UM-SJTU JOINT INSTITUTE
PHYSICS LABORATORY
(VP241)

LABORATORY REPORT

EXERCISE 3
Solar Cells: I-V Characteristics

Name: Pan Chongdan
ID: 516370910121
Partner:Chen Yuxin
ID:516370910128
Group: 6

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1 Objectives

1. To get familiar with the working principle of a solar cell.
2. Study the solar cell's current-voltage characteristics.

2 Introduction and Theoretical Background

Solar cells can transform solar radiation into electrical energy directly. They're very useful because they won't consume energy and it's operation is silent. It also has a long lifetime without moving parts. In addition, they are easy to maintain and never cause air pollution. Therefore, they become one of the leading energy sources because they can produce 15-20% of the total electrical energy generated in the world.

2.1 Solar Cell Structure

A crystalline silicon solar cell consists of $\frac{n}{p}$ homo-junctions, a 10 cm $\times$ 10 cm $p-$type silicon plate of thickness 500 μm, covered with a heavily doped $n-$type layer with thickness 0.3 μm. The metallic balls on the $n-$ type layer is like an electrode with a metallic film at the bottom playing the role of another one. To reduce the loss of energy caused by reflection, an anti-reflective film is often used to cover the surface exposed to light.

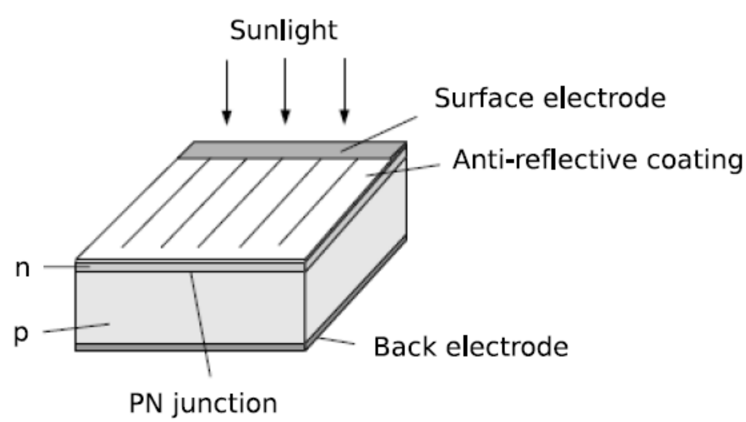

Figure 1: Structure of a crystalline silicon solar cell.

2.2 Photovoltaic Effect

The incident photons are absorbed and excite electron pairs 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 E_g.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, which 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, or to the n-type area. This cause more positive charge accumulated in the p-type area and negative charge in the n-type area. Therefore, a photoelectric potential difference is generated.

2.3 Solar Cell Parameters

Solar cells can generate an electric current I_{ph} from the n-type area to the p-type area when there is light incident on the solar cell due to the photovoltaic effect.

At the same time, a forward diode current I_D from the p-type to the n-type area exists in the device, which has an opposite direction to I_{ph}. As a result, the net current:

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

where V_D is the junction voltage, I_0 is the diode inverse saturation current, I_{ph} is the photo current determined by the structure and material characteristics of the solar cell. The coefficient n is a theoretical coefficient whose value ranges from 1 to 2, which characterizes the $p-n$ junction. Additionally, q, k_B, T denote the electron's charge, Boltzmann's constant, and temperature in the Kelvin scale respectively. If we ignore the internal resistance R_S, V_D will equals to the terminal voltage V ,so

$$I = I_{ph} - I_0[\exp(\frac{dV}{nk_BT}) - 1]$$

1. If the output circuit is short so $V = 0$, then

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

2. If the output circuit is open so $I = 0$, then

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

3. If there is a load resistance R, the corresponding $I-V$ characteristic curve is shown in Figure 2. When the maximum power P_m is generated with $R = R_m, I = I_m, V = V_m$, then

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

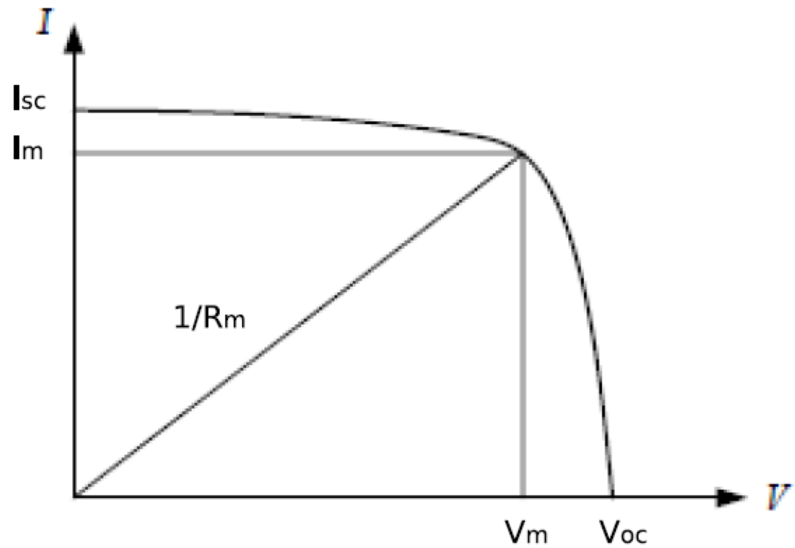

Figure 2: The current-voltage characteristics of a solar cell.

FF is called the $fillfactor$, which is very important and it's determined by some parameters such as the incident light intensity, the forbidden bandwidth, the value of the theoretical coefficient n, and the series/parallel resistance.

The solar cell energy conversion efficiency η is defined as

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

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

2.4 Solar Cell Equivalent Circuit

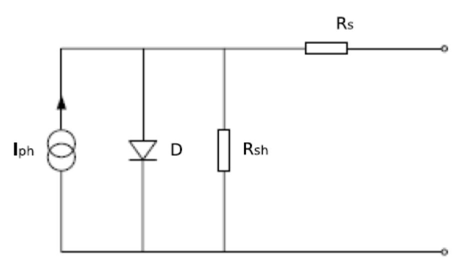

Figure 3: Solar cell equivalent circuit.

The figure 3 shows that a solar cell can be thought of as composed of $p-n$ junction diode D and a constant current source I_{ph} along with a series resistance R_s due to the electrodes in the solar cell and a parallel resistance R_{sh}, all elements form a circuit equivalent to a $p-n$ junction leak-circuit. The relation between the current and the voltage,

$$I = I_{ph} - I_0\{\exp[\frac{q(V + R_s I)}{nk_B T}] - 1\} - \frac{V + R_S I}{R_{sh}}$$

We can decrease R_s and increase R_{sh} to provide a greater power.

3 Measurement Set up and Procedure

3.1 Measurement Set up

The set up consists of a 5W photovoltaic device, a 300W tungsten-halogen lamp serving as a radiation source, two digital multimeter, two adjustable resistors, a solar power meter, a wiring board and a measuring tape.

3.2 Measurement Procedure and Data Presentation

1. I turned on the light and the fan, then waited for a few minutes until the light reach its working intensity.

2. I designed a measuring circuit with the photovoltaic device, multimeter sets in an appropriate range, and the resistance and connected the elements into a circuit using the provided wiring board.

3. I changed resistance and measured the relevant current and voltage to draw the $I-V$ characteristic curve.

4. I measured the $I-V$ characteristic curves and the values of V_{oc} and I_{sc} under four conditions:

   i The distance between the light source and the photovoltaic device is 100 cm.

   ii The distance between the light source and the photovoltaic device is 120 cm.

   iii The distance between the light source and the photovoltaic device is 120 cm, with two devices in series.

   iv The distance between the light source and the photovoltaic device is 120 cm, with two devices in parallel.

5. I plot the $I-V$ characteristic curves and the graph of the output power to determine the values of $I_{sc}, V_{oc}, P_m, I_m, V_m, R_m, FF$ and η.

4 Results and Calculation

4.1 Measurement Data

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

Table 1: Multimeter precision

Length[cm]	Width[cm]
20.9	26.2

Table 2: Measurement data for area

	0	1	2	3	4
P_{100}[W/m^2]	213	265	240	237	295
P_{120}[W/m^2]	206	240	182	163	255

Table 3: Measurement data for solar power

	100cm	120cm	series	parallel
U_{oc}[V]	8.91	8.38	18.06	9.01
I_{sc}[mA]	83.2	72.4	77.2	146.7

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

	100cm		120cm	
	U[V]	I[mA]	U[V]	I[mA]
1	0.44	83.0	0.39	73.7
2	0.78	82.1	0.72	72.9
3	1.12	81.6	1.05	72.2
4	1.46	80.8	1.38	71.5
5	1.80	80.0	1.71	70.5
6	2.14	78.8	2.04	69.4
7	2.48	77.8	2.37	68.6
8	2.82	76.8	2.70	67.8
9	3.16	76.0	3.03	66.7
10	3.50	74.9	3.36	65.8
11	3.84	73.7	3.69	64.2
12	4.18	72.3	4.02	63.1
13	4.52	70.5	4.35	61.9
14	4.86	68.2	4.68	60.3
15	5.20	65.2	5.01	58.2
16	5.54	62.7	5.34	56.1
17	5.88	59.3	5.67	53.8
18	6.22	55.3	6.00	50.5
19	6.56	51.0	6.33	46.5
20	6.90	45.9	6.66	42.0
21	7.24	40.1	6.99	36.7
22	7.58	33.9	7.32	31.1
23	7.92	26.7	7.65	24.8
24	8.26	18.3	7.98	17.9
25	8.65	7.9	8.36	7.7

Table 5: Measurement data for the U vs. I relation (100 cm/120 cm configuration)

	series		parallel	
	U[V]	I[mA]	U[V]	I[mA]
1	0.34	77.2	0.66	146.2
2	0.94	76.8	1.24	143.5
3	1.51	76.2	1.55	142.3
4	2.08	75.5	1.79	140.9
5	2.54	69.0	2.15	139.1
6	3.26	73.7	2.49	137.1
7	3.82	73.0	2.79	134.7
8	4.76	71.4	3.29	130.9
9	5.37	70.3	3.62	128.5
10	6.15	68.6	3.94	125.6
11	6.93	67.3	4.35	122.5
12	7.68	66.1	4.65	120.1
13	8.11	65.2	4.92	117.0
14	8.51	64.5	5.28	113.4
15	8.89	63.9	5.60	109.2
16	9.61	62.3	5.99	103.1
17	10.01	61.3	6.33	97.9
18	11.20	57.9	6.69	91.3
19	12.20	55.0	7.04	83.2
20	12.75	53.1	7.28	78.2
21	14.14	46.7	7.60	70.0
22	15.17	38.6	8.03	54.9
23	15.82	32.0	8.39	39.0
24	16.46	24.7	8.71	20.5
25	17.11	15.7	8.90	0.81

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

4.2 Calculation

4.2.1 Calculation of Area and Solar Power

$$A = l \cdot d = 20.9 \cdot 26.2 = 547.6[cm^2] = 5.476 \cdot 10^{-2}[m^2]$$

$$\bar{P}_{100} = \sum_{i=0}^{4} P_i = \frac{213 + 265 + 240 + 237 + 205}{5} = 250[W/m^2]$$

$$P_{100} = 5.476 \cdot 250 = 13.7[W]$$

$$\bar{P}_{120} = \sum_{i=0}^{4} P_i = \frac{206 + 240 + 182 + 163 + 255}{5} = 209[W/m^2]$$

$$P_{120} = 5.476 \cdot 209 = 11.5[W]$$

4.3 Calculation of Power and Resistance

For the first pair data, when the distance between the light source and the photovoltaic is $100[cm]$

$$P = UI = 0.44 \cdot 83 = 36.5[mW]$$

$$R = \frac{U}{I} = 5.30[\Omega]$$

	100 cm				120 cm			
	U[V]	I[mA]	P[mW]	R[Ω]	U[V]	I[mA]	P[mW]	R[Ω]
1	0.44	83.0	36.5	5.3	0.39	73.7	28.7	5.3
2	0.78	82.1	64.0	9.5	0.72	72.9	52.5	9.9
3	1.12	81.6	91.4	13.7	1.05	72.2	75.8	14.5
4	1.46	80.8	118	18.1	1.38	71.5	98.7	19.3
5	1.80	80.0	144	22.5	1.71	70.5	120.6	24.3
6	2.14	78.8	169	27.2	2.04	69.4	142	29.4
7	2.48	77.8	193	31.9	2.37	68.6	163	34.5
8	2.82	76.8	217	36.7	2.70	67.8	183	39.8
9	3.16	76.0	240	41.6	3.03	66.7	202	45.4
10	3.50	74.9	262	46.7	3.36	65.8	221	51.1
11	3.84	73.7	283	52.1	3.69	64.2	237	57.5
12	4.18	72.3	302	57.8	4.02	63.1	254	63.7
13	4.52	70.5	319	64.1	4.35	61.9	269	70.3
14	4.86	68.2	331	71.2	4.68	60.3	282	77.6
15	5.20	65.2	339	79.8	5.01	58.2	292	86.1
16	5.54	62.7	347	88.4	5.34	56.1	300	95.2
17	**5.88**	**59.3**	**349**	**99.2**	**5.67**	**53.8**	**305**	**105.4**
18	6.22	55.3	344	112.5	6.00	50.5	303	118.8
19	6.56	51.0	335	128.6	6.33	46.5	294	136.1
20	6.90	45.9	317	150.3	6.66	42.0	280	158.6
21	7.24	40.1	290	180.5	6.99	36.7	257	190.5
22	7.58	33.9	257	223.6	7.32	31.1	228	235.4
23	7.92	26.7	211	296.6	7.65	24.8	190	308.5
24	8.26	18.3	151	451.4	7.98	17.9	143	445.8
25	8.65	7.9	68.3	1094.9	8.36	7.7	64.4	1085.7

	series				parallel			
	U[V]	I[mA]	P[mW]	R[Ω]	U[V]	I[mA]	P[mW]	R[Ω]
1	0.34	77.2	26.2	4.4	0.66	146.2	96.5	4.5
2	0.94	76.8	72.2	12.2	1.24	143.5	178	8.6
3	1.51	76.2	115	19.8	1.55	142.3	221	10.9
4	2.08	75.5	157	27.5	1.79	140.9	252	12.7
5	2.54	69.0	175	36.8	2.15	139.1	298.9	15.5
6	3.26	73.7	240	44.2	2.49	137.1	341	18.2
7	3.82	73.0	279	52.3	2.79	134.7	376	20.7
8	4.76	71.4	340	66.7	3.29	130.9	431	24.9
9	5.37	70.3	378	76.4	3.62	128.5	465.2	28.2
10	6.15	68.6	422	89.7	3.94	125.6	495	31.4
11	6.93	67.3	466	103.0	4.35	122.5	533	35.5
12	7.68	66.1	508	116.2	4.65	120.1	558	38.7
13	8.11	65.2	528	124.4	4.92	117.0	576	42.1
14	8.51	64.5	549	131.9	5.28	113.4	599	46.6
15	8.89	63.9	568	139.1	5.60	109.2	612	51.3
16	9.61	62.3	599	154.3	5.99	103.1	618	58.1
17	10.01	61.3	614	163.3	**6.33**	**97.9**	**620**	**64.7**
18	11.20	57.9	648	193.4	6.69	91.3	611	73.3
19	12.20	55.0	671	221.8	7.04	83.2	586	84.6
20	**12.75**	**53.1**	**677**	**240.1**	7.28	78.2	570	93.1
21	14.14	46.7	660	302.8	7.60	70.0	532	108.6
22	15.17	38.6	586	393.0	8.03	54.9	441	146.3
23	15.82	32.0	506	494.4	8.39	39.0	327	215.1
24	16.46	24.7	407	666.4	8.71	20.5	179	424.9
25	17.11	15.7	269	1089.8	8.90	0.81	7.21	10987.7

The bold text are the data for $P_m, I_m.V_m$ for each condition.

4.4 Calculations of FF and η

1. When the distance between the light source and the photovoltaic device is 100 cm:

$$FF = \frac{P_m}{V_{oc}I_{sc}} = \frac{349}{8.91 \cdot 83.2} = 0.47$$

$$\eta = \frac{P_m}{P_{in}} = \frac{0.349}{13.7} \cdot 100\% = 2.55\%$$

2. When the distance between the light source and the photovoltaic device is 120 cm:

$$FF = \frac{P_m}{V_{oc}I_{sc}} = \frac{305}{8.38 \cdot 72.4} = 0.50$$

$$\eta = \frac{P_m}{P_{in}} = \frac{0.305}{11.5} \cdot 100\% = 2.65\%$$

3. When the two photovoltaic devices are in series:

$$FF = \frac{P_m}{V_{oc} I_{sc}} = \frac{677}{18.06 \cdot 77.2} = 0.49$$

$$\eta = \frac{P_m}{P_{in}} = \frac{0.677}{2 \cdot 11.5} \cdot 100\% = 2.94\%$$

4. When the two photovoltaic devices are in parallel:

$$FF = \frac{P_m}{V_{oc} I_{sc}} = \frac{620}{9.01 \cdot 146.7} = 0.47$$

$$\eta = \frac{P_m}{P_{in}} = \frac{0.620}{2 \cdot 11.5} \cdot 100\% = 2.70\%$$

4.5 Plots

The figure including error bar and uncertainty calculated in next part. The black points is when the distance is 100 cm, the red points is 120 cm, the blue points is when the two devices are in series, and the green points is when the two devices are in parallel.

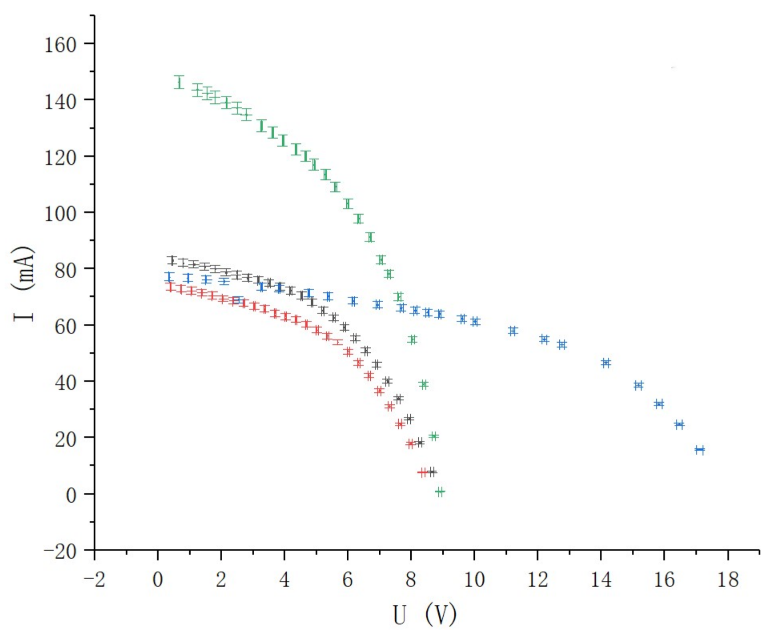

Figure 4: Relation of I and V

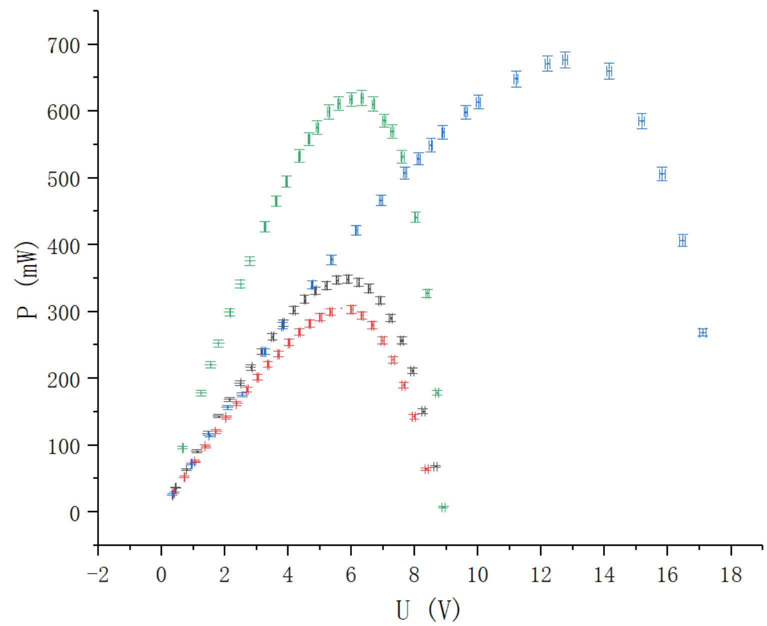

Figure 5: Relation of P and V

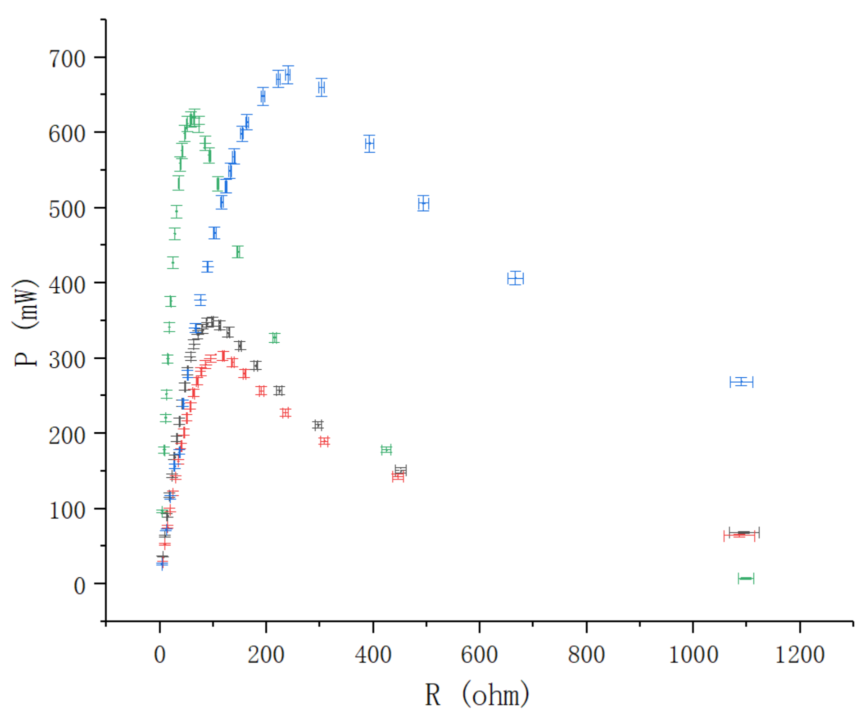

Figure 6: Relation of P and R

5 Uncertainty Analysis

5.1 Uncertainty of Area

$$u_A = \sqrt{(\frac{\partial A}{\partial d} \cdot u_d)^2 + (\frac{\partial A}{\partial l} \cdot u_l)^2} = \sqrt{(20.9 \cdot 0.1)^2 + (26.2 \cdot 0.1)^2} = 3.35[cm^2] = 3.35 \cdot 10^{-4}[m^2]$$

5.2 Uncertainty of Solar Power per Area

$$s_{\bar{X}} = \frac{s_X}{\sqrt{n-1}} = \frac{21.3}{2} = 10.65[W/m^2]$$

$$\triangle_A = s_{\bar{X}} \cdot \frac{t_{0.95}}{\sqrt{5}} = 10.65 \cdot 1.204 = 12.82[W/m^2]$$

$$\triangle_B = 10[W/m^2]$$

$$u_{100} = \sqrt{\triangle_A^2 + \triangle_B^2} = \sqrt{10^2 + 12.82^2} = 16.26[W/m^2]$$

$$u_r = \frac{u_{100}}{P_{100}} \cdot 100\% = \frac{16.26}{250} \cdot 100\% = 6.50\%$$

Similarly, $u_{120} = 13.2[W/m^2], u_r = 6.32\%$

5.3 Uncertainty of Solar Power

When the distance is $100[cm]$,

$$u_P = \sqrt{(\frac{\partial P}{\partial A} \cdot u_A)^2 + (\frac{\partial P}{\partial A} \cdot u_{100})^2} = \sqrt{(5.476 \cdot 10^{-2} \cdot 16.26)^2 + (250 \cdot 3.35 \cdot 10^{-4})^2} = 0.89[W]$$

$$u_r = \frac{u_P}{P} \cdot 100\% = \frac{0.89}{13.7} \cdot 100\% = 6.50\%$$

Similarly, when the distance is $120[cm], u_P = 0.73[W], u_r = 3.22\%$

5.4 Uncertainty of U_{oc} and I_{sc}

	U_{oc}[V]	I_{sc}[mA]	u_u	u_I
100 cm	8.91	83.2	1.35	0.05
120 cm	8.38	72.4	1.19	0.05
series	18.06	77.2	1.26	0.10
parallel	9.01	146.7	2.30	0.06

5.5 Uncertainty of I and V

For the first pair data, when the distance between the light source and the photovoltaic is $100[cm]$

$$u_v = 0.44 \cdot 0.5\% + 0.01 = 0.01[V]$$

$$u_r = \frac{0.01}{0.44} \cdot 100\% = 2.27\%$$

$$u_I = 83 \cdot 1.5\% + 0.1 = 1.3[mA]$$

$$u_r = \frac{1.3}{85} \cdot 100\% = 1.53\%$$

	100 cm				120 cm			
	U[V]	u_v[V]	I[mA]	u_I[mA]	U[V]	u_v[V]	I[mA]	u_I[mA]
1	0.44	0.01	83.0	1.3	0.39	0.01	73.7	1.2
2	0.78	0.01	82.1	1.3	0.72	0.01	72.9	1.2
3	1.12	0.02	81.6	1.3	1.05	0.02	72.2	1.2
4	1.46	0.02	80.8	1.3	1.38	0.02	71.5	1.2
5	1.80	0.02	80.0	1.3	1.71	0.02	70.5	1.2
6	2.14	0.02	78.8	1.3	2.04	0.02	69.4	1.1
7	2.48	0.02	77.8	1.3	2.37	0.02	68.6	1.1
8	2.82	0.02	76.8	1.3	2.70	0.02	67.8	1.1
9	3.16	0.03	76.0	1.2	3.03	0.03	66.7	1.1
10	3.50	0.03	74.9	1.2	3.36	0.03	65.8	1.1
11	3.84	0.03	73.7	1.2	3.69	0.03	64.2	1.1
12	4.18	0.03	72.3	1.2	4.02	0.03	63.1	1.1
13	4.52	0.03	70.5	1.2	4.35	0.03	61.9	1.0
14	4.86	0.03	68.2	1.1	4.68	0.03	60.3	1.0
15	5.20	0.04	65.2	1.1	5.01	0.04	58.2	1.0
16	5.54	0.04	62.7	1.0	5.34	0.04	56.1	0.9
17	5.88	0.04	59.3	1.0	5.67	0.04	53.8	0.9
18	6.22	0.04	55.3	0.9	6.00	0.04	50.5	0.9
19	6.56	0.04	51.0	0.9	6.33	0.04	46.5	0.8
20	6.90	0.04	45.9	0.8	6.66	0.04	42.0	0.7
21	7.24	0.05	40.1	0.7	6.99	0.05	36.7	0.7
22	7.58	0.05	33.9	0.6	7.32	0.05	31.1	0.6
23	7.92	0.05	26.7	0.5	7.65	0.05	24.8	0.5
24	8.26	0.05	18.3	0.4	7.98	0.05	17.9	0.4
25	8.65	0.05	7.9	0.2	8.36	0.05	7.7	0.2

Table 7: Uncertainty for I vs. U relation (100 cm/120 cm configuration)

	series				parallel			
	U[V]	u_v[V]	I[mA]	u_I[mA]	U[V]	u_v[V]	I[mA]	u_I[mA]
1	0.34	0.01	77.2	1.3	0.66	0.01	146.2	2.3
2	0.94	0.01	76.8	1.3	1.24	0.02	143.5	2.3
3	1.51	0.02	76.2	1.3	1.55	0.02	142.3	2.2
4	2.08	0.02	75.5	1.2	1.79	0.02	140.9	2.2
5	2.54	0.02	69.0	1.1	2.15	0.02	139.1	2.2
6	3.26	0.03	73.7	1.2	2.49	0.02	137.1	2.2
7	3.82	0.03	73.0	1.2	2.79	0.02	134.7	2.1
8	4.76	0.03	71.4	1.2	3.29	0.03	130.9	2.1
9	5.37	0.04	70.3	1.2	3.62	0.03	128.5	2.0
10	6.15	0.04	68.6	1.1	3.94	0.03	125.6	2.0
11	6.93	0.04	67.3	1.1	4.35	0.03	122.5	2.0
12	7.68	0.05	66.1	1.1	4.65	0.03	120.1	1.9
13	8.11	0.05	65.2	1.1	4.92	0.03	117.0	1.9
14	8.51	0.05	64.5	1.1	5.28	0.04	113.4	1.8
15	8.89	0.05	63.9	1.1	5.60	0.04	109.2	1.7
16	9.61	0.06	62.3	1.0	5.99	0.04	103.1	1.6
17	10.01	0.06	61.3	1.0	6.33	0.04	97.9	1.6
18	11.20	0.07	57.9	1.0	6.69	0.04	91.3	1.5
19	12.20	0.07	55.0	0.9	7.04	0.05	83.2	1.3
20	12.75	0.07	53.1	0.9	7.28	0.05	78.2	1.3
21	14.14	0.08	46.7	0.8	7.60	0.05	70.0	1.2
22	15.17	0.09	38.6	0.7	8.03	0.05	54.9	0.9
23	15.82	0.09	32.0	0.6	8.39	0.05	39.0	0.7
24	16.46	0.09	24.7	0.5	8.71	0.05	20.5	0.4
25	17.11	0.10	15.7	0.3	8.90	0.05	0.81	0.1

Table 8: Uncertainty data for the I vs. U relation (series/parallel configuration)

5.6 Uncertainty for P

For the first pair data, when the distance between the light source and the photovoltaic is $100[cm]$

$$u_p = \sqrt{(\frac{\partial p}{\partial I}u_I)^2 + ((\frac{\partial p}{\partial u}u_u)^2} = \sqrt{(0.44 \cdot 1.3)^2 + (83 \cdot 0.01)^2} = 1.01[mW]$$

$$u_r \frac{u_p}{p} \cdot 100\% = \frac{1}{36.5} \cdot 100\% = 2.74\%$$

	100 cm				120 cm			
	U[V]	I[mA]	P[mW]	u_P[mW]	U[V]	I[mA]	P[mW]	u_P[mW]
1	0.44	83.0	36.5	1.01	0.39	73.7	28.7	0.87
2	0.78	82.1	64.0	1.30	0.72	72.9	52.5	1.13
3	1.12	81.6	91.4	2.19	1.05	72.2	75.8	1.92
4	1.46	80.8	118	2.49	1.38	71.5	98.7	2.19
5	1.80	80.0	144	2.83	1.71	70.5	120	2.49
6	2.14	78.8	169	3.20	2.04	69.4	142	2.64
7	2.48	77.8	193	3.58	2.37	68.6	163	2.95
8	2.82	76.8	217	3.97	2.70	67.8	183	3.26
9	3.16	76.0	240	4.42	3.03	66.7	202	3.89
10	3.50	74.9	262	4.76	3.36	65.8	221	4.19
11	3.84	73.7	283	5.11	3.69	64.2	237	4.49
12	4.18	72.3	302	5.46	4.02	63.1	254	4.81
13	4.52	70.5	319	5.82	4.35	61.9	269	4.73
14	4.86	68.2	331	5.72	4.68	60.3	282	5.02
15	5.20	65.2	339	6.28	5.01	58.2	292	5.52
16	5.54	62.7	347	6.08	5.34	56.1	300	5.30
17	5.88	59.3	349	6.34	5.67	53.8	305	5.54
18	6.22	55.3	344	6.02	6.00	50.5	303	5.76
19	6.56	51.0	335	6.24	6.33	46.5	294	5.39
20	6.90	45.9	317	5.81	6.66	42.0	280	4.96
21	7.24	40.1	290	5.45	6.99	36.7	257	5.23
22	7.58	33.9	257	4.85	7.32	31.1	228	4.66
23	7.92	26.7	211	4.17	7.65	24.8	190	4.02
24	8.26	18.3	151	3.43	7.98	17.9	143	3.32
25	8.65	7.9	68.3	1.1	8.36	7.7	64.4	1.72

Table 9: Uncertainty for P vs. U relation (100 cm/120 cm configuration)

	series				parallel			
	U[V]	I[mA]	P[mW]	u_P[mW]	U[V]	I[mA]	P[mW]	u_P[mW]
1	0.34	77.2	26.2	0.89	0.66	146.2	96.5	2.11
2	0.94	76.8	72.2	1.44	1.24	143.5	178	4.05
3	1.51	76.2	115	2.48	1.55	142.3	221	4.44
4	2.08	75.5	157	2.92	1.79	140.9	252	4.84
5	2.54	69.0	175	3.12	2.15	139.1	298.9	5.49
6	3.26	73.7	240	4.49	2.49	137.1	341	6.13
7	3.82	73.0	279	5.08	2.79	134.7	376	6.45
8	4.76	71.4	340	6.10	3.29	130.9	431	7.89
9	5.37	70.3	378	7.03	3.62	128.5	465.2	8.20
10	6.15	68.6	422	7.30	3.94	125.6	495	8.73
11	6.93	67.3	466	8.08	4.35	122.5	533	9.44
12	7.68	66.1	508	9.07	4.65	120.1	558	9.54
13	8.11	65.2	528	9.50	4.92	117.0	576	9.98
14	8.51	64.5	549	9.90	5.28	113.4	599	10.5
15	8.89	63.9	568	10.3	5.60	109.2	612	10.5
16	9.61	62.3	599	10.3	5.99	103.1	618	10.4
17	10.01	61.3	614	10.7	6.33	97.9	620	10.9
18	11.20	57.9	648	11.9	6.69	91.3	611	10.7
19	12.20	55.0	671	11.6	7.04	83.2	586	10.1
20	12.75	53.1	677	12.1	7.28	78.2	570	10.2
21	14.14	46.7	660	11.9	7.60	70.0	532	9.77
22	15.17	38.6	586	11.2	8.03	54.9	441	7.73
23	15.82	32.0	506	9.92	8.39	39.0	327	6.19
24	16.46	24.7	407	8.52	8.71	20.5	179	3.63
25	17.11	15.7	269	5.37	8.90	0.81	7.21	0.89

Table 10: Uncertainty data for the P vs. U relation (series/parallel configuration)

5.7 Uncertainty of R

For the first pair data, when the distance between the light source and the photovoltaic is 100[cm]

$$u_R = \sqrt{(\frac{\partial R}{\partial I}u_I)^2 + ((\frac{\partial p}{\partial u}u_u)^2} = \sqrt{(\frac{0.44}{83^2} \cdot 1.3)^2 + (\frac{0.01}{83})^2} \cdot 1000 = 0.15[\Omega]$$

$$u_r\frac{u_R}{R} \cdot 100\% = \frac{0.15}{5.3} \cdot 100\% = 2.76\%$$

	100 cm				120 cm			
	R[Ω]	u_R[Ω]	P[mW]	u_P[mW]	R[Ω]	u_R[Ω]	P[mW]	u_P[mW]
1	5.3	0.15	36.5	1.01	5.3	0.16	28.7	0.87
2	9.5	0.19	64.0	1.30	9.88	0.21	52.5	1.13
3	13.7	0.33	91.4	2.19	14.5	0.37	75.8	1.92
4	18.1	0.38	118	2.49	19.3	0.43	98.7	2.19
5	22.5	0.44	144	2.83	24.3	0.50	120	2.49
6	27.2	0.51	169	3.20	29.4	0.63	142	2.64
7	31.9	0.59	193	3.58	34.5	0.71	163	2.95
8	36.7	0.67	217	3.97	39.8	0.87	183	3.26
9	41.6	0.77	240	4.42	45.4	0.97	202	3.89
10	46.7	0.85	262	4.76	51.1	1.09	221	4.19
11	52.1	0.94	283	5.11	57.5	1.21	237	4.49
12	57.8	1.05	302	5.46	63.7	1.23	254	4.81
13	64.1	1.17	319	5.82	70.3	1.38	269	4.73
14	71.3	1.23	331	5.72	77.6	1.63	282	5.02
15	79.8	1.48	339	6.28	86.1	1.69	292	5.52
16	88.4	1.55	347	6.08	95.2	1.69	300	5.30
17	99.2	1.80	349	6.34	105.4	1.91	305	5.54
18	112.5	1.97	344	6.02	118.8	2.26	303	5.76
19	128.6	2.40	335	6.24	136.1	2.49	294	5.39
20	150.3	2.76	317	5.81	158.6	2.81	280	4.96
21	180.5	3.39	290	5.45	190.5	3.88	257	5.23
22	223.6	4.22	257	4.85	235.4	4.82	228	4.66
23	296.6	5.86	211	4.17	308.5	6.54	190	4.02
24	451.4	10.2	151	3.43	445.8	10.3	143	3.32
25	1094.9	28.4	68.3	1.1	1085.7	28.9	64.4	1.72

Table 11: Uncertainty for P vs. R relation (100 cm/120 cm configuration)

	series				parallel			
	R[Ω]	u_R[Ω]	P[mW]	u_P[mW]	R[Ω]	u_R[Ω]	P[mW]	u_P[mW]
1	4.40	0.15	26.2	0.89	4.51	0.09	96.5	2.11
2	12.2	0.24	72.2	1.44	8.64	0.20	178	4.05
3	19.8	0.43	115	2.48	10.9	0.22	221	4.44
4	27.5	0.51	157	2.92	12.7	0.24	252	4.84
5	36.8	0.65	175	3.12	15.5	0.28	298.9	5.49
6	44.2	0.83	240	4.49	18.2	0.33	341	6.13
7	52.3	0.95	279	5.08	20.7	0.36	376	6.45
8	66.7	1.20	340	6.10	24.9	0.46	431	7.89
9	76.4	1.42	378	7.03	28.2	0.50	465.2	8.20
10	89.7	1.55	422	7.30	31.7	0.55	495	8.73
11	103.0	1.78	466	8.08	35.5	0.63	533	9.44
12	116.2	2.08	508	9.07	38.7	0.66	558	9.54
13	124.4	2.23	528	9.50	42.1	0.73	576	9.98
14	131.9	2.38	549	9.90	46.6	0.82	599	10.5
15	139.1	2.52	568	10.3	51.3	0.88	612	10.5
16	154.3	2.66	599	10.3	58.1	0.98	618	10.4
17	163.3	2.84	614	10.7	64.7	1.13	620	10.9
18	193.4	3.55	648	11.9	73.3	1.28	611	10.7
19	221.8	3.85	671	11.6	84.6	1.45	586	10.1
20	240.1	4.28	677	12.1	93.1	1.67	570	10.2
21	302.8	5.46	660	11.9	108.6	1.99	532	9.77
22	393.0	7.50	586	11.2	146.3	2.56	441	7.73
23	494.4	9.69	506	9.92	215.1	4.06	327	6.19
24	666.4	14.0	407	8.52	424.9	8.64	179	3.63
25	1089.8	21.8	269	5.37	1098.6	14.9	7.21	0.89

Table 12: Uncertainty data for the P vs. R relation (series/parallel configuration)

5.8 Uncertainty of FF and η

when the distance between the light source and the photovoltaic is 100 [cm]

$$u_{FF} = \sqrt{(\frac{\partial FF}{\partial P_m})^2 + (\frac{\partial FF}{\partial V_{oc}})^2 + (\frac{\partial FF}{\partial I_{sc}})^2} = \sqrt{(\frac{349 \cdot 1.35}{83.2^2 \cdot 8.91})^2 + (\frac{349 \cdot 0.05}{83.2 \cdot 8.91^2})^2 + (\frac{6.34}{83.2 \cdot 8.91})^2} = 0.01$$

$$U_r = \frac{u_{FF}}{FF} \cdot 100\% = \frac{0.01}{0.47} \cdot 100\% = 2.51\%$$

$$u_\eta = \sqrt{(\frac{\partial \eta}{\partial P_m})^2 + (\frac{\partial \eta}{\partial P_{in}})^2} = \sqrt{(\frac{0.00634}{13.7})^2 + (\frac{0.349 \cdot 0.89}{13.7^2})^2} = 0.17\%$$

$$u_r = \frac{u_\eta}{\eta} \cdot 100\% = \frac{0.17}{2.55} \cdot 100\% = 6.75\%$$

	FF	u_{FF}	u_r	$\eta\%$	u_η	u_r
100 cm	0.47	0.01	2.51	2.55	0.17	0.07
120 cm	0.50	0.01	2.54	2.65	0.18	0.07
series	0.49	0.01	2.46	2.94	0.19	0.07
parallel	0.47	0.01	2.43	2.70	0.18	0.07

6 Conclusion

In this exercise, I know about the working principle of solar cells and photovoltaic effect. In the lab work, I built a solar cell equivalent circuit to stimulate the solar cell. I changed the value of the resistance in the circuit and got the voltage and current through a multimeter, and got the power of the solar cell through a power meter, then I calculated and compared the power to get the filter factor FF and working efficiency η. Also I draw the three plot about the U vs. I, U vs. P, and R vs. P relation under four conditions.

1. When the distance between the light source and the photovoltaic device is 100 cm:

   $U_{oc} = 8.91 \pm 1.35$[V], $I_{sc} = 83.2 \pm 0.05$[mA], $P_m = 349 \pm 6.34$[mW], $I_m = 59.3 \pm 1$[mA], $V_m = 5.88 \pm 0.04$[V], $R_m = 99.2 \pm 1.8[\Omega], FF = 0.47 \pm 0.01, \eta = 2.55 \pm 0.17\%$

2. When the distance between the light source and the photovoltaic device is 120 cm:

   $U_{oc} = 8.38 \pm 1.19$[V], $I_{sc} = 72.4 \pm 0.05$[mA], $P_m = 305 \pm 5.54$[mW], $I_m = 53.8 \pm 0.9$[mA], $V_m = 5.67 \pm 0.04$[V], $R_m = 105.4 \pm 1.91[\Omega], FF = 0.450 \pm 0.01, \eta = 2.65 \pm 0.18\%$

3. When the distance is 120 cm and the two devices are connected in series:

   $U_{oc} = 18.06 \pm 1.26$[V], $I_{sc} = 77.2 \pm 0.1$[mA], $P_m = 677 \pm 12.1$[mW], $I_m = 53.1 \pm 0.9$[mA], $V_m = 12.75 \pm 0.07$[V], $R_m = 240.1 \pm 12.1[\Omega], FF = 0.49 \pm 0.01, \eta = 2.94 \pm 0.19\%$

4. When the distance is 120 cm and the two devices are connected in parallel:

   $U_{oc} = 9.01 \pm 2.3$[V], $I_{sc} = 146.7 \pm 0.06$[mA], $P_m = 620 \pm 10.9$[mW], $I_m = 97.9 \pm 1.6$[mA], $V_m = 6.33 \pm 0.04$[V], $R_m = 64.7 \pm 1.13[\Omega], FF = 0.47 \pm 0.01, \eta = 2.70 \pm 0.18\%$

For a solar cell equivalent circuit, I becomes smaller as U grows bigger while P will increase first and then drop down. Also, P will increase first and then drop down as R increases.

In the three plot, the red dots are always at the bottom and the blacks dots are just above the red ones, which means when the distance is 120 cm, I and P are both at lost but when the distance is 100 cm, it has the lost η, while when the two devices are connected in series, it has the biggest η, leading to the most efficiency way of solar cell.

7 Error Analysis

1. The relative uncertainty of the solar power per area is very high, which is about 6.5%, I think it's because the distribution of the light on photovoltaic is not uniform enough. Additionally, the angle of the photovoltaic between the light source will also have significant effect on the solar power.

2. There is a slight difference between I_{sc} and the the current when the resistance is 0. I think it's because there is still some internal resistance of the resistor which you can set to 0. Also, the wire and the photovoltaic device have their own resistances, which can explain the R calculated in my table is bigger than 1000ω sometimes.

3. When the two photovoltaic devices are in parallel, I calculated the last R is more than 10000Ω, I examined the data and found the current is to smaller as 0.81. I thought I might make a mistake in reading the number from the multimeter. The error bar for it is more than 1000, so I eliminate the dot from the plot.

4. In the 5th,6th and 7th pair of data collected when the two devices are connected in series, the current is smaller when the voltage is bigger, which is contradict to the rule in other data. I remember when I was doing these measurement, the multimeter suddenly turned off itself. After I opened, the current is much smaller. I thought there must be some wrong with the multimeter.

8 Data Sheet

Data sheet is attach to the report

9 Reference

Applied Photovoltaics, S.R. Wenham et al. (Earthscan, 2007)
Krzyzosiak,M. Lab Manual of Exercise 3.
Qin Tian, Zeng Ming, Zhao Xijian, Krzyzosiak,M. Handbook-Uncertainty Analysis.