

Degree programme	Type	Course
Applied Nanoscience: From Materials to Devices	OP	1

Contact lecturer

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Group languages

You can consult this information at the [end](#) of the document.

Prerequisites

Students participating in this module should have prior training in Physics, as well as knowledge of Chemistry and Materials Science. They should also be proficient in the use of standard office software applications and possess a sufficient level of English to understand lectures, scientific texts, documents, seminars, and conferences.

Objectives

The objectives of this module can be summarized as follows:

1. Analyze electronic correlation phenomena in nanomaterials and relate them to emerging quantum properties, applying knowledge of advanced materials physics.
2. Select and classify quantum materials according to their functionality and potential for integration into devices, taking into account their electronic and quantum properties.
3. Interpret and evaluate the effects of quantum correlations on the behavior of nanostructured devices, including their characterization and measurement.
4. Conceptually design devices based on quantum materials, identifying potential applications in technological and industrial sectors.

Learning outcomes

- CA26 (Design devices based on quantum materials with potential applications in production sectors.)
Design devices based on quantum materials with potential applications in production sectors.

- CA27 (Measure quantum correlation effects on devices.) Measure quantum correlation effects on devices.
- KA26 (Identify the basic phenomena of electronic correlation in nanomaterials.) Identify the basic phenomena of electronic correlation in nanomaterials.
- KA27 (Select quantum materials based on their functionality for integration into devices.) Select quantum materials based on their functionality for integration into devices.
- KA28 (Relate nanomaterials to quantum phenomena and their applications in devices.) Relate nanomaterials to quantum phenomena and their applications in devices.
- SA34 (Categorize quantum materials according to their functionality.) Categorize quantum materials according to their functionality.
- SA35 (Relate the different phenomena emerging from the electronic correlation with properties.) Relate the different phenomena emerging from the electronic correlation with properties.
- SA36 (Predict the possible emergence of a quantum correlation property according to fundamental material parameters.) Predict the possible emergence of a quantum correlation property according to fundamental material parameters.

Contents

Block 1. Fundamentals of Electronic Correlations in Quantum Materials

Introduction to quantum materials: quantum versus classical properties. Quantum superposition and qubits. Electronic correlations: basic concepts and the metal-insulator transition. BCS theory of superconductivity. Spintronics. Size effects and emergent properties at the nanoscale: the quantum tunneling effect. Introduction to charge ordering and non-trivial electronic phases. Topological materials, van der Waals heterostructures, and Moiré systems. Perovskite oxides as a versatile materials platform.

Block 2. Spintronics and Quantum Transport

Nanomagnetism and quantum mechanics. Ferromagnetism and antiferromagnetism. Principles of spintronics and spin-orbitronics. Spin-charge and spin-orbit interactions. Transport phenomena in nanostructured systems. Spintronic materials. Spin-polarized exchange. Magnetoresistive devices (spin valves and magnetic tunnel junctions). Spin waves (magnons). Topological magnetic textures (skyrmions, vortices, and hopfions).

Block 3. Phase Transitions, Ferroic Materials, and Ferroelectric Devices

Ferroelectric and multiferroic materials. Ferroelectric domains, domain walls, and emergent properties. Symmetry-protected electronic phases. Size and depolarization effects. Strain effects: strain engineering and flexoelectricity. Devices based on ferroelectric tunnel junctions. Applications in memory devices and functional electronics.

Block 4. Collective States and Quantum Excitations

Phase transitions in strongly correlated systems. Metal-insulator transitions. Electron-phonon and electron-magnon interactions. Conventional and unconventional superconductivity. High-temperature superconductors. Charge-density waves and spin-density waves (CDW/SDW). Quasiparticles in superconductors and strongly correlated systems. Superconducting spintronics. Josephson junctions and superconducting devices. Superconducting qubits. Emergence of collective properties in superconducting and hybrid nanodevices. Applications in sensors and quantum technologies.

Learning activities and methodology

Title	Hours	ECTS	Learning outcomes
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Lab sessions	2	0.08	CA26, CA27, KA27, KA28, SA36
Lectures (theory and exercises)	15	0.6	CA26, CA27, KA26, KA27, KA28, SA34, SA35, SA36
Mentoring	2	0.08	CA26, CA27, KA26, KA27, KA28, SA34, SA35, SA36
Presentations on selected topics by students	2	0.08	KA26, KA27, KA28, SA34, SA35, SA36
Self-study and preparation of the class presentation	46	1.84	CA26, CA27, KA26, KA27, KA28, SA34, SA35, SA36

The course methodology will combine traditional classroom lectures with independent student activities aimed at consolidating and deepening the concepts covered during the face-to-face sessions. These activities will include the reading of specialized literature (scientific articles) and the critical analysis of experimental results and case studies related to quantum materials and their applications in advanced devices.

In particular, the course will include a series of demonstration sessions in the quantum materials characterization laboratory, with the objective of introducing students to experimental techniques commonly used in current research. Different local probe microscopy techniques based on atomic force microscopy (AFM) will be presented, including magnetic force microscopy (MFM), piezoresponse force microscopy (PFM), and Kelvin probe force microscopy (KPFM), as well as electrical conductivity measurements, among other characterization techniques. The physical principles underlying these methods, measurement preparation, data acquisition and analysis, as well as examples of their application to the study of magnetic, ferroelectric, electronic, and topological properties in advanced materials, will be discussed.

Annotation: within the schedule set by the centre or degree programme, 15 minutes of one class will be reserved for students to evaluate their lecturers and their courses or modules through questionnaires.

Assessment

Continuous assessment activities

Title	Weight	Hours	ECTS	Learning outcomes
Final Exam	50%	4	0.16	CA26, CA27, KA26, KA27, KA28, SA34, SA35, SA36
Lab demonstration session (characterization of quantum materials for devices) using scanning probe microscopy	25%	2	0.08	CA27, KA27, KA28, SA34
Class presentation of relevant scientific articles on quantum materials for devices	25%	2	0.08	CA26, KA26, KA27, KA28, SA34, SA35, SA36

The assessment of the module will be based on three complementary activities. The final exam will account for 50% of the final grade and aims to evaluate the assimilation of fundamental concepts and the ability to relate them to the properties and applications of the quantum materials studied throughout the course.

25% of the grade will correspond to an oral presentation in class, carried out individually or in pairs depending on the number of enrolled students. This activity will consist of the analysis and discussion of relevant scientific articles in the field of quantum materials for devices, with special emphasis on the understanding of results, their contextualization within the state of the art, and scientific communication skills.

Finally, the remaining 25% will be assessed through the submission of an individual report on the laboratory

demonstration session. The report must reflect an understanding of the physical and methodological principles of the characterization techniques presented, as well as the ability to critically interpret experimental data and relate them to the properties of the studied materials.

To pass the course, a final grade equal to or higher than 5 out of 10 is required. If the assessment is not passed, students will be entitled to a written resit exam covering the entire syllabus. In order to access the resit, the student must have been previously assessed in a set of activities whose weight represents at least two-thirds of the total continuous assessment grade. In this case, moreover, the grades obtained in short in-class tests and those corresponding to laboratory report submissions will not be taken into account.

If a student commits any type of irregularity that may lead to a significant change in the grade of an assessment activity, it will be graded with a 0, regardless of any disciplinary procedure that may follow. If multiple irregularities are detected in assessment activities of the same course, the final grade of the course will be 0.

This course does not allow single assessment.

This course allows the use of Artificial Intelligence (AI) technologies exclusively for bibliographic or information search and text editing. Lack of transparency in the use of AI in any assessed activity will be considered academic dishonesty and will result in a grade of 0 for the activity, with no possibility of resit, or more severe penalties in serious cases.

Bibliography

* Igor Žutić, Jaroslav Fabian, S. Das Sarma, "Spintronics: Fundamentals and applications", *Reviews of Modern Physics* 76, 323-410 (2004), DOI: <https://doi.org/10.1103/RevModPhys.76.323>.

* Atsufumi Hirohata et al., "Review on spintronics: Principles and device applications", *Journal of Magnetism and Magnetic Materials* 509, 166711 (2020)

DOI: <https://doi.org/10.1016/j.jmmm.2020.166711>

* Pavlo Zubko et al., "Interface Physics in Complex Oxide Heterostructures", *Annual Review of Condensed Matter Physics* 2, 141-165 (2011): <https://doi.org/10.1146/annurev-conmatphys-062910-140445>.

* Dobrovolskiy et al., Roadmap on nanoscale superconductivity for quantum technologies, *Superconductor Science & Technology* 39, 023502 (2026), DOI: <https://doi.org/10.1088/1361-6668/ae3030>

Software

N/A

Course groups and languages

The information provided is provisional until November 30. After this date, you will be able to consult the language of each group through this [link](#). To access the information, you will need to enter the course CODE

Type of teaching	Group	Language	Semester	Shift
(TE)m Theory (master)	1	English	first semester	afternoon