UM-SJTU Joint Institute
Physicis Laboratory II
(VP241)

Laboratory Report

Exercise 3

Solar Cells: $I-V$ Characteristics

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1 Introduction

1.1 The Structure of a Solar Cell

Solar cells can directly transform solar radiation into electrical energy. They have many advantages, including no consumption of energy resources on Earth, low pollution, a long lifetime, etc.

The structure of a typical solar cell is shown in Figure1. It is made up of n/p homo-junctions, a 10cm$\times$ 10cm

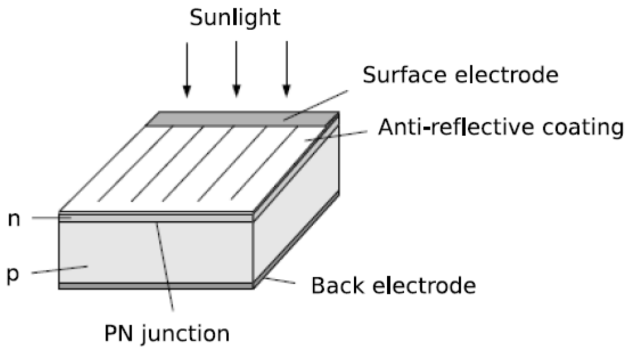

Figure 1: The Structure of a Crystalline Silicon Solar Cell.

p-type silicon plate of thickness 500μm, covered with a heavily doped n-type layer with thickness 0.3μm. The metallic bars on the n-type layer serve as one electrode, with a metallic film at the bottom playing the role of another one. In order to reduce the loss of energy due to reflection, an anti-reflective film is often applied to cover the surface exposed to sunlight.

1.2 Photovoltatic Effect

When the light enters the p-n junction near the solar cell surface, and the energy of the photon ($E = h\nu$) is larger than the energy gap (E_g), the photon's energy is absorbed and the electron-hole pair is excited. Minority charge carriers in the n- or p-area diffuse due to their density gradient. Some of the carriers can diffuse to the region of the p-n junction zone, where there is a built-in electric field. Under the electric force, these carriers either move to the n-type area (in case of the electron) or move to the p-type area (in case of the hole). As a result, the negative charge accumulates in the n-type area, and positive charge accumulates in the p-type area, and a photoelectric potential difference is generated. The phenomenon described above is known as the *photovoltaic effect*.

1.3 Solar Cell Parameters

Because of the photovoltatic effect, the 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. Meanwhile, in this device there is a forward diode current I_{D} from the p-type to the n-type area, opposite to I_{ph}. In the end, the net current is

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

where V_{D} is the junction voltage, I_0 is diode inverse saturation current, I_{ph} is the photocurrent determined by the structure and material characteristics of the solar cell. The coefficient n is a theoretical coefficient, with its values ranging from 1 to 2, that characterize the p-n junction. In addition, q is the electron's charge, k_{B} is the Boltzmann's constant, and T is the temperature in Kelvin scale. If we neglect the internal series resistance R_{s}, the voltage V_{D} is equal to the terminal voltage V and Equation 1 can be rewritten as

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

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

$$I_{\mathrm{sc}} = I_{\mathrm{ph}},$$

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

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

When there is a load resistance R (with the value of R ranging from zero to infinity), the corresponding I-V characteristics curve is shown in Figure 2. If for a certain load resistance $R = R_{\mathrm{m}}$, the maximum output power P_{m} is reached, then the value of P_{m} is

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

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

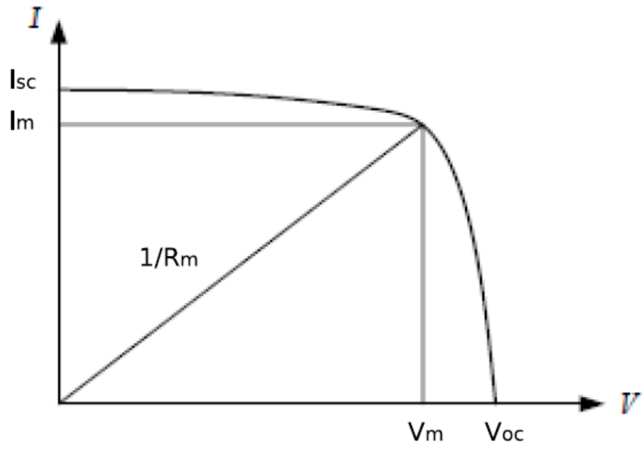

Figure 2: The Theoretical Current-Voltage Characteristics of a Solar Cell.

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

The quantity FF is an important parameter of solar cells called the *fill factor*. The greater the fill factor is, the greater the output power. The fill factor is determined by a number of parameters, such as the incident light intensity, the forbidden bandwidth, the value of the theoretical coeffcient n, and the series/parallel resistance.

The solar cell energy conversion efficiency η is defined as

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

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

1.4 Solar Cell Equivalent Circuit

As shown in Figure 3, a solar cell can be thought of as composed of a *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. For the equivalent circuit one can find the following relationship between the current and the voltage

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

In order to provide a greater output power, the value of R_{s} should be decreased, while R_{sh} should be increased.

2 Apparatus & Measurement Procedure

2.1 Apparatus

The setup consists of 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. Table 1 lists the uncertainty of the measurement in this lab.

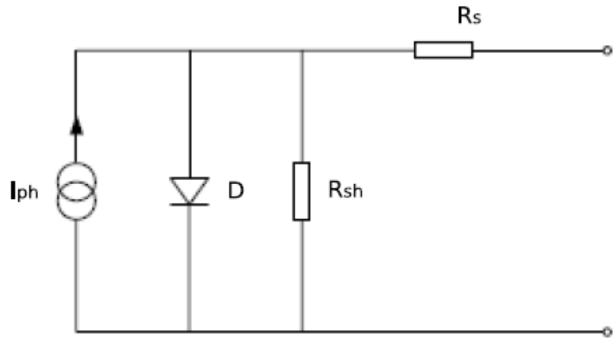

Figure 3: Solar Cell Equivalent Circuit

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

Table 1: The Uncertainty of the Measurement

2.2 Measurement Procedure

1. I(TA) turned on both the light and the fan and waited for more than five minutes, so that the light reached its working intensity.
2. I, together with my teammates, adjusted the distance of the two lamps from the solar cells to make the open-circuit voltage and the short-circuit current is approximately the same.
3. I then measured the length, width of the solar cell and its distance from the lamp with the measuring tape provided.
4. Then, I measured the solar power incident on the board with the solar power meter on six different points on the solar cell.
5. I measured the open-circuit voltage and short-circuit current for all of the three circuits: series and parallel connection of two solar cells and a single solar cell.
6. I then connected the solar cell of these three configurations to a adjustable resistor, and measured the voltage across the resistor and the current through the resistor for 25 different resistance.
7. Then I change the distance between the lamp and the solar cell, measured the new distance, the new open-circuit voltage and short-circuit current, and 25 more sets of current-voltage relations.

3 Results

3.1 The I-U Characteristic Graph

Configurations	U_{oc}[V]	Uncertainty[V]	I_{sc}[A]	Uncertainty[A]
110.9cm	9.48	0.06	0.0839	0.0014
73.6cm	10.17	0.06	0.162	0.003
series	18.56	0.10	0.0877	0.0014
parallel	9.28	0.06	0.174	0.003

Table 2: The Data of I_{sc} and U_{oc} for Different Configurations

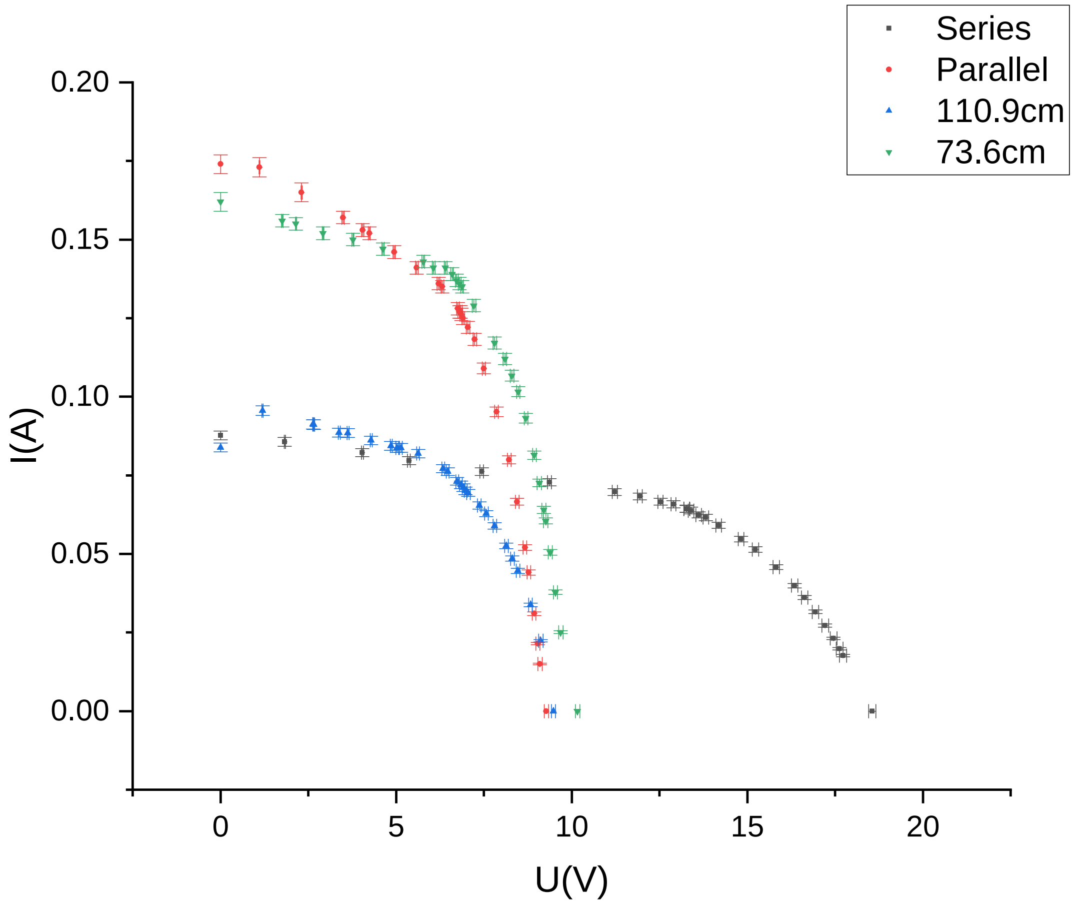

Figure 4: The $I-U$ Characteristics Curve of the Four Configurations of the Solar Cell

Table 6 and 7 list a total of 100 sets of data (I vs U) in SI unit. The conversion of I from unit [mA] to [A] can be calculated as $I = I'/1000$. For example, when $I' = 156.0$[mA],

$$I = 156.0/1000 = 0.156[\text{A}].$$

Table 2 lists the short-circuit current and open-circuit voltage for four configurations. And I used these three tables to plot Figure 4, the I-U characteristics of four different (configurations) solar cells.

3.2 The P-U Relation

Table 8 and 9 list the power-voltage relation of four different configurations of the solar cells. In order to calculated the power, $P = UI$. For example, when $U = 1.830$[V], $I = 0.0856$[A],

$$P = 1.830 \times 0.0856 = 0.157[\text{W}] \pm 0.003[\text{W}].$$

I used these two tables to plot Figure 5.

3.3 The P-R Relation

Table 10 and 11 list the power-resistance relation of four different configurations of solar cells. The (load) resistance is calculated as $R = U/I$. For example, when $U = 1.830$[V], $I = 0.0856$[A],

$$R = \frac{1.830}{0.0856} = 21.4[\Omega] \pm 0.4[\Omega].$$

Then I used these two tables to plot Figure 6.

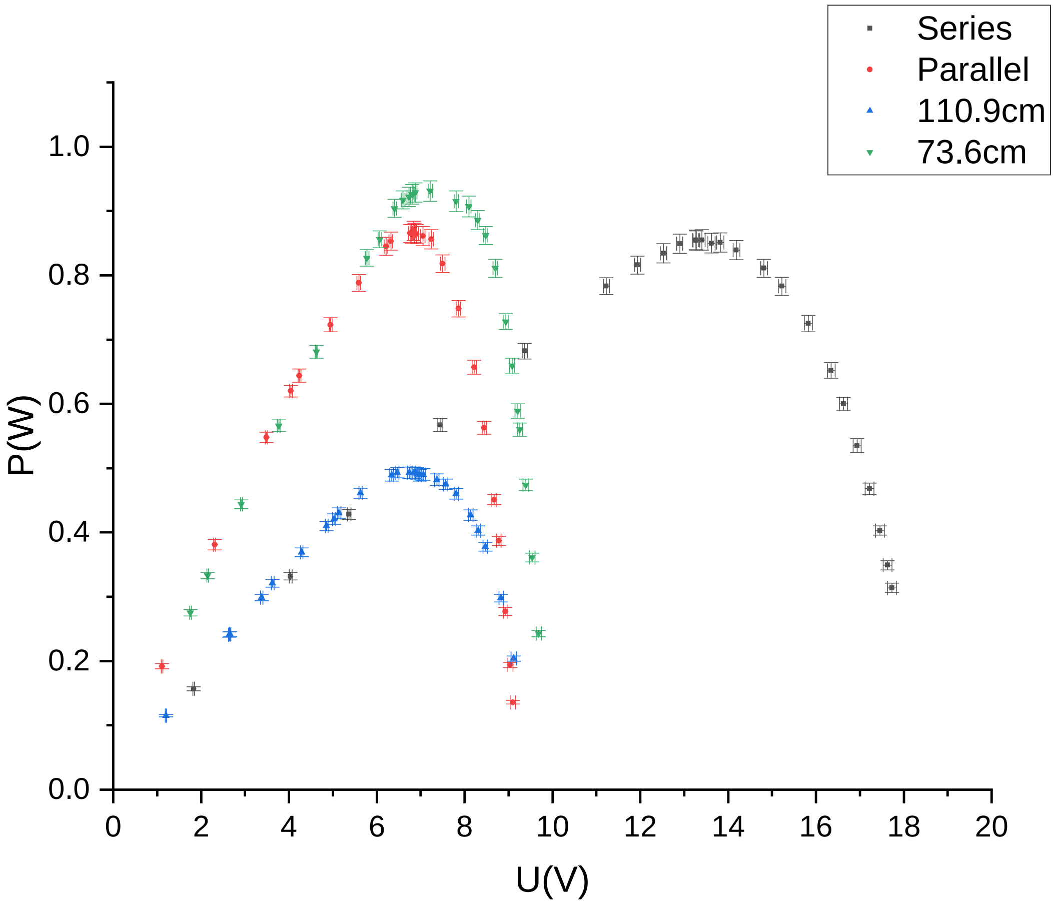

Figure 5: The relation of P vs. U for Four Configurations of Solar Cells

3.4 The Calculation of Parameters of Each Configuration

We need to obtain eight parameters. V_{oc} and I_{sc} can be obtained directly from Table 2. P_{m}, V_{m} and I_{m} can be obtained directly from Table 6, 7, 8 and 9. R_{m} can be read from Table 10 and 11. So I will show the calculation of the parameters FF and η.

The fill factor is given by

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

For example, in the circuit of distance 110.9[cm], $P_m = 0.493$[W], $V_{\mathrm{oc}} = 9.48$[V], $I_{\mathrm{sc}} = 0.0839$[A], and

$$FF = \frac{0.493}{9.48 \times 0.0839} = 0.620 \pm 0.016.$$

In order to calculate η, we first need to calculate the total radiation incident on the solar cell. Table 3 shows the original data of the power incident on unit area on the solar cell, and Table 4 shows the length and width of the solar cell. We first calculate the average value of the power on unit area

$$\bar{P} = \frac{\sum_{i=1}^{6} P_i}{6}.$$

When the distance is 110.9[cm],

$$\bar{P} = \frac{395 + 451 + 389 + 248 + 417 + 268}{6} = 360[\mathrm{W/m^2}] \pm 80[\mathrm{W/m^2}].$$

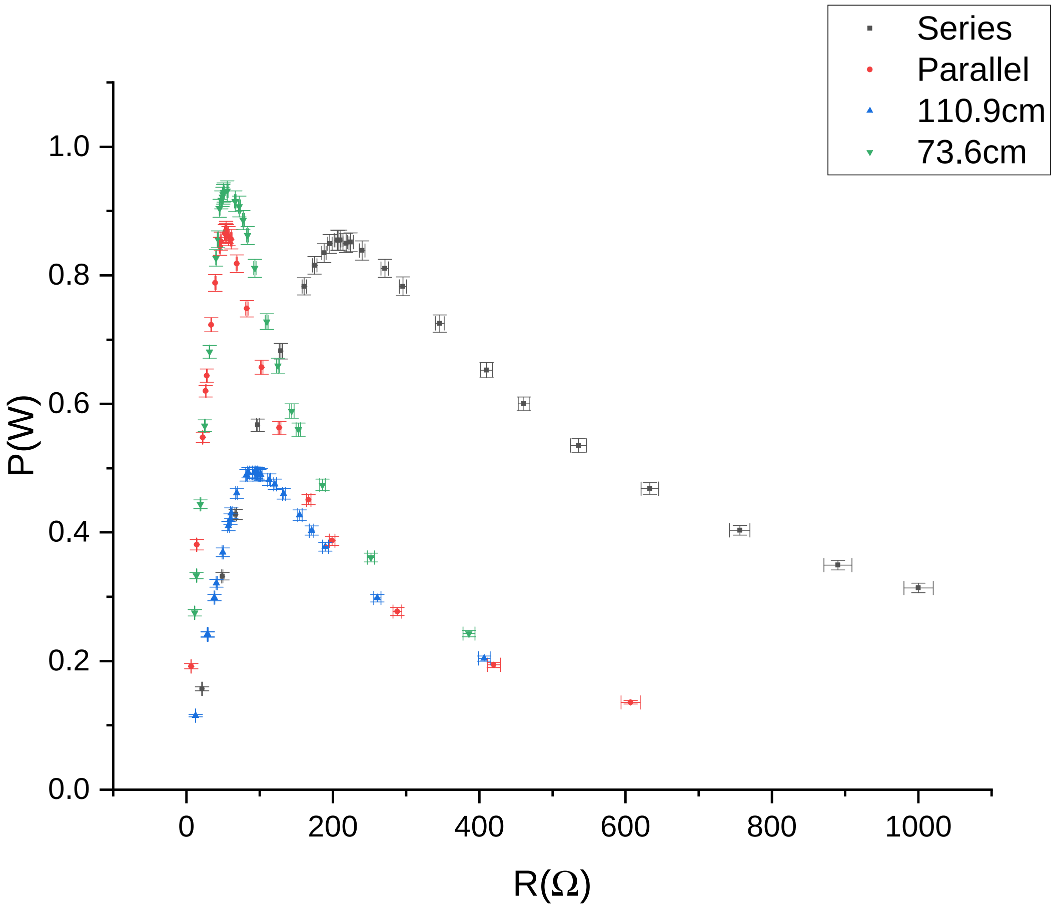

Figure 6: The relation of P vs. R for Four Configurations of Solar Cells

The area of the solar cell is $S = \text{length} \times \text{width}$. So,

$$S = 0.255 \times 0.206 = 0.0525[\mathrm{m}^2] \pm 0.0003[\mathrm{m}^2].$$

And the total power is given as $P_{\text{in}} = \bar{P}S$. So,

$$P_{\text{in}} = 360 \times 0.0525 = 19[\mathrm{W}] \pm 4[\mathrm{W}].$$

Since $\eta = P_{\mathrm{m}}/P_{\text{in}} \times 100\%$,

$$\eta = \frac{0.493}{19} = 2.6\% \pm 0.6\%.$$

The same calculation can be applied when the distance is 73.6[cm], and $\eta = 2.3\% \pm 0.6\%$.

	1	2	3	4	5	6
$P_{110.9}[\mathrm{W/m^2}]$	395	451	389	248	417	268
$P_{73.6}[\mathrm{W/m^2}]$	1160	837	536	783	619	574

Table 3: The Power Incident on the Unit Area of a Solar Cell

length[cm]	width[cm]
25.5	20.6

Table 4: The Length and Width of the Solar Cell

	Series	Parallel	110.9[cm]	73.6[cm]
V_{oc}[V]	18.56 ± 0.10	9.28 ± 0.06	9.48 ± 0.06	10.17 ± 0.06
I_{sc}[A]	0.0877 ± 0.0014	0.174 ± 0.003	0.0839 ± 0.0014	0.162 ± 0.003
P_{m}[W]	0.855 ± 0.016	0.869 ± 0.015	0.493 ± 0.009	0.931 ± 0.016
V_{m}[V]	13.27 ± 0.08	6.84 ± 0.04	6.74 ± 0.04	7.22 ± 0.05
I_{m}[A]	0.0644 ± 0.0011	0.127 ± 0.002	0.0731 ± 0.0012	0.129 ± 0.002
$R_{\mathrm{m}}[\Omega]$	206 ± 4	53.9 ± 0.9	92.2 ± 1.7	56.0 ± 1.0
FF	/	/	0.620 ± 0.016	0.565 ± 0.015
η	/	/	$2.6\% \pm 0.6\%$	$2.3\% \pm 0.6\%$

Table 5: The Parameters of Each Configurations

4 Discussion

First, we can conclude from Figure 4 that the solar cell is not a linear emf, whose inner resistance should remain a constant, because none of the four $I - U$ characteristics curve is a straight line. However, there is a small problem in this plot. See the blue triangle at $U = 0$. It is the short circuit current. It should, in theory, be larger than any other current values. Yet, it lies below some of the triangle points. This is because during the experiment, I first measured the short circuit current and open circuit voltage for 110.9[cm], but when I was measuring the voltage and current for different load resistance, the group next to me moved their lamp to a different configuration, so the short circuit current and the open circuit voltage is not valid any more for this configuration. But besides this false data, the open circuit voltage is larger than any other voltage values and the short circuit current is larger than any other current values.

Second, for the series configuration, while near the maximum power, the power is not monotonic with respect to the resistance any more, *i.e.*, the maximum power is not reached for a certain value of resistance and then declines. In Table 10, we can see that when $R = 206, 207, 210[\Omega]$, the power first decreases and then increases, which is a violation of the theory. One possible explanation concerns the uncertainty. By observation, we can see that the uncertainty for both the power and the resistance is not small compared with its value. So the actual maximum value may be closer to the plus side of the uncertainty.

Apart from this, from Figure 5 and 6, we can conclude that the maximum power transferred to the load reaches the maximum value for a certain value of voltage and resistance.

From Table 5, we can come to many conclusions. First, for maximum power, the voltage of the series configuration is approximately two times of that of the parallel configuration. Also the current of the series is approximately one half of that of the parallel configuration. This is because I adjusted the distance of the two lamps so that the short circuit current and the open circuit voltage is almost the same, so basically it is the parallel or series connection of two identical batteries. For series connection, the open circuit voltage(emf) doubles and the short circuit current remains the same compared to a single solar cell, while for parallel connection, the emf remains the same and the short circuit current doubles.

Second, the efficiency (η) for both configuration of a single solar cell is small. 2.6% and 2.3% are not big numbers, which means that the conversion from the light radiation to electric power is not efficient enough compared to conventional energy sources.

5 Conclusion

In this lab section, I have studied the $I - U$ characteristics curve of the solar cell. In general, the experiment is quite successful, as the theory matches the experiment results quite well. However, there are some minor problems in the experiment listed below and I have given some solutions.

1. The configuration of the group next to me will affect the result of my own. When they move their lamp, my voltage and current will change. This has caused me some trouble in data analysis. The solution is simple. Make sure the instructor (teaching assistant) tells students that lamps next to each group also affect the experiment result so that the students will ask for permission of the group next to them before they move their lamps.

2. Due to the low resolution of the multimeters, the power does not coincide with theory. So getting higher resolution equipment will make the experiment's result more valid and convincing.

6 Reference

1. Qin Tian, Han Xugen, Zheng Huan, Mateusz Krzyzosiak, "Exercise 3- lab manual [rev. 4.1]".

A Uncertainty Analysis

A.1 The Uncertainty of U and I for the Original Data

Based on the information given in Table 1, the uncertainty of U is $u = U \times 0.5\% + 0.01$. For example, when $U = 9.12$[V],

$$u = 9.12 \times 0.5\% + 0.01 = 0.06[\mathrm{V}].$$

The uncertainty of I is $u = (I \times 1.5\% + 0.1)/1000$. For instance, when $I = 25.1$[mA],

$$u = \frac{25.1 \times 1.5\% + 0.1}{1000} = 0.0005[\mathrm{A}].$$

The same calculations can be applied to calculate the uncertainty of U_{oc} and I_{sc}.

A.2 The Uncertainty of P and R

The power P is given by $P = UI$, so the uncertainty is

$$\begin{aligned} u &= \sqrt{\left(\frac{\partial P}{\partial U} u_U\right)^2 + \left(\frac{\partial P}{\partial I} u_I\right)^2} \\ &= \sqrt{I^2 u_U^2 + U^2 u_I^2} \end{aligned}$$

For example, when $U = 1.830$[V], $I = 0.0856$[A], $u_U = 0.019$[V], $u_I = 0.0014$[A], the uncertainty is

$$u = \sqrt{1.830^2 \times 0.0014^2 + 0.019^2 \times 0.0856^2} = 0.003[\mathrm{W}].$$

The (load) resistance is given by $R = U/I$, so the uncertainty is

$$\begin{aligned} u &= \sqrt{\left(\frac{\partial R}{\partial U} u_U\right)^2 + \left(\frac{\partial R}{\partial I} u_I\right)^2} \\ &= \sqrt{\frac{u_U^2}{I^2} + \frac{U^2 u_I^2}{I^4}} \\ &= \frac{1}{I^2}\sqrt{I^2 u_U^2 + U^2 u_I^2} \end{aligned}$$

For example, when $U = 1.830$[V], $I = 0.0856$[A], $u_U = 0.019$[V], $u_I = 0.0014$[A], the uncertainty is

$$u = \frac{1}{0.0856^2} \times \sqrt{1.830^2 \times 0.0014^2 + 0.019^2 \times 0.0856^2} = 0.4[\Omega].$$

A.3 The Uncertainty of FF and η

Since $FF = P_m/(V_{\mathrm{oc}} I_{\mathrm{sc}})$,

$$\begin{aligned} u &= \sqrt{\left(\frac{\partial FF}{\partial P_m} u_{P_m}\right)^2 + \left(\frac{\partial FF}{\partial V_{\mathrm{oc}}} u_{V_{\mathrm{oc}}}\right)^2 + \left(\frac{\partial FF}{\partial I_{\mathrm{sc}}} u_{I_{\mathrm{sc}}}\right)^2} \\ &= \sqrt{\frac{u_{P_m}^2}{{V_{\mathrm{oc}}}^2 {I_{\mathrm{sc}}}^2} + \frac{P_m^2 u_{V_{\mathrm{oc}}}^2}{{V_{\mathrm{oc}}}^4 {I_{\mathrm{sc}}}^2} + \frac{P_m^2 u_{I_{\mathrm{sc}}}^2}{{I_{\mathrm{sc}}}^4 {V_{\mathrm{oc}}}^2}} \\ &= \frac{1}{{V_{\mathrm{oc}}}^2 {I_{\mathrm{sc}}}^2}\sqrt{u_{P_m}^2 {V_{\mathrm{oc}}}^2 {I_{\mathrm{sc}}}^2 + P_m^2 u_{V_{\mathrm{oc}}}^2 {I_{\mathrm{sc}}}^2 + P_m^2 u_{I_{\mathrm{sc}}}^2 {V_{\mathrm{oc}}}^2}. \end{aligned}$$

For example, in the series circuit, $P_m = 0.493$[W], $V_{\mathrm{oc}} = 9.48$[V], $I_{\mathrm{sc}} = 0.0839$[A], $u_{P_m} = 0.009$[W], $u_{V_{\mathrm{oc}}} = 0.06$[V], $u_{I_{\mathrm{sc}}} = 0.0014$[A], so the uncertainty is

$$\begin{aligned} u &= \frac{1}{9.48^2 \times 0.0839^2}\sqrt{0.009^2 \times 9.48^2 \times 0.0839^2 + 0.493^2 \times 0.06^2 \times 0.0839^2 + 0.493^2 \times 0.0014^2 \times 9.48^2} \\ &= 0.016. \end{aligned}$$

To calculate the uncertainty of η, we first consider the uncertainty of the mean value of the six sets of power on unit area.

$$u = \sqrt{\Delta_A^2 + \Delta_B^2},$$

where $\Delta_B = 10[\mathrm{W/m^2}]$. Δ_A is given as

$$\Delta_A = s_X \frac{t_{0.95}}{\sqrt{n}}.$$

Since $n = 6$ for my measurement, $\frac{t_{0.95}}{\sqrt{n}} = 1$ and $\Delta_A = s_X$. The standard deviation is calculated as

$$s_X = \sqrt{\frac{1}{5}\sum_{i=1}^{6}(P_i - \bar{P})^2}.$$

So when the distance is 110.9[cm],

$$\begin{aligned} s_X &= \sqrt{\frac{1}{5}((395-360)^2 + (451-360)^2 + (389-360)^2 + (248-360)^2 + (417-360)^2 + (268-360)^2)} \\ &= 75.9[\mathrm{W/m^2}]. \end{aligned}$$

So,

$$u_{\bar{P}} = \sqrt{10^2 + 75.9^2} = 80[\mathrm{W/m^2}].$$

Then the uncertainty of the area is given as

$$u_S = \sqrt{\left(\frac{\partial S}{\partial l}u_l\right)^2 + \left(\frac{\partial S}{\partial w}u_w\right)^2} = u_l\sqrt{l^2 + w^2}.$$

Here $u_l = 0.001[m]$, $l = 0.255[\mathrm{m}]$, $w = 0.206[\mathrm{m}]$, so the uncertainty is

$$u_S = 0.001 \times \sqrt{0.255^2 + 0.206^2} = 0.0003[\mathrm{m^2}].$$

Then the uncertainty of the total power is given as

$$u = \sqrt{u_{\bar{P}}^2 S^2 + u_S^2 \bar{P}^2}.$$

When $\bar{P} = 360[\mathrm{W/m^2}]$, $u_{\bar{P}} = 80[\mathrm{W/m^2}]$, $S = 0.05[\mathrm{m^2}]$, $u_S = 0.0003[\mathrm{m^2}]$, we get

$$u_P = \sqrt{80^2 \times 0.05^2 + 0.0003^2 \times 360^2} = 4[\mathrm{W}].$$

As for u_η,

$$\begin{aligned} u_\eta &= \sqrt{\left(\frac{\partial \eta}{\partial P_{\mathrm{in}}}u_{P_{\mathrm{in}}}\right)^2 + \left(\frac{\partial \eta}{\partial P_{\mathrm{m}}}u_{P_{\mathrm{m}}}\right)^2} \\ &= \frac{1}{P_{\mathrm{in}}^2}\sqrt{P_{\mathrm{in}}^2 u_{P_{\mathrm{m}}}^2 + P_{\mathrm{m}}^2 u_{P_{\mathrm{in}}}^2} \end{aligned}$$

Here, $P_{\mathrm{in}} = 19[\mathrm{W}]$, $u_{P_{\mathrm{in}}} = 4[\mathrm{W}]$, $P_{\mathrm{m}} = 0.493[\mathrm{W}]$, $u_{P_{\mathrm{m}}} = 0.009[\mathrm{W}]$, and then the uncertainty is

$$\begin{aligned} u &= \frac{1}{19^2} \times \sqrt{19^2 \times 0.009^2 + 4^2 \times 0.493^2} \\ &= 0.006 = 0.6\% \end{aligned}$$

The same calculation can be applied to the η when the distance is 73.6[cm]. $u_\eta = 0.6\%$.

B The Data Tables Used to Plot

series				parallel			
U[V]	Uncertainty[V]	I[A]	Uncertainty[A]	U[V]	Uncertainty[V]	I[A]	Uncertainty[A]
1.830	0.019	0.0856	0.0014	1.110	0.016	0.173	0.003
4.04	0.03	0.0822	0.0013	2.31	0.02	0.165	0.003
5.37	0.04	0.0797	0.0013	3.49	0.03	0.157	0.002
7.44	0.05	0.0762	0.0012	4.05	0.03	0.153	0.002
9.37	0.06	0.0728	0.0012	4.24	0.03	0.152	0.002
11.23	0.07	0.0697	0.0011	4.95	0.03	0.146	0.002
11.94	0.07	0.0683	0.0011	5.59	0.04	0.141	0.002
12.53	0.07	0.0666	0.0011	6.21	0.04	0.136	0.002
12.90	0.07	0.0658	0.0011	6.32	0.04	0.135	0.002
13.27	0.08	0.0644	0.0011	6.76	0.04	0.128	0.002
13.28	0.08	0.0643	0.0011	6.80	0.04	0.127	0.002
13.40	0.08	0.0638	0.0011	6.84	0.04	0.127	0.002
13.62	0.08	0.0624	0.0010	6.86	0.04	0.126	0.002
13.82	0.08	0.0616	0.0010	6.91	0.04	0.125	0.002
14.19	0.08	0.0591	0.0010	7.05	0.05	0.1221	0.0019
14.82	0.08	0.0547	0.0009	7.24	0.05	0.1182	0.0019
15.23	0.09	0.0514	0.0009	7.50	0.05	0.1090	0.0017
15.83	0.09	0.0458	0.0008	7.86	0.05	0.0952	0.0015
16.35	0.09	0.0399	0.0007	8.22	0.05	0.0799	0.0013
16.63	0.09	0.0361	0.0006	8.45	0.05	0.0666	0.0011
16.94	0.09	0.0316	0.0006	8.67	0.05	0.0520	0.0009
17.22	0.10	0.0272	0.0005	8.78	0.05	0.0441	0.0008
17.46	0.10	0.0231	0.0004	8.93	0.05	0.0310	0.0006
17.63	0.10	0.0198	0.0004	9.04	0.06	0.0215	0.0004
17.73	0.10	0.0177	0.0004	9.10	0.06	0.0150	0.0003

Table 6: The Series and Parallel Solar Cells $I-U$ Relation

110.9[cm]				73.6[cm]			
U[V]	Uncertainty[V]	I[A]	Uncertainty[A]	U[V]	Uncertainty[V]	I[A]	Uncertainty[A]
1.200	0.016	0.0956	0.0015	1.760	0.019	0.156	0.002
2.64	0.02	0.0912	0.0015	2.15	0.02	0.155	0.002
2.66	0.02	0.0911	0.0015	2.92	0.02	0.152	0.002
3.38	0.03	0.0886	0.0014	3.77	0.03	0.150	0.002
3.63	0.03	0.0884	0.0014	4.63	0.03	0.147	0.002
4.29	0.03	0.0861	0.0014	5.78	0.04	0.143	0.002
4.86	0.03	0.0844	0.0014	6.07	0.04	0.141	0.002
5.03	0.04	0.0837	0.0014	6.41	0.04	0.141	0.002
5.14	0.04	0.0837	0.0014	6.60	0.04	0.139	0.002
5.63	0.04	0.0819	0.0013	6.73	0.04	0.137	0.002
6.34	0.04	0.0771	0.0013	6.81	0.04	0.136	0.002
6.47	0.04	0.0762	0.0012	6.88	0.04	0.135	0.002
6.74	0.04	0.0731	0.0012	7.22	0.05	0.129	0.002
6.85	0.04	0.0720	0.0012	7.81	0.05	0.1171	0.0019
6.92	0.04	0.0711	0.0012	8.10	0.05	0.1120	0.0018
6.98	0.04	0.0701	0.0012	8.30	0.05	0.1067	0.0017
7.06	0.05	0.0694	0.0011	8.48	0.05	0.1016	0.0016
7.37	0.05	0.0654	0.0011	8.70	0.05	0.0932	0.0015
7.57	0.05	0.0628	0.0010	8.94	0.05	0.0814	0.0013
7.81	0.05	0.0589	0.0010	9.08	0.06	0.0726	0.0012
8.14	0.05	0.0525	0.0009	9.21	0.06	0.0640	0.0011
8.31	0.05	0.0485	0.0008	9.26	0.06	0.0605	0.0010
8.47	0.05	0.0446	0.0008	9.39	0.06	0.0505	0.0009
8.83	0.05	0.0338	0.0006	9.54	0.06	0.0378	0.0007
9.12	0.06	0.0224	0.0004	9.69	0.06	0.0251	0.0005

Table 7: The $I-U$ Relation of a Single Solar Cell with Different Distances

series				parallel			
U[V]	Uncertainty[V]	P[W]	Uncertainty[W]	U[V]	Uncertainty[V]	P[W]	Uncertainty[W]
1.830	0.019	0.157	0.003	1.110	0.016	0.192	0.004
4.04	0.03	0.332	0.006	2.31	0.02	0.381	0.008
5.37	0.04	0.428	0.008	3.49	0.03	0.548	0.008
7.44	0.05	0.567	0.010	4.05	0.03	0.620	0.009
9.37	0.06	0.682	0.012	4.24	0.03	0.644	0.010
11.23	0.07	0.783	0.013	4.95	0.03	0.723	0.011
11.94	0.07	0.816	0.014	5.59	0.04	0.788	0.013
12.53	0.07	0.834	0.015	6.21	0.04	0.845	0.014
12.90	0.07	0.849	0.015	6.32	0.04	0.853	0.014
13.27	0.08	0.855	0.015	6.76	0.04	0.865	0.014
13.28	0.08	0.854	0.015	6.80	0.04	0.864	0.015
13.40	0.08	0.855	0.016	6.84	0.04	0.869	0.015
13.62	0.08	0.850	0.015	6.86	0.04	0.866	0.015
13.82	0.08	0.851	0.015	6.91	0.04	0.864	0.015
14.19	0.08	0.839	0.015	7.05	0.05	0.861	0.015
14.82	0.08	0.811	0.014	7.24	0.05	0.856	0.015
15.23	0.09	0.783	0.014	7.50	0.05	0.818	0.014
15.83	0.09	0.725	0.013	7.86	0.05	0.748	0.013
16.35	0.09	0.652	0.012	8.22	0.05	0.657	0.011
16.63	0.09	0.600	0.010	8.45	0.05	0.563	0.010
16.94	0.09	0.535	0.011	8.67	0.05	0.451	0.008
17.22	0.10	0.468	0.009	8.78	0.05	0.387	0.007
17.46	0.10	0.403	0.007	8.93	0.05	0.277	0.006
17.63	0.10	0.349	0.007	9.04	0.06	0.194	0.004
17.73	0.10	0.314	0.007	9.10	0.06	0.136	0.003

Table 8: The Series and Parallel Solar Cells $P-U$ Relation

110.9[cm]				73.6[cm]			
U[V]	Uncertainty[V]	P[W]	Uncertainty[W]	U[V]	Uncertainty[V]	P[W]	Uncertainty[W]
1.200	0.016	0.115	0.002	1.760	0.019	0.275	0.005
2.64	0.02	0.241	0.004	2.15	0.02	0.333	0.005
2.66	0.02	0.242	0.004	2.92	0.02	0.444	0.007
3.38	0.03	0.299	0.005	3.77	0.03	0.566	0.009
3.63	0.03	0.321	0.006	4.63	0.03	0.681	0.010
4.29	0.03	0.369	0.007	5.78	0.04	0.827	0.013
4.86	0.03	0.410	0.007	6.07	0.04	0.856	0.013
5.03	0.04	0.421	0.008	6.41	0.04	0.904	0.014
5.14	0.04	0.430	0.008	6.60	0.04	0.917	0.014
5.63	0.04	0.461	0.008	6.73	0.04	0.922	0.015
6.34	0.04	0.489	0.009	6.81	0.04	0.926	0.015
6.47	0.04	0.493	0.008	6.88	0.04	0.929	0.015
6.74	0.04	0.493	0.009	7.22	0.05	0.931	0.016
6.85	0.04	0.493	0.009	7.81	0.05	0.915	0.016
6.92	0.04	0.492	0.009	8.10	0.05	0.907	0.016
6.98	0.04	0.489	0.009	8.30	0.05	0.886	0.015
7.06	0.05	0.490	0.009	8.48	0.05	0.862	0.014
7.37	0.05	0.482	0.009	8.70	0.05	0.811	0.014
7.57	0.05	0.475	0.008	8.94	0.05	0.728	0.012
7.81	0.05	0.460	0.008	9.08	0.06	0.659	0.012
8.14	0.05	0.427	0.008	9.21	0.06	0.589	0.011
8.31	0.05	0.403	0.007	9.26	0.06	0.560	0.010
8.47	0.05	0.378	0.007	9.39	0.06	0.474	0.009
8.83	0.05	0.298	0.006	9.54	0.06	0.361	0.007
9.12	0.06	0.204	0.004	9.69	0.06	0.243	0.005

Table 9: The $P-U$ Relation of a Single Solar Cell with Different Distances

series				parallel			
$R[\Omega]$	Uncertainty$[\Omega]$	P[W]	Uncertainty[W]	$R[\Omega]$	Uncertainty$[\Omega]$	P[W]	Uncertainty[W]
21.4	0.4	0.157	0.003	6.42	0.13	0.192	0.004
49.1	0.9	0.332	0.006	14.0	0.3	0.381	0.008
67.4	1.3	0.428	0.008	22.2	0.3	0.548	0.008
97.6	1.7	0.567	0.010	26.5	0.4	0.620	0.009
129	2	0.682	0.012	27.9	0.4	0.644	0.010
161	3	0.783	0.013	33.9	0.5	0.723	0.011
175	3	0.816	0.014	39.6	0.7	0.788	0.013
188	3	0.834	0.015	45.7	0.8	0.845	0.014
196	3	0.849	0.015	46.8	0.8	0.853	0.014
206	4	0.855	0.015	52.8	0.9	0.865	0.014
207	4	0.854	0.015	53.5	0.9	0.864	0.015
210	4	0.855	0.016	53.9	0.9	0.869	0.015
218	4	0.850	0.015	54.4	0.9	0.866	0.015
224	4	0.851	0.015	55.3	1.0	0.864	0.015
240	4	0.839	0.015	57.7	1.0	0.861	0.015
271	5	0.811	0.014	61.3	1.1	0.856	0.015
296	5	0.783	0.014	68.8	1.2	0.818	0.014
346	6	0.725	0.013	82.6	1.4	0.748	0.013
410	8	0.652	0.012	102.9	1.7	0.657	0.011
461	8	0.600	0.010	127	2	0.563	0.010
536	11	0.535	0.011	167	3	0.451	0.008
633	12	0.468	0.009	199	4	0.387	0.007
756	13	0.403	0.007	288	6	0.277	0.006
890	18	0.349	0.007	420	9	0.194	0.004
1000	20	0.314	0.007	607	13	0.136	0.003

Table 10: The Series and Parallel Solar Cells $P - R$ Relation

110.9[cm]				73.6[cm]			
$R[\Omega]$	Uncertainty$[\Omega]$	P[W]	Uncertainty[W]	$R[\Omega]$	Uncertainty$[\Omega]$	P[W]	Uncertainty[W]
12.6	0.2	0.115	0.002	11.3	0.2	0.275	0.005
28.9	0.5	0.241	0.004	13.9	0.2	0.333	0.005
29.2	0.5	0.242	0.004	19.2	0.3	0.444	0.007
38.1	0.6	0.299	0.005	25.1	0.4	0.566	0.009
41.1	0.8	0.321	0.006	31.5	0.5	0.681	0.010
49.8	0.9	0.369	0.007	40.4	0.6	0.827	0.013
57.6	1.0	0.410	0.007	43.0	0.7	0.856	0.013
60.1	1.1	0.421	0.008	45.5	0.7	0.904	0.014
61.4	1.1	0.430	0.008	47.5	0.7	0.917	0.014
68.7	1.2	0.461	0.008	49.1	0.8	0.922	0.015
82.2	1.5	0.489	0.009	50.1	0.8	0.926	0.015
84.9	1.4	0.493	0.008	51.0	0.8	0.929	0.015
92.2	1.7	0.493	0.009	56.0	1.0	0.931	0.016
95.1	1.7	0.493	0.009	66.7	1.2	0.915	0.016
97.3	1.8	0.492	0.009	72.3	1.3	0.907	0.016
99.6	1.8	0.489	0.009	77.8	1.3	0.886	0.015
101.7	1.9	0.490	0.009	83.5	1.4	0.862	0.014
113	2	0.482	0.009	93.3	1.6	0.811	0.014
121	2	0.475	0.008	109.8	1.8	0.728	0.012
133	2	0.460	0.008	125	2	0.659	0.012
155	3	0.427	0.008	144	3	0.589	0.011
171	3	0.403	0.007	153	3	0.560	0.010
190	4	0.378	0.007	186	4	0.474	0.009
261	5	0.298	0.006	252	5	0.361	0.007
407	8	0.204	0.004	386	8	0.243	0.005

Table 11: The $P-R$ Relation of a Single Solar Cell with Different Distances

C Data Sheet

The original data sheet is attached to this report.