1. Introduction

Semiconductor physics revolutionized the use of electronics and paved the way to complex new devices such as personal computers and mobile phones. The reduction in size created a giant increase of calculating power and consequently new areas of application. Today almost no part of our daily life goes without devices based on semiconductor physics. While the microcontrollers got smaller and smaller, another property of the electron than the charge came into the focus of attention: the spin. It is one of the puzzling foundations of quantum mechanics, that for a given direction in space there are only spin-up and/or spin-down electrons, nothing in between. It is the target of the emerging area of research, that was baptized *spintronics* by S.A. Wolf in 1996, to understand and utilize the electron's spin to create useful sensors, memories, and logic devices with properties not possible with charge-based devices [Par04]. New devices may combine the standard microelectronics with spin-dependent effects that arise from the interaction between the spin of the carrier and a spin-dependent detector. Ferromagnets are naturally well suited as spin-dependent detectors, since in ferromagnets the degeneracy of the density of states of spin-up and spin-down electrons is lifted. Thus it is natural that the first applications which use the spin of the electron are based on ferromagnetic materials. However, for future integration of spin-dependent properties, semiconductor based devices are desirable, because an easy and effective integration into existing top-level semiconductor technology would be feasible. In such a scenario magnetic materials would serve as non-volatile memory components and thus the speed of electronics may be combined with the non-volatility of magnetic devices. The use of the spin promises to bring increased data processing and integration density, together with a decreased power consumption compared to conventional semiconductor devices [Wol01].

The research in spintronics is based on results obtained in diverse areas of research, such as magnetism, semiconductor physics, superconductivity, optics, and mesoscopic physics [Zut04]. It benefits from a large class of new materials, such as ferromagnetic semiconductors, organic semiconductors, organic ferromagnets, high-temperature superconductors, and carbon nanotubes. Fundamental research is necessary, before devices that use the full potential of spintronics will be realized.

In spintronics the control of the spin is either the control of the population and the phase of the spin of an ensemble of particles, or a coherent spin manipulation of a single electron or a few-spin system [Zut04]. The first is apparent in devices using magnetic properties of layers or electrodes, e.g., the **g**iant **m**agneto **r**esistance (GMR) effect. This effect is used in hard-disk drives since 1997 [Grü89]. The resistance through two ferromagnetic layers depends on the relative alignment of their magnetizations. Other examples include magnetic field sensors that work with the **t**unneling **m**agneto **r**esistance (TMR) [Jul75], race-track memories [Par03], and domain-wall logic [All05]. The last two are sketched in Fig. 1.1(a) and (b). Both use a domain wall, i.e., the

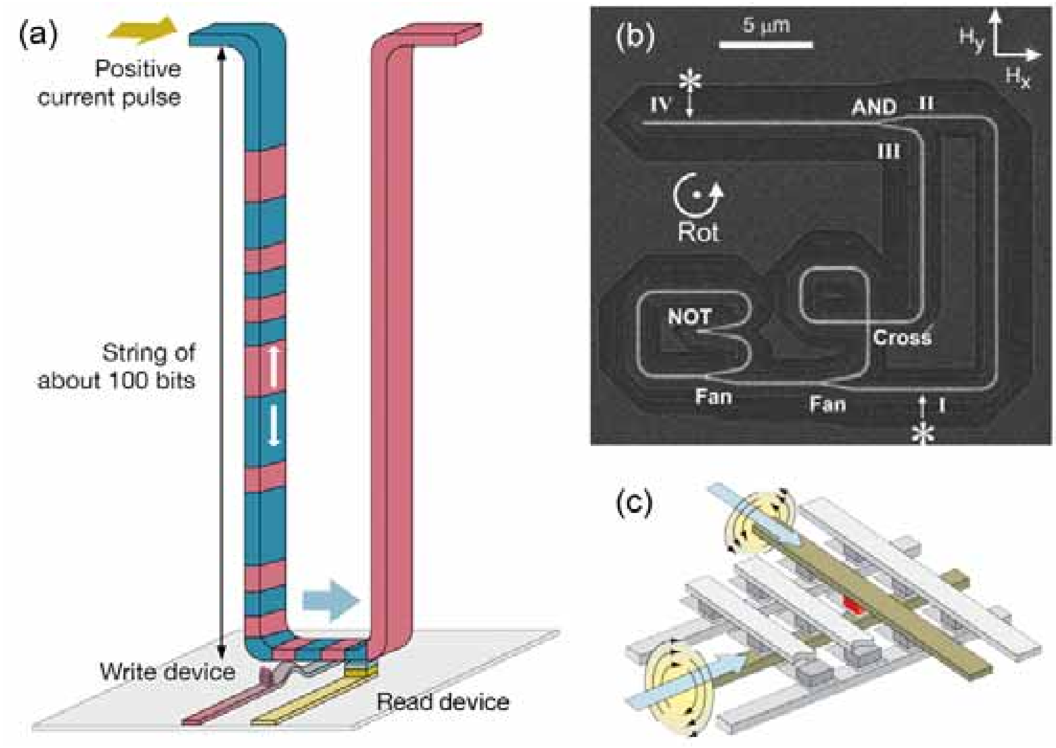

Fig. 1.1.: Examples of spintronic devices. (a) Race-track memory by IBM [Par03]. Domains with alternating magnetic orientation are driven through the device by a current. (b) Domain wall logic by Allwood et al. [All05]. A rotating magnetic field drives a domain wall through the device that consists in this example of one NOT gate, one AND gate, two fan-out junctions, and one cross-over junction. (c) Write process in an MRAM element [Maf06] that is made of a magnetic tunnel junction. The tunneling current between the two magnetic layers depends on their relative orientation, that can be altered by switching the magnetization of one of the layers by the magnetic field accompanying a current in the write lead.

boarder between two areas that exhibit differently oriented magnetizations, as the carrier of information. An application of the TMR is the **m**agnetic **r**andom **a**ccess **m**emory (MRAM) [Maf06]. A sketch of an MRAM element is shown in Fig. 1.1(c). It is based on a magnetic tunnel junction and promises a high performance memory with high density, high speed and non-volatility [Par04].

The spin manipulation of single electrons plays an important role in devices that include semiconductors. The fact that the electron spin in metals and semiconductors lives relatively long (typically a nanosecond), allowing spin-encoded information to travel macroscopic distances, is what makes spintronics a viable option for technology [Zut04].

The great impact that semiconductors had on electronics is founded on the invention of the transistor by Shockley et al. in 1947 [Sho49]. Since then Moore's law describes the development to smaller devices [Moo65]. A further reduction in size will lead to one-dimensional electron channels. The spin of single electrons can then no longer be neglected. A spintronic analog to the electronic transistor, that motivated much research, is the *spin transistor* proposed by Datta and Das in 1990 [Dat90]. It is shown in Fig. 1.2(a). It combines a ferromagnet and a semiconduc-

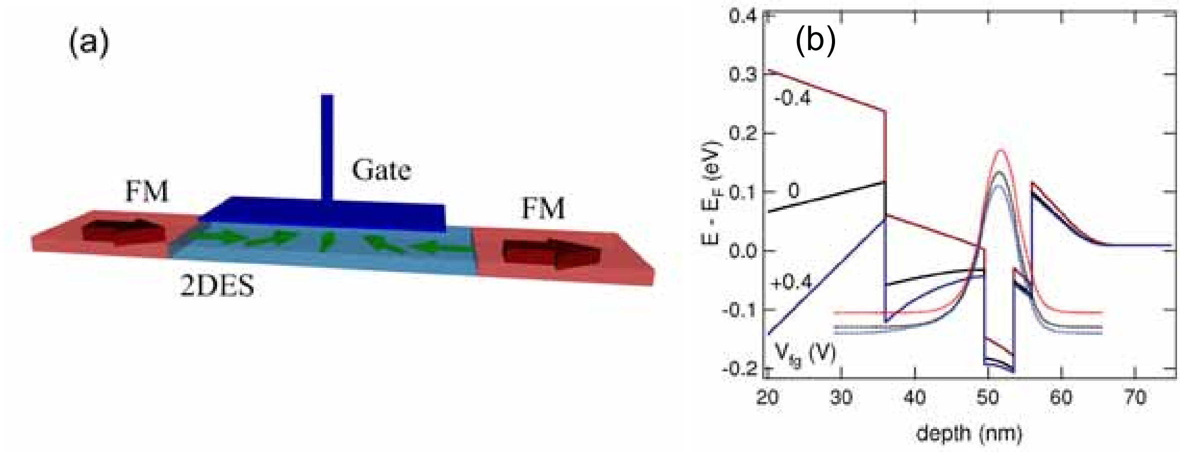

Fig. 1.2.: (a) Spin transistor proposed by Datta and Das [Dat90]. Two ferromagnetic electrodes with parallel spins are used as spin injector and detector. The spin is manipulated in the central semiconducting part by a gate voltage. The resistance of the device depends on the spin orientation of the current relative to the detector electrode. (b) Calculated conductance band in an InAs heterostructure for three different gate voltages V_{fg} applied to a frontgate [Sch05]. The gradient of the potential in the two-dimensional electron gas $\approx$ 50 nm underneath the surface changes with gate voltage.

tor and is therefore an excellent example for future spintronic devices. Based on this device we will discuss some of the main areas of research in spintronics. In the center of the structure a semiconductor is placed. It contains a two-dimensional electron gas, that is created by growth of semiconductor layers with different band gaps as shown in Fig. 1.2(b). If its potential is asymmetric, a moving electron senses an effective magnetic field that interacts with its spin [Ras60]. This spin-orbit interaction leads to a precession of the spin. With an electric field applied by a gate electrode the spin orientation of single electrons can be manipulated by changing the strength of the spin-orbit interaction [Nit97, Sch05]. The change of the potential due to a gate voltage is also displayed in Fig. 1.2(b). The loss of spin-information by scattering can be limited by confining the two-dimensional channel to a one-dimensional channel. This can be done by, e.g., reducing the width of the conducting channel by etching and by applying a gate voltage to finger-like gates. These gates form a so-called quantum point contact. Measurements performed in GaAs heterostructures by van Wees et al. in 1988 [vW88] first proved conductance quantization in quantum point contacts. For small channel widths only multiples of the conductance quantum $2e^2/h$ are observed. In this thesis we investigate a number of different designs for quantum point contacts in heterostructures based on the III-V semiconductor InAs, that possesses a high spin-orbit interaction.

In the spin transistor at both sides of the semiconducting channel ferromagnetic electrodes are located. In a ferromagnetic material the spins of the electrons are aligned parallel to each other due to the exchange interaction. Sufficiently small electrodes will form only one magnetic domain, i.e., all spins are aligned parallel. However, depending on the size and the shape of the electrodes multiple ferromagnetic domains appear [Sch99, Ste04, Pel05]. Especially at the edges of the electrodes

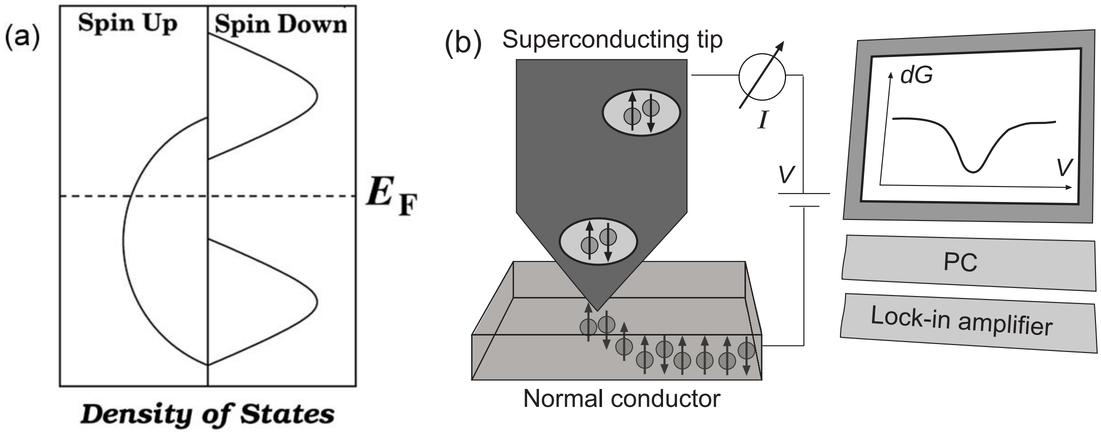

Fig. 1.3.: (a) Schematic representation of the density of states $D(E)$ close to the Fermi energy for a half metal. Modified from [Gal06]. (b) Sketch of the point-contact Andreev reflection (PCAR) technique. The normal current is converted into a supercurrent at the interface to the superconductor. For a high spin polarization, i.e., an imbalance of the density of states for spin-up and spin-down electrons, this results in a lower conductance.

complex domain structures are apparent. The control of the ensemble of spins in such electrodes is an important prerequisite for the spin transistor. Micromagnetic simulations are used to understand the domain-wall structure and the changes of magnetization in space and time [Mei00, Bol06].
When a voltage is applied to the spin transistor, a current flows through the device. The electrons in the ferromagnetic electrodes are spin polarized. The spin of the electrons in the current will align with the spins of the conduction band in the first electrode. The thus spin-polarized current will be injected into the semiconductor. Spin injection opened up another field of research. The first evidence of spin injection was given by Johnson and Silsbee in an Al/Py sample[1] in 1985 [Joh85]. More recently spin injection was demonstrated using tunnel barriers in samples with electrodes of Py [Jed03, vS06]. In contrast to normal metals and superconductors direct electrical spin injection from a metallic ferromagnet into a semiconductor proved to be more difficult [Zut04, Mei02, Mat02]. It has been found that the mismatch of the conductivities in ferromagnetic metals and semiconductors destroys most of the spin information at the interface [Sch00]. The problems of the conductivity mismatch can be overcome in the ballistic regime [Mat02]. To reach ballistic transport through the device ohmic contacts are necessary. Most semiconductor must be heavily doped to get low-resistive contacts. It is a major advantage of InAs that it allows ohmic contacts to almost all metals. In Fe/GaAs devices spin injection rates of 3% at room temperature have been observed [Zhu01]. More recently it has been reported that the rate of spin injection is increased by adding tunneling barriers between semiconductor and metal [Mot02].
An alternative way to overcome the conductivity mismatch is the use of new materials. One interesting group of materials are the so-called half-metals. The concept of a half-metal was introduced by de Groot et al. [dG83]. They performed bandstructure calculations of Mn-based Heusler alloys. A half-metal has a metallic density of states in one of the spin subbands and a

[1] Py: permalloy, ferromagnetic alloy with composition $Ni_{80}Fe_{20}$.

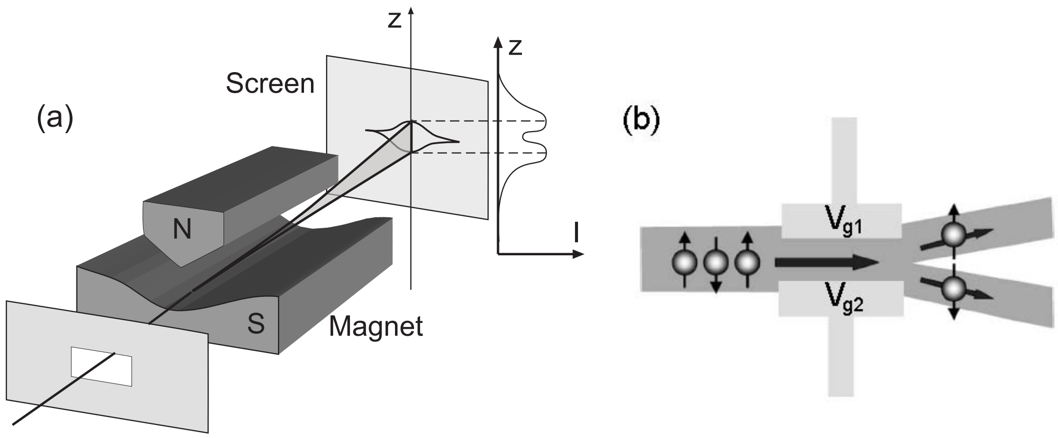

Fig. 1.4.: (a) Scheme of the classical Stern-Gerlach experiment. A beam of silver atoms is separated into two single beams in a magnetic field. This is due to the two possible alignments of the spin $\frac{1}{2}$ of silver atoms. The spintronic analog is shown in (b). Two gate electrodes manipulate the strength of spin-orbit interaction at the junction. This results in a gradient of the effective magnetic field, which separates the electrons.

gap in the density of states in the other spin subband. This is sketched in Fig. 1.3(a). Within any reasonable definition of spin polarization this corresponds to a spin-polarization value of 100% [Zie02]. Even for diffusive transport through the interface to the semiconductor this results in a high rate of spin injection [Zut04]. For the Heusler alloy Ni_2MnIn half metallicity is proposed at the interface to InAs [Kil00]. The alloy can be grown strainless and epitaxially on the semiconductor InAs [Kur03]. This makes the system Ni_2MnIn/InAs a promising candidate for the use as spin injector. Thin films of Ni_2MnIn are prepared in our institute [Kur03, Kur05a, Kur05b, vO05, Sch07, Boc07]. In order to optimize the preparation of the Heusler alloy it is necessary to determine its degree of spin polarization. This is achieved amongst others by photoemission spectroscopy, spin-polarized electron tunneling, and point-contact Andreev reflection spectroscopy. The latter method is used in this work. It allows the quick and simple measurement of the degree of spin polarization of thin films in conductance measurements at low temperatures. Figure 1.3(b) displays a sketch of the technique. At the interface between a superconducting tip and the thin ferromagnetic film Andreev reflection [And64] occurs depending on the spin polarization of the film. Pioneering works have been performed by Soulen et al. [Sou98]. In this work we present measurements on thin films of Ni and Ni_2MnIn and for reasons of comparison of Au. Other promising materials for electrodes are ferromagnetic semiconductors. The use of a semiconductor material as spin aligner and/or spin injector would facilitate the integration of spintronics and semiconductor-based electronics. Pioneering works have been performed on Eu-based ferromagnetic semiconductors [Osi90]. However, the highest Curie temperatures reached so far are much lower than room temperature.

The resistance of the whole Datta-Das spin transistor will depend on the relative orientation of the magnetization of the two electrodes and on the gate voltage. This way it could be used as a metal-semiconductor hybrid transistor.

A completely different ansatz for the generation and detection of spin-polarized currents is a non-magnetic, solely semiconducting device known as spin filter. Such a device can easily be integrated into existing semiconductor devices. Further advantages of this approach are a high integration density and the absence of magnetic stray fields. Also, a conductivity mismatch cannot appear. Recently it has been suggested to utilize the spin-orbit interaction in semiconductors like InAs to create a spin filter [Kis01, Yam05, Ohe05, Dit04]. Different three-terminal devices are suggested that show opposite spin polarizations at the two exits of the device. A so-called Stern-Gerlach spin filter and its classical analog are shown in Fig. 1.4. A three-terminal device in a Y-shaped design proposed by Dittmer et al. [Dit07] is prepared and investigated within the second part of this work. Interestingly point-contact Andreev reflection as well as spin filters depend on spatial constrictions of the conductors. Constrictions ensure ballistic transport in a low number of conductance channels. This way quantum mechanical properties like the spin are not covered by scattering of electrons. Spintronic devices that use the spin of single electrons inescapably require small dimensions to avoid the loss of spin information by scattering. This is reached by the design of the spin filters with quantum point contacts.

The thesis is organized as follows: the second chapter describes point-contact Andreev reflection spectroscopy. Theoretical models to describe the measured data are explained and the measurement setup is described. Experimental results and fits to the data are presented. The method is compared to other methods that yield the spin polarization of metals. The third chapter describes first the basics of quantum point contacts, spin-orbit interaction, and spin filters. Then experimental results of measurements on quantum point contacts and on a spin filter are presented. The thesis ends with a conclusion and an outlook.