UM-SJTU Joint Institute

Physics Laboratory

(Vp241)

Laboratory Report

Exercise 3
Solar Cells:
I-V Characteristics

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1. Objective

The objective of this lab is to learn the working principle of solar cell and study its current-voltage characteristics.

2. Theoretical Background

Solar cells can transform solar radiations into electrical energy directly. Their advantages include no consumption of energy, silent operation, no moving parts and a long life time. They are also easy to maintain and do not cause air pollution. Hence, solar cells are regarded as a promising energy source in the 21st century. It is estimated that by the mid-21st century, 15-20% of the total electrical energy generated in the world will be produced by solar cells. Solar cells will become one of the leading energy sources in the near future.

2.1 Solar Cell Structure

Shown in Figure 1 is the structure of a crystalline silicon solar cell. It consists of n/p homo-junctions, a 10cm$\times$ 10cm p-type silicon plate of thickness 500μm, 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. To reduce energy loss due to reflection, an anti-reflective film is often applied to cover the surface exposed to sunlight.

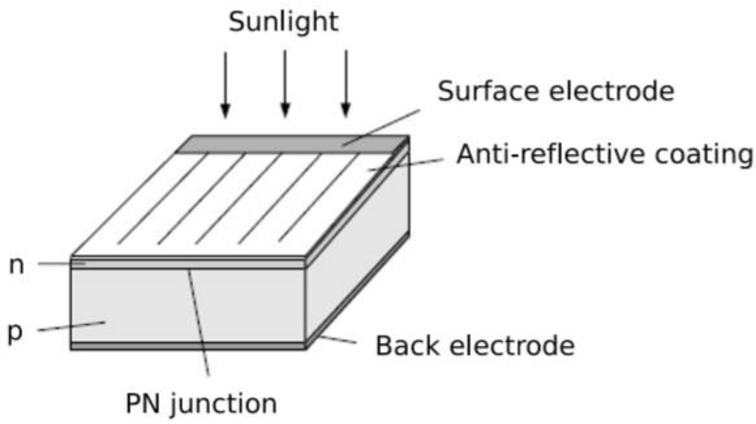

Figure 1 Structure of a crystalline silicon solar cell

2.2 Photovoltaic Effect

When the light enters the p-n junction near the solar cell surface, and the energy of incident photons is larger than the forbidden bandwidth(energy gap) Eg, the incident photons are absorbed and electron-hole pairs are excited. Minority charge carriers in the n- or p-type area diffuse due to their density gradient. Some of them can diffuse to the p-n junction where a built-in electric field which is directed from n to p exists. The diffused minority carriers are drown by this electric field, with holes to the p-type area and electrons to the n-type area. Therefore, an increase of positive charge will accumulate in the p-type area and negative charge in the n-type area. In this way, a photoelectric potential difference is generated. The phenomenon is known as the photovoltaic effect.

2.3 Solar Cell Parameters

Due to photovoltaic effect solar cell 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. In the device there is a forward diode current I_D from the p-type area to the n-type area, which is opposite to I_{ph}. Hence, the net current is

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

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 value ranging from 1 to 2, that characterizes the p-n junction. Furthermore, q denoted the electron's charge, kB 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

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

When the output is short, i.e. V=0, the short-circuit current is $I_c = I_{ph}$
Whereas when the output is open, i.e. I=0, the open-circuit voltage is

$$V_{oc} = \frac{nk_BT}{q} \ln \left(\frac{I_{sc}}{I_0} + 1\right)$$

When there is a load resistance R(the value of R ranging from zero to infinity), then 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 $P_m = I_m V_m$, where I_m is the optimal operating current, and V_m is the optimal operating voltage. Then, FF=$\frac{P_m}{V_{oc}I_{sc}} = \frac{V_m I_m}{V_{oc}I_{sc}}$. 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 defined as $\eta = \frac{P_m}{P_{in}} \times 100\%$.

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

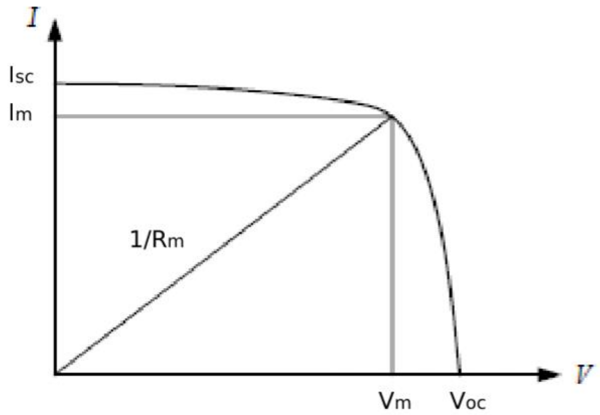

Figure 2 The current-voltage characteristics of a solar cell

2.4 Solar Cell Equivalent Circuit

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 Rs due to the electrodes in the solar cell and a parallel resistance Rsh, 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

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

In order to provide a greater output power, the value of Rs should be decreased, while Rsh should increase.

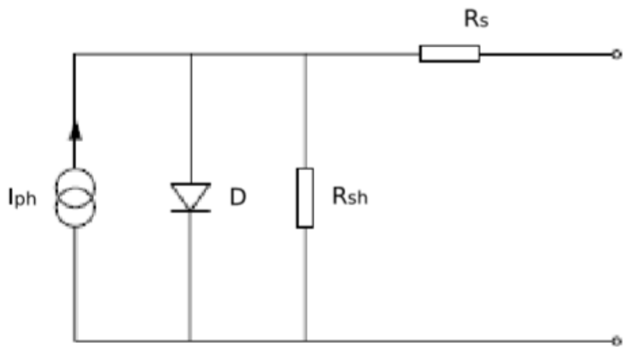

Figure 3 Solar cell equivalent circuit

3. Experimental Setup

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.

3.2 Device Information

The information of each measurement device is shown in Table 2.

apparatus	range	Minimum scale of value	Maximum uncertainty
DC voltage multimeter	/	0.01V	$\pm 0.5\% + 0.01\mathrm{V}$
DC current multimeter	/	0.1mA	$\pm 1.5\% + 0.1\mathrm{mA}$
Measuring tape	/	0.1cm	$\pm 0.1\mathrm{cm}$
Solar power meter	/	$0.1\mathrm{W}/m^2$	$\pm 10\mathrm{W}/m^2$

Table 1 Information of Each Measurement Device

4. Measurement Procedure

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 photovoltaic device, multimeters set in an appropriate range, and the resistance. Connect the elements into a circuit using the provided wiring board.
3. Work in pairs. Adjust the distance between the light source and the photovoltaic device until the V_{oc} and I_{sc} of the two devices are about the same. Measure the solar power by the provided solar power meter.

In order to collect the data to draw the I-V characteristics curve, change the resistance and measure the relevant current and voltage. Keep the distance between the light source and the photovoltaic device and do not move around the workstation during the measurement, to ensure the same light intensity is maintained during the whole process.

Measure the I-V characteristics curves and the values of V_{oc} and I_{sc} under each of the following conditions:

(a) Two devices in series;

(b) Two devices in parallel;

(c) A single device

4. Change the distance between the light source and the photovoltaic device and measure the I-V characteristics curves and the values of V_{oc} and I_{sc} in a single-device configuration. The new distance should be about 80% or 120% of the original one. Measure the solar power at this distance.
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, FF, and η. Compile the data in the form of a table.

5. Results

5.1 Multimeter precision

QUANTITY	PRECISION
DC voltage	$\pm(0.5\% + 0.01)\mathrm{V}$
DC current	$\pm(1.5\% + 0.1)\mathrm{mA}$
Distance	$\pm 0.1\mathrm{cm}$
Solar power	$\pm 10\mathrm{W}/m^2$

Table 2 Multimeter precision

5.2 Measurement of P_{in}

5.2.1 Measurement of area

We measure the length and width of the black area of the cell:

Length[cm]	Width[cm]
26.0	21.0

Table 3 Measurement data for area

Then we calculate the surface area of the solar cell:

$$A = ab = 0.26 \times 0.21 = 0.0546 \pm 0.0003m^2$$

5.2.2 Measurement of solar power

We measure the solar power of six different area of the solar cell with the distance 120cm and 140cm respectively:

	1	2	3	4	5	6
$P_{120}[\mathrm{W}/m^2]$	199.3	165.7	183.3	185.1	162.0	176.0
$P_{140}[\mathrm{W}/m^2]$	166.9	147.8	165.7	143.5	153.4	147.2

Table 4 Measurement data for solar power

Then we calculate the average solar power of the solar cell at 120cm and 140cm:

$$\overline{P_{120}} = \frac{199.3 + 165.7 + 183.3 + 185.1 + 162.0 + 176.0}{6} = 178.6 \pm 18.5\mathrm{W/m^2}$$

$$\overline{P_{140}} = \frac{166.9 + 147.8 + 165.7 + 143.5 + 153.4 + 147.2}{6} = 154.1 \pm 15.1\mathrm{W/m^2}$$

5.2.3 Calculation of input power P_{in}

$$P_{in,120} = \overline{P_{120}} \times A = 178.6 \times 0.0546 = 9.75 \pm 1W$$

$$P_{in,140} = \overline{P_{140}} \times A = 154.1 \times 0.0546 = 8.41 \pm 0.8W$$

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

	Single device at 120cm	Single device at 140cm	series	parallel
U_{oc}[V]	7.93	7.68	15.93	7.96
$I_{sc}[mA]$	54.4	48.1	55.1	108.0

Table 5 Measurement data for Uoc and Isc

The uncertainty of these values will be shown in Table 14.

5.4 Measurement of U and I relations of 4 types

We measure U and I of the series connection, parallel connection, a single device at 120cm, and a single device of 140cm, and record them in Table 6,7,8,9.

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$
1	0.06	0.01	55.5	0.9
2	1.43	0.02	53.9	0.9
3	2.22	0.02	52.9	0.9
4	4.20	0.03	50.3	0.9
5	6.16	0.04	47.1	0.8
6	7.90	0.05	43.7	0.8
7	9.43	0.06	39.5	0.7
8	10.42	0.06	36.2	0.6
9	10.99	0.06	33.9	0.6
10	11.45	0.07	31.0	0.6
11	11.79	0.07	30.2	0.6
12	12.22	0.07	28.0	0.5
13	12.55	0.07	26.2	0.5
14	12.86	0.07	24.5	0.5
15	13.12	0.08	22.9	0.4
16	13.27	0.08	22.0	0.4
17	13.40	0.08	21.1	0.4
18	13.65	0.08	19.4	0.4
19	13.90	0.08	17.6	0.4
20	14.06	0.08	16.4	0.3
21	14.22	0.08	15.1	0.3
22	14.30	0.08	14.6	0.3
23	14.18	0.08	15.5	0.3
24	14.09	0.08	16.1	0.3
25	13.98	0.08	17.0	0.4
oc	15.93	0.09	0	0
sc	0	0	55.1	0.9

Table 6 Measurement data for U and I relation of series connection

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$
1	0.12	0.01	106.7	1.7
2	1.40	0.02	100.6	1.6
3	2.58	0.02	94.3	1.5
4	3.48	0.03	87.7	1.4
5	4.31	0.03	79.8	1.3
6	5.06	0.04	70.2	1.2
7	5.65	0.04	60.8	1.0
8	5.98	0.04	54.5	0.9
9	6.30	0.04	47.5	0.8
10	6.47	0.04	43.5	0.8
11	6.65	0.04	39.3	0.7
12	6.77	0.04	36.2	0.6
13	6.58	0.04	40.3	0.7
14	6.64	0.04	39.4	0.7
15	6.71	0.04	37.6	0.7
16	6.83	0.04	34.7	0.6
17	6.94	0.04	31.6	0.6
18	7.02	0.04	29.4	0.5
19	7.11	0.05	27.1	0.5
20	7.17	0.05	25.7	0.5
21	7.25	0.05	23.1	0.4
22	7.31	0.05	21.3	0.4
23	7.37	0.05	19.7	0.4
24	7.40	0.05	18.7	0.4
25	7.46	0.05	16.9	0.4
oc	7.96	0.05	0	0
sc	0	0	108.0	1.7

Table 7 Measurement data for U and I relation for parallel connection

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$
1	0.01	0.01	57.2	1.0
2	0.40	0.01	56.5	0.9
3	1.12	0.02	55.0	0.9
4	2.06	0.02	53.0	0.9
5	2.51	0.02	51.7	0.9
6	3.04	0.03	49.4	0.8
7	3.77	0.03	46.4	0.8
8	3.81	0.03	46.7	0.8
9	4.70	0.03	42.0	0.7
10	5.08	0.04	39.2	0.7
11	5.56	0.04	35.2	0.6
12	5.96	0.04	31.7	0.6
13	6.26	0.04	28.5	0.5
14	6.56	0.04	24.9	0.5
15	6.72	0.04	22.7	0.4
16	6.93	0.04	20.0	0.4
17	7.08	0.05	17.7	0.4
18	7.20	0.05	15.9	0.3
19	7.41	0.05	12.6	0.3
20	7.51	0.05	10.9	0.3
21	7.57	0.05	9.8	0.2
22	7.65	0.05	8.4	0.2
23	7.68	0.05	7.8	0.2
24	7.70	0.05	7.4	0.2
25	7.76	0.05	0.0	0.1
oc	7.93	0.05	0	0
sc	0	0	54.4	0.9

Table 8 Measurement data for U and I relation for single device at 120cm

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$
1	0.01	0.01	48.4	0.8
2	0.83	0.01	46.9	0.8
3	1.65	0.02	45.1	0.8
4	2.61	0.02	42.7	0.7
5	3.64	0.03	38.9	0.7
6	4.28	0.03	36.0	0.6
7	4.63	0.03	34.2	0.6
8	5.10	0.04	31.0	0.6
9	5.63	0.04	26.7	0.5
10	6.04	0.04	22.8	0.4
11	6.23	0.04	20.8	0.4
12	6.39	0.04	19.0	0.4
13	6.52	0.04	17.4	0.4
14	6.62	0.04	16.1	0.3
15	6.73	0.04	14.8	0.3
16	6.79	0.04	14.0	0.3
17	6.86	0.04	13.0	0.3
18	6.88	0.04	12.0	0.3
19	6.94	0.04	11.1	0.3
20	7.00	0.05	9.8	0.2
21	7.09	0.05	8.8	0.2
22	7.16	0.05	7.8	0.2
23	7.22	0.05	7.3	0.2
24	7.24	0.05	8.3	0.2
25	7.27	0.05	6.3	0.2
oc	7.68	0.05	0	0
sc	0	0	48.1	0.8

Table 9 Measurement data for U and I relation for single device at 140cm

Then we plot the I-V characteristics in Figure 4.

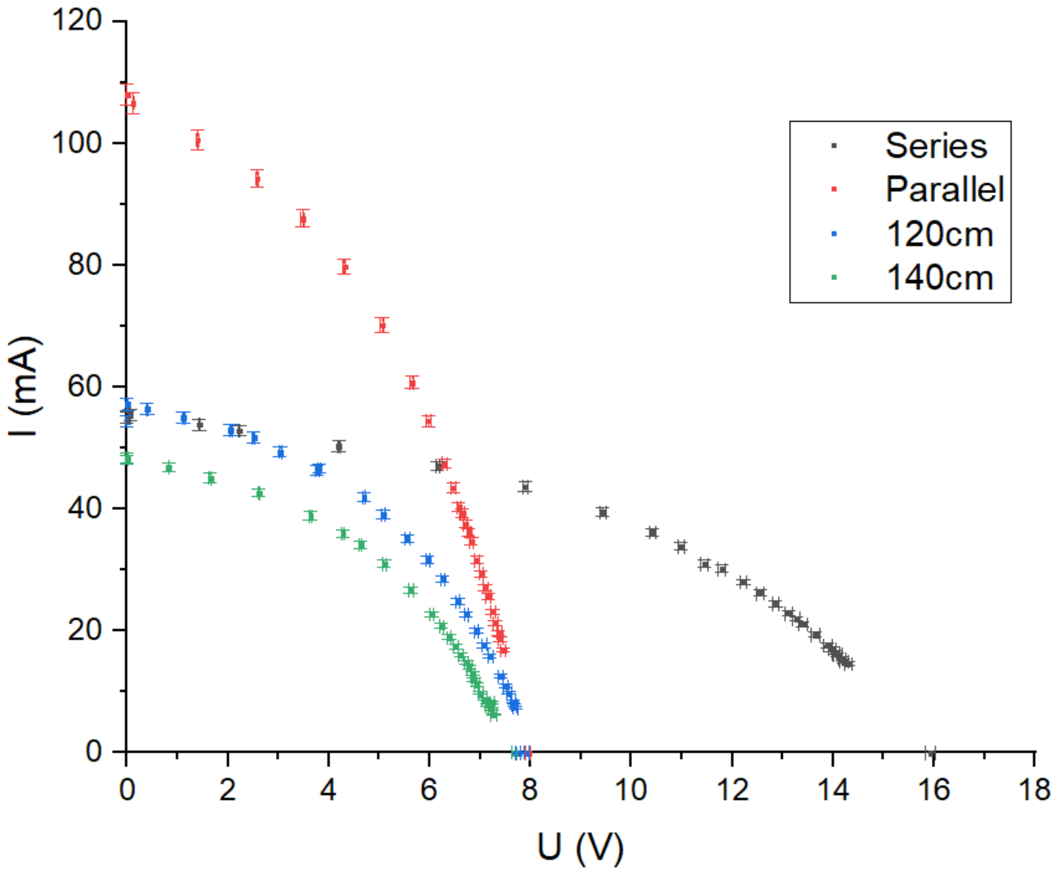

Figure 4 I-V characteristics plot of the 4 types

5.4 Calculation of P and R

Using data from Table 6,7,8,9, we calculate P and R of each type, and record them in Table 10,11,12,13.

Take the first row of data from Table 6 for example:

$$P = UI = 0.06 \times 55.5 \times 10^{-3} = 0.0033 \pm 0.0006W$$

$$R = \frac{U}{I} = \frac{0.06}{55.5 \times 10^{-3}} = 1.081 \pm 0.2\Omega$$

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$	P[W]	$u_P[W]$	R[Ω]	$u_R[\Omega]$
1	0.06	0.01	55.5	0.9	0.0033	0.0006	1.081	0.2
2	1.43	0.02	53.9	0.9	0.0771	0.002	26.531	0.5
3	2.22	0.02	52.9	0.9	0.1174	0.002	41.966	0.8
4	4.20	0.03	50.3	0.9	0.2113	0.004	83.499	1.5
5	6.16	0.04	47.1	0.8	0.2901	0.005	130.786	2.4
6	7.90	0.05	43.7	0.8	0.3452	0.006	180.778	3.3
7	9.43	0.06	39.5	0.7	0.3725	0.007	238.734	4.4
8	10.42	0.06	36.2	0.6	0.3772	0.007	287.845	5.4
9	10.99	0.07	33.9	0.6	0.3726	0.007	324.189	6.1
10	11.45	0.07	31.0	0.6	0.3550	0.007	369.355	7.1
11	11.79	0.07	30.2	0.6	0.3561	0.007	390.397	7.5
12	12.22	0.07	28.0	0.5	0.3422	0.007	436.429	8.5
13	12.55	0.07	26.2	0.5	0.3288	0.007	479.008	9.4
14	12.86	0.07	24.5	0.5	0.3151	0.006	524.898	10.5
15	13.12	0.08	22.9	0.4	0.3004	0.006	572.926	11.6
16	13.27	0.08	22.0	0.4	0.2919	0.006	603.182	12.3
17	13.40	0.08	21.1	0.4	0.2827	0.006	635.071	13.1
18	13.65	0.08	19.4	0.4	0.2648	0.006	703.608	14.7
19	13.90	0.08	17.6	0.4	0.2446	0.005	789.773	16.9
20	14.06	0.08	16.4	0.3	0.2306	0.005	857.317	18.7
21	14.22	0.08	15.1	0.3	0.2147	0.005	941.722	21.1
22	14.30	0.08	14.6	0.3	0.2088	0.005	979.452	22.1
23	14.18	0.08	15.5	0.3	0.2198	0.005	914.839	20.3
24	14.09	0.08	16.1	0.3	0.2268	0.005	875.155	19.2
25	13.98	0.08	17.0	0.4	0.2377	0.005	822.353	17.8

Table 10 Calculation of P and R of series connection

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$	P[W]	$u_P[W]$	R[Ω]	$u_R[\Omega]$
1	0.12	0.01	106.7	1.7	0.0128	0.001	1.125	0.1
2	1.40	0.02	100.6	1.6	0.1408	0.003	13.917	0.3
3	2.58	0.02	94.3	1.5	0.2433	0.005	27.359	0.5
4	3.48	0.03	87.7	1.4	0.3052	0.006	39.681	0.7
5	4.31	0.03	79.8	1.3	0.3439	0.006	54.010	1.0
6	5.06	0.04	70.2	1.2	0.3552	0.006	72.080	1.3
7	5.65	0.04	60.8	1.0	0.3435	0.006	92.928	1.7
8	5.98	0.04	54.5	0.9	0.3259	0.006	109.725	2.0
9	6.30	0.04	47.5	0.8	0.2993	0.006	132.632	2.4
10	6.47	0.04	43.5	0.8	0.2814	0.005	148.736	2.8
11	6.65	0.04	39.3	0.7	0.2613	0.005	169.211	3.2
12	6.77	0.04	36.2	0.6	0.2451	0.005	187.017	3.5
13	6.58	0.04	40.3	0.7	0.2652	0.005	163.275	3.0
14	6.64	0.04	39.4	0.7	0.2616	0.005	168.528	3.2
15	6.71	0.04	37.6	0.7	0.2523	0.005	178.457	3.4
16	6.83	0.04	34.7	0.6	0.2370	0.005	196.830	3.7
17	6.94	0.04	31.6	0.6	0.2193	0.004	219.620	4.2
18	7.02	0.05	29.4	0.5	0.2064	0.004	238.776	4.7
19	7.11	0.05	27.1	0.5	0.1927	0.004	262.362	5.2
20	7.17	0.05	25.7	0.5	0.1843	0.004	278.988	5.6
21	7.25	0.05	23.1	0.4	0.1675	0.003	313.853	6.4
22	7.31	0.05	21.3	0.4	0.1557	0.003	343.192	7.1
23	7.37	0.05	19.7	0.3	0.1452	0.003	374.112	7.9
24	7.40	0.05	18.7	0.4	0.1384	0.003	395.722	8.4
25	7.46	0.05	16.9	0.3	0.1261	0.003	441.420	9.6

Table 11 Calculation of P and R for parallel connection

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$	P[W]	$u_P[W]$	R[Ω]	$u_R[\Omega]$
1	0.01	0.01	57.2	1.0	0.0006	0.0006	0.175	0.2
2	0.40	0.01	56.5	1.0	0.0226	0.0008	7.080	0.2
3	1.12	0.02	55.0	0.9	0.0616	0.001	20.364	0.4
4	2.06	0.02	53.0	0.9	0.1092	0.002	38.868	0.8
5	2.51	0.02	51.7	0.9	0.1298	0.003	48.549	0.9
6	3.04	0.03	49.4	0.8	0.1502	0.003	61.538	1.2
7	3.77	0.03	46.4	0.8	0.1749	0.003	81.250	1.5
8	3.81	0.03	46.7	0.8	0.1779	0.003	81.585	1.5
9	4.70	0.03	42.0	0.7	0.1974	0.004	111.905	2.1
10	5.08	0.04	39.2	0.7	0.1991	0.004	129.592	2.4
11	5.56	0.04	35.2	0.6	0.1957	0.004	157.955	3.0
12	5.96	0.04	31.7	0.6	0.1889	0.004	188.013	3.6
13	6.26	0.04	28.5	0.5	0.1784	0.004	219.649	4.3
14	6.56	0.04	24.9	0.5	0.1633	0.003	263.454	5.3
15	6.72	0.04	22.7	0.4	0.1525	0.003	296.035	6.1
16	6.93	0.04	20.0	0.4	0.1386	0.003	346.500	7.3
17	7.08	0.05	17.7	0.4	0.1253	0.003	400.000	8.6
18	7.20	0.05	15.9	0.4	0.1145	0.003	452.830	10.1
19	7.41	0.05	12.6	0.3	0.0934	0.002	588.095	14.0
20	7.51	0.05	10.9	0.3	0.0819	0.002	688.991	17.2
21	7.57	0.05	9.8	0.2	0.0742	0.002	772.449	20.1
22	7.65	0.05	8.4	0.2	0.0643	0.002	910.714	25.2
23	7.68	0.05	7.8	0.2	0.0599	0.002	984.615	28.1
24	7.70	0.05	7.4	0.2	0.0570	0.002	1040.541	30.4
25	7.76	0.05	0.0	0.1	0.0000	0.001	/	/

Table 12 Calculation of P and R for single device at 120cm

	U[V]	$u_U[V]$	I[mA]	$u_I[mA]$	P[W]	$u_P[W]$	R[Ω]	$u_R[\Omega]$
1	0.01	0.01	48.4	0.8	0.0005	0.0005	0.207	0.2
2	0.83	0.01	46.9	0.8	0.0389	0.001	17.697	0.4
3	1.65	0.02	45.1	0.8	0.0744	0.002	36.585	0.7
4	2.61	0.02	42.7	0.7	0.1114	0.002	61.124	1.2
5	3.64	0.03	38.9	0.7	0.1416	0.003	93.573	1.8
6	4.28	0.03	36.0	0.6	0.1541	0.003	118.889	2.3
7	4.63	0.03	34.2	0.6	0.1583	0.003	135.380	2.6
8	5.10	0.04	31.0	0.6	0.1581	0.003	164.516	3.2
9	5.63	0.04	26.7	0.5	0.1503	0.003	210.861	4.2
10	6.04	0.04	22.8	0.4	0.1377	0.003	264.912	5.4
11	6.23	0.04	20.8	0.4	0.1296	0.003	299.519	6.3
12	6.39	0.04	19.0	0.4	0.1214	0.003	336.316	7.2
13	6.52	0.04	17.4	0.4	0.1134	0.003	374.713	8.2
14	6.62	0.04	16.1	0.3	0.1066	0.002	411.180	9.1
15	6.73	0.04	14.8	0.3	0.0996	0.002	454.730	10.3
16	6.79	0.04	14.0	0.3	0.0951	0.002	485.000	11.2
17	6.86	0.04	13.0	0.3	0.0892	0.002	527.692	12.4
18	6.88	0.04	12.0	0.3	0.0826	0.002	573.333	13.9
19	6.94	0.04	11.1	0.3	0.0770	0.002	625.225	15.5
20	7.00	0.05	9.8	0.2	0.0686	0.002	714.286	18.6
21	7.09	0.05	8.8	0.2	0.0624	0.002	805.682	21.9
22	7.16	0.05	7.8	0.2	0.0558	0.002	917.949	26.2
23	7.22	0.05	7.3	0.2	0.0527	0.002	989.041	29.1
24	7.24	0.05	8.3	0.2	0.0601	0.002	872.289	24.2
25	7.27	0.05	6.3	0.2	0.0458	0.001	1153.968	36.4

Table 13 Calculation of P and R for single device at 140cm

Then we plot the P-U and P-R relation in Figure 5 and Figure 6.

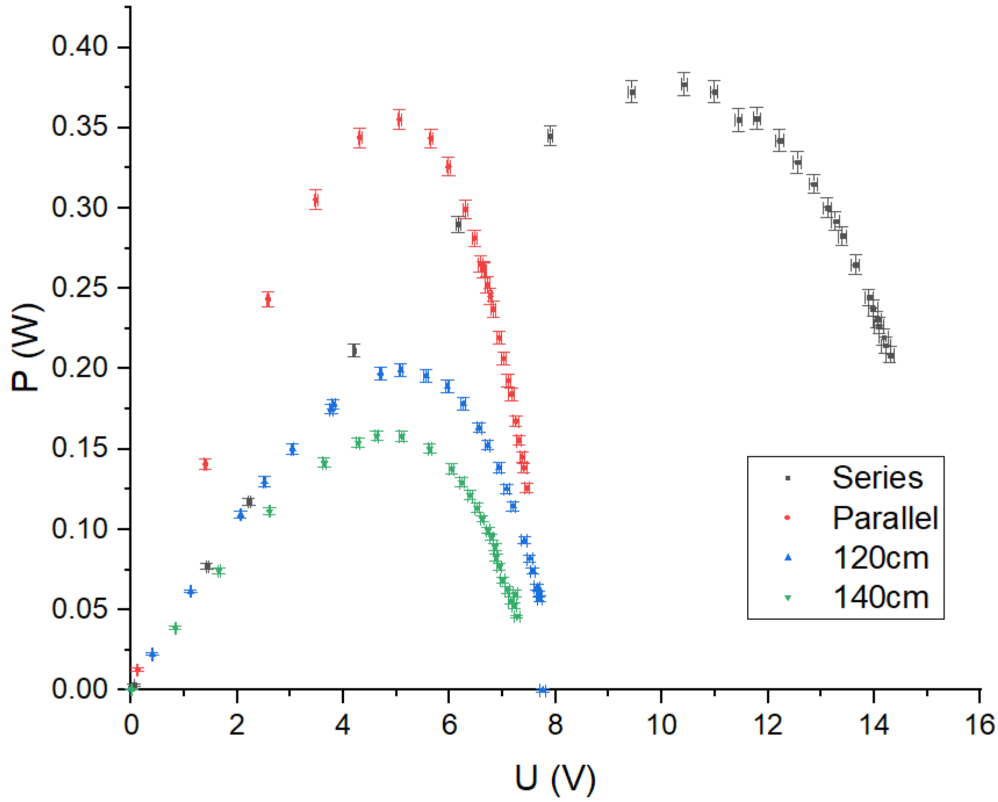

Figure 5 P-U relation

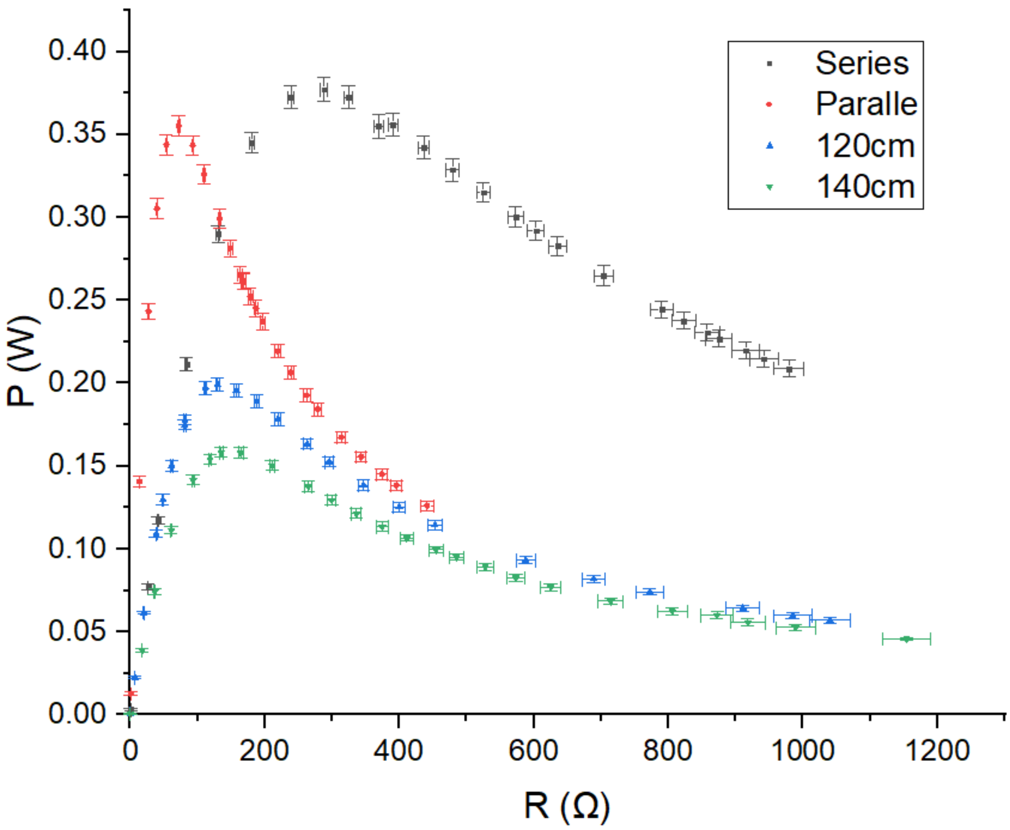

Figure 6 P-R relation

5.5 Calculation of FF and η

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

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

For a single device at 120cm, P_m=0.1991±0.0038$W, V_{oc}=7.93V, I_{sc}=54.4mA$

$$\text{FF}=\frac{P_m}{V_{oc}I_{sc}}=\frac{0.1991}{7.93\times 54.4\times 10^{-3}}=0.4615\pm 0.009$$

$$\eta=\frac{P_m}{P_{in}}\times 100\%=\frac{0.1991}{9.75}\times 100\%=2.04\%\pm 0.2\%$$

For a single device at 140cm, P_m=0.1583±0.0031$W, V_{oc}=7.68V, I_{sc}=48.1mA$

$$\text{FF}=\frac{P_m}{V_{oc}I_{sc}}=\frac{0.1583}{7.68\times 48.1\times 10^{-3}}=0.4285\pm 0.008$$

$$\eta=\frac{P_m}{P_{in}}\times 100\%=\frac{0.1583}{8.41}\times 100\%=1.88\%\pm 0.2\%$$

	Series	Parallel	120cm	140cm
$V_{oc}[V]$	15.93±0.09	7.96±0.05	7.93±0.05	7.68±0.05
I_{sc}[mA]	55.1±0.9	108.0±1.7	54.4±0.9	48.1±0.8
$P_m[W]$	0.3772±0.007	0.3552±0.006	0.1991±0.004	0.1583±0.003
V_m[V]	10.42±0.06	5.06±0.04	5.08±0.04	4.63±0.03
$I_m[mA]$	36.2±0.6	70.2±1.2	39.2±0.7	34.2±0.6
$R_m[\Omega]$	287.845±5.4	72.080±1.3	129.592±2.4	135.3±2.6
FF	/	/	0.4615±0.01	0.4285±0.01
η	/	/	2.04% ± 0.2%	1.88% ± 0.2%

Table 14 Factors

6. Conclusions and discussion

6.1 Conclusions

In this lab, we learn the working principle of solar cell and study its current voltage characteristics. We repeat U and I measurement for 4 types of solar cell circuits:

i. Two solar cells in series
ii. Two solar cells in parallel
iii. One solar cell at the distance 120cm from light source
iv. One solar cell at the distance 140cm from light source

Based on the different behavior of the four types, we then analyze the effect of the changing factors.

6.1.1 Effects of Configuration

The two combining solar cells have the same distance as one single device.
By comparing the I-U plot of the types, we observe the following characteristics.

- Under the same voltage, the current through the solar cells in parallel is twice as much as that of one single cell.
- Under the same current, the voltage of the solar cells in series is twice as much as that of one single cell.
- The solar cells in parallel have the same open-circuit voltage as one single device.
- The solar cells in series have the same short-circuit current as one single device.

By comparing the data in Table14, we observe the following characteristics.

- The maximum power of the two configurations are almost the same, and they are twice as much as that of one single device.
- When the power reaches the maximum, compared with one single device, solar cells in series show a double voltage while solar cells in parallel show a double current. R_m of cells in series doubles R_m of one single cell and is four times of R_m of cells in parallel.

6.1.2 Effects of Distance

One single device is studied with the distance of 120cm and 140cm from the light source respectively.
By comparing the I-U plot of the types, we observe the following characteristics.

- Under the same voltage, the current of the cell is negatively related with the distance.
- Under the same current, the voltage of the cell is positively related with the distance.
- When the distance increases, both the open-circuit voltage and short-circuit current decrease.

By comparing the data in Table14, we observe the following characteristics.

- With the distance increasing, the maximum power decreases and the corresponding I_m and V_m decrease. R_m increases.
- With the distance increasing, η decreases which means the utilization of energy decreases, since more energy is consumed due to greater inner resistance.
- With the distance increasing, FF decreases, which means the output power of the solar cell is smaller. This is reasonable because the incident light density is smaller.

6.2 Error Analysis

- In Table 6 and Table 8, we can see that the first rows of data show larger currents than the short-circuit currents measured previously. This might be caused by the fact that neighboring groups have moved their devices, resulting in the light intensity change on our solar cells. This error might exist throughout the whole experiment.

- Sheltering the light source accidentally may also cause errors.
- The light intensity distributes nonuniformly on the solar cell, which causes inaccuracy of calculation of Pin.
- The circuits have inner resistance, which causes inaccuracies in U and I measurements.
- The multimeter readings are unstable, which causes inaccuracies of the data.

6.3 Improvements

- This experiment should be carried out in light-stable environment. The light condition should remain the same throughout the experiment.
- The approximate value of I_m and U_m should be calculated or provided before the measurement in case of missing of the interval where the maximum P exists.
- We should do more contrast experiments.

7. Reference

[1] M. Krzyzosiak (2019). Exercise 3 - lab manual [rev. 5].pdf Shanghai: UMJI-SJTU.

A. Measurement uncertainty analysis

A.1 Uncertainty in Calculation of $\boldsymbol{P_{in}}$

A.1.1 Uncertainty in Calculation of Area

$$A = ab$$

$$\frac{\partial A}{\partial a} = b \quad \frac{\partial A}{\partial b} = a$$

$$u_A = \sqrt{(\frac{\partial A}{\partial a})^2 {u_a}^2 + (\frac{\partial A}{\partial b})^2 {u_b}^2} = \sqrt{(0.021)^2 \times 0.001^2 + (0.026)^2 \times 0.001^2} = 3 \times 10^{-5} m$$

A.1.2 Uncertainty in Measurement of solar power

A.1.2.1 Uncertainty of $\overline{\boldsymbol{P_{120}}}$

$$\Delta_A = \frac{t_{0.95}}{\sqrt{n}} S_d = \frac{t_{0.95}}{\sqrt{n}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (d_i - \bar{d})^2} = \frac{2.78}{\sqrt{6}} \sqrt{\frac{1}{6-1} \sum_{i=1}^{6} (P_{120,i} - \overline{P_{120}})^2} = 15.57 W/m^2$$

$$\Delta_B = 10 W/m^2$$

$$u_{\overline{\boldsymbol{P_{120}}}} = \sqrt{{\Delta_A}^2 + {\Delta_B}^2} = \sqrt{15.57^2 + 10^2} = 18.5 W/m^2$$

A.1.2.2 Uncertainty of $\overline{\boldsymbol{P_{140}}}$

$$\Delta_A = \frac{t_{0.95}}{\sqrt{n}} S_d = \frac{t_{0.95}}{\sqrt{n}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (d_i - \bar{d})^2} = \frac{2.78}{\sqrt{6}} \sqrt{\frac{1}{6-1} \sum_{i=1}^{6} (P_{120,i} - \overline{P_{120}})^2} = 11.3 W/m^2$$

$$\Delta_B = 10 W/m^2$$

$$u_{\overline{\boldsymbol{P_{140}}}} = \sqrt{{\Delta_A}^2 + {\Delta_B}^2} = \sqrt{11.3^2 + 10^2} = 15.1 W/m^2$$

A.1.3 Uncertainty in Calculation of $\boldsymbol{P_{in}}$

$$P_{in} = \bar{P} A$$

$$\frac{\partial P_{in}}{\partial \bar{P}} = A \quad \frac{\partial P_{in}}{\partial A} = \bar{P}$$

$$u_{P_{in,120}} = \sqrt{(\frac{\partial P_{in}}{\partial \bar{P}})^2 {u_{\bar{P}}}^2 + (\frac{\partial P_{in}}{\partial A})^2 {u_A}^2} = \sqrt{0.0546^2 \times 18.5^2 + 178.6^2 \times 0.00003^2} = 1W$$

$$u_{P_{in,140}} = \sqrt{(\frac{\partial P_{in}}{\partial \bar{P}})^2 {u_{\bar{P}}}^2 + (\frac{\partial P_{in}}{\partial A})^2 {u_A}^2} = \sqrt{0.0546^2 \times 15.1^2 + 154.1^2 \times 0.00003^2} = 0.8W$$

A.2 Uncertainty in I-V Characteristics

$$u_U = 0.5\%U + 0.01$$
$$u_I = 1.5\%I + 0.1$$

Take U=0.06V, I=55.5mA for example,

$$u_U = 0.5\% \times 0.06 + 0.01 = 0.01V$$
$$u_I = 1.5\% \times 55.5 + 0.1 = 0.9mA$$

For the uncertainty of open-circuit voltage and short-circuit current in Table 5, we record them in Table:

	Single device at 120cm	Single device at 140cm	series	parallel
U_{oc}[V]	7.93	7.68	15.93	7.96
$u_{U_{oc}}$[V]	0.05	0.05	0.09	0.05
$I_{sc}[mA]$	54.4	48.1	55.1	108.0
$u_{I_{sc}}$[mA]	0.9	0.8	0.9	1.7

Table 15 Voc and Isc with uncertainties

A.3 Uncertainty in Calculation of P and R

$$P = UI$$

$$\frac{\partial P}{\partial U} = I \quad \frac{\partial P}{\partial I} = U$$

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

Take U=0.06V and I=55.5mA for example:

$$u_P = \sqrt{0.0555^2 \times 0.01^2 + 0.06^2 \times 0.0009^2} = 0.0006W$$

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

$$\frac{\partial P}{\partial U} = \frac{1}{I} \qquad \frac{\partial P}{\partial I} = -\frac{U}{I^2}$$

$$u_P = \sqrt{\left(\frac{\partial P}{\partial U}\right)^2 {u_U}^2 + \left(\frac{\partial P}{\partial I}\right)^2 {u_I}^2} = \sqrt{\left(\frac{1}{I}\right)^2 {u_U}^2 + \left(\frac{U}{I^2}\right)^2 {u_I}^2}$$

Take U=0.06V and I=55.5mA for example:

$$u_P = \sqrt{\left(\frac{1}{0.0555}\right)^2 \times 0.01^2 + \left(\frac{0.06}{0.0555^2}\right)^2 \times 0.0009^2} = 0.2W$$

A.4 Uncertainty in Calculation of FF and η

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

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

$$u_{FF}=\sqrt{\left(\frac{\partial FF}{\partial P_m}\right)^2 {u_{P_m}}^2+\left(\frac{\partial FF}{\partial V_{oc}}\right)^2 {u_{V_{oc}}}^2+\left(\frac{\partial FF}{\partial I_{sc}}\right)^2 {u_{I_{sc}}}^2}$$

$$=\sqrt{\left(\frac{1}{V_{oc}I_{sc}}\right)^2 {u_{P_m}}^2+\left(\frac{P_m}{{V_{oc}}^2\times I_{sc}}\right)^2 {u_{V_{oc}}}^2+\left(\frac{P_m}{{I_{sc}}^2\times V_{oc}}\right)^2 {u_{I_{sc}}}^2}$$

$$u_\eta=\sqrt{\left(\frac{\partial \eta}{\partial P_m}\right)^2 {u_{P_m}}^2+\left(\frac{\partial \eta}{\partial P_{in}}\right)^2 {u_{P_{in}}}^2}\times 100\%=\sqrt{\left(\frac{1}{P_{in}}\right)^2 {u_{P_m}}^2+\left(\frac{P_m}{P_{in}^2}\right)^2 {u_{P_{in}}}^2}\times 100\%$$

For a single device at 120cm:

$$u_{FF}$$

$$=\sqrt{\left(\frac{0.004}{7.93\times 54.4\times 10^{-3}}\right)^2+\left(\frac{0.1991\times 0.05}{7.93^2\times 54.4\times 10^{-3}}\right)^2++\left(\frac{0.1991\times 0.0009}{7.93\times 54.4^2\times 10^{-6}}\right)^2}$$

$$=0.01$$

$$u_\eta=\sqrt{\left(\frac{1}{9.75}\right)^2\times 0.004^2+\left(\frac{0.1991}{9.75^2}\right)^2\times 1^2}\times 100\%=0.2\%$$

For a single device at 140cm:

$$u_{FF}$$

$$=\sqrt{\left(\frac{0.003}{7.68\times 48.1\times 10^{-3}}\right)^2+\left(\frac{0.1583\times 0.05}{7.68^2\times 48.1\times 10^{-3}}\right)^2++\left(\frac{0.1583\times 0.0008}{7.68\times 48.1^2\times 10^{-6}}\right)^2}$$

$$=0.01$$

$$u_\eta=\sqrt{\left(\frac{1}{8.41}\right)^2\times 0.003^2+\left(\frac{0.1583}{8.41^2}\right)^2\times 0.8^2}\times 100\%=0.2\%$$

B. Data Sheet

UM-SJTU Physics Laboratory Vp241
Data Sheet (Exercise 3)

Name: 何雯欣　　Student ID: 518370910117

Name: 王晓煊　　Student ID: 518021910460

Group: 1　　Date: 2019/11/1

NOTICE. Please remember to show the data sheet to your instructor before leaving the laboratory. The data sheet will not be accepted if the data are recorded with pencil or modified by correction fluid/tape. If a mistake is made in recording a datum item, cancel the wrong value by drawing a fine line through it, record the correct value legibly, and ask your instructor to confirm the correction. Please remember to take a record of the precision of the instruments used.
You are required to hand in the original data with your lab report, so please keep the data sheet properly.

QUANTITY	PRECISION
DC voltage	±0.5%+0.01 [V]
DC current	±1.5%+0.1 [mA]
distance	±0.1 [cm]
solar power	±10 [W/m²]

Table 1. Multimeter precision.

length [cm]	width [cm]
26.0	21.0

Table 2. Measurement data for area.

	1	2	3	4	5	6
P_{120} [W/m²]	199.3	165.7	183.3	185.1	162.0	176.0
P_{140} [W/m²]	166.9	147.8	165.7	143.5	153.4	147.2

Table 3. Measurement data for solar power.

	single device at 120 cm	single device at 140 cm	series	parallel
U_{oc} [V]	7.93	7.68	15.93	7.96
I_{sc} [mA]	54.4	48.1	55.1	108.0

Table 4. Measurement data for U_{oc} and I_{sc}.

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	series		parallel	
	U [V]	I [mA]	U [V]	I [mA]
1	0.06	55.5	0.12	106.7
2	1.43	53.9	1.41	100.6
3	2.22	52.9	2.58	94.3
4	4.20	50.3	3.48	87.7
5	6.16	47.1	4.31	79.8
6	7.90	43.7	5.06	70.2
7	9.43	39.5	5.65	60.8
8	10.42	36.2	5.98	54.5
9	10.99	33.9	6.30	47.5
10	11.45	31.0	6.47	43.5
11	11.79	30.2	6.65	39.3
12	12.22	28.0	6.77	36.2
13	12.55	26.2	6.58	40.3
14	12.86	24.5	6.64	39.4
15	13.12	22.9	6.71	37.6
16	13.27	22.0	6.83	34.7
17	13.41	21.1	6.94	31.6
18	13.65	19.4	7.02	29.4
19	13.90	17.6	7.11	27.1
20	14.06	16.4	7.17	25.7
21	14.22	15.1	7.25	23.1
22	14.30	14.6	7.31	21.3
23	14.18	15.5	7.37	19.7
24	14.09	16.1	7.41	18.7
25	13.98	17.0	7.46	16.9

Table 5. Measurement data for the U vs. I relation (series/parallel configuration).

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	120 cm		140 cm	
	U [V]	I [mA]	U [V]	I [mA]
1	0.01	57.2	0.01	48.4
2	0.40	56.5	0.83	46.9
3	1.12	55.0	1.65	45.1
4	2.06	53.0	2.61	42.7
5	2.51	51.7	3.64	38.9
6	3.04	49.4	4.28	36.0
7	3.77	46.4	4.63	34.2
8	3.81	46.7	5.10	31.0
9	4.70	42.0	5.63	26.7
10	5.08	39.2	6.04	22.8
11	5.56	35.2	6.23	20.8
12	5.96	31.7	6.39	19.0
13	6.26	28.5	6.52	17.4
14	6.56	24.9	6.62	16.1
15	6.72	22.7	6.73	14.8
16	6.93	20.0	6.73	14.0
17	7.08	17.7	6.79	13.0
18	7.20	15.9	6.86	12.0
19	7.41	12.6	6.94	11.8
20	7.51	10.9	7.00	9.8
21	7.57	9.8	7.09	8.8
22	7.65	8.4	7.16	7.8
23	7.68	7.8	7.22	7.3
24	7.70	7.4	7.24	8.3
25	7.76	0.0	7.27	6.3

Table 6. Measurement data for the U vs. I relation (120 cm/140 cm configuration).

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