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Magnetization Measurements on Low-Dimensional Electron Systems in High-Mobility GaAs and SiGe Heterostructures

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Abstract

In this work micromechanical cantilever magnetometers have been used to measure the orbital magnetization of low-dimensional electron systems. The magnetization oscillations observed in the experiment at low temperature reflect the ground state energy of the electron systems. In particular we investigated two-dimensional electron systems (2DESs) of different mobility in GaAs as well as a high-mobility 2DES in Si as a function of magnetic field, temperature and tilt angle between 2DES normal and magnetic field. The 2DESs were realized by molecular beam epitaxy of AlGaAs/GaAs and SiGe/Si. Furthermore, GaAs quantum wires have been investigated.

In the GaAs 2DESs we observe the de Haas-van Alphen (dHvA) effect at filling factors corresponding to the Fermi energy being located between Landau levels. In a sample of mobility $\mu = 9 \times 10^6$ cm^2/Vs the dHvA effect is very close to an ideal sawtooth. Additional dHvA oscillations occur at fillings corresponding to the Fermi energy lying between spin split levels. The latter are found to be strongly enhanced by the Coulomb exchange interaction. In Si we additionally observe a splitting of the two occupied conduction band valleys in high magnetic fields that is also dominated by electron-electron interaction. Measurements in tilted fields revealed the coupling between the electric confinement and the magnetic confinement induced by a parallel magnetic field component. This led to a characteristic dependence of the dHvA effect on the tilt angle. Coincidence measurements have been used as an independent method to determine the spin splitting quantitatively. The valley splitting was found to be independent of the tilt angle. Comparison with calculations based on a model density of states (DOS) showed that a filling factor dependent background DOS has to be assumed in order to quantitatively model the data. This background can be attributed to the influence of the edge states. The measurements on quantum wires with many occupied subbands show that the confinement potential is effectively screened by the electron-electron interaction down to an electronic wire width of 160 nm. The dHvA oscillations directly reflect this effect. Comparison with calculations assuming a parabolic confinement shows that the DOS between Landau levels increases with decreasing wire width.

Inhaltsangabe

In dieser Arbeit wurden mikromechanische Cantilever-Magnetometer benutzt, um die orbitale Magnetisierung von niedrigdimensionalen Elektronensystemen zu untersuchen. Die Magnetisierungsoszillationen, die im Experiment bei tiefer Temperatur auftreten, spiegeln den Verlauf der Grundzustandsenergie wider. Im Speziellen wurden zweidimensionale Elektronensysteme (2DES) verschiedener Beweglichkeit in GaAs sowie ein hochbewegliches 2DES in Si als Funktion des Magnetfeldes, der Temperatur und des Verkippungswinkels zwischen 2DES Normale und Magnetfeld untersucht. Die 2DES wurden mittels Molekularstrahlepitaxie von AlGaAs/GaAs und SiGe/Si realisiert. Weiterhin wurden GaAs Quantendrähte untersucht.

In den GaAs 2DES wurde der de Haas-van Alphen (dHvA) Effekt an Füllfaktoren beobachtet, die einer Lage der Fermienergie zwischen den Landau-Niveaus entsprechen. In einer Probe mit 9×10^6 cm^2/Vs ist der dHvA Effekt nahezu perfekt sägezahnförmig. Weitere dHvA Oszillationen treten bei Füllgraden auf, an denen die Fermienergie zwischen spinaufgespaltenen Niveaus liegt. Letztere sind durch die Coulomb-Austauschwechselwirkung stark vergrößert. In Si beobachten wir zusätzlich eine energetische Aufspaltung der beiden besetzten Leitungsband-Täler in starken Magnetfeldern, die ebenfalls von der Elektron-Elektron Wechselwirkung dominiert wird. Messungen in verkippten Magnetfeldern zeigten den Einfluss der Kopplung zwischen dem elektrischen Einschlußpotenzial und dem magnetischen Einschluß aufgrund der parallelen Magnetfeldkomponente. Dies führte zu einer charakteristischen Abhängigkeit des dHvA Effektes vom Verkippungswinkel. Koinzidenz-Messungen wurden als unabhängige Methode benutzt, um die Spin-Aufspaltung quantitativ zu bestimmen. Die Täler-Aufspaltung erwies sich als unabhängig vom Verkippungswinkel. Der Vergleich mit auf einer Modellzustandsdichte basierenden Rechnungen zeigte, daß eine linear vom Füllfaktor abhängige Untergrundzustandsdichte angenommen werden muss, um die Messergebnisse quantitativ zu modellieren. Dieser Untergrund kann dem Einfluss der Randzustände zugeschrieben werden. Die Messungen an Quantendrähten mit vielen besetzten Subbändern zeigen, daß das Einschlußpotenzial bei einer elektronischen Drahtbreite von 160 nm noch effektiv durch die Elektron-Elektron Wechselwirkung abgeschirmt wird. Die dHvA Oszillationen spiegeln diesen Effekt direkt wider. Der Vergleich mit Modellrechnungen für ein parabolisches Einschlußpotenzial zeigt, daß die Zustandsdichte zwischen den Niveaus mit abnehmender Drahtbreite ansteigt.

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Chapter 1

Introduction

The properties of electron systems that are quantum mechanically confined in one or more spatial directions are of considerable research interest both for a fundamental physical understanding as well as for the progress of semiconductor technology. The discovery of the quantum Hall effect [vK80] and the fractional quantum Hall effect [Tsu82] in two-dimensional electron systems (2DESs) are famous examples of the new physics resulting from the reduced dimensionality. Both discoveries have been awarded with the Nobel prize and the former led to a new definition of the resistance standard. While the quantum Hall effect was discovered in 2DESs in silicon MOSFETs (Metal Oxide Semiconductor Field Effect Transistor), the observation of the fractional quantum Hall effect was made possible by the high electron mobilities achieved by molecular beam epitaxy (MBE) of the AlGaAs and GaAs compounds. Here, 2DESs are realized at the interface between different semiconductors with similar lattice constant that are epitaxially grown on top of each other with atomic layer precision. Its properties make the AlGaAs/GaAs material system ideal for basic research in semiconductor physics.[Sto84] In technological applications it is mainly used where ultra fast processing times are required. The incompatibility to Si and the lack of a natural oxide serving as an insulator hinder a very large scale integration (VLSI) of GaAs circuits. Here, the SiGe material system offers the possibility to combine the advantageous properties of Si/SiO_2 with its VLSI capability and the design freedom of heterostructures due to the band offsets.[Sch97] The availability of high-mobility SiGe heterostructures also gives rise to a renewed interest in the fundamental research on the unique properties of the material system. In particular, only a rudimentary understanding of the splitting of the two occupied conduction band valleys in high magnetic fields has been reached so far. Even after more than 20 years of intense fundamental research, new and totally unexpected properties of 2DESs are discovered, as, for instance, the recent observation of novel zero-resistance states induced by microwave irradiation.[Man02, Zud03]

One- and zero-dimensional systems have been realized, in a bottom-up approach by self-organization or in a top-down approach starting from 2DESs by introducing an additional lateral confinement potential through structured gate electrodes or etching. These systems again open up new fields both in fundamental research as well as for possible technological applications.

A variety of experimental tools has been used for the investigation of low-dimensional systems. The majority of the experimental results were obtained using magneto-transport measurements and spectroscopic methods. These experiments probe the excitation spectrum of the system and conclusions about the ground state properties can hence only be drawn indirectly. A direct relation to the systems ground state is given for thermodynamic equilibrium quantities. Investigations of thermodynamic properties included magnetocapacitance [Smi85, Mos86, Ash93, Dol97, MR02], specific heat [Gor85], compressibility [Eis94] and the magnetization.[Sto83, Eis85b, Wie97, Mei99, Har01] However, direct measurements of the oscillatory behavior of the magnetization as a function of the magnetic field or the carrier density turns out to be a challenging experiment due to the small absolute number of electrons.

In this work the thermodynamic equilibrium magnetization of low-dimensional electron systems has been investigated experimentally using a micromechanical cantilever technique. In particular the magnetization oscillations of 2DESs formed in MBE-grown AlGaAs/GaAs and SiGe/Si heterostructures have been studied as a function of magnetic field, temperature and tilt angle between 2DES normal and magnetic field. Additionally, the magnetization of quantum wire arrays prepared starting from GaAs 2DESs has been investigated. Special attention has been paid to the influence of electron-electron interaction on the de Haas-van Alphen effect. Detailed information about the density of states of the electron systems was gained by comparison of the experimental data with model calculations.

This thesis is organized as follows. In Chapter 2 a brief introduction to the properties of 2DESs subjected to a strong magnetic field is given. A thermodynamic approach to calculate the magnetization from a model density of states is discussed. The experimental technique and the preparation of the cantilever magnetometers is explained in Chapter 3 and Chapter 4, respectively. In Chapter 5 the experimental results are presented. This chapter is divided into three main parts. In the first section the magnetization of modulation-doped AlGaAs/GaAs heterostructures is