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:	Basics of Semiconductor Electronics/Основы полупроводниковой электроники
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: 1 (fall) - 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. Svintsov, candidate of physics and mathematical sciences

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

Annotation

The course is devoted to an introduction to the basic physical principles underlying processes in semiconductors as well as to mathematical and numerical modeling of classical semiconductor structures (p-n junction, bipolar transistor, field transistor).

1. Study objective

Purpose of the course

The aim is to give students knowledge about the basic physical principles of description of semiconductor materials, the basics of mathematical and numerical modeling of processes occurring in semiconductors and semiconductor structures, review of standard (classical) semiconductor structures and devices based on them.

Tasks of the course

-Knowing the necessary fundamentals of semiconductor theory;
-studying methods of describing electron transport in semiconductors;
-gaining knowledge of standard semiconductor devices.

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-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
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

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

As a result of studying the course the student should:

know:

-basic principles of describing charge transport in semiconductors
-basic principles of standard semiconductor devices operation

be able to:

-Calculate the volt-current characteristics of devices (diodes, field-effect transistors)

master:

-calculate characteristics of semiconductor structures
-Methods for calculating the characteristics of semiconductor nanoelectronic devices
-the basic methods of solving the equations of electrodynamics and electron transport (Boltzmann equation, diffusion-drift and hydrodynamic equations) as applied to semiconductor devices
-methods for estimating the parameters of charge carriers (energy spectrum, mobility, free path) in low-dimensional systems

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	Band structure and statistics of charge carriers in semiconductors	3			3
2	Low-dimensional systems	2			2
3	Kinetic theory of transport in semiconductors: general concepts	4			4
4	Electrical conductivity of semiconductors	2			2
5	Thermo- and galvano-magnetic phenomena	2			2
6	"Advanced" methods for solving the kinetic equation	3			3
7	Recombination of charge carriers in semiconductors	2			2
8	Contact phenomena in semiconductors	2			2
9	Current-voltage characteristic of the p-n junction	2			2
10	Current-voltage characteristic of "metal-semiconductor" structure	2			2
11	Metal-oxide semiconductor field-effect transistors (MOSFETs)	4			4
12	Miniaturization of MOS transistors and scaling laws	2			2
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: 1 (Fall)

1. Band structure and statistics of charge carriers in semiconductors

Band structure of semiconductors, electrons and holes. Effective mass and its origin. Direct-gap and indirect-gap semiconductors - examples of silicon, germanium and gallium arsenide. Carrier statistics and calculation of the Fermi level. Doped semiconductors, estimate of donor level energy. Carrier concentration in doped semiconductor vs temperature. Heavily doped semiconductors.

2. Low-dimensional systems

The concept of heterostructure. Dimensional quantization and quantum wells. Two-dimensional semiconductors based on mono- and bi-layers: graphene, bilayer graphene, transition metal chalcogenides. Band structure of basic two-dimensional materials. Application of the tight binding method for calculations of the band structure.

3. Kinetic theory of transport in semiconductors: general concepts

Boltzmann kinetic equation for the single-particle distribution function. Collisions of carriers with impurities, phonons, and with each other. Quantum mechanical calculation of the scattering probability. The collision integral in the kinetic equation for various scattering mechanisms.

4. Electrical conductivity of semiconductors

Transport relaxation time and its microscopic calculation for scattering by impurities and phonons. Calculation of conductivity in uniform fields and its dependence on temperature for semiconductors and metals. Electrical conductivity of graphene. Diffusion of charge carriers and electrochemical potential. Relation between mobility and diffusion coefficient.

5. Thermo- and galvano-magnetic phenomena

Kinetic equation in the presence of a temperature gradient. Calculation of electronic thermal conductivity and Seebeck coefficient (example of electrons in graphene). Operating principle of a thermoelectric generator and a Peltier element. Kinetic equation in a magnetic field. Hall effect and calculation of Hall resistance. Features of the Hall effect in a two-dimensional system. A method for measuring the carrier mobility using the Hall effect.

6. "Advanced" methods for solving the kinetic equation

Variational principle for the distribution function. Calculation of the graphene conductivity limited by electron-hole scattering using the variational principle. Hydrodynamic approach to kinetic equation. Analysis of electrical and thermal conductivity near the neutrality point in graphene.

7. Recombination of charge carriers in semiconductors

Origins of nonequilibrium electrons and holes: photoexcitation and electrical injection of carriers. The concept of quasi-Fermi levels. Microscopic mechanisms of recombination of electrons and holes: radiative recombination, Auger process, recombination with phonon emission. Calculation of the rate and characteristic time of radiative recombination.

8. Contact phenomena in semiconductors

P-n-junction and its band diagram. Calculation of the field distribution in the p-n-junction (Poisson's equation). Depletion layer width. Metal-semiconductor contact (Schottky contact), calculation of its band diagram. Features of screening in two-dimensional systems, features of two-dimensional p-n-junctions and Schottky contacts, methods of their calculation.

9. Current-voltage characteristic of the p-n junction

Macroscopic equations of drift and diffusion for electrons and holes, their simplification for the doped and depleted regions. Shockley theory for the recombination-limited current. Behavior of p-n junction under reverse bias. Applicability limits of the drift-diffusion theory for ultrashort p-n-junctions. Application of p-n-junctions for rectification (detection) of radiation.

10. Current-voltage characteristic of "metal-semiconductor" structure

Drift-diffusion theory for the transport of majority carriers. Microscopic boundary conditions at the contact with the metal (surface recombination). Current limitation by carrier injection and diffusion in a semiconductor. Applications of Schottky contacts.

11. Metal-oxide semiconductor field-effect transistors (MOSFETs)

Electrostatics of MOS - structures, dependence of the carrier concentration on the gate voltage. Inversion layer. The principle of field-effect transistor operation. Drift-diffusion model of carrier transport in a field-effect transistor. Nonlinear section of current-voltage characteristic and current saturation mechanisms: velocity saturation and channel cutoff. Characteristics of a graphene-based field effect transistor.

12. Miniaturization of MOS transistors and scaling laws

The cutoff frequency of the field-effect transistors as a logic switch mode and as a signal amplifier. External and internal factors affecting the cutoff frequency. Dependence of the cutoff frequency on the channel length for drift-diffusion and ballistic transport modes. Scaling laws for frequency and power dissipation. The problem of threshold voltage reduction. Effects of doping density fluctuations and structural parameters in nanoscale field-effect transistors.

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

1. Физика полупроводниковых приборов [Текст]/С. М. Зи , -М., Энергия, 1973

2. Физика полупроводников [Текст] : учеб. пособие для вузов / В. Л. Бонч-Бруевич, С. Г. Калашников .— М. : Наука, 1990 .— 688 с.

Literature fund of the basic departament:

3. С. Датта «Квантовый транспорт: от атома к транзистору», Москва, НИЦ «Регулярная и хаотическая динамика», 2009

Additional literature

Literature fund of the basic departament:

1. L. Venema “Silicon electronics and beyond” Nature 479 стр. 309 (2011) – коллекция статей, посвященная проблемам миниатюризации в кремниевой электронике и альтернативным принципам транзисторов

2. H. Lu, A. Seabaugh. "Tunnel field-effect transistors: State-of-the-art" IEEE Journal of the Electron Devices Society vol. 2 iss. 4 p. 44-49 (2014); S. Cristoloveanu, J. Wan, A. Zaslavsky “A review of sharp-switching devices for ultra-low power applications” IEEE Journal of the Electron Devices Society,vol. 4 iss. 5, 215-226 (2016).

3. S. Salahuddin, S. Datta “Use of negative capacitance to provide voltage amplification for low power nanoscale devices” Nano letters,vol. 8 iss. 2, 405-410 (2008); W. Cao and K. Banerjee “Is negative capacitance FET a steep-slope logic switch?” Nat. Commun. vol. 11, p. 196 (2020).

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

Not used

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.

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: 1 (fall) - Exam

Author: D.A. Svintsov, 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-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
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

2. Competency assessment indicators

As a result of studying the course the student should:

know:

-basic principles of describing charge transport in semiconductors
-basic principles of standard semiconductor devices operation

be able to:

-Calculate the volt-current characteristics of devices (diodes, field-effect transistors)

master:

-calculate characteristics of semiconductor structures
-Methods for calculating the characteristics of semiconductor nanoelectronic devices
-the basic methods of solving the equations of electrodynamics and electron transport (Boltzmann equation, diffusion-drift and hydrodynamic equations) as applied to semiconductor devices
-methods for estimating the parameters of charge carriers (energy spectrum, mobility, free path) in low-dimensional systems

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

Not provided.

4. Evaluation criteria

Examples of control questions:

1. Graph qualitatively the electronic spectrum of charge carriers in silicon, germanium and gallium arsenide with indication of characteristic energies.

2. Based on the laws of conservation of momentum and energy, analyze the possibility of the following processes in direct-gap and indirect-gap semiconductors (a) inter- and intra-gap photon absorption (b) inter-gap recombination involving an optical phonon (c) Auger recombination

3. Under what conditions the relaxation time approximation for the collision integral is applicable (a) on impurities (b) on acoustic phonons

4. Do the contributions of electrons and holes to (a) conduction (b) the Hall effect (c) thermal EMF add up or subtract?

5. Depict the band diagram and the positions of the Fermi quasi-levels in the p-n junction (a) at equilibrium (b) at forward bias (c) at reverse bias.

6. Draw the voltage-voltage characteristic of a p-n junction. How does it change with temperature? A. When a p-n junction is illuminated.

7. Schematically depict the dependence of the concentration of charge carriers on the voltage at the gate in the TIR structure.

8. The dielectric permittivity of the sub-gate dielectric of the TIR-transistor was doubled. How did it change: (a) threshold voltage (b) open state current (c) energy to switch from closed to open state

9. Picture the dependence of the voltage at the output of a CMOS pair-based logic inverter on the gate voltages. How will this dependence change if the transistors do not have a well-defined current saturation (i.e., the current continues to rise slowly as the voltage at the drain rises).

10. Graph the dependence of the channel conductivity of a field-effect transistor on the degree of doping, assuming that all impurities are ionized. Also depict the dependence of mobility on the concentration of doping impurities. At what concentration of dopant impurities in silicon will the frequency of scattering on impurities become comparable to the frequency of scattering on phonons? The temperature is T=300 K.

11. Schematically plot the volt/gate characteristics of MOSFET transistor and field effect transistor with controlled tunneling p-n junction. Specify the voltage ranges at which the power consumption of the tunneling transistor in the logic key mode is less than that of the TIR transistor.

List of control tasks:

1. Obtain the relation between the effective electron and hole masses in the two-gap and three-gap Kane models. Check its fulfillment (or non-fulfillment) in GaAs, InSb, InP semiconductors.

Estimate the limiting velocity of charge carriers in silicon in a strong electric field, assuming that it is limited by fast emission of optical phonons. Compare the value obtained with the experimentally measured value.

3. Analyze the change in total current during electron-electron collisions and conclude under what conditions electron-electron scattering can affect the conductivity of semiconductors

4. Calculate the width of the depleted layer in a silicon p-n junction with a donor and acceptor concentration of 1018 cm-3 at room temperature.

5. Estimate the degree of doping of a gallium arsenide p-n junction at which the interband electron tunneling probability becomes about 10-3.

6. Calculate the voltage-voltage characteristic of a field-effect transistor assuming that the local electron density in the channel is proportional to the local potential difference between the channel and the gate (smooth channel approximation) and Ohm's law is true for the local current density. What boundary conditions for potential and electron density at the drain and the source should be used in this model to correctly describe the current saturation regime?

7. Estimate the switching frequency limit of a silicon field effect transistor with 90 nm channel length if the supply voltage used is Vdd=0.5 volts. There is no channel lagging. Compare under these conditions the free path length of an electron with an energy of 25 meV (counted from the bottom of the zone, at T=300 K) and the channel length of the transistor.

8. Estimate whether direct tunneling between the drain and the source can limit the closed state current of a silicon field effect transistor? For estimates, assume the barrier height is 0.25 eV, the channel length is 10 nm, and the temperature is T=300 K. The Fermi level in the contacts lies at the edge of the conduction zone.

9. The channel of some types of modern silicon transistors is a "bar" with characteristic dimensions of 10 x 10 x 30 nm. At what concentration of donors the number of impurities in such transistors will fluctuate to the order of 10% of their total number?

10. Write down the classical Hamilton equations of motion for a massless electron in an alternating electric field. State the mutual orientations of the initial impulse of the electron and the field at which even at a low intensity the generation of higher harmonics of alternating electric current is possible. Estimate the amplitudes of higher harmonics.

11. Under the conditions of the previous problem, calculate the total optical conductivity including the intrazone contribution, which can be calculated using Boltzmann's kinetic equation. Considering acoustic phonons with strain potential eV and velocity m/s as the main scattering mechanism, plot the frequency dependence of the total conductivity (a) in the equilibrium state (b) under inverse population between the zones. In the second case, specify the frequency ranges where the interzone emission gain can exceed the intrazone absorption.

Examples of examination papers:

Paper 1.

1. Graph qualitatively the electronic spectrum of charge carriers in silicon, germanium and gallium arsenide with indication of characteristic energies.

2. Under the conditions of the previous problem, calculate the total optical conductivity including the intrazone contribution, which can be calculated using Boltzmann's kinetic equation. Considering acoustic phonons with strain potential eV and velocity m/s as the main scattering mechanism, plot the frequency dependence of the total conductivity (a) in the equilibrium state (b) under inverse population between the zones. In the second case, specify the frequency ranges where the interzone emission gain can exceed the intrazone absorption.

Paper 2.

1. Based on the laws of conservation of momentum and energy, analyze the possibility of the following processes in direct-gap and indirect-gap semiconductors (a) inter- and intra-gap photon absorption (b) inter-gap recombination involving an optical phonon (c) Auger recombination

2. Write down the classical Hamilton equations of motion for a massless electron in an alternating electric field. State the mutual orientations of the initial impulse of the electron and the field at which even at a low intensity the generation of higher harmonics of alternating electric current is possible. Estimate the amplitudes of higher harmonics.

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.