Introduction to Transport and Topological Properties of Matter

Educational subject description sheet

Basic information

Study programme Fizyka **Speciality** INFORMACJA KWANTOWA I SPINTRONIKA **Organizational unit** Faculty of Physics **Study level** Second-cycle programme **Study form** Full-time **Education profile** General academic	**Didactic cycle** 2023/24 **Subject code** 04FIZIKSS.22KU.04354.23 **Lecture languages** English **Course type** Elective **Block** Complementary major subjects
Subject coordinator	Anna Dyrdał
Lecturer	Anna Dyrdał

Period	**Activities and hours**	**Number of ECTS points**
Semester 2	• Lecture: 30, Exam • Seminar: 15, Graded credit	4

Goals

Code	Goal
C1	The aim of this lecture is to present and overview modern aspects of solid-state physics related to electronic, spin, and transport properties in new 2D materials such as graphene and graphene-like crystals, topological insulators, interfacial hybrid structures (e.g., semiconductor or oxides interfaces). The scope of this lecture contains the following topics: (1) Symmetry and topological properties of matter, e.g., Berry Phase (Zak phase), topological invariants, skyrmions; (2) Band structure – introduction to the modelling and construction of effective Hamiltonians based on symmetry consideration; (3) Description of selected transport and spin effects.

Subject learning outcomes

Code	Outcomes in terms of	Learning outcomes	Examination methods
Knowledge – Student:			
W1	will know the basic models and theories describing graphene (and the other graphene-like materials) and topological insulators	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W03	Oral exam, Oral colloquium, Project, Multimedia presentation
W2	will know basic methods of transport theory applied to 2D systems: Landauer formula, Boltzmann equation, linear response theory (Kubo formula and Green function formalism) and will be able to use them to simple models	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W03	Oral exam, Oral colloquium, Project
W3	will know and will be able to explain the most important spin end transport phenomena determined by electronic structure of graphene, graphene-like materials and topological insulators	FIZ_K2_W03, FIZ_K2_W04, FIZ_K2_W05	Oral exam, Oral colloquium, Project, Multimedia presentation
Skills – Student:			
U1	will be able to perform simple analytical calculations of electronic structure and characteristics describing topological properties of topological insulator, graphene and other 2D structures	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U04, FIZ_K2_U05	Oral colloquium, Project
U2	will be able to perform simple computer simulations of band structure and transport properties	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U04, FIZ_K2_U05	Oral exam, Oral colloquium, Project
U3	will be able to prepare works/reports in the area of transport and topological properties in condensed matter (based on literature, materials for this lecture, and independent works)	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U05, FIZ_K2_U07	Oral colloquium, Project, Multimedia presentation

Study content

No.	Course content	Subject learning outcomes	Activities
1.	Nobel Prizes in Physics in years 2007, 2010, and 2016 for discoveries that indicated the main directions of modern solid-state physics and spintronics	W1, W3	Lecture
2.	Crystallographic structure and tight-binding model of graphene, effective low-energy model ('kp' method, Kane-Mele Hamiltonian)	W1, W2, U2	Lecture
3.	Tight-binding models and low-energy effective models defined based on symmetry considerations – based on graphene example	W1, W2, U1	Lecture
4.	Overview and characteristics of graphene-like crystals and van-der-Waals heterostructures	W1, W3	Lecture
5.	Introduction to the physics of topological insulators; model describing 3D topological insulator Bi2X3 (X = Se, Te) and model describing thin films of topological insulators, bulk-boundary correspondence, spin-momentum locking	W1, U1, U2	Lecture, Seminar

No.	Course content	Subject learning outcomes	Activities
6.	Models describing topological states of matter, e.g., Haldane model, Kane-Mele model, Rice-Mele model, Bernevig-Hughes-Zhang model (possible usage of 'PyTBand' and 'kwant' packages)	W1, W2, W3, U1, U2, U3	Lecture, Seminar
7.	Berry phase and topological invariants, geometric phase and Zak phase, Berry connection and Berry curvature, Berry curvature behavior under symmetry operations, Chern number, TKNN, winding number, Z2 index, Pfaffian, TRIM, phase diagrams, classification of topological insulators	W1, W2, W3, U1, U2, U3	Lecture, Seminar
8.	Quantum Hall effect, Quantum Spin Hall effect, and anomalous Hall effect and their connection to topological invariants; anomalous velocity	W1, W2, W3, U1, U2, U3	Lecture, Seminar
9.	Formalism used for electron transport description in 2D systems: Landauer Formula, Landauer-Buttiker Formalism, Green’s function methods, Kubo formula, Boltzmann theory, Floquet theory; introduction to 'kwant' package	W1, W2, W3, U1, U2, U3	Lecture, Seminar
10.	Spin and transport phenomena determined by band structure in graphene, graphene-like systems, topological insulators, semiconductor heterostructures, e.g., Klein tunneling, anomalous, spin, valley Hall effect, Andreev reflection in graphene, exchange interaction in topological insulators, superconductivity, anomalous and spin Hall effect in semiconductor heterostructures, spin-orbit torque, etc.	W1, W2, W3, U1, U2, U3	Lecture, Seminar
11.	DMI interaction, skyrmions, transport in systems with noncollinear magnetization, domain walls and skyrmions dynamics; introduction to 'spirit' package	W1, W2, W3, U1, U2, U3	Lecture, Seminar

Additional information

Activities	Teaching and learning methods and activities
Lecture	Lecture with a multimedia presentation of selected issues, Problem-based learning, Solving tasks (e.g. computational, artistic, practical), Research method (scientific inquiry)
Seminar	Problem-based learning, Solving tasks (e.g. computational, artistic, practical), Research method (scientific inquiry), Project method

Activities	Credit conditions
Lecture	The final grade will be based on the project and oral exam grades (average of grades obtained from project and oral exam; student should obtain at least satisfactory grade from each of them). The project should be written in the form of report that should contain the introduction based on specialist literature (original and review articles, books); the description of the considered model/problem and own results (calculations/simulations); summary.
Seminar	Preparation of presentation (seminar) on a given problem.

Literature

Obligatory

1. All the literature used during the lecture and suggested additional literature will be provided by the lecturer. - Original articles provided during the lecture - L. E. F. Foa Torres, S. Roche and J.-Chr. Charlier, Introduction to Graphene-Based Nanomaterials. From Electronic Structure to Quantum Transport, Cambridge 2020 ‒ V. Litvinov, Magnetism in Topological Insulators, Springer 2019

Optional

1. ‒ Shun-Qing Shen, Topological Insulators. Dirac Equation in Condensed Matters, Springer 2012 ‒ G. Tkachov, Topological Insulators. The physics of Spin Helicity in Quantum Transport, Pan Stanford Publishing 2016 ‒ J. Inoue, A. Yamakage, S. Honda, Graphene in Spintronics, Pan Stanford Publishing 2016 ‒ G. D. Mahan, Many-Particle Physics, Springer 2000 ‒ S. Seki, M. Mochizuki, Skyrmions in Magnetic Materials, Springer 2016 ‒ N.W. Ashcroft, N.D. Mermin, Solid State Physics

Calculation of ECTS points

Activities	**Activity hours***
Lecture	30
Seminar	15
Preparation for classes	10
Reading the indicated literature	10
Preparation of a multimedia presentation	10
Preparation of a project	25
Preparation for the exam	20
Student workload	**Hours** 120
Number of ECTS points	**ECTS** 4

* academic hour = 45 minutes

Efekty uczenia się dla kierunku

Kod	Treść
FIZ_K2_U01	The graduate can use their knowledge to formulate and solve complex and unusual problems in the field of physical sciences; select and apply appropriate methods and tools necessary to solve a given problem (including advanced IT techniques), as well as adapt existing methods and tools or develop completely new ones
FIZ_K2_U02	The graduate can find the necessary information in the professional literature, databases and other sources, in particular in scientific journals basic to physics, and perform critical analysis, synthesis and creative interpretation of the collected information
FIZ_K2_U03	The graduate can formulate and test hypotheses related to simple research problems in physics (plan and perform observations, experiments, theoretical calculations or computer simulations and critically evaluate and discuss the results obtained)
FIZ_K2_U04	The graduate can prepare, for various audiences, oral presentations and written studies presenting specialized topics in the field of physical sciences in a communicative way, as well as debate on such topics
FIZ_K2_U05	The graduate can use English in accordance with the requirements set out for level B2+ of the Common European Framework of Reference for Languages, as well as specialist English terminology in the field of physical sciences
FIZ_K2_U07	The graduate can independently determine the directions of further learning and implement a self-education program, learn throughout lifetime using the available international literature and be able to guide others in this regard
FIZ_K2_W01	The graduate knows and understands in-depth selected facts, phenomena, concepts and theories specific to physics and complex relationships between them (constituting advanced general knowledge in the field of physical sciences and representing both key and other selected issues in the field of advanced detailed knowledge in this discipline)
FIZ_K2_W02	The graduate knows and understands in-depth selected research methods and tools as well as mathematical models used in physics
FIZ_K2_W03	The graduate knows and understands in-depth selected computational methods and information technology tools and techniques used to solve complex problems in physics
FIZ_K2_W04	The graduate knows and understands main development trends in the discipline of physical sciences
FIZ_K2_W05	The graduate knows and understands the role of physical sciences in the context of fundamental dilemmas and challenges of modern civilization