Master 2 Quantum Devices

OVERVIEW

The ‘Quantum Devices’ program provides its students with a high level theoretical and experimental training on different kinds of quantum phenomena with particular emphasis on quantum devices and nanotechnologies. Students receive state of the art training in nanofabrication and nanocharacterizing, with access to cleanroom facilities and a dedicated nanoscience teaching platform. The training courses are given by high-level scientists from Ile de France laboratories working in the domain of quantum devices. Thanks to this well established network, students find many opportunities after graduation both in academics as well as in the industrial sector.

Language of instruction: English
ECTS: 60
Oriented: academic research or industrial sector
Duration: 1 year
Courses Location: Université Paris-Diderot, Ecole Polytechnique

EDUCATIONAL OBJECTIVES

In the field of Quantum Devices and Nanotechnologies, the boundaries between physics, chemistry, materials science, biology and molecular medicine have become blurred. Fundamental and applied research enrich each other: theoretical advances are accompanied by progress in material science (synthesis of new materials, control of their elaboration) and by the realization of new and unique experimental
techniques (near field microscopy, electron microscopy techniques). These advances have had important consequences in fundamental physics; today we are able to observe and manipulate single atoms or conceive quantum devices: semiconductor sources and detectors, molecular transistors, superconducting circuits for quantum information, hard disks based on giant magnetoresistance, DNA chips,.... The « Quantum Devices » program introduces students to this rich field, enabling them to become themselves actors contributing to it, within academic or industrial research sectors.

PROGRAM STRUCTURE

The first term (September-January) includes lectures on the fundamental concepts and tools of quantum photonics and electronics in condensed matter, high-tech analysis tools (electronic microscopy, STM, AFM...), a large panorama of quantum devices and functional materials and proposes a series of seminars on hot research topics.

The second term (January-June) details the different fields of research (Electronic transport, Spintronics, Quantum Photonics) and includes a research project.

The course is given by lecturers from different laboratories specializing in quantum devices and nanosystems. The training is based on a permanent interaction between students and research teams, and includes: experimental projects, guided tours of laboratories and a research project.

1. OVERVIEW OF COURSES

FIRST TERM ECTS

Electrons and phonons in nanostructures, 3 ECTS
Quantum theory of light, 3 ECTS
Advanced solid state physics, 3 ECTS
Photonic quantum devices, 3 ECTS
Electronic quantum device, 3 ECTS
Bidimensional Materials, 3 ECTS
Imaging nano-objects, 3 ECTS
Experimental projects in nanoscience, 6 ECTS
Visits to Lab, 3 ECTS

SECOND TERM ECTS
Quantum Computing, 3 ECTS
Quantum Information, 3 ECTS
Nanomagnetism and spintronics, 3 ECTS
Functional materials, 3 ECTS
Internship, 18 ECTS

2. COURSES DESCRIPTION

FIRST SEMESTER

ELECTRONS AND PHONONS IN NANOSTRUCTURES (3ECTS)

Professors
Christophe Voisin (Prof. UPD, LPA),
Emmanuelle Deleporte (Prof. ENS Cachan, LPQM),
Francesca Carosella (MCF UPD, LPA)

Program
Fundamentals of Solid-State Physics
- Band structure and Bloch theorem
- Density of states
- Effective mass
- Overview of phonons

Envelope function approximation
Electron/phonons interaction: weak coupling regime
- Fermi golden rule
- Rabi oscillations
- Importance of energy loss in opto-electronic devices

Electron/phonons interaction: strong coupling regime
- Polaron in quantum dots
- Energy relaxation within polaron framework

QUANTUM THEORY OF LIGHT (3ECTS)

Professors
- Edouard Boulat (MCF UPD,MPQ)
- Cristiano Ciuti (Prof UPD, MPQ)
Program

Semi-classical theory of light matter interaction
Free particle of Spin 1/2
- Jauge invariance of Schroedinger equation ; Pauli Hamiltonian
- Semiclassical theory of light – matter interaction
- Electron-field interaction and Fermi golden rule ; transition rate

Quantum nature of light: photons
Fock space
- Operators : electric field, momentum, photon number
- The Casimir effect
- Special states of the electromagnetic field : coherent states, squeezed states

Photon emission and absorption
- Hamiltonian electron-photon; revisiting the Fermi golden rule
- Spontaneous and stimulated emission
- Natural linewidth
- Dipolar electric emission
- Diffusion of a photon from an atom

ADVANCED SOLID STATE PHYSICS (3ECTS)

Professors
- Alain Sacuto (Prof. UPD, MPQ)
- Francesco Sottile (IR, LSI, École Polytechnique)
- Fausto Sirotti (DR CNRS, PMC, École Polytechnique)

Program
Reminder of solid-state physics and Introduction (F. Sottile)

Scope of this first introductory session is to give the outline of the course, remind few concepts of basic solid-state theory, and assess the knowledge of the students on the different topics.

- Electrons and nuclei
- Born-Oppenheimer approximation
- Bloch theorem
- spin and k-points
- Magnetism (diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic, etc.)

Superconductivity (A. Sacuto)
An introduction to Superconductivity:

Introduction to a short story of superconductivity and its fascinating properties

- The quest of very low temperature
- The discovery of superconductivity
- The high-Tc superconductors
- Their properties with experiments performed during the lecture

The Cooper’s model:

- Bound electrons in a degenerate Fermi gas
- The superconducting gap

A first approach to the microscopic theory of Bardeen Cooper Schrieffer (BCS)

- Description of the ground state
- The BCS Hamiltonian
- The energy of the ground state and the superconducting gap

Signatures of the superconductivity in some spectroscopy probes

- Tunnelling and ARPES
- Infrared and Raman
- NMR

Electronic structure, the ground state (F. Sottile)

The electronic problem is introduced. In particular the state-of-the-art approach for the ground-state, Density Functional theory is presented. The needs for certain spectroscopy, introduced here, stimulates the need for the next experimental sessions.

- Ground-state quantities (lattice parameters, phonons, Bulk modulus, phase transitions)
- The many-body problem: independent particles
- Hartree and Hartree-Fock approaches
- Koopmans’s theorem and self-interaction concerns
- Density Functional Theory (theory, approximations and examples)
- Band-structure and Density of States
- Absorption in DFT ?

Photoemission and Spectroscopy (F. Sirotti)

- Energy and momentum conservation
- ARPES, XPS, Spin-resolution
- Bulk surfaces and interfaces, Cross sections.
- Experimental issues: Ultra High Vacuum, X-rays sources, Electron energy analyzers,
- Examples

Green’s functions theory I (F. Sottile)

The green’s function approach is presented, with particular emphasis on the one-particle Green’s function, that contains the removal and addiction energies of the electrons, for a direct comparison with photoemission spectroscopy.

- The need for the Green’s function
- Spectral representation
- The self-energy
- Hedin’s equations
- The GW approximations
- Quasiparticle and satellites
- Results and examples

X-ray absorption ellipsometry (F. Sirotti)

Valence spectroscopy and ellipsometry
Core electrons: XAS, XANES, EXAFS
Magnetic systems: Linear and circular Dichroism
Applications
Green’s functions theory II (F. Sottile)

Absorption spectroscopy require the two-particle Green’s function, which is presented briefly here.

The need for the two-particle Green’s function
The Bethe-Salpeter equation
  4 points quantities
Results and examples

Scattering spectroscopies and TDDFT (F. Sottile and F. Sirotti)

Scattering spectroscopies are presented in the first half of the session, namely Electron Energy Loss Spectroscopy and Inelastic X-ray Scattering. This gives the occasion to introduced the concept of screening and the theoretical approach Time Dependent Density Functional Theory.

  - scattering process and the inverse dielectric function
- electron energy loss
- electron microscope
- inelastic x-ray scattering
- experimental resolution: energy, momentum, space, time
- Time Dependent Density Functional Theory (theory, linear response and polarizability, approximations and applications)

PHOTONICS QUANTUM DEVICES (3ECTS)

Professors

C. Sirtori (Prof. ENS, LPA)
A. Vasanelli (Prof. UPD, LPA)

Program
Quantum devices in current technologies

- Introduction to quantum optoelectronic devices
- p-n diodes
- Tunnel diodes
- Transfer matrix and tunnelling current
- Mobility and modulation doping
- Two-dimensional electron gas
- Field effect transistors
- Bipolar transistors
- Transistor HEMT

Charge oscillations of quantized states

- Superlattices
- Bloch oscillations and Wannier Stark quantization
- Intersubband transitions and electron dispersion
- Oscillator strength
- Dipole charge oscillations
- Quantum cascade lasers

- Introduction: Laser diodes vs quantum cascade lasers
- Reminder of guided optics
- Plasmon waveguides
- Rate equations
- Gain
- From near infrared to THz optoelectronics

Quantum detectors
Quantum well infrared photodetectors
Quantum cascade detectors

Magnetic field applied to 2D structures
- Landau quantization
- Magneto-transport
- Shubnikov-de Haas effect
- Aharonov-Bohm effect

Light-matter coupling in microcavities
- Two level atom in an ideal cavity: Jaynes-Cummings Hamiltonian
- Spontaneous emission in a cavity
- Strong coupling / Weak coupling regime
- Strong coupling regime in semiconductor systems: polaritons
- Microcavity polaritons: exciton – polaritons, intersubband polaritons

ELECTRONIC QUANTUM DEVICES (3ECTS)

Professors
Philippe Joyez (DR SPEC, CEA Saclay)
Philippe Lafarge (Prof. UPD, MPQ)

Program
Rappels de physique des solides : structures de bandes, métaux, semiconducteurs, phonons, transport diffusif…
Seconde quantification
Transport quantique : longueurs caractéristiques, quantification de la conductance, formule de Landauer, bruit de courant dans les conducteurs quantiques, localisation…
Electrons en champ magnétique : niveaux de Landau, effet Hall quantique entier, fractionnaire, états de bord.
Supraconductivité : Théorie BCS, effet Josephson, supraconductivité mésoscopique, réflexion d’Andreev.
Transport dans les nanotubes de carbone.

BIDIMENSIONAL MATERIALS (3ECTS)

Professors
Clément Barraud (MCF UPD, MPQ)
Jérôme Lagoute (CR CNRS, MPQ)
Yann Gallais (Prof. UPD, MPQ)
Program

Since the discovery of graphene with its remarkable transport and optical properties, the field of two-dimensional crystals has flourished, and many materials can now be studied down to the single atomic layers. Compared to bulk materials two dimensional materials provide highly tunable platforms for novel functionalities and exotic opto-electronic phenomena. The goal of this course is to give an overview of this vibrant field by providing some basic concepts of two-dimensional materials (device fabrication, electronic and optical properties) and then focus on a selection of recent developments in the field (van der Waals heterostructures, defect engineering, di-chalcogenides, topological insulators...).

We will first review the basics of the physical properties of graphene with an emphasis on the properties of graphene-based devices and the means to characterize them. We will then introduce the physics of other two-dimensional materials like di-chalcogenides and black phosphorus which have been discovered more recently and whose optical and electrical properties differs from graphene. The course will end by an introduction to the unusual two-dimensional electronic states that forms at the surface of topological insulators.

The Physics of graphene and its devices (12h)

- Introduction: graphene and its band-structure
- Transport properties of graphene devices
- Optical properties and application to opto-electronic devices
- Local spectroscopies and defect engineering
- Graphene based heterostructures and van der Waals engineering: concept and fabrication

Beyond graphene: dichalcogenides, black phosphorus and topological insulators (12h)

- Introduction to dichalcogenides and their band structure in the 2D limit: the case of semiconducting MoS2
- Spin and valley degrees of freedom in semiconducting dichalcogenide + proximity effect
- Correlated states in metallic dichalcogenides: density wave and superconductivity
- Black-phosphorus
- Introduction to topological insulators

IMAGING NANO-OBJECTS
Professors
Damien Alloyeau (CR CNRS, MPQ)
Vincent Repain (Prof. UPD, MPQ)

Program
Single nano-objects imaging: from nanometer to sub-angstrom scale (8h)

Microscopes history and state-of-the-art optical microscopes
Electron microscopy
  - Microscope and Image formation
  - Transmission mode: high resolution imaging
  - Aberrations corrector: principle and unprecedented performances
  - Tridimensional imaging
  - Future challenges in electron optic

Near field microscopy
  - A brief history
  - General principle of working
  - Scanning Tunneling Microscope, Atomic Force Microscope, Scanning Near-field Optical Microscope: signal to noise and resolution
  - State-of-the-art examples: from single atoms to biological proteins

Structural and chemical analysis of nano-objects (8 h)

Structural analysis
  - Structure of surfaces with near field microscopes
  - X-ray diffraction and synchrotron radiation
  - Electron diffraction: quantitative analysis of single nano-objects

Chemical analysis
  - Probing atomic-scale chemistry by electron spectroscopy (Electron Energy Loss Spectroscopy) and photo-electron spectroscopy (Energy Dispersive X-ray analysis, X-ray Photoelectron Spectroscopy, Angle Resolved PhotoEmission Spectroscopy…)
  - Indirect ‘chemical’ mapping with near field microscopes (Inelastic Electron Tunneling Spectroscopy, Chemical Force Microscopy…)

Measuring physical properties of nano-objects (8 h)

Electronic mapping of nano-objects
• Wavefunctions in quantum dots and complex systems with Scanning Tunneling Spectroscopy
• Plasmon imaging using EELS

Magnetic properties of nano-objects

• Holography and magnetic circular dichroism
• Magnetic Force Microscope and Spin Polarized-STM

EXPERIMENTAL PROJECTS IN NANOSCIENCES (6ECTS)

Professors
Maria Luisa Della Rocca (MCF UPD, MPQ)
Fabrice Raineri (MCF UPD, C2N)
R. Braive (MCF UPD, C2N)

In this original course, students will get trained with experimental techniques used in nanosciences. During the first three weeks of the Master, students will have to make an experimental project in the nanosciences field like the elaboration and characterization of metallic nanoparticles, the optic of semiconducting laser, the electronic conduction in atomic contacts or organic materials, nanotubes physics, quantum optics…

A specific nanoscience area dedicated to teaching will be available with free of use instruments like an atomic force microscope, a scanning tunnelling microscope, a transmission electron microscope or an optic microscope. All students will also be initiated to clean room techniques during three days of practise.

SECOND SEMESTER

QUANTUM COMPUTING (3ECTS)

Professors
Perola Millman (DR CNRS, MPQ)
Hélène Perrin (DR CNRS, LPL)

Program:
Introduction to Quantum Computing (3h)
Quantum complexity classes
Quantum communication
Universal gates
Discrete and continuous variables
Qubit coding
Trapped ions for quantum computing (3h)
Methods for ions trapping
Cooling of ions
Microwave quantum logic gates

Quantum algorithms (6h)
- Shor algorithm
- Grover algorithm
- Presentation of the IBM qubits project
- Implementation of the Shor algorithm with trapped ions
- Superconducting qubits

Quantum error correction (6h)
- Quantum error correction codes
- Computing by superconducting qubits with quantum error correction codes (exp)
- ther platforms for quantum computing (Si, RMN, photons,…)

Quantum simulation (6h)
- Dicrete and continuous quantum simulation
- Quantum simulation platforms: quantum gases (bulk or lattice), Rydberg cold atoms in optical lattices, ions, microwaves, polaritons …

QUANTUM INFORMATION (3ECTS)

Professors
Eleni Diamanti (CR CNRS, LIP6)
Sara Ducci (Prof. UPD,MPQ)

Program
Theoretical Quantum Information

The qubit and its states
- quick review of the basic quantum formalism (kets, bras and density matrices)
- No cloning theorem and Wiesner’s unforgeable banknotes
- Quantum Key Distribution and BB84 protocol

Quantum Entanglement 1: Definition and some Properties
• Formal definition (as non-separable state)
• Apparent Heisenberg inequality violation
• Link with partial trace
• Entanglement detection for pure and mixed states
• Entanglement monogamy and application to QKD
• Partial transpose and its physical meaning

Quantum Entanglement 2: Bell inequalities and Application

• Entanglement is not a limitation of quantum formalism
• Bell inequalities (mainly CHSH)
• GHZ Paradox
• Some Entanglement application
• The 4 Bell States
• Quantum Dense Coding
• Quantum Teleportation

Device for Quantum Information

Introduction: Experimental implementation of quantum information: challenges and some famous experiments.

Photon sources: Single photon sources and their characterization: Hanbury Brown and Twiss interferometry, colloidal and grown quantum dots, colored centers in diamonds,...
Entangled photon sources and their characterization: Bell inequality test, density matrix reconstruction, nonlinear dielectric crystals and fibers, quantum dots, semiconductor waveguides, ...

Single photon detectors: Photomultipliers, single photons avalanche photodiodes, supraconducting detectors

Quantum metrology: absolute detector calibration, absolute radiance measurement, polarization mode dispersion, quantum ellipsometry …

Physical implementations of quantum computation: General overview, example of trapped ions.

NANOMAGNETISM AND SPINTRONICS (3ECTS)

Professors
Program

The ‘NanoMagnetism and Spintronics’ course targets the physics of Magnetism, of Magnetism at the nanometer scale (NanoMagnetism) and the spin-dependant transport in magnetic Nanostructures, scientific discipline designated today as Spin Electronics. After having introduced the fundamentals of orbital and spin localized magnetism in ionic systems, the course will tackle the important notions of paramagnetic, ferromagnetic and antiferromagnetic order. An important effort will be brought on the understanding of the establishment of band-ferromagnetism of 3d transition metals taking into account atomic exchange interactions. The second part of this course will be devoted some more actual problems of spin-dependent transport in Magnetic nanostructures (magnetic multilayers, nanowires, Magnetic tunnel junctions). The concepts of spin-dependent conduction in the diffusive regime, spin diffusion length and spin accumulation will be clearly emphasized to explain Giant MagnetoResistance (GMR) and Tunnel Magnetoresistance (TMR) effects. An opening will be done on the Magneto-Coulomb effects obtained with nanoparticles dispersed between ferromagnetic reservoirs and on spin transfer effects observed on metallic nanopillars and magnetic tunnel junctions.

FUNCTIONAL MATERIALS (3ECTS)

Professor
Silke Biermann (Prof. École Polytechnique, CPHT)

This course consists mainly of invited seminars given by international researchers on topics at the interface between fundamental and applied physics/materials science (i.e. Meta-Materials, 2d Materials for Valleytronics, 2d oxide heterostructures, Nanoparticles, battery materials, ….). The lectures are held at Ecole Polytechnique.

MASTER THESIS PROJECT (mars to june):

The final four-month Master thesis project can be conducted in one of the academic or industrial laboratory supporting the formation or in another Lab in France or abroad. The evaluation is based on a project report and an oral presentation.
LABORATORIES INVOLVED

- PMC
- CPHT
- LSI

CAREER PROSPECTS

The opportunities at the end of the thesis are academic careers in universities or in major research organisations (CNRS, CEA, IN2P3) or applied research in an industrial environment.

INSTITUTIONAL PARTNERS

- Université Paris-Diderot,
- Ecole Normale Supérieure Paris Saclay,
- L’Ecole Polytechnique.

TUITION FEES

Academic Prerequisites

- BSc in physics
- This course addresses students that have validated the first year of a master’s degree in physics, materials science, engineering (with physics orientation) and to students of the French Grandes Ecoles. Classes will be given in English.
- The selection committee will evaluate prospective students on their academic background and their motivation letter. Language certificates and recommendation letters will be taken into account as well.

Language prerequisites:
- Good working knowledge of English is a requirement

CONTACT

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