Ministry of Education and Science of the Russian Federation
Federal Independent Educational Institution
«NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY»

Research School of Chemical and Biomedical Technologies
Direction of training 12.04.04 «Biotechnical systems and technologies»

MASTER'S THESIS

Topic of the work
Integration of graphene nanomaterials with 3D printing for biomedical and sensor applications **Интеграция наноматериалов из графена с применением 3D- печати для биомедицинских и сенсорных применений**

UDC 616.666.2-022.532:004.925.84:61

Student

Group	Full name	Signature	Date
9DM8I	Vladimir Mikhailovich Bogoslovskiy		

Scientific Supervisor and Technical Advisor

Position	Full name	Academic degree, rank	Signature	Date
Associate professor	Raul David Rodriguez	PhD in Physics and Chemistry of Nanomaterials		

ADVISORS:

Section «Financial Management, Resource Efficiency and Resource Saving»

Position	Full name	Academic degree, rank	Signature	Date
Associate professor	Ekaterina V. Menshikova	PhD in Philosophy		

Section «Social Responsibility»

Position	Full name	Academic degree, rank	Signature	Date
Associate professor	Michael V. Gorbenko	PhD in Egeneering		

ADMIT OT DEFENSE:

Head of the Program	Full name	Academic degree, rank	Signature	Date
Associate professor	Gubarev Fedor Aleksandrovich	PhD in Physics		

Tomsk – 2020

Planned program learning outcomes

Код резуль-тата	Результат обучения (выпускник должен быть готов)	Требования ФГОС, критериев и/или заинтересованных сторон
	Профессиональные компетенции	
Р1	Применять глубокие специальные естественнонаучные, математические, социально-экономические и профессиональные знания в инновационной инженерной деятельности при разработке, производстве, исследовании, эксплуатации, обслуживании и ремонте современной биомедицинской и экологической техники	Требования ФГОС (ОК-2, ОПК-2), Критерий 5 АИОР (п. 5.2.1), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р2	Ставить и решать инновационные задачи инженерного анализа и синтеза с использованием специальных знаний, современных аналитических методов и моделей	Требования ФГОС (ОПК-1, 3; ПК- 1 – 4), Критерий 5 АИОР (п. 5.2.2), согласованный с требованиями международных стандартов EUR-ACE и FEANI
Р3	Выбирать и использовать необходимое оборудование, инструменты и технологии для ведения инновационной практической инженерной деятельности с учетом экономических, экологических, социальных и иных ограничений	Требования ФГОС (ОК-9, ПК-10, 14, 18). Критерий 5 АИОР (пп. 5.2.3, 5.2.5), согласованный с требованиями международных стандартов EUR-ACE и FEANI
Р4	Выполнять комплексные инженерные проекты по разработке высокоэффективной биомедицинской и экологической техники конкурентоспособной на мировом рынке	Требования ФГОС (ОК-2, 3; ПК-5 – 11, 14), Критерий 5 АИОР (пп. 5.2.3, 5.2.5), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р5	Проводить комплексные инженерные исследования, включая поиск необходимой информации, эксперимент, анализ и интерпретацию данных с применением глубоких специальных знаний и современных методов для достижения требуемых результатов в сложных и неопределенных условиях	Требования ФГОС (ОК-2, 3; ОПК-5, ПК-1 – 4). Критерий 5 АИОР (пп. 5.2.2, 5.2.4), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р6	Внедрять, эксплуатировать и обслуживать современное высокотехнологичное оборудование в предметной сфере биотехнических систем и технологий, обеспечивать его высокую эффективность, соблюдать правила охраны здоровья и безопасности труда, выполнять требования по защите окружающей среды	Требования ФГОС (ОПК-1, 2), Критерий 5 АИОР (пп. 5.2.5, 5.2.6), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
	Универсальные компетенции	
Р7	Использовать глубокие знания в области проектного менеджмента для ведения инновационной инженерной деятельности с учетом юридических аспектов защиты интеллектуальной собственности	Требования ФГОС (ОПК-2; ПК-14, 15). Критерий 5 АИОР (п. 5.3.1), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р8	Владеть иностранным языком на уровне, позволяющем активно осуществлять коммуникации в профессиональной среде и в обществе, разрабатывать документацию, презентовать и защищать результаты инновационной инженерной деятельности	Требования ФГОС (ОК-1), Критерий 5 АИОР (п. 5.3.2), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р9	Эффективно работать индивидуально и в качестве члена и руководителя команды, состоящей из специалистов различных направлений и квалификаций, с делением ответственности и полномочий при решении инновационных инженерных задач	Требования ФГОС (ОК-3, ОПК-3; ПК-3, 12, 13), Критерий 5 АИОР (п. 5.3.3), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р10	Демонстрировать личную ответственность, приверженность и готовность следовать профессиональной этике и нормам ведения инновационной инженерной деятельности	Критерий 5 АИОР (п. 5.3.4), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р11	Демонстрировать глубокие знание правовых социальных, экологических и культурных аспектов инновационной инженерной деятельности, компетентность в вопросах охраны здоровья и безопасности жизнедеятельности	Критерий 5 АИОР (п. 5.3.5), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*
Р12	Самостоятельно учиться и непрерывно повышать квалификацию в течение всего периода профессиональной деятельности	Требования ФГОС (ОК-2, 4; ОПК-4), Критерий 5 АИОР (п.5.3.6), согласованный с требованиями международных стандартов *EUR-ACE* и *FEANI*

TASK FOR SECTION
"FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING"

To a student:

Group	Full name
9DM8I	Vladimir Mikhailovich Bogoslovskiy

School	Research School of Chemical and Biomedical Technologies	**School Department**	RSCBT
The level of education	Master	**Direction / specialty**	12.04.04 Biotechnical systems and technologies

Background data to the section "Financial management, resource efficiency and resource saving":	
1. *Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human*	Salary costs –264193 rub; STR budget –821753 rub;
2. *Expenditure rates and expenditure standards for resources*	Electricity costs – 5,8 rub per 1 kW
3. *Current tax system, tax rates, charges rates, discounting rates and interest rates*	Labor tax – 27,1 %; Overhead costs – 30%;
The list of issues to be investigated, designed and developed:	
1. *Assessment of commercial and innovative potential of STR*	comparative analysis with other researches in this field;
2. *Development of charter for scientific-research project*	SWOT-analysis
3. *Scheduling of STR management process: structure and timeline, budget, risk management*	calculation of working hours for project; creation of the time schedule of the project; calculation of scientific and technical research budget;
4. *Resource efficiency*	integral indicator of resource efficiency for the developed project.
The list of graphic material (with the exact indication of the mandatory drawings):	
1. *Competitiveness analysis* 2. *SWOT- analysis* 3. *Gantt chart and budget of scientific research* 4. *Assessment of resource, financial and economic efficiency of STR* 5. *Potential risks*	

Date of assignment for the section on a linear schedule	3.02.2020

Assignment issued by a consultant:

Position	Full name	Degree, title	Signature	Date
Associate professor	E.V. Menshikova	Candidate of Philosophy Sciences -		

The task was accepted for execution by the student:

Group	Full name	Signature	Date
9DM8I	Vladimir Mikhailovich Bogoslovskiy		

TASK FOR SECTION
« SOCIAL RESPONSIBILITY»

To the student:

Group	Full name
9DM8I	Vladimir Mikhailovich Bogoslovskiy

School	RSCBT	**Department**	
Degree	Master's degree	**Educational Program**	12.04.04 Biotechnical systems and technologies

Topic of the work

Integration of graphene nanomaterials with 3D printing for biomedical and sensor applications Интеграция наноматериалов из графена с применением 3D- печати для биомедицинских и сенсорных применений	
Input data to the section «Social responsibility»:	
1. Characteristics of the object of study (substance, material, device, algorithm, method, working area) and its areas of application	The object of study is a prototype of sensors for biomedical applications. In this work were created temperature sensor, bending sensor and humidity sensor.
The list of subjects to study, design and develop:	
1. Legal and organizational safety issues: 1.1. Special legal norms of labor legislation 1.2. Organizational arrangements for the layout of the working area	1. GOST 12.2.032-78 Occupational safety standards system (SSBT). Workplace while doing work while sitting. General ergonomic; 2.The Labor Code of the Russian Federation dated December 30, 2001 N 197; 3.GOST 31581-2012 Laser safety. General safety requirements for the development and operation of laser products; 4. GOST 31508-2012 Medical devices. Classification according to potential risk of use. General requirements; 5.GOST 12.2.049-80 Occupational safety standards system (SSBT). Industrial equipment. General ergonomic requirements.
2. Industrial safety: 2.1. Analysis of harmful and dangerous factors that can be created by object of study 2.3. Justification of measures to protect the researcher from the effects of hazardous and harmful factors.	1. The increased gas contamination of the air of the working area; 2. Deviation of microclimate indicators; 3. Laser radiation; 4. Chemical active substances (plasma, whole blood); 5. Fire; 6. Electrical current.
3. Environmental safety:	Environmental pollutions: 1. Household waste; 2. Chemical waste; 3. Industrial waste; The atmosphere is not polluted
4. Safety in emergency situations:	1. Electricity 2. Fire safety

Date of issue of the task for the section according to the schedule	03.02.2020

Task issued by adviser:

Position	Full name	Scientific degree, rank	Signature	Date
Associate professor	Mikhail Vladimirovich Gorbenko	PhD in Egeneering		

The task was accepted by the student:

Group	Full name	Signature	Date
9DM8I	Vladimir Mikhailovich Bogoslovskiy		

Ministry of Education and Science of the Russian Federation
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Research School of Chemical and Biomedical Technologies
Direction of training 12.04.04 «Biotechnical systems and technologies»

APPROVED BY
Head of the Program
_________ _________F.A. Gubarev
09.03.2020

ASSIGNMENT
for the Master's Thesis completion

In the form:

Master's Thesis

For a student:

Group	**Full Name**

Topic of the work:

Approved by the order of the Head (date, number)	

Deadline for completion of the Master's Thesis:	03.06.2020

TERMS OF REFERENCE:

Initial data for work: *(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.).*	The object of the research: Integration of graphene nanomaterial. Subject of research: competition for enhancing the quality of integration of films of reduced graphene oxide to create flexible structures for biomedical applications. The purpose of this work: to develop flexible sensors based on films of reduced graphene oxide and a polymer substrate, created by 3D printing methods for biomedical applications Results of this research can be used for developing commercial versions of the presented sensors and consider the accreditation of these sensors for use in biomedical purposes.
List of the issues to be investigated, designed and developed *(analytical review of literary sources in order to elucidate the achievements of world science and technology in the field under consideration, the formulation of the problem of research, design, construction, the content of the procedure of the research, design, construction, discussion of the performed work results, the name of additional sections to be developed; work conclusion).*	To accomplish the task, it is necessary to investigate a number of questions: 1. Writing a literature review on the topic; 2. Research of existing solutions in this area; 3. Make the prototypes of the next sensors • Temperature sensor • Humidity sensor • Bending sensor 4. To research characteristics of the developed sensors 5. To do the data analysis 6. Evaluation of the competitiveness of solutions

List of graphic material *(with an exact indication of mandatory drawings)*	
Advisors on the sections of the Master's Thesis	
Chapter	**Advisor**
Section «Financial Management, Resource Efficiency and Resource Saving»	Associate professor, Menshikova Ekaterina Valerievna
Section «Social Responsibility»	Associate Professor, Mikhail Vladimirovich Gorbenko

Date of issuance of the assignment for Master's Thesis completion according to a line schedule	09.03.2020

The task was issued by the Scientific Supervisor and Technical Advisor:

Position	Full Name	Academic degree, rank	Signature	Date
Associate professor	Raul David Rodriguez	PhD in Physics and Chemistry of Nanomaterials		09.03.2020

The assignment was accepted for execution by the student:

Group	Full Name	Подпись	Дата
9DM8I	Vladimir Mikhailovich Bogoslovskiy		09.03.2020

Abstract

This Master's thesis contains 94 pages, 25 figures, 20 tables, 48 references.

Key words: graphene, graphene oxide, reduced graphene oxide, 3D printing, nanoparticles, sensors, temperature sensor, bending sensor, humidity sensor, temperature, bending, humidity.

Object of the research: Integration of graphene nanomaterial.

Subject of research: competition for enhancing the quality of integration of films of reduced graphene oxide to create flexible structures for biomedical applications.

The purpose of this work: to develop flexible sensors based on films of reduced graphene oxide and a polymer substrate, created by 3D printing methods for biomedical applications.

The use of reduced graphene oxide films to create semiconductor structures and various conductive surfaces is popular all over the world. The role of 3D printing to create flexible structures is still controversial. In this paper, we combined these two technologies to study flexible electronics based on rGO. Our results show that depending on the properties of the substrate and the method of irradiation of graphene oxide, it is possible to create many sensors with preset properties. This paper presents a temperature sensor, a bend sensor, and a humidity sensor to demonstrate how these two promising technologies can be combined.

Results of this research can be used for developing commercial versions of the presented sensors and consider the accreditation of these sensors for use in biomedical purposes.

Contents

Introduction

Today, the development of scientific and technological progress requires constant updating of the material and technical base as well as the use of new technologies. These conditions served as the choice of such direction as flexible electronics.

The development of competitive, flexible electronics is an important task in priority support programs. The development of this direction, in particular, flexible sensors based on graphene-containing materials, makes it possible to close the need for cheap flexible medical sensors. [1]

With the development of the level of medicine, various implants and biocompatible sensors have become available to monitor vital functions. The need for new technical solutions is ahead of the offer of scientists from around the world. At the moment, we are on the verge of using flexible and biocompatible electronics. These devices can be used to monitor the life of patients, as well as for implantation in the body for a more accurate diagnosis.

Flexible electronics has recently attracted much attention because of their potential in providing cost-efficient solutions to large-area applications such as rollable displays and TVs, e-paper, smart sensors and transparent RFIDs. The key advantages of flexible electronics, compared with current silicon technologies, are low-cost manufacturing (e.g. ink-jet printing and roll-to-roll imprinting) and inexpensive flexible substrates (e.g. plastics). These advantages make flexible electronics an attractive candidate for next-generation consumer products which require lightweight, bendable, portable, and low-cost electronics.

From the other hand, the use of flexible electronics becomes justified in medicine, in sports, in scientific research and in other activities where monitoring of the activity of human biological indicators are supposed. Monitoring such a parameter as the temperature of the human body will allow for a more accurate diagnosis and monitor the human condition in real time. This decision will help to predict the possible risks associated with the state of health based on the obtained data.

We have developed a fundamentally new technical solution that will allow combining several functions, like flexibility, waterproof and etc. The use of polylactide as a biocompatible base and graphene oxide as a conductive structure that can be upgraded for special purposes. Graphene oxide is a non-conductive biocompatible material used in flexible electronics and for creating conductive surfaces. Our work is based on this property of graphene oxide, which allows us to create conductive structures of the desired geometric shape with various functions.

Goals and objectives

Object of the research: Integration of graphene nanomaterial.

Subject of research: competition for enhancing the quality of integration of films of reduced graphene oxide to create flexible structures for biomedical applications.

The purpose of this work: to develop flexible sensors based on films of reduced graphene oxide and a polymer substrate, created by 3D printing methods for biomedical applications.

To achieve the purpose, it is necessary to solve a number of tasks:

7. Writing a literature review on the topic;
8. Research of existing solutions in this area;
9. Make the prototypes of the next sensors

- Temperature sensor
- Humidity sensor
- Bending sensor

10. To research characteristics of the developed sensors
11. To do the data analysis
12. Evaluation of the competitiveness of solutions.

1 Literature review

1.1 Devices and applications

Due to continuous technological development and the rapid growth in the field of additive technologies and materials science, there is a need for miniature sensors that can be integrated into various surfaces [1,2]. Since temperature is a fundamental physical parameter and has a significant impact in all life processes, including simple physiological processes in the body [3,4].

Most temperature sensors are based on the use of certain physical changes to determine the temperature. One of the most widely used types of sensors is a resistive temperature sensor, which has a high accuracy of the obtained values [5,6]. Moreover, the use of temperature sensors infrared temperature sensors [7,8] and mercury thermometers is widespread. Metal oxides, ceramics, metal oxides, etc. They have not only flexibility, volume, and fragility, but also the difficulty of attaching them to the curved surfaces of the test objects. Heat-sensitive materials based on carbon, including soot, graphene, carbon fiber and carbon nanotubes, are attracting more and more attention due to their excellent mechanical and physical properties . The flexibility of the sensors is necessary so that they can be adapted to any surface for monitoring data.. In order to attach the sensor to the temperature unit, such as polydimethylsiloxane (PDMS)[9], polyethylene terephthalate (PET), paper, textiles or polyimide.

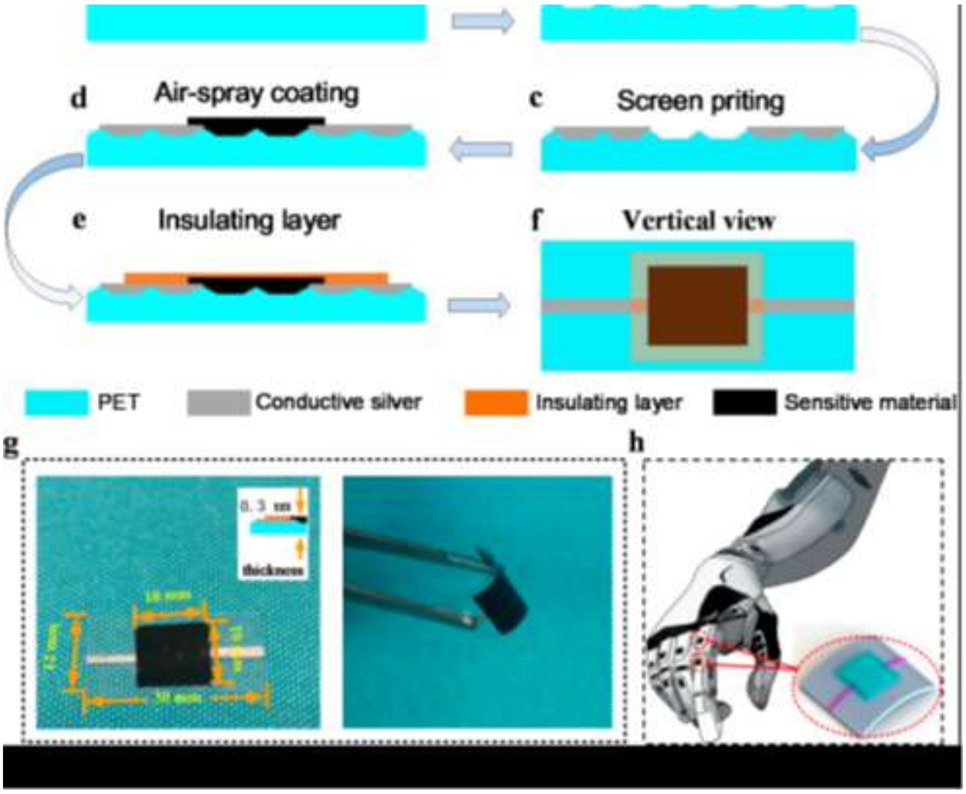


Figure 1.1 The process of manufacturing temperature sensors: (a) polyethylene terephthalate (PET) cleaning with acetone, alcohol and deionized (DI) water; (b) plasma etching O2; (c) printing two conductive thin wires; (d) manufacturing a sensitive layer using air spray; (e) manufacturing an insulating layer process; (f) vertical view of a temperature sensor; (g) the diagram on the left is a dimensional view of the sensor, including the size of the sensitive area, total size and thickness. The chart on the left shows good sensor flexibility; (h) one of the possible applications of the temperature sensor. [9]

The authors of this scientific work [9] presented a temperature sensor for the skin of a robot, which is flexible, lightweight, easy to manufacture, and inexpensive. In the first section, we present the manufacturing process of sensors.

In particular, the sensor consists of four layers: an insulating layer, a sensitive layer, conductive silver wires and flexible PET. Conductive silver wires are deposited to measure resistance variation.

The sensitive layer, which is sandwiched between the insulating layer and PET, consists of carbon materials. The authors made three temperature sensors from three popular carbon materials - graphene oxide (r-GO), single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNTs) - were used as materials for determining the temperature. These three temperature sensors were compared in terms of their linearity, sensitivity and repeatability, and the sensitive layer made with r-GO showed a balanced view. Meanwhile, the resistance of the r-GO temperature sensor remained virtually unchanged under full pressure, point pressure, or strip pressure. In addition, the R-GO temperature sensor demonstrates stable performance at various deformation levels. Due to the insulating layer on the sensitive layer, the r-GO temperature sensor is not affected by humidity or other gases.

To test the operability of three temperature sensors, we measured the change in resistance using a digital multimeter (UNI-T UT61) with a change in temperature from 30 C to 100 C.

A change in resistance was recorded with each measurement step of 5 ° C, and the temperature was maintained at each step 5 degrees Celsius for 5 minutes to observe a change in resistance. Figure 1.2 shows typical experimental characteristics of temperature sensors whose sensitive materials are R-GO, MWCNTS, and SWCNTS, respectively. Figure 1.2a, d, g illustrates the resistance to change with temperature for three different temperature sensors. This clearly indicates that the temperature sensor curves of graphene and multi-walled carbon nanotubes (MWCNTS) are closer to linear, which is more suitable for a temperature sensor. Temperature Resistance Coefficient (TCR) is often used to describe temperature-sensitive properties, commonly known as sensitivity, ddwhere R, R0, and ΔT are the measured resistance at 30 ° C and the temperature deviation (° C) from 30 ° C, respectively [10]. Resistance change with temperature shown in Figure 1.2b, f, h. As can be seen from these figures, the change in resistance with temperature of r-GO graphene oxide and MWCNTS multi-walled carbon nanotubes decreases linearly, and the curve of the SWCNTS sensor is nonlinear.

In addition, it was found that the extracted corresponding sensitivity values are 0.6345% and 0.068%. in degrees Celsius for r-GO and MWCNTS sensors, respectively, using a linear curve fit. The r-GO and MWCNTS sensors respectively use a linear curve. In addition, temperature sensors showed good repeatability and stability, as shown in Figure 1.2c, f, i. After three cycles of heating and cooling, the curve of resistance with temperature has not changed, which is important for the use of temperature sensors.

Based on the above factors, we assume that r-GO is more suitable for temperature sensitive material. So, all subsequent analyzes are based on the r-GO temperature sensor.

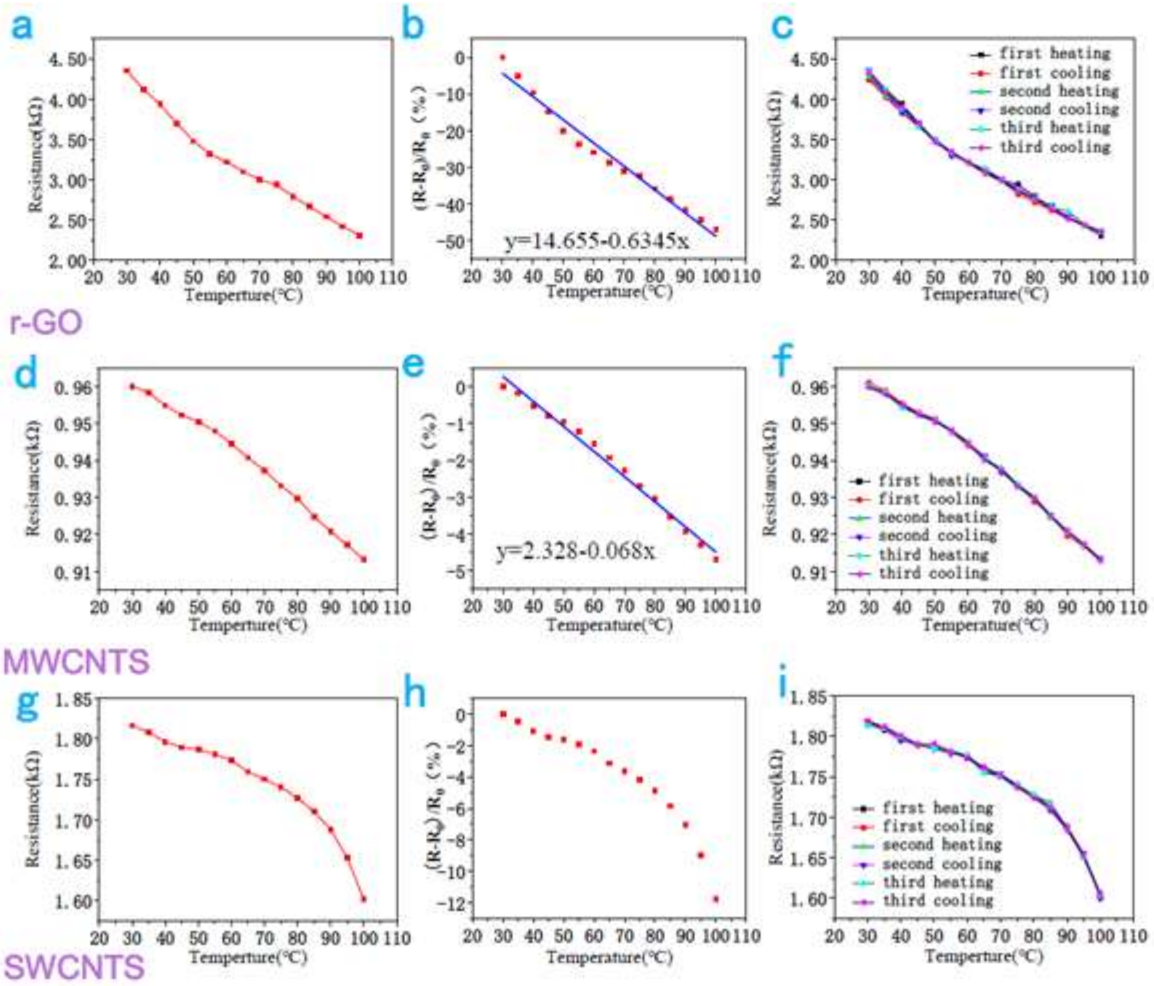


Figure 1.2 − Experimental characteristics of flexible temperature sensors: (a, d, g) resistance change for r-GO, MWCNTS and SWCNTS, respectively; (b, f, h) change in relative resistance in three temperature sensors for temperatures from 30 to 100 C; (c, f, i) resistance data of these three sensors in reaction with three heating and cooling cycles.

1.2 Graphene Oxide

Graphene, which consists of a one-atom-thick planar sheet comprising an sp2-bonded carbon structure with exceptionally high crystal and electronic quality, is a novel material that has emerged as a rapidly rising star in the field of material science.[11−13] Ever since its discovery in 2004,[14] graphene has been making a profound impact in many areas of science and technology due to its remarkable physicochemical properties. These include a high specific surface area (theoretically 2630 m^2/g for single-layer graphene), extraordinary electronic properties and electron transport capabilities, unprecedented pliability and impermeability,[15] strong mechanical stability and excellent thermal and electrical conductivities[16].

The material of the mass is immediately scattered in basic positions or it can be scattered by the ultrasound in polar solvents to forming monomolecular sheets as known as graphene oxide, by the analogy with graphene, which is single-layer graphite.[16] Graphene oxide sheets have been utilized to get ready solid paper-like materials, layers, and composite materials.[17]

One specific branch of graphene research deals with graphene oxide (GO). This can be considered as a precursor for graphene synthesis by either chemical or thermal reduction processes. GO consists of a single layer of graphite oxide and is usually produced by the chemical treatment of graphite through oxidation, with subsequent dispersion and exfoliation in water or suitable organic solvents. With respect to its structure, there have been several structural models proposed over the years. These assume the presence of various oxygen containing functional groups in the GO. The oxygen functional groups have been identified as mostly in the form of hydroxyl and epoxy groups on the basal plane, with smaller amounts of carboxy, carbonyl, phenol, lactone, and quinone at the sheet edges. However, currently the precise atomic structure of GO is still uncertain and remains to be fully elucidated.

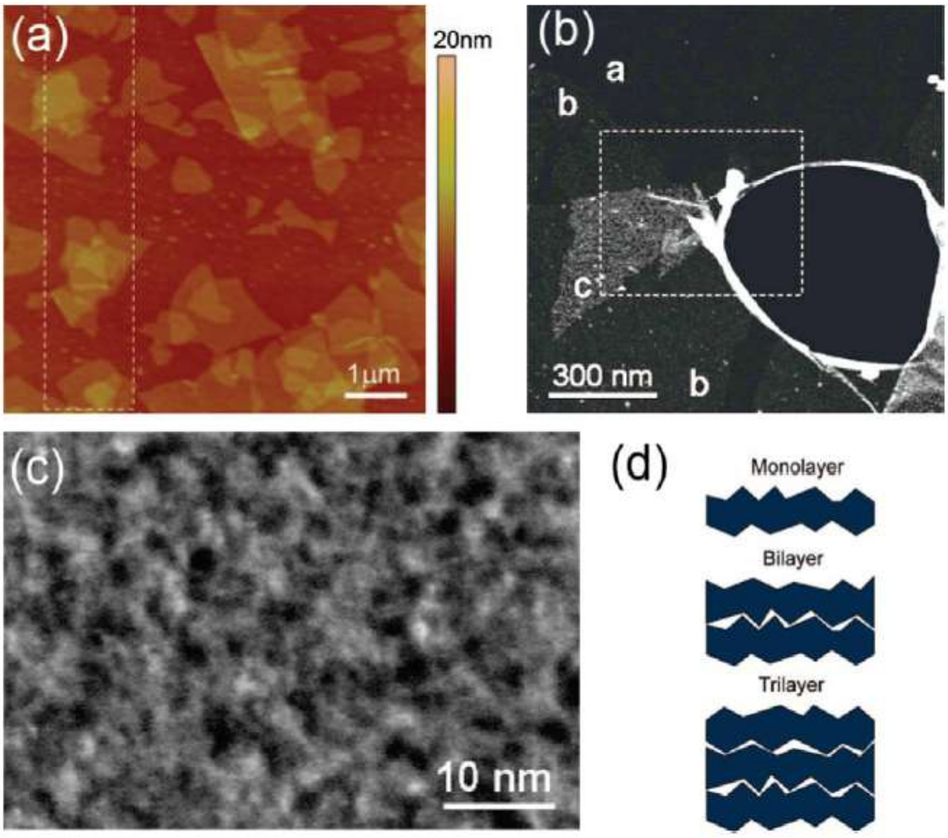


Figure 1.3 – (a) AFM image of GO sheets. (b) STEM-ADF image of a GO film where mono-, bi- and tri-layers are labeled as a, b, and c. The round opening in the middle is a hole through the single film. (c) High-magnification ADF image of a monolayer GO film. (d) Simple drawing of monolayer and possible packing of bi- and tri-layers[17]

1.2.1 Reduction of Graphene Oxide

Optical observation is a direct way to see the changes in GO before and after reduction. Since a reduction process can dramatically improve the electrical conductivity of GO, the increased charge carrier concentration and mobility will improve the reflection to incident light, which makes a rGO film have a metallic luster compared to its GO film precursor with a brown color and semi-transparency, as shown in Figure 2.3a[18].

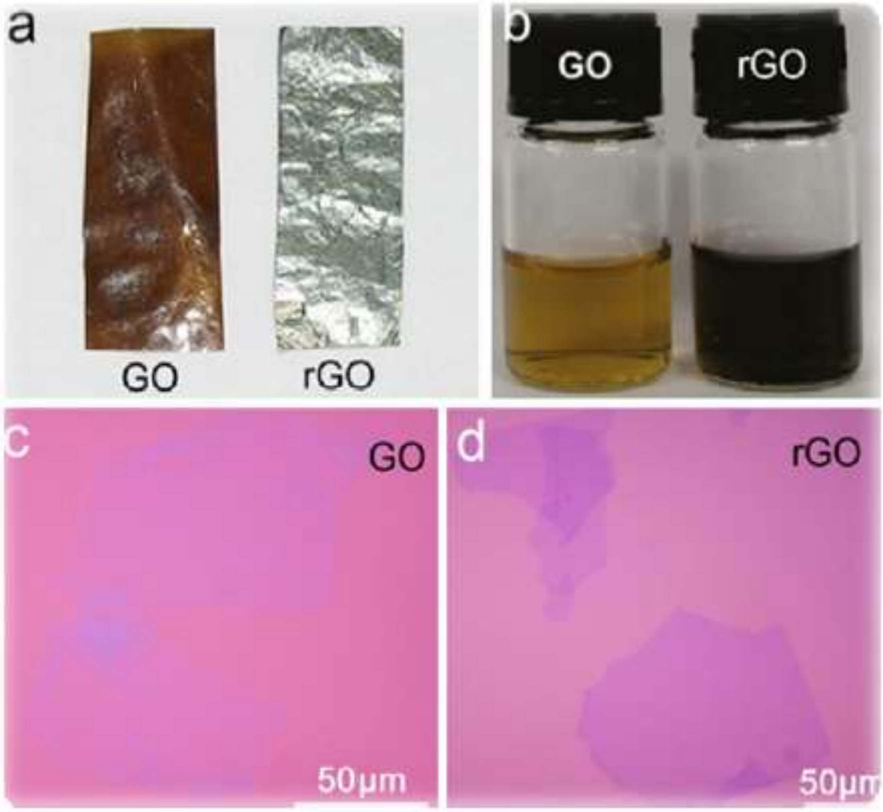


Figure 1.4 – Typical optical images of (a) a GO film and rGO film , (b) GO solution and rGO solution [18], (c, d) GO and rGO sheets on a 300 nm SiO2/Si substrate [19].

GO can be reduced solely by heat treatment and the process is named thermal annealing reduction. In the initial stages of graphene research, rapid heating (>2000 C/min) was usually used to exfoliate graphite oxide to achieve graphene. The mechanism of exfoliation is mainly the sudden expansion of CO or CO^2 gases evolved into the spaces between graphene sheets during rapid heating of the graphite oxide. The rapid temperature increase makes the oxygen containing functional groups attached on carbon plane decompose into gases that create huge pressure between the stacked layers.

The other way of reduction is a laser irradiation. In that case, the sample is heated by point laser irradiation of the required power. In this case, it is possible to generate the necessary temperature for the reduction of graphene oxide in the size of the point of the laser beam. The advantages of adopting this technology allow you to create conductive structures of various shapes and on different planes and them without fear of damage to the material due to general overheating when the irradiated area is heated.

1.3 Biomedical applications

Flexible sensors have captured the imagination for applications in biomedicine, artificial skin, and wearable electronics.

The development of the flexible electronics industry has enabled the integration of some of the resulting devices for biomedical applications. The use of new and combined technologies in biomedicine became a trend in the last decade. Worldwide, tens of thousands of research teams are improving existing technology solutions. Tens of billions a year are allocated for the development of this industry[20]. Creating lightweight and competitive devices based on existing technological conditions is one of the main tasks of our scientific group.

Today, Russia pays attention to the development of promising scientific sectors. Biomedicine and biomedical technology are one of these industries.

Based on the experience and articles of foreign colleagues, this work will present developments in the field of sensors and flexible electronics with the possibility of application in the biomedical field.

To date, in this area, special attention is paid to the healthcare sector and devices for monitoring vital parameters. These include various sensors for measuring body temperature, bioelectrodes and cardiac monitoring, various bending sensors, gas and breathing sensors, glucose sensors, pH sensors, sensors measuring brain activity, and many others.

The main conditions for creating devices for biomedical applications are:

Nontoxicity - the materials and components of which the device is made should not be toxic and if the integrity of the device is damaged, will not be able to harm health.

Biocompatibility - the materials from which the device is produced should be biocompatible and not cause allergic and chemical reactions in contact with external and internal human tissues and fluids.

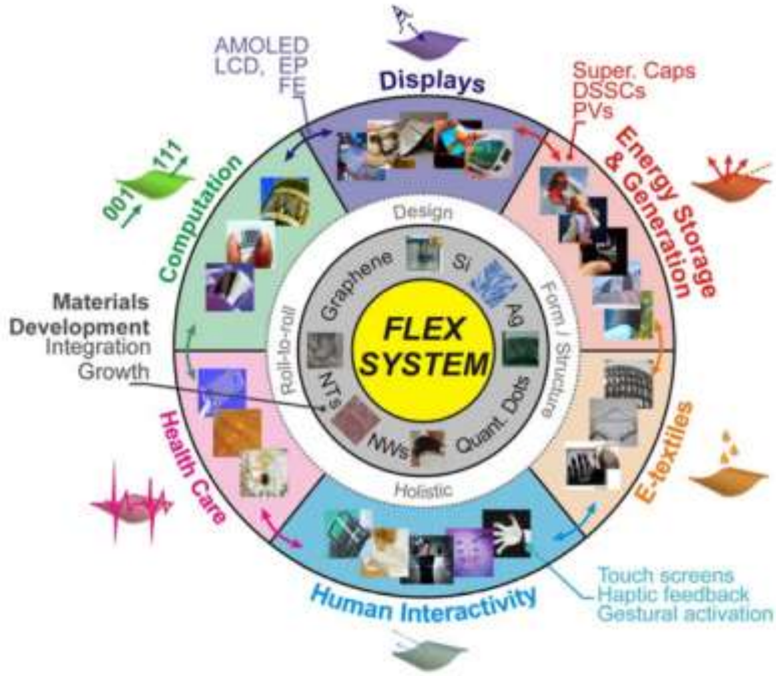


Figure 1.5 Variations of flexible electronics and applications[20]

When you are looking at picture 1.5 you can see a combination of different technologies for industries such as health care, human interactivity, e-textiles, energy storage and generations, displays and computation. By the way with combining of these industries we are creating our devices

1.4 Classification of 3D printing technologies

1.4.1 Fused Deposition Modeling (FDM)

The most common 3D printing technology, especially among personal and desktop 3D printers.

The technology works on the principle of layer deposition. Plastic or metal threads are unwound from the reel (cartridge) and fed to the print head (extruder). The extruder heats the threads to a molten state and squeezes the material through the nozzle, moving in the horizontal and vertical directions, forming an object layer by layer.

Advantages of 3D printing technology by FDM technology:

• speed and ease of manufacturing models;

• availability;

• safety, environmental friendliness and non-toxicity of most materials;

• accuracy of construction;

• ease of use and maintenance;

• strength of parts;

• ease of disposal.

Printing material: thermoplastics (PLA, ABS, PVA, HIPS, etc.), low-melting metals and alloys. Plus, various culinary printers that use glaze, cheese, dough, as well as medical printers that print “live ink” (a set of living cells placed in a special medical gel).

Spray simulation followed by milling of the layer (Drop On Demand Jet, DODJet).

This 3D printing technology uses two types of materials: model and support material.

The print head sprays both types of consumables at the same time. Then, a special milling head cools the sprayed layer and machines it. DODJet technology allows you to build high-precision models with an absolutely smooth surface. Since the spraying of the working layer occurs due to the mechanical moving head, the prototype manufacturing speed largely depends on the complexity of the printed model.

Printing material: foundry wax, polymers, resign.

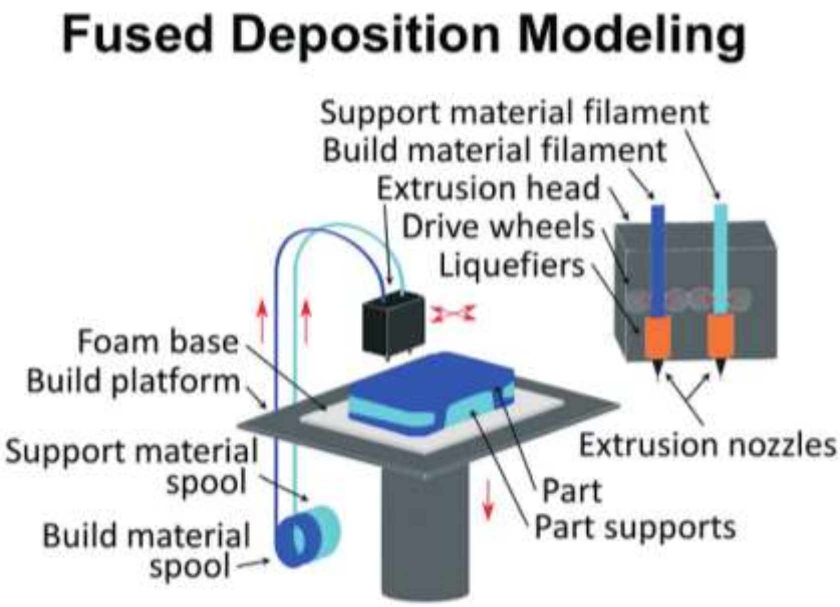


Figure 1.6 − Fused Deposition Modeling[21]

Figure 1.7 − Fused Deposition Modeling Products[15]

1.4.2 Photopolymerization

Technology was invented by Charles Hull. Having received a patent for it, Hull founded 3D Systems, which today remains the leading company producing SLA machines.

The technology involves the use of a special photopolymer - a photosensitive resin as a model material. The basis in this process is an ultraviolet laser, which sequentially transfers the cross sections of the model to the surface of the container with a photosensitive resin. The photopolymer cures only in the place where the laser beam passed. Then a new layer of resin is applied to the cured layer, and a new contour is outlined by a laser. The process is repeated until the completion of the model building.

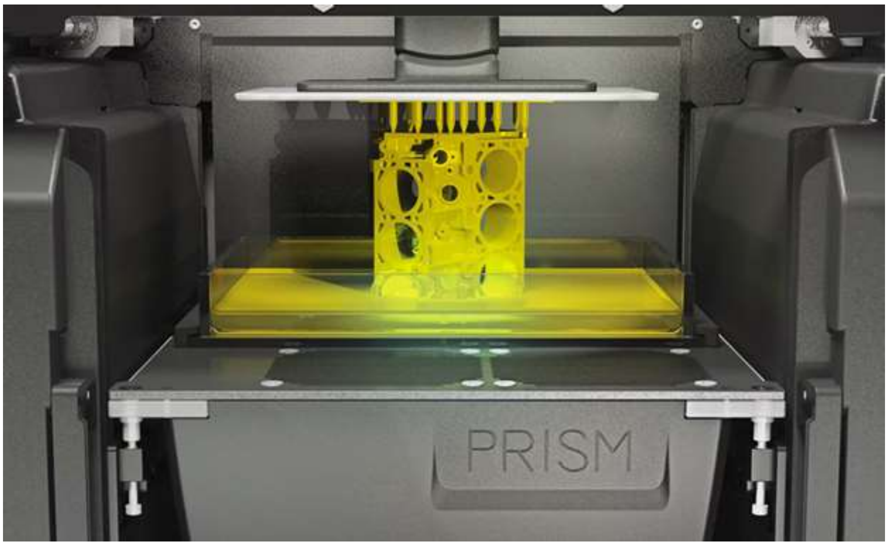


Figure 1.8 – Photopolymerization[15]

1.4.3 Laser Stereolithography (SLA)

Stereolithography is the most popular rapid prototyping technology for producing high-precision models. It covers almost all branches of material production - from medicine to heavy engineering. SLA - technology allows you to build a product model of almost any size quickly and accurately. The quality of the surfaces depends on the step of construction. Modern machines provide a pitch of 0.025-15 mm.

SLA - technology gives the best result in the manufacture of master models for the subsequent manufacture of silicone molds and casting polymer resins in them, and is also used for growing jewelry master models.

Depending on the required properties of the final object, the model is baked in the so-called ultraviolet ovens.

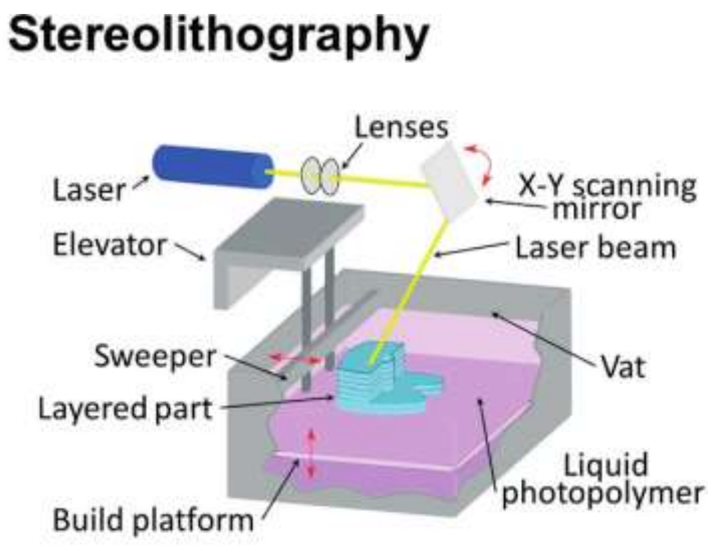


Figure 1.9 − Stereolithography process[21]

Figure 1.10 − Brush, fully printed in one session using PolyJet technology

Photopolymer is often toxic, so when working with it you need to use protective equipment and respirators. Maintaining and maintaining such a printer at home is difficult and expensive. Advantages: speed and accuracy (accuracy - up to 10 microns). A laser from a Blu-ray player is sufficient for sintering the photopolymer, so cheap and precise printers using this technology appear on the market. Material for printing: photopolymer resin[16]

1.4.4 Technology MJM (Multi-Jet-Modeling)

The 3D printing MJM technology is based on a layered section of a CAD file into horizontal layers that are sequentially sent to a 3D printer. Each layer is formed by a printhead, which through groups of nozzles releases a molten (temperature of about 80 ° C) photopolymer or molten wax onto a horizontal moving platform. The material is melted in the feed system before it enters the print head. If 3D printing is performed from a photopolymer, then after printing each layer, the platform on which the layer is grown moves off behind the print head under an ultraviolet lamp. A flash of an ultraviolet lamp causes a reaction due to which the material hardens. After that, the platform moves off again under the print head and the cycle of layer formation is repeated. The print head forms a new layer. Features of MJM technology is the ability to reproduce 3D models with high accuracy. The 3D printing process uses support material - wax (supplied with separate cartridges). If 3D printing is performed from a photopolymer, then the support material is removed by means of high temperature: the support part is placed in a furnace with a temperature of ~ 60 ° C. If 3D printing is made from wax, then the support is removed using a special solution. It is also important that dyes can be added to the glue, and therefore, it is possible to obtain not only a three-dimensional model, but also a multi-colored one[16].

Printing material: photopolymer resin, acrylic plastic, casting wax.

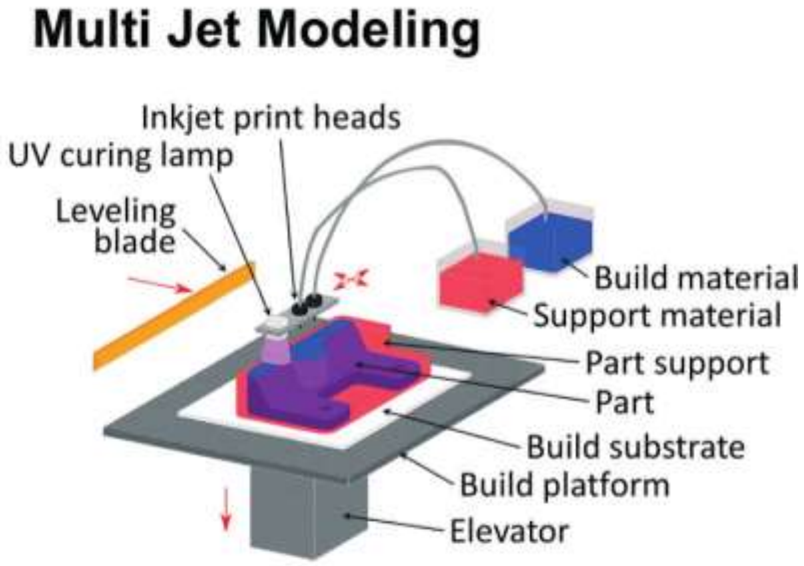


Figure 1.11 − The principle of Multi Jet Modeling[21]

1.4.5 Selective Laser Sintering (SLS)

The SLS method was invented by Carl Deckard in 1986. According to this technology, models are created from powder materials due to the sintering effect using the energy of a laser beam. Unlike the SLA process, in this case the laser beam is not a light source, but a heat source. Getting on a thin layer of powder, the laser beam sintering its particles and forms a solid mass in accordance with the geometry of the part. The materials used are polyamide, polystyrene, sand and powders of some metals.

A significant advantage of the SLS process is the lack of so-called support when building the model. In the SLA and MJM processes, special supports are used to construct the overhanging elements of the part, which protect the newly built thin layers of the model from collapse. In the SLS process, such supports are not necessary, since the construction is carried out in a homogeneous mass of powder. After construction, the model is extracted from the powder array and cleaned. The leading manufacturers of SLS machines are Concept Laser (Germany), 3D Systems (USA) and EOS GmbH (Germany)[16].

Printing material: thermoplastic, metal powder, ceramic powder, glass powder.

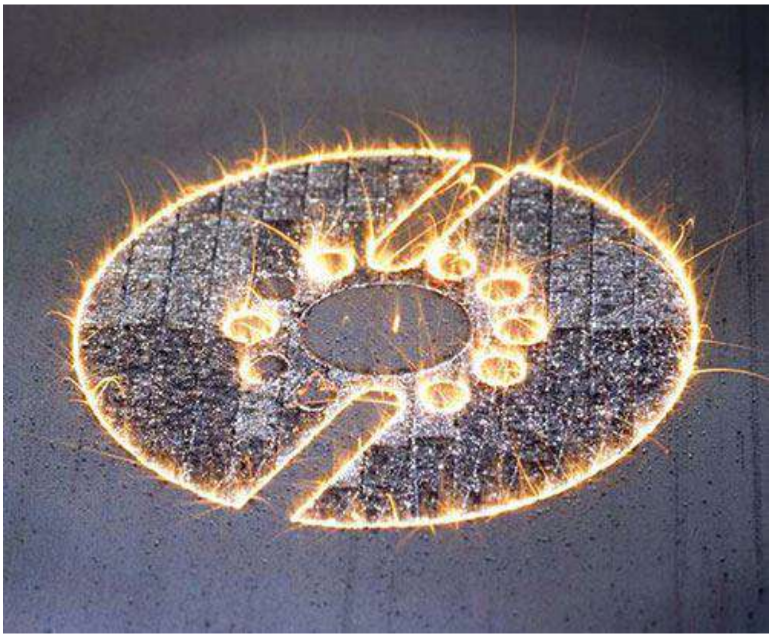


Figure 1.12 − Laser sintering process using Selective Laser Sintering Technology[16]

1.4.6 Direct Metal Selective Laser Melting (SLM)

SLM is a variation of SLS technology. This technology is similar to SLS, they are sometimes even confused, but at the same time they have cardinal differences. But, if in SLS technology the powder particles are sintered with each other, then here the metal particles are brought to a state of melting and welded together, forming a rigid frame. The material is metals and alloys in the form of a powder. The following metals and alloys are available for printing: steel, stainless steel, tool steel, aluminum, cobalt chromium alloy, titanium.

Extrusion in conventional 3D printers is an extrusion of material from special syringes - very similar to extruding decorative glaze or cream onto a cake from a pastry syringe. This leads to the fact that the details are printed with a rather low resolution, which makes the final product coarse. (The diameter of the hole cannot be reduced to microscopic values, since the surface tension will not allow a drop of substance to be squeezed out).

The MultiFab system works differently. It mixes microscopic droplets of photopolymers, which are then sent through inkjet printheads, similar to those built into a conventional office printer. This provides a high resolution layer-by-layer application of materials and the quality of the final product. The total cost of materials used to design the MultiFab printer amounted to only [7] thousand dollars, which is almost 20 times cheaper than existing analogues. Thin layers of high-quality metal powder are evenly distributed using a special coating mechanism. The platform on which the powder is located can be lowered vertically. The whole process takes place inside the chamber, which maintains tight control of atmospheric inert gases such as argon, nitrogen, oxygen, the level of which does not exceed 500 ppm. Then, each layer is formed by the selective action of lasers on the powder surface using two high-frequency scanners of the X and Y axes. The focusing system directs a high-power laser to metal particles, melting and welding them together. Continuous welding takes place along the contours of the section, and the insides of the walls of the object can be welded in accordance with the filling pattern. By the way, the powder remaining from the manufacture of the part can be reused to print the next model. Material for printing: almost any metal alloy in the form of granules, crumbs, powder.

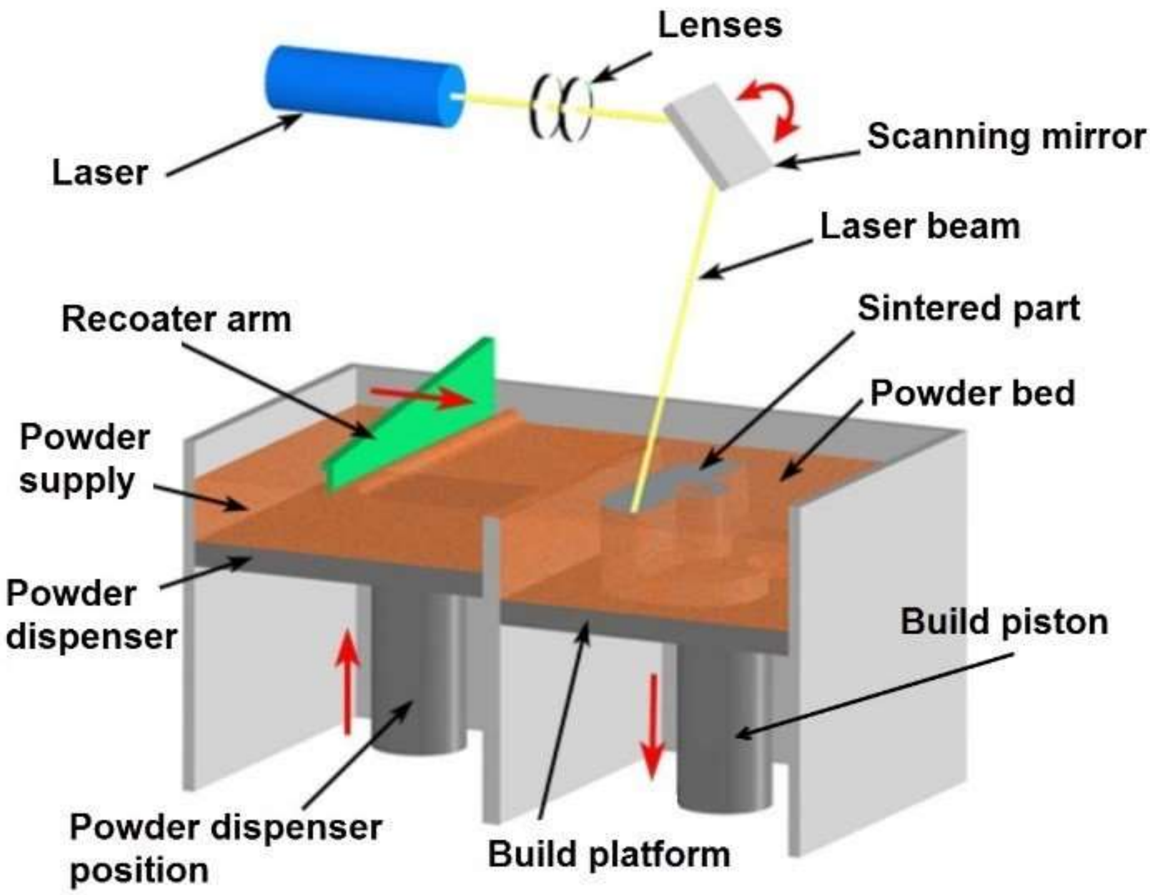


Figure 1.13 Direct Metal Selective Laser Melting (SLM)[7]

1.4.7 Electron Beam Melting (EBM)

This technology was developed by Arcam AB in Sweden. The technology is the manufacture of parts by melting a metal powder, applied layer by layer, by a powerful electron beam in a vacuum. Unlike some metal sintering methods, parts are obtained without voids, exceptionally durable. EBM is the most advanced among other 3D printing technologies. The technology allows the manufacture of parts of any geometric shape with the parameters of the material used. The EBM machine reads data from a 3D model, usually located in a CAD file, and sequentially forms it layer by layer. These layers are fused together using a computer-controlled electron beam. In this way he builds whole parts. The process takes place in a vacuum, which makes it suitable for the manufacture of parts from materials highly susceptible to oxygen, such as titanium. An important advantage is that the powder is a pure final material without any fillers, and therefore, the printed part does not need to be subjected to additional heat treatment. EBM operates at temperatures typically between 700 and 1000 ° C. Parts are made ready almost immediately after cooling. The combination of vacuum and overall high temperature allows the phenomenon of so-called unloading of internal stress to be achieved. Steelmakers are obviously familiar with this term, and for everyone else, we just say that the final product gets a strength comparable to forged alloys. Titanium alloys, as noted above, are easily processed using this technology, which makes it a suitable choice for the medical implant market. Printing Material: Titanium Alloys[8].

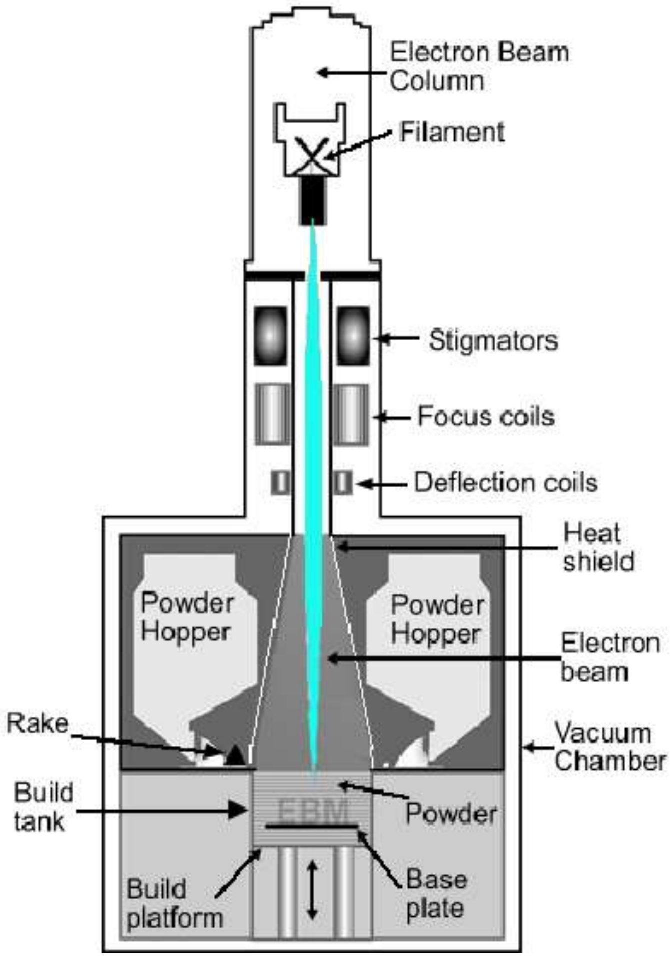


Figure 1.14 − Electron Beam Melting (EBM)[8]

1.5 Filaments

1.5.1 ABS

ABS (acrylonitrile butadiene styrene, ABS) is an impact resistant technical thermoplastic resin based on a copolymer of acrylonitrile with butadiene and styrene. The raw material for its production is oil. This plastic is opaque, easily painted in different colors.

ABS is a great choice for printing plastic automotive parts, moving parts, musical instruments, kitchen appliances, electronic housings, and various toys, like LEGO. It has other applications too, aside from 3D printing. For example, traditional manufacturers use ABS to make plastic wrap, water bottles, and cups, to name a few uses. Despite its popularity for 3D printing, ABS is not the best filament for most home users. This is because it has a high melting point that needs to print on a heated surface, or bed. A heated printer bed is not something a lot of budget-range 3D printers come equipped with. Printing with ABS also produces unpleasant fumes that can irritate some people. Needless to say, good ventilation is essential. These things combined make ABS a material favored more by professionals than amateur users.[20]

ABS advantages:

- A durable, strong 3D filament
- Quite flexible and lightweight
- Cheapest thermoplastic available at the time of writing
- Most favored material among professional 3D printers and keen armatures

ABS disadvantages:

- ABS is petroleum-based, making it a non-biodegradable material
- Needs a high temperature to reach its melting point
- Creates unpleasant fumes, most notable in poorly ventilated spaces

ABS is tough – able to withstand high stress and temperature. It’s also moderately flexible, though there are certainly better options for that further down the list. Together these properties make ABS a good general-purpose 3D printer filament, but where it really shines is with items that are frequently handled, dropped, or heated. Examples include phone cases, high-wear toys, tool handles, automotive trim components, and electrical enclosures.

1.5.2 PLA

PLA (polylactide, PLA) is a biodegradable, biocompatible polyester, the monomer of which is lactic acid.[20] The raw materials for production are renewable resources - for example, corn or sugarcane, so the material is non-toxic and can be used for the production of environmentally friendly packaging and disposable tableware, as well as in medicine and personal hygiene products.

PLA has wide-ranging uses. At the professional level, PLA filament uses include medical suturing (stitching).[21] We can also see PLA used for various surgical implants, including surgically implanted pins, rods, screws, and mesh. The applications work thanks to the material's degradable properties. All the aforementioned 3D printed parts break down in the human body [22-24]. They can take anywhere between six months to two years, depending on the part and its purpose. At the amateur level, PLA filament is great for producing a whole range of consumer items.[25] Other benefits of PLA are that it prints faster than ABS, and there's no need for a heated printer bed. The end products are a decent strength, durable, and offer some degree of impact resistance. Aside from 3D printing, other products that use PLA include food packaging, disposable tableware, and diapers, as a few examples.

PLA advantages:

- No harmful fumes, produces a sweet aroma when heated
- Easier to work with compared to ABS (great material for beginners)
- Compared to ABS, PLA is less prone to warping
- Available in special effects like glow-in-the-dark colors and translucency

PLA disadvantages

- Susceptible to clogging the printer nozzle
- Can attract moisture that makes it potentially brittle and more difficult to print
- Less sturdy overall than ABS

1.5.3 PET

Polyethylene Terephthalate (PET) is a popular 3D material. Another common use for PET is in everyday plastic bottles. This plastic is both stable and harmless, emits no unpleasant or harmful odors, and is 100% recyclable. In its raw state, the filament has no color and is crystal clear.[26] Once exposed to cold or heat the material quickly changes to a non-transparent state. A more advanced version if PET is a filament called PETG, also marketed as Amphora AM1800. The ‘G’ in PETG stands for “glycol-modified”, and the result is a filament that is clearer, less brittle, and most importantly, easier to print with than its base form.[27] For this reason, PETG is often considered a good middle ground between ABS and PLA, the two most commonly used types of 3D printer filament, as it is more flexible and durable than PLA and easier to print than ABS.

PET is on a list of FDA approved polymers. This makes it completely ‘food safe’, meaning it’s safe for products like cups, and plates, etc. Needless to say, common applications for PET filament include food containers and various kitchen utensils.[28]

PET advantages:

- Strong, flexible, and with biocompatibility
- Does not warp
- Does not shrink
- Does not absorb moisture from the air
- Does not degrade in water
- FDA approved, food safe
- Prices for PETT are falling

PET disadvantages:

- Not an easy material for beginners to work with
- Nozzle and printer bed temperatures needs fine-tuning for best results

1.5.4 Polydioxanone (PDS)

Polydioxanone (PDO, PDS) or poly-*p*-dioxanone is a colorless, crystalline, biodegradable synthetic polymer.

Biomedical applications:

•Orthopedics

•Maxillofacial surgery

•Plastic surgery

•Drug delivery

•Cardiovascular applications

•Tissue engineering

Fig 1.15 Polydioxanone[29]

1.6 Conclusion

According to the results of the literature review, the following conclusions were made:

1. Based on the studied devices and technologies, promising developments are those that could perform several functions or track several parameters.
2. For surface reduction of graphene oxide without damaging the polymer substrate, it is most promising to use laser irradiation.
3. For biomedical applications, the device must be made of biocompatible and non-toxic materials.
4. The most suitable 3D printing technology for creating the basis of the device is Fused Deposition Modeling. Since when using this technology, a combination of various materials with the necessary properties for biomedical applications is possible.
5. The most suitable material for creating a polymer substrate is PLA, since it has biocompatible properties, is non-toxic, and easy to process.

2 Fabrication of sensors

2.1.1 Fabrication of temperature sensor

The main objective of the present research is to combine 3D printing and the use of graphene materials by developing sandwich-like graphene-based structures for prototyping in flexible microelectronics.[29] The integration of these two technologies allows creating a conductive surface and the introduction of this surface into a personalized enclosure.[30] For this, as shown in Figure 1, we used laser modification of the surface of graphene oxide and the 3D printing to encapsulate the device.[29-31] After creating and preparing the 3D-printed device case, copper contacts are created and a layer of GO is deposited on the working surface of the device. The next step is the laser irradiation of the deposited GO film and its subsequent surface processing with the removal of oxygen groups that creates an electrically conductive layer.[33] After investigating and optimizing the operability of the device, it is encapsulated using 3D printing. During this technological step, molten plastic fills all the voids and sinters the upper conductive layer of reduced GO, improving the properties of the final device and ensuring the tightness of the structure.

This configuration shows a negative temperature coefficient of resistance suggesting that the sensitive material has semiconducting properties. Thus it can be used as a temperature sensor.

2.1.2Materials and reagents

Graphene oxide was ordered from the company «Graphenea» and diluted to a concentration of 4 mg / ml using distilled water.

The material of the diluted material was mixed using an ultrasonic bath.

PLA plastic was used for 3D printing

The original design was designed to create closed samples, which made it possible to combine flexibility, mechanical stability and protection against water.

The flexible sensor consists of the following parts:

Substrates from PLA made using 3D printing technology.

Flexible copper strips acting as external contacts.

Reduced graphene oxide located between the copper contacts.

The top cover of the PLA is made using 3D printing technology which encapsulate the entire structure and makes it airtight.

The temperature sensors were fabricated on a mechanical flexible PLA. (PLA from Bestfillament, Russia, Tomsk). Substrate with one carbon material - -GO.

In order to manufacture a temperature sensor, a design of the structure was developed in which it was possible to combine strength, flexibility and the durability of the workpiece for the subsequent preparation of the sensor.

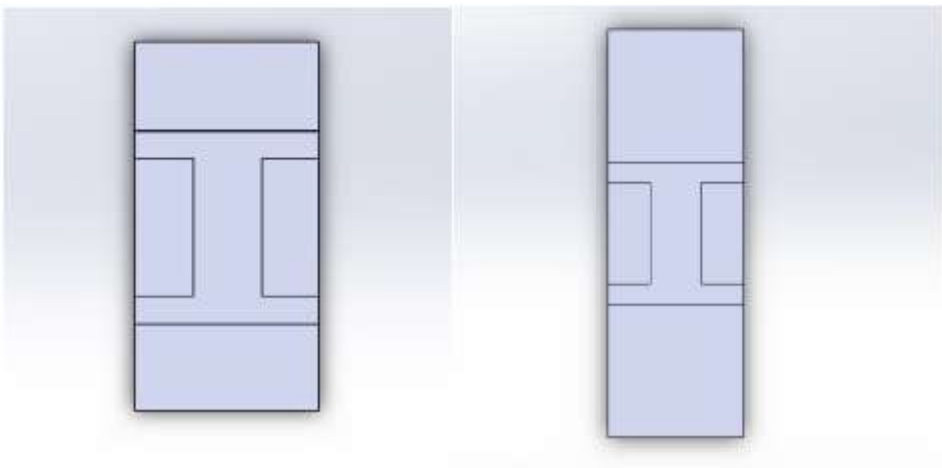


Fig 2.1 Design of temperature sensor

Firstly, special-shaped substrates were made using 3D printing technology by using PLA plastic, Fig 2.2a.

Secondly , the PLA was cleaned with Ethanol and deionized water for 3 minutes for every step, Fig 2.2b.

After surface preparation, a copper tape is glued into special grooves that will later act as contact pads, Fig 2.2c.

Due to the fact that the substrate is printed on a 3D printer, the surface structure has defects, which in turn increases the adhesion properties of graphene oxide to this surface.

Due to the developed design for the temperature sensor, graphene oxide is in a hollow resembling a “bath”. This structure improves the adhesion properties and contributes to a more uniform distribution of graphene oxide inside the sensor. This allows obtaining a film on the surface of the PLA without significant drops. Also, this design prevents the occurrence of a "coffee ring", Fig 2.2d.

After applying the solution of graphene oxide, the substrates were dried on a hot plate at a temperature of 40° C for 60 minutes.

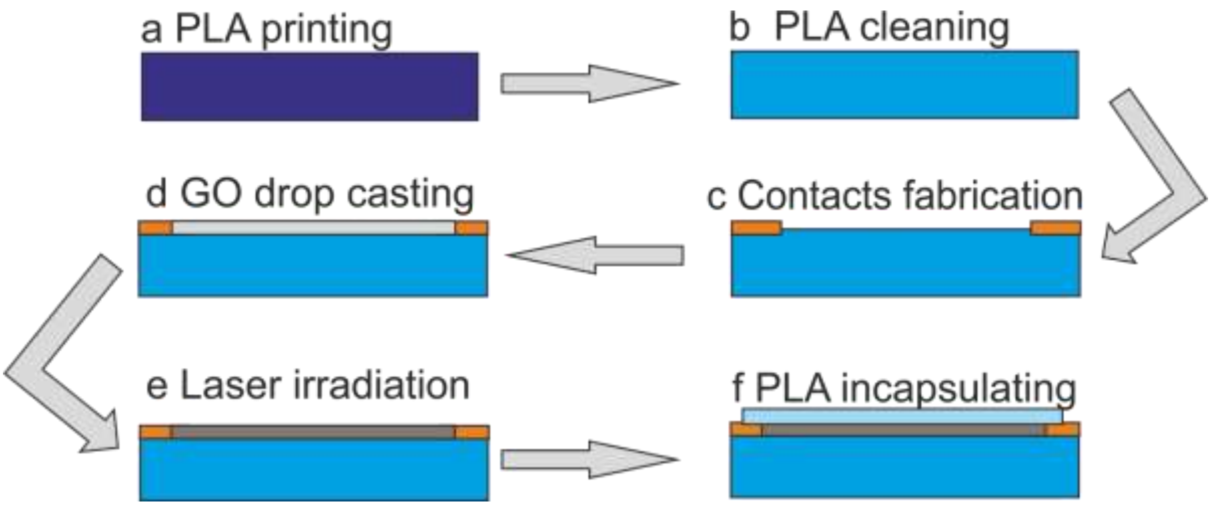


Figure 2.2 Fabrication of temperature sensor

Then we reduced the surface of the graphene oxide using a diode laser. Experimentally, the optimal mode was found to create a stable conductive structure. for it, we used the focal length of the 170 mW at 405 nm. Laser power was 80 ms%, and the filter with light transmission at 45% at 405 nm was also used, Fig 2.2e.

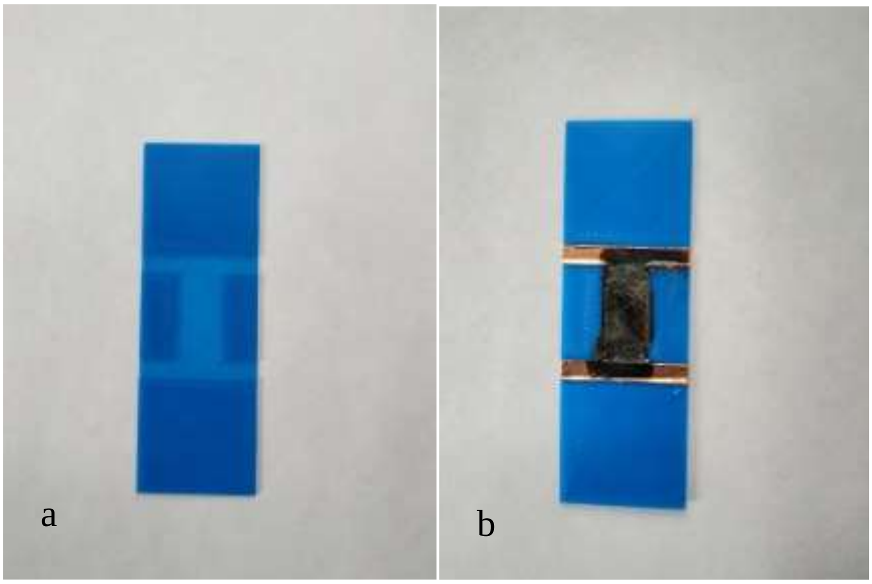


Fig 2.3 Prototype of temperature sensor, a) body of sensor, b) body of sensor with copper contacts and GO.

The next step is to improve the conductivity of the contact pad between the copper electrodes and the reduced graphene oxide. For this, we used a silver suspension, at Fig 2.4 you can see it.

Figure 2.4 Structure model of sensor

The final action is to encapsulate the structure using 3D printing technology. Through the use of this technology, the upper layers are soldered into the substrate, creating a protected and hermetic structure that contributes to its original properties, Fig 2.2f.

2.2 Humidity sensor

2.2.1 Fabrication of humidity sensor

This project is based on the combined use of laser surface reconstruction of graphene oxide films to create a detector layer and the use of 3D printing technology to design a flexible substrate.

With the development of the Internet of things, there is an increasing need to create multifunction detectors from modern competitive materials that are replacing standard semiconductor sensors and devices.

In modern conditions, with their rapid changes and an increasing need for the determination of various physical parameters and chemical parameters form the need for the creation of new humidity sensors.

This chapter will introduce a flexible humidity sensor using a biocompatible material acting as the substrate-base of the device.

The sensitive part of the device has a unique microporous structure. In the manufacture of the device in this microporous structure, microparticles of silver settle. Silver particles are forming a secondary matrix on the surface of the device, which improves the sensitivity of the device to changes in humidity.

This device can be used to create a biomedical respiratory detector for the patient, as it is able to track local changes in humidity. Since when breathing out, human breathing contains heated particles of carbon dioxide and microdrops of internal fluids. Due to the fact that this exhaled mixture differs in chemical composition from air, it will be clearly detected by this sensor even in small quantities when the breathing sensor is placed at a small distance from the patient's face.

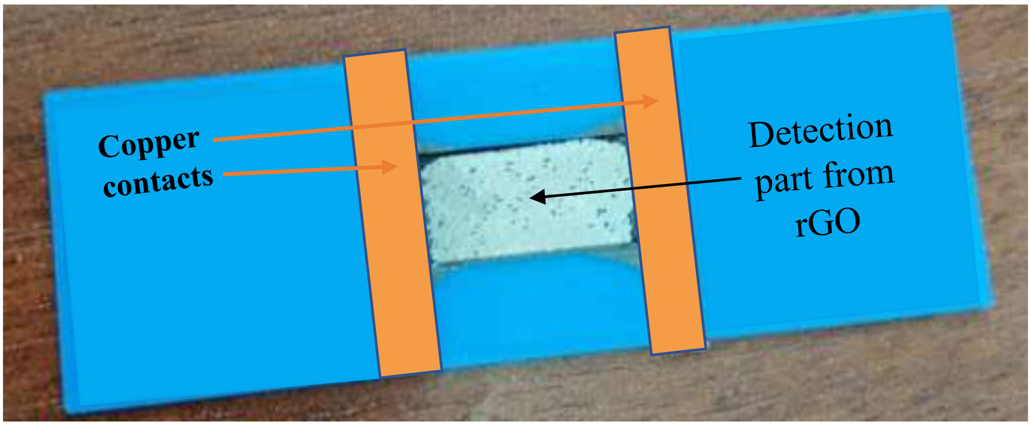


Figure 2.5 Humidity sensor

2.2.2 Materials and reagents

For the manufacture of this sensor, high-quality graphene oxide was used. As the basis of the sensor, a substrate made by 3D printing from PLA polylactide was used. A laser engraver was used to restore graphene oxide. To improve the sensitivity of the sensor, a solution of silver salts of $AgNO_3$ was used. For creative active sensitive layer from silver microparticles.

Next the text bellow, the process of creating a humidity sensor will be shown:

1. Design and creation the body from flexible polymer substrate by using 3D printing, Fig 2.6 a
2. Preparation and purification with ethanol and distilled water of the polymer substrate, Fig 2.6 b.
3. Application of a suspension of graphene oxide onto a polymer substrate, Fig 2.6 c.
4. Drying at a constant temperature of 40 degrees, this stage allows you to avoid the appearance of the "coffee ring" and contributes to a more uniform distribution of particles, Fig 2.6 d.
5. Application of a solution of $AgNO_3$ and subsequent drying, Fig 2.3 6.
6. Laser reducing process of the resulting combined structure, Fig 2.3 6.
7. Making copper contacts Fig 2.6g.
8. Humidity testing, Fig 2.6 h.

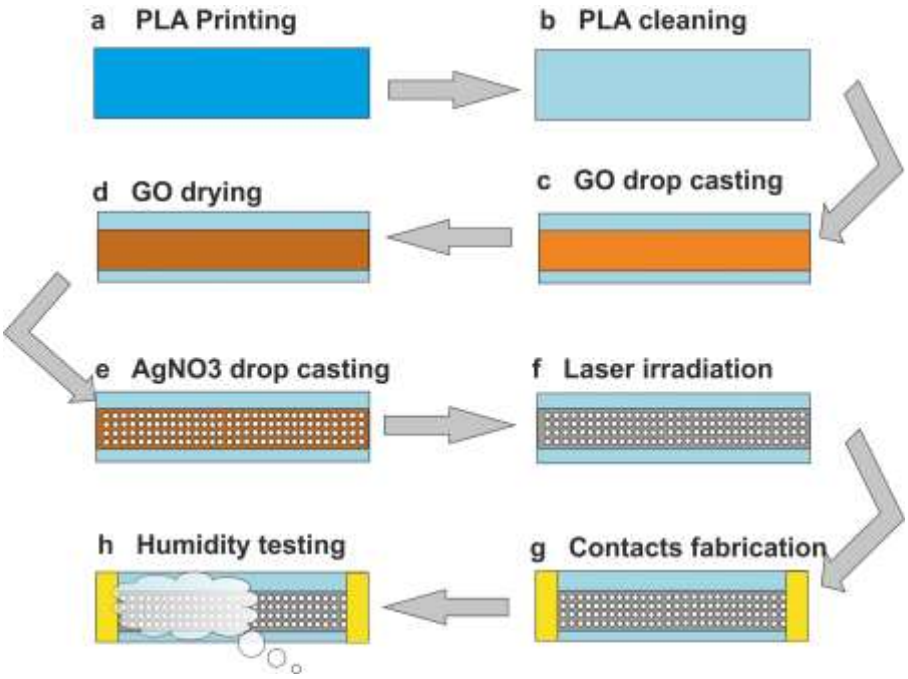


Figure 2.6 Fabrication of humidity sensor

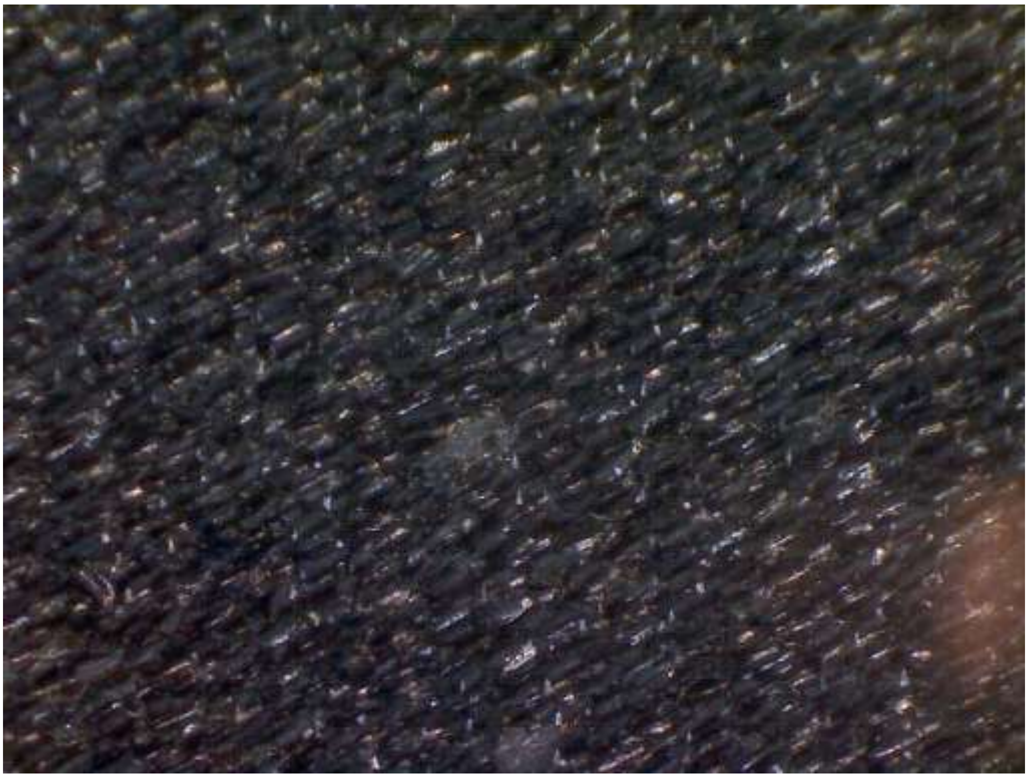


Figure 2.7 GO after depositing $AgNO_3$

2.3 Bending sensor

2.3.1 Fabrication of bending sensor

The creation of various sensors and detectors for multipurpose use is one of the priority tasks. Having studied promising areas in sensorics and flexible electronics, technological solutions were identified that require refinement.

Based on this problem, the development of a bend sensor using biocompatible materials was started.[34] This solution will allow you to adapt the resulting sensor for biomedical use, for example, to control limb mobility. Since bend sensors are becoming increasingly developed for use in robotics, new commercial and scientific developments are emerging with varying degrees of sensitivity.

Our development of a flexible sensor combines two promising technologies, this is laser surface restoration of graphene oxide films and the use of 3D printing technology to create a flexible polymer substrate from a biocompatible material.

The effective design of the substrate made it possible to create a sensor with a long service life despite the fatigue factor of polymeric materials, which is detected in similar sensors made using other technologies.

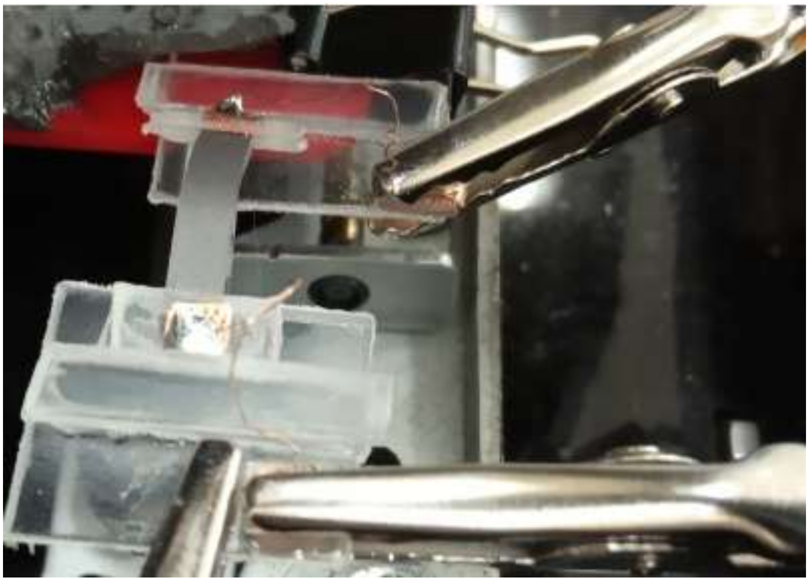


Figure 2.5 Bending sensor

2.3.2 Materials and reagents

For the manufacture of this sensor, high-quality graphene oxide was used. As the basis of the sensor, a substrate made by 3D printing from PLA polylactide was used. 170 mW at 405 nm diode laser with 1 kHz repetition rate and 150 us pulses was focusing in ~20-50 um spot.

Next the text bellow, the process of creating a bending sensor will be shown:

1. Design and creation of a flexible polymer substrate using 3D printing, Fig 2.6 a
2. Preparation and purification with ethanol and distilled water of the polymer substrate, Fig 2.6 b.
3. Application of a suspension of graphene oxide onto a polymer substrate, Fig 2.6c.
4. Drying at a constant temperature of 40 degrees, this stage allows you to avoid the appearance of the "coffee ring" and contributes to a more uniform distribution of particles, Fig 2.6 d.
5. Laser irradiation of Graphene Oxide Fig 2.6 e.
6. Making a copper contacts, Fig 2.6 f.
7. Bending test

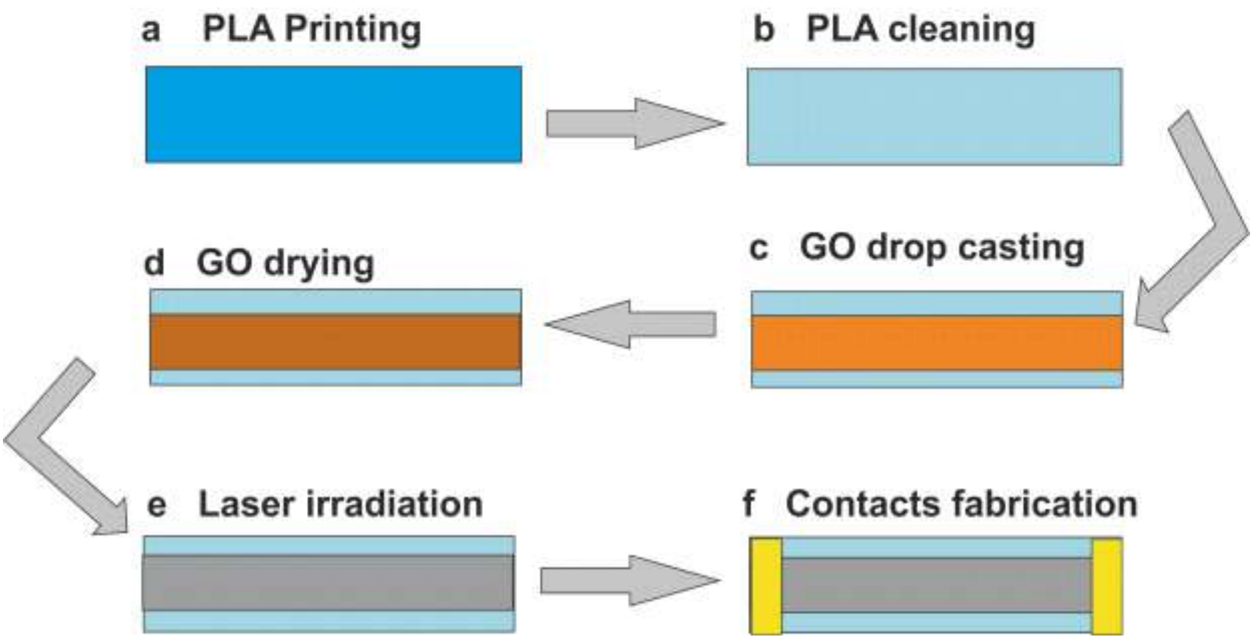


Fig 2.6 fabrication of bending sensor

3 Results and discussion

3.1 Temperature sensor

In this part of the paper, an overview of the data obtained during testing of the temperature sensor will be presented. The received data has been processed and will be presented in graphical form.

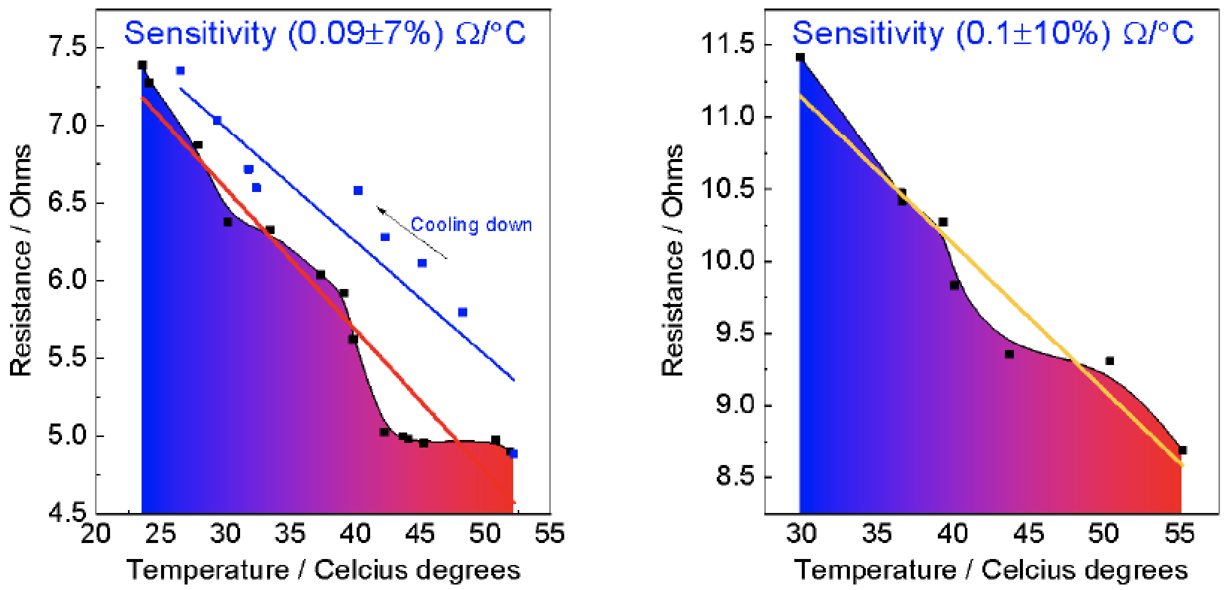
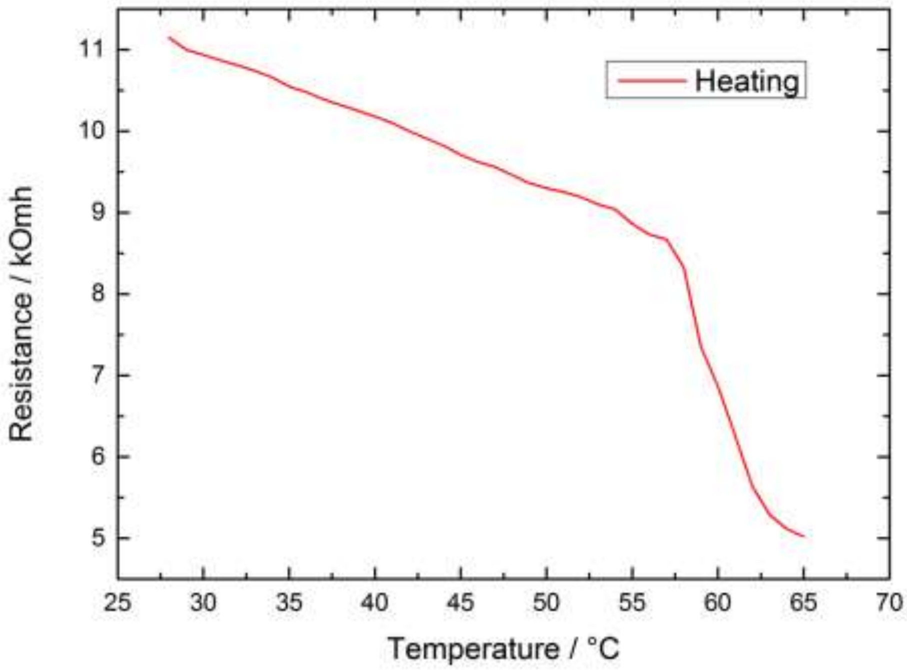


Figure 3.1 Sensitivity test

After processing the data, a sensitivity graph of the temperature sensor sensor was constructed, image 3.1. This image processed data from two sensors of different generations, the left graph is a sensor of the first generation. As you can see, the first-generation sensor was not extremely sensitive and was subjected from external noise, which is expressed by multiple dots above and below the line indicating cooling, highlighted in blue. The study of the occurrence of the appearance of noise made it possible to modify the resulting sensor and positively affected the development of second-generation sensors.

The graph on the right shows the second-generation sensor. As can be seen from the graph, the second-generation sensor does not have such a large amount of external noise and is characterized by a smoother sensitivity characteristic.

The stability indicators of this sensor allow you to use this temperature sensor as an independent device for temperature analysis. The using of a polylactide polymer substrate makes it possible to consider applying of this sensor in biomedicine.



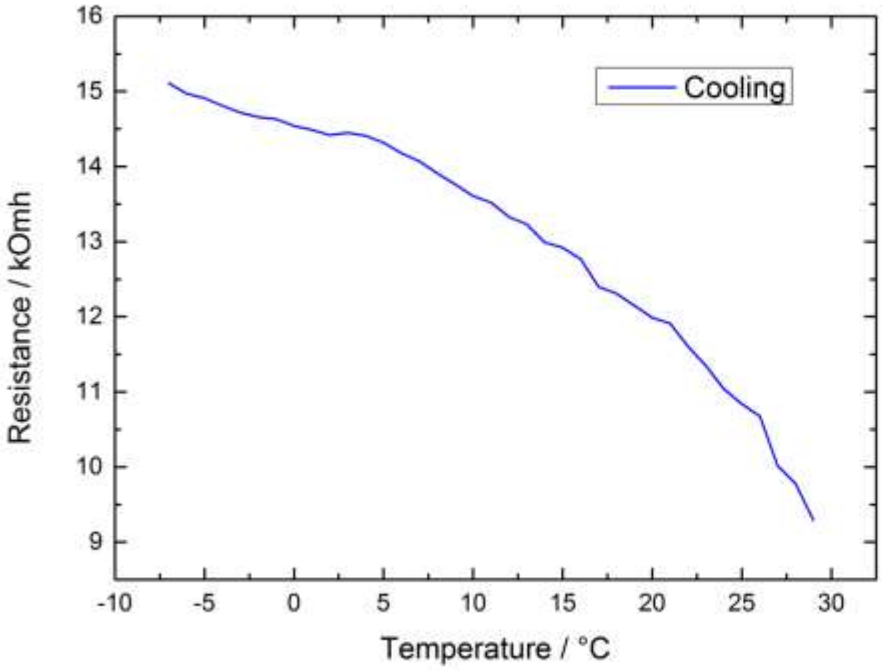


Figure 3.2 Heating and cooling graphics

The second-generation temperature sensor was tested in different temperature modes, based on the data obtained, graphs of the dependence of resistance change on temperature were built, Figure 3.2

Consider a graph of heating the temperature sensor. From 25°C to 55°C there is a smooth dependence of the change in the graph, which reflects the stable operation of the system. At 55°C, the copper contacts are heated. And this affects the sensitivity of the system, this is a marked hill between 55°C and 60°C, after which stabilization occurs and the sensor acquires a higher sensitivity.

Consider the graph of the cooling of the sensor, when the temperature drops from 30°C to 5°C, the stability of the sensor is visible, with a smooth change in resistance. On the interval between 5°C and 0°C, you can see that the graph is "subsiding", this moment is due to the cooling of the copper contacts, which affected the smoothness of the graph. After the temperature drops below 0°C, you can notice that the sensor stabilizes and again shows a smooth dependence.

3.2 Humidity sensor

In this part of the work, we will consider the data obtained during the testing of the humidity sensor. Having studied and processed the data obtained, a graph was plotted against the change in resistance over time.

Consider the graph below in Figure 3.3

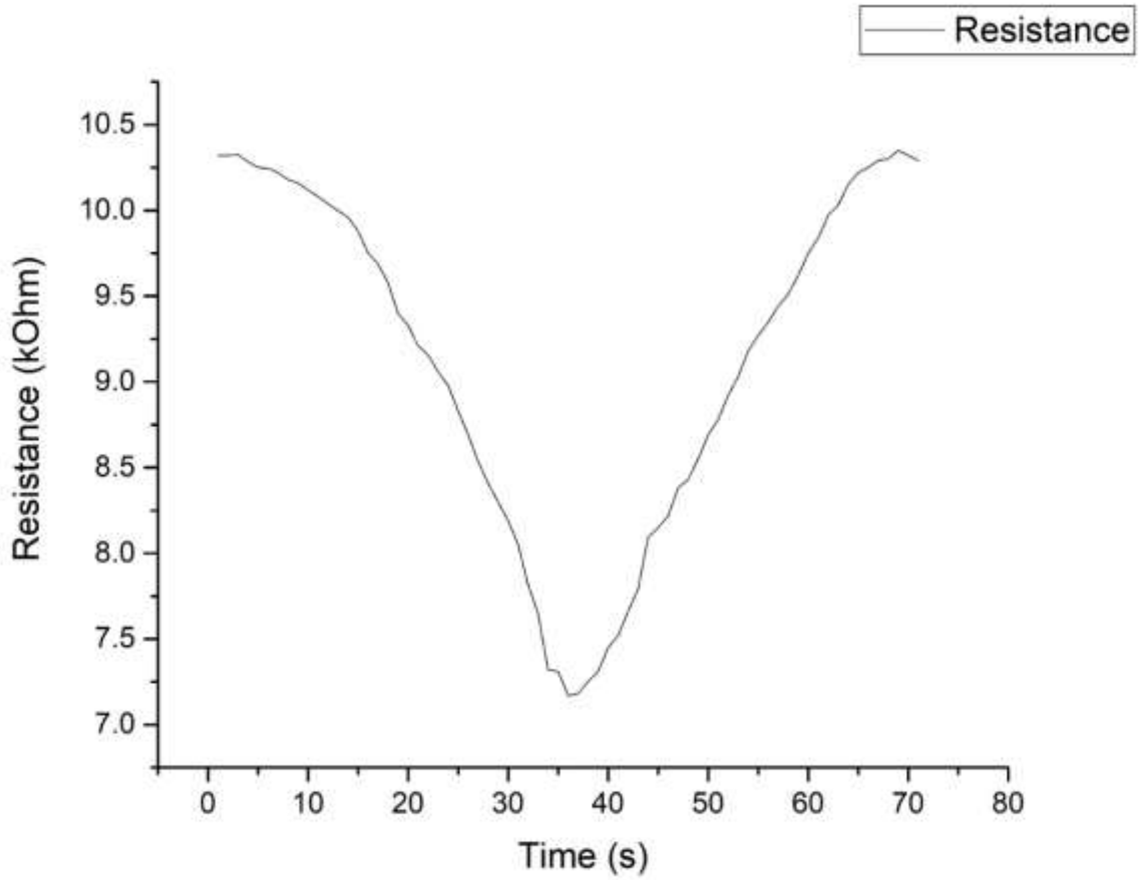


Figure 3.3 Graphic of humidity experiment

How can be seen in the graph, the first 10 seconds of the graph show the graph’s response to humidity in the room in which the experiment is being conducted. From 11 seconds you can notice the beginning of the registration of the changed humidity. This happened spraying water near the sensor using a spray gun. From 15 to 30 seconds, a boundary drop in resistance can be observed indicating a local change in humidity, which the sensor detects. From 30 to 35 seconds, you can observe the "step" that occurs characterizing the process of stabilization of humidity near the sensor.

From 35 to 40 seconds, you can observe the beginning of the process of dispersing humidity indoors. from 40 seconds, a gradual leveling of the humidity level near the sensor begins, relative to the humidity level in the room. At 70 seconds it can be seen that the sensor detects the return of the moisture level to the initial values as before spraying water. The peak at 75 seconds shows abrupt changes in the air that appeared from the approached laboratory assistant. In the interval of 75-80 seconds, one can again notice the stabilization of values before the end of the experiment.

3.3 Bending sensor

In this part of the work, the results obtained will be considered. An installation was created for bending the sensor, which carried out bending for 200 cycles of bending test. After 2000 cycles of bending test, the device has not yet exhausted its resource, which indicates the reliability of the design

Based on the results obtained, the graphs below were constructed. It can be noted that after every 100 cycles the resistance of the device increased by 5-10 kOhm, this effect is associated with a gradual wear of the structure and deformation of the internal structures of the reduced graphene oxide, which in turn increases the distance between particles and worsens the conductivity of the structure, as can be seen from the above graphs.

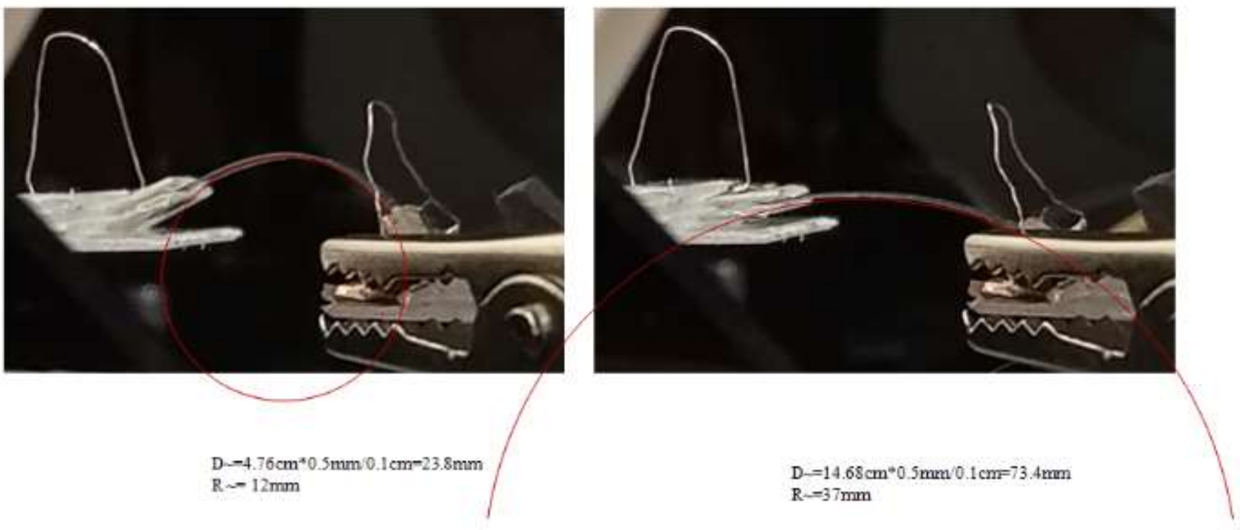


Figure 3.4 Calculation of bending angle

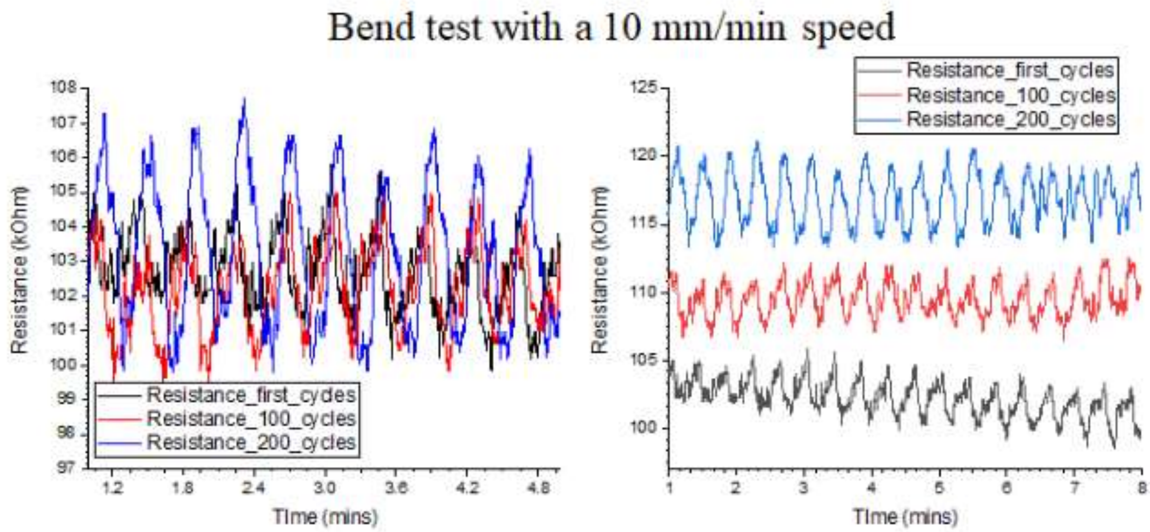


Figure 3.5 Bending test

After conducting bending tests, data were obtained and processed based on which the following graphs were built, figure 3.5.

Consider the left graph in which the amplitude changes in resistance are visible after passing a certain number of cycles.

As can be seen from the graph after passing 1 cycle, the resistance amplitude was 2 kOhm. After passing through 100 cycles, you can notice that the amplitude of the resistance change increased to 4 kOhm. After passing 200 cycles, the increase in amplitude was 6–7 kOhm.

On the right graph, you can see in more detail the difference in changes in resistance at the bend sensor after passing 1,100 and 200 bending cycles.

Based on the data obtained, it can be concluded that after 100 cycles, the sensor resistance increases by 2 kOhm. This effect is associated with the surface tension of the reduced graphene oxide films and the fatigue of the substrate on which the films were deposited, with many bends, the substrate gradually deforms, due to which the distance between the particles of the reduced graphene oxide increases and they “creep” from each other, increasing resistance.

After 2,000 cycles, the sensor continued to perform its functions, but with a significantly different resistance compared to the one at the beginning.

3.4 Conclusion

Based on the results of the experiments, the following conclusions can be drawn:

The second generation of the temperature sensor fully satisfies the tasks of the obtained characteristics and accuracy of the created device.

Since reduced graphene oxide is a semiconductor structure, the temperature sensor has a negative temperature coefficient. This feature is traced in the graphs. When the sensor is heated, the resistance of the conductive structure decreases. When the sensor cools, the resistance of the conductive structure increases. The sensor has a smooth temperature characteristic. Sensor accuracy 0.1 + - 10%.

According to the results of the experiment and the data obtained, the humidity sensor fully satisfies the goals and objectives.

Since reduced graphene oxide is a semiconductor structure, and the presence of silver particles of AgNO3 in it increases the sensitivity of the sensor to changes in the chemical composition of the environment. Then, when a region with high humidity arises, a drop in resistance occurs at the sensor due to the interaction of the sensor surface with the environment. The humidity sensor has a smooth resistance characteristic when humidity levels change.

According to the results of the experiments, the bending sensor fully satisfies the tasks and tasks.

Since the sensor works due to the effect of surface tension and deformation of the particles and the substrate on which they are located. Over time, a gradual deformation of the polymer surface occurs, as a result of which the polymer stretches. Since the distance between the reduced graphene oxide particles in the presence of surface tension depends on the state of the substrate, they deform, which is directly proportional to the deformation of the substrate on which they are located. The destruction of the sensor occurs 2 kOhm after every 100 continuous bending cycles for 5 minutes. The sensor remains operational after testing in 2000 continuous cycles.

All sensors are made on the basis of PLA plastic, which is a non-toxic and biocompatible material.

The manufactured sensors meet the minimum biocompatibility requirements and can be considered for biomedical applications.

Financial management, resource efficiency and resource saving

The purpose of this section discusses the issues of competitiveness, resource efficiency and resource saving, as well as financial costs regarding the object of study of Master's thesis. Competitiveness analysis is carried out for this purpose. SWOT analysis helps to identify strengths, weaknesses, opportunities and threats associated with the project, and give an idea of working with them in each particular case. For the development of the project requires funds that go to the salaries of project participants and the necessary equipment, a complete list is given in the relevant section. The calculation of the resource efficiency indicator helps to make a final assessment of the technical decision on individual criteria and in general.

1 Competitiveness analysis of technical solutions

In order to find sources of financing for the project, it is necessary, first, to determine the commercial value of the work. Analysis of competitive technical and methodical solutions in terms of resource efficiency and resource saving allows to evaluate the comparative effectiveness of scientific development. This analysis is advisable to carry out using an evaluation card.

First of all, it is necessary to analyze possible technical solutions and choose the best one based on the considered technical and economic criteria.

Evaluation map analysis presented in Table 1 The position of our flexible temperature sensor and robot’s skin temperature sensor and basic temperature sensor is evaluated for each indicator on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators in the amount should be 1. Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i \cdot P_i , \quad (1)$$

C - the competitiveness of research or a competitor;

Wi– criterion weight;

Pi – point of i-th criteria.

In the course of work, a flexible device was developed by using 3D printing technology and graphene-containing materials for temperature control in flexible electronic systems (P_f).

Competitors usually implements the following methods with some simulation in relative programs: robot's skin temperature sensor (P_{i1}) and basic temperature sensor (P_{i2}).

Table 1. Evaluation card for comparison of competitive technical solutions.

Evaluation criteria	**Criterion weight**	**Points**			**Competitiveness** Taking into account weight		
		P_f	P_{i1}	P_{i2}	C_f	C_{i1}	C_{i2}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Sensitivity	0.15	4	5	5	0.6	0.75	0.75
2. Flexibility	0.2	4	4	1	0.8	0.8	0.1
3. Safety	0.1	5	3	2	0.5	0.3	0.2
4. Temperature range	0.1	4	3	4	0.4	0.3	0.4
5. Measurements accuracy	0.2	4	3	4	0.8	0.6	0.8
Economic criteria for performance evaluation							
1. Development cost	0.05	3	4	5	0.15	0.2	0.25
2. Scientific developments market penetration rate	0.15	5	3	2	0.75	0.45	0.3
3. Methodology perspectives	0.15	5	3	3	0.75	0.45	0.45
Total	**1**	**34**	**28**	**26**	**4.75**	**3.85**	**3.25**

As we can see after competitiveness analysis the highest competitiveness points is for our flexible temperature sensor (C_{if}) and equal 4.75 in total, meanwhile for : robot's skin temperature sensor (C_{i1}) total points equal 3.85 and basic temperature sensor (C_{i2}) equal 3.25. Most of the points of our flexible temperature sensor received for safety, methodology perspective and scientific developments market penetration rate.

However, despite the fact that our sensor bypasses the other two in total, there are some problems with the cost of equipment and operation, which is a little high. In terms of costit is most acceptable to use the robot's skin temperature sensor and basic temperature sensor, but these devices will not give the most accurate result and are not the latest in scientific community.

2 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. The analysis has several stages. The first stage consists of describing the strengths and weaknesses of the project, identifying opportunities and threats to the project that have emerged or may appear in its external environment. The second stage consists of identifying the compatibility of the strengths and weaknesses of the project with the external environmental conditions. This compatibility or incompatibility should help to identify what strategic changes are needed.

Table 2. SWOT analysis

	Strengths: S1. Water resistant design S2. Huge temperature range S3. Can be integrated into the other devises S4. The functionality of this technique allows to compare the results with the results obtained using already known and new techniques.	**Weaknesses:** W1. Temperature resistance depends from the material of sensor's body W2. High cost of equipment. W3. Equipment are constantly used by other researchers and engineers.
Opportunities:	Using our device, you can create multi-functional	The material from which is made the device case very

O1. Get information of temperature from single device. O2. The ability to integrating and connecting with different sensors O3. The ability to control the time of the experiment. O4. Possibility of heating and cooling the sample.	system which includes the simultaneous usage of temperature sensors, bio-electrodes, and other devises for health monitoring. While currently, most techniques do not allow to obtain similar results with high resolution on the long-time range. The functionality of the equipment used will allow us to vary the parameters we need over a wide range and observe how they affect the sensitivity of devises	strongly affects the sensitivity and thermal conductivity of the device, as well as the maximum and minimum temperature ranges where you can use device. Equipment is constantly used by other researchers. Since the materials are mainly custom-made or synthesized in different parts of Russia and then brought to Tomsk, it is necessary to plan what and how many specific materials we need, and then make an order in advance.
Threats: T1. Since our methodology takes a long time, other scientists can get other results, process them and publish faster than we do. T2. Different surface modifications can give different results and affect the sensitivity of the sensor, based on this, disputes with other scientific groups that conduct similar studies T3. After the publication of our results, disputes may arise with other scientific researchers who use other methods.	The technique that we use requires a lot of time to create a device with the necessary parameters, since it is impossible to accelerate the mechanical process of creating a device, this parameter remains unchanged. However, we can speed up the process of describing and interpreting experimental data, as well as the process of preparing material for publication in scientific journals. Based on the fact that our results are different from the results of our colleagues and sometimes contradictory, but they still carry great potential for the entire scientific community.	Considering the weaknesses and threats to our device, technological advantage and time are decisive factors. With constantly evolving technologies, new methods appear every year. To accelerate research in our field, it is possible to conclude partnership contracts with other research institutes and conduct joint research in this area.

3 Project Initiation

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. In the initiation processes, the initial purpose and content are determined, and the initial financial resources are fixed. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined.

Table 3. Stakeholders of the project

Project stakeholders	**Stakeholder expectations**
RSCBT TPU	Prototypes of the device were created, material was prepared for publication in scientific journals.

Table 4. Purpose and results of the project

Purpose of project:	To investigate and show the role of graphene oxide as a semiconductor structure for use in flexible electronics.
Expected results of the project:	The results show that graphene oxide can be used to create semiconductor structures that can be used in flexible electronics, including as flexible temperature sensors.
Criteria for acceptance of the project result:	Results are repeatable and interpretable.
Requirements for the project result:	with increasing temperature decreases the resistance of the device, with decreasing temperature increases the resistance of the device
	High resolution of plasmon photocatalysis of a single nanoparticle is obtained
	The results are interpreted, processed and published.

	An assessment of the possibility of conducting *in-vitro* clinical trials is given.

The organizational structure of the project

It is necessary to solve some questions: who will be part of the working group of this project, determine the role of each participant in this project, and prescribe the functions of the participants and their number of labor hours in the project.

Table 5. Structure of the project

№	Participant	Role in the project	Functions	Labor time, hours (working days (from table 7) × 6)
1	Vladimir Mikhailovich Bogoslovskiy	Researcher/engineer	Experimentation, Prototype design, Data processing, Papers writing, Report writing	498
2	Raul David Rodriguez Contreras	Researcher/Project leader	Experimentation, Data processing, Planning, Communication, Papers writing, Report checking	246

Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members.

Table 6. Project limitations

Factors	**Limitations / Assumptions**
3.1. Total planned costs	1000000 rubs
3.1.1. Source of financing	RSCBT TPU
3.2. Project timeline:	
3.2.1. Date of approval of plan of project	**27.01.2020**
3.2.2. Completion date	**25.05.2020**

Project Schedule

As part of planning a science project, you need to build a project timeline and a Gantt Chart.

Table 7. Project Schedule

Job title	Duration, working days	Start date	Date of completion	Participants
Literature review	**6**	**3.02.2020**	**8.02.2020**	V.M. Bogoslovskiy
Research planning	**6**	**10.02.2020**	**15.02.2020**	R.D. Rodriquez/ V.M. Bogoslovskiy
Design and creating the device	**11**	**17.02.2020**	**29.02.2020**	R.D. Rodriquez/ V.M. Bogoslovskiy
Experimental part and device testing	**22**	**17.02.2020**	**14.03.2020**	V.M. Bogoslovskiy
Results discussion	**6**	**16.03.2020**	**21.03.2020**	R.D. Rodriquez/ V.M. Bogoslovskiy
Consultation with colleges	**6**	**16.03.2020**	**21.03.2020**	R.D. Rodriquez
Scientific manuscript writing	**12**	**23.03.2020**	**4.04.2020**	V.M. Bogoslovskiy/ R.D. Rodriquez
Report writing	**31**	**6.04.2020**	**16.05.2020**	V.M. Bogoslovskiy
Report checking and corrections	**6**	**18.05.2020**	**23.05.2020**	R.D. Rodriquez

Total duration of working time – 89 days

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 8. A Gantt chart

№	Activities	Participants	T_c, days	Duration of the project											
				February			March			April			May		
				1	2	3	1	2	3	1	2	3	1	2	3
1	Literature review	V.M. Bogoslovskiy	6												
2	Research planning	R.D. Rodriquez/ V.M. Bogoslovskiy	6												
3	Design and creating the device	R.D. Rodriquez/ V.M. Bogoslovskiy	11												
4	Experimental part and device testing	V.M. Bogoslovskiy	11												
5	Results discussion	R.D. Rodriquez/ V.M. Bogoslovskiy	6												
6	Consultation with colleges	R.D. Rodriquez	6												
7	Scientific manuscript writing	V.M. Bogoslovskiy/ R.D. Rodriquez	11												
8	Report writing	V.M. Bogoslovskiy	31												
9	Report checking and corrections	R.D. Rodriquez	6												

V.M. Bogoslovskiy - [redacted]   R.D. Rodriguez -

4 Scientific and technical research budget

The amount of costs associated with the implementation of this work is the basis for the formation of the project budget. This budget will be presented as the lower limit of project costs when forming a contract with the customer.

To form the final cost value, all calculated costs for individual items related to the manager and the student are summed.

In the process of budgeting, the following grouping of costs by items is used:

- Material costs of scientific and technical research;
- costs of special equipment for scientific work (Depreciation of equipment used for design);
- basic salary;
- additional salary;
- labor tax;
- overhead.

Calculation of material costs

The calculation of material costs is carried out according to the formula:

$$C_m = (1 + k_T) \cdot \sum_{i=1}^{m} P_i \cdot N_{consi}, \quad (2)$$

where m – the number of types of material resources consumed in the performance of scientific research;

N_{consi} – the amount of material resources of the i-th species planned to be used when performing scientific research (units, kg, m, m^2, etc.);

P_i – the acquisition price of a unit of the i-th type of material resources consumed (rub./units, rub./kg, rub./m, rub./m^2, etc.);

k_T – coefficient taking into account transportation costs.

Prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations).

Table 9. Material costs

Name	Unit	Amount	Price per unit, rub.	Material costs, rub.
PLA filament	1 kg	3	2000	6000
ABS filament	1 kg	3	2000	6000
Graphene oxide	1 l	1	50000	50000
Silver conductive paste	100 g	1	15000	15000
Total				77000

Costs of special equipment

This point includes the costs associated with the acquirement of special equipment (instruments, stands, devices and mechanisms) necessary to carry out work on a specific topic.

Table 10. Costs of special equipment and software

№	equipment and software identification	Quantity of equipment	Price per unit, rub.	Total cost of equipment, rub.
1.	Solidworks 2017	1	212000	212000
2.	3D printer Tevo Black Widow	1	66500	66500
3.	Laser Engraver	1	50000	50000
Total				327500

Calculation of the depreciation

If you use available equipment, then you need to calculate depreciation:

$$A = \frac{C_{перв} * H_a}{100}$$

(3)

A - annual amount of depreciation;

$C_{перв}$ - initial cost of the equipment;

$H_a = \frac{100}{T_{сл}}$ - rate of depreciation;

$T_{сл}$ - life expectancy.

Table 11 Costs of depreciation

№	Equipment identification	Quantity of equipment	Total cost of equipment, rub.	Life expectancy, year	Depreciation for the duration of the project, rub.
1.	3D printer Tevo Black Widow	1	66500	5	3024
2.	Laser Engraver	1	50000	3	2273
3.	PC	1	75000	5	3410

Total for the title "Costs of depreciation " – 8707 rubles.

Basic salary

This point includes the basic salary of participants directly involved in the implementation of work on this research. The value of salary costs is determined based on the labor intensity of the work performed and the current salary system The basic salary (S_b) is calculated according to the formula:

$$S_b = S_d \cdot T_w, \quad (4)$$

where S_b – basic salary per participant;

T_w – the duration of the work performed by the scientific and technical worker, working days;

S_d - the average daily salary of a participant, rub.

The average daily salary is calculated by the formula:

$$S_d = \frac{S_m \cdot M}{F_v}, \quad (5)$$

где S_m – monthly salary of an participant, rub.;

M – the number of months of work without leave during the year:

at holiday in 48 days, M = 11.2 months, 6 day per week;

– valid annual fund of working time of scientific and technical personnel (244 days).

Table 12. The valid annual fund of working time

Working time indicators	
Calendar number of days	365
The number of non-working days - weekend - holidays	 52 14
Loss of working time - vacation - isolation period - sick absence	 48 7
The valid annual fund of working time (F_d)	244

Monthly salary is calculated by formula:

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg}, \quad (6)$$

where S_{base} – base salary, rubles;

$k_{premium}$ – premium rate; `

k_{bonus} – bonus rate;

k_{reg} – regional rate.

Table 13. Calculation of the base salaries

Performers	S_{base}, rubles	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, rub.	W_d, rub.	T_p, work days	W_{base}, rub.
V.M. Bogoslovskiy Engineer	17 890	0.45	0.55	1,3	23257	1228	83	101924
R.D. Rodriquez Professor	49141				73466	3372	41	138252

Total for the title "Basic salary" - 240176 rubles.

Additional salary

This point includes the amount of payments stipulated by the legislation on labor, for example, payment of regular and additional holidays; payment of time associated with state and public duties; payment for work experience, etc.

Additional salaries are calculated on the basis of 10-15% of the base salary of workers:

$$W_{add} = k_{\text{extra}} \cdot W_{base}, \tag{7}$$

where W_{add} – additional salary, rubles;

k_{extra} – additional salary coefficient (10%);

W_{base} – base salary, rubles.

W_{add} (V.M. Bogoslovskiy) = 10192 rubles;

W_{add} (R.D. Rodriguez) = 13825 rubles;

Total for the title "Additional salary" – 24017 rubles.

Labor tax

Tax to extra-budgetary funds are compulsory according to the norms established by the legislation of the Russian Federation to the state social insurance (SIF), pension fund (PF) and medical insurance (FCMIF) from the costs of workers.

Payment to extra-budgetary funds is determined of the formula:

$$P_{social} = k_b \cdot (W_{base} + W_{add}) \quad (8)$$

where k_b – coefficient of deductions for labor tax.

In accordance with the Federal law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. Institutions conducting educational and scientific activities have rate - 27.1%.

Table 14. Labor tax

	Project leader (R.D. Rodriguez)	**Engineer (V.M. Bogoslovskiy)**
Coefficient of deductions	0.271	
Salary (basic and additional), rubles	152077	112116
Labor tax, rubles	41213	30383

Total for the title "Labor tax" – 71596 rubles.

Overhead costs

Overhead costs include other management and maintenance costs that can be allocated directly to the project. In addition, this includes expenses for the maintenance, operation and repair of equipment, production tools and equipment, buildings, structures, etc.

Overhead costs account from 30% to 90% of the amount of base and additional salary of employees.

Overhead is calculated according to the formula:

$$C_{\text{ov}} = k_{ov} \cdot (W_{\text{base}} + W_{add}) \quad (9)$$

where k_{ov} – overhead rate.

Table 15. Overhead

	Project leader (R.D. Rodriguez)	Engineer (V.M. Bogoslovskiy)
Overhead rate	0.3	
Salary, rubles	152077	112116
Overhead, rubles	45623	33635

Total for the title "Overhead costs" – 79258 rubles.

Other direct costs

Energy costs for equipment are calculated by the formula:

$$C = P_{el} \cdot P \cdot F_{eq},$$

where

P_{el} – power rates (5.8 rubles per 1 kWh);
P – power of equipment, kW;
F_{eq} – equipment usage time, hours.
C (3D printerTevo Black Widow) = 650rubles;
C (Laser engraver) = 356 rubles;
C (PC) = 1200 rubles.

Total for the title "Other direct costs" – 2206 rubles.

Formation of budget costs

The calculated cost of research is the basis for budgeting project costs.

Determining the budget for the scientific research is given in the table 15.

Table 16. Items expenses grouping

Name	Cost, rubles
1. Material costs	77000
2. Equipment costs	327500
3. Basic salary	240176
4. Additional salary	24017
5. Labor tax	71596
6. Overhead	79258
7. Other direct costs	2206
Total planned costs	**821753**

5. Evaluation of the comparative effectiveness of the project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated.

The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{max}}, \quad (10)$$

where I_f^d – integral financial measure of development;

C_i – the cost of the i-th version;

$C_{\max}$ – the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial measure of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one performance, then $I_f^d = 1$.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a, I_m^p = \sum_{i=1}^{n} a_i b_i^p, \quad (11)$$

where I_m – integral indicator of resource efficiency for the i-th version of the development;

a_i– the weighting factor of the i-th version of the development;

b_i^a, b_i^p – score rating of the i-th version of the development, is established by an expert on the selected rating scale;

n – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of table 17.

Table 17 – Evaluation of the performance of the project

Criteria	**Weight criterion**	**Points**
1. Sensitivity	0.15	4
2. Flexibility	0.2	4
3. Safety	0.1	5
4. Temperature range	0.1	4
5. Measurements accuracy	0.2	4
Economic criteria for performance evaluation		
1. Development cost	0.05	3
2. Scientific developments market penetration rate	0.15	5
3. Methodology perspectives	0.15	5
Total	1	34

Integral indicator of resource efficiency:

$$I_m = 0.15 + 0.2 * 4 + 0.1 * 5 + 0.1 * 4 + 0.2 * 4 + 0.05 * 3 + 0.15 * 5 + 0.15 * 4 + 0.1 * 5 = 5.1$$

The integral indicator of the development efficiency (I_e^p) is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_e^p = \frac{I_m^p}{I_f^d}, I_e^a = \frac{I_m^a}{I_f^a} \text{ and etc.} \quad (12)$$

Since the development has one performance: $I_e^p = \frac{5.1}{1} = 5.1$;

Comparison of the integral indicator of the current project efficiency and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$E_c = \frac{I_e^p}{I_e^a}. \quad (13)$$

Thus, the effectiveness of the development is presented in table 18.

Table 18 – Efficiency of development

№	**Indicators**	**Points**
1	Integral financial measure of development	1
2	Integral indicator of resource efficiency of development	5.1
3	Integral indicator of the development efficiency	5.1

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency.

Social responsibility

Introduction

In this paper, sensors for biomedical applications are developed. The work includes the manufacture of a temperature sensor, a bend sensor, and a humidity sensor.

In the process, a series of experiments was carried out to restore graphene oxide films. The experiments, technical calculations, design and testing of the device were carried out in TPU laboratory, Science park building, 306 room.

The development of protective measures against these factors, the assessment of working conditions. Also in this section, issues related to safety, fire prevention and environmental protection, recommendations for creating optimal working conditions are considered.

During the development and operation of the designed solution, the following harmful factors should be considered: reduced graphene structures are made from liquid graphen oxide suspensions by illuminating the studied object with an Impulse laser. This type of laser poses a danger when the eyes are exposed to direct or specularly reflected radiation. This type of suspensions are highly danger due to its chemical composition. When conducting experiments, special measures are taken to ensure the safety. During the solution preparation special care is given, due to handling of the harmful chemicals.

For the production of polymer substrates, a 3D printer is used. Hot surfaces on the printer are especially dangerous.

When working with a laser, one should be guided by the following document: GOST 31581-2012 Laser safety. General safety requirements for the development and operation of laser products. According to the degree of danger, the Impulse laser belongs to class 3a.

Collective protective equipment includes the use of a special room for research. Individual protective equipment includes: when working with a laser - avoid contact with direct laser beams, use individual glasses that do not transmit laser wavelengths; when working with plasma and whole blood, use disposable rubber or plastic gloves.

Lab coats and gloves are mandatory for conducting the experiments to avoid any chemical hazards.

1 Legal and institutional security issues

1.1 Special legal norms of labor legislation

In according to [35]

1. The normal duration of working time cannot exceed 40 hours per week;
2. During the working day, the employee should be given a break for rest and meals lasting no more than two hours and at least 30 minutes, which is not included in working hours;
3. All employees are given days off (weekly continuous rest). With a five-day working week, employees are given two days off per week; with a six-day working week, one day off;
4. Annual vacations with retention of the place of work and average wage should be paid to employees;
5. Annual paid leave is granted to employees lasting 28 calendar days, in accordance with [36].

In accordance with [37], persons over 18 years old, who don't have medical contraindications, who have undergone special training. Who training in the prescribed manner to work with a specific laser product and certification to the labor protection group during a work on electrical installations with the appropriate equipment are allowed to work with laser products voltage.

Workers involved in laser installations are required to:

1. A medical examination by a qualified professional after a suspected or obvious traumatic effect on the eyes. Such an inspection should be supplemented by a full investigation of the circumstances in which the accident occurred;
2. Preliminary and subsequent ophthalmological examination of workers. Verification of the visual function is required for each case;
3. Additional payments.

According to [38] involved in work with class 2a medical devices employees are required to:

1. Compulsory medical examination;
2. Additional payments.

1.2 Organizational measures in the layout of the working area

When performing research for this project, the work is doing by the operator in a sitting position. In accordance with [39]:

The workplace should ensure the performance of labor operations within the reach of the motor field. The performance of labor operations “often” and “very often” must be ensured within the zone of easy reach and the optimal zone of the motor field.

The design of production equipment and the workplace should ensure the optimal position of the worker, which is achieved by regulation:

1. Height of the working surface, seat and leg space;
2. The height of the seat and footrest (with unregulated height of the working surface).

The optimal working position for working man of lower growth is achieved by increasing the height of the working seat and footrest by an amount equal to the difference between the height of the working surface for a worker with a height of 1800 mm and the height of the working surface that is optimal for the growth of this worker. Requirements for the height of the workplace are shown in table 1.

Table 1 - A height of a workplace surface with various types of work

Name of works	A height of a workplace surface, mm		
	Women	Men	Women and men
Delicate work	700	750	725
Light work	630	680	655

Workplaces should be organized in such a way as to exclude the possibility of laser radiation exposure to personnel. Laser products must be operated in specially designated areas that comply with fire safety requirements and have the necessary fire prevention and fire protection equipment [37].

2 Industrial safety

Harmful and dangerous factors are analyzed that may occur during the development or operation of the device under development in this section

GOST 12.0.003-201 is used to select factors. A list of hazardous and harmful factors is presented, which are typical for the designed production environment in the form of a table

Table 2 - Hazardous and harmful factors in the development of a method

The source of the factor, the name of the type of work	List of factors (according to GOST 12.0.003-2015)		Normative document
	Harmful	Dangerous	
1. Work with the He- Ne laser; 2. Use of RNP plasma and blood.	1. The increased gas contamination of the air of the working area; 2. Deviation of microclimate indicators; 3. Laser 4. Chemical hazards	1. Fire; 2. Electrical current.	1. GOST 31581-2013; 2. MU-287-113 (materials disinfection); 3. GOST 12.1.030-81; 4. GOST 12.1.005-88; 5. GN 2.1.6.3492-17; 6. SP 60.13330.2012.

Identified harmful and dangerous factors are discussed in more detail below. Each factor is considered in sequence: the source of the factor; reduction of permissible norms with the required dimension; safety products (collective and individual) to minimize the impact of the factor.

2.1 Analysis of hazardous and harmful industrial factors

2.1.1 Requirements for safe operation of laser systems

The following special rules must be observed when operating the laser system: systematically monitor and maintain all safety devices (screen, panels, doors, locks, alarms) in good condition. The shutdown procedure must be strictly observed, at the end of which remove the key of the main switch from the lock.

The laser used is class 3A. Laser products are safe for observation with an unprotected eye. For laser products that generate radiation in the wavelength range from 400 to 700 nm, protection is provided by natural reactions, including the flashing reflex.

When detecting disorders in the operating mode of the laser system, immediately stop the flow of the optical head, coordinate table, and, if necessary, make an emergency shutdown of the system. In the event of an emergency failure of the optical element from zinc selenide (lens, exit window), turn off the emergency button, immediately leave the room and begin to replace this element no earlier than 30 minutes later.

When the laser system is attendanced, use only expendable materials (especially lubricants and cleaning agents), spare parts and replaceable components that are specified in the manufacturer's instructions [37].

2.1.2 Precautions measures during operations with 3D printer

Requirements for safe operation of 3D printer

The following special rules must be observed when operating the 3D printer: systematically monitor and maintain all safety devices (screen, panels, hot table, extruder) in good condition. The shutdown procedure must be strictly followed, at the end of which turn off the main printer toggle switch.

During the experiment, blowing of the extruder should always be turned on. The ground wire must be properly grounded.

Disinfect all used materials in accordance with the requirements [40].

2.2 Analysis of harmful and dangerous factors that may arise in the laboratory during research

2.2.1 Increased noise level

During 3D printing, an abundant noise occurs, At the workplace, noise occurs when the 3D printer is working, the ventilation of a personal computer and when exposed to external factors.

Noise adversely affects the human body, causes mental and physiological disorders, hearing loss, performance, creates the prerequisites for common and occupational diseases and industrial injuries, as well as weakening of memory, attention, violation of blood pressure and heart rate.

Noise levels should not exceed the values specified in GOST 12.1.003 - 2014, and they should be checked at least twice a year. The main characteristic of noise is the maximum permissible noise level (RC)[41]. The maximum permissible level (noise level) of a noise is the level of a factor that, when working daily (except weekends), but not more than 40 hours a week during the entire working period, should not cause diseases or deviations in health, which are detected by modern research methods process of work or in the remote periods of life of the present and subsequent generations. Compliance with the noise level of the remote control does not preclude health problems in hypersensitive individuals.

According to GOST 12.1.003 - 2014, the noise parameters are normalized and during the work the noise level should not exceed 82 dB;

At values above the permissible level, it is necessary to provide for personal protective equipment and collective protection devices against noise.

Collective protection:

- elimination of the causes of noise or its significant weakening in the source of education;
- isolation of noise sources from the environment (use of silencers, screens, sound-absorbing building materials);
- the use of tools that reduce noise and vibration in the way of their distribution;
- The use of protective clothing and hearing aids: headphones, earplugs, antiphons.

2.2.2 Climate deviation

Favorable conditions for the workplace microclimate must be created while working in the laboratory. Prolonged exposure of a person to adverse weather conditions can dramatically worsen his well-being, reduce labor productivity and lead to diseases. The microclimate is determined by combinations of temperature, humidity, air velocity and thermal radiation acting on the human body. High air temperature contributes to the rapid fatigue of the worker, and can lead to overheating of the body, cause a violation of thermoregulation, impairment of well-being, decreased attention, heat stroke, increased stress on the heart. Low air temperature can cause local or general hypothermia, cause colds, and lead to diseases of the peripheral nervous system (radiculitis, bronchitis, rheumatism). Low humidity can cause the mucous membranes of the respiratory tract to dry out. Air mobility effectively contributes to the heat transfer of the human body and is positively manifested at high temperatures and negatively at low. optimal and permissible microclimate indicators of industrial premises are given according to [42].

Table 4 - Optimum microclimate indicators at workplaces of industrial premises

Period of the year	Category of work on the level of energy consumption, W	Air temperature, C	Relative humidity, %	Air velocity, m/s
Cold	IIa(175-232)	19-21	60-40	0.2
Warm	IIa(175-232)	20-22	60-40	0.2

Table 5 - Permissible microclimate indicators

Period of the year	Air temperature, C		Relative humidity, %	Air velocity, m/s	
	Upper bound	Lower bound		Upper bound	Lower bound
Cold	23-24	15-17	40-60	0.1	0.2
Warm	27-29	17-18	40-60	0.1	0.3

2.2.3 Electrical safety

Electrical safety is a system of organizational and technical measures aimed at protecting people from the harmful and dangerous effects of electric current.

There is a danger of electric shock in all cases where electrical installations and equipment are used. Electrical installations are classified by voltage - with a rated voltage of up to 1000 V (rooms without increased danger), up to 1000 V with the presence of an aggressive environment (rooms with increased danger) and over 1000 V (rooms especially dangerous) (according to the Rules for the Installation of Electrical Installations).

To ensure safe operation, it is necessary to exclude possible sources of electric shock:

1. Accidental contact with live parts under voltage;
2. The appearance of voltage on the mechanical parts of electrical equipment (cases, covers, etc.) due to insulation damage or other reasons;
3. The occurrence of stress on the ground or supporting surface.

According to the degree of danger of electric shock, this laboratory belongs to rooms without increased danger, it is a dry room without increased dusting, the air temperature is normal, the floor is covered with insulating material. All electrical equipment and devices are in place and have protective grounding with a resistance of not more than 4 Ohms [43]. All employees undergo initial electrical safety training.

It is necessary to check the serviceability of conductive wires before starting work. It is forbidden to use wires with damaged insulation or without insulation, as well as wires that are not equipped with plugs or soldered terminals, to connect electrical appliances.

Instruments must be kept clean. It is necessary to disconnect the equipment from the network at the end of work.

Electric shock may occur because of careless operations with connecting wires. In addition, a short circuit can occur when current-carrying parts close on the device about absence of nulling or grounding and cause the electric shock.

Table 6 - Permissible levels of effective touch voltage and currents

Mode	Current type					
	AC, 50 Hz			DC		
	U, V	I, mA	Duration, min	U, V	I, mA	Duration, min
Normal	2	0,3	<10	8	1	<10

First aid to the victim should consist in immediately disconnecting the current that caused the injury, disconnecting (in rubber gloves) the victim from the leads and calling the doctor. If the victim is conscious, but before that he was swooning or has been under current for a long time, he needs to ensure peace before the doctor arrives. If the victim lost consciousness, but breathing persists, it is necessary to put it comfortably, evenly, unfasten tight clothing, create an influx of fresh air, remove unnecessary people from the room, breathe ammonia, spray with water, rub and warm the body. It is necessary to apply artificial respiration with convulsive and rare breathing. In the absence of signs of life (lack of pulse and breathing), the victim cannot be considered dead. It is necessary immediately, without wasting time, before the arrival of the doctor to do artificial respiration.

2.2.4 Room illumination

Light sources with a color temperature of 2400 to 6800 K should be used for general and local lighting of rooms. The intensity of ultraviolet radiation in the wavelength range of 320-400 nm should not exceed 0.03 W/m [44].

The presence in the radiation spectrum of wavelengths less than 320 nm is not allowed.

For artificial lighting, energy-efficient light sources should be used, giving preference to equal power sources of light with the highest light output and service life, taking into account the requirements for color differentiation.

2.3 Justification of measures to reduce the impact of hazardous factors on the researcher

2.3.1 Fire safety

The laboratory room where the work was carried out belongs to category B [45].

The causes of the fire may be:

1. Short circuit currents;
2. Malfunction of electric networks;
3. Ignorance of fire safety rules or negligence of staff;
4. Smoking in the wrong places.

In this regard the following fire safety standards must be met in the laboratory:

1. It is forbidden to include additional non-intended consumers to protect the network from congestion;
2. Carry out work in the laboratory only when the equipment and electrical wiring are in good condition;
3. To extinguish a fire (fire extinguisher);
4. Have a plan of evacuation of people, which should hang in a conspicuous place;
5. Place the equipment so that there is sufficient passage to the exit.

The TPU building in which the laboratory is located complies with fire safety requirements.

2.3.2 Determination of air exchange in laboratory

Air exchange in public buildings is necessary to clean the air of harmful substances: to remove harmful substances (emitted harmful gases, vapors and dust), to remove water vapor and excess heat.

In residential and public buildings, carbon dioxide (CO_2) exhaled by people is a constant harmful emission. The required air exchange is determined by the amount of carbon dioxide exhaled by a person and by its permissible concentration. The amount of carbon dioxide, depending on the age of the person and the work performed, as well as the permissible concentration of carbon dioxide for different rooms. The carbon dioxide content in the air can be determined by the chemical composition of the air. However, given the increased carbon dioxide content in the atmosphere of settlements, the CO_2 content should be taken into account when calculating:

-for large cities (over 300 thousand inhabitants)- 0.5 l/m^3[46].

Determine the required rate of air exchange in a laboratory in Science Park, room 306 for three people, if the volume of the room is V=72 m^3. The amount of carbon dioxide exhaled by an adult with light work in an institution is 25 l/h [46]. The maximum permissible concentration of carbon dioxide for institutions is 1.25 l/m^3[46]. The required air exchange in the laboratory is determined by the formula 1:

$$L = \frac{G*P}{X_v - X_n}, \qquad (1)$$

where L - air exchange required, m^3/h;

G - the amount of harmful substances released into the room air, g/h;

P - number of people working in the laboratory;

x_v - maximum permissible concentration of harmfulness in the air of the working area of the room [46], mg/m^3;

x_n - the maximum possible concentration of the same harmfulness in the air of populated areas [46], mg/m^3.

The rate of air exchange (n), which shows how many times in one hour the air is completely replaced in the room, which is determined by the formula 2.

$$n = \frac{L}{V_n}, h^{-1} \qquad (2)$$

where V_n is the internal volume of the room, m^3.

According to [47], the permissible air exchange rate should be in the range from 3 to 10 h^{-1}.

Required air exchange in the laboratory, according to 1:

$$L = \frac{23 * 3}{1.25 - 0.5} = 92\frac{m^3}{h},$$

The required air exchange rate is:

$$n = \frac{92}{72} = 1.27h^{-1}$$

Thus, the calculated consumed air exchange in the laboratory should be 92 m^3/h.

2.3.3 Laser safety

The laser product must have protective devices to prevent unauthorized exposure to laser radiation personnel, as well as protective interlocks to ensure safety during maintenance and operation.

Protective interlocks must include shutting off the supply of hazardous electrical voltage to the laser product or its component parts. The possibility of generating laser radiation in the event of accidental disconnection of locks should be excluded.

Screens should be used as laser protection for class 3A, 3B, and 4 lasers. Screens should be made of fire-resistant and impervious to laser radiation material and to close the area of interaction of the laser beam with the target.

If the level of laser radiation does not exceed the permissible level for class 3A: "Do not look into the beam and do not observe directly using optical instruments."

3 Environmental safety

3.1 Analysis of the impact of the object of research on the environment

This subsection considers the environmental impact of the laboratory facility. The alleged sources of environmental pollution resulting from the implementation of the solutions proposed in the are identified.

During operation of the facility, the main types of impacts of the designed facility are established:

- Household waste;

- Industrial waste;
- Chemical waste.

Measures to reduce the intensity of environmental pollution is the creation of obstacles to the distribution and treatment of waste by various methods.

Utilization of household, Industrial and Chemical waste is the Main Event. Glass, metal waste, waste paper, as well as plastics are processed into secondary raw materials.

Class B industrial wastes (syringe needles, metal pieces and waste wires) are collected in separate disposable soft or hard packaging. The choice of packaging depends on the morphological composition of the waste.

To collect chemical waste of class B, disposable, non-punctureable, moisture-resistant containers with a lid (containers) must be used to ensure their sealing and exclude the possibility of spontaneous opening.

After filling the bag by no more than 3/4, the person responsible for the collection of waste in this unit fastens the bag or closes it using tag tags or other devices that prevent the discharge of Class B waste. Solid containers are closed with lids. Class B waste disposal outside the unit in open containers is not permitted. At the final packaging of class B waste to remove it from the unit (organization), disposable containers with class B waste are marked with the inscription "Waste.

Class B" with the name of the organization, unit, date and name of the person responsible for collecting the waste.

Class B medical waste (gloves and containers) from units in closed disposable containers is placed in containers. Then they are moved to a waste management site or a temporary storage room for medical waste until the next transport of specialized organizations to the place of disinfection. Access by unauthorized persons to the temporary storage of medical waste is prohibited. [48].

During operation, the atmosphere is not polluted.

4.1 Analysis of probable emergencies that may occur in the laboratory during research

In case of emergency, you must immediately call the fire department at number “01” from your business phone or “101” from your mobile phone.

The notification of civil defense alerts in the event of an emergency to the personnel of the facilities is carried out using voice information via broadcasting channels, radio broadcast networks and communication networks. On the territory of TPU they do not use, do not produce, do not process, do not store radioactive, fire hazardous, as well as explosive substances that create a real threat of an emergency source. As the most probable technological emergencies, the project considers:

- fire in the facility.

Fire hazards for humans include toxic combustion products, low oxygen concentration, open flames, smoke, and high air temperatures.

The following measures must be observed to prevent fire:

1. Reducing the determining size of the combustible medium.
2. Prevention of the formation of a combustible medium.

In case of overheating, short circuits, etc. possible ignition of electrical installations, wiring. To extinguish the fire, it is necessary to use special means, it is impossible to use water and other conductive substances. Therefore, the premises should be equipped with means for extinguishing electrical installations and electrical wiring under voltage.

Conclusion

The analysis and assessment of harmful and dangerous labor factors that could affect the personnel involved in the development of the project was carried out. Protective measures were developed against these factors, on the basis of a labor assessment conducted, an assessment of working conditions. Issues related to safety, fire protection and environmental protection were considered. Recommendations on creating optimal working conditions were given.

Conclusion

According to the results of the literature review, the following conclusions were made:

1. Based on the studied devices and technologies, promising developments are those that could perform several functions or track several parameters.
2. For surface reduction of graphene oxide without damaging the polymer substrate, it is most promising to use laser irradiation.
3. For biomedical applications, the device must be made of biocompatible and non-toxic materials.
4. The most suitable 3D printing technology for creating the basis of the device is Fused Deposition Modeling. Since when using this technology, a combination of various materials with the necessary properties for biomedical applications is possible.
5. The most suitable material for creating a polymer substrate is PLA, since it has biocompatible properties, is non-toxic, and easy to process.

Based on the results of the experiments, the following conclusions can be drawn:

Based on the results of the experiments, the following conclusions can be drawn:

1. The second generation of the temperature sensor fully satisfies the tasks of the obtained characteristics and accuracy of the created device. Since reduced graphene oxide is a semiconductor structure, the temperature sensor has a negative temperature coefficient. This feature is traced in the graphs. When the sensor is heated, the resistance of the conductive structure decreases. When the sensor cools, the resistance of the conductive structure increases. The sensor has a smooth temperature characteristic. Sensor accuracy 0.1 + - 10%. According to the results of the experiment and the data obtained, the humidity sensor fully satisfies the goals and objectives.

2. Since reduced graphene oxide is a semiconductor structure, and the presence of silver particles of $AgNO_3$ in it increases the sensitivity of the sensor to changes in the chemical composition of the environment. Then, when a region with high humidity arises, a drop in resistance occurs at the sensor due to the interaction of the sensor surface with the environment. The humidity sensor has a smooth resistance characteristic when humidity levels change. According to the results of the experiments, the bending sensor fully satisfies the tasks and tasks.
3. Since the sensor works due to the effect of surface tension and deformation of the particles and the substrate on which they are located. Over time, a gradual deformation of the polymer surface occurs, as a result of which the polymer stretches. Since the distance between the reduced graphene oxide particles in the presence of surface tension depends on the state of the substrate, they deform, which is directly proportional to the deformation of the substrate on which they are located. The destruction of the sensor occurs 2 kOhm after every 100 continuous bending cycles for 5 minutes. The sensor remains operational after testing in 2000 continuous cycles.

In conclusion, we can conclude on the work done. All set goals and objectives were fulfilled. Sensors of temperature, bending and humidity were developed, experiments were carried out, data were obtained and processed. Based on the data obtained, graphs are plotted demonstrating the sensibility and accuracy of the sensors. To create the sensors, a PLA was used, which is non-toxic and biocompatible material, which allows us to consider the use of these sensors for biomedical applications.

Results of this research can be used for developing commercial versions of the presented sensors and consider the accreditation of these sensors for use in biomedical purposes .

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