Low cost (using LabView) CV Profiling of Diodes

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Abstract

This report presents the results of an experiment on the capacitance-voltage (CV) profiling of Schottky diode, LEDs, and solar cells. The experiment involved designing a lock-in amplifier algorithm using LabVIEW software to take the input from the circuit containing the diode sample to obtain DC output voltages. The capacitance of the sample is studied in reverse bias and plotted with the voltage. The doping density and built in potential have also been found out. The report provides detailed information on the theory behind lock-in amplifiers, diodes, and circuitry used in the study, as well as the observations and conclusions drawn from the experiment.

1 Equipments Required

- Lock-in Amplifier: A signal-processing device that extracts a small signal from a noisy background.
- Power Supply: To supply power to the samples.
- Function Generator: To generate a small AC voltage signal that is applied to the samples.
- Op-Amps
- Multimeter: To measure the DC output voltage from the samples.
- LabVIEW Software: To design the lock-in amplifier algorithm.
- Data Acquisition Device (DAQ)
- Schottky, LED, and Solar Cell Samples: To perform the CV profiling experiment.
- Beradboard, Cables and Connectors

2 Introduction and Theory

2.1 Diodes used

2.1.1 Schottky Diode

A Schottky diode is a type of diode that is formed by the junction of a metal and a semiconductor. In a Schottky diode, a metal layer is deposited on a semiconductor substrate to form a junction. When a voltage is applied across the junction, the metal layer forms a barrier to the flow of electrons, which results in the formation of a depletion region. The Schottky diode has a low forward voltage drop and high switching speed, making it useful for high-frequency applications.

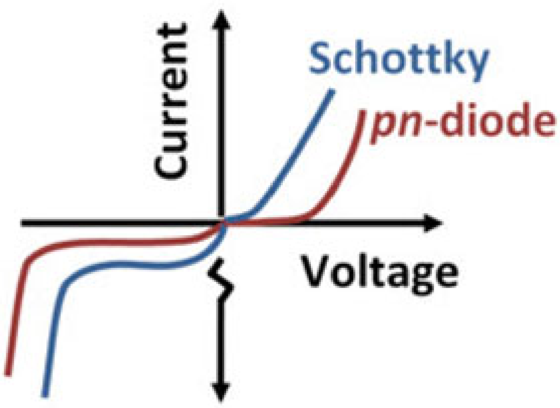

Figure 1: IV Characteristics of Schottky and p-n diodes. The figure has been taken from Reference[1]

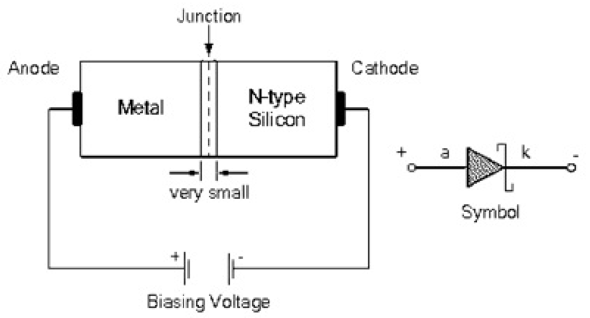

Figure 2: Schottky diode construction. The figure has been taken from Refernce[2]

2.1.2 LEDs

An LED (light-emitting diode) is a semiconductor device that emits light when current passes through it. When a forward bias is applied to the p-n junction of an LED, electrons from the n-type material and holes from the p-type material combine at the junction, emitting photons in the process. The energy of the photons emitted depends on the bandgap energy of the material used in the LED.

2.1.3 Solar cell

A solar cell is a semiconductor device that converts light energy into electrical energy. When light falls on the semiconductor material of the solar cell, electrons are excited to a higher energy level and can be collected at the contacts of the cell. The amount of current generated by the solar cell depends on the intensity and wavelength of the light falling on the cell, as well as the efficiency of the cell.

2.2 Capacitance in diodes!

Capacitance arises in diodes due to the presence of depletion region, which is a region in a semiconductor device where majority carriers are depleted, leaving behind immobile charged ions. The depletion region acts as a dielectric material, separating the two regions of opposite charges (i.e., the p-type and n-type regions in a pn junction diode).

When a voltage is applied to a diode, the depletion region width changes, which affects the capacitance of the device. The capacitance of a diode can be measured using its capacitance-voltage (CV) characteristics. The CV characteristics of a diode show the relationship between the capacitance of the diode and the voltage applied across it.

At low voltages, the capacitance of the diode is high because the depletion region is narrow. As the voltage is increased, the depletion region width increases, and the capacitance of the diode decreases. The CV characteristics of a diode can provide important information about the doping concentration, thickness, and quality of the diode, which can be used to optimize its performance in various applications.

2.3 Working Formulae for C-V characteristics

The Schottky barrier's capacitance as a function of reverse bias V_R is

$$C = A\sqrt{\frac{e\epsilon\epsilon_0\rho_0}{2\left(V_R + V_{\mathrm{bi}}\right)}} \qquad .....(1)$$

This expression can be re-written as

$$\frac{1}{C^2} = \frac{2}{A^2 e\epsilon\epsilon_0\rho_0}\left(V_R + V_{\mathrm{bi}}\right)$$

suggesting the following capacitance-voltage characterization method:
For a Schottky barrier with uniform doping density, a plot of $1/C^2$ versus V_R will yield a straight line with:
slope $m = \frac{2}{A^2 e\epsilon\epsilon_0\rho_0}$, and y-intercept $b = \frac{2V_o}{A^2 e\epsilon\epsilon 0\rho_0}$.
Then, the doping density and built-in potential are found from

$$\rho_0 = \frac{2}{A^2 e\epsilon\epsilon_0 m}$$

and

$$V_{\mathrm{m}} = \frac{b}{m}$$

On extending equation (1) with distance dependent doping density, we get;

$$\frac{d}{dV_R}\left(\frac{1}{C^2}\right) = \frac{1}{\left(\epsilon\epsilon_0 A\right)^2}2W\left(\frac{\epsilon\epsilon_0}{eW\rho(W)}\right) = \frac{2}{A^2 e\epsilon\epsilon_0\rho(W)}.$$

This equation is called the "Profiler's Equation" and can be used to characterize the spatial distribution of dopants in the semiconductor. Here, W is the doping density distance from the metal contact.

2.4 Lock-in detection

The lock-in detection algorithm is a signal processing technique that is used to extract a small signal from a noisy background. It is commonly used in experimental physics and engineering applications, where the signals of interest are small and buried in noise.

The lock-in detection algorithm works by multiplying the input signal with a reference signal and then integrating the product over a specific time period. The reference signal is typically a sinusoidal waveform with a known frequency and phase. The product of the input and reference signals is then passed through a low-pass filter to remove high-frequency noise and to retain only the signal component at the reference frequency. The output of the filter is then integrated over a specified time period to obtain the amplitude of the input signal at the frequency of the reference signal.

**The following mathematical analysis is inspired (not taken verbatim) from Reference[3]. If we have an input signal of the form $V_{sig}\sin(\omega_{sig}t)$, where V_{sig} and ω_{sig} are the signal's amplitude and angular frequency, respectively. We generate a reference signal sinusoid $2\sin(\omega_{ref}t)$ of amplitude 2 and angular frequency ω_{sig} , and multiply both the signals to get the following expression:

$$2V_{sig}\sin(\omega_{sig}t)\sin(\omega_{\text{ref}}\,t) = V_{\text{sig}}\,\left[\cos(\omega_{\text{sig}} - \omega_{\text{ref}})\,t - \cos(\omega_{sig}+\omega_{ref})\,t\right] \tag{1}$$

This expression denotes two AC sinusoidal signals, with amplitude V_{sig} . The frequencies of these two signals are $(\omega_{sig}-\omega_{ref})$ and one with the "sum" frequency $(\omega_{sig}+\omega_{ref})$. $\omega_{ref}=\omega_{sig}$, the first signal is actually the DC voltage V_{sig} . This means that if a waveform conatins multiple signals of different frequencies, we can multiply it with $2\sin(\omega_{\text{ref}}\,t)$ and use a low-pass filter to get the DC output, and hence obtain the amplitude of the signal which has the same frequency as the reference.

3 Experimental Setup

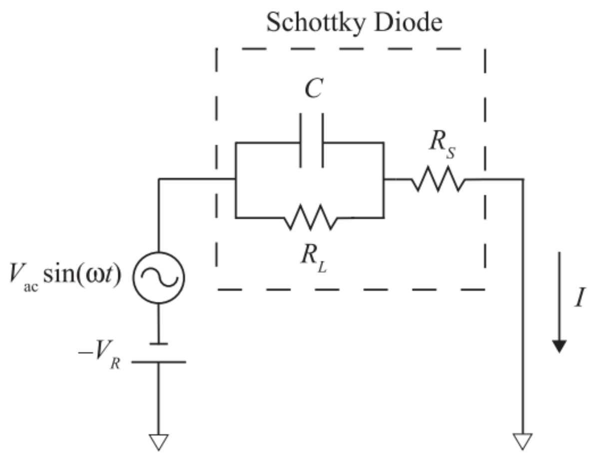

Figure 3: . Equivalent circuit of the CV characterization setup. The figure is taken from Ref[3]

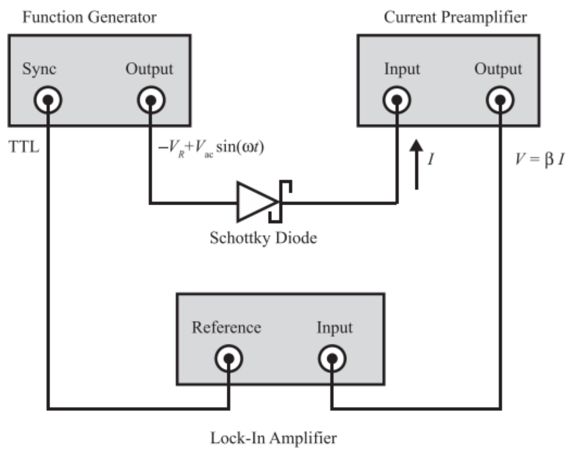

Figure 4: Research-grade implementation of CV profiling method. Reference[3]

We use the following formula for diode's capacitance:

$$C_{\text{diode}} = \frac{(V_xV_{0x}+V_yV_{0y})}{V_{0x}^2+V_{0y}^2}C_{cal}$$

here, V_{ox} is the in-phase reading of the calibration capacitor;
V_{oy} is the quadrature reading of the calibration capacitor;
V_x is the in-phase reading of the diode;
V_y is the quadrature reading of the diode;

4 Observations

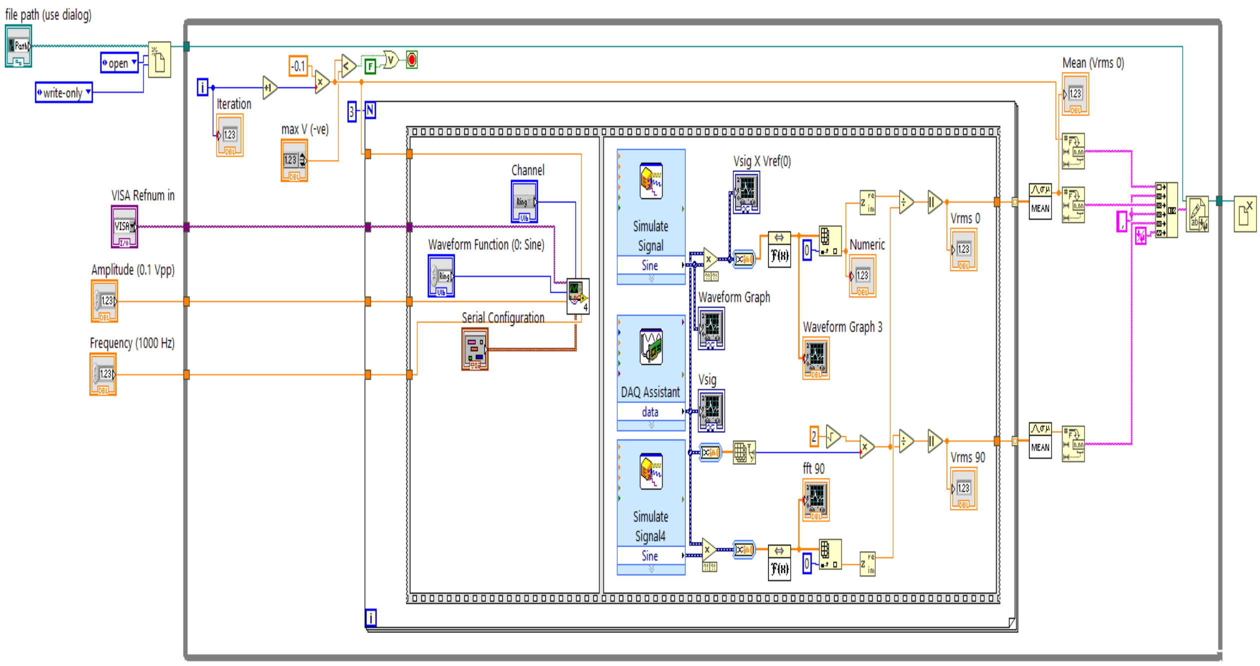

Figure 5: Labview code for the Lockin detection algorithm

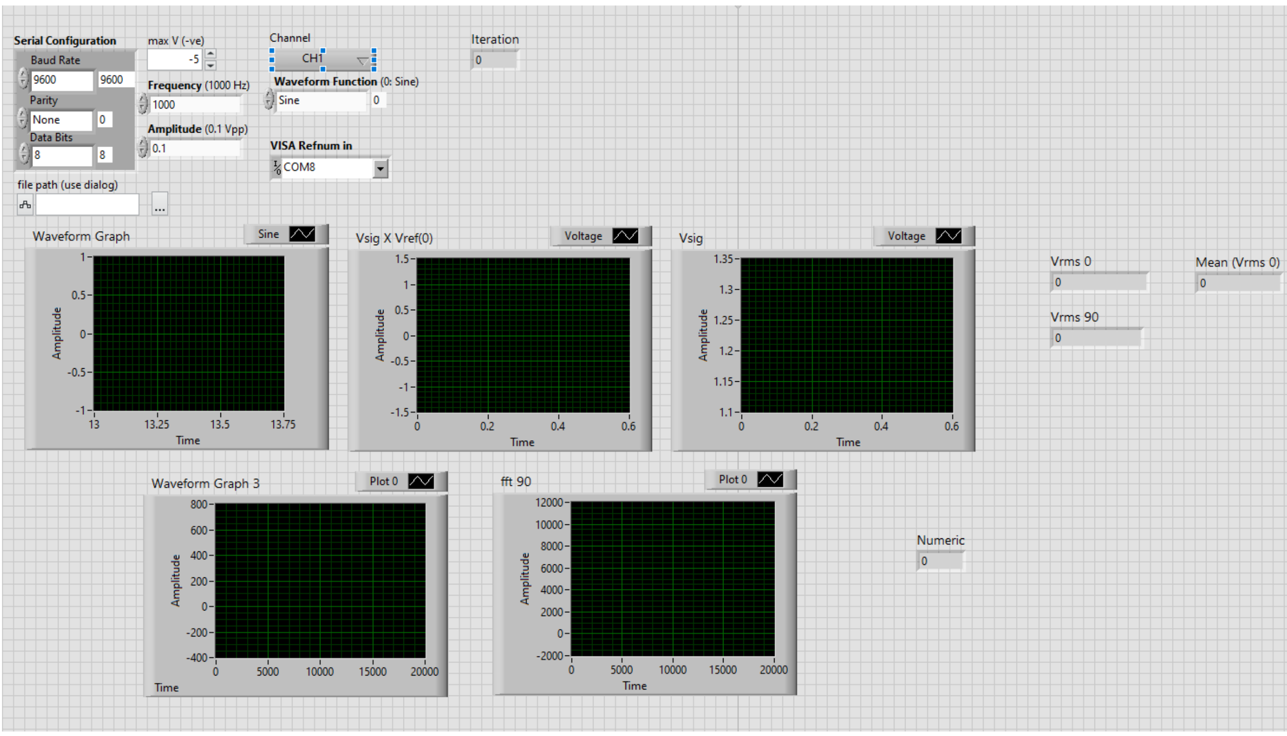

Figure 6: Front panel of the Labview. The display contains the output of the signal and the referenes along with the DC output voltage.

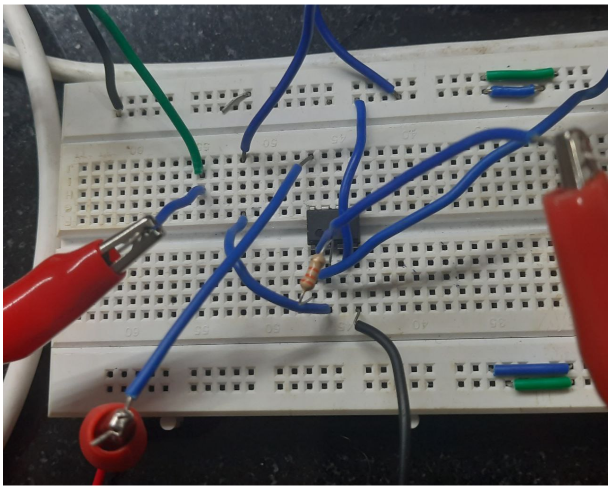

Figure 7: The circuit for the experiment. It has the OpAmp and the sample under study.

5 Calculations

5.1 Plots

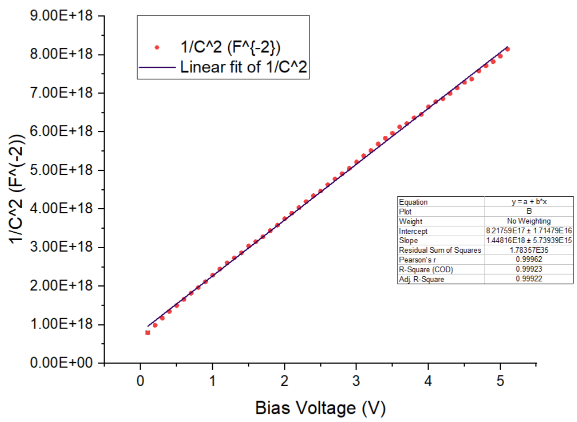

Figure 8: For Schottky diode: $\frac{1}{C^2}$ vs reverse bias voltage

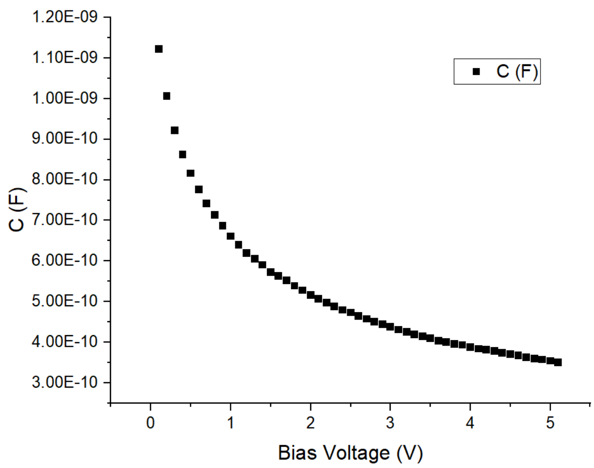

Figure 9: For Schottky diode: Capacitance vs Reverse bias Voltage

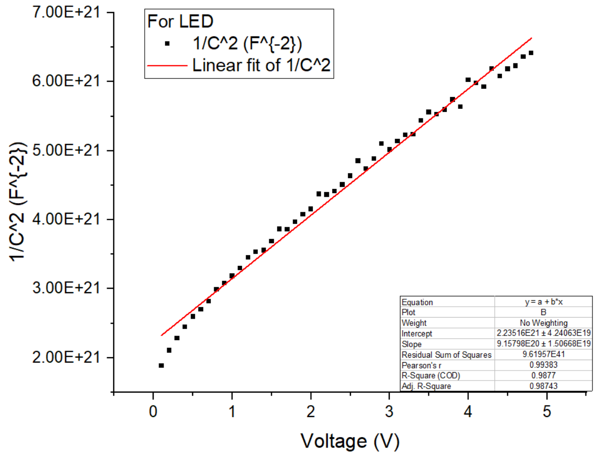

Figure 10: For LED: $\frac{1}{C^2}$ vs reverse bias voltage

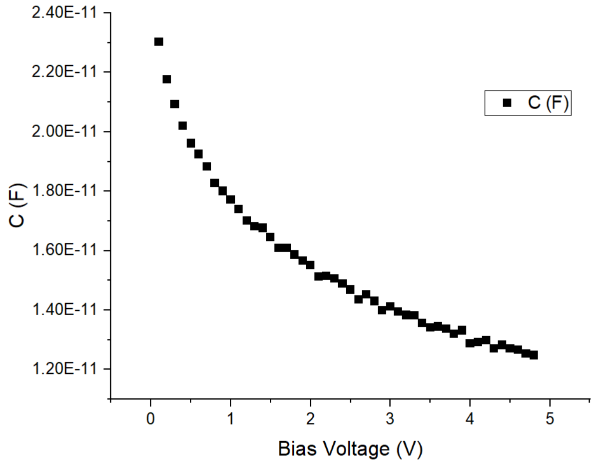

Figure 11: For LED: Capacitance vs Reverse bias Voltage

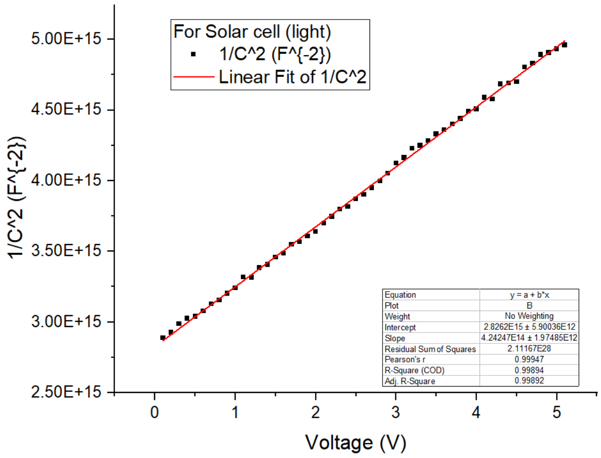

Figure 12: For SOlar cell in light: $\frac{1}{C^2}$ vs reverse bias voltage for solar cell under light

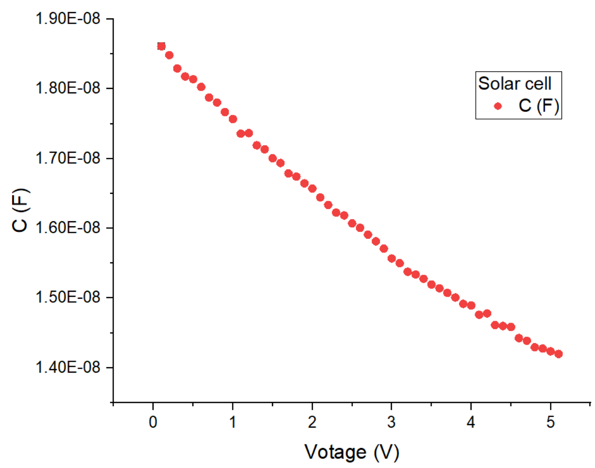

Figure 13: C- V characteristics of Solar cell under light

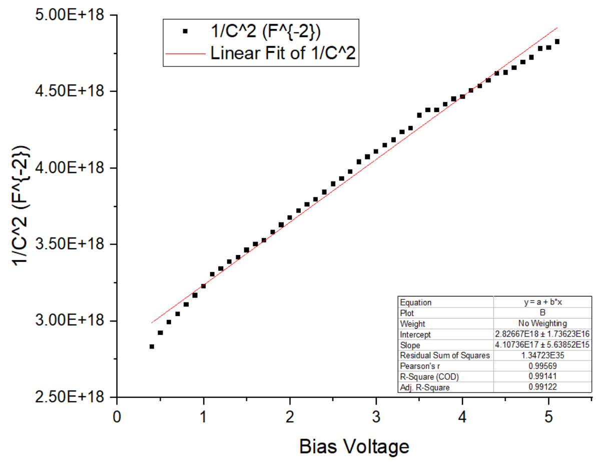

Figure 14: For Solar cell in dark: $\frac{1}{C^2}$ vs reverse bias voltage

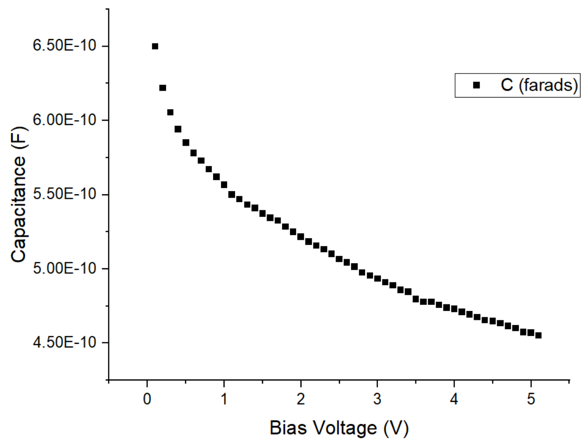

Figure 15: For solar cell in dark: C- V characteristics

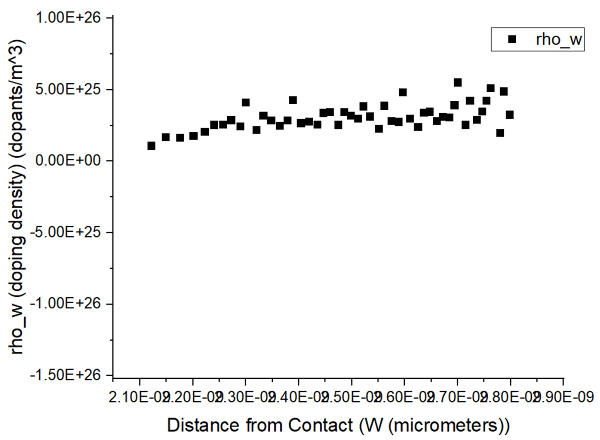

Figure 16: Spatial profile of doping density (doping density as a function of distance of contact).

5.2 CV characteristics calculations

We have plotted $\frac{1}{C^2}$ vs V and C vs V curves to study the capcacitive behaviour of the diodes. We also aim to find their built-in potential and the doping density .
Recall that, doping density and built-in potential are;

$$\rho_0 = \frac{2}{A^2 e \epsilon \epsilon_0 m}$$

and

$$V_{\text{bi}} = \frac{b}{m}$$

They can found using the slope and intercept of the $\frac{1}{C^2}$ vs V curve.

Schottky diode:

The area of cross-section, $A = 5.38 \times 10^{-6}$ m^2.

The dielectric constant is, $\epsilon = 4.1$

The slope and intercept of the $\frac{1}{C^2}$ vs V are $m = 1.448 \times 10^{18}$ and $b = 8.218 \times 10^{15}$ respectively.

So, the built-in potential;

$$V_{\text{bi}} = \frac{b}{m} = 0.568\ V$$

and, the doping density:

$$\rho_0 = \frac{2}{A^2 e \epsilon \epsilon_0 m} = 8.22 \times 10^{15}\ dopants/cc$$

LED:

The area of cross-section, $A = 1.96 \times 10^{-5}$ m^2.

The dielectric constant is, $\epsilon = 13.1$

The slope and intercept of the $\frac{1}{C^2}$ vs V are $m = 9.158 \times 10^{20}$ and $b = 2.235 \times 10^{21}$ respectively.

So, the built-in potential;

$$V_{\text{bi}} = \frac{b}{m} = 0.017\ V$$

and, the doping density:

$$\rho_0 = \frac{2}{A^2 e\epsilon\epsilon_0 m} = 3.06 \times 10^{11}\ dopants/cc$$

Solar cell in light condition:

The area of cross-section, $A = 6.016 \times 10^{-3}$ m^2

The dielectric constant is, $\epsilon = 11.7$

The slope and intercept of the $\frac{1}{C^2}$ vs V are $m = 4.242 \times 10^{14}$ and $b = 2.826 \times 10^{15}$ respectively.

So, the built-in potential;

$$V_{\text{bi}} = \frac{b}{m} = 6.66\ V$$

and, the doping density:

$$\rho_0 = \frac{2}{A^2 e\epsilon\epsilon_0 m} = 7.86 \times 10^{12}\ dopants/cc$$

Solar cell in dark condition

The area of cross-section, $A = 6.016 \times 10^{-3}$ m^2
The dielectric constant is, $\epsilon = 11.7$
The slope and intercept of the $\frac{1}{C^2}$ vs V are $m = 4.107 \times 10^{17}$
and $b = 2.827 \times 10^{18}$ respectively.

So, the built-in potential;

$$V_{\text{bi}} = \frac{b}{m} = 6.88\ V$$

and, the doping density:

$$\rho_0 = \frac{2}{A^2 e\epsilon\epsilon_0 m} = 8.12 \times 10^{15}\ dopants/cc$$

6 Error Analysis

6.1 For Schottky diode:

Error in built-in potential:

$$\frac{\Delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.006 \times 10^{18}}{1.448 \times 10^{18}}\right)^2 + \left(\frac{0.171 \times 10^{17}}{8.218 \times 10^{17}}\right)^2}$$

$$\Rightarrow \frac{\Delta V_{bi}}{V_{bi}} = 0.021$$

$$\Rightarrow \Delta V_{bi} = 0.021 \times 0.568 = 0.012\ V \qquad (2)$$

Error in Doping Density:

$$\frac{\Delta\rho_0}{\rho_0} = \frac{0.006 \times 10^{18}}{1.448 \times 10^{18}} = 4.14 \times 10^{-3}$$

$$\Rightarrow \Delta\rho_0 = 4.14 \times 10^{-3} \times 8.22 \times 10^{21}$$

$$\Rightarrow \Delta\rho_0 = 3.40 \times 10^{13}\ dopants/cc \qquad (3)$$

6.2 For LED:

Error in built-in potential:

$$\frac{\Delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.151 \times 10^{20}}{9.158 \times 10^{20}}\right)^2 + \left(\frac{0.004 \times 10^{21}}{2.235 \times 10^{21}}\right)^2}$$

$$\Rightarrow \frac{\Delta V_{bi}}{V_{bi}} = 0.016$$

$$\Rightarrow \Delta V_{bi} = 0.016 \times 0.016 = 0.0002\ V \qquad (4)$$

Error in Doping Density:

$$\frac{\Delta\rho_0}{\rho_0} = \frac{0.151 \times 10^{20}}{9.158 \times 10^{20}} = 0.016$$

$$\Rightarrow \Delta\rho_0 = 0.016 \times 3.06 \times 10^{17}$$

$$\Rightarrow \Delta\rho_0 = 0.049 \times 10^{11}\ dopants/cc \qquad (5)$$

6.3 For Solar cell under light:

Error in built-in potential:

$$\frac{\Delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.002 \times 10^{14}}{4.242 \times 10^{14}}\right)^2 + \left(\frac{0.006 \times 10^{15}}{2.826 \times 10^{15}}\right)^2}$$

$$\Rightarrow \frac{\Delta V_{bi}}{V_{bi}} = 2.17 \times 10^{-3}$$

$$\Rightarrow \Delta V_{bi} = 2.17 \times 10^{-3} \times 6.66 = 0.014\ V \qquad (6)$$

Error in Doping Density:

$$\frac{\Delta\rho_0}{\rho_0} = \frac{0.002 \times 10^{14}}{4.242 \times 10^{14}} = 4.71 \times 10^{-4}$$

$$\Rightarrow \Delta\rho_0 = 4.71 \times 10^{-4} \times 7.86 \times 10^{18}$$

$$\Rightarrow \Delta\rho_0 = 0.37 \times 10^{12}\ dopants/cc \qquad (7)$$

6.4 For Solar cell in dark:

Error in built-in potential:

$$\frac{\Delta V_{bi}}{V_{bi}} = \sqrt{\left(\frac{0.006 \times 10^{17}}{4.107 \times 10^{17}}\right)^2 + \left(\frac{0.002 \times 10^{18}}{2.827 \times 10^{18}}\right)^2}$$

$$\Rightarrow \frac{\Delta V_{bi}}{V_{bi}} = 1.62 \times 10^{-3}$$

$$\Rightarrow \Delta V_{bi} = 1.62 \times 10^{-3} \times 6.88 = 0.01V \tag{8}$$

Error in Doping Density:

$$\frac{\Delta \rho_0}{\rho_0} = \frac{0.006 \times 10^{17}}{4.107 \times 10^{17}} = 1.46 \times 10^{-3}$$

$$\Rightarrow \Delta \rho_0 = 1.46 \times 10^{-3} \times 8.12 \times 10^{15}$$

$$\Rightarrow \Delta \rho_0 = 0.01 \times 10^9 \; dopants/cc \tag{9}$$

7 Results and Discussion

- We have performed the CV profiling of Schottky diode, a red LED, and solar cell in light and dark conditions.
- The behavior of the plots $\frac{1}{C^2}$ vs reverse bias voltage(V) and, C vs V are expected and in accordance with theory.
- Figures 8, 10, 12 and 14, represent the $\frac{1}{C^2}$ vs reverse bias voltage for the diodes and they are almost linear as expected. The linear fitting has been done with $R^2 = 0.987$.
- Figures 9, 11, 13, and 15 represent the C vs V curves. As expected, they show the decay of capacitance with increase in reverse bias voltage. This is because **the depletion region of the diode increases (and so the capacitance decreases) on increasing the bias voltage.**
- For Schottky diode, **the doping density obtained is** $8.22 \times 10^{15} \pm 3.40 \times 10^{13}$ $dopants/cc$ **and the built in potential is found to be** 0.568 ± 0.012 **Volts.**
- For LED, the **doping density obtained is** $3.06 \times 10^{11} \pm 0.049 \times 10^{11}$ $dopants/cc$ **and the built in potential is found to be** 0.0171 ± 0.0002 **Volts.**
- For Solar cell in light, the **doping density obtained is** $7.86 \times 10^{12} \pm 0.37 \times 10^{12}$ $dopants/cc$ **and the built in potential is found to be** 6.661 ± 0.014 V
- For Solar cell in dark condition, the **doping density obtained is** $8.12 \times 10^{15} \pm 0.01 \times 10^9$ **and the built in potential is found to be** 6.88 ± 0.01 V
- It is important to keep in mind that the experiments are performed under reverse bias as the depletion region of a diode increases and can be well studied for the capacitance.
- We made the Lock-in detection algorithm using Labview, while taking the input from the circuit and simulating the in-phase and out-phase(with a phase difference of 90°) reference signals in the software itself.
- We have tried our best to compact the code by efficiently using the loops, file reading variable and mathematical functions. Our code is significantly shorter and more readable than the previous works in this experiment. We also automated the data collection using DAQ.
- We can see from the C-V plot for Solar cell that the capacitance under light is greater than that in dark by a factor of 10^2. This is because the depletion region of the solar cell diode decreases under illumination due to the photogenerated charge carriers, and so the capacitance increases.
- We have also reproduced the spatial profiling of doping density for Schottky diode from the reference[3].
- It is important to ensure that the LABVIEW code works correctly, otherwise the output V_{rms} values will be incorrect and so will the plots and further results.
- In the Lock-in algorithm, we have also replaced the external phase shifter by doing Fast Fourier Transform to perform the phase change of the signal.
- No fitting has been done for the plots of C vs V, as this plot is just to observe the behavior of the capacitance with bias

voltage, and we are not inferring anything quantitatively from it.

8 Conclusion

- The capacitance -Voltage (CV) profiling has been studied for diodes such as schottky diode, LED, solar cells and the behavior of the relevant plots has been verified with the theory.
- We have found out the important parameters such as built in potential and doping density for these diodes.
- So, we can say that a low-cost CV profiling is possible and convenient.

9 References

1. https://www.semiconductorforu.com/v-i-characteristics-of-schottky-barrier-diode/

2. https://www.watelectronics.com/schottky-diode/

3. Reynolds Neal D, Panda Cristian D, Essick John M. "Capacitance-voltage profiling: Research-grade approach versus low-cost alternatives". American Journal of Physics 82, 196 (2014)

4. https://www.electricaltechnology.org/2018/12/types-of-diodes-their-applications.html

10 Appendix

10.1 Data collected for the diodes

Table 1: CV Profiling Readings for Schottky Diode

Voltage (Reverse bias)	V_x	V_y	V_{0x}	V_{0y}	C	$1/C^2$
0.1	0.002458	0.111486	0.03485	0.919926	1.12155E-09	7.94994E+17
0.2	0.003952	0.103504	0.034395	0.953296	1.00548E-09	9.8913E+17
0.3	0.003682	0.096911	0.035506	0.973046	9.22305E-10	1.17558E+18
0.4	0.003499	0.091689	0.037086	0.984432	8.62483E-10	1.34431E+18
0.5	0.003451	0.087423	0.036058	0.992129	8.16052E-10	1.50163E+18
0.6	0.003225	0.083618	0.035961	0.998155	7.75805E-10	1.66148E+18
0.7	0.003144	0.080129	0.035667	1.001225	7.41182E-10	1.82033E+18
0.8	0.003135	0.077338	0.036983	1.004203	7.1325E-10	1.9657E+18
0.9	0.003053	0.074682	0.036894	1.006254	6.87363E-10	2.11654E+18
1.0	0.002943	0.072117	0.037217	1.010317	6.61081E-10	2.28819E+18
1.1	0.002786	0.069981	0.036735	1.013312	6.39593E-10	2.44451E+18
1.2	0.002732	0.067845	0.036926	1.014102	6.19595E-10	2.60486E+18
1.3	0.002513	0.066262	0.0378	1.014343	6.04925E-10	2.73273E+18
1.4	0.002487	0.064621	0.037591	1.013105	5.9068E-10	2.86613E+18
1.5	0.002486	0.062756	0.037649	1.013746	5.73293E-10	3.04261E+18
1.6	0.002348	0.061554	0.036415	1.012654	5.62912E-10	3.15587E+18
1.7	0.002365	0.060294	0.03696	1.011684	5.51929E-10	3.28272E+18
1.8	0.00231	0.058892	0.037704	1.011671	5.39088E-10	3.44097E+18
1.9	0.002329	0.057725	0.03664	1.012235	5.28152E-10	3.58495E+18
2.0	0.002142	0.05649	0.036497	1.012946	5.16447E-10	3.74929E+18
2.1	0.002062	0.055507	0.03656	1.013959	5.06939E-10	3.89125E+18
2.2	0.002193	0.054509	0.036673	1.01432	4.97701E-10	4.03705E+18
2.3	0.002138	0.053479	0.03757	1.014075	4.88395E-10	4.19235E+18
2.4	0.001903	0.052494	0.036464	1.013502	4.79623E-10	4.3471E+18
2.5	0.001984	0.051837	0.036945	1.014566	4.73151E-10	4.46684E+18
2.6	0.002045	0.050946	0.037399	1.015214	4.64747E-10	4.62986E+18
2.7	0.002015	0.050173	0.036317	1.015742	4.57474E-10	4.77824E+18
2.8	0.001982	0.049499	0.037219	1.016293	4.51069E-10	4.9149E+18
2.9	0.002005	0.04878	0.03724	1.015739	4.44776E-10	5.05496E+18
3.0	0.001883	0.048053	0.03684	1.016792	4.37669E-10	5.22046E+18
3.1	0.001952	0.047361	0.036674	1.017515	4.31094E-10	5.38092E+18
3.2	0.001827	0.046755	0.038196	1.017039	4.25722E-10	5.51757E+18
3.3	0.001837	0.046082	0.037259	1.017764	4.19321E-10	5.6873E+18
3.4	0.001912	0.045455	0.038737	1.016987	4.13945E-10	5.83599E+18
3.5	0.00181	0.045059	0.038755	1.018714	4.09615E-10	5.96004E+18
3.6	0.001754	0.044379	0.037371	1.017697	4.03845E-10	6.13156E+18
3.7	0.001767	0.044003	0.037719	1.016042	4.01079E-10	6.2164E+18
3.8	0.001871	0.043452	0.036745	1.01531	3.96397E-10	6.36415E+18
3.9	0.001746	0.043138	0.037938	1.014873	3.93649E-10	6.45329E+18
4.0	0.001727	0.042455	0.037219	1.013829	3.87827E-10	6.6485E+18
4.1	0.00162	0.042028	0.037457	1.013423	3.84047E-10	6.78002E+18
4.2	0.001678	0.041721	0.036812	1.011873	3.81857E-10	6.85803E+18
4.3	0.001684	0.04129	0.036725	1.011532	3.78048E-10	6.99691E+18
4.4	0.001522	0.040845	0.037047	1.010806	3.7419E-10	7.14194E+18
4.5	0.001565	0.040418	0.037158	1.010114	3.7055E-10	7.28295E+18
4.6	0.001465	0.040149	0.037017	1.009285	3.68357E-10	7.36991E+18
4.7	0.001601	0.039567	0.036924	1.008764	3.63259E-10	7.57824E+18
4.8	0.001561	0.039192	0.036724	1.008057	3.60062E-10	7.7134E+18
4.9	0.001578	0.038912	0.036424	1.007818	3.57587E-10	7.82054E+18
5.0	0.001444	0.03857	0.036062	1.007857	3.54395E-10	7.96205E+18
5.1	0.001521	0.038142	0.037237	1.007819	3.50493E-10	8.14034E+18

Table 2: CV Profiling Readings for LED

Voltage (Reverse bias)	V_x	V_y	V_{0x}	V_{0y}	C	$1/C^2$
0.1	0.000082	0.002288	0.03485	0.919926	2.30293E-11	1.88555E+21
0.2	0.000109	0.00224	0.034395	0.953296	2.17685E-11	2.1103E+21
0.3	0.00009	0.002199	0.035506	0.973046	2.09302E-11	2.28273E+21
0.4	0.000067	0.002148	0.037086	0.984432	2.02001E-11	2.45071E+21
0.5	0.000091	0.002101	0.036058	0.992129	1.96146E-11	2.59922E+21
0.6	0.000088	0.002074	0.035961	0.998155	1.92452E-11	2.69995E+21
0.7	0.000088	0.002036	0.035667	1.001225	1.88354E-11	2.81871E+21
0.8	0.000077	0.001982	0.036983	1.004203	1.82779E-11	2.99329E+21
0.9	0.000091	0.001956	0.036894	1.006254	1.80065E-11	3.0842E+21
1.0	0.000098	0.001932	0.037217	1.010317	1.77167E-11	3.18592E+21
1.1	0.000072	0.001904	0.036735	1.013312	1.74004E-11	3.30279E+21
1.2	0.000089	0.001862	0.036926	1.014102	1.70094E-11	3.45639E+21
1.3	0.000063	0.001843	0.0378	1.014343	1.68229E-11	3.53343E+21
1.4	0.000074	0.001834	0.037591	1.013105	1.67652E-11	3.55782E+21
1.5	0.000061	0.001802	0.037649	1.013746	1.64583E-11	3.69175E+21
1.6	0.000069	0.001759	0.036415	1.012654	1.60867E-11	3.86426E+21
1.7	0.000081	0.001758	0.03696	1.011684	1.60967E-11	3.85947E+21
1.8	0.000073	0.001733	0.037704	1.011671	1.58653E-11	3.97285E+21
1.9	0.000076	0.001711	0.03664	1.012235	1.5657E-11	4.07927E+21
2.0	0.000056	0.001697	0.036497	1.012946	1.55117E-11	4.15606E+21
2.1	0.000058	0.001656	0.03656	1.013959	1.51229E-11	4.37251E+21
2.2	0.000073	0.001658	0.036673	1.01432	1.51406E-11	4.36226E+21
2.3	0.000078	0.001648	0.03757	1.014075	1.50544E-11	4.41239E+21
2.4	0.00006	0.00163	0.036464	1.013502	1.48932E-11	4.50844E+21
2.5	0.000066	0.001609	0.036945	1.014566	1.46879E-11	4.63533E+21
2.6	0.000052	0.001574	0.037399	1.015214	1.43548E-11	4.85294E+21
2.7	0.000067	0.001593	0.036317	1.015742	1.45258E-11	4.73934E+21
2.8	0.00006	0.00157	0.037219	1.016293	1.4306E-11	4.88614E+21
2.9	0.000068	0.001535	0.03724	1.015739	1.39978E-11	5.10367E+21
3.0	0.000072	0.00155	0.03684	1.016792	1.41212E-11	5.01485E+21
3.1	0.000087	0.001532	0.036674	1.017515	1.39525E-11	5.13681E+21
3.2	0.000058	0.001519	0.038196	1.017039	1.38306E-11	5.22778E+21
3.3	0.000095	0.001517	0.037259	1.017764	1.38154E-11	5.23932E+21
3.4	0.000076	0.001489	0.038737	1.016987	1.35645E-11	5.4349E+21
3.5	0.000032	0.001476	0.038755	1.018714	1.34083E-11	5.56224E+21
3.6	0.000079	0.001477	0.037371	1.017697	1.34474E-11	5.52994E+21
3.7	0.000068	0.001466	0.037719	1.016042	1.33654E-11	5.59803E+21
3.8	0.000055	0.001447	0.036745	1.01531	1.3198E-11	5.74092E+21
3.9	0.000041	0.00146	0.037938	1.014873	1.33168E-11	5.63894E+21
4.0	0.000061	0.00141	0.037219	1.013829	1.28816E-11	6.02644E+21
4.1	0.000054	0.001415	0.037457	1.013423	1.29299E-11	5.98147E+21
4.2	0.000053	0.001419	0.036812	1.011873	1.29862E-11	5.92973E+21
4.3	0.00006	0.001388	0.036725	1.011532	1.27095E-11	6.19071E+21
4.4	0.000055	0.0014	0.037047	1.010806	1.28266E-11	6.07818E+21
4.5	0.000077	0.001386	0.037158	1.010114	1.27146E-11	6.18577E+21
4.6	0.000049	0.001381	0.037017	1.009285	1.26699E-11	6.22954E+21
4.7	0.000066	0.001365	0.036924	1.008764	1.25355E-11	6.36384E+21
4.8	0.000072	0.001358	0.036724	1.008057	1.24821E-11	6.41837E+21

Table 3: CV Profiling Readings for Solar cell in light condition

Voltage (Reverse bias)	V_x	V_y	V_{0x}	V_{0y}	C	$1/C^2$
0.1	0.013793	0.064742	0.001843	0.032498	1.86107E-08	2.8872E+15
0.2	0.013525	0.064314	0.001817	0.032495	1.84851E-08	2.92656E+15
0.3	0.013052	0.063869	0.001917	0.032605	1.82939E-08	2.98806E+15
0.4	0.012737	0.063478	0.001837	0.032597	1.81787E-08	3.02604E+15
0.5	0.012458	0.062949	0.001933	0.032402	1.81377E-08	3.03973E+15
0.6	0.012031	0.062584	0.001922	0.032401	1.80266E-08	3.0773E+15
0.7	0.01184	0.062109	0.00179	0.032412	1.78766E-08	3.12917E+15
0.8	0.01161	0.061765	0.001798	0.032359	1.78046E-08	3.15454E+15
0.9	0.011527	0.061475	0.001787	0.032454	1.7668E-08	3.2035E+15
1.0	0.01123	0.060978	0.001745	0.032367	1.75676E-08	3.24023E+15
1.1	0.011082	0.060432	0.001828	0.032468	1.73584E-08	3.31881E+15
1.2	0.010968	0.060216	0.001753	0.032333	1.73648E-08	3.31635E+15
1.3	0.010854	0.059695	0.001898	0.032387	1.71907E-08	3.38388E+15
1.4	0.010738	0.059353	0.001812	0.032302	1.71335E-08	3.40651E+15
1.5	0.010586	0.058919	0.001834	0.03231	1.70035E-08	3.45877E+15
1.6	0.010489	0.058504	0.001813	0.032206	1.69374E-08	3.48583E+15
1.7	0.010544	0.058123	0.001783	0.032284	1.67872E-08	3.54848E+15
1.8	0.010325	0.057854	0.001791	0.032218	1.67415E-08	3.56791E+15
1.9	0.010332	0.057559	0.001657	0.032229	1.66464E-08	3.60877E+15
2.0	0.010296	0.057191	0.001696	0.032171	1.65719E-08	3.64131E+15
2.1	0.010208	0.056892	0.001763	0.032255	1.6444E-08	3.69814E+15
2.2	0.010149	0.05648	0.001902	0.032241	1.63368E-08	3.74683E+15
2.3	0.010271	0.056211	0.001788	0.032304	1.62262E-08	3.79808E+15
2.4	0.010272	0.055886	0.001801	0.0322	1.61862E-08	3.81692E+15
2.5	0.010164	0.055505	0.001816	0.032209	1.60712E-08	3.87171E+15
2.6	0.010287	0.05519	0.001715	0.032152	1.60076E-08	3.90255E+15
2.7	0.010314	0.054975	0.001768	0.03223	1.59095E-08	3.95079E+15
2.8	0.010402	0.054795	0.001764	0.03232	1.58149E-08	3.99824E+15
2.9	0.010355	0.054423	0.001735	0.032315	1.57092E-08	4.05222E+15
3.0	0.010477	0.05408	0.001835	0.032414	1.55691E-08	4.12548E+15
3.1	0.010449	0.053879	0.001778	0.032433	1.55E-08	4.16231E+15
3.2	0.010567	0.05349	0.001802	0.03246	1.53793E-08	4.22794E+15
3.3	0.010739	0.053226	0.001757	0.032388	1.53392E-08	4.25007E+15
3.4	0.010781	0.052965	0.001725	0.032358	1.52782E-08	4.28404E+15
3.5	0.010844	0.05273	0.001786	0.032398	1.5196E-08	4.33055E+15
3.6	0.010881	0.052479	0.001837	0.032365	1.51428E-08	4.36104E+15
3.7	0.011064	0.052208	0.001701	0.032335	1.50761E-08	4.39967E+15
3.8	0.011224	0.051944	0.001678	0.032321	1.50085E-08	4.43941E+15
3.9	0.011326	0.051789	0.001928	0.032448	1.49189E-08	4.49289E+15
4.0	0.011569	0.051498	0.001857	0.032323	1.48946E-08	4.50759E+15
4.1	0.011586	0.051248	0.001787	0.032448	1.47625E-08	4.58863E+15
4.2	0.011692	0.051194	0.001759	0.032375	1.47807E-08	4.57729E+15
4.3	0.011716	0.050782	0.001754	0.032487	1.46125E-08	4.68331E+15
4.4	0.012019	0.05064	0.001709	0.03243	1.46E-08	4.69134E+15
4.5	0.012065	0.050561	0.001729	0.032413	1.4587E-08	4.69966E+15
4.6	0.012307	0.050095	0.001873	0.032499	1.44278E-08	4.80394E+15
4.7	0.012363	0.049933	0.001831	0.032481	1.43883E-08	4.83034E+15
4.8	0.012631	0.049689	0.001786	0.032536	1.42961E-08	4.89286E+15
4.9	0.01264	0.049463	0.00178	0.032434	1.42769E-08	4.90607E+15
5.0	0.012986	0.049305	0.001842	0.032443	1.42374E-08	4.93334E+15
5.1	0.013007	0.049185	0.001747	0.032437	1.42E-08	4.95936E+15

Table 4: CV Profiling Readings for Solar cell in dark condition

Voltage (Reverse bias)	V_x	V_y	V_{0x}	V_{0y}	C	$1/C^2$
0.1	0.013091	0.064163	0.03485	0.919926	6.49926E-10	2.3674E+18
0.2	0.012242	0.063664	0.034395	0.953296	6.21892E-10	2.58565E+18
0.3	0.011762	0.063273	0.035506	0.973046	6.05416E-10	2.7283E+18
0.4	0.011381	0.062818	0.037086	0.984432	5.94084E-10	2.83338E+18
0.5	0.011222	0.062348	0.036058	0.992129	5.84957E-10	2.92249E+18
0.6	0.010939	0.062007	0.035961	0.998155	5.78152E-10	2.99169E+18
0.7	0.010762	0.061644	0.035667	1.001225	5.72944E-10	3.04632E+18
0.8	0.010516	0.061208	0.036983	1.004203	5.67216E-10	3.10816E+18
0.9	0.010583	0.060756	0.036894	1.006254	5.61919E-10	3.16703E+18
1	0.010375	0.060437	0.037217	1.010317	5.56679E-10	3.22693E+18
1.1	0.010216	0.059901	0.036735	1.013312	5.50058E-10	3.30509E+18
1.2	0.010233	0.059613	0.036926	1.014102	5.47017E-10	3.34194E+18
1.3	0.010107	0.059223	0.0378	1.014343	5.43334E-10	3.38739E+18
1.4	0.010026	0.058892	0.037591	1.013105	5.40941E-10	3.41743E+18
1.5	0.010055	0.058522	0.037649	1.013746	5.37236E-10	3.46474E+18
1.6	0.010012	0.058146	0.036415	1.012654	5.34305E-10	3.50285E+18
1.7	0.009969	0.057886	0.03696	1.011684	5.32457E-10	3.52721E+18
1.8	0.010021	0.057432	0.037704	1.011671	5.2837E-10	3.58199E+18
1.9	0.00995	0.057094	0.03664	1.012235	5.24907E-10	3.6294E+18
2	0.010034	0.056767	0.036497	1.012946	5.21572E-10	3.67597E+18
2.1	0.009905	0.05647	0.03656	1.013959	5.18301E-10	3.72251E+18
2.2	0.009993	0.056185	0.036673	1.01432	5.15552E-10	3.76231E+18
2.3	0.010165	0.055908	0.03757	1.014075	5.13257E-10	3.79604E+18
2.4	0.010193	0.055529	0.036464	1.013502	5.10039E-10	3.84409E+18
2.5	0.010056	0.055203	0.036945	1.014566	5.06511E-10	3.89782E+18
2.6	0.010151	0.055	0.037399	1.015214	5.04394E-10	3.93061E+18
2.7	0.010373	0.054699	0.036317	1.015742	5.01403E-10	3.97765E+18
2.8	0.010386	0.05429	0.037219	1.016293	4.97464E-10	4.04088E+18
2.9	0.010387	0.054037	0.03724	1.015739	4.95435E-10	4.07405E+18
3	0.010495	0.053865	0.03684	1.016792	4.93368E-10	4.10826E+18
3.1	0.010672	0.053628	0.036674	1.017515	4.9091E-10	4.14951E+18
3.2	0.010727	0.053364	0.038196	1.017039	4.8885E-10	4.18454E+18
3.3	0.010767	0.053074	0.037259	1.017764	4.85822E-10	4.23687E+18
3.4	0.010993	0.052868	0.038737	1.016987	4.8449E-10	4.2602E+18
3.5	0.011019	0.052431	0.038755	1.018714	4.79708E-10	4.34556E+18
3.6	0.011263	0.052171	0.037371	1.017697	4.77822E-10	4.37994E+18
3.7	0.011246	0.052075	0.037719	1.016042	4.77747E-10	4.3813E+18
3.8	0.011466	0.051822	0.036745	1.01531	4.75797E-10	4.41729E+18
3.9	0.011516	0.051577	0.037938	1.014873	4.73869E-10	4.45331E+18
4	0.011686	0.051439	0.037219	1.013829	4.73109E-10	4.46764E+18
4.1	0.01167	0.051177	0.037457	1.013423	4.7092E-10	4.50926E+18
4.2	0.011816	0.050939	0.036812	1.011873	4.69473E-10	4.53711E+18
4.3	0.01197	0.050712	0.036725	1.011532	4.67602E-10	4.57349E+18
4.4	0.012084	0.050418	0.037047	1.010806	4.65312E-10	4.61861E+18
4.5	0.012365	0.050331	0.037158	1.010114	4.64939E-10	4.62602E+18
4.6	0.01251	0.050115	0.037017	1.009285	4.63382E-10	4.65717E+18
4.7	0.012632	0.049889	0.036924	1.008764	4.61585E-10	4.69351E+18
4.8	0.012785	0.049682	0.036724	1.008057	4.60046E-10	4.72495E+18
4.9	0.013027	0.049366	0.036424	1.007818	4.57312E-10	4.78162E+18
5.0	0.013126	0.049339	0.036062	1.007857	4.57047E-10	4.78715E+18
5.1	0.013338	0.049106	0.037237	1.007819	4.551E-10	4.8282E+18