Electron spin transport in quantum dots and point contacts

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Chapter 1

Introduction

1.1 Electrons: charge and spin

In classical mechanics, the spin angular momentum is associated with the rotation of a body around its own center of mass. For example, the spin of the Earth is associated with its daily rotation about the polar axis, not to be confused with the orbital angular momentum of the Earth which is associated with its annual motion around the Sun.

The concept spin for elementary particles was first proposed in 1925 by Uhlenbeck and Goudsmit [1, 2]. However, the first experimental observations that were in fact due to spin were made long before that, when in 1857 the Anisotropic MagnetoResistance (AMR) was discovered [3]. The classic experiment by Stern and Gerlach in 1922 showed there was more to the electron than only its charge and was the first direct observation of the quantization of angular momentum [4].

In some ways an electron can be considered as a spinning sphere of charge. In classical terms that means that it possesses a magnetic dipole moment and that it can be described as a vector that is (for a free electron) antiparallel to the direction of its spin. Consequently, a magnetic field can exert a torque such that the spin vector undergoes precession. However, spin is a purely quantum mechanical property. Quantum mechanics states that whenever the spin of an electron is measured along a certain axis, there are only two possible outcomes, either spin-up or spin-down. The field of spintronics (or spin-based electronics) was founded on this quantum mechanical form of binary logic. Currently, several research efforts investigate whether spin can play a role in the electron transport properties of materials and electronic devices.

1.2 Motivation

This thesis presents research that aims at improving the understanding and control of the dynamics of electrons and electron spin in electronic nanodevices. Our work contributes mainly to fundamental research on these topics. The behavior of electrons and spins is studied in nanodevices that are fabricated with ultra-clean non-magnetic semiconductors, and by state-of-the-art nanofabrication processes. Further, the experiments are performed at very low temperatures (less than one degree above absolute zero), such that thermal fluctuations do not impede an analysis of how fundamental interactions in materials influence electron and spin states in nanodevices. Even though this work is fundamental in character, this research is related to application-driven research in the field of spintronics. In the remainder of this section, I will first introduce the two experimental systems that were used in this research (the quantum point contact and the quantum dot), and discuss for each system the scientific questions that underlie the work. After this, I will shortly summarize why these studies are of importance for developing practical spintronic devices.

Research on Quantum Point Contacts

The first part of this thesis presents experiments on Quantum Point Contacts (QPCs). A QPC is a narrow constriction between two large electron reservoirs and is essentially a short one-dimensional transport channel in which the electron transport is ballistic. It is one of the most fundamental electronic systems and a key model system for showing how modern nanotechnology can give electronic devices in which there is very high control over the electronic states and transport. In particular, these devices show quantized conductance [5, 6], an effect that has now been observed and understood for 20 years already. Furthermore, the electron emission from QPCs can be spin-polarized when a strong in-plane magnetic field is applied [7]. The conductance of this device also shows several features that reveal signatures of electron many-body effects, which include the so-called 0.7 anomaly, enhancement of the electron g-factor, and the Kondo effect.

In particular the 0.7 anomaly has been observed in nearly all QPC studies in these last 20 years, but it is still not fully understood. At the same time, this phenomenon is very interesting. Several models have been proposed that relate the 0.7 anomaly to a spontaneous spin splitting in zero magnetic field [8, 9]. The Kondo effect is a many-body interaction effect between a single magnetic impurity and a sea of conduction electrons [10]. An earlier study on QPCs [11] investigated a feature in the QPC conductance that shows remarkable similarity to a characteristic of the Kondo effect seen in few-electron quantum dots [12], where a localized state with a magnetic impurity is deliberately formed. The Kondo signatures in a QPC suggest that by only making a narrow constriction in a clean non-magnetic semiconductor, a localized state can spontaneously form, while a QPC is in fact an open quantum system.

Thus, the QPC provides a very simple model system, that is suited for investigating how many-body effects and electron spin can affect electron and spin transport in nanodevices. Notably, the QPC is a key element in several proposal for spintronics and quantum information devices, and for this the understanding of these many-body effects is important. The work on QPCs that is presented in this thesis aims to improve the understanding of these many-body effects by looking at the influence of a change in QPC geometry, and hence Coulomb effects, on the signatures of these many-body phenomena. Further, we studied the possible correlation between the 0.7 anomaly and signatures of the Kondo effect. We also used this work to determine how the spin-polarized emission of electrons from QPCs in strong magnetic fields can be optimized.

Spin relaxation in large Quantum Dots

The second part of this thesis presents experiments on electron spin relaxation in large open quantum dots. Spin accumulation and relaxation of the spin ensemble is in these systems influenced by ballistic scattering of electrons in the device structure. Such a system is best described as an electron ensemble that is ballistically scattering inside a chaotic cavity., thus providing a regime in between bulk samples (that have been mainly studied with optical techniques [13]) and ultra small dots [14]. For large open dots, however, spin relaxation occurs in a fundamentally different manner and its full understanding is still a challenge to the spintronics community [15]. It is expected that spin-orbit effects have a dominant role, and that the scattering rate at the edge of the dot is important.

Spin-orbit interaction results from the motion of an electron in an electric field [16]. The electric field is felt as a magnetic field in the electron's rest frame and interacts with the spin of the electron, leading to precession of the spin state. This effect is a source of relaxation but also a possible means for controlled spin manipulation. This is in contrast with spin relaxation in few-electron dots, where electrons are highly localized due to quantum confinement, and the spin relaxation due to momentum scattering inside the dot and spin-orbit effects is thereby nearly irrelevant [17].

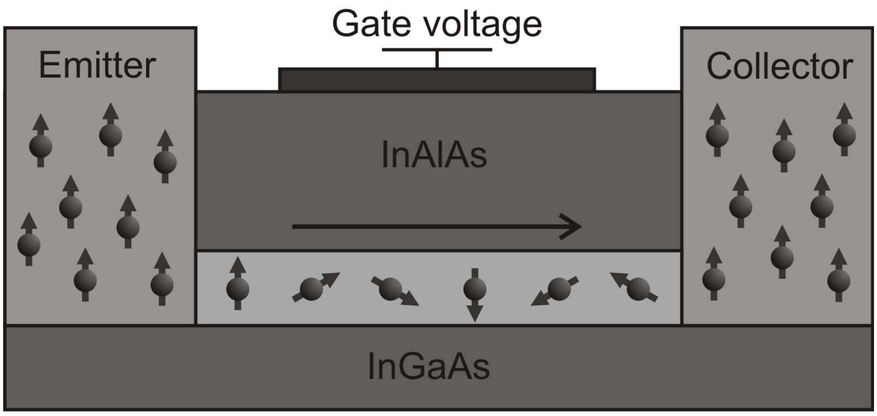

Figure 1.1: Schematic drawing of the Datta-Das spin transistor. A ferromagnetic electrode emits spin-aligned electrons into a narrow semiconducting channel. During transport in the channel towards the ferromagnetic collector the electrons precess around the spin-orbit fields that can be controlled by the gate electrode. The resistance of the device is determined by the alignment of the spins with the direction of magnetization of the ferromagnetic collector electrode when they arrive at the collector. The resistance, and thus also the emitter-collector current can be modulated by the gate voltage.

The work in this thesis aims at observing spin signals from large quantum dots and to understand the relaxation mechanism in these systems. At the same time, such results are indeed relevant for developing spintronic devices that work with large spin ensembles in device structures (as for example the Datta-Das transistor) instead of few-electron dots. We succeeded in measuring electronically the spin relaxation time, which is a measure for how long the spin polarization of the ensemble of electrons can be maintained. We also performed a numerical study of the interaction of the oriented spin ensemble with its environment via the spin-orbit interaction. In particular, we wanted to understand how the spin polarization evolves in various device geometries.

Relation with the field of spintronics

Besides being an interesting topic for fundamental research on its own, the spin degree of freedom may offer new device functionalities that cannot be achieved with charge transport alone, and that could lead to a new generation of computational devices [18, 19].

The field of metallic spintronics originates from the discovery of the Giant

MagnetoResistance (GMR) in 1988 [20, 21] and subsequent development of the spin valve [22]. Since then, the GMR effect has already found many practical applications, mainly in the read heads used for high density data storage on computer hard disks. The discovery of this effect has therefore been rewarded with the 2007 Nobel prize in physics. The interest in semiconductor spintronics was greatly stimulated by a proposal in 1990 by Datta and Das for a field-effect spin transistor [23]. We will present it here as an archetype example of a device that shows spintronic functionality. In this device, shown schematically in Fig. 1.1, spins are injected into a two-dimensional semiconductor transport channel by a ferromagnetic emitter electrode and detected by a ferromagnetic collector electrode. The emitter injects electrons with their spin oriented along the direction of its magnetization. The electrons are precessing during transport from emitter to collector as a result of spin-orbit coupling. The resistance of this device is high when on average electrons arrive at the collector with their spin anti-parallel to the magnetization of the collector and low when their spin is parallel to this magnetization. The gate electrode influences the strength of the spin-orbit interaction and therefore modulates the resistance of the device.

This example shows that the ability to generate, transport, and detect electron spin in a controlled manner is important for the field of spintronics and is also a very useful tool for investigating basic properties of spin in electronic systems. The electrical injection, transport and detection of spin has been demonstrated for metals in a non-local measurement geometry [24, 25]. Non-local experiments sensitive to precession of the spins around an externally applied magnetic field were also performed [26, 27]. Early efforts towards realization of spin injection in semiconductors using a ferromagnetic metal, as proposed for the Datta-Das spin transistor, were complicated by an effect known as the conductivity mismatch [28]. A solution to this fundamental limitation in polarization of the injected current was the use of tunnel barriers [29, 30], but only very recently experimental results were presented for the all-electrical injection, detection [31], and precession [32] of spin polarization in an n-doped GaAs channel using ferromagnetic contacts. The work that is presented in this thesis is therefore clearly relevant for open questions regarding spin injection and manipulation, and contributes to the understanding of fundamental properties of electron and spin transport in semiconductor nanostructures.

1.3 Outline of this thesis

In this thesis we thus present experimental and numerical results on quantum point contacts and quantum dots. *Chapter 3* then forms the first part devoted measurements on individual quantum point contacts. *Chapters 4*, *5*, and *6* form the second part, presenting experiments and a numerical study, related to spin accumulation and relaxation in a quantum dot. In addition we present in *Chapter 7* an experimental study of the fabrication of ohmic contacts to a GaAs heterostructure. We start in *Chapter 2* with an explanation of the basic theory of quantum dots and point contacts. Further, this chapter describes how we fabricate our devices and we present the measurement techniques and set-up used in this work.

In *Chapter 3* we present an experimental study of the dependence of many-body effects, like the 0.7 anomaly, the enhancement of the electron g-factor, and the Kondo effect, on the geometry of a QPC. We determine these properties for a set of 12 QPCs with identical material parameters, where we used different values for the length L and width W for the electrode spacing that defines the device. We find a clear relation between the enhanced g-factor and the subband spacing in our QPCs, and can relate this to the device geometry with electrostatic modeling of the QPC potential. The many-body electron physics that causes the apparent energy splitting of the 0.7 anomaly does not show a clear dependence on QPC geometry, but we do find a clear correlation with a field-independent exchange effect that contributes to spin splittings in high magnetic fields. Signatures of the Kondo effect also show no regular dependence on QPC geometry, but are possibly correlated with the splitting of the 0.7 anomaly.

In *Chapter 4* we present experimental results on a four-terminal quantum dot system in a GaAs heterostructure. We use a non-local measurement geometry for studying spin accumulation and relaxation. We find that this can be used to extract in a single measurement the relaxation time for electron spins inside the dot ($\tau_{sf} \approx 300$ ps), contributions to the relaxation from coupling to the reservoirs, and the degree of spin polarization of the contacts ($P \approx 0.8$). In this Chapter we also study the two-terminal conductance of a quantum dot, where one of the contacts is used as a spin filter. We find that this method is harder to implement since it requires a very flat spin-resolved conductance plateau for a QPC. We could therefore not get a clear conclusion for the spin relaxation time or polarization of the contacts using this method.

In *Chapter 5* we present a numerical study of electron spin relaxation due to spin-orbit interaction in confined systems where we study the effects of confinement and large external magnetic fields. We used an approach where the relaxation was simulated with semiclassical electron trajectories, and studied 2D and confined systems with realistic device parameters. We find that confinement in a micronscale dot can result in enhanced relaxation with respect to a free two-dimensional electron ensemble, contrary to the established result that strong confinement or frequent momentum scattering reduces relaxation.

Chapter 6 presents additional experimental results on quantum dots, where we investigate quantum fluctuations in the non-local resistance of an open quantum dot which is connected to four reservoirs via quantum point contacts. The amplitude of the resistance fluctuations is strongly reduced when the coupling between the voltage probe reservoirs and the dot is enhanced. Along with experimental results, we present a theoretical analysis based on the Landauer-Büttiker formalism.

Ohmic contacts to a two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures are often realized by annealing of AuGe/Ni/Au that is deposited on its surface. In the last chapter of this thesis, *Chapter 7*, we study how the quality of this type of ohmic contact depends on the annealing time and temperature, where we focussed on the question how the optimum parameters change for a different depth of the 2DEG. Combined with transmission electron microscopy and energy dispersive X-ray spectroscopy studies of the annealed contacts, our results allow for identifying the annealing mechanism and describing a model that can predict optimal annealing parameters for a certain heterostructure.

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