Master 2 Nanosciences

OVERVIEW

With more than 2000 researchers in the field of nanosciences, the Ile de France Paris area is the leading European “territory” in terms of scientific publications concerning nanosciences and nanotechnologies. This production represents nearly 40% of the domain's total production in France. This program is intended for students who have validated the equivalent of 4 year of undergraduate studies in physics, materials sciences or engineering sciences in France or abroad. Its objective is to enable students of Physics and Electrical Engineering to acquire specific scientific skills in order to study the extraordinary properties of nanostructures and nano-objects both from a fundamental point of view and through various applications such as the physical sciences, engineering sciences, biology, medicine...

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

EDUCATIONAL OBJECTIVES

The main goal of the track is to unravel – from a fundamental physics perspective -- the key concepts of nanosciences, while also providing advanced training on device fabrication and characterization techniques. The program hence spans from fundamental concepts to practical labworks, involving the different participating institutions and industrial labs.
All modules account for 3 ECTS

1. Program overview

Mandatory modules are:
- Light Matter Interactions in Semiconducting Nanostructures
- Manufacturing and Characterizations
- Microscopy, Near-field Microscopy and Spectroscopy
- Microtechnology
- Mobile charges
- Nanoelectronics and Molecular Electronics
- Nanomagnetism and spintronics
- Nanophotonics
- Non-Equilibrium Statistical Physics
- Numerical Simulations

Optional modules:
- Nanothermics
- Outstanding Compounds
- Photovoltaics
- Research Project/Paper

Courses Description

Light-matter interaction in semiconducting nanostructures

Objectives
The objective of this course is the study of the physical phenomena appearing in the semiconducting nanostructures, in relationship with optics. These phenomena are the source of lasers devices and quantum detectors, which are currently and widely used or which are still being developed.

Outline

Part I: Electronic structure of nanometric objects

- Bloch theorem, bands, 0D, 1D 2D confinement, excitons
- Absorption coefficient, emission.
- Effect of an external electric field on the electronic structure of the semiconducting heterostructures
Doping: p-n junction
Electron-phonon interaction

Part II: Laser effect, quantum detectors

- Optical properties of the semiconductors and of the semiconducting heterostructures
- Waveguides
- Physics of the laser oscillation
- Semiconductors based lasers (interband and intersubband)
- Quantum detectors
- Non-linear optics of quantum structures

Part III: Quantum dots and cavities

- Micro and nanocavities: Bragg mirrors, micropillars, microdiscs, photonic crystals
- Quantum dots: radiative cascade, single photon emission, entanglement, spin manipulation
- Quantum dots in cavity: weak coupling regime: Purcell effect, strong coupling regime: mixed light-matter states
- Quantum wells in cavity: cavity polaritons, their properties, non-linear regime (Bose condensation, polaritons laser, parametric interaction)

Main professor:
Jean-Sébastien Lauret, Professor, ENS Paris-Saclay
Jacqueline Bloch, Research director, CNRS

Nanomagnetism and spintronics

- Course overview:
The objective of this course is to provide a solid background in magnetism and spin-dependent transport. The course material will range from fundamental aspects to current research in magnetic recording and novel spintronic devices based on magnetic materials.

Outline:
- Microscopic origins of magnetism
- Paramagnetism, ferromagnetism, antiferromagnetism, spin waves
- Magnetic anisotropies
- Low-dimensional magnetism
- Experimental techniques
- Magnetisation dynamics
- Magnetic recording
- Spin-dependent transport (GMR, TMR…)
- Spin transfer torques
- Spin electronics and devices
Mobile Charges in physics and chemistry

Objectives
Mobile charges as electrons in a solid or ions in solutions are involved in most of the systems and phenomena in physics, chemistry and biology. The study of their spatial and time distributions is therefore fundamental to understand these phenomena. The objective of this course is to give a solid background allowing to deal with practical problems involving mobile charges in physics as well as in chemistry and biology.

Outline
Space dependent charge distribution in a weak potential:

- Poisson equation, Debye length
- Poisson equation in the Fourier space, dielectric constant
- influence of the system dimensionality
- case of fermion’s gas (in the linear approximation)
- Time and space dependent charge distribution:
  - Formalism
  - Time dependent correction of the dielectric constant
  - Perturbation approach to determine the $\mathcal{Q}(q,\omega)$
  - Calculation of the stopping power due to mobile charges
- Examples: inelastic electron scattering, Raman effect, ion mobility, plasmons
- Charge distribution beyond the linear approximation in physics, chemistry and biology:
  - Semiconductor surface (space charge, depletion/accumulation)
  - Semiconductor/oxide/metal and semiconductor/metal interfaces (band bending, Fermi level determination)
  - Electrode/electrolyte interface (double layer, influence of the electrode morphology, colloid formation and manipulation)
- Biological interface (DNA denaturation, DNA adhesion on charged surfaces). Charge distribution and transport far from equilibrium:
  - Quasi-neutrality approximation
  - Semiconductors: Dember effect and p-n junction
  - Electrochemistry: ion transport of a redox couple and electrodeposition
  - Ion transport trough membranes
Nanophotonics

Objective
The objective of this module is to train students in the fields of nanophotonics and its applications through the study of the properties of light propagation in nanostructured environments as well as the benefits from nanostructures for optoelectronics.

Outline

I. Photonic integrated circuits
   Properties of light waves
   Guiding, photonic integrated circuits: building blocks
   Example of application: silicon photonics

II. Propagation of light in nanostructured environments
   Photonic crystals
   Plasmonics
   Metamaterial

III. Photonics active devices
   Nanostructures for optoelectronics (quantum well, quantum dots, nanowires)

Competences
Ability to analyze and understand the challenges in photonics and nanophotonics. Be able to explain the basic phenomenon in the field

Professor in charge
Delphine Marris-Morini, Professor, Université Paris-Sud

Nanoelectronics and Molecular Electronics

Objective
The objectives are to acquire the basic knowledge of (i) the physics of transport in semiconductor nanodevices through different formalisms of semiclassical and quantum transport description, computational methods, and typical examples of nanodevices, (ii) the physics of transport in molecular electronics from both theoretical and experimental perspectives, including conjugate/functionalized molecules and carbon-based materials, and (iii) the possible use of nanodevices in appropriate circuit architectures through examples from neuromorphic electronics.

Outline
I. Nanoelectronics
- Introduction to nanoelectronics: Typical examples, the limitations of the semi-classical approach of transport
- From classical to quantum transport: Transport equations from Boltzmann to Wigner, Landauer equation, Green’s functions, Computational methods, Decoherence phenomena
- Nanotransistors: ballistic and quantum effects
- Resonant tunneling effect and applications
- Quantum dots – Coulomb blockade – Single electron devices

II. Molecular electronics
- Introduction to molecular electronics: an overview
- Conjugate and functionalized molecules, molecular transport: Nanoparticles, synthetic molecules, DNA/RNA, transport properties
- Fullerenes, carbon nanotubes, graphene devices: Principles, theory and experiments

III. Nanoarchitectures and Neuromorphic electronics
- Introduction to the integration of nanodevices
- Examples: The neuromorphic electronics (nanodevices as synapses), Unsupervised learning (use of stochasticity and variability)

Skills
Ability to analyze and understand the conduction phenomena through nano-objects and the physics of transport in semiconductor and molecular nanodevices, with the perspective of their applications

Professor in charge:
Philippe Dollfus, Research director, CNRS

Other teachers:
Arianna Filoramo, Researcher, CEA
Damien Querlioz, Resercher, CNRS

Microtechnology

Objective
This course presents different fabrication methods of micro and nano-devices using very high technological processes. We describe technics from microelectronics and other specific technics as micromolding, wafer bonding, etc

Outline
- Introduction
- Material structures
- growth technics (oxidation, CVD, PVD, MBE)
• Lithography (UV)
• Etching
• Specific processes for hybrid systems: transfer technics, advanced micromolding...

Professor in charge

Elisabeth Dufour-Gergam, Professor, Université Paris-Sud

Other teachers
Thierry Gacoin, Research director, CNRS
Bernard Bartenlian, Researcher, CNRS

Numerical Simulation of Nanosystems

Objectives
The simulation on computer is a necessary tool of research in physics. It is considered to be a third scientific supplementary way to experimental and theoretical approaches. The purpose of this course is to introduce the most common methods in simulation: molecular dynamics and Monte Carlo methods.

Outline
Modelling of interatomic interactions
Configuration integral and generalized equipartition theorem.
Monte Carlo Metropolis (MC) method Molecular Dynamics method and comparison with MC.
Methods to derive microscopic and macroscopic properties: heat capacity, radial distribution function, diffusion coefficient, order parameters, surface energy, frequency dependence of polarisability…
Examples of subjects proposed to students during supervised sessions: 1) Order-disorder transition. 2) Diffusion coefficient in argon. 3) Surface reconstruction and reordering. 4) Influence of cluster size on structural and optical properties. 5) Density of vibration states and dielectric constant in ferroelectrics. 6) Ferromagnetic et antiferromagnetic transition…

Professor in charge
Hichem Dammak, Professor, CentraleSupélec

Other teachers
Marc HAYOUN, Researcher, CEA
Igor KORNEV, Professor, CentraleSupélec

Nonequilibrium Statistical Physics
Objectives
The course starts by reviewing equilibrium statistical physics with emphasis on fluctuations. Several approaches to non-equilibrium statistical physics are then presented: linear response theory, Langevin model, Boltzmann equation and irreversible thermodynamics.

Content
Microcanonical, canonical and grand canonical ensembles
Thermodynamic functions, potentials
Linear response theory
Fluctuation-dissipation theorem.
Langevin model
Boltzmann equation
Transport phenomena in gases
Transport phenomena in solids
Introduction to irreversible thermodynamics

Professor in charge
Jean-Jacques Greffet, Professor, IOGS

Nanothermics

Objectives
Heat generation and propagation at the nanoscale has become a challenging issue, not only for applications such as energy transport and conversion, nanoelectronics, microscopy and metrology, nanoscale chemical reactors or novel therapies against cancer, but also for the new physics it contains, due to confinement.
In this lecture, different aspects will be covered, in the form of lectures and labworks devoted to formal basis, modelling approaches, recent experimental results and applications in various fields. Topics included: phonon transport in nanostructures, near-field radiative heat transfer, light-heat conversion in metal nanoparticles, thermoelectricity, metrology tools (scanning thermal microscopy, topological probes and thermal imaging of nanostructures), numerical modelling of heat transfers. A special emphasis is put on examples of relevant applications such as energy transport and conversion, thermophotovoltaics, nanoelectronics, microscopy and metrology, photothermal imaging or novel therapies against cancer.

Outline

Lectures Thermo-electricity

- Nanoscale conduction (phonons)
- Near field heat exchange by nanoscale radiative transfer (photons)
- Localised plasmon in metal nanoparticles for efficient energy input
- Optical generation and detection of heat at the nanoscale (models, experiments) and applications
- Melting point depression in nanoparticles
Simulation and metrology

- Molecular dynamics simulation of the heat properties (vibrational DOS of carbon nanotubes on Si substrate) (in Ecole Centrale Paris)
- Measurement of surface heat topography by infrared AFM (in Orsay)
- Thermal topography measurements with Scanning Thermal Microscopy (in Orsay).

**Professor in charge:**
Bruno Palpant, Professor, CentraleSupélec

**Other teachers:**
Sebastian Volz, Research director, CNRS
Alexandre Dazzi, Professor, Université Paris-Sud
Yann Chalopin, Researcher, CNRS

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**TUITION FEES**

**National Master:** Official tuition fees of the Ministry of Higher Education, Research and innovation (2019-2020, EU students: 243 euros / Non-EU students: 3770 euros)

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