M2 QLMN- Track « Condensed Matter and its Interfaces"

Labwork (6 ECTS)

		Track*	Localisation	Hours
Lab work: - Advanced research experiments (Bell's inequalities, Quantum Hall Effect, Optical tweezers…) - Microscopy and spectroscopy; - Numerical physics or State of the art clean room fabrication of quantum and nano-devices	6 ECTS	CM/ND	UFR, UVSQ, ENS, IPP, IOGS, CS, Thales	60h TP

Core UE (6 UE =18 ECTS)

Choice of 6 UE among 9

		Track*	Localisation	Hours
Introduction to second quantization: from quantum optics to condensed matter	3 ECTS	LM / CM	IOGS	30 h exam included
Statistical physics: Fluctuations, Transport and Phase Transitions	3 ECTS	LM/CM	CS	30 h exam included
Quantum theory of condensed matter	3 ECTS	CM	UFR	30 h exam included
Solid states devices	3 ECTS	CM/ND	UFR	30 h exam included
Nanomagnetism & Spintronics	3 ECTS	CM	IOGS	30 h exam included
Light Matter Interaction	3 ECTS	LM / CM	IOGS	30 h exam included
Integrated optics and Nanophotonics	3 ECTS	CM/ND	UFR	30 h exam included
Physical-chemistry of low dimensional materials	3 ECTS	CM	IPP	30 h exam included
Microscopy and Spectroscopy	3 ECTS	CM/ND	UFR	30 h exam included

"QuThCM" and "Solid State Devices" cannot be taken altogether (mutually exclusive)
"Light Matter Interaction" and "Integrated optics and Nanophotonics" are mutually exclusive

* LM=Light and Matter ; CM = Condensed Matter and its Interfaces ; ND = Nanodevices and Technologies

Electives UE (5 UE=15 ECTS)

Choice of 5 UE among this list (2 in the 4 firsts)

		Track*	Localisation	Hours
Numerical Simulations	3 ECTS	CM	CS	30 h exam included
Fundamentals of Micro and Nanofabrication	3 ECTS	CM/ND	UFR	30 h exam included
Quantum transport	3 ECTS	CM	IOGS	30 h exam included
Nanoelectronics and molecular electronics	3 ECTS	CM/ND	UFR	30 h exam included
Fundamentals of Nanophotonics	3 ECTS	LM/CM	IOGS	30 h exam included
Energy harvesting in nanostructures	3 ECTS	CM	CS	30 h exam included
Quantum Sensing	3 ECTS	LM/CM	ENS	30 h exam included
Quantum technologies: communication, computing and sensors	3 ECTS	LM/CM/ND	CS	30 h exam included
Exciton physics	3 ECTS	LM/CM	IOGS	30 h exam included
Photovoltaics	3 ECTS	CM	IPP	30 h exam included
Topology	3 ECTS	CM	IPP/UFR	30 h exam included
Physics experiments in Quantum Technologies	3 ECTS	LM/CM/ND	IOGS	30 h exam included
Quantum Computing	3 ECTS	CM	ENS /CS	30 h exam included
Outstanding Compounds	3 ECTS	CM	CS,IPP,UFR	30 h exam included
Mobile charges: from semiconductors to biology	3 ECTS	CM	IPP	30 h exam included
Research Project	3 ECTS	CM/ND	UFR, UVSQ, ENS, IPP, IOGS, CS, Thales	30 h project
Other UE from “Light Matter” or “Nanodevices and Tech.” track	3 ECTS	-	-	-

* LM=Light and Matter ; CM = Condensed Matter and its Interfaces ; ND = Nanodevices and Technologies

Course code:	Nonequilibrium Statistical Physics and Phase Transitions	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Jean-Jacques Greffet Denis Grebenkov	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Written examination	
Language of tuition:	English	

Course Objectives:
Introductory courses on statistical physics deal with non-interacting particles in equilibrium. The first part of this course deals with nonequilibrium. The second part deals with interacting particles. Several approaches to non-equilibrium statistical physics will be presented: linear response theory, Langevin model, Boltzmann equation and irreversible thermodynamics. The role of inter-particle interactions and resulting collective phenomena such as phase transitions will be discussed.

Course prerequisites:
Basic quantum mechanics, introduction to statistical physics

Syllabus

Linear response theory
Fluctuation-dissipation theorem
Brownian motion: Langevin model
Introduction to transport phenomena
Boltzmann equation
Introduction to irreversible thermodynamics
Inter-particles interactions, Ising model
Mean field approximation, critical behavior
Order parameter, symmetry breaking
Examples of phase transitions

On completion of the course students should be able to:
deal with nonequilibrium systems and systems of interacting particles. They should be able to extract information from correlations, master the key concepts of transport phenomena and phase transition.

Textbooks/bibliography:
R. Balian, From microphysics to Macrophysics Vol.1 Springe-Verlag, Berlin, 1982
R. Balian, From microphysics to Macrophysics Vol.2 Springe-Verlag, Berlin, 1991
R. Kubo, M. Toda, N. Hashitsume, Staistical Physics II, Springer Verlag, Berlin, 1985

Course code:	Integrated optics and nanophotonics	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	D. Morini	
Volume: Period:	27 Hours	3 ects
Assessment:		
Language of tuition:		

Course Objectives:
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.

Course prerequisites:
Basic knowledge of electromagnetism and semiconductor device physics.

Syllabus

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

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

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

On completion of the course students should be able to:

Textbooks/bibliography:
E. Rosencher : optoelectronique
Mooc Nanosciences : https://www.fun-mooc.fr/courses/course-v1:UPSay+42003+session02/about.

Course code:	Light Matter interaction	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	David Clément and Jean-Sébastien Lauret	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives: The interaction between light and matter holds a central place in experimental physics, to manipulate and to probe properties of light and/or matter. This ranges from the early spectroscopic studies of solids to the emergence of quantum technologies and the manipulation of individual quantum systems.

This course provides a comprehensive introduction to the interaction between light and matter, from a modern and transversal view. Starting from the structure of matter (atoms, solids) and classical models (Lorentz, Einstein), a semi-classical description of light-matter interaction is introduced. Both systems with discrete levels of energy (atoms, molecules, defect centers, quantum dots, ...) and with band structures (solids, excitons, …) are considered, and their similarities and differences are illustrated. The role of quantum coherences and of the dissipation are discussed, with descriptions based on rate equations and Optical Bloch equations. The course covers the manifestations of light-matter interaction in modern research and quantum technologies.
(Non-linear optics and ultrafast dynamics with short light pulses are treated in dedicated, separate courses).

Course prerequisites: Atomic Physics (M1); Solid State physics (M1); Quantum mechanics

Syllabus

1. Introduction
   Atomic structure (H atom, atoms with several electrons); Electronic structure of solids (Bloch functions, band structure, electron-hole pairs)
2. Lorentz and Einstein models; illustration of coherent manipulation (Lorentz) and of rate equations (Einstein)
3. Semi-classical description of light-matter interaction; Rabi oscillations, coherent manipulation of discrete systems; out of resonance Rabi, passage to a continuum, Fermi golden rule, semi-classical dielectric constant in solids
4. Excitonic transitions / Dimensionality
5. Dissipation in discrete systems; Optical Bloch Equations; Coupling to a continuum and rate equations
6. Manipulation of three level systems; optical pumping, superpositions of coherent states and two photons transitions
7. Impulsion exchange between light and matter; optical trapping of particles et laser cooling force
8. Mollow triplet (examples in atomics physics, quantum dots); field confinement (Jaynes-Cummings); molecules/colored centers; illustrations with quantum technologies

On completion of the course students should be able to: The students will have acquired a broad knowledge of the light-matter interaction, both in dilute and condensed matter systems. Following this course, students can specialize by choosing appropriate elective courses focused on excitonic or atomic physics. This course opens the way to a PhD in the broad domain of light-matter interaction (cold atoms, solid state quantum optics, single molecule quantum optics, polariton physics, optical properties of new semiconductor materials etc.…)

Textbooks/bibliography:

- "Optical properties of solids" M. Fox
- "Fundamental of semiconductors" PY Yu & M. Cardona
- "Optical processes in Solids" Y. Toyozawa
- "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light", G. Grynberg, A. Aspect, C. Fabre – Cambridge Univ. Press, 2010 (in particular the first chapters describe the semi-classical approach and the Optical Bloch Equations)
- "Optical Resonance and Two-Level Atoms", L. Allen, J. H. Eberly, Dover 1975.
- "The quantum theory of light", L. Loudon, 3rd Ed. Oxford Press, 1997.
- Online lectures of C. Cohen-Tannoudji at Collège de France on Laser cooling and manipulation of atoms - years 1981, 1982 and 1983.
- Online lectures of J. Dalibard at Collège de France on Laser cooling of atoms - year 2014/2015.

Course code:	Quantum Theory of Condensed Matter	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Pascal SIMON Pascal Simon/Andrej Mesaros	
Volume: Period:	27 Hours	**3 ects**
Assessment:	2 homeworks and one final written exam	
Language of tuition:	English	

Course Objectives:
This course gives an introduction to modern condensed matter theory. Starting from the notions of Bloch theory known from the introductory classes at 1st year master level, we will extend them to more complex band structures and deliver some introductory concepts to topological properties of matter. We make also first steps in Green's function theory to describe excitations in interacting quantum systems. We end this course by exploring collective phenomena and emergent properties of matter and their theoretical description.

Course prerequisites:
Solid State Physics I (M1 level); A good handle on quantum mechanics and statistical physics.

Syllabus

0) Crystal lattices

I) Band theory
- Bloch theorem, Bloch waves, Bravais lattice
- Tight binding models in first and second quantized form
- Beyond the mono-atomic crystal : crystal lattices with basis (ex: graphene): Metals, insulators (semi-conductors), semi-metals, etc. Notion of band mass
- Symmetries: time-reversal symmetry, particle-hole symmetry, chiral symmetry .

II) Dirac materials and Dirac matter: Introduction to topology in Dirac 2-band Hamiltonians such as graphene and its derivatives (Dirac monopole, Berry phases, Chern insulators)

III) The free Fermi gas and its thermodynamical properties: the key role of the density of states.

IV) Green functions
- Definition and relations to spectroscopic properties
- Single-particles Green functions (T=0) for free fermions. spectral functions, interpretation using Lehman decomposition

V) Response functions

Response function (T=0) for free fermions. Spectral decomposition and interpretation of Lindhard function (dynamic and static limit ω->0): applications to static impurities and Friedel oscillations. RKKY interaction

VI) A first attempt to include interactions: screening and justification of the Hubbard model.

On completion of the course students should be able to:
To write some tight binding models for some simple materials, calculate its band structure and characterize some its properties;
Characterize the single-particle properties and spectral functions of a material,

Textbooks/bibliography:
N. W. Ashcroft, N. D. Mermin, Solid state Physics, Saunders College Publishing (1976).
D. Vanderbilt, Berry Phases in Electronic Structure Theory, Cambridge University Press (2018).
P. Coleman, Introduction to many body physics, Cambridge University Press (2016).

Course code:	Solid state devices	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	A. Bournel (C2N)	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:		

Course Objectives:
Study the solid states physics of semiconductors materials. The operation principles of the basic components of microelectronics will be described.

Course prerequisites:
Basic knowledge of quantum mechanics, solid state physics, electronics.

Syllabus:
- Introduction, semiconductor materials and crystal lattices
- Vibration properties of a crystal lattice (phonons)
- Electronic structure, energy bands
- Light / matter interaction in semiconductors
- Energy levels introduced by impurities
- Density of carriers in a semiconductor
- Transport and phenomena out of equilibrium
- PN junction, Schottky diode
- Bipolar transistors, application to amplification
- Field effect transistors, application to the CMOS logic inverter.

On completion of the course students should be able to:

Textbooks/bibliography:
- C. Kittel, Introduction à la physique de l'état solide (ou Wiley en langue anglaise) - P.Y. Yu, M. Cardona, Fundamentals of semiconductors, Springer - S. M. Sze, Physics of semiconductor devices, Wiley - Nanoscience : Nanotechnologies et Nanophysique, edité par C. Dupas, P. Houdy, M. Lahmani, Belin (Springer en langue anglaise).

Course code:	Spintronics and Nanomagnetism	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	P. Seneor (UMPhy CNRS/Thales/UPSay) P. Seneor (UMPhy CNRS/Thales/UPSay), J.-P. Adam (C2N)	
Volume: Period:	27 Hours 1rst period	**3 ects**
Assessment:		
Language of tuition:	english	

Course Objectives:
The objective of this course is to address the key and fundamental concepts in nanomagnetism, spin-dependent transport and their applications. The course material will range from the most fundamental aspects (including GMR discovery with Nobel Prize in Saclay) to the latest research in topology, dynamics and spintronic devices for green electronics.

Course prerequisites:

Syllabus:

- Fundamentals and microscopic origins of magnetism, from atoms to magnetic materials:
  - Atomic, itinerant magnetism, stoner criterion…
  - Paramagnetism, ferromagnetism, antiferromagnetism… Magnetic anisotropies, exchange energy…
  - Low-dimensional magnetism, novel properties, magnetic textures, real-space topology…
- Fundamentals of spin-dependent transport and spintronics
  - Giant Magnetoresistance (GMR): from fundamental concepts and discovery to the information storage revolution
  - Tunnel Magnetoresistance (TMR): form fundamental concepts to next gen MRAM for green electronics …
  - Spin information transport physics (spin resistance, spin accumulation …)
  - Novel phenomena: spin hall effect, Rashba, k-space topology, spinterface…
- Magnetisation dynamics :
  - Domain-wall dynamics
  - Magnetic vortex dynamics
  - Spin waves
  - Spin transfert torques

This will include illustrative technological use cases and challenges in spintronics research.

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Introduction to 2nd Quantizatoin	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Guillaume Roux, Christoph Westbrook	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Written exam	
Language of tuition:	English	

Course Objectives: We Introduce the formalism and first applications. Starting from the quantization of the electromagnetic field, we discuss the emergence of quantum states without classical counterparts and two-photon correlation effects. The formalism is then extended to the quantization of matter for both Bose and Fermi systems. Some widely used approximation methods are discussed as well as their applications to superfluidity and superconductivity. The notions of quasi-particles and collective modes are introduced and some universal aspects resulting from the mapping between Bose, Fermi, and spin systems are discussed. Students will be asked to read and analyse some landmark papers in the field.

Course prerequisites:
Elementary quantum mechanics
Statistical physics

Syllabus

1. **Quantization of electromagnetic field.** Quantum harmonic oscillator, Coulomb gauge. Fock states, Coherent states, Thermal states. Means and and variances of observables in these states
2. **Interaction with a bound electron in the dipole approximation.** Time dependent perturbation theory. Stimulated emission and absorption, spontaneous emission. Connection to Einstein's treatment of BLackbody radiation. Inhibition of Spontaneous emission, Porcell factors.
3. **Single photon detection.** Photo electric effect, for a classical and a quantum field. Action of a beam splitter in terms of the fields
4. **Two photon detection.** Anticorrelation at beam splitter, antibunching. Hong Ou Mandel effect
5. **Second quantization of massive particles.** Bosons and fermions, two-particle case, Fock states and annihilation / creation operators, field operator, correlators and Green's function, Wick's theorem.
6. **Bose fluids.** Bose-Einstein condensation, the effect of interactions, Bogoliubov approximation for bosons. Introduction to phonons.
7. **Fermi fluids and pairing.** Fermi gases. Paired state and BCS wave-function, gap equation
8. **Quantum magnetism.** Spin models, spin-wave theory, Jordan-Wigner transform, quantum phase transitions.

There will be 4 or 5 homework problems to be worked at home

On completion of the course students should be able to: read some of the basic literature and advanced textbooks in the field

Textbooks/bibliography:

"Introductory Quantum Optics", C.C. Gerry and P.L. Knight, Cambridge Univ. Press (2005)

"Introduction aux lasers et à l'Optique Quantique", G. Grynberg, A. Aspect, C. Fabre, Ellipses, English version (september 2010) significantly updated "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light"

"Quantum Mechanics, Volume 3: Fermions, Bosons, Photons, Correlations, and Entanglement", Cohen-Tannoudji, B. Diu, F. Laloë, Wiley
"Many-body problems and quantum field theory", Ph.A. Martin, F. Rothen, Springer

"Many-body quantum theory in condensed matter physics", H. Bruus, K. Flensberg, Oxford Press

"An introduction to quantum spin systems", J.B. Parkinson, D.J.J. Farnell, Springer

Course code:	Microscopy, Spectroscopy and Diffraction	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	E. Boer-Duchemin (ISMO) E. Boer-Duchemin (ISMO),C. Laulhe (SOLEIL), A. Zobelli (LPS)	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Homework (5%), Final examination (95%)	
Language of tuition:	English	

Course Objectives:
"How was that graph obtained in that article I just read?" "How can I learn more about the sample I just made?" "What are the state-of-the-art techniques used to explore the physical properties of materials today?" This course will help you answer these questions.

Course prerequisites:
Basic knowledge of quantum mechanics and solid state physics

Syllabus

The goal of this course is to provide the student with a basic understanding of a set of microscopic, spectroscopic and diffraction techniques, particularly suited for nanoscience and condensed matter physics. Some of the different techniques to be explored include:

- scanning tunneling microscopy (STM)
- atomic force microscopy (AFM)
- transmission electron microscopy (TEM)
- scanning electron microscopy (SEM)
- electron energy loss spectroscopy (EELS)
- X-ray diffraction
- X-ray absorption
- angle-resolved photoemission spectroscopy (ARPES)
- X-ray magnetic circular dichroism (XMCD)

Some of the different questions to be answered include:

- --What is the basic physical principle of the technique?
- --What information can I gain from my sample thanks to this analysis?
- --Which techniques have the best spatial and/or energy resolution? Why should I choose one technique over another?
- --What are the advantages and disadvantages of such a technique?

On completion of the course students should be able to:
...answer the questions posed in the Course objectives

Textbooks/bibliography: to be provided at the start of the class

Course code:	Microscopy and Spectroscopy	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	E. Boer-Duchemin (ISMO) E. Boer-Duchemin (ISMO),C. Laulhe (SOLEIL), A. Zobelli (LPS)	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives:

"How was that graph obtained in that article I just read?" "How can I learn more about the sample I just made?" "What are the state-of-the-art techniques used to explore the physical properties of materials today?" This course will help you answer these questions.

Course prerequisites:

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Syllabus

The goal of this course is to provide the student with a basic understanding of a set of microscopic, spectroscopic and diffraction techniques, particularly suited for nanoscience and condensed matter physics. Some of the different techniques to be explored include:

- scanning tunneling microscopy (STM)
- atomic force microscopy (AFM)
- transmission electron microscopy (TEM)
- scanning electron microscopy (SEM)
- electron energy loss spectroscopy (EELS)
- X-ray diffraction
- X-ray absorption
- angle-resolved photoemission spectroscopy (ARPES)
- X-ray magnetic circular dichroism (XMCD)

Some of the different questions to be answered include:

- --What is the basic physical principle of the technique?
- --What information can I gain from my sample thanks to this analysis?
- --Which techniques have the best spatial and/or energy resolution? Why should I choose one technique over another?
- --What are the advantages and disadvantages of such a technique?

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Research Project	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	P. Seneor (UMPhy CNRS/Thales/Upsay)	
Volume: Period:	27 Hours	3 ects
Assessment:	Oral presentation	
Language of tuition:		

Course Objectives: Discover a research topic by spending approximately half-day/week in a lab of your choice.

Course prerequisites:

Syllabus:

Integration into a research team on a topic related to the QLMN master. Minimum 10 half-days distributed along the academic year. Bibliographic research, simulation, or characterization on one of the associated subjects.

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Recent Experiments in Quantum Information	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN)	

Course director: Course teachers :	J.-P. Hermier (UVSQ) J.-P. Hermier (UVSQ), Y. Dumont (UVSQ), S. Buil (UVSQ), A. Delteil (CNRS)	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives:

1. Analyze recent experiments in the field of nanophysics and quantum information.
2. Methodology: document analysis (general structure of an article, detailed analysis, overview).
3. Provide an overview of the scientific publishing field.
4. Enlighten and illustrate concepts addressed in other courses through articles.

Various systems (NV, SiV centers, QDs, atomic physics). Various concepts and their physical implementation: coherence, entangled states, fidelity, Bloch sphere, logic gates, quantum sensing. Progressivity: from the simplest to complex protocols.

Course prerequisites:

General concepts in nanophysics, nanophotonics and a first approach in quantum information processing. Key concepts for each paper will be shortly presented at the beginning of each session.

Syllabus

1. Operations on single qubits: coherence, one-qubit gates (Bloch sphere, fidelity), initialization and output.
2. Two qubit operations and protocols: two qubit gates, remote entanglement, teleportation, quantum sensing.

On completion of the course students should be able to:

- Analyze a scientific paper in detail.
- Identify quickly the key points of a publication.

Textbooks/bibliography:

Course code:	Fundamentals of micro and nanofabrication	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :		
Volume: Period:	27 Hours	3 ects
Assessment:		
Language of tuition:		

Course Objectives:

This course presents different fabrication methods of micro and nano-devices using very high technological processes classicely used in Micro-Nanotechnologies. Some of these techniques are directly derived from microelectronics. For others, they concern the manufacture of MEMS, NEMS, micro and nanodevices using nanostructured material.

Course prerequisites:

Syllabus

1. - Introduction
2. - Material structures
3. - Growth technics (oxidation, CVD, PVD, MBE, …)
4. - UV lithography/ Electron beam lithography
5. - Etching technics

- Specific processes for hybrid systems: transfer technics, advanced micromolding...

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Nanoscale energy conversion and harvesting (NECH)	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Bruno Palpant, professor at CentraleSupélec Emmanuelle Deleporte, professor at ENS Paris-Saclay ; Jérôme Saint-Martin, assistant professor at U. Paris-Saclay	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Numerical labwork project based on online simulations (https://nanohub.org) Depending on the number of students: final oral examination or final written examination based on a study of recent scientific journal papers, + labwork reports.	
Language of tuition:	English (or French if all French-speaking students)	

Course Objectives:

Energy conversion and management at small scales have become a pivotal point in many new technologies. Miniaturization no longer allows the application of simple scale laws but brings out new properties that must be understood, mastered, and exploited for all these developments. Hence, nanosciences bring new prospects in many fields. This course offers students to approach the energy conversion mechanisms through three emblematic aspects: light into electricity, light into heat, heat into electricity. We will see how conversion and transport phenomena are modified at small scales and how they can be exploited in photovoltaics, thermoelectricity, new biomedical approaches, functional materials. On the one hand, the objective is to link the physical effects at stake in the conversion and the performances of a device, and on the other hand, to apprehend the new improvement strategies allowed thanks to nanotechnologies.

Course prerequisites:

Solid-state physics, optics and electromagnetism in matter, thermodynamics (L3 level)

Syllabus

1. **Thermoelectric conversion (7h)**
   - Introduction to thermoelectric conversion (2h)
     - ✓ Reminder on thermal machines, finite time thermodynamics
     - ✓ Thermoelectric effects: Seebeck, Peltier and Thomson
     - ✓ Efficiency and figure of merit of a thermoelectric system
     - ✓ Current applications of thermoelectric conversion.
   - Thermoelectrics at the nanoscale (3h)
     - ✓ The two main optimization strategies
       1. Improvement of the Seebeck coefficient by band engineering
       2. Thermal conductivity limitation by nanostructuring
     - ✓ New targeted applications.
   - Current developments in thermoelectrics (2h)
     - ✓ Thermoelectric nanomaterials
     - ✓ Modeling methods
     - ✓ Characterization methods.

2. **Photovoltaic conversion (8h)**
   - Silicon solar cells: PN junction
     - ✓ Interface phenomena (electric field, potential barrier, space charge zone, charge separation at the interface)
     - ✓ I(V) characteristics.
     - ✓ Optimization of sunlight absorption: band engineering, exciton binding energy engineering, nanostructuration.
   - Dye-sensitized solar cells
     - ✓ Principle: inspired by photosynthesis
     - ✓ Problems to overcome (high exciton binding energy, low charge carrier mobility)
     - ✓ Nanotechnology for charge separation.
   - Hybrid perovskites solar cells
     - ✓ A combination of advantageous properties for high efficiencies
     - ✓ Different possible architectures
     - ✓ Management of the interfaces.
   - Si/Perovskite tandem solar cells
     - ✓ Towards efficiencies of 30%
     - ✓ Management of the interface between the two coupled solar cells.

3. **Photothermal conversion (12h)**
   - Bulk noble metals: From electronic to optical properties (2h)
   - Localized plasmon resonance (2h)
     - ✓ Mechanical analogy
     - ✓ Dielectric contrast
     - ✓ Local field enhancement.
   - Converting far-field radiation into optical near-field: principle and applications (1h)
   - Influence of morphological parameters (1.5h)
     - ✓ Size
     - ✓ Shape

- ✓ Spatial organization: ordered/random, couplings.
- Historical illustrations in the domain of Decorative Arts (0.5h)
- Light-heat nano-conversion (5h)
  - ✓ Basic approaches
  - ✓ Emblematic applications: functional materials, photothermal imaging, new targeted therapies
  - ✓ Heating with pulsed light: characteristics, applications
  - ✓ Influence of morphology.
- Melting point depression in metal nano-objects.

On completion of the course students should be able to:

- Understand the mechanisms involved in different kinds of energy conversion at different scales
- Master some fundamentals of optical, thermal and electronic properties in nanostructures
- Conceive nanoscale functional materials for applications in different fields such as biomedicine, photovoltaics, energy harvesting, storage and transport

Textbooks/bibliography:

Documents will be provided by the teachers at the beginning of each part.

Course code:	Nanoelectronics and molecular electronics	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	P. Dolffus, C2N A. Filoramo, CEA	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:		

Course Objectives:
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.

Course prerequisites:
Basic knowledge of quantum mechanics and semiconductor physics

Syllabus
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
- The neuromorphic electronics, Unsupervised learning.

On completion of the course students should be able to:

Textbooks/bibliography: M. Lundstrom, Fundamentals of Carrier Transport, Cambridge University Press, 2009 - D.K. Ferry, S.M. Goodnick and J. Bird, Transport in Nanostructures, Cambridge University Press, 2009 - D. Querlioz and P. Dollfus, The Wigner Monte Carlo Method for Nanoelectronic Devices: A Particle Description of Quantum Transport and Decoherence, ISTE/Wiley, 2010.

Course code:	Numerical simulation and modeling	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Hichem DAMMAK Igor Kornev, M. Hayoun, M. Ayouz, Y. Chalopin	
Volume: Period:	27 Hours	**3 ects**
Assessment:	3 quiz, report and oral presentation	
Language of tuition:	English	

Course Objectives:

Computer simulations are a necessary tool for research in physics. It is at the crossroad of experimental and theoretical approaches. The purpose of this course is to introduce the most common methods in simulation: molecular dynamics and Monte Carlo methods.

Course prerequisites:

Quantum Physics
Equilibrium Statistical Physics
Mechanics of point particles
Fourier transform

Syllabus

- Modeling of interatomic interactions and introduction to the DFT method
- 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: the heat capacity, the radial distribution function, the diffusion coefficient, the order parameters, the surface energy, the frequency dependence of the polarisability …

  - Four class sessions
  - Four supervised sessions : Each pair of students chooses a project and works on it during the tutorial sessions by carrying out the imulations necessary to achieve the objective. Depending on the students' backgrounds they will be asked to either (i) write a program or a subroutine, (ii) modify an existing program, or (iii) use an existing program to generate simulations and explain their results.

- Examples of subjects proposed to students during supervised sessions: 1) Order-disorder transition. 2) The diffusion coefficient in argon. 3) The surface reconstruction and reordering. 4) Influence of cluster size on structural and optical properties. 5) The density of vibration states and dielectric constant in ferroelectrics. 6) Ferromagnetic et anti-ferromagnetic transition, …

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On completion of the course students should be able to:

We expect the students to choose and apply the suitable numerical method for solving a given physics problem. They should be able to analyze and discuss their obtained results:

- Selecting the appropriate interaction potential to describe the properties of a system according to the nature of the atomic bonds
- Applying Verlet's algorithm to solve equilibrium atom dynamics equations in the microcanonical ensemble
- Using the Metropolis Monte Carlo algorithm to determine the equilibrium configurations in the canonical ensemble

Textbooks/bibliography:

Handout provided in French
Lecture notes (slides) in English
English book chapters from “Computer Simulation of Liquids” of Michael P. Allen, and Dominic J. Tildesley.

Course code:	Technologies quantiques : communication, calcul et capteurs	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	T. Antoni/B. Valiron	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Différente suivant chacune des études de cas, elle seront annoncée par les intervenant lors de chacune de leur premières séances.	
Language of tuition:		

Course Objectives:
Le but de ce module est de présenter trois axes principaux identifiés à la fois comme critiques et prometteurs par la Commission Européennes dans le cadre de la seconde révolution quantique. Actuellement en train de sortir des laboratoires les retombées grand public sont attendues à 5-15 ans. l'enseignements se fera sous forme d'une étude de cas en partant des concepts physiques mis à jeu pour aboutir au dimensionnement d'un système permettant d'adresser un enjeu concret.

Course prerequisites:

Syllabus
Cours sous forme d'étude de cas quantiques :
1. Communication et cryptographie
2. Ordinateur et calcul
3. Capteurs

On completion of the course students should be able to:
Connaissance des principales technologies quantiques actuelles et de leurs applications, ainsi que des rudiments de recherche et développement.
(C1.2) Identifier, formuler et analyser un problème dans ses dimensions scientifiques, économiques et humaines.
(C1.3) Utiliser et développer les modèles adaptés, choisir la bonne échelle de modélisation et les hypothèses simplificatrices pertinentes pour traiter le problème.
(C1.4) Résoudre le problème avec une pratique de l'approximation, de la simulation et de l'expérimentation.
(C1.5) Spécifier, concevoir, réaliser et valider tout ou partie d'un système complexe.
(C2.2) Maîtriser les compétences d'un des métiers de base de l'ingénieur (au niveau junior).

Textbooks/bibliography:

Course code:	Quantum electronics	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Hugues POTHIER and Philippe JOYEZ, Quantronics group, CEA-Saclay	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Oral (on scientific publications)	
Language of tuition:	English	

Course Objectives: Learn about quantum effect in electrical circuits, in particular superconducting circuits

Course prerequisites: Basic knowledge in solid states physics and second quantization

Syllabus Quantum transport in coherent conductors. Conductance quantization. Quantum noise. Quantum Hall effect. Single electron effects. Superconductivity (from scratch). Josephson effect. Dynamical Coulomb blockade. Superconducting qubits. Circuit Quantum Electrodynamics.

On completion of the course students should be able to: understand scientific publications on mesoscopic quantum transport and on superconducting quantum circuits

Textbooks/bibliography:

Quantum transport – Introduction to nanoscience. Yu. Nazarov and Ya. Blanter, Cambridge University Press (2009)
The physics of nanoelectronics. Tero Heikkilä, Oxford University Press (2013)

Course code:	Introduction to Topological Materials	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Mark Oliver GOERBIG	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives:

Topological materials have recently emerged as a major research field of condensed-matter and quantum physics. These materials are governed by quantum mechanics beyond the usual Bloch bands, with topological (or more generally geometrical) properties encoded in the quantum wave functions. The latter properties are at the origin of unusual transport phenomena, such as the quantum (anomalous) Hall effect and the quantum spin Hall effect. The aim of the course is to provide an introduction to this essential field of research, both in view of quantum transport and spectroscopic properties.

Course prerequisites:

Quantum mechanics, basic solid state physics, statistical physics

Syllabus

- basic materials and nanofabrication
- emergent relativistic properties and the role of the Dirac equation in condensed-matter systems
- diffusive vs. ballistic transport in nanoscopic devices
- Landau-level quantization and quantum Hall effect
- introduction to topological band theory: Berry curvature and Chern numbers
- 2D models for topological insulators (from Haldane to Kane-Mele)
- role of time-reversal symmetry and spin-orbit coupling
- bulk-edge correspondence in topological materials
- towards 3D topological materials

On completion of the course students should be able to:

Textbooks/bibliography:

J. Cayssol and J.N. Fuchs, “Topological and geometrical aspects of band theory” (https://arxiv.org/pdf/2012.11941.pdf)
B. Andrei Bernevig, “Topological Insulators and Topological Superconductors” (Princeton UP, 2013)
M.O. Goerbig, Lecture Notes (in work)

Course code:	Screening by mobile charges in Physics, Chemistry and Biology: from a pn junction to nerve impulse propagation	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	C. Renault (Ecole Polytechnique)	
Volume: Period:	27 Hours	**3 ects**
Assessment:		
Language of tuition:	English	

Course Objectives:
The course "Screening by Mobile Charges in Physics and Chemistry" aims at providing classical and semiclassical electrostatic models for a phenomenon widely encountered in physics, screening of a static charge surrounded by mobile charges. Analytical solutions of the Poisson equation at equilibrium and then far from equilibrium will be discussed to cover a wide spectrum of systems including semiconducting devices, stopping power of metals, electro-plating and action potential in neurones.

Course prerequisites: basics of quantum and statistical physics, semiconductor physics, electrochemistry

Syllabus:
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 ε(q,w)
- 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

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Fundamentals of Nanophotonics	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Jean-Jacques Greffet Henri Benisty	
Volume: Period:	27 Hours	**3 ects**
Assessment:	written exam	
Language of tuition:	English	

Course Objectives:
The goal of the course is to provide an introduction to the research topics in the field of nanophotonics. To achieve this goal, the course discusses the main concepts, structures and tools used to generate, detect and manipulate light at the nanoscale.

Course prerequisites:
Knowledge of Maxwell equations in material media, complex refractive index, reflection and refraction, guided waves.

Syllabus

Introduction to near-field optics: angular spectrum, evanescent waves.
Super-resolution imaging: breaking the diffraction limit.
Theory of electromagnetic fields at the nanoscale: scattering, Green tensor and local density of states.
Propagating surface plasmons.
Localized surface plasmons.
Tailoring spontaneous emission and scattering with antennas and cavities.
Propagation in periodic media: homogenization.
Propagation in periodic media: photonic crystals.
Metamaterials and metasurfaces.

On completion of the course students should be able to:
At the end of the course, the student will be able to read research papers on nanophotonics.

Textbooks/bibliography:
L. Novotny, B. Hecht, Principles of nano-optics, Cambridge University press, 2012
H. Benisty, J.J. Greffet, P. Lalanne, Introduction to Nanophotonics, Oxford University Press, 2022

Course code:	Optical excitations and quantum optics at the nanoscale	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	J. Bloch (C2N), E. Deleporte (ENS-Paris-Saclay),Sylvain Ravets (C2N)	
Volume: Period:	21 Hours	3 ects
Assessment:	Written exam 3h	
Language of tuition:	English	

Course Objectives:

The course aims at describing light-matter interaction in condensed matter systems in close connection with on-going state of the art research. It constitutes the logical continuation of the Light-matter interaction course for people interested in condensed matter systems. It focuses on semiconductor nanostructures and their use to tailor light matter interaction, realize sources of quantum light and explore quantum fluids of light.

Course prerequisites:

Syllabus:

In quantum confined semiconductors, the elementary excitations created by the absorption of a photon is an exciton. The course starts with a description of these elementary excitations in different condensed matter systems. The description is illustrated both using textbook examples from the history of semiconductors as well as recent publications related to the advent of new materials. The second part of the course is dedicated to cavity quantum electrodynamics (CQED) using solid-state quantum emitters embedded in integrated high finesse cavities. The properties of quantum dots (fermionic systems behaving as artificial atoms) and their use as bright sources of quantum light will be discussed. Then we will discuss how quantum wells in microcavities provide a platform for the exploration of quantum fluids of light.

Part I: Semiconductor nanostructures and excitons (3x3h)

- Excitons in inorganic and organic semiconductors, Excitons in hybrid semiconductors (perovskites),
- Influence of the dimensionality: heterostructures, 2D materials
- Control of the exciton properties using electric field, magnetic field

Part II: Cavity Quantum Electrodynamics at the nanoscale (6x3h)

1) Quantum emitters
- Quantum dots: Carrier confinement, Spectrum of emission, Single photon source
- Quantum dots in cavity: semiconductor microcavities, Purcell effect, bright source of single photons

2) Quantum fluids of light
- Excitons in 2D: selection rules, bosonic properties; effective mass for photons in 2D; Exciton photon strong coupling
- Quantum fluids of light. Polariton dispersion; Interactions (Gross Pitaevskii equation). Discussion of experiments: superfluidity, Bose Einstein condensation, Lattices (ex: polariton graphene)

On completion of the course students should be able to:

Textbooks/bibliography:

Course code:	Photovoltaics	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	Pere ROCA i CABARROCAS , (Ecole Polytechnique) Jean Paul KLEIDER, Stéphane COLLIN, Olivier BETHOUX, Nicolas BARREAU, Marie GUEUNIER-FARRET, Arouna DARGA, Daniel SUCHET	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Students are evaluated based on a final written exam plus homework based on critical reading and presentation of research articles. Each student gets an article to review and present to the class.	
Language of tuition:	Englaish	

<u>**Course Objectives:**</u>
Screening by mobile charges in Physics, Chemistry and Biology: from a pn junction to nerve impulse propagation

<u>**Course prerequisites:**</u> Physics of Solar Cell Devices (or equivalent course in basics of semiconductors and P/N junctions on crystalline silicon)

<u>**Syllabus:**</u> The course will focus on the two main families of materials at the basis of the second generation of solar cells, namely silicon thin films (amorphous, microcrystalline, thin film crystalline, and alloys with O, C and Ge) and chalcogenides (CdTe and CIGS). It will provide the basis for a deeper understanding of the materials used to build up the solar cells, their structural and electrical characterization, as well as provide the basis to foresee the future of thin film PV in a very competitive arena. Professors will present the solar cell technologies and give the elements of material science to understand both fundamental and technological aspects of Thin-Film Photovoltaics.
The course consists of 9 units of four hours divided as follows:

- Lecture 1: Introduction to the physics of solar cells: basics of photovoltaic conversion, thermodynamics of light to electricity conversion, fundamental key properties of photovoltaic materials and basic device structures, limits of photovoltaic conversion
- Lectures 2-3: Solar cells based on II-VI compounds and chalcogenides (CdTe and Copper indium gallium diselenide) : basics of polycrystalline compound semiconductors, devices, fabrication processes and manufacturing
- Lectures 4-5: Silicon thin film technology: plasma enhanced chemical vapor deposition as a versatile tool to deposit silicon thin films and synthesize nanomaterials which are combined in various kinds of solar cell structures (homojunctions, heterojunctions, radial junction solar cells,...) in order to achieve high efficiency at low cost
- Lecture 6: High efficiency concepts for solar cells: III-V and multijunctions materials and devices, up and down conversion, nanophotonics. The lecture will also include an introduction to modeling of solar cells
- Lecture 7: Optical properties of solar cells: Students will learn from the basic concepts for the reduction of the spectral reflectance to more advanced nanostructures. In particular, the focus will be on periodic structures such as diffraction gratings or photonic crystals, the exploitation of one dimensional nanowires or metallic nanoantennas, progressive techniques based on plasmonic or photonic effects ...
- Lecture 8: Electronic characterization of thin films, based on examples from silicon thin films. 1) Measurements in planar configuration including dark conductivity vs temperature, steady-state photoconductivity, modulated photocurrent, constant photocurrent method and steady-state photocarrier grating. 2) Measurements in diode configuration including admittance spectroscopy, quasi steady-state measurements as a function of bias, frequency and temperature, quasi-static capacitance and transient capacitance (ICTS and DLTS, photocapacitance). The principle of each technique and the use to extract material or interface parameters will be described
- Lecture 9: Photovoltaic modules and systems: making modules out of cells; strategies for getting the maximum power out of the module thanks to power electronics; PV in isolated areas and related storage issues; grid connected systems

<u>**On completion of the course students should be able to:**</u>
After the course the student should be able to:

- Provide a critical view on thin film technologies and their position with respect to the leading crystalline silicon
- Describe the operating principles of various types of solar cells structures: P-N junction, P-I-N, Heterojunction solar cells
- Possess a detailed knowledge of thin film deposition processes and characterization techniques.
- Determine the efficiency of solar cells based on their opto-electrical modeling
- Understand the various steps involved in the value chain from materials to modules

<u>**Textbooks/bibliography:**</u>

Course code:	Quantum Sensing	Semester 1
Contributes to:	M2 Quantum, Light, Materials and Nano Sciences (QLMN) -	

Course director: Course teachers :	François Marquier François Marquier, François Treussart, Christoph Westbrook	
Volume: Period:	27 Hours	**3 ects**
Assessment:	Oral or written exam depending on the number of students	
Language of tuition:	English or French depending on the students' origin	

Course Objectives:
Understand how quantum states can improve the sensing of properties of different systems. The concepts will be illustrated by examples in physics and biology.

Course prerequisites:
Quantum mechanics and basics of light-matter interaction, some familiarity with quantized electromagnetic fields

Syllabus
Each time slot is separated into a concept introduction and tutorials, often illustrated by scientific papers. The aim of the course is to highlight classical limits that can be overcome by a quantum approach of the measurements. We will come back on the notion of discrete and continuous quantum bits, and how to use it to measure magnetic fields, orientation of particles, temperature, pH... To this aim we will consider the unique system of negatively charged nitrogen-vacancy centers in diamond, possessing an electron spin resonance that can be detected optically.
We will also discuss the detection of inertial effects (acceleration and rotation) using atom interferometry, and the use of squeezed and other non-classical states to improve the performance of (mostly) optical interferometers, such as gravitational wave detectors.

On completion of the course students should be able to:
- Know how to use a quantum state to perform a measurement and get a better signal-to-noise ratio.
- Understand some of the basic scientific papers in this field

Textbooks/bibliography:
"Introductory Quantum Optics", C.C. Gerry and P.L. Knight, Cambridge Univ. Press (2005)