Nanophysics, Nanostructures

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SEMESTRE 3 – SEMESTER 3 30 ECTS

Cours obligatoires – Compulsory courses 18 ECTS

- **PPHY538I** - 3 ECTS - *Physique et élaboration des nanostructures. Physics and elaboration of nanostructures.*
  Philippe Peyla (UJF) et Henri Mariette (CNRS) 24h Cours

- **PPHY538N** - 3 ECTS - *Nanomagnétisme. Nanomagnetism.*
  Olivier Fruchart (CNRS) 24h cours

- **PPHY538M** - 9 ECTS - *Formation expérimentale. Research training*
  Chantal Tardif (CEA), Philippe Peyla(UJF) 3x5 days spent in a lab (3 different labs)

- **PPHY538J** - 3 ECTS - *Nanostructures de semiconducteurs. Semiconductor nanostructures*
  David Ferrand (UJF) 24h Cours

Cours optionnels – Broadening courses 12 ECTS

- **PPHY538K** - 3 ECTS – *Fonctionnalisation des surfaces. Surface functionalization.*
  Didier Delabouglise (G-INP) 24h cours

- **PPHY538L** - 3 ECTS - *Sécurité des nanos. Nanosafety*
  Chantal Tardif (CEA) 24h cours

- **PPHY538O** – 3 ECTS - *Physique mesoscopique. Mesoscopic physics*
  Tristan Meunier (CNRS) 24h cours

- **PPHY538P** - 3 ECTS - *Transport quantique et électronique moléculaire. Quantum transport and molecular electronics.*
Vincent Bouchiat (CNRS) 24h cours

- **PPHY538Q** - 3 ECTS -
  Introduction à la nanofluidics, force faibles et adhésion. Introduction to nanofluidics, soft forces and adhesion.
  Elizabeth Charlaix (UJF) 24h cours

- **PPHY538R** - 3 ECTS -
  Photonique et information quantique. Photonics and quantum information.
  Jean-Philippe Poizat (CNRS), Alexia Aufève (CNRS), Jean-Michel Girard (CEA) 24h cours

- **PPHY531O** - 3 ECTS
  Properties of nanotubes, fullérène and graphene.
  Didier Mayou (CNRS) 24h cours

- **PPHY538S** - 3 ECTS
  Méthodes de caractérisation des surfaces. Surface Characterization techniques.
  Sirona Valdueza-felip(CEA) and Laurens Kwakman (FEI Compagny) 24h cours

- **PPHY538T** - 3 ECTS
  Microscopie en champ proche. Near Field Microscopy.
  Florence Marchi (UJF) and Hervé Courtois (UJF) 12h cours 12h TP

- **PPHY538U** - 6 ECTS –
  Caractérisation des interactions (bio) moléculaires, nanomatériaux, surfaces et interfaces. Characterization of (bio) molecular interactions, nanomaterials, surfaces and interfaces
  Frederic Dubreuil (UJF), Jean-Luc Putaux (CNRS),Yvonne Soldo(CNRS), Bruno Gilles (CNRS), Pierre Labbé (UJF) 34h Cours

- **PPHY538V** - (Master PMCR) 3 ECTS –
  Physics on synchrotron radiations.
  Luigi Paolasini (ESRF) 24 Cours (Cours PMCR en mutualisation partielle)

- Any other Master courses (if compatible with the time table) 3ECTS

**SEMMESTRE 4 – SEMESTER 4**  **30 ECTS**
List of courses and outlines:

- **PHYS538I** - 3 ECTS - Erasmus Mundus Course *Specializing Courses in Physics and Elaboration of Nanostructures*. 

  Philippe Peyla (UJF) et Henri Mariette (CNRS) 24h cours

  This course gives an overview of the physics concerning elaboration (growth) of nanostructures. Theoretical and experimental aspects are shown.

  Prerequisites: Quantum mechanics, solid state physics and statistical physics.

  **Part I Introduction to growth mechanisms.**

  I - Thermodynamics of surfaces
  - Langmuir isotherms.
  II - Surface tension
  III - Surface stress
  - Introduction to elasticity and dislocations

  IV – Grinfeld instability
  V – Surface out of equilibrium
  a) Roughness and surface morphologies
  b) Adatom, island, terrace, kink, step
  c) Surface models: discreet or continuous
  d) Chemical potential
  - and evolution of a rough surface
  e) Irreversible evolution of a rough surface
  f) Kinetic roughening during growth
Part II Growth mechanisms and molecular beam epitaxy

1. Introduction to the different semiconductor materials.
2. Introduction to nanostructures:
   possible applications.
4. The different techniques of thin layer epitaxy.
5. Vapor phase epitaxy.

• PPHY538J - 3 ECTS
  Nanostructures de semiconducteurs. Semiconductor nanostructures
  David Ferrand (UJF) 24h cours

The first chapter will be devoted to a review of the main properties of bulk semiconductors and of their alloys. For the different groups of semiconductors (IV-IV, III-V, II-VI), the crystallographic properties of bulk materials, epilayers (strain and stress tensors) and surfaces will be discussed. A detailed description of the band edges (electron/hole pairs, spin orbit coupling, effective mass, Luttinger Hamiltonian, Bir & Pikus Hamiltonian) will be developed for the conduction band and valence band. The second chapter will be devoted to the electronic properties of nanostructures (quantum wells, quantum dots, nanowires, nanocrystals). After a short introduction of the growth methods (molecular beam epitaxy), some fundamental aspects will be discussed using the envelop function formalism (calculation of 2D, 1D, 0D electronic confinement, electron and hole wavefunctions, interband and intersubband optical transitions). The last chapter will be devoted to modulation doped nanostructures (quantum wells, heterojunctions) and to the introduction of the Schrodinger-Poisson formalism.

Prerequisite Solid State physics, quantum mechanics

Outline:

Part I: Fundamental properties

1 Presentation of the different groups of semiconductors, group IV, III-V and II-VI:
   Diamond, zinc blende and wurtzite crystallographic structures
   Band gap, alloys (virtual crystal approximation),
   Strain and stress in epilayers, phonons spectra.
2. Band extrema
Effective mass approximation, wave function symmetry
Conduction band: direct and indirect band gap
Valence band: concept of hole, spin orbit coupling
Luttinger Hamiltonian, Bir et Pikus Hamiltonian.
Density of states

**Part II: Semiconducting Nanostructures**
1. Introduction
Introduction to epitaxial growth method
Band offsets, type I and type II heterostructures
2. Quantum confinement
Envelop function formalism,
Electron and hole confined levels
Applications: quantum wells, superlattices, nanowires,
SK quantum dots, nanocrystals
3. Optical spectroscopy of nanostructures
Interaction with light (A.p Hamiltonian)
Interband and inter-subband transitions
Experimental spectra

**Part III: Modulation doped nanostructures**
1. Doped semiconductors
Short introduction and recall on donor and acceptor impurities
Intrinsic, lightly doped semiconductors and degenerate semiconductors
2. Modulation doped nanostructures
Introduction to modulation doping techniques
Schrödinger-Poisson formalism,
Example for quantum wells and heterojunctions

- **PPHY538K** 3 ECTS - Erasmus Mundus Course
  **Surface functionalization.**
  Didier Delabouglise (INP) . 24h cours
This course is intended to be an introductory course accessible for both chemists and Physicists. It will present in an illustrated and accessible fashion the principles of surface functionalization

Course content
Functionalization of surfaces, methods

Organic/ inorganic functionnalization

Molecule-Metal interface

Applications to functionalized biological surfaces

• **PPHY538M** - 9 ECTS  Specializing Courses  
  *Formation expérimentale. Research training*
  Chantal Tardif (CEA), Philippe Peyla(UJF)  3x5 days spent in a lab (3 different labs)

Each student spends 10 days with three (or two for EM students) different research teams. This training gives an overview of the physics of nanostructures in Grenoble and the way of investigations of laboratories. In Grenoble 30 laboratories collaborate to this training.

This is a short list of labs which collaborate: LETI (CEA), ESRF, Institut Néel, Laboratoire Interdisciplinaire de Physique (LIPhy), INAC (CEA), Département de chimie moléculaire, Spintec, SPRAM, etc.

• **PPHY538N** - 3 ECTS- Erasmus Mundus Course Specializing Courses  
  *Nanomagnétisme. Nanomagnetism.*
  Olivier Fruchart (CNRS) 24h Cours

The development of nanostructures opened a wide range of new possibilities for exploring magnetism at the nanometer scale. In this rapidly growing area, the two main challenges are to deepen our fundamental understanding and to develop new technological applications, especially in the field of magnetic recording and spintronics. The lectures aim at providing the solid basis in magnetism required to understand the magnetic properties of nanostructures. The fundamental concepts will be illustrated by examples of recent research results in the field of nanomagnetism.

**Preriquisites:** Quantum mechanics, solid state physics, statistical physics

1. Introduction
   - Definitions of magnetic moment, magnetization, magnetic field and induction, susceptibility.
2. Study of magnetism at a continuous scale: micromagnetism
   - Energy: exchange energy, magnetocrystalline energy, magnetoelastic energy, magnetostatic energy and demagnetizing field.
   - Theory of micromagnetism.
   - Magnetization dynamics.
   - Domains and domain walls in bulk materials and in thin films.
   - Examples of magnetic configurations of nano-objects
   - Effect of an applied magnetic field.
3. Experimental methods for studying magnetic properties of nanostructures
4. Examples of magnetic nanostructures
   - Coherent magnetic switching.
   - Magnetic recording: state of the art and future developments.
   - Brief introduction to spintronics.
5. Magnetism at the atomic scale
   - Origin of magnetic moments in an isolated atom.
   - Influence of environment: crystal field effects
   - Response of localized magnetic moments without interactions to a magnetic field:
     - Paramagnetism and diamagnetism.
6. Magnetic order. Magnetic phase transitions
   - Interactions between moments. Direct and indirect exchange (insulators and metals).
   - Ferromagnetism: mean field and beyond.
   - Antiferromagnetism. Ferrimagnetism. Other kinds of magnetic order.
   - Magnetism in frustrated systems.
   - Itinerant ferromagnetism.

- **PPHY5380** – 3 ECTS - Erasmus Mundus Course
  *Physique mesoscopique. Mesoscopic physics*
  Tristan Meunier (CNRS) 24h Cours

This course will describe concepts of mesoscopic physics illustrated by experimental realizations and applications.

**Prerequisites:** Quantum mechanics, solid state physics, statistical physics.

1. Introduction
   Characteristic length scales
   Classical and quantum ballistic transport
   Landauer formula and QPC

2. Interference phenomena
   Aharonov-Bohm effect, AAS, Weak localization, UCF
   Decoherence mechanism: electron-electron interaction
   Application to the measurement of the quantum coherence time
3. Quantum dots
Artificial atoms, Hund’s rule
Coulomb blockade, Sequential tunneling, Kondo, Fabry Perot
Coherence properties and decoherence mechanism
Application: SET and charge detection

4. Mesoscopic with Superconducting systems
Andreev reflection, SNS junction, RCHJ model, Josephson junction, fictitious particle, Washburn potential, SQUID
Application: SQUID and magnetic field detection

5. Introduction to quantum Hall effect
Landau levels
Edge states and Landauer-Büttiker formalism
Application: Mach Zender interferometer

6. Noise in mesoscopic systems
Nyquist noises, Partition noise
Quantum shot noise
Application: Hanbury Brown experiment

7. Spins in mesoscopic systems
Control and detection of spin degree of freedom in mesoscopic systems
Coherence properties and decoherence mechanism
Experimental realization

- **PPHY538P** - 3 ECTS - Erasmus Mundus Course
  Transport quantique et électronique moléculaire. Quantum transport and molecular electronics.
  Vincent Bouchiat (CNRS) 24h cours.

This course is intended to be an introductory course accessible for both chemists and physicists. It will present in an illustrated and accessible fashion the principles of quantum electron transport in molecular and nanoscale devices and offer an overview of this active field of Nanosciences.

Prerequisites: Quantum mechanics, solid state physics, statistical physics.

1. General Introduction 1/3: The foundation of Nanoelectronics: illustrated historical presentation of new concepts and recent experiments
   Objects: heterostructures, nanocristals, nanotubes and nanowires
First introduction of concepts: low dimension transport, quantum confinement, Coulomb blockade and quantum dot

2. General Introduction 2/3: The future of Nanoelectronics: beyond the MOSFET.
   - New materials (beyond silicon)
   - New architectures and New ideas: Spintronics and Quantum information.

3. General Introduction 3/3:
   The Instruments of Nanoelectronics: Fabrication and Measurement techniques:
   - Physics: electron microscopies, techniques of nanolithography, scanning probes, cryogenics...
   - Chemistry: Self assembly, supramolecular chemistry
   - Bio-inspired approaches: DNA guided assembly, bioelectronics (neurons/solid), state devices interfacing)

4. Introduction to Electron Transport: Concepts and new phenomena
   - Hamiltonian description of Electron in a lattice, Bloch waves
   - Band structure and Density of states
   - Effect of confinement on the density of states,

5. From the bulk 3D to the single molecule:
   - Application to the Benzene molecule and to the carbon nanotubes
   - Illustrated presentation of the effect of Quantum confinement: Electronic spectroscopy

6. Semiclassical Transport:
   - Effect of disorder and geometry, notion of elastic/inelastic mean free path, localization of electrons, Phase coherence and mesoscopic effects

7. Quantum transport
   - Ballistic transport and Quantum interferences
   - Landauer formula, quantization of conductance, example of Quantum point contact.

8. Single electronics, introduction to Coulomb blockade and tunneling phenomena
· The single electron box (and its superconducting counterpart)

· The single Electron Transistor and its applications (electrometers, Thermometers)

· Electron pumps and Single electron memories

9. The Quantum dot : an artificial and tunable atom

· Theory of the quantum dot : definition of the addition energy

· Spectroscopy of a quantum dot,

· electron/electron interactions (spin effects (Kondo resonance, Zeeman splitting))

10. From Organic Electronics to Single Atom transistors

· Notions of Quantum Chemistry

· Theory of the molecular junction

· strong and weak coupling,

· analogies with the previously introduced concepts (single electron devices and quantum dots)

· Links between chemical structure/functions and electron properties diodes, molecular transistors, memories and switches

Introduction to Molecular Spintronics

• **PPHY538Q** - 3 ECTS - Erasmus Mundus Course *Broadening Courses*
  Introduction à la nanofluidics, force faibles et adhésion. Introduction to nanofluidics, soft forces and adhesion.
  Elizabeth Charlaix 24h cours

The understanding of small scale dynamic phenomena in fluid systems is a challenge of condensed matter physics with outcomes in nanosciences (NEMS and MEMS), transport in biologic systems (transmembrane transport, aquaporins, ionic channels) as well as in colloid science and nanostructured materials.

This course describes the multiples phenomena whose interplay determines small scale dynamics in fluids: Brownian motion, surface interactions and long range forces (Casimir-Van der Waals, electrostatic, depletion...), osmotic transport, ratchets, fluctuating hydrodynamics, interfacial dynamics, etc... We will discuss the limit of validity of continuum models, the description of molecular phenomena acting at nanoscale, and the specific transport properties in nanochannels resulting from the interplay between hydrodynamics and surface interactions.
PPHY538R - 3 ECTS- Erasmus Mundus Course  
**Photonique et information quantique. Photonics and quantum information.**  
Jean-Philippe Poizat (CNRS), Alexia Aufève (UJF), Jean-Michel Gerard (CEA)  
24h Cours  

Prerequisites: Quantum mechanics, solid state physics, statistical physics.

Basics of quantum optics including single photon and entanglement will be given and topics like quantum cryptography and quantum teleportation will be developed. Emphasis will be put on the study of the system made of a single semi-conducting quantum dot in a microcavity.  

1 - Introduction to quantum optics (4h)  
2 - Quantum information and communication (8h)  
3 - Quantum dot in a microcavity (8h)  

PPHY531O- 3 ECTS  
**Properties of nanotubes, fullérène and graphene.**  
Didier Mayou (CNRS) 24h Cours  

Prerequisites: Quantum mechanics, solid state physics, statistical physics.

This course is an introduction to electronic structure and transport properties of nanostructures. The course focuses in particular on carbon based materials such as nanotubes and graphene but provides also comparison with nanostructures based on standard semi-conductors. The first part deals with the electronic structure of graphene, nanotubes and related structures. The second part deals with electrons in an external field: static electric field, static magnetic field, electromagnetic wave. Semi-classical as well as fully quantum approaches are used and compared which gives insight in the transport properties.

Required knowledge: basic quantum mechanics,  

**PART I : ELECTRONIC STRUCTURE**  

I) Introduction to graphene  
- General introduction to graphene, nanotubes and fullerene  
Objective of the course, required knowledge  
Presentation of the course  

II) Basics of electronic structure  
- Lattice, Reciprocal lattice  
- Tight-binding description, Bloch theorem  
- Band structure of graphene  

III) The Dirac equation  
- Linearized bandstructure close to the Dirac point
- Dirac equation for a slowly varying potential. The Klein paradox
- Orders of magnitude

IV) Electronic structure of related systems
- Band structure of nanotubes
- Band structure of nanoribbons
- Graphene Bilayers

PART II : ELECTRONS IN AN EXTERNAL FIELD

V) Electrons in an electrostatic potential
- Semi-classical theory and geometrical optics analogies
- Transmission through a barrier, evanescent waves guided modes
- Fabry-Perot oscillations of the conductance

VI) Electrons in a magnetic field
- Semiclassical approach
- Quantum approach

VII) Optical conductivity
- The linear response theory for optical absorption
- Universal value of the optical conductivity of graphene
- Optical conductivity under a magnetic field

VIII) Transport properties : the semi-classical approach
- Distribution function
- Scattering by defects
- Application to different type of scatterers

IX) Transport properties : the quantum approach
- Conduction and diffusion
- Classical diffusion
- Quantum diffusion : localization phenomena, minimum conductivity

X) Transport properties : the Landauer approach
- Notion of channels and reservoir
- Conductance and transmission
- Transmission

XI) Transport properties : the Landauer approach
- Nanotubes nanoribbons
- QHE
- Fabry-Perot oscillations of the conductance
• PPHY538S - 3 ECTS
Méthodes de caractérisation des surfaces. Surface Characterization techniques.
Eva Monroy (CEA) and Laurens Kwakman (FEI Company) 24h Cours

Préréquisistes: Quantum mechanics, solid state physics, statistical physics.

To remain competitive, IC manufacturers have to accelerate the development of most advanced (CMOS) technology and to deliver high yielding products with best cycle times and at a competitive pricing. With the increase of technology complexity, also the need for physical characterization support increases, however many of the existing techniques are no longer adequate to effectively support the 65-32 nm technology node developments.

New and improved techniques are definitely needed to better characterize the often marginal processes, but these should not significantly impact fabrication costs or cycle times. Hence, characterization and metrology challenges in state-of-the-art IC manufacturing are both of technical and economical nature. This course allows the student to develop an understanding of the role and importance of Physical Characterization in the Microelectronics industry. In this course, the various, often very advanced analytical techniques will be reviewed and explained. Both theory and practical use-cases will be covered and illustrated through examples stemming from most recent, industrial CMOS technology development programs.

1. The Microelectronics Industry:
history, business challenges, technology challenges, trends and strategies

2. Characterization, Metrology & Failure Analysis:
analytical needs, overview of existing techniques.

3. The device fabrication process:
a 65 nm CMOS process flow-chart explained, process steps to control.

4. Microscopy:
TEM microscopy, TEM-EELS spectroscopy

5. Material Analysis:
chemical Analysis (SIMS, µ-AES, ToF-SIMS, XRF) and structural Analysis (XRD, EBSD)

6. Transistor engineering and Strain Analysis:
TEM-CBED, μ-Raman spectroscopy

7. Copper and low K dielectrics metallization schemes:

Analysis of Thermo-mechanical properties of materials (nano-indentation, Photo-acoustics, Ellipsometric Porosimetry, X-ray reflectivity)

8. Metrology and FAB economics:
queueing theory (cycletime vs. equipment utilization), metrology capability indicators, tool matching

- **PHY538T- 3 ECTS**
  Microscopie en champ proche. Near Field Microscopy.
  Florence Marchi (UJF) and Hervé Courtois (UJF) 12h Cours 12h TP

Theoretical courses with a practice on real AFM and STM apparatus.

Prerequisites: Quantum mechanics, solid state physics.

Architecture of a Scanning-Probe Microscope
General concepts
Instrumental aspects: piezo-electric actuators, displacements on the nanometer scale, regulation, tip effects.

Scanning Tunnelling Microscopy (STM)
Principles of STM
Tunneling versus Field emission
STM imaging: the atomic resolution, origin of corrugation
STM spectroscopy: charge density waves, superconductors, nanotubes, inelastic spectroscopy, spin resolved STM

Nanomanipulation by means of Scanning Tunneling Microscopy
Quantum corrals,
AFM nanolithography, ...

- **PHY538V (en partie mutualisé avec PMCR)- 3 ECTS – Erasmus Mundus Course
  Physics on synchrotron radiations**
  Giulio Monaco (ESRF) 24h Cours (cours PMCR, Mutualisation)

An introduction to research on analysis with synchrotron radiation.

Prerequisites: Quantum mechanics, solid state physics, statistical physics.

- Synchrotron radiation – 4h
  X-ray tubes
  Synchrotron radiation from a circular arc
  Insertion devices
Emittance and the diffraction limit
The free-electron laser

Refraction and reflection from interfaces – 6h
Refraction and phase shift in scattering
Snell’s law and the Fresnel equations in the X-ray region
Reflection from a homogeneous slab
Reflection from multilayers
Reflection from a graded interface
Rough interfaces and surfaces
Examples of reflectivity studies
X-ray optics

Kinematical diffraction – 6h
Scattering from an atom and a molecule
Scattering from a crystal lattice
Scattering from a quasiperiodic lattice
Scattering from a surface
Lattice vibrations, the Debye-Waller factor and TDS
The measured intensity from a crystallite
Applications of kinematical diffraction

Diffraction by perfect crystals – 2h
Darwin theory and dynamical diffraction
DuMond diagrams

Photoelectric absorption – 2h
X-ray absorption from an isolated atom
EXAFS and near-edge structure
Applications of photoelectric absorption

Visit of the ESRF – 2h

- **PPHY538U** - 6 ECTS – Erasmu Mundus Course
  Caractérisation des interactions (bio) moléculaires, nanomatériaux, surfaces et interfaces. Characterization of (bio) molecular interactions, nanomaterials, surfaces and interfaces
  Frederic Dubreuil (UJF), Jean-Luc Putaux (CNRS), Yvonne Soldo(CNRS), Bruno Gilles (CNRS), Pierre Labbé (UJF)  34h Cours

  The main analytical techniques to characterize molecular and biomolecular interactions, nanomaterials, surfaces and interfaces.

  **Preriquistes**: Quantum mechanics, solid state physics, statistical physics.

  - Electronic microscopies
  - Near field microscopies (AFM, STM, SNOM, …)
  - Surface analysis (XPS, AES, SIMS, EXAFS…)
  - Large facilities (neutrons, ESRF)
- Optical techniques (ellipsometry, spectroscopies, SPR, OWLS, ..)
- Nanogravimetry

- **PPHY541B - 3 ECTS** *This course holds during Semester 3*

  *Introduction aux nanostructures, élaboration de nano-objets.*
  *Introduction to nanostructures, elaboration of nano-objects.*
  A. Danel (CNRS), T. Fournier (CEA), T. Baron (CEA), P. Mailley (UJF), D. Boturyn (CEA) (24h Cours)

This course is common to the four specialties of the master N².

The course is composed of 5 independent parts. It gives a large overview of different techniques used in nanoscience and nanotechnologies.

Prerequisites: basis in physico chemistry

I. Engineering of surfaces and substrates (A. Danel, Ingénieur CEA Léti)

II. Micro et nanofabrication (T. Fournier, Ingénieur CNRS, Centre de Recherche sur les Très Basses Températures, plate-forme "nanofab")

III. Nanomaterials elaboration (*T. Baron, Chercheur CNRS, Labo Technologies de la Microélectronique*)

IV. Surface functionnalisation (*P. Mailley, Maître de Conférences UJF, CEA-Inac-Labo Structure et Propriétés d'Architecture Moléculaire*)

V. Molecular recognition, vectorization, imaging : toward intelligent nanosystems (*Didier Boturyn, Maître de Conférences UJF – LEDSS*)