

Marc Wilde

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



Cuvillier Verlag Göttingen

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

Dissertation
zur Erlangung des Doktorgrades
des Fachbereichs Physik
der Universität Hamburg

vorgelegt von
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aus Hamburg

Hamburg
2004

Bibliografische Information Der Deutschen Bibliothek

Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über <http://dnb.ddb.de> abrufbar.

1. Aufl. - Göttingen : Cuvillier, 2005
Zugl.: Hamburg, Univ., Diss., 2004
ISBN 3-89873-397-6

Gutachter der Dissertation:	Professor Dr. D. Heitmann Professor Dr. W. Hansen
Gutachter der Disputation:	Professor Dr. D. Heitmann Professor Dr. U. Merkt
Datum der Disputation:	04.01.2005
Dekan des Fachbereichs Physik und Vorsitzender des Promotionsausschusses:	Professor Dr. G. Huber

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1. Auflage, 2005
Gedruckt auf säurefreiem Papier

ISBN 3-86537-397-6

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 $\mu = 9 \times 10^6 \text{ cm}^2/\text{Vs}$ 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 Magnetisierungssoszillationen, 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 Verkippfungswinkels 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 $9 \times 10^6 \text{ cm}^2/\text{Vs}$ 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 Verkippfungswinkel. Koinzidenz-Messungen wurden als unabhängige Methode benutzt, um die Spin-Aufspaltung quantitativ zu bestimmen. Die Täler-Aufspaltung erwies sich als unabhängig vom Verkippfungswinkel. 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.

Contents

Abstract	i
Inhaltsangabe	ii
1 Introduction	1
2 Fundamental theoretical concepts	4
2.1 2DES in a perpendicular magnetic field	5
2.2 Thermodynamic properties of a 2DES	6
2.3 Spin and valley splitting	10
2.4 Effect of an in-plane magnetic field component	16
2.5 Additional lateral confinement in one dimension	19
3 Micromechanical Cantilever Magnetometer	23
3.1 Principle of operation	24
3.2 Experimental setup	26
3.3 Calibration	27
3.4 Elastomechanical properties and sensitivity	29
4 Sample design and sensor fabrication	34
4.1 AlGaAs/GaAs material system	34
4.2 SiGe/Si material system	36
4.3 Preparation of the electronic system	37

4.4	Selective etching process	38
4.5	Preparational methods	39
5	Experimental results	41
5.1	Magnetization of 2DESs in AlGaAs/GaAs heterostructures	43
5.1.1	De Haas-van Alphen effect at Landau filling factors	44
5.1.2	Numerical calculations based on the DOS model	50
5.1.3	De Haas-van Alphen effect at spin filling factors	54
5.1.4	Anisotropic magnetization in tilted magnetic fields	59
5.2	Magnetization of a 2DES in a SiGe/Si heterostructure	70
5.2.1	Magnetization of SiGe/Si in tilted magnetic fields	76
5.2.2	Coincidence techniques	81
5.3	Magnetization of AlGaAs/GaAs quantum wires	87
6	Summary	95
A	Layer sequences of the investigated wafers	99
B	Preparational processes	102
C	1D density of states	104
D	Elasticity theory	105
	Acknowledgments	119

List of Figures

2.1	Calculated DOS, chemical potential and magnetization for a spin-degenerate 2DES in GaAs	8
2.2	Calculated DOS and chemical potential for a 2DES in GaAs including spin splitting	14
2.3	Calculated DOS and chemical potential for a 2DES in Si including spin and valley splitting	15
2.4	Calculated DOS, chemical potential and magnetization for a 2DES in GaAs in a tilted magnetic field	17
2.5	Calculated DOS, chemical potential and magnetization for a 1DES in GaAs with parabolic confinement	21
3.1	Schematic side view of a cantilever magnetometer, illustrating the principle of operation	25
3.2	Design of the MCM	27
3.3	Electrostatic and magnetostatic calibration curves	29
3.4	Cantilever sections for the calculation of bending lines	31
3.5	Bending lines of a cantilever for the case of a force or a torque acting on the sample area	32
4.1	Layer sequence of wafer hh#972	35
4.2	Laser-interference lithography	38
4.3	Sensor preparation	40
5.1	Magnetic background and dHvA effect of sample hh#972-30	42

5.2	Experimental magnetization and temperature dependence for sample hh#972-33	45
5.3	Comparison of experimental magnetization traces for 2DESs in GaAs heterostructures at $T = 2$ K	47
5.4	Normalized dHvA amplitude vs reduced temperature $k_B T / \hbar \omega_c$ for hh#693-1	48
5.5	Experimental energy gaps and background DOS for GaAs 2DESs . .	49
5.6	Comparison of model calculations and experimental magnetization traces	52
5.7	Thermodynamic energy gap at spin filling factors for sample bo#1121-1	55
5.8	Exchange energy versus $B_\perp$ for sample bo#1121-1	57
5.9	DHvA amplitude versus temperature for $\nu = 1$ in sample bo#1121-1 .	58
5.10	Magnetization versus $1/B_\perp$ for high tilt angles α	60
5.11	Model calculation: components of $\vec{M}$ parallel and perpendicular to the 2DES surface	62
5.12	Experimental and theoretical magnetic moment and energy gap as a function of $B_\parallel/B_\perp$	63
5.13	Thermodynamic energy gap at spin filling factors as a function of $B_\parallel/B_\perp$	65
5.14	Fast Fourier Transform of the dHvA oscillations at high tilt angles .	67
5.15	Magnetization of a SiGe/Si modulation doped quantum well	71
5.16	ΔM and ΔE vs $B_\perp$ for the SiGe quantum well	73
5.17	Temperature dependence of ΔM in SiGe/Si	75
5.18	Experimental magnetization of #SiGe7-2 for different tilt angles . . .	77
5.19	ΔE at $\nu = 4N + 2$ vs tilt angle	78
5.20	Energy gaps at spin filling factors vs Zeeman energy	79
5.21	Evolution of thermodynamic energy gaps as a function of tilt angle in SiGe	81
5.22	Magnetization traces for the 1^{st} and 2^{nd} coincidence conditions	83

5.23	Scanning-electron micrograph of an array of quantum wires	87
5.24	Calculated external confinement potential for a quantum wire	89
5.25	Experimental magnetization of quantum wire arrays with different wire widths	90
5.26	Experimental magnetization of sample <i>W160</i> and comparison with model calculation	91
5.27	Average DOS between the subband edges D_g normalized to the zero- field DOS D_0 in the wire arrays	92
5.28	Comparison of the T dependence of ΔM for quantum wires and a 2DES	93
A.1	Layer sequence of wafer hh#693	99
A.2	Layer sequence of wafer bo#1121	100
A.3	Layer sequence of wafer SiGe#1	100
A.4	Layer sequence of wafer hhbo#1839	101
D.1	Sections of the MCM	106

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/SiO₂ 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