

II E5

Modul Electricity II

Solar Cells

The aim of this experiment is to investigate the electrical properties of a solar cell under controlled illumination. More specifically, we will measure the voltage and current generated by a solar cell for different load resistances. From these measurements, the current-voltage characteristic and the electrical power as a function of voltage will be determined. The maximum power point (MPP) of the solar cell will then be identified. Finally, the incident optical power will be estimated from a separate measurement at the position of the solar cell. This allows an estimate of the conversion efficiency of the solar cell.

Experiment IIE5 - Solar Cells

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1.1 Preliminary Questions

Before starting the experiment, think about the following questions:

- What is the photovoltaic effect?
- How does a solar cell convert light into electrical energy?
- What are the roles of the semiconductor, the p -type region and the n -type region in a solar cell?
- What is a photon and how is its energy related to its frequency?
- What happens when the energy of an incoming photon is larger than the band gap of the semiconductor?
- What is the difference between open-circuit voltage and short-circuit current?
- How are voltage, current and electrical power related?
- Why does a solar cell not necessarily deliver its maximum power when either the voltage or the current is at its maximum?
- What is meant by the maximum power point (MPP)?
- How does the temperature of a solar cell affect its electrical output?
- What is the difference between irradiance, measured in W m^{-2} , and illuminance, measured in lux? Which of the two quantities is important in this experiment? Therefore, which of these two modes should be applied when measuring?

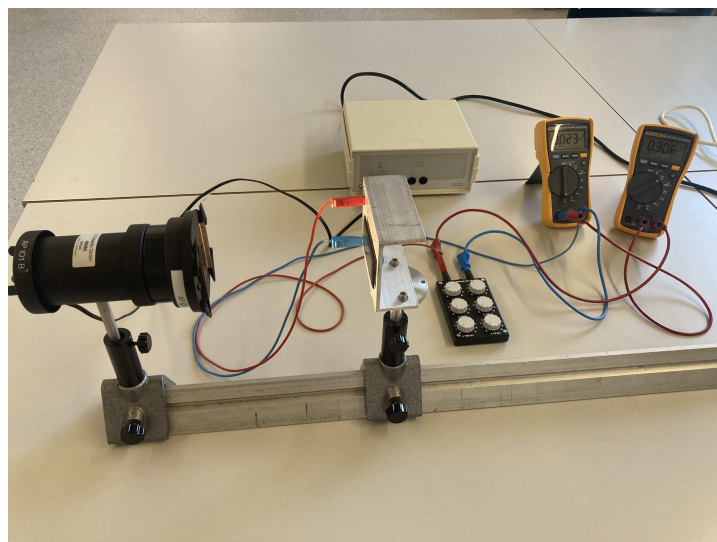


Figure 1.1: The figure shows the experimental setup. A halogen lamp is pointing towards a solar cell. The solar cell is connected to digital multimeter in order to measure the voltage and the current for different load resistances.

1.2 Theory

1.2.1 Photovoltaic effect

A solar cell converts electromagnetic radiation (1) into electrical energy by means of the photovoltaic effect. Most conventional solar cells are based on semiconductor materials containing a $p-n$ junction.

Photons incident on the semiconductor can transfer their energy to electrons. A photon with frequency ν has the energy

$$E_\gamma = h\nu = \frac{hc}{\lambda}, \quad (1.1)$$

where h is Planck's constant, c is the speed of light and λ is the wavelength of the radiation. If the photon energy is sufficiently large, an electron-hole pair can be generated (2). The electric field associated with the $p-n$ junction separates the charge carriers (3) and thereby produces a photovoltage (4). Once the electrodes are connected, a recombination happens and an electric current flows (5).

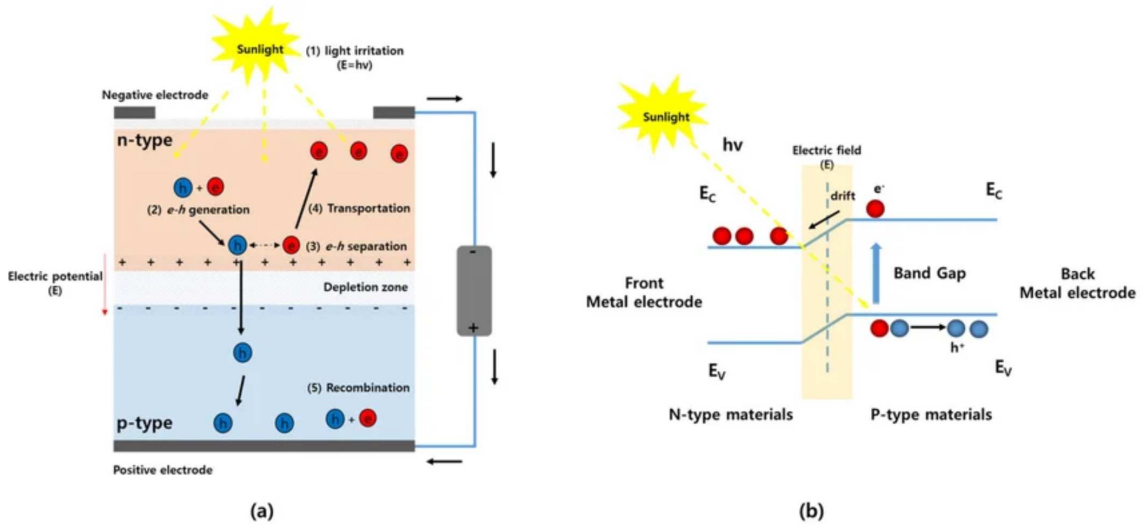


Figure 1.2: (a) working principle of solar cell with $p-n$ junction structure and (b) loss mechanism in standard $p-n$ junction solar cells.

The electrical behaviour of a solar cell can be described by its current-voltage (I - V) characteristic. The exact characteristic depends on the semiconductor material, the illumination level, the temperature and the properties of the particular solar cell.

1.2.2 Equivalent circuit of a solar cell

A simplified model of a solar cell consists of a current source representing the photocurrent and a diode representing the $p-n$ junction. More realistic models additionally contain a series resistance R_s and a parallel (shunt) resistance R_{sh} .

A commonly used model equation is

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + IR_s)}{nk_B T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}, \quad (1.2)$$

where I_{ph} is the photocurrent, I_0 is the diode saturation current, q is the elementary charge, n is the ideality factor, k_B is Boltzmann's constant and T is the absolute temperature. For the purposes of this experiment, it is not necessary to determine all parameters of this model. The experimentally measured I - V characteristic is sufficient to determine the maximum electrical power.

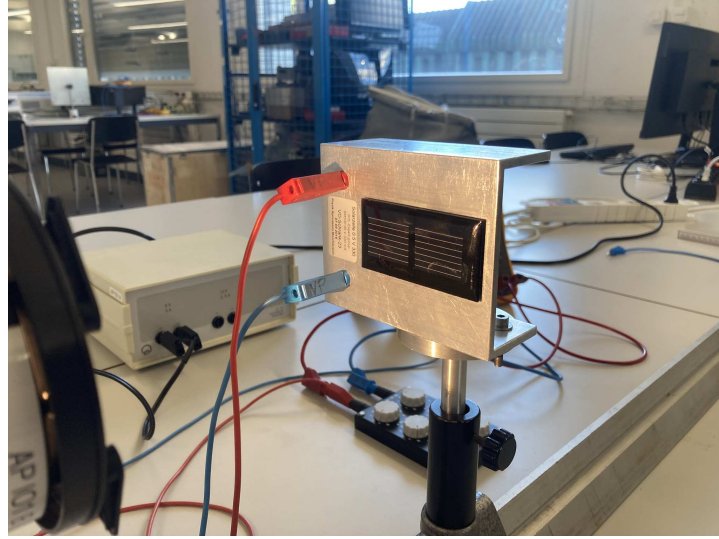


Figure 1.3: The specifications of the given solar cell are 0.5 V and 330 mA.

1.2.3 Load resistance

The solar cell is connected to a variable resistance R . According to Ohm's law,

$$I = \frac{U}{R}. \quad (1.3)$$

Thus, changing the resistance changes the operating point of the solar cell. For every value of R , the corresponding voltage U and current I can be measured.

The electrical power delivered to the load is

$$P = UI. \quad (1.4)$$

Since $I = U/R$, the power can also be calculated from

$$P = \frac{U^2}{R} \quad (1.5)$$

or

$$P = I^2 R. \quad (1.6)$$

The *maximum power point* (MPP) is the operating point for which the electrical power is maximal:

$$P_{MPP} = \max P(R). \quad (1.7)$$

The corresponding voltage and current are denoted by U_{MPP} and I_{MPP} .

1.2.4 Open-circuit voltage and short-circuit current

Two particularly important points of the I - V characteristic are the open-circuit voltage U_{OC} and the short-circuit current I_{SC} .

For an open circuit,

$$I = 0, \quad (1.8)$$

and therefore

$$U = U_{OC}. \quad (1.9)$$

For a short circuit,

$$U = 0, \quad (1.10)$$

and therefore

$$I = I_{SC}. \quad (1.11)$$

In both cases, the electrical output power is zero:

$$P = UI = 0 \text{ W}. \quad (1.12)$$

The maximum power therefore occurs at an intermediate operating point.

1.2.5 Power characteristic and maximum power point

For each measured resistance, the corresponding power can be calculated. The power P is then plotted as a function of voltage.

$$P(U) = U \cdot I(U). \quad (1.13)$$

The maximum of the $P(U)$ -curve defines the *maximum power point* (MPP).

Alternatively, the $I(U)$ -curve is also helpful to assess the quality of a solar cell.

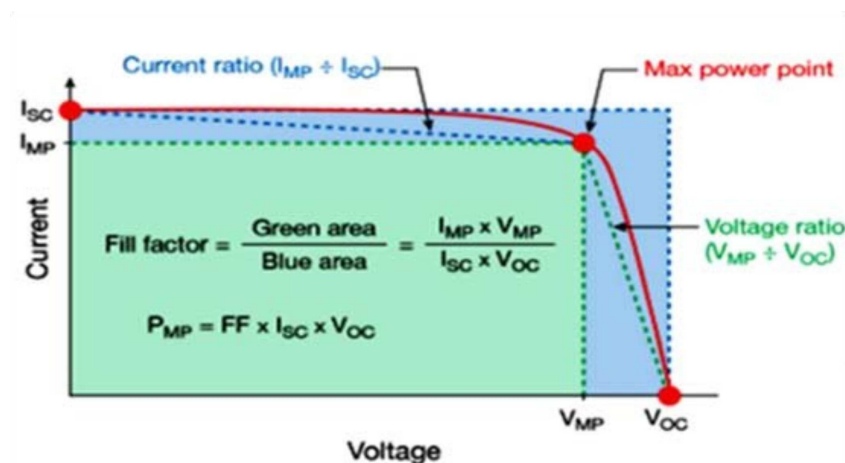


Figure 1.4: The fill factor describes how close the measured I - V characteristic is to an ideal rectangular characteristic. In the diagram, it is the ration between the blue and the green area.

The *fill factor* is another useful quantity for characterising a solar cell:

$$FF = \frac{U_{MPP} I_{MPP}}{U_{OC} I_{SC}}. \quad (1.14)$$

A high fill factor corresponds to a more “square-shaped” I–U characteristic with a pronounced knee, where the voltage and current at the maximum power point remain relatively close to (U_{OC}) and (I_{SC}), respectively. A low FF indicates a more strongly curved characteristic, and therefore a lower maximum usable power.

1.2.6 Influence of temperature

The electrical properties of a semiconductor depend on temperature. For a conventional silicon solar cell, increasing the temperature generally reduces the open-circuit voltage. The short-circuit current usually changes much less strongly and may increase slightly with temperature.

Consequently, the maximum power of a silicon solar cell generally decreases with increasing cell temperature. The temperature dependence can be investigated experimentally by recording the surface temperature T of the solar cell together with the electrical operating point.

However, in the present experiment the temperature is not independently controlled. The measured temperature therefore cannot by itself establish a quantitative temperature coefficient. It can nevertheless be used to investigate whether systematic changes in the electrical output are associated with changes in cell temperature.

1.2.7 Optical power and efficiency

The conversion efficiency of a solar cell is defined as

$$\eta = \frac{P_{el}}{P_{opt}}, \quad (1.15)$$

where P_{el} is the electrical output power and P_{opt} is the optical power incident on the active area of the solar cell.

If the irradiance E_e in W m^{-2} is known, the incident optical power is

$$P_{opt} = E_e A, \quad (1.16)$$

where A is the illuminated area of the solar cell.

The efficiency at the maximum power point is therefore

$$\eta_{MPP} = \frac{P_{MPP}}{E_e A}. \quad (1.17)$$

1.2.8 Illuminance versus irradiance

A luxmeter measures illuminance E_v in lux. Illuminance is a photometric quantity and describes the illumination according to the sensitivity of the human eye.

Irradiance E_e , on the other hand, is a radiometric quantity and describes the optical power incident per unit area:

$$[E_e] = \text{W m}^{-2}. \quad (1.18)$$

In general, there is no universal conversion factor between lux and W m^{-2} , because the conversion depends on the spectral distribution of the radiation.

1.3 Experiment

1.3.1 Equipment

Component	Number
Solar cell	1
Halogen lamp	1
Resistance decade	1
Digital multimeter for voltage	1
Digital multimeter for current	1
Infrared thermometer	1
Luxmeter	1
Ruler / measuring tape	1
Connecting wires	several
Tripod or holder for solar cell	1

1.3.2 Experimental setup and execution

Safety notes

The halogen **lamp becomes hot** during operation. Do not touch the lamp housing or the bulb during or immediately after the experiment.
Please be careful not to burn yourself, nor to damage the solar cell. Solar cells are semiconductor devices, and therefore heat sensitive. Always keep a **minimum distance of 15 cm** between the lamp and the solar cell.

Preliminary work

Start by looking attentively at the experimental setup and reflect on the following questions:

- Which terminals of the solar cell provide the electrical output?
- How are the voltmeter and ammeter connected?
- How is the resistance decade connected to the solar cell?
- Which measuring instrument measures voltage and which measures current?
- What happens to the operating point when the resistance is increased?

Make sure that the measurement instruments are configured for DC measurements and that the selected measurement ranges are appropriate.

Positioning the solar cell

Place the halogen lamp and the solar cell on the rail. Position the solar cell such that its active surface faces the lamp perpendicular to the rail.

Measure the distance from the lamp to the surface of the solar cell and adjust it to a **minimum** of

$$d = 15 \text{ cm.} \quad (1.19)$$

or more. This same distance must be maintained throughout the experiment.

Switch on the halogen lamp and allow the setup to reach a reasonably stable thermal condition before starting the main measurement.

Part I: Measurement of the I - V characteristic

Connect the solar cell to the resistance decade and the measuring instruments. Please note, voltage is measured in parallel, while current is measured in series.

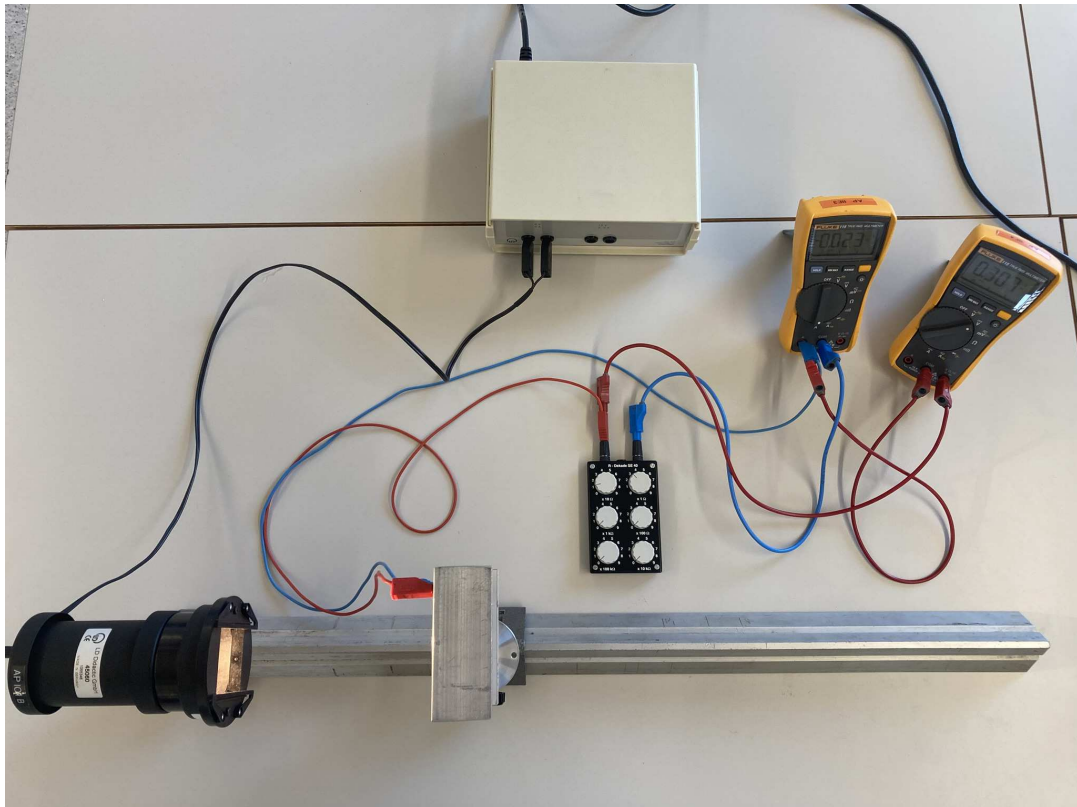


Figure 1.5: Top view of the experimental setup. A halogen lamp is used as a light source. The solar cell can be slid along a rail. The solar cell is connected to the resistance decade and two digital multimeters.

Get familiar with the *resistance decade*. The layout of the switches is counter-intuitive, because it increases from right to left. Do you understand how to implement i.e. $R = 45\,\Omega$, $R = 39\,052\,\Omega$, etcetera?

Start with a relatively large resistance and measure the voltage U across the solar cell and the current I through the load. Then change the resistance step by step and record the corresponding voltage and current. From time to time, check with the infrared thermometer that the temperature is stable.

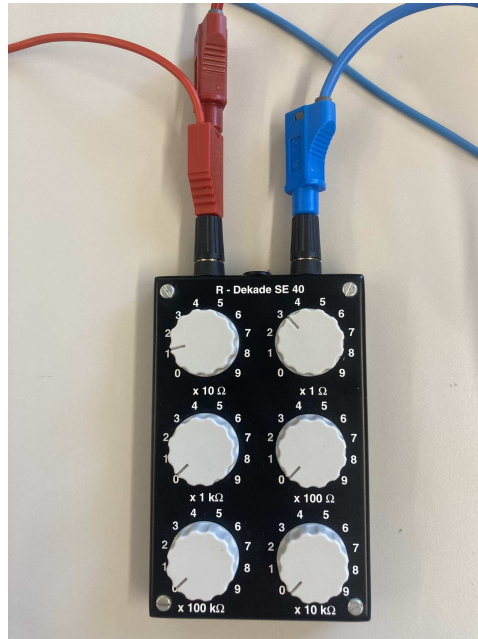


Figure 1.6: A *decade resistor* is an instrument that allows any desired resistance value to be set by turning rotary switches. The R-Dekade SE 40 designed for any resistances between $1\ \Omega$ and $1\ \text{M}\Omega$. Please note the layout of the switches is counter-intuitive.

Use a sufficiently large number of resistance values, particularly in the region where the electrical power is expected to be maximal.

A possible measurement table is:

R	U	I	$P = UI$	T	Notes
Ω	V	A	W	$^{\circ}\text{C}$	
...					

At each measurement point, allow some time for the values to stabilise before recording them.

Part II: Temperature investigation

Look at your data from the first part of the experiment. Apply a resistance for which the solar cell is close to the maximal power point (MPP).

Before you start with this last part of the experiment, switch off the halogen lamp, and wait until the solar cell reaches approximately room temperature. Check with the infrared thermometer.

Then, switch on the halogen lamp. Keep the irradiation conditions as well as the resistance as constant as possible and perform several I - V measurements after the solar cell has reached different thermal states. Like that, you can find the maximum power for different temperatures of the solar cell, until the cell temperature has stabilized.

Part III: Measurement of the irradiance

First, measure the active area of the solar cell.



Figure 1.7: A *luxmeter* measures illuminance, which is the total amount of visible light falling on a surface per unit area. Please do not forget to remove the protective rubber cap before starting the measurement.

Then, determine the irradiance in W m^{-2} at the position of the solar cell using the luxmeter. Therefore, place the sensor of the luxmeter at the same position and orientation as the active surface of the solar cell.

Record the measured illuminance E_e several times, and determine the mean value and its uncertainty.

1.4 Tasks for the Evaluation

Determination of the electrical power

- For every measurement point, calculate

$$P = UI.$$

- Plot the electrical power P as a function of voltage U .
- Determine graphically or numerically

$$U_{\text{MPP}}, \quad I_{\text{MPP}}, \quad P_{\text{MPP}}. \quad (1.20)$$

- Mark the maximum power point clearly in the graph.
- Discuss whether the maximum of the power curve corresponds to an intermediate value of both voltage and current, as expected.

Fill factor

- Calculate the fill factor

$$FF = \frac{U_{\text{MPP}} I_{\text{MPP}}}{U_{\text{OC}} I_{\text{SC}}}.$$

- Discuss what the obtained value tells you about the shape of the I - V characteristic.

Determination of the I - V characteristic

- Plot the measured current I as a function of the voltage U .
- Include appropriate uncertainties for the measured quantities for the error bars.
- Determine and plot the open-circuit voltage U_{OC} .
- Determine and plot the short-circuit current I_{SC} .
- Plot the maximum power point, I_{MPP} and U_{MPP} .
- Visualize the fill factor for your solar cell as it is done in Figure 1.4. and label your plot correctly.

Discuss the shape of the measured I - V characteristic.

Determination of the conversion efficiency

Use the measured active area A of the solar cell, as well as the irradiance E_e in W m^{-2} . With this, calculate the incident optical power:

$$P_{\text{opt}} = E_e \cdot A. \quad (1.21)$$

Then determine the efficiency at the maximum power point:

$$\eta_{\text{MPP}} = \frac{P_{\text{MPP}}}{P_{\text{opt}}}. \quad (1.22)$$

Discuss the uncertainty of the obtained efficiency.

Investigation of the temperature dependence

Plot the measured electrical power P as a function of the measured surface temperature T . If several measurement series at different thermal states were performed, plot P_{MPP} as a function of temperature.

Important: Do not interpret a correlation between power and temperature as proof of a temperature coefficient unless the temperature was independently varied and controlled.

1.5 Discussion

Discuss your results. In particular, consider the following questions:

- Does the measured I - V characteristic have the expected qualitative shape?
- Where is the maximum power point?
- How strongly does the electrical power depend on the load resistance?
- How large is the measured maximum electrical power?
- Is the maximum power point or the fill factor better to indicate the quality of a solar cell? Why?

- How does the cell temperature change during the experiment?
- Is there evidence for a temperature dependence of the electrical output?
- What are the dominant sources of uncertainty?
- How could the experiment be improved to obtain a more accurate absolute efficiency?

1.6 Literature

- V. Wesselak, S. Voswinckel, *Photovoltaik – Wie Sonne zu Strom wird*, Springer Verlag (2012)
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- W. Demtröder, *Experimentalphysik 2*, Springer.