CV Characteristics of Solar cell

Biswaranjan Meher
Integrated M.Sc.
Roll No.-2011050
School of Physical Sciences
National Institute of Science Education and Research, Bhubaneswar
(Dated: February 14, 2023)

This report is mainly focused on determining the CV characteristics of a given solar cell, which can then be used to improve the efficiency of the solar cell to produce energy. The parameters involved in the whole experiment give us an approximate idea of the electrical properties of a solar cell and various ways to improve the efficiency of the solar cell. We studied the variation in the capacitance of the solar cell (when connected in reverse bias) and calculated the doping density from the different parameters of the plots.

I. OBJECTIVES

- To study the CV characteristics of a solar cell in dark and light environments and determine various useful parameters.

II. THEORY

A. Resemblance with capacitor

A solar cell is basically a p-n junction diode. When we apply reverse bias to it, the depletion region widens, free charge carriers move away from the interface, the electric field across the junction increases, and the barrier increases leading to difficulty in moving of the charge carriers from one side to the other. Since there are no charge carriers in this region and they reside only on the surface of the boundary of the depletion region, this resembles a capacitor.
The ions in the depletion region act like a dielectric. Now, this capacitance is given by:

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

where
Q = charge
V_{DC} = applied reverse bias voltage
ϵ_o = permittivity of free space
ϵ_s = dielectric constant of the semiconductor = 11.7 for Si
A = area of the p-n junction (Area of the solar cell=19.8cm^2)

B. Working principle

This p-n junction capacitance is divided into two components namely diffusion and depletion capacitance.
Under reverse bias, due to high barrier voltage free carrier injection does not occur so the diffusion capacitance vanishes. Now, the dominant contribution to the total capacitance is made by depletion capacitance only. The opposite case happens in the case of forward bias.
As depicted in the above paragraph, the capacitance can be changed by changing the width of the depletion region which is achieved by changing the applied bias voltage.
Assuming $N_d >> N_a$, i.e. the junction is heavily n-doped, the depletion region width x_d of a reverse biased junction with a constant doping density N_d is given by:

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

where
q = charge of the electron
V_{bi} = built-in voltage.
From Eqn.(1) and (2), we get,

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

The capacitance of the solar cell i.e., the device under test(DUT) depends strongly on the applied DC voltage. Since the experiment involves the measurement of the C-V profile of the capacitor, we should apply an additional DC voltage across the capacitor (solar cell) that can be varied, while using the AC current to measure the capacitance. Here, we apply a variable DC voltage to vary the capacitance of the solar cell and a small AC signal to the solar cell to measure the resulting capacitance. We can do this by using inverting summing amplifier that adds the variable DC voltage with unity gain $R/R2$ and the small signal AC voltage with attenuation factor $R/R1 = 1/10$, the output voltage of which is then connected to the DUT.
The voltage, V_{DUT} is given by the following equation:

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

where
V_{DC} = applied DC voltage
V_{AC} = applied AC voltage

R_1, R_2, and R are the resistances mentioned in the circuit diagram FIG.1.
The magnitude of the AC component of the output voltage is given by:

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

where
$\omega = 2\pi$f
f = frequency of the applied AC signal
R_F = resistance of the trans-impedance amplifier circuit
C_F = capacitance of the trans-impedance amplifier circuit.

III. EXPERIMENTAL SETUP

A. Circuit

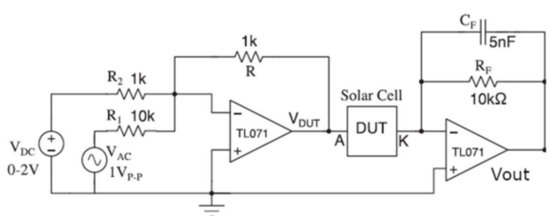

FIG. 1. Circuit diagram

The AC voltage amplitude across the DUT is one-tenth of the applied DC bias, as mentioned in the previous paragraph. Anode(A) of the solar cell is connected to the output of the summing circuit while the cathode(K) is virtually grounded due to negative feedback in the op-amp circuit. Current through a capacitor is proportional to the applied AC sinusoidal voltage. We use a trans-impedance amplifier to convert the current flowing across the capacitor to voltage and measure it using a multimeter. The trans-impedance amplifier generates a voltage that is proportional to the DUT capacitance (C_{DUT}) and V_{DUT}. **Components required :**

- IC741- op-amp used (we haven't used TL071 op-amp).
- Solar cell of a given area.
- IC 741 (trans-impedance amplifier to convert current to voltage output).
- Resistors, capacitors, cables, breadboards, connecting wires, etc.

Instruments required : DC power supply, Function generators, and Oscilloscope.

IV. OBSERVATIONS AND DATA

Table 1: For dark and light environmental conditions with and without capacitor C_F

With Capacitor									
Dark					Room light				
Vdc	V(dut)	Vout	Cdut	1/Cdut^2	Vdc	V(dut)	Vout	Cdut	1/Cdut^2
0	0.025	0.366	115.4554	7.5019E-05	0	0.048	0.382	62.7618	0.000254
0.1	0.053	0.382	56.84088	0.000309513	0.1	0.083	0.387	36.77106	0.00074
0.2	0.156	0.367	18.55303	0.002905163	0.2	0.148	0.393	20.94132	0.00228
0.3	0.272	0.365	10.58272	0.008929055	0.3	0.256	0.416	12.81524	0.006089
0.4	0.361	0.374	8.170294	0.014980441	0.4	0.36	0.432	9.46356	0.011166
0.5	0.485	0.385	6.260259	0.025516167	0.5	0.51	0.423	6.54099	0.023373
0.6	0.569	0.393	5.446952	0.033704885	0.6	0.593	0.426	5.665369	0.031156
0.7	0.698	0.405	4.575862	0.047758889	0.7	0.705	0.437	4.888387	0.041847
0.8	0.762	0.412	4.263984	0.055000789	0.8	0.807	0.447	4.368248	0.052407
0.9	0.908	0.43	3.734702	0.071694889	0.9	0.902	0.458	4.004352	0.062364
1	0.971	0.438	3.557363	0.079021206	1	0.992	0.468	3.720553	0.072241
1.1	1.114	0.457	3.235224	0.095541354	1.1	1.081	0.476	3.472598	0.082926
1.2	1.156	0.469	3.199546	0.097683991	1.2	1.214	0.498	3.235072	0.09555
1.3	1.263	0.501	3.128295	0.102184415	1.3	1.299	0.524	3.181233	0.098812
1.4	1.387	0.565	3.212516	0.096896801	1.4	1.395	0.574	3.244972	0.094968
1.5	1.484	0.664	3.528641	0.080312853	1.5	1.521	0.704	3.650201	0.075053

f=4.927kHz
Rf=9.97kohm
Cf=7.19 nF

Without capacitor									
Dark(without Cf)					Room light(without Cf)				
Vdc	V(dut)	Vout	Cdut	1/Cdut^2	Vdc	V(dut)	Vout	Cdut	1/Cdut^2
0	0.053	0.945	140.6142	5.05757E-05	0	0.055	0.846	121.3056	6.8E-05
0.1	0.112	0.961	67.66727	0.000218395	0.1	0.071	0.868	96.41279	0.000108
0.2	0.214	1.005	37.03613	0.000729036	0.2	0.161	0.966	47.3178	0.000447
0.3	0.285	1.054	29.16547	0.001175606	0.3	0.278	0.958	27.17653	0.001354
0.4	0.362	0.912	19.86825	0.002533266	0.4	0.396	1.005	20.01447	0.002496
0.5	0.487	0.946	15.31918	0.004261172	0.5	0.495	1.059	16.8719	0.003513
0.6	0.562	0.97	13.61159	0.005397375	0.6	0.596	1.016	13.44376	0.005533
0.7	0.638	1.002	12.38569	0.006518675	0.7	0.692	1.055	12.02319	0.006918
0.8	0.801	1.076	10.59383	0.008910332	0.8	0.744	1.078	11.42666	0.007659
0.9	0.913	1.09	9.415188	0.011280854	0.9	0.849	1.1	10.21782	0.009578
1	0.958	1.096	9.022322	0.012284665	1	0.955	1.106	9.133244	0.011988
1.1	1.043	1.116	8.438265	0.014044091	1.1	1.113	1.154	8.176811	0.014957
1.2	1.178	1.186	7.939857	0.015862609	1.2	1.168	1.183	7.98758	0.015674
1.3	1.276	1.27	7.849217	0.016231076	1.3	1.266	1.26	7.848924	0.016232
1.4	1.357	1.376	7.99672	0.015637821	1.4	1.336	1.338	7.898106	0.016031
1.5	1.476	1.639	8.757213	0.013039719	1.5	1.466	1.602	8.617908	0.013465

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V. PLOTS AND CALCULATIONS

A. Dark condition

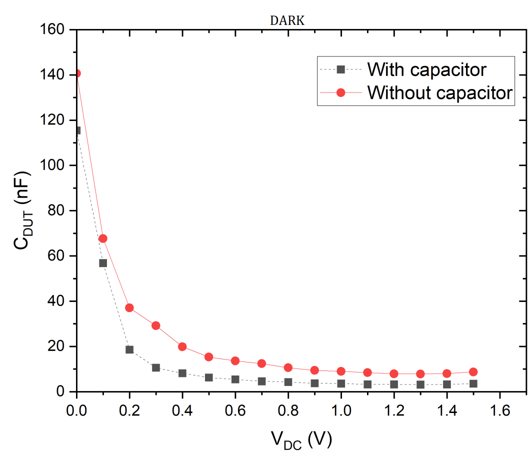

FIG. 2. Plot of C_{DUT} vs V_{DC} in dark condition with and without capacitor C_F

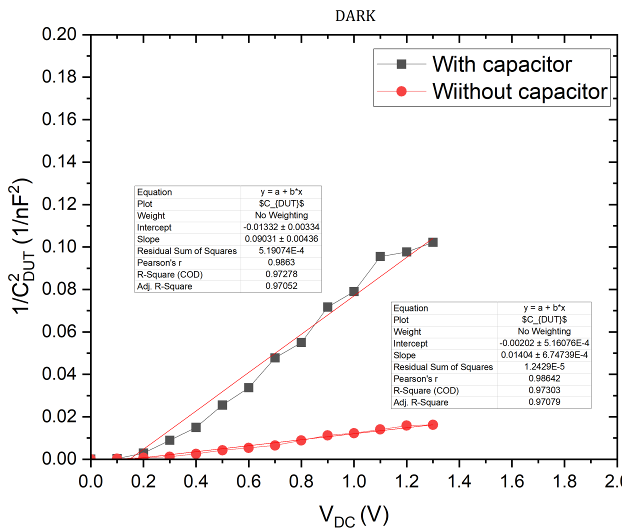

FIG. 3. Plot of $\frac{1}{C^2_{DUT}}$ vs V_{DC} in dark condition with and without capacitor C_F

From Fig.(3), we got the following values:

- **With capacitor:**
  Slope $= (0.09031 \pm 0.00436) \times 10^{18} V^{-1}F^{-2}$
  Intercept $= (-0.01332 \pm 0.00334) \times 10^{18} F^{-2}$
  Substituting the values in Eqn.(3), we get,
  Doping density:
  $N_d = 3.407 \times 10^{17} m^{-3}$
  Error in doping density,
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{2\delta l}{l}\right)^2 + \left(\frac{2\delta b}{b}\right)^2}$
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{0.00436}{0.09031}\right)^2 + \left(\frac{0.2}{4.4}\right)^2 + \left(\frac{0.2}{4.5}\right)^2} = 0.0798$
  $\delta N_d = 0.2719 \times 10^{17} m^{-3}$
  Doping density: $N_d = (3.407 \pm 0.2719) \times 10^{17} m^{-3}$
  Built-in voltage:
  $V_{bi} = \frac{slope}{intercept} = -0.1475$ V
  Error in built-in voltage:
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta intercept}{intercept}\right)^2}$
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.00436}{0.09031}\right)^2 + \left(\frac{0.00334}{-0.01332}\right)^2} = 0.255$
  $\delta V_{bi} = 0.0376V$
  Built-in voltage: $V_{bi} = (-0.1475 \pm 0.0376)V$

- **Without capacitor:**
  Slope $= (0.01404 \pm 0.0006747) \times 10^{18} V^{-1}F^{-2}$
  Intercept $= (-0.00202 \pm 0.000516) \times 10^{18} F^{-2}$
  Substituting the values in Eqn.(3), we get,
  Doping density:
  $N_d = 2.1916 \times 10^{18} m^{-3}$
  Error in doping density:
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{2\delta l}{l}\right)^2 + \left(\frac{2\delta b}{b}\right)^2}$
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{0.0006747}{0.01404}\right)^2 + \left(\frac{0.2}{4.4}\right)^2 + \left(\frac{0.2}{4.5}\right)^2} = 0.07968$
  $\delta N_d = 0.1746 \times 10^{18} m^{-3}$
  Doping density: $N_d = (2.1916 \pm 0.1746) \times 10^{18} m^{-3}$
  Built-in voltage:
  $V_{bi} = -0.14387$ V
  Error in built-in voltage:
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta intercept}{intercept}\right)^2}$
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.0006747}{0.01404}\right)^2 + \left(\frac{0.000516}{-0.00202}\right)^2} = 0.26$
  $\delta V_{bi} = 0.0374V$
  Built-in voltage: $V_{bi} = (-0.14387 \pm 0.0374)V$

B. Light condition

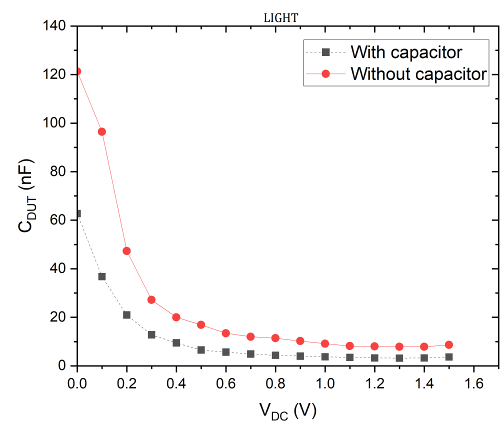

FIG. 4. Plot of C_{DUT} vs V_{DC} in light condition with and without capacitor C_F

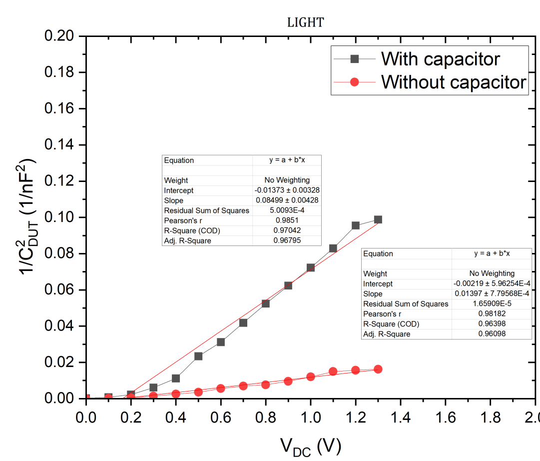

FIG. 5. Plot of $\frac{1}{C^2_{DUT}}$ vs V_{DC} in light condition with and without capacitor C_F

From Fig.(5), we got the following values:

- **With capacitor:**
  Slope $= (0.08499 \pm 0.00428) \times 10^{18} V^{-1} F^{-2}$
  Intercept $= (-0.01373 \pm 0.00328) \times 10^{18} F^{-2}$
  Substituting the values in Eqn.(3), we get,
  Doping density:
  $N_d = 3.62 \times 10^{17} m^{-3}$
  Error in doping density,
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{2\delta l}{l}\right)^2 + \left(\frac{2\delta b}{b}\right)^2}$
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{0.00428}{0.08499}\right)^2 + \left(\frac{0.2}{4.4}\right)^2 + \left(\frac{0.2}{4.5}\right)^2} = 0.0811$
  $\delta N_d = 0.2936 \times 10^{17} m^{-3}$
  Doping density: $N_d = (3.62 \pm 0.2936) \times 10^{17} m^{-3}$
  Built-in voltage:
  $V_{bi} = -0.1615$ V
  Error in built-in voltage:
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta intercept}{intercept}\right)^2}$
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.00428}{0.08499}\right)^2 + \left(\frac{0.00328}{-0.01373}\right)^2} = 0.244$
  $\delta V_{bi} = 0.0394V$
  Built-in voltage: $V_{bi} = (-0.1615 \pm 0.0394)V$

- **Without capacitor:**
  Slope $= (0.01397 \pm 0.0007796) \times 10^{18} V^{-1} F^{-2}$
  Intercept $= (-0.00219 \pm 0.000596) \times 10^{18} F^{-2}$
  Substituting the values in Eqn.(3), we get,
  Doping density:
  $N_d = 2.2026 \times 10^{18} m^{-3}$
  Error in doping density,
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{2\delta l}{l}\right)^2 + \left(\frac{2\delta b}{b}\right)^2}$
  $\frac{\delta N_d}{N_d} = \sqrt{\left(\frac{0.0007796}{0.01397}\right)^2 + \left(\frac{0.2}{4.4}\right)^2 + \left(\frac{0.2}{4.5}\right)^2} = 0.0846$
  $\delta N_d = 0.186 \times 10^{18} m^{-3}$
  Doping density: $N_d = (2.2026 \pm 0.186) \times 10^{18} m^{-3}$
  Built-in voltage:
  $V_{bi} = -0.1567$ V
  Error in built-in voltage:
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{\delta slope}{slope}\right)^2 + \left(\frac{\delta intercept}{intercept}\right)^2}$
  $\frac{\delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.0007796}{0.01397}\right)^2 + \left(\frac{0.000596}{-0.00219}\right)^2} = 0.278$
  $\delta V_{bi} = 0.0436V$
  Built-in voltage: $V_{bi} = (-0.1567 \pm 0.0436)V$

VI. RESULTS

- **DARK condition:**
  - **With capacitor:**
    Doping density:
    $$N_d = (3.407 \pm 0.2719) \times 10^{17} m^{-3}$$
    Built-in barrier potential:
    $$V_{bi} = (-0.1475 \pm 0.0376)V$$
  - **Without capacitor:**
    Doping density:
    $$N_d = (2.1916 \pm 0.1746) \times 10^{18} m^{-3}$$
    Built-in barrier potential:
    $$V_{bi} = (-0.14387 \pm 0.0374)V$$
- **LIGHT condition:**
  - **With capacitor:**
    Doping density:
    $$N_d = (3.62 \pm 0.2936) \times 10^{17} m^{-3}$$
    Built-in barrier potential:
    $$V_{bi} = (-0.1615 \pm 0.0394)V$$
  - **Without capacitor:**
    Doping density:
    $$N_d = (2.2026 \pm 0.186) \times 10^{18} m^{-3}$$
    Built-in barrier potential:
    $$V_{bi} = (-0.1567 \pm 0.0436)V$$

VII. CONCLUSIONS AND DISCUSSIONS

- From FIG.2 and 4, we observed that the capacitance decreases with an increase in reverse bias voltage. From FIG.3 and 5, we verified that the capacitance decreases with a power dependence of 2 with an increase in reverse bias voltage. Hence, we verified the theory that as we increase the reverse bias voltage the mobile charge carriers are pushed away from the junction toward the boundary and this leads to an increase in the width of the depletion region, causing a decrease in the capacitance as $C = \frac{\epsilon_o A}{d}$.

- The trans-impedance amplifier that is used in the circuit is an active low-pass filter with capacitance in the feedback path. One common type of trans-impedance amplifier is in the form of an inverting integrator.
  When a sine wave having a varying frequency is passed through the integrator, it will stop behaving like an integrator and will start to behave like a low-pass filter. It will begin to pass the low-frequency signals and attenuate the higher frequencies. When the frequency is zero, the behavior of the capacitor is similar to that open circuit. As there is a gradual increase in the frequency, the capacitor will start to get charged. When the frequency is considerably higher, the capacitor will behave like a short circuit.

- After completing the required experiment, we tried to repeat the experiment without the feedback capacitor in the trans-impedance amplifier. The corresponding plots we got were good, but the capacitance of the solar cell has higher values as compared to the one with the feedback capacitor. Since we have no feedback capacitor in this case, there is no alternate path for the current to transfer other than through the feedback resistor. Thus, at low input frequencies, the plots might be good, but there should be some distortion in the plots when we give an input of higher frequencies.

- Next, we tried to extend the experiment in a dark room and using a lamp. In this case, we found much difficulty in observing the data for V_{DUT} as it was fluctuating very much. It should be because of the following reasons:

  - In the dark room, we were observing the multimeter data using a phone torch, which could possibly be affecting the solar cell output.
  - While using a lamp, there is a range of frequencies of light emitted by the lamp falling on the solar cell, causing a different number of charge carriers to be affected in the depletion region of the solar cell each time, causing a difference in the voltage across the solar cell.

  In the lamp case, the plot was distorted due to fluctuations in readings and the abovementioned reason.

VIII. SOURCES OF ERRORS AND PRECAUTIONS

- Loose connections in the circuit.
- Fluctuations in the reading of the multimeters.
- Human errors, personal errors, etc.
- The solar cell is not in perfect dark condition. Some light is being incident on it leading to extra addition of light generated current.

IX. REFERENCES

- NISER Lab Manual
- `https://www.scirp.org/pdf/22-1.476.pdf`
- `https://download.tek.com/document/1KW-60642-0_SolarCellChar_4200A-SCS_AN.pdf`