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Electron spin transport in quantum dots and point contacts

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Summary

This thesis presents research that contributes to the understanding of fundamental properties of electrons and electron spin in quantum point contacts and quantum dots. These nanodevices are fabricated with ultra-clean non-magnetic semiconductors, using state-of-the-art nanofabrication techniques. Furthermore, the experiments are done at very low temperatures. This allows for a study of how fundamental interactions in materials influence electron and spin states. Although this work has a fundamental character, it is also motivated by open questions in the field of spintronics regarding the ability to generate, transport, and detect electron spin in a controlled manner. We report research on two types of devices, the quantum point contact and the quantum dot. Both type of devices are defined with electrostatic gating techniques in a two-dimensional electron gas (2DEG) on a GaAs/AlGaAs heterostructure.

The first part of this thesis presents experimental work on Quantum Point Contacts (QPCs). A QPC can be though of as a short one-dimensional transport channel in which the electron transport is ballistic. Due to the transverse confinement, the conductance of a QPC is quantized in steps of $2e^2/h$ in zero magnetic field, where e is the electron charge and h Planck's constant. Furthermore, the electron emission from QPCs can be spin-polarized when a strong in-plane magnetic field is applied. Besides this well understood conductance quantization there are also several features in the conductance of a QPC due to many-body effects that still cannot be fully explained. In particular, the 0.7 anomaly, a shoulder in the conductance around $0.7(2e^2/h)$ in zero magnetic field, has been a topic of debate for more than a decade now. Other many-body effects in QPCs include the enhancement of the electron g-factor, and the zero-bias anomaly, a feature in the QPC conductance that shows similarities with transport though a Kondo impurity.

Since a QPC is one of the most fundamental electronic systems, it makes an ideal model system for studying the consequences of many-body effects for transport of spin-polarized electrons and spin coherence in nanodevices. We per-

formed electron transport measurements to study how these many-body effects in QPCs depend on the QPC geometry. We studied the energy spacing between the one-dimensional subbands and spin-splittings within one-dimensional subbands, both in zero field and high magnetic fields, for a set of 12 QPCs with identical material parameters. We found a clear relation between the subband spacing and the enhancement of the effective electron g-factor. These parameters depend on geometry in a regular manner that we can understand from electrostatic modeling of the QPC potential. The appearance of the 0.7 anomaly does not show a regular dependence on QPC geometry. However, we do find that in high magnetic fields there is a field-independent exchange contribution to the spin-splitting for the lowest one-dimensional subband in addition to the regular Zeeman splitting, and this exchange contribution is clearly correlated with the apparent zero-field splitting of the 0.7 anomaly. This suggests that the splitting of the 0.7 anomaly is dominated by this exchange contribution. Also for the zero-bias anomaly we do not find a clear dependence on QPC geometry, but our data suggests that it is worthwhile to further study its correlation with the splitting of the 0.7 anomaly. At this time, our analysis of experimental data is very phenomenological, presenting parameters and correlations for which it is not possible to make quantitative comparison with theory, since no analytical models are available. However, the trends allow for conclusions about the qualitative behavior.

The second part of this thesis reports experimental and numerical work on electron spin relaxation in large open Quantum Dots (QDs). We studied spin accumulation and relaxation of an electron spin ensemble that is confined to a microscale QD. Our system is thus best described as an electron ensemble that is ballistically scattering inside a chaotic cavity. Such systems allow for studying spin relaxation in a regime in between bulk samples and ultra small dots, and in this regime spin-orbit effects have a dominant role. Therefore the scattering rate at the edge of the dot has an important influence on the relaxation time.

We have developed a non-local measurement geometry, using QPCs to operate a four-terminal quantum dot system. We demonstrated that this can be exploited to determine for a single device the spin relaxation rate inside the dot ($\tau_{sf} \approx 300\ ps$), contributions to spin relaxation from coupling the dot to reservoirs, and the degree of polarization for spin-selective transport in the contacts ($P \approx 0.8$). We can reproduce the spin relaxation in large quantum dots qualitatively with Monte-Carlo simulations. The values of polarization that we find, are consistent with the short length of our QPCs.

In the Monte-Carlo simulations we used an approach where the relaxation

was simulated with semiclassical electron trajectories in 2D and confined systems using realistic device parameters. This approach allows for fully including three SO effects that occur in realistic 2DEG materials. We calculate values for spin relaxation in micronscale dots with frequent scattering on the edge of the dot, and these values are much lower than calculated values for large high-mobility 2DEG areas, contrary to the established result that strong confinement or frequent momentum scattering reduces relaxation. In this regime of confinement enhanced relaxation, the relaxation time can decrease by more than two orders of magnitude by applying a strong external magnetic field parallel to the initial spin direction. An analogue to confinement enhanced relaxation was also found for large 2D systems with extremely high mobilities.

We also investigated quantum fluctuations in the non-local resistance of the four-terminal quantum dot. In practice, transport in large open QDs always shows mesoscopic fluctuations of the conductance, a characteristic that results from the interference of multiple transport paths through the sample. The amplitude of these fluctuations is strongly reduced when the coupling between the voltage probes and the dot is enhanced. Along with experimental results, we present a theoretical analysis based on the Landauer-Büttiker formalism. Agreement with theory is very good if it is scaled with a factor that accounts for the influence of orbital dephasing inside the dot.

Finally, we report on the annealing mechanism of ohmic contacts to a two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures. These contacts are often realized by annealing of AuGe/Ni/Au that is deposited on its surface. We have obtained optimal annealing parameters for three different heterostructures where the 2DEG lies at a different depth with respect to the surface of the wafer. TEM images of several annealed contacts provided further insight into the annealing mechanism and the formation of a good ohmic contact. Combining this information we have developed a model that can predict the optimal annealing parameters for contacting a 2DEG at a certain depth in a GaAs/AlGaAs heterostructure. This model should have predictive value for many heterostructures, as long the temperature of the samples as a function of time during the annealing process is known.