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Electrical properties mono- and polycrystalline silicon solar cells

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Properties

ABSTRACT

Purpose: The goal of this article was to compare the properties of mono- and polycrystalline silicon solar cells. It was based on measurements performed of current-voltage characteristics and calculated parameters using mathematical formulas.

Design/methodology/approach: Light and dark current-voltage characteristics of solar cells were measured using a solar simulator PV Test Solutions company SS150AAA model. The measurements were performed under standard conditions (Pin = 1000 W/m^2, AM1.5G spectrum, T = 25°C). The basic characteristic of the solar cells were determined using the software SolarLab and calculated using mathematical formulas.

Findings: Results and their analysis allow to conclude that measurements of current-voltage characteristics enable characterization of the basic parameters of solar cells. Can give important information about the property of prepared metallic contacts on the solar cells.

Practical implications: Knowledge about the current-voltage characteristics of solar cells and their basic parameters enables the assessment of the quality of their production and the improvement.

Originality/value: The paper presents some researches of the basic parameters of mono- and polycrystalline solar cells determining the current-voltage characteristics.

Keywords: Photovoltaics; Silicon solar cells; Current-voltage characteristics; Monocrystalline; Polycrystalline; Efficiency; Open circuit voltage; Short circuit current; Maximum power point; Fill factor characteristics

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1. Introduction

Photovoltaics is a field of science and technology relying on the processing of sunlight into electricity. Despite the high costs compared to conventional sources it is used for two main reasons: ecological and practical. It's because solar radiation is available practically everywhere. Photovoltaics, as a discipline engaged in the generation of electricity from renewable sources, is now developing rapidly and it appears that in the near future the common use of it will increase [5]. For example, small solar cells that generate few milliwatts are used in watches, calculators, small toys, radios and portable televisions. Whereas large installations are combined into modules and used to supply power grid [1,6].

2. Construction and manufacturing of a silicon solar cell

A solar cell is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. The basic material used for production of the solar cells is silicon.

Monocrystalline silicon is made using the Czochralski process. Single-crystal wafer cells are expensive because they are cut from cylindrical ingots. The surface of a cutted wafer does not cover whole solar cell module square without a substantial waste of refined silicon [21,22].

Polycrystalline silicon is made from cast square ingots - large blocks of molten silicon carefully cooled and solidified. Poly-Si cells are less expensive to produce than single crystal silicon cells, but are less efficient [2,6,20].

Solar cell consists of the following elements (Fig. 1) [4,12,16]:

- Silicon wafer (mono- or polycrystalline) with p-n junctions on the surface,
- Front and back contact; front contact should have proper shape to make the most of the incident radiation,
- Antireflection layer - covering the front surface.

There are three main types of solar cells:

- Monocrystalline (Fig. 2a) are formed on the silicon crystal with a homogeneous structure. The basis for the formation of cells are suitable size blocks of silicon. They are cut into a wafer whose thickness is about 0.3 mm. Monocrystalline solar cells achieve the highest levels of performance and life [3,4].
- Polycrystalline (Fig. 2b) are consisting of many small silicon grain. These solar cells are less efficient than monocrystalline. The production process is easier and have lower price [3,4].
- Amorphous (thin film) - are produced through embedding few layers of silicon on the surface of another material, such as a glass. In these solar cells, we cannot distinguish individual cells. Amorphous solar cells are usually used in small devices such as calculators and watches. [3,4,8,15].

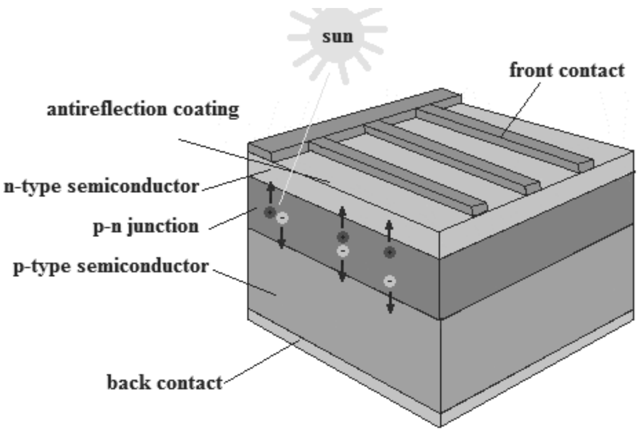

Fig. 1. Construction of a solar cell [19]

Solar cells are semiconductor devices, so they can made in the same processing and manufacturing techniques as other semiconductor devices. However, the stringent requirements for cleanliness and quality control of semiconductor fabrication are necessary.

Poly-crystalline silicon wafers are made by wire-sawing block-cast silicon ingots into a very thin (180 to 350 micrometer) slices or wafers. The wafers are usually lightly p-type doped. To create a solar cell from such wafer, a surface diffusion of n-type dopants is performed on the front side of the wafer. This forms the p–n junction few hundred nanometers below the surface.

a) b)

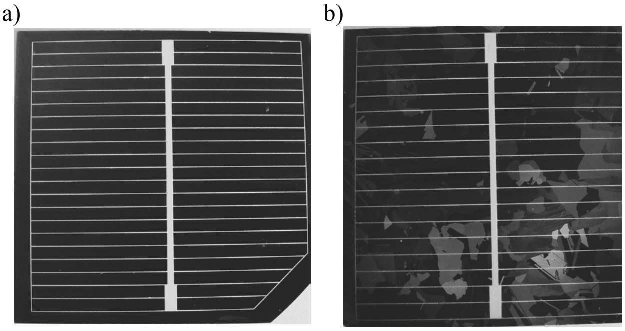

Fig. 2. Silicon solar cell a) monocrystalline; b) polycrystalline

To increase the amount of light reaching the p-n junction we use an anti-reflection coatings, coupled into the solar cell. For antireflection coatings the titanium dioxide was used recently, but now a silicon nitride are used mostly, because of its excellent surface passivation properties.

Then the wafer has a full area metal contact made on the back, and a grid-like metal contact made up of fine "bus bars" are screen-printed onto the front surface using a silver paste. The rear contact is also formed by screen-printing a metal paste, typically aluminium. Usually this contact covers the whole back area of the solar cell. The paste is then heated at several hundred degrees Celsius to form metal electrodes. After the metal contacts are made, solar cells are interconnected by flat wires or metal ribbons, and assembled into modules or solar panels [1,11,14,16-18].

2.1. Photovoltaic phenomenon in p-n junctions

When the p-n junction is hit by the light beam, photon with energy greater when semiconductors energy hole generates electron-hole pairs. The newly created electric charge carriers are mostly recombined, which generates heat. The condition for the creation of the photovoltaic phenomenon is to separate these pairs before recombination. This requires a presence of an internal electric field. This strong electric field exist in the p-n junction due to spatial cargo. In this electric field the electrons are moved from p-type to n-type semiconductor and holes are moved from the n-type semiconductor to p-type, resulting in separation of generated electron-hole pairs. Separated minority carriers on the one side of the connector, are becoming majority carriers with limitless lifetime on the other side, thus they create voltage (V_{PH}) and current (J_{PH}) of a solar cell.

As a result of the reflection on the surface, not the whole light beam takes part in the photovoltaic conversion. When determined by R (λ) light reflection coefficient for the cell, the term (1 - R (λ)) determines the value of the light beam that passes into the cells and is involved in photovoltaic conversion. The occurrence of reflection results in reduced power that is obtained. It depends on the state of the surface polishing. In order to reduce the reflection of light from the surface the solar cells are covered with a antireflection coating.

With a stream of photons incident on the surface of the semiconductor, just a part of (1 - R (λ)) is absorbed. These photons penetrate the semiconductor, but because its thickness is low, some of them manage to go through it and then through the of its rear surface [4,7].

3. The current - voltage characteristics of solar cells

Single solar cells are connected into panels, and panels can be connected into modules. Properties of the solar cell are described by current-voltage characteristics. We understand it by the intensity of electric current generated by different values of radiation. If you omit the resistance to the flow of current, the output current of the panel is a multiple of the current cell and is related to the parallel connections of cells and modules. Similarly, the output voltage of the module is dependent on the number of series-connected cells and modules [3,14].

Photovoltaic solar cell produces electricity only when it is illuminated, electricity is not retained [3].

3.1. The basic parameters - illuminated solar cell

Determination of the basic characteristics of solar cells is obtained by examining current-voltage characteristics (Fig. 3). When the cell is illuminated, the electrons are formed between the potential difference, it's known as the open circuit voltage V_{oc}. Resistance cell R_L causes current to flow in the circuit, the value of which depends on it. The largest amount of current flowing through the cell at R_L=0 Ω is called the short-circuit current I_{SC}.

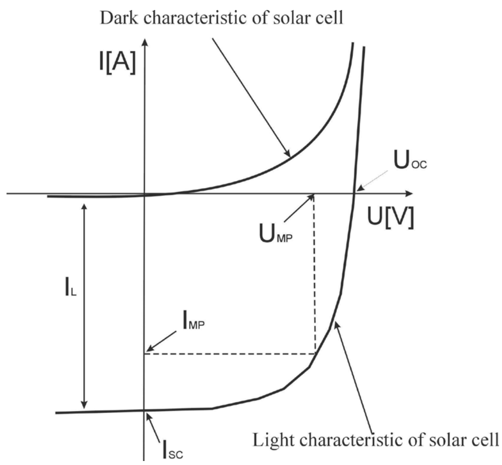

Fig. 3. The light and dark current-voltage characteristics of the solar cell and parameters defining the efficiency of solar cell [19]

Current-voltage characteristics of the cell are a graph of the output current of the PV generator as a function of voltage at a given temperature and irradiance. Characteristic sections of the I (U) are shown in the Fig. 4 [1,17]:

- Open circuit voltage (U_{OC}) - voltage at the terminals of unloaded (open) PV generator at a given temperature and irradiance,
- Short circuit current (I_{SC}) - the output current photovoltaic generative at a given temperature and irradiance,
- P_{MPP} - Point MPP (Maximum Power Point) is a point whose coordinates U_{MPP} I_{MPP} and form a rectangular shape with the largest possible area under the curve I (U) (Fig. 5) [1,4,24].

Voltage generated by a single photovoltaic cell depends on the type of material from which it was produced and is about 0.6 V. The output voltage is a weakly dependent on the intensity of the radiation, while the current increases significantly with an increase in radiation intensity (Fig. 6) [1,4,15].

Position of the operating point is strongly dependent on the resistance and radiation. The output voltage depends significantly on the temperature of solar cells: increased results are in a lower working temperature and efficiency (Fig. 7) [1,9].

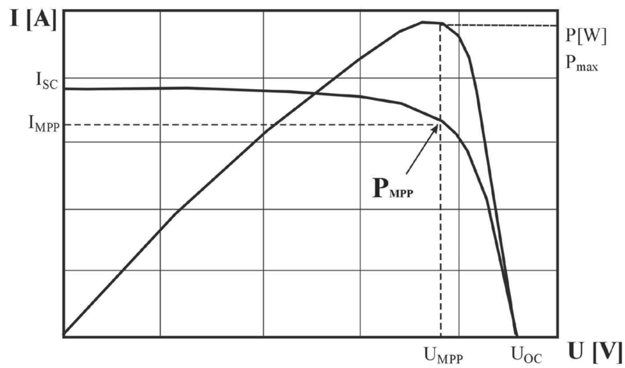

Fig. 4. Current-voltage characteristics and the power of solar cells in a function of voltage [1]

Photovoltaic conversion efficiency is defined as the ratio of the maximum output of electrical power to the total power of the incident radiation [1,8,9,23].

$$FF = \frac{U_{MPP} * I_{MPP}}{U_{oc} * I_{sc}} \quad (1)$$

where:
FF - fill factor characteristics - is determines the quality of solar cell
I_{MPP} - current value at the point of maximum power
U_{MPP} - voltage corresponding to the position of the point of maximum power
P_λ - the power of the incident solar radiation, corresponding to a wavelength λ
R (λ) - reflectance from the upper surface of the absorber,
λg - wavelength limit.

$$\eta = \frac{J_{SC} * U_{OC} * FF}{J * S} \quad (2)$$

were:
J - the intensity of the radiation incident on the cell [W/m^2]
S - surface area of the cell

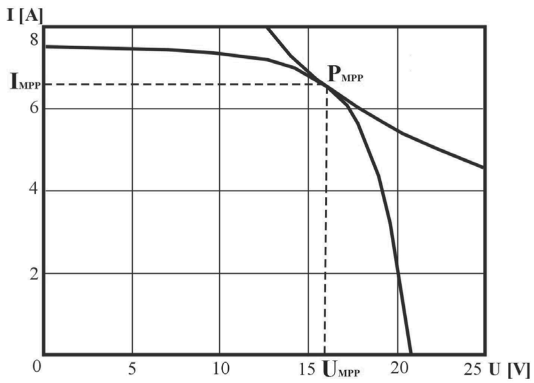

Fig. 5. Current-voltage characteristics of the photovoltaic module under STC (standard test conditions) [1,10]

FF characteristic, like the U_{OC} depends on the structure and type of semiconductor (monocrystalline, polycrystalline, thin film), the level of doping p-n junction of the two areas and the amount of built-in potential barrier and junction temperature. Very good cells, obtained by doping with boron at 1 Ω cm resistivity are characterized by a value of FF> 0.8 [1,24].

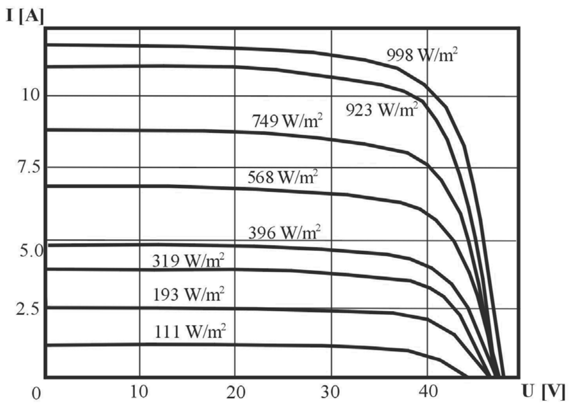

Fig. 6. Effect of light intensity of solar radiation on the course of current-voltage characteristics [1]

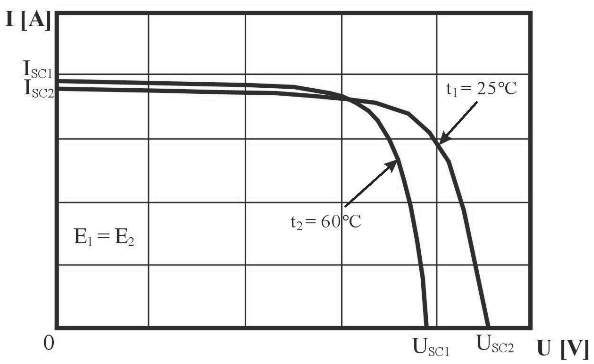

Fig. 7. The effect of temperature on the current-voltage characteristics [1]

3.2. Dark characteristic of the current - voltage solar cell

In accordance with the principle of superposition, which is valid for small values of solar radiation and is also satisfied for the natural conditions of radiation, illuminated I-V characteristics of the solar cell is a result of the reverse shift characteristics of the dark (without light) along with the current value of photocurrent (Fig. 8) [3].

Total current real dark cell consists of generation-recombination component of the space charge region connectors I_R and component diffusion J_{dyf} mainly from the reduction of barriers to potential barrier layer [3].

$$J_d = J_R + J_{dyf} \tag{3}$$

with the:

$$J_{dyf} = J_{S2}\left(e^{\frac{V}{\varphi}} - 1\right) \tag{4}$$

$$J_R = J_{S1}\left(e^{\frac{V}{2\varphi}} - 1\right) \tag{5}$$

where:
J_{S1} and J_{S2} - recombination and diffusion components of the current density saturation,
φ=kT/q - thermodynamic potential for silicon, amounting to 26 mV at 300 K.

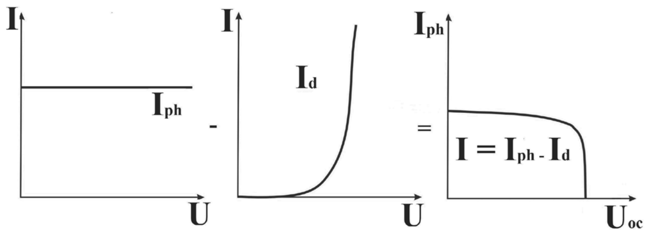

Fig. 8. Characteristics I-V cell as a result of the difference photocurrent and current values of the characteristics of dark solar cells [3]

4. Materials and methodology

In these research the 50x50 mm mono- and polycrystalline silicon solar cells with one bus bar are used. The metallic contacts were prepared by screen printing method and covered with antireflection coating TiO_2 by CVD (Chemical Vapour Deposition) method - is a chemical process used to produce high-purity and high-performance solid materials. The process is often used in the semiconductor industry to produce thin films. In a typical CVD process, the wafer (substrate) is exposed to one or more volatile precursors, which react with the substrates surface or decompose on in to produce the desired layer.

Light and dark current-voltage characteristics of mono and polycrystalline solar cells were measured using a solar simulator

PV Test Solutions performed by Tadeusz Zdanowicz. The measurements were performed under standard conditions (Pin= 1000 W/m^2, AM1.5G spectrum, T=25°C). The basic characteristics of the solar cells was determined using the software I-V Curve Tracer and calculated using mathematical formulas.

5. Results and discussion

The research was conducted at room temperature, parameters in light and dark current-voltage characteristics, are shown in Table 1.

Table 1.
Parameters in light and dark current-voltage characteristics

	Parameters	
	Light current-voltage	Dark current-voltage
Current range	10 A	AUTO
Voltage range	5.00 V	5.00 V
Volute range	10.00 V	10.00 V

Light and dark current-voltage characteristics are shows on Figs. 9-12. Result of measurements using a solar simulator PV Test Solutions are shown in Table 2.

Additionally a algebraic calculations were made by which the research results were confirmed. This leads to conclusion that the research were conducted correctly. The result of calculations using mathematical formulas are shown in Table 3. Two monocrystalline silicon solar cells (No. 1 and No. 2) and two polycrystalline silicon solar cells (No. 3 and No. 4) were used in this research. The values of short circuit current and open circuit voltage were taken from the chart for calculations. But the Fill factor parameter and solar cells efficiency were calculated using equations (1) and (2). After analysing properties that affect solar cells efficiency we can observe that for sample No. 1 the short circuit current parameter is equal 830.990 mA by measurement and 840 mA by calculations, similarly the open circuit voltages are equal 0.6015 V and 0.64 V, the fill factors parameters are equal 0.748 and 0.693, and the solar cells efficiencies are equal 14.95 and14,89%. The shape of the light characteristics curve (Fig. 9a) is similar to the shape of dark characteristics curve (Fig. 9b), both have similar values of currents.

Similary for sample No. 2 short circuit currents parameters are equal 862.787 mA and 850 mA, open circuit voltages are equal 0.6013V and 0.66V, fill factors parameters are equal 0.709 and 0.655, efficiencies of solar cell are equal 14.71% and 14.69%. The light characteristics curve (Fig. 10a) is also ver simillar as the shape of dark characteristics curve (Fig. 10b), current value is very close for both.

In case of polycrystalline cells, by analysing values that affect solar cells efficiency we can observe that for sample No. 3 parameters are as following: short circuit currents are equal 734.118 mA and 730 mA, open circuit voltages are equal 0.6015 V and 0.62 V, fill factors are equal 0.754 and 0.721, the cells efficiencies is equal 13.07% and 13.05%. Shapes of both light and dark characteristic curves are similar and the values of current are similar.

For the last cell values of the parameters are as follow: short circuit current 722.626 mA and 720 mA, open circuit voltage 0.5879 V and 0.63 V, fill factors 0.739 and 0.694, efficiencies of solar cells 12,56% and 12.60%. Shapes of light (Fig. 11a) and dark (Fig. 11b) characteristics curves are also similar.

Best results were obtained by monocrystalline solar cells No. 1, the efficiency is equal to 14.95%. In the light, the current-voltage characteristics can be seen that the open circuit voltage is 0.6015 V, short circuit voltage is 0.5879 V and short circuit is equal 830.990 mA. The lowest results were obtained for the polycrystalline cell No. 4, the efficiency is 12.56%. The light current-voltage is equal 0.5879 V and short circuit current is 722.626 mA. The basic characteristics of solar cells in the I-V set Curve Tracker and calculated via mathemical formulas are similar. The dark current-voltage characteristic of solar cells No. 3 and No. 4, can determined the weaker quality of metal contacts.

a) b)

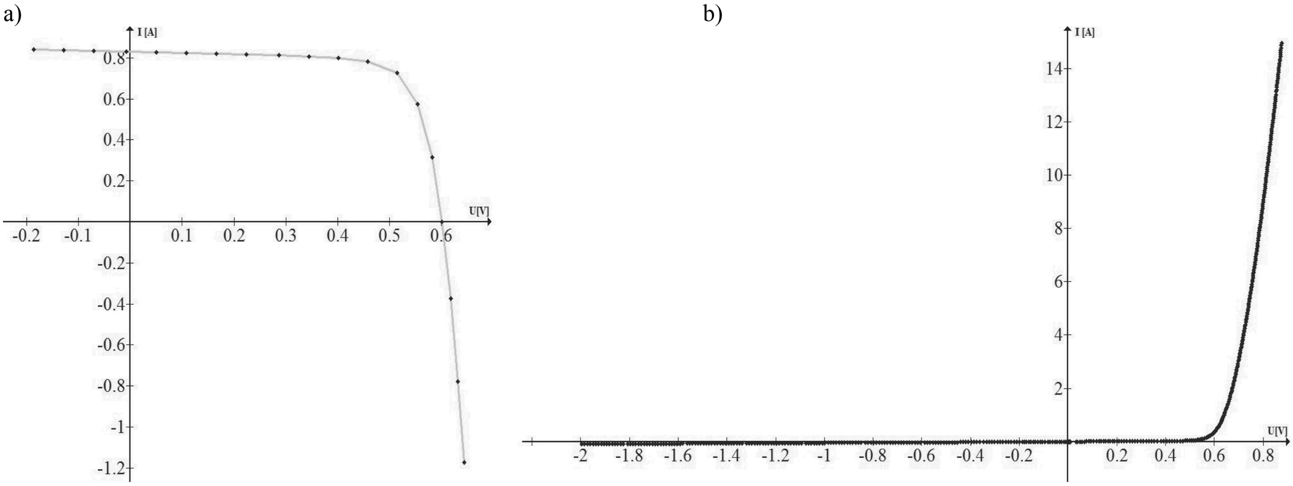

Fig. 9. Current-voltage characteristics of the solar cell No. 1: a) light, b) dark

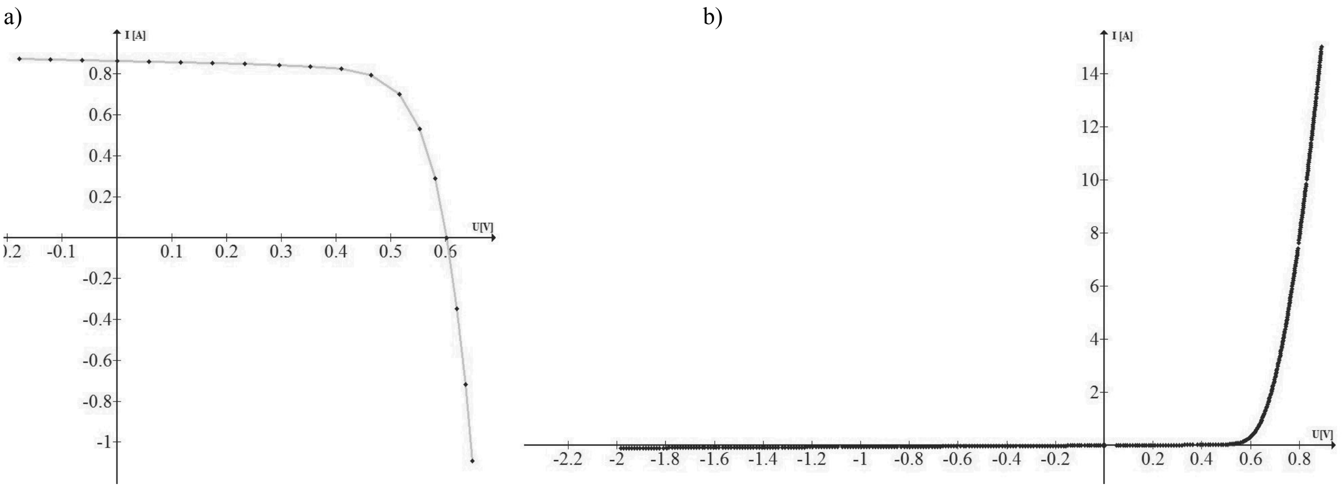

Fig. 10. Current-voltage characteristics of the solar cell No. 2: a) light, b) dark

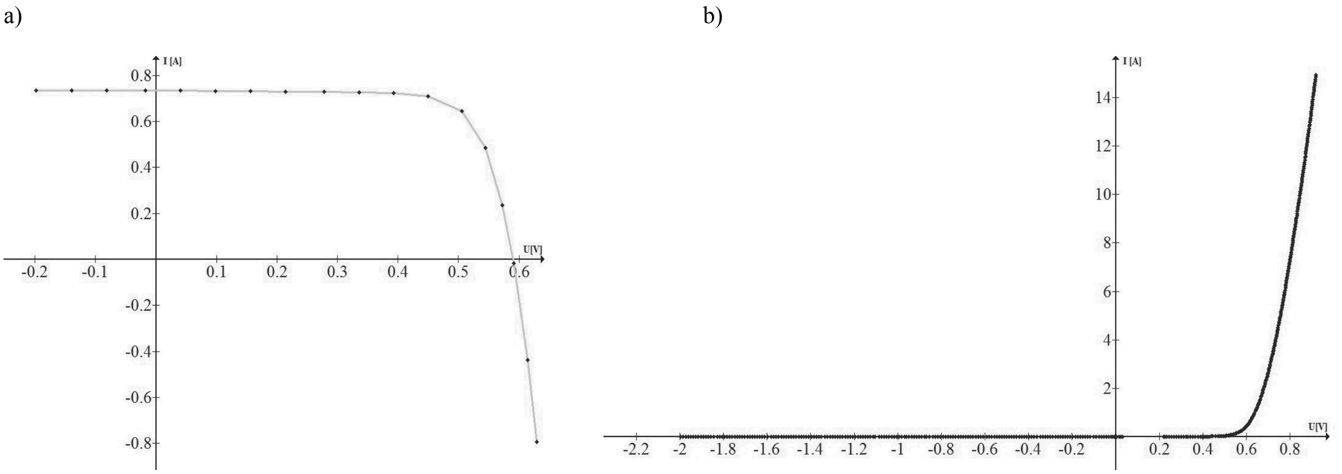

Fig. 11. Current-voltage characteristics of the solar cell No. 3: a) light, b) dark

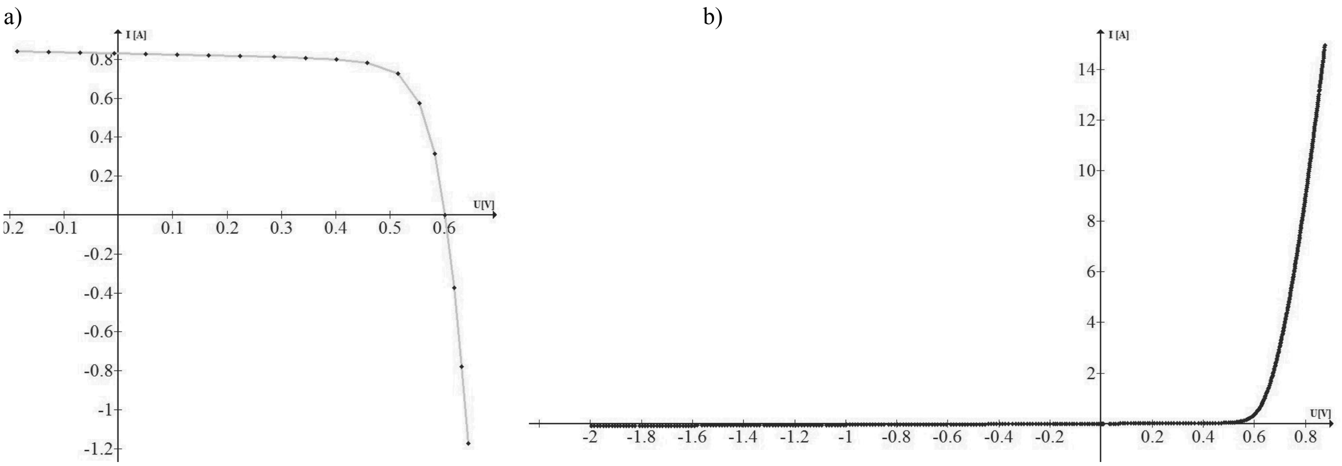

Fig. 12. Current-voltage characteristics of the solar cell No. 4: a) light, b) dark

Table 2.
The results of measurements performed in light

		No 1. Monocrystalline solar cell	No. 2 Monocrystalline solar cell	No. 3 Polycrystalline solar cell	No. 4 Polycrystalline solar cell
Cell parameters	U_{OC} [V]	0.6015	0.6013	0.5901	0.5879
	I_{SC} [mA]	830.990	862.787	734.118	722.626
	U_{MPP} [V]	0.5151	0.4636	0.5057	313.966
	I_{MPP}[mA]	725.785	793.317	654.880	629.086
	P_{max} [mW]	373.872	367.768	326.628	313.699
	FF	0.748	0.709	0.754	0.739
	η [%]	14.95	14.71	13.07	12.56
	R_s [mΩ]	51.17	59.48	66.21	64.67
	R_{sh} [Ω]	16.53	15.16	59.09	14.93
Measurement results	Temperature °C	25	25	25	25
	Irradiance [W/m^2]	1000	1000	1000	1000
	No. of point	19	19	18	17
	Scan Time [ms]	67	67	64	50
	Meas. Time [ms]	207	207	267	221
	Full Time [ms]	1021	1021	1021	975

I_{SC} -short circuit current of solar cell, I_{MPP} - current in maximum power point of solar cell, U_{MPP} - voltage in maximum power point of solar cell, U_{OC} - open circuit voltage of solar cell, FF - fill factor of solar cell, P_{max} - power of solar cell, η - efficiency of solar cell, R_{sh} - parallel resistance of solar cell, Rs- series resistance of solar cel

Table 3.
The results of calculations

	No 1. Monocrystalline solar cell	No. 2 Monocrystalline solar cell	No. 3 Polycrystalline solar cell	No. 4 Polycrystalline solar cell
U_{OC} [V]	0.64	0.66	0.62	0.63
I_{SC} [mA]	840	850	730	720
U_{MPP} [V]	0.51	0.51	0.51	0.51
I_{MPP} [A]	0.73	0.72	0.64	0.64
J [W/m^2]	1000	1000	1000	1000
S [m^2]	0.025	0.025	0.025	0.025
FF	0.693	0.655	0.721	0.694
η [%]	14.89	14.69	13.05	12.60
P_{max} [mV]	384.80	368.00	336.60	315.00

I_{SC} -short circuit current of solar cell, I_{MPP} – current in maximum power point of solar cell, U_{MPP} - voltage in maximum power point of solar cell, U_{OC} - opencircuit voltage of solar cell, FF - fill factor of solar cell, P_{max} - power of solar cell, η - efficiency of solar cell, S-Sollar cell area; J - irradiance.

The parameter FF is a better in a polycrystalline cells. Cells with a high fill factor have a low equivalent series resistance and a high equivalent shunt resistance, so less of the current produced by the cell is dissipated in internal losses.

Analysing the dark characteristics of solar calls, we can state that the faster grow irradiance, we have better efficiency of solar cells. It can be concluded the research of dark characteristics photovoltaic cells can determine a method to analysis parameter module efficiency.

6. Conclusions

Results and their analysis allow to conclude that measurements of current-voltage characteristics allows characterization of the basic solar cells properties. Also they can give important information about the quality of prepared metallic contacts. The basic parameters of solar cells in the I-V set Curve Tracer and calculated via mathematical formulas are similar. This proves the properly conducted measurements.

Summarizing the best efficiency received by monocrystalline solar cell No. 1 it is 14.95% (measurement result) and 14.89% (result of the calculation), the worst efficiency have polycrystalline solar cell No. 4 it is 12.56% (outcome measure) and 12.60% (the calculation). Therefore, we can conclude that the monocrystalline solar cells have better efficiency and maximum power than polycrystalline silicon solar cells.

The parameter FF is better in polycrystalline cells, so the polycrystalline solar cells have better quality.

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