1 Preparation

The following background knowledge is required:

1.1 Questions about the theoretical foundations:

- What is the difference between metals, insulators and semiconductors?
- What is the role of electrons, holes, and doping in semiconductor's physics?
- How is a semiconducting diode build up? What is the diode equation and how does the IV curve of a diode looks like?
- Explain the internal photoelectric effect and the photovoltaic effect.
- How does the IV-curve of a solar cell looks like? How can the most important cell parameters be extracted from the IV curve, i.e., the short circuit current, the open circuit voltage, the maximum power point, the fill factor, the efficiency, the parallel resistance and the serial resistance?

A MATLAB script is available to compare experimental results with numerical simulations of current-voltage curves (IV curve) of solar cell based on different semiconducting materials.

2 Literature review

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3 Motivation and Basics

3.1 Introduction

A solar cell converts solar energy into an electrical current. According to the internal photoelectric effect photons are absorbed in the semiconducting material and yield moving electron-hole pairs. The electron-hole pairs are separated at the p-n junction of the cell yielding an electrical photocurrent, this effect is known as photovoltaic effect. This photovoltaic effect yields an electric voltage at the contact areas, which drives an electric current through a load resistance if attached to the cell. Over the last 60 years, the efficiency of solar cells could be increased from 4% to 44,7% under laboratory conditions.

In this experiment, the efficiency and other cell parameters of a single crystalline solar cell will be measured. Furthermore, the origin of optical and in particular electrical losses will be explained and investigated. For this, the current-voltage curves (IV curves) will be acquired on a solar cell, being characteristic for each device. The cell parameters of the solar cell will be extracted from the curves. They strongly depend on the selected material, the design of the cell, the manufacturing process and measurement conditions such as temperature and illuminance. These cell parameters are easily accessible and allow to compare the effectiveness of the solar cell and, in particular, allow to verify and optimize electrical losses.

3.2 Semiconductor physics

3.2.1 The p-n junction of a diode

Many solar cells are based on semiconducting silicon. A crystalline Si solar cell body is build up by a p-doped (base) and n-doped (emitter) region which directly adjoin to each other. The contact area is referred to as p-n junction, which strongly determines the physics of this device. The gradient of charge carrier concentrations across this junction yields diffusion of holes from the p-doped region into the n-doped region and, in complementary, diffusion of electrons from the n-doped region into the p-doped region. The remaining negatively ionized acceptors and positively ionized donors are no longer electrically compensated. Therefore, a negative space charge will arise in the p-region and a positive space charge in the n-region. (Fig. 1b). This space charges with opposite sign yield an electric field and thus a field current in opposite direction to the diffusion current until diffusion flow is compensated.

3.2.2 Internal Photoelectric effect

Under illuminated conditions photons will be absorbed if their energy is equal or larger than the band gap ($E_\mathrm{g} = 0{,}1 - 3\,\mathrm{eV}$, $E_\mathrm{g} = 1{,}12\,\mathrm{eV}$ for Si at $300\,\mathrm{K}$) of the semiconducting material. Absorption of a photon yields a transition of a fixed electron from an occupied level within the valence band into a freely moving conduction electron in an unoccupied level of the conduction band and, simultaneously, a freely moving and positively charged hole in the valence band (Fig. 1a).

3.2.3 Photovoltaic Effect

Suppose a photon is absorbed at the space charge region. Then, the electron-hole pair is immediately separated by the electric field across the p-n junction. The electron will be accelerated towards the n-region and the hole towards the p-region. Suppose the electron-hole pair was generated outside the space charge region. This pair might diffuse due to thermal movement towards the space charge region. Also in that case the electric field will separate this pair and accelerate the minority charge carriers towards the correspondingly doped region, i.e. electrons towards the n-region and holes towards the p-region. In both cases, generation of charge carriers inside or outside the space charge region, a photocurrent I_{ph} results with electrons driven from the p-side to the n-side and holes driven from the n-side to the p-side. A voltage drop will arise across the contacts on both sides of the diode with a negative potential at the n-side and a positive potential at the p-side. Without a load resistance this voltage drop is referred to as open circuit voltage. This light induced separation of charge carriers at the p-n junction of a diode is known as p-n photoeffect or photovoltaic effect and is shown schematically in Figure 1b.

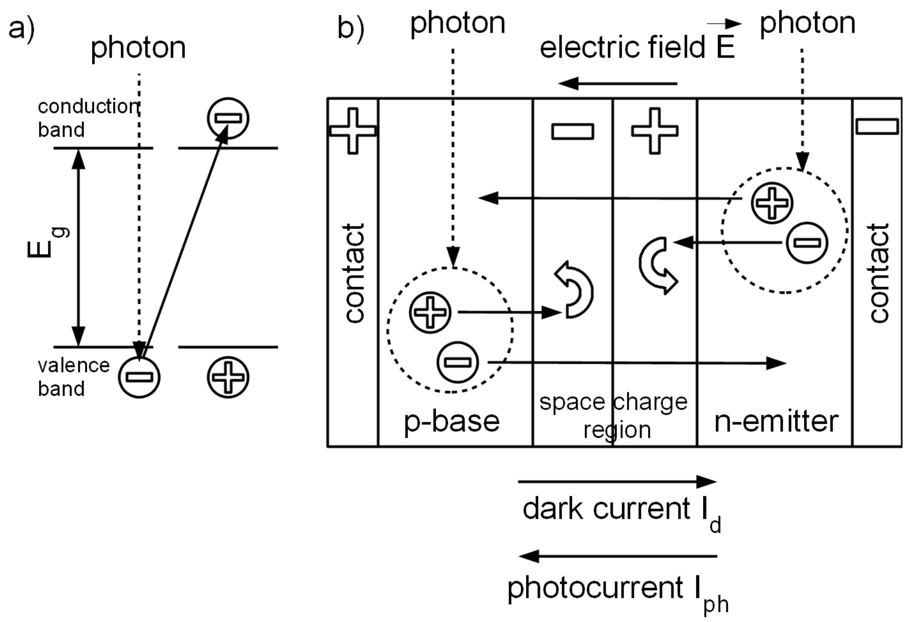

Abbildung 1: a) Schematics of the internal photoelectric effect. b) Schematics of the photovoltaic effect.

3.3 Optical and electrical losses

Optical losses reduce the output current and can be explained as follows:

- The Si surface reflects 35 – 50% of the light, depending on the wavelength. A thin antireflecting SiO_2 coating and a texturing of the cell surface reduces these losses (Fig. 2a).

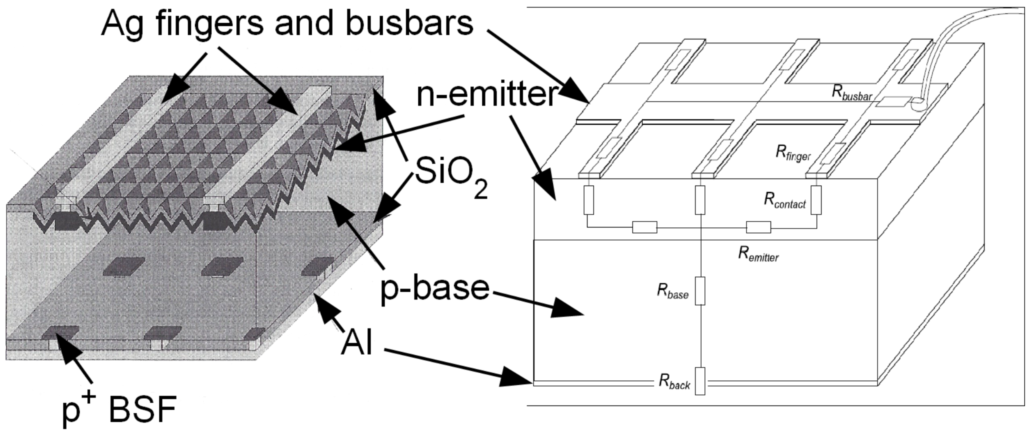

Abbildung 2: a) Schematics of the layers in crystalline Si solar cells. b) Schematics of contributions to the serial resistance of a solar cell.

- The grid structure of the front contact consisting of the fingers and busbars (Fig. 2a,b) shadows 3 – 5% of the light, depending upon the design.

- Absorption in silicon - indirect semiconductor - is very low in the long wavelength sunlight range, i.e., near to the band edge. This light is absorbed in the back surface contact without any photoelectric effect. These losses due to unabsorbed radiation can be reduced by use of a reflecting Al back contact (Fig. 2a,b).

The electrical losses are based on semiconductor physics and technology. They reduce the output current an in particular the output voltage. **Minimizing these electrical losses is the center of work into achieving high efficiency solar cells.** The electrical losses can be explained as follows:

- Radiative recombination is the inverse process of the internal photoelectric effect. It plays a minor role for indirect semiconductors such as Si.

- Recombination via defect levels introduced by impurities and crystal defects plays a major role for doping levels of $< 10^{17}\,\mathrm{cm}^{-3}$. Recombination takes place in the bulk material, at the p-n junction and at the surfaces of the semiconducting material. Impurities might yield energy levels deeper in the forbidden band, which act as traps for charge carriers. The impurity density is in particular large at the surface of the semiconductors and can be decreased by passivating the surface with a thin SiO_2 coating (Fig. 2a). Recombination losses at the interface between the p-type base and the metallic contact at the back side can be reduced by creation of a highly doped p^+ zone on the back surface of the solar cell base. This p^+p junction (high-low junction) is also known as a 'back surface field' (BSF) and acts as an electrical mirror on the charge carriers. (Fig. 2a).

- Auger recombination is dominant for doping levels of $> 10^{18}\,\mathrm{cm}^{-3}$. An electron transfers its energy to a second electron in the conduction or valence band. This excited electron looses its excess energy in a series of collision with the crystal lattice.

- Ohmic resistance losses might appear due to leaking currents along the edges of the solar cell or due to point defects in the p-n junction. Both effects are considered by a parallel resistance R_p in an equivalent electrical diagram of the solar cell.
- Furthermore, ohmic resistance losses are present in the bulk of the semiconducting material (base R_{base} and emitter R_{emitter}), in the bulk of the metal contacts (finger R_{finger},, busbar R_{busbar}, back contact R_{back}), and at metal-semiconductor interfaces (R_{contact}). These resistances sum up and are considered by a serial resistance R_s in the equivalent electrical diagram of the solar cell (Fig. 2b).

3.4 The One-Diode Model

A theoretical explanation of the current-voltage curve will be given for a solar cell used as a battery as intended in this experiment.

The individual contributions to the output current I are schematically shown in the equivalent circuit diagram of a real solar cell (Fig. 3a). The solar cell can be understood as a current source, a diode operated in forward direction, and a resistance R_p connected in parallel. The current source generates the constant photocurrent I_ph. The photocurrent I_ph is reduced by the current through the diode I_d and the leaking current I_p through the parallel resistance. Finally, the serial resistance R_s reduces the output current as well as the output voltage.

Under illumination, the solar cell reveals an IV curve of a diode due to the p-n junction. The IV curve of an ideal diode is determined by the diode equation

$$I_\text{d}(U_\text{D}) = I_0 \left[\exp\left(\frac{e\,U_\text{D}}{n\,k_\text{B}\,T} \right) - 1 \right] \tag{1}$$

with the dark current I_d, the saturation current I_0 and the voltage drop U_D at the diode. The other quantities are referred to as elementary charge e, the Boltzmann constant k_B, the ideality factor $n \approx 1$ and the cell temperature T.

The saturation current can be calculated from the diffusion coefficients and diffusion lengths of the electron and holes, the donator and acceptor concentrations and the intrinsic carrier density. Finally, the saturation current shows a temperature dependence according to

$$I_0(T) \propto T^s \exp\left(-\frac{E_\text{g}}{k_\text{B}\,T} \right) \tag{2}$$

with the band gap energy E_g and material depended exponent s ($s = 0$ for Si, Ge, GaAs; $s = 3$ for CdS, CdTe, InP).

The IV curve of an ideal solar cell is obtained by superposition of the dark current I_d and the photocurrent I_ph, yielding

$$\begin{aligned} I_\text{D}(U_\text{D}) &= I_\text{ph} - I_\text{d}(U_\text{D}) && (3)\\ I_\text{D}(U_\text{D}) &= I_\text{ph} - I_0 \left[\exp\left(\frac{e\,U_\text{D}}{n\,k_\text{B}\,T} \right) - 1 \right] && (4) \end{aligned}$$

Photocurrent and dark current flow in opposite directions, with the dark current flowing from the p- to the n-region as for a diode operated in forward direction (Fig. 1b).

For a real solar cell the parallel resistance R_p and the serial resistance R_s have to be considered in addition. Due to the relationships $R_p = U_D/I_p$ and $R_s = (U_D - U)/I$ equation 4 can be extended, yielding

$$
\begin{aligned}
I(U_D) &= I_{ph} - I_d(U_D) - I_p(U_D) && (5)\\
I(U) &= I_{ph} - I_0\left[\exp\left(\frac{e(U+IR_s)}{nk_BT}\right) - 1\right] - \frac{U+IR_s}{R_p} && (6)
\end{aligned}
$$

with the output current I and the output voltage U, which can be extracted at the contacts.

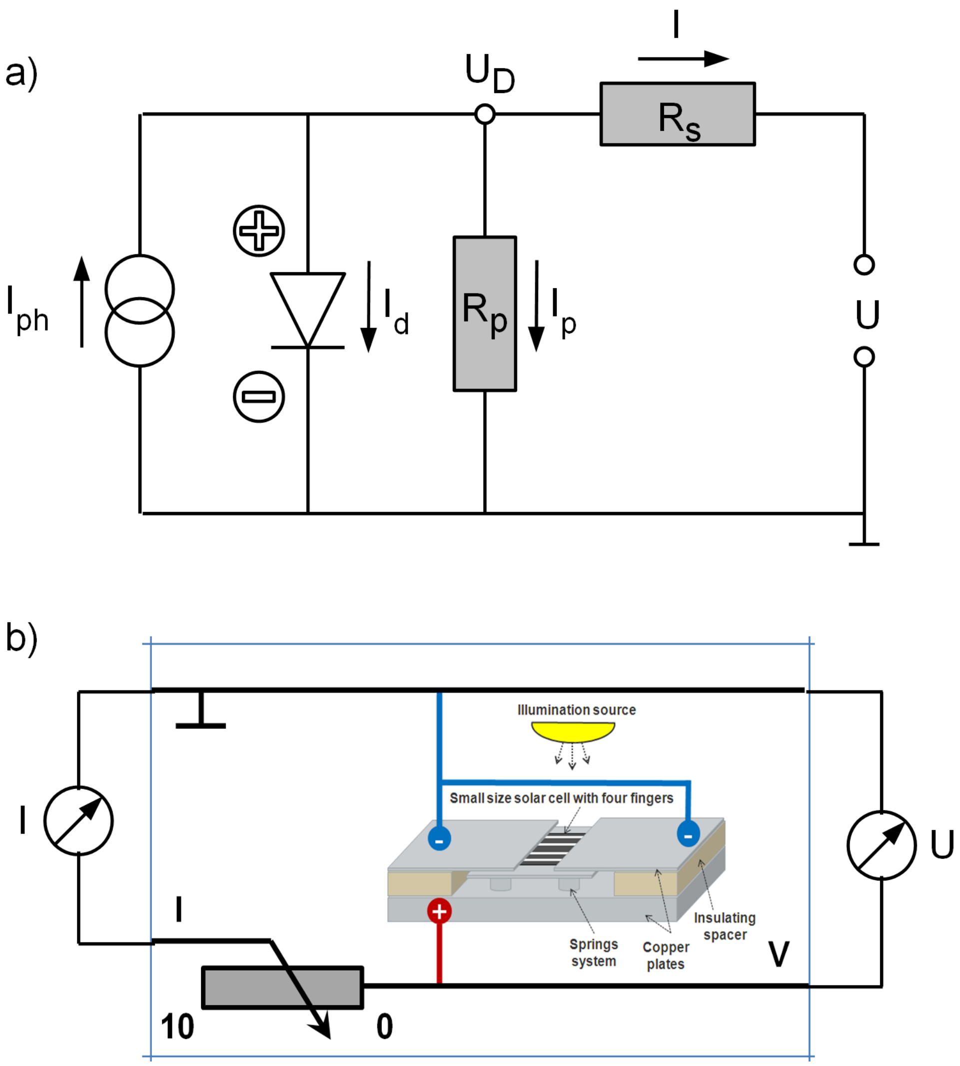

Abbildung 3: a) Equivalent circuit diagram of a solar cell according the one-diode model. b) Circuit diagram for the experiment.

3.5 Determination of the solar cell parameters from the IV curves

Different cell parameters can be extracted from the current-voltage curves (Fig. 4). In this section formulas will be given which allow to approximately calculate these parameters. A derivation of these formulas is given elsewhere.

3.5.1 Short circuit current

A short circuit current I_{sc} is obtained in case of a short circuit ($U = 0\,\mathrm{V}$) between the solar cell contacts:

$$I_{\mathrm{sc}} \approx I_{\mathrm{ph}} \left(1 + \frac{R_{\mathrm{s}}}{R_{\mathrm{p}}} \right) \tag{7}$$

3.5.2 Open circuit voltage

The open circuit voltage V_{oc} is measured at the contacts if there is no load resistance ($I = 0\,\mathrm{A}$):

$$V_{\mathrm{oc}} \approx \frac{k_{\mathrm{B}} T}{e} \ln \left(\frac{I_{\mathrm{sc}}}{I_0} \right) \tag{8}$$

3.5.3 Maximum Power Point

The maximum power point (MPP) is defined by the value pair ($U_{\mathrm{m}}, I_{\mathrm{m}}$) of the IV curve for which the output power $P_{\mathrm{out}} = U \cdot I$ of the solar cell is maximum:

$$P_{\mathrm{MPP}} = U_{\mathrm{m}} \, I_{\mathrm{m}} = P_{\mathrm{out,max}} \tag{9}$$

3.5.4 Fill factor

The fill factor FF corresponds in the IV curve to the ratio of the rectangle with maximum area $I_{\mathrm{m}} \cdot V_{\mathrm{m}}$ which can be drawn under the IV curve to the outer rectangle $I_{\mathrm{sc}} \cdot V_{\mathrm{oc}}$ given by the short circuit current and open circuit voltage

$$FF = \frac{U_{\mathrm{m}} \, I_{\mathrm{m}}}{I_{\mathrm{sc}} \, V_{\mathrm{oc}}} = \frac{P_{\mathrm{MPP}}}{I_{\mathrm{sc}} \, V_{\mathrm{oc}}} \tag{10}$$

3.5.5 Efficiency

The efficiency η is defined by the ratio of the maximum output power P_{MPP} to the light input P_{in}:

$$\eta = \frac{P_{\mathrm{MPP}}}{P_{\mathrm{in}}} = \frac{P_{\mathrm{MPP}}}{A \, E_{\mathrm{e}}} \tag{11}$$

with the exposed area A and the irradiance E_{e}.

3.5.6 Parallel resistance

The slope at the point ($U = 0\,\mathrm{V}$, $I = I_{sc}$) of the IV curves yields the parallel resistance R_p:

$$R_\mathrm{p} \approx \left[- \left(\frac{\partial I}{\partial U} \right)_{I_\mathrm{sc}} \right]^{-1} \tag{12}$$

3.5.7 Serial resistance

The slope at the point ($U = V_{oc}, I = 0\,\mathrm{A}$) of the IV curves yields the serial resistance R_s:

$$R_\mathrm{s} \approx \left[- \left(\frac{\partial I}{\partial U} \right)_{V_\mathrm{oc}} \right]^{-1} \tag{13}$$

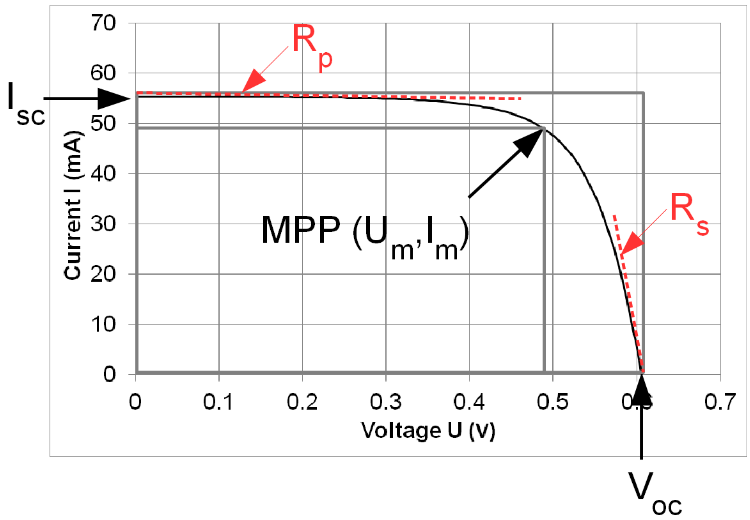

Abbildung 4: a) Determination of the cell parameters from the IV curve.

4 Experimental Procedure

4.1 Measurement principle

The aim is to acquire various current-voltage curves for different illuminances, parallel resistances and serial resistances and to extract the cell parameters. The circuit has to be set up according to the diagram in Figure 3b. The illuminance can be controlled by adjusting the distance between the lamp and the solar cell. A potentiometer is used as a variable load resistance and allows to acquire the current-voltage curves.

4.2 Sample, measurement holder and measurement procedure

The samples have a size of 15 mm × 10 mm and were cut out of a solar cell 156 mm × 156 mm in size. The solar cell is based on a single crystalline p-type Czochralski-Si Al-BSF Wafer. Texturing of the surface was obtained in a alkaline KOH solution. The n-type emitter was obtained by diffusion of $POCl_3$ into the structure during annealing in an tube furnace. The passivating and antireflecting thin layer was coated using the PECVD technique. The metal contacts at the front and back side were obtained via a screen-printing technique. The fingers and busbars on the front side consist of a silver paste which was fired in continuous annealing line.

The solar cell is already mounted on a measurement holder. A spring system is used to press the solar cell against two Cu contact plates (Fig. 3b). The measurement holder and the light source are mounted on an optical bench. The measurement holder is mounted on a displacing rider which allows a displacement of the solar cell in a direction perpendicular to the optical bench for optimizing illumination.

There is one socket with connectors for the solar cell, a voltmeter and an amperemeter (Abb. 3b). The amperemeter has to be connected in series to a 10-turn-potentiometer which is integrated in the socket. The potentiometer has a maximum resistance of 500 Ω, 1 turn corresponds to 50 Ω and one scale division to 1 Ω.

There is a second socket with two resistors. They are used for the acquisition of IV curves with additional resistors connected in parallel or in series to the solar cell.

An analog and a digital mutlimeter are available for the measurement of currents and voltages. The analog instrument is used for current measurements due to its smaller internal resistance (0,6 Ω for the analog multimeter at a measurement range up to 100 mA, 2,7 Ω for the digital multimeter at a measurement range up to 200 mA). The currents to be measured will be limited to 100 mA, the voltages are limited to 1 V. Please select the appropriate measurement ranges. The digital multimeter is equipped with an additional temperature sensor for measuring the temperature of the solar cell.

Two halogen lamps and a LED lamp are available as light sources with different luminous intensities. The lamps can be plugged to a lamp socket which is mounted on a rider on the optical bench. All lamps are operated at 12 V which is provided by an additional power supply. The power supply BT-305 of the manufacturer BASETech is operated as a constant voltage source. For this, the control knob 'Voltage Coarse' is used to preselect a voltage of 12 V. Then, the control knob 'Current' is set to maximum output current. The lamp current flows as soon as the switch 'Output' is activated. The power supply operates the lamp then with the maximum acceptable power of the lamp.

4.3 Tasks

1. A halogen lamp (12 V, 35 W, output angle 10 °, color temperature 3000 K, maximum luminosity intensity 11000 Cd) is used for the following tests. They should demonstrate the effect of different measurement conditions. Note down your observations.

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- A short circuit current of 60 mA has to be adjusted by selecting the appropriate distance of the lamp to the solar cell. For that, the 10-turn potentiometer has to be adjusted to a resistance of $0\,\Omega$.
- Change the position of the solar cell and the angle of incidence of the lamp until the solar cell is fully illuminated and a maximum short circuit current is obtained.
- Investigate the effect of reducing the illuminance by a factor of two on the short circuit current. The illuminance can be regulated by the lamp current. Measure the illuminance with a luxmeter.
- Investigate the effect of increasing the distance between the lamp and the solar cell by a factor of two on the illuminance (=luminosity intensity $\times$ solid angle $\times$ distance^{-2}). A measuring tape is available for measuring the distance. Measure the illuminance with a luxmeter.
- What is the effect of the internal resistance of the multimeters on the measurement results. For that, use the analog multimeter for measuring the voltage and the digital multimeter for measuring the current at short circuit conditions.

2. Following experiments have to be conducted for acquiring experimental IV curves

   - Measure the size of the exposed area of the solar cell using the caliper.
   - Adjust a short circuit current of 60 mA by selecting an appropriate distance between the lamp and the solar cell. The short circuit current will slightly decrease during the first 30 min until the lamp reaches thermal equilibrium. Wait for the thermal equilibrium and readjust the short circuit current by correcting the distance of the lamp to the solar cell. For the estimation of the efficiency measure the illuminance E_v with the lux meter.
   - Acquire IV curve #1 of the solar cell for a short circuit current of 60 mA. For that, increase the load resistance in steps of $1\,\Omega$ for the range $0\,\Omega$ to $30\,\Omega$, $5\,\Omega$ for the range $30\,\Omega$ to $60\,\Omega$, and $10\,\Omega$ for the range $60\,\Omega$ to $120\,\Omega$.
   - Connect a resistance of $15\,\Omega$ in parallel to the solar cell and acquire IV curve #2.
   - Connect a resistance of $5.1\,\Omega$ in series to the solar cell and acquire IV curve #3.
   - Remove the serial resistance and reduce the short circuit current to 30 mA by reducing the lamp current. Wait for thermal equilibrium of the lamp and acquire IV curve #4. For the estimation of the efficiency also measure the illuminance E_v with the lux meter here.

3. Simulation of a temperature series

   - A MATLAB script is available for numerical simulations and plotting of IV curves of solar cell based on different semiconducting materials. Investigate for Si solar cells the effect of temperature on the cell parameters for temperatures of −15°C, 25°C and 40°C. Generate the corresponding IV curves #5, #6, and #7 and save the screenshots of the GUIs as figures and the IV curves as Excel files. Start with simulation of the IV curve for a temperature of 25°C and for a short circuit current of 60 mA. Then, just change the temperature whereas all other input parameters remain constant.

4.4 Evaluation of IV curves and questions

1. What is the effect on the short circuit current a) when the illuminance is reduced by a factor of two and b) when the distance between lamp and solar cell is increased by a factor of two?

2. Plot for all four experimental IV curves the output current I vs. the output voltage in one diagram.

3. Plot for all four experimental IV curves the output power $P = U \cdot I$ vs. the output voltage in one diagram.

4. Extract from all four experimental IV curves the short circuit current I_{sc}, the open circuit voltage V_{oc}, the maximum power P_{MPP}, the fill factor FF, and the efficiency η. Extract the parallel resistance R_p from the slope in the interval ($U = 0 - 0.2\,V_{oc}$). Extract the serial resistance R_s from the slope in the interval ($I = 0 - 0.2\,I_{sc}$).

   Usually, for the determination of the efficiency of a solar cell a light source with the radiation conditions 'Standard AM1,5 global' is used. These conditions are present in nature, when the sun is at an angle of 41.8° above the horizon and the cell is collecting direct as well as diffuse light with irradiance of the solar constant $E_{sun} = 1367\,\mathrm{Wm^{-2}}$. Here, we need for the estimation of the efficiency according to Equation 11 the exposed area A and the actual irradiance E_e (in $\mathrm{W/m^2}$). It follows from the illuminance measured with the lux meter E_v (in lux, or lumen per square meter, $1\,\mathrm{lx} = 1\,\mathrm{lm/m^2}$) using the spectral luminous efficacy $K = E_v / E_e$. For the light of the halogen lamp used here assume $K \cong 300\,\mathrm{lm/W}$.

   What is the effect of the illuminance, of a parallel resistance, and of a serial resistance on the cell parameters? For that, summarize the cell parameters in a table as follows:

No.	Measurement	E_e ($\mathrm{W/m^2}$)	I_{sc} (mA)	V_{oc} (V)	P_{MPP} (mW)	FF (%)	η (%)	R_p (Ω)	R_s (Ω)
#1	$I_{sc} = 60\,\mathrm{mA}$								
#2	$I_{sc} = 60\,\mathrm{mA}$, $R_p = 15\,\Omega$								
#3	$I_{sc} = 60\,\mathrm{mA}$, $R_s = 5{,}1\,\Omega$								
#4	$I_{sc} = 30\,\mathrm{mA}$								

5. Plot for all three simulated IV curves the output current I vs. the output voltage U in one diagram.

   The MATLAB script extracts all cell parameters from the IV curves. What is the effect of temperature on the cell parameters? For that, note down the cell parameters from the screenshots of the GUIs and summarize them in a table as follows:

No.	Temperature	I_{sc} (mA)	V_{oc} (V)	P_{MPP} (mW)	FF	η
#5	−15°C = 258 K	60				
#6	25°C = 298 K					
#7	40°C = 313 K					

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