UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Quantum Materials Synthesis

2223-2-F5302Q036

Aims

The course aims at introducing the basic physical principles and unique features behind quantum materials, the main growth methods used to synthesize them, as well as the main experimental techniques used to investigate and control their quantum behavior. 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.

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.
- 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 (Crystalline symmetries, 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.
- Introduction to fractal and scaling concepts in crystal growth.
- Modelling material deposition: Ballistic Deposition, Randon Deposition, Random Deposition with relaxation, Edwards-Wilkinson (EW) equation.
- Molecular Beam Epitaxy (MBE): Basic phenomena (adsorption, diffusion, and desorption), Linear theory, Scaling aspects of MBE.
- Practical and technical aspects of 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).
- Angle-Resolved Photoelectron Emission Spectroscopy (ARPES): basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.
- Resonant Inelastic X-Ray Scattering (RIXS): basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.
- Ultrafast optical and electron spectroscopies and microscopies for dynamic investigation: basic concepts, theoretical framework, practical aspects, and examples of investigation of quantum materials.

Prerequisites

Basic quantum mechanics and solid state physics concepts. Attendance of the “Surface and Interface” course is advised.

Teaching form

Frontal lectures and exercise sessions using slides and/or blackboard.

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. J Lloyd-Hughes et al (2021) The 2021 ultrafast spectroscopic probes of condensed matter roadmap. J. Phys.: Condens. Matter 33 353001

Semester

First semester (from October to January)

Assessment method

Students’ knowledge will be evaluated through an oral exam focusing on the topics discussed during the course.

Office hours

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

Sustainable Development Goals

INDUSTRY, INNOVATION AND INFRASTRUCTURE