SOLAR CELLS AND BATTERIES TESTING

1. SOLAR ENERGY

The outer layer of the Sun – the photosphere – has an effective temperature of 5778K (5505°C), and is a source of radiation. Only a very small part of its emitted energy, amounting to 5*10-10 , falls on the Earth's surface. This amount of energy is sufficient to maintain the Earth's surface temperature at the current average level of approx. 14.9°C [5]. The basic quantity characterizing the amount of energy coming from the Sun is the so-called solar constant - the amount of energy arriving in a unit of time and perpendicular surface unit determined at the upper boundary of the atmosphere. This quantity is currently measured using equipment in satellites. The average value of the solar constant is 1361 W/m2. When passing through the atmosphere, some of the energy is dispersed. The intensity of solar radiation falling directly on the Earth's surface depends on the geographic location of the measurement point, the position of the sun (seasons, time of day), height above sea level, type and degree of cloud cover. For places located near the tropics with maximum air transparency it can reach values of about 1100 W/m2. The intensity of diffuse radiation from the total area of the sky ranges from about 70 W/m2 (clear sky) to 280 W/m2 (total cloud cover).

Solar radiation is a renewable source of energy used in the power industry to obtain heat energy (solar collectors) and electricity (photovoltaic batteries).

2. PHOTOVOLTAIC CELL

A photovoltaic cell (solar cell) is a device in which the energy of solar radiation is converted into electrical energy. The cell uses the phenomenon of the photovoltaic effect discovered in 1938 by the French scientist Becquerel. In the cell he built, consisting of two platinum plates (one covered with silver chloride), after illuminating the electrodes with sunlight, a potential difference appeared in the external circuit. Further work in this field resulted in the construction of a selenium-based photovoltaic cell. The photovoltaic effect was observed in the connections of two materials: selenium and gold, copper and copper oxide. The development of semiconductor material production technology allowed the use of silicon and the p-n junction created in it to build photovoltaic cells. Pure silicon is doped with trivalent and pentavalent doping atoms to obtain an n-type or p-type semiconductor, respectively. Figure 1a [4] shows, in an illustrative way, an n-type material containing electrons and a p-type material containing holes in the state just before their contact.

After the two materials are in contact, electrons and holes diffuse across the interface of the materials. Electrons from the n-region at the junction diffuse into the p-region and combine with dopant atoms to form negative ions. Holes from the p-region at the junction diffuse into the n-region and combine with dopant atoms to form positive ions. The flow of carriers is called a diffusion (recombination) current – Figure 1b. At the interface of both materials, a barrier layer is formed, depleted of carriers, and zones composed of positive ions in the n-region and negative ions in the p-region generate an electric field that counteracts further diffusion. An equilibrium state is established, characterized by the cessation of further flow of electrons and holes. The diffusion current takes on a value of zero. This state is shown in Figure 1c.

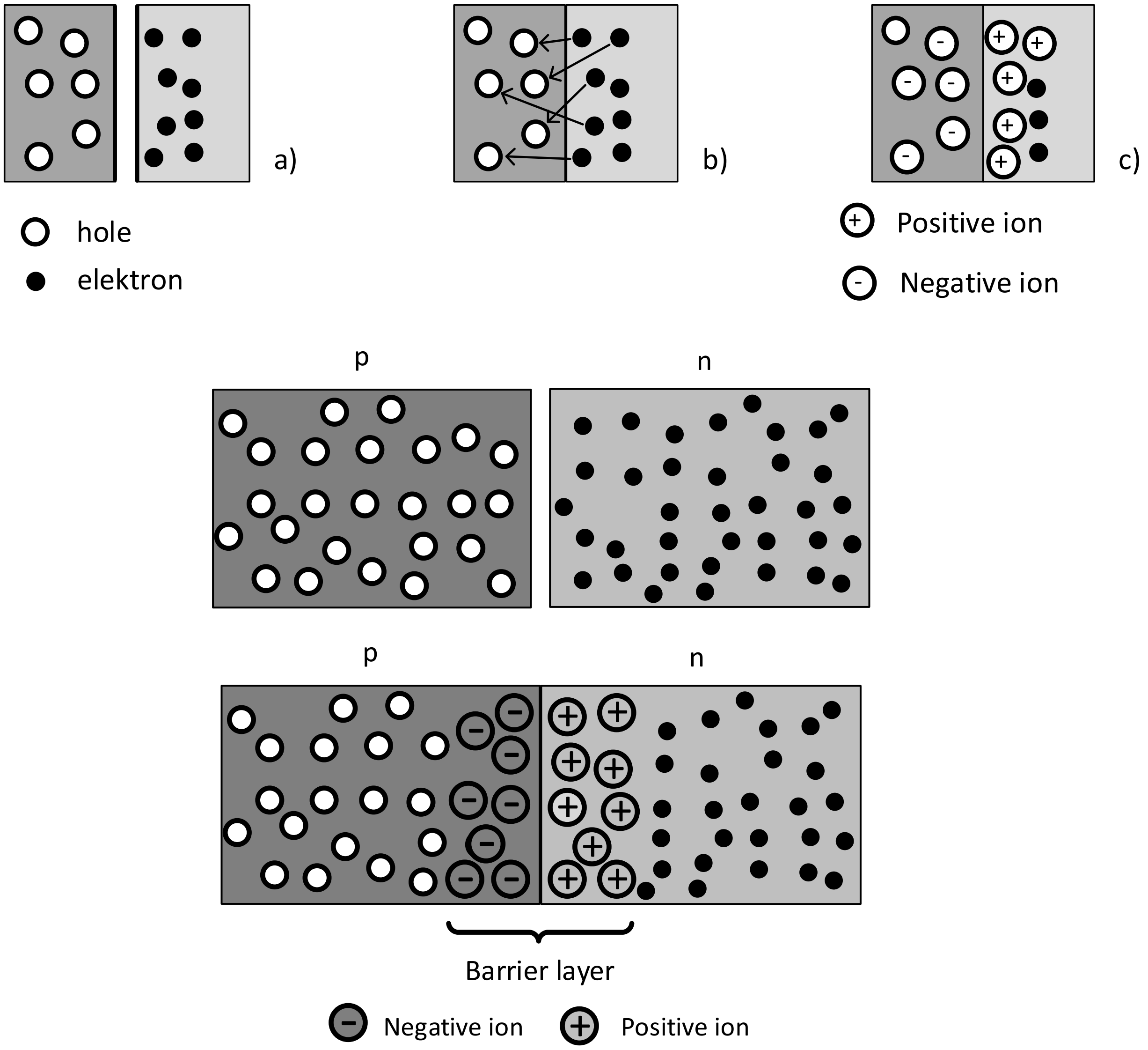
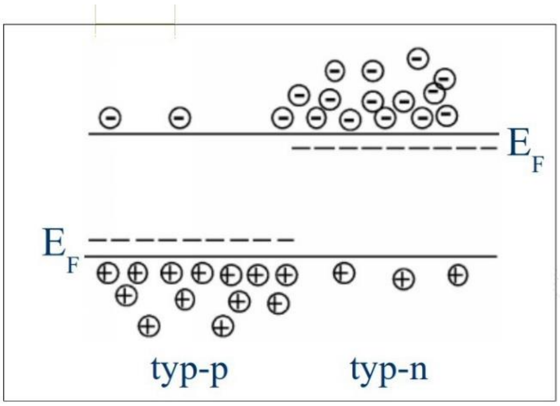


Fig.1 Formation of a p-n junction [4]

The process of forming a p-n junction can be presented in a band model – Figure 2. Before joining, both semiconductors have different Fermi levels – Figure 2a. After joining, electrons and holes flow, which recombine with dopant ions (Figure 2b). As a result, a space charge is created and the process of modifying energy levels occurs, such that the Fermi levels for both semiconductors equalize – Figure 2c.



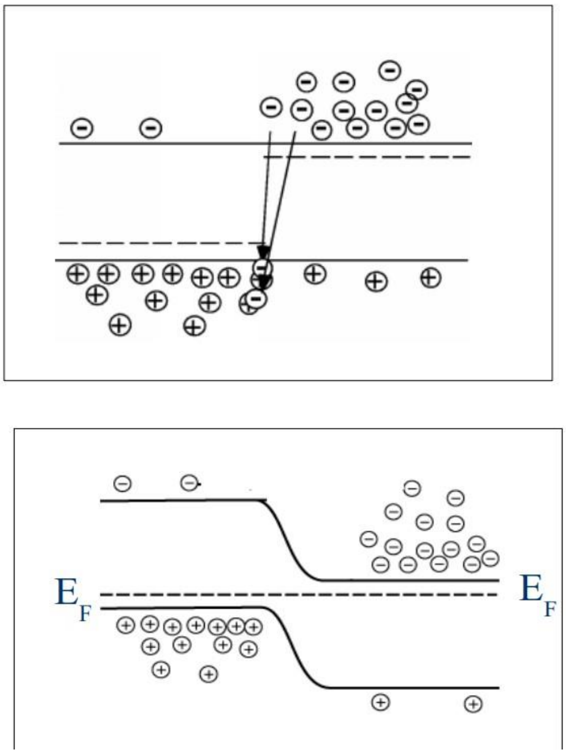


Fig.2 Band model of p-n junction formation [4]

In a semiconductor solar cell, the p-n junction is a type of electron-hole pair separator in the semiconductor. When solar radiation falls on the p-n junction, the absorption of photons with energy greater than the energy of the barrier layer causes the generation of electron-hole pairs. The number of electron-hole pairs is proportional to the intensity of light falling on the semiconductor.. The electric field in the barrier layer forces the flow of electrons towards the n semiconductor and holes towards the p semiconductor. Such a movement of electric charges causes the appearance of a potential difference - electric voltage U. When an external load is connected to the cell, an electric current will flow through it. The schematic construction and operation of a photovoltaic cell is shown in Figure 3.

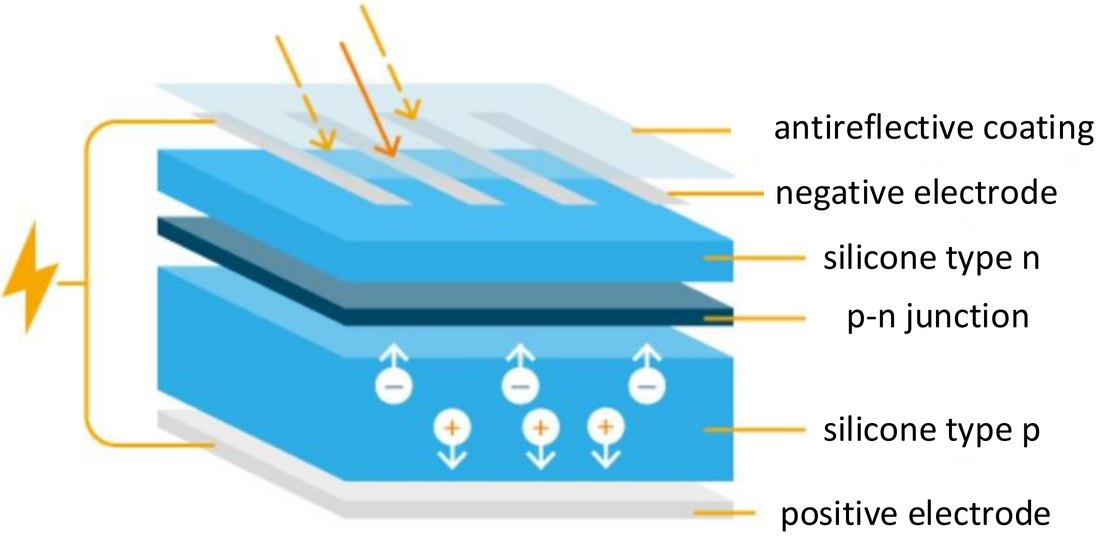


Fig. 3 Photovoltaic cell structure [5]

The diffusion potential U_D in the p-n junction depends on the number of impurities and corresponds to the original difference between the energies of the Fermi levels separately for the p and n regions. The energy difference between the valence and conduction bands for silicon at room temperature is E = 1.1 eV [1,2,6,7]. For silicon, the diffusion potential U_D is 0.5V to 0.7V [1,2]. The voltage U can at most reach the value of the diffusion potential U_D.

The electron and hole flux density is

$$i = \boldsymbol{e} \cdot \left(\mathrm{e}^{\frac{eU}{kT}} - 1\right)\left(\frac{n_0 D_e t}{L_e^2} + \frac{p_0 D_h}{L_h^{\square}}\right) - \boldsymbol{e} \cdot g \qquad (1)$$

where: g – number of electron-hole pairs generated per unit area, U – generated voltage, e – elementary charge ($1.602 \cdot 10^{-19}$ [C]), k – Boltzmann constant, T – temperature [K], L_e, L_h – mean free path of electrons (e) and holes (h), respectively, D_e and D_h – electron and hole diffusion constant, n_0 and p_0 – concentration of minority carriers in equilibrium.

Hence, for the short-circuit current (U=0) this density is

$$i_S = -\boldsymbol{e} \cdot g \qquad (2)$$

It is proportional to the intensity of the incident light at a constant cell temperature. The parameter g takes on slightly higher values with increasing temperature (increase less than $10^{-4}\ \frac{1}{K}$) . Equilibrium concentrations $p_0$and n_0 increase with increasing temperature [1,2]

$$n_0 \approx \mathrm{e}^{-\frac{\Delta E}{2kT}} \qquad (3)$$

The generated EMF decreases with increasing cell temperature, with a typical value being a change of $-2{,}3\ \frac{mV}{K}$.

The most commonly used photovoltaic cells currently use silicon as a semiconductor material. Among the photovoltaic cells built on the basis of silicon, we can distinguish solar cells using crystalline silicon in monocrystalline or polycrystalline form.

- Monocrystalline silicon cells have an efficiency of about 15% - 17% (in mass production). A significant disadvantage is the very high purity of the monocrystalline and the limited surface of a single cell to 40 cm2, for technological reasons. This entails significant production costs. The maximum power delivered by such a cell is about 0.6 W at a voltage of 0.5 V.

- Polycrystalline silicon cells using hydrogenated amorphous silicon have a low efficiency of about 6% to 8%. Despite the low production costs, further development of this technology has been suspended. The technology using a three-layer p-i-n structure with an additional semiconductor layer between the p-type and n-type areas is still being developed. The efficiency of such a structure reaches 10%. An additional advantage is the low production costs.

The production of photovoltaic cells uses many types of materials (semiconductors and others) that enable the photovoltaic effect to be obtained. These include semiconductors from groups III-V, whose high efficiency of 30% to 40% is determined by the very high purity of the materials used. Cadmium telluride CdTe and indium gallium copper selenide CIGS are also used here. Polymers and structures based on titanium dioxide TiO_2 are also used in the construction of photovoltaic cells. Due to technological difficulties and high production costs, despite high efficiency, such cells are mainly used in special applications.

A single photovoltaic cell has limited values of the generated current and voltage. In order to obtain the desired (higher) values of the output current and voltage, photovoltaic batteries are built by connecting individual photovoltaic cells in series and parallel, respectively.

3. APPLICATION OF SOLAR BATTERIES AS A SOURCE OF RENEWABLE ENERGY

The basic application of solar batteries is the production of electricity for the needs of the economy. This applies especially to batteries using silicon as a semiconductor material. An autonomous source of electricity is particularly valuable in places far from the stationary power supply network.

Solar batteries are used as energy sources in special applications, e.g. in space technology to power space stations and satellites.

The use of solar batteries brings with it many conveniences and at the same time limitations.

The basic advantage of using solar batteries to produce electricity is the use of the Sun as an infinite source of energy.

There are a number of reasons that limit the possibilities of using this source:

- lack of a source of energy at night, cloud cover during the day,
- the need to set the optimal position of solar batteries towards the sun for a given geographical location,
- a change in the battery lighting intensity related to the time of day (tracking systems are helpful here),
- a decrease in battery efficiency related to an increase in its temperature,
- a shift in the spectral characteristics of sunlight relative to the spectral sensitivity characteristics of silicon used to build solar batteries (Fig. 4).

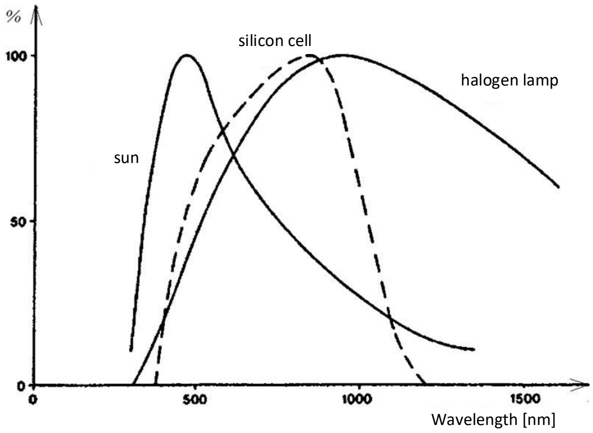


Fig. 4. The radiation spectrum of the Sun and a halogen bulb and the spectral sensitivity characteristics of a silicon solar cell [1, 2].

- high costs of battery production due to the technologies and materials used,
- technological difficulties in storing electrical energy.

Despite these difficulties, many solar farms are currently being built (multi-hectare fields covered with solar batteries) and solar batteries are also installed on many roofs of buildings.

4. LABORATORY EXERCISE PROCEDURE

The aim of the exercise is to determine the basic parameters and characteristics of photovoltaic batteries at the laboratory stand. The general view of the station is shown in Figure 5.

The station consists of the following elements:

- large solar battery - surface,
- lamp on a tripod stand with a 1000 W halogen bulb,
- small solar battery (4 cells connected in series),
- lamp on a stand with a 75 W bulb, the stand can be moved along the rail of the optical bench,
- optical bench,
- digital voltmeter (5 and ½ digits) with a resolution of at least 0.1 mV,
- analogue ammeter, pointer - adjustable range from 30 mA to 30A, reading accuracy 0.5%.,
- decade resistor 1Ω to 9999Ω as an external load for the cell.

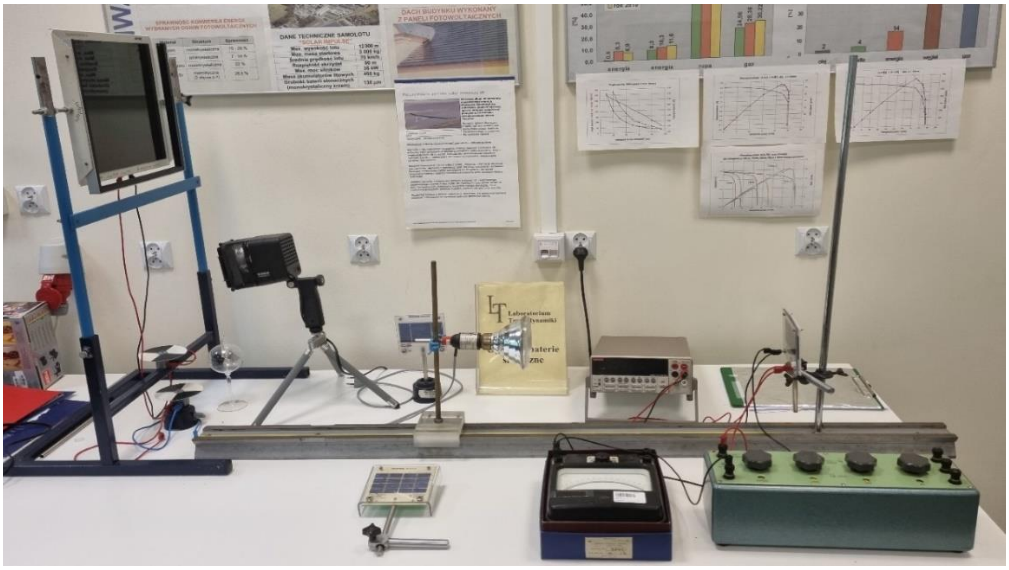


Fig. 5. General view of the laboratory stand

In the following part, descriptions of experiments are separated for small and large solar batteries.

First, the object of the research will be a small solar battery. Figure 6 shows the elements of the stand that will be used in this part of the exercise.

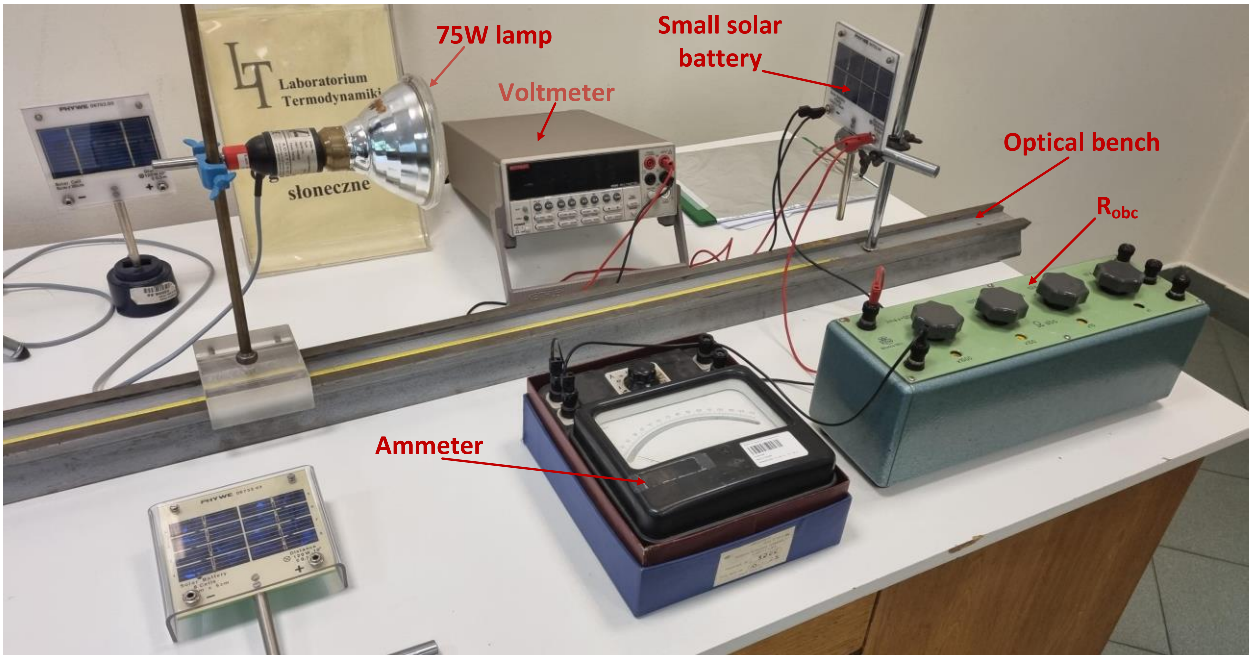


Fig.6. General view of part of the laboratory stand for determining the parameters of a small solar battery

3.1 Determination of the characteristic E=f(x) of the battery illuminance variable as a function of the distance from the lamp to the solar battery.

The set of instruments was expanded with the HD-2102.2 Photo-Radiometer with the LP 471–`PHOT probe(Fig. 7) for measuring illuminance – the density of the luminous flux incident on a given surface.

Rys. 7 Foto-Radiometer HD-2102.2 with LP 471 – PHOT probe. LP 471-RAD probe for measuring heat flux density lies next to it.

A point source of light with luminous intensity *I* produces illuminance at a point on the surface, defined by the formula:

$$E = \frac{I}{r^2} \cos \alpha$$

where E – illuminance, α – angle between the perpendicular line to the surface and the vector directed at the light source, r – distance of the surface point from the light source.

The unit of illuminance is lux [lx] equal to lumen per square meter [cd·sr·m^{-2}].

The measuring range of the used LP 471-PHOT probe is from 0.01 to 200×103 lx.

Description of the measurement:

1. Set up the measuring system shown in Figure 8.

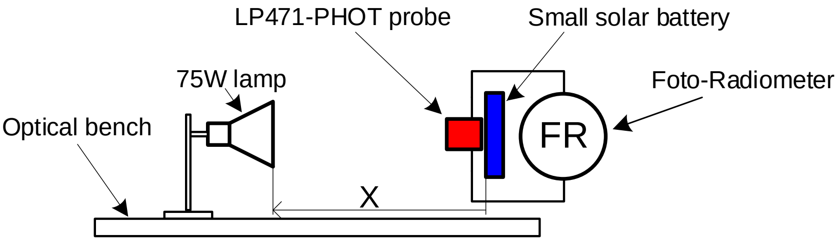


Fig. 8. Measurement system for task 3.1. X – distance of the front of the 75W illuminating lamp from the front surface of the battery

2. Place the LP471-PHOT probe (connected to the Photo-Radiometer) in front of the surface of the solar battery.

3. Measure the illuminance value E of the solar battery surface for eight positions X_i of the 75W lamp stand on the optical bench. Select the stand settings as evenly as possible, starting from the position X_{max} of the maximum distance of the stand from the battery to the position of 30 cm from the battery.

   Note: Do not bring the 75W lamp closer than 30 cm to the solar battery.

4. Record the measurement results in Table 1.

Table 1

Distance X_i from lamp to battery [cm]								
Illuminance E [lx]								

5. Draw a graph E=f(X)

6. Determine the analytical form (formula) of the E=f(X) relationship that allows determining the battery illuminance value for any X in the range <30cm, X_{max}>

3.2 Determination of the short-circuit current characteristic I_{zw} = f(E) as a function of the illuminance E

Description of the measurements:

1. Set up the measurement system shown in Figure 9.

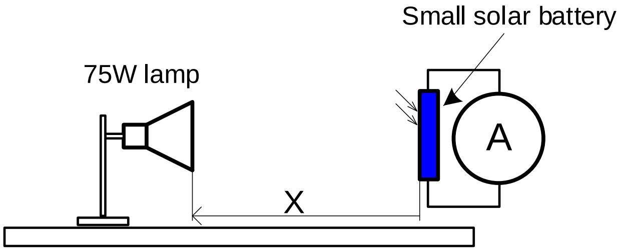


Fig. 9. Measuring system for task 3.2.

2. Measure the value of the short-circuit current I_{zw} for eight positions X_i of the 75W lamp stand on the optical bench. Select the stand settings relatively evenly, starting from position X_{max}, the maximum distance of the stand from the battery, to the position of 30 cm from the battery.

   Note: Do not bring the 75W lamp closer to the solar battery than 30 cm.

3. Record the measurement results in Table 2.

Table 2

Distance X_i from lamp to battery [cm]								
Illuminance E [lx]								
Short-circuit current I_{zw} [mA]								

3. Plot the characteristic of the short-circuit current $I_{zw} = f(E)$ as a function of the illuminance E. Use the analytical form (formula) of the dependence E=f(X) determined in task 3.1.

3.3 Determination of the characteristic of the generated EMF as a function of the illuminance E

Description of the measurement:

1. Set up the measurement system shown in Figure 10.

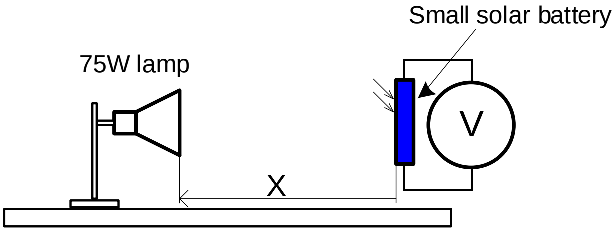


Fig. 10. Measuring system for task 3.3.

2. Measure the value of the EMF generated by the solar panel without an external load connected, for eight positions X_i of the 75W lamp stand on the optical bench. Select the stand settings as evenly as possible, starting from the position X_{max} of the maximum distance of the lampfrom the battery to the position of 30 cm from the battery.

   Note: Do not bring the 75W lamp closer to the solar panel than 30 cm.

3. Record the measurement results in Table 3.

Table 3

Distance X_i from lamp to battery [cm]								
Illuminance E [lx]								
EMF [V]								

4. Plot the characteristic of the generated EMF U = f(E) as a function of the illuminance E. Use the analytical form (formula) of the E=f(X) relationship determined in task 3.

3.4 Determination of the voltage-current characteristic U = f(I) for the selected/selected values of the distance X_i of the lamp from the small solar battery. Determination of the P =U*I courses, determination of P_{max} for the obtained characteristics

Description of the measurement:

1. Set up the measurement system shown in Figure 11.

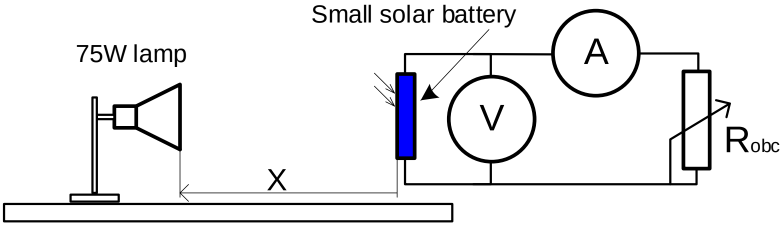


Fig. 11. Measuring system for task 3.4.

2. Set the 75W lamp stand in the selected position on the optical bench.
3. By changing the load resistance R_{obc} according to the values from Table 4, note the values of the generated voltage and current flowing through the load each time.
4. Calculate the power value P for all rows of Table 4.
5. Plot the voltage-current characteristic U = f(I) and the power characteristic P = f(I) on the same graph (two y axes). Determine the maximum power value for the given battery lighting conditions. Below the graph, provide the values: distance of the 75W lamp front from the battery, solar battery illumination, voltage, current and maximum power generated by the battery for the chosen position of the lamp stand.

To determine another voltage-current characteristic of the battery, move the 75W lamp stand to another position and repeat the steps described in points 3 to 5 of this task.

The next task concerns determining the voltage-current characteristic of a large solar battery illuminated by a lamp with a 1000 W halogen bulb.

3.5 Determining the voltage-current characteristic of a large solar battery

Description of the measurement:

1. Set up the measurement system shown in Figure 12. Place the 1000W lamp at a distance of approx. 70 cm from the surface of the large solar battery.

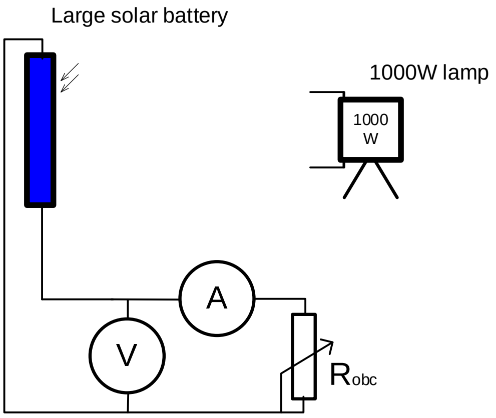


Fig. 12. Measuring system for task 3.5.

2. Perform steps 3 to 5 of task 3.4.

Note: Do not unplug the 1000W lamp from the power outlet - the fan cools the lamp.

Figure 13 shows example test results of the voltage-current characteristic and battery power characteristic obtained at the laboratory stand.

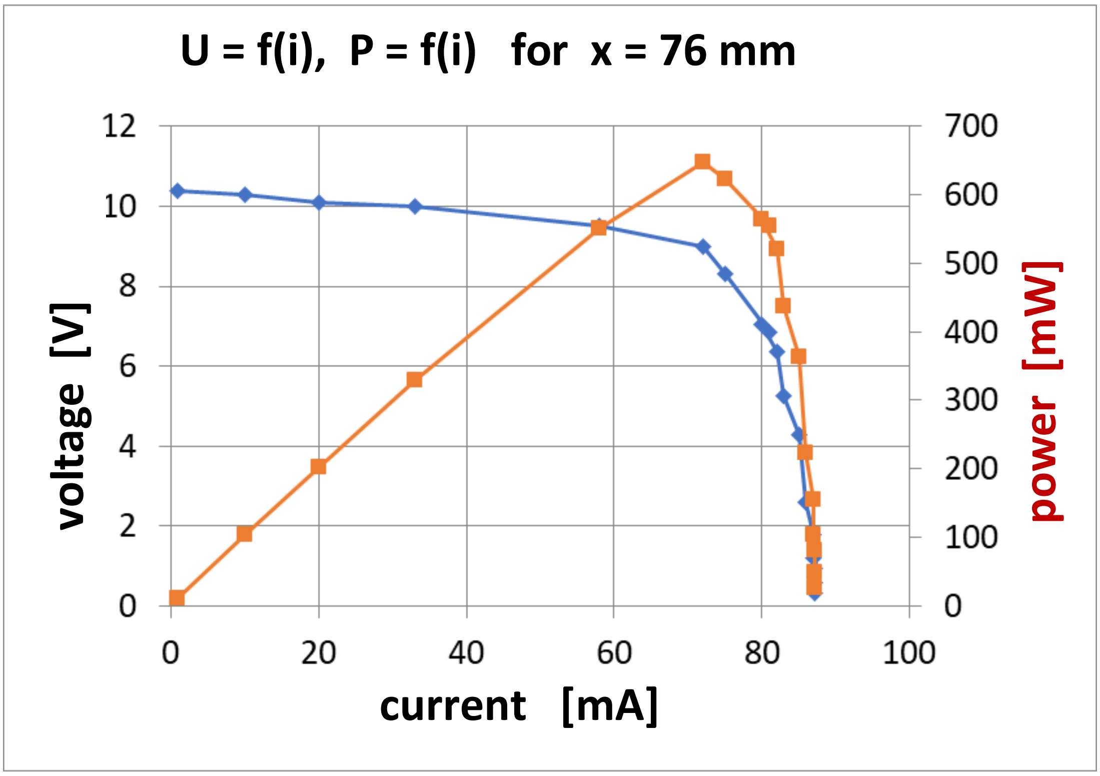


Fig.13 Example test results of a small solar battery.

REPORT

In the Report from the laboratory exercise, place the results for all tasks: all tables, graphs, calculations and approximations. Formulate an evaluation of the obtained results.

LITERATURE

[1] Phywe: *Characteristic curves of a solar cell*, LEP 4.1.09

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Table 4 for 3.4 i 3.5 tasks

R_{obc}	U	I	P
Ω	V	mA	mW
10 000			
9 000			
8 000			
7 000			
6 000			
5 000			
4 000			
3 000			
2 000			
1 000			
900			
800			
700			
600			
500			
400			
300			
200			
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