MSN 524: Introduction to Mesoscopic Solid-State Materials

When a particular quantity of a system under study becomes comparable or smaller than a relevant correlation length, the system shows vastly different properties than its macroscopic counterpart. For instance, when electronic mean free path becomes smaller than the Fermi wavelength in solids, the wave character of the electrons become important and starts governing the materials properties. Mesoscopic solid-state systems become growingly important in the last 30 years as the miniaturization of electronic components happen at an exponential rate. This course aims to introduce such systems where the quantities in solid state systems become smaller than the relevant correlation lengths particularly in nanoscale materials.

Catalog Description

Introduction to Mesoscopic Solid-State Physics; What is Mesoscale; Electronic transport in solids; Transport in ballistic, diffusive and quantum transport; metal-insulator transition; Quantum Hall Effect; Quantum objects; Electronic Phase Coherence; Single Electron Tunneling; Superconductivity; Experimental methods; Cryogenics; Electronic Measurements

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Course website: http://serkankasirga.com/
Office hours: Friday's before the class
Lectures: Wed- 8:30-10:20 Fri- 14:40-15:30
Assistants: No assitants

Recommended Text

Thomas Heinzel, Mesoscopic Electronics in Solid State Nanostructures *Wiley-VCH*
Yoseph Imry, Introduction to Mesoscopic Physics *Oxford*

Course Contents

Introduction to Mesoscopic Solid-State Physics

- What is mesoscale?
- Relevant length scales
- Electronic transport in solids
- Solid state physics basics

Mesoscopic transport

- Ballistic, diffusive and quantum transport, metal-insulator transition
- Quantum Hall effect, transport under magnetic field
- Quantum wires, dots, point contacts

Relevant concepts in mesoscopic physics

- Electronic phase coherence
- Single electron tunneling
- Superconductivity at mesoscale

Experimental realization of mesoscopic systems

- Sample fabrication
- Electronic measurements
- Cryogenics
- New horizons with 2D materials

Course Assignments (Impacts on the Grading)

Midterm Test (25%)

There will be one midterm test.

Final Test (25%)

There will be a final test during the final's week.

Project (50%)

One project that studies a mesoscopic phenomenon in detail.

Weekly Syllabus

1. **Introduction to mesoscopic systems-**
   What is mesoscale? Relevant length scales, electronic transport in solids
2. **A reminder of solid state physics**
   Electronic energy bands, occupation of energy bands, doping, scattering, screening
3. **Surface, interfaces, and layered devices**
   Electronic surface states, semiconductor/metal interfaces, 2D van der Waals heterostructures
4. **Mesoscopic transport concepts**
   Ballistic transport, diffusive transport, quantum transport, Anderson localization
5. **Magnetotransport properties of normal/quantum films I**
   Hall effect, Landau quantization, Schubnikov- de Haas oscillations, quasi-2D electron gasses
6. **Magnetotransport properties of normal/quantum films II**
   Hall effect, Landau quantization, Schubnikov- de Haas oscillations, quasi-2D electron gasses
7. **Quantum Hall effect**
   A detailed study of quantum Hall effect
8. **Quantum wires**
   Diffusive and ballistic quantum wires, edge states
9. **Quantum point contacts**
   Quantum point contact circuits and their properties
10. **Quantum dots**
    Properties of quantum dots
11. **Electronic phase coherence**
    Aharonov-Bohm effect in solids, weak localization, resonant tunneling
12. **Single electron tunneling**
    Coulomb blockade, examples of SET circuits
13. **Superconducting mesoscopic devices**
    Superconducting rings, thin wires, Josephson junctions, Andreev reflection, Majorana fermions
14. **Experimental measurement of mesoscopic systems**
    Sample preparation, cryogenics, electronic measurements, new horizons with 2D layered materials

Similarity With Other Courses on Campus

There are no similar courses offered on Campus.

Similar Courses Around the World

University of Basel

Introduction to Mesoscopic Physics and Quantum Dots (15466-01 and 20400-01)

Spring semester 2013

Prof. Dr. Dominik Zumbühl, Dominik.Zumbuhl@unibas.ch

last updated Mar 10, 2013

previous year: Spring 2012

lectures Tuesday, 4:15pm - 6pm, HS2 (alter Hoersaal)

exercises Thursday, 10:15am-12pm, room 3.12

syllabus semiconductor surfaces and interfaces, 2D electron gas, quantum point contacts, quantum dots, conductance fluctuations, quantum phase coherence, Coulomb blockade, Kondo effect, few electron dots, spin blockade, spin relaxation, charge sensing, single spin measurement, spin manipulation and coherence, nuclear spins, electron spin resonance, spin qubits, quantum computation. syllabus pdf

mainly for masters students in nanoscience and physics. Physics III and condensed matter physics lecture is a prerequisite. 6. semester bachelor students are also allowed to take the class.

credit points 2 credit points lecture and (optional) 2 credit points exercises. Lecture is a two hours per week course, final presentation with number grade 1-6. The exercises (pass/fail) will consist of 3-4 problem sets and reading a series of scientific publications relevant to class, meeting one to two hours per week where papers discussed by the students in depth.

purpose of this lecture is to introduce the class to the physics of quantum transport in electronic nanostructures and electron spin qubits, discussing among other topics spin qubits in GaAs. The lecture will inevitably discuss some simple condensed matter theory but **will *mainly focus on experiments***.

structure will be a combination of lectures on my part to introduce the basics and subsequent presentations done by students towards the end of the semester on topics that can be chosen by students from a selection. There will be 3-4 problem sets, and moderate amounts of reading assignments in weeks without problem sets as preparation for lectures. The class grade will be based on the presentation given by each student taking the class for credit (presentation toward the end of the semester during class). Sit-ins/students auditing the class (not for credit) *are also welcome*.

preliminary meeting / Vorbesprechung Thursday (28.2.2013), 11:15-12:00, Room 4.1 scheduling, contents (Festlegung der Termine, Vorbesprechung), Syllabus pdf

Lecture Schedule and Content, FS 2013

date	lecture content
Thursday, Feb 28, 11:15am, Room 4.1	**preliminary meeting**, flyer pdf
Thursday, Mar 7, 10:15am room 3.1	***solid state physics background*** crystals, bands, effective mass approximation, spin-orbit coupling, GaAs conduction and valence bands, DOS, Fermi distribution, doping lecture notes pdf, slides pdf additional reading: Introduction and Motivation pdf

Tuesday, Mar 12, 4:15pm HS2	***semiconductor surfaces and interfaces*** surface states, semiconductor-vacuum interface, band bending, Fermi level pinning, Schottky barrier and diode lecture notes Chapter 2 pdf ***2D electron gases*** (GaAs) properties of 2DEGs, scattering mechanisms in 2DEGs and bulk GaAs, screening in 2D and 3D, Friedel Oscillations, ohmic contacts to 2DEGs, lateral gating and nanoscale devices lecture notes pdf
Tuesday, Mar 19, 4:15pm HS2	***concepts in mesoscopic physics (I)*** Drude conductivity, Einstein relation, mesoscopic time and length scales, classical Hall effect, (integer) quantum Hall effect, 1D subbands, quantum point contacts, 0.7 structure lecture notes chapter 3 pdf lecture slides pdf
Tuesday, Mar 26, 4:15pm HS2	***concepts in mesoscopic physics (II)*** classical Hall effect, (integer) quantum Hall effect, 1D subbands, quantum point contacts, 0.7 structure lecture notes chapter 3 pdf lecture slides pdf ***quantum point contacts (QPCs)*** van Wees et al., PRL**60**, 848 (1988) pdf van Wees et al., PRB**38**, 3625 (1988) pdf Cronenwett et al., PRL**88**, 226805 (2002) pdf lecture notes pdf
Tuesday, Apr 9, 4:15pm HS2	***quantum dots I: Introduction*** types of quantum dots, open and closed dot regimes, Coulomb blockade and diamonds, quantum confinement energy, constant interaction model, ground state and excited state spectroscopy, sequential and cotunneling transport, Coulomb peak line shapes lecture notes pdf articles: Kouwenhoven et al., dot review article, pp 1-28 pdf van Houten et al., CB review, NATO ASI, pp 1-15 pdf Foxman et al., PRB47, 10020 (1993) pdf Foxman et al., PRB50, 14193 (1994) pdf
Tuesday, Apr 16, 4:15pm HS2	***quantum dots II: Few Electron Dots*** lateral / vertical few electron structures, circular symmetry: shell filling, Fock-Darwin states, Singlet-Triplet states, Singlet Triplet ground state transition, lecture notes pdf *Few Electron Dots* Tarucha et al., PRL77, 3613 (1996) pdf Ciorga et al., PRB61, 16315 (2000) pdf Kouwenhoven et al., Science 278, 1788 (1997) pdf Kouwenhoven, Austing & Tarucha, RPP 64, 701 (2002) pdf ***quantum dots III: Double Quantum Dots*** double quantum dots, honey comb stability diagrams, finite bias transport, anticrossings lecture notes pdf *Double Dots* van der Wiel et al., RMP75, 1 (2003) pdf

Tuesday, Apr 23, 4:15pm HS2	***quantum dots IV: Kondo Effect*** Kondo effect (metals, quantum dots), Kondo screening cloud, zero bias peak, logarithmic temperature dependence, even-odd structure lecture notes pdf *Kondo effect* Goldhaber-Gordon et al., Nature 391, 156 (1998) pdf Cronenwett et al., Science 281, 540 (1998) pdf
Tuesday, Apr 30, 4:15pm HS2	***quantum dots V: Open Dots*** open dot regime, conductance fluctuations, weak localization, phase coherence, random matrix theory, spin-orbit coupling in semiconductors and quantum dots, weak antilocalization lecture notes pf *open dot regime* Huibers et al., PRL83, 5090 (1999) pdf
tbd	**presentations I** (3 student presentations)
tbd	**presentations II** (3 student presentation)
tbd	**presentations III** (3 student presentation)

ETH Zurich

402-0595-00L Semiconductor Nanostructures

Semester	Autumn Semester 2016
Lecturers	T. M. Ihn
Periodicity	yearly course
Language of instruction	English

- Catalogue data
- Performance assessment
- Learning materials
- Courses
- Restrictions
- Offered in
- Overview

Abstract The course covers the foundations of semiconductor nanostructures, e.g., materials, band structures, bandgap engineering and doping, field-effect transistors. The physics of the quantum Hall effect and of

common nanostructures based on two-dimensional electron gases will be discussed, i.e., quantum point contacts, Aharonov-Bohm rings and quantum dots.

Objective

At the end of the lecture the student should understand four key phenomena of electron transport in semiconductor nanostructures:
1. The integer quantum Hall effect
2. Conductance quantization in quantum point contacts
3. the Aharonov-Bohm effect
4. Coulomb blockade in quantum dots

Content

1. Introduction and overview
2. Semiconductor crystals: Fabrication and band structures
3. k.p-theory, effective mass
4. Envelope functions and effective mass approximation, heterostructures and band engineering
5. Fabrication of semiconductor nanostructures
6. Elektrostatics and quantum mechanics of semiconductor nanostructures
7. Heterostructures and two-dimensional electron gases
8. Drude Transport
9. Electron transport in quantum point contacts; Landauer-Büttiker description
10. Ballistic transport experiments
11. Interference effects in Aharonov-Bohm rings
12. Electron in a magnetic field, Shubnikov-de Haas effect
13. Integer quantum Hall effect
14. Coulomb blockade and quantum dots

Lecture notes

T. Ihn, Semiconductor Nanostructures, Quantum States and Electronic Transport, Oxford University Press, 2010.

Literature

In addition to the lecture notes, the following supplementary books can be recommended:
1. J. H. Davies: The Physics of Low-Dimensional Semiconductors, Cambridge University Press (1998)
2. S. Datta: Electronic Transport in Mesoscopic Systems, Cambridge University Press (1997)
3. D. Ferry: Transport in Nanostructures, Cambridge University Press (1997)
4. T. M. Heinzel: Mesoscopic Electronics in Solid State Nanostructures: an Introduction, Wiley-VCH (2003)
5. Beenakker, van Houten: Quantum Transport in Semiconductor Nanostructures, in: Semiconductor Heterostructures and Nanostructures, Academic Press (1991)
6. Y. Imry: Introduction to Mesoscopic Physics, Oxford University Press (1997)

Prerequisites / Notice

The lecture is suitable for all physics students beyond the bachelor of science degree. Basic knowledge of solid state physics is recommended. Very ambitioned students in the third year may be able to follow. The lecture can be chosen as part of the PhD-program. The course is taught in English.

Code	Course Name	Lec	Lab	Credits	AKTS
MSN 5xx	Introduction to Mesoscopic Solid-State Materials	3	0	3	7

ECTS - WORK LOAD TABLE

ACTIVITIES	Number	Hours	Workload
Course hours	14	3	42
Individual or group work			
Laboratory (including preparation)			
Homework	7	5	35

Project (including preparation and presentation if applicable)	1	30	30
Report (including preparation and presentation if applicable)	1	10	10
Presentation (including preparation)			0
Quiz	12	0,1	1,2
Preperation for Quiz	12	1	12
Midterm exam	2	2	4
Preparation for Midterm exam	2	25	50
Final exam	1	2	2
Preperation for Final exam	1	25	25
Total workload			211,2
Total workload / 30			211,2/30
			7,04000
ECTS credits of the course			**7**

Learning Outcomes

Demonstrate understanding of basic physics required to understand advanced topics in mesoscopic physics	Midterm I, Homework and Quizzes
Demonstrate understanding of mesoscopic transport under magnetic field, magnetotransport and quantum Hall effect	Midterm II, Homework and Quizzes
Demonstrate understanding of the contemporary research topics in mesoscopic physics	Final, Project