17 Spin Transport in Semiconductors

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17.1 Introduction

Recent months have seen a startling activity and a rapid development in the area of spin-coherent transport in semiconductors. This research is driven by the need for integration of spin-electronic devices into conventional semiconductor technology. Devices based on spin-dependent effects such as read heads for hard disks or non-volatile magnetic random access memory (MRAM) had (and are supposed to have in the near future) a strong impact on storage technology [1,2]. These areas, however, are well separated from standard Si technology and, although these are highly market relevant, a new approach has to be developed in order to transfer the benefits of spin-electronics into MOSFET technology.

Historically, the idea of spin-injection into semiconductors was first proposed during the early seventies in the context of tunnelling studies using ferromagnetic electrodes [3]. A theoretical account of spin-injection from a ferromagnet into a semiconductor was given by Aronov and Pikus by calculating the spatially decaying polarization of majority and minority carriers [4]. Alvarado and Renaud successfully observed vacuum tunnelling of spin-polarized electrons from a Ni tip into GaAs [5]. The spin-polarization was determined from the polarization of the emitted radiation and a negative value of about \(-30\%\) was found at small injection energies. This early experiment proved that spin injection into semiconductors is possible; the negative spin-polarization indicates that minority \(3d\) electrons are preferentially emitted from the Ni tip. Further tunnelling studies with semiconducting barriers were conducted by Prins \textit{et al.} [6].

The problem of spin-coherent transport in semiconductors can be conveniently split into three issues: the investigation of spin-coherence effects within the semiconductor, spin-injection into the semiconductor from the outside world and detection of a spin-polarized current. The first problem is mainly addressed with ultra-fast optical spectroscopy techniques and will be discussed later. Currently two spin-injection methods are investigated, namely injection of spin-polarized carriers from a metallic ferromagnetic electrode or through a ferromagnetic semiconductor. Whereas the first method seems to be the obvious choice, results so far have proven to be poor and the second technique might actually lead to a breakthrough. Some information on magnetic semiconductors can be found in this volume in M. Coey’s chapter on ‘Materials for Spin Electronics’. Recent work on ferromagnetic semiconductors has been reviewed by Ohno [7]; an account of early work was given by Methfessel and Mattis [8]; see also various review articles on diluted magnetic semiconductors in [9]. The methods in use.
to study spin-injection from ferromagnetic electrodes have been pioneered by Johnson in his investigations of spin-injection and -detection in metals \cite{10,11} and superconductors \cite{12}. Johnson’s spin-transistor experiment was analyzed in detail by Fert and Lee \cite{13}.

This chapter concludes with a discussion of devices. A great deal of the present research activity was initiated by the proposal of Datta and Das for a spin-electronic transistor that is analogous to an electro-optic modulator \cite{14}. In this transistor, spin-polarized electrons are injected into a two-dimensional electron gas (2DEG) via a ferromagnetic electrode and are analyzed by a ferromagnetic detector electrode. The spin direction can be controlled by a gate voltage through the Rashba effect. This device promised a straightforward route to a spin-transistor; the experiments, however, are so far disappointing.

17.2 Basics

In this section a simple idealization of spin-injection into semiconductors is discussed in order to introduce the relevant length scales. The discussion follows the treatment by Aronov and Pikus \cite{4} slightly modified by recent ideas of Flatté and Byers \cite{15} on spin diffusion.

The basic length scale relevant for spin-coherent transport processes is the spin-diffusion length given by

\[
\lambda_s = \sqrt{D_s \tau_s},
\]

where \(\tau_s\) denotes the spin-relaxation time and \(D_s\) the spin-diffusion constant. \(\lambda_s\) is the average distance a spin can diffuse without losing its spin memory. The spin-diffusion constant \(D_s\) is not necessarily equal to the charge-diffusion constant \(D\). This is addressed in more detail at the end of this section. There is experimental evidence, see Sect. \ref{sec:exp}, that the spin-diffusion constant \(D_s\) is considerably larger than \(D\).

Consider the following simple model: a doped semiconductor fills the half-space \(x > 0\) and spin-polarized carriers are injected into this semiconductor by some kind of process. The spin-polarization of the injected carriers is given by \(P\) and the current density is denoted by \(j\). The evolution of the spin-density \(S\) in the semiconductor can be calculated from the Bloch equation

\[
\frac{\partial S}{\partial t} = S \times \Omega - S \frac{1}{\tau_s} - \nabla \cdot J_s.
\]

\(\Omega = g \mu_B B / \hbar\) is the precession frequency of carriers with gyromagnetic ratio \(g\) around a magnetic field \(B\). \(\mu_B\) denotes the Bohr magneton. The second rank tensor \(J_s\) denotes the spin-current density. The boundary condition at \(x = 0\) is given by

\[
J_s(x = 0) = q^{-1} j \otimes P.
\]

Here spin-relaxation effects at the boundary are neglected and \(P\) has to be interpreted as some effective spin-polarization. \(q\) is the charge of the carrier.