UM–SJTU Joint Institute

Physics Laboratory
(Vp241)

Laboratory Report

Exercise 3
Solar Cells: I-V Characteristics

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1 Introduction

The objective of this exercise is to learn about the solar cell and explore its characteristic (I-V, P-V, P_{max}, fill factor, energy conversion efficiency etc.).

Solar cells (Figure 1) are devices that transforms solar radiation into electrical energy. The principle of it is the photovoltaic effect, which is introduced in the following:

Photovoltaic Effect

"When the light enters the p-n junction near the solar cell surface, and the energy of incident photons is greater than the forbidden bandwidth (energy gap) E_{g}, the incident photons are absorbed and excite electron-hole pairs. Minority charge carriers in the n- or p-type area diffuse due to their density gradient. Some of them are able to diffuse to the region of the p-n junction where a built-in electric field exists. This field is directed from the n-type to the p-type area. The minority carriers diffusing to the p-n junction zone between the n-type area and the p-type area are drawn by this electric field to the p-type area (in case of the holes), or to the n-type area (in case of the electrons). This results in an increase of positive charge accumulated in the p-type area and negative charge in the n-type area. Consequently, a photoelectric potential difference is generated" [1].

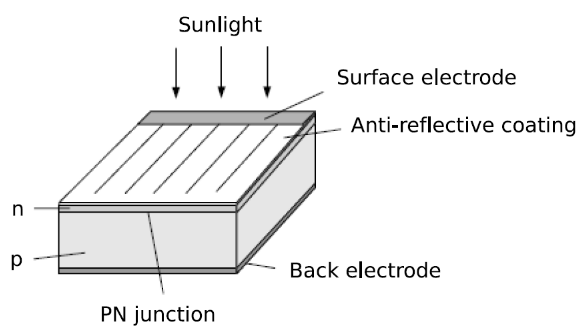

Figure 1: Structure of a crystalline silicon solar cell.

Solar Cell Parameters

The open-circuit voltage V_{oc} and the short-circuit current I_{sc} are two basic parameters for a solar cell. Also, when there is a load resistance R (with the value of R ranging from zero to infinity), the corresponding I-V values vary. If for a certain load resistance $R = R_{\mathrm{m}}$ the maximum output power P_{m} is generated, then the value of P_{m} is

$$P_{\mathrm{m}} = I_{\mathrm{m}} V_{\mathrm{m}},$$

where I_{m} is called the optimal operating current, and V_{m} is called the optimal operating voltage.

The fill factor is another important parameter of solar cells, defined as

$$FF = \frac{P_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}} = \frac{V_{\mathrm{m}} I_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}}. \tag{1}$$

Generally, the greater the fill factor is, the greater the output power.

The solar cell energy conversion efficiency η is defined as

$$\eta = \frac{P_{\mathrm{m}}}{P_{\mathrm{in}}} \times 100\%, \tag{2}$$

where P_{in} denotes the total radiant power incident on the solar cell.

2 Experimental Setup

The experimental setup includes a photovoltaic device (5 W), a 300 W tungstenhalogen lamp serving as a radiation source, two digital multimeters, two adjustable resistors, a solar power meter, a wiring board and a measuring tape.

The precision of the devices used is shown in Table 1.

Quantity	Precision
DC voltage	$0.5\% + 0.01$ [V]
DC current	$1.5\% + 0.1$ [mA]
Distance	0.1 [cm]
Solar power	10 [W/m^2]

Table 1: Precision of the measurement instruments.

3 Measurement Procedure

In this experiment, the characteristic of four configurations of the solar cell are studied. For each configuration, the I-V, P-V, P-R relation are studied and for the single configurations, the information about fill factor and energy conversion efficiency are also explored.

1. First, the characteristics of two devices in series and in parallel are explored. The two devices are adjusted so that they are of the same V_{oc} and I_{sc}. Connect the measurement circuit. Then adjust the resistance connected so that enough data of V and I are obtained.
2. Then, repeat the first step for a single device, with the distance maintained the same.
3. Measure the power on the surface of the solar board.
4. Measure the area of the solar board.
5. Change the distance, repeat the first step, still for a single device.

Caution

1. Do **NOT** touch the cover of the light source in case of getting burnt.
2. Beware of the high voltage supply of the light source.
3. Keep the distance from step 1 to 4.
4. Do **NOT** move around so as to maintain a constant incident power.

4 Results

4.1 I-V Relation

The measurement data for U and I under different conditions are shown in Table 2 and 3.

	Series		Parallel	
	V [V]	I [mA]	V [V]	I [mA]
1	0.84 ± 0.01	39.1 ± 0.7	1.10 ± 0.02	78.6 ± 1.3
2	1.81 ± 0.02	38.6 ± 0.7	1.75 ± 0.02	77.0 ± 1.3
3	2.72 ± 0.02	38.1 ± 0.7	2.56 ± 0.02	75.0 ± 1.2
4	3.72 ± 0.03	37.6 ± 0.7	3.38 ± 0.03	73.1 ± 1.2
5	4.82 ± 0.03	36.9 ± 0.7	4.06 ± 0.03	71.3 ± 1.2
6	6.04 ± 0.04	36.1 ± 0.6	4.58 ± 0.03	69.7 ± 1.1
7	6.94 ± 0.04	35.6 ± 0.6	4.92 ± 0.03	68.2 ± 1.1
8	7.74 ± 0.05	35.1 ± 0.6	5.12 ± 0.04	67.5 ± 1.1
9	8.82 ± 0.05	34.3 ± 0.6	5.26 ± 0.04	66.3 ± 1.1
10	9.90 ± 0.06	33.4 ± 0.6	5.39 ± 0.04	65.6 ± 1.1
11	11.08 ± 0.07	32.0 ± 0.6	5.50 ± 0.04	64.8 ± 1.1
12	11.34 ± 0.07	31.4 ± 0.6	5.78 ± 0.04	62.6 ± 1.0
13	11.59 ± 0.07	31.0 ± 0.6	5.95 ± 0.04	61.4 ± 1.0
14	11.85 ± 0.07	30.7 ± 0.6	6.04 ± 0.04	60.5 ± 1.0
15	12.29 ± 0.07	29.7 ± 0.5	6.12 ± 0.04	59.8 ± 1.0
16	12.50 ± 0.07	29.2 ± 0.5	6.23 ± 0.04	58.6 ± 1.0
17	12.76 ± 0.07	28.6 ± 0.5	6.32 ± 0.04	57.9 ± 1.0
18	13.13 ± 0.08	27.7 ± 0.5	6.72 ± 0.04	53.7 ± 0.9
19	13.45 ± 0.08	26.7 ± 0.5	7.06 ± 0.05	48.8 ± 0.8
20	13.85 ± 0.08	25.4 ± 0.5	7.41 ± 0.05	42.8 ± 0.7
21	14.28 ± 0.08	23.9 ± 0.5	7.74 ± 0.05	35.7 ± 0.6
22	14.68 ± 0.08	22.1 ± 0.4	8.06 ± 0.05	27.4 ± 0.5
23	15.08 ± 0.09	20.2 ± 0.4	8.33 ± 0.05	19.1 ± 0.4
24	15.46 ± 0.09	18.1 ± 0.4	8.57 ± 0.05	10.2 ± 0.3
25	15.83 ± 0.09	15.9 ± 0.3	8.61 ± 0.05	8.7 ± 0.2

Table 2: Measurement data for the U vs. I relation (series/parallel configuration).

	197.5 cm		165.6 cm	
	V [V]	I [mA]	V [V]	I [mA]
1	1.14 ± 0.02	36.4 ± 0.6	1.09 ± 0.02	52.0 ± 0.9
2	1.74 ± 0.02	35.9 ± 0.6	1.73 ± 0.02	51.6 ± 0.9
3	2.65 ± 0.02	35.0 ± 0.6	2.57 ± 0.02	50.6 ± 0.9
4	3.35 ± 0.03	34.4 ± 0.6	3.23 ± 0.03	49.6 ± 0.8
5	4.11 ± 0.03	33.6 ± 0.6	3.88 ± 0.03	48.4 ± 0.8
6	4.65 ± 0.03	32.9 ± 0.6	4.52 ± 0.03	47.4 ± 0.8
7	4.93 ± 0.03	32.6 ± 0.6	5.11 ± 0.04	46.3 ± 0.8
8	5.09 ± 0.04	32.0 ± 0.6	5.40 ± 0.04	45.6 ± 0.8
9	5.33 ± 0.04	31.7 ± 0.6	5.71 ± 0.04	45.0 ± 0.8
10	5.72 ± 0.04	30.6 ± 0.6	5.92 ± 0.04	44.6 ± 0.8
11	5.91 ± 0.04	29.9 ± 0.5	6.04 ± 0.04	44.3 ± 0.8
12	6.01 ± 0.04	29.4 ± 0.5	6.19 ± 0.04	43.8 ± 0.8
13	6.06 ± 0.04	29.3 ± 0.5	6.32 ± 0.04	43.6 ± 0.8
14	6.11 ± 0.04	29.1 ± 0.5	6.45 ± 0.04	42.8 ± 0.7
15	6.16 ± 0.04	28.7 ± 0.5	6.54 ± 0.04	42.4 ± 0.7
16	6.21 ± 0.04	28.5 ± 0.5	6.66 ± 0.04	41.9 ± 0.7
17	6.31 ± 0.04	28.1 ± 0.5	6.72 ± 0.04	41.6 ± 0.7
18	6.50 ± 0.04	27.1 ± 0.5	6.76 ± 0.04	41.4 ± 0.7
19	6.73 ± 0.04	25.7 ± 0.5	6.90 ± 0.04	40.2 ± 0.7
20	7.02 ± 0.05	23.8 ± 0.5	7.15 ± 0.05	38.5 ± 0.7
21	7.36 ± 0.05	20.8 ± 0.4	7.44 ± 0.05	36.0 ± 0.6
22	7.73 ± 0.05	17.2 ± 0.4	7.73 ± 0.05	32.9 ± 0.6
23	7.91 ± 0.05	14.6 ± 0.3	8.18 ± 0.05	26.7 ± 0.5
24	8.09 ± 0.05	12.5 ± 0.3	8.78 ± 0.05	15.3 ± 0.3
25	8.34 ± 0.05	8.4 ± 0.2	9.01 ± 0.06	9.1 ± 0.2

Table 3: Measurement data for the U vs. I relation (197.5 cm/165.6 cm configuration).

The I-V characteristic curves of the four configurations are plotted using Originlab. The plots are presented in Figure 2.

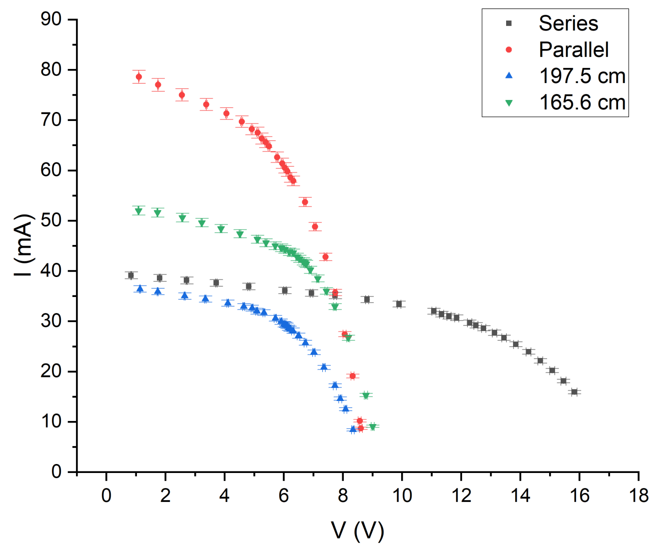

Figure 2: I-V characteristic curves of each configuration.

4.2 P-V and P-R Relation

The power of the solar cell is calculated as the product of V and I. Take the first set of data as an example,

$$P = VI = 0.84 \times 39.1 \times 10^{-3} = 0.0328 \pm 0.0008 \text{ W}.$$

The resistance of the external load are caluclated through Ohm's law $R = \dfrac{V}{I}$. Take the first set of data as an example,

$$R = \frac{V}{I} = \frac{0.84}{39.1 \times 10^{-3}} = 21.5 \pm 0.5 \ \Omega.$$

Perform simialr calculation for each set of data, the results are presented in Table 4 and Table 5.

	Series		Parallel	
	P [W]	R [Ω]	P [W]	R [Ω]
1	0.0328 ± 0.0008	21.5 ± 0.5	0.0865 ± 0.0019	14.0 ± 0.3
2	0.069 ± 0.0014	46.9 ± 1.0	0.135 ± 0.003	22.7 ± 0.4
3	0.104 ± 0.002	71.4 ± 1.4	0.192 ± 0.004	34.1 ± 0.6
4	0.140 ± 0.003	98.9 ± 1.9	0.247 ± 0.004	46.2 ± 0.8
5	0.178 ± 0.003	131 ± 2	0.289 ± 0.005	56.9 ± 1.0
6	0.218 ± 0.004	167 ± 3	0.319 ± 0.006	65.7 ± 1.2
7	0.247 ± 0.005	195 ± 4	0.336 ± 0.006	72.1 ± 1.3
8	0.272 ± 0.005	221 ± 4	0.346 ± 0.006	75.9 ± 1.4
9	0.303 ± 0.006	257 ± 5	0.349 ± 0.006	79.3 ± 1.4
10	0.331 ± 0.006	296 ± 6	0.354 ± 0.006	82.2 ± 1.5
11	0.355 ± 0.007	346 ± 7	0.356 ± 0.006	84.9 ± 1.5
12	0.356 ± 0.007	361 ± 7	0.362 ± 0.006	92.3 ± 1.7
13	0.359 ± 0.007	374 ± 7	0.365 ± 0.007	96.9 ± 1.7
14	0.364 ± 0.007	386 ± 7	0.365 ± 0.007	99.8 ± 1.8
15	0.365 ± 0.007	414 ± 8	0.366 ± 0.007	102.3 ± 1.8
16	0.365 ± 0.007	428 ± 8	0.365 ± 0.007	106.3 ± 1.9
17	0.365 ± 0.007	446 ± 9	0.366 ± 0.007	109.2 ± 2.0
18	0.364 ± 0.007	474 ± 9	0.361 ± 0.007	125 ± 2
19	0.359 ± 0.007	504 ± 10	0.345 ± 0.006	145 ± 3
20	0.352 ± 0.007	545 ± 11	0.317 ± 0.006	173 ± 3
21	0.341 ± 0.007	597 ± 12	0.276 ± 0.005	217 ± 4
22	0.324 ± 0.007	664 ± 14	0.221 ± 0.004	294 ± 6
23	0.305 ± 0.006	747 ± 15	0.159 ± 0.003	436 ± 9
24	0.280 ± 0.006	854 ± 18	0.087 ± 0.002	$(84 \pm 2) \times 10^1$
25	0.252 ± 0.006	$(100 \pm 2) \times 10^1$	0.075 ± 0.002	$(99 \pm 2) \times 10^1$

Table 4: Power P and resistance R for the series/parallel configuration.

	197.5 cm		165.5 cm	
	P [W]	R [Ω]	P [W]	R [Ω]
1	0.0415 ± 0.0009	31.3 ± 0.7	0.0567 ± 0.0013	21.0 ± 0.5
2	0.0625 ± 0.0013	48.5 ± 1.0	0.0893 ± 0.0018	33.5 ± 0.7
3	0.0928 ± 0.0018	75.7 ± 1.5	0.130 ± 0.002	50.8 ± 1.0
4	0.115 ± 0.002	97.4 ± 1.9	0.160 ± 0.003	65.1 ± 1.2
5	0.138 ± 0.003	122 ± 2	0.188 ± 0.004	80.2 ± 1.5
6	0.153 ± 0.003	141 ± 3	0.214 ± 0.004	95.4 ± 1.8
7	0.161 ± 0.003	151 ± 3	0.237 ± 0.004	110 ± 2
8	0.163 ± 0.003	159 ± 3	0.246 ± 0.005	118 ± 2
9	0.169 ± 0.003	168 ± 3	0.257 ± 0.005	127 ± 2
10	0.175 ± 0.003	187 ± 4	0.264 ± 0.005	133 ± 2
11	0.177 ± 0.003	198 ± 4	0.268 ± 0.005	136 ± 3
12	0.177 ± 0.003	204 ± 4	0.271 ± 0.005	141 ± 3
13	0.178 ± 0.003	207 ± 4	0.276 ± 0.005	145 ± 3
14	0.178 ± 0.003	210 ± 4	0.276 ± 0.005	151 ± 3
15	0.177 ± 0.003	215 ± 4	0.277 ± 0.005	154 ± 3
16	0.177 ± 0.003	218 ± 4	0.279 ± 0.005	159 ± 3
17	0.177 ± 0.003	225 ± 4	0.280 ± 0.005	162 ± 3
18	0.176 ± 0.003	240 ± 5	0.280 ± 0.005	163 ± 3
19	0.173 ± 0.003	262 ± 5	0.277 ± 0.005	172 ± 3
20	0.167 ± 0.003	295 ± 6	0.275 ± 0.005	186 ± 3
21	0.153 ± 0.003	354 ± 7	0.268 ± 0.005	207 ± 4
22	0.133 ± 0.003	449 ± 10	0.254 ± 0.005	235 ± 4
23	0.115 ± 0.003	542 ± 12	0.218 ± 0.004	306 ± 6
24	0.101 ± 0.002	647 ± 15	0.134 ± 0.003	574 ± 13
25	0.0701 ± 0.0019	$(99 \pm 2) \times 10^1$	0.082 ± 0.002	$(99 \pm 2) \times 10^1$

Table 5: Power P and resistance R for the 197.5 cm/165.6 cm configuration.

The P-V and P-R characteristic curves of the four configurations are plotted using Originlab. The plots are presented in Figure 3 and 4.

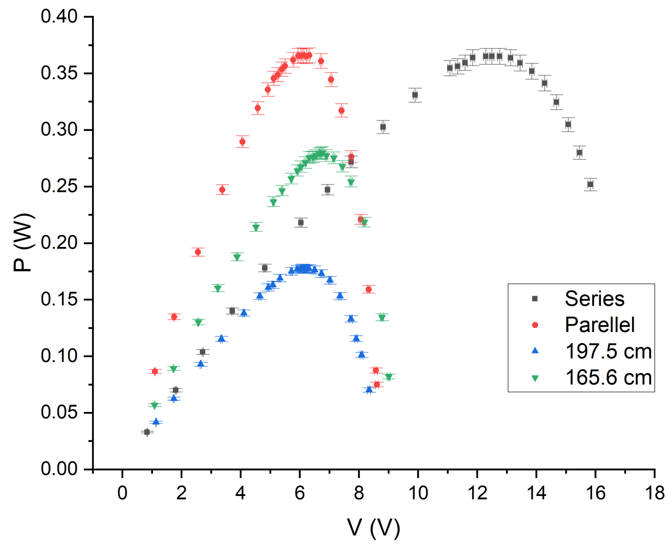

Figure 3: P-V characteristic curves of each configuration.

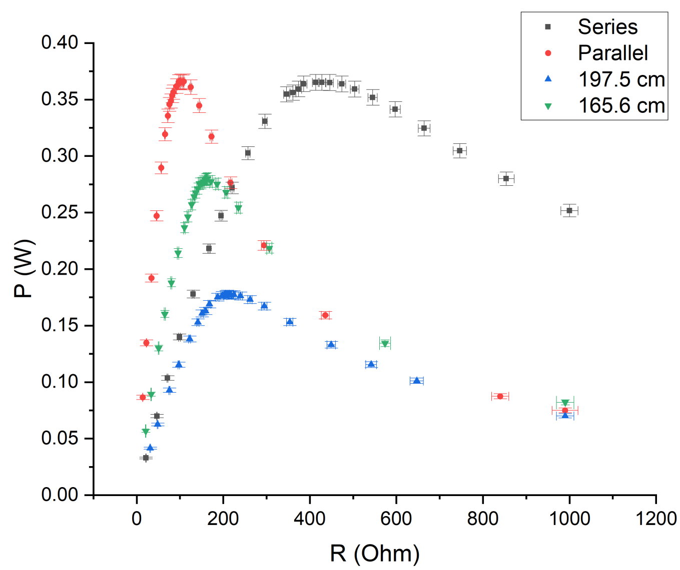

Figure 4: P-R characteristic curves of each configuration.

4.3 Maximum Output Power

The maximum output power and the corresponding $V_\mathrm{m}, I_\mathrm{m}, R_\mathrm{m}$ can be found by consulting Table 4 and 5. The results are presented in Table 6.

	V_m [V]	I_m [mA]	P_m [W]	R_m [Ω]
Series	12.29 ± 0.07	29.7 ± 0.5	0.365 ± 0.007	414 ± 8
Parallel	6.12 ± 0.04	59.8 ± 1.0	0.366 ± 0.007	102.3 ± 1.8
197.5 cm	6.11 ± 0.04	29.1 ± 0.5	0.178 ± 0.003	210 ± 4
165.6 cm	6.76 ± 0.04	41.4 ± 0.7	0.280 ± 0.005	163 ± 3

Table 6: V_m, I_m and P_m in each configuration.

4.4 Fill Factor (Single Configuration)

To figure out the fill factor, U_oc and I_sc are measured. The data are shown in Table 7.

	V_oc [V]	I_sc [mA]
197.5 cm	8.77 ± 0.05	37.2 ± 0.7
165.6 cm	9.29 ± 0.06	52.9 ± 0.9

Table 7: Measurement data for U_oc and I_sc.

The fill factor FF can be then calculated out of Eq.1. Take the series configuration as an example,

$$FF = \frac{P_\mathrm{m}}{V_\mathrm{oc} I_\mathrm{sc}} = \frac{0.178}{8.77 \times 37.2 \times 10^{-3}} = 0.545 \pm 0.015.$$

The fill factor of each single configuration are calculated as shown and the results are presented in Table 8.

	FF
197.5 cm	0.545 ± 0.015
165.6 cm	0.569 ± 0.015

Table 8: Fill factor of single configuration.

4.5 Energy Conversion Efficiency (Single Configuration)

The measurement data for the area are shown in Table 9.

Length L_1 [cm] $\pm$ 0.1 [cm]	Width L_2 [cm] $\pm$ 0.1 [cm]
26.0	21.1

Table 9: Measurement data for area.

The measurement result of power of six points on the board are shown in Table 10.

	1	2	3	4	5	6
$P_{197.5}$ [W/m^2] $\pm$ 10 [W/m^2]	100.6	141.7	113	140	120.1	136.2
$P_{165.6}$ [W/m^2] $\pm$ 10 [W/m^2]	157.3	178.5	166	185	189.5	188

Table 10: Measurement data for solar power.

The average of the power per square meter is

$$\overline{P_{197.5}} = \frac{1}{6}(100.6 + 141.7 + 113 + 140 + 120.1 + 136.2) = (13 \pm 2) \times 10^1 \text{ W/m}^2,$$

$$\overline{P_{165.6}} = \frac{1}{6}(157.3 + 178.5 + 166 + 185 + 189.5 + 188) = (17.7 \pm 1.7) \times 10^1 \text{ W/m}^2.$$

The total power is

$$P_{\text{in},197.5} = \overline{P_{197.5}} L_1 L_2 = 130 \times 0.260 \times 0.211 = 7.1 \pm 1.1 \text{ W},$$

$$P_{\text{in},165.6} = \overline{P_{165.6}} L_1 L_2 = 177 \times 0.260 \times 0.211 = 9.7 \pm 0.9 \text{ W}.$$

The power energy conversion efficiency can then be calculated from Eq.2, as

$$\eta_{197.5} = \frac{P_\text{m}}{P_{\text{in},197.5}} \times 100\% = \frac{0.178}{7.13} \times 100\% = 2.5\% \pm 0.4\%,$$

$$\eta_{165.6} = \frac{P_\text{m}}{P_{\text{in},165.6}} \times 100\% = \frac{0.280}{9.71} \times 100\% = 2.9\% \pm 0.2\%,$$

5 Conclusions and Discussion

5.1 I-V, P-V, P-R Relation

From Figure 2, we can see that I decreases as the V increases. Besides, its absolute value of the slope gets larger. This conforms to the characteristic if the diode in the solar sell.

From Figure 3 and 4, we can see that the as the R (or V, since increase of R will result in increase of V according to Ohm's laws) increases, the power first increases and then decreases. The output power attains its maximum at some $R = R_m$. This agrees with the theoretical conclusions that are derived from the Ohm's laws.

5.2 Parameters of the solar cell

The parameters measured of the solar cell are summarized in Table 11. It can be seen that for V_m and V_oc, the series is about twice of the single and the parallel is about equal to the single; for I_m and I_sc, the series is about equal to the single and the parallel is about twice of the single. This conforms to the theoretical results.

Also, the fll factor and the energy conversion efficiency obtained also implies that the greater the fill factor, the greater the energy conversion efficiency. This verifies the idea stated in the Introduction part.

Furthermore, our results also implies that the closer the solar board is to the light source, that is, the greater the incident intensity, the greater the fill factor [2]. Also, the fill factor conforms to the fact that most solar cell is of fill factor 0.5∼0.8 [2].

The energy conversion efficiency we obtained is rather low, which agrees with the fact that "traditional solar cell are of low efficiency" [3].

	Series	Parallel	197.5 cm	165.6 cm
V_{m} [V]	12.29 ± 0.07	6.12 ± 0.04	6.11 ± 0.04	6.76 ± 0.04
I_{m} [mA]	29.7 ± 0.5	59.8 ± 1.0	29.1 ± 0.5	41.4 ± 0.7
P_{m} [W]	0.365 ± 0.007	0.366 ± 0.007	0.178 ± 0.003	0.280 ± 0.005
R_{m} [Ω]	414 ± 8	102.3 ± 1.8	210 ± 4	163 ± 3
V_{oc} [V]	17.380 ± 0.010	8.83 ± 0.05	8.77 ± 0.05	9.29 ± 0.06
I_{sc} [mA]	39.2 ± 0.7	80.1 ± 1.3	37.2 ± 0.7	52.90 ± 0.9
FF	/	/	0.545 ± 0.015	0.569 ± 0.015
η	/	/	$2.5\% \pm 0.4\%$	$2.9\% \pm 0.3\%$

Table 11: Results.

5.3 Causes for errors and uncertainties

1. Our movement during the measurement may affect the incident intensity.
2. The input power of the solar cell is measured by choosing six points on the board, which can cause a huge uncertainty and further errors.
3. The internal resistance of the solar cell may cause deviation from the theoretical conclusions, since it is assumed that the solar cell is of no internal resistance.
4. The wire board we used has resistance itself, which caused the error in the experiment
5. Only discrete data are obtained in our experiment. The maximum point is only the approximated one and may have a significant deviation from the real value.
6. The loading resistance are obtained through the V-I method. As is known, the method itself has systematic error.

5.4 Suggestions

1. Measure the loading resistance using a multimeter instead of using the V-I method.
2. Make the incident intensity less sensitive to the surroundings.
3. Use apparatus with higher precision.

5.5 Conclusions

To sum up, in this exercise, we got familiar with the working principle of a solar cell and studied the parameters and characteristic of the solar cell in different configuration. Some basic parameters are measured and calculated and characteristics of the solar cell are verified. The results all conforms to the theoretical values and conclusions.

References

[1] VP241 Exercise 3: Solar Cells: I-V Characteristics, UM-SJTU Joint Institude.

[2] https://doi.org/10.1016/0379-6787(83)90067-4

[3] https://www.worldscientific.com/doi/abs/10.1142/9781783264469_0006

A Measurement Uncertainty Analysis

A.1 Uncertainty of I, V

The uncertainty of V is $0.5\% + 0.01$ V, and the uncertainty of I is $1.5\% + 0.1$ mA. Take the first set of data as an example,

$$u_V = 0.5\% \times 0.84 + 0.01 = 0.01\,\mathrm{V}.$$

$$u_I = 1.5\% \times 39.1 + 0.1 = 0.7\,\mathrm{mA}.$$

All the uncertainties of V and I are calculated in this way and the results are shown in Table 12.

	Series		Parallel		197.5 cm		165.6 cm	
	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]	u_V [V]	u_I [mA]
1	0.01	0.7	0.02	1.3	0.02	0.6	0.02	0.9
2	0.02	0.7	0.02	1.3	0.02	0.6	0.02	0.9
3	0.02	0.7	0.02	1.2	0.02	0.6	0.02	0.9
4	0.03	0.7	0.03	1.2	0.03	0.6	0.03	0.8
5	0.03	0.7	0.03	1.2	0.03	0.6	0.03	0.8
6	0.04	0.6	0.03	1.1	0.03	0.6	0.03	0.8
7	0.04	0.6	0.03	1.1	0.03	0.6	0.04	0.8
8	0.05	0.6	0.04	1.1	0.04	0.6	0.04	0.8
9	0.05	0.6	0.04	1.1	0.04	0.6	0.04	0.8
10	0.06	0.6	0.04	1.1	0.04	0.6	0.04	0.8
11	0.07	0.6	0.04	1.1	0.04	0.5	0.04	0.8
12	0.07	0.6	0.04	1.0	0.04	0.5	0.04	0.8
13	0.07	0.6	0.04	1.0	0.04	0.5	0.04	0.8
14	0.07	0.6	0.04	1.0	0.04	0.5	0.04	0.7
15	0.07	0.5	0.04	1.0	0.04	0.5	0.04	0.7
16	0.07	0.5	0.04	1.0	0.04	0.5	0.04	0.7
17	0.07	0.5	0.04	1.0	0.04	0.5	0.04	0.7
18	0.08	0.5	0.04	0.9	0.04	0.5	0.04	0.7
19	0.08	0.5	0.05	0.8	0.04	0.5	0.04	0.7
20	0.08	0.5	0.05	0.7	0.05	0.5	0.05	0.7
21	0.08	0.5	0.05	0.6	0.05	0.4	0.05	0.6
22	0.08	0.4	0.05	0.5	0.05	0.4	0.05	0.6
23	0.09	0.4	0.05	0.4	0.05	0.3	0.05	0.5
24	0.09	0.4	0.05	0.3	0.05	0.3	0.05	0.3
25	0.09	0.3	0.05	0.2	0.05	0.2	0.06	0.2

Table 12: Uncertainty of the data for I-V characteristic.

A.2 Uncertainty of P, R

For $P = VI$, its uncertainty is calculated as

$$u_P = \sqrt{(\frac{\partial P}{\partial V}u_V)^2 + (\frac{\partial P}{\partial I}u_I)^2} = \sqrt{(Iu_V)^2 + (Vu_I)^2}.$$

For $R = \frac{V}{I}$, its uncertainty is calculated as

$$u_R = \sqrt{(\frac{\partial R}{\partial V} u_V)^2 + (\frac{\partial R}{\partial I} u_I)^2} = \sqrt{(\frac{u_V}{I})^2 + (-\frac{V}{I^2} u_I)^2}.$$

Take the first set of data as an example,

$$u_P = \sqrt{(I u_V)^2 + (V u_I)^2} = \sqrt{(39.1 \times 10^{-3} \times 0.01)^2 + (0.84 \times 0.7 \times 10^{-3})^2} = 0.0008\,\text{W}.$$

$$u_R = \sqrt{(\frac{u_V}{I})^2 + (-\frac{V}{I^2} u_I)^2} = \sqrt{(\frac{0.01}{39.1 \times 10^{-3}})^2 + (-\frac{0.84}{39.1^2} \times 0.7)^2} = 0.5\,\Omega.$$

The uncertainty of P and R of all data are calculated in this way and the results are shown in Table 13.

	Series		Parallel		197.5 cm		165.6 cm	
	u_P [W]	u_R [Ω]	u_P [W]	u_R [Ω]	u_P [W]	u_R [Ω]	u_P [W]	u_R [Ω]
1	0.0008	0.5	0.0019	0.3	0.0009	0.7	0.0013	0.5
2	0.0014	1.0	0.003	0.4	0.0013	1.0	0.0018	0.7
3	0.002	1.4	0.004	0.6	0.0018	1.5	0.002	1.0
4	0.003	1.9	0.004	0.8	0.002	1.9	0.003	1.2
5	0.003	2	0.005	1.0	0.003	2	0.004	1.5
6	0.004	3	0.006	1.2	0.003	3	0.004	1.8
7	0.005	4	0.006	1.3	0.003	3	0.004	2
8	0.005	4	0.006	1.4	0.003	3	0.005	2
9	0.006	5	0.006	1.4	0.003	3	0.005	2
10	0.006	6	0.006	1.5	0.003	4	0.005	2
11	0.007	7	0.006	1.5	0.003	4	0.005	3
12	0.007	7	0.006	1.7	0.003	4	0.005	3
13	0.007	7	0.007	1.7	0.003	4	0.005	3
14	0.007	7	0.007	1.8	0.003	4	0.005	3
15	0.007	8	0.007	1.8	0.003	4	0.005	3
16	0.007	8	0.007	1.9	0.003	4	0.005	3
17	0.007	9	0.007	2.0	0.003	4	0.005	3
18	0.007	9	0.007	2	0.003	5	0.005	3
19	0.007	10	0.006	3	0.003	5	0.005	3
20	0.007	11	0.006	3	0.003	6	0.005	3
21	0.007	12	0.005	4	0.003	7	0.005	4
22	0.007	14	0.004	6	0.003	10	0.005	4
23	0.006	15	0.003	9	0.003	12	0.004	6
24	0.006	18	0.002	2×10^1	0.002	15	0.003	13
25	0.006	2×10^1	0.002	3×10^1	0.0019	2×10^1	0.002	2×10^1

Table 13: Uncertainty of data for P and R.

A.3 Uncertainty of Fill Factor (Single Configuration)

The uncertainty of V_{oc} and I_{sc} is calulated in the same way as V and I. The results are displayed in Table 14, together with the uncertainty of the maximum power.

	$u_{V_{\rm oc}}$ [V]	$u_{I_{\rm sc}}$ [mA]	$u_{P_{\rm m}}$ [W]
197.5 cm	0.04	0.5	0.003
165.6 cm	0.04	0.7	0.005

Table 14: Uncertainty of $V_{\rm oc}$ and $I_{\rm sc}$.

The uncertainty of fill factor, $FF = P_{\rm m}/(V_{\rm oc}I_{\rm sc})$, is calculated as

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{\partial FF}{\partial P_{\rm m}}u_{P_{\rm m}})^2 + (\frac{\partial FF}{\partial V_{\rm oc}}u_{V_{\rm oc}})^2 + (\frac{\partial FF}{\partial I_{\rm sc}}u_{I_{\rm sc}})^2} \\ &= \sqrt{(\frac{1}{V_{\rm oc}I_{\rm sc}}u_{P_{\rm m}})^2 + (-\frac{P_{\rm m}}{V_{\rm oc}^2 I_{\rm sc}}u_{V_{\rm oc}})^2 + (-\frac{P_{\rm m}}{V_{\rm oc}I_{\rm sc}^2}u_{I_{\rm sc}})^2}, \end{aligned}$$

Take the first set of data as an example,

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{1}{V_{\rm oc}I_{\rm sc}}u_{P_{\rm m}})^2 + (-\frac{P_{\rm m}}{V_{\rm oc}^2 I_{\rm sc}}u_{V_{\rm oc}})^2 + (-\frac{P_{\rm m}}{V_{\rm oc}I_{\rm sc}^2}u_{I_{\rm sc}})^2} \\ &= \sqrt{(\frac{1}{8.77 \times 37.2 \times 10^{-3}} \times 0.003)^2 + (-\frac{0.178}{8.77^2 \times 37.2 \times 10^{-3}} \times 0.05)^2 + (-\frac{0.178}{8.77 \times (37.2 \times 10^{-3})^2} \times 0.0007)^2} \\ &= 0.015. \end{aligned}$$

The uncertainties are calculated as shown above and the results are shown in Table 15.

	u_{FF}
197.5 cm	0.015
165.6 cm	0.015

Table 15: Uncertainty of FF.

A.4 Uncertainty of Energy Conversion Efficiency (Single Configuration)

The type–B uncertainty of power measurement is $u_P = \Delta_{P,B} = \Delta_{dev} = 10$ [W/m^2]. Since the power measurement is repeated for 6 times, the type–A uncertainty needs to be considered.

In this case, $n = 6$, $t_{0.95} = 2.57$, the type—A uncertainty is

$$\begin{aligned} \Delta_{P,A} =& \frac{t_{0.95}}{\sqrt{n}} s_{\overline{P}} \\ =& \frac{t_{0.95}}{\sqrt{n}} \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(P_i - \overline{P})^2} \\ =& \frac{2.57}{\sqrt{6}} \sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - \overline{P})^2}. \end{aligned}$$

The total uncertainty is then

$$u_{\overline{P}} = \sqrt{\Delta_{P,A}^2 + \Delta_{P,B}^2} = \sqrt{\left(\frac{2.57}{\sqrt{6}}\sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - \overline{P})^2}\right)^2 + 10^2}.$$

Hence, for the two single configurations,

$$u_{\overline{P_{197.5}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}}\sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 125.27)^2}\right)^2 + 10^2} = 2.0 \times 10^1 \ \mathrm{W/m^2},$$

$$u_{\overline{P_{165.6}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}}\sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 177.38)^2}\right)^2 + 10^2} = 1.7 \times 10^1 \ \mathrm{W/m^2},$$

The uncertainty of $P_{\mathrm{in}} = \overline{P}L_1L_2$ is calculated as

$$\begin{aligned} u_{P_{\mathrm{in}}} &= \sqrt{(\frac{\partial P_{\mathrm{in}}}{\partial \overline{P}}u_{\overline{P}})^2 + (\frac{\partial P_{\mathrm{in}}}{\partial L_1}u_{L_1})^2 + (\frac{\partial P_{\mathrm{in}}}{\partial L_2}u_{L_2})^2} \\ &= \sqrt{(L_1L_2u_{\overline{P}})^2 + (\overline{P}L_2u_{L_1})^2 + (\overline{P}L_1u_{L_2})^2}. \end{aligned}$$

Hence, substituting the values, it can be obtained that

$$u_{P_{\mathrm{in},197.5}} = 1.1 \ \mathrm{W}, \qquad u_{P_{\mathrm{in},165.6}} = 0.9 \ \mathrm{W}.$$

Finally, the uncertainty of $\eta = (P_{\mathrm{m}}/P_{\mathrm{in}}) \times 100\%$ can be calculated, as

$$\begin{aligned} u_\eta &= \sqrt{(\frac{\partial \eta}{\partial P_{\mathrm{m}}}u_{P_{\mathrm{m}}})^2 + (\frac{\partial \eta}{\partial P_{\mathrm{in}}}u_{P_{\mathrm{in}}})^2} \times 100\% \\ &= \sqrt{(\frac{1}{P_{\mathrm{in}}}u_{P_{\mathrm{m}}})^2 + (-\frac{P_{\mathrm{m}}}{P_{\mathrm{in}}^2}u_{P_{\mathrm{in}}})^2} \times 100\%. \end{aligned}$$

Substituting the values, it is derived in the end that

$$u_{\eta_{197.5}} = 0.4\,\%, \qquad u_{\eta_{165.6}} = 0.2\,\%.$$

B Data Sheet

Please find the original data sheet at the end of this report.

UM-SJTU Physics Laboratory Vp241

Data Sheet (Exercise 3)

Name: [illegible]　　　　Student ID: 518021911220

Name: 肖 宇　　　　Student ID: 518021910696.

Group: 17　　　　Date: 11.1

NOTICE. Please remember to show the data sheet to your instructor before leaving the laboratory. The data sheet will not be accepted if the data are recorded with pencil or modified by correction fluid/tape. If a mistake is made in recording a datum item, cancel the wrong value by drawing a fine line through it, record the correct value legibly, and ask your instructor to confirm the correction. Please remember to take a record of the precision of the instruments used.

You are required to hand in the original data with your lab report, so please keep the data sheet properly.

QUANTITY	PRECISION
DC voltage	±(0.5% +0.01) [V]
DC current	±(1.5% +0.1) [mA]
distance	±0.1 [cm]
solar power	± ~~[illegible]~~ 10 [W/m²]

Table 1. Multimeter precision.

length [cm]	width [cm]
26.0	21.1

Table 2. Measurement data for area.

	1	2	3	4	5	6
$P_{\cancel{\ }137.5}$ [W/m²]	100.6	141.7	113.0	140.0	120.1	136.2
$P_{\cancel{\ }\cancel{\ }165.6}$ [W/m²]	157.3	178.5	166.0	185.0	189.5	188.0

Table 3. Measurement data for solar power.

	single device at 137.5 cm	single device at 165.6 cm	series	parallel
U_{oc} [V]	8.77	9.29	17.38	8.83
I_{sc} [mA]	~~[illegible]~~ 37.2	52.9	39.2	80.1

Table 4. Measurement data for U_{oc} and I_{sc}.

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		197.5 cm		165.6 cm		
		U [V]	I [mA]	U [V]	I [mA]	
	1	1.14	36.4	1.09	52.0	
	2	1.74	35.9	1.73	51.6	
	3	2.65	35.0	2.57	50.6	
	4	3.35	34.4	3.23	49.6	
137.76	5	4.11	33.6	3.88	48.4	
152.9	6	4.65	32.9	4.52	47.4	
161.7	7	4.93	32.6	5.11	46.3	
168.37	8	5.33	31.7	5.40	45.6	
175.0	9	5.72	30.6	5.71	45.0	256.9
177.8	10	6.11	29.1	5.92	44.6	264.0
176.1	11	6.50	27.1	6.04	44.3	267.57
	12	7.02	23.8	6.19	43.8	271.1
	13	7.36	20.8	6.32	43.6	275.5
	14	7.73	17.2	6.45	42.8	276. 279
	15	8.09	12.5	6.66	41.9	
	16	8.34	8.4	6.90	40.2	277.38
176.4	17	5.91	29.9	7.15	38.5	275
177.3	18	6.31	28.1	7.44	36.0	267.8
170.0 ~~176.9~~	19	6.21	28.5	7.73	32.9	254.3
176.6	20	6.01	29.4	8.18	26.7	
177.5	21	6.06	29.3	8.78	15.3	
176.7	22	6.16	28.7	9.01	9.1	
	23	6.73	25.7	6.54	42.4	277
	24	7.91	14.6	6.76	41.4	279
	25	5.09	32	6.72	41.6	

Table 6. Measurement data for the U vs. I relation (197.5 cm/165.6 cm configuration).

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rev. 5

	series		parallel	
	U [V]	I [mA]	U [V]	I [mA]
1	0.84	39.1	1.10	78.6
2	1.81	38.6	1.75	77.0
3	2.72	38.1	2.56	75.0
4	3.72	37.6	3.38	73.1
5	4.82	36.9	4.06	71.3
6	6.04	36.1	4.58	69.7
7	6.94	35.6	5.12	67.5
8	7.74	35.1	5.50	64.8
9	8.82	34.3	5.78	62.6
10	9.90	33.4	5.95	61.4
11	11.08	32.0	6.12	59.8
12	11.85	30.7	6.32	57.9
13	12.29	29.7	6.72	53.7
14	12.50	29.2	7.06	48.8
15	12.76	28.6	7.41	42.8
16	13.13	27.7	7.74	35.7
17	13.45	26.7	8.06	27.4
18	13.85	25.4	8.33	19.1
19	14.28	23.9	8.57	10.2
20	14.68	22.1	8.61	8.7
21	15.08	20.2	4.92	68.2
22	15.46	18.1	5.26	66.3
23	15.83	15.9	5.39	65.6
24	11.34	31.4	6.04	60.5
25	11.59	31.0	6.23	58.6

365
365
11.34
11.59

Table 5. Measurement data for the U vs. I relation (series/parallel configuration).

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