Study of the C-V Characteristics of a Solar Cell

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In this experiment, we investigated the C-V characteristics of a solar cell under various conditions. Our results showed that the capacitance of the solar cell is inversely proportional to the intensity of light, indicating a strong dependence on light intensity. Furthermore, by analyzing the data obtained under total dark conditions, we determined the doping density of the solar cell to be $(4.4 \pm 0.021) \times 10^{17} m^{-3}$, with a built-in voltage of $0.76 \pm 0.0427V$. Our analysis also revealed that both doping density and built-in voltage decrease as light intensity increases. Finally, we observed that the capacitance of the solar cell decreases as the applied reverse DC voltage increases, indicating the presence of a strong electric field within the cell.

I. THEORY

A capacitor stores electric charge using two conducting plates separated by a dielectric material. A reverse-biased p-n junction diode has p-type and n-type regions acting as the capacitor's electrodes, while the depletion region acts as the dielectric. Hence, the diode acts as a parallel plate capacitor, with its capacitance changing as the applied voltage changes. Increasing the reverse bias voltage moves the majority carriers away from the p-n junction, widening the depletion region and reducing the size of the p-type and n-type regions.

The p-n junction capacitance is given by,

$$C = \frac{dQ}{dV_{dc}} = \frac{\epsilon_o \epsilon_s A}{x_d} \tag{1}$$

where Q is the charge, V_{DC} is the reverse bias voltage applied, ϵ_0 is the permittivity of empty space, ϵ_s is the semiconductor's dielectric constant, and A is the area of the 'p-n' junction. In a reverse biassed junction with constant doping density "Nd," the depletion area width is determined by,

$$x_d = \sqrt{\frac{2\epsilon_o \epsilon_s (V_{bi} + V_{dc})}{qN_d}} \tag{2}$$

V_{bi} is the built-in voltage,V_{dc} is the reverse voltage, and q is the charge of an electron. From equations (1) and (2), we have,

$$\frac{1}{C^2} = \left(\frac{x_d}{\epsilon_o \epsilon_s A}\right)^2 = \frac{2(V_{bi} + V_{dc})}{qN_d \epsilon_o \epsilon_s A^2} \tag{3}$$

By plotting $\frac{1}{C^2}$ versus V_{DC}, doping density and built-in potential can be determined.

II. EXPERIMENTAL SETUP TO FIND THE CAPACITANCE OF SOLAR CELL

The circuit shown in Figure 1 can measure the capacitance of a p-n junction device, such as a solar cell. The capacitance of the device depends on the applied DC voltage. To measure the C-V profile, the circuit applies a variable DC bias and a small AC signal to the solar cell. The circuit uses an inverting summing amplifier that adds the variable DC voltage (with unity gain R/R_2) and the small signal AC voltage (with attenuation factor $1/10 = R/R_1$). The output voltage of the amplifier is connected to the solar cell. The AC signal is small enough not to perturb the DC bias or affect the charge polarization due to the DC bias. The voltage V_{DUT} in Figure 1 is thus given by the following equation:

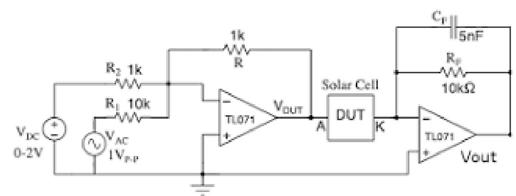

FIG. 1: Circuit for taking CV data

$$V_{DUT} = -R\left(\frac{V_{DC}}{R_2} + \frac{V_{AC}}{R_1}\right) \tag{4}$$

In our experiment, the AC voltage across the solar cell (measuring 4×4 cm) is set to be one-tenth of the input DC voltage, due to instrument sensitivity limitations. The summing circuit connects the solar cell's anode (A) to its output, while negative feedback grounds the cathode (K). The capacitor's current is proportional to the applied AC sinusoidal voltage, and an I to V converter (trans-impedance amplifier) is used to convert this current into a voltage reading on a multimeter. The trans-impedance amplifier generates a voltage output that is proportional to the capacitance of the solar cell (C_{DUT}) and V_{DUT}. The following equation gives the magnitude of the AC component of the output voltage:

$$V_{OUT} = V_{DUT}\frac{C_{DUT}}{C_F}\frac{1}{\sqrt{1 + \frac{1}{(\Omega R_F C_F)^2}}} \tag{5}$$

In our setup, we use the function generator to apply an AC voltage of 5 kHz. Since operational amplifiers exhibit 1/f noise at low frequencies (0.1 to 10 Hz), and this noise can go up to 2 kHz for fast operational amplifiers, we limit our frequency range to high frequencies. We use 741 opamps instead of TL071 opamps, and the circuit is shown in Figure 1. By varying the DC voltage in steps from 0 to 1.5 V using a DC power supply, we record V_{OUT} (AC) and V_{DUT} using different multimeters. We calculate C_{DUT} using Equation 4.

III. OBSERVATIONS

A. Dark condition

The data collected for the C-V characteristics of the solar cell in Room light by covering the solar cell with black cloth is given in Table 1

V_{DC}	V_{DUT}	V_{OUT}	C_{DUT}
0.0	0.074	5.927	1650.815
0.1	0.109	5.927	1120.737
0.2	0.232	5.927	526.553
0.3	0.299	5.927	408.563
0.4	0.389	5.927	314.037
0.5	0.463	5.927	263.845
0.6	0.564	5.927	216.596
0.7	0.662	5.927	184.532
0.8	0.760	5.927	160.737
0.9	0.846	5.927	144.398
1.0	0.941	5.927	129.820
1.1	1.058	5.927	115.463
1.2	1.174	5.927	104.055
1.3	1.267	5.927	96.417
1.4	1.357	5.927	90.022
1.5	1.464	5.927	83.443
1.6	1.559	5.927	78.358

TABLE I: Data for dark condition

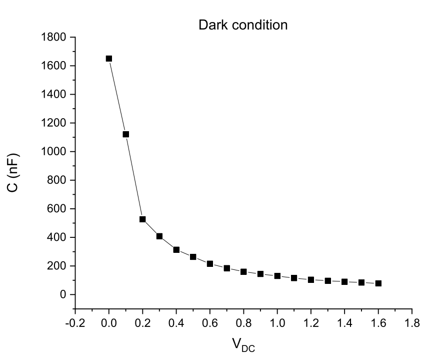

FIG. 2: C vs V_{DC} for dark condition

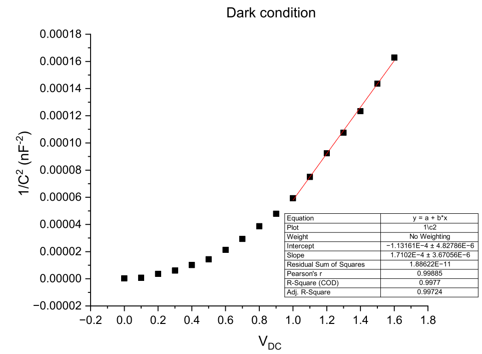

FIG. 3: $\frac{1}{C^2}$ vs V_{DC} for dark condition

B. Light condition

The data collected for the C-V characteristics of the solar cell in Room light without covering the solar cell with black cloth is given in Table 2

V_{DC}	V_{DUT}	V_{OUT}	C_{DUT}
0	0.074	0.459	127.837
0.1	0.109	0.451	85.276
0.2	0.232	0.447	39.709
0.3	0.299	0.438	30.191
0.4	0.389	0.432	22.888
0.5	0.463	0.432	19.230
0.6	0.564	0.426	15.567
0.7	0.662	0.420	13.075
0.8	0.760	0.435	11.796
0.9	0.846	0.430	10.475
1	0.941	0.426	9.330
1.1	1.058	0.427	8.318
1.2	1.174	0.422	7.408
1.3	1.267	0.418	6.799
1.4	1.357	0.416	6.318
1.5	1.464	0.412	5.800
1.6	1.559	0.409	5.406

TABLE II: Data for light condition

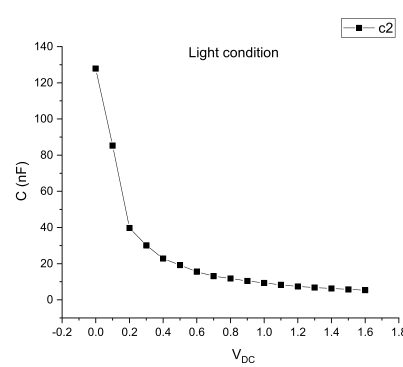

FIG. 4: C vs V_{DC} for light condition

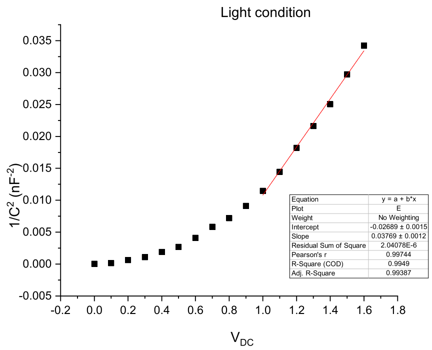

FIG. 5: $\frac{1}{C^2}$ vs V_{DC} for light condition

C. One incandescent lamp condition

The data collected for the C-V characteristics of the solar cell under one incandescent lamp is given in Table 3

V_{DC}	V_{DUT}	V_{OUT}	C_{DUT}
0.0	0.07	0.010	2.944
0.1	0.111	0.009	1.671
0.2	0.176	0.009	1.053
0.3	0.263	0.009	0.705
0.4	0.353	0.009	0.525
0.5	0.431	0.009	0.430
0.6	0.511	0.009	0.362
0.7	0.608	0.010	0.338
0.8	0.716	0.010	0.287
0.9	0.809	0.009	0.229
1.0	0.903	0.009	0.205
1.1	0.982	0.009	0.188
1.2	1.060	0.009	0.174
1.3	1.177	0.009	0.157
1.4	1.294	0.009	0.143
1.5	1.389	0.009	0.133
1.6	1.490	0.009	0.124

TABLE III: Data for one incandescent lamp conditions

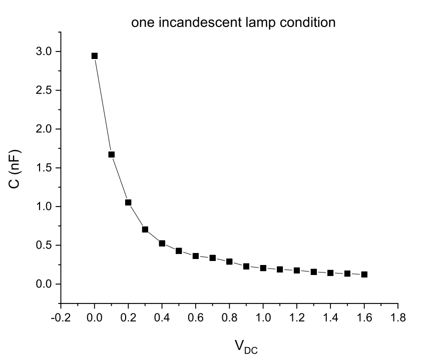

FIG. 6: C vs V_{DC} for one incandescent lamp condition

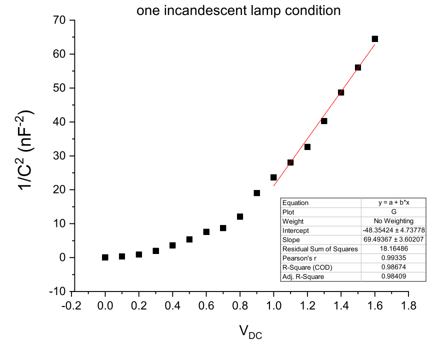

FIG. 7: $\frac{1}{C^2}$ vs V_{DC} forone incandescent lamp condition condition

D. Two incandescent lamp condition

The data collected for the C-V characteristics of the solar cell under two incandescent lamp is given in Table 3

V_{DC}	V_{DUT}	V_{OUT}	C_{DUT}
0.0	0.070	0.006	1.767
0.1	0.147	0.006	0.841
0.2	0.233	0.005	0.442
0.3	0.328	0.005	0.314
0.4	0.418	0.005	0.247
0.5	0.506	0.006	0.244
0.6	0.606	0.005	0.170
0.7	0.728	0.005	0.142
0.8	0.811	0.005	0.127
0.9	0.903	0.005	0.114
1.0	1.007	0.005	0.102
1.1	1.117	0.005	0.092
1.2	1.203	0.005	0.086
1.3	1.304	0.005	0.079
1.4	1.386	0.005	0.074
1.5	1.497	0.005	0.069
1.6	1.627	0.005	0.063

TABLE IV: Data for two incandescent lamp condition

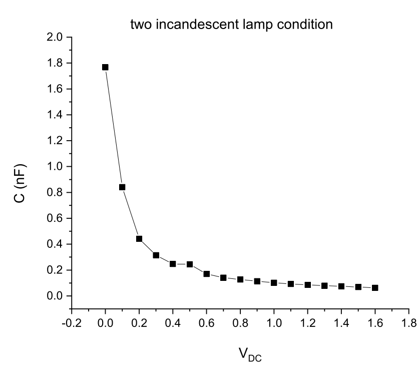

FIG. 8: C vs V_{DC} for two incandescent lamp condition

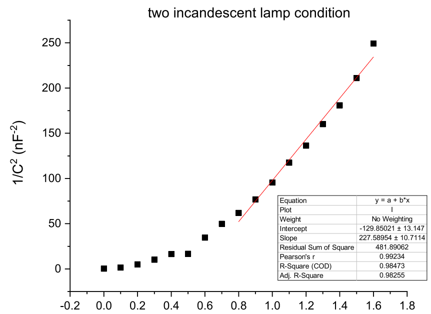

FIG. 9: $\frac{1}{C^2}$ vs V_{DC} for two incandescent lamp condition condition

IV. CALCULATION

From equation 3, in $\frac{1}{C^2}$ vs V_{DC} graphs the slope value is,

$$slope = \frac{2}{qN_d\epsilon_o\epsilon_s A^2} \tag{6}$$

and intercept has form,

$$intercept = \frac{2V_{bi}}{qN_d\epsilon_o\epsilon_s A^2} \tag{7}$$

Using equations (6) and (7) we find the value of N_d and V_{bi} for each condition as shown in Table 5.

Condition	slope	intercept	N_d	Vbi
Dark	1.71×10^{-6}	1.30×10^{-4}	4.41×10^{17}	0.760
Well lit room	0.03769	0.01689	2.00×10^{15}	0.448
One lamp	69.4936	48.35	1.09×10^{12}	0.696
Two lamp	227.58	129.85021	3.31×10^{11}	0.571

TABLE V: N_d AND Vbi for different conditions

A. error analysis

we have an error in N_d,

$$\Delta n_d = \frac{\delta slope}{slope} \times N_d \tag{8}$$

and error in V_{bi} is

$$\Delta V_{bi} = V_{bi}\sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta intercept}{intercept}\right)^2} \tag{9}$$

Using equations (8) and (9), we find the error as given in table 6. we can see that error for both N_d and V_{bi} is less is acceptable

Condition	δ Slope	δ intercept	$\frac{\delta N_d}{N_d}\%$	$\frac{\delta v V_{bi}}{V_{bi}}\%$
Dark Room	3.60×10^{-6}	4.83×10^{-6}	2.11	4.27
Well lit room	0.00121	0.0015	3.21	9.44
One lamp	3.6	4.7337	5.1818	11.11
Two lamp	10.7114	13.147	4.71	11.2

TABLE VI: Error analysis table

V. CONCLUSION

Based on the collected data, it can be concluded that the capacitance of solar cells is inversely proportional to the light intensity. This implies that the capacitance of a solar cell will be lower in the presence of higher light intensities such as during sunny days. The reason for this behavior can be attributed to the dependence of capacitance on the doping density of the p-n junction. Hence, it is possible to increase capacitance by doping the p-n junction more. Another way to enhance capacitance is by using a material with a high dielectric constant. As a result, it can be predicted that larger solar cells will have higher capacitance values since capacitance is dependent on the area.

To further explain, doping is a process of introducing impurities into the semiconductor material to increase the number of free charge carriers. This increases the capacitance by decreasing the depletion region width of the p-n junction. Similarly, the use of materials with a high dielectric constant results in higher capacitance since the dielectric constant directly affects the amount of electric charge that can be stored per unit area. The area-dependent nature of capacitance can be understood from the fact that it is proportional to the area of the p-n junction. Therefore, larger solar cells will have a higher capacitance value compared to smaller ones.

[1] SPS, Lab manual, Website (2022), `https://www.niser.ac.in/sps/sites/default/files/basic_page/p347_2023/8.CV_characeristics_Solarcell.pdf`.