Federal State Autonomous Educational Institution of Higher Education "Moscow Institute of Physics and Technology (National Research University)"

APPROVED
Head of Landau Phystech-School of Physics & Research
A.V. Rogachev

Work program of the course (training module)

course:	Electronic Transport in 2D Materials/Электронный транспорт в двумерных материалах
major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of Physics and Technology of nanostructures
term:	1
qualification:	Master

Semester, form of interim assessment: 2 (spring) - Exam

Academic hours: 30 AH in total, including:
- lectures: 30 AH.
- seminars: 0 AH.
- laboratory practical: 0 AH.

Independent work: 30 AH.

Exam preparation: 30 AH.

In total: 90 AH, credits in total: 2

Author of the program: D.A. Kazaryan, candidate of physics and mathematical sciences

The program was discussed at the Chair of Physics and Technology of nanostructures 01.02.2021

Annotation

The program of the course "Electronic Transport in 2D Materials" is devoted to the study of electronic states and quantum phenomena in separate 2D crystals, as well as in various low-D systems integrated into van der Waals heterostructures. Additionally, the course program comprises an overview of the latest research and technological advances in the field of physics of 2D electronic systems.

1. Study objective

Purpose of the course

1. To learn and master the modern solutions to problems of physics of 2D electronic systems.
2. To develop practical and creative skills for the independent organization of progressive experimental research.

Tasks of the course

1. To study the electronic bandstructures of classical 2D crystals.
2. To introduce general research methodologies of an electronic state investigation in various 2D crystals and van der Waals heterostructures.
3. To introduce mechanisms of quantum electronic transport in various 2D crystals and various van der Waals heterostructures.
4. To hold theoretical knowledge of common fabrication methods of 2D crystals and van der Waals heterostructures.
5. To study the working principles of advanced electronic and optoelectronic devices based on 2D crystals and van der Waals heterostructures.

2. List of the planned results of the course (training module), correlated with the planned results of the mastering the educational program

Mastering the discipline is aimed at the formation of the following competencies:

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
	Gen.Pro.C-1.2 Able to summarise and critically evaluate experiences and research results in the field of photonics and opto-informatics
	Gen.Pro.C-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.1 Has an understanding of the current state of research in photonics and opto-informatics
Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.1 Apply ICT knowledge and skills to find and study scientific literature and use software products
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.1 Locate, analyze, and summarize information on current research findings within a selected subject field
	Pro.C-1.2 Make hypotheses, build mathematical models of the studied phenomena and processes, evaluate the quality of the developed model
	Pro.C-1.3 Able to apply theoretical and/or experimental research methods in photonics and opto-informatics to a specific scientific problem and interpret the results obtained

Pro.C-2 Organize and conduct scientific research and testing independently or as a member (leader) of a small research team	Pro.C-2.1 Able to plan and carry out research in photonics and opto-informatics independently or as part of a research team
	Pro.C-2.2 Conduct tests of research results through scientific publications and participation in conferences
Pro.C-3 Professionally use research and testing equipment (devices and installations, specialized software) in a selected subject field	Pro.C-3.1 Understand the operating principles of the equipment and specialized software
	Pro.C-3.2 Conduct an experiment (simulation), using research equipment (software)
	Pro.C-3.3 Evaluate the accuracy of the experimental (numerical) results

3. List of the planned results of the course (training module)

As a result of studying the course the student should:

know:

1. General research methodologies for studying electronic states and quantum phenomena in various 2D crystals, van der Waals heterostructures, and corresponding 2D systems.
2. Principal mechanisms of quantum electronic transport in various 2D crystals, van der Waals heterostructures, and corresponding 2D systems.
3. Working principles of advanced electronic and optoelectronic devices based on 2D crystals and van der Waals heterostructures.

be able to:

1. Derive dispersion laws, electronic densities of states and charge carrier densities of classical 2D crystals.
2. Derive electrostatic parameters of various van der Waals heterostructures consisting of classical 2D crystals.
3. Evaluate electronic characteristics (charge carrier mobility, mean free path, and so on) of classical 2D crystals integrated into various van der Waals heterostructures.

master:

1. General knowledge of research and technological advances in the field of electronic transport properties in 2D systems.
2. Theoretical knowledge of common fabrication methods of 2D crystals and van der Waals heterostructures.
3. Attainments necessary for solving current research and technological problems.

4. Content of the course (training module), structured by topics (sections), indicating the number of allocated academic hours and types of training sessions

4.1. The sections of the course (training module) and the complexity of the types of training sessions

№	Topic (section) of the course	Types of training sessions, including independent work			
		Lectures	Seminars	Laboratory practical	Independent work
1	Solid State Fundamentals, towards 2D crystals	2			2
2	Graphene Fundamentals, an experimentalist perspective	6			6
3	Hexagonal boron nitride for graphene, enabling remarkable electronic properties	12			12
4	Introduction to 2D Semiconductors, superconductors, and ferromagnets	6			6
5	Special topics on today’s frontier	4			4
AH in total		30			30

Exam preparation	30 AH.
Total complexity	90 AH., credits in total 2

4.2. Content of the course (training module), structured by topics (sections)

Semester: 2 (Spring)

1. Solid State Fundamentals, towards 2D crystals

1. Introduction to the theory of electronic transport in 2D crystals. Classical Drude model of electrical conduction, Boltzmann transport equation, diffusive and ballistic transport regimes, notes on electron liquids, Euler and Navier-Stokes equations for kinetic-hydrodynamic transport regime.
2. Introduction to the theories of quantum tunnelling and capacitance in 2D crystals. The stationary point and effective transfer Hamiltonian approaches.

2. Graphene Fundamentals, an experimentalist perspective

3. Graphene monolayer. Tight-binding approach to the electronic band structure of monolayer graphene, Dirac cones and pseudospin degree of freedom, chiral electrons and Klein paradox, anomalous quantum Hall effect.
4. Graphene bilayer. Tight-binding approach to the electronic band structure of Bernal bilayer graphene, neutrality points and trigonal warping, electric field tunable electronic bandgap and Mexican hat of electronic band structure, Berry phase and unconventional quantum Hall effect.
5. Hexagonal and rhombohedral graphite. Tight-binding approach to the electronic band structure of rhombohedral graphite, bandgap induced by displacement field, electronic phase separation and stacking order of individual layers, surface and bulk states.

3. Hexagonal boron nitride for graphene, enabling remarkable electronic properties

6. Hexagonal boron nitride for graphene encapsulation. Notes on viscosity, Hall viscosity of electron fluid in graphene and its constrictions.
7. Graphene and hexagonal boron nitride twists. Electronic bandstructure and cloning of Dirac fermions, formation of superlattices and moiré patterns, notes on direct visualization methods: AFM and STM.
8. Graphene and hexagonal boron nitride twists at high magnetic fields, Hofstadter butterfly, mini-zone formation, recurring Bloch and high order fractal states.
9. Graphene and hexagonal boron nitride for vertical tunnelling transistors. Phonon-assisted inelastic resonant tunnelling, impurity-assisted sequential and twist-controlled resonant tunnelling transitions. Valley tuning and chiral quantum state of graphene electrons.
10. Graphene quantum dots. Single-electron charging, Coulomb blockade and size quantization, planar and vertical single-electron transistors based on graphene quantum dots.
11. Graphene double-layers. Counterflow currents, Coulomb drag and magneto-Coulomb drag, indirect exciton condensation at high magnetic fields.
12. Graphene p-n junctions. Electron flow focusing, Veselago lensing, transverse magnetic focusing, and electronic transport with snake trajectories.

4. Introduction to 2D Semiconductors, superconductors, and ferromagnets

13. Introduction to 2D semiconductors: $MoX2$ and $WX2$ (X = S, Se). Electronic band structure, direct electronic bandgap monolayers, spin-orbit and -valley couplings, interlayer interactions and quantum Hall effect.
14. Introduction to 2D superconductors: $NbX2$ (X = S, Se). Electronic band structure, critical temperatures, and superconducting energy gaps.
15. Introduction to 2D ferromagnets: $CrX3$ (X= I, Br). Electronic band structure, interlayer coupling strength, magnetic anisotropy, Curie temperatures, and magnon states.

5. Special topics on today's frontier

16. Established fabrication methods of 2D crystals and van der Waals heterostructures.
17. Introduction to electronic properties of the magic-angle twisted bilayer (MATBG) graphene systems*.
18. Introduction to electronic properties of the magic-angle twisted trilayer (MATTG) graphene systems*.

5. Description of the material and technical facilities that are necessary for the implementation of the educational process of the course (training module)

A set of electronic presentations/slides; an audience equipped with presentation equipment (projector, screen, computer / laptop); if necessary, special technical means for students with disabilities and persons with disabilities.

6. List of the main and additional literature, that is necessary for the course (training module) mastering

Main literature
Literature fund of the basic departament:
1. The Physics of Graphene by M. I. Kastnelson, Cambridge University Press 2020, ISBN: 97811086175671.
2. Graphene, A New Paradigm in Condensed Matter and Device Physics by E. L. Wolf, Cambridge University Press 2014, ISBN: 9780199645862.
3. Introduction to Graphene-Based Nanomaterials: From Electronic Structure to Quantum Transport by Luis E. F. Foa Torres, Stephan Roche, Jean-Christophe Charlier, Cambridge University Press 2020, SBN:9781108476997, 1108476996.

Additional literature
Literature fund of the basic departament:
1. 2D materials properties and devices, by Phaedon Avouris, Tony F. Heinz, Tony Low, Cambridge University Press 2017, ISBN: 9781107163713.
2. 2D semiconductor materials and devices, by Dongzhi Chi, K.E.Johnson Goh, Andrew Wee, Elsevier 2019, ISBN: 9780128161876.
3. Электронные конспекты (презентации) лекций, включающие перечень контрольных задач, разработанные для данного курса.

7. List of web resources that are necessary for the course (training module) mastering

1. Электронные ресурсы, включая доступ к базам данных WoS, SCOPUS, e-library и arXiv (Condensed Matter).
2. Информационные ресурсы, профильные научные издания: Science, Nature Publishing group, Physical Review Journals, AIP Publishing, Письма в ЖЭТФ, ЖЭТФ, УФН.

8. List of information technologies used for implementation of the educational process, including a list of software and information reference systems (if necessary)

When preparing and conducting lectures, the Internet is used.
In addition, Libre Office is used, as well as the Ink Scape graphics package.

9. Guidelines for students to master the course

A student studying the discipline must, on the one hand, master the general conceptual apparatus, and on the other hand, must learn to apply theoretical knowledge in practice.
As a result of studying the discipline, the student must know the basic definitions and concepts, be able to apply the knowledge gained to solve various problems.
Successful completion of the course requires:

- attendance of all classes provided for by the curriculum for the discipline;
- keeping a synopsis of classes;
- student's intense independent work.

Independent work includes:

- reading recommended literature;
- study of educational material, preparation of answers to questions intended for independent study;
- solving problems offered to students in the classroom;
- preparation for the performance of tasks of the intermediate certification.

An indicator of mastery of the material is the ability to answer questions on the topics of the discipline without a synopsis.

It is important to achieve an understanding of the material being studied, not its mechanical memorization. If a student finds it difficult to study certain topics, questions, he/she should seek advice from a teacher.

Intermediate control of students' knowledge is possible in the form of solving problems in accordance with the topic of classes.

SUPPLEMENT

Assessment funds for course (training module)

major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of Physics and Technology of nanostructures
term:	1
qualification:	Master

Semester, form of interim assessment: 2 (spring) - Exam

Author: D.A. Kazaryan, candidate of physics and mathematical sciences

1. Competencies formed during the process of studying the course

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
	Gen.Pro.C-1.2 Able to summarise and critically evaluate experiences and research results in the field of photonics and opto-informatics
	Gen.Pro.C-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.1 Has an understanding of the current state of research in photonics and opto-informatics
Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.1 Apply ICT knowledge and skills to find and study scientific literature and use software products
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.1 Locate, analyze, and summarize information on current research findings within a selected subject field
	Pro.C-1.2 Make hypotheses, build mathematical models of the studied phenomena and processes, evaluate the quality of the developed model
	Pro.C-1.3 Able to apply theoretical and/or experimental research methods in photonics and opto-informatics to a specific scientific problem and interpret the results obtained
Pro.C-2 Organize and conduct scientific research and testing independently or as a member (leader) of a small research team	Pro.C-2.1 Able to plan and carry out research in photonics and opto-informatics independently or as part of a research team
	Pro.C-2.2 Conduct tests of research results through scientific publications and participation in conferences
Pro.C-3 Professionally use research and testing equipment (devices and installations, specialized software) in a selected subject field	Pro.C-3.1 Understand the operating principles of the equipment and specialized software
	Pro.C-3.2 Conduct an experiment (simulation), using research equipment (software)
	Pro.C-3.3 Evaluate the accuracy of the experimental (numerical) results

2. Competency assessment indicators

As a result of studying the course the student should:

know:

1. General research methodologies for studying electronic states and quantum phenomena in various 2D crystals, van der Waals heterostructures, and corresponding 2D systems.
2. Principal mechanisms of quantum electronic transport in various 2D crystals, van der Waals heterostructures, and corresponding 2D systems.
3. Working principles of advanced electronic and optoelectronic devices based on 2D crystals and van der Waals heterostructures.

be able to:

1. Derive dispersion laws, electronic densities of states and charge carrier densities of classical 2D crystals.
2. Derive electrostatic parameters of various van der Waals heterostructures consisting of classical 2D crystals.
3. Evaluate electronic characteristics (charge carrier mobility, mean free path, and so on) of classical 2D crystals integrated into various van der Waals heterostructures.

master:

1. General knowledge of research and technological advances in the field of electronic transport properties in 2D systems.
2. Theoretical knowledge of common fabrication methods of 2D crystals and van der Waals heterostructures.
3. Attainments necessary for solving current research and technological problems.

3. List of typical control tasks used to evaluate knowledge and skills

Not provided.

4. Evaluation criteria

Examples of control questions:

Introduction to the theories of quantum tunnelling and capacitance in 2D crystals. The stationary point and effective transfer Hamiltonian approaches.

Graphene and hexagonal boron nitride twists. Electronic bandstructure and cloning of Dirac fermions, formation of superlattices and moiré patterns, notes on direct visualization methods: AFM and STM.

Hexagonal and rhombohedral graphite. Tight-binding approach to the electronic band structure of rhombohedral graphite, bandgap induced by displacement field, electronic phase separation and stacking order of individual layers, surface and bulk states.

Examples of assessment questions:

Construct a system of electrostatic equations for a tunnelling transistor consisting of Si/SiO2/hBN/Gr/6-hBN/BGr/hBN layers using the parallel plate capacitor model, and neglecting the hopping parameters of □_1 and □_4, the interlayer asymmetry parameter in the dispersion relation of BGr (Gr – monolayer graphene, hBN – hexagonal boron nitride, BGr – Bernal AB bilayer graphene). Using the obtained results, evaluate the conditions of resonant tunnelling for θ = 2o twist angle of the crystal lattices of Gr-BGr.

Derive the expression for electronic density of states of monolayer graphene from the dispersion relation. Using the obtained result, derive an expression for the dependence of the carrier density on the chemical potential at finite temperatures.

Derive an expression for the dependence of the energies of Van Hove singularities on the twist angle of crystal lattices in tBGr systems (tBGr – twisted bilayer graphene).

Examples of examination papers:

Paper 1.

Graphene monolayer. Tight-binding approach to the electronic band structure of monolayer graphene, Dirac cones and pseudospin degree of freedom, chiral electrons and Klein paradox, anomalous quantum Hall effect.

Construct a system of electrostatic equations for a tunnelling transistor consisting of Si/SiO2/hBN/BGr/4-hBN/BGr/hBN layers using the parallel plate capacitor model, and considering BGr as a classical 2DEG (hBN – hexagonal boron nitride, BGr – Bernal AB bilayer graphene). Using the obtained results, evaluate the conditions of resonant tunnelling for θ = 3o twist angle of the crystal lattices of BGr-BGr.

Paper 2.

Graphene quantum dots. Single-electron charging, Coulomb blockade and size quantization, planar and vertical single-electron transistors based on graphene quantum dots.

Derive the superlattice constant and calculate the backgate voltage required to achieve the satellite neutrality points in the Si/SiO2/hBN/Gr field-effect transistor with crystal lattice twist angle of θ = 1.5 ° for hBN-Gr, and thicknesses of SiO2 = 90 nm, hBN = 10 nm (Gr – monolayer graphene, hBN - hexagonal boron nitride).

Paper 3.

Introduction to 2D ferromagnets: CrX3 (X= I, Br). Electronic band structure, interlayer coupling strength, magnetic anisotropy, Curie temperatures, and magnon states.

Derive the expression for electronic density of states of a bilayer AB Bernal graphene from the dispersion relation neglecting the hopping parameters of □_3 and □_4. Using the obtained results, derive an expression for the dependence of the carrier density on the Fermi energy at T = 0 K.

Assessment “excellent (10)” is given to a student who has displayed comprehensive, systematic and deep knowledge of the educational program material, has independently performed all the tasks stipulated by the program, has deeply studied the basic and additional literature recommended by the program, has been actively working in the classroom, and understands the basic scientific concepts on studied discipline, who showed creativity and scientific approach in understanding and presenting educational program material, whose answer is characterized by using rich and adequate terms, and by the consistent and logical presentation of the material;

Assessment “excellent (9)” is given to a student who has displayed comprehensive, systematic knowledge of the educational program material, has independently performed all the tasks provided by the program, has deeply mastered the basic literature and is familiar with the additional literature recommended by the program, has been actively working in the classroom, has shown the systematic nature of knowledge on discipline sufficient for further study, as well as the ability to amplify it on one’s own, whose answer is distinguished by the accuracy of the terms used, and the presentation of the material in it is consistent and logical;

Assessment “excellent (8)” is given to a student who has displayed complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently performed all the tasks stipulated by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (7)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in the answer, has independently performed all the tasks provided by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (6)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently carried out the main tasks stipulated by the program, studied the basic literature recommended by the program, showed systematic character of his knowledge of the discipline, which is sufficient for further study;

Assessment “good (5)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, mastered the basic literature recommended by the program, made some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors by himself;

Assessment “satisfactory (4)” is given to a student who has discovered knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, learned the main literature but allowed some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors under the guidance of a teacher;

Assessment “satisfactory (3)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, not showed activity in the classroom, independently fulfilled the main tasks envisaged by the program, but allowed errors in their implementation and in the answer during the test, but possessing necessary knowledge for elimination under the guidance of the teacher of the most essential errors;

Assessment “unsatisfactory (2)” is given to a student who showed gaps in knowledge or lack of knowledge on a significant part of the basic educational program material, who has not performed independently the main tasks demanded by the program, made fundamental errors in the fulfillment of the tasks stipulated by the program, who is not able to continue his studies or start professional activities without additional training in the discipline in question;

Assessment “unsatisfactory (1)” is given to a student when there is no answer (refusal to answer), or when the submitted answer does not correspond at all to the essence of the questions contained in the task.

5. Methodological materials defining the procedures for the assessment of knowledge, skills, abilities and/or experience

The course is graded at an exam. The questioning starts with a random task assigned to each student and time given for completion of the task. No aids are allowed. The student then proceeds to a chat with the examiner, at which he/she presents his/her solution to the assigned task. The examiner then asks the student several questions that evenly cover the course content. A final grade is assigned based on the quality of answers and demonstrated level of understanding.