I. THEORETICAL BACKGROUND

1.1 Solar Cell Structure

As an example, the structure of a crystalline silicon solar cell is shown in Figure 1. It consists of n/p homo-junctions, a 10 cm × 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 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.

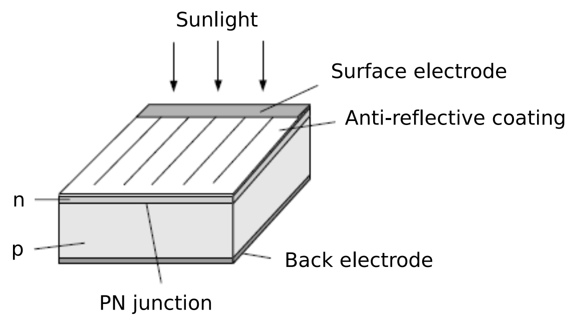

Figure 1. Structure of a crystalline silicon solar cell.

1.2 Photo-voltaic Effect

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 (energy gap) E_g, the incident photons are absorbed and excite electron-hole pairs. 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. This field 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 (in case of the holes), or to the n-type area (in case of the electrons). This results in an increase of positive charge accumulated in the p-type area and negative charge in the n-type area. Consequently, a photoelectric potential difference is generated. The phenomenon described above is known as the *photovoltaic effect*.

1.3 Solar Cell Parameters

Relying on the photo-voltaic effect, solar cells can generate an electric current I_{ph} from the n–type 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, 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 the 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 characterizes the p-n junction. Furthermore, q denotes the electron's charge, k_B is the Boltzmann's constant, and T is the temperature in the absolute (Kelvin) scale. Ignoring the internal series resistance R_s, the voltage V_D equals the terminal voltage V and Eq.(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-circuit current 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 $R = R_m$ the maximum output power P_m is generated, then the value of P_m is

$$P_m = I_m V_m,$$

where I_m is the optimal operating current, and V_m is the optimal operating voltage. Then,

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

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 coefficient n, and the series/parallel resistance. The solar cell energy conversion efficiency η is

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

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

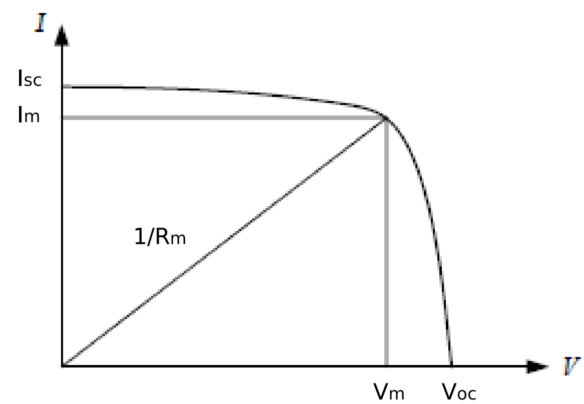

Figure 2. The current-voltage characteristics of a solar cell.

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

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

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

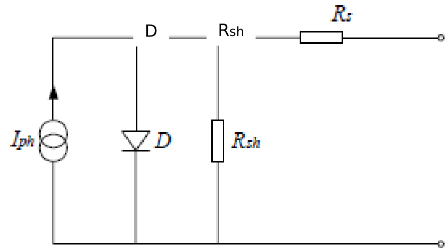

Figure 3. Solar cell equivalent circuit.

II. APPARATUS

The setup consists of a photo-voltaic device (5W), a 300W tungsten–halogen lamp serving as a radiation source, two digital multi-meters, two adjustable resistors, a solar power meter, a wiring board and a measuring tape.

The uncertainty of the DC voltage meter is 0.5%+$10^{-2 \text{or} -3}$ [V], of the DC current meter is 1.5%+$10^{-1 \text{or} -2}$ [mA], of the ruler is 0.1 [cm], of the solar power detector is 10 [W/m^2].

III. PROCEDURES

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. Design a measuring circuit with the photo-voltaic device, multimeters set in an appropriate range, and the resistance. Connect the elements into a circuit using the provided wiring board.
3. Change the resistance, measure the relevant current and voltage to draw the I–V characteristics curve. Keep the distance between the light source and the photo-voltaic device and do not move around the workstation during the measurement, to ensure the same light intensity is maintained during the whole process.
4. Measure the I–V characteristics curves and the values of V_{oc} and I_{sc} under each of the following conditions:
   (a) The distance between the light source and the photovoltaic device is 100 cm; Measure the solar power by the provided solar power meter.
   (b) The distance between the light source and the photo-voltaic device is 120 cm; Measure the solar power by the provided solar power meter.
   (c) The distance between the light source and the photo-voltaic device is 120 cm, with two devices in series.
   (d) The distance between the light source and the photovoltaic device is 120 cm, with two devices in parallel.
5. Plot (use a computer)
   (a) the I–V characteristics curves;
   (b) the graph of the output power vs. the voltage. Determine the values of I_{sc}, V_{oc}, P_m, I_m, V_m, R_m, F F , and η. Compile the data in the form of a table.

IV. RESULTS & UNCERTAINTIES

4.1 I-V Relation

The I-V values can be read directly from the data sheet. Below is the sample calculation for uncertainty

$$u_U = 0.502 \times 0.5\% + 0.001 = 0.004 \text{ [V]}$$

$$u_{r,U} = \frac{u_U}{U} = 0.7\%$$

$$u_I = 104.8 \times 0.5\% + 0.1 = 1.7 \text{ [mA]}$$

$$u_{r,I} = \frac{u_I}{I} = 1.6\%$$

The results with corresponding uncertainties are as followings (Table 1).

Table 1: Results for U and I.

100cm	U[V]	uncertainty		I[mA]	uncertainty	
1	0.502	0.004	0.7%	104.8	1.7	1.6%
2	1.211	0.007	0.6%	103.7	1.7	1.6%
3	2.08	0.02	1.0%	102.3	1.6	1.6%
4	2.96	0.02	0.8%	101.3	1.6	1.6%
5	3.72	0.03	0.8%	99.0	1.6	1.6%
6	4.65	0.03	0.7%	93.9	1.5	1.6%
7	5.36	0.04	0.7%	89.0	1.4	1.6%
8	5.70	0.04	0.7%	84.7	1.4	1.6%
9	6.01	0.04	0.7%	80.5	1.3	1.6%
10	6.32	0.04	0.7%	75.9	1.2	1.6%
11	6.71	0.04	0.6%	69.3	1.1	1.6%
12	7.06	0.05	0.6%	63.1	1.0	1.7%
13	7.40	0.05	0.6%	56.6	0.9	1.7%
14	7.70	0.05	0.6%	49.1	0.8	1.7%
15	7.86	0.05	0.6%	44.6	0.8	1.7%
16	8.01	0.05	0.6%	40.3	0.7	1.7%
17	8.13	0.05	0.6%	36.3	0.6	1.8%
18	8.26	0.05	0.6%	32.0	0.6	1.8%
19	8.39	0.05	0.6%	27.3	0.5	1.9%
20	8.50	0.05	0.6%	23.2	0.4	1.9%
21	8.59	0.05	0.6%	19.4	0.3	1.6%
22	8.70	0.05	0.6%	15.3	0.2	1.6%
23	8.77	0.05	0.6%	11.55	0.18	1.6%
24	8.82	0.05	0.6%	9.45	0.15	1.6%
25	8.86	0.05	0.6%	7.48	0.12	1.6%
OC	9.02			0.00		
SC	0.00			104.9		

120cm	U[V]	uncertainty		I[mA]	uncertainty	
1	0.416	0.003	0.7%	82.7	1.3	1.6%
2	1.571	0.009	0.6%	81.0	1.3	1.6%
3	2.38	0.02	0.9%	79.9	1.3	1.6%
4	3.23	0.03	0.8%	77.1	1.3	1.6%
5	3.78	0.03	0.8%	74.6	1.2	1.6%
6	4.14	0.03	0.7%	72.9	1.2	1.6%
7	4.32	0.03	0.7%	71.6	1.2	1.6%
8	4.54	0.03	0.7%	69.9	1.1	1.6%
9	4.71	0.03	0.7%	68.2	1.1	1.6%
10	4.92	0.03	0.7%	66.1	1.1	1.7%
11	5.14	0.04	0.7%	63.5	1.1	1.7%
12	5.45	0.04	0.7%	60.1	1.0	1.7%
13	5.66	0.04	0.7%	57.6	1.0	1.7%
14	5.80	0.04	0.7%	55.6	0.9	1.7%
15	6.01	0.04	0.7%	52.6	0.9	1.7%
16	6.34	0.04	0.7%	47.8	0.8	1.7%
17	6.78	0.04	0.6%	40.9	0.7	1.7%
18	7.11	0.05	0.6%	34.7	0.6	1.8%
19	7.26	0.05	0.6%	31.6	0.6	1.8%
20	7.44	0.05	0.6%	27.9	0.5	1.9%
21	7.60	0.05	0.6%	24.3	0.4	1.5%
22	7.76	0.05	0.6%	20.5	0.3	1.5%
23	7.94	0.05	0.6%	16.0	0.2	1.6%
24	8.11	0.05	0.6%	11.54	0.18	1.6%
25	8.24	0.05	0.6%	7.60	0.12	1.6%
OC	8.44			0.00		
SC	0.00			82.3		

Series	U[V]	Uncertainty		I[mA]	Uncertainty	
1	0.258	0.002	0.9%	52.3	0.9	1.7%
2	2.41	0.02	0.9%	49.3	0.8	1.7%
3	4.32	0.03	0.7%	46.6	0.8	1.7%
4	6.23	0.04	0.7%	43.5	0.8	1.7%
5	7.14	0.05	0.6%	41.7	0.7	1.7%
6	7.55	0.05	0.6%	41.0	0.7	1.7%
7	8.03	0.05	0.6%	40.0	0.7	1.8%
8	8.37	0.05	0.6%	39.2	0.7	1.8%
9	8.73	0.05	0.6%	38.3	0.7	1.8%
10	9.13	0.06	0.6%	37.5	0.7	1.8%
11	9.55	0.06	0.6%	36.4	0.6	1.8%
12	9.92	0.06	0.6%	35.4	0.6	1.8%
13	10.39	0.06	0.6%	34.2	0.6	1.8%
14	10.82	0.06	0.6%	32.8	0.6	1.8%
15	11.37	0.07	0.6%	30.7	0.6	1.8%

Parallel	U[V]	Uncertainty		I[mA]	Uncertainty	
1	0.638	0.004	0.7%	123.0	1.9	1.6%
2	1.692	0.009	0.6%	119.0	1.9	1.6%
3	2.49	0.02	0.9%	115.5	1.8	1.6%
4	3.09	0.03	0.8%	111.8	1.8	1.6%
5	3.28	0.03	0.8%	110.3	1.8	1.6%
6	3.44	0.03	0.8%	108.7	1.7	1.6%
7	3.65	0.03	0.8%	106.9	1.7	1.6%
8	3.84	0.03	0.8%	104.9	1.7	1.6%
9	4.07	0.03	0.7%	102.9	1.6	1.6%
10	4.24	0.03	0.7%	101.3	1.6	1.6%
11	4.41	0.03	0.7%	99.2	1.6	1.6%
12	4.62	0.03	0.7%	95.9	1.5	1.6%
13	4.83	0.03	0.7%	92.6	1.5	1.6%
14	5.05	0.04	0.7%	88.7	1.4	1.6%
15	5.21	0.04	0.7%	85.7	1.4	1.6%

16	11.95	0.07	0.6%	28.1	0.5	1.9%		16	5.43	0.04	0.7%	81.2	1.3	1.6%
17	12.33	0.07	0.6%	26.3	0.5	1.9%		17	5.69	0.04	0.7%	75.9	1.2	1.6%
18	12.70	0.07	0.6%	23.6	0.5	1.9%		18	5.85	0.04	0.7%	72.2	1.2	1.6%
19	13.09	0.08	0.6%	21.3	0.4	2%		19	6.04	0.04	0.7%	68.0	1.1	1.6%
20	13.42	0.08	0.6%	19.1	0.3	1.6%		20	6.42	0.04	0.7%	58.4	1.0	1.7%
21	13.85	0.08	0.6%	16.3	0.3	1.6%		21	6.77	0.04	0.6%	48.5	0.8	1.7%
22	14.12	0.08	0.6%	14.8	0.2	1.6%		22	7.17	0.05	0.6%	35.4	0.6	1.8%
23	14.52	0.08	0.6%	11.51	0.18	1.6%		23	7.44	0.05	0.6%	26.4	0.5	1.9%
24	14.76	0.08	0.6%	9.54	0.15	1.6%		24	7.67	0.05	0.6%	16.54	0.3	1.6%
25	15.04	0.09	0.6%	6.93	0.11	1.6%		25	7.90	0.05	0.6%	6.66	0.11	1.7%
OC	15.78			0.00				OC	8.01			0.00		
SC	0.00			52.5				SC	0.00			123.1		

Below is the scatter for the I-V relation (Figure 4).

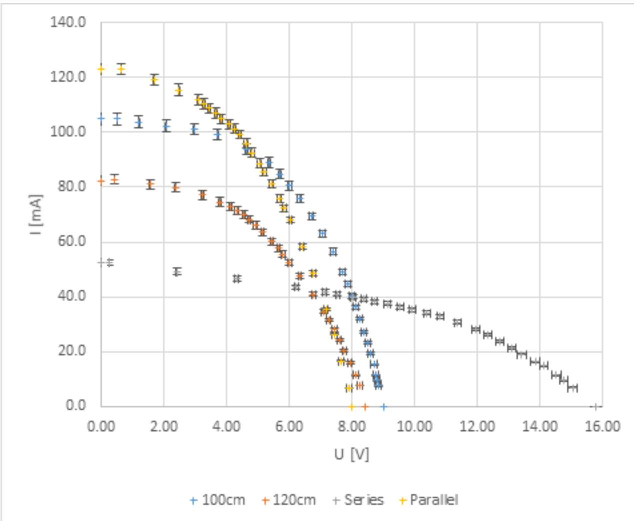

Figure 4: I-V relation.

4.2 P-V Relation

The power P can be calculated as

$$P = UI = 0.502\text{V} \times 104.8\text{mA} = 52.6 \pm 0.9 \text{ [mW]}$$

The uncertainty can be calculated as

$$u_P = \sqrt{\left(\frac{\partial P}{\partial I} \cdot I\right)^2 + \left(\frac{\partial P}{\partial U} \cdot U\right)^2} = 0.9[\text{mW}]$$

$$u_{r,P} = \frac{u_P}{P} = 1.7\%$$

Then the results with corresponding uncertainties can be found in Table 2 (see Part 4.3 “P-R Relation”).

Below is the scatter for the P-V relation (Figure 5).

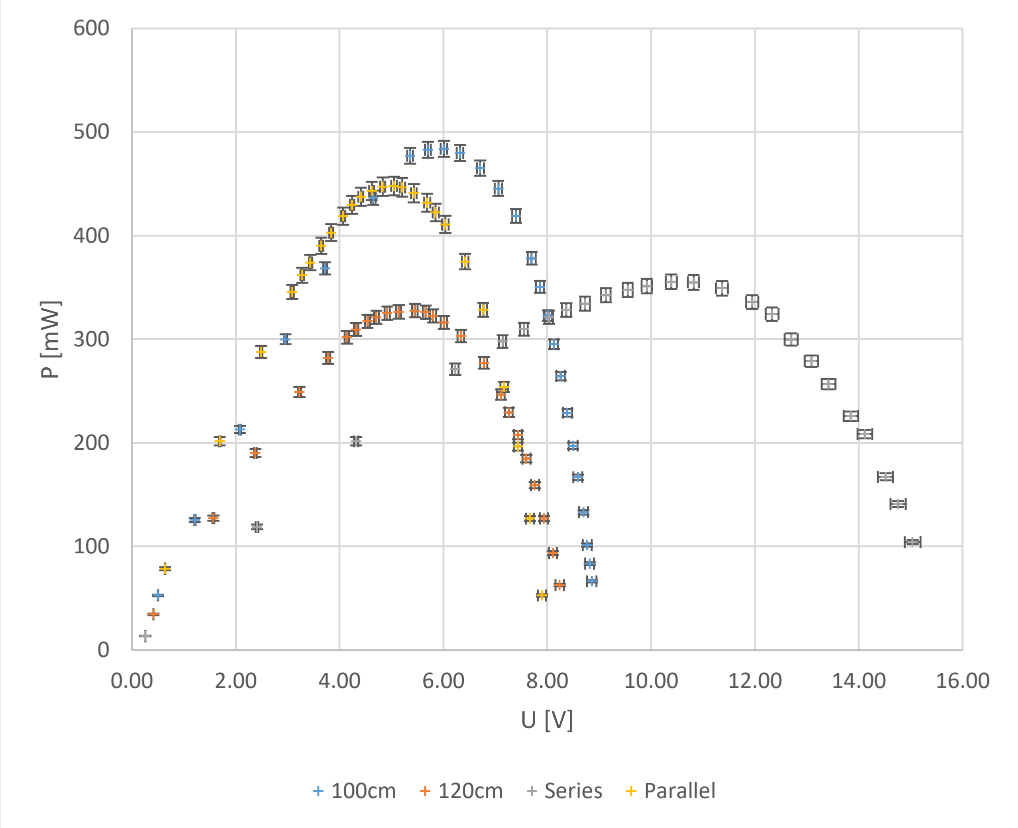

Figure 5: P-V Relation.

4.3 P-R Relation

The power P has already been calculated in Part 4.2 "P-V Relation." The resistance R can be calculated as

$$R = \frac{U}{I} = \frac{0.502V}{104.8mA} = 4.79 \pm 0.08\ [\Omega]$$

The uncertainty can be calculated as

$$u_R = \sqrt{\left(\frac{\partial R}{\partial I} \cdot I\right)^2 + \left(\frac{\partial R}{\partial U} \cdot U\right)^2} = 0.08[\Omega]$$

$$u_{r,R} = \frac{u_R}{R} = 1.7\%$$

Then the results with corresponding uncertainties can be found in Table 2.

Table 2: The results for P and R.

100cm	P[mW]	Uncertainty		R[Ω]	Uncertainty			120cm	P[mW]	Uncertainty		R[Ω]	Uncertainty	
1	52.6	0.9	1.7%	4.79	0.08	1.7%		1	34.4	0.6	1.8%	5.03	0.09	1.8%
2	126	2	1.7%	11.7	0.2	1.7%		2	127	2	1.7%	19.4	0.3	1.7%
3	213	4	1.9%	20.3	0.4	1.9%		3	190	4	1.9%	29.8	0.6	1.9%
4	300	5	1.8%	29.2	0.5	1.8%		4	249	5	1.8%	41.9	0.8	1.8%
5	368	7	1.8%	37.6	0.7	1.8%		5	282	5	1.8%	50.7	0.9	1.8%
6	437	8	1.8%	49.5	0.9	1.8%		6	302	5	1.8%	56.8	1.0	1.8%
7	477	8	1.8%	60.2	1.1	1.8%		7	309	6	1.8%	60.3	1.1	1.8%
8	483	8	1.8%	67.3	1.2	1.8%		8	317	6	1.8%	64.9	1.2	1.8%
9	484	8	1.8%	74.7	1.3	1.8%		9	321	6	1.8%	69.1	1.2	1.8%
10	480	8	1.8%	83.3	1.5	1.8%		10	325	6	1.8%	74.4	1.3	1.8%
11	465	8	1.8%	96.8	1.7	1.8%		11	326	6	1.8%	80.9	1.5	1.8%

12	445	8	1.8%	112	2	1.8%		12	328	6	1.8%	90.7	1.6	1.8%
13	419	8	1.8%	131	2	1.8%		13	326	6	1.8%	98.3	1.8	1.8%
14	378	7	1.8%	157	3	1.8%		14	322	6	1.8%	104.3	1.9	1.8%
15	351	6	1.8%	176	3	1.8%		15	316	6	1.8%	114	2	1.8%
16	323	6	1.9%	199	4	1.9%		16	303	6	1.8%	133	2	1.8%
17	295	6	1.9%	224	4	1.9%		17	277	5	1.9%	166	3	1.9%
18	264	5	1.9%	258	5	1.9%		18	247	5	1.9%	205	4	1.9%
19	229	5	2.0%	307	6	2.0%		19	229	4	1.9%	230	4	1.9%
20	197	4	2.0%	366	7	2.0%		20	208	4	2.0%	267	5	2.0%
21	167	3	1.7%	443	7	1.7%		21	185	3	1.7%	313	5	1.7%
22	133	2	1.7%	569	10	1.7%		22	159	3	1.7%	379	6	1.7%
23	101.3	1.7	1.7%	759	13	1.7%		23	127	2	1.7%	497	8	1.7%
24	83.3	1.4	1.7%	933	16	1.7%		24	93.6	1.6	1.7%	703	12	1.7%
25	66.3	1.2	1.7%	1184	21	1.7%		25	62.6	1.1	1.7%	1084	19	1.7%

Series	P[mW]	uncertainty		R[Ω]	uncertainty			Parallel	P[mW]	uncertainty		R[Ω]	uncertainty	
1	13.5	0.3	1.9%	4.93	0.09	1.9%		1	78.5	1.3	1.7%	5.19	0.09	1.7%
2	119	2	1.9%	48.9	0.9	1.9%		2	201	3	1.7%	14.2	0.2	1.7%
3	201	4	1.9%	92.7	1.7	1.9%		3	288	5	1.8%	21.6	0.4	1.8%
4	271	5	1.9%	143	3	1.9%		4	345	6	1.8%	27.6	0.5	1.8%
5	298	6	1.9%	171	3	1.9%		5	362	6	1.8%	29.7	0.5	1.8%
6	310	6	1.9%	184	3	1.9%		6	374	7	1.8%	31.6	0.6	1.8%
7	321	6	1.9%	201	4	1.9%		7	390	7	1.8%	34.1	0.6	1.8%
8	328	6	1.9%	214	4	1.9%		8	403	7	1.8%	36.6	0.6	1.8%
9	334	6	1.9%	228	4	1.9%		9	419	7	1.8%	39.6	0.7	1.8%
10	342	6	1.9%	243	5	1.9%		10	430	8	1.8%	41.9	0.7	1.8%
11	348	7	1.9%	262	5	1.9%		11	437	8	1.8%	44.5	0.8	1.8%
12	351	7	1.9%	280	5	1.9%		12	443	8	1.8%	48.2	0.8	1.8%
13	355	7	1.9%	304	6	1.9%		13	447	8	1.8%	52.2	0.9	1.8%
14	355	7	1.9%	330	6	1.9%		14	448	8	1.8%	57	1	1.8%
15	349	7	1.9%	370	7	1.9%		15	446	8	1.8%	61	1	1.8%
16	336	7	1.9%	425	8	1.9%		16	441	8	1.8%	67	1	1.8%
17	324	6	2.0%	469	9	2.0%		17	432	8	1.8%	75	1	1.8%
18	300	6	2.0%	538	11	2.0%		18	422	7	1.8%	81	1	1.8%
19	279	6	2.1%	615	13	2.1%		19	411	7	1.8%	89	2	1.8%
20	257	4	1.7%	702	12	1.7%		20	375	7	1.8%	110	2	1.8%
21	226	4	1.7%	850	14	1.7%		21	328	6	1.8%	140	3	1.8%
22	208	3	1.7%	957	16	1.7%		22	254	5	1.9%	203	4	1.9%
23	167	3	1.7%	1262	21	1.7%		23	196	4	2.0%	282	6	2.0%
24	141	2	1.7%	1547	26	1.7%		24	127	2	1.7%	464	8	1.7%
25	104.2	1.8	1.7%	2170	38	1.7%		25	52.6	0.9	1.8%	1186	21	1.8%

Below is the scatter for the P-R relation (Figure 6).

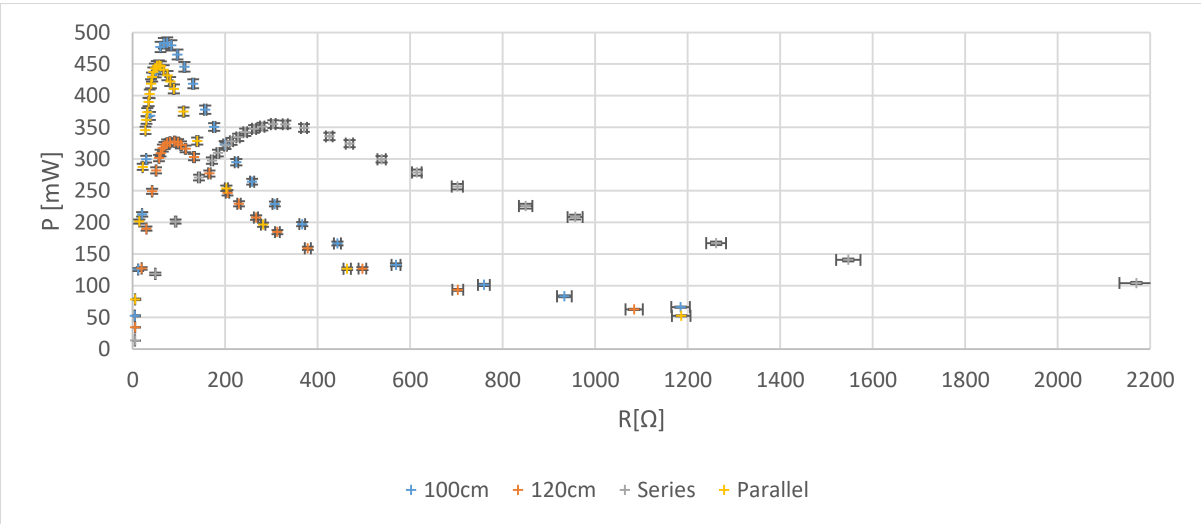

Figure 6: P-R Relation

4.4 Data Tables

The solar power measured by the meter can be calculated[1]:

$$P_{100} = \frac{465 + 380 + 318 + 313 + 480}{5} = (3.9 \pm 0.9) \times 10^2[\mathrm{W/m^2}]$$

$$P_{120} = \frac{388 + 346 + 253 + 236 + 330}{5} = (3.1 \pm 0.8) \times 10^2[\mathrm{W/m^2}]$$

The area of the solar cell can be calculated:

$$\mathrm{A} = \mathrm{Length} \times \mathrm{Width} = 26.00 \times 21.00 = 0.0546 \pm 0.0005\ [\mathrm{m^2}]$$

$$u_A = \sqrt{(\frac{\partial A}{\partial L} \cdot L)^2 + (\frac{\partial A}{\partial W} \cdot W)^2} = 0.0005[\Omega]$$

$$u_{r,A} = \frac{u_A}{A} = 0.9\%$$

FF can be calculated as followings:

$$\mathrm{FF} = \frac{P_m}{V_{OC} I_{SC}} = \frac{484\mathrm{mW}}{9.02\mathrm{V} \times 104.9\mathrm{mA}} = 0.5115 \pm 0.0002$$

$$u_{FF} = \sqrt{(\frac{\partial FF}{\partial V_{OC}} \cdot V_{OC})^2 + (\frac{\partial FF}{\partial I_{SC}} \cdot I_{SC})^2} = 0.0002$$

$$u_{r,FF} = \frac{u_{FF}}{FF} = 0.04\%$$

η can be found as followings:

$$\eta = \frac{P_m}{P_{in}} = \frac{P_m}{P_{100} \cdot A} = \frac{484\mathrm{mW}}{390\mathrm{W/m^2} \times 0.0546\mathrm{m^2}} = 2.3\%$$

$$u_\eta = \sqrt{(\frac{\partial \eta}{\partial A} \cdot A)^2 + (\frac{\partial \eta}{\partial P_{100}} \cdot P_{100})^2} = 0.4\%$$

$$u_{r,\eta} = \frac{u_\eta}{\eta} = 17\%$$

Based on the calculations in Parts 4.1~4.3, the following table (Table 3) can be got[2].

Table 3: The table for the required data.

	U_{OC} [V]	I_{SC} [mA]	P_m [mW]	U_m [V]	I_m [mA]	R_m [Ω]	FF	η
100cm	9.02	104.9	484	6.01	80.5	74.7	0.5115±0.0002	2.3±0.4%
120cm	8.44	82.3	328	5.45	60.1	90.7	0.4722±0.0002	1.9±0.4%
Series	15.78	52.5	355	10.39	34.2	304	N/A	
Parallel	8.01	123.1	448	5.05	88.7	57		

V. CONCLUSIONS & DISCUSSIONS

[1] The uncertainties are directly given by Excel.

[2] The uncertainties that are not listed here can be found in Tables 1 and 2 in Parts 4.1 and 4.3.

In this lab, we got familiar with the working principle of a solar cell and we also studied its current–voltage (I–V) characteristics.

The results we got in this experiment are generally quite satisfying, except that in the parallel-cell experiment, we got an initial current greater than the short-circuit current, which is theoretically impossible. We suggest that this may be resulted from the lack of waiting time for the meter to get steady value; this may also be resulted from the uncertainty of the measuring tools.

The inaccuracies in this experiment may also come from: i) the inner resistance; ii) the error due to the limited waiting time for a meter to maintain at a very steady value; iii) the error due to naked-eye observation on the ruler; iv) the inaccuracy of the meters.

In addition, I have the following suggestions and ideas:

- To avoid the effect of the reflecting lights from students, students should not wear anything glittering. It would be better if they could wear dark, non-reflecting stuff. Meanwhile, they should try to remain at a place that will not block nor reflect any light.
- The experiment can also be influenced by the voltage supplied by the State Grid (国家电网), as the voltage can be varying and is not always 220V (then the lightness can be changed as well). Therefore, it would be better if the SJTU Lab could establish their own power supply.
- We can use some special (large-scaled) optical benches for this experiment. In this way, the light source can be fixed and moved with ease. We can also easily read the distance between the light source and the solar cell directly from the optical bench.
- The efficiency of a solar cell is really low. Therefore, the method of generating power through solar cells are not suitable for the regions where there are lots of rains and clouds.