UM-SJTU Joint Institute
Physics Laboratory
(Vp241)

Laboratory Report

Exercise 3

SOLAR CELLS: I-V CHARACTERISTICS

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Date: December 2, 2021

1 Introduction

In this lab we study the working principle of solar cells, its features, and its current-voltage (I-V) characteristics.

2 Theoretical Background

Solar cells are devices that can transform solar radiation into electrical energy. They consumes no energy and has no pollution, so they are regarded as clean and promising energy source.

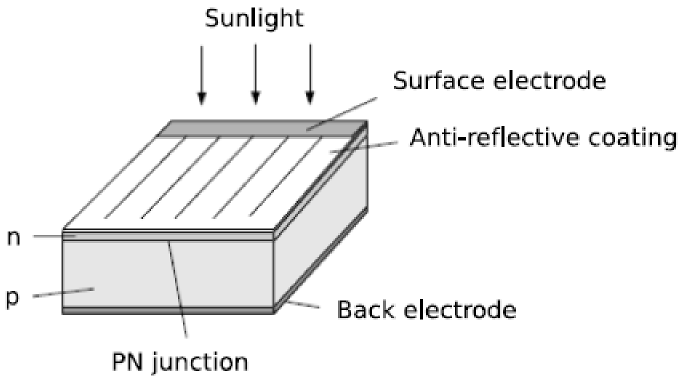

Figure 1: Structure of crystalline solar cell

The figure above shows the structure of a crystalline silicon solar cell.It has n/p homo-junctions, a $10cm \times 10cm$ p–type silicon plate of thickness $500\mu m$, covered with a heavily doped n-type layer with thickness $0.3\mu m$. The metallic bars on the n-type layer is one electrode, and a metallic film at the bottom is another. An anti-reflective film is often applied to reduce the loss of energy reflection.

Photovoltaic Effect describes a process, when the energy of incident photons are absorbed and excite electron-hole pairs. Some charges can diffuse to the region of the p-n junction of a built-in electric field. Then these charges are drawn to either p-type or n-type area, and thus create a photoelectric potential difference.

Solar cells can generate an electric current I_{ph} from the n–type area to the p-area based on this effect:

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

where V_D is the junction voltage, I_0 is the diode inverse saturation current, I_ph is the photocurrent determined by the structure and material characteristics of the solar cell, I_D is a forward diode current current from the p-type to the n-type area, q denotes the electron's charge, k_B is the Boltzmann's constant, and T is the temperature in the absolute (Kelvin) scale.

Now we define the fill factor of solar cells FF. If FF is bigger, it shows that the output power of the solar cell is bigger. This fill factor can be determined by the incident light intensity, the forbidden bandwidth, the value of the theoretical coefficient n, and the series/parallel resistance.

The fill factor FF can be calculated as:

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

We can also define the solar cell energy conversion efficiency η as

$$\eta = \frac{P_m}{P_i n} \times 100\%$$

where P_{in} denotes the total radiant power incident on the solar cell. Now we can plot the current-voltage characteristics of a solar cell:

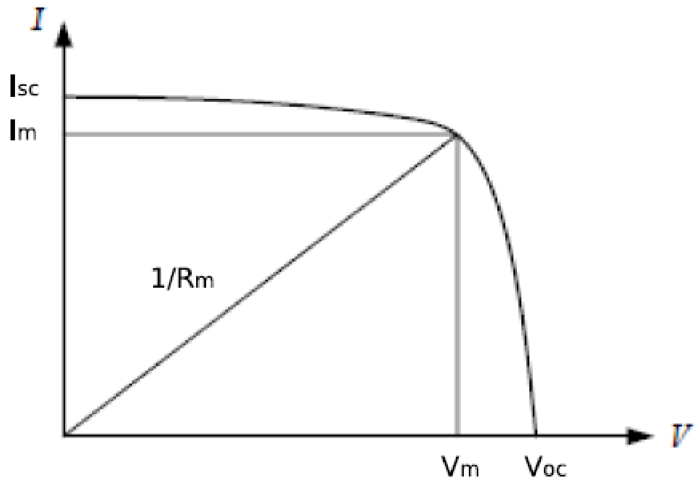

Figure 2: The current-voltage characteristics of a solar cell.

3 Experimental setup and Measurement procedure

3.1 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.

The multimeter precisions are recorded in ”Uncertainty analysis” section.

3.2 Measurement Procedure

3.2.1 I-V characteristics in series/ parallel configuration

In this part we applied two solar power shells. We first adjust the distance of two solar shells to the light source, and make them have almost the same output power. Then we connect the two shells in series and in parallel. We also connect some load resistors into the circuit. We adjust the resistance of the load resistors and measure the open-circuit voltage V_{oc} and short-circuit current I_{sc}, and finally plot these data to get a I-V characteristics curve.

3.2.2 I-V characteristics under different solar power input

In this part, we use only one single solar power shell. We connect a load resistor into the circuit, and measure the open-circuit voltage V_{oc} and short-circuit current I_{sc} under different resistance values. We also change the distance of the shell to the light source to about 80% of orginal, and do exactly the same experiment. Finally we plot two I-V characteristics curves under two different distances.

We also need to measure some other values, such as the size(width and length) of the solar power shell, and the power of light measured at different places of the surface of the solar power shell.

4 Results

The data sheet is attached to the end of this report.

The uncertainty calculation is included in the next part.

4.1 I-V characteristics in series/ parallel configuration

We first measure the solar power input on two solar cells using solar power meter. The measured data are listed below:

	1	2	3	4	5	6
$P_{84cm}[W/m^2]$	366	324	250	246	336	377
$P_{80cm}[W/m^2]$	775	786	669	258	241	218

Table 1: Measurement data for solar power

The measured data taken from my neighbor group might have huge errors. The possible reasons will be discussed in the "Conclusion and discussion" section.

We also measure the I_{sc} and V_{oc} of a single solar power shell, and two power shells in series and in parallel, without adding any extra resistor. The measured raw data is shown below:

	single device at 84 cm	single device at 80 cm	series	parallel
$U_{oc}[V]$	9.89	9.82	19.65	9.83
$I_{sc}[mA]$	76.4	76.5	77.0	150.5

Table 2: Measurement data for U_{oc} and I_{sc}

So that we can determine the relevant values. For two solar power shells connected in series:

$$U_{oc} = 19.65 \pm 0.11V$$
$$I_{sc} = 77.0 \pm 1.3mA$$
$$U_m = 16.15 \pm 0.09V$$
$$I_m = 53.7 \pm 0.9mA$$
$$P_m = 867.3 \pm 15.3mW$$
$$R_m = 301 \pm 5\Omega$$
$$P_{in} = 22.71 \pm 0.02W$$
$$FF = 0.573 \pm 0.014$$
$$\eta = 3.82\% \pm 0.07\%$$

And for two solar powers connected in parallel:

$$U_{oc} = 9.83 \pm 0.06V$$
$$I_{sc} = 150.5 \pm 2.4mA$$
$$U_m = 7.82 \pm 0.05V$$
$$I_m = 116.9 \pm 1.9mA$$
$$P_m = 914.2 \pm 16.0mW$$
$$R_m = 67 \pm 1\Omega$$
$$P_{in} = 22.71 \pm 0.02W$$
$$FF = 0.618 \pm 0.015$$
$$\eta = 4.02\% \pm 0.07\%$$

Then we can plot the scatter relations of I vs. U and P vs. U:

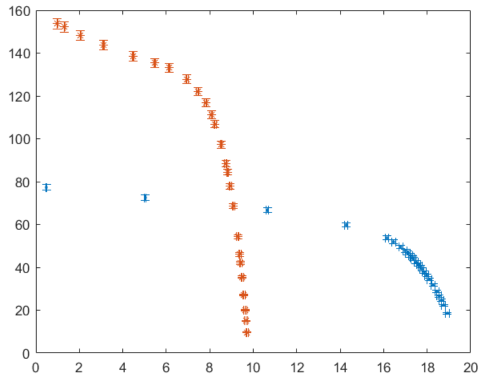

Figure 3: I vs. U (series/parallel)

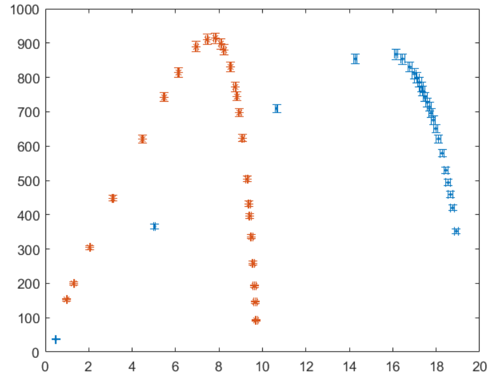

Figure 4: P vs. U (series/parallel)

Note that the red scatters represent for parallel data and blue scatters represent for series data.

The measured and calculated data are listed below:

	series				parallel			
	$U[V]$	$I[mA]$	$P[mW]$	$u_P[mW]$	$U[V]$	$I[mA]$	P[mW]	$u_P[mW]$
1	0.48	77.3	37.1	1.1	9.72	9.6	93.3	2.4
2	5.04	72.5	365.4	6.5	9.67	15.0	145.1	3.3
3	10.65	66.6	709.3	12.4	9.63	19.9	191.6	4.0
4	14.28	59.8	853.9	15.0	9.57	27.1	259.3	5.1
5	16.15	53.7	867.3	15.4	9.50	35.4	336.3	6.3
6	16.45	51.9	853.8	15.2	9.42	42.1	396.6	7.3
7	16.78	49.5	830.6	14.9	9.38	46.0	431.5	7.9
8	16.99	47.7	810.4	14.6	9.29	54.3	504.4	9.0
9	17.11	46.7	799.0	14.4	9.09	68.6	623.6	10.9
10	17.23	45.6	785.7	14.2	8.95	77.9	697.2	12.1
11	17.32	44.6	772.5	14.0	8.82	84.4	744.4	12.9
12	17.37	43.8	760.8	13.8	8.74	88.4	772.6	13.3
13	17.49	42.5	743.3	13.5	8.53	97.3	830.0	14.3
14	17.60	41.3	726.9	13.3	8.24	106.8	880.0	15.1
15	17.68	40.4	714.3	13.1	8.07	111.2	897.4	15.3
16	17.76	39.2	696.2	12.8	7.82	116.9	914.2	15.6
17	17.87	37.8	675.5	12.5	7.45	122.2	910.4	15.5
18	17.98	36.2	650.9	12.1	6.96	127.8	889.5	15.2
19	18.11	34.3	621.2	11.7	6.12	133.1	814.6	13.9
20	18.27	31.7	579.2	11.0	5.48	135.4	742.0	12.7
21	18.45	28.7	529.5	10.2	4.48	138.5	620.5	10.7
22	18.55	26.6	493.4	9.7	3.12	143.7	448.3	7.9
23	18.66	24.6	459.0	9.1	2.05	148.3	304.0	5.6
24	18.75	22.4	420.0	8.5	1.31	152.2	199.4	4.0
25	18.93	18.6	352.1	7.4	0.99	153.8	152.3	3.3

Table 3: Measurement and calculated data for U, I and P (series/parallel)

4.2 I-V characteristics under different solar power input

We first measure the solar power input on one single solar cell of different distance to light source, using solar power meter. The measured data are listed below:

	1	2	3	4	5	6
$P_{84cm}[W/m^2]$	366	324	250	246	336	377
$P_{66cm}[W/m^2]$	494	231	607	430	196	216

Table 4: Measurement data for solar power

So that we can determine the relevant values. For the distance of 84 cm:

$$\begin{aligned} U_{oc} &= 9.89 \pm 0.06V \\ I_{sc} &= 76.4 \pm 1.2mA \\ U_m &= 7.73 \pm 0.05V \\ I_m &= 63.4 \pm 1.1mA \\ P_m &= 490.1 \pm 9.1mW \\ R_m &= 122 \pm 2\Omega \\ P_in &= 17.80 \pm 0.02W \\ FF &= 0.648 \pm 0.016 \\ \eta &= 2.75\% \pm 0.05\% \end{aligned}$$

And for the distance of 66 cm:

$$\begin{aligned} U_{oc} &= 9.82 \pm 0.06V \\ I_{sc} &= 76.5 \pm 1.2mA \\ U_m &= 8.45 \pm 0.05V \\ I_m &= 84.5 \pm 1.4mA \\ P_m &= 714.0 \pm 12.6mW \\ R_m &= 100 \pm 2\Omega \\ P_in &= 20.38 \pm 0.02W \\ FF &= 0.950 \pm 0.023 \\ \eta &= 3.50\% \pm 0.06\% \end{aligned}$$

Then we can plot the scatter relations of I vs. U and P vs. U:

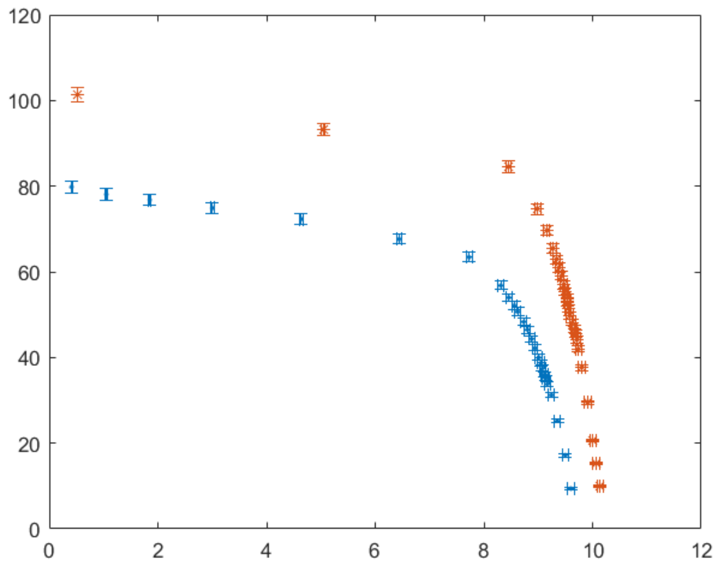

Figure 5: I vs. U (88cm/66cm)

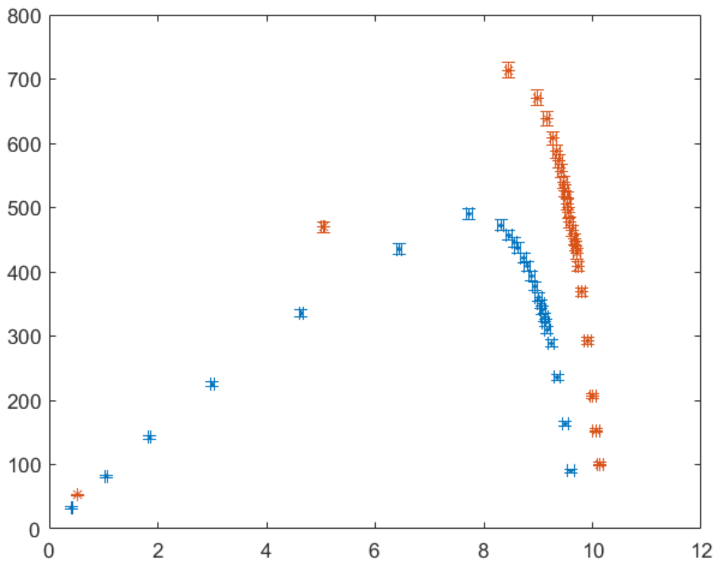

Figure 6: P vs. U (88cm/66cm)

Note that the red scatters represent for 66 cm data and blue scatters represent for 88 cm data.

The measured and calculated data are listed below:

	66cm				84cm			
	$U[V]$	$I[mA]$	P[mW]	$u_P[mW]$	$U[V]$	$I[mA]$	P[mW]	$u_P[mW]$
1	10.14	9.9	100.4	2.6	9.60	9.4	90.2	2.4
2	10.07	15.2	153.1	3.4	9.50	17.2	163.4	3.5
3	10.01	20.6	206.2	4.3	9.35	25.2	235.6	4.7
4	9.91	29.5	292.3	5.7	9.24	31.2	288.3	5.5
5	9.80	37.6	368.5	6.9	9.17	33.8	309.9	5.9
6	9.74	42.0	409.1	7.5	9.14	35.1	320.8	6.1
7	9.71	44.1	428.2	7.8	9.12	36.1	329.2	6.2
8	9.68	45.5	440.4	8.0	9.08	37.5	340.5	6.4
9	9.66	46.7	451.1	8.2	9.05	38.7	350.2	6.5
10	9.63	48.2	464.2	8.4	9.01	40.0	360.4	6.7
11	9.58	49.8	477.1	8.6	8.94	42.2	377.3	6.9
12	9.55	51.5	491.8	8.8	8.88	44.3	393.4	7.2
13	9.54	52.9	504.7	9.1	8.80	46.5	409.2	7.5
14	9.53	54.0	514.6	9.2	8.73	48.3	421.7	7.7
15	9.50	55.3	525.4	9.4	8.62	50.7	437.0	7.9
16	9.47	57.0	539.8	9.6	8.56	52.1	446.0	8.0
17	9.42	59.1	556.7	9.9	8.46	54.0	456.8	8.2
18	9.38	61.0	572.2	10.1	8.31	56.8	472.0	8.4
19	9.34	62.9	587.5	10.4	7.73	63.4	490.1	8.7
20	9.28	65.5	607.8	10.7	6.44	67.6	435.3	7.7
21	9.15	69.7	637.8	11.2	4.64	72.3	335.5	6.0
22	8.99	74.6	670.7	11.7	3.00	74.9	224.7	4.1
23	8.45	84.5	714.0	12.4	1.85	76.8	142.1	2.7
24	5.04	93.2	469.7	8.2	1.05	78.1	82.0	1.8
25	0.52	101.4	52.7	1.5	0.41	79.8	32.7	1.1

Table 5: Measured and calculated data for U, I and P (66 cm/84 cm)

5 Uncertainty analysis

The uncertainty caused by multimeter precision limits are listed below:

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 6: Multimeter precision

So that the uncertainties for raw data can be calculated as:

	series				parallel			
	$U[V]$	$u_U[V]$	$I[mA]$	$u_I[mA]$	$U[V]$	$u_U[V]$	$I[mA]$	$u_I[mA]$
1	0.48	0.01	77.3	1.3	9.72	0.06	9.6	0.2
2	5.04	0.04	72.5	1.2	9.67	0.06	15.0	0.3
3	10.65	0.06	66.6	1.1	9.63	0.06	19.9	0.4
4	14.28	0.08	59.8	1.0	9.57	0.06	27.1	0.5
5	16.15	0.09	53.7	0.9	9.50	0.06	35.4	0.6
6	16.45	0.09	51.9	0.9	9.42	0.06	42.1	0.7
7	16.78	0.09	49.5	0.8	9.38	0.06	46.0	0.8
8	16.99	0.09	47.7	0.8	9.29	0.06	54.3	0.9
9	17.11	0.10	46.7	0.8	9.09	0.06	68.6	1.1
10	17.23	0.10	45.6	0.8	8.95	0.05	77.9	1.3
11	17.32	0.10	44.6	0.8	8.82	0.05	84.4	1.4
12	17.37	0.10	43.8	0.8	8.74	0.05	88.4	1.4
13	17.49	0.10	42.5	0.7	8.53	0.05	97.3	1.6
14	17.60	0.10	41.3	0.7	8.24	0.05	106.8	1.7
15	17.68	0.10	40.4	0.7	8.07	0.05	111.2	1.8
16	17.76	0.10	39.2	0.7	7.82	0.05	116.9	1.9
17	17.87	0.10	37.8	0.7	7.45	0.05	122.2	1.9
18	17.98	0.10	36.2	0.6	6.96	0.04	127.8	2.0
19	18.11	0.10	34.3	0.6	6.12	0.04	133.1	2.1
20	18.27	0.10	31.7	0.6	5.48	0.04	135.4	2.1
21	18.45	0.10	28.7	0.5	4.48	0.03	138.5	2.2
22	18.55	0.10	26.6	0.5	3.12	0.03	143.7	2.3
23	18.66	0.10	24.6	0.5	2.05	0.02	148.3	2.3
24	18.75	0.10	22.4	0.4	1.31	0.02	152.2	2.4
25	18.93	0.10	18.6	0.4	0.99	0.01	153.8	2.4

Table 7: Measurement and uncertainties for U vs. I (series/parallel)

	66cm				84cm			
	$U[V]$	$u_U[V]$	$I[mA]$	$u_I[mA]$	$U[V]$	$u_U[V]$	$I[mA]$	$u_I[mA]$
1	10.14	0.06	9.9	0.2	9.60	0.06	9.4	0.2
2	10.07	0.06	15.2	0.3	9.50	0.06	17.2	0.4
3	10.01	0.06	20.6	0.4	9.35	0.06	25.2	0.5
4	9.91	0.06	29.5	0.5	9.24	0.06	31.2	0.6
5	9.80	0.06	37.6	0.7	9.17	0.06	33.8	0.6
6	9.74	0.06	42.0	0.7	9.14	0.06	35.1	0.6
7	9.71	0.06	44.1	0.8	9.12	0.06	36.1	0.6
8	9.68	0.06	45.5	0.8	9.08	0.06	37.5	0.7
9	9.66	0.06	46.7	0.8	9.05	0.06	38.7	0.7
10	9.63	0.06	48.2	0.8	9.01	0.06	40.0	0.7
11	9.58	0.06	49.8	0.8	8.94	0.05	42.2	0.7
12	9.55	0.06	51.5	0.9	8.88	0.05	44.3	0.8
13	9.54	0.06	52.9	0.9	8.80	0.05	46.5	0.8
14	9.53	0.06	54.0	0.9	8.73	0.05	48.3	0.8
15	9.50	0.06	55.3	0.9	8.62	0.05	50.7	0.9
16	9.47	0.06	57.0	1.0	8.56	0.05	52.1	0.9
17	9.42	0.06	59.1	1.0	8.46	0.05	54.0	0.9
18	9.38	0.06	61.0	1.0	8.31	0.05	56.8	1.0
19	9.34	0.06	62.9	1.0	7.73	0.05	63.4	1.1
20	9.28	0.06	65.5	1.1	6.44	0.04	67.6	1.1
21	9.15	0.06	69.7	1.1	4.64	0.03	72.3	1.2
22	8.99	0.05	74.6	1.2	3.00	0.03	74.9	1.2
23	8.45	0.05	84.5	1.4	1.85	0.02	76.8	1.3
24	5.04	0.04	93.2	1.5	1.05	0.02	78.1	1.3
25	0.52	0.01	101.4	1.6	0.41	0.01	79.8	1.3

Table 8: Measurement and uncertainties for U vs. I (66cm/84cm)

5.1 Uncertainty of Power P

Since we have $P = U \times I$, we can calculate its uncertainty through:

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

When $I = 53.7 \pm 0.9mA$ and $U = 16.15 \pm 0.09V$, the calculation is:

$$P = UI = 53.7 \cdot 16.15 = 867.3mW$$

$$u_P = \sqrt{(53.7 \cdot 0.09)^2 + (16.15 \cdot 0.9)^2} = 15.3mW$$

So that $P = 867.3 \pm 15.3mW$

5.2 Uncertainty of Resistance R

Since we have $R = U/I$, we can calculate the uncertainty through:

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

When $I = 53.7 \pm 0.9mA$ and $U = 16.15 \pm 0.09V$, the calculation is:

$$R = U/I = 16.15/(53.7/1000) = 301\Omega$$
$$u_R = 301 \cdot \sqrt{(0.09/16.15)^2 + (0.9/53.7)^2} = 5\Omega$$

So that $R = 301 \pm 5\Omega$

5.3 Uncertainty of Fill Factor FF

Since we have $FF = P_m/(U_{oc} \cdot I_{sc}) = (U_m \cdot I_m)/(U_{oc} \cdot I_{sc})$, we can calculate the uncertainty through:

$$\begin{aligned} u_{FF} &= \sqrt{(\frac{\partial FF}{\partial P_m} u_{P_m})^2 + (\frac{\partial FF}{\partial U_{oc}} u_{U_{oc}})^2 + (\frac{\partial FF}{\partial I_{sc}} u_{I_{sc}})^2} \\ &= FF \sqrt{(\frac{u_{U_m}}{U_m})^2 + (\frac{u_{I_m}}{I_m})^2 + (\frac{u_{U_{oc}}}{U_{oc}})^2 + (\frac{u_{I_{sc}}}{I_{sc}})^2} \end{aligned}$$

When $U_{oc} = 19.65 \pm 0.11V$, $I_{sc} = 77.0 \pm 1.3mA$, $U_m = 16.15 \pm 0.09V$, $I_m = 53.7 \pm 0.9mA$, the calculation is:

$$\begin{aligned} FF &= \frac{16.15 \cdot 53.7}{19.65 \cdot 77.0} = 0.573 \\ u_{FF} &= 0.573 \cdot \sqrt{(0.09/16.15)^2 + (0.9/53.7)^2 + (0.11/19.65)^2 + (1.3/77.0)^2} \\ &= 0.014 \end{aligned}$$

So that $FF = 0.573 \pm 0.014$

5.4 Uncertainty of Energy Conversion Efficiency η

Since we have $\eta = U_m \cdot I_m/P_{in}$, we can calculate the uncertainty through:

$$\begin{aligned} u_\eta &= \sqrt{(\frac{\partial \eta}{\partial U_m} u_{U_m})^2 + (\frac{\partial \eta}{\partial I_m} u_{I_m})^2 + (\frac{\partial \eta}{\partial P_{in}} u_{P_{in}})^2} \\ &= \eta \sqrt{(\frac{u_{I_m}}{I_m})^2 + (\frac{u_{U_m}}{U_m})^2 + (\frac{u_{P_{in}}}{P_{in}})^2} \end{aligned}$$

When $U_m = 16.15 \pm 0.09V$, $I_m = 53.7 \pm 0.9mA$, $P_{in} = 22.71 \pm 0.02W$, the calculation is:

$$\begin{aligned} \eta &= 16.15 \cdot 53.7/1000/22.71 = 3.82\% \\ u_\eta &= 3.82\% \cdot \sqrt{(0.9/53.7)^2 + (0.09/16.15)^2 + (0.02/22.71)^2} \\ &= 0.07\% \end{aligned}$$

So that $\eta = 3.82\% \pm 0.07\%$

6 Conclusion and discussion

In this lab we explored the I-V characteristics of the solar power cell of different configurations. We did the experiment by connecting two solar power shells of similar output powers in series and in parallel, and by one single solar power shell with two different distance to the light source. We also connect a resistor into the circuit and change its resistance widly, and measure the short-circuit current I_{sc} and the open-circuit voltage V_{oc}. Finally we calculate the maximum output power P_m, the power factor FF, the energy conversion efficiency η, and we plot the graphs of I vs. U and P vs. U to find their relations.

There are a lot of reasons that might cause huge uncertainties. In the first section involving two solar power shells, the light source of two neighbor groups are so close to each other, that the light of one group can easily cover the solar power shell of the neighbor group, and thus greatly affect the experiment data. I also find that the measurement data for solar power recorded from my neighbor group is very weird and varies largely. This is possibly because their light source did not face perpendicularly to the solar power shell, so that the middle of the solar power shell actually gets less light than one of its corner.

In section two involving one single solar power shell, I recorded the data for U_{oc} and I_{sc} wrongly. I should have recorded the data with distance of 66 cm, but I measured them at 80 cm. This made both U_{oc} and I_{sc} smaller than theoretical data, and eventually it made the FF very big. So this unreasonable result is actually caused by measurement mistake.

To inprove the experiment, we can insert a pure black plastic board between groups. This board can not only prevent the light from other groups from dusturbing the solar power shell, but also absorbe extra light and prevent light reflection. It is also better to pull down the curtain and turn off indoor lights, to prevent all extra light sources from disturbing.

Regardless of these two sets of data mentioned above, all other data are quite reasonable, with relatively small errors. We can see than when the light source is closer to the solar power shell, more power are absorbed and thus the power produced is bigger. The four plotted graphs are also quite match with that introduced in lab manual, witch indicates that the experiment is quite successful overal, and the experiment data indicates the theory is correct.

7 References

1. Qin Tian, Cao Jianjun, Yi Hankun, Wu Ziyou, Zhang Yifei, Yao Yuan, Mateusz Krzyzosiak