ANNOTATION

Specialty “6D072300 – Technical Physics”
research work for the degree of Doctor of Philosophy (PhD)

Aimaganbetov Kazybek Pirzhanuly

LOW TEMPERATURE MEASUREMENT CELL FOR CHARACTERISATION OF SEMICONDUCTOR OPTOELECTRONIC MATERIALS AND DEVICES

General description of the research work.

Scientific work is aimed at developing a cell for measuring the electrophysical characteristics of semiconductor optoelectronic materials and devices.

Relevance of the topic.

In-depth research into semiconductor materials has a direct impact on the development and implementation of new effective and competitive solutions based on them . Low-temperature electrical and optical measurements play an important role in studying the optoelectronic properties of semiconductor materials. DC and AC studies at low temperatures provide valuable information about the electrical conductivity of materials, the nature and influence of carriers, the location of defects and impurities, and other characteristics associated with free charge carriers. It is necessary to take into account that carrying out electrical measurements on experimental samples under environmental conditions is accompanied by a number of problems associated with the quality of electrical contacts, which can ultimately lead to distortion of the electrical signal and incorrect measurement results. Solving these problems requires the use of high-quality measurement instruments, proven measurement methodology, consideration of the environment, and careful consideration of parameters that may affect the quality of the results. In this regard, the development of new and improved measurement devices and methods is relevant.

It is known that atmospheric parameters can affect the quality of electrical measurements. This is observed, first of all, in studies of the electrical properties of samples carried out at low temperatures. In such cases, the main problem is the condensation of atmospheric vapors or gases on the sample, which can lead to signal distortion and loss. Thus, control of the temperature of the sample under study and the atmosphere around it is an important condition for performing low-temperature measurements. In addition, certain types of measurements or certain types of samples often require the use of separate measuring cells adapted, for example, to the shape of the electrical contact pads. The design of the measurement cell, placed in an insulating vacuum environment for measurements at cryogenic temperatures, involves system integration of complex devices. This design must provide integration of electrical contact monitoring, cryogenic monitoring (temperature, pressure level) and control devices.

One of the technically important tasks of a comprehensive study of the electrical properties of semiconductor materials, identified as an **urgent task** in this work, is to find the possibility of implementing several types of electrical measurements in the dark and under light, providing comprehensive information about the properties of the samples under study, using a universal measuring device.

The purpose of the dissertation work is to develop measuring systems for studying the electrophysical characteristics of semiconductor materials and optoelectronic devices and to use the developed measuring system in practice.

The object of study is a low-temperature system for studying the electrophysical and optoelectronic properties of semiconductor materials and devices.

The subject of the study is expanded measuring capabilities of a low-temperature system for studying the electrophysical and optoelectronic properties of semiconductor materials and devices.

Research methods: current-voltage characteristics, capacitance-voltage characteristics, impedance spectroscopy.

To achieve this goal, it is necessary to solve the following tasks:

1. Development of a modernized low-temperature measuring device for studying the electrophysical and optoelectronic properties of semiconductor materials and devices;
2. Transfer of multilayer graphene synthesized on copper foil using the liquid-phase transfer method to a quartz glass substrate and study of its electrical properties in a developed measuring device using impedance spectroscopy in the temperature range 10 - 350 K;
3. Obtaining a highly efficient heterojunction silicon solar cell and studying its electrophysical and optoelectronic properties using the developed measuring device, determining the relaxation time and carrier lifetime based on complex impedance measurements in the dark and under illumination, studying the frequency-capacitive characteristics when changing the bias voltage and temperature range 10 - 350 K.
4. Determine the reliability of experimental results by comparison with previously obtained scientific works.

Scientific novelty of the work. The novelty and originality of the work lies in the fact that for the first time:

1. For the first time, a low-temperature measuring cell has been developed that makes it possible to carry out complex low- and high-frequency measurements of the electrophysical and optoelectronic properties of semiconductor materials and devices with different locations of electrical contact pads, in the dark and under light, in the temperature range of 10-350 K;
2. For the first time, in a developed measuring cell using impedance spectroscopy, temperature studies of the electrical conductivity of thin-film graphene obtained by liquid-phase transfer to a quartz substrate were carried out, and the activation energy associated with the transport of free charge carriers was determined;
3. For the first time, in the developed measuring cell, using impedance spectroscopy, the capacitance spectra of a heterojunction silicon solar cell were

measured in a wide temperature range and the activation energy associated with the thermal activation of charges captured in traps was determined.

Main provisions submitted for defense:

1. An upgraded version of a low-temperature measuring cell based on a microcryogenic machine, equipped with three universal electrical measuring contacts, makes it possible to measure the electrical properties of semiconductor materials and devices with both one-sided and two-sided contact pads at different light intensities, in the temperature range of 10-350 K, at low and high frequencies.
2. In the developed measuring cell, when measuring the electrical conductivity of thin-layer graphene in the temperature range 150-350 K using impedance spectroscopy, the thermal activation energy of 22 meV was determined, while the electrical conductivity of the sample changed depending on temperature, similar to the behavior of semiconductor materials.
3. In the developed measuring cell, when studying a heterojunction silicon solar cell with an efficiency above 20% by impedance spectroscopy in the temperature range of 16-300 K, a center for trapping free charge carriers with a thermal activation energy of 15 meV was determined.

Theoretical and practical significance of the research.

An upgraded version of the measuring cell based on a microcryogenic machine, allowing low-temperature measurements of flat semiconductor materials and devices with electrical contacts on one and/or two sides, complex impedance measurements in the frequency range from 1 Hz to 1 MHz and from 10 to 300 K allow the determination of electrophysical characteristics in a range of temperatures, in the dark and in the light. The significance of the results obtained is confirmed by publications in international peer-reviewed publications and international conferences, as well as patents of the Republic of Kazakhstan No. 6056, No. 4647. Results of experimental studies of semiconductor structures using the developed cell allow you to expand knowledge in the field of thermophysics, alternative energy, electronics, materials science and nanomaterials.

Reliability and validity of the results obtained - experimental results obtained in the course of scientific work are determined by their exact correspondence to the results presented in the scientific literature in this area. In addition, the reliability of the results obtained is confirmed by the presence of publications in foreign journals, present in quartiles Q2, Q3 in the Web database of Science and Scopus, as well as the presence of publications in collections of international scientific conferences and publications recognized by the KOKSON Ministry of Education and Science of the Republic of Kazakhstan.

Connection of the topic with the research plan and various government programs.

Scientific work was carried out within the framework of projects and programs of the Scientific Committee of the Ministry of Education and Science of the Republic of Kazakhstan:

1. “AP05133645-OT-20, Monitoring the state of the surface layer of crystalline silicon by passivation with hydrogenated self-conducting amorphous silicon, 2018 – 2020”

2. "AP05133651-OT-19, Development and research of promising renewable energy sources based on flexible organic semiconductor materials, 2018-2020"

3. "BR05236498-OT-20, Creation of optimal systems for autonomous power supply of agricultural facilities using alternative energy sources and development of elements, 2018 – 2020"

The author's personal contribution is the entire volume of the dissertation work, including experimental and theoretical work, computer modeling and quantitative evaluation of the experiment, analysis of scientific materials and preparation for publication. Problem setting, selection of research methods and discussion of results were carried out jointly with scientific supervisors.

Publications.

In order to obtain the scientific degree of Doctor of Science, 14 scientific publications were published based on the materials of research work and the results of work: 4 in journals from the list of Scientific Committee of the Ministry of Education and Science of the Republic of Kazakhstan, 3 works in materials of International scientific conferences, 6 articles in journals with a high impact factor included in international information resources Web of Science (Clarivate Analytics, USA) and Scopus (Elsevier, Netherlands), 2 utility model patents received.

Approbation of dissertation work.

The results of the research work were published in journals with a high impact factor included in the international information resources Web of Science (Clarivate Analytics, USA) and Scopus (Elsevier, the Netherlands) :

1. **Aimaganbetov, K.**, Almas, N., Kurbanova, B., Muratov, D., Serikkanov, A., Insepov, Z., & Tokmoldin, N. (2022). Electrical and Structural Characterization of Few-Layer Graphene Sheets on Quartz. Materials, 15(15), 5330. https://doi.org/10.3390/ma15155330 (Web of Science: IF=3.4, Q2; Scopus: Percentile=70%)

2. **Aimaganbetov, K.**, Yerezhep, D., Kishkenebayev, M., Chuchvaga, N., Almas, N., Tokmoldin, S., & Tokmoldin, N. (2024). Characterization of a Heterojunction Silicon Solar Cell by Means of Impedance Spectroscopy. Micromachines, 15(2), 184. https://doi.org/10.3390/mi15020184 (Web of Science: IF=3.4, Q2; Scopus: Percentile=72%)

3. Chuchvaga, N., Zholdybayev, K., **Aimaganbetov K.**, Zhantuarov, S., & Serikkanov, A. (2023). Development of Hetero-Junction Silicon Solar Cells with Intrinsic Thin Layer: A Review. Coatings, 13(4), 796. https://doi.org/10.3390/coatings13040796 (Web of Science: IF=3.4, Q2; Scopus: Percentile=64%)

4. **Aimaganbetov, K.**, Ospanov, K., & Almas, N. (2023). Mobility of hydronium ion for graphene oxide–and poly (acrylate)-based proton exchange membranes at the molecular level. Ionics, 29(12), 5405-5415. https://doi.org/10.1007/s11581-023-05245-y (Web of Science: IF=2.8, Q3; Scopus: Percentile=80%)

5. **Aimaganbetov, K. P.**, Aldiyarov, A. U., Zhantuarov, S. R., Almasov, N. Z., Terukov, E. I., & Tokmoldin, N. S. (2021). A Low Temperature Cell for High Frequency Electrophysical Measurements of Semiconductor Devices. Instruments and Experimental Techniques, 64, 886-890. https://doi.org/10.1134/S0020441221050146 (Web of Science: IF=0.6, Q4; Scopus: Percentile=9%)

6. Almasov, N., Kurbanova, B., Kuanyshbekov, T., Akatan, K., Kabdrakhmanova, S., & **Aimaganbetov, K.** (2024). Study of the structure and electrical properties of graphene oxide (GO) and graphene oxide+ nanocellulose (GO+ NC). Kompleksnoe Ispolzovanie Mineralnogo Syra= Complex use of mineral resources, 329(2), 103-109. https://doi.org/10.31643/2024/6445.21 (Web of Science: IF=0.7; Q3;)

Articles published in publications from the list of Ministry of Education and Science of the Republic of Kazakhstan:

1. **Aimaganbetov, K. P.**, Shegebay, S. K., Aldiyarov, A. U., Zhantuarov, S. R., & Tokmoldin, N. S. (2021). Research of electrophysical properties of solar elements by impedance spectroscopy method using a specially designed low temperature microcryogenic measuring cell. Вестник КазНУ. Серия Физическая (ВКФ), 76(1), 68-74. https://doi.org/10.26577/RCPh.2021.v76.i1.08

2. Chuchvaga, N. A., **Aimaganbetov, K. P.**, Tokmoldin, N. S., & Tokmoldin, S. Z. (2019). Моделирование и расчёт тепло-и фотофизических характеристик высокоэффективных кремниевых солнечных элементов. Вестник. Серия Физическая (ВКФ), 70(3), 55-62. https://doi.org/10.26577/RCPh-2019-i3-7

3. **Аймағанбетов Қ.П.**, Чучвага Н.А., Жантуаров С.Р., Шонғалова А.К., Тоқмолдин Н.С. Гетероөткелді кремнийлі күн элементтерінің баға факторлары мен операциондық шығыс сипаттамасының өтелу мерзіміне байланысты әсерін зерттеу. Хабаршы. Физика сериясы. №1 (64). 2018. 19-24 б.

4. Чучвага Н.А., Кислякова Н.М., **Аймаганбетов К.П.**, Ракыметов Б.А., Токмолдин Н.С. // Исследование влияния влажной химической обработки на поверхность кремниевых монокристаллических пластин // Вестник КазНУ. Серия физическая. №4 (67). 2018

Articles published in other scientific journals and publications

1. Chuchvaga, N. A., Schulze, J., Klimenov, V. V., Zholdybayev, K. S., **Aimaganbetov, K. P.**, Zhantuarov, S. R., ... & Tokmoldin, N. S. (2020). Optimization and Fabrication of Heterojunction Silicon Solar Cells Using an Experimental-Industrial Facility AK-1000 Inline. Известия высших учебных заведений России. Радиоэлектроника, 23(5), 57-62. https://doi.org/10.32603/1993-8985-2020-23-5-57-62

Publications in collections of international conferences:

1. Аймаганбетов К.П., Алдияров А.У., Теруков Е.И., Алмасов Н.Ж., ТокмолдинН.С., Токмолдин С.Ж. // Разработка установки для проведения комплексных адмиттансных измерений при исследовании полупроводниковых структур // XI Международная конференция, «Аморфные и микрокристаллические полупроводники», Физико-технический институт им. А. Ф. Иоффе, Российской Академи и Наук, Санкт-Петербург, Россия//19–21 ноября 2018 года

2. Аймаганбетов К.П., Гирин Д.В., Клименов В.В., Токмолдин Н.С., Токмолдин С.Ж., // Фотоэнергетикалық қондырғыларды тестілеуге арналған аса жарық диодты негізіндегі бақылау-өлшеу жүйесін әзірлеу// VI МЕЖДУНАРОДНЫЕ ФАРАБИЕВСКИЕ ЧТЕНИЯ Международная научная конференция студентов и молодых ученых, «ФАРАБИ ӘЛЕМІ» // Энергетика и энергоэффективность // КазНУ им. Аль Фараби// 2-12 апреля, 2019 г.

3. Kurbanova, B., Aimaganbetov, K., Karibayev, M., Almas, N., Ospanov, K., Kuanyshbekov, T., ... & Kabdrakhmanova, S. (2023). Formation of Nanochannels by Heavy Ions in Graphene Oxide Reinforced Carboxymethylcellulose Membranes for Proton Exchange Membrane Fuel Cells Applications. ASAM-8. THE 8TH ASIAN SYMPOSIUM ON ADVANCED MATERIALS, 349-350

Utility model patent

1. **Aimaganbetov K.P.** , Aldiyarov A.U., Zhantuarov S.R., Serikkanov A.S., Tokmoldin S.Zh., Tokmoldin N.S., Low temperature measurement chamber for complex electrical testing research of semiconductor materials // Patent for utility model No. 6056. – 2021.

2. Tokmoldin S.Zh., Keshuov S.A., Klimenov V.V., Girin D.V., **Aimaganbetov K.P.** , Tokmoldin N.S., A device for testing the output characteristics of photovoltaic installations. Patent No. 4647 (01/29/2020).