Study of C-V Characterstics of a Solar Cell

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The capacitance-voltage (C-V) characteristics of a solar cell provide essential insights into its doping profile and junction properties. This experiment measures the C-V profile by applying a variable DC voltage and a small AC signal to the solar cell and observing the resulting capacitance. A summing amplifier combines the signals, while a transimpedance amplifier converts the AC current into a measurable voltage. We then try to estimate the doping density and the built in voltage of the solar 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 N_d, 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.

In commercially available diodes, the junction capacitance is designed to be as low as possible to enable fast switching operation. This poses problems in the measurement of capacitance of such devices in the laboratory using educational grade measurement equipment. To overcome this limitation, we use a solar cell, which is essentially a large area p-n junction diode that thereby has larger and hence measurable capacitance.

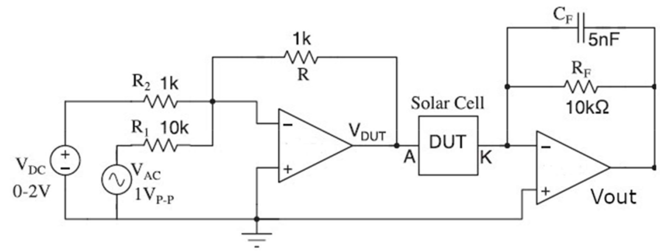

FIG. 1: Circuit for experimental setup

II. EXPERIMENTAL SETUP

Apparatus

1. Solar cell
2. Resistors of 1kΩ and 10kΩ
3. IC 741 opamps
4. DC power supply
5. Function Generator
6. Connecting wires

The circuit shown in Fig. 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 Fig. 1 is thus given by the following equation:

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

In our experiment, the AC voltage across the solar cell 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.

V_{DC} (V)	V_{DUT} (V)	V_{OUT} (V)	C_{DUT} (nF)
0.134	0.136	0.225	18.497
0.232	0.237	0.220	10.378
0.299	0.303	0.218	8.044
0.400	0.405	0.214	5.908
0.526	0.533	0.209	4.384
0.635	0.642	0.205	3.570
0.701	0.710	0.203	3.197
0.802	0.811	0.200	2.757
0.907	0.917	0.197	2.402
1.077	1.089	0.192	1.971
1.100	1.113	0.191	1.919
1.216	1.229	0.188	1.710
1.300	1.314	0.186	1.583
1.448	1.463	0.182	1.391
1.546	1.562	0.179	1.281
1.644	1.661	0.177	1.191
1.733	1.750	0.175	1.118
1.835	1.853	0.173	1.044
1.913	1.932	0.171	0.990
2.076	2.097	0.168	0.896

TABLE I: Data for study of CV characteristics of solar cell in dark conditions

III. OBSERVATION AND CALCULATIONS

The resistance values are measured to be 9.81kΩ, 9.94kΩ, 0.999 kΩ and 0.999 kΩ. Hence the average value of $R_1 = 9.875$ kΩ and $R_2 = 0.999$ kΩ.

The capacitances used are 10.87nF and 10.91nF. The power supplied to the IC 741 opamp are roughly ±15 V. The amplitude of the AC wave is 1.000V (pp) and the frequency is 5.000 kHz. Dielectric Constant of the solar cell ϵ_s is 11.7. The area of the solar cell was measured to be 5.2×3.6 cm^2.

A. Dark Environment

The observed values of V_{DC},V_{DUT} and V_{OUT} are shown in Table I. Using the parameters above and Eq. 5, C_{DUT} was calculated and was plotted as shown.

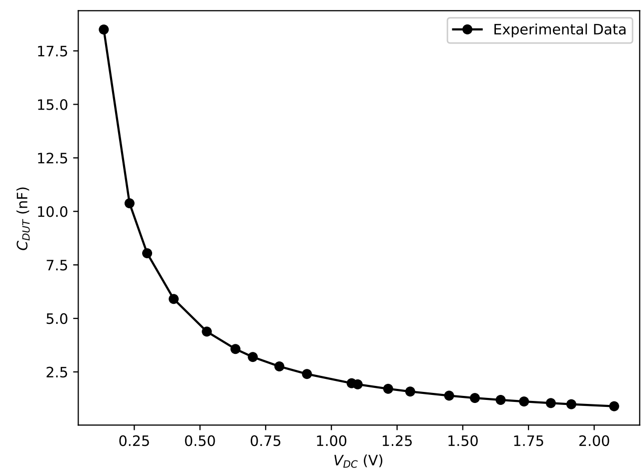

FIG. 2: Plot of C_{DUT} vs V_{DC} for dark condition

The curve in the above figure is clearly non linear The region of interest is the region in which the $1/C^2_{DUT}$ vs V_{DC} behaves almost linearly.

Now, consider Eq. 3, which can be rewritten as,

$$\begin{aligned} \frac{1}{C^2} &= \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{V_{DC}}{N_d} + \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{V_{bi}}{N_d} \\ \frac{1}{C^2} &= \alpha\frac{V_{DC}}{N_d} + \alpha\frac{V_{bi}}{N_d} \end{aligned} \tag{6}$$

Here, $\alpha = \frac{2}{q\epsilon_0\epsilon_s A^2}$ is constant for all values of C_{DUT} and V_{DC}. The above equation is of the form of a straight line. Hence plotting $1/C^2_{DUT}$ vs V_{DC} and using linear regression to fit a straight line through the linerar region, we can calculate N_d and V_{bi}.

Plugging in the values,

$$\text{slope} = \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{1}{N_d}$$
$$\implies N_d = 2.984 \times 10^{16}\ \text{m}^{-3}$$

And, from the y-intercept (ignoring the negative sign),

$$\text{intercept} = \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{V_{bi}}{N_d}$$
$$\implies V_{bi} = 1.022\ \text{V}$$

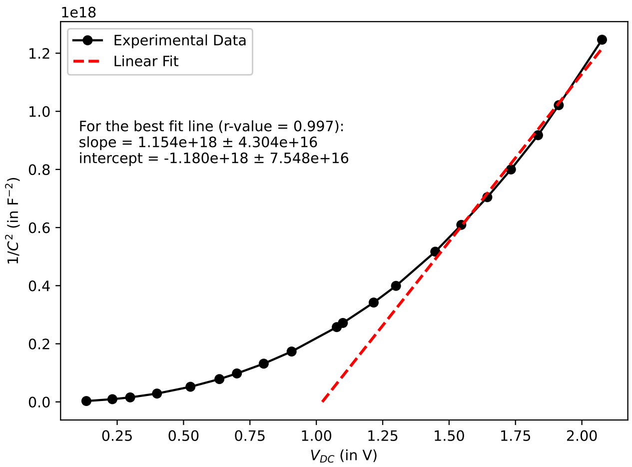

FIG. 3: Plot of $1/C_{DUT}^2$ vs V_{DC} for dark condition

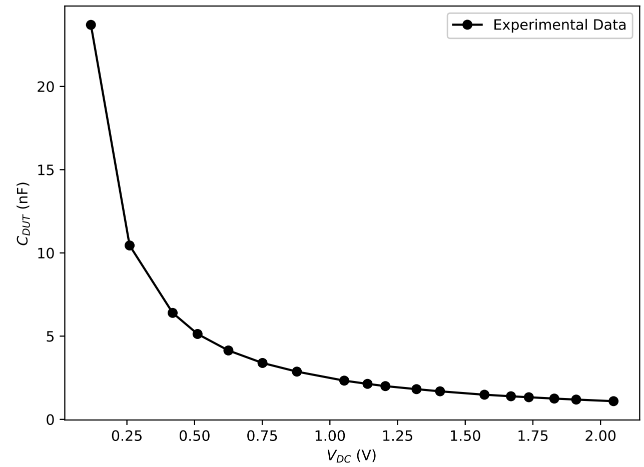

FIG. 4: Plot of C_{DUT} vs V_{DC} for light condition

V_{DC} (V)	V_{DUT} (V)	V_{OUT} (V)	C_{DUT} (nF)
0.117	0.117	0.248	23.698
0.26	0.259	0.242	10.446
0.419	0.416	0.238	6.396
0.511	0.51	0.234	5.130
0.625	0.624	0.231	4.139
0.751	0.749	0.227	3.388
0.878	0.873	0.224	2.869
1.053	1.052	0.219	2.327
1.139	1.137	0.217	2.134
1.205	1.203	0.215	1.998
1.32	1.318	0.214	1.815
1.407	1.406	0.212	1.686
1.571	1.569	0.208	1.482
1.669	1.667	0.207	1.388
1.735	1.732	0.206	1.330
1.829	1.825	0.204	1.250
1.91	1.908	0.203	1.190
2.048	2.045	0.200	1.093

TABLE II: Data for study of CV characteristics of solar cell in ambient light conditions

Note that V_{bi} is also the value of the x-intercept of the above plot.

B. In Ambient Light

The observed values of V_{DC},V_{DUT} and V_{OUT} are shown in Table II. Using the parameters above and Eq. 5, C_{DUT} was calculated and was plotted as shown.

Similarly to the dark condition, a linear fit was performed on the linear region of the $1/C_{DUT}^2$ vs V_{DC} plot.

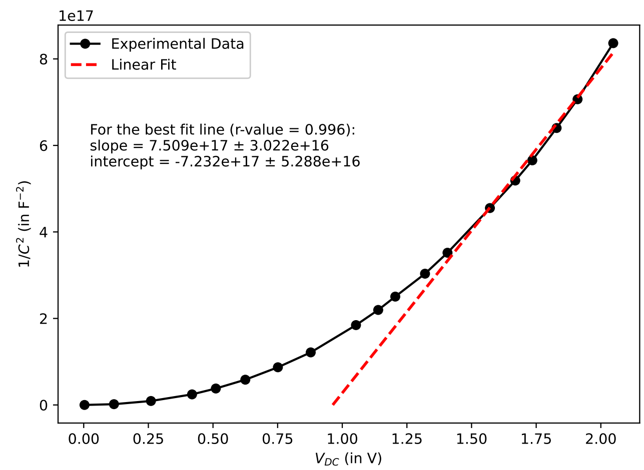

FIG. 5: Plot of $1/C_{DUT}^2$ vs V_{DC} for light condition

Plugging in the values,

$$\text{slope} = \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{1}{N_d}$$
$$\implies N_d = 4.588 \times 10^{16}\ \text{m}^{-3}$$

And, from the y-intercept,

$$\text{intercept} = \left(\frac{2}{q\epsilon_0\epsilon_s A^2}\right)\frac{V_{bi}}{N_d}$$
$$\implies V_{bi} = 0.963\ \text{V}$$

IV. ERROR ANALYSIS

From Eq. 6, the error in α can be calculated Using

$$\Delta\alpha = \alpha\left(\frac{2\Delta A}{A}\right) \tag{7}$$

since A is the only measured parameter. Using $\Delta A = 0.01$ cm^2 and $\alpha = 3.445 \times 10^{34}$ C^{-1} F^{-1} m^{-3}, we get $\Delta\alpha = 3.680 \times 10^{31}$ C^{-1} F^{-1} m^{-3}.

The error in N_d and V_{bi} can be calculated using,

$$\Delta N_d = N_d \sqrt{\left(\frac{\Delta \text{slope}}{\text{slope}}\right)^2 + \left(\frac{\Delta\alpha}{\alpha}\right)^2} \tag{8}$$

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

These come out to be,

- Dark conditions,

$$\Delta N_d = 0.111 \times 10^{16} \text{ m}^{-3}$$
$$\Delta V_{bi} = 0.076 \text{ V}$$

- Ambient conditions,

$$\Delta N_d = 0.185 \times 10^{16} \text{ m}^{-3}$$
$$\Delta V_{bi} = 0.080 \text{ V}$$

V. DISCUSSION & CONCLUSION

We have successfully done the C-V characterization of the solar cell under testing in reverse bias. The first part of the circuit consists of a summing amplifier which sums up a variable DC voltage and a small AC signal. The second part othis circuit uses a transimpedance amplifier, which convertings the small AC currents produced by the solar cell into measurable voltage signals. The transimpedance amplifier uses an op-amp and a feedback resistor to generate an output voltage that is proportional to an input current. Like a resistor, a transimpedance amplifier converts current to voltage, but unlike a resistor, it has low input impedance and low output impedance even with very high gain. Hence, it basically generates a voltage output that is proportional to the capacitance of the solar cell and the output of the summing amplifier.

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.

We were also able to estimate the doping density and the built-in potential of the solar cell for two different lighting conditions.

- Dark conditions,

$$N_d = (2.984 \pm 0.111) \times 10^{16} \text{ m}^{-3}$$
$$V_{bi} = (1.022 \pm 0.076) \text{ V}$$

- Ambient conditions,

$$N_d = (4.588 \pm 0.185) \times 10^{16} \text{ m}^{-3}$$
$$V_{bi} = (0.963 \pm 0.080) \text{ V}$$

Hence, the mean value of doping density and built-in potential of the solar cell is,

$$N_d = (3.782 \pm 0.153) \times 10^{16} \text{ m}^{-3}$$
$$V_{bi} = (0.993 \pm 0.078) \text{ V}$$

VI. PRECAUTIONS AND SOURCES OF ERROR

1. The noise scales as $1/f$. To reduce this noise in the operational amplifiers, the experiment should be performed at higher frequencies.
2. While testing under dark condition, the solar cell must be properly covered
3. All components of the circuit should be checked and it should be ensured that excess voltage is not applied across the solar cell as it may damage the solar cell.
4. While performing the experiment in ambient light, the intensity if the light should not be too high as it may cause the output to saturate and the linear region would not be properly observed.

[1] SPS, *Capacitance-Voltage (C-V) characteristics of a solar cell*, NISER (2023).

[2] J. Joy, M. P. Date, B. Arora, K. L. Narasimhan, and T. S., Capacitance-voltage profiling of mos capacitors: A case study of hands-on semiconductor testing for an undergraduate laboratory., American Journal of Physics **86**, 10.1119/1.5052360 (2018).