UM-SJTU JOINT INSTITUTE
PHYSICS LABORATORY
(VP 241)

LABORATORY REPORT

EXERCISE 3

SOLAR CELLS: *I-V* CHARACTERISTICS

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1. Introduction

1.1. Objectives

- Get familiar with the working principle of a solar cell
- Study the current-voltage (*I-V*) characteristics

1.2. Theoretical background

Solar cells can directly transform solar radiation into electrical energy. No consumption of energy, silent operation, no moving parts, a long lifetime and so on are their advantages. Moreover, it is easy to maintain solar cells and they do not pollute air. Therefore, they are thought to be a promising energy source in the 21st century and people hope that by the mid-21st century, solar cells will produce 15–20% of the total electrical energy generated in the world. After that, solar energy will become one of the leading energy sources.

1.2.1. Solar cell structure

As shown in Figure 1, a crystalline silicon solar cell consists of *n*/*p* homo-junctions, a 10 cm × 10 cm *p*–type silicon plate of thickness 500 μm, covered with a heavily doped *n*-type layer with thickness 0.3 μm. The function of the metallic bars on the *n*-type layer is one electrode, while a metallic film at the bottom serves the role of another one. An anti-reflective film is often applied to cover the surface exposed to sunlight so that we can reduce the loss of energy due to reflection.

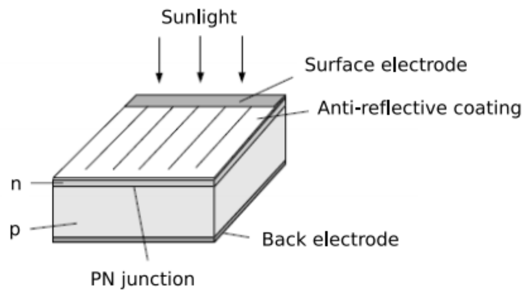

Figure 1. Structure of a crystalline silicon solar cell

1.2.2. Photovoltaic effect

When the light enters the *p-n* junction, if the energy of incident photons is greater than the forbidden bandwidth, which can be also called as 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 because of the density gradient. Some of them can diffuse to the region of the *p-n* junction and there is a built-in electric field. The direction of this field is from the *n*-type to the *p*-type area. This electric field will draw the carriers which are diffused to the *p-n* junction zone between the *n*-type area and the *p*-type area to the *p*-type area (in case of the holes), or to the *n*-type area (in case of the electrons). Therefore, more positive charge will accumulate in the *p*-type area and negative charge accumulate in the *n*-type area. Finally, there will form a photoelectric potential difference.

1.2.3. Solar cell parameters

Based on photovoltaic effect, electric current I_{ph} will be generated by solar cells from the *n*–type area to the *p*-area when there is light which is large enough incident on the solar cell.

Meanwhile, there is a forward diode current I_D from the *p*-type to the *n*-type area, which is opposite to I_{ph}. Then, we can calculate the net current as

$$I = I_{ph} - I_D = I_{ph} - I_0 \left[exp\left(\frac{qV_D}{nk_BT}\right) - 1\right], \tag{1}$$

where I_0 is the diode inverse saturation current, V_D is the junction voltage, and I_{ph} is the photocurrent determined by the structure and material characteristics of the solar cell. *n* is a theoretical coefficient characterizing the *p-n* junction, with its values ranging from 1 to 2. Furthermore, q denotes the electron's charge, k_B is the Boltzmann's constant, and *T* is the temperature in the absolute (Kelvin) scale. If we ignore the internal series resistance R_s , the voltage V_D equals the terminal voltage *V* and Eq. (1) can be rewritten in another form

$$I = I_{ph} - I_0 \left[exp\left(\frac{qV}{nk_BT}\right) - 1\right].$$

When $V = 0$, the short-circuit current is

$$I_{sc} = I_{ph}.$$

whereas $I = 0$, the open-circuit voltage is

$$V_{oc} = \frac{nk_BT}{q} ln\left(\frac{I_{sc}}{I_0} + 1\right).$$

When there is a load resistance *R* ranging from 0 to ∞, the corresponding *I–V* characteristics curve is shown in Figure 2. For a certain load resistance $R = R_m$, if we know that the maximum output power P_m is generated, then we can calculate it as

$$P_m = I_m V_m,$$

where I_m and V_m are the optimal operating current and the optimal operating voltage respectively. Then we introduce a new term, which is called the *fill factor* (*FF*).

$$FF = \frac{P_m}{V_{oc}I_{sc}} = \frac{V_m I_m}{V_{oc}I_{sc}}.$$

The greater it is, the greater the output power. It depends on numeric factors, like the forbidden bandwidth, the incident light intensity, the value of the theoretical coefficient *n*, and the series/parallel resistance.

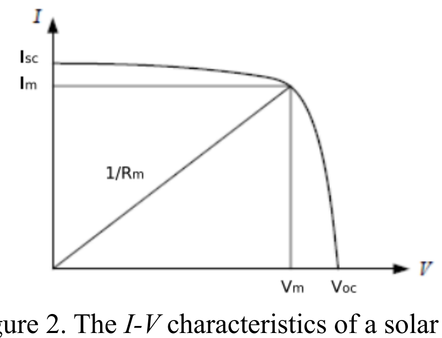

Figure 2. The *I-V* characteristics of a solar cell

Next, we need to define the solar cell energy conversion efficiency η

$$\eta = \frac{P_m}{P_{in}} \times 100\%,$$

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

1.2.4. Solar cell equivalent circuit

Figure 3 has told us the information that a solar cell can be thought of as composed of a *p-n* junction diode *D* and a constant current source I_{ph}. All elements form a circuit equivalent to a *p-n* junction leak-circuit along with a series resistance R_s and a parallel resistance R_{sh}. We can find the relationship between the current and the voltage through the equivalent circuit

$$I = I_{ph} - I_0 \left\{ exp\left[\frac{q(V+R_sI)}{nk_BT}\right] - 1\right\} - \frac{V+R_sI}{R_{sh}}.$$

And we should decrease the value of R_s and increase the value of R_{sh} to provide a greater output power.

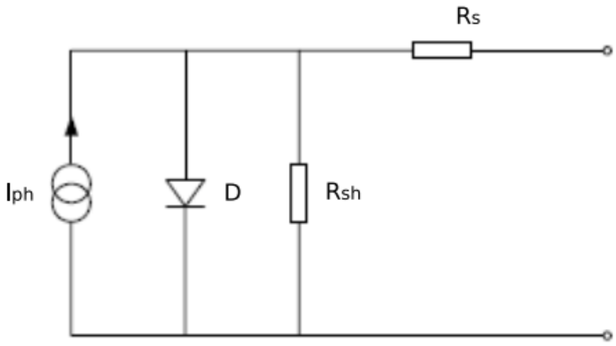

Figure 3. Solar cell equivalent circuit

2. Apparatus

2.1. Experimental setup

A photovoltaic device (5 W), a 300 W tungsten–halogen lamp serving as a radiation source, two digital multimeters, two adjustable resistors, a solar power meter, a wiring board and a measuring tape are the setup of this experiment.

2.2. Precision or uncertainty

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

Table 1. Precision or uncertainty of the equipment

3. Measurement procedure

3.1. We should first turn on both the light and the fan, and wait for at least five minutes, so that the light can reach its working intensity.

3.2. Then, we should design a measuring circuit with the photovoltaic device, multimeters set in an appropriate range and the resistance, and connect them into a circuit using the provided wiring board.

3.3. Next, we should work in pairs. We should keep adjusting the distance between the light source and the photovoltaic device until the V_{oc} and I_{sc} of the two devices are about the same. Then, with the help of the solar power meter, we should measure the solar power.

We should change the resistance and measure the relevant current and voltage, so that we can collect the data to draw the *I–V* characteristics curve. We need to remember that keeping the distance between the light source and the photovoltaic device and not moving around the workstation during the measurement is important. Otherwise, the light intensity will not be maintained during the whole process.

Moreover, we should measure the *I-V* characteristics curves and the values of V_{oc} and I_{oc} under the following three conditions:

(a) Two devices in series;

(b) Two devices in parallel;

(c) A single device.

3.4. Then, we can change the distance between the light source and the photovoltaic device and measure the *I–V* characteristics curves and the values of V_{oc} and I_{sc} in a single-device configuration. We should pay attention that the new distance should be about 80% or 120% of the original distance. And we also need to measure the solar power at this distance.

3.5. Finally, with the help of a computer, we can plot the *I–V* characteristics curves and the graph of the output power vs. the voltage. We then should try to determine the values of I_{sc}, V_{oc}, P_m, I_m, V_m, R_m, FF and η. And we should compile the data in the form of a table.

4. Results and discussion

First, we record the precision of the equipment, as shown in Table 2.

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

Table 2. Multimeter precision

Then we measure the length and width of the photovoltaic device, as shown in Table 3.

Length [$\pm$0.1 cm]	Width [$\pm$0.1 cm]
26.2	21.1

Table 3. Measurement data for area

Then we are able to calculate the area of the photovoltaic:

$$26.2 \times 21.1 = 553 \pm 3\text{cm}^2$$

	1	2	3	4	5	6
$P_{131.0}$ [$\pm$10 W/m^2]	161.8	172.9	185.6	169.0	177.8	181.5
$P_{100.3}$ [$\pm$10 W/m^2]	195.8	198.3	194.3	196.6	194.8	197.9

Table 4. Measurement data for solar power

Then, we can calculate the average value of solar power measurements:

$$\overline{P_{131.0}} = \frac{1}{6}\sum_{i=1}^{6} P_i = 174.8 \pm 13.5\ \text{W/m}^2$$

$$\overline{P_{100.3}} = \frac{1}{6}\sum_{i=1}^{6} P_i = 196.3 \pm 10.1\ \text{W/m}^2$$

Therefore, we can get

$$P_{in1} = 553 \times 10^{-4} \times 174.76 = 9.7 \pm 0.7\ \text{W}$$
$$P_{in2} = 553 \times 10^{-4} \times 196.28 = 10.9 \pm 0.6\ \text{W}$$

Then, we measured the open circuit voltage and short circuit current for the single device at 131.0 cm, single device at 100.3 cm, series connected and parallel connected. The data is shown in Table 5.

	Single device at 131.0 cm	Single device at 100.3 cm	Series	Parallel
U_{oc} [V]	9.01$\pm$0.06	9.58$\pm$0.06	16.28$\pm$0.09	8.24$\pm$0.05
I_{sc} [mA]	49.8$\pm$0.8	81.3$\pm$1.3	47.4$\pm$0.8	90.8$\pm$1.5

Table 5. Measurement data for U_{oc} and I_{sc}

Then, we change the resistance and measure the relevant current and voltage. The result is listed in Table 6 and 7.

	Series				Parallel			
	U [V]	u_U [±V]	I [mA]	u_I [±mA]	U [V]	u_U [±V]	I [mA]	u_I [±mA]
1	0.05	0.01	47.1	0.8	0.83	0.01	90.2	1.5
2	1.52	0.02	45.5	0.8	1.26	0.02	88.4	1.4
3	2.08	0.02	44.9	0.8	1.81	0.02	86.2	1.4
4	2.50	0.02	44.4	0.8	2.32	0.02	83.6	1.4
5	3.21	0.03	43.6	0.8	2.82	0.02	80.9	1.3
6	4.13	0.03	42.5	0.7	3.06	0.03	79.7	1.3
7	5.21	0.04	41.1	0.7	3.22	0.03	78.7	1.3
8	6.33	0.04	39.7	0.7	3.36	0.03	77.6	1.3
9	7.24	0.05	38.6	0.7	3.52	0.03	76.5	1.2
10	8.03	0.05	37.6	0.7	3.71	0.03	74.8	1.2
11	8.40	0.05	37.1	0.7	3.93	0.03	73.3	1.2
12	8.82	0.05	36.3	0.6	4.08	0.03	72.1	1.2
13	9.17	0.06	35.5	0.6	4.25	0.03	70.5	1.2
14	9.53	0.06	34.7	0.6	4.37	0.03	69.3	1.1
15	9.93	0.06	33.8	0.6	4.57	0.03	68.1	1.1
16	10.30	0.06	32.9	0.6	4.71	0.03	66.7	1.1
17	10.63	0.06	31.9	0.6	4.88	0.03	65.3	1.1
18	10.89	0.06	31.1	0.6	5.13	0.04	63.2	1.0
19	11.23	0.07	29.9	0.5	5.41	0.04	60.5	1.0
20	11.52	0.07	28.9	0.5	5.78	0.04	56.8	1.0
21	11.94	0.07	27.2	0.5	6.19	0.04	51.7	0.9
22	12.44	0.07	25.2	0.5	6.66	0.04	45.5	0.8
23	13.07	0.08	22.5	0.4	7.17	0.05	35.5	0.6
24	13.76	0.08	19.1	0.4	7.59	0.05	24.3	0.5
25	14.50	0.08	14.7	0.3	8.06	0.05	8.1	0.2

Table 6. Measurement data for the U vs. I relation (series/parallel configuration)

	131.0 cm				100.3 cm			
	U [V]	u_U[±V]	I [mA]	u_I[±mA]	U [V]	u_U[±V]	I [mA]	u_I[±mA]
1	0.69	0.01	49.6	0.8	0.46	0.01	80.7	1.3
2	1.09	0.02	49.0	0.8	1.04	0.02	79.5	1.3
3	1.70	0.02	48.2	0.8	1.78	0.02	78.2	1.3
4	2.31	0.02	47.1	0.8	2.34	0.02	77.0	1.3
5	2.83	0.02	46.1	0.8	2.82	0.02	75.9	1.2
6	3.18	0.03	45.3	0.8	3.29	0.03	75.0	1.2
7	3.53	0.03	44.3	0.8	3.60	0.03	74.0	1.2
8	3.76	0.03	43.7	0.8	3.83	0.03	73.4	1.2
9	3.97	0.03	43.3	0.7	3.98	0.03	73.0	1.2
10	4.18	0.03	42.8	0.7	4.14	0.03	72.7	1.2
11	4.42	0.03	42.1	0.7	4.44	0.03	72.1	1.2
12	4.66	0.03	41.8	0.7	4.72	0.03	71.5	1.2
13	4.90	0.03	41.2	0.7	4.95	0.03	70.7	1.2
14	5.15	0.04	40.7	0.7	5.17	0.04	70.1	1.2
15	5.37	0.04	40.0	0.7	5.37	0.04	69.8	1.1
16	5.63	0.04	39.4	0.7	5.74	0.04	68.9	1.1
17	5.84	0.04	38.9	0.7	6.11	0.04	68.0	1.1
18	6.13	0.04	38.3	0.7	6.40	0.04	67.5	1.1
19	6.46	0.04	37.5	0.7	6.80	0.04	66.0	1.1
20	6.70	0.04	36.6	0.6	7.15	0.05	63.4	1.1
21	6.96	0.04	35.0	0.6	7.61	0.05	58.8	1.0
22	7.13	0.05	33.4	0.6	8.07	0.05	52.2	0.9
23	7.54	0.05	29.0	0.5	8.53	0.05	43.2	0.7
24	8.04	0.05	22.2	0.4	9.06	0.06	28.0	0.5
25	8.71	0.05	8.8	0.2	9.51	0.06	9.6	0.2

Table 7. Measurement data for the U vs. I relation (131.0 cm/100.3 cm configuration)

From these two tables, we can use origin to get I-U graph (Figure 4) shown below.

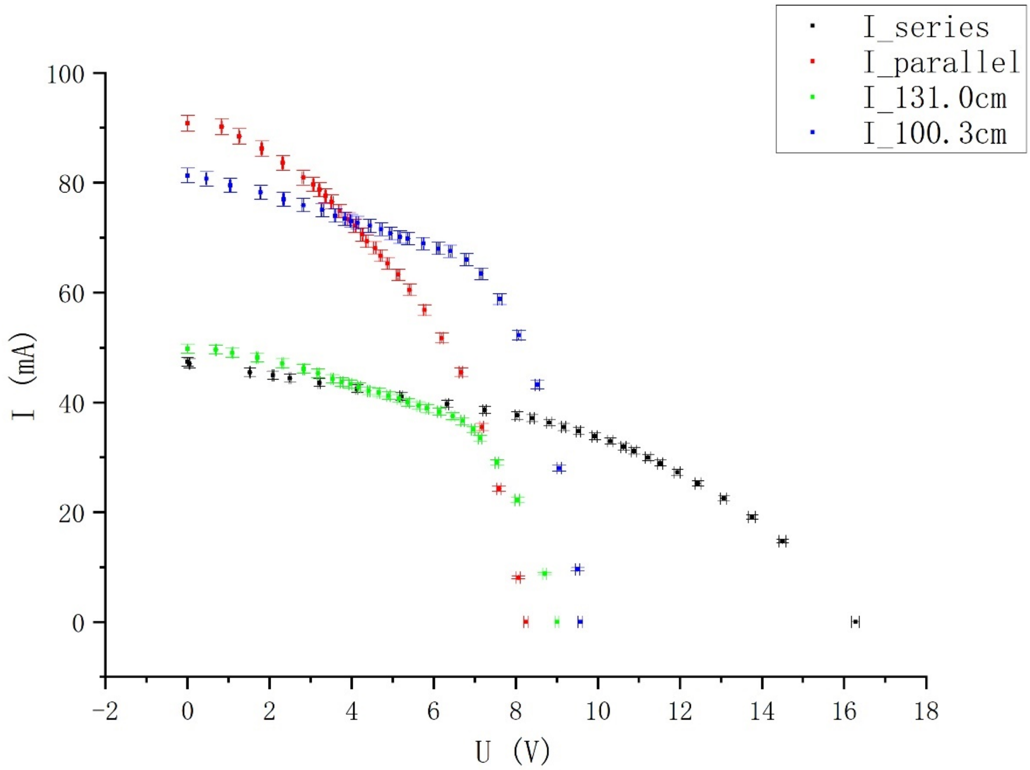

Figure 4. *I-U* graph

Form this graph, we can see that with the increase of U, I first decreases slowly and after some point, it decreases quickly, which corresponds to the theoretical knowledge we learnt. Actually, this point indicates the maximum output power. In order to find P_m, we will further draw *P-U* and *P-R* graph. Moreover, we find that the closer the light source is, the more current it will generate. For the parallel and series connection, we find that more current is generated by the parallel connection while more voltage is generated by the series connection, and this corresponds to the basic knowledge of circuits.

According to the equation $P = UI$ and $R = \frac{V}{I}$, and with the help of Table 6 and 7, we can calculate P and R respectively, which are shown in Table 8 and 9.

	Series				Parallel			
	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$
1	0.0024	0.0005	1.1	0.2	0.0749	0.0018	9.2	0.2
2	0.0692	0.0014	33.4	0.7	0.111	0.002	14.3	0.3
3	0.093	0.002	46.3	0.9	0.156	0.003	21.0	0.4
4	0.111	0.002	56.3	1.1	0.194	0.004	27.8	0.5
5	0.140	0.003	73.6	1.4	0.228	0.004	34.9	0.6
6	0.176	0.003	97	2	0.244	0.004	38.4	0.7
7	0.214	0.004	127	2	0.253	0.005	40.9	0.7
8	0.251	0.005	159	3	0.261	0.005	43.3	0.8
9	0.279	0.005	188	4	0.269	0.005	46.0	0.8
10	0.302	0.006	214	4	0.278	0.005	49.6	0.9
11	0.312	0.006	226	4	0.288	0.005	53.6	1.0
12	0.320	0.006	243	5	0.294	0.005	56.6	1.0
13	0.326	0.006	258	5	0.300	0.005	60.3	1.1
14	0.331	0.006	275	5	0.303	0.005	63.1	1.1
15	0.336	0.006	294	6	0.311	0.006	67.1	1.2
16	0.339	0.006	313	6	0.314	0.006	70.6	1.3
17	0.339	0.006	333	6	0.319	0.006	74.7	1.3
18	0.339	0.006	350	7	0.324	0.006	81	2
19	0.336	0.006	376	7	0.327	0.006	89	2
20	0.333	0.006	399	8	0.328	0.006	102	2
21	0.325	0.006	439	9	0.320	0.006	120	2
22	0.313	0.006	494	10	0.303	0.006	146	3
23	0.294	0.006	581	12	0.255	0.005	202	4
24	0.263	0.006	720	15	0.184	0.004	312	6
25	0.213	0.005	990	20	0.0653	0.0018	1000	30

Table 8. *P, U* and *R* for the *U* vs. *I* relation (series/parallel configuration)

	131.0 cm				100.3 cm			
	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$
1	0.0342	0.0009	13.9	0.4	0.0371	0.0012	5.7	0.2
2	0.0534	0.0012	22.2	0.5	0.0827	0.0018	13.1	0.3
3	0.082	0.002	35.3	0.7	0.139	0.003	22.8	0.4
4	0.109	0.002	49.0	1.0	0.180	0.003	30.4	0.6
5	0.130	0.003	61.4	1.2	0.214	0.004	37.2	0.7
6	0.144	0.003	70.2	1.3	0.247	0.004	43.9	0.8
7	0.156	0.003	80	2	0.266	0.005	48.6	0.9
8	0.164	0.003	86	2	0.281	0.005	52.2	0.9
9	0.172	0.003	92	2	0.291	0.005	54.5	1.0
10	0.179	0.003	98	2	0.301	0.005	56.9	1.0
11	0.186	0.004	105	2	0.320	0.006	61.6	1.1
12	0.195	0.004	111	2	0.337	0.006	66.0	1.2
13	0.202	0.004	119	2	0.350	0.006	70.0	1.2
14	0.210	0.004	127	2	0.362	0.006	73.8	1.3
15	0.215	0.004	134	3	0.375	0.007	76.9	1.4
16	0.222	0.004	143	3	0.395	0.007	83	2
17	0.227	0.004	150	3	0.415	0.007	90	2
18	0.235	0.004	160	3	0.432	0.008	95	2
19	0.242	0.005	172	3	0.449	0.008	103	2
20	0.245	0.005	183	3	0.453	0.008	113	2
21	0.244	0.005	199	4	0.447	0.008	129	2
22	0.238	0.005	213	4	0.421	0.008	155	3
23	0.219	0.004	260	5	0.368	0.007	197	4
24	0.178	0.004	362	7	0.254	0.005	324	6
25	0.077	0.002	990	30	0.091	0.002	990	30

Table 9. *P, U* and *R* for the *U* vs. *I* relation (131.0 cm/100.3 cm configuration)

Based on these two tables, we can get *P-U* and *P-R* graphs (Figure 5 and 6) respectively.

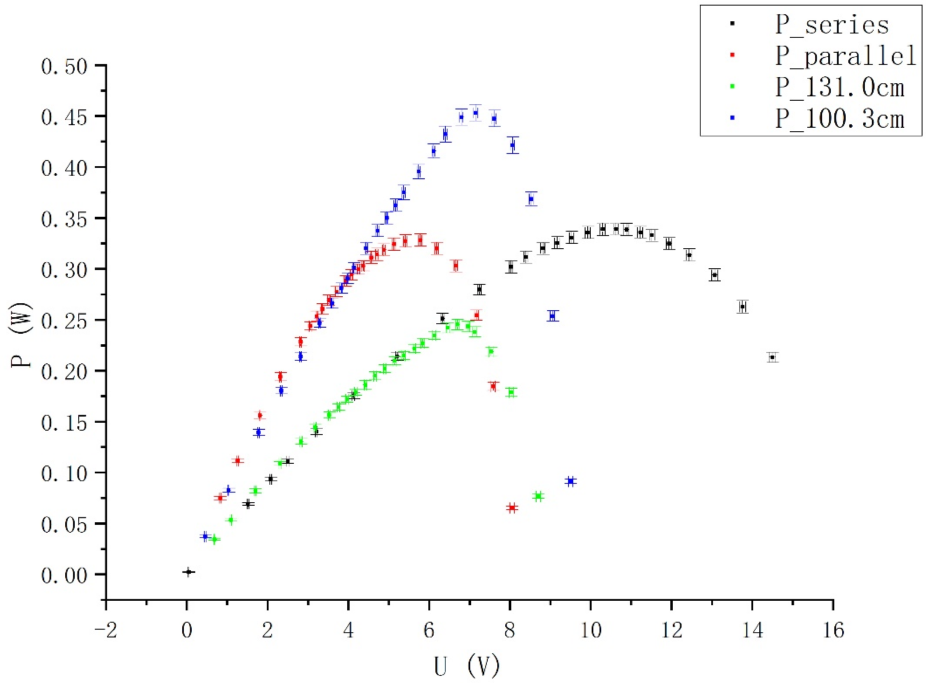

Figure 5. *P-U* graph

We can see that, with the increase of *U*, *P* first increases and then decreases. Then there exists a peak that indicates the maximum power output. For the series and parallel connection, they have almost the same maximum output power, but it takes about two times voltage of the parallel connection for the series to get maximum output power. For the 131.0 cm and 100.3 cm, they almost at the same voltage to reach maximum power output. And the closer the light source is, the larger the maximum output power can be.

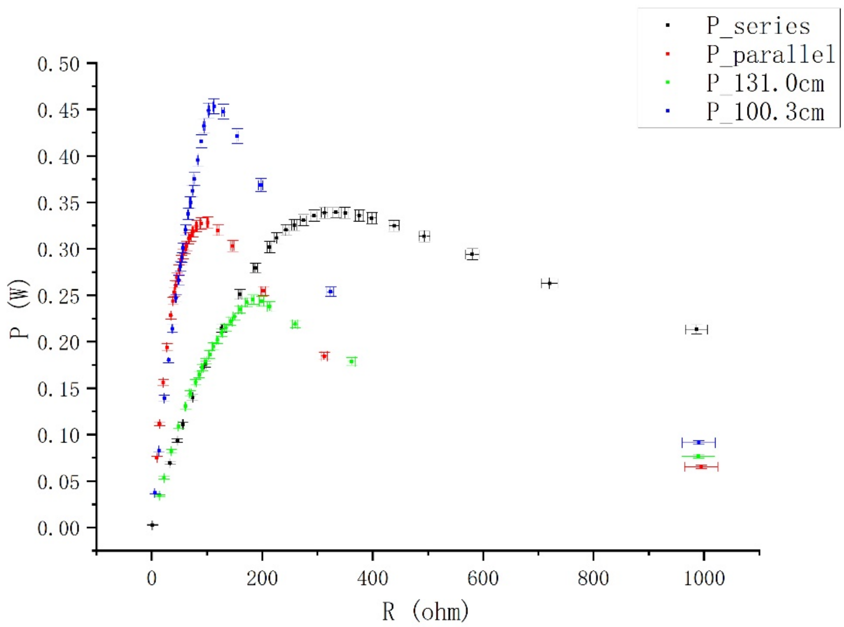

Figure 6. *P-R* graph

We can see that, with the increase of R, P first increases and then decreases. Then there exists a peak that indicates the maximum power output. For the series and parallel connection, they have almost the same maximum output power, but it takes about two times of resistance of the parallel connection for the series to get maximum output power. For the 131.0 cm and 100.3 cm, they almost at the same resistance to reach maximum power output. And the closer the light source is, the larger the maximum output power can be.

However, the resistance or the voltage needed for the 131.0 cm and 100.3 cm to achieve maximum power output are not exactly the same. We may consider that the inner resistance of the solar cell will be affected by temperature because the closer the light source, the more heat will be generated and influence the inner resistance of the solar cell.

Finally, we can calculate the FF and η using the following equations:

$$FF = \frac{P_m}{V_{oc}I_{sc}} = \frac{V_m I_m}{V_{oc}I_{sc}}$$

$$\eta = \frac{P_m}{P_{in}} \times 100\%$$

Then, we get the table below (Table 10).

	V_{oc} [V]	$u_{V_{oc}}$ [$\pm V$]	I_{sc} [mA]	u_{Isc} [$\pm mA$]	P_m [W]	u_{P_m} [$\pm W$]	V_m [V]	u_{V_m} [±V]
Series	16.28	0.09	47.4	0.8	0.339	0.006	10.63	0.06
Parallel	8.24	0.05	90.8	2.5	0.328	0.006	5.78	0.04
131.0cm	9.01	0.06	49.8	0.8	0.245	0.005	6.70	0.04
100.3cm	9.58	0.06	81.3	1.3	0.453	0.008	7.15	0.05

	I_m [mA]	u_{I_m} [$\pm mA$]	R [Ω]	u_R [±Ω]	FF	u_{FF}	η	u_η
Series	31.9	0.6	333	6	0.439	0.011	1.76%	0.13%
Parallel	56.8	1.0	102	2	0.439	0.015	1.70%	0.13%
131.0cm	36.6	0.6	183	3	0.547	0.015	2.5%	0.2%
100.3cm	63.4	1.1	113	2	0.582	0.014	4.2%	0.2%

Table 10. Other important variables

From the above table, we find that η for 100.3 cm is relatively larger. Considering the procedures, I think that during our experiment, we have moved the light source about 20 % closer to the photovoltaic. However, when we try to measure the solar power with a solar power meter, we find there are some places out of the range of the meter. Therefore, the actual P_{in} may be larger. In order to solve this problem, we can move the light source about 20% further than the original distance.

5. Conclusion

In this lab, we get familiar with the working principle of a solar cell, and study the current-voltage (*I-V*) characteristics. We measured the open circuit voltage and short circuit current.

Then we change the resistance and get the *I-V* data. Then, with the help of the computer, we plot *I-V, P-V* and *P-R* curves. Watching these figures, we have some interesting finds, which have been talked in the “Results and discussion” part.

However, in the experiment, we have made some mistakes. For example, when we move the light source about 20 % closer to the photovoltaic, we find that some places on the photovoltaic is actually out of the range of the solar power meter, which will lead to the inaccuracy of our P_{in}. Therefore, in the future experiment, I recommend that students had better move the photovoltaic about 20% further than the original distance.

6. References

[1] Exercise 3 - lab manual [rev 5.2], UM-JI SJTU. Edited by Qin Tian, Zheng Huan, Li Yingyu, Li Tiantian, Mateusz Krzyzosiak.

[2] Uncertainty analysis handbook, UM-JI SJTU.

A. Uncertainty analysis

A.1. Uncertainty for P_{in}

Since length and width are measured directly, there is only type B uncertainty.

$$u_m = \Delta_B = 0.1 \text{ cm}$$

Since $S = L \times W$ in our experiment,

$$u_S = \sqrt{(\frac{\partial S}{\partial L} u_L)^2 + (\frac{\partial S}{\partial W} u_W)^2} = \sqrt{(W u_L)^2 + (L u_W)^2} = 3 \text{ [cm}^2\text{]}$$

For the uncertainty of average value of solar power measurements

$$\Delta_A = \frac{t_{0.95}}{\sqrt{6}} \sqrt{\frac{1}{5} \sum_{i=1}^{6} \left(p_i - \overline{P_{131.0}}\right)^2} = 9.11 \text{ [W/m}^2\text{]}$$

$$\Delta_B = 10 \text{ W/m}^2$$

$$u_{P103.0} = \sqrt{\Delta_A^2 + \Delta_B^2} = 13.5 \text{ [W/m}^2\text{]}$$

Similarly,

$$u_{P100.3} = \sqrt{\Delta_A^2 + \Delta_B^2} = 10.1 \text{ [W/m}^2\text{]}$$

Since $P_{in} = S \times \overline{P}$, we can get

$$u_{pin1} = \sqrt{(\frac{\partial P_{in1}}{\partial S} u_S)^2 + (\frac{\partial P_{in2}}{\partial \overline{P}} u_{\overline{P}})^2} = 0.7 \text{ [W]}$$

Similarly,

$$u_{pin2} = 0.6 \text{ [W]}$$

A.2. Uncertainty for measurement data

These data are measured directly, therefore, there is only type B uncertainty. For DC voltage, $u_m = \Delta_B = \pm 0.5\% + 0.01$ [V], and for DC current, $u_m = \Delta_B = \pm 1.5\%$+0.1 [mA]. Therefore, their uncertainty can be calculated below.

	Single device at 131.0 cm	Single device at 100.3 cm	Series	Parallel
U_{oc} [V]	0.06	0.06	0.09	0.05
I_{sc} [mA]	0.8	1.3	0.8	1.5

Table 11. Uncertainty for measurement data for U_{oc} and I_{sc}

	Series		Parallel	
	U uncertainty [V]	*I* uncertainty [mA]	*U* uncertainty [V]	*I* uncertainty [mA]
1	0.01	0.8	0.01	1.5
2	0.02	0.8	0.02	1.4
3	0.02	0.8	0.02	1.4
4	0.02	0.8	0.02	1.4
5	0.03	0.8	0.02	1.3
6	0.03	0.7	0.03	1.3
7	0.04	0.7	0.03	1.3
8	0.04	0.7	0.03	1.3
9	0.05	0.7	0.03	1.2
10	0.05	0.7	0.03	1.2
11	0.05	0.7	0.03	1.2
12	0.05	0.6	0.03	1.2
13	0.06	0.6	0.03	1.2
14	0.06	0.6	0.03	1.1
15	0.06	0.6	0.03	1.1
16	0.06	0.6	0.03	1.1
17	0.06	0.6	0.03	1.1
18	0.06	0.6	0.04	1.0
19	0.07	0.5	0.04	1.0
20	0.07	0.5	0.04	1.0
21	0.07	0.5	0.04	0.9
22	0.07	0.5	0.04	0.8
23	0.08	0.4	0.05	0.6
24	0.08	0.4	0.05	0.5
25	0.08	0.3	0.05	0.2

Table 12. Uncertainty for measurement data for the *U* vs. *I* relation (series/parallel configuration)

	131.0 cm		100.3 cm	
	U uncertainty [V]	*I* uncertainty [mA]	*U* uncertainty [V]	*I* uncertainty [mA]
1	0.01	0.8	0.01	1.3
2	0.02	0.8	0.02	1.3
3	0.02	0.8	0.02	1.3
4	0.02	0.8	0.02	1.3
5	0.02	0.8	0.02	1.2
6	0.03	0.8	0.03	1.2
7	0.03	0.8	0.03	1.2
8	0.03	0.8	0.03	1.2
9	0.03	0.7	0.03	1.2
10	0.03	0.7	0.03	1.2
11	0.03	0.7	0.03	1.2
12	0.03	0.7	0.03	1.2
13	0.03	0.7	0.03	1.2
14	0.04	0.7	0.04	1.2
15	0.04	0.7	0.04	1.1
16	0.04	0.7	0.04	1.1
17	0.04	0.7	0.04	1.1
18	0.04	0.7	0.04	1.1
19	0.04	0.7	0.04	1.1
20	0.04	0.6	0.05	1.1
21	0.04	0.6	0.05	1.0
22	0.05	0.6	0.05	0.9
23	0.05	0.5	0.05	0.7
24	0.05	0.4	0.06	0.5
25	0.05	0.2	0.06	0.2

Table 13. Uncertainty for measurement data for the *U* vs. *I* relation (131.0 cm/100.3 cm configuration)

A.3. Uncertainty for *P* and *R*

Since $P = UI$ and $R = \frac{U}{I}$, we can get that

$$u_P = \sqrt{(\frac{\partial P}{\partial U}u_U)^2 + (\frac{\partial P}{\partial I}u_I)^2} = \sqrt{(Iu_U)^2 + (Uu_I)^2}$$

$$u_R = \sqrt{(\frac{\partial R}{\partial U}u_U)^2 + (\frac{\partial R}{\partial I}u_I)^2} = \sqrt{(\frac{u_U}{I})^2 + (\frac{U}{I^2}u_I)^2}$$

Then, we can get the following two tables.

	Series				Parallel			
	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$
1	0.0024	0.0005	1.1	0.2	0.0749	0.0018	9.2	0.2
2	0.0692	0.0014	33.4	0.7	0.111	0.002	14.3	0.3
3	0.093	0.002	46.3	0.9	0.156	0.003	21.0	0.4
4	0.111	0.002	56.3	1.1	0.194	0.004	27.8	0.5
5	0.140	0.003	73.6	1.4	0.228	0.004	34.9	0.6
6	0.176	0.003	97	2	0.244	0.004	38.4	0.7
7	0.214	0.004	127	2	0.253	0.005	40.9	0.7
8	0.251	0.005	159	3	0.261	0.005	43.3	0.8
9	0.279	0.005	188	4	0.269	0.005	46.0	0.8
10	0.302	0.006	214	4	0.278	0.005	49.6	0.9
11	0.312	0.006	226	4	0.288	0.005	53.6	1.0
12	0.320	0.006	243	5	0.294	0.005	56.6	1.0
13	0.326	0.006	258	5	0.300	0.005	60.3	1.1
14	0.331	0.006	275	5	0.303	0.005	63.1	1.1
15	0.336	0.006	294	6	0.311	0.006	67.1	1.2
16	0.339	0.006	313	6	0.314	0.006	70.6	1.3
17	0.339	0.006	333	6	0.319	0.006	74.7	1.3
18	0.339	0.006	350	7	0.324	0.006	81	2
19	0.336	0.006	376	7	0.327	0.006	89	2
20	0.333	0.006	399	8	0.328	0.006	102	2
21	0.325	0.006	439	9	0.320	0.006	120	2
22	0.313	0.006	494	10	0.303	0.006	146	3
23	0.294	0.006	581	12	0.255	0.005	202	4
24	0.263	0.006	720	15	0.184	0.004	312	6
25	0.213	0.005	990	20	0.0653	0.0018	1000	30

Table 14. Uncertainty for *P, U* and *R* for the *U* vs. *I* relation (series/parallel configuration)

	131.0 cm				100.3 cm			
	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$	P [W]	$u_P[\pm W]$	R [Ω]	$u_R[\pm\Omega]$
1	0.0342	0.0009	13.9	0.4	0.0371	0.0012	5.7	0.2
2	0.0534	0.0012	22.2	0.5	0.0827	0.0018	13.1	0.3
3	0.082	0.002	35.3	0.7	0.139	0.003	22.8	0.4
4	0.109	0.002	49.0	1.0	0.180	0.003	30.4	0.6
5	0.130	0.003	61.4	1.2	0.214	0.004	37.2	0.7
6	0.144	0.003	70.2	1.3	0.247	0.004	43.9	0.8
7	0.156	0.003	80	2	0.266	0.005	48.6	0.9
8	0.164	0.003	86	2	0.281	0.005	52.2	0.9
9	0.172	0.003	92	2	0.291	0.005	54.5	1.0
10	0.179	0.003	98	2	0.301	0.005	56.9	1.0
11	0.186	0.004	105	2	0.320	0.006	61.6	1.1
12	0.195	0.004	111	2	0.337	0.006	66.0	1.2
13	0.202	0.004	119	2	0.350	0.006	70.0	1.2
14	0.210	0.004	127	2	0.362	0.006	73.8	1.3
15	0.215	0.004	134	3	0.375	0.007	76.9	1.4
16	0.222	0.004	143	3	0.395	0.007	83	2
17	0.227	0.004	150	3	0.415	0.007	90	2
18	0.235	0.004	160	3	0.432	0.008	95	2
19	0.242	0.005	172	3	0.449	0.008	103	2
20	0.245	0.005	183	3	0.453	0.008	113	2
21	0.244	0.005	199	4	0.447	0.008	129	2
22	0.238	0.005	213	4	0.421	0.008	155	3
23	0.219	0.004	260	5	0.368	0.007	197	4
24	0.178	0.004	362	7	0.254	0.005	324	6
25	0.077	0.002	990	30	0.091	0.002	990	30

Table 15. Uncertainty for *P, U* and *R* for the *U* vs. *I* relation (131.0 cm/100.3 cm configuration)

A.4. Uncertainty for *FF* and η

Since

$$FF = \frac{P_m}{V_{oc}I_{sc}} = \frac{V_m I_m}{V_{oc}I_{sc}}$$

$$\eta = \frac{P_m}{P_{in}} \times 100\%$$

We can get that

$$u_{FF} = \sqrt{(\frac{\partial FF}{\partial P_m}u_{P_m})^2 + (\frac{\partial FF}{\partial V_{oc}}u_{V_{oc}})^2 + (\frac{\partial FF}{\partial I_{sc}}u_{I_{sc}})^2} = \sqrt{(\frac{u_{P_m}}{V_{oc}I_{sc}})^2 + (\frac{P_m u_{V_{oc}}}{{V_{oc}}^2 I_{sc}})^2 + (\frac{P_m u_{I_{sc}}}{V_{oc}{I_{sc}}^2})^2}$$

$$u_\eta = \sqrt{(\frac{\partial\eta}{\partial P_m} u_{P_m})^2 + (\frac{\partial\eta}{\partial P_{in}} u_{P_{in}})^2} = \sqrt{(\frac{u_{P_m}}{P_{in}})^2 + (\frac{P_m}{{P_{in}}^2} u_{P_{in}})^2}$$

Therefore, we can get that

	FF	u_{FF}	η	u_η
Series	0.439	0.011	1.76%	0.13%
Parallel	0.439	0.015	1.70%	0.13%
131.0cm	0.547	0.015	2.5%	0.2%
100.3cm	0.582	0.014	4.2%	0.2%

Table 15. Uncertainty for FF and η