Chapter 9

Spintransport in Semiconductors
Why are semiconductors of interest in spintronics? They provide a control of the charge – as in conventional microelectronic devices – but also of the spin, as we will see in the following.

9.0 Motivation

"Simple" device in semiconductor physics: Field effect transistor (FET).

Three-terminal device with source (S), gate (G) and drain (D).

"electric valve": current between source and drain controlled by gate voltage $V_g$. On-off ratio may be $< 10^2 \Rightarrow$ much larger than in spin valves: $\Delta R/R < 100 \% \Rightarrow$ factor of 2

Essential ingredient in a FET: two-dimensional electron gas (2-DEG) below the gate electrode.

Transfer to magnetic systems: Spin transistor
proposed by Datta and Das in 1990 (in a different context).

Idea: modulate a spin-polarized current by an electrical voltage, not only by affecting the charge distribution, but also directly the spin polarization $P$ of the current. This is possible via the Rashba effect (see below).

This idea has stimulated a tremendous amount of work over the last 15 years, which revealed the numerous difficulties that must be solved. Three major problems have to be addressed:

- spin injection into the semiconductor
- spin transport through the semiconductor channel
- spin detection of the electrons at the end of the semiconductor channel

9.1 Semiconductor Properties – Reminder

Semiconductors are insulators with a small band gap ($\Delta E \leq 1.5$ eV). For undoped semiconductors, the Fermi levels usually lies mid-gap.

Intrinsic conductivity of semiconductors is very low and strongly temperature dependent (thermal activation of free charge carriers)

Thermal activation of an intrinsic semiconductor creates electrons $n_0$ and holes $p_0$ at the same rate

$$n_0 = p_0 = n; \quad \text{charge neutrality}$$

$$n_i^2 = N_c \cdot N_v \cdot \exp \left( -\frac{E_g}{kT} \right)$$

$N_c$, $N_v$: density of states in conduction and valence band.

The carrier density in semiconductors is much lower ($<10^{19}$ cm$^{-3}$ in a non-degenerate semiconductor) than in metals ($\sim 10^{23}$ cm$^{-3}$). This low carrier density has a significant consequence for the electrostatics:

- screening length is much larger than in metals
- electrostatically induced carrier profiles may extend over large distances ($\sim 100$ nm)

Charge carrier density may be increased by doping:

- Donors $\rightarrow$ n conductivity
- Acceptors $\rightarrow$ p conductivity

Usually the dopant electronic levels are close to the valence band $E_v$ (acceptors) or conduction band edge $E_c$ (donors) and are ionized already at low temperatures.
\( E_F \) is the electrochemical potential and shifts with temperature

\[
E_F = \frac{\varepsilon_e + \varepsilon_v}{2} - \frac{kT}{2} \ln\left(\frac{p}{n}\right) + \frac{3}{4} kT \cdot \ln \frac{m_p^*}{m_n^*}
\]

intrinsic semiconductor \( p = n \)

more complicated dependence for doped systems.

Special case: degenerate semiconductor with very high doping \( N_D \geq 10^{19} \text{cm}^{-3} \)
- quasi-metallic conductivity
- many defects in the lattice (scattering)

### 9.2 Charge transport in semiconductors

Charge transport is described by Boltzmann equation as in the case of metals. Thus, the current is limited through the drift velocity, which is determined by the influence of scattering processes.

The main scattering processes are:

\[ \Rightarrow \]
- phonons (Si, Ge acoustic phonons \( \mu \sim T^{3/2} \))
  - GaAs optical phonons \( \mu \sim T^{1/2} \)
- ionized defects (dopant)
- neutral defects (lattice) \( \rightarrow \) GaN

Scattering from ionized defect can also be seen as 3-step process
- electron moves through crystal
- electron recombines with donor (recombination time)
- electron is emitted from donor (emission time)

for shallow impurity levels: recombination time \( \sim 10^{-7} \text{ sec} \)
emission time \( \sim 10^{-11} \text{ sec} \)

\( \Rightarrow \) in very clean (undoped!) semiconductors recombination time dominates and the charge carriers may have extremely long scattering lengths of up to micrometers!

\( \Rightarrow \) ballistic transport!
Speciality in semiconductors: Because of low charge carrier concentration, drift and diffusion terms in the transport can have similar size → diffusion in metals usually neglected, but must be considered in semiconductors.

Consequence:

\[
\begin{align*}
\vec{J}_N &= en\mu_n \vec{E} + eD_n \nabla n \\
\vec{J}_P &= ep\mu_p \vec{E} - eD_p \nabla p
\end{align*}
\]

\( \mu \) and \( D \) are linked by the Einstein relations

\[
eD_n = \mu_n kT \quad eD_p = \mu_p kT
\]

Total current density

\[
\vec{J} = e\left(n\mu_n + p\mu_p\right)\vec{E} + eD_n \nabla n - eD_p \nabla p
\]

Full treatment of the semiconductor situation must also include charge generation and recombination → \( n = n(\vec{r},t) \)

\[
\begin{align*}
\frac{\partial n}{\partial t} &= \frac{1}{e} \cdot \text{div} \vec{J}_n + g_{eh} + r_{eh} \\
\frac{\partial p}{\partial t} &= \frac{1}{e} \cdot \text{div} \vec{J}_p + g_{eh} + r_{eh}
\end{align*}
\]

with \( g_{eh} \) and \( r_{eh} \) generation and recombination rates of electron-hole pairs.

9.3 Spin transport in SC – Observations

Semiconductors are non-magnetic, therefore, spin-polarized electrons do not exist in conventional semiconductors in the ground state!

Exception: ferromagnetic semiconductors

Let us concentrate on Si or GaAs:

low carrier density → inefficient electrostatic shielding

low spin density → weak shielding of magnetic fields

⇒ We have basically isolated spins (ensemble) moving through the crystal.
Intrinsic semiconductors do not contain spin-dependent scattering centers:

- Si (Z=14) light element → weak s.o. effects
- Ge (Z=23) and GaAs similar
- GaN may be even better due to lower SOC, but has much more structural defects.

GaAs reveals spin diffusion lengths of $\lambda_s \geq 100 \mu m$ (4.2K)
$\tau_s \geq 200 \mu s - 10 ns$

ZnSe, GaN show similar values, persisting even up to 300 K.
Observation: Spin dephasing time $\tau_s$ becomes largest at the MIT (upon doping).

### 9.4 Spin transport in semiconductors

For the moment, we assume to have an ensemble of spin-polarized electrons in the semiconductor – no matter, how it has been created!

Time evolution of the spin density $\vec{S}$ in the solid is described by Bloch equation (which has a form similar to that of the Boltzmann equation, but deals with the vector quantity spin polarization), which describes precession of the spin around the magnetic field axis

$$\frac{\partial \vec{S}}{\partial t} = \vec{S} \times \vec{B}_B \mu_B g / h - \frac{\vec{S}}{\tau_s} - \nabla \cdot \vec{J}_S$$

precession – damping – spin current contribution

As in the case of the charge current in semiconductors, the spin current $\vec{J}_S$ is composed of two contributions and takes the form of a 2. rank tensor

$$\vec{J}_S = \vec{v} \otimes \vec{s} - D_s \nabla \otimes \vec{s}$$

(dyadic prod.)

with drift velocity $\vec{v} = j / (\vec{q} n)$ and spin diffusion const. $D_s$.

In order to get some insight into the problem, we consider a simple one-dimensional
geometry: the semiconductor starts at \( x=0 \) and and a spin-polarized current (characterized by the current density \( j \) and the polarization \( P \)) flows into the \( x>0 \) direction.

The boundary condition fixes \( \vec{J}_s (x = 0) = \frac{1}{q} \vec{j} \otimes \vec{P} \)

Because of the vector character of the spin polarization, \( \vec{J}_s \) takes a complicated form

\[
j_s = \pmatrix{v_x S_x & v_y S_y & v_z S_z \\
v_x S_x & v_y S_y & v_z S_z \\
v_x S_x & v_y S_y & v_z S_z}
\end{pmatrix}
- D_s
\pmatrix{\frac{\partial S_x}{\partial x} & \frac{\partial S_y}{\partial y} & \frac{\partial S_z}{\partial z} \\
\frac{\partial S_x}{\partial x} & \frac{\partial S_y}{\partial y} & \frac{\partial S_z}{\partial z} \\
\frac{\partial S_x}{\partial x} & \frac{\partial S_y}{\partial y} & \frac{\partial S_z}{\partial z}}
\]

In the one-dimensional problem, we can solve these differential equation for the steady state and in the absence of a magnetic field, i.e., \( \frac{\partial s}{\partial t} = 0 \), \( B = 0 \)

\[
\Rightarrow \vec{s} = \tau_s \cdot \vec{V} \cdot \vec{J}_s
\]

The solutions have to be considered for different situations and carrier types.

**Majority carriers:** recombination can be neglected and \( n \neq n(x) \)

\[
\bar{P}_s(x) = \frac{\bar{S}}{n} = \frac{2 \lambda_d \bar{P}}{\lambda_d + \sqrt{\lambda_d^2 + 4 \lambda_s^2}} \exp \left[ -\frac{x}{2 \lambda_s} \left( \sqrt{\lambda_d^2 + 4 \lambda_s^2} - \lambda_d \right) \right]
\]

\( \lambda_d = v \cdot \tau_s \) drift length

\( \lambda_s = \sqrt{D_s \tau_s} \) diffusion length

nondegenerate semiconductor: \( \lambda_d / \lambda_s = qE \lambda_s / (k_B T) >> 1 \)

(drift dominated)

\[
\bar{P}_s(x) = \bar{P} \exp \left( -\frac{x}{\lambda_d} \right)
\]
opposite limit \( \lambda_s / \lambda_s \ll 1 \)

(diffusion dominated) \( \bar{P}_s(x) = \frac{\lambda_{sd}}{\lambda_s} P \cdot \exp\left(-\frac{x}{\lambda_s}\right) \)

the prefactor leads to an interface-induced reduction of the polarization in the semiconductor

*minority carriers* diffusion is more important, as long as \( n_{\text{min}} < < n_{\text{maj}} \).

\[
P_s = \frac{\lambda_s}{\lambda_r} \bar{P} \cdot \exp\left(-x \left(1 - \frac{1}{\lambda_s/\lambda_r}\right)\right)
\]

\( \lambda_s \quad \text{minority carrier spin diffusion length} \)
\( \lambda_r \quad \text{minority carrier charge diffusion length} \)

The carrier density varies as a function of \( x \) according to

\[
n(x) = \frac{\lambda_r J}{D} \exp\left(-\frac{x}{\lambda_r}\right)
\]

thus \( \lambda_r \) includes effects from both recombination + relaxation.
Spinelektronik

Chapter 9

Spin Transport in Semiconductors

Field effect transistor

- relatively simple device
- requires interfacial engineering
- voltage repels holes from the material and changes conductivity character below the gate electrode (p-type $\rightarrow$ intrinsic $\rightarrow$ n-type)
- two-dimensional electron gas (2-DEG)
Datta & Das proposal

- FET structure
- ferromagnetic electrodes
- charge control
- spin control (rotation due to Rashba effect)
- not proposed as a device!!

spin injection
spin transfer
spin detection

Conductivity in intrinsic semiconductors

- intrinsic semiconductors
- thermal activation of charge carriers from $E_V$ to $E_C$
- conductivity depends on band gap of semiconductor
Doping semiconductors

- shallow impurity levels
- easily to ionize
- control of charge density up to $N_D \sim 10^{20} \text{ cm}^{-3}$ (degenerate)
Conductivity: temperature dependence

- 3 conductivity regimes
- freeze-out
- extrinsic
- intrinsic
Spin dephasing times

• spin dephasing times up to 100 ns!
• $T_2$ highest close to the metal-insulator transition
• similar behavior for GaAs, GaN, ZnSe
Bloch equations

Time evolution of spin-polarization:

\[
\frac{\partial \vec{S}}{\partial t} = \vec{S} \times \vec{B} \mu_B g / \hbar - \frac{\vec{S}}{\tau_S} - \nabla \cdot \vec{J}_S
\]

- precession
- damping
- spin current

Spin current:

\[
\vec{J}_S = \vec{v} \otimes \vec{S} - D_S \nabla \otimes \vec{S}
\]

- equation similar to Boltzmann equation for \( f \)
- complication: spin polarization is a vector
Spin current

3x3 tensor to describe spin current density:

\[ \mathbf{j}_S = \begin{pmatrix}
    v_x S_x - D_S \frac{\partial S_x}{\partial x} & \cdots & v_x S_z - D_S \frac{\partial S_z}{\partial x} \\
    \vdots & \ddots & \vdots \\
    v_z S_x - D_S \frac{\partial S_x}{\partial x} & \cdots & v_z S_z - D_S \frac{\partial S_z}{\partial x}
\end{pmatrix} \]
**Spin current**

majority carriers:

\[
\bar{P}_S(x) = \frac{\bar{S}}{n} = \frac{2\lambda_d \bar{P}}{\lambda_d + \sqrt{\lambda_d^2 + 4\lambda_s^2}} \exp\left[-\frac{x}{2\lambda_s^2} \left(\sqrt{\lambda_d^2 + 4\lambda_s^2} - \lambda_d\right)\right]
\]

minority carriers:

\[
\bar{P}_S(x) = \frac{\lambda_s}{\lambda_r} \bar{P} \exp\left[-x \left(\frac{1}{\lambda_s} - \frac{1}{\lambda_r}\right)\right]
\]
Spin current

majority carriers:

\[
\tilde{P}_S(x) = \frac{\tilde{S}}{n} = \frac{2\lambda_d \tilde{P}}{\lambda_d + \sqrt{\lambda_d^2 + 4\lambda_s^2}} \exp \left[ -\frac{x}{2\lambda_s^2} \left( \sqrt{\lambda_d^2 + 4\lambda_s^2} - \lambda_d \right) \right]
\]

\[
\tilde{P}_S(x) = \frac{\lambda_d}{\lambda_s} \tilde{P} \exp \left[ -\frac{x}{\lambda_s} \right]
\]

- equation similar to Boltzmann equation for \( f \)
- complication: spin polarization is a vector