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
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Work program of the course (training module)

course:	Semiconductor Nanoelectronic Devices/Полупроводниковые наноэлектронные устройства
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. 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 focused on physical principles, technologies and modeling of semiconductor nanoelectronic devices, including those based on new materials - various quantum materials, including graphene, other two-dimensional materials and van der Waals heterostructures. The problems solved in the lecture course and tasks can be further adapted for further research activities of students. The course is aimed at development of creative skills of setting promising scientific problems in the field of semiconductor nanoelectronic devices and quantum materials.

1. Study objective

Purpose of the course

The aim of the discipline is gaining knowledge about physical principles, technology and modeling of concurrent semiconductor nanoelectronic devices, including those based on new materials - various quantum materials, including graphene, other two-dimensional materials and van der Waals heterostructures. Problems solved in the lecture course can be further adapted for further research activities of students. The course is aimed at development of creative skills of setting promising scientific problems in the field of semiconductor nanoelectronic devices and quantum materials.

Tasks of the course

-Acquiring knowledge of modern semiconductor devices;
-acquiring knowledge about devices based on low-dimensional electronic systems;
-studying the problems of creating optoelectronic devices in the terahertz range;
-Gaining knowledge about the physics of two-dimensional materials;
-Study the problems of creating electronic, optoelectronic and photonic devices based on two-dimensional materials.

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-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice
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 operation of modern semiconductor devices

-basic approaches to development of modern optoelectronic devices

be able to:

-Calculate the distribution of electrostatic potential and charge carrier density in semiconductor structures

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	Tunnel transistors for low-voltage electronics	3			3
2	Field-effect transistors based on phase transitions	2			2
3	Transistors with high electron mobility based on 2d electrons in III-V compounds	4			4
4	Resonant tunneling devices	2			2
5	Graphene and its applications in analog and digital electronics	2			2
6	Derivatives of graphene and their applications in electronics	3			3
7	Electronic transport in one-dimensional systems	2			2
8	Field-effect transistors based on one-dimensional systems	2			2

9	Optical transitions in semiconductors: general theory	2			2
10	Semiconductor lasers	2			2
11	Semiconductor photodetectors	4			4
12	Photodetectors based on two-dimensional materials	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: 2 (Spring)

1. Tunnel transistors for low-voltage electronics

The problem of power dissipation in field-effect transistors. "Thermionic limit" of the subthreshold steepness of MOS FET. Tunneling in Schottky barriers and Schottky-barrier FET. Interband tunneling in semiconductors, calculation of the tunneling current for direct and phonon-assisted tunneling. Field-effect transistor with gate-controlled tunnel junction, its ultimate subthreshold slope. Interband tunneling in semiconductors in the presence of electric potential fluctuations. Influence of the channel dimensionality on the tunneling characteristic. Density of states effects in interband tunneling.

2. Field-effect transistors based on phase transitions

Ferroelectric phase transition: phenomenological description within the Landau theory. Features of the transition in hafnium dioxide. Negative differential capacitance and its effect on the switching voltage of MOSFETs. Current state of negative capacitance devices. Metal-insulator phase transition with a change in the electron density. The nature of the "metal-insulator" phase transition in vanadium dioxide.

3. Transistors with high electron mobility based on 2d electrons in III-V compounds

Methods for localization of electrons in two dimensions: quantum wells and heterointerfaces. Doping of two-dimensional systems, remote doping. High electron mobility transistor (HEMT) schematic and band diagram. Calculation of electron mobility limited by scattering by distant impurities. Distributed capacitance and inductance effects in high frequency transistors. Cutoff frequency and maximum oscillation frequency.

4. Resonant tunneling devices

Tunneling transport in two-barrier heterostructures, calculation of tunneling transparency and current-voltage characteristic of a resonant tunneling diode (RTD). Negative differential resistance and its applications for high-frequency generation. Excess current mechanisms in resonant tunneling diodes.

5. Graphene and its applications in analog and digital electronics

Effective Hamiltonian and energy spectrum of charge carriers in single- and bi-layer graphene. Influence of charge carrier chirality on transport properties: suppression of backscattering and strong interband tunneling. The problem of the minimum conductivity of graphene, the effect of potential fluctuations on the concentration of charge carriers and conductivity. Limiting factors for electron mobility in graphene: scattering by impurities, optical and acoustic phonons, grain boundaries, and local lattice stresses. Features of charge carrier scattering in suspended and encapsulated graphene. Field effect in graphene and characteristics of a graphene transistor, ambipolar transport. Maximum switching frequency and off-state current problem. Current saturation mechanisms in graphene field-effect transistors.

6. Derivatives of graphene and their applications in electronics

Graphene-based structures with a finite band gap: bilayer graphene and nanoribbons. Relation between the band gap and the transverse field (bilayer graphene) and the nanoribbon width. Resolution of the off-state current problem in transistors based on graphene derivatives. Edge effects in transistors based on bilayer graphene and nanoribbons: current flow through edge channels and electron scattering at edges. Features of tunnel transport in bilayer graphene.

7. Electronic transport in one-dimensional systems

Calculation of coherent electron transport in a one-dimensional system: calculation of the electron density matrix in the channel upon maintaining constant states' filling in the leads. Level broadening effects caused by the presence of leads (concept of self-energy). Derivation of Landauer formula for conductance.

8. Field-effect transistors based on one-dimensional systems

Electronic spectrum and transport of charge carriers in graphene nanoribbons and nanotubes. Relation between geometric chirality of nanotubes and their band structure. Semiconductor and metal nanotubes. Relationship between the edge structure of nanoribbons and the energy spectrum of charge carriers. Ballistic conductivity of one-dimensional systems. Landauer formula and its application for characteristics of a ballistic FET with 1d channel. Interaction of charge carriers in 1d systems and its manifestations in transport.

9. Optical transitions in semiconductors: general theory

K-p Hamiltonian for bulk semiconductors. Matrix element of electron interaction with an electromagnetic wave. Interband and intraband transitions, their symmetry and conservation-law constraints. Density of states effects in optical absorption spectra. Light absorption by two-dimensional systems. Universal optical conductivity of graphene.

10. Semiconductor lasers

Lasing condition in semiconductors in terms of quasi-Fermi levels. Methods for creating interband population inversion. Laser based on a heavily doped p-n-junction. Heterostructure-based laser: effects of super-injection, optical confinement and carrier confinement. Quantum well lasers, their gain spectra, comparison with heterostructure lasers. Quantum cascade lasers and their principle of operation. The problem of terahertz lasing.

11. Semiconductor photodetectors

Main figures of merit for photodetectors: responsivity, noise equivalent power (NEP), detectivity. A "classical" photodetector based on p-n-junction. Principle of operation, calculation of voltage and current responsivity. Influence of recombination on the characteristics of p-n-junction based detector. Factors limiting the NEP: dark current and p-n junction noise. Thermal (Johnson-Nyquist) and generation-recombination noise. Problems for detection of far infrared radiation.

12. Photodetectors based on two-dimensional materials

Photoresponse mechanisms in graphene: photovoltaic, thermoelectric, bolometric, resistive mixing. Dependences of the current generated by these mechanisms on the charge carrier density, temperature, radiation polarization. Response time of graphene-based photodetectors and its limiting factors. Characteristics of a graphene-based thermoelectric photodetector with induced p-n junctions. Photo-gating effect in two-dimensional systems, origins of photoinduced charge. Formation time of photo-induced charge. Origins of anomalously high current responsivity of detectors based on two-dimensional transition metal chalcogenides.

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
4. Enoki T., Ando T. (eds.). Physics and chemistry of graphene: graphene to nanographene. – Pan Stanford Publishing, 2013.

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).
4. F. Schwierz “Graphene transistors: status, prospects, and problems” Proceedings of the IEEE vol. 101 iss. 7, p. 1567-1584 (2013).
5. M. Asada, S. Suzuki, and N. Kishimoto “Resonant tunneling diodes for sub-terahertz and terahertz oscillators” Jpn. J. Appl. Phys. vol. 47, p. 4375 (2008).
6. F. Koppens, T. Mueller, P. Avouris, A. Ferrari, M. Vitiello, M. Polini. “Photodetectors based on graphene, other two-dimensional materials and hybrid systems” Nature nanotechnology,vol. 9 iss. 10, 780-793 (2014); A. Rogalski, M. Kopytko, P. Martyniuk “Two-dimensional infrared and terahertz detectors: Outlook and status” Applied Physics Reviews,vol. 6 iss. 2, 021316 (2019).
7. M. S. Vitiello, G. Scalari, B. Williams, P. De Natale “Quantum cascade lasers: 20 years of challenges” Optics express vol. 23 iss. 4, p. 5167-5182 (2015).

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: 2 (spring) - 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-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice
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 operation of modern semiconductor devices

-basic approaches to development of modern optoelectronic devices

be able to:

-Calculate the distribution of electrostatic potential and charge carrier density in semiconductor structures

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. List the basic mechanisms of leakage currents in tunneling transistors with gate-controlled p-n junction.

Schematically depict the energy dependence of the density of states in a heavily doped semiconductor on a logarithmic scale. Also calculate the dependence of the rms fluctuation of the electric potential on the concentrations of donor and acceptor impurities (object dimension d=3). Give a numerical estimate of this value for silicon doped with donors with Nd=1019 cm-3.

3. List the main causes of surface states at the metal-semiconductor interface?
4. Write out a general expression for the barrier height and contact resistance in the metal-semiconductor system which takes into account both the difference in the yield works of materials and the presence of surface states in the bandgap zone.
5. Depict the zone diagram of a HEMT transistor in the source-to-drain and gate-to-channel directions. Explain the delta doping principle.
6. State the applicability criterion for the hydrodynamic description of electron transport in semiconductors. Consider the limitations on the characteristic length of the external potential change and on the frequency of its change.
7. Picture the frequency dependence on the wave vector for plasmons in a two-dimensional electron system if the gate is (a) at a distance much longer than the wavelength (b) much shorter than the wavelength. Consider that electron transport obeys the equations of hydrodynamics. How would the appearance of the spectrum change if the electrons were gatingless?
8. Draw schematically the dependence of the density of states on the energy in the inversion layer of a silicon field transistor when the gate voltage is large positive.
9. Schematically depict the dependence of the transparency of the stepped potential barrier in graphene on the direction of the impulse of an incoming electron (Klein's paradox). How does the answer change qualitatively when a finite value of the field strength in the barrier is taken into account?
10. Schematically depict the volt-ampere and volt-gate characteristics of a graphene-based field-effect transistor. Comment on the main qualitative differences from the characteristics of silicon field effect transistors and explain the reasons for the differences.

Examples of examination papers:

Paper 1.

1. List the basic mechanisms of leakage currents in tunneling transistors with gate-controlled p-n junction.
2. Schematically depict the energy dependence of the density of states in a heavily doped semiconductor on a logarithmic scale. Also calculate the dependence of the rms fluctuation of the electric potential on the concentrations of donor and acceptor impurities (object dimension d=3). Give a numerical estimate of this value for silicon doped with donors with Nd=1019 cm-3.

Paper 2.

1. Schematically depict the volt-ampere and volt-gate characteristics of a graphene-based field-effect transistor. Comment on the main qualitative differences from the characteristics of silicon field effect transistors and explain the reasons for the differences.

2. Draw a schematic diagram of a terahertz radiation generator based on a resonant-tunnel diode. Considering antenna impedance, diode capacitance and its differential (negative) conductivity, write down the condition of self-excitation of electric oscillations in this circuit.

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.