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Physics Education Research

Guided inquiry laboratory works in investigations of the photoelectric properties of semiconductors

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The aim of the present study is to create the guided inquiry laboratory works in studying the photoelectric properties of semiconductors in order to foster the students' research experiences. In this context, the general structure of guided inquiry laboratory work is proposed and described. Each laboratory work includes preparation section, experiment section, interpretation section and consolidation section. Two created laboratory works include five experimental investigations in luminous and current-voltage characteristics of CdS photoresistors, selenium and silicon solar cells. The use of self-made equipment allows students to be introduced to the general principles of creating installation for these experimental investigations. The advantages and possibilities of self-made device for studying the photoelectric properties of semiconductors have been formulated. The design of the device allows changing the illumination of the photodetectors, measure dark currents, determining the photocurrent, calculate the sensitivity of photodetectors, confirm sublinear law for photoresistors, and study the current-voltage characteristics for different luminous flux. The cost of manufacturing the device is quite low. The questions to consolidate knowledge are offered for each laboratory work. Described general method of performing guided inquiry laboratory work could be used in the study of other topics of physics. Proposed level of inquiry-based learning is successfully used by the authors of the present article during professional training of Bachelor's and Master's students, future physics teachers.
Keywords: Future teachers, professional training, inquiry-based learning, guided inquiry laboratory work in physics, photoelectric properties of semiconductors, photoresistors, solar cells.

1. Introduction

Physics is an experimental science. Therefore, the physical experiment is a source of knowledge in physics teaching. American Association of Physics Teachers (AAPT) Committee on Laboratories has created Recommendations for the Undergraduate Physics Laboratory Curriculum (Recommendations) [1]. Recommendations has made for foster the development of many key 21st century competencies and coincide with an ongoing national focus on authentic and engaging STEM educational experiences.

It is valid to think that "learning to teach yourself is a goal for the long term" [2, p. 10]. In this sense, the call for more authentic research practices is relevant in today's education because "the current era demands scientifically literate and skilled individuals" [3, p. 64]. We agree that "educational institution is the most important place to nourish the creative talents and abilities of students and also as an important medium in the generation of creative minds of the students" [4, p. 467]. In this context, Oliver et al. [5] encourage lecturers to develop courses in order to foster research experiences of students.

The inclusion of laboratory experiences help the development of the scientific thinking [6]. In this sense, the potential benefits laboratory experiments for the professional competences of students are discussed [7], and "guided inquiry learning model is one of the learning models that can be integrated into laboratory activity" [8, p. 1].

In 1839, E. Becquerel (1820–1891) described the photovoltaic effect produced by solar rays, and the first experiments with selenium-based semiconductors were conducted in 1876. The photoelectric properties of semiconductors are widely used in different fields of science and technology nowadays. Therefore, it is advisable to explore the photoelectric properties of semiconductors in the physics course.

The aim of the present study is to create the guided inquiry laboratory works in studying the photoelectric properties of semiconductors in order to foster the students' research experiences.

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2. Method

2.1. Structure of guided inquiry laboratory work

According to Recommendations, "physics is a way of approaching problem solving, which requires direct observation and physical experimentation" [1, p. iii]. Investigative Science Learning Environment (ISLE) involves students' development of their own ideas by observing phenomena and looking for patterns, developing explanations for these patterns [9, p. 1]. In this sense, "in-text investigations involve students in hands-on science, including creating their own experiments to solve problems" [10, p. T19] and well-crafted questions stimulate critical thinking because they lead to new insights [11].

Harmonizing with these thoughts, we offer the structure of guided inquiry laboratory work (Figure 1).

Guided inquiry laboratory work includes preparation section, experiment section, interpretation section and consolidation section. Students conduct a theoretical analysis of the issue and designing of experiment at the preparation section. The designing of experiment is a crucial part of research skills [12, 13]. Experiment section is designed to give students experience in observing, measuring and analysing data. Interpretation section asks students to evaluate practical use. This section is related to the motivation of the research because it answers on the question: "why we are researching?" Questions in consolidation section will encourage critical thinking by requiring students to summarize results, make comparisons and predict outcomes [10], and offer own ideas for solving problems.

Preparation, interpretation and consolidation are the homework of students. Students wrote reports and gave oral presentations. The laboratory workis reported in the form of a written report. At the university, the students gave a short oral presentation. This stage of work makes it possible to ensure communication because the results of the work were discussed.

According to Recommendations, curriculum learning outcomes are based on focus areas: Constructing knowledge, Modeling, Design Experiments, Developing technical and practical laboratory skills, Analyzing and visualizing data, and Communicating Physics. In this way, the proposed structure of guided inquiry laboratory work agrees with Recommendations [1].

Algorithm of actions at each stage is shown in Figure 2.

We used the developed framework for the study the photoelectric properties of semiconductors in order to foster the students' research experiences.

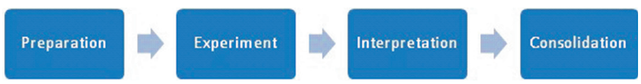

Figure 1: The structure of guided inquiry laboratory work.

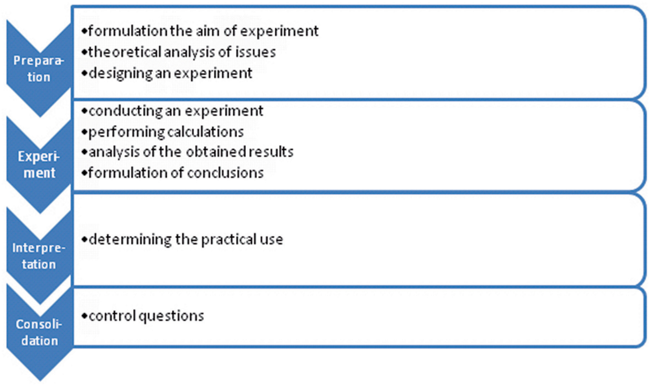

Figure 2: Algorithm of actions at each stage.

2.2. Description of self-made device

The work on the manufacture of a self-made device for study the photoelectric properties of semiconductors was started by the employees of our university. We continued this work and successfully completed it. The self-made device was manufactured in accordance with all safety rules. The cost of manufacturing the device is quite low. But making the device takes a lot of time. In addition, we have not found an analogue of a factory device that provides the same opportunities for research.

The construction of self-made device and its advantages are described in Appendix A.

The possibilities of self-made device is:

(1) study of sublinear law for photoresistors;
(2) study of specific sensitivity of photoresistors;
(3) study of current-voltage characteristics of photoresistors;
(4) study of sensitivity of solar cells;
(5) study of current-voltage characteristics of solar cells.

2.3. The investigations of the photoelectric properties of CdS photoresistors

2.3.1. Study of sublinear law

The link between the photocurrent and luminous flux is given by sublinear law

$$I = B\Phi^{\alpha}, \tag{1}$$

where I is the photocurrent, Φ is the luminous flux, B is the constant, α is the coefficient $(0 < \alpha < 1)$.

We want to create a graph of photocurrent I versus luminous flux Φ, but the law (1) contains unknown constant B and unknown coefficient α. Therefore, we rewrite formula (1) taking the natural logarithm:

$$\ln I = \ln B + \alpha \ln \Phi. \tag{2}$$

The illumination E of the photodetector is given by formula

$$E = \frac{\Phi}{S}, \tag{3}$$

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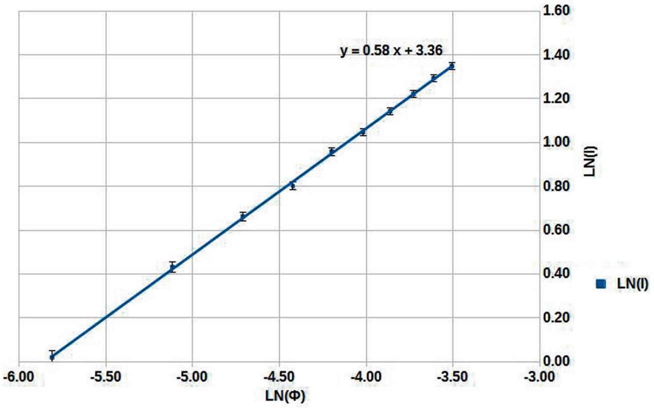

Figure 3: Graph of $\ln I$ versus $\ln \Phi$ for CdS photoresistor.

where Φ is the luminous flux, S is the surface area of the photodetector.

Using formula (3) we can determine the value of the luminous flux Φ.

According to our experimental data, we created a graph of $\ln I$ versus $\ln \Phi$ for cadmium sulfide (CdS) photoresistor (Figure 3).

The graph has the same form as an equation of a straight line:

$$y = mx + c. \tag{4}$$

In this case, the coefficient α is numerically equal to the slope coefficient m of a straight line ($\alpha = 0.58$) and the constant $\ln B$ is numerically equal to the number c ($B = 28.8 \frac{mA}{lm}$). The coefficient α is consistent with the table data for the CdS photoresistor ($\alpha = 0.5 - 0.8$).

So we can rewrite sublinear law (1) as

$$I = 28.8\Phi^{0.58}. \tag{5}$$

The research procedure includes the following steps:

1. Please use the laws of illumination by determining the illuminance E on the photoresistor. In our case, the intensity of light source is equal to 21 cd.
2. Please determine the luminous flux Φ when the surface area of the photoresistor is equal to 2.88×10^{-5} m^2.
3. Please use the movable rod to change the distance d from the light source to the photoresistor. This makes it possible to obtain certain values of illuminance E and luminous flux Φ.
4. Please measure the photocurrent I at certain values of luminous flux Φ.
5. Please create a graph of $\ln I$ versus $ln\Phi$.
6. Please compare the created graph with graph of a straight line.
7. Please determine the constant B and coefficient α using the graph.
8. Please check the obtained constant B and coefficient α with tabular data.
9. Please write down the sublinear law using formula (1).

2.3.2. Study of specific sensitivity

Integral, specific and spectral sensitivities are distinguished. Integral sensitivity demonstrates the dependence of photocurrent flowing through the photoelectric device on the all light flux. The specific sensitivity for photoresistor is measured at constant voltage of 1 V. The spectral characteristic demonstrates the dependence of the photocurrent on the luminous flux for a given wavelength.

Specific sensitivity K is given by formula

$$K = \frac{I}{\Phi \times V}, \tag{6}$$

where V is the voltage.

Since the dependence of photocurrent I on luminous flux Φ is not linear, then we can rewrite formula (6) as

$$K = \frac{\Delta I}{U \Delta \Phi}, \tag{7}$$

where ΔI is the small change in photocurrent I, $\Delta\Phi$ is the small change in luminous flux Φ.

In this case, specific sensitivity K is given by formula

$$K = \frac{1}{U} \frac{dI}{d\Phi}, \tag{8}$$

where $\frac{dI}{d\Phi}$ is the derivative.

We find the derivative of the photocurrent I with respect to luminous flux Φ using law (1):

$$\frac{dI}{d\Phi} = \alpha B \Phi^{\alpha-1}. \tag{9}$$

Using expressions (8) and (9) we can write formula for specific sensitivity K as

$$K = \alpha \frac{B}{U} \Phi^{\alpha-1}. \tag{10}$$

According to formula (10), we calculated the specific sensitivity of CdS photoresistor at illumination of 200 lx. The calculated value $(2900 \pm 260) \frac{\mu A}{lm \times V}$ agree with the accepted value 3000 $\frac{\mu A}{lm \times V}$.

The research procedure includes the following steps:

1. Please determine the luminous flux Φ at illumination of 200 lx.
2. Please calculate the specific sensitivity at illumination of 200 lx using formula (10).
3. Please calculate the absolute and relative errors.
4. Please check the calculated value with tabular data.

2.3.3. Study of current-voltage characteristics

The current-voltage characteristic demonstrates the dependence of the photocurrent on the applied voltage at constant light flux. The current-voltage characteristics for the photoresistor are shown in Figure 4. Current-voltage characteristics of the photoresistors are linear at low voltages, constant temperature and illumination. The deviation is observed at limit voltages. Current-voltage characteristics have no saturation. Therefore, the light sensitivity of the photoresistor is proportional to the applied voltage.

Slop of the straight line increases with increasing luminous flux. The steeper curve (in red) corresponds to an illumination of 200 lx. Shallow curve (in blue) corresponds to a dark current at illumination of 0 lx. Current-voltage characteristics make it possible to determine the numerical value of the photocurrent. Photocurrent is numerically equal to the difference between light current and dark current at given voltage (Figure 4).

The research procedure includes the following steps:

1. Please theoretically determine the distance d that corresponds to the illumination of 200 lx.
2. Please place the light source at determined distance d from the photoresistor.
3. Please measure light current at given voltage and illumination of 200 lx.
4. Please measure dark current at given voltage.
5. Please plot the relevant graphs and analyze them.

The electrical diagram of the performed experiments is shown in Figure 5.

2.3.4. Practical use of CdS photoresistors

The light sensitivity of the photoresistor is proportional to the applied voltage. In this sense, photoresistors are most used as light sensors to measure the light intensity. CdS photoresistors have high integral sensitivity. In our case, the specific sensitivity of CdS photoresistor at illumination of 200 lx is equal to $(2900 \pm 260)\frac{\mu A}{lm \times V}$. Therefore, photoresistors are used as light sensors when it is required to detect the presence and absence of light or measure the light intensity. Nonlinear dependence of photocurrent on light flux, dependence of their properties on temperature, inertia, which increases with increasing sensitivity are disadvantages of photoresistors.

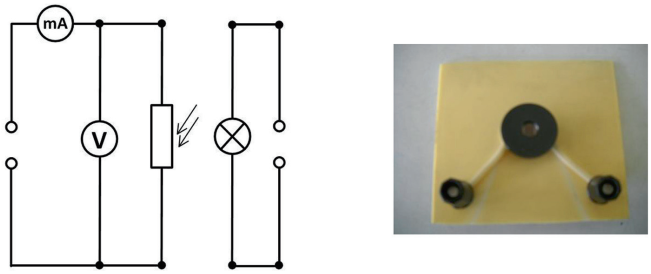

Figure 5: The electrical diagram (left); CdS photoresistor (right) that used in experiments.

2.3.5. Questions to consolidate knowledge

Questions of consolidation section are proposed in Appendix B.

2.4. The investigations of the photoelectric properties of solar cells

2.4.1. Study of sensitivity

Solar cells have a number of parameters that are not inherent in photoresistors because they are the current sources in contrast to photoresistors.

According to our experimental data, we created a graph of photocurrent I versus luminous flux Φ for selenium and silicon solar cells (Figure 6). Sensitivity of the solar cell is numerically equal to the slope coefficient of a straight line. In our case, sensitivity of selenium solar cell is equal to (492.4 ± 24.6) μA/lm, and sensitivity of silicon solar cell is equal to (5824.0 ± 320.0) μA/lm. The accepted values for selenium solar cells of 500 μA/lm and silicon solar cells of 6000 μA/lm are within these uncertainties.

The research procedure includes the following steps:

1. Please use the movable rod to change the distance d from the light source to the solar cell. This makes it possible to obtain certain values of illuminance E and luminous flux Φ. In our case, intensity of light source is equal to 21cd, the surface area of selenium

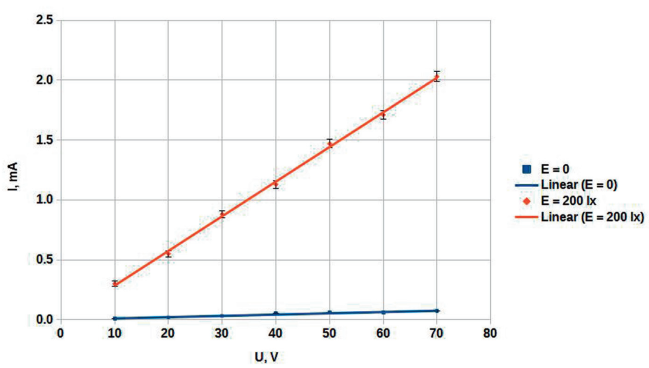

Figure 4: Current-voltage characteristics of CdS photoresistor.

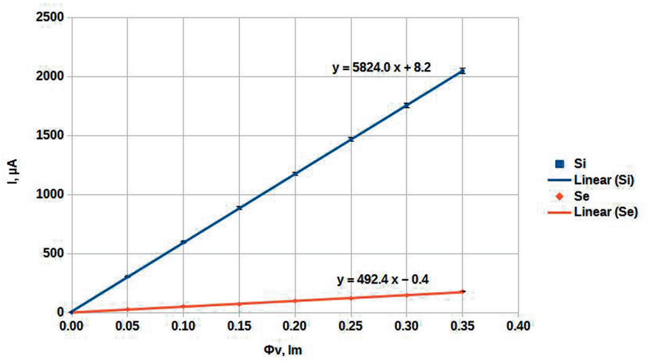

Figure 6: A graph of photocurrent I versus luminous flux Φ.

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solar cell is equal to 9.62×10^{-4} m^2 and the surface area of silicon solar cell is equal to 7.07×10^{-4} m^2.
2. Please measure the photocurrent I at certain values of luminous flux Φ for selenium and silicon solar cells.
3. Please create a graph of photocurrent I versus luminous flux Φ.
4. Please determine the sensitivity of selenium solar cell using the graph.
5. Please determine the sensitivity of silicon solar cell using the graph.
6. Please calculate the absolute and relative errors.
7. Please check the obtained values with tabular data.

2.4.2. Study of current-voltage characteristics of selenium solar cell

The solar cell supplies an approximately constant current at low load resistance. Figure 7 shows the current-voltage characteristics of selenium solar cell for different luminous flux. The experiments demonstrate that the current depends on the luminous flux.

The research procedure includes the following steps:

1. Please use the movable rod to change the distance d from the light source to the solar cell. This makes it possible to obtain certain values of illuminance E and luminous flux Φ.
2. Please measure the current-voltage characteristics for each value of luminous flux Φ.
3. Please create the current-voltage characteristics for different luminous flux Φ.
4. Please analyze the created graphs and draw a conclusion.

The electrical diagram of the performed experiments is shown in Figure 8.

2.4.3. Practical use of selenium and silicon solar cells

Selenium solar cells have spectral sensitivity characteristics that cover the entire visible region of light. Spectral

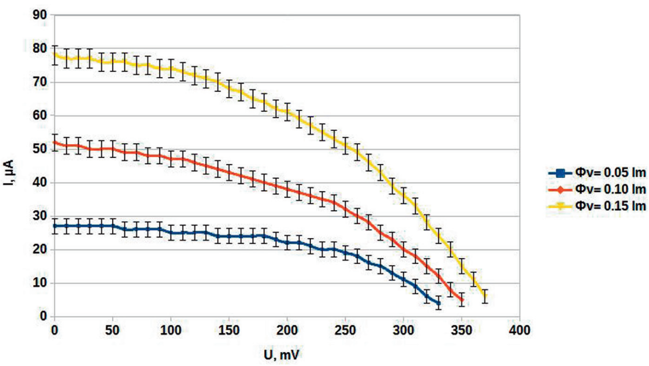

Figure 7: The current-voltage characteristics of selenium solar cell for different luminous flux.

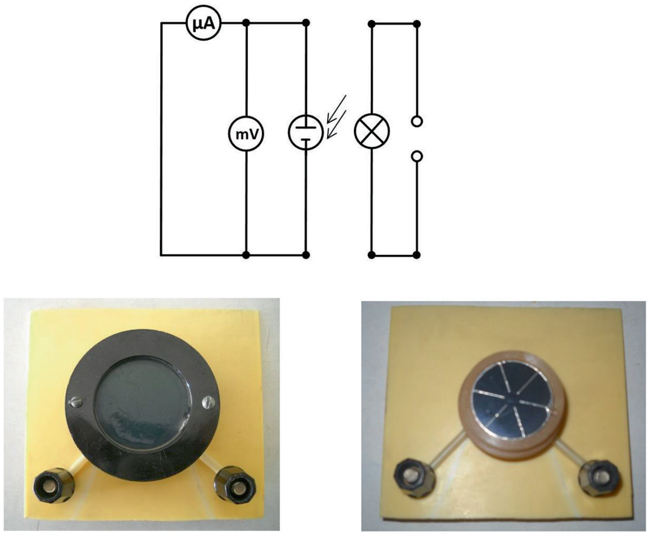

Figure 8: The electrical diagram (above); selenium solar cell (left) and silicon solar cell (right) that used in experiments.

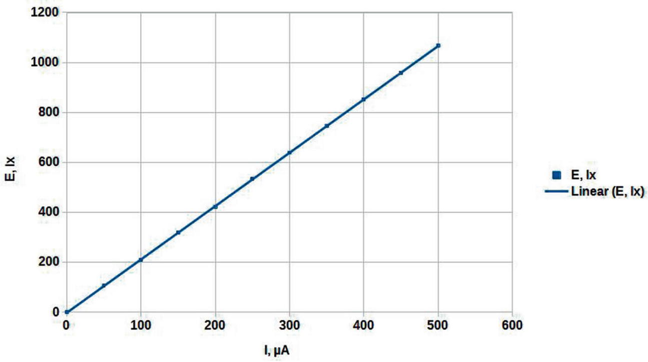

Figure 9: A graph of illuminance E versus photocurrent I for selenium solar cell.

characteristics of the selenium solar cell are similar to the sensitivity of the human eye [14]. Therefore, selenium solar cells are used in photometric measurement. In this case, a filter to correct the spectral sensitivity curve of a selenium solar cell to sensitivity of the human eye can be used [15].

Since photocurrent is directly proportional to the luminous flux (Figure 6), the selenium solar cells are used for objective measurement of illuminance (Figure 9).

In our study, the sensitivity of selenium solar cell equals to (492.4 ± 24.6) μA/lm, the sensitivity of silicon solar cell equals to (5824.0 ± 320.0) μA/lm, and the specific sensitivity of CdS photoresistor at illumination of 200 lx is equal to $(2900 \pm 260)\frac{\mu A}{lm \times V}$. The sensitivity of selenium solar cell is significantly lower than the sensitivity of silicon solar or CdS photoresistor. Therefore, selenium sensors are unable to measure very low light, such as moonlight or starlight. In this case, most modern light meters use silicon or CdS sensors.

2.4.4. Questions to consolidate knowledge

Questions of consolidation section are proposed in Appendix C.

3. Results

Using the created device, students conducted investigations of luminous and current-voltage characteristics of CdS photoresistors, selenium and silicon solar cells. Five experimental investigations are described. All measured and calculated values agree with the accepted values.

The sublinear law for photoresistors which expresses the connection between photocurrent I and luminous flux Φ has been confirmed. The coefficient ($\alpha = 0.58$) and constant ($B = 28.8$ mA/lm) in the sublinear law for CdS photoresistor has been determined. The specific sensitivity of CdS photoresistor at illumination of 200 lx has been calculated. The calculated value (2900 ± 260) μA/(lm $\times$ V) agree with the accepted value 3000 μA/(lm $\times$ V). Current-voltage characteristics of CdS photoresistor allowed determining the numerical value of the photocurrent that numerically equals to the difference between light current and dark current at given voltage.

The sensitivity of selenium solar cell ((492.4 ± 24.6) μA/lm) and sensitivity of silicon solar cell ((5824.0 ± 320.0) μA/lm) have been determined. The accepted values for selenium solar cells of 500 μA/lm and silicon solar cells of 6000 μA/lm are within these uncertainties. Photocurrent I is directly proportional to the luminous flux Φ.

4. Discussion

Laboratory work in physics may serve to provide training in how to do experiments [16, p. 1]. In our case, the proposed experimental investigations make it possible not only to deepen and supplement the theoretical knowledge obtained at the lectures, but also make it possible to study the methods of researching the physical parameters of semiconductor devices. Studying research methods is an important in context of order to foster the students' research experiences. The proposed investigations are built according to the principle "from simple to complex". For example, first it is proposed to investigate how to determine illumination, light flux. Then the students determine the illuminance at a given light flux.

Less expensive equipment is one category of improvement on existing laboratory works [17, 18]. In this context, the cost of manufactured device is low. The ability to perform several experimental investigations using a single device is also an advantage of the proposed self-made device.

The use of self made apparatus in measurements gives the students the ability to improve their research experimental skills [19]. In our case, the use of self-made equipment allows students to be introduced by some principles of creating installations for experimental investigations. Students can look "inside" the installation. The use of digital light sensor will reduce the measurement time. But the performance of this laboratory work will not develop in full the appropriate practical skills and abilities. For example, we propose to determine the illuminance using law of illumination by measuring the necessary parameters.

We chose the LibreOffice Calc spreadsheet to process the results of the experiment. This program is part of the free-running Libre Office office suite and allows us to present data as a spreadsheet and automatically perform calculations using built-in functions, to create graphs and seek approximation of the data points, to build trend lines on graphs, get their equations and plot the error bars. We do not describe the creation of graph and calculation of errors because these issues were covered in previous work [20].

5. Conclusions

Today semiconductors are widely used in different fields of science and technology. In this sense, the study of their properties is important in physics teaching. In addition, the basics ideas of study the illumination engineering is important for future teachers because it is necessary to observe sanitary standards of lighting when organizing the educational process.

The general structure of guided inquiry laboratory work is described. Each laboratory work includes preparation section, experiment section, interpretation section and consolidation section. Algorithm of actions at each stage is proposed. This method of performing guided inquiry laboratory work could be used in the study of other topics of physics.

Two created guided inquiry laboratory works include five experimental investigations in luminous and current-voltage characteristics of CdS photoresistors, selenium and silicon solar cells. The laboratory instructions are included. Proposed experimental investigations can be performed also without using the described self-made device.

The use of self-made equipment allows students to be introduced to the general principles of creating installation for these experimental investigations. The benefits of using self-made device for studying the photoelectric properties of semiconductors have been formulated. The design of the device allows changing the illumination of the photodetectors, measure dark currents, determining the photocurrent, calculate the sensitivity of photodetectors, confirm sublinear law for photoresistors, and study the current-voltage characteristics for different luminous flux.

Described method is successfully used by the authors of the present article during the teaching of

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Bachelor's and Master's students, future physics teachers, in Ternopil Volodymyr Hnatiuk National Pedagogical University (Ukraine). Students perform proposed experimental investigations in the course of Quantum Physics when studying topics "Photoconductivity" (Experimental Investigation of CdS photoresistors) and "Photovoltaic effect" (Experimental Investigation of Solar Cells). These topics in a simplified form are studied in the school course. In this way, guided inquiry laboratory works has been designed with the future in mind – for students' future work as physics teachers.

Acknowledgments

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Supplementary material

The following online material is available for this article
Appendix A: The construction of self-made device.
Appendix B: Experimental investigation of CdS photoresistors.
Appendix C: Experimental investigation of solar cells.

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