UM–SJTU Joint Institute

Physics Laboratory

(VP241)

Laboratory Report

Exercise 3

Solar Cells: I-V Characteristics

Name: Yihao Liu   ID: 515370910207
Name: Guangzheng Wu   ID: 515370910175   Group: 7

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Contents

1   Objectives

The objective of this exercise is to get familiar with the working principle of a solar cell and study its current-voltage (I-V) characteristics.

2   Theoretical Background

Solar cells are devices which are able to directly transform solar radiation into electrical energy. They have many advantages such as no consumption of energy, silent operation, no moving parts, and a long lifetime. Moreover, solar cells are easy to maintain and they do not contribute to air pollution. Therefore, solar cells are regarded as a promising energy source in the 21st century and it is estimated that by the mid-21st century solar cells will produce 15-20% of the total electrical energy generated in the world, and therefore become one of the leading energy sources.

2.1   Solar Cell Structure

As an example, the structure of a crystalline silicon solar cell is shown in Figure 1. It consists of n/ρ homo-junctions, a 10 cm $\times$ 10 cm ptype silicon plate of thickness 500 μm, 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.
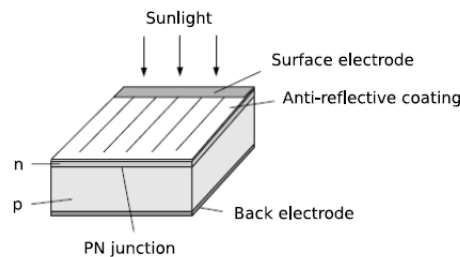

Figure 1: Structure of a crystalline silicon solar cell.

2.2   Photovoltaic Effect

When the light enters the p-n junction near the solar cell surface, and the energy of incident photons is 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

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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.

2.3 Solar Cell Parameters

Relying on the photovoltaic 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 ID from the p-type to the n-type area, opposite to I_ph. Eventually, the net current is

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

where V_D is the junction voltage, I0 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

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

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

$$I_{sc} = I_{ph}$$

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 (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,

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

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

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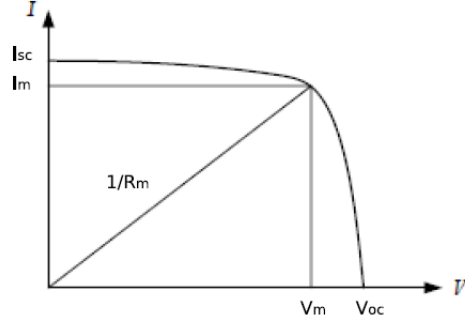where P_{in} denotes the total radiant power incident on the solar cell.

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

2.4 Solar Cell Equivalent Circuit

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

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

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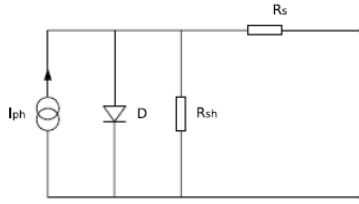

Figure 3: Solar cell equivalent circuit.

3   Measurement Setup and Procedure

3.1   Measurement Setup

The setup consists of a photovoltaic device (5 W), a 300 W tungstenhalogen 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   Measurement Procedure and Data Presentation

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. 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 photovoltaic device is 120 cm; Measure the solar power by the provided solar power meter.

   (c) The distance between the light source and the photovoltaic 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, FF, and η. Compile the data in the form of a table.

4   Results

The multimeter precision was shown in Table 1.
The measurement data for area was shown in Table 2.

$$S = 21 \times 26 = 546.0 \pm 3.3\,\mathrm{cm}^2$$

The measurement data for solar power was shown in Table 3.

QUANTITY	PRECISION
DC voltage	$0.5\% + \Delta$ [V]
DC current	$1.5\% + \Delta$ [mA]
distance	0.1 [cm]
solar power	10 [W/m^2]

Table 1: Multimeter precision.

length [cm]	width [cm]
21.0	26.0

Table 2: Measurement data for area.

	0	1	2	3	4
P_{100} [W/m^2]	270	324	439	499	532
P_{120} [W/m^2]	203	257	334	381	406

Table 3: Measurement data for solar power.

$$P_{100} = \frac{270 + 324 + 439 + 499 + 532}{5} = 412.6 \pm 10.0 \, \text{W/m}^2$$

$$P_{in} = 22.52 \pm 0.56 \, \text{W}$$

$$P_{120} = \frac{203 + 257 + 334 + 381 + 406}{5} = 316.2 \pm 10.0 \, \text{W/m}^2$$

$$P_{in} = 17.26 \pm 0.56 \, \text{W}$$

The measurement data for U_{oc} and I_{sc} was shown in Table 4.

	100 cm	120 cm	series	parallel
U_{oc} [V]	9.98	9.66	19.10	9.55
I_{sc} [mA]	105.2	84.4	92.3	184.0

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

The measurement of a solar cell was shown in Table 5.

	100 cm		120 cm	
	U [V]	I [mA]	U [V]	I [mA]
1	0.18	104.7	0.34	89.9
2	0.92	102.7	1.06	88.1
3	1.78	99.8	1.93	85.7
4	2.32	97.9	2.72	83.9
5	2.81	95.7	3.09	83.0
6	3.21	94.1	3.63	81.7
7	3.76	91.9	4.29	79.5
8	4.47	89.6	4.76	77.6
9	4.94	88.5	5.29	76.2
10	5.95	84.2	5.85	74.0
11	6.65	81.3	6.24	72.2
12	7.30	78.4	6.43	70.3
13	7.69	76.5	6.61	68.5
14	7.69	76.5	7.11	67.2
15	7.85	75.4	7.60	63.9
16	8.04	74.1	8.07	59.5
17	8.26	72.2	8.33	55.6
18	8.52	70.7	8.52	51.9
19	8.70	65.9	8.66	48.5
20	8.78	63.8	8.78	45.3
21	8.89	61.0	8.91	41.4
22	9.34	44.3	9.03	37.1
23	9.66	26.7	9.27	27.6
24	9.82	15.2	9.52	14.9
25	9.92	8.5	9.62	8.2

Table 5: Measurement Data for the U vs. I relation (100 cm/120 cm configuration).

The measurement of two solar cells was shown in Table 6.

	100 cm		120 cm	
	U [V]	I [mA]	U [V]	I [mA]
1	0.22	92.3	0.11	184.5
2	1.23	91.3	0.69	180.8
3	2.21	90.1	1.28	177.8
4	3.23	88.5	1.72	175.2
5	4.21	87.2	2.27	172.0
6	5.20	85.8	2.83	169.2
7	6.25	84.1	3.33	166.2
8	7.29	82.7	3.82	162.6
9	8.10	80.9	4.38	159.0
10	8.43	80.4	4.61	157.4
11	9.01	78.8	4.83	156.2
12	9.40	78.2	5.03	154.5
13	10.03	77.0	5.26	152.7
14	10.85	75.6	5.44	150.7
15	11.60	73.7	5.64	148.5
16	12.43	70.9	5.99	143.6
17	13.30	67.3	6.43	136.4
18	14.04	64.6	6.83	128.6
19	14.86	60.3	7.22	119.9
20	15.71	53.4	7.67	108.2
21	16.54	44.9	8.05	95.5
22	17.45	32.6	8.43	79.5
23	17.96	24.0	8.93	50.8
24	18.20	20.1	9.34	20.0
25	18.41	16.2	9.46	8.2

Table 6: Measurement Data for the U vs. I relation (series/parallel configuration).

For the first 100 cm circuit,

The compiled data was shown in Table 7.

	U [V]	I [mA]	P [mW]	R [Ω]
1	0.18 ± 0.01	104.7 ± 1.7	18.85 ± 1.18	1.72 ± 0.11
2	0.92 ± 0.01	102.7 ± 1.6	94.48 ± 2.13	8.96 ± 0.20
3	1.78 ± 0.02	99.8 ± 1.6	177.64 ± 3.41	17.84 ± 0.34
4	2.32 ± 0.02	97.9 ± 1.6	227.13 ± 4.21	23.70 ± 0.44
5	2.81 ± 0.02	95.7 ± 1.5	268.92 ± 4.89	29.36 ± 0.53
6	3.21 ± 0.03	94.1 ± 1.5	302.06 ± 5.44	34.11 ± 0.61
7	3.76 ± 0.03	91.9 ± 1.5	345.54 ± 6.16	40.91 ± 0.73
8	4.47 ± 0.03	89.6 ± 1.4	400.51 ± 7.08	49.89 ± 0.88
9	4.94 ± 0.03	88.5 ± 1.4	437.19 ± 7.69	55.82 ± 0.98
10	5.95 ± 0.04	84.2 ± 1.4	500.99 ± 8.77	70.67 ± 1.24
11	6.65 ± 0.04	81.3 ± 1.3	540.64 ± 9.45	81.80 ± 1.43
12	7.30 ± 0.05	78.4 ± 1.3	572.32 ± 10.00	93.11 ± 1.63
13	7.69 ± 0.05	76.5 ± 1.2	588.29 ± 10.28	100.52 ± 1.76
14	7.69 ± 0.05	76.5 ± 1.2	588.29 ± 10.28	100.52 ± 1.76
15	7.85 ± 0.05	75.4 ± 1.2	591.89 ± 10.35	104.11 ± 1.82
16	8.04 ± 0.05	74.1 ± 1.2	595.76 ± 10.43	108.50 ± 1.90
17	8.26 ± 0.05	72.2 ± 1.2	596.37 ± 10.45	114.40 ± 2.00
18	8.52 ± 0.05	70.7 ± 1.2	602.36 ± 10.56	120.51 ± 2.11
19	8.70 ± 0.05	65.9 ± 1.1	573.33 ± 10.10	132.02 ± 2.33
20	8.78 ± 0.05	63.8 ± 1.1	560.16 ± 9.90	137.62 ± 2.43
21	8.89 ± 0.05	61.0 ± 1.0	542.29 ± 9.62	145.74 ± 2.58
22	9.34 ± 0.06	44.3 ± 0.8	413.76 ± 7.57	210.84 ± 3.86
23	9.66 ± 0.06	26.7 ± 0.5	257.92 ± 5.08	361.80 ± 7.12
24	9.82 ± 0.06	15.2 ± 0.3	149.26 ± 3.34	646.05 ± 14.47
25	9.92 ± 0.06	8.5 ± 0.2	84.32 ± 2.31	1167.06 ± 32.01

Table 7: Compiled data for the first 100 cm circuit.

$$I_{sc} = 105.2 \pm 1.7 \,\text{mA}, \quad U_{oc} = 9.98 \pm 0.06 \,\text{V}$$

$$P_m = 602.36 \pm 10.56 \,\text{mW}, \quad I_m = 70.7 \pm 1.2 \,\text{mA}, \quad U_m = 8.52 \pm 0.05 \,\text{V}$$

$$R_m = \frac{U_m}{I_m} = 120.51 \pm 2.11 \,\Omega$$

$$FF = \frac{P_m}{U_{oc}I_{sc}} = 0.574 \pm 0.014$$

$$\eta = \frac{P_m}{P_{in}} = 2.67 \pm 0.08 \,\%$$

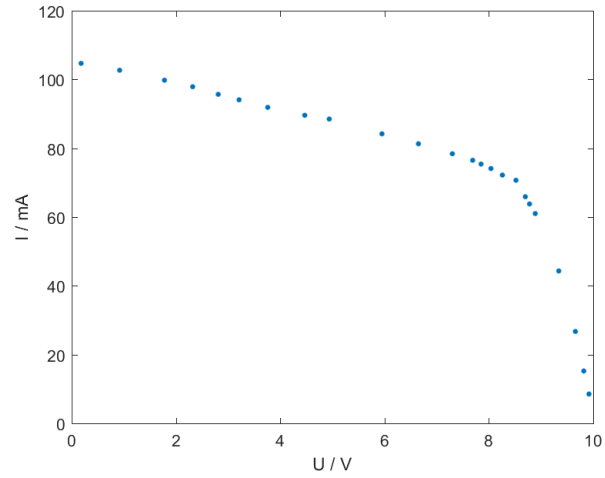The $I - V$ characteristics curve is plotted in Figure 4.

Figure 4: The $I - V$ characteristics curve.

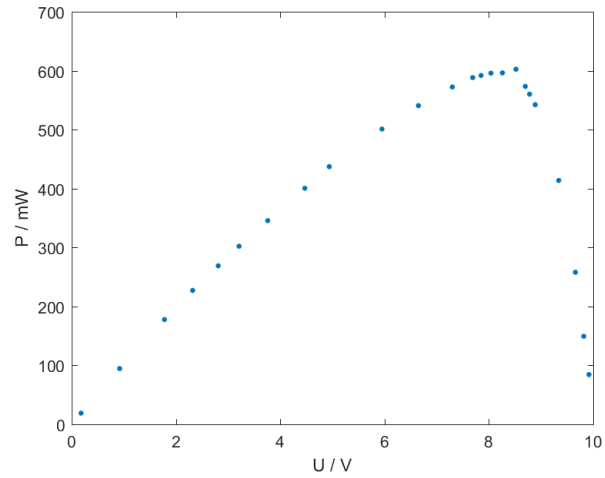The graph of the output power vs. the vlotage is plotted in Figure 5.

Figure 5: The graph of the output power vs. the voltage.

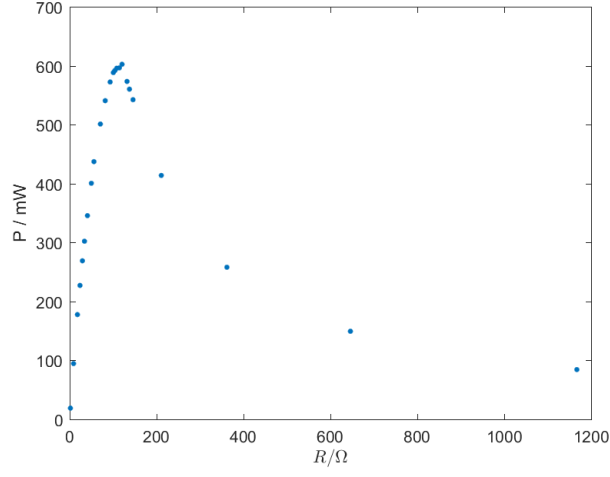The graph of the output power vs. the resistance is plotted in Figure 6.

Figure 6: The graph of the output power vs. the resistance.

For the second 120 cm circuit,

The compiled data was shown in Table 8.

$$I_{sc} = 84.4 \pm 1.4 \,\text{mA}, \quad U_{oc} = 9.66 \pm 0.06 \,\text{V}$$

$$P_m = 485.64 \pm 8.61 \,\text{mW}, \quad I_m = 63.9 \pm 1.1 \,\text{mA}, \quad U_m = 7.60 \pm 0.05 \,\text{V}$$

$$R_m = \frac{U_m}{I_m} = 118.94 \pm 2.11 \,\Omega$$

$$FF = \frac{P_m}{U_{oc}I_{sc}} = 0.596 \pm 0.015$$

$$\eta = \frac{P_m}{P_{in}} = 2.81 \pm 0.10 \,\%$$

The $I - V$ characteristics curve is plotted in Figure 7.

	U [V]	I [mA]	P [mW]	R [Ω]
1	0.34 ± 0.01	89.9 ± 1.4	30.57 ± 1.16	3.78 ± 0.14
2	1.06 ± 0.02	88.1 ± 1.4	93.39 ± 2.02	12.03 ± 0.26
3	1.93 ± 0.02	85.7 ± 1.4	165.40 ± 3.16	22.52 ± 0.43
4	2.72 ± 0.02	83.9 ± 1.4	228.21 ± 4.19	32.42 ± 0.60
5	3.09 ± 0.03	83.0 ± 1.3	256.47 ± 4.66	37.23 ± 0.68
6	3.63 ± 0.03	81.7 ± 1.3	296.57 ± 5.33	44.43 ± 0.80
7	4.29 ± 0.03	79.5 ± 1.3	341.06 ± 6.08	53.96 ± 0.96
8	4.76 ± 0.03	77.6 ± 1.3	369.38 ± 6.56	61.34 ± 1.09
9	5.29 ± 0.04	76.2 ± 1.2	403.10 ± 7.14	69.42 ± 1.23
10	5.85 ± 0.04	74.0 ± 1.2	432.90 ± 7.65	79.05 ± 1.40
11	6.24 ± 0.04	72.2 ± 1.2	450.53 ± 7.96	86.43 ± 1.53
12	6.43 ± 0.04	70.3 ± 1.2	452.03 ± 7.99	91.47 ± 1.62
13	6.61 ± 0.04	68.5 ± 1.1	452.79 ± 8.01	96.50 ± 1.71
14	7.11 ± 0.05	67.2 ± 1.1	477.79 ± 8.45	105.80 ± 1.87
15	7.60 ± 0.05	63.9 ± 1.1	485.64 ± 8.61	118.94 ± 2.11
16	8.07 ± 0.05	59.5 ± 1.0	480.17 ± 8.55	135.63 ± 2.42
17	8.33 ± 0.05	55.6 ± 0.9	463.15 ± 8.29	149.82 ± 2.68
18	8.52 ± 0.05	51.9 ± 0.9	442.19 ± 7.97	164.16 ± 2.96
19	8.66 ± 0.05	48.5 ± 0.8	420.01 ± 7.62	178.56 ± 3.24
20	8.78 ± 0.05	45.3 ± 0.8	397.73 ± 7.27	193.82 ± 3.54
21	8.91 ± 0.05	41.4 ± 0.7	368.87 ± 6.81	215.22 ± 3.97
22	9.03 ± 0.06	37.1 ± 0.7	335.01 ± 6.27	243.40 ± 4.56
23	9.27 ± 0.06	27.6 ± 0.5	255.85 ± 5.01	335.87 ± 6.58
24	9.52 ± 0.06	14.9 ± 0.3	141.85 ± 3.20	638.93 ± 14.40
25	9.62 ± 0.06	8.2 ± 0.2	78.88 ± 2.20	1173.17 ± 32.68

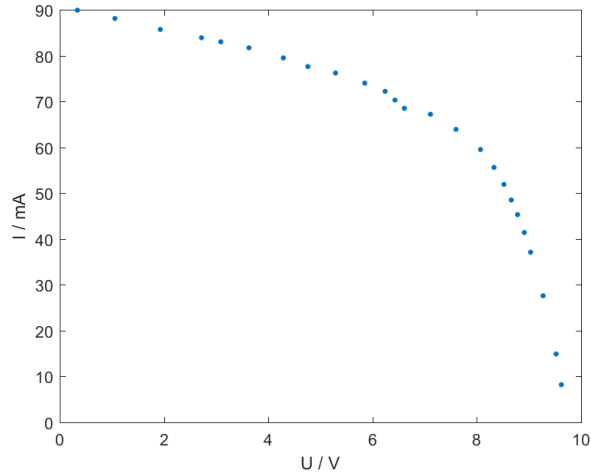Table 8: Compiled data for the second 120 cm circuit.

Figure 7: The $I - V$ characteristics curve.

The graph of the output power vs. the vlotage is plotted in Figure 8.
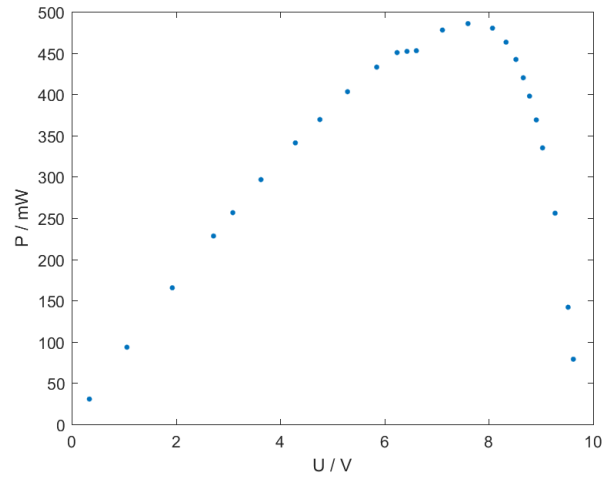

Figure 8: The graph of the output power vs. the voltage.

The graph of the output power vs. the resistance is plotted in Figure 9.
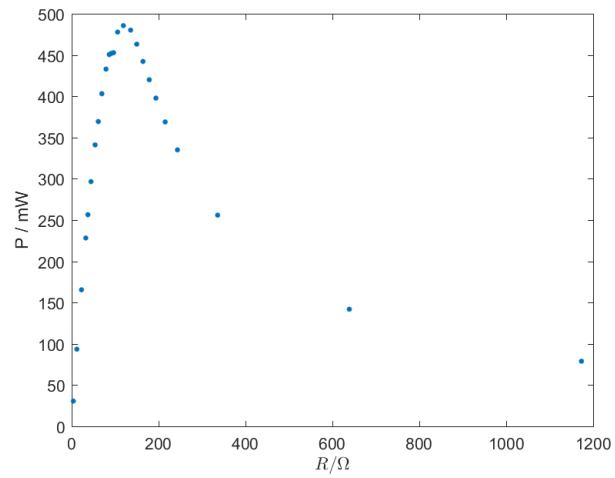

Figure 9: The graph of the output power vs. the resistance.

For the third series circuit,

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The compiled data was shown in Table 9.

	U [V]	I [mA]	P [mW]	R [Ω]
1	0.22 ± 0.01	92.3 ± 1.5	20.31 ± 1.08	2.38 ± 0.13
2	1.23 ± 0.02	91.3 ± 1.5	112.30 ± 2.33	13.47 ± 0.28
3	2.21 ± 0.02	90.1 ± 1.5	199.12 ± 3.73	24.53 ± 0.46
4	3.23 ± 0.03	88.5 ± 1.4	285.86 ± 5.16	36.50 ± 0.66
5	4.21 ± 0.03	87.2 ± 1.4	367.11 ± 6.52	48.28 ± 0.86
6	5.20 ± 0.04	85.8 ± 1.4	446.16 ± 7.85	60.61 ± 1.07
7	6.25 ± 0.04	84.1 ± 1.4	525.63 ± 9.19	74.32 ± 1.30
8	7.29 ± 0.05	82.7 ± 1.3	602.88 ± 10.50	88.15 ± 1.54
9	8.10 ± 0.05	80.9 ± 1.3	655.29 ± 11.40	100.12 ± 1.74
10	8.43 ± 0.05	80.4 ± 1.3	677.77 ± 11.78	104.85 ± 1.82
11	9.01 ± 0.06	78.8 ± 1.3	709.99 ± 12.34	114.34 ± 1.99
12	9.40 ± 0.06	78.2 ± 1.3	735.08 ± 12.77	120.20 ± 2.09
13	10.03 ± 0.06	77.0 ± 1.3	772.31 ± 13.41	130.26 ± 2.26
14	10.85 ± 0.06	75.6 ± 1.2	820.26 ± 14.24	143.52 ± 2.49
15	11.60 ± 0.07	73.7 ± 1.2	854.92 ± 14.85	157.39 ± 2.73
16	12.43 ± 0.07	70.9 ± 1.2	881.29 ± 15.34	175.32 ± 3.05
17	13.30 ± 0.08	67.3 ± 1.1	895.09 ± 15.63	197.62 ± 3.45
18	14.04 ± 0.08	64.6 ± 1.1	906.98 ± 15.88	217.34 ± 3.80
19	14.86 ± 0.08	60.3 ± 1.0	896.06 ± 15.77	246.43 ± 4.34
20	15.71 ± 0.09	53.4 ± 0.9	838.91 ± 14.92	294.19 ± 5.23
21	16.54 ± 0.09	44.9 ± 0.8	742.65 ± 13.45	368.37 ± 6.67
22	17.45 ± 0.10	32.6 ± 0.6	568.87 ± 10.76	535.28 ± 10.12
23	17.96 ± 0.10	24.0 ± 0.5	431.04 ± 8.60	748.33 ± 14.93
24	18.20 ± 0.10	20.1 ± 0.4	365.82 ± 7.58	905.47 ± 18.77
25	18.41 ± 0.10	16.2 ± 0.3	298.24 ± 6.53	1136.42 ± 24.87

Table 9: Compiled data for the third series circuit.

$$I_{sc} = 82.3 \pm 1.3 \,\text{mA}, \quad U_{oc} = 19.10 \pm 0.11 \,\text{V}$$

$$P_m = 906.98 \pm 15.88 \,\text{mW}, \quad I_m = 64.6 \pm 1.1 \,\text{mA}, \quad U_m = 14.04 \pm 0.08 \,\text{V}$$

$$R_m = \frac{U_m}{I_m} = 217.34 \pm 3.80 \,\Omega$$

$$FF = \frac{P_m}{U_{oc}I_{sc}} = 0.577 \pm 0.014$$

$$\eta = \frac{P_m}{P_{in}} = 2.01 \pm 0.06 \,\%$$

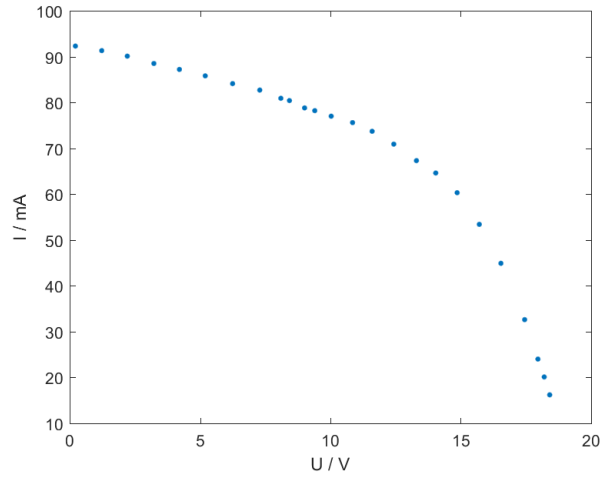The $I - V$ characteristics curve is plotted in Figure 10.

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Figure 10: The $I - V$ characteristics curve.

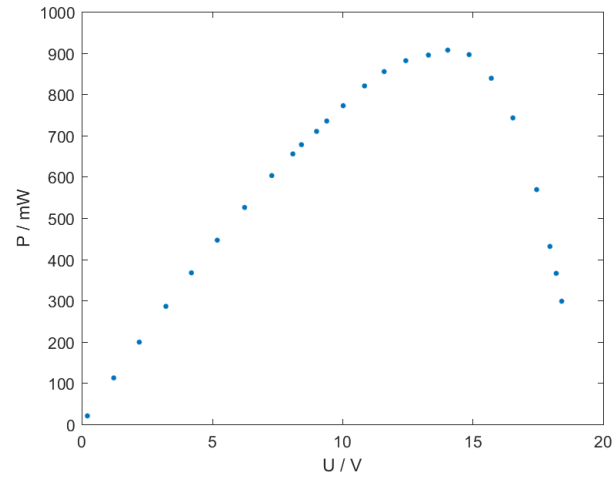The graph of the output power vs. the vlotage is plotted in Figure 11.

Figure 11: The graph of the output power vs. the voltage.

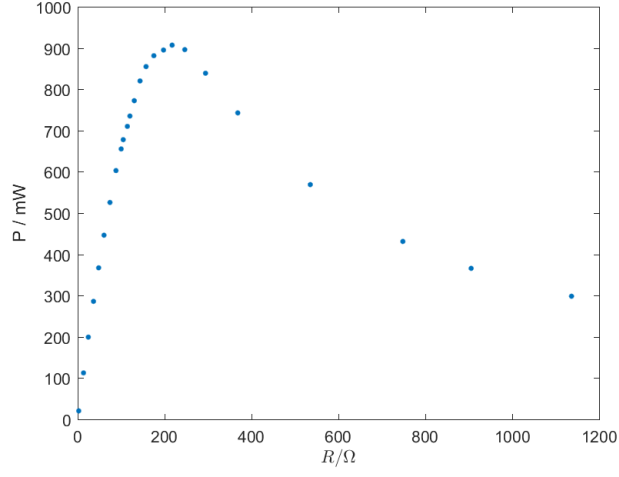The graph of the output power vs. the resistance is plotted in Figure 12.

Figure 12: The graph of the output power vs. the resistance.

For the fourth parallel circuit,

The compiled data was shown in Table 10.

$$I_{sc} = 184.0 \pm 2.9 \, \text{mA}, \quad U_{oc} = 9.55 \pm 0.06 \, \text{V}$$

$$P_m = 878.34 \pm 14.98 \, \text{mW}, \quad I_m = 128.6 \pm 2.0 \, \text{mA}, \quad U_m = 6.83 \pm 0.04 \, \text{V}$$

$$R_m = \frac{U_m}{I_m} = 53.11 \pm 0.91 \, \Omega$$

$$FF = \frac{P_m}{U_{oc} I_{sc}} = 0.500 \pm 0.012$$

$$\eta = \frac{P_m}{P_{in}} = 2.54 \pm 0.09 \, \%$$

The $I - V$ characteristics curve is plotted in Figure 13.

	U [V]	I [mA]	P [mW]	R [Ω]
1	0.11 ± 0.01	184.5 ± 2.9	20.30 ± 1.97	0.60 ± 0.06
2	0.69 ± 0.01	180.8 ± 2.8	124.75 ± 3.11	3.82 ± 0.10
3	1.28 ± 0.02	177.8 ± 2.8	227.58 ± 4.59	7.20 ± 0.15
4	1.72 ± 0.02	175.2 ± 2.7	301.34 ± 5.71	9.82 ± 0.19
5	2.27 ± 0.02	172.0 ± 2.7	390.44 ± 7.11	13.20 ± 0.24
6	2.83 ± 0.02	169.2 ± 2.6	478.84 ± 8.51	16.73 ± 0.30
7	3.33 ± 0.03	166.2 ± 2.6	553.45 ± 9.70	20.04 ± 0.35
8	3.82 ± 0.03	162.6 ± 2.5	621.13 ± 10.79	23.49 ± 0.41
9	4.38 ± 0.03	159.0 ± 2.5	696.42 ± 12.01	27.55 ± 0.47
10	4.61 ± 0.03	157.4 ± 2.5	725.61 ± 12.48	29.29 ± 0.50
11	4.83 ± 0.03	156.2 ± 2.4	754.45 ± 12.95	30.92 ± 0.53
12	5.03 ± 0.04	154.5 ± 2.4	777.13 ± 13.32	32.56 ± 0.56
13	5.26 ± 0.04	152.7 ± 2.4	803.20 ± 13.74	34.45 ± 0.59
14	5.44 ± 0.04	150.7 ± 2.4	819.81 ± 14.01	36.10 ± 0.62
15	5.64 ± 0.04	148.5 ± 2.3	837.54 ± 14.30	37.98 ± 0.65
16	5.99 ± 0.04	143.6 ± 2.3	860.16 ± 14.67	41.71 ± 0.71
17	6.43 ± 0.04	136.4 ± 2.1	877.05 ± 14.95	47.14 ± 0.80
18	6.83 ± 0.04	128.6 ± 2.0	878.34 ± 14.98	53.11 ± 0.91
19	7.22 ± 0.05	119.9 ± 1.9	865.68 ± 14.78	60.22 ± 1.03
20	7.67 ± 0.05	108.2 ± 1.7	829.89 ± 14.21	70.89 ± 1.21
21	8.05 ± 0.05	95.5 ± 1.5	768.78 ± 13.24	84.29 ± 1.45
22	8.43 ± 0.05	79.5 ± 1.3	670.18 ± 11.66	106.04 ± 1.84
23	8.93 ± 0.05	50.8 ± 0.9	453.64 ± 8.18	175.79 ± 3.17
24	9.34 ± 0.06	20.0 ± 0.4	186.80 ± 3.90	467.00 ± 9.76
25	9.46 ± 0.06	8.2 ± 0.2	77.57 ± 2.16	1153.66 ± 32.14

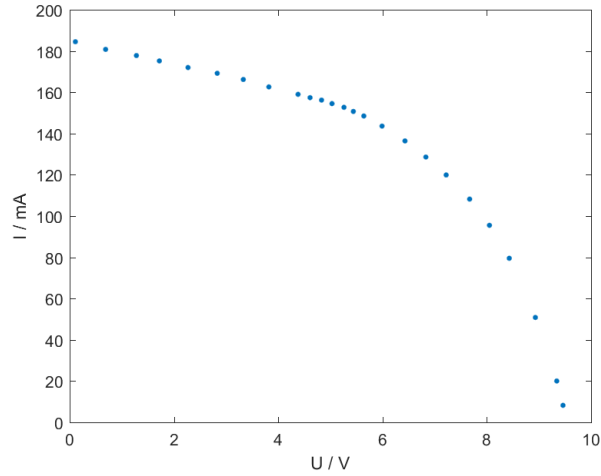Table 10: Compiled data for the fourth parallel circuit.

Figure 13: The $I - V$ characteristics curve.

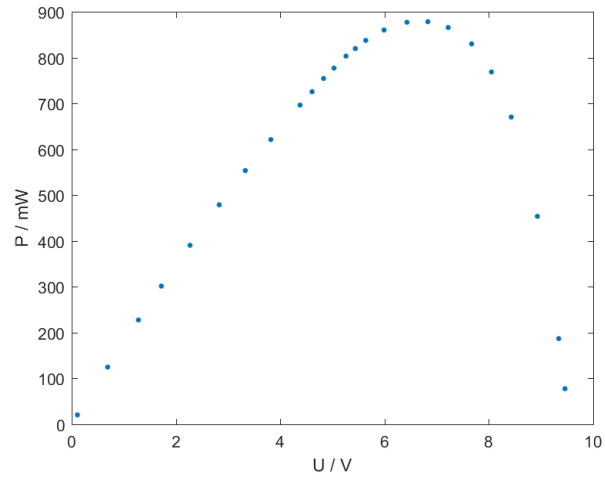The graph of the output power vs. the vlotage is plotted in Figure 14.

Figure 14: The graph of the output power vs. the voltage.

The graph of the output power vs. the resistance is plotted in Figure 15.
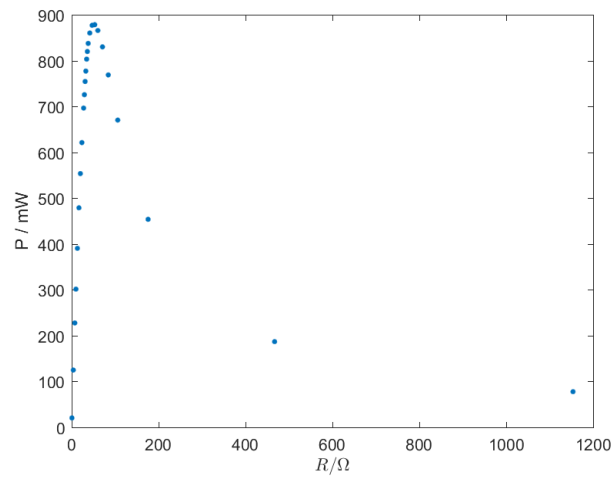

Figure 15: The graph of the output power vs. the resistance.

5 Measurement uncertainty analysis

S can be calculated by the equation $S = ab$. Therefore its uncertainty u_S is found by applying the uncertainty propagation formula

$$u_S = \sqrt{\left(\frac{\partial S}{\partial a}\right)^2 u_a^2 + \left(\frac{\partial S}{\partial b}\right)^2 u_b^2}$$

$$= \sqrt{b^2 u_a^2 + a^2 u_b^2}$$

$$= 3.3\,\text{cm}^2$$

$$S = 546.0 \pm 3.3\,\text{cm}^2$$

P_{in} can be calculated by the equation $P_{in} = P_x S$. Therefore its uncertainty u_P is found by applying the uncertainty propagation formula

$$u_P = \sqrt{\left(\frac{\partial P}{\partial P_x}\right)^2 u_{P_x}^2 + \left(\frac{\partial P}{\partial S}\right)^2 u_S^2}$$

$$= \sqrt{S^2 u_{P_x}^2 + P_x^2 u_S^2}$$

$$u_{P_{100}} = 0.56\,\text{W}$$

$$u_{P_{120}} = 0.56\,\text{W}$$

According to Table 1,

$$u_I = 1.5\%I + 0.1\,\text{mA}$$

$$u_U = 0.5\%U + 0.01\,\text{V}$$

P can be calculated by the equation $P = UI$. Therefore its uncertainty u_P is found by applying the uncertainty propagation formula

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

$$= \sqrt{I^2 u_U^2 + U^2 u_I^2}$$

R can be calculated by the equation $R = \frac{U}{I}$. Therefore its uncertainty u_R is found by applying the uncertainty propagation formula

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

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

FF can be calculated by the equation $FF = \frac{P_m}{P_c}$. Therefore its uncertainty u_{FF} is found by applying the uncertainty propagation formula

$$u_{FF} = \sqrt{\left(\frac{\partial FF}{\partial P_m}\right)^2 u_{P_m}^2 + \left(\frac{\partial FF}{\partial P_c}\right)^2 u_{P_c}^2}$$

$$= \sqrt{\left(\frac{1}{P_c}\right)^2 u_{P_m}^2 + \left(\frac{P_m}{P_c^2}\right)^2 u_{P_c}^2}$$

η can be calculated by the equation $\eta = \frac{P_m}{P_{in}}$. Therefore its uncertainty u_η is found by applying the uncertainty propagation formula

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

$$= \sqrt{\left(\frac{1}{P_{in}}\right)^2 u_{P_m}^2 + \left(\frac{P_m}{P_{in}^2}\right)^2 u_{P_{in}}^2}$$

6   Conclusion

In this experiment, we measured the power supplied by the source and the power absorbed by the solar cells.

We found some properties of the solar cell by determine the values of I_{sc}, V_{oc}, P_m, I_m, V_m, R_m, FF, and η.

We also plotted the I-V characteristics curve and the relation between power, voltage and resistance of the solar cell.

We use series and parallel method to connect two solar cells together and find that in a series circuit, the voltage superposed and in a parallel circuit the current superposed.

According the the value of η, we found that the efficiency of solar cell is very low.

7 Reference

(a) Qin Tian, Han Xugen, Zheng Huan, Mateusz Krzyzosiak, VP241 Exercise 3, Solar Cells: I-V Characteristics, based on materials provided by the Department of Physics, Shanghai Jiaotong University.

8 Data sheet

The Data sheet is attached at the end of the report.