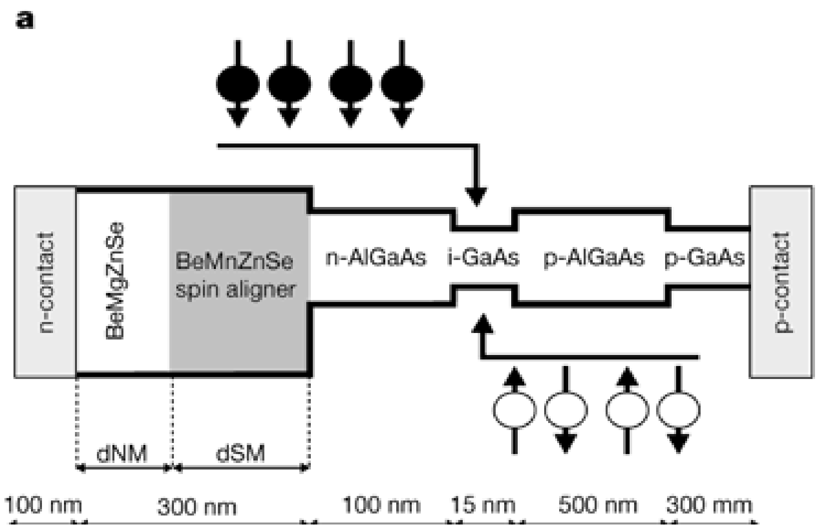
Theoretically predicted by

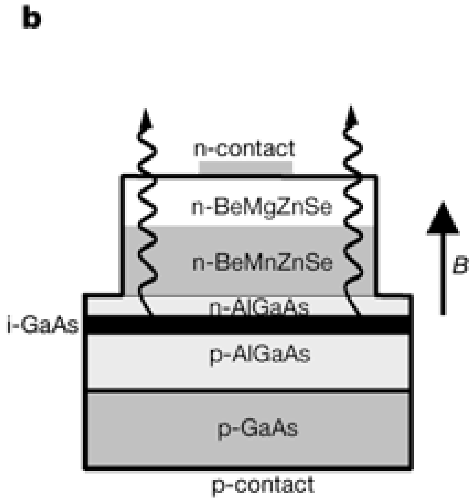
A. G. Aronov and G. E. Pikus, Fiz. Tekh. Poluprovodn. 10, 1177 (1976) [Sov. Phys. Semicond. 10, 698-700 (1976)]

Experimentally first realized by

M. Johnson and R. H. Silsbee, Phys. Rev. Lett. 55, 1790 (1985)

Experimental realization in semiconductors:



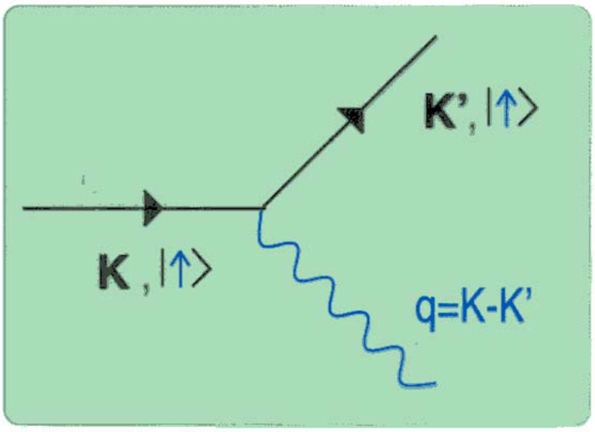


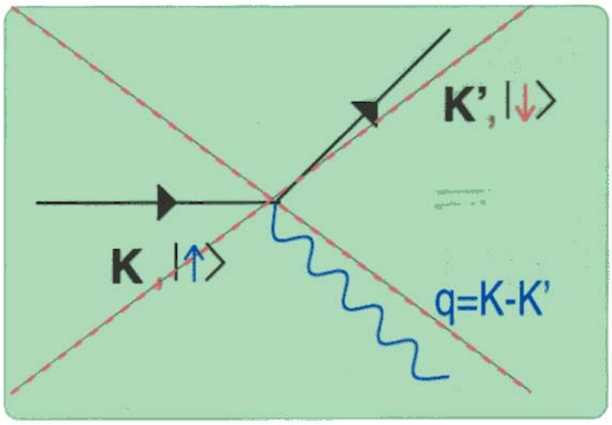
Fiederling et al. Nature 402, 787 (1999).
Ohno et al. Nature 402, 790 (1999).

2. SPIN RELAXATION IN METALS

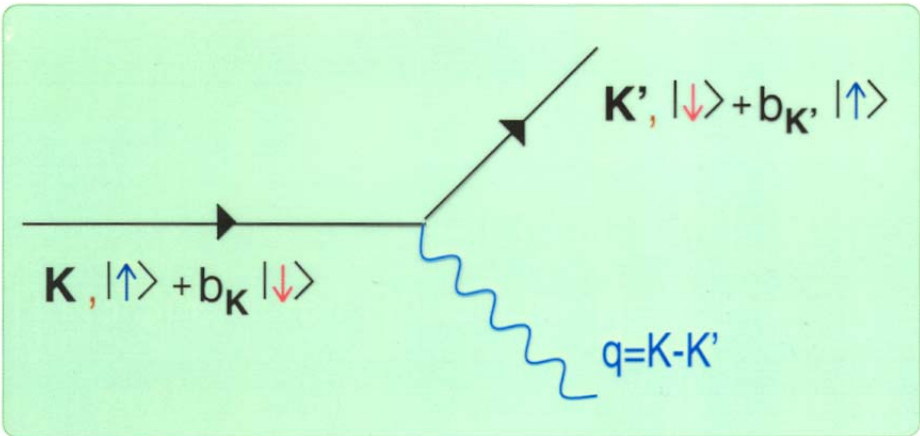
ELLIOTT-YAFET THEORY

No Spin-Orbit Coupling: $H = T + V$





2) With Spin-Orbit Coupling: $H + V_{SO}$ $\quad V_{SO} = \lambda\, \mathbf{L} \cdot \mathbf{S}$

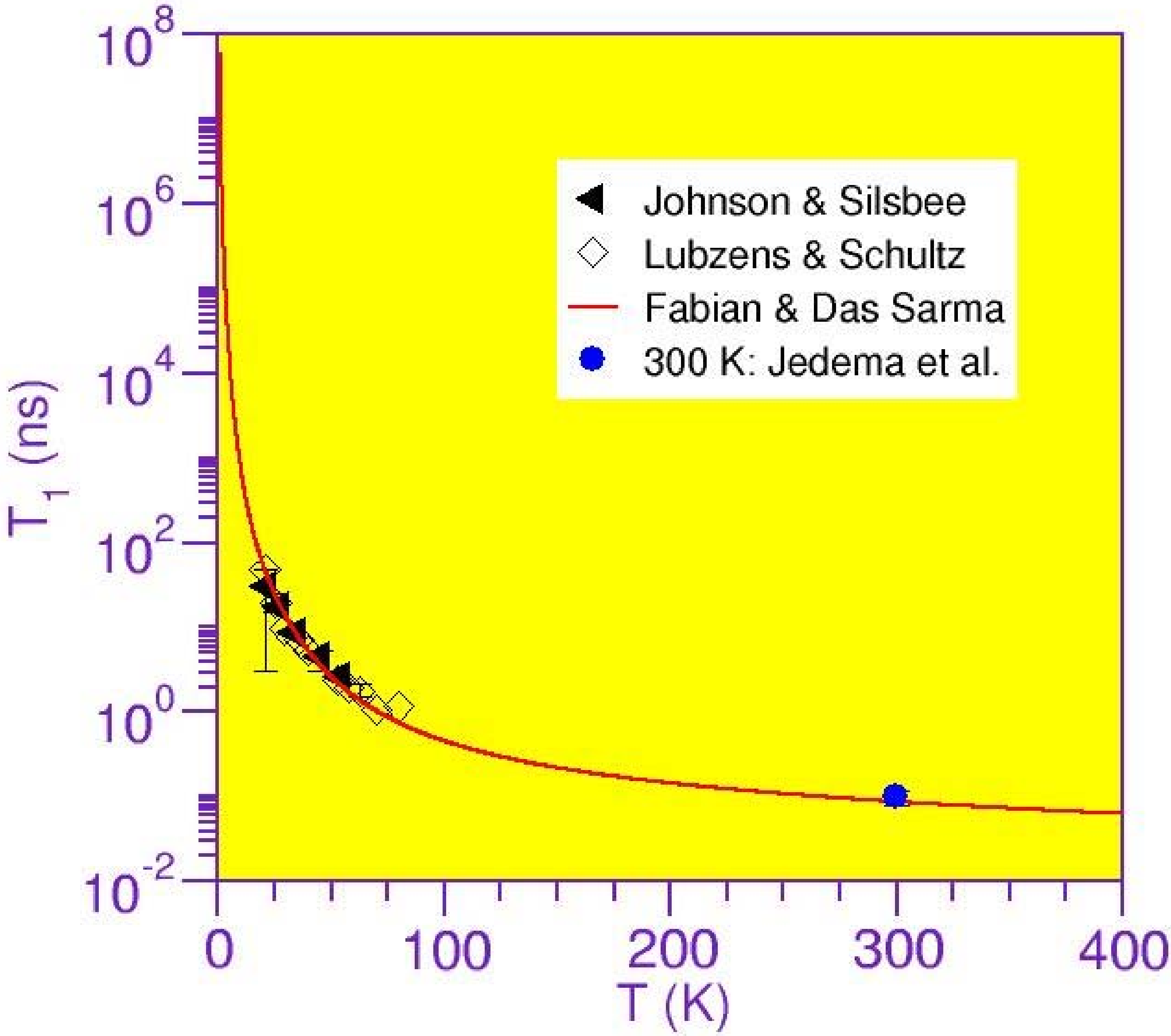


$\sim b \sim \frac{V_{SO}}{\Delta E}$

↑ central quantity

R. J. Elliott, Phys. Rev. B 96, 266 (1954)
Y. Yafet, in Solid State Physics, Vol. 14, p.2 (1963)

PHONON-INDUCED SPIN RELAXATION in Al



J. Fabian and S. Das Sarma, Phys. Rev. Lett. 81, 5624 (1998), 83, 1211 (1999).

Spin-Hot-Spot model: J. Fabian and S. Das Sarma, Phys. Rev. Lett. 81, 5624 (1998).

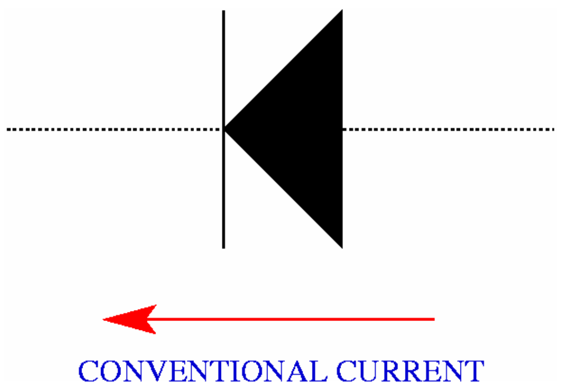
3.BIPOLAR SPINTRONICS

Semiconductor spintronics with
both electrons and holes

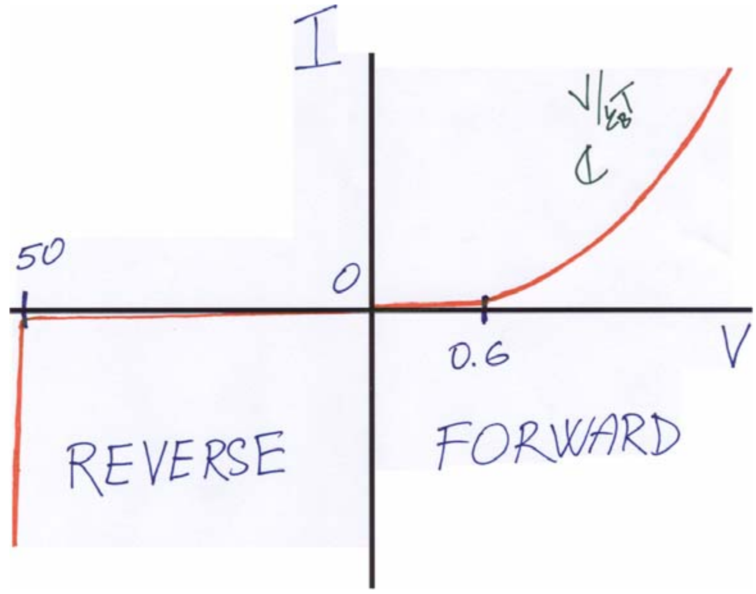
Q: Why bipolar spintronics?

A: Make use of the existing device structures (bipolar junction diodes and transistors) to manipulate electronics with spin and magnetic field.

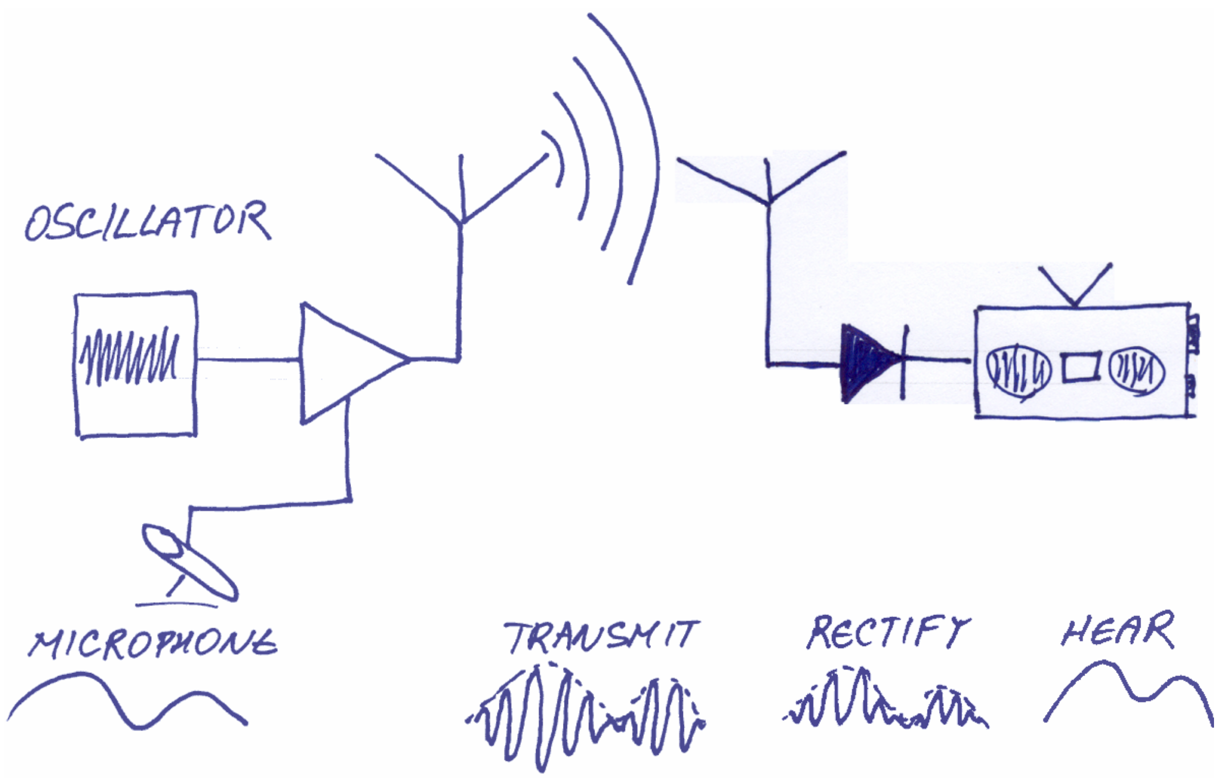
CONVENTIONAL BIPOLAR DIODE 101



SCHEME

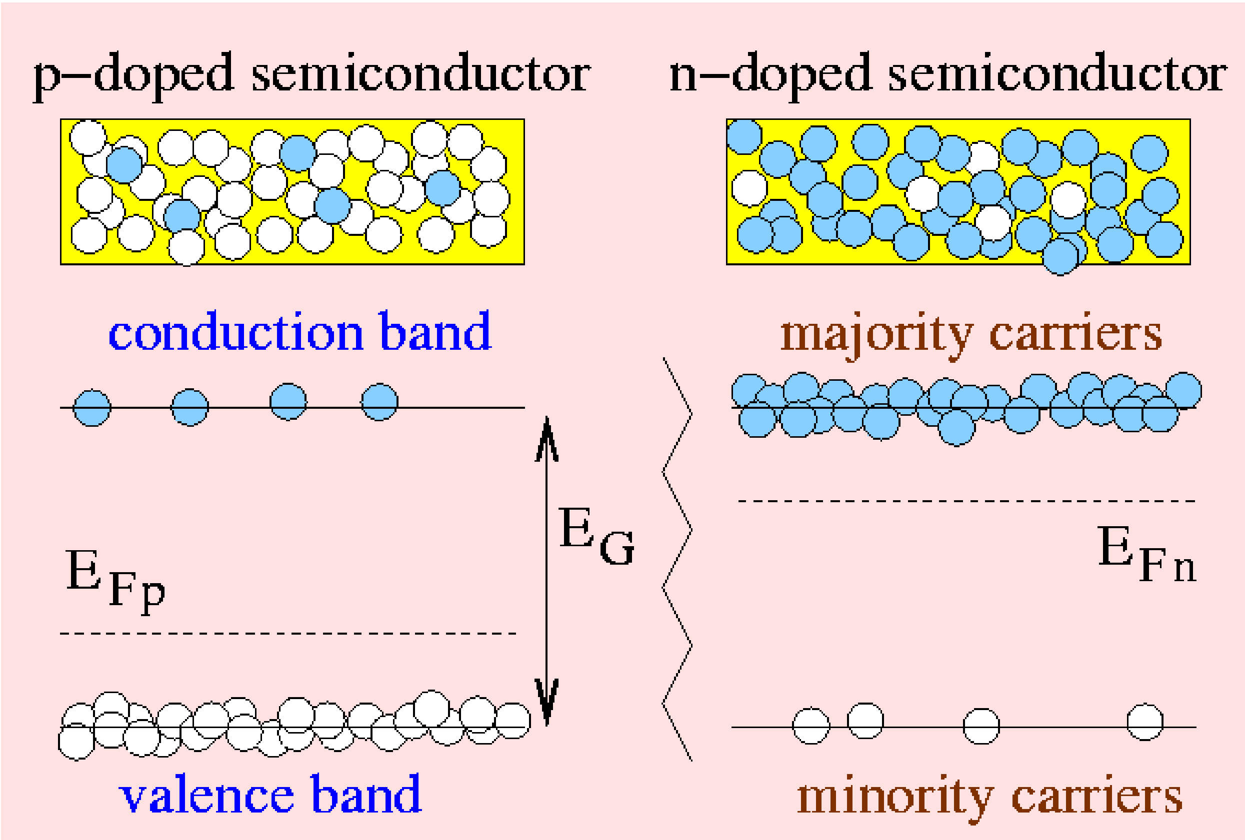


I-V CURVE

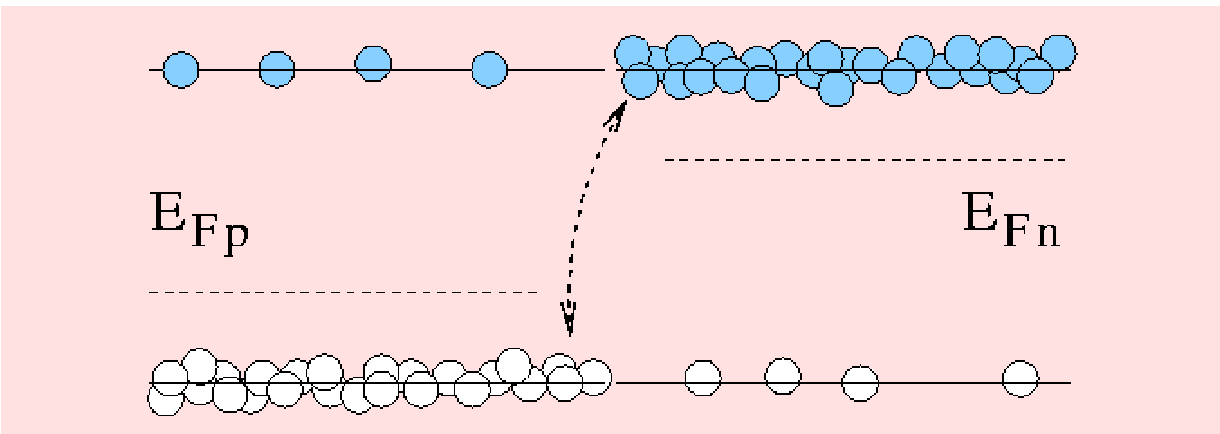


p-n JUNCTION FORMATION

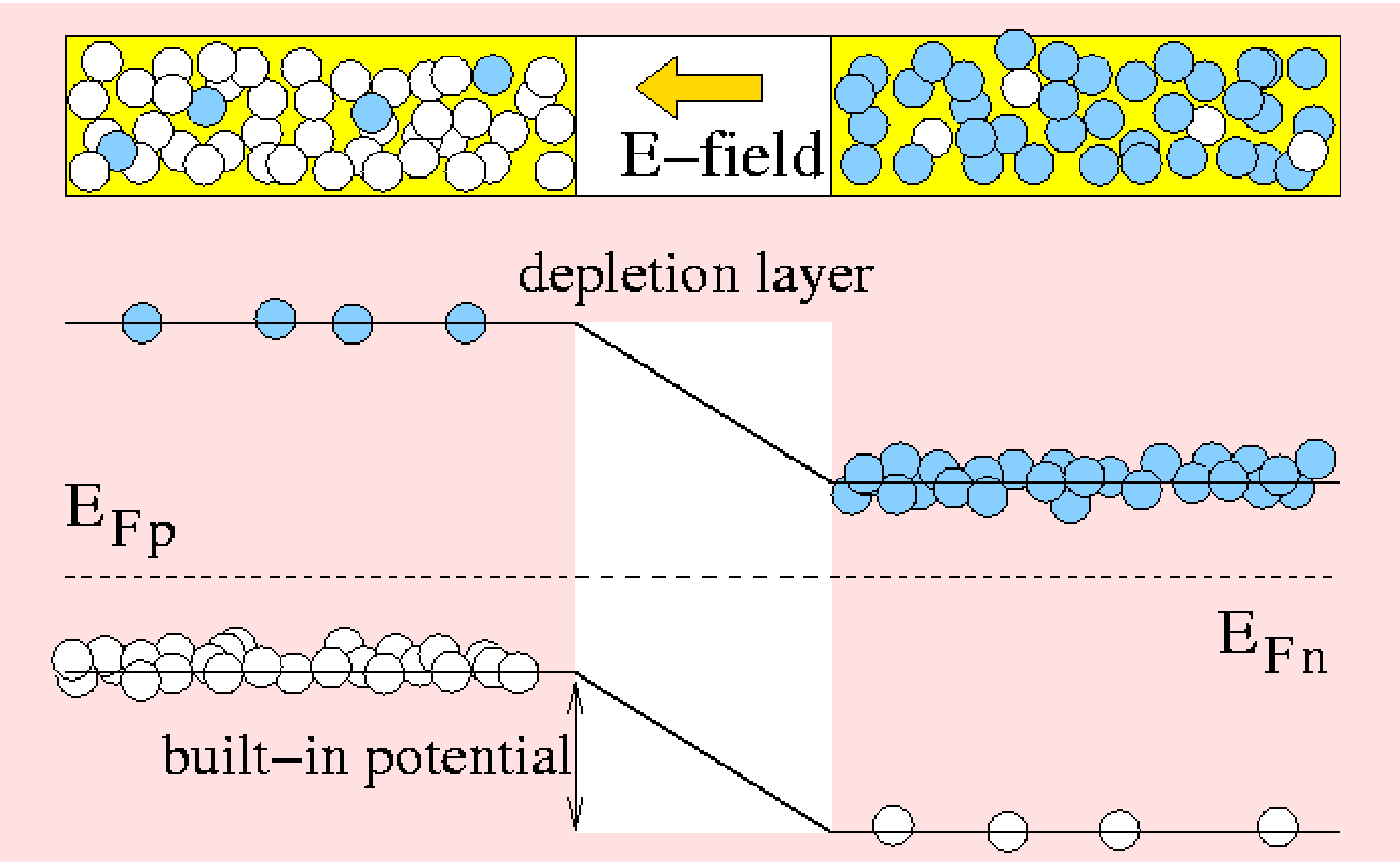
Before



junction formation

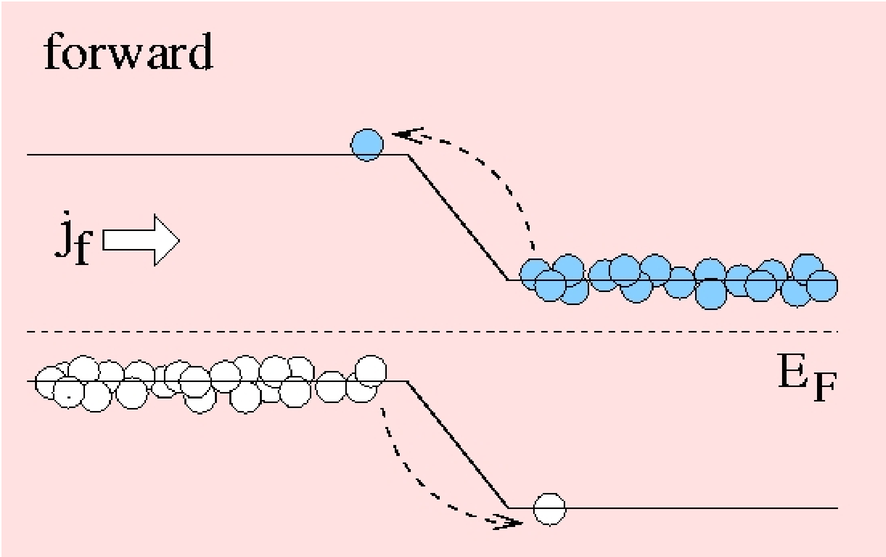


junction diode

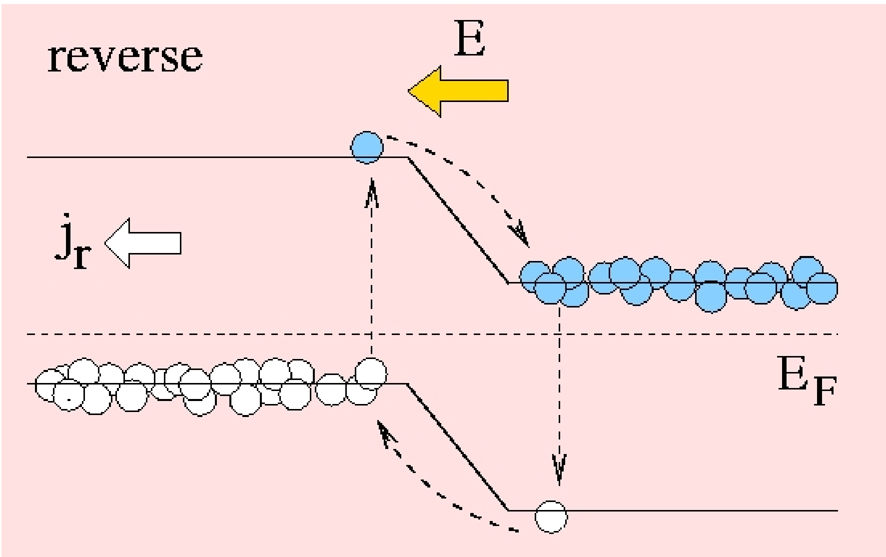


EQUILIBRIUM p-n junction

Thermal activation



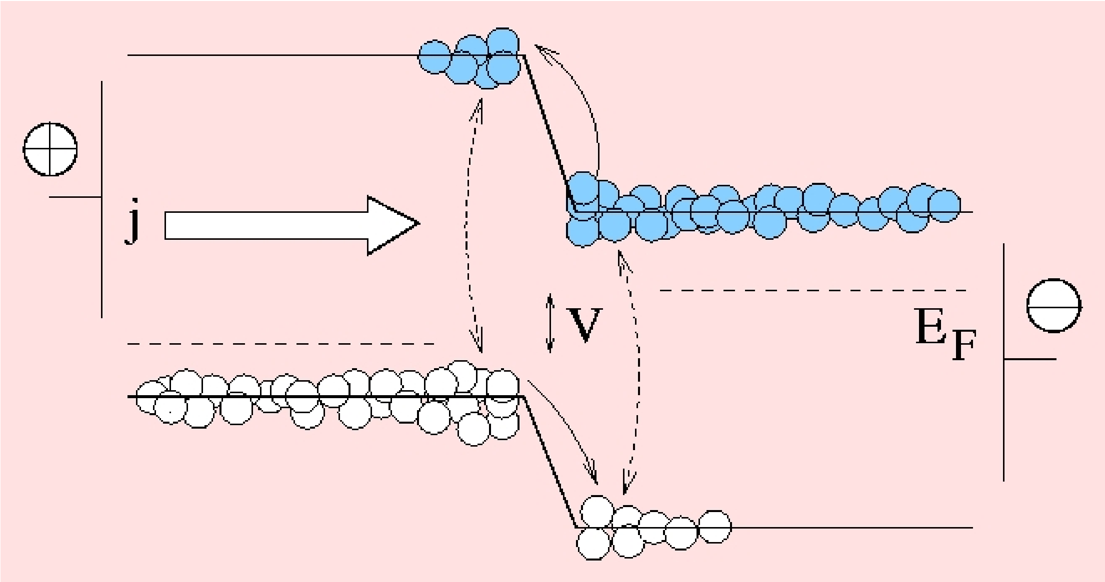
thermal generation



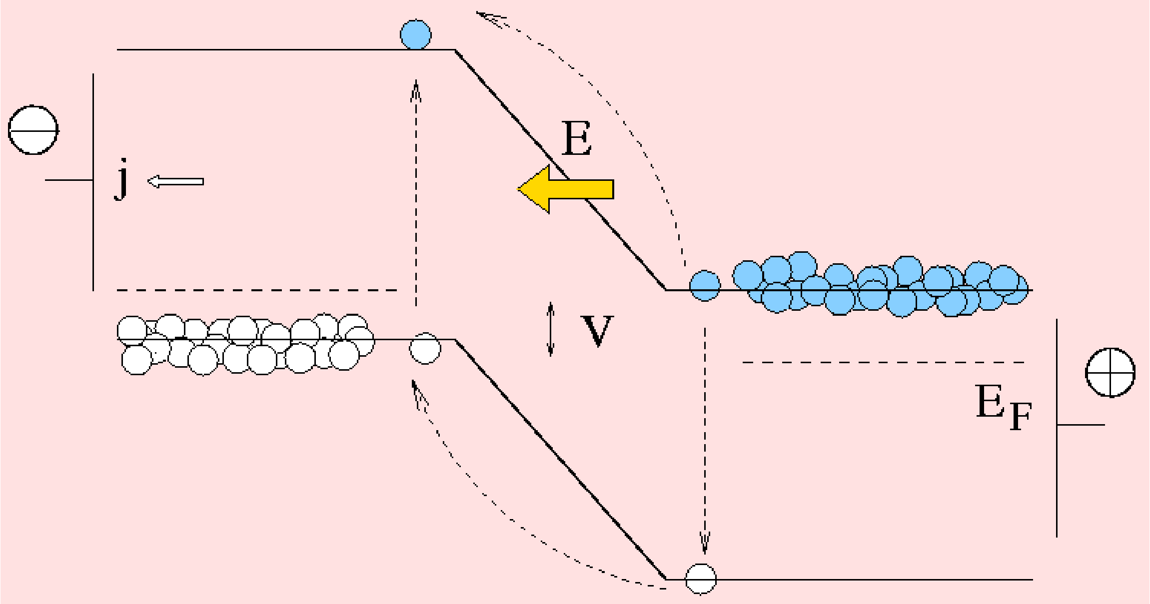
in equilibrium $J_f = J_r = J_g$

NONEQUILIBRIUM p-n JUNCTION

Forward bias: $J=J_g \exp(V/k_BT)$

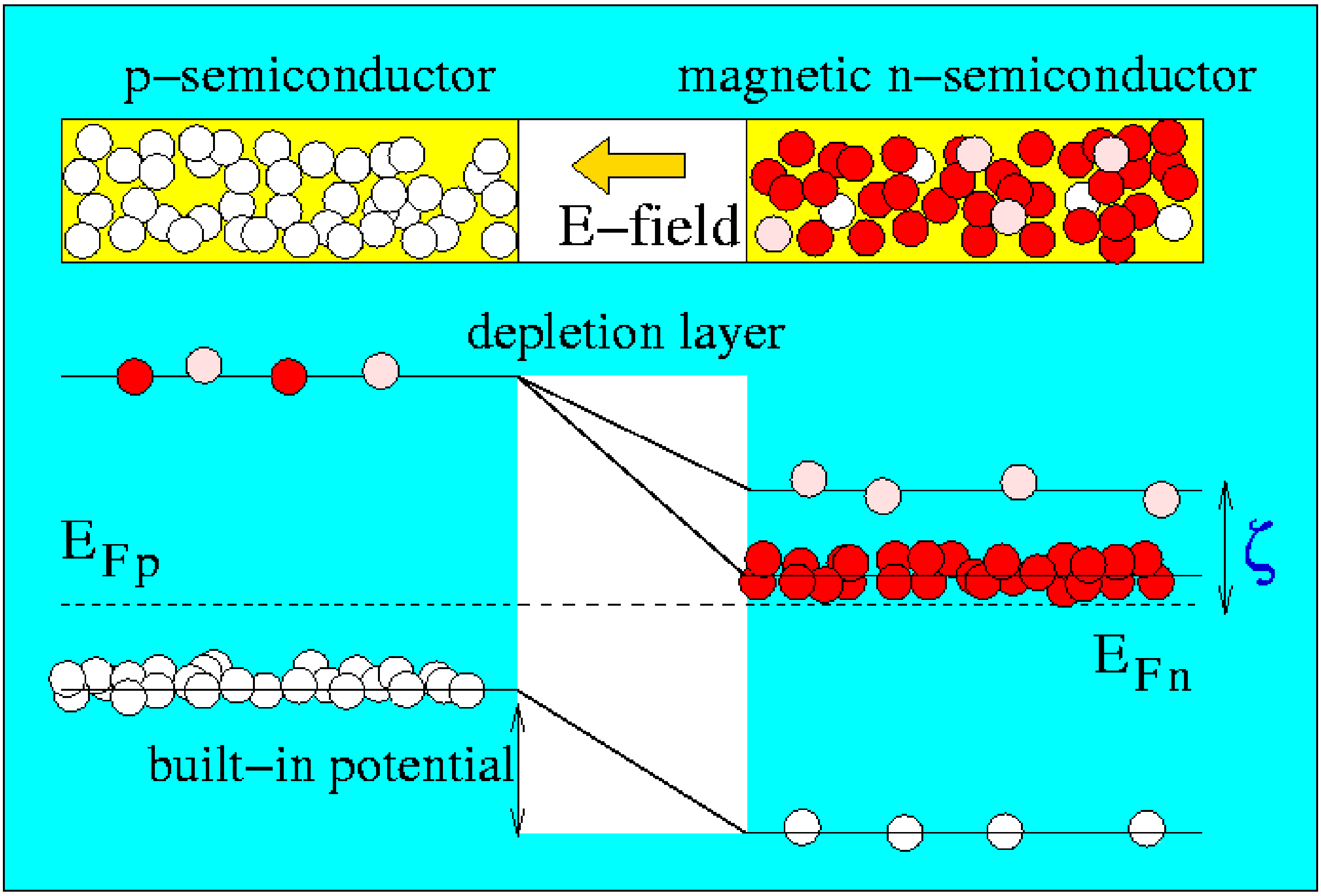


Reverse bias: $J=J_g$



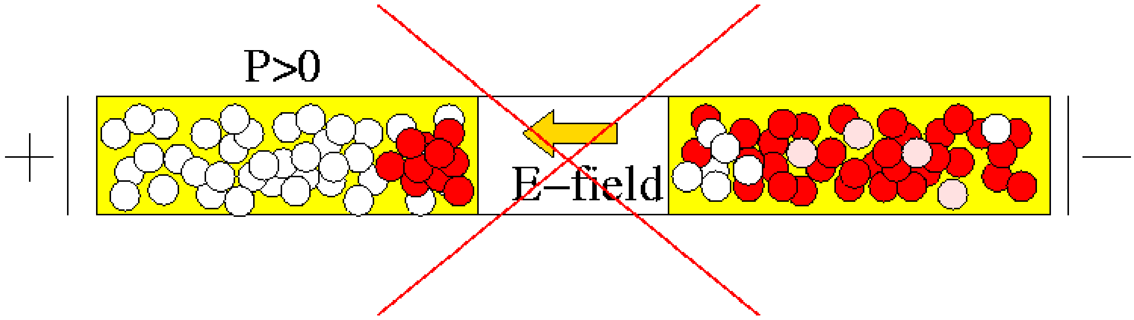
MAGNETIC DIODE

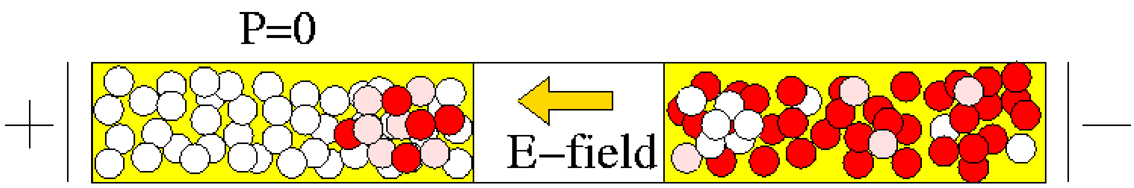
equilibrium

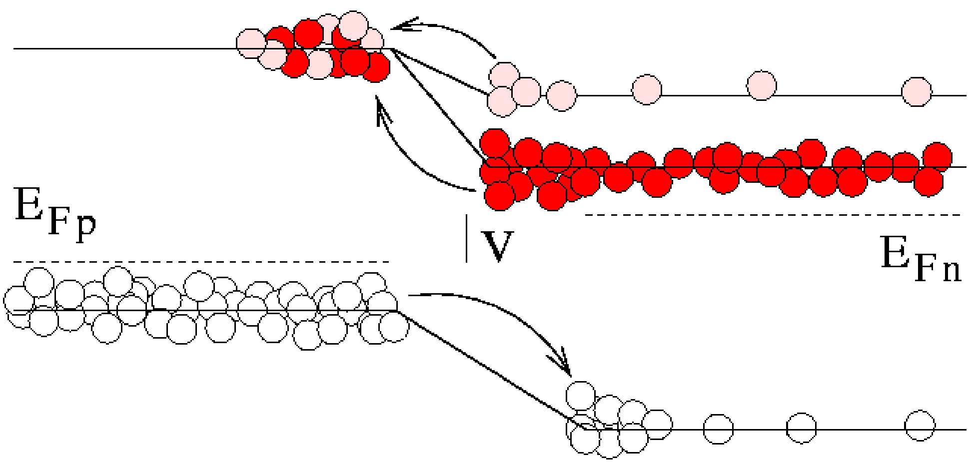


SPIN INJECTION?

I. Zutic, J. Fabian, S. Das Sarma, Phys. Rev. B. 64, 121201 (2001).







$$\frac{J_\uparrow}{J_\downarrow} = \left(\frac{n_\uparrow}{n_\downarrow}\right) \frac{e^{\frac{V-\xi/e}{kT}}}{e^{\frac{V+\xi/2}{kT}}} = \left(e^{\xi/kT}\right) e^{-\xi/kT} = 1$$

ONLY AT LARGE BIASES!

BIPOLAR SPINTRONIC DEVICES

- **Spin-polarized p-n junction diode**
  I. Zutic, J. Fabian and S. Das Sarma, Phys. Rev. B 64, 121201 (2001).

- **Spin-polarized solar cell**
  I. Zutic, J. Fabian and S. Das Sarma, Appl. Phys. Lett. 79, 1558 (2001).

- **Magnetic bipolar diode (MBD)**
  I. Zutic, J. Fabian and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002).

- **Magnetic bipolar transistor (MBT)**
  J. Fabian, I. Zutic, and S. Das Sarma, Appl. Phys. Lett. 84, 85 (2004).

- **General theory of magnetic bipolar devices**
  J. Fabian. I. Zutic, and S. Das Sarma, Phys. Rev. B 66, 165301 (2002).

NOVEL PHENOMENA

- SPIN INJECTION THROUGH THE DEPLETION LAYER
- SPIN PUMPING BY THE MINORITY CARRIERS
- SPIN CAPACITANCE EFFECT
- SPATIAL SPIN DENSITY AMPLIFICATION
- SPIN-VOLTAIC EFFECT
- GMR in MAGNETIC DIODES
- SPIN INJECTION THROUGH MAGNETIC BIPOLAR TRANSISTOR
- MAGNETOAMPLIFICATION EFFECT
- GIANT MAGNETOAMPLIFICATION

BIPOLAR
SPIN-POLARIZED
TRANSPORT

MODELING MAGNETIC BIPOLAR DEVICES

INGREDIENTS:

- ELECTRIC DRIFT
- CARRIER DIFFUSION
- MAGNETIC DRIFT
- SPIN DIFFUSION
- ELECTRON-HOLE RECOMBINATION
- SPIN RELAXATION
- POISSON EQUATION (selfconsistency)

+ boundary conditions (Ohmic contact, spin injection)

FORMALISM

DRIFT – DIFFUSION

$$\vec{J}_{n\lambda} = q\mu_{n\lambda} n_\lambda \vec{E} + q D_{n\lambda}\vec{\nabla} n_\lambda - q\lambda\mu_{n\lambda} n_\lambda \vec{\nabla}\varsigma_n$$

$$\vec{J}_{p\lambda} = q\mu_{p\lambda} p_\lambda \vec{E} - q D_{p\lambda}\vec{\nabla} p_\lambda - q\lambda\mu_{p\lambda} p_\lambda \vec{\nabla}\varsigma_p$$

CONTINUITY (CHARGE + SPIN)

$$\vec{\nabla}\cdot\frac{\vec{J}_{n\lambda}}{q} = +w_{n\lambda}\left(n_\lambda p - n_{\lambda 0}p_0\right) + \frac{n_\lambda - n_{-\lambda} - \lambda\tilde{s}_n}{2T_{1n}}$$

$$\vec{\nabla}\cdot\frac{\vec{J}_{p\lambda}}{q} = -w_{p\lambda}\left(p_\lambda n - p_{\lambda 0}n_0\right) - \frac{p_\lambda - p_{-\lambda} - \lambda\tilde{s}_p}{2T_{1p}}$$

POISSON

$$\vec{\nabla}\cdot\vec{E} = \rho/\epsilon$$

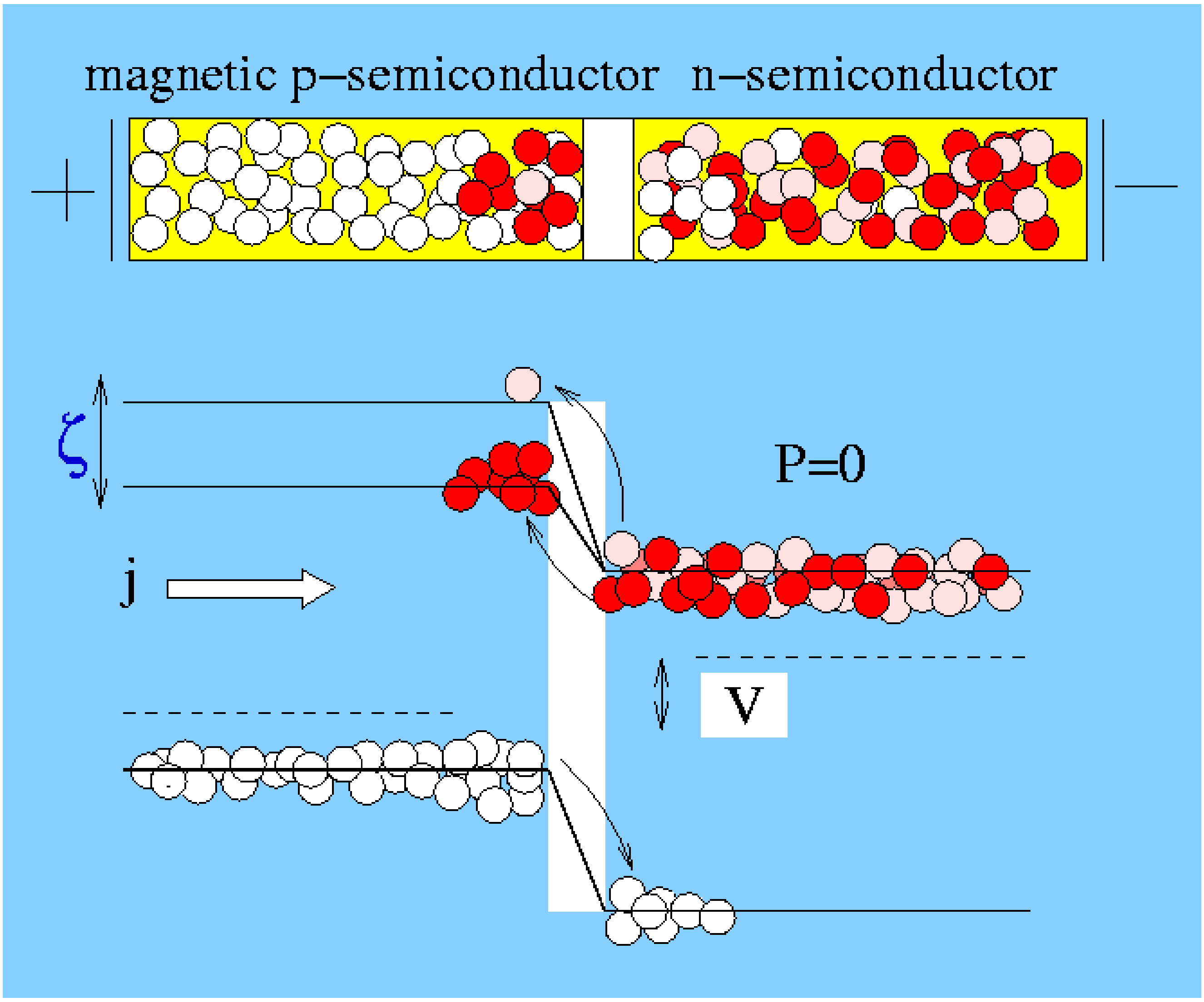
$$\rho = q\left(p - n + N_d - N_a\right)$$

$$\left.\begin{aligned} s &= n_\uparrow - n_\downarrow \\ n &= n_\uparrow + n_\downarrow \end{aligned}\right\} P = \frac{s}{n}$$

I. Zutic, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002)
J. Fabian, I. Zutic, and S. Das Sarma, Phys. Rev. B 66, 165301 (2002).

GMR IN MAGNETIC DIODES

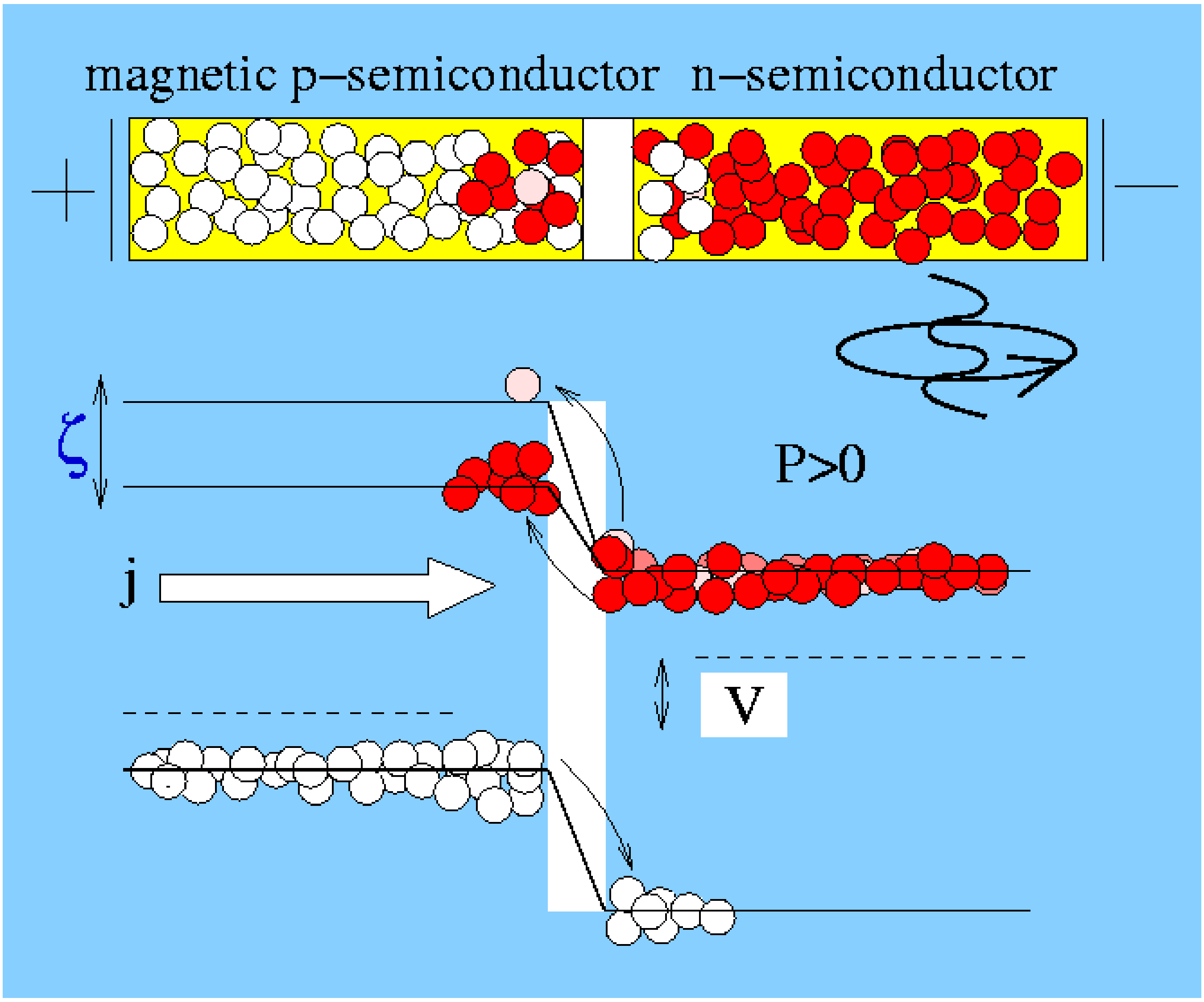
Equilibrium spin only: no spin/charge coupling



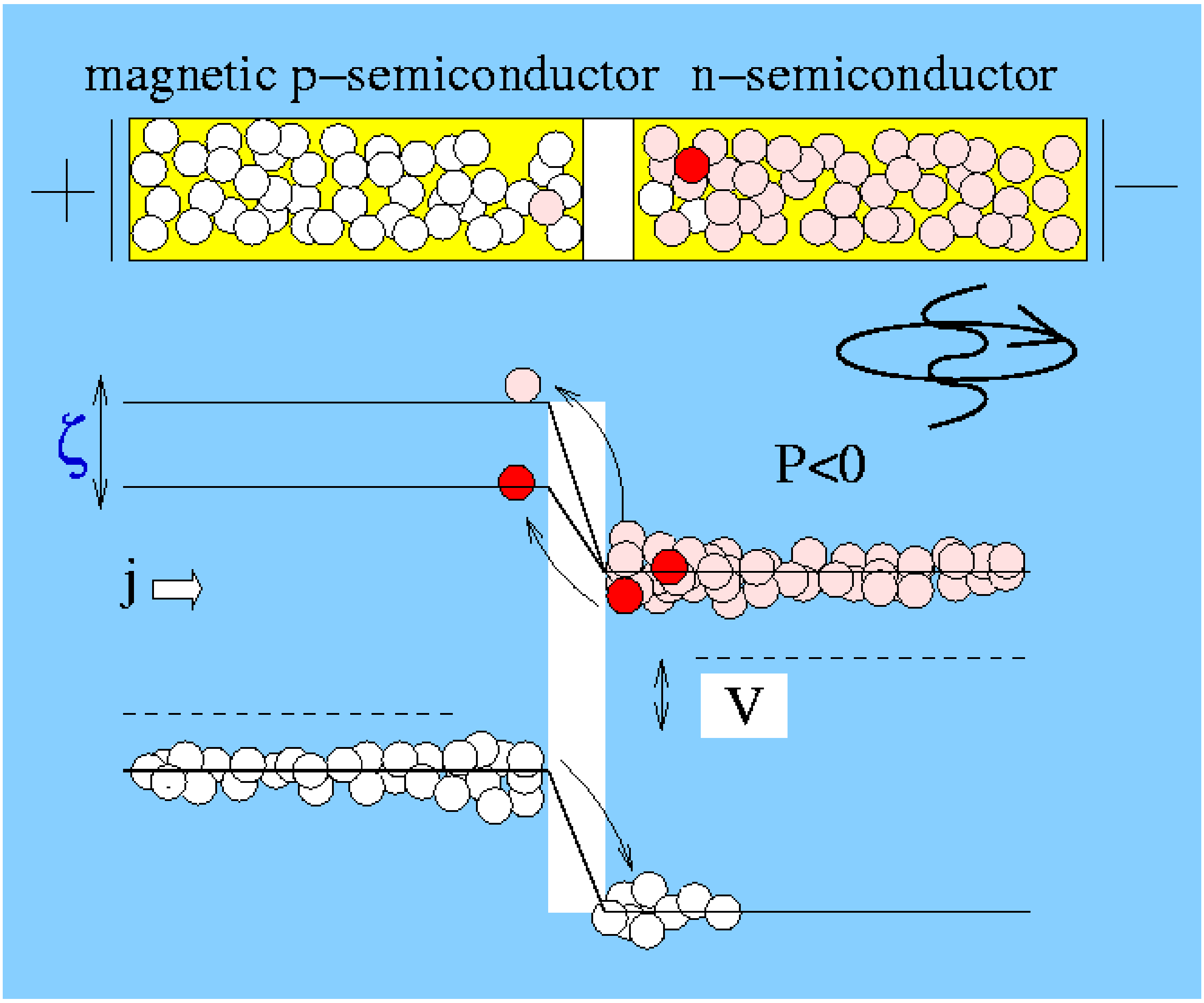
NONEQULIBRIUM SPIN

(SPIN-CHARGE COUPLING IN p-n JUNCTIONS)

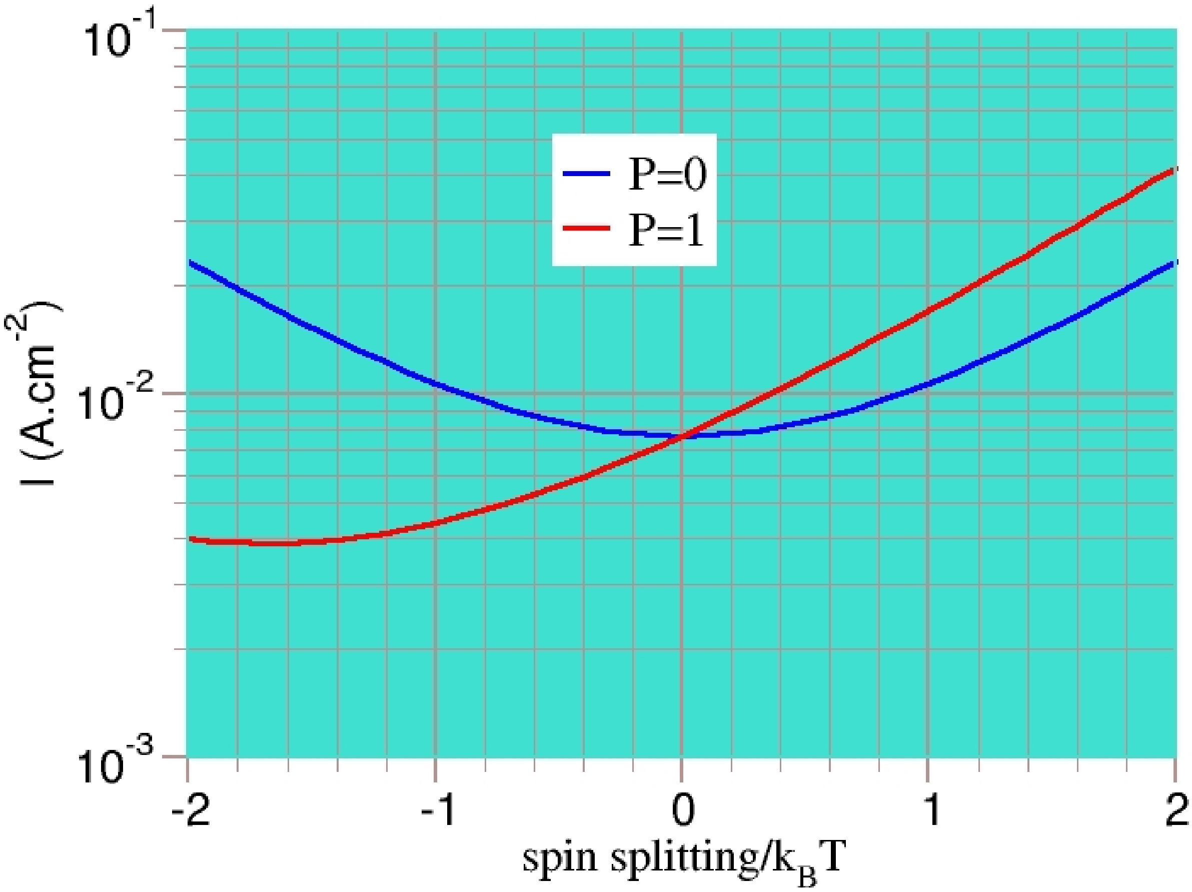
LARGE CURRENT (SMALL R)



SMALL CURRENT (LARGE R)

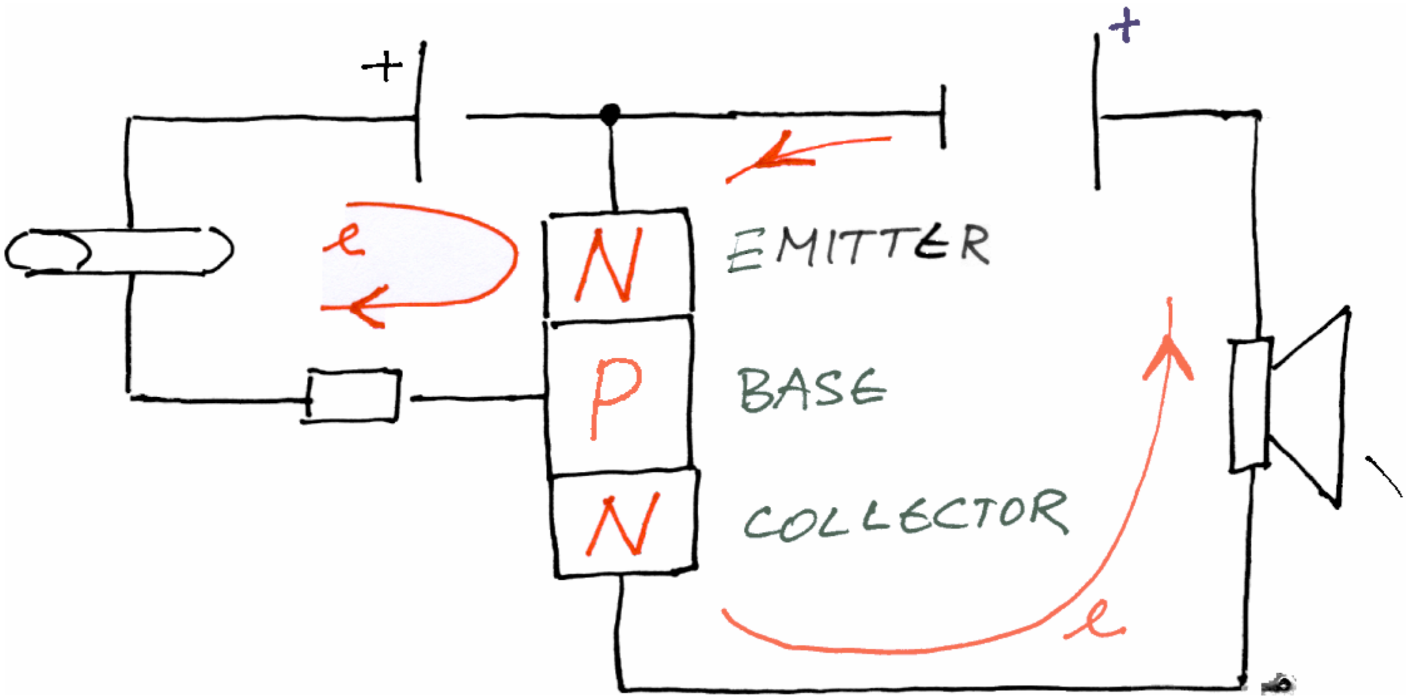


NUMERICAL CALCULATION OF GMR

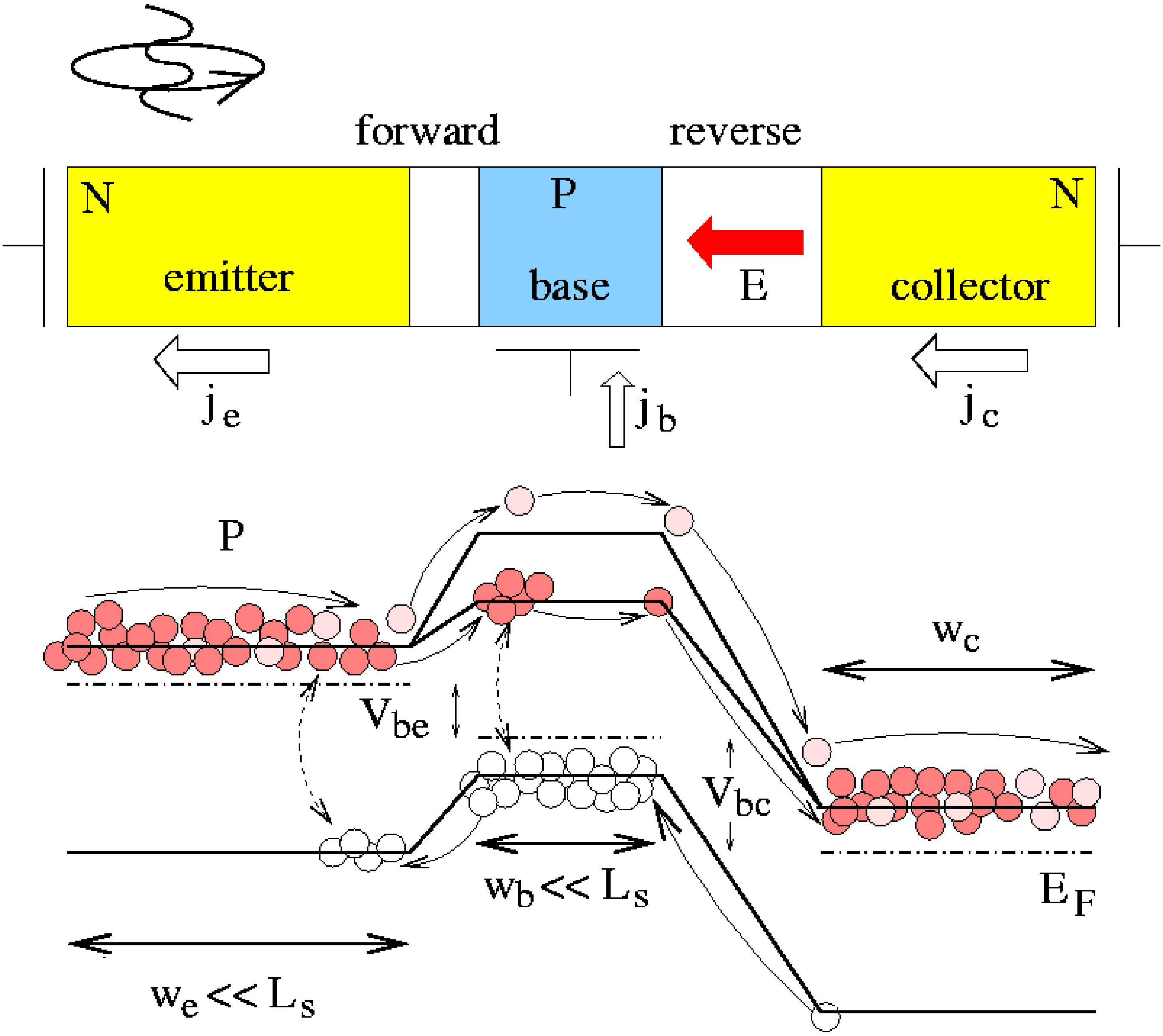


I. Zutic, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002).

CONVENTIONAL BIPOLAR TRANSISTOR AT WORK

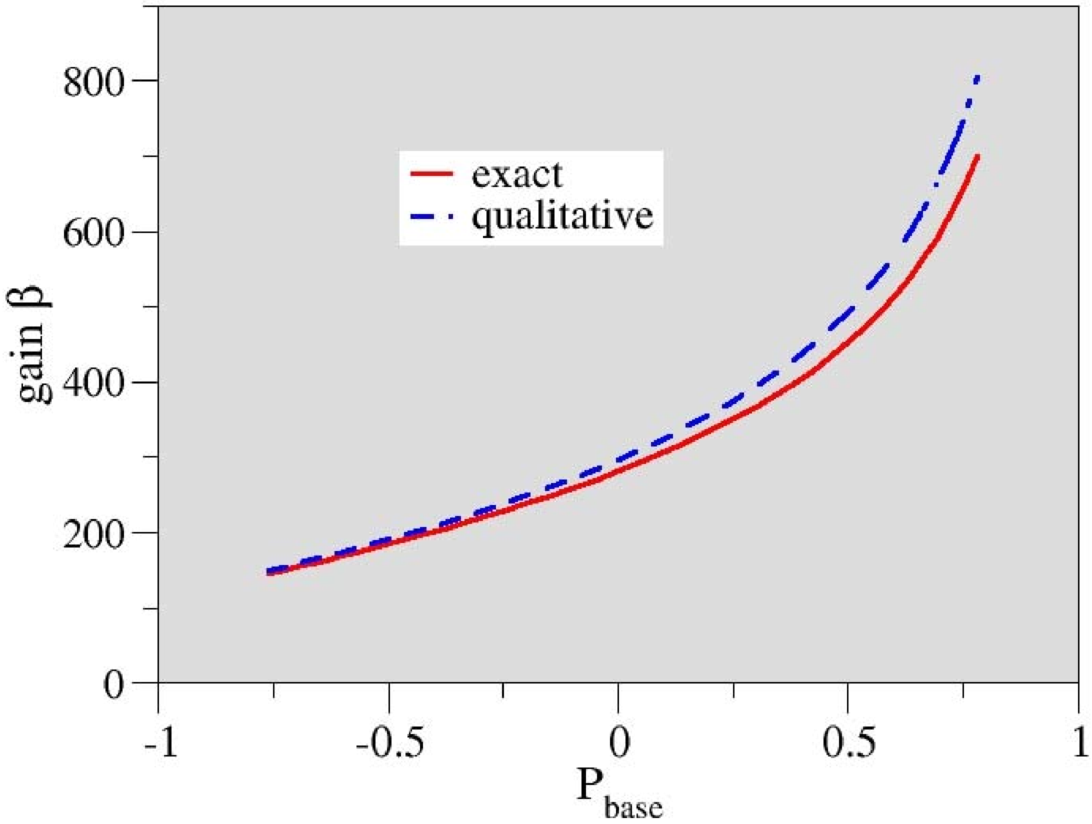


MAGNETIC BIPOLAR TRANSISTOR



GIANT MAGNETO-AMPLIFICATION (GAIN)

$$\beta \quad \frac{I_c}{I_b} \approx 100$$



J. Fabian, I. Zutic, and S. Das Sarma, Appl. Phys. Lett. 84, 85 (2004).

$$\beta(P_e, P_{0b}) = \beta(0,0) \times \frac{1 + P_e \cdot P_{0b}}{\sqrt{1 - P_{0b}^2}}$$

EXPERIMENTS

- Ferromagnetic p-n junction based on $CdCr_2Se_4$ [C. P. Wen et al., IEEE Trans. Magn. 4, 702 (1968)]
- Spin-polarized p-n junction: I-V modified by ESR on recombination centers [I. Solomon, SSC 20, 215 (1976)]
- Heavily doped p-GaMnAs/n-GaAs junction fabricated [I. Arata et al., Physica E 10, 288 (2001)]
- Spin-polarized tunneling through magnetic tunnel p-n junctions [M. Kohda et al., Jpn. J. Appl. Phys. 40 L1274 (2001); E. Johnston-Halperin et al., Phys. Rev. B 65, 041306 (2002)]
- Magnetization-dependent rectification in CoMn-doped Ge/n-Ge [F. Tsui et al., Appl. Phys. Lett. 83, 954 (2003)]]

RELATED THEORETICAL WORK

Magnetic bipolar transistors

- N. Lebedeva and P. Kuivalainen, J. Appl. Phys. 93, 9845 (2003)
- M. Flatte et al., Appl. Phys. Lett. 82, 4740 (2003)

SUMMARY

Novel spintronic device schemes proposed and modeled numerically and analytically:

- magnetic bipolar diode
- magnetic bipolar transistor

New spin and charge transport phenomena in semiconductor junctions predicted:

- spin injection through diode and transistor
- spin-voltaic effects
- giant-magnetoresistance
- spin capacitance
- spatial spin amplification
- spin control over current amplification
- magnetoamplification
- giant magnetoamplification

OUTLOOK

- EXPERIMENTAL REALIZATION
- MAGNETIC HETEROSTRUCTURE ENGINEERING
- LARGE g-FACTOR MATERIALS
- SEMICONDUCTOR OPTOMAGNETOELECTRONICS
- SPIN INJECTION IN SILICON
- SILICON SPINTRONICS
- SPIN COHERENCE AND SPIN DYNAMICS IN LOW-DIMENSIONAL SYSTEMS
- SPIN-BASED QUANTUM COMPUTING

REVIEW:

I. Zutic, J. Fabian, and S. Das Sarma, Spintronics: fundamentals and applications, Rev. Mod. Phys. to appear in April 2004.