UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Fabrication and Characterization of Nano and Quantum Materials

2526-1-FSM02Q039

Aims

The course aims at:

1. Knowledge and understanding: introducing the basic physical principles and unique features behind nano and quantum materials, the main growth methods used to synthesize them, as well as the main experimental techniques used to investigate their quantum behavior.
2. Applying knowledge and understanding: The course will treat the most important and most powerful experimental deposition and characterization methods used to fabricate and understand these complex materials down to a subatomic level. The course will show how and why these materials have the potential to open up new technological opportunities in the future.
3. Making judgements: The students will be able to evaluate the best fabrication and characterization techniques and the optimization parameters for the study of nano and quantum materials.
4. Communication skills: The students will acquire specialized terminology on the topics covered in the course.
5. Learning skills: The students will be able to take more advanced courses, attend seminars, and independently consult books on the topics covered in the course.

Contents

- Introduction: Quantum materials for modern quantum technology.
- Physical principles of quantum solid state materials.
- Detailed investigation of two classes of quantum materials: van der Waals solids and topological insulators.
- Theory of nucleation and crystal growth, epitaxy and heteroepitaxy.
- Advanced fabrication methods for precise composition, strain, and morphology control.
- Advanced experimental techniques for analysis of the materials quantum state.

Detailed program

- Introduction: Use of quantum materials for modern quantum technologies. Overview of course pre-requisite, lecture contents, textbooks/literature, and assessment methods.
- Symmetries in solid state: point groups, space groups, magnetic groups, irreducible representations and band dispersions.
- Additional symmetries in solid state: Noehter's theorem and examples, Time-reversal symmetry, Spin-Orbit coupling.
- Low-dimensionality (quantum confinement in 2D, 1D and 0D).
- Topology and topologically protected states: Topological Band Theory, Quantum Hall State, TKNN invariant, Chiral edge states, Berry phase, Chern number.
- 2D and 3D topological insulators: Haldane model, Kane-Mele model, Z2 invariant, HgTe/CdTe quantum well, Bismuth antimonide, Bismuth selenide.
- 2D materials and graphene (band structure, pseudospin, effective mass and density of states)
- van der Waals solids: electronic and structural properties of single-layers, multi-layers and heterostructures.
- Introduction to the synthesis of crystals. Crystal-Ambient Phase Equilibrium.
- Theory of nucleation: homogeneous and heterogeneous formation of 2D and 3D nuclei. Rate of nucleation.
- Theory of crystal growth: normal growth of rough faces; layer growth of flat faces (rate of step advancement); layer-by-layer and multi-layer growth.
- Epitaxy, heteroepitaxy, strain and relaxation.
- Practical and technical aspects of molecular beam epitaxy (MBE).
- Use of MBE for the growth of selected quantum materials.
- Chemical Vapour Deposition (CVD): Basic concepts, practical aspects, and examples of growth of quantum materials.
- Sputter Deposition, Pulsed Laser Deposition (PLD) and Atomic Layer Deposition (ALD).
- Photoelectron spectroscopies: introduction to X-Rays (generation and detection), core-hole transitions and labelling, practical and theoretical aspects, relevance for solid state physics investigation.
- Ultraviolet photoelectron spectroscopy (UPS) and Angle-Resolved Photoelectron Emission Spectroscopy (ARPES): basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.
- X-ray absorption spectroscopies (NEFAFX and EXAFS) and Electron Energy Loss Spectroscopy (EELS): basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.
- Resonant techniques: Resonant Photoelectron Spectroscopies (ResPES and Res-ARPES) and Resonant Inelastic X-Ray Scattering (RIXS): basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.
- Ultrafast optical and electron techniques for dynamic investigation of materials: basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.

Prerequisites

Basic quantum mechanics and solid state physics concepts.

Teaching form

Frontal lectures and exercise sessions using slides and/or blackboard.
In particular, there will be:
a) 12 two-hour lectures, in person, Delivered Didactics.
b) 15 two-hour practical classes, in person, Delivered Didactics.

Textbook and teaching resource

Textbooks

1. Tinkham M. (2004), Group Theory and Quantum Mechanics. Dover Publications Inc.
2. El-Batanouny, M. (2020). Advanced Quantum Condensed Matter Physics: One-Body, Many-Body, and Topological Perspectives. Cambridge University Press.
3. B. Andrei Bernevig, Taylor L. Hughes (2013). Topological Insulators and Topological Superconductors, Princeton University Press.
4. Jia-Ming Liu and I-Tan Lin (2018). Graphene Photonics. Cambridge University Press.
5. Avouris, P., Heinz, T., & Low, T. (Eds.). (2017). 2D Materials: Properties and Devices. Cambridge University Press.
6. Ivan V Markov (2003), Crystal Growth for Beginners: Fundamentals of Nucleation, Crystal Growth and Epitaxy, 2nd Edition, World Scientific.
7. Hans Lüth (2014). Solid Surfaces, Interfaces and Thin Films. Graduate Texts in Physics.
8. Barabási, A., & Stanley, H. (1995). Fractal Concepts in Surface Growth. Cambridge University Press.

Scientific articles

Different topics of the course are also well presented in scientific articles, such as:

1. Feliciano Giustino et al (2020) The 2021 quantum materials roadmap. J. Phys. Mater. 3 042006.
2. B. Keimer & J. E. Moore (2017) The physics of quantum materials. Nature Physics 13, 1045–1055.
3. Hasan MZ, Kane CL (2010) Colloquium: Topological insulators. Reviews of Modern Physics, 82(4):3045–3067.
4. N. T. Ziani, L. Vannucci, M. Sassetti (2018) Topological insulators: a beautiful revolution. Il Nuovo Saggiatore, 34, 13.
5. N. Kumar, S. N. Guin, K. Manna, C. Shekhar, and C. Felser (2021), Topological Quantum Materials from the Viewpoint of Chemistry, Chem. Rev. 2021, 121, 2780?2815.
6. Novoselov KS, Mishchenko A, Carvalho A, Neto AHC (2016) 2D materials and van der Waals heterostructures. Science, 353, aac9439.
7. Jonathan A. Sobota, Yu He, and Zhi-Xun Shen (2021). Angle-resolved photoemission studies of quantum materials. Rev. Mod. Phys. 93, 025006.
8. Fink, J., Schierle, E., Weschke, E. & Geck, J. (2013) Resonant elastic soft x-ray scattering. Reports on Progress in Physics 76, 056502.
9. Ament, L. J. P., van Veenendaal, M., Devereaux, T. P., Hill, J. P. & van den Brink, J. (2011) Resonant inelastic x-ray scattering studies of elementary excitations. Rev. Mod. Phys. 83, 705–767.
10. Y. Zhu and H. Dürr (2015). The future of electron microscopy. Physics Today 68(4), 32.
11. C. Colliex (2019). Chapter Three - Electron energy loss spectroscopy in the electron microscope. Advances in Imaging and Electron Physics 211, 187-304.
12. Caruso, F., & Novko, D. (2022). Ultrafast dynamics of electrons and phonons: from the two-temperature model to the time-dependent Boltzmann equation. Advances in Physics: X, 7(1).
13. J. Orenstein (2012), Ultrafast spectroscopy of quantum materials, Physics Today 65, 9, 44.
14. J Lloyd-Hughes et al (2021) The 2021 ultrafast spectroscopic probes of condensed matter roadmap. J. Phys.: Condens. Matter 33 353001.

Semester

Second semester.

Assessment method

a) Final exam. Students’ knowledge will be evaluated through an oral exam focusing on the topics discussed during the course. The exam will take place at the end of the course, and there will not be any ongoing tests during the course.

b) Skills assessed. In the final exam the following competences are evaluated: 1. Knowledge of the fundamental concepts in the physics of nano and quantum materials, with a specific focus on 2D materials and topological insulators; 2. Knowledge of the fundamental concepts regarding the growth methods and techniques of nano and quantum materials; 3. Ability to design fabrication strategies for specific materials, and ability to identify the most suitable measurement techniques to be used for characterizing their quantum properties.

c) Criteria for evaluation. During the oral exam we will evaluate the following parameters: i) percentage of questions which are answered correctly; ii) for each answer, percentage of experimental and theoretical details provided by the student compared to those exposed, discussed and applied during the course; iii) for each topic proposed during the exam, percentage of comments on applicative aspects compared to those discussed and included in the contents of the program.

Office hours

From Monday to Friday at any working hour (an appointment should be arranged with the teacher by email).

Sustainable Development Goals

QUALITY EDUCATION | INDUSTRY, INNOVATION AND INFRASTRUCTURE