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PHYSICS EDUCATION

TEACHING/ LEARNING PHOTOVOLTAIC EFFECT IN HIGH SCHOOL

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Abstract. Because the technique and technology progress, and finally progress of human society can only be achieved through research and study, and conventional energy sources are exhaustible, we consider that the study of renewable energy sources is a subject of really interest for physics curricula in high school. In this paper the alternative based on direct conversion of solar light in electricity by photovoltaic effect is described. We focused our paper on the characterization of a solar cell based on monocrystalline silicon p-n junction, prepared in laboratory conditions, with the tools available at high school. We propose a Lesson plan, showing how the teacher can to integrate the photovoltaic experiments in students instruction

Key words: solar cells, photovoltaic effect, renewable energy sources, education,

1. INTRODUCTION

As you know, in energy field, humanity has passed in 19th century from wood to coal, and in the 20th century from coal to oil and there are indications that now is preparing a third transition, world being on the verge of a new era of advanced technologies and new types of fuel. Soon, will be totally different ways to produce and use energy and will appear, certainly new professions and experts in the field.

Subject using the new energy sources versus the classic one is on increased interest for humanity, therefore it can be proposed to the young students to prepare them as the main beneficiaries of use such renewable energy sources and to develop a positive attitude about the environmental protection [1–3].

Structural changes on recent years in our country highlights the need for the Romanian education reconstruction on new bases, according to current social and economic needs. The economic needs require improvement of human resources, qualification and labor flexibility. School wants to be the promoter of such an attitude, and this requires a diversification of supply school in order to give to each generation the individualized courses to school.

Aims of individualized course is to open education to student's aspirations, which may lead to increased the school efficiency and high training in social and economic context in current society.

Council of Europe recommended that the laws of each state must recognize and respect individual differences [4, 5]. Gifted children, like other categories, have required special education to develop the full availability of skills. School system must be sufficiently flexible to meet the specific needs of talented children.

For this purpose is required organization of activities the initiation of students in scientific research, aiming for:

- development the creative skills of students with high interest for a particular area, through scientific research;
- acquisition of additional knowledge in various areas, familiarity with research methods, with specific literature and improvement of skills on intellectual work.

In order to develop scientific research capacity of students from high school, we describe here a method of characterization of a solar cell based on a monocrystalline silicon *p-n* junction, prepared in laboratory conditions. Method of investigation is a part of the training process and represents the link of connection between theory and practice, ensuring on a hand the understanding of physical processes which take place in a photovoltaic cell and on the other hand the gain of the experimental skills needed to develop the scientific research in high school laboratories and further in universities or research institutes. This work is addressed for the moment to a group of students involved in a special training for national and international physics Olympiads, or in a center of excellence which promote the scientific research during high school education, but with possibilities to be extended to the whole curriculum in high school.

2. THEORETICAL BACKGROUND

2.1. GENERAL ASPECTS ON PHYSICAL PROCESSES IN THE *p-n* JUNCTION. CURRENT-VOLTAGE CHARACTERISTICS IN THE DARK

A *p-n* junction consists in a semiconductor wafer in which the abrupt transition from *n*- to *p*-type conductivity takes place [6, 7]. To electrodynamic equilibrium (Fig. 1), the electrons from region *n* will diffuse to region *p* where they will recombine with holes, leaving back ionized donors.

Thus, by both sides of junction plan is formed a spatial electric charge region, giving rise to an internal electric field $\vec{E}_i$ oriented from n- to p- region.

Thus, appears a potential barrier U_b. (Because $\vec{E}_i$ opposes to the continuum diffusion of majority charge carriers: holes in the p region, with the concentration p_p and electrons in n region, with the concentration n_n.)

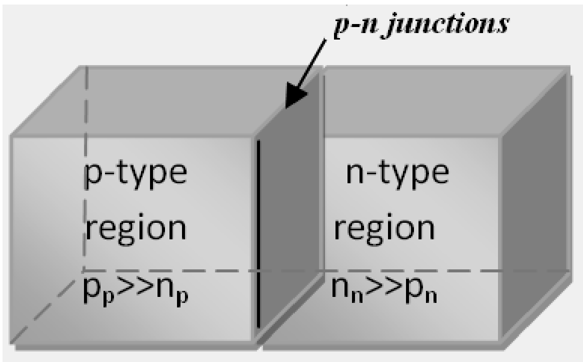

Fig. 1 – The physical model of a *p-n* junction.

Minority charge carriers (holes in the n region with concentration p_n and electrons in the p region with concentration n_p) are accelerated by the internal electric field of junction in opposite direction than that of displacement of majority charge carriers.

At thermal equilibrium and in the absence of polarization, the current I_{m0}, generated by the majority charge carriers flow, must be equal with the current I_{s0}, determined by the flow of minority charge carriers:

$$I_{m0} = I_{s0} = I_s . \tag{1}$$

If the voltage U is applied on *p-n* junction, in forward bias conditions, the potential barrier drop with the value qU, and the flux of majority charge carriers through junction, rapidly increases quickly, while the flux of minority charge carriers remains unchanged.

The intensity of electric current determined by flux of majority charge carriers increases exponentially with the applied voltage, following the relationship:

$$I_f = I_{m_0} \mathrm{e}^{\frac{eU}{kT}} . \tag{2}$$

In the reverse bias conditions the current rest about constant having the intensity

$$I_r = -I_s \tag{3}$$

Then the current-voltage (*I-U*) characteristic in the dark is given by:

$$I = I_f - I_s = I_s\left(\mathrm{e}^{\frac{eU}{kT}} - 1\right). \tag{4}$$

This relation is very well known as Shockley equation for an ideally *p-n* junction. Generally for a really *p-n* junction diode the dark current –voltage characteristics is described by the modified Shockley equation [8–10]:

$$I = I_0\left\{\exp\left[\frac{q\left(U - IR_s\right)}{nkT}\right] - 1\right\} + \frac{U - IR_s}{R_{sh}}, \tag{5}$$

where: I_0, n, R_s and R_{sh} are the reverse saturation current, diode quality factor, series and shunt resistance of the cell, respectively, and q is the electronic charge.

2.2. CURRENT-VOLTAGE CHARACTERISTIC OF A *p-n* JUNCTION PHOTOVOLTAIC CELL

Under illumination the incident photons on the cell will give rise to the pairs of electrons and holes. The concentrations of the photogenerated charge carriers electrons and holes are Δn and Δp, respectively. In absence of light, majority charge carrier's concentrations are much higher than concentrations of the majority charge carriers generated by light, while the concentrations of minority charge carriers on dark are much lower than the concentration of minority charge carriers generated by light.

The holes photogene rated in the n region, may reach by diffusion the region of barrier layer (depletion layer) where are accelerated by internal field $\vec{E}_i$ to region p. Electrons generated by light in the p region, which reach the depletion layer, are accelerated to n region. The electron-hole pairs directly photo generated in the depletion layer are also separed by the internal electric field, the electrons send in n side and holes in p side of the junction. In open circuit conditions the photovoltaic cell is polarized, appearing the open circuit photovoltage U_{oc} (+ to *p*-region and - to *n*-region, like in reverse bias conditions). Closing the circuit by a load resistor a current will flow to it in opposite direction than the current flowing through a *p-n* junction in forward bias conditions. This current reach the maximum values in short circuit conditions (I_{sc}), and this parameter is strongly dependent on the energy and the flux of incident photons. The current of the minority charge carriers flowing through the junction at illumination can be written as:

$$I_{s1} = I_s + eSq\Phi_0 = I_s + I_L, \tag{6}$$

where: I_s is the saturation current, e is the elementary charge, S is the area of *p-n* junction, q is the collection factor (a dimensionless quantity, representing the fraction of electron-holes pairs separated by the internal electric field $\vec{E}_i$ from the total number by pairs generated by incident photons), and Φ_0 is the photon incident flux.

Then, following the above treatment used for the current-voltage (*I*-*U*) characteristics in the dark (Shockley equation) and taking into account the equation (6), the current – voltage characteristics at illumination will be:

$$I = I_s\left(\mathrm{e}^{\frac{eU}{kT}} - 1\right) - I_L\,, \tag{7}$$

where $I_L = eSq\Phi_0$ is the photocurrent.

In open-circuit condition ($I = 0$), we obtain the open-circuit photovoltage U_{0c} (Fig. 2), given by:

$$U_{oc} = \frac{kT}{e}\ln\left(1 + \frac{I_L}{I_s}\right). \tag{8}$$

In short-circuit conditions ($U = 0$) the current is given by:

$$I_{sc} = -I_L \tag{9}$$

representing the photocurrent.

Current-voltage characteristics of a photovoltaic cell, in the absence of illumination ($\Phi_0 = 0$), coincides with the *I*-*U* characteristics of an ordinary *p*-*n* junction in the dark. At illumination ($\Phi_0 \neq 0$) the current-voltage characteristics is translated with the size I_L towards negative axis of currents (Fig. 2).

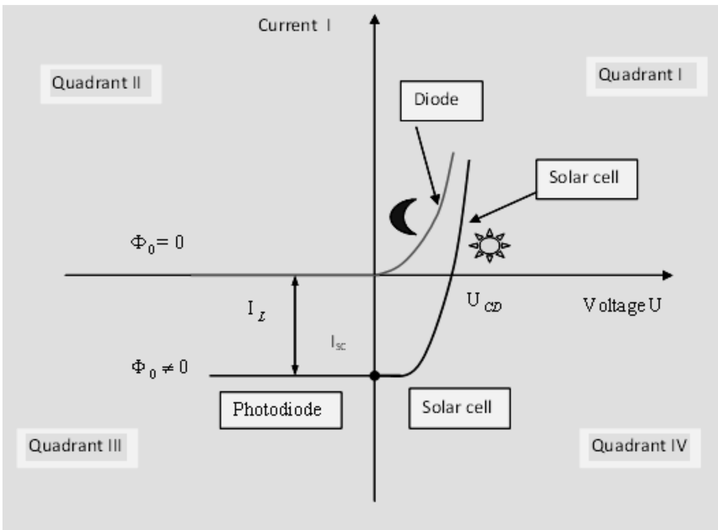

Fig. 2 – Current-voltage characteristic of *p*-*n* junction in the dark $(\Phi_0 = 0)$ and at illumination $(\Phi_0 \neq 0)$, respectively.

With a positive voltage and negative current, in fourth quadrant the photovoltaic cell run in regime of photo element, representing a really energy source, according with the First Thermodynamic Principle.

2.3. APPLICATIONS OF PHOTOVOLTAIC CELLS

The *p*-*n* junction structures specifically builded to convert directly the solar energy into electricity with high efficiency, are called *solar cells*.

Solar cell was invented 50 years ago, in 1954. It is a device, which in incidence of light radiation, acts as an electrical generator, converting solar energy into electricity. The bases of this process are three basic phenomena [11–13]:

- *Absorption of light which generate the nonequillibrium electron-hole pairs;*
- *Separation of the photogenerated charge carriers in the internal electric field;*
- *Collection of the photogenerated charge carriers in the external circuit.*

Schematically these processes are illustrated in the Fig. 3:

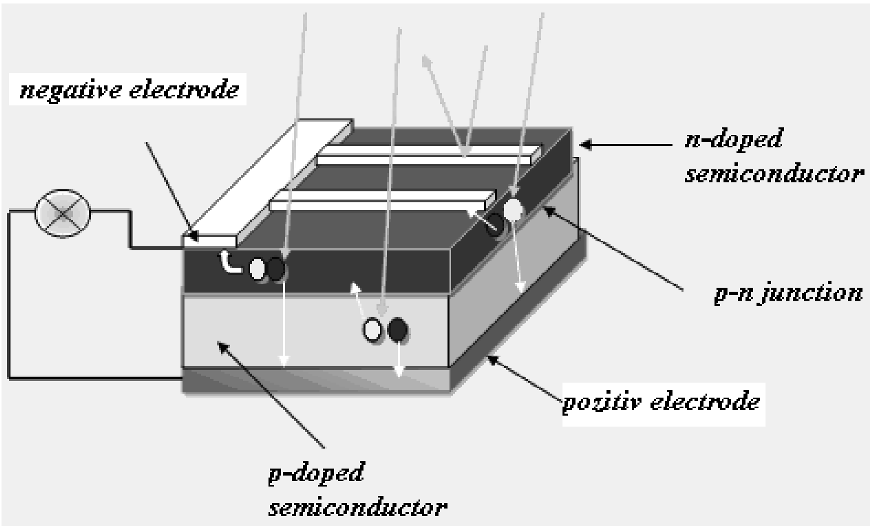

Fig. 3 – Physical processes of solar cell.

Currently, there are many types of solar cells, but those based on silicon semiconductor diodes are the most used in the large scale application, due to their high power conversion efficiency, more than 27%.

The power produced by a solar cell by a load resistor R_s can be calculated using the expression:

$$P = UI = U[I_s(\mathrm{e}^{\frac{eU}{kT}} - 1) - I_L]. \tag{10}$$

Taking into account the definitions of U_{oc} and I_{sc} (eqs. (8) and (9)), there is a value of the load resistor, for which the power transferred from the cell rich its maximum value $P_m = U_m I_m$. Using the coordinates of this point (U_m and I_m) the Fill Factor, defined by:

$$\mathrm{FF} = \frac{I_m \cdot U_m}{U_{oc} \cdot I_{sc}} \tag{11}$$

is introduced, as a parameter showing how much the solar cell behaves like an ideal generator ($R_{ss} \to 0, \quad R_{sh} \to \infty$).

With these parameters, the power conversion efficiency of the cell is given by:

$$\eta[\%] = \frac{U_m I_m}{I_{inc}^{'}} = \frac{FF \times J_{sc} \times U_{oc}}{I_{inc}^{'}} \times 100, \tag{12}$$

where: $I_{inc}^{'}$ is the light power density incident on the cell and J_{sc} is the short-circuit current density.

So, the typical cell parameters in regime of photoelement (in fourth quadrant) are: U_{0c}, I_{sc}, FF and η.

A briefly characterization [14–16] of a solar cell supposes the measurement and analysis of:

- Action – spectra ($I_f = f(\lambda)$ characteristics)
- Current-Voltage characteristic in the dark
- Current-voltage characteristic at illumination, in fourth quadrant (in regime of photoelement).

3. EXPERIMENTAL RESULTS AND DISSCUSIONS

3.1. THE ACTION-SPECTRUM OF THE MONOCRYSTALLINE SI *p-n* JUNCTION SOLAR CELL

The action-spectrum or spectral response of a photovoltaic cell means the dependence of the short-circuit photocurrent on the energy of incident photons. This characteristic will give information about the photoactive region and permits also to determine the band gap of the semiconductor, from which the cell is fabricated. Using the experimental setup shown in Fig. 4, the action spectrum was recorded, measuring the short-circuit photocurrent for each value of the wavelength ranging between 400 and 1 200nm. The action spectrum is shown in Fig. 5, where the dependence of short-circuit current I_{sc}(u.a.) normalized to the unit, as a function on the wavelength λ(μm) it was shown. The maximum value of the photocurrent of $I_{sc} = 51.6\mu A$ is obtained for $\lambda = 0.97\mu m$. Region of maximum sensitivity is between 0.8 and $1.1\mu m$, suggesting that the photoactive region is in the *p-n* junction what it is presented in structure. Using Mott's formula:

$$E_g = \frac{hc}{\lambda_{1/2}}, \tag{13}$$

where: h is Plank's constant, c is the light speed and $\lambda_{1/2}$ is the wavelength corresponding to the half of the maximum spectral response, the band gap energy of Si was determined. Using the value $\lambda_{1/2} = 1.08\mu m$ from the action spectrum (Fig. 5) the value $E_g = hc/\lambda_{1/2} = 1.14 eV$ for the band gap Si was obtained, a very closely value to those determined by other methods.

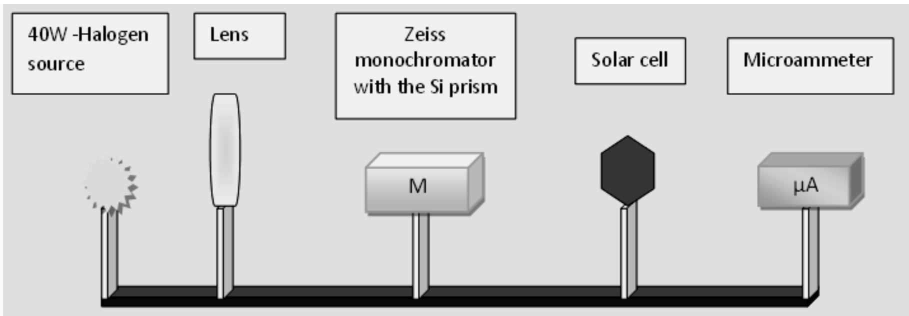

Fig. 4 – Experimental setup for measuring the spectral characteristic of a *p-n* junction solar cell.

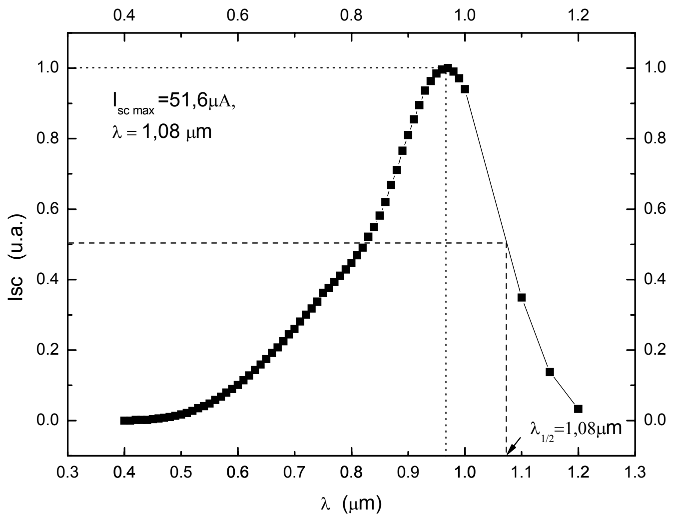

Fig. 5 – Action spectrum of the monocrystalline Si *p-n* junction solar cell.

3.2. STUDY OF DARK CURRENT-VOLTAGE CHARACTERISTICS AND DETERMINING OF THE DIODE PARAMETERS (RECTIFYING FACTOR RR, *N* AND I_0)

Information on the presence of barrier layer of the junction and its quality can be obtained from the analysis of dark current-voltage characteristic, both in forward and reverse bias conditions. Using the experimental setup shown in Fig. 6, the dark *I-U* characteristic was drawn.

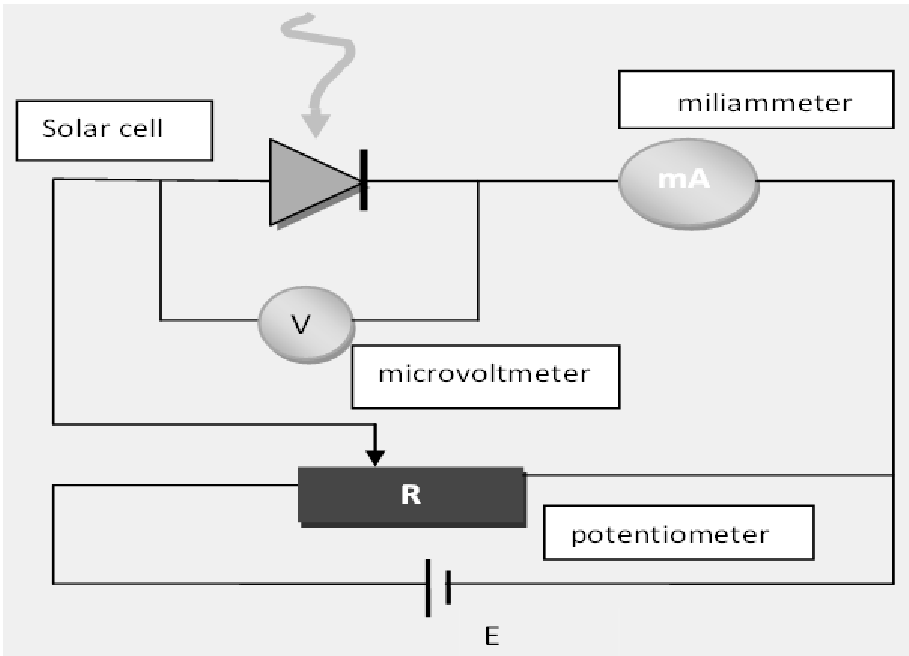

Fig. 6 – The scheme of experimental setup used to ambipolar current-voltage characteristics measurements.

In Fig. 6, solar cell (C. S.) was connected to a DC voltage source in a connection with a Helipot potentiometer, providing a resolution of 10mV. The current was measured with a Philips Digital miliammeter and voltage on diode with a Philips microvoltmeter. Based on experimental data acquisition, the current – voltage characteristic was plotted, in Fig. 7. It can observe the asymmetry for this characteristic due to the presence of *p-n* junction. The rectifying ratio (R_R), representing the ratio of forward current to reverse current at a same voltage, was 20 for the voltage of 0.5V. Information on quality of junction was obtained from the forward current-voltage characteristics plotted in semi-logarithmic scale, Fig. 8.

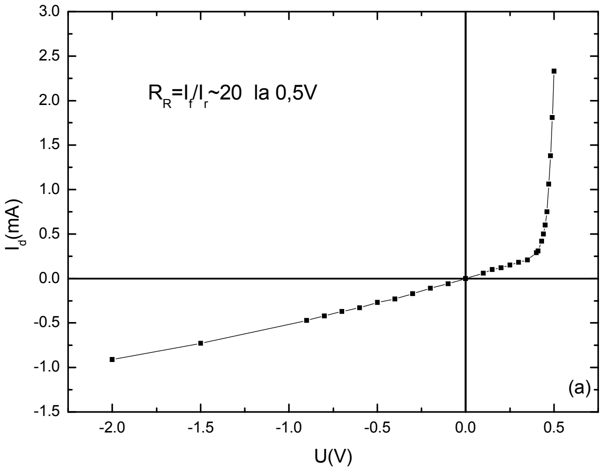

Fig. 7 – Dark current-voltage characteristic of a solar cell with *p-n* junction monocrystalline Si.

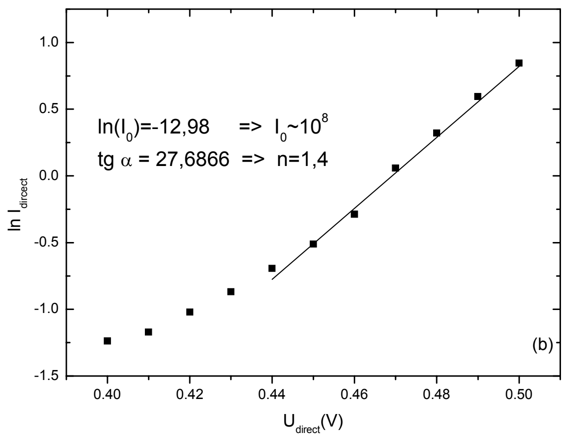

Fig. 8 – The forward bias current-voltage characteristics in semi-logarithmic scale.

In this range of voltage the, *I-U* characteristics is described by $I \cong I_0 e^{\frac{qU}{nkT}}$. So, $\ln I$ as a function on applied voltage is:

$$\ln I = \ln I_0 + \frac{qU}{nkT}. \tag{14}$$

Fitting the experimental data with equation (14), the values $n = \frac{1}{V_T} \cdot \mathrm{tg}\alpha = 1.4$ and $I_0 \approx 10^{-8}\,\mathrm{A}$, were obtained for the diode ideality factor and saturation current, respectively. In the above relationship for *n* ideality the thermal potential to room temperature was used with the value of $V_T = {kT}/{q} = 0.025\text{V}$ and the slope of straight line tgα shown as inset in Fig. 8.

3.3. THE STUDY OF *I-U* CHARACTERISTIC UNDER ILLUMINATION, IN FORTH QUADRANT

To measure the *I-U* characteristic under illumination in forth quadrant, the solar cell was series connected with a variable load resistance, (changing in the range $10-10^5\,\Omega$) and illuminated with white light of $20\text{mW}/\text{cm}^2$. For each value of load resistor in the above range, the current and voltage delivered on it were measured. The experimental setup used is shown in Fig. 9.

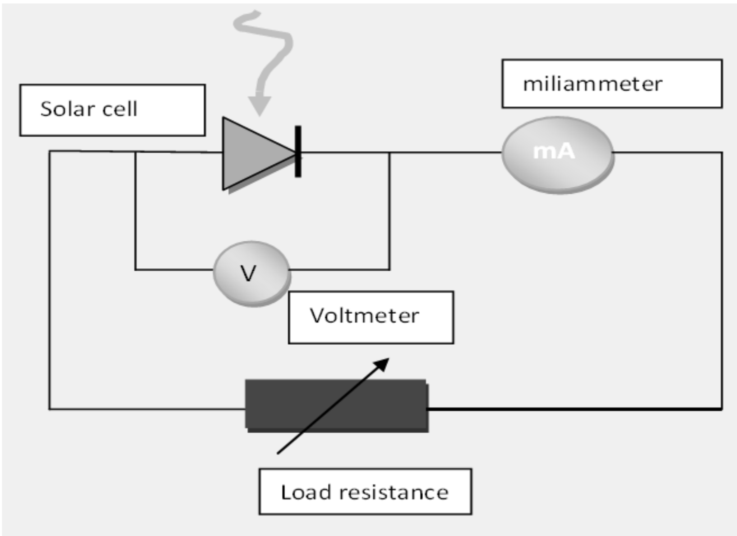

Fig. 9 – Experimental setup used to measure the *I-U* characteristics in regime of photoelement.

Using the experimental data, the current-voltage characteristic in forth quadrant, at illumination, was plotted in Fig. 10.

From this figure were determined the typical parameters as photoelement:

$$U_{oc} = 0.5\text{ V},\ I_{sc} = -3.89\text{ mA}.$$

To determine fill factor with accuracy, the power-voltage dependence was plotted in Fig. 11. The coordinates of the maximum point from Fig. 11, related with Fig. 10, lead to the values: $U_m = 0.42\text{ V}$, $I_m = -3.2\text{ mA}$.

Using these parameters in equation (11), the fill factor was obtained, of 0.74, value which suggests the presence of a structure with low series resistance and high shunt resistance, respectively.

Replacing the values of U_{oc}, I_{sc}, FF and I'_{inc}, in equation (12) a value of 7.3% was obtained for power conversion efficiency *h*, good value for a cell prepared in student laboratory conditions.

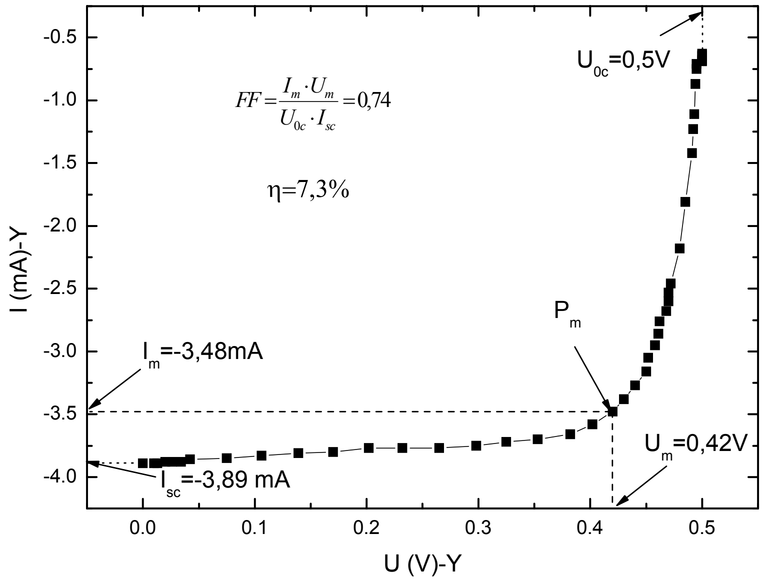

Fig. 10 – Current-voltage characteristic in quadrant IV of a photovoltaic cell with *p*-*n* junction on Si monocrystalline illuminated in integral light with incident power $P_i = 20\text{mW}/\text{cm}^2$.

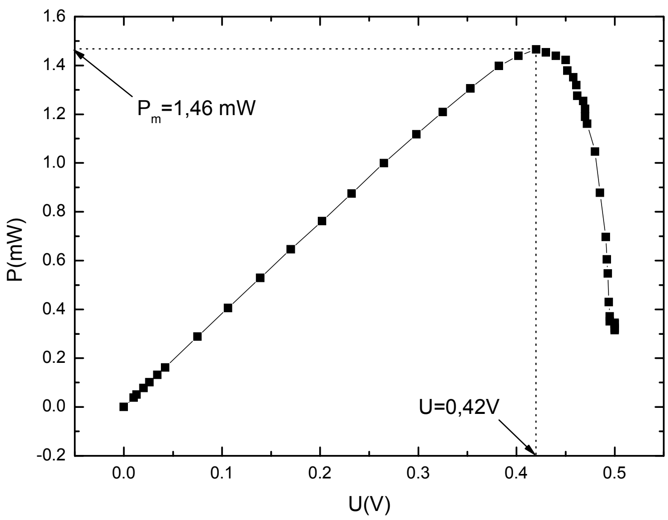

Fig. 11 – The power-voltage characteristic.

For all these data analysis was used an Origin Software. The Origin Lab is professional software specializing in data analysis and plotting of graphs. It contains several sheets, data import capabilities, query databases, making professional graphics. The software is used in colleges and universities worldwide, with friendly interface that is a very good tool in experimental data processing laboratory [17, 18].

4. CONCLUSIONS

Laboratory work has achieved its objectives. Students were fascinated by this new way to make an experiment. Processing of experimental data using Origin Lab 7.0 proves that it can be used in physics laboratory of high school.

The students understand the mechanism of photovoltaic effect generally and gain the experimental skills to characterize a solar cell.

Measuring the action spectra and using the Mott's Formula the students determined the band gap of Si observing the good agreement between their value and the values obtained by other measurements.

Plotting the current-voltage characteristics in both forward and reverse conditions, in the dark, the students observe that the *p*-*n* junction Si cell is a nonlinear element of circuit, with high asymmetry, and fitting the experimental data with the Shockley's equation they determined the parameters R_R, n, I_0.

The measured current-voltage characteristics in fourth quadrant under the light, gave the possibility to the students to find with accuracy, the typical parameters of the cell working in regime of photoelement (U_{oc}, I_{sc}, FF, and η).

The students were fascinated by their good results obtained using the experimental setups available in their laboratories, acquiring the really skills for research in this field.

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