Experimental Study of the I-V Characteristics of a Solar Cell

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Using various filters, we investigated the operation of a solar cell and its I-V characteristics in the experiment. As a result of the relationship between the current and voltage across the cell, we were able to determine several characteristics such as open circuit voltage, short circuit current, and maximum power. We observed that the values of these parameters changed for the various filters employed as they blocked different wavelengths of light, affecting the intensity and energy of the falling photons. As a result, the I-V characteristics of various filters differ.

I. THEORY

A. P-N Junction Diode

A diode is any device that permits current to flow in just one direction. As a result, it functions as a variable resistor. A p-n junction is formed by joining two semiconductor materials, a p-type and an n-type. A p-type semiconductor is created by doping a semiconductor material (for example, Silicon) with a Group 13 acceptor material, which results in the generation of holes since the acceptor atom has one electron fewer in the valence shell to allow pairing with the electron of Si. Similarly, a Group 15 element is utilised in doping in an n-type semiconductor, resulting in an excess of electrons in the material, as seen in Figure 1.
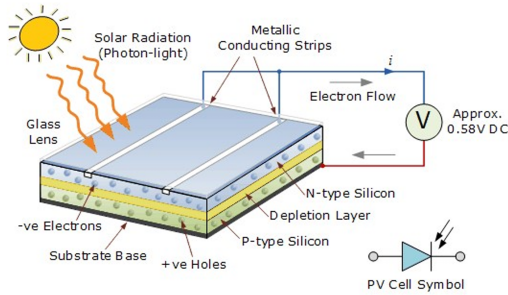

FIG. 1: Construction of Solar Cell

Surplus electrons from the n side and excess holes from the p side migrate towards the junction to recombine when the two types of materials are combined (more stable state). When they join at the junction, they leave positively charged ions on the n side and negatively charged ions on the p side behind. When the electric field formed by the charged ions balances the diffusion of electron hole pairs, it becomes saturated. As a result, in the state, a depletion area forms at the diode junction, with a junction potential that prohibits further passage of electrons and holes. There are still motions such as drift current when, as a result of collisions, certain electrons and holes (e-h) on the n and p sides may obtain enough kinetic energy to overcome the potential barrier. When e-h couples develop within the depletion area, the diffusion current is cancelled out by the drift current, which is swiftly dragged towards the n and p sides by the electric field on the ions. This drift current becomes noticeable in a solar cell.

B. Solar Cell

A solar cell, also known as a photovoltaic cell, is a form of active transducer and the fundamental unit of a solar energy generation system that converts light energy directly into electrical energy. It is essentially a semiconductor p-n junction diode that generates charge carriers (e-h pair) by absorbing energy from falling radiation. When sunlight strikes a solar cell, photons with energies larger than the band gap of the semiconductor are absorbed by the cell, resulting in the formation of an electron-hole (e-h) pair. When these e-h pairs develop in the depletion zone, they migrate to the n- and p- sides of the p-n junction as drift current due to the electrostatic force of the field across the junction. As more radiation is absorbed, charges accumulate on the two sides of the cell, resulting in a potential difference. A solar or photovoltaic cell typically features a negative front contact and a positive rear contact. When connected to the terminals of a battery, the charge carriers begin to flow, producing current. At ambient temperature, the band gap for silicon is $E_g = 1.1eV$, and the diffusion potential is $U_D = 0.5$ to $0.7V$.

C. I-V Characteristics

Solar Cell I-V Characteristics Curve is the superposition of the I-V curves of the solar cell diode in absence (dark) and in presence of light. The connection is made in reverse bias, and depending on the load of the circuit, we get different values. Solar Cell I-V Characteristics Curve is the superposition of the I-V curves of the solar cell diode in absence (dark) and in presence of light. Illuminating a cell adds to the normal "dark" currents in

the diode so that the diode law for q electronic charge, n ideality factor and at T temperature becomes:

$$I(V) = I_0 \left[e^{\frac{qV}{nKT}} - 1 \right] - I_L \tag{1}$$

where I_0 is the diode leakage current in absence of light and I_L is the current generated by light. A typical circuit for measuring I-V characteristics is shown in the Figure 2.
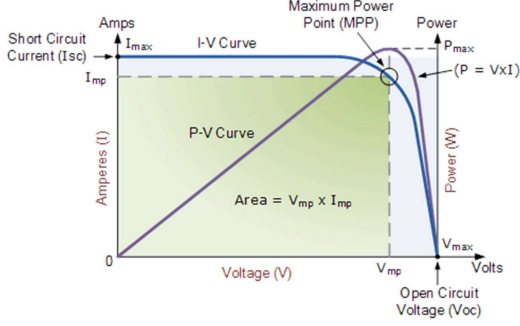

FIG. 2: I-V curve and power curve of a typical solar cell

Due to comparable characteristics, the curve approaches the forward bias I-V curve of an inverted diode. The solar cell's many properties may be calculated from these features. These factors determine a solar panel's rating:

1. **Short-circuit current (ISC):** the flow of electricity through a solar cell when it is shorted out. The voltage across the solar cell is 0 since there are no charge carriers that have accumulated in the event of a short circuit. Therefore, the highest current that may be extracted from a solar cell is the short-circuit current.

2. **Open-circuit voltage (VOC):** At zero current, it is the greatest voltage a solar cell is capable of producing. When the circuit is open, something happens. The solar cell's forward bias, which results from the junction's bias with the light-generated current, is represented by the open-circuit voltage.

3. **Maximum power point (MPP):** Maximum power, which occurs when the tangency of the curve is −1 and is designated as the MPP in the picture, is a visual representation of the 'squareness' of the solar cell. It is also the size of the biggest rectangle that will fit in the I-V curve.

4. **Fill Factor (FF):** The FF is defined as the ratio of the maximum power from the solar cell to the product of VOC and ISC.

5. **Efficiency:** It determines the performance of one solar cell to another and is defined as the ratio of energy output from the solar cell to input energy from the sun.

D. Direct and Indirect Band Gap

The lowest energy difference between the top of the valence band and the bottom of the conduction band determines the band gap. However, the top of the valence band and the bottom of the conduction band might not be at the same electron momentum value in the momentum space. If so, it is referred to as an indirect band gap. A straight band gap is what is known when the conduction minima and value maxima occur at the same value of the electron momentum, as seen in the Figure 3.
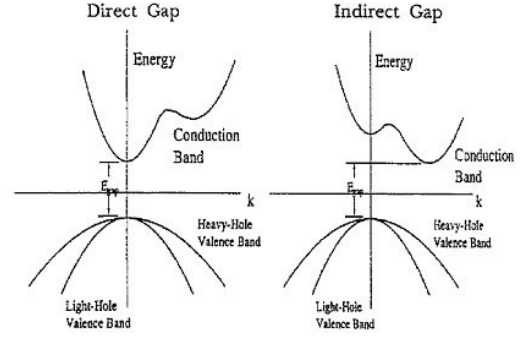

FIG. 3: Direct and Indirect Band Gap

When it comes to a direct band gap semiconductor, generating an electron-hole pair by a photon with energy E is relatively easy because the electron does not need to have much momentum. Conversely, creating an e-h pair in the indirect band gap takes more time as a photon has to alter the momentum. To gain or lose momentum, the electron must interact with both the photon and a phonon, a lattice vibration.

As a result, e-h pairs created indirectly have longer lifetimes compared to those generated directly. For solar cells, we require high e-h pair lifetimes to enable their movement and buildup on the diode's sides. Hence, we make use of indirect band gap semiconductors like silicon. Conversely, we utilize direct gap materials like gallium arsenide in creating optical devices such as LEDs and semiconductor lasers, as the photodiode effect mandates the excited electron to rapidly de-excite and discharge radiation

E. Experimental Setup

The circuit schematic below in Figure 4 shows the experimental setup. A potentiometer is used to modulate resistance in the circuit, and a multimeter is used to measure current. The solar cell is put in a well-lit area. For the purpose of measuring the voltage across the cell, a second multimeter is connected in parallel. To cover the solar cell and tabulate the values of I and V for various loads applied, we have several filters, including green, yellow, pink, and red.
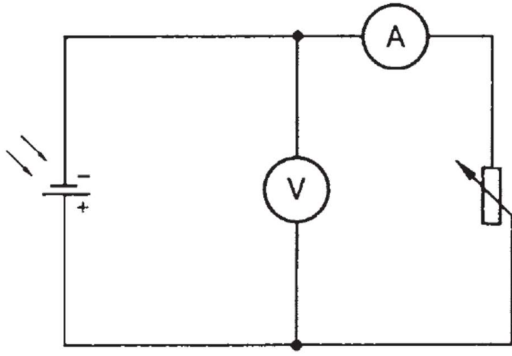
FIG. 4: Experimental Setup

II. OBSERVATIONS

We carried out the experiment under two different conditions:

1. Indoors in presence of incandescent lamp

2. In presence of sunlight

All the curves have been fitted with equation:

$$I(V) = Ae^{BV} - C. \tag{2}$$

Here, A, B, and C are the parameters. The I-V Characteristics of the solar cell under those conditions are as follows:

A. Indoors in presence of Incandescent lamp

The data collected for the I-V characteristics of the solar cell under incandescent lamp is given in Table 1. The I-V curve for no filter has been shown in Figure 5 and the I-V curve for different filters has been shown in Figure 6.

FIG. 5: I vs V curve for solar filter under white light indoors
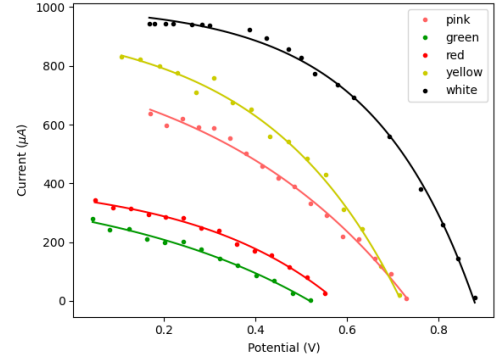
FIG. 6: I-V curve for data with different filters indoors

B. Outdoors in presence of Sunlight

White		Pink		Green		Red		Yellow	
V	I (μA)	V	I (μA)	V	I (μA)	V	I (μA)	V	I (μA)
0.88	10.6	0.731	7	0.521	2	0.553	27	0.715	21
0.843	143.2	0.696	91	0.481	26	0.513	80	0.675	119
0.81	259.5	0.661	145	0.441	69	0.475	116	0.634	244
0.762	381.5	0.626	211	0.402	86	0.436	156	0.593	312
0.693	560	0.591	218	0.361	121	0.398	169	0.554	431
0.615	693	0.556	292	0.322	145	0.360	193	0.513	485
0.579	737	0.521	332	0.282	176	0.320	240	0.472	541
0.53	773	0.486	388	0.242	201	0.281	248	0.432	560
0.5	829	0.450	418	0.202	198	0.243	283	0.39	651
0.473	856	0.415	460	0.162	211	0.204	285	0.35	674
0.425	896	0.380	502	0.124	246	0.166	294	0.31	759
0.388	923	0.345	554	0.082	243	0.128	313	0.27	710
0.3	939	0.310	589	0.044	280	0.089	318	0.229	777
0.284	941	0.275	592			0.049	342	0.19	798
0.261	942	0.240	620					0.148	822
0.22	943	0.205	596					0.107	831
0.204	944	0.170	637						
0.18	945								
0.168	945								

TABLE I: Data indoors in the presence of an incandescent lamp

White		Pink		Green		Red		Yellow	
V	I (mA)	V	I (mA)	V	I (mA)	V	I (mA)	V	I (mA)
1.531	12	1.53	2	1.494	10	1.540	9	1.540	1
1.475	78	1.494	23	1.445	45	1.491	35	1.457	70
1.420	113	1.445	46	1.395	62	1.441	72	1.372	113
1.365	138	1.395	64	1.346	76	1.392	90	1.290	133
1.309	146	1.346	82	1.296	87	1.343	104	1.207	149
1.254	158	1.296	95	1.246	95	1.293	112	1.123	160
1.198	170	1.246	110	1.197	96	1.244	131	1.038	162
1.143	164	1.197	120	1.147	96	1.195	137	0.955	163
1.087	169	1.147	131	1.098	98	1.145	144	0.873	164
1.031	178	1.098	145	1.048	102	1.096	150	0.788	165
0.976	174	1.048	151	0.998	105	1.047	155	0.703	164
0.921	182	0.998	156	0.949	106	0.997	157	0.620	170
0.865	191	0.949	158	0.899	107	0.948	160	0.539	168
0.810	184	0.899	165	0.850	108	0.899	162		
0.754	182	0.850	174	0.800	108	0.849	162		
0.698	198	0.800	176			0.800	163		
0.643	189								

TABLE II: Data outdoors in the presence of the Sun

The data collected for the I-V characteristics of the solar cell under incandescent lamp is given in Table 2. The I-V curve for no filter has been shown in Figure 7 and the I-V curve for different filters has been shown in Figure 8.
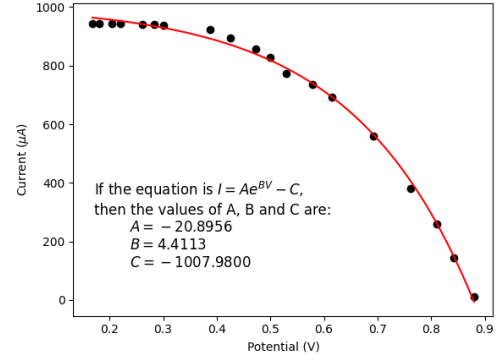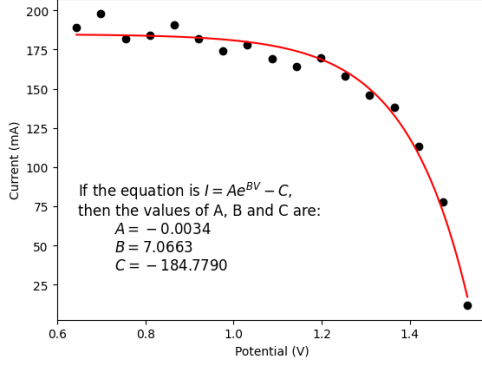

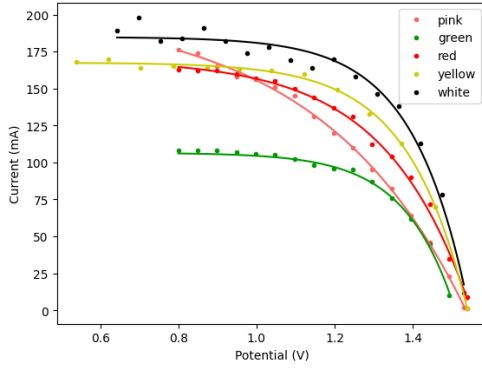FIG. 7: I vs V curve for solar filter under white light outdoors

FIG. 8: I-V curve for data with different filters outdoors

III.   CALCULATION & ERROR ANANLYSIS

The no load voltage (VOC), the short circuit current (ISC) and the maximum power output P_{max} and the corresponding error in its value (δP) for each filter in each case (Lamp and Sun) are given in the Table 3. From Equation 1 and our fitting function used in graph, we find the equation for the maximum for power. It is given for the point on the I-V characteristic curve, where the slope is equal to $\tan 135° = -1$.

Differentiating Equation 2 with respect to V and equating it to -1 (for maximum power), we get:

$$\frac{dI}{dV} = ABe^{BV} = -1$$

$$\therefore V = \frac{-1}{B} \ln\left(-AB\right)$$

Finding corresponding value of I and calculatind $P_{max} = VI$, we get:

$$P_{max} = \left(\frac{C}{B} - \frac{1}{B^2}\right) \ln\left(-AB\right) \qquad (3)$$

The error in the value of P_{max} is calculated in this way: Let $M = \left(\frac{C}{B} - \frac{1}{B^2}\right)$ & $N = \ln\left(-AB\right)$.

$$\therefore \left(\frac{dM}{M}\right)^2 = 3 \times \left(\frac{dB}{B}\right)^2 + \times \left(\frac{dC}{C}\right)^2$$

$$\therefore \left(\frac{dN}{N}\right)^2 = \frac{1}{(\ln(-AB))^2}\left(\left(\frac{dA}{A}\right)^2 + \left(\frac{dB}{B}\right)^2\right)$$

$$\frac{\delta P_{max}}{P_{max}} = \sqrt{\left(\frac{dM}{M}\right)^2 + \left(\frac{dN}{N}\right)^2} \qquad (4)$$

Now, using equation Equation 3 and Equation 4, we get make the table Table 3.

	Colour	VOC (V)	ISC (mA)	P_{max} (nW)	δP_{max} (nW)
Indoors	White	0.879	0.987	428.278	64.242
	Pink	0.736	0.733	192.943	25.083
	Green	0.519	0.282	47.221	7.555
	Red	0.577	0.347	74.123	13.342
	Yellow	0.719	0.873	256.312	48.699
Outdoors	White	1.545	184.776	202.760	20.276
	Pink	1.536	200.924	156.031	28.086
	Green	1.509	106.477	116.192	18.591
	Red	1.550	169.607	164.680	26.349
	Yellow	1.541	167.496	179.477	34.101

TABLE III: Calculations and Error

IV.   CONCLUSION

Hence we have studied the I-V characteristics of solar cell and how it behaves under different filters. The results are mostly in accordance with the theory.

1. The imperfections in the filters, more being transmitting than the others.

2. Noises in the multimeter reading. It happened especially for the lamp case and lower resistance case for sunlight case. The reading should be allowed to be settled or average value should be noted. The reading was left as the discernment of the experimeters.

3. Incorrect placement of the solar cell either in shadow or not correctly covered with filter. There should be no opening left when covering the cell.

4. Cloudy conditions for yellow, pink and red filters in sunlight case. We could find the impact of cloudy conditions on the reading by using a correction factor from the lamp case and finding the deviation of the power output from the ideal case and cloudy case.

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[1] SPS, Lab manual, Website (2022), https://www.niser.ac.in/sps/sites/default/files/basic_page/p347_2023/7.IV_characeristics_Solarcell.pdf.

[2] J. Ardila, A. Cardenas, H. Hernandez, and J. Lopez, Analysis of i-v characteristics of a solar cell using labview, Energies **14**, 409 (2021).

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[4] Y. Xu, Y. Wang, and K. Lian, Experiment and analysis of i-v characteristics of solar cells under different illumination conditions, Journal of Physics: Conference Series **1195**, 032066 (2019).