UM-SJTU Joint Institute
Physics Laboratory
(Vp241)

Laboratory Report

Exercise 4
Polarization of Light

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1 Abstract

In order to understand the solar cell, we did this experiment. We have tested the following cases: one cell at different distances, series cells, and parallel cells. For them, there will be I-U, P-U and P-R curves. We can found that distance and connecting method will have influence on the cell. The ff tested is about 0.637±0.012 and 0.65±0.04. Also, η is about 4.0%±0.3% and 3.2%±0.6%. Through these analysis, we can get the preliminary understanding of solar cell.

2 Introduction

2.1 Motivation

The solar cell is useful at various of fields. In some inland regions, such as GanSu and ShanXi, solar energy is abundant because of long-time sunny days. To use environmental-friendly energy, we should have some basic understanding of the solar cell. Find out its most efficient and effective use method through this experiment may help us fulfill part of the goal.

2.2 Theoretical Background

Solar cells are used to turn solar energy into electic energy that we can use.

2.2.1 Solar Cell Structure

The most common solar cell is crystalline silicon. From Figure1, we can find that there exist n/p homo-junctions, the n-type part is thin while the p-type part is thick and they share the same surface area. There exists some metallic bars to act as electode. An anti-reflective regularly used to help decrease the reflecting loss energy.

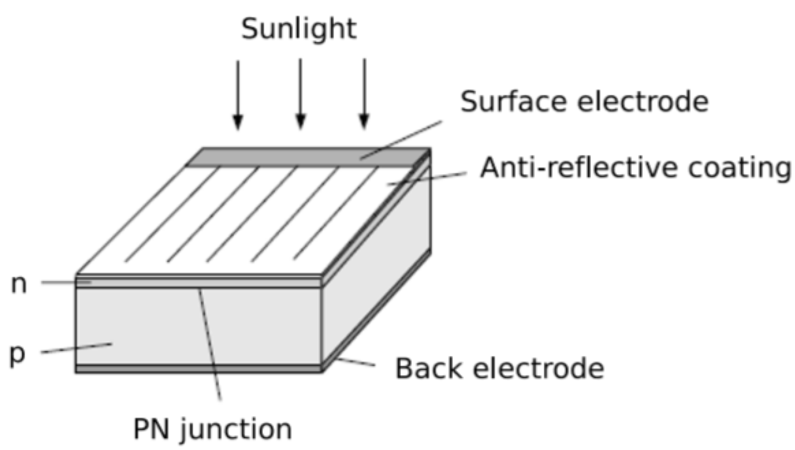

Figure 1: Structure of a crystalline silicon solar cell [1]

2.2.2 Photovoltaic Effect

When the light of appropriate strength incident the solar cell. Certain potential difference will occur because of the diffusion of minority carriers. And the current direction is from n to p.

2.2.3 Solar Cell Parameters

The generated I_{ph} and an opposite current called "forward diode current I_D"[1]. So, the net current can be determined as

$$I = I_{ph} - I_D = I_{ph} - I_0 \left[e^{\frac{qV_D}{nk_B T}} - 1 \right] \quad [1] \tag{1}$$

"V_D is junction voltage, I_0 is the diode inverse saturation current, I_{ph} is the photocurrent."[1] n ranges from 1 to 2,. q is the charge of electron, k_B is the Boltzmann's constant, and T is temperature(K). So, we can rewrite the equation as

$$I = I_{ph} - I_0 \left[e^{\frac{qV}{nk_B T}} - 1 \right] \quad [1]$$

We can deduce that short-circuit current is $I_c = I_{ph}$[1] as well as the open-circuit voltage is

$$V_{oc} = \frac{nk_B T}{q} ln(\frac{I_{sc}}{I_0} + 1) \quad [1]$$

For some load resistance R_m, we can P_m is $P_m = I_m V_m$. Then we can get $FF = \frac{P_m}{V_{oc} I_{sc}} = \frac{V_m I_m}{V_{oc} I_{sc}}$[1]. Also, energy conversion efficiency η is $\eta = \frac{P_m}{P_{in}} \times 100\%$[1]. P_{in} is the "total incident radiant power"[1].

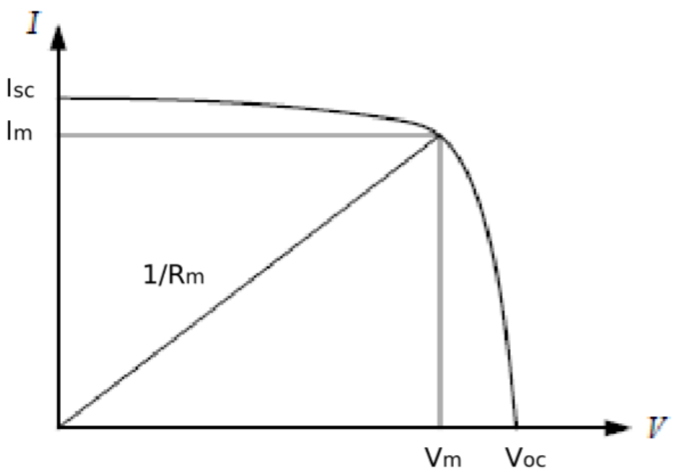

Figure 2: The current-voltage characteristics of a solar cell [1]

Uncertainty of $T^2[s^2]$					
horizontal		incline 1		incline 2	
m_1	0.00002	m_1	0.00002	m_1	0.00002
m_2	0.00003	m_2	0.00003	m_2	0.00003
m_3	0.00003	m_3	0.00003	m_3	0.00003
m_4	0.00003	m_4	0.00003	m_4	0.00003
m_5	0.00003	m_5	0.00003	m_5	0.00003
m_6	0.00003	m_6	0.00003	m_6	0.00003

Table 1: Uncertainty of T^2

2.2.4 Solar Cell Equivalent Circuit

In Fig.3, a solar cell can be thought as a circuit with the current

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

To have higher efficiency, we should have small R_s as well as large R_{sh}.

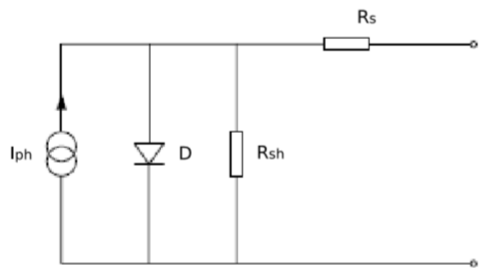

Figure 3: Solar cell equivalent circuit [1]

3 Discription of Experiment

3.1 Apparatus

The setup consists of "a photovoltaic device(5W), a 300W 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."[1]

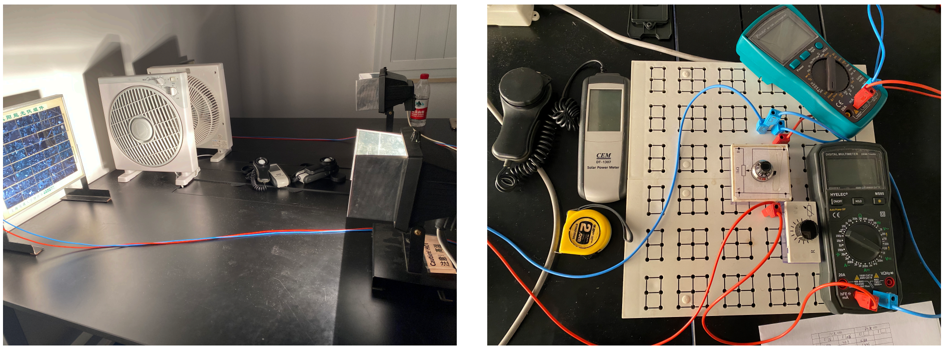

Figure 4: Apparatus

Apparatus	Minimum Scale	Uncertainty
DC Voltage multimeter	0.01V	±0.5%+0.01V
DC Current multimeter	0.1mA	±0.5%+0.1mA
Measuring tape	0.1cm	±0.1cm
Solar power meter	$0.1W/m^2$	$\pm 10W/m^2$

Table 2: Apparatus Information

3.2 Measurement Procedure

First, open light and fan. Measure the surface area of solar cell and the distance between light and the cell. Cooperate with other groups. Make two device of similar I_{sc} and V_{oc}. Directly, put the multimeters on the solar cell to test I_{sc} and V_{oc} for series, parallel and different distances for single apparatus. And meadure P_{in} at several places to get average value. Change the load resistance and get respectively current and voltage. Calculate P and R. Draw corresponding I-V and P-V and P-R plot of series, parallel, and single device of different distances. Finally, get "Isc; Voc; Pm; Im; Vm;Rm, FF, and η"[1].

3.2.1 Caution

While making the experiment, we should not touch the light in the same series of experiment to get constant light intensity.

4 Result

4.1 Multimeter precision

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

Table 3: Multimeter precision

4.2 Measurement of P_{in}

4.2.1 Measurement of area

We have measured the length and width of the cell (black area):

Length[cm]	Width[cm]
25.9±0.1	21.2±0.1

Table 4: Measurement data for area

Then we calculate the surface area of the solar cell:

$$A = ab = 0.259 \times 0.212 = 0.05491 \pm 0.0003m^2$$

4.2.2 Measurement of solar power

We have measure six different place on the solar cell, 100.8cm and 80.6cm respectively from the solar cell:

	1	2	3	4	5	6
$P_{100.8}[W/m^2]$	235	240	232	225	250	263
$P_{80.6}[W/m^2]$	345	358	346	374	712	648

Table 5: Measurement data for solar power

Then we can calculate the average solar power at respectively 100.8cm and 80.6cm:

$$\overline{P_{100.8}} = \frac{235 + 240 + 232 + 225 + 250 + 263}{6} = 241 \pm 14W/m^2$$

$$\overline{P_{80.6}} = \frac{345 + 358 + 346 + 374 + 712 + 648}{6} = 4.60 \pm 1.7 \times 10^2 W/m^2$$

4.2.3 Caculation of Input Power P_{in}

$$P_{in,100.8} = \overline{P_{100.8}} \times A241 \times 0.05491 = 13 \pm 1W$$

$$P_{in,80.6} = \overline{P_{80.6}} \times A = 25 \pm 5W$$

4.3 Measurement of U_{oc} and I_{sc}

	Single device at 100.8cm	Single device at 80.6cm	series	parallel
U_{oc}[V]	10.01	10.43	19.84	9.89
$u_{U_{oc}}$[V]	0.06	0.06	0.11	0.06
I_{sc}[mA]	80.4	118.2	82.6	166.2
$u_{I_{sc}}$[mA]	0.5	0.7	0.5	0.9

Table 6: Measurement data for u_{oc} and I_{sc}

4.4 Measurement of U and I relations of 4 types and their corresponding P and R

By using $P = UI$ and $R = \frac{U}{I}$, we can get the data of following four tables.

U[V]	u_U[V]	I[mA]	u_I[mA]	P[mW]	u_P[mW]	R[kΩ]	u_R[kΩ]
0.660	0.013	82.3	1.3	54.3	1.4	0.0080	0.0002
3.01	0.03	81.0	1.3	244	4	0.0372	0.0007
5.49	0.04	79.3	1.3	435	8	0.0692	0.0012
7.28	0.05	78.2	1.3	569	10	0.0931	0.0016
9.70	0.06	75.0	1.2	728	13	0.129	0.002
9.97	0.06	74.7	1.2	744	13	0.133	0.002
10.93	0.06	73.1	1.2	799	14	0.149	0.003
11.95	0.07	71.4	1.2	853	15	0.167	0.003
12.75	0.07	70.2	1.2	895	16	0.182	0.003
13.66	0.08	67.4	1.1	920	16	0.203	0.004
14.51	0.08	64.4	1.1	934	16	0.225	0.004
15.01	0.09	62.3	1.0	**935**	16	0.241	0.004
15.69	0.09	59.0	1.0	926	16	0.266	0.005
15.92	0.09	57.6	1.0	917	16	0.276	0.005
16.06	0.09	56.5	0.9	908	16	0.284	0.005
16.36	0.09	54.5	0.9	891	16	0.300	0.005
16.74	0.09	51.4	0.9	860	15	0.326	0.006
16.87	0.09	50.1	0.9	845	15	0.337	0.006
17.45	0.10	44.4	0.8	775	14	0.393	0.007
17.93	0.10	38.8	0.7	695	13	0.462	0.009
18.09	0.10	36.4	0.6	659	12	0.497	0.009
18.51	0.10	29.8	0.5	552	11	0.621	0.012
18.94	0.10	21.8	0.4	413	8	0.869	0.018
19.06	0.11	19.2	0.4	366	8	0.99	0.02
19.12	0.11	17.6	0.4	337	7	1.09	0.02

Table 7: Calculation of P and R of series connection

U[V]	u_U[V]	I[mA]	u_I[mA]	P[mW]	u_P[mW]	R[kΩ]	u_R[kΩ]
9.82	0.06	9.0	0.2	88	2	1.09	0.03
9.75	0.06	16.9	0.4	165	4	0.577	0.013
9.68	0.06	24.6	0.5	238	5	0.393	0.008
9.62	0.06	30.3	0.6	291	6	0.317	0.006
9.51	0.06	40.1	0.7	381	7	0.237	0.004
9.37	0.06	51.3	0.9	481	9	0.183	0.003
9.21	0.06	62.4	1.0	575	10	0.148	0.003
9.02	0.06	74.1	1.2	669	12	0.122	0.002
8.83	0.05	83.8	1.4	740	13	0.1054	0.0018
8.76	0.05	87.3	1.4	765	13	0.1003	0.0017
8.72	0.05	88.9	1.4	775	13	0.0981	0.0017
8.67	0.05	91.2	1.5	791	14	0.0951	0.0016
8.39	0.05	102.1	1.6	856	15	0.0821	0.0014
8.01	0.05	113.9	1.8	912	16	0.0703	0.0012
7.50	0.05	125	2	**938**	16	0.0600	0.0010
7.10	0.05	131	2	933	16	0.0541	0.0009
6.91	0.05	134	2	925	16	0.0517	0.0009
6.77	0.04	135	2	917	16	0.0500	0.0009
6.41	0.04	140	2	896	15	0.0459	0.0008
5.64	0.04	146	2	825	14	0.0386	0.0007
4.77	0.03	152	2	723	12	0.0315	0.0005
3.79	0.03	156	2	589	10	0.0244	0.0004
2.93	0.03	159	2	465	8	0.0185	0.0003
2.00	0.02	162	3	324	6	0.0124	0.0002
0.974	0.015	165	3	161	4	0.00589	0.00013

Table 8: Calculation of P and R for parallel connection

U[V]	u_U[V]	I[mA]	u_I[mA]	P[mW]	u_P[mW]	R[kΩ]	u_R[kΩ]
0.402	0.012	79.9	1.3	32.1	1.1	0.00503	0.00017
2.00	0.02	79.1	1.3	159	3	0.0253	0.0005
4.54	0.03	75.2	1.2	342	6	0.0604	0.0011
6.68	0.04	70.5	1.2	471	8	0.0947	0.0017
7.18	0.05	69.3	1.1	498	9	0.1036	0.0018
7.21	0.05	69.1	1.1	498	9	0.1043	0.0018
7.36	0.05	68.2	1.1	502	9	0.1079	0.0019
7.53	0.05	67.3	1.1	507	9	0.112	0.002
7.79	0.05	65.8	1.1	**513**	9	0.118	0.002
7.89	0.05	64.1	1.1	505	9	0.123	0.002
8.02	0.05	62.6	1.0	502	9	0.128	0.002
8.05	0.05	61.5	1.0	495	9	0.131	0.002
8.36	0.05	57.6	1.0	481	9	0.145	0.003
8.60	0.05	53.7	0.9	462	8	0.160	0.003
8.88	0.05	48.3	0.8	429	8	0.184	0.003
9.02	0.06	45.2	0.8	408	7	0.200	0.004
9.15	0.06	41.9	0.7	384	7	0.218	0.004
9.26	0.06	38.8	0.7	359	7	0.239	0.004
9.36	0.06	35.7	0.6	334	6	0.262	0.005
9.50	0.06	30.6	0.6	291	6	0.310	0.006
9.62	0.06	25.6	0.5	246	5	0.376	0.007
9.72	0.06	20.6	0.4	200	4	0.472	0.010
9.82	0.06	15.4	0.3	151	3	0.637	0.014
9.90	0.06	10.8	0.3	107	3	0.92	0.02
9.93	0.06	8.0	0.2	79	2	1.24	0.03

Table 9: Calculation of P and R for single device at 100.8cm

U[V]	u_U[V]	I[mA]	u_I[mA]	P[mW]	u_P[mW]	R[kΩ]	u_R[kΩ]
0.588	0.013	118.6	1.9	69.7	1.9	0.00496	0.00013
3.45	0.03	115.2	1.8	397	7	0.0299	0.0005
4.63	0.03	113.7	1.8	526	9	0.0407	0.0007
5.65	0.04	112.6	1.8	636	11	0.0502	0.0009
6.02	0.04	111.7	1.8	672	12	0.0538	0.0009
7.52	0.05	104.3	1.7	784	13	0.0721	0.0012
7.75	0.05	102.2	1.6	792	14	0.0758	0.0013
7.95	0.05	100.1	1.6	796	14	0.0794	0.0014
8.19	0.05	97.4	1.6	**798**	14	0.0841	0.0014
8.37	0.05	94.6	1.5	792	14	0.0885	0.0015
8.53	0.05	92.4	1.5	788	14	0.0923	0.0016
8.72	0.05	88.4	1.4	771	13	0.0987	0.0017
8.93	0.05	83.9	1.4	749	13	0.1064	0.0018
9.12	0.06	79.3	1.3	724	13	0.115	0.002
9.20	0.06	76.1	1.2	700	12	0.121	0.002
9.36	0.06	70.3	1.2	658	12	0.133	0.002
9.45	0.06	66.6	1.1	629	11	0.142	0.002
9.54	0.06	62.8	1.0	599	11	0.152	0.003
9.63	0.06	58.1	1.0	560	10	0.166	0.003
9.75	0.06	51.7	0.9	504	9	0.189	0.003
9.85	0.06	45.4	0.8	447	8	0.217	0.004
10.01	0.06	33.8	0.6	338	6	0.296	0.006
10.15	0.06	22.0	0.4	223	5	0.461	0.009
10.22	0.06	16.2	0.3	166	4	0.631	0.014
10.28	0.06	9.9	0.2	102	3	1.04	0.03

Table 10: Calculation of P and R for single device at 80.6cm

Then we can plot I-U, P-U, and P-R as follow.

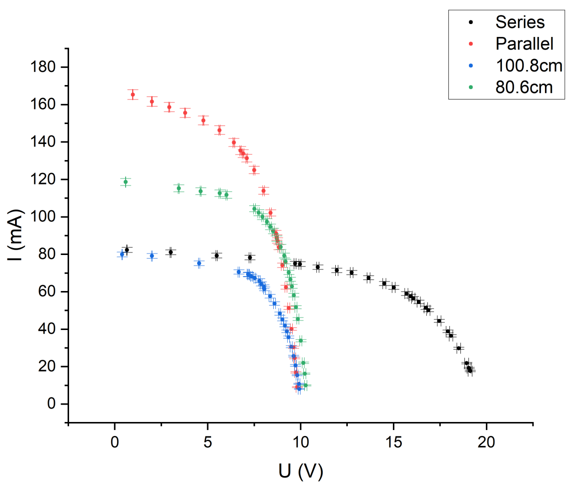

Figure 5: I-V characteristic

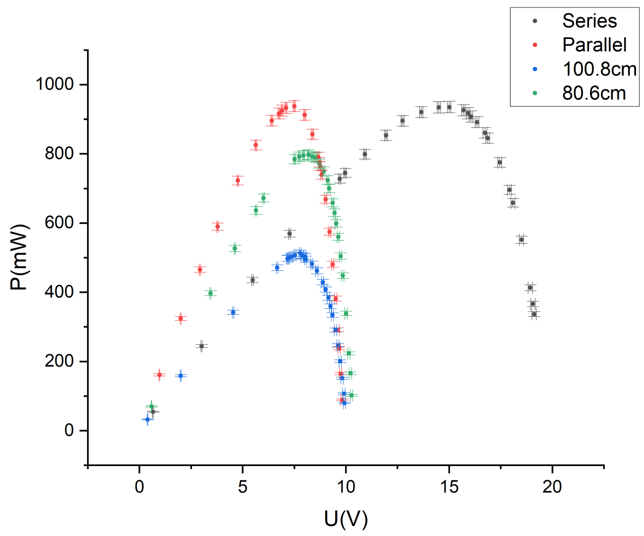

Figure 6: P-U relation

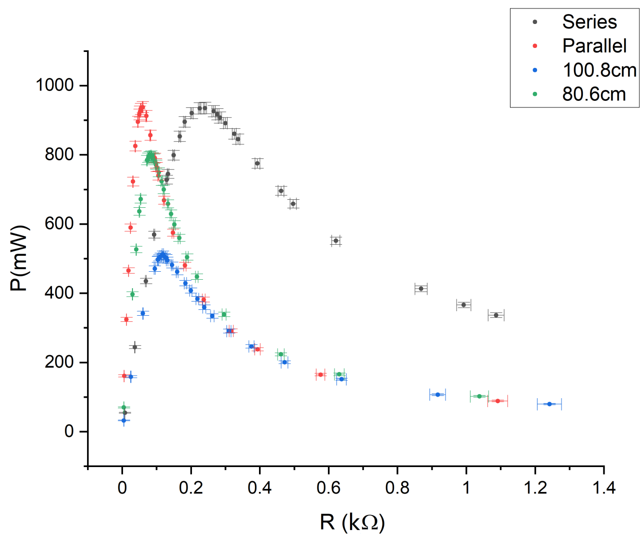

Figure 7: P-R relation

5 Calculation of FF and η

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

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

For a single device at 100.8cm, $P_m = 513 \pm 9mW = 0.513 \pm 0.009W$, $V_{oc} = 10.01 \pm 0.06V$,

$I_{sc} = 80.4 \pm 0.5mA = 0.0804 \pm 0.0005A$

$$FF_{100.8cm} = \frac{P_m}{V_{oc}I_{sc}} = \frac{0.513}{10.01 \times 0.0804} = 0.637 \pm 0.012$$

$$\eta_{100.8cm} = \frac{P_m}{P_{in}} \times 100\% = \frac{0.513}{13} \times 100\% = 4.0\% \pm 0.3\%$$

For a single device at 80.6cm, $P_m = 798 \pm 14mW = 0.798 \pm 0.014W$, $V_{oc} = 10.43 \pm 0.06V$, $I_{sc} = 118.2 \pm 0.7mA = 0.1182 \pm 0.0007A$

$$FF_{80.6cm} = \frac{P_m}{V_{oc}I_{sc}} = \frac{0.798}{10.43 \times 0.1182} = 0.65 \pm 0.04$$

$$\eta_{80.6cm} = \frac{P_m}{P_{in}} \times 100\% = \frac{0.798}{25} \times 100\% = 3.2\% \pm 0.6\%$$

And we can get following table:

	Series	Parallel	100.8cm	80.6cm
Voc[V]	19.84±0.11	9.89±0.06	10.01±0.06	10.43±0.06
Isc[mA]	82.6±0.5	166.2±0.9	80.4±0.5	118.2±0.7
Pm[mW]	935±16	938±16	513±9	798±14
Vm[V]	19.12±0.11	9.82±0.06	9.93±0.06	10.28±0.06
Im[mA]	82.3±1.3	165±3	79.9±1.3	**118.6±1.9**
Rm[kω]	0.241±0.004	0.0600±0.0010	0.118±0.002	0.0841±0.0014
FF	-	-	0.637±0.012	0.65±0.04
eta	-	-	4.0%±0.3%	3.2%±0.6%

Table 11: Experiment Result

6 Conclusions

We have learnt the principle of solar cell and its I-U characteristics. We have did following four series of experiment:

- Two solar cells in series
- Two solar cells in parallel
- One solar cell at the distance 100.8cm from light source
- One solar cell at the distance 80.6cm from light source

Based on the calculated data and figures we plot, we can do some analysis, thus finding the most efficient usage. So, we can better use the solar energy and protect our environment. This is the significance of this experiment.

The solar cells in series and parallel have the same distance as single device at 100.8cm. Through I-U plots and Table.11, we can get the effect of different connections.

- When sharing same voltage, the current through parallel cells doubled then one single cell.

- When sharing same current, the voltage over parallel series doubled than one single cell.
- Parallel cells have similar V_{oc} as one single device.
- Series cells have similar I_{sc} as one single device.
- The P_m of two different connections are almost the same, and they are doubled than single device.
- When we gwt P_m, series cell have doubled voltage while parallel cells have doubled current. R_m of series cells doubles of single cell and is four times of parallel cells.

Also, there exists certain effect of distance.

- When sharing same voltage, the current is connected to distance negatively.
- When sharing same current, the voltage is connected to distance positively.
- When distance increase, both V_{oc} and I_{sc} decrease.
- When distance increase, P_m decreases and R_m increases.
- With distance increase, FF decrease. This is because of smaller incident light.

The error may cause by following reasons.

- In Table.11, we see fourth line have larger currents than the I_{sc} measured previously. This might because of neighboring groups moved their light source, thus changing the light intensity.
- In Table.11, we can find one value of resistor is bigger than $1.1k\Omega$, this may because of the wrongly measured current. Since current then is so small that it will be effected at a large range.
- Sheltering the light source accidentally may also cause errors.
- Light non-uniformly incident on the solar cell, which causes inaccuracy of calculation of P_{in}.
- The inner resistance of multimeters, which causes error in current and voltage.

We can do following to help improve the accuracy

- Find an environment with stable light source.
- Do more set of experiments to make contrasts.

7 Reference

[1] Qin Tian, Feng Yaming, Gu Yichen, Mateusz Krzyzosiak. Physics Laboratory VP241 Exercise 5: RC, RL, and RLC Circuits.

APPENDIX

A Data Sheet