Control of Spin-Polarized Currents for Semiconductor Spintronics

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Collaborators

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Essence of Spintronics

Memory: electron spin $\rightarrow$ magnetization of FM
Processing: electron charge $\rightarrow$ 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

Fringe field has a definite orientation with respect to the magnetization \( \mathbf{M} \)

The reflection generated spin polarization can be either PARALLEL or ANTIPARALLEL to the magnetization \( \mathbf{M} \)

\[ S \propto |r_-|^2 - |r_+|^2 \]

Proximity induced order

n-GaAs FM

Growth axis

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

Theory by Ciuti, McGuire & Sham
Calculation of polarized tunnel currents

Spin current vs voltage bias
Conductance $\sim 10^2 - 10^3 / \Omega \text{ cm}^2$

Doping profile

Reverse bias

Forward bias

Current polarization

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

25% -- 30%
Spin injection in the reverse direction

Schottky barrier

GaAs QW

Al$_{0.1}$ Ga$_{0.9}$ As

Fe

A. T. Hanbicki and B. T. Jonker
G. Itskos, G. Kioseoglou, and A. Petrou

$\alpha = \frac{j^\uparrow - j^\downarrow}{j^\uparrow + j^\downarrow}$
Spin injection in the reverse direction

![Graph showing EL polarization vs temperature and current-voltage characteristics for MgO barrier devices.](graph.png)

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 $\Rightarrow$ diffusion current; $E$ field $\Rightarrow$ drift

$$j_s = \sigma_s E + \frac{1}{e} D_s \nabla \rho_s$$

Yu-Flatté $\sigma_s \propto n_s$

Spin-dependent diffusion coefficient

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

Spin-flip rate
Electrical Expression by Spin Valve

Metal spin valve

Semiconductor spin valve

Magneto-resistance

\[ MR \approx \left( \frac{j_{\uparrow} - j_{\downarrow}}{j_{\uparrow} + j_{\downarrow}} \right)^2 \left( \frac{R_{SC} L_{SC}}{R_b} \right) \frac{d}{d} \approx 10\% \text{ in commercial devices} \]

FM/SC tunnel barrier

200 nm

1 µm GaAs

Barrier resistance must be large for spin injection
Planar (horizontal) devices

Semiconductor spin valve

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

T = 300 K

2D flow important

1D transverse flow approx

Barrier/channel: conductance ratio \( \alpha \), spin finesse \( \beta \)

Closed channel

Open channel

Dery, Cywinski & Sham, PRB 73, 161307 R (2006)
Three terminal planar (horizontal) devices

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

All metal

Otani

Semiconductor

Crowell’s talk

T = 4 K

Switch Py3

Ratio ~1.5

- Datta & Das
- Ciuti, McGuire, Sham
- Zutic, Fabian, Das Sarma
- Flatté, Yu, Halperin-Johnson, & Awschalom
- Schliemann, Egues, Loss
A three-terminal spin transistor

Operation

- 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 ($\uparrow=1, \downarrow=0$) $\implies$ current measured ($J_R^{AP}\neq0, J_R^P = 0$).

Spin Physics

Kirchoff's law

integramble in a circuit -- ECE

FM with reversible magnetization

FM with fixed magnetization

3 magnetizations

P = ↓↓↓

AP = ↑↓↓

1μm

100 nm

200 nm

tunnel barrier

drain

source

drain

GaAs

$J_L$ n-channel $J_R$
Two-terminal nonequilibrium spin physics

Non-equilibrium spin density
~ electrochemical potential

Difference between P and AP

spin current density

P = ↓↓

AP = ↑↓

large

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

- **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

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

\[\mu_s \propto \delta n_s\]

**Current density distribution in 2D**

- P = \(\downarrow \downarrow \downarrow\)
- AP = \(\uparrow \downarrow \downarrow\)
Analogy with bipolar transistor

L~Emitter  M~Base  R~collector

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

Add noise boundaries: $V_R / V_L = \text{optimal} \pm 0.2\%$

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

L reversal detected by R current signal

Dery, Cywinski & Sham, cond-mat/0601632
Measurement of circular polarization of light

Contact width/spin diffusion length

Current asymmetry

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

Cywinski, Dery & Sham, cond-mat/0601632

\[ \alpha = 3|\beta| \]

\[ \alpha_{L_S} = 1 \]

\[ \sigma- (LCP) \Rightarrow e \uparrow \]

\[ \sigma+ (RCP) \Rightarrow e \downarrow \]
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?