Semester 1:

Common core lectures (6*2=12 ECTS, Common with Nantes, Lorient and Brest Universities) :

-Nanophysics (20h)

-Nanoelectronics (20h)

-Nanomaterials (20h)

-Nanocharacterization (20h)

-Nanobio-objects (20h)

-Nanocomposites (20h)

Practical teaching 1 (5 ECTS, In Rennes) :

-Nanotechnology (8h+20h lab)

-Thin films (12h+6h lab)

-Sensitization to nanotoxicology (5h)

Practical teaching 2 (5 ECTS, In Rennes) :

-Numerical project (20h lab)

-Innovation and intelligence information (10h)

-English

Specialization lectures (8 ECTS, In Rennes) :

-Nanomagnetism (16h), Nanophotonics (12h)

-Surface functionalization (16h), Monte-Carlo molecular simulation (16h), Microfluidics (16h)

Semester 2:

Internship (5 months or more, in academic or industrial laboratory)

APPENDIX

Hereafter are presented the detailed contents of Master 2 lectures.

Nanophysics (20 hours)

I- Fundamentals and confinement

- *"in a box" confined systems, eigenstates spectra*
- *Dispersion relation, density of states*
- *Classical transport reminder*

II- Photons confinement

- *Photons confinement in a cavity: Bragg mirrors, Fabry-Perot cavity*
- *The photonic crystal concept*
- *Plasmonics*

III- Electrons confinement

- *Classical transport, characteristic length*
- *Ballistic transport, diffusive transport, Landauer Buttiker approach*
- *Coulombian interactions, SET, quantum dots*
- *Quantum interferences : AB, AAS*

IV- Spin transport

- *Spin-polarized electrons/matter interactions*
- *Diffusion equation for spins*
- *Giant- and Tunneling- magnetoresistance effects*
- *Spin electronics in semiconducting nanostructures*

Nanoelectronics (20h)

I- General Introduction : "Historical" introduction to the route leading to nanoelectronics
II- Future architectures for nanoelectronics elementary devices : multi-level logics, cellular automates, neuronal networks, quantum computing
III- Systems operating with a limited number of electrons – Single Electron Transistors, memory cells
IV- Possible applications of nanotubes and nanowires to the
V- microelectronics industry
VI- Semiconductor nanowires, fundamentals and applications
VII- Spin electronics devices (GMR and TMR based sensors, spin-transistors)
VIII-Molecular electronics : from fundamentals to applications

- *Conclusion*

Nanomaterials (20h)

Introduction

I- General considerations related to the nanoscale

II- Main strategies of synthesis of nanoparticles (vapor phase, liquid phase)

III- Self-organisation, self-assembly and manipulation of nanoparticules ; colloids

IV- Metallic nanoparticules

- *some methods of synthesis*
- *electrical, optical and plasmonic properties ; catalytic effects ; interest for applications.*

V- Magnetic nanoparticles

- *ferromagnetic metal nanoparticles*
- *metal oxide nanoparticles*

VI- Semiconducting and dielectric nanoparticules

VII- Carbon nanostructures

- *structure and electronic structure of carbon allotropes*
- *fullerenes and derivatives*
- *carbon nanotubes*
- *graphene and single layer materials (BN,MoS_2…)*

Nanocharacterization (20h)

I- Nano-characterization by photons and neutrons

- *Introduction : interaction light-matter, interaction neutron-matter,*
- *Elastic Scattering by nano-objects Processes: Small angle scatterings, wide angle scatterings, diffractions,*
- *Dynamic light scattering,*
- *Examples of application,*

II- Inelastic scattering and resonant processes

- *Inelastic scattering and absorption-emission processes: polarizabilty-electric susceptibility*
- *Vibrational and Electronic transitions*
- *Raman scattering et inelastic neutron scattering : phonon*
- *Nano-scale and phonon,*
- *Spatial resolution: Optical Microscopy in far field and in near-field: Near field Scanning Optical Microscopy, Tip Enhanced Raman Spectroscopy, Super-spatially-resolved optical methods*

III- Transmission Electron Microscopy (TEM)

- *Introduction*
- *Electron/Matter interaction*
- *Constitutive elements of the microscope*

- *Imaging and diffraction in the TEM*
- *Analytical microscopy*

IV- Scanning Tunneling Microscopy (STM)

- *Introduction : from tunneling to the microscope*
- *Experimental setup*
- *Applications*
- *Derived methods : BEEM, SP-STM*

V- Atomic Force Microscopy (AFM)

- *Cantilever/surface interactions*
- *Contact, non-contact, tapping mode*
- *Applications and derived techniques (force spectroscopy, MFM, EFM, nanolithography…)*

Nanobio-objects (20h)

Introduction

I- Biomolecules and their organization

- *Introduction*
- *Bacteria, mammals and plants cells*
- *Biomolecules : structure, conformation and functions*
  - Nucleotides, ADN and ARN
  - Amino acids, peptides and proteins
  - Lipids
  - Oligo- and polysaccharides
- *Biochemistry principles*
  - Molecular recognition (specific interactions, diffusion and thermal motion)
  - Water and its effect on molecules in solutions

II- From unique molecule to supramolecular assemblies

- *Manipulation methods at the single molecule scale*
- *Supramolecular assemblies and bio-mimetic models*

III- Nanobiomaterials

- *Natural nanomaterials, nanocomposites examples : Structure and properties of remarkable natural nanocomposites (bones, wood, silk) (bois, os, soie, …).*
- *Organic/inorganic hybrid nanomaterials*
  -Bio-sourced nanocomposites
  -dispersed systems : emulsions, gels, foams
  -Thin films
  -Biosensors
  -Hybrid biomolecules/inorganic nanomaterials (Biomolecules/CNT, protein/SiO2,…)

Nanocomposites (20h)

Metallic nanocomposites:

Part I: Bases in metallurgy

A. *Bases on thermomechanical properties of materials:*
   Stresses, strains, tensile test, creep.
B. *Bases on general metallurgy:*
   Polycristals, grains, grain boundaries, dislocations, point defects, phase diagrams, precipitation.
C. *Bases on physical metallurgy:*
   Plasticity of crystals and polycrystals, strain hardening, solid solution and precipitation hardening, influence of grain size (Hall-Petch), creep, recrystallization.

Part II: Bulk nanostructured metallic materials: fabrication, microstructure and properties

A. *Microstructure-property relations:*
   Observations and elements of theory.
B. *Examples of bulk nanostructured metals and alloys – Associated processes:*
   Dispersed phases alloys, compaction of powders, electrodeposition, severe plastic deformation, crystallisation of amorphous metals, martensitic and bainitic steels.

Polymer nanocomposites:

Part I. conductive polymer nanocomposites CPC

- *Developing and processing techniques (molten route, solvent coating)*
- *Control tools of conductive architectures (adsorption interactions, containment)*
- *Characterization of conductive networks by microscopy and electrical measurements*
- *Thermal and chemo-resistive properties, thermal conductivity*
- *Applications of CPC to self-regulated heating and vapour, strain and temperature sensors*

Part II. Non-conductive polymer nanocomposites

- *Formulation and implementation*
- *Interactions-repulsion-changes in polymer systems.*
- *Physical properties*
- *Applications to packaging and fireproofing*

Nanotechnology (28h=8h lectures+20h clean room hands on practicals)

Lectures (8h) : Issues of nanotechnologies and Moore's law, technologies for nano-objects synthesis (nanowires, nanotubes), metals insulator semiconductor thin films deposition techniques (CVD, PVD, MBE), lithography (UV, electronic, AFM nanolithography), doping techniques, dry and wet etching, micro- and nanodevices fabrication.

Hands on clean room practicals (20h) : complete realization and electrical characterization of a diode in a clean room facility, preparation of nano-objects by AFM nanolithography, nanomanipulation and electrical characterization of silicon nanowires.

Thin films (18h=12h lectures+6h in lab practicals)

Introduction

Nucleation – Growth: thin films nucleation/growth modes, structure and morphology (amorphous, polycristalline, textured, epitaxial), strain and stress, examples of structure/properties relationships.

Deposition techniques :

CSD, CVD, ALD, MBE, PVD, PLD : principles, advantages, limitations

Characterization techniques:

Chemical analysis : EDX – XPS – RBS – SIMS

Cristallinity : phase determination, epitaxy and heterostructures analysis by XRD, RBS and XPD

Morphology: SEM, AFM, X-ray reflectometry, thickness determination (ellipsometry, profilometry)

In lab practicals : growth and complete analysis of a thin film by PLD, XRD, SEM, TEM

Numerical project (20h):

This UE aims to give a practical training on some classical numerical methods (and associated computational tools) pertinent for the modelling of physical properties of (nano-)materials. The investigated systems should be relevant in one or several domains of application addressed in the common core modules of the CNANO Master.
The student will be able :
• to develop a modelling approach for the description of a physical system and its properties
• to identify by modelling the pertinent physical parameter(s) responsible for the observed properties

• to develop a rigorous numerical experiment strategy towards an optimized description of the studied physical problem
• to identify and explain the eventual limitation(s) of the developed simulations
• to compare the simulation results with available experimental data from literature or other published numerical results
• to produce a synthetic scientific report summarizing the developed modelling strategy, main results and associated interpretations

Contents :

1. *Introduction to Density Functional Theory (DFT)*
2. *Tutorial on GPAW code*
3. *Introduction to Multiple Scattering (MS) theory for electron spectroscopies*
4. *Tutorial on MSPEC code*
5. *Personal project on DFT or MS simulations : scientific cases*

Nanomagnetism (P. Schieffer 12h lectures+4h tutorials) and nanophotonics (B. Bêche 12h lectures)

This module aims at providing a broad picture of magnetism and optics in nanoscale systems ranging from fundamentals to an applied level. Starting from the rudimentary concepts, the broad scope of the module brings in expertise to understand the physical properties of system at various scales and times using analytical and numerical approaches. Particular interest will be paid to the new materials.

Part I : Nanomagnetism (P. Schieffer 16h)

I and II Introduction-Generalities

III- Magnetism of thin films and multilayers

IV- Magnetic coupling mechanisms in multilayers

V- Micromagnetism concept

VI- Introduction to the dynamics of magnetization reversal

VII- Spin transfer

VIII-The magnetic inorganic colloids: ferrofluids

IX-New materials for spintronics : diluted magnetic semiconductors, half-metallic ferromagnets, multiferroics

Part II: Nanosciences and Nanosystems in Photonics (B. Bêche 12h)

***1-** Introduction to nanosciences in photonics, materials and thin layer processes for integration and packaging, photonics nanotechnologies.*

***2-** Theory mathematical concept to describe the quantification in photonics.*

Notion of photonics modes, guided/leaky/radiation modes ; geometrical approach of the quantification in optics ; fundamentals on the electromagnetic theory of integrated photonics ; notions of eigenvalues and eigenvectors, dispersion relations and calculus of photonic's modes ; dispersion phenomena and pulse's spread ; historic methods on the calculus of effective indices ; extended approaches to another structures ; multilayer and global matrix formalism ; finite difference spatial methods ; spectral methods; modes expansion and normalization ; numerical analysis for various geometries; stored energy and power flow. Resonance effect in photonics ; quality factor and energy-management.

***3-** Sensors and components*

MOEMs ; generic devices for nanophotonic measurements (physical, chemical, biologic measurements) ; methods of characterisations of photonic structures.

***4-** Sub-wavelength photonics regime, photonic crystals, near field, nanowires in photonics*

Electron-photon analogies, development of the basics on photonic crystals ; equations and eigenvalues; one-dimensional model ; spatial periodicities and photonics band gap; two- and three-dimensional crystals cases ; photonic band calculation ; cavity and decay time of a mode ; bands engineering and control of the photonic dispersion curves ; localized defect modes; cavity ; photonic structures based on photonic crystals. Near field optical ; introduction to the main concepts ; presentation of specific probes, and near optical field microscopy. Nano-wires and -tubes in nanophotonics ; biomimetic and auto-assembled molecular nano-materials.

Surface functionalization (16h)

This lecture presents the necessary concepts for the understanding and prediction of surface self-organization phenomena at surfaces (bottom-up approach).

- *Surface and interface thermodynamics : surface tension, surface free energy, surface free enthalpy, chemical potential, stress and strain effect*
- *Adsorption, nuclei critical size during growth*
- *Structural description of crystalline surfaces, relaxation, reconstructions*
- *Electronic structure at surfaces*
- *Scientific cases : nano-object self-organized growth on metallic surface templates, self-organization of molecules on semiconductors surfaces*

Monte-Carlo molecular simulations (16h)

Objectives: Molecular simulations to predict macroscopic properties in fundamental and applied science and for the understanding of microscopic processes in matter. No pre-requisite of physics is necessary.

Content

- *Fundamental concepts of molecular and mesoscopic simulation: molecular dynamics and Monte-Carlo method*
- *Statistical physics, micro-macro transition, multi-scale simulations, calculation of macroscopic properties: free enthalpy, surface tension, diffusion coefficient, viscocity, adsorption properties*
- *Exploring microscopic processes: radial distribution, average force potential, density profile, etc*
- *Direct application to nanotechnology: confinement of fluids in nanopores; phase transitions, greenhouse gas capture and removal*

Microfluidics (16h)

The recent advances of soft lithography techniques offer possibilities for designing mechanical devices that allow handling precisely very small amounts of liquid; typically of the order of a few tens of picoliters. This scaling down in size of fluidic devices coupled with analyses techniques pave the way to numerous applications in a variety of domains that include biology, analytical chemistry, physics, and pharmacy. A lively topic these days is the quest for the lab on a chip: the massive integration of basic operations on fluids in devices as small as a few square inches. This aspect of microfluidics is important for biology but also for chemistry, for instance, to increase the yield of chemical reactions. We will discuss the general principles behind these developments in high-throughput microfluidics. We will then illustrate these advances using various examples in chemical process, material formulation, and biology.

Knowledge / Capabilities / Skills:

- Soft lithography techniques: production of microfluidic devices made of PDMS, glass etching, multilayer devices and pumps;

- Monophasic Flows at small scales: Flows in rigid conducts, Darcy's law, Hydrodynamic resistance, analogy with electricity, Flows in soft conduct, flows in porous media

-Capillary effects: Washburn's law, Maragoni's effect

- Theory of Lubrication: instability of Saffman Taylor, flows induced by thermo-capillary effects.

- Two Phase flows (drops/bubbles): Transport of drop and bubble in a microchannel; Hydrodynamic interaction, Bretherton's law, Traffic at a junction.

-Basic functions used in digital microfluidics: drop generation, dilution/concentration of droplet trains, drop deformation, production of alternated droplet trains, encapsulation, mixing, etc;

-Developments in process engineering: screening of fast chemical reactions, phase transfer, liquid-liquid extraction, capillary viscometer, surface tension measurements, and protein crystallization;

- Microfluidics for the design of novel colloidal materials.