

Technical University of Lodz

Department of Semiconductor and Optoelectronics
Devices

Laboratory of Optoelectronics

Exercise 8

Configuration of the photovoltaic
module

I. Goal

The main goal for this exercise is to understand the operation of the photovoltaic modules built from monocrystalline, silicon solar cells connected in series, parallel and series-parallel and to analyze the effects of partial shading of the installation on the quantity of the produced energy. In this exercise we will appoint the voltage-current characteristics and some electrical parameters resulting from different configurations.

II. Theory

1. Principle of operation and construction of a solar cell

The principle of solar cells is based on the phenomenon of the photovoltaic conversion, which consists of a direct conversion of solar energy into electrical energy. The process for a crystalline silicon solar cell based on a p-n junction is shown in *Fig. 1.1*. The first figure shows us the physical construction of the device and the transport of electrons and holes in opposite directions which illustrates the photovoltaic conversion process. The second picture shows the same phenomenon in the semiconductor band diagram (energy levels in semiconductor devices) [1].

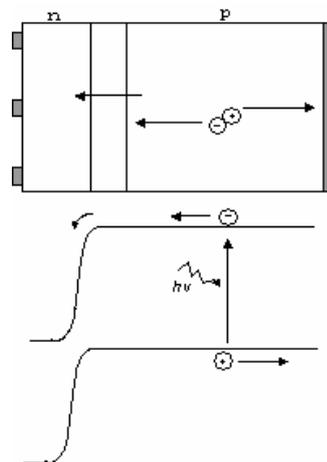


Fig. 1.1 Physical structure and band diagram of a solar cell made of crystalline silicon [1].

The structure of the silicon solar cell with single junction based on p-n junction shown in Fig. 1.2

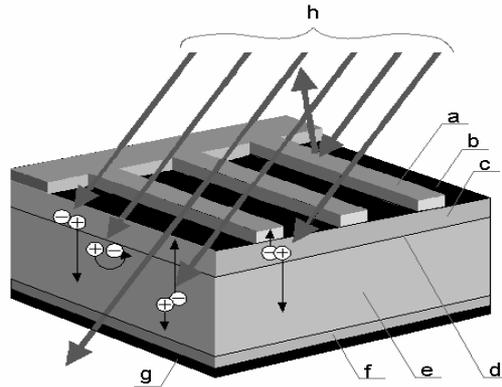


Fig. 1.2 Schematic diagram of the monocrystalline solar cell: (a) front contacts -, (b) textured surface, (c) the area of the emitter n-type, (d) p-n junction, (e) p-type base, (f) built-in p⁺-type field BSF, (g) back contact +, (h) incident photons [3].

2. I-V characteristic and the associated parameters

The basic characteristics which determining the most important parameters of a solar cell is the I-V characteristic. From this curve we can read the parameters such as: short circuit current I_{SC} and open circuit voltage V_{OC} . Moreover we can appoint the current I_m and the voltage V_m . These two values define the point of maximum solar cell power on the I-V characteristic. When we have these values we can easily calculated more parameter, such as: the fill factor FF, the maximum power P_{max} or the cell efficiency η . All these parameters are described in details later.

The sample I-V characteristic (with parameters) for the real solar cell is shown in Fig. 2.2. It is a heterojunction solar cell made on silicon n-type substrate (CZ-Si).

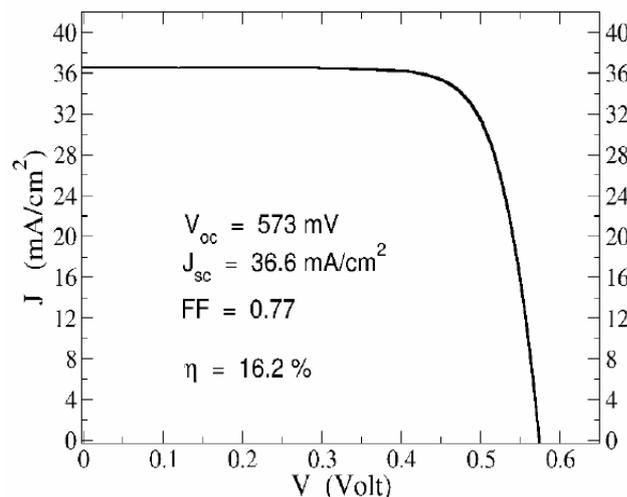


Fig. 2.1 I-V characteristic of the real solar cell [4].

Maximum Power

The current-voltage characteristic for ideal solar cell should have a rectangle shape with sides I_{SC} and V_{OC} . In practice, of course, there is no ideal cells. The maximum power of the real cell is always smaller than the ideal cell's power, equal to the ratio of the open circuit voltage V_{OC} to short circuit current I_{SC} , because it is almost impossible to achieve a rectangular sheet. The maximum electrical power P_{max} of the real solar cell actual is given by the formula:

$$P_{max} = I_m V_m \quad (2.1)$$

where:

I_m, V_m – current and voltage for which the rectangle area is the biggest

The curve of a cell's power shows Fig. 2.3(b), the Maximum Power Point MPP is a area under the graph.

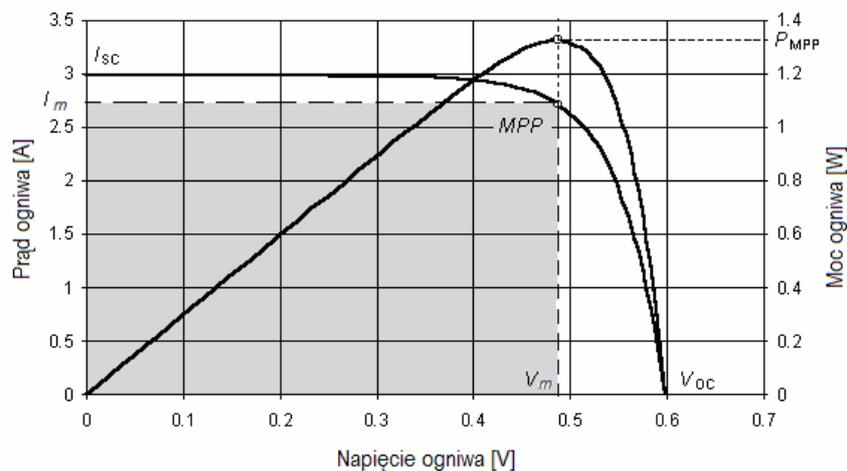


Fig. 2.3 : (a) the voltage-current characteristic of a solar cell, (b) the power generated by a solar cell as a function of voltage [6].

Fill Factor

Next important parameter which describe the quality of photovoltaic solar cell is a fill factor FF. The value of this factor is bigger when the shape of the I-V characteristic is similar to the rectangle. It is a ratio of rectangle with sides I_m i V_m to rectangle with sides I_{SC} i V_{OC} . It can be expressed in percentages or as a dimensionless value, less then 1:

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}} \quad \text{or} \quad FF = \frac{I_m V_m}{I_{SC} V_{OC}} \cdot 100\% \quad (2.2)$$

Efficiency

The most important parameter which describe the quality o photovoltaic solar cell is a efficiency. It is defined as a ratio of the maximum cell's power to the solar irradiation power. Efficiency is given by the formula (2.3) [7].

$$\eta = \frac{I_m V_m}{P_0} \cdot 100\% \quad (2.3)$$

where:

P_0 – the solar irradiation power

3. Connection method of a solar cells in modules.

Series connection

The series connection due to combination of the front contact (-) of previous cell with the bottom contact (+) of next cell, or vice versa. All voltages in this kind of connection are summed. Fig. 3.1 shows the schematic diagram of the series connection built of six cells and Fig. 3.2 shows three solar cells connected in series with I-V characteristic for this configuration.

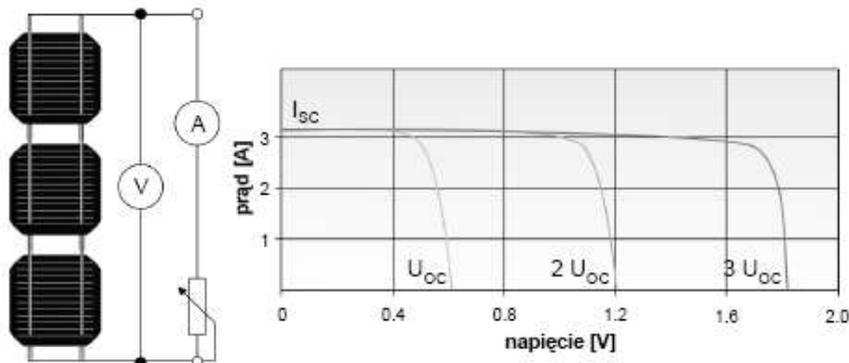


Fig. 3.1 The PV module built from three solar cells connected in series and the expected I-V characteristic. [5].

Parallel connection

The parallel connection due to combination of the front contact (-) of previous cell with the front contact (-) of next cell with simultaneous connection of bottom contacts (+). All currents in this kind of connection are summed. Fig. 3.3 shows the schematic diagram of the parallel connection built of six solar cells and Fig. 3.4 shows three solar cells connected in parallel with I-V characteristic for this configuration.

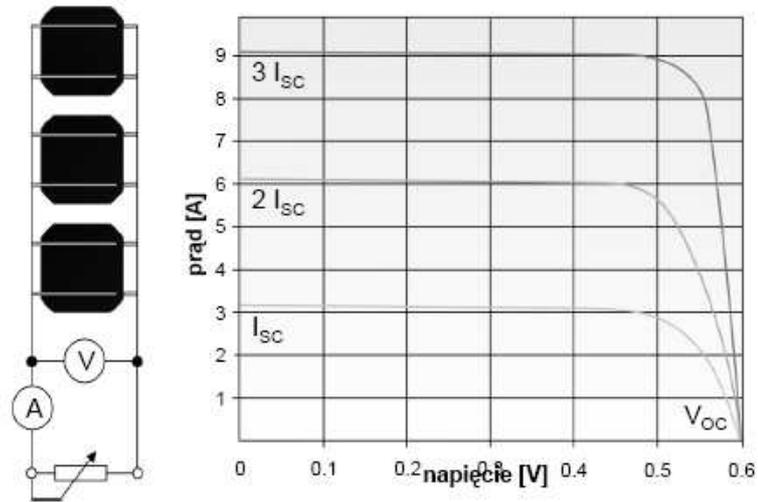


Fig. 3.2 The PV module built from three solar cells connected in parallel and the expected I-V characteristic [5].

Series-parallel connection

The series-parallel connection due to simultaneous connection of cells in series and in parallel. The below Fig. 3.5 shows the schematic diagram of this series-parallel connection built of nine solar cells and it show the I-V characteristic in this configuration.

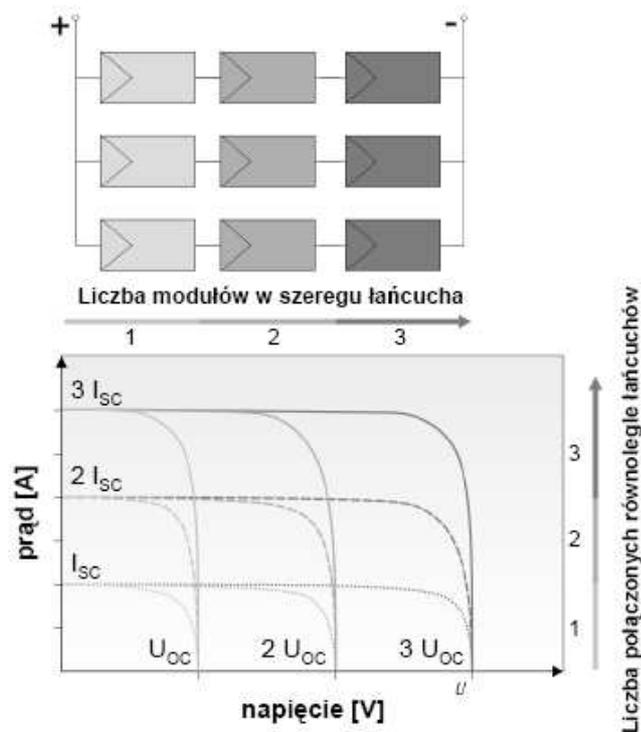


Fig. 3.3 The PV module built from nine solar cells connected in series-parallel and expected I-V characteristic [5].

4. Partial shading of the installation

Partial shading of the electric installation causes a decrease of the energy produced by the photovoltaic module.

When the solar cells are connected in series the short circuit current is not bigger than a current generated by a single illuminated solar cell - *Fig. 3.2*. So if one solar cell is completely shaded, then output power generated by the modules is zero. The reason for limiting the capacity of photovoltaic installation is a partial or complete shading of a cells in module caused by, for example leaves, branches or snow. An example of a partial shading in the cells connected in series is shown in *Fig. 4.1*.

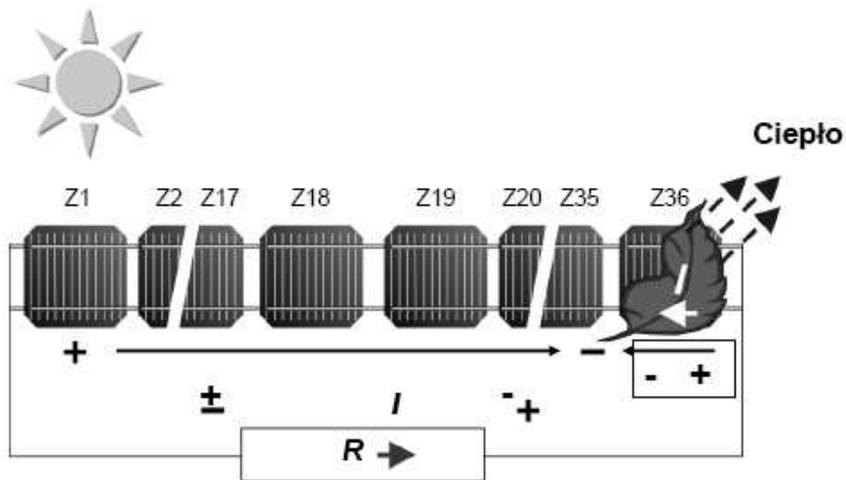


Fig. 4.1 Partial shading system in the serial connection [5].

To reduce the effects of irregular lighting of cell's modules we can use a shunt diodes, which are responsible for protecting other elements from damage caused by the overheating of module when one of it is shaded. The shunt diode is connected parallel to the cell or to the cell's series *Fig. 4.2*.

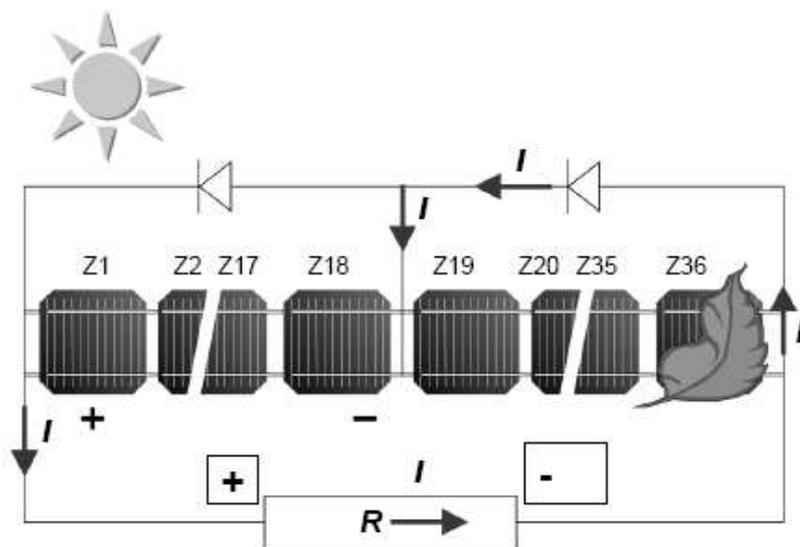


Fig. 4.2 Partial shading system with the diode shunt after each 18 solar cells [5].

The below graph shows the voltage-current characteristic of a solar cell modules in three cases: without shading, in partial shading without a shunt diode and in partial shading with a shunt diode after each 18 solar cells.

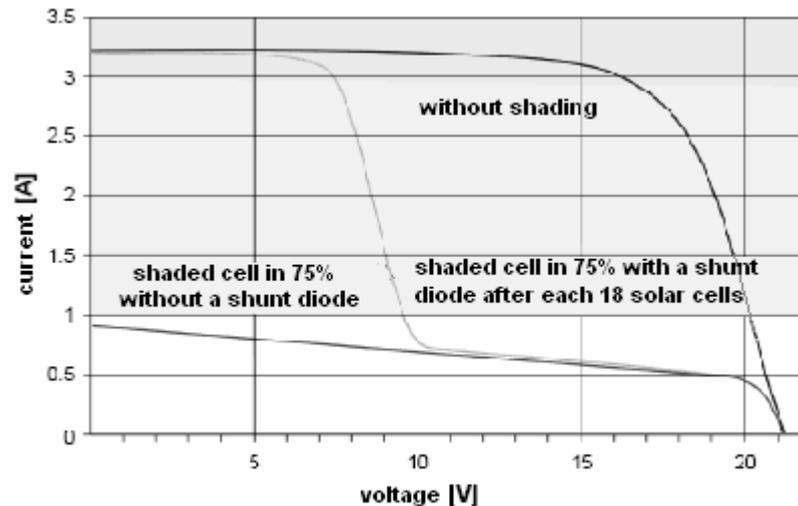


Fig. 4.3 Effect of the diode shunt with partial shadows of photovoltaic installations [5].

III. Exercise

1. Characterization of the analyzed solar cells and of the light.

The analyzed system consists of nine monocrystalline solar cells MOTECH IS125-R150-B with the following parameters:

- dimensions 125 mm x 125 mm \pm 1.5 mm,
- thickness 320 μ m \pm 40 μ m,
- front surface with a blue antireflective layer of silicon nitride,
- front silver contacts with a width of 1.5 mm,
- aluminum back surface is a back cells contact

The electrical parameters of single cell provided by the manufacturer: η (%) 17,25 – 17,49; P_{max} (W) 2,57 – 2,61; I_m (A) 5,02 - 5,18; I_{SC} (A) 5,59; max. V_m (V) 0,511, V_{OC} (V) 0,613.

Illuminator with a total power 315W consists of nine DECOSTAR OSRAM halogen lamps. Each lamp is powered by standard voltage 12 V, 35 W.

1. Measurements of single cell

Connect one selected solar cell to the ammeter and to the voltmeter. By adjusting the resistance value from $R = 0$ to $R = R_{\max}$ measure current and voltage values. The results of measurements place in the table:

Lp.	Current I [A]	Voltage V [V]	Power P [W]
1.			
2.			
3.			
4.			
5.			
6.			

Based on the obtained results draw the voltage-current characteristic for the analyzed solar cell and the power curve (on one graph) and the parameters such as: the short circuit current I_{SC} , the open circuit voltage V_{OC} , the maximum power P_{\max} .

2. Series connection

a) Connect in series 3 cells. By adjusting the resistance value from $R = 0$ to $R = R_{\max}$ measure current and voltage values. The results of measurements place in the table:

Lp.	Current I [A]	Voltage V [V]	Power P [W]
1.			
2.			
3.			
4.			
5.			
6.			

Based on the obtained results draw the voltage-current characteristic for the analyzed solar cell and the power curve (on one graph) and the parameters such as: the short circuit current I_{SC} , the open circuit voltage V_{OC} , the maximum power P_{\max} .

3. Parallel connection

Connect in parallel 3 solar cells. By adjusting the resistance value from $R = 0$ to $R = R_{\max}$ measure current and voltage values. The results of measurements place in the table:

Lp.	Current I [A]	Voltage V [V]	Power P [W]
1.			
2.			
3.			
4.			
5.			
6.			

Based on the obtained results draw the voltage-current characteristic for the analyzed solar cell and the power curve (on one graph) and the parameters such as: the current I_{SC} , the voltage V_{OC} , the power P_{\max} .

IV. Literature and other recommended materials

- [1] T. Markvart, L. Castaner „*Solar Cells: Materials, Manufacture and Operation*” Elsevier, Oxford 2005.
- [2] Z. M. Jarzębski „*Energia słoneczna, konwersja fotowoltaiczna*” Państwowe Wydawnictwo Naukowe, Warszawa 1990.
- [3] URL: www.solar-is-future.com
- [4] E. Centurioni, C. Summonte, „*Optical: an open source program for the optical simulation of multilayer systems, 22th EPVSEC*” Milano, Italy 2007.
- [5] M. Sibiński „*Odnawialne źródła energii. Model obwodu elektrycznego z ogniwem słonecznym. Warunki pracy w sieci energetycznej.*” Katedra Przyrządów Półprzewodnikowych i Optoelektronicznych, Politechnika Łódzka 2005.
- [6] „*Photovoltaic systems, Technology Fundamentals*” Renewable Energy World 1/2004.
- [7] M. Pociask „*Energetyka odnawialna. O korzyściach ze Słońca i fotowoltaice*” Instytut Fizyki, Uniwersytet Rzeszowski 2006.