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CYBER-PHYSICAL SYSTEM FOR MONITORING AND ANALYZING HUMAN BIOMEDICAL DATA

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***Abstract*: The measurement of arterial hemoglobin oxygen saturation, pulse, and blood pressure was presented. A review of methods for measuring arterial hemoglobin oxygen saturation based on photoplethysmography was provided. The architecture of the hardware and software platform of a cyber-physical system for the primary processing and transmission of information signals, based on a microcontroller with hardware encryption and a Bluetooth module for transmitting encrypted data to a mobile device and a remote server, was considered. Algorithms for measuring blood oxygen saturation and blood pressure were developed. An application for the Android operating system was designed for measuring human biomedical data in real time and analyzing their parameters over a specified period. The developed cyber-physical system is intended for use in medical institutions.**

***Index Terms*: Cyber-Physical Systems, Biomedical data, Photoplethysmography, Pulse, Blood pressure.**

I. INTRODUCTION

Continuous non-invasive monitoring of human health is important for the rapid detection and preliminary diagnosis of abnormalities in vital signs necessary for the timely and effective provision of medical care and resuscitation [1-4].

An urgent task for today is to develop algorithms and software and hardware for non-invasive continuous monitoring and analysis of human biosignals, in particular, blood pressure, heart rate and respiration, oxygen levels in human blood, which will allow for quick and effective diagnosis deviations in human health [3-5].

Measuring the oxygen saturation of arterial haemoglobin (saturation) provides the doctor with important information about the physiological state of the patient. Saturation is an indicator of blood oxygen saturation. Low blood oxygen saturation levels may indicate lung problems. This has become especially relevant after the emergence of the new coronavirus infection (COVID-19), but in addition, the level of blood oxygen saturation makes it possible to detect pulmonary diseases in time [5-7].

The following methods are most commonly used to measure blood pressure (BP): auscultatory method; direct BP measurement method; oscillometric method; palpation method; and direct method [8-11].

The main goal of the work is to develop a cyber-physical system for monitoring and analyzing human biomedical parameters, namely, blood oxygen saturation, pulse, and blood pressure based on photoplethysmography methods. To achieve this goal, we have chosen modern hardware modules and developed special software allowing for the real-time monitoring and analysis of vital human health indicators.

II. LITERATURE REVIEW AND PROBLEM STATEMENT

Currently, along with classical invasive methods, non-invasive diagnostic methods are increasingly used, which, although less accurate, allow for continuous monitoring of pulse, saturation, and other patient parameters [1]. In particular, non-invasive methods of photoplethysmography are widely used, and they are available on the market in the form of both portable devices and stationary medical devices for continuous monitoring of saturation [2].

The electrocardiogram (ECG) has always been a popular measurement scheme for the assessment and diagnosis of cardiovascular diseases. The number of scientific publications on ECG monitoring systems is constantly growing. Paper [4] presents a real-time ECG monitoring and processing system for remote monitoring of patients with cardiac diseases. Combining photoplethysmography and ECG methods into a single mobile system for monitoring human health is promising.

Article [4] develops a structural and functional diagram of medical diagnostic devices and proposes an algorithm for a system of continuous monitoring of human health.

Publications [5-7] develop and investigate means of non-contact diagnostics, temperature sensors, technologies based on measurements of electrical, magnetic, and optical signals and their spatial and temporal analysis; optoelectronics, nanoelectronics, molecular electronics, quantum computing; thin-film technologies for sensor elements and devices. As can be seen from the publications, the research of sensor elements and devices is based on thin-film technologies.

Article [8], elements and devices of organic electronics and primary information converters, signal processing circuits, and software of microelectronic sensor devices, including the use of microprocessors, microconverters, and programmable electronic systems-on-chips, were developed.

Article [10] solves the problem of developing a universal software and hardware control system for diagnosing biological objects. The main requirements for such systems are multifunctionality in terms of combining different methods of signal processing and compliance with modern trends in the development of microelectronic sensing.

In publications [11,12], pulse waveforming methods were investigated. There are several problems with analyzing the photoplethysmogram (PPG) signal, which makes extracting vital information from PPGs a difficult task.

To implement a cyber-physical system for monitoring and analyzing human biosignals, additional research is needed, which is as follows:

- development of a specialized architecture of a cyber-physical system for non-invasive monitoring of heart rate, oxygen level in human blood, and blood pressure;
- experimental studies of the spectral characteristics of discrete infrared sensor elements and optical filters for specified wavelengths of biomedical response;
- development of a hardware and software platform for non-invasive monitoring of heart rate, oxygen level in human blood, and blood pressure.

III. SCOPE OF WORK AND OBJECTIVES

This article uses the materials and results obtained by the authors during the research work "Multifunctional sensor microsystem for non-invasive continuous monitoring and analysis of human biosignals" state registration number 0124U000384 dated 01.01.2024, which is carried out at the Department of Computer Engineering and Electronics, of the Vasyl Stefanyk Precarpathian National University in 2024-2026.

The main goal of the work is to develop a cyber-physical system with integrated and discrete sensors for non-invasive continuous monitoring and analysis of human biosignals, in particular, heart rate, blood glucose level, and blood pressure.

IV. METHODS FOR MEASURING BLOOD OXYGEN SATURATION

The photoplethysmogram (PPG) signal is widely used in clinical and consumer devices due to its non-invasive nature and cost-effectiveness [10-12]. Currently, it has been mainly used to measure blood oxygen saturation and monitor heart rate. In addition, the PPG signal contains valuable information about the cardiovascular, respiratory systems, and blood components, which is not yet widely used. Together, these factors make it possible to use PPG to provide detailed health information. The development of photoplethysmography represents several relevant areas for the development of both hardware and software signal processing methods.

Photoplethysmography measures changes in blood volume within vascular tissue. Optical radiation is used to illuminate the peripheral tissue, where it is scattered and absorbed as it passes through different layers of tissue before passing through or reflecting off the tissue surface. This attenuated light intensity is detected by an optical sensor and recorded as a voltage signal known as a photoplethysmogram. There are two main modes of PPG, the first is when light that has passed through living tissue is analyzed (Fig. 1a), and the second is when light that has reflected from blood-filled tissue is analyzed (Fig. 1b) [10].

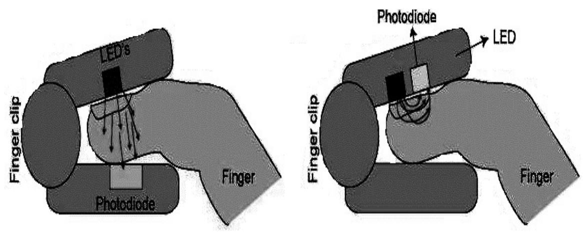

Fig. 1. Two modes of contact photoplethysmography: (a) transmission mode and (b) reflection mode

The raw PPG waveform reflects variations in the attenuation of incident optical radiation by different tissue components in the tissue volume, as shown in Fig. 2 [11].

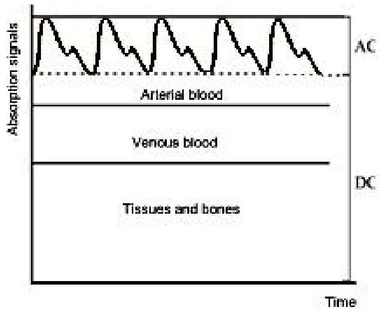

Fig. 2. Typical distribution of light absorption as it passes through body tissues

High-frequency variations (part "AC") are caused by changes in arterial blood volume with each heartbeat, and lower-frequency variations (part "DC") are caused by changes in other tissue components, such as venous and capillary blood, bone, etc.

There are several problems with analyzing the PPG signal, which makes extracting reliable information from PPG a challenging task [12,13]. The PPG signal shows several physiological variations, as shown in Fig. 3 [10].

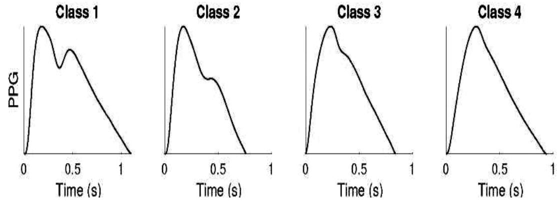

Fig. 3. Pulse waveform classes on the photoplethysmogram (PPG): the PPG pulse wave often shows a diastolic peak in young people (class 1), which decreases with age

The input useful signal is quite weak and noisy against the background of a large constant component.

V. DEVELOPMENT OF THE STRUCTURE OF THE CYBER-PHYSICAL SYSTEM FOR MONITORING AND ANALYSIS OF HUMAN BIOMEDICAL DATA

The cyber-physical system for monitoring and analyzing human biomedical data (Fig. 4) contains the following modules: microcontroller (ATmega328PU), biosensor (MAX86150) for measuring heart rate (recording pulsating human heartbeats) and the level of oxygen saturation in arterial blood, blood pressure sensor (HX710B), microphone (MAX4466), wireless communication interface based on the Bluetooth HC-06 module for transmitting data on human indicators, encoder and buttons for setting device operating modes, and a sound speaker for signalling changes in human health parameters; OLED display for displaying the necessary data and the ability to connect external memory to record the history of the device.

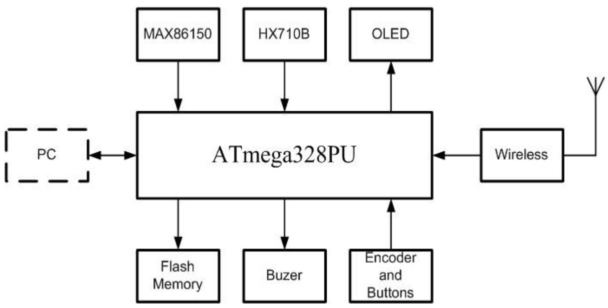

Fig. 4. Structure of a cyber-physical system for monitoring and analyzing human biomedical data

The microcontroller is the basis of the cyber-physical system and performs the functions of collecting data from sensors, processing signals from control modules (encoder, button), outputting information (text, sound, light), and communicating with a PC for programming, configuration, and input/output of information in an integrated programming environment or application software.

For integration with a PC, the structure provides a serial port for configuration, calibration, displaying indicators in text or in the form of graphs, keeping statistics with recording in files on a PC and transferring them to cloud storage (Cloud IoT). Any high-level programming language can be used to write application software, and Bluetooth or Wi-Fi wireless interface can be used as a data exchange protocol [15].

The MAX86150 biosensor is integrated with a pulse oximeter and a heart rate sensor. It contains internal light diodes (red and infrared), a photodetector, and low-noise electronics with ambient light suppression. Communication with the module is via the I2C interface. The internal electronic signal processing circuit of the biosensor is characterized by a low level of intrinsic noise and provides for the suppression of intrinsic illumination.

The measurement process uses a channel of red and infrared light with programmable luminescence intensity and duration of measurement sessions.

The MAX86150 biosensor operates on a 1.8 V power supply. A separate 3.5 V power supply is required for LED emission.

The LED driver in the MAX86150 chip is designed to control the built-in light-emitting diodes (red and infrared). The LED driver is used to modulate the length of the LED pulses for SpO_2 (percentage of blood oxygen saturation) and HR (heart rate) measurement. The diode current can be programmed from 0 mA to 100 mA with the appropriate supply voltage. The pulse width can be programmed between 50 μs and 400 μs to allow the algorithm to optimize SpO_2 calculation, HR accuracy, and power consumption. The ADC data rate can be programmed from 10 sps to 3200 sps. In this case, measurement accuracy and power consumption can be optimized for each specific situation.

The blood pressure measurement is performed as follows: the user connects the pressure sensor to the cuff, the heart rate microphone is placed in the cuff, and the system software analyzes the force of inflation of the cuff with a pear. When the pumping force reaches 200 mmHg, the user is alerted by an audible warning to stop pumping the pear and the process of measuring blood pressure begins, using the microphone to track the beginning of the heart rate of the correct measurement until the heart rate disappears, which will be characterized as a lower measurement. In case the microphone does not detect the heart rate, a message will be displayed on the LCD display indicating that the measurement process must be started over.

VI. DEVELOPMENT OF ALGORITHMS FOR MEASURING HUMAN BIOMEDICAL DATA

Figure 5 presents a block diagram of the algorithm for the main blood oxygen saturation measurement function of the cyberphysical system.

The device works in power saving mode. In the process of measurements, a channel of red and infrared light is used with software regulation of the intensity of the light and the frequency of the measurement sessions. In the initialization block, all variables, specifications for starting the sensor and connected libraries and files are specified.

After reading the first 100 samples, the function of calculating pulse and blood oxygen saturation occurs, while reading data from the sensor continues. Next, the result is output and the following data are recalculated. IR - the value of infrared light, RED - the value of red light,

SpO_2 - the percentage value of blood oxygen saturation, which is measured from the ratio of the wavelengths of red and infrared light. When implementing this function, it is necessary to measure and evaluate blood oxygen saturation. The method is based on the difference in absorption of oxyhemoglobin and deoxyhemoglobin. The maximum absorption of deoxyhemoglobin is in the red range, and the maximum absorption of oxyhemoglobin is in the infrared ranges.

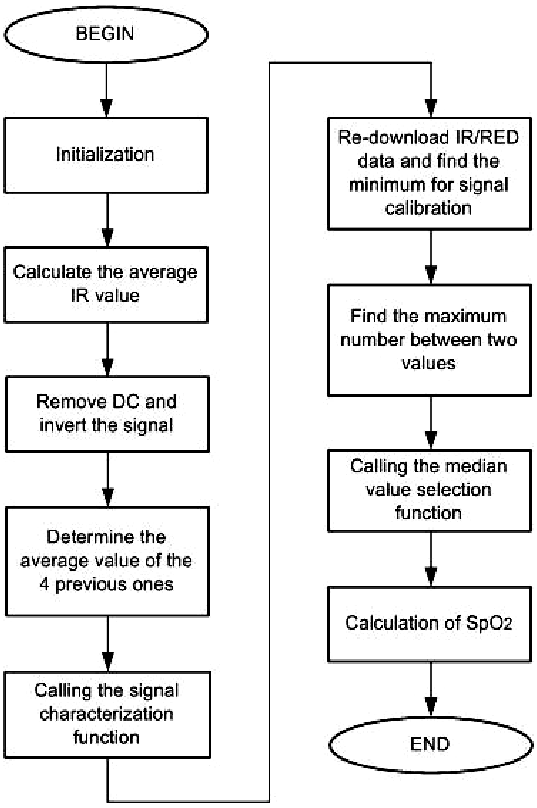

Fig. 5. Block diagram of the algorithm for measuring the blood oxygen saturation level of the cyberphysical system

The percentage of oxygen in the blood is determined non-invasively through the human skin as the percentage of oxygenated hemoglobin (HbO_2) to total hemoglobin (HbO_2+RHb), which is determined using a photodetector, a red and an infrared LED MAX86150.

The SpO_2 measurement subsystem consists of an external illumination compensation circuit, a sigma-delta ADC and a digital filter. Backlight compensation has an internal signal blocking circuit to eliminate backlight and decipher the effective dynamic range. The ADC is programmable over the entire measurement range of 2...16 μA. External illumination compensation allows to block the external illumination signal up to 200 μA. Fig. 6 shows the results of the software implementation of the blood saturation measurement function in the Arduino IDE software environment.

In this figure, you can see how the output data from the biosensor is formed when measuring SpO2 and HR: IR - numerical value of infrared light; Red – numerical value of red light; HR - number of beats per minute; SpO_2 is the percentage value of blood oxygen saturation.

Fig. 7 shows a graph of changes in the percentage value of blood oxygen saturation in the Arduino IDE environment.

```
red=1385, ir=1310, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1369, ir=1298, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1374, ir=1284, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1360, ir=1280, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1367, ir=1258, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1360, ir=1274, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1358, ir=1272, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1373, ir=1242, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
red=1363, ir=1251, HR=107, HRvalid=1, SPO2=92, SPO2Valid=1
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Fig. 6. Results of the blood saturation measurement function

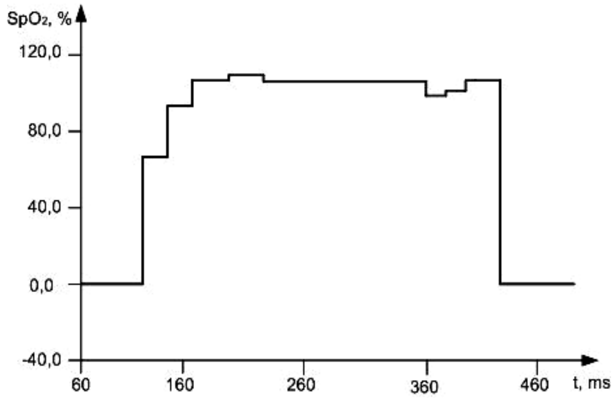

Fig. 7. Results of the blood saturation measurement function

In this graph you can see how the output signal from SpO2 changes gradually. Initially, the transmitter is turned off and not in contact with the hand, generating the 0th signal. Then, when the hand is raised and fixed, the measured values are recorded.

Fig. 8 presents a block diagram of the blood pressure measurement algorithm.

The algorithm for measuring a person's blood pressure consists of the following steps:

1. We initialize the pressure transmitter and the microphone - initialization of libraries, constants, variables. After initialization, the main cycle of the program starts.

2. Receiving data - we receive data from the pressure sensor.

3. Checking the "Maximum pressure" condition - checking if the pressure transmitter has not recorded the set maximum value, continue reading the data.

4. Checking the "Minimum pressure" condition - checking if the pressure sensor has recorded the set minimum value, we start calculating the data.

5. The microphone listens to the heartbeat - the microphone reads the heartbeat.

6. Calculating data is basically the conversion of blood pressure level indicators from kP to mm. Hg

7. Output of blood pressure on the display - after the completion of the measurement cycle, information is displayed on the display

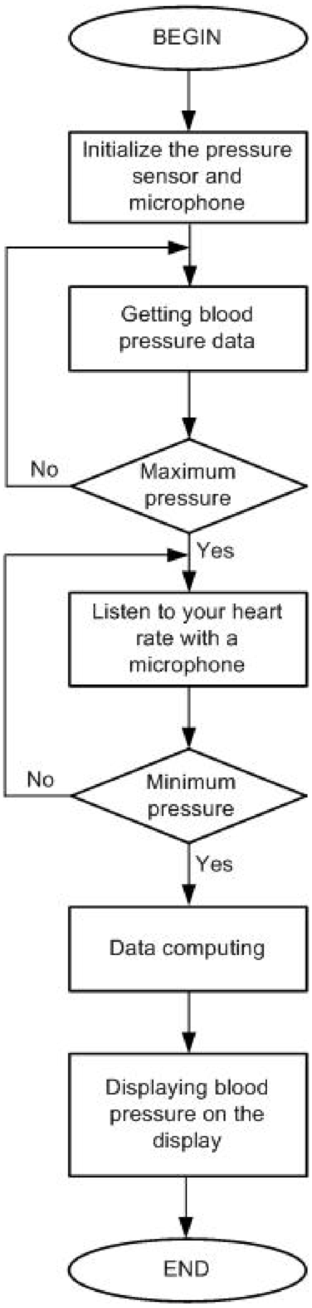

Fig. 8. Block diagram of the blood pressure measurement algorithm

VII. DEVELOPMENT OF A WEB APPLICATION FOR MONITORING AND ANALYSIS OF BIOMEDICAL DATA

The Android operating system was chosen for the development of the application, as the most common mobile operating system [16]. According to Statcounter, as of February 2023, 72.27% of the market is occupied by Android. 27.1% — iOS.

The general structure of the application is shown in Fig.9.

The MPAndroidChart library is used to display graphs and charts. The library is very popular, has a free license, and is well documented.

Fig. 9. Structure of the developed application

For each parameter stored in the database (such as weight, heart rate, blood pressure, number of steps taken, blood glucose level, etc.), a separate relation (table) is created, which contains the data received from the monitoring device or entered manually, the date their receipt and a synthetic key for connection with the relationship with the user's data (Name, date of birth, gender).

To display the statistics of changes in monitoring parameters, a separate fragment is implemented in the application. The user can choose the non-lunch data to display and the corresponding display period. At the moment, monitoring of dynamics for a day, week, month, year is implemented.

Part of the data, in particular, heart rate, blood pressure, saturation are displayed in the form of a graph. The rest of the data, including weight, blood glucose level, and the number of steps taken, are displayed in the form of a bar chart. Data on specific values and display periods are specified in the settings

VIII. CONCLUSION

Features for measuring arterial hemoglobin oxygen saturation in human blood, pulse and blood pressure were determined. An overview of the methods of determining biomedical indicators of a person was conducted. The possibility of monitoring the state of human health by the photoplethysmography method was studied. It is shown that photoplethysmography methods are promising for non-invasive monitoring of biomedical parameters such as human arterial blood saturation, heart rate and respiratory rate. A cyber-physical system for measuring arterial hemoglobin oxygen saturation, pulse and blood pressure based on the Atmega328PU microcontroller was developed. The developed system incorporated a MAX86150 biosensor microcircuit for measuring pulse rate by detecting pulsating heartbeats, as well as arterial blood oxygen saturation levels. It also included a transmitter and a wireless communication interface based on the Bluetooth HC-06 module for transmitting human physiological data, along with additional components. The software function for blood oxygen saturation measurement was implemented using the Arduino IDE environment. This software enabled reading data from the sensors and displaying it through visualization tools. Additionally, a web application was developed and synchronized with the hardware components of the system to facilitate data integration and analysis.

The developed cyber-physical system is capable of providing accurate and reliable data on the level of arterial hemoglobin oxygen saturation in real time, which allows it to be effectively used for monitoring and analyzing important indicators of human health.

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Research interests: research and development of advanced element base for computing, specialized computer systems for control systems, sensor electronics, microsystems-on-a-chip based on advanced microelectronic technologies of large and ultra-large integrated circuits with silicon-on-insulator structures, including their three-dimensional architectures.

Volodymyr Hryha was born in Nadvirna, Ivano-Frankivsk region in 1982. Engineering of Computer Systems. Lviv Polytechnic University, Ukraine (2004). He received Ph.D. in Technical (Computer) Sciences in 2015 at Ternopil National Economic University.

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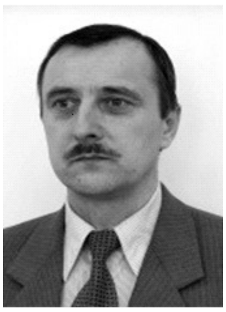
Bogdan Dzundza was born in Bodnariv village, Kalush district, Ivano-Frankivsk region in 1982. 2004 – 2007 postgraduate studies at Vasyl Stefanyk Precarpathian National University, specialty Solid State Chemistry. In 2008 successfully defended his thesis and received a PhD.

He started teaching in 2010, and in 2013 – received the title of Senior Research Fellow in the specialty "Physics and Chemistry of Surface".

He is co-author of ten textbooks, two monographs, more than 130 publications in professional scientific journals, and has participated in many international scientific conferences.

Research interests: studying the physical properties of semiconductor thin films and nanostructures (pure and doped materials, solid solutions, and multicomponent semiconductor compounds), thermoelectric and photovoltaic semiconductor materials development of automated laboratory research systems computer science, microcontroller systems and the Internet of Things.



Victor Holota was born in Ivano-Frankivsk in 1952. He earned a Bachelor's degree in Electronic Computers from Kiev Polytechnic Institute in 1984, and a Ph.D. in Solid State Electronics from Lviv Polytechnic University, Ukraine, in 2009**.**

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His main Areas of Research Interest are Micro- and Nanoelectronics, SoC, Hardware Design Language, Artificial neural networks.

Taras Benko was born in Ivano-Frankivsk in 1989. In 2012, he graduated from Vasyl Stefanyk Prykarpattia National University, located in Ivano-Frankivsk, Ukraine, obtaining a Master's degree in the field of Radio Physics and Electronics.

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Research interests: physics and astronomy, condensed matter physics, studying the physical properties of semiconductor thin films and nanostructures (pure and doped materials, solid solutions, and multicomponent semiconductor compounds).