Summary

Ferromagnetic materials are materials in which, due to the presence of the exchange interaction, the two spin subbands are shifted in energy with respect of each other. This accounts for a finite magnetization and different densities of states at the Fermi level. It also implies that any electrical current flowing through a bulk ferromagnetic material is spin polarized. For the transport properties of hybrid ferromagnetic/non magnetic systems, which form the focus of this thesis, there are two effects that are of main interest:

the spin valve effect: The conductance of a ferromagnet/non-magnetic material/ferromagnet sandwich depends on the relative magnetization of the two ferromagnetic layers. This is known as the spin valve effect. Physically, it can be understood in terms of the simple two currents model, in which the total conductance of the system is given by adding the conductance of the two spin channels in parallel. A change in the direction of the magnetization of second layer leads to a change in the conductance of each spin channel.

the spin-field effect transistor(FET): It was suggested by Datta and Dus that, starting from a standard spin valve junction, a transistor-like device can be obtained if one is able induce spin precession in a controllable way in the non-magnetic layer. They proposed to use a two dimensional electron gas(2DEG), where the electron gas is confined in a asymmetric quantum well. The asymmetry of the well causes a Rashba-type spin-orbit interaction and therefore can induce spin precession. The magnitude of the Rashba spin-splitting is proportional to the well asymmetry parameter and, in principle, can be controlled by an external gate. Hence the average angle of spin precession depends on the applied gate voltage. As a consequence that the total channel conductance is a function of the applied gate voltage, i.e. the device will have a FET-like behavior.

this thesis:

The original goal when the research was started was the realization of the spin-FET device. In the long run, the goal was to use the device to obtain information
about the spin-flip processes in semiconductors. For the actual device, we chose to use an InAs 2DEG channel in contact with metallic ferromagnetic source and drain (Ni, Co or permalloy). The choice for InAs-based systems was due to the fact that InAs forms a surface accumulation layer and no Schottky barrier is present when brought in contact to metals. Consequently, by using InAs based materials, it is possible to obtain highly transparent metal-2DEG contacts. Simultaneously, a similar approach was taken by other groups. However, we were not able to observe spin injection in the semiconductor and the results reported in literature were also inconclusive. Therefore the actual focus of the research was shifted towards understanding the fundamental physics behind spin injection and the intrinsic limitations therein.

This thesis starts with the first chapters dedicated to introducing the fundamental concepts required to understand the physics of spin transport in hybrid ferromagnet/normal systems, and in semiconductor heterostructures in particular. As long as the spin interaction are weak (i.e. the spin flip time is much longer than the momentum scattering time), each spin species can be treated as an independent fermionic system in thermal equilibrium. Hence an independent electrochemical potential can be defined for each species. The transport transport in such ferromagnet/normal systems can be described exclusively in terms of spin diffusion between reservoirs kept at different potentials.

With respect to the physics underlying spin injection, it will be shown in this thesis that the difference in conductivities between a metal and a semiconductor gives a basic obstacle to spin injection. We have calculated the spin-polarization effects of a current in a two dimensional electron gas which is contacted by two ferromagnetic metals. It turns out that even in the case when the spin flip in the semiconductor is negligibly small, the efficiency of the spin injection is heavily reduced by the unfavorable ratio between the conductivities of the two materials. For a typical device geometry the degree of spin-polarization of the current is limited to less than 0.1%, only. The change in device resistance for parallel and antiparallel magnetization of the contacts is up to quadratically smaller, and will thus be difficult to detect.

Before performing the spin injection experiments, we studied the magnetization reversal processes in submicron Ni wires by means of magnetoresistance (AMR) measurements. The goal was to gain insight into the magnetization reversal processes. The switching behavior was analyzed as function of the width and of the aspect ratio of the wires. We examined the dependence of the switching field on
the angle between the applied external field and the wire. We found out that for angles close to 90° degrees the switching is best described by the Stoner Wohlfarth model, while for lower angles the reversal process is probably due to domain wall nucleation and motion.

Experimentally, we studied submicron lateral spin valve junctions, based on high mobility InAs/AlSb 2DEG, with Ni, Co and Permalloy as ferromagnetic electrodes. In a standard HEMT geometry it is very difficult to separate true spin injection from other effects, including local Hall effect, anomalous magnetoresistance (AMR) contribution from the ferromagnetic electrodes and weak localization/anti-localization corrections, which can closely mimic the signal expected from spin valve effect. Therefore we chose for a non-local type of measurement, where the current and voltage paths were spatially separated. However, despite all our efforts, we have not been able to observe spin injection in InAs. This ‘negative’ result in Fm/2DEG/Fm devices was actually consistent with the conductivity mismatch arguments. This is due to the fact that the spin dependent part, which is proportional to the resistance of the ferromagnetic leads over a spin flip length, is much smaller then the spin independent part of the semiconductor resistance.

This insight was used in designing and analyzing experiments on all metal systems, where the conductivity mismatch problems are expected to be less severe. A connection was made with the work of Friso Jedema, who was trying to observed spin injection in metallic systems. Therefore, in this thesis the results for all metal-systems are also given. We report the electrical injection and detection of spin currents in an all-metal lateral mesoscopic spin valve. The junction was made out of Py ferromagnetic electrodes, making good ohmic contact to a copper cross. A non-local geometry was used in order to eliminate the spurious magnetoresistive contribution of the ferromagnetic electrodes. The observed spin signals were in quantitative agreement with the diffusive model that we developed. Moreover, by looking at the signal dependence on the electrode spacing the spin flip length in Cu could be determined.

It has been suggested theoretically by M. Johnson, and later claimed to have been measured experimentally by Hammar et al., that one can use the Rashba interaction to detect spin injection. In chapter eight we discuss spin transport in the presence of the Rashba interaction. Here we show that within the linear transport, the presence of the Rashba spin splitting does not allow the detection of spin injection. We also discuss the implication of the Onsager reciprocity relations and show that by by looking at the symmetry of the IV characteristics one can discriminate
between a local Hall effect and a putative direction dependent rectification due the Rashba interaction.

The last chapter of the thesis deals with a different subject: mesoscopic superconductivity. However, there is a clear technological link to the previous work, as this work is based on the same semiconductor technology, and a key issue is the quality of the metal-2DEG interface. We investigated the phase coherent transport in devices obtained by coupling a semiconductor quantum dot to superconducting electrodes via transparent contacts. For this purpose 500x500nm dots, etched in high mobility InAs/AlSb heterostructures were contacted to Nb superconducting electrodes. The inclusion of an Aharonov-Bohm superconducting loop allowed to study the influence of the phase on the transport properties. By comparing samples with different cleaning procedures, we concluded that the InAs surface treatment has an essential role in determining the junction properties. In the finite bias regime we observed lower then expected gap voltages and an anomalous temperature dependence. This behavior was tentatively attributed to the presence of an induced gap in the InAs beneath the superconducting electrodes.