I-V CHARACTERISTICS OF A SOLAR CELL

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Abstract

The I-V characteristics of silion solar cell were studied under illumination by a lamp and by direct sunlight using different filter papers. Important parameters like short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) & maximum power point (MPP) were obtained from the I-V curves. Fill factors & their errors were calculated for all filters and sources. Power output from sunlight was found to be almost 2 orders of magnitude higher than the lamp. The experiment shows the dependence of solar cell performance on nature of incident light.

Objectives :-

i) Study of I-V Characteristic of a solar cell illuminated by an incandescent lamp, at different frequencies.

ii) Study of I-V Characteristic of a solar cell illuminated by sun, at different frequencies.

Theory :-

The solar cell is a semiconductor device that converts light energy directly into electrical energy by the photovoltaic effect. It is a p-n junction diode which absorbs light to create charge carriers. A depletion region is formed at the junction when p-type & n-type semiconductors are joined together, due to diffusion of e^- & holes. This causes an internal electric field across the junction due to fixed ionized donors/acceptors left behind after diffusion.

When light with photon of energy greater than the band gap of semiconductor falls on the solar cell, e^- - hole pairs are generated in the depletion region. Due to the internal $\vec{E}$, e^- & hole drift towards n & p side respectively. This separation of charge carriers leads to a potential difference across the cell & current is obtained in an external circuit. Thus, a solar cell acts as a source of electrical energy under illumination.

The I-V Characteristics of solar cell is the superposition of I-V curves of solar cell in absence (dark) & presence of light. We have the diode law,

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

where I_0 = "dark saturation current" (diode leakage current in absence of light)

q = electronic charge

V = ~~Va~~ Applied voltage across the diode

n = ideality factor

T = temperature

k_B = Boltzmann constant

I_L = "Light generated current"

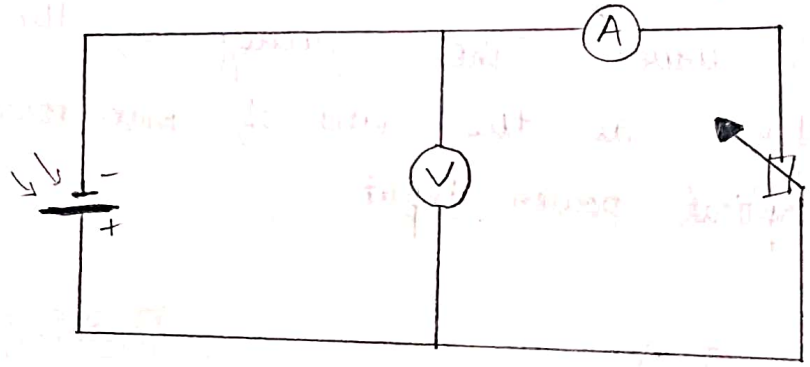

Fig: Circuit for I-V Characteristics of Solar Cell

From the I-V characteristic curve (obtained from above circuit), several parameters are determined for the solar cell. The short-circuit current I_{sc} is the current through the cell when the terminal voltage is zero, it represents max. current the cell can deliver under a fixed illumination.

The open-circuit ~~Voc~~ voltage (V_{oc}) is the voltage across the cell when output current is zero, corresponding to the maximum voltage available from the cell.
The maximum power point (MPP) is the operating point at which $P = VI$ is maximum.

The quality / rating of a solar cell is ~~m~~ quantified by the fill-factor (FF), defined as:

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

where V_{max}, I_{max} are voltage & current @ max. power point (MPP). The fill factor indicates the 'squareness' of the I-V curve. The efficiency of the solar cell (η) is defined as the ratio of max. power output (electrical) to incident optical power input

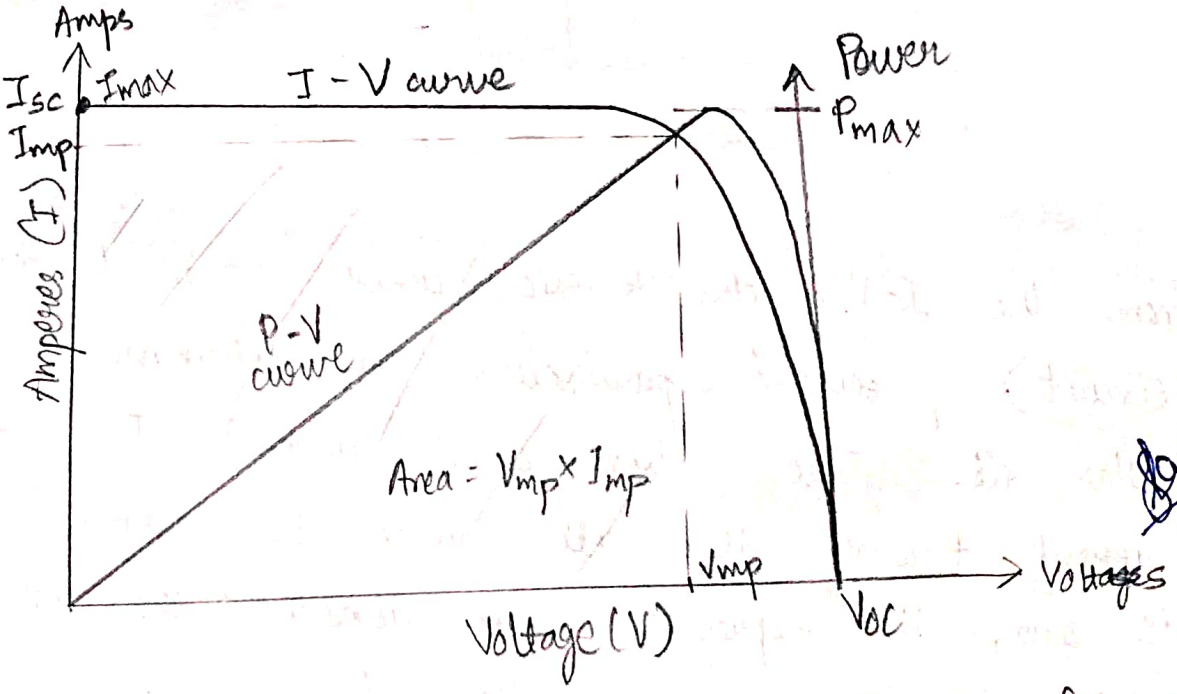

Fig. A typical I-V curve & power curve of a solar cell

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Observations :

Table I :- I - V Characteristics of solar cell illuminated under room lamp.

No filter		Filter 1 (pink)		Filter 2 (green)		Filter 3 (Yellow)	
I (μA)	V (V)	I (μA)	V (V)	I (μA)	V (V)	I (μA)	V (V)
1617	0.260	~~1057~~	~~0.17~~	460	0.074	1273	0.204
1520	1.430	~~1007~~	~~0.893~~	457.9	0.165	1261	0.454
1458	1.979	~~980~~	~~1.244~~	455.4	0.252	1242	0.805
1412	2.277	~~957~~	~~1.558~~	451.2	0.426	1226	1.069
1389	2.674	~~929~~	~~1.875~~	447.7	0.537	1194	1.534
1263	3.020	~~9~~	~~1.8~~	443.6	0.672	1174	1.773
1168	3.314	1099	0.18	441.1	0.742	1145	2.058
950	3.686	1084	0.426	435.6	0.900	1132	2.168
906	3.740	1072	0.600	429.9	1.041	1104	2.377
827	3.809	1020	1.368	424.9	1.164	1088	2.470
731	3.901	984	1.792	419.9	1.272	1073	2.563
640	3.978	940	2.207	414.2	1.390	1026	2.804
579.4	4.025	883	2.580	409.2	1.486	954	3.059
527.7	4.062	813	2.927	401.7	1.615	902	3.197
455.5	4.111	752	3.142	394.6	1.725	890	3.222
428	4.129	662	3.358	387.1	1.825	850	3.310
393.6	4.149	564.3	3.533	379.4	1.922	824	3.360
356.7	4.171	479.3	3.653	371.5	2.018	780	3.440
303.9	4.201	427.8	3.714	360.3	2.131	745	3.497
265.3	4.223	378.1	3.773	346.5	2.250	705	3.557
182.9	4.236			340.8	2.296	675	3.598
						652	3.628
						638	3.647

No filter		Filter 1		Filter 2		Filter 3	
I (μA)	V (V)	I (μA)	V (V)	I (μA)	V (V)	I (μA)	V (V)
145.4	4.243	351.1	3.802	335.2	2.339	616	3.673
120.7	4.284	339.1	3.816	319.7	2.447	576.3	3.720
107.7	4.290	326.0	3.830	313.0	2.488	554.6	3.745
87.8	4.300	315.8	3.833	309.0	2.517	531.8	3.770
74.8	4.306	306.7	3.842	304.2	2.640	511.1	3.792
66.6	4.324	299.5	3.849	316.6	2.676	491.4	3.811
59.8	4.327	287.7	3.861	302.1	2.740	480.8	3.822
50.8	4.331	283.0	3.866	288.4	2.799	471.8	3.830
46.6	4.334	277.2	3.870	284.9	2.815	430.5	3.868
43.3	4.336	265.2	3.883	277.63	2.845	384.8	3.909
43.0	4.303	258.5	3.897	271.6	2.865	344.8	3.942
		222.4	3.918	256.9	2.919	295.6	3.981
		207.9	3.931	238.1	2.982	241.6	4.021
		177.7	3.956	202.5	3.089	196.4	4.053
		168.7	3.967	176.5	3.159	168.3	4.072
		144.9	3.982	148.5	3.227	140.4	4.090
		116.5	4.004	131.5	3.265	120.5	4.103
		94.1	4.020	119.0	3.292	102.1	4.114
		75.8	4.033	106.9	3.313	87.5	4.123
		56.9	→ 4.046	93.2	3.344	76.0	4.130
		43.1	→ 4.056	75.5	3.378	64.5	4.137
		40.5	→ 4.057	59.2	→ 3.407	53.9	4.143
				52.0	→ 3.421	45.4	4.146
				42.0	→ 3.446	41.4	4.151
				34.5	→ 3.459		

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Source : Lamp.

Filter 4 (blue)	
I (μA)	V (V)
634	0.102
627	0.351
608	0.893
599	1.087
583	1.404
569.2	1.643
549.8	1.899
519.7	2.022
491.1	2.417
479.6	2.489
453.3	2.635
424.6	2.766
399.0	2.887
381.5	2.929
373.4	2.956
364.4	2.980
362.7	2.991
343.5	3.049
330.3	3.086
322.5	3.108
306.8	3.149
295.1	3.177
280.2	3.125
271.4	3.235
261.5	3.257
256.0	3.268
245.3	3.291
238.0	3.300
227.0	3.321
213.7	3.349
198.0	3.383
174.6	3.422

Filter 4 (blue)	
I (μA)	V (V)
155.3	3.456
139.0	3.483
123.7	3.509
110	3.530
102.9	3.538
84.3	3.540
74.6	3.550
60.0	3.570
51.4	3.580
43.4	3.592
36.0	3.600

Observations: I-V Characteristics of a solar cell illuminated under the sun

No filter		Filter 1 (yellow)		Filter 2 (green)		Filter 3 (pink)		Filter 4 (blue)	
$I_{(\mu A)}$	$V_{(V)}$	$I_{(\mu A)}$	$V_{(V)}$	$I_{(\mu A)}$	$V_{(V)}$	$I_{(\mu A)}$	$V_{(V)}$	$I_{(\mu A)}$	$V_{(V)}$
73.8	0.489	51.48	0.432	31.53	0.159	38.50	0.219	26.19	0.301
73.8	0.821	51.5	0.569	31.27	0.754	37.85	0.888	26.12	0.716
73.5	1.288	50.70	1.060	31.04	0.954	36.76	1.123	26.04	0.804
73.2	1.609	50.39	1.397	30.88	1.051	36.70	1.532	25.90	1.134
72.6	1.823	49.80	1.888	30.72	1.157	36.65	1.716	25.85	1.510
72.2	2.332	49.74	2.122	30.34	1.544	36.55	2.165	25.79	1.667
72.0	2.437	49.63	2.715	30.24	2.079	36.41	2.570	25.64	1.703
72.5	2.860	49.34	2.938	29.90	2.233	35.80	2.890	24.85	2.114
71.1	3.572	49.03	3.237	29.14	2.737	35.33	3.194	24.72	2.592
70.0	3.743	48.10	3.834	28.52	3.501	33.80	3.787	23.82	2.960
69.3	3.852	43.61	4.584	28.37	3.648	31.13	4.364	22.59	3.084
66.8	4.116	40.27	4.784	27.90	3.949	29.83	4.503	22.47	3.730
64.8	4.291	37.61	4.970	26.60	4.320	28.75	4.855	21.73	4.014
60.8	4.605	37.20	5.001	26.16	4.386	27.21	4.966	20	4.0
55.06	4.927	34.90	5.090	26.07	4.417	22.89	5.026	19.84	4.368
50.38	5.113	33.45	5.148	26.64	4.608	22.30	5.056	19.28	4.454
43.20	5.313	31.09	5.231	23.67	4.909	20.37	5.154	18.23	4.560
37.07	5.443	29.33	5.282	20.98	4.938	17.24	5.280	17.35	4.670
33.64	5.528	25.18	5.388	17.23	5.139	16.95	5.285	16.74	4.734
26.35	5.649	23.90	5.412	15.44	5.269	13.83	5.385	14.67	4.932
21.88	5.710	17.76	5.530	14.96	5.226	12.17	5.433	15.58	4.863
13.50	5.823	14.74	5.580	11.27	5.345	10.91	5.457	13.83	4.945
8.96	5.873			8.96	5.411	9.69	5.480	12.91	4.973
				7.36	5.446				

No filter		Filter 1		Filter 2		filter 3		Filter 4	
I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)
6.00	5.900	11.27	5.632	3.80	5.528	7.60	5.530	8.96	5.200
1.19	5.941	7.50	5.683	2.66	5.546	5.78	5.572	6.20	5.316
		5.34	5.711	1.88	5.559	3.55	5.616	5.89	5.329
		2.94	5.737	1.11	5.565	2.44	5.636	4.16	5.390
		1.15	5.751			1.61	5.652	3.02	5.427
						1.13	5.660	1.75	5.465
								1.09	5.481

Apparatus Required:-

i) Solar cell
ii) Potentiometer
iii) Optical filter papers
iv) Multimeters
v) Connecting wires.

Calculations:-

(I) For Lamp as Source:-

From the attached plots, we obtain MPP, I_{sc}, V_{oc} & fill factor for various filters on a solar cell illuminated by a Lamp.

i) No filter:

$I_{sc} = I_{max} = 1617\ \mu A$

$V_{oc} = 4.303\ V$

Maximum Power output, $P = 3870.75\ \mu W$

$I_{mp} = 1168.0\ \mu A$ $V_{mp} = 3.314\ V$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.5563$$

ii) Filter 1: (pink)

$I_{sc} = I_{max} = 1099\ \mu A$

$V_{oc} = 4.057\ V$

Maximum Power, $P = 2379.65\ \mu W$

$I_{mp} = 813\ \mu A$ $V_{mp} = 2.927\ V$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = \cancel{1.002}\ 0.53437$$

iii) filter 2: (green)

$I_{sc} = I_{max} = 460\ \mu A$

$V_{oc} = 3.459\ V$

Maximum power, $P = 847.22\ \mu W$

$I_{mp} = 316.6\ \mu A$ $V_{mp} = 2.676\ V$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.5325$$

iii) filter 3:- (yellow)

$I_{sc} = 1273\ \mu A$ $V_{oc} = 4.151\ V$

$P_{max} = 2918.28\ \mu W$ $V_{mp} = 3.059\ V$ $I_{mp} = 954.0\ \mu A$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.5523$$

iv) filter 4:- (Blue)

$I_{sc} = 634\ \mu A$ $V_{oc} = 3.600\ V$ $P_{max} = 1194.45\ \mu W$

$V_{mp} = 2.635\ V$ $I_{mp} = 453.3\ \mu A$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.5233$$

(II) for Sun as a source:-

i) No filter :

$I_{sc} = 73.8\ mA$ $V_{oc} = 5.941\ V$ $P_{max} = 280.0\ mW$

$V_{mp} = 4.606\ V$ $I_{mp} = 60.80\ mA$

Fill factor, $$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.6386$$

ii) Filter 1 : (yellow)

$I_{sc} = 51.48$ mA $\quad V_{oc} = 5.751$ V

$P_{max} = 199.9$ mW $\quad V_{mp} = 4.584$ V $\quad I_{mp} = 43.61$ mA

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.6752$$

iii) Filter 2 : (green)

$I_{sc} = 31.53$ mA $\quad V_{oc} = 5.565$ V $\quad P_{max} = 122.75$ mW

$V_{mp} = 4.608$ V $\quad I_{mp} = 26.64$ mA

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = \cancel{0.700}\ 0.6996$$

iv) Filter 3 : (pink)

$I_{sc} = 38.5$ mA $\quad V_{oc} = 5.660$ V $\quad P_{max} = 139.58$ mW

$V_{mp} = 4.855$ V $\quad I_{mp} = 28.75$

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = 0.6405$$

v) Filter 4 : (blue)

$I_{sc} = 26.19$ mA $\quad V_{oc} = 5.481$ V $\quad P_{max} = 87.22$ mW

$V_{mp} = 4.014$ V $\quad I_{mp} = 21.73$ mA

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} = \cancel{0.607}\ 0.6076$$

(III) Comparing Maximum Power output for room light & sunlight for various filters.

Filter	Maximum Power (Lamp)	Pmax (Sunlight)
No-filter	3870.75 μW	280.0 mW
Yellow	2918.28 μW	199.9 mW
Pink	2379.65 μW	139.58 mW
Blue	1194.45 μW	87.22 mW
Green	847.22 μW	122.75 mW

The maximum power output for roomlight & sunlight differs by 2 orders of magnitude (i.e. ~x100). This difference can be attributed to higher intensity & broader spectral distribution of sunlight compared to the lamp. Each filter allows only a certain range of wavelengths in the spectrum to pass & the power output depends on how much intensity of that transmitted wavelength was present in the source spectrum.

Therefore, the max. power output depends on source spectrum & properties of the optical filter both.

NOTE :- The plots attached for Max. power output for different filters with sun & lamp as source have filter color on the x-axis. The filter color are 'not' arranged in terms of wavelength (since exact value is unknown).

Error Analysis :-

We have used the formula, for fill factor

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

Error propagation,

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

$$\Delta FF = \sqrt{\left(\frac{I_{mp}}{V_{oc} I_{sc}} \cdot \Delta V_{mp}\right)^2 + \left(\frac{V_{mp}}{V_{oc} I_{sc}} \cdot \Delta I_{mp}\right)^2 + \left(\frac{-V_{mp} I_{mp}}{V_{oc}^2 I_{sc}} \cdot \Delta V_{oc}\right)^2 + \left(\frac{-V_{mp} I_{mp}}{V_{oc} I_{sc}^2} \cdot \Delta I_{sc}\right)^2}$$

$$\Delta FF = \sqrt{\left(\frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \cdot \frac{\Delta V_{mp}}{V_{mp}}\right)^2 + \left(\frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \cdot \frac{\Delta I_{mp}}{I_{mp}}\right)^2 + \left(\frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \cdot \frac{\Delta I_{sc}}{I_{sc}}\right)^2 + \left(\frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \cdot \frac{\Delta V_{oc}}{V_{oc}}\right)^2}$$

$$\Delta FF = FF \sqrt{\left(\frac{\Delta V_{mp}}{V_{mp}}\right)^2 + \left(\frac{\Delta I_{mp}}{I_{mp}}\right)^2 + \left(\frac{\Delta I_{sc}}{I_{sc}}\right)^2 + \left(\frac{\Delta V_{oc}}{V_{oc}}\right)^2} \quad \text{— (I)}$$

Using this formula, for each filter & source,

& considering, $\Delta V_{mp} = 0.001\ V$ $\quad \Delta I_{mp} = \cancel{0.001}\ 1\ \mu A$ (for lamp)

$\Delta V_{oc} = 0.001\ V$ $\quad \Delta I_{mp} = 0.01\ mA$ (for sun)

$\Delta I_{sc} = 1\ \mu A$ (for lamp)

$\Delta I_{sc} = \cancel{0.1}\ 0.01\ mA$ (for sun)

~~This~~ These are chosen according to the multimeter's least count in these range of values.

~~Filters~~ ~~Δ(FF) (Lamp source)~~ ~~Δ(FF) (Sunlight)~~

Table :- Fill factor calculations & uncertainties ~~&~~ calculated using (I).

Filters	(FF) (Lamp)	Δ(FF) (Lamp)	(FF) (sun)	Δ(FF) (sun)
No-filter	0.5563	0.0006	0.6386	0.0002
Yellow	0.5523	0.0008	0.6752	0.0003
Green	0.5325	0.0021	0.6996	0.0004
Pink	0.5337	0.0008	0.6405	0.0003
Blue	0.5233	0.0014	0.6076	0.0004

Results & Discussion :-

The I-V Characteristics of a solar cell were obtained under illumination under an incandescent lamp & direct sunlight using various optical filter papers. From the attached I-V curve plots, short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) & maximum ~~ou~~ power output (MPP) were ~~ed~~ obtained & the fill factor was calculated along with the associated uncertainties (mentioned in table above).

The maximum power output was plotted as a function of filter color & compared for the case of lamp as a source & sun as a source. It is observed that MPP in both cases differ by ~~ao~~ 2 orders of magnitude. This is because it depends on transmission properties of the filters and the spectral distribution of the incident source. Sunlight had ~100 times higher MPP than lamp source.

Conclusion :-

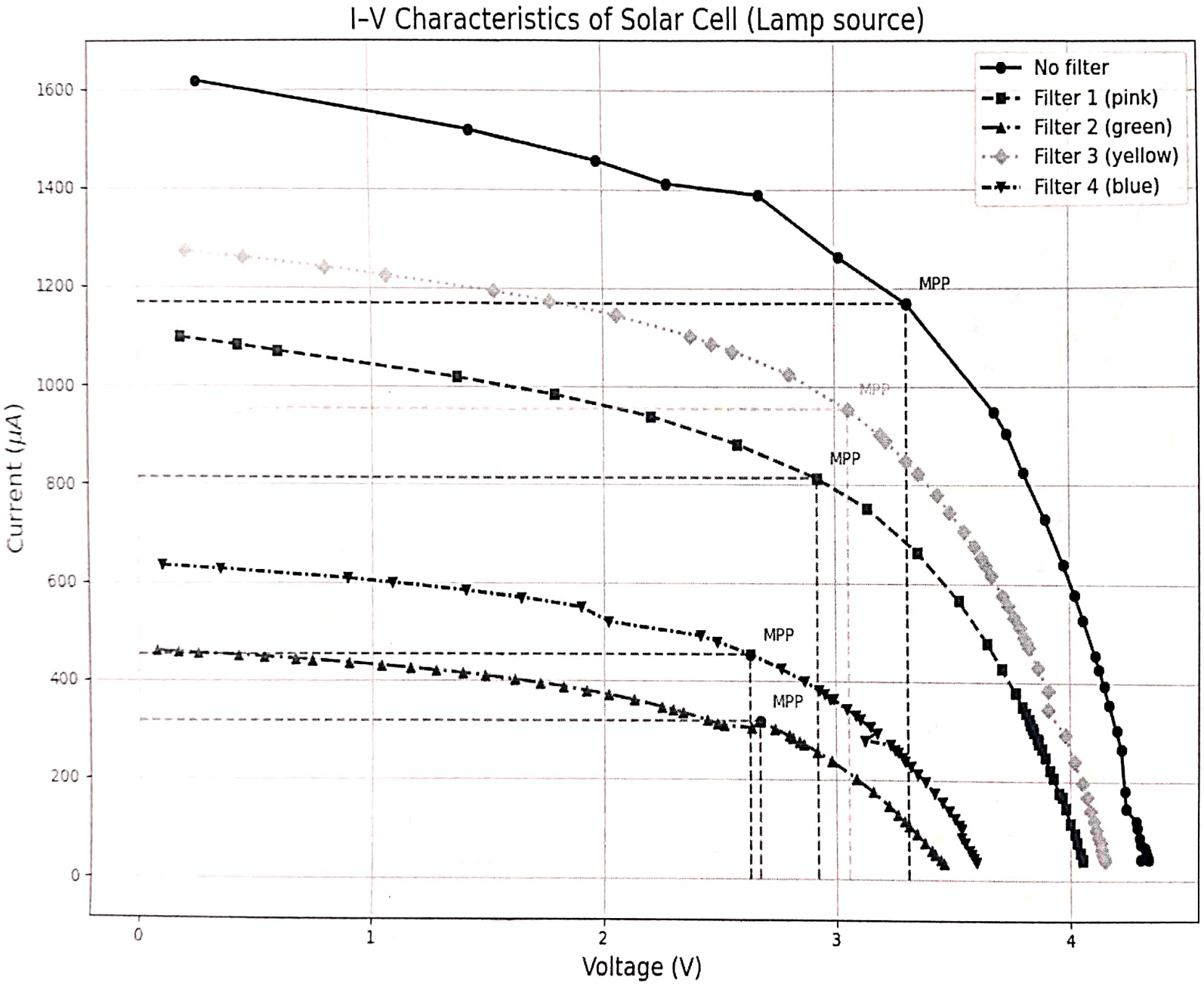
The experiment demonstrated the I-V Characteristics of a Si solar cell & determination of its maximum power point & fill factor. The output power strongly depended on the intensity & nature of the source, with sunlight producing significantly higher power than lamp. Overall, the experiment ~~demonstrates I-V chara~~ highlights the importance of measurement conditions & spectral properties of light & photovoltaic energy conservation in Silicon solar cells.

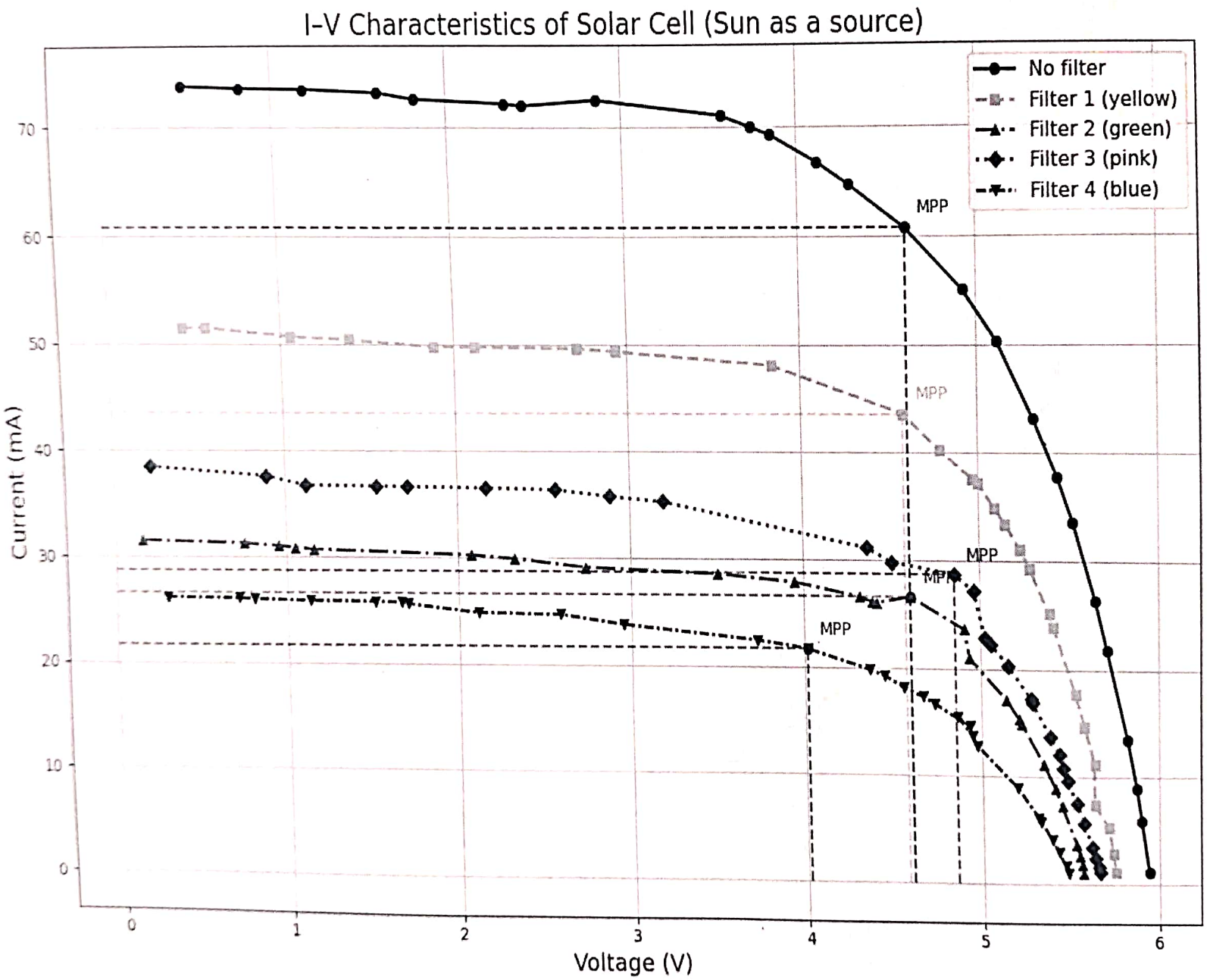
Sources of Error :-

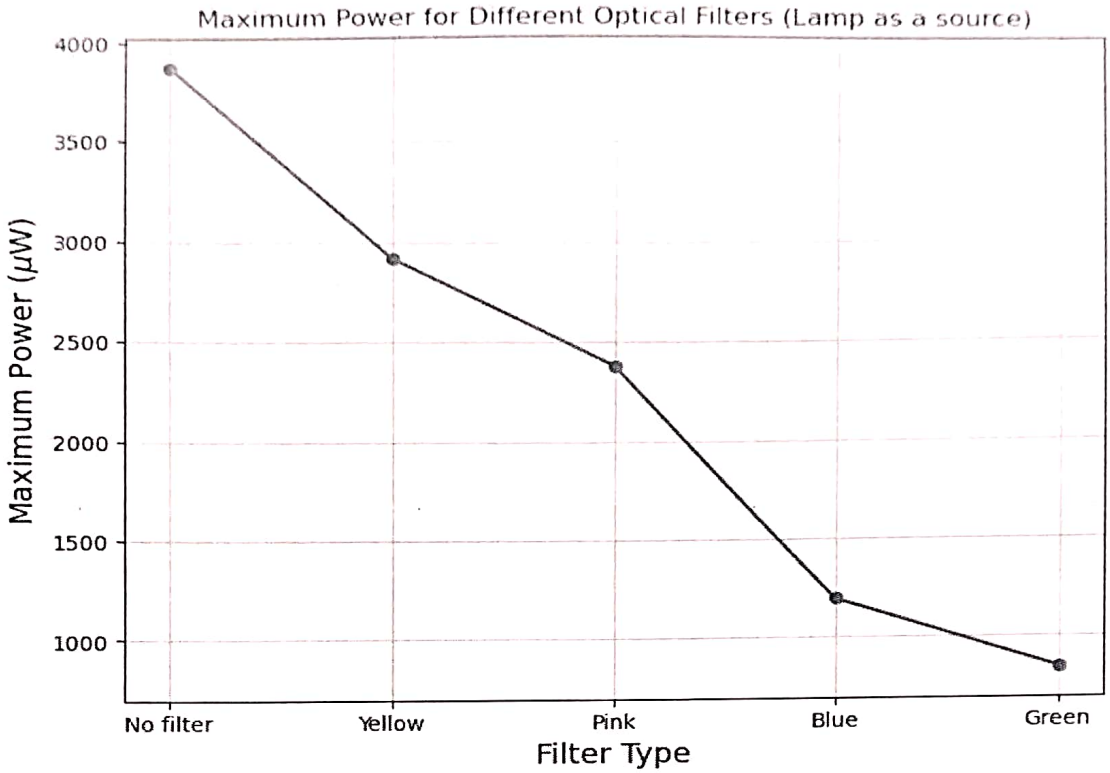
i) Fluctuations of intensity of sunlight during measurement significantly affects the results.

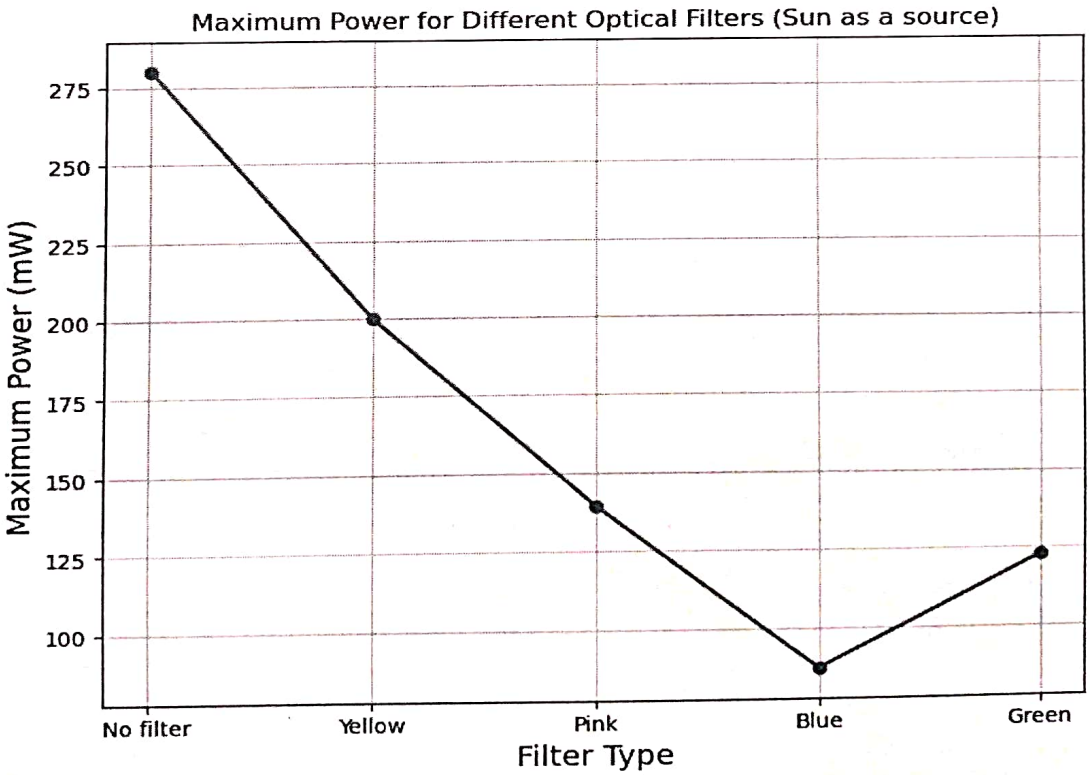
ii) Improper placement of filter paper of solar cell (causes uneven illumination)

iii) ~~Heat~~ Uncertainty in bandwidth of colored filter papers.


I-V Characteristics of Solar Cell (Lamp source)
No filter
Filter 1 (pink)
Filter 2 (green)
Filter 3 (yellow)
Filter 4 (blue)
MPP
MPP
MPP
MPP
MPP
Current (μA)
Voltage (V)
0
200
400
600
800
1000
1200
1400
1600
0
1
2
3
4


I-V Characteristics of Solar Cell (Sun as a source)
No filter
Filter 1 (yellow)
Filter 2 (green)
Filter 3 (pink)
Filter 4 (blue)
MPP
MPP
MPP
MPP
MPP
Current (mA)
Voltage (V)
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6


Maximum Power for Different Optical Filters (Lamp as a source)
Maximum Power (μW)
4000
3500
3000
2500
2000
1500
1000
No filter
Yellow
Pink
Blue
Green
Filter Type


Maximum Power for Different Optical Filters (Sun as a source)
Maximum Power (mW)
275
250
225
200
175
150
125
100
No filter
Yellow
Pink
Blue
Green
Filter Type