Friedrich-Alexander-Universität
Erlangen-Nürnberg

Advanced Laboratory Course

Photovoltaic: Function and electrical Characterization of Solar Cells [EN]

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Group ♣

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Contents

1 Preparation

1.1 Abstract

In this experiment we measure the main parameters of two solar cells (amorphous and crystalline), related to their volt-ampere characteristic. We make measurements both without illuminating them and with illuminating them by Halogen light bulb and by sunlight.

Below we briefly describe the corresponding theory and our experiment, mostly following [1] and [2].

1.2 Theoretical basics

1.2.1 Band Model

An electron with energy E and wave-function Ψ in a periodic crystal structure giving potential $U(\vec{r})$ is described by some Schrodinger equation:

$$\nabla^2\Psi + \frac{2m}{\hbar^2}(E - U(\vec{r}))\Psi = 0 \tag{1}$$

This leads to the spectrum $E(p)$, giving dependence of energy E on momentum p. It is known that this spectrum is given by Fig. 1 and can be approximated by two parabolas.

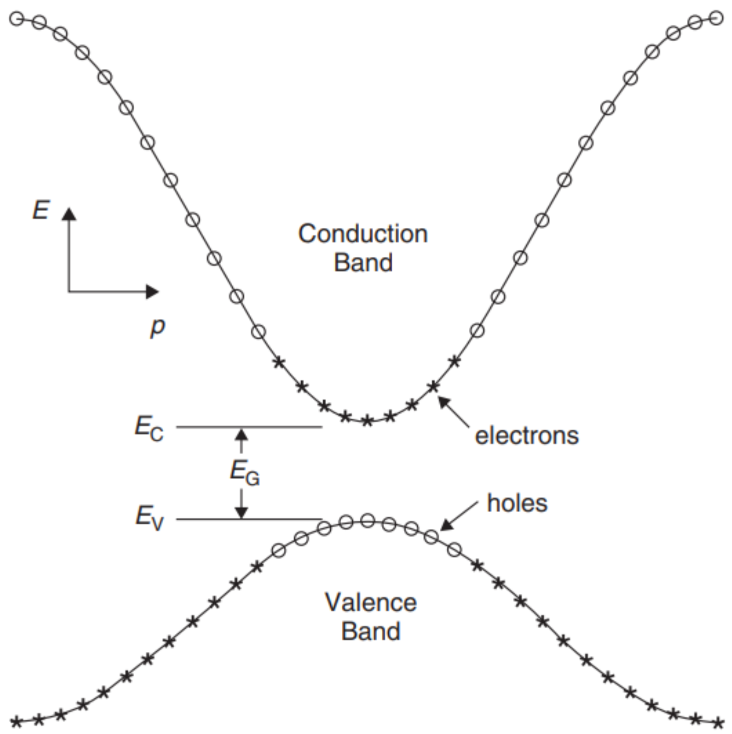

Figure 1: Spectrum in periodic crystal structure.

The second order coefficients of this parabolas are called effective masses. Electrons from the bottom (valence) band can go to the top (conduction) band. They are usually called just electrons (labeled n), with an effective mass m_n^*, while corresponding left empty states from the bottom usually called holes (labeled p), with the mass m_p^*. Holes are interpreted as particles themselves, having positive charge $+e$.

1.2.2 Densities of states

One of the most fundamental quantities in quantum solid state physics is density of states $g(E) = \frac{\partial n(E)}{\partial E}$, where number of states $n(E)$ per volume with energy E differentiating with respect to it. It is known that for the conduction band we have:

$$g_{\mathrm{C}}(E) = \frac{m_n^* \sqrt{2m_n^* \left(E - E_{\mathrm{C}}\right)}}{\pi^2 \hbar^3} \ \mathrm{cm}^{-3}\mathrm{eV}^{-1} \tag{2}$$

While for the valence band:

$$g_{\mathrm{V}}(E) = \frac{m_p^* \sqrt{2m_p^* \left(E_{\mathrm{V}} - E\right)}}{\pi^2 \hbar^3} \ \mathrm{cm}^{-3}\mathrm{eV}^{-1} \tag{3}$$

Taking in account the temperature, one need to useFermi distribution, which describes average number of electrons as

$$f(E) = \frac{1}{1 + \mathrm{e}^{(E - E_{\mathrm{F}})/kT}}, \tag{4}$$

where E_F is Fermi energy. It is important to note that holes are then described by $1 - f(E)$, resulting in formula of the same kind but with replaced $E_F \to -E_F$ and $E \to -E$. This leads to the following concentrationes of, respectively, electron and holes:

$$n_o = \int_{E_{\mathrm{C}}}^{\infty} g_{\mathrm{C}}(E) f(E) \mathrm{d}E = \frac{2N_{\mathrm{C}}}{\sqrt{\pi}} F_{1/2}\left(\left(E_{\mathrm{F}} - E_{\mathrm{C}}\right)/kT\right) \tag{5}$$

$$p_o = \int_{-\infty}^{E_{\mathrm{V}}} g_{\mathrm{V}}(E)[1 - f(E)] \mathrm{d}E = \frac{2N_{\mathrm{V}}}{\sqrt{\pi}} F_{1/2}\left(\left(E_{\mathrm{V}} - E_{\mathrm{F}}\right)/kT\right) \tag{6}$$

$$F_{1/2}(\xi) = \int_0^{\infty} \frac{\sqrt{\xi'} \mathrm{d}\xi'}{1 + \mathrm{e}^{\xi' - \xi}} \tag{7}$$

1.2.3 Doping

Conducting properties of the semiconductor are variable on practice using so-call doping, which means adding other materials which have their own carries of the charge. There two types of the doping: n-type, where additional carries are electrons, and p-type, where additional carries are holes. Thus, the current can flow mainly with holes or electrons, which are called majority carriers, while secondary ones are minority.

1.2.4 pn-junction diode

Consider coupled p-doped semiconductor on one side and n-doped semiconductor on the other side. Due to having different densities of electrons and holes they create diffusion zone, where, as well known in general, the concentration of the neighbor's majority carrier exponentially decreases. In addition, without electrical equilibrium, the existing electrical field leads to so-called drift current.

Thus, there are two currents, one diffusion current and one drift current, all them involves moving holes and electrons. Considering statistical current situation neglecting displacement current from Maxwell equations, total current is simply given by:

$$I = I_{diff} + I_{drift} = I_{diff\,p} + I_{diff\,n} + I_{drift\,p} + I_{drift\,n} \tag{8}$$

The equilibrium between p-type and n-type semiconductors leads to the well-known band bending structure, shown on Figure 2. Consider U-I characteristics of the diod. Roughly speaking,

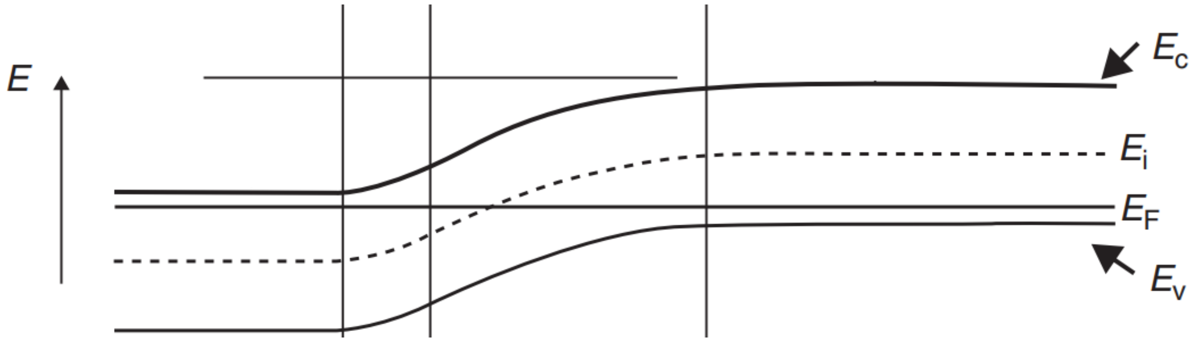

Figure 2: Band bending for connection of p-type and n-type superconductors. The main thing to note is that the fermi level becomes the same, and the energy levels shift, remaining unchanged relative to it. Here E_i is Fermi energy in an intrinsic, without dopping, semiconductor in thermal equilibrium.

we have applied voltage U and barrier voltage between the types U_B, which leads to:

$$I_{diff} \sim e^{\frac{(U-U_B)e}{kT}} \tag{9}$$

Using also the fact that at $U = 0$ diffusion ad drift current cancels each other due to the equilibrium, so $I_{drift} \sim e^{\frac{-eU_B}{kT}}$, we finally get the total current:

$$I(U) \sim \left(e^{\frac{Ue}{kT}} - 1\right) \tag{10}$$

However, due to several reasons, real diod is not ideally described by this simple consideration, and one more factor A (so-called diod factor, showing this deviation) need to be introduced in U-I characteristic of the diod:

$$I(U) = I_0 \left(e^{\frac{Ue}{AkT}} - 1\right) \tag{11}$$

1.2.5 Light absorption

The main effect, on which photovoltaic is based, is the absorption of light leading to creation of an electron-hole pair.

Consider photon with frequency ν falling on the semiconductor. If $h\nu$ is bigger than E_G, this could lead to absorption and transition of the (fundamental) electron from valence band to the conduction band, see Figure 3. Due to conservation of the total energy and the momentum of that electron p, we have:

$$h\nu = E_2 - E_1 \tag{12}$$

$$E_V - E_1 = \frac{p^2}{2m_p^*} \tag{13}$$

$$E_2 - E_C = \frac{p^2}{2m_n^*} \tag{14}$$

This leads to:

$$hv - E_G = \frac{p^2}{2}\left(\frac{1}{m_n^*} + \frac{1}{m_p^*}\right) \tag{15}$$

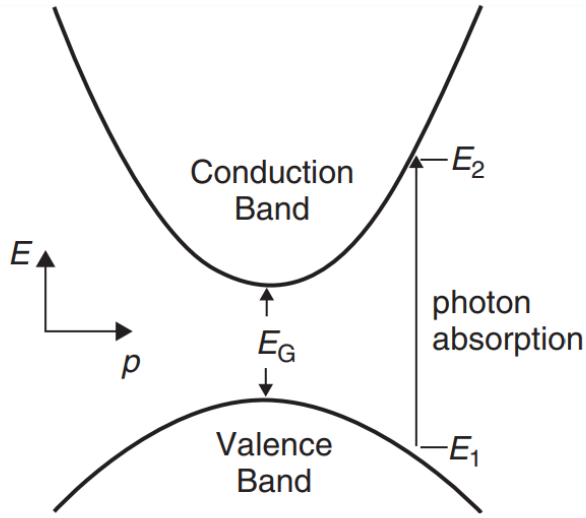

Figure 3: Absorption of the photon leading to the transition.

Thus, this result can be interpreted in terms of solid state terminology as creation of an electron and a hole, both with momentum p.

1.2.6 Solar cells

The solar cell is basically pn-diod which is illuminated by a light. The falling light reaches the diffusion zone between p-type and n-type semiconductors and creates holes and electrons. Light destroys thermal equilibrium and holes ca move to the p-type as electrons can move to the n-type. Due to the existing potential difference, it is impossible for them to go back. Thus, solar cell generates it's own voltage leading to the current in the electrical circuit.

U-I characteristics of the illuminated solar cell is generalized to the following form:

$$I(U) = I_0\left(e^{\frac{Ue}{AkT}} - 1\right) - I_{photo} \tag{16}$$

The example of the corresponding graph can be viewed from Figure 4.

There are several usual characteristic of any solar cell:

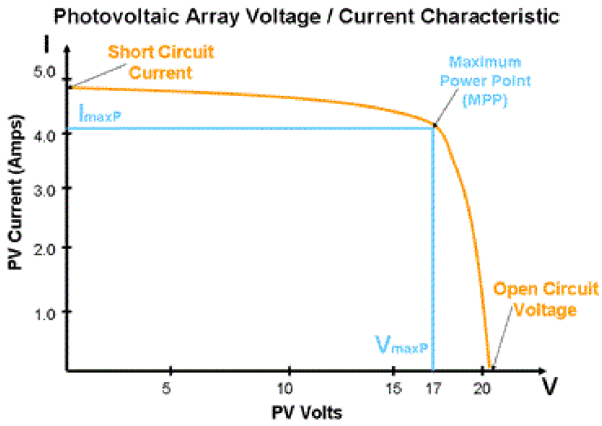

Figure 4: Example of U-I characteristic of the solar cell, taken from [3].

Open circuit voltage U_0: $I(U_0) = 0$.
Short circuit current I_k: $I_k = -I(U = 0)$
Point of maximum power P_{max}.
Efficiency η: $\eta = \frac{P_{max}}{P_{radiation}}$
Optimum load resistance R_{opt}: resistance for which the solar sell work at it's maximum power.
Filling factor F: $F = \frac{P_{max}}{U_0 I_k}$

There two the most important type of solar cells:the crystalline and the amorphous solar cell.

Although they generally work in the same way, it is important to note some differences. As follows from the name, they are made from crystalline or amorphous silicon. Although they generally work in the same way, it is important to note some main differences.

First, the diffusion length of the formed particles in the crystalline cells is much greater than in the amorphous cells. Roughly speaking, this is explained by the fact that there is a translation symmetry in the crystal lattice, so that the fundamental electrons can be ideally described by a wave function with equal probability through all the space. While in amorphous lattice the wave function is localized in space due to no translation symmetry. Thus, it comes to use additional material between n and p types in the construction for the amorphous solar cell.

Second, the absorption characteristics of the amorphous material are better. Roughly speaking, this is explained by the energy band structure, because for amorphous lattice there is no forbidden zone (the parabolas touch each other), so it absorbs more energy spectrum of photons.

In addition, amorphous solar cells are cheaper.

1.3 The experiment

1.3.1 Experimental setup

In this experiment, we will use solar cells (crystalline and the amorphous) by connecting them to various electrical circuits, using voltmeters, ammeters, resistors, a voltage source. In addition we use a dark box, a silicon reference diode, a Halogen light bulb, KG 2 filter. Below we shortly describe parts of the experiment.

1.3.2 Dark curve measurement

In the first part we measure the U-I curve of the two solar cells without any illumination. We connect them according to the picture with $R_p = 100\Omega$.

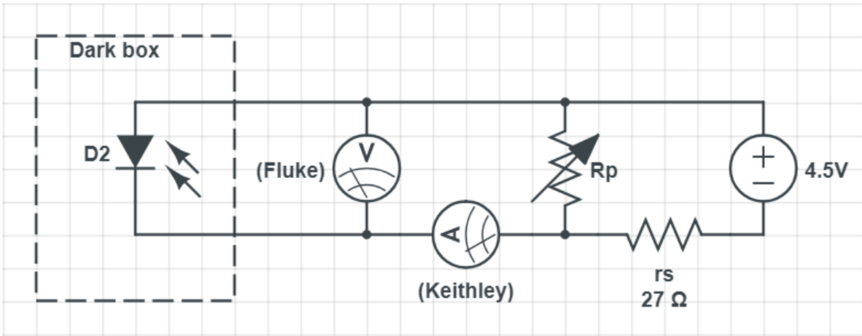

Figure 5: The solar cell (D2) connection diagram for the measurements with the power supply. Here A is ammeter, B is voltmeter, Rp1 ad Rp2 are resistors

1.3.3 Measurement under illumination

The values we measure in the presence of illumination correspond to a different U-I graph quadrant than those in the preceding section. Using a 100W halogen lamp and a KG 2 filter, which blocks out the majority of IR intensity, creates light that‘s spectrally similar to that of the sun. Calibration of the setup is the initial stage. To do this, we adjust the distance between the silicon detector and the lamp while using the silicon reference diode to measure the light intensity at least 15 separate times. The diode’s 118 W/cm2 A calibration factor is only valid when the KG 2 filter used. We pick two points on the positioning rail, one with a low intensity and one with a high intensity (for instance, 2.5mW/cm^2 and 10mW/cm^2), whose light intensities are now known. While the cells are illuminated, measure the U-I curve of each cell at both of these positions (4 curves altogether). The calibration diode (34mm), crystalline (7mm), and amorphous (10mm) cells have varying distances from the center of the mounting pole on the rail to the photo-sensitive surface. See figure 6.

1.3.4 Open circuit voltage and short circuit current

At 15 different distances from the filter, measure the short circuit current Ik and the open circuit voltage U0. Make a note of the corresponding intensity that the calibration diode measured. The measurement could be affected by the cells heating up.

1.3.5 Field experiment

Finally, we take the solar cells out to some sunny place and measure the characteristics U_0 and I_k. We also take in account the time of the day and the angle between the cells and the ground. Using the calibration diod, we also measure the sunlight intensity.

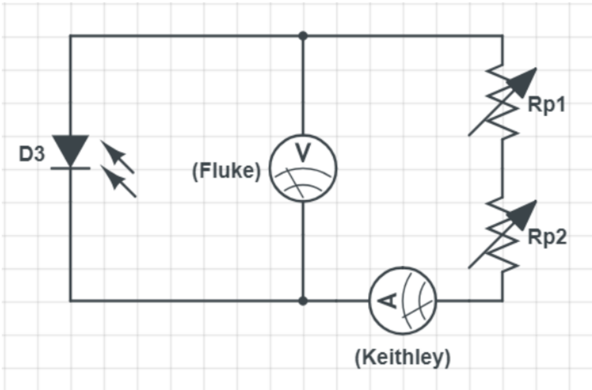

Figure 6: The solar cell (D3) connection diagram for the measurements with illumination. Here A is ammeter, B is voltmeter, Rp1 ad Rp2 are resistors

1.3.6 Experimental notes

Following [1], it is important to note:

(4.2a) According to the U-I characteristics, derived before, we don't need external voltage source to have nonzero voltage and current due to the I_{photo} term.
(4.2b) It is important to wait at least 20 after turning on the bulb min to make sure that created temperature is homogeneous.
(4.2c) The known calibration factor is related to the system using KG2. Using other filters or without filters will change the properties, so the information will not be correct.
(4.3a) Heating up of the cells leads to increasing of the radiation which can influences the measurement.
(4.3b) Measuring the time of the day and data is important since the sunlight varies in composition and intensity depending on the angle of passage through the atmosphere because its path is different. The angle of radiation incident on the cells is also important, since the flux depends on it.

2 Solar cells in darkness and under illumination

2.1 Calibration

As described earlier, in order to know the dependence of the light intensity on the position of the solar cells, we put a diode in their place and measure the current through it, varying the position x. Then get the intensity using calibration factor known for our experimental setup.

Since it is known that radiation depends as the inverse square of the distance to the illuminant, we fit our experimental data with the function

$$\sigma(x) \sim \frac{1}{(x-a)^2} \tag{17}$$

and get the results:

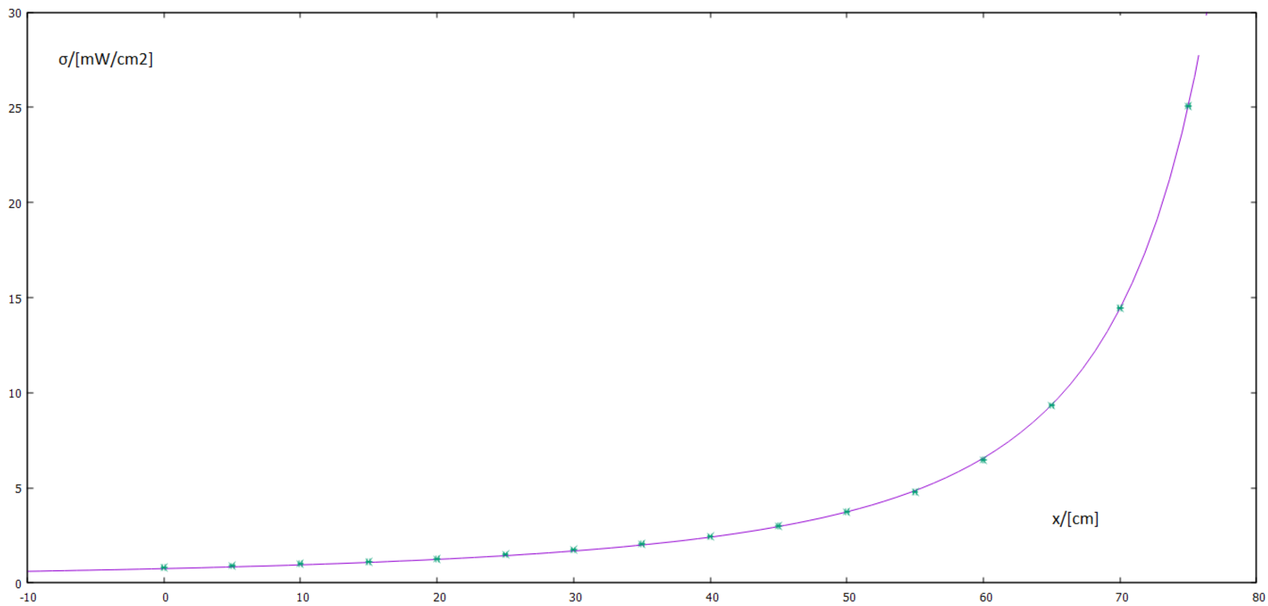

Figure 7: Dependence of the radiation intensity on the position of the diode.

$$\sigma/[\mathrm{mW/cm^2}] = \frac{(6194.5 \pm 43.9)\mathrm{mW}}{(x/[\mathrm{cm}] - 90.7 \pm 0.07)^2} \tag{18}$$

The obtained value a, describing the position of the Halogen light bulb, consistent with what we observed. The points fit the curve very well.

We use these data in our further analysis.

2.2 Crystalline solar cell

In this section, we present the results of measuring the characteristics of a crystalline solar cell. Both in the dark and under two different radiation intensities.

Here, on the figure below, is its U-I characteristics data without any illumination, fitted by corresponding exponential curve from the theory $I(U) = b(e^{aU} - 1)$, as considered in details in the preparation part:

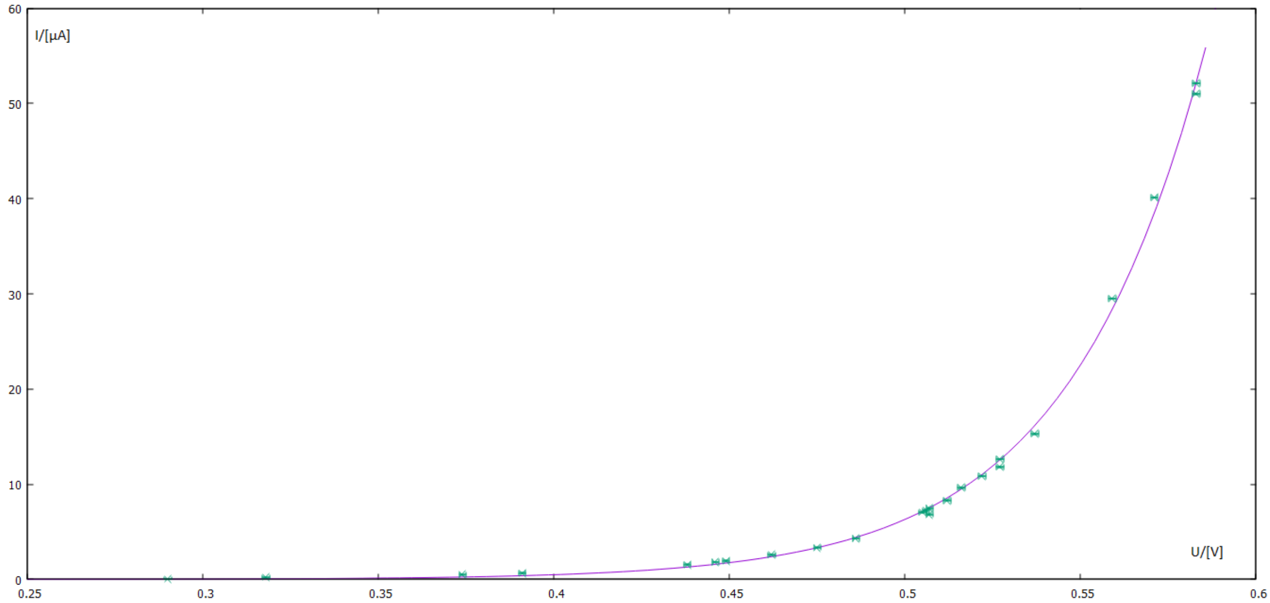

Figure 8: Dependence of the current on the voltage of the crystalline solar cell for darkness.

We see that the points fit quite well on the curve. However, there are some very small deviations due to the statistical errors.

Next, we make measurements with a light source at the position of the solar cell $x = 15$cm (far field) and $x = 60$cm (close field) according to our setup.

On the figure below we present all three graphs fitted independently by the theoretical curves with the illumination current:

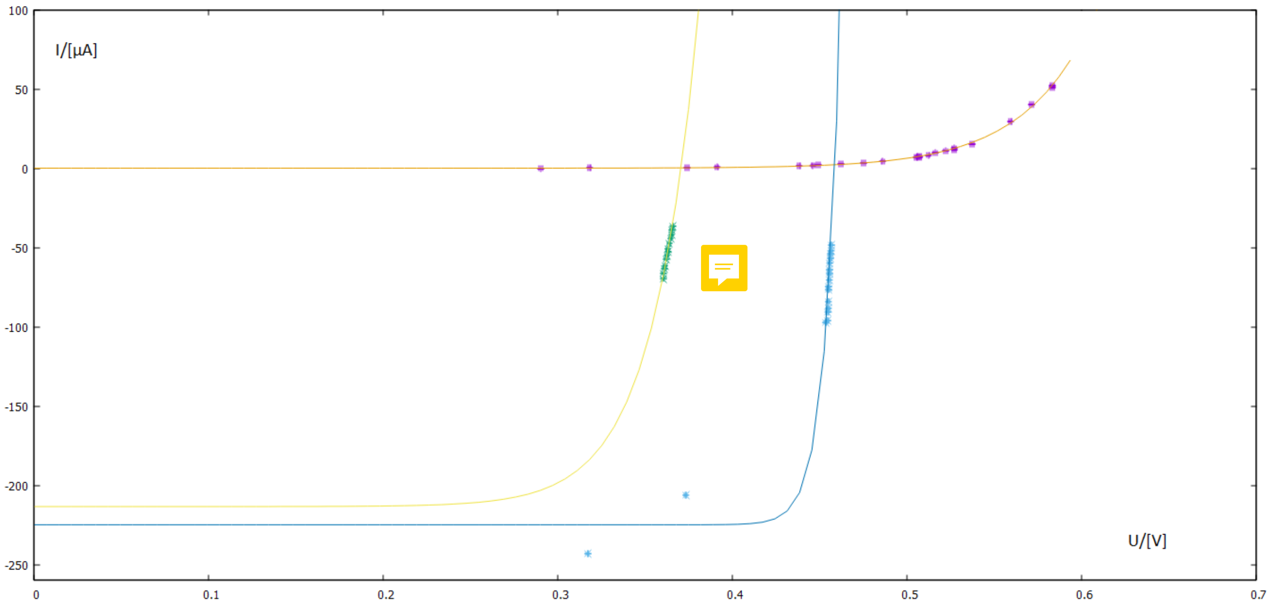

Figure 9: Dependence of the current on the voltage of the crystalline solar cell for darkness (orange), far field (yellow), close field (blue).

Data from the far field fits the curves also well. The data from the close field, however, has two points deviating from the curve. It would be reasonable to expect the curve to go lower including these points, nevertheless, fitting the curve fixing them does not give satisfactory results. Therefore, we fit it as it is.

Errors and causes will be discussed later.

Here we present the characteristics of this solar cell obtained with the help of graphs:

	P_{rad}/[mW]	I_k/[mA]	U_0/[V]	F	R_{opt}/[kΩ]	η
Close	25.27 ± 0.46	0.225 ± 0.092	0.459 ± 0.187	0.901 ± 0.367	1.959 ± 0.719	0.0037 ± 0.0022
Far	4.37 ± 0.46	0.213 ± 0.057	0.370 ± 0.099	0.761 ± 0.288	1.601 ± 0.461	0.0137 ± 0.0068

Table 1: Short circuit current, the optimum load resistivity, the filling factor and the efficiency of the crystalline solar cell for two different radiation power.

We also use the fact that the area of the crystalline cell is 3.9cm^2. [1]

2.3 Amorphous solar cell

Next, here we provide the same measurements for the amorphous solar sell sample.

First, it is important note that the amorphous solar cell sample consists of 10 single solar cells connected in series. By default, unless otherwise noted, we will consider the entire sample as a whole.

On the figure below one can see the U-I characteristics data without any illumination, fitted by corresponding exponential curve from the theory:

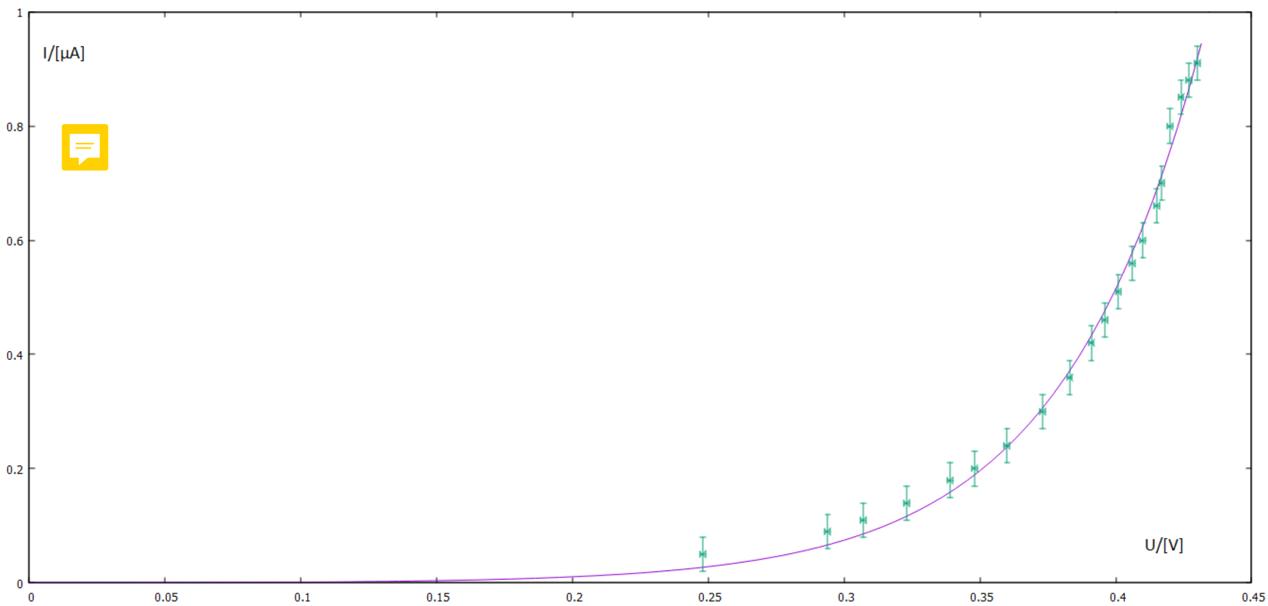

Figure 10: Dependence of the current on the voltage of the single amorphous solar cell for darkness.

The data, despite some not big deviations, smaller than assumed errors of the measurements, fit the curve well.

Here are all three U-I-curves (darkness, far field ($x = 15$cm) and close ($x = 60$cm)), fitted by theoretical formula:

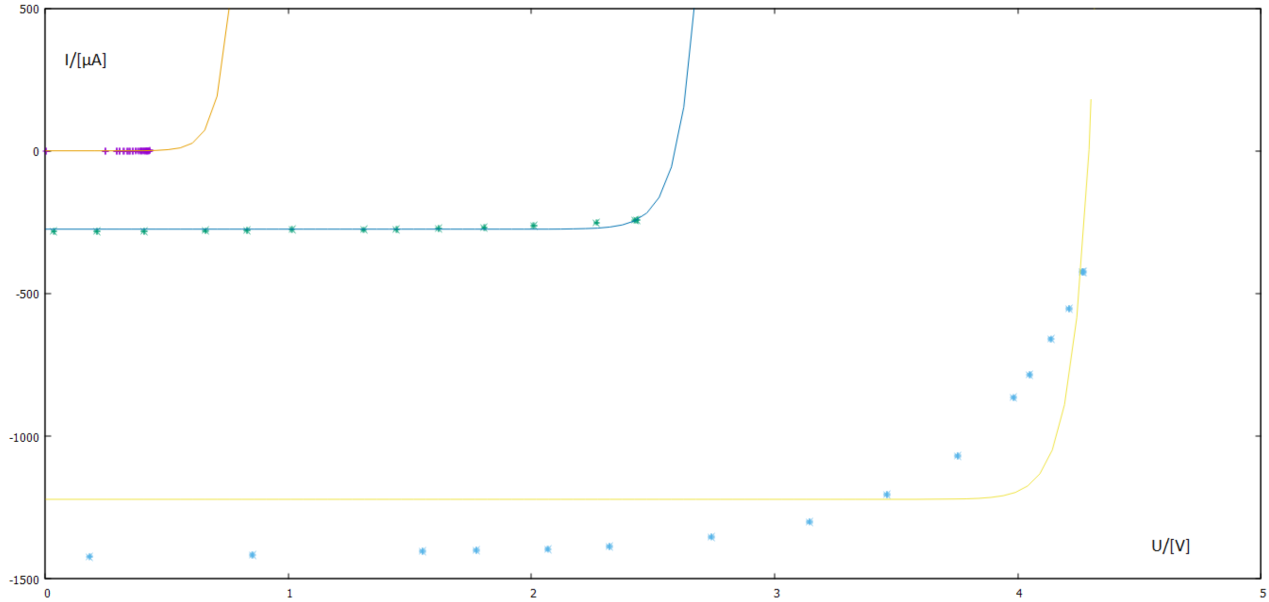

Figure 11: Dependence of the current on the voltage of the amorphous solar cell for darkness (orange)(it is single), far field (blue), close field (yellow).

Data fit the curves well enough, but for the close field there are some bigger deviation, however, it is still exponential.

Here we consider, as said before, and present the technical characteristics for a whole sample.

Characteristic of the amorphous solar cell sample:

	$P_{rad}/[\text{mW}]$	$I_k/[\text{mA}]$	$U_0/[\text{V}]$	F	$R_{opt}/[\text{k}\Omega]$	η
Close	164.55 ± 3.00	1.220 ± 0.251	4.293 ± 0.881	0.911 ± 0.264	3.337 ± 0.967	0.0290 ± 0.0084
Far	28.47 ± 3.00	0.274 ± 0.003	2.594 ± 0.022	0.872 ± 0.012	8.990 ± 0.123	0.0217 ± 0.0023

Table 2: Short circuit current, the optimum load resistivity, the filling factor and the efficiency of the amorphous solar cell for two different radiation power.

We also use the fact that the area of the cell is 25.4cm^2. [1]

3 Dependence on illumination intensity

3.1 Crystalline solar cell

Here we analyse the data with short circuit current, open circuit voltage under different light intensity conditions for the crystalline solar cell.

On the two figures below (figure 12, figure 13) we present the measured dependence of the short circuit current and open circuit voltage on the light intensity. The first if fitted by linear curve and the second is fitted by logarithmic curve.

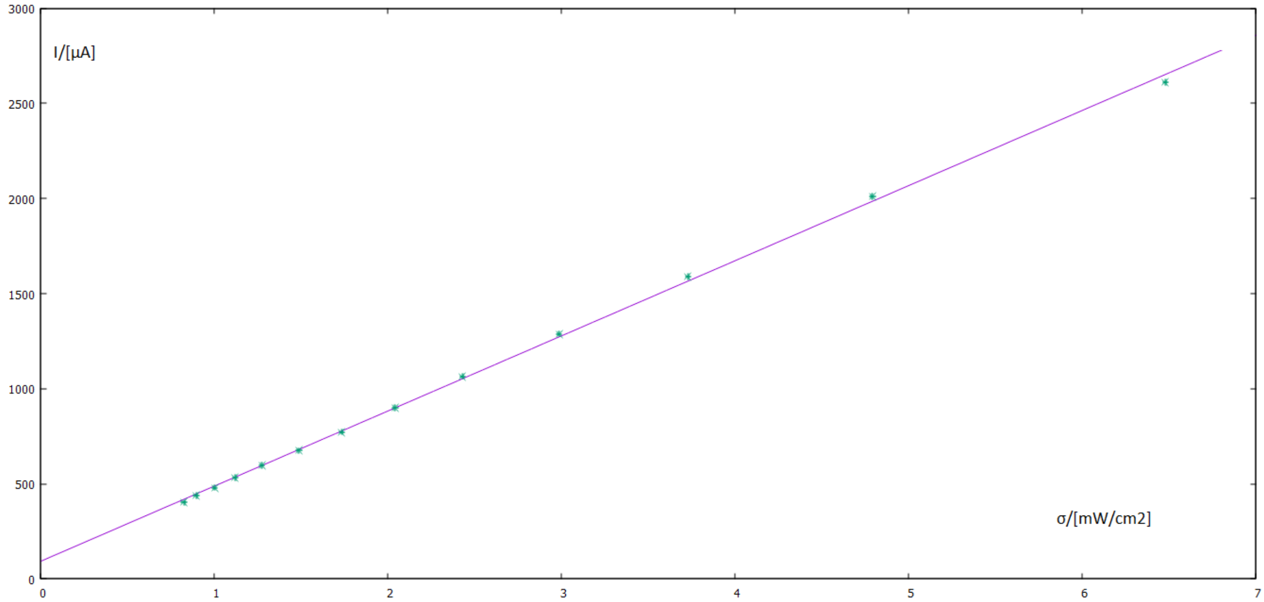

Figure 12: Dependence of the short circuit current on the light intensity for the crystalline solar sell.

All data fit the curves well.

Next, we are interested to determine the diod factor. To do so, we use the approximation $1 \ll \frac{I_k}{I_0}$ (in fact these values differs in about 10^3 times), which gives us:

$$\ln I_k \approx \frac{e}{AkT} U_0 + \ln I_0 \tag{19}$$

On the figure 14 there is the data with the fitting line.

As one can see, the linear relationship describes this data well.

Assuming the temperature to be about 20°C, as usual room temperature, we get the diod factor:

$$A = 2.289 \pm 0.070 \tag{20}$$

3.2 Amorphous solar cell

Here we analyse the data with short circuit current, open circuit voltage under different light intensity conditions for the crystalline solar cell.

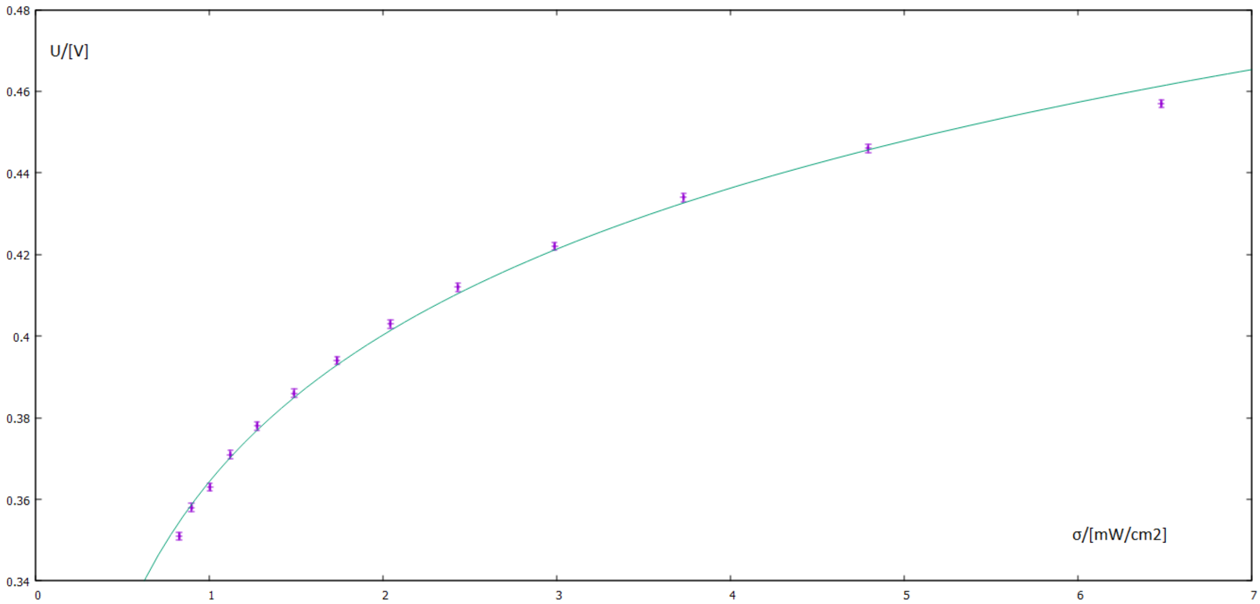

Figure 13: Dependence of the open circuit voltage on the light intensity for the crystalline solar sell.

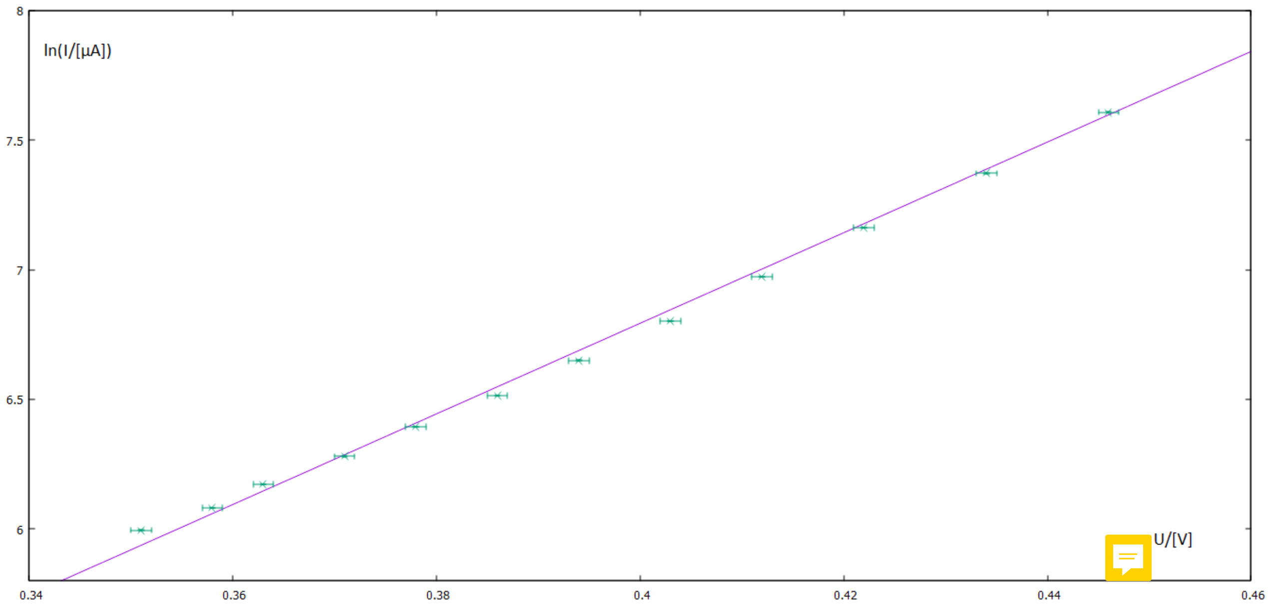

Figure 14: Dependence of the logarithm of an open circuit voltage on the light intensity for the crystalline solar sell.

On the two figures below (figure 15 and figure 16) we present the measured dependence of the short circuit current and open circuit voltage on the light intensity, fitted by linear curve and by logarithmic curve.

Fitting the data $\ln I_k$, U_0 using $1 \ll \frac{I_k}{I_0}$ approximation, we get the graph (figure 17), which which also looks fairly accurate.

Now, taking into account that in the amorphous solar cell sample, there are 10 single

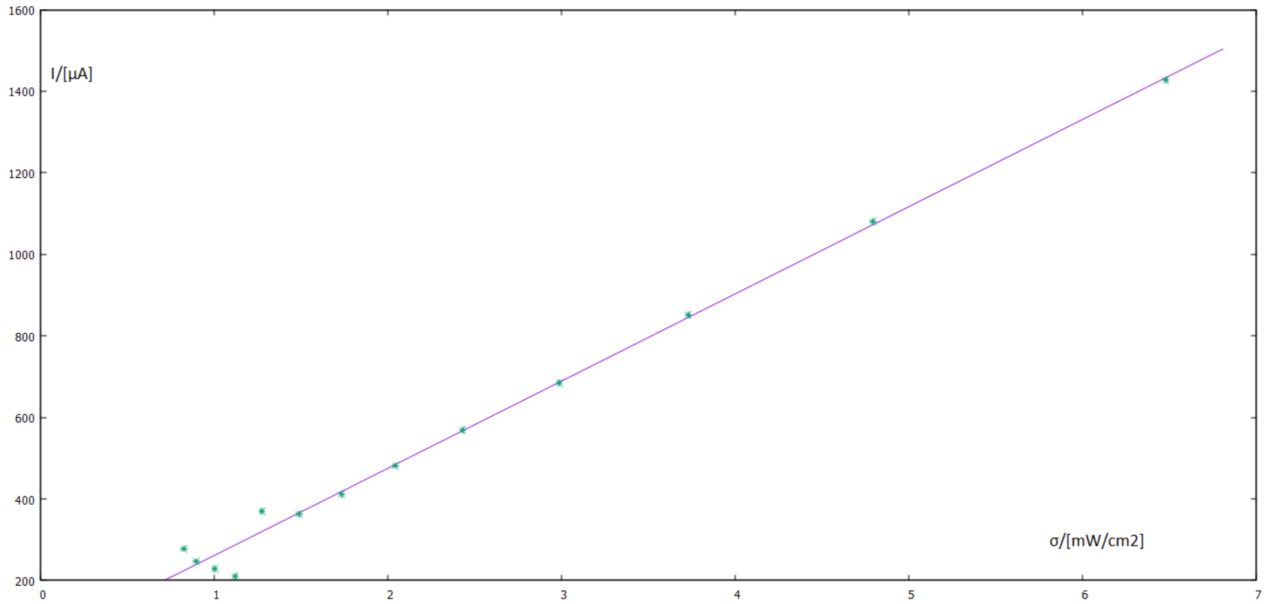

Figure 15: Dependence of the short circuit current on the light intensity for the amorphous solar sell.

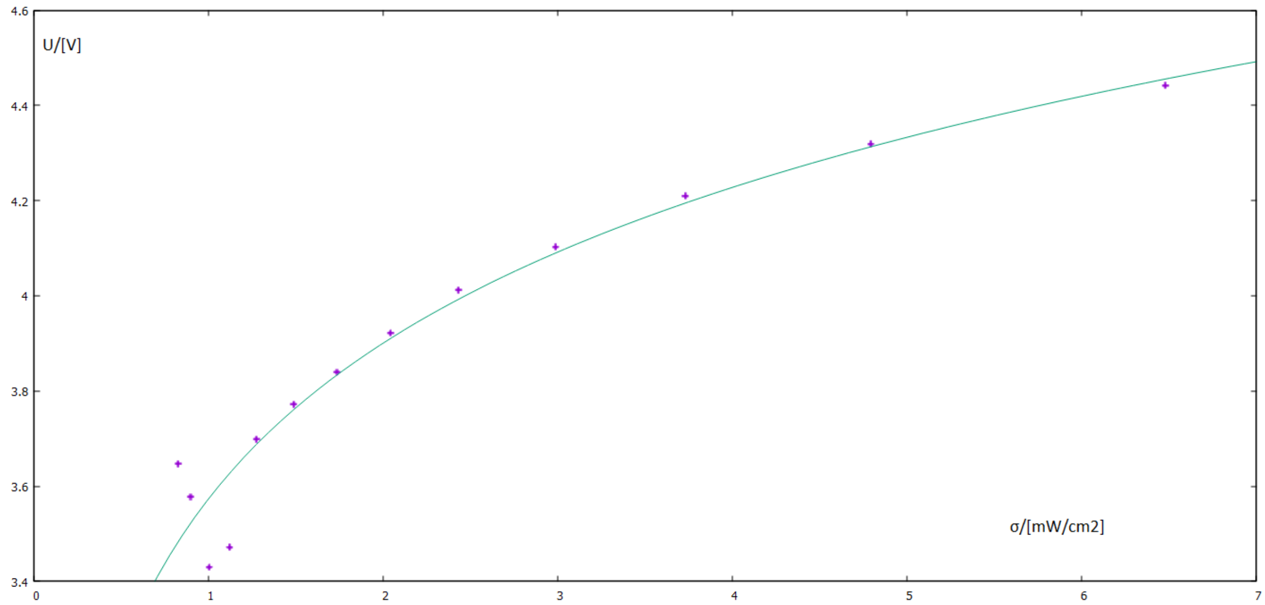

Figure 16: Dependence of the open circuit voltage on the light intensity for the amorphous solar sell.

solar cell connected in series (so the voltage increases 10 times), and using the assumed room temperature, we get the diod factor:

$$A = 2.130 \pm 0.081 \tag{21}$$

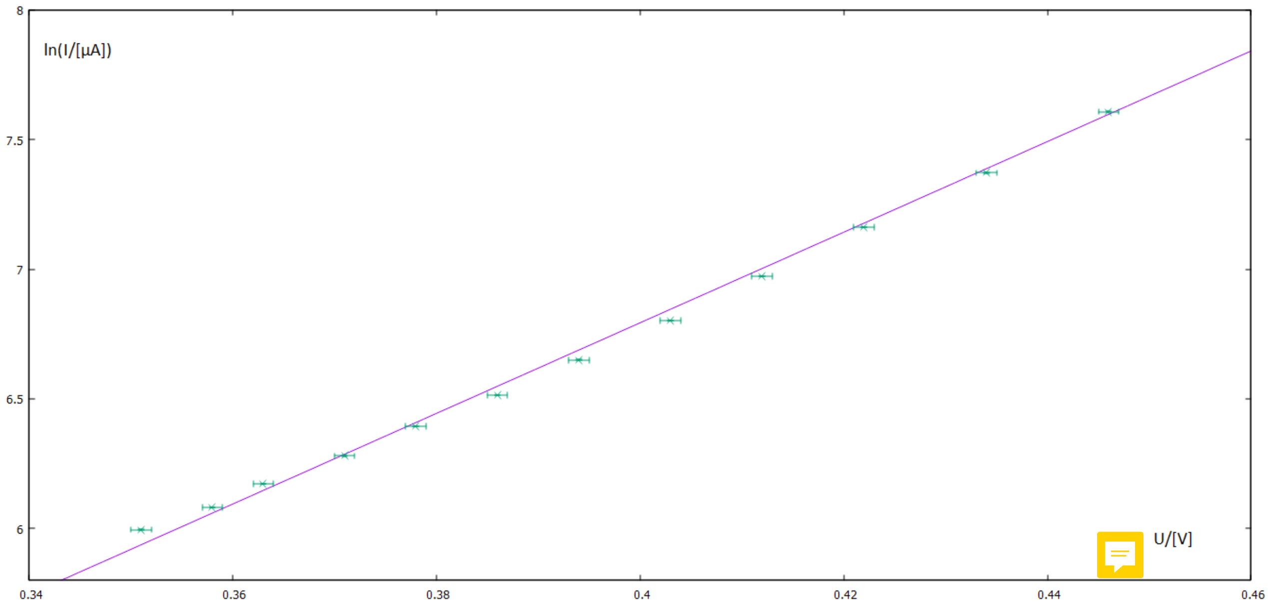

Figure 17: Dependence of the logarithm of an open circuit voltage on the light intensity for the amorphous solar sell.

4 Characteristics under sunlight

4.1 Sunlight calibration

In this section we determine the efficiency of the two solar cells from the field experiment using sunlight. To do so, we need at first to know the illumination power.

We note that the time of the experiment is 2 May, 4pm, the place is Germany, Erlangen. Unfortunately, the weather was not sunny, it was rainy day.

We measure the sunlight intensity directly to the Sun (front), parallel to the ground and perpendicular to the ground, using the calibration diod. Here are the results:

$$\sigma_{\perp} = (35.49 \pm 0.354)\mathrm{mW/cm^2} \tag{22}$$

$$\sigma_{||} = (3.13 \pm 0.354)\mathrm{mW/cm^2} \tag{23}$$

$$\sigma_{direct} = (56.88 \pm 0.354)\mathrm{mW/cm^2} \tag{24}$$

4.2 Amorphous solar cell

Next, me measure the I_k and U_k, finally obtaining η as $\frac{U_0 I_k}{P_{rad}} F$, using the factor F , since sunlight is very powerful, obtained earlier for close field illumination (as simple approximation). Here are the results:

	$P_{rad}/[\mathrm{mW}]$	$I_k/[\mathrm{mA}]$	$U_0/[\mathrm{V}]$	η
Directly to the Sun	1444.650 ± 8.992	52.8 ± 0.1	5.61 ± 0.01	0.1868 ± 0.0415
Parallel to the ground	79.629 ± 8.992	2.7 ± 0.1	5.49 ± 0.01	0.1683 ± 0.0373
Perpendicular to the ground	901.446 ± 8.992	45.4 ± 0.1	5.69 ± 0.01	0.2611 ± 0.0581

Table 3: Radiation power, short circuit current, open circuit voltage, efficiency of amorphous solar cell.

4.3 Crystalline solar cell

By analogy, we get these characteristics for the crystalline solar cell illuminated by the sunlight:

	$P_{rad}/[\mathrm{mW}]$	$I_k/[\mathrm{mA}]$	$U_0/[\mathrm{V}]$	η
Directly to the Sun	221.816 ± 13.806	99.6 ± 0.1	0.56 ± 0.01	0.2266 ± 0.0761
Parallel to the ground	12.227 ± 13.806	5.4 ± 0.1	0.54 ± 0.01	0.2148 ± 0.0729
Perpendicular to the ground	138.411 ± 13.806	78.9 ± 0.1	0.55 ± 0.01	0.2825 ± 0.0951

Table 4: Radiation power, short circuit current, open circuit voltage, efficiency of crystalline solar cell.

5 Conclusion

In this experiment, we were able to measure the characteristics of the amorphous and the crystalline solar cells under different condition: in darkness, under the Halogen bulb radiation with variable power, under the sunlight.

The obtained qualitative results fully confirm the theoretical description.

However, talking about quantitative results, the experiment is not perfect. Although the scale of the data obtained looks good, there are quite big errors and discrepancies in some places, especially in the last part.

One of the main contribution to the errors comes from fitting some data. Not enough good fitting can be caused, for example, by spontaneous rotation of the sample, leading to changes of the radiation power, and also bad range selection of the points.

Speaking about the last part, where the difference from the room measurements is quite big, the main factor is the weather (clouds). The power of sunlight varied between experiments and calibrations. In particular, its increase during the experiments probably led to larger efficiency values.

More accurate measurements could be made, for example, by fitting and analysing the data immediately on site, also by more rigid fixation of samples and measurement of their angle with respect to the light, and by making measurement and calibration both at the same time.

However, it seems to be quite hard to increase the accuracy of this experiment much using our experimental procedure and setup.

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