Study of I-V Characterstics of a Solar Cell

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(Dated: March 11, 2025)

This experiment investigates the I-V characteristics of a solar cell under different illumination conditions – room light and sunlight, using various optical filters. We try to analyze the impact of different light intensities and wavelengths on the performance of the solar cell. The experiment was performed by measuring current and voltage characteristics using a potentiometer and multimeter while varying external parameters such as light source and filters. Key performance metrics such as short-circuit current ($I_{\rm sc}$), open-circuit voltage ($V_{\rm oc}$), fill factor (FF) are determined for each scenario.

I. OBJECTIVE

1. Study of I-V Characteristic of a solar cell illuminated by an incandescent lamp, at different frequencies.
2. Study of I-V Characteristic of a solar cell illuminated by the Sun, at different frequencies.

II. THEORY

Solar cells, also known as photovoltaic (PV) cells can convert sunlight directly into electricity using the photovoltaic effect. This technology is widely used in satellites, power grids, and renewable energy solutions, with research fo- cusing on efficiency, cost reduction, and integration into everyday applications such as electric vehicles and smart grids.

The fundamental working principle of these cells are based on the behavior of p-n junction diodes. At the p-n junction, electrons from the n-type region diffuse towards the p-type region, while holes from the p-type region move toward the n-type region. This diffusion process exposes positively charged ion cores in the n-region and negatively charged ion cores in the p-region, leading to the formation of an electric field across the junction. This potential barrier is known as the depletion region.

When sunlight strikes the surface of a solar cell, photons with energy greater than the band gap energy of the semiconductor material excite electrons from the valence band to the conduction band. These electron-hole pairs are then separated due to the existing potential barrier, creating a potential difference across the solar cell, similar to a battery.

A solar cell typically consists of the following key components:

- **Front Contact:** A transparent conductive layer (usually made of materials like indium tin oxide) that allows sunlight to pass through while also conducting the generated current.
- **p-n Junction:** The heart of the solar cell, where the p-type and n-type semiconductors meet. This junction creates an electric field that helps in the separation of electron-hole pairs generated by the absorbed sunlight. that allows sunlight to pass through while also conducting the generated current.
- **Absorber Layer:** This is where the majority of sunlight is absorbed to generate electron-hole pairs. Silicon is commonly used in this layer due to its effective light-absorbing properties.
- **Back Contact:** A conductive layer at the rear of the cell that completes the electrical circuit, allowing electrons to return after passing through the external load.

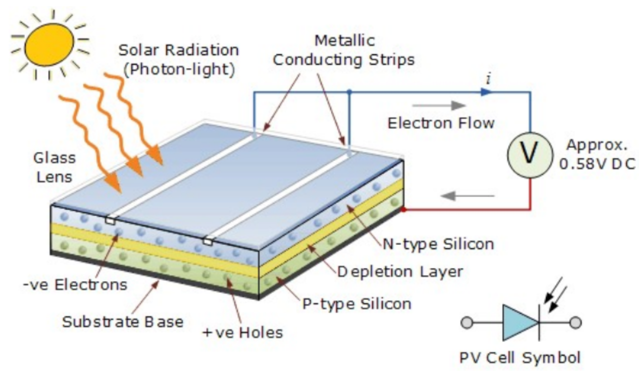

FIG. 1: Parts of a Solar Cell

Additionally, to enhance efficiency, modern solar cells incorporate anti-reflective coatings to minimize light loss, passivation layers to reduce recombination, and multi-junction structures that utilize different semiconductor materials to capture a broader range of the solar spectrum.

Mathematically, the diode equation is expressed as:

$$I = I_0\left(e^{\frac{qV}{nk_BT}} - 1\right) - I_L \tag{1}$$

where, I_0 is the dark saturation current (leakage current in the absence of light), q is the charge of an electron, V is the applied voltage, k_B is the Boltzmann constant, T is the absolute temperature, I_L is the light generated

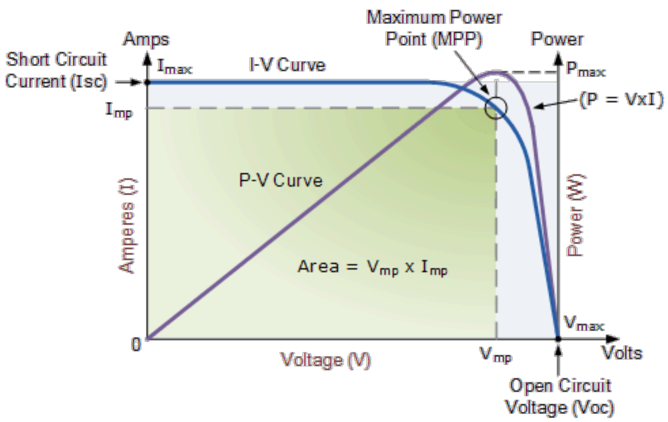

FIG. 2: Typical I-V and power curves of a solar cell

current (The additional currentproduced due to photon absorption, which enhances the overall current output) and n is the ideality factor (a measure of how closely the diode follows the ideal diode equation).

The performance of a solar cell is measured by the following parameters:

- **Short-Circuit Current (I_{sc}):** The maximum current generated when the solar cell is short-circuited (V = 0). It depends on the intensity of incident light and the material properties of the cell.
- **Open Circuit Voltage (V_{oc}):** The maximum voltage produced when no current flows (I = 0). It is influenced by the semiconductor material and temperature.
- **Fill Factor (FF):** A measure of how 'square' the I-V curve appears, defined as:

$$FF = \frac{V_{\mathrm{mp}} I_{\mathrm{mp}}}{V_{\mathrm{oc}} I_{\mathrm{oc}}} \tag{2}$$

  where V_{mp} and I_{mp} are the voltage and current at maximum power output, respectively.
- **Efficiency (η):** The ratio of the electrical output power to the incident solar power, expressed as:

$$\eta = \frac{P_{\mathrm{max}}}{P_{\mathrm{in}}} = \frac{V_{\mathrm{oc}} I_{\mathrm{sc}} \cdot FF}{P_{\mathrm{in}}} \tag{3}$$

  where P_{in} denotes the incident light power per unit area. The efficiency is influenced by light intensity, temperature, and the material properties of the solar cell.

III. EXPERIMENTAL SETUP

Apparatus

1. Solar cell
2. Potentiometer
3. Optical filter papers
4. Multimeters
5. Incandescent lamp
6. Connecting wires

A circuit diagram of the experimental setup is illustrated in Figure 3. A potentiometer is employed to vary the resistance within the circuit, allowing for controlled adjustment of the load. A multimeter is connected in series with the solar cell to measure the current (I), while a second multimeter is connected in parallel to measure the voltage (V) across the solar cell. Now we use this to analyze the impact of different light intensities and wavelengths on the performance of the solar cell under both incandescent light and sunlight.

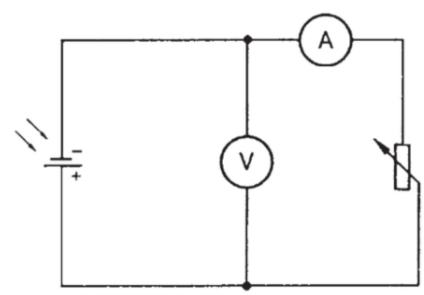

FIG. 3: Circuit diagram of the experimental setup

IV. OBSERVATION AND CALCULATIONS

Tables I and II show the observed current and voltage values for different filters under the two lighting conditions. The corresponsind plots are shown below. The exponential curves have been fitted with the general equation:

$$I(V) = Ae^{BV} + C \tag{4}$$

A. Under Incandescent Lamp

1. No Filter

- $V_{\mathrm{mp}} = 2.318$ V and $I_{\mathrm{mp}} = 0.395$ mA
- Max. Power (P_{max}) $= 0.916 \pm 0.023$ mW
- Short Circuit Current (I_{sc}) $= 0.555 \pm 0.001$ mA
- Open Circuit Voltage (V_{oc}) $= 3.257 \pm 0.001$ V
- Fill Factor $= 0.507 \pm 0.016$

TABLE I: I-V Data for Solar Cell under Incandescent Light

No Filter		Red		Yellow		Magenta		Green		Blue	
V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)
0.009	0.555	0.031	0.175	0.023	0.33	0.028	0.36	2.135	0.01	0.018	0.25
0.097	0.554	0.136	0.174	0.124	0.33	0.314	0.36	2.165	0.01	0.121	0.25
0.172	0.554	0.241	0.172	0.272	0.33	0.523	0.36	1.995	0.03	0.207	0.25
0.300	0.551	0.389	0.170	0.346	0.33	0.667	0.35	2.038	0.03	0.214	0.25
0.581	0.548	0.518	0.167	0.462	0.33	0.952	0.34	1.906	0.04	0.386	0.25
0.773	0.544	0.656	0.164	0.521	0.33	1.148	0.33	1.978	0.04	0.412	0.25
0.865	0.541	0.744	0.161	0.695	0.33	1.460	0.32	1.847	0.05	0.676	0.24
1.067	0.532	0.822	0.158	0.749	0.32	1.811	0.28	1.887	0.05	0.922	0.23
1.176	0.528	0.890	0.156	0.972	0.31	1.928	0.27	1.729	0.06	1.192	0.22
1.350	0.516	0.960	0.153	1.072	0.31	2.018	0.25	1.769	0.06	1.226	0.22
1.452	0.508	1.064	0.149	1.161	0.31	2.029	0.25	1.791	0.06	1.326	0.22
1.608	0.496	1.139	0.145	1.288	0.30	2.114	0.24	1.641	0.07	1.410	0.21
1.737	0.483	1.204	0.142	1.324	0.30	2.181	0.23	1.679	0.07	1.518	0.20
1.792	0.476	1.302	0.136	1.427	0.29	2.263	0.22	1.491	0.08	1.815	0.18
1.892	0.463	1.414	0.129	1.529	0.28	2.381	0.19	1.528	0.08	2.041	0.15
1.967	0.455	1.523	0.121	1.612	0.28	2.483	0.17	1.583	0.08	2.208	0.12
2.043	0.443	1.610	0.114	1.652	0.27	2.573	0.15	1.346	0.09	2.376	0.09
2.109	0.433	1.711	0.104	1.710	0.27	2.672	0.12	1.421	0.09	2.496	0.07
2.230	0.410	1.782	0.097	1.727	0.26	2.745	0.10	1.191	0.10	2.593	0.04
2.290	0.394	1.841	0.091	1.846	0.25	2.831	0.07	1.229	0.10	2.695	0.01
2.318	0.395	1.905	0.084	1.957	0.24	2.887	0.05	1.297	0.10		
2.364	0.385	1.971	0.076	2.035	0.23	2.949	0.03	1.007	0.11		
2.431	0.370	2.020	0.070	2.134	0.21	2.971	0.02	1.117	0.11		
2.547	0.341	2.110	0.058	2.210	0.20			0.750	0.12		
2.645	0.310	2.167	0.050	2.325	0.18			0.859	0.12		
2.708	0.280	2.203	0.044	2.501	0.14			0.997	0.12		
2.729	0.273	2.241	0.038	2.619	0.11			0.250	0.13		
2.772	0.260	2.274	0.032	2.715	0.08			0.474	0.13		
2.829	0.241	2.306	0.027	2.784	0.06			0.637	0.13		
2.860	0.229	2.323	0.023	2.866	0.03			0.009	0.14		
2.905	0.211			2.909	0.02			0.107	0.14		
2.958	0.190			2.910	0.00						
3.023	0.161										
3.070	0.140										
3.112	0.119										
3.127	0.111										
3.196	0.070										
3.212	0.060										
3.240	0.042										
3.257	0.032										

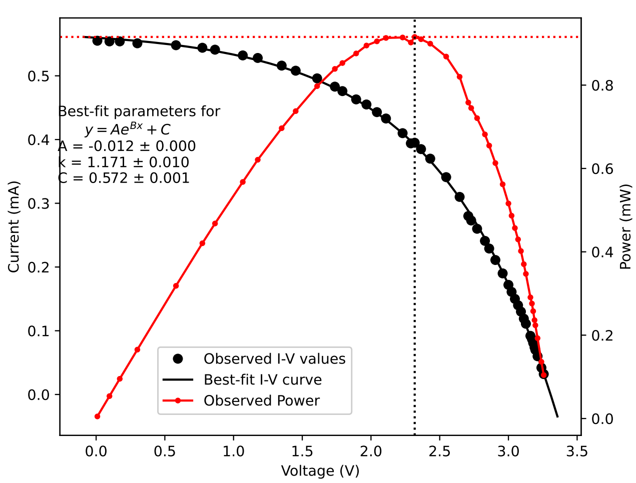

FIG. 4: I-V and P-V curves for the solar cell with no filter indoors

2. *Red Filter*

- $V_{\mathrm{mp}} = 1.523$ V and $I_{\mathrm{mp}} = 0.121$ mA
- Max. Power ($P_{\max}$) $= 0.184 \pm 0.015$ mW
- Short Circuit Current (I_{sc}) $= 0.175 \pm 0.001$ mA
- Open Circuit Voltage (V_{oc}) $= 2.323 \pm 0.001$ V
- Fill Factor $= 0.453 \pm 0.046$

TABLE II: I-V Data for Solar Cell under Sunlight

No Filter		Red		Yellow		Magenta		Green		Blue	
V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)	V (V)	I (mA)
0.254	77.10	0.286	52.61	0.391	77.10	0.181	31.38	0.190	37.35	0.231	43.41
0.781	76.10	0.781	44.31	1.771	76.10	0.982	28.38	1.400	36.53	0.572	43.01
2.548	73.10	1.361	38.72	4.122	73.10	2.132	26.89	4.426	33.72	1.841	42.61
4.895	63.10	2.861	33.81	4.724	63.10	4.215	24.69	4.819	26.60	4.508	40.98
5.276	57.55	4.312	30.87	4.931	55.80	4.591	22.19	4.910	23.10	4.689	38.76
5.405	49.32	4.500	27.20	4.982	53.43	4.612	19.78	4.912	21.99	4.821	35.68
5.421	45.86	4.669	23.18	5.032	48.54	4.782	17.72	4.956	19.93	4.936	31.79
5.441	43.35	4.697	20.21	5.098	41.24	4.853	15.24	4.995	17.93	4.983	29.86
5.444	40.67	4.845	17.61	5.180	37.75	4.905	13.40	5.015	16.56	5.052	26.03
5.492	33.09	4.880	15.90	5.222	32.34	4.939	12.30	5.038	15.29	5.081	24.77
5.494	38.81	4.870	15.87	5.237	31.38	4.922	10.35	5.050	14.72	5.139	22.36
5.497	28.72	4.933	14.23	5.251	29.42	5.008	9.45	5.086	13.91	5.164	20.35
5.502	36.71	4.969	12.47	5.263	27.25	5.019	8.70	5.093	12.86	5.197	17.68
5.506	34.98	4.999	10.67	5.279	24.92	5.033	7.68	5.116	11.47	5.220	16.09
5.511	26.78	4.979	9.60	5.302	22.63	5.057	6.70	5.121	10.57	5.237	14.45
5.517	23.12	5.030	8.00	5.319	20.29	5.041	6.38	5.144	8.76	5.243	13.13
5.528	31.68	5.041	6.23	5.325	18.55	5.064	6.00	5.169	7.57	5.258	12.42
5.540	19.27	5.058	5.23	5.333	17.09	5.068	5.04	5.173	6.98	5.265	11.13
5.549	18.86	5.091	4.28	5.330	16.53	5.086	4.39	5.235	3.68	5.275	10.43
5.580	15.61	5.104	3.44	5.334	15.18	5.092	3.85	5.240	3.20	5.281	9.56
5.588	13.53	5.128	1.00	5.342	13.84	5.103	3.42	5.279	2.94	5.301	8.68
5.594	11.93			5.344	12.89	5.111	2.85	5.300	1.07	5.298	7.15
5.598	10.82			5.351	11.74	5.124	2.29	5.309	1.03	5.300	6.43
5.606	7.25			5.356	10.81	5.125	1.82			5.276	5.81
5.617	5.18			5.354	9.68	5.151	1.00			5.291	4.06
5.630	2.55			5.356	7.97					5.296	2.82
5.633	0.15			5.355	7.05					5.292	2.03
5.634	1.93			5.351	6.51					5.296	1.29
5.638	1.30			5.347	5.85						
5.639	1.00			5.355	3.46						
5.639	0.62			5.348	1.64						
5.641	0.04			5.369	1.04						

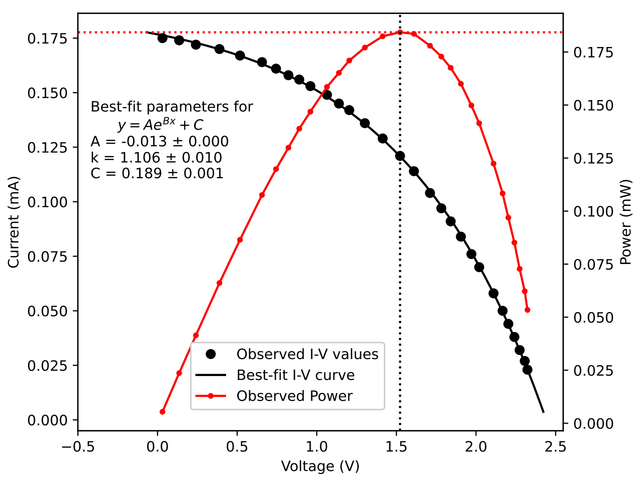

FIG. 5: I-V and P-V curves for the solar cell with red filter indoors

3. *Blue Filter*

- $V_{\mathrm{mp}} = 1.815$ V and $I_{\mathrm{mp}} = 0.18$ mA
- Max. Power (P_{max}) $= 0.327 \pm 0.018$ mW
- Short Circuit Current (I_{sc}) $= 0.25 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 2.695 \pm 0.001$ V
- Fill Factor $= 0.485 \pm 0.033$

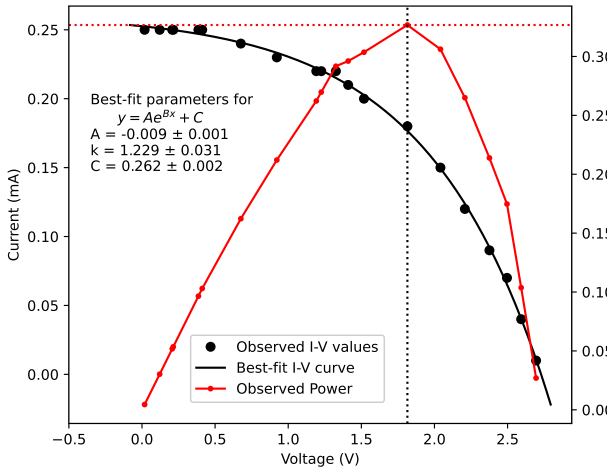

FIG. 6: I-V and P-V curves for the solar cell with blue filter indoors

4. *Green Filter*

- $V_{\text{mp}} = 1.297$ V and $I_{\text{mp}} = 0.10$ mA
- Max. Power (P_{max}) $= 0.130 \pm 0.013$ mW
- Short Circuit Current (I_{sc}) $= 0.14 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 2.165 \pm 0.001$ V
- Fill Factor $= 0.428 \pm 0.053$

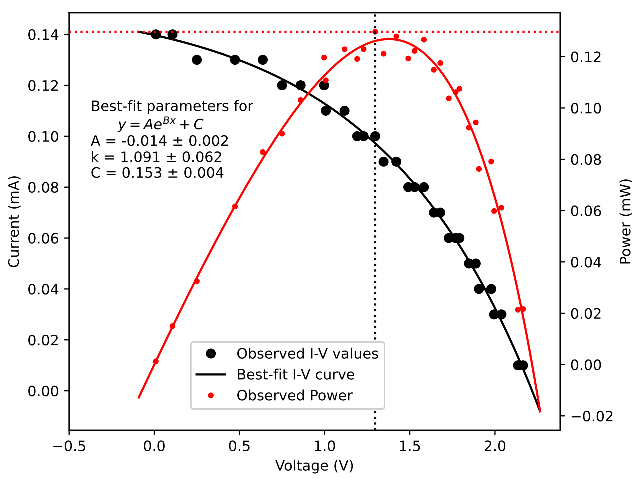

FIG. 7: I-V and P-V curves for the solar cell with green filter indoors

5. *Magenta Filter*

- $V_{\text{mp}} = 1.928$ V and $I_{\text{mp}} = 0.27$ mA
- Max. Power (P_{max}) $= 0.521 \pm 0.019$ mW
- Short Circuit Current (I_{sc}) $= 0.36 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 2.971 \pm 0.001$ V
- Fill Factor $= 0.487 \pm 0.023$

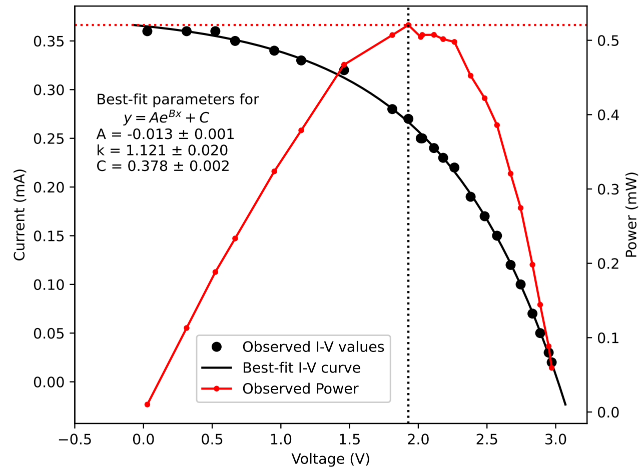

FIG. 8: I-V and P-V curves for the solar cell with magenta filter indoors

6. *Yellow Filter*

- $V_{\text{mp}} = 1.957$ V and $I_{\text{mp}} = 0.24$ mA
- Max. Power (P_{max}) $= 0.470 \pm 0.020$ mW
- Short Circuit Current (I_{sc}) $= 0.33 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 2.91 \pm 0.01$ V
- Fill Factor $= 0.489 \pm 0.025$

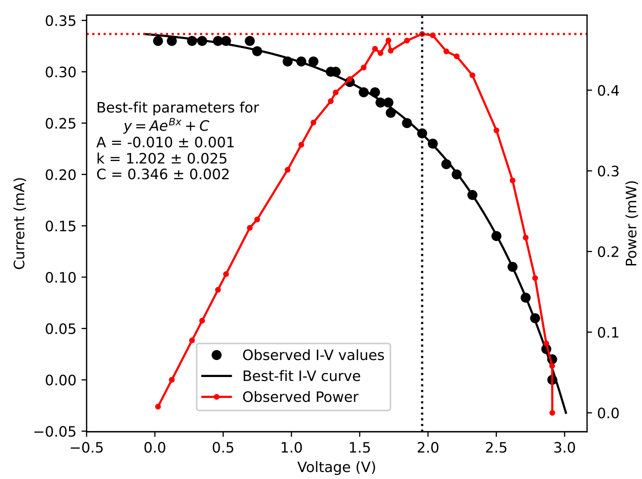

FIG. 9: I-V and P-V curves for the solar cell with yellow filter indoors

B. Under Sunlight

1. *No Filter*

- $V_{\text{mp}} = 4.895$ V and $I_{\text{mp}} = 63.1$ mA
- Max. Power (P_{max}) $= 308.874 \pm 0.080$ mW
- Short Circuit Current (I_{sc}) $= 77.10 \pm 0.01$ mA

- Open Circuit Voltage (V_{oc}) $= 5.641 \pm 0.001$ V
- Fill Factor $= 0.710 \pm 0.001$

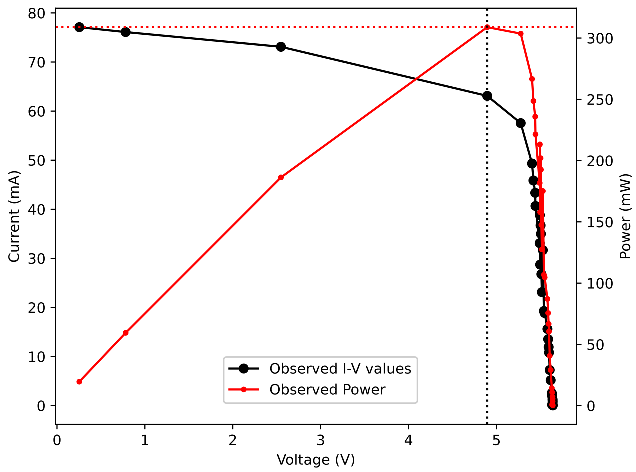

FIG. 10: I-V and P-V curves for the solar cell with no filter outdoors

2. *Red Filter*

- $V_{mp} = 4.312$ V and $I_{mp} = 30.87$ mA
- Max. Power (P_{max}) $= 133.111 \pm 0.053$ mW
- Short Circuit Current (I_{sc}) $= 52.61 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 5.128 \pm 0.001$ V
- Fill Factor $= 0.493 \pm 0.001$

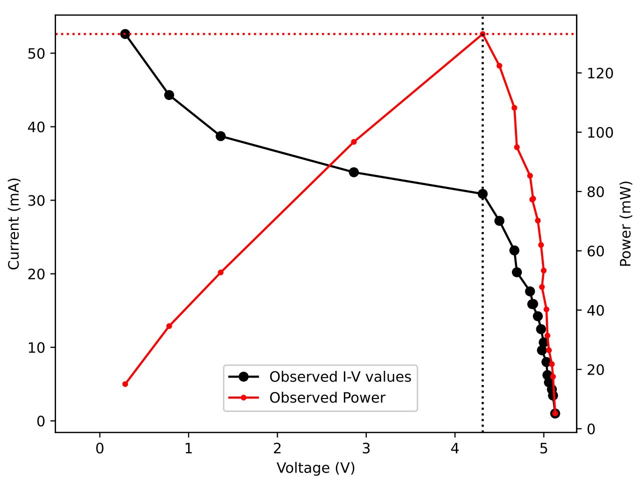

FIG. 11: I-V and P-V curves for the solar cell with red filter outdoors

3. *Blue Filter*

- $V_{mp} = 4.508$ V and $I_{mp} = 40.98$ mA
- Max. Power (P_{max}) $= 184.738 \pm 0.061$ mW
- Short Circuit Current (I_{sc}) $= 43.41 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 5.301 \pm 0.001$ V
- Fill Factor $= 0.803 \pm 0.001$

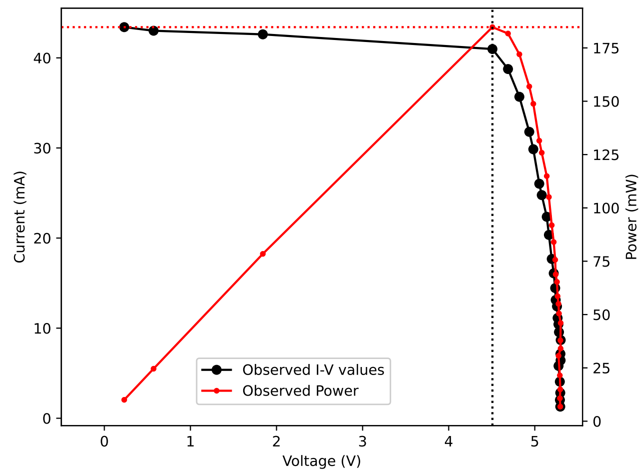

FIG. 12: I-V and P-V curves for the solar cell with blue filter outdoors

4. *Green Filter*

- $V_{mp} = 4.426$ V and $I_{mp} = 33.72$ mA
- Max. Power (P_{max}) $= 149.245 \pm 0.056$ mW
- Short Circuit Current (I_{sc}) $= 37.35 \pm 0.01$ mA
- Open Circuit Voltage (V_{oc}) $= 5.309 \pm 0.001$ V
- Fill Factor $= 0.753 \pm 0.001$

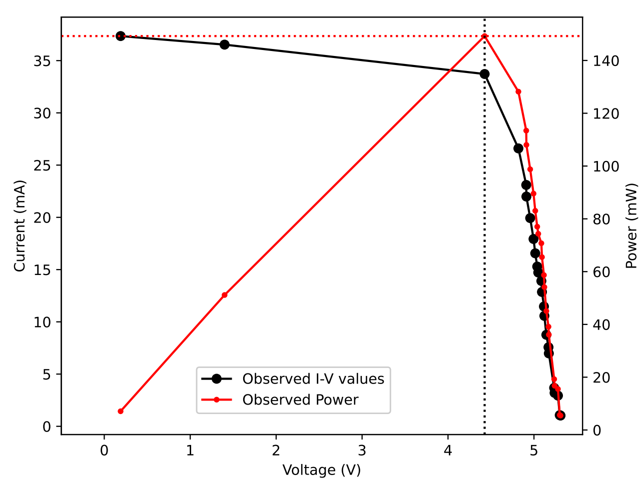

FIG. 13: I-V and P-V curves for the solar cell with green filter outdoors

5. *Magenta Filter*

- $V_{mp} = 4.215$ V and $I_{mp} = 24.69$ mA

- Max. Power ($P_{\max}$) $= 104.068 \pm 0.049$ mW
- Short Circuit Current ($I_{\rm sc}$) $= 31.38 \pm 0.01$ mA
- Open Circuit Voltage ($V_{\rm oc}$) $= 5.151 \pm 0.001$ V
- Fill Factor $= 0.644 \pm 0.001$

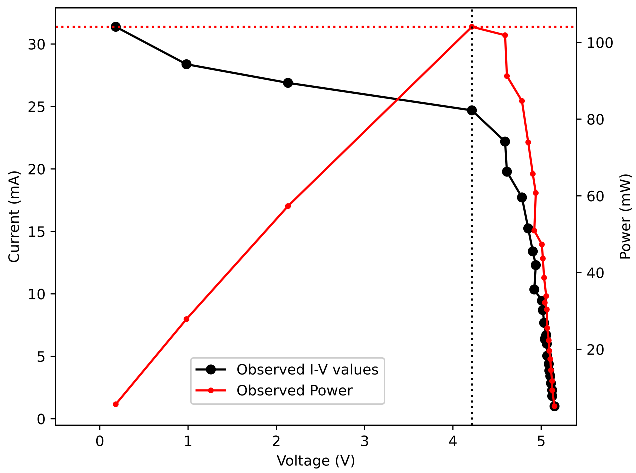

FIG. 14: I-V and P-V curves for the solar cell with magenta filter outdoors

6. Yellow Filter

- $V_{\rm mp} = 4.122$ V and $I_{\rm mp} = 73.1$ mA
- Max. Power ($P_{\max}$) $= 301.318 \pm 0.084$ mW
- Short Circuit Current ($I_{\rm sc}$) $= 77.10 \pm 0.01$ mA
- Open Circuit Voltage ($V_{\rm oc}$) $= 5.369 \pm 0.001$ V
- Fill Factor $= 0.728 \pm 0.001$

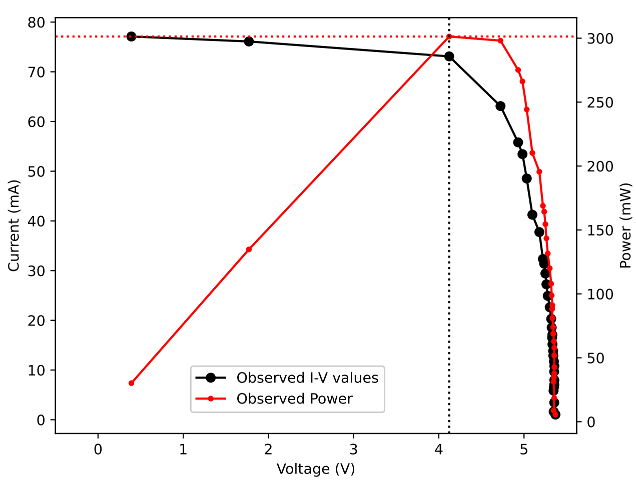

FIG. 15: I-V and P-V curves for the solar cell with yellow filter outdoors

A summary of all the parameters are shown below in Tables III and IV.

Filter	$P_{\max}$ (mW)	$V_{\rm oc}$ (V)	$I_{\rm sc}$ (mA)	FF
No Filter	0.916 ± 0.023	3.257	0.555	0.507 ± 0.016
Red	0.184 ± 0.015	2.323	0.175	0.453 ± 0.046
Yellow	0.470 ± 0.020	2.910	0.33	0.489 ± 0.025
Magenta	0.521 ± 0.019	2.971	0.36	0.487 ± 0.023
Green	0.130 ± 0.013	2.165	0.14	0.428 ± 0.053
Blue	0.327 ± 0.018	2.695	0.25	0.485 ± 0.033

TABLE III: Open-circuit voltage, short-circuit current, maximum power output, and Fill Factor for the solar cell under incandescent lamp

Filter	$P_{\max}$ (mW)	$V_{\rm oc}$ (V)	$I_{\rm sc}$ (mA)	FF
No Filter	308.874 ± 0.080	5.641	77.1	0.701 ± 0.001
Red	133.111 ± 0.053	5.128	52.61	0.493 ± 0.001
Yellow	301.318 ± 0.084	5.369	77.10	0.728 ± 0.001
Magenta	104.068 ± 0.049	5.151	31.38	0.644 ± 0.001
Green	149.245 ± 0.056	5.309	37.35	0.753 ± 0.001
Blue	184.738 ± 0.061	5.301	43.41	0.803 ± 0.001

TABLE IV: Open-circuit voltage, short-circuit current, maximum power output, and Fill Factor for the solar cell under sunlight

Below are the comparative plots for I-V and P-V with different filters.

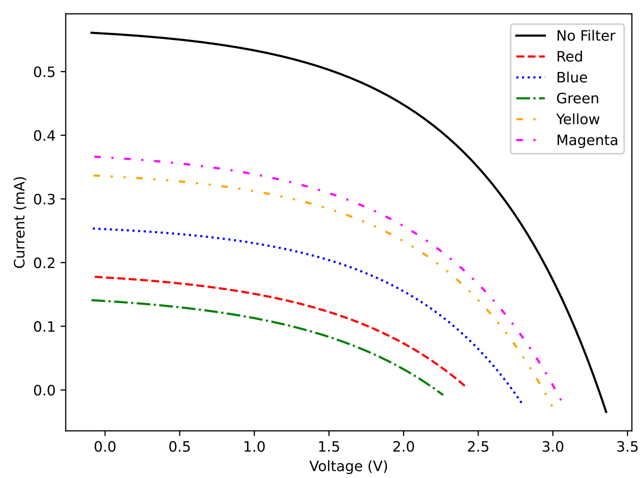

FIG. 16: I-V curves for the solar cell with different filters under incandescent lamp

V. ERROR ANALYSIS

Error estimation is based on the least count of the measur- ing instruments. A digital multimeter was used to measure voltage and current. The least count for voltage was either 0.01 V or 0.001 V depending on the range.

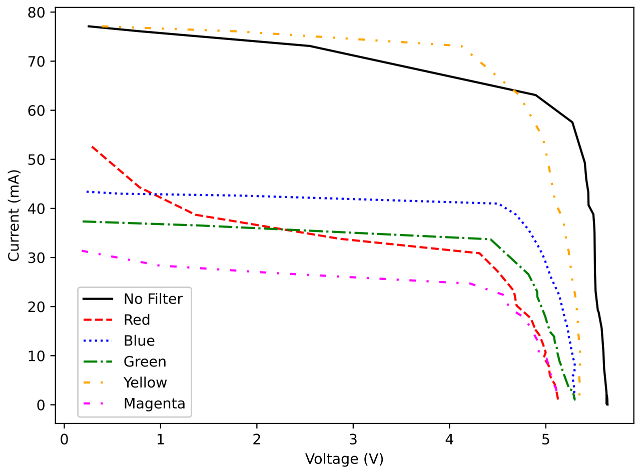

FIG. 17: I-V curves for the solar cell with different filters under sunlight

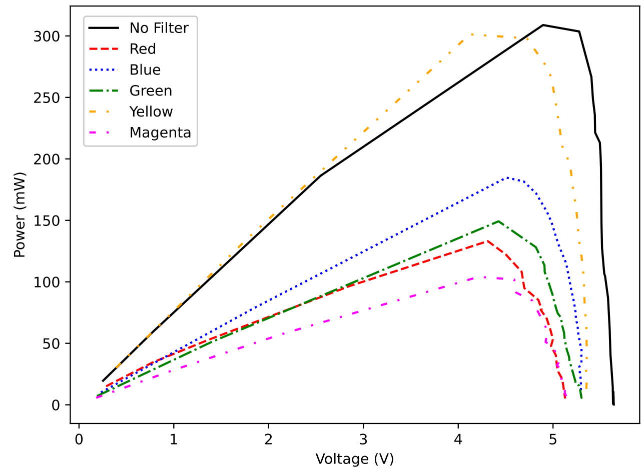

FIG. 19: P-V curves for the solar cell with different filters under sunlight

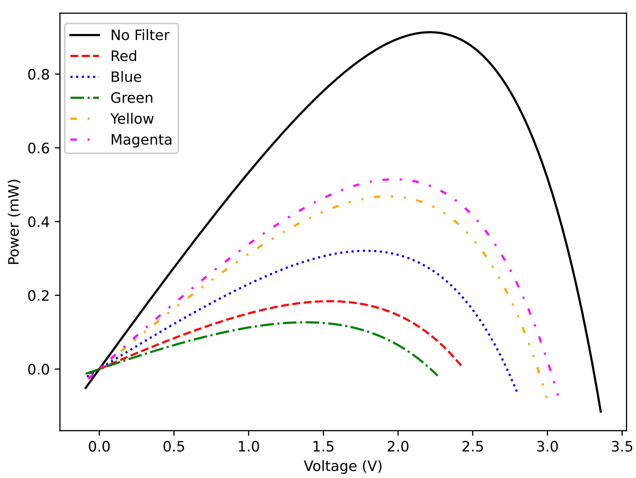

FIG. 18: P-V curves for the solar cell with different filters under incandescent lamp

The least count of the current readings were similarly 0.01 or 0.001 mA depending on the range.

The uncertainty in maximum power is determined using quadrature propagation,

$$\Delta P = P\sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \tag{5}$$

Similarly, the uncertainity in fill factor can be calculated using,

$$\Delta FF = FF\sqrt{\left(\frac{\Delta P}{P_{\max}}\right)^2 + \left(\frac{\Delta I_{\rm sc}}{I_{\rm sc}}\right)^2 + \left(\frac{\Delta V_{\rm oc}}{V_{\rm oc}}\right)^2} \tag{6}$$

VI. DISCUSSION & CONCLUSION

In this experiment we successfully analyzed the I-V characteristics of the solar cell under different illumination conditions, including an incandescent lamp and sunlight. The obtained I-V curves exhibited the expected nonlinear behavior, confirming the photovoltaic nature of the solar cell. We were able to fit the diode equation on the observed I-V plots which confirms our theoretical predictions (Not for the data outdoors as there was a large amount of variability and noise in the data).

A significant difference was observed in the power output between these two conditions the maximum power generated under room lighting was considerably lower than that achieved under sunlight for the same filter. This discrepancy can be attributed to the difference in incident radiation intensity. The Sun delivers a significantly higher amount of energy per unit area per unit time compared to artificial room lighting.

The highest power output was recorded in the absence of any filter in both cases, as expected. However, the highest power ouput was seen with magenta and yellow filters indoors, and yellow and blue filters outdoors. This might indicate that the respective light sources are rich in those particular frequencies more than the others. The P-V plot using the yellow filter outdoors was almost similar to the no filter case, indicating that yellow filter allows through a significant part of sun's spectrum.

The fill factor, which measures the efficiency of the solar cell, at room temperature ranges between 0.4 and 0.5 for different filters. However, under direct sunlight, the feel factor increases significantly, falling within the range of approximately 0.5 to 0.7. This indicates that solar panels exhibit enhanced efficiency in natural sunlight compared to artificial lighting. The highest fill factor outdoors for recorder for the green filter, which is expected as the peak of sun's blackbody curve lies near 500 nm, i.e. green light.

However yellow filter was close behind.

While taking measurements under sunlight, there was significant cloud cover which was varying with time due to the bad weather conditions. This could be the reason why the readings for the I-V and P-V characteristics under sunlight is not as smooth as that under an incandescent lamp.

VII. PRECAUTIONS AND SOURCES OF ERROR

1. Stable Light Source: Ensure that the light source (room light or sunlight) remains consistent throughout the experiment to obtain accurate measurements. Variations in light intensity can affect the readings.
2. Proper Electrical Connections: Verify that all electrical connections, including the load and measuring instruments, are secure to minimize resistance errors and fluctuations in readings.
3. Avoid Shadows and Reflections: Make sure no unwanted objects or reflections interfere with the light falling on the solar cell, as they can alter the output and lead to incorrect results.

[1] SPS, *I-V Characteristics of a Solar Cell*, NISER (2023).