UM–SJTU JOINT INSTITUTE

PHYSICS LABORATORY

(VP241)

LABORATORY REPORT

EXERCISE 3

SOLAR CELLS: $I - V$ CHARACTERISTICS

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1 Introduction

1.1 Objective

The objective of this exercise is to preliminarily study the working principle of a solar cell and its current-voltage $(I - V)$ characteristics.

1.2 Theoretical Background

1.2.1 Solar Cell Structure

A typical crystalline silicon solar cell consists of 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 bars on the n-type layer and the metallic film at the bottom play the role of two electrodes respectively. An anti-reflective film is applied to cover the surface that is exposed to light for reducing energy loss. Figure 1 shows the sketch of a crystalline silicon cell used in this lab.

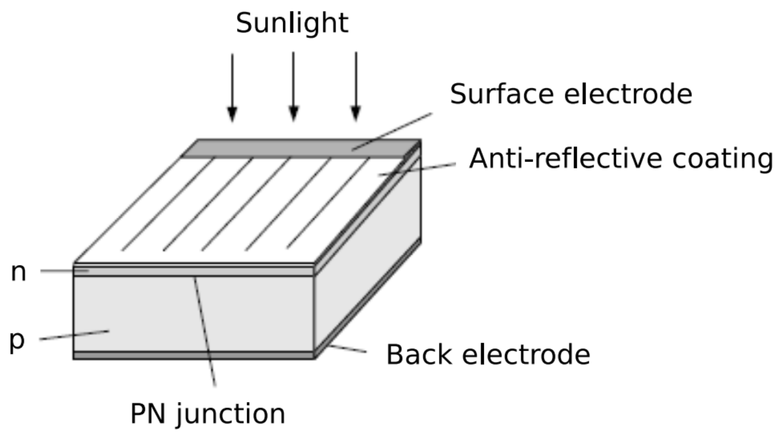

Figure 1: Structure of a crystalline silicon solar cell.

1.2.2 Photovoltaic Effect

Photovoltaic effect is a phenomenon that when some incident photons with energy greater than the energy gap E_g enter the p-n junction near the solar cell surface, these photons will be absorbed and excite electron-hole pairs. When some charge carriers' energy exceed a certain value, they may diffuse from the n- or p-type area and arrive at the p-n junction, where a built-in electric field (directed from n- to p-type area) exists. Then those minority carries will be drawn by this electric filed to the p-/n-type area in case of holes/electrons. This generates a potential called photoelectric potential.

1.2.3 Solar Cell Parameters

Due to the photovoltaic effect, solar cells can generate an electric current I_ph from the n-area to the p-area when there is light incident on the solar cell.

At the same time, in the device there exists a forward diode current I_D from the p-type to the n-type area, opposite to I_ph. Eventually, this leads to a net current:

$$I = I_\text{ph} - I_\text{D} = I_\text{ph} - I_0 \left[\exp\left(\frac{qV_\text{D}}{nk_\text{B}T}\right) - 1\right] \tag{1}$$

the quantities in the equation are listed below:

V_D	Junction voltage
I_D	Diode inverse saturation current
I_{ph}	Photo-current determined by the structure and material characteristics of the solar cell
n	Characteristic theoretical coefficient of p-n Junction, ranging from 1 to 2
q	Electron's charge
k_B	Boltzmann's constant
T	Temperature in the absolute (Kelvin) scale
R_s	Internal series resistance
V	Terminal voltage

Ignoring the internal series resistance R_s, the voltage V_D equals the terminal voltage V and (1) can be rewritten as

$$I = I_{\mathrm{ph}} - I_0 \left[\exp\left(\frac{qV}{nk_{\mathrm{B}}T}\right) - 1\right] \tag{2}$$

When the output is short, $i.e. V = 0$, the short circuit current is

$$I_{\mathrm{sc}} = I_{\mathrm{ph}} \tag{3}$$

whereas when the output is open, i.e. I = 0, the open-circuit voltage is

$$V_{oc} = \frac{nk_{\mathrm{B}}T}{q} ln(\frac{I_{\mathrm{sc}}}{I_0} + 1) \tag{4}$$

When there is a load resistance R (with the value of R ranging from zero to infinity), the corresponding I-V values vary. The figure below shows the relationship between I and V.

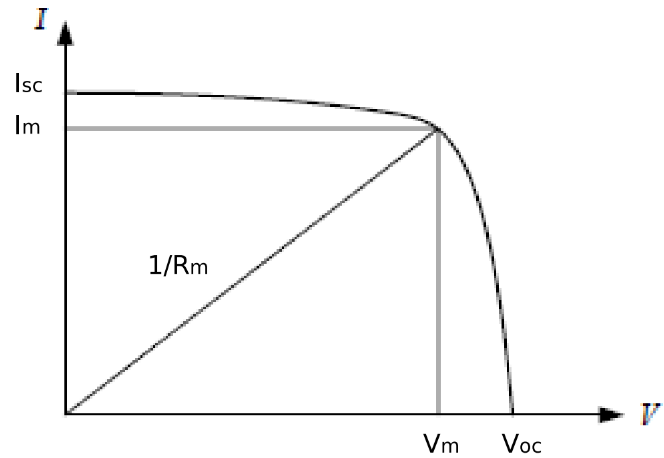

Figure 2: The current-voltage characteristics of a solar cell.

If 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 $fillfactor$ is another important parameter of solar cells, defined as

$$FF = \frac{P_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}} = \frac{V_{\mathrm{m}} I_{\mathrm{m}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}}. \tag{5}$$

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

The solar cell energy conversion efficiency η is defined as

$$\eta = \frac{P_{\mathrm{m}}}{P_{\mathrm{in}}} \times 100\%, \tag{6}$$

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

1.2.4 Solar Cell Equivalent Circuit

For convenience, a solar cell can be viewed as composed of p-n junctions diode D and a constant current source I_{ph}. In reality, there will be inner resistance within the cell, therefore the circuit can be viewed as being in series with a resistor R_{s} and in parallel with a resistor R_{sh}. Combining all these, a p-n junction leak-circuit is formed (Figure 3), with current

$$I = I_{\mathrm{ph}} - I_0 \left\{ \exp\left[\frac{q\,(V + R_{\mathrm{s}} I)}{n k_{\mathrm{B}} T} \right] - 1 \right\} - \frac{V + R_{\mathrm{s}} I}{R_{\mathrm{sh}}} \tag{7}$$

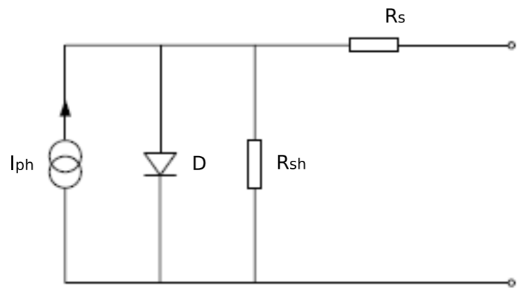

Figure 3: Solar cell equivalent circuit.

2 Measurement Setup and Procedure

The apparatus consists of 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	Uncertainties
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 1: Precision of the measurement instruments.

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

The general experiment procedures are summary below:

1. Turn on both the light and the fan. Wait for at least five minutes, in order to let the light reach its working intensity.

2. Measure the basic parameters of a single panel, including length and width.

3. In pairs, adjust two panel so that they have same (or very close) V_{oc} and I_{sc}. Then use the solar power meter to measure the power of the lights on the two panels.

4. Connect the measurement circuit. Then adjust the resistance so that different data of V and I are obtained. Perform this step for both in series and in parallel configurations.

5. Repeat the measurement procedure for a single device, with the distance maintained the same. Then change the distance and repeat this step.The new distance should be about 80% or 120% of the original one.

3 Result

3.1 I-V Relation

3.1.1 Series and Parallel Configuration

The measurement results under in series and in parallel configurations are shown in Table 4 and Table 3.

	single device at 109.00 cm	single device at 111.21 cm	series	parallel
U_{OC} [V]	9.12	9.48	18.60	9.31
I_{SC} [mA]	52.5	52.0	52.3	104.9

Table 2: Measurement data for U_{OC} and I_{SC}

	Series		Parallel	
	U[V]	I[mA]	U[V]	I[mA]
1	0.24	52.3	9.19	9.0
2	0.66	52.1	9.13	12.6
3	0.99	51.8	9.08	15.7
4	1.28	51.6	9.00	20.2
5	2.17	51.1	8.93	24.0
6	3.09	50.3	8.85	28.1
7	4.11	49.5	8.76	32.6
8	5.33	48.4	8.54	41.8
9	6.51	47.3	8.47	44.3
10	7.50	46.3	8.47	47.9
11	8.26	45.7	8.26	51.7
12	9.25	44.5	8.14	55.4
13	10.48	42.9	7.96	60.4
14	12.02	40.8	7.81	63.6
15	13.34	38.8	7.56	68.1
16	14.40	36.3	7.26	72.5
17	15.18	33.5	6.66	77.8
18	16.34	26.7	5.70	84.4
19	16.68	24.0	4.76	89.6
20	16.96	21.5	4.02	92.8
21	17.12	20.0	2.66	97.8
22	17.29	18.2	1.78	100.8
23	17.37	17.5	1.00	103.7
24	17.42	17.1	0.49	105.0
25	11.15	42.4	8.65	37.7

Table 3: Measurement data for the U vs. I relation (series/parallel configuration).

3.1.2 Configurations of Different Distances

	single device at 109.00 cm	single device at 86.80 cm
U_{OC} [V]	9.12	9.48
I_{SC} [mA]	52.5	68.2

Table 4: Measurement data for U_{OC} and I_{SC}

	109.00 cm		86.80 cm	
	U[V]	I[mA]	U[V]	I[mA]
1	0.39	52.4	0.37	68.4
2	1.70	50.0	1.66	66.9
3	2.76	48.4	2.69	64.7
4	4.03	46.3	3.64	62.6
5	*5.00*	44.1	5.34	59.0
6	5.52	42.3	5.52	58.7
7	6.12	39.7	6.06	56.6
8	6.69	36.8	6.46	54.5
9	7.15	34.1	6.95	51.5
10	7.41	32.0	7.27	49.4
11	7.58	30.4	7.54	47.5
12	7.77	28.3	7.79	45.5
13	7.93	26.1	8.05	42.2
14	8.12	23.2	8.19	40.1
15	8.25	21.0	8.33	37.7
16	8.35	19.2	8.49	34.6
17	8.43	17.7	8.56	33.0
18	8.55	15.1	8.66	30.8
19	8.62	13.4	8.77	28.1
20	8.71	11.4	8.83	26.3
21	8.75	10.4	8.89	24.6
22	8.79	9.5	8.94	23.0
23	8.82	8.6	8.98	21.7
24	8.39	18.3	9.32	9.1
25	5.26	43.0		

Table 5: Measurement data for the U vs. I relation (109.00 cm/86.80 cm configuration).

The $I - V$ characteristics curves of the four configurations are plotted in Figure 4 using ***Origin***.

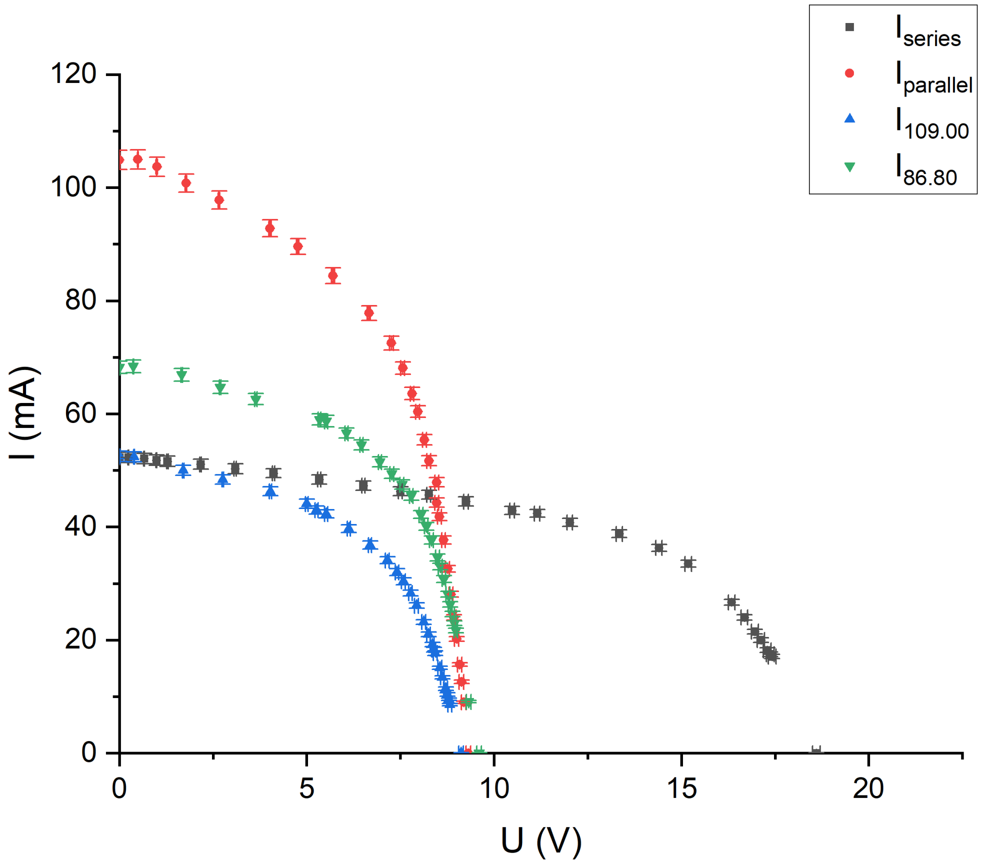

Figure 4: I-U Characteristics Curves of 4 Configurations

3.2 Relation Between Output Power and Voltage

The power P of the solar cell is calculated using

$$P = I \cdot U.$$

Take the first set of data (Table 3, series) as an example,

$$P = U \cdot I = 0.24 \times 52.3 \times 10^{-3} = 0.0126 \pm 0.0004 \text{ W}.$$

The resistance of the external load are caluclated through Ohm's law

$$R = \frac{U}{I}$$

. Take the first set of data (Table 3, series) as an example,

$$R = \frac{U}{I} = \frac{0.24}{52.3 \times 10^{-3}} = 4.6 \pm 0.4\ \Omega.$$

The data are presented in Table 6.
The characteristics curves of $P-U$ and $P-R$ are shown in Figure 5 and Figure 6.

	Series				Parallel			
	P [W]	u_P [W]	R [Ω]	u_R [Ω]	P [W]	u_P [W]	R [Ω]	u_R [Ω]
1	0.0126	0.0006	4.6	0.4	0.083	0.002	1021	8
2	0.0344	0.0009	12.7	0.5	0.115	0.003	725	6
3	0.0513	0.0012	19.1	0.6	0.143	0.003	578	5
4	0.0660	0.0014	24.8	0.7	0.182	0.004	446	4
5	0.111	0.002	42.5	0.9	0.214	0.004	372	4
6	0.155	0.003	61.4	1.1	0.249	0.005	315	3
7	0.203	0.004	83.0	1.3	0.286	0.005	269	3
8	0.258	0.005	110	2	0.357	0.007	204	2
9	0.308	0.006	138	2	0.375	0.007	191	2
10	0.347	0.006	162	2	0.406	0.007	177	2
11	0.377	0.007	181	2	0.427	0.008	160	2
12	0.412	0.008	208	2	0.451	0.008	147	2
13	0.450	0.008	244	3	0.481	0.009	132	2
14	0.490	0.009	295	3	0.497	0.009	123	2
15	0.518	0.010	344	3	0.515	0.009	111	2
16	0.523	0.010	397	3	0.526	0.009	100.1	1.4
17	0.509	0.010	453	4	0.518	0.009	85.6	1.3
18	0.436	0.009	612	5	0.481	0.008	67.5	1.1
19	0.400	0.008	695	5	0.426	0.008	53.1	1.0
20	0.365	0.007	789	6	0.373	0.007	43.3	0.9
21	0.342	0.007	856	6	0.260	0.005	27.2	0.7
22	0.315	0.007	950	7	0.179	0.003	17.7	0.6
23	0.304	0.007	993	7	0.104	0.002	9.6	0.4
24	0.298	0.006	1019	7	0.051	0.002	4.7	0.3
25	0.473	0.009	263	3	0.326	0.006	229	3

	109.00 cm				86.80 cm			
	P [W]	u_P [W]	R [Ω]	u_R [Ω]	P [W]	u_P [W]	R [Ω]	u_R [Ω]
1	0.0204	0.0007	7.4	0.4	0.0253	0.0009	5.4	0.3
2	0.085	0.002	34.0	0.8	0.111	0.002	24.8	0.7
3	0.134	0.003	57.0	1.1	0.174	0.003	41.6	0.9
4	0.187	0.003	87.0	1.4	0.228	0.004	58.1	1.1
5	0.221	0.004	113	2	0.315	0.006	90.5	1.4
6	0.233	0.004	130	2	0.324	0.006	94.0	1.4
7	0.243	0.005	154	2	0.343	0.006	107	2
8	0.246	0.005	182	2	0.352	0.006	119	2
9	0.244	0.005	210	2	0.358	0.006	135	2
10	0.237	0.005	232	3	0.359	0.007	147	2
11	0.230	0.004	249	3	0.358	0.007	159	2
12	0.220	0.004	275	3	0.354	0.006	171	2
13	0.207	0.004	304	3	0.340	0.006	191	2
14	0.188	0.004	350	3	0.328	0.006	204	2
15	0.173	0.004	393	4	0.314	0.006	221	2
16	0.160	0.003	435	4	0.294	0.006	245	3
17	0.149	0.003	476	4	0.282	0.005	259	3
18	0.129	0.003	566	5	0.267	0.005	281	3
19	0.116	0.003	643	5	0.246	0.005	312	3
20	0.099	0.002	764	6	0.232	0.005	336	3
21	0.091	0.002	841	7	0.219	0.004	361	3
22	0.084	0.002	925	7	0.206	0.004	389	4
23	0.076	0.002	1026	8	0.195	0.004	414	4
24	0.154	0.003	458	4	0.085	0.002	1024	8
25	0.226	0.004	122	2				

Table 6: Power P and resistance R for the different configurations.

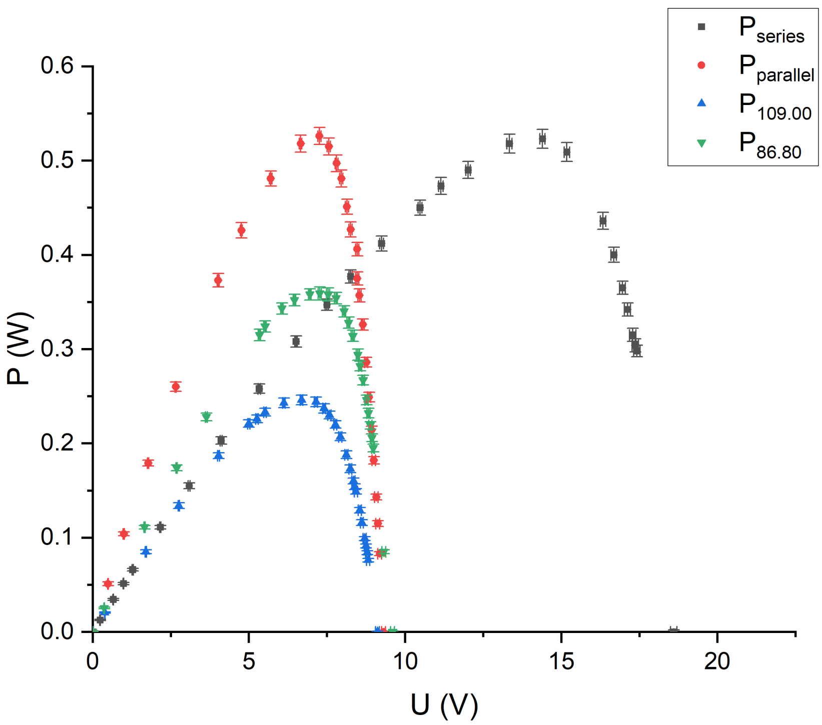

Figure 5: P-U characteristic curves of each configuration.

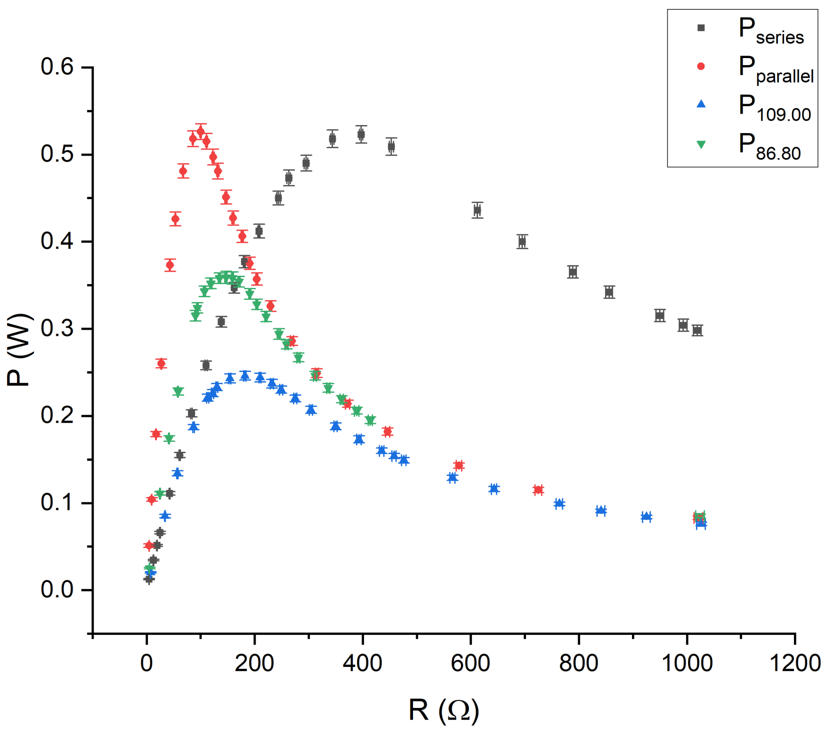

Figure 6: P-R characteristic curves of each configuration.

3.3 Maximum Output Power

According to Table 6, when the output powers of different configurations maximize, the corresponding I_m, V_m, R_m are compiled in the table below.

	P_{m} [W]	V_{m} [V]	I_{m} [mA]	R_{m} [Ω]
Series	0.523 ± 0.010	14.40 ± 0.08	36.3 ± 0.6	397 ± 3
Parallel	0.526 ± 0.009	7.26 ± 0.05	72.5 ± 1.2	100.1 ± 1.4
109.00 cm	0.246 ± 0.005	6.69 ± 0.04	36.8 ± 0.7	182 ± 2
86.80 cm	0.359 ± 0.007	7.27 ± 0.05	49.4 ± 0.8	147 ± 2

Table 7: V_{m}, I_{m} and P_{m} in each configuration.

3.4 Fill Factor

According to the definition of fill factor, it can be calculated as

$$FF = \frac{P_{\mathrm{m}}}{I_{\mathrm{SC}} U_{\mathrm{OC}}}$$

Therefore, take the series configuration as an example, the fill factor FF_{Series} can be calculated as

$$FF_{\mathrm{Series}} = \frac{P_{\mathrm{m}}}{I_{\mathrm{SC}} U_{\mathrm{OC}}} = \frac{0.523}{18.60 \times 52.3 \times 10^{-3}} = 0.538 \ \pm 0.015$$

The rest of the data are presented in Table 8.

Configuration	FF	u_{FF}
Series	0.538	0.015
Parallel	0.539	0.015
109.00 cm	0.514	0.010
86.80 cm	0.555	0.018

Table 8: Fill factors for different configurations.

3.5 Energy Conversion Efficiency

The measurement data are shown in Table 9 and Table 10.

Length L_1 [cm] $\pm$ 0.1 [cm]	Width L_2 [cm] $\pm$ 0.1 [cm]
26.00	21.00

Table 9: Measurement data for area.

	1	2	3	4	5	6
$P_{109.00}$ [W/m^2] $\pm$ 10 [W/m^2]	388	332	217	174	152	129
$P_{86.80}$ [W/m^2] $\pm$ 10 [W/m^2]	686	550	294	190	175	287

Table 10: Measurement data for solar power.

Therefore,the average power per square meter can be calculated as

$$\overline{P_{109.00}} = \frac{1}{6}(388 + 332 + 217 + 174 + 152 + 129) = (232.0 \ \pm 1.3 \times 10^1)\ \mathrm{W/m^2},$$

$$\overline{P_{86.80}} = \frac{1}{6}(686 + 550 + 294 + 190 + 175 + 287) = (363.7 \pm 2.2 \times 10^1)\,\mathrm{W/m^2}.$$

Then the total power is

$$P_{\mathrm{in},109.00} = \overline{P_{109.00}} L_1 L_2 = 232 \times 0.260 \times 0.210 = 12.7 \pm 0.9\ \mathrm{W},$$

$$P_{\mathrm{in},86.80} = \overline{P_{86.80}} L_1 L_2 = 363.7 \times 0.260 \times 0.210 = 19.9 \pm 1.5\ \mathrm{W}.$$

The power energy conversion efficiency η can be calculated as

$$\eta_{109.00} = \frac{P_\mathrm{m}}{P_{\mathrm{in},109.00}} \times 100\% = \frac{0.246}{12.7} \times 100\% = 1.9\% \pm 0.2\%,$$

$$\eta_{86.80} = \frac{P_\mathrm{m}}{P_{\mathrm{in},86.80}} \times 100\% = \frac{0.359}{19.9} \times 100\% = 1.8\% \pm 0.2\%,$$

4 Conclusion and Discussion

4.1 I-V Relation

In this part, the relation between the current I and the voltage V is studied. From Figure 4, it can be seen that generally, as voltage V increases, current I decreases. And the rate of change of current I also increases as voltage V increases. Comparing the curves of **series** and **parallel** configurations, it can be seen that the open circuit voltage U_{OC} doubled as the circuit changes from parallel configuration to series configuration, while the short circuit current I_{SC} halved. This trend fits with the characteristics of series and parallel circuit.

4.2 P-V and P-R Relation, and Maximum Power Output

For the $P - V$ relation, from Figure 5,it can be summarized that as the voltage U increases, the power P first increases from 0, reaching a peak, and then decreases to zero again.

As for thr $P - R$ relation, from Figure 6, it is obvious that, similarly, as the voltage U increases, the power P first increases from 0, reaching a peak, and then decreases to zero again. Furthermore,the output power attains its maximum at approximately $R = R_m$. The curves fit with the result in section 3.3 about maximum power output, verifying both results.

4.3 Fill Factor and Energy Conversion Efficiency

The fill factors and energy conversion efficiencies of two groups of result of different distances don't differentiate much from each other. However, according to the lab manual [1], theoretically speaking, the greater the fill factor, the greater the energy conversion efficiency should be, which is no the case in this lab. This will be discussed in the later part.

One conclusion can be derived is that the closer the solar board is to the light source, the greater the incident intensity, the greater the fill factor will be. This agree with out common sense and theory.

The experimental results of energy conversion efficiency are 1.9% and 1.8%. Notice that the energy conversion efficiency of the solar board is very low, which can explain that in real life, the solar panels are often of big area and large number, which compensates the defect in low energy conversion efficiency.

4.4 Discussion and Suggestion

There are several factors that might cause errors in this experiment:

1. The light source used in the lab is highly non-uniform, which means there may exist huge difference in the distribution of light on the solar board. Therefore the average power absorbed by the solar board may be inaccurate, causing errors in the calculation of energy conversion efficiency.

2. About the determination of the maximum power output and corresponding parameters, as only discrete data points are obtained and no fitting is performed, the values of V_m, I_m, R_m of maximum power output might be inaccurate, which are only selected from the existing data points.

3. In the experiment, the solar board is viewed to be ideal and with no resistance. However, there are actually considerable inner resistance, causing errors in determining the $P-R$ relation.

Some possible improvements can be made to the experiment:

1. Measure more data for the power per square meter on the solar board;
2. Perform fitting to correct the $P-R$ and $P-V$ curves, then obtain the corresponding parameters of maximum power output from the fitting curves;
3. Measure the inner resistance of the solar board and subtract when calculating the outer resistance.

References

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

A Uncertainty Analysis

A.1 I-V Relation

The uncertainty of V is $\pm(0.5\% + 0.01)$ V, and the uncertainty of I is $\pm(1.5\% + 0.1)$ mA.
For uncertainty calculation, take the first set of data as an example,

$$u_V = 0.5\% \times 0.24 + 0.01 = 0.011\,\mathrm{V}.$$

$$u_I = 1.5\% \times 52.3 + 0.1 = 0.9\,\mathrm{mA}.$$

All the uncertainties of V and I are calculated in this way and the results are shown in Table 11.

	Series		**Parallel**		**109.00 cm**		**86.80 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	0.011	0.9	0.06	0.2	0.012	0.9	0.01	1.1
2	0.013	0.9	0.06	0.3	0.02	0.9	0.02	1.1
3	0.015	0.9	0.06	0.3	0.02	0.8	0.02	1.1
4	0.02	0.9	0.06	0.4	0.03	0.8	0.03	1.0
5	0.02	0.9	0.05	0.5	0.04	0.8	0.04	1.0
6	0.03	0.9	0.05	0.5	0.04	0.7	0.04	1.0
7	0.03	0.8	0.05	0.6	0.04	0.7	0.04	0.9
8	0.04	0.8	0.05	0.7	0.04	0.7	0.04	0.9
9	0.04	0.8	0.05	0.8	0.05	0.6	0.04	0.9
10	0.05	0.8	0.05	0.8	0.05	0.6	0.05	0.8
11	0.05	0.8	0.05	0.9	0.05	0.6	0.05	0.8
12	0.06	0.8	0.05	0.9	0.05	0.5	0.05	0.8
13	0.06	0.7	0.05	1.0	0.05	0.5	0.05	0.7
14	0.07	0.7	0.05	1.1	0.05	0.4	0.05	0.7
15	0.08	0.7	0.05	1.1	0.05	0.4	0.05	0.7
16	0.08	0.6	0.05	1.2	0.05	0.4	0.05	0.6
17	0.09	0.6	0.04	1.3	0.05	0.4	0.05	0.6
18	0.09	0.5	0.04	1.4	0.05	0.3	0.05	0.6
19	0.09	0.5	0.03	1.4	0.05	0.3	0.05	0.5
20	0.09	0.4	0.03	1.5	0.05	0.3	0.05	0.5
21	0.10	0.4	0.02	1.6	0.05	0.3	0.05	0.5
22	0.10	0.4	0.02	1.6	0.05	0.2	0.05	0.4
23	0.10	0.4	0.02	1.7	0.05	0.2	0.05	0.4
24	0.10	0.4	0.012	1.7	0.05	0.4	0.06	0.2
25	0.07	0.7	0.05	0.7	0.04	0.7		

Table 11: Uncertainty of the data for I-V characteristic.

A.2 P-V and P-R Relation

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,

$$u_P = \sqrt{(Iu_V)^2 + (Vu_I)^2} = \sqrt{(52.3 \times 10^{-3} \times 0.011)^2 + (0.24 \times 0.9 \times 10^{-3})^2} = 0.0006\,\mathrm{W}.$$

$$u_R = \sqrt{(\frac{u_V}{I})^2 + (-\frac{V}{I^2}u_I)^2} = \sqrt{(\frac{0.01}{52.3\times 10^{-3}})^2 + (-\frac{0.24}{(52.3\times 10^{-3})^2}\times 0.9)^2} = 0.4\,\Omega.$$

The uncertainty of P and R of all data are calculated in this way and the results are shown in Table 6 in the **Result** part, following the values of P and R.

A.3 Fill Factor

The uncertainty of V_{oc} and I_{sc} is calculated in the same way as V and I in the previous part. The results are shown below.

	$u_{V_{\text{oc}}}$ [V]	$u_{I_{\text{sc}}}$ [mA]	$u_{P_{\text{m}}}$ [W]
Series	0.10	0.9	0.010
Parallel	0.06	1.7	0.009
109.00 cm	0.06	0.9	0.005
86.80 cm	0.06	1.1	0.007

Table 12: Uncertainty of V_{oc} and I_{sc}.

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

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

Take the first set of data as an example,

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{1}{V_{\text{oc}}I_{\text{sc}}}u_{P_{\text{m}}})^2 + (-\frac{P_{\text{m}}}{V_{\text{oc}}^2 I_{\text{sc}}}u_{V_{\text{oc}}})^2 + (-\frac{P_{\text{m}}}{V_{\text{oc}}I_{\text{sc}}^2}u_{I_{\text{sc}}})^2} \\ &= \sqrt{(\frac{1}{18.6\times 52.3\times 10^{-3}}\times 0.010)^2 + (-\frac{0.523}{18.60^2\times 52.3\times 10^{-3}}\times 0.010)^2 + (-\frac{0.523}{18.60\times (52.3\times 10^{-3})^2}\times 0.0009)^2} \\ &= 0.015. \end{aligned}$$

The uncertainties are calculated as shown above and the rest of the results are shown in Table 8 in the **Result** part.

A.4 Energy Conversion Efficiency

In this part, as multiple measurements are performed, both type-A and type-B uncertainty need to be considered. The type–B uncertainty of power measurement is $u_P = \Delta_{P,B} = \Delta_{dev} = 10$ [W/m^2].

Since the power measurement is carried for 6 times, the type–A is

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

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,

$$u_{\overline{P_{109.00}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}}\sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 232.0)^2}\right)^2 + 10^2} = 1.3 \times 10^1 \text{ W/m}^2,$$

$$u_{\overline{P_{86.80}}} = \sqrt{\left(\frac{2.57}{\sqrt{6}}\sqrt{\frac{1}{6-1}\sum_{i=1}^{6}(P_i - 363.7)^2}\right)^2 + 10^2} = 2.2 \times 10^1 \text{ W/m}^2,$$

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

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

Hence, plugging in the values yields that

$$u_{P_{\text{in},109.00}} = 0.9 \text{ W}, \qquad u_{P_{\text{in},86.80}} = 1.5 \text{ W}.$$

Finally, the uncertainty of $\eta = \frac{P_{\text{m}}}{P_{\text{in}}} \times 100\%$ can be calculated as

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

Plugging in the values yields

$$u_{\eta_{109.00}} = 0.2\,\%, \qquad u_{\eta_{86.80}} = 0.2\,\%.$$

B Data Sheet

The original data sheet is appended in the last part.